การหาปริมาณน้ำในดินด้วยวิธีหยั่งลึกลงดินเรดาร์ ในศูนย์เครือข่ายการเรียนรู้เพื่อภูมิภาค จุฬาลงกรณ์มหาวิทยาลัย จังหวัดสระบุรี

นายศุภณัฐ คุ้มโหมด

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2557

DETERMINATION OF SOIL WATER CONTENT BY GROUND PENETRATING RADAR METHOD IN THE CENTER OF LEARNING NETWORK FOR THE REGION, CHULALONGKORN UNIVERSITY, CHANGWAT SARABURI

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A Thesis Submitted in Partial Fulfillment of the Requirements
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การหาปริมาณน้ำในดินเชิงปริมาตรมีความสำคัญในศาสตร์หลายๆ ด้าน เช่น เกษตรกรรม อุทกวิทยา นิเวศวิทยา เป็นต้น โดยทั่วไปการหาปริมาณน้ำในดินเชิงปริมาตรมีได้หลายวิธี เช่น การชั่งน้ำหนัก การใช้เครื่องวัดโดยใช้หลักการสะท้อนในโดเมนเวลาหรือทีดีอาร์ การใช้เครื่องวัดแบบคาปาซิแตนซ์ เป็นต้น ในงานวิจัยนี้สนใจที่จะนำเครื่องหยั่งลึกลงดินเรดาร์มาใช้หาปริมาณน้ำในดินเชิงปริมาตรในพื้นที่ศึกษาที่เป็นดินร่วน ซึ่งอยู่ในศูนย์เครือข่ายการเรียนรู้เพื่อภูมิภาค จุฬาลงกรณ์มหาวิทยาลัย จังหวัดสระบุรี ประเทศไทย ความถี่ของเครื่องหยั่งลึกลงดินเรดาร์ที่ใช้เท่ากับ 400 และ 900 เมกะเฮิรตซ์ เทคนิคที่ใช้คือการสำรวจแบบระยะคงที่โดยใช้คลื่นดินซึ่งมีระยะห่างระหว่างตัวส่งสัญญาณและตัวรับสัญญาณสำหรับแต่ละความถี่เป็น 1.00 เมตร และ 0.405 เมตร ตามลำดับ โดยการหาค่าคงที่ไดอิเล็กตริกของดิน ค่าที่ได้จะถูกนำไปแปลงเป็นปริมาณน้ำในดินเชิงปริมาตรด้วยสมการของท็อป ผลลัพธ์ที่ได้จากเครื่องหยั่งลึกลงดินเรดาร์นั้นจะนำไปเปรียบเทียบกับผลที่ได้จากการชั่งน้ำหนักที่วัดจากตัวอย่างดินที่เก็บที่ความลึกต่างกัน (10, 20 และ 30 เซนติเมตร) นอกจากนี้ยังมีการเปรียบเทียบผลของการตรวจวัดปริมาณน้ำในดินที่ต่างกันเนื่องมาจากการเปลี่ยนแปลงตามเวลา ผลลัพธ์ที่ได้สำหรับเครื่องหยั่งลึกลงดินเรดาร์ความถี่ 400 เมกะเฮิรตซ์ คือ ในสภาวะแล้งมีค่าสหสัมพันธ์ที่สูงเทียบกับวิธีการชั่งน้ำหนักในช่วงความลึก 10 ถึง 30 เซนติเมตร ในช่วงของค่าปริมาณน้ำในดินเชิงปริมาตรที่ร้อยละ 10 ถึง 15 ในสภาวะชื้นผลลัพธ์มีความน่าเชื่อถือในช่วงความลึก 10 ถึง 20 เซนติเมตร ในช่วงของค่าปริมาณน้ำในดินเชิงปริมาตรที่ร้อยละ 30 ส่วนความถี่ 900 เมกะเฮิรตซ์นั้น ผลลัพธ์ที่ได้ไม่สอดคล้องกับผลลัพธ์ที่ได้จากการชั่งน้ำหนัก แต่มีความสัมพันธ์ที่ดีขึ้นในสภาวะแห้ง ในส่วนของการทดลองการเปลี่ยนแปลงเทียบกับเวลา ผลลัพธ์ของความถี่ 400 เมกะเฮิรตซ์ เห็นการเปลี่ยนแปลงเทียบกับเวลา แต่สำหรับความถี่ 900 เมกะเฮิรตซ์ ไม่เห็นการเปลี่ยนแปลง ดังนั้นเครื่องหยั่งลึกลงดินเรดาร์มีความเหมาะสมในการหารปริมาณน้ำในดินเชิงปริมาตรเนื่องมาจากความสะดวกในการเก็บข้อมูลและประมวลผลข้อมูล นอกจากนี้ผลลัพธ์ที่ได้จากเครื่องวัดแบบคาปาซิแตนซ์ไม่สอดคล้องกับผลจากการชั่งน้ำหนักเนื่องมาจากข้อจำกัดในการทดลอง

ภาควิชา ธรณีวิทยา	ลายมือชื่อนิสิต ....
สาขาวิชา โลกศาสตร์	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
ปีการศึกษา 2557	

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KEYWORDS: VOLUMETRIC SOIL WATER CONTENT / GPR / GROUND WAVE

SUPPANUT KUMMODE: DETERMINATION OF SOIL WATER CONTENT BY GROUND PENETRATING RADAR METHOD IN THE CENTER OF LEARNING NETWORK FOR THE REGION, CHULALONGKORN UNIVERSITY, CHANGWAT SARABURI. ADVISOR: ASST. PROF. THANOP THITIMAKORN, Ph.D., 67 pp.

Determination of volumetric soil water content (VSWC) is essential in many fields such as agriculture, hydrology, and ecology, etc. Currently, there are several methods to determine VSWC for example gravimetric, time-domain reflectrometry (TDR), capacitance probe methods, etc. In this research, ground penetrating radar (GPR) was used to determine VSWC of a loamy soil at experimental field in the center of learning network for the region, Chulalongkorn University, Changwat Saraburi, Thailand. The GPR was set up in the ground wave fixed offset method with 400 and 900 MHz central frequency antennas, which have transmitter and receiver offsets of 1.00 m and 0.405 m, respectively. By estimate the relative dielectric permittivity of soils, these values were converted to VSWC by Topp's equation. The results of VSWC calculated from soil samples at different depths (10, 20 and 30 cm) were used as the references. Besides, there were three experiments to see how GPR can detect variation of VSWC with times. The results revealed that GPR 400 MHz has high correlation with gravimetric method at dry condition at depth of 10 to 30 cm with VSWC about 10 to 15%. And at wet condition, the result is reasonable at depth 10 to 20 cm with VSWC around 30%. GPR 900 MHz is not related to gravimetric method but the results are looked well in dry condition. In the time monitoring of VSWC, the results of GPR 400 MHz in three experiments changed with time, but not for GPR 900 MHz. So, GPR method is appropriate for estimating VSWC due to the easy of data acquisition and processing. In addition, the soil water content from capacitance probe was not reliable when comparing to the VSWC from gravimetric method due to the limitation of experiment.

Department: Geology — Student's Signature ....
Field of Study: Earth Sciences — Advisor's Signature ....
Academic Year: 2014

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I would like to thank my fellow students Mr. Prayot Puangjakta, Mr. Watcharapol Seeyangnok, Mr. Noppadol Yoojam, Mr. Irapot Saengrayab, Miss Ratchadaporn Jintaprasat for the assistance and the friendship. Because of their well and full supporting, every field surveying was success. I would like to thank my old friend, Miss Porntip Jaimun, who took care of the studying in this program, helped for experiment in laboratory, and advised for electronic thesis writing.

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LIST OF ABBREVIATIONS

CLNR	: Center of Learning Network for the Region
EMW	: Electromagnetic Wave
FO	: Fixed Offset
GPR	: Ground Penetrating Radar
RMSE	: Root Mean Square Error
Rx	: Receiving Antenna
TDR	: Time Domain Reflectrometry
Tx	: Transmitting Antenna
VSWC	: Volumetric Soil Water Content
WARR	: Wide Angle Reflection and Refraction

CHAPTER 1
INTRODUCTION

1.1 Background

Knowledge about determining soil water content in root zone, which is in term of vadose zone or unsaturated zone, is important in many fields including soil science, hydrology, ecology, etc. because they provide the data of spatial distribution of water at land subsurface. Example in hydrology, soil water content has a relationship with water cycle system that is a part of infiltration at land surface and land-atmosphere interaction (Entekhabi et al., 1996), and also needed in order to improve discharge prediction in hydrological model of small-scales basin (Pauwels et al., 2001). In agriculture, soil water data is needed for irrigation planning. Much or less water has influence for crop yields, so accurate irrigation planning is important for limited agricultural field. Besides, there is an application of determining soil water content that influences the infiltration in sub-asphalt soil of pavement layers (Grote et al., 2005). So, an accurate soil water content estimation is important and still has been researching.

There are many methods for determining soil water content. Gravimetric is a basic point measurement method which is simple but time consuming, and invasive sampling, so many methods were created in order to reduce those disadvantages. Each methods have different resolution of measurement and observation scale, e.g. for large scale, remote sensing is an admirable surveying method. Either air borne or space borne can observe in large scale but low depth of investigation. For small to field scale, point-measurement sensors are conventional methods such as neutron probe, time domain reflectrometry (TDR), capacitance probe. By the development of petrophysics, a relationship of soil dielectric constant and volumetric soil water content (VSWC) makes more accurate in-situ soil moisture measurement (Topp et al., 1980). Although they provide accurate spatial soil moisture information, they are invasive sampling, and not suitable in large scale measurements because of tedious and time-consuming, and sometimes need a permanent installation for monitoring. So, geophysical methods are offered a non-invasive measurement with faster than conventional sensors. These methods are; such as resistivity (Samouelian et al., 2005), electromagnetic induction (Doolittle and Brevik, 2014), or using electromagnetic wave (EMW) such as ground penetrating radar (GPR) technique which has been developing for last decades.

GPR is a geophysical method which uses high-frequency EMW. Transmitter antenna (Tx) of GPR send an EMW signal into mediums with different properties, then signal reflects or refracts to receiver antenna (Rx) and will be analyzed. One property of medium that is significant for effecting GPR signals is the dielectric permittivity. Liquid water has the dielectric permittivity, as a function of temperature; about 80 at 20°C while air has 1, and dry loamy soil is about 4 to 6, so the large contrast of dielectric constant of water and other geologic materials results the appropriate technique for measuring the VSWC by EMW, i.e. GPR. However, the accurate estimation of VSWC is required the appropriate petrophysical relationship between VSWC and dielectric permittivity of soil.

The configurations of GPR surveying are also important because of the different accuracy and resolution that depends on frequency of signals, ray paths, soil conditions, advantage of technology, etc (Jol, 2009). Suitable surveying technique and data processing is required for accuracy VSWC estimating to provide high quality data as conventional methods.

1.2 Research Objectives

1. Determining of VSWC in the center of learning network for the region, Chulalongkorn University, Changwat Saraburi, and compared with time variation.

2. Developing appropriate data acquisition, processing and interpretation methods of GPR for determining VSWC.

3. Evaluating a capability of using GPR for determining VSWC compared with a direct method.

1.3 Scope of the Study

This research aims for determining VSWC with GPR of study area in the center of learning network for the region, Chulalongkorn University, Changwat Saraburi. The results will be compared with conventional measurement for developing appropriate data acquisition, processing and interpretation methods of GPR for using in other study area.

1.4 Benefits

1. VSWC of study area in the center of learning network for the region, Chulalongkorn University, Changwat Saraburi, that compared with different time.

2. An appropriate data acquisition, processing and interpretation methods of GPR for determining VSWC.

3. A capability of using GPR for determining VSWC compared with a direct method.

CHAPTER 2

LITERATURE REVIEW

2.1 Conventional Method

There are many methods for determining soil water content which have advantages for each objective and conditions. In small scale, gravimetric is a conventional point-measurement method that is a dry soil weighting, baked with 105 to 110°C for 24 hr (or until definitely dry). Then compared it with the weight of fresh soil, and calculated for soil water content as equation below.

$$\theta_m = \frac{m_w}{m_s} \tag{2.1}$$

which θ_m is gravimetric soil water content (dimensionless)

m_w is mass of soil water (g)

m_s is mass of dry soil (g)

Gravimetric soil water content can be converted to VSWC with

$$\theta_V = \theta_m \frac{\rho_b}{\rho_w} \tag{2.2}$$

which θ_V is volumetric soil water content (dimensionless)

ρ_b is bulk density of dry soil ($g.cm^{-3}$)

ρ_w is density of water ($g.cm^{-3}$)

The accurate value of bulk density of dry soil and density of water are very important for the correct conversion. That is needed a carefully undisturbed sampling.

This method is simple, accurate but tedious, time-consuming, invasive sampling and point-measurement. By using physics principle, many sensors were developed to be easy to use by putting their probe in to measurement point. For example, neutron probe, using radioactive principle, sends neutrons to react with hydrogen atom of soil water, and count for reaction events. TDR, using electromagnetic principle, propagates a high-frequency electromagnetic pulse along probes into soil for detecting amplitude that changed with time from reflection events (Robinson et al., 2003). Capacitance sensor, like capacitor in electrical circuit, has probe that is like plate of capacitor and soil is like dielectric material, i.e. the different of soil's dielectric constant makes different of electrical capacity (Francesca et al., 2010).

Both TDR and capacitance sensor are dependent on the dielectric constant of medium around the probes that be converted to VSWC by petrophysical relationship. In 1980, Topp determined relationship between VSWC and relative dielectric permittivity of various mineral soil textures ranging from clay to sandy loam. By using TDR to measure the dielectric constant of soil samples, the most common equation was proposed to

$$\theta = 4.3\times10^{-6}\varepsilon_r^3 - 5.5\times10^{-4}\varepsilon_r^2 + 2.92\times10^{-2}\varepsilon_r - 5.3\times10^{-2} \quad (2.3)$$

which θ is volumetric soil water content (dimensionless)

ε_r is relative dielectric permittivity of soil (dimensionless)

These sensors are handily and non-invasive but the probe size (i.e., in order to few decimeters) result to the small volume of measurement (i.e., cm^3), so they are point-measurement like gravimetric. In large scale, remote sensing, both air borne and space borne, use EMW in the band of radio wave, infrared and visible light. The advantage is large scale surveying in small time but has low resolution data and be simply disturbed. So, alternative method has researched for last decade to reduce those disadvantages, i.e. GPR, which suits for small to field scale and has acceptable accuracy for estimating VSWC with larger volumes of soil sampling (i.e., dm^3 to m^3) than standard point measurement (e.g., (Galagedara et al., 2005; Grote et al., 2003; Hubbard et al., 2002; Huisman et al., 2003; Weihermuller et al., 2007).

2.2 Ground Penetrating Radar

GPR is a geophysical method which uses high-frequency EMW in radar range (microwave band of radio spectrum). It was designed for the shallow subsurface investigation such as earth, construction, roads, etc. GPR is a time-domain geophysical technique which can illustrate a three dimensional image of the subsurface and can estimate an accurate depth of subsurface objects.

GPR equipment generally consists of antennas, electronics device, and recording device. The operation of GPR system can be shown as a diagram in figure 2.1. GPR transmitted a wave that is composed of multiple frequencies in finite time duration (i.e., a pulse of EMW energy). Transmitting antenna (Tx) propagate a pulse of wave into subsurface with a particular amplitude and velocity. EMW is radiated through medium with spherical wavefront spreading. Some electrical properties of medium have significant affected to the energy (amplitude and velocity) of EMW, i.e. the dielectric permittivity. With different velocity, the signals are arrived to receiving antenna (Rx) at different times. So, Rx records a changing of signal amplitude and travel time of pulse.

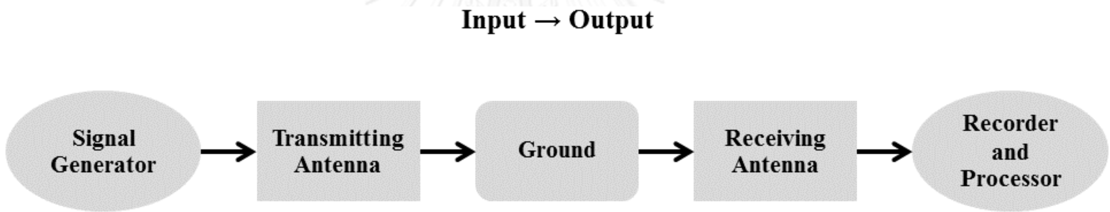


Figure 2.1 Diagram of the operation of GPR system
(Modified from (Allred et al., 2008).

The dielectric permittivity or dielectric constant is directly related to the velocity of EMW propagated in medium by the following relationship.

$$v_m = \frac{c}{\sqrt{\frac{\varepsilon_m}{\varepsilon_0}}} \tag{2.1}$$

which v_m is velocity of EMW through any material ($m.s^{-1}$)

c is speed of light in free space (299,792,458 $m.s^{-1}$)

ε_m is the dielectric permittivity of the material ($Farads.m^{-1}$)

ε_0 is the dielectric permittivity in free space (8.85×10^{-12} $Farads.m^{-1}$)

The ratio of the dielectric permittivity of the material to the dielectric permittivity of free space is called the relative dielectric permittivity

$$\varepsilon_r = \frac{\varepsilon_m}{\varepsilon_0} \quad (2.2)$$

which ε_r is relative dielectric permittivity of the material (dimensionless)

ε_m is the dielectric permittivity of the material (Farads.m^{-1})

ε_0 is the dielectric permittivity in free space (8.85 × 10^{-12} Farads.m^{-1})

The range of values of relative dielectric permittivity is from 1 for air, about 16 for average soil, and about 81 for water, as table 2.1. The high dielectric constant of water, caused by the polarization of the water molecule, dominates to the affecting of reducing the velocity of EMW. The large contrast of dielectric constant of water and other geologic materials results the appropriate technique for measuring the VSWC by EMW, i.e. GPR.

EMW traveled from Tx with some different paths to Rx. The first signal arrived to Rx is the wave travels directly through the air because the velocity of EMW in air is greater than any material, i.e. called air wave (figure 2.2). The second signal is the pulse that travels through the material along subsurface, i.e. called ground wave, which is slower than air wave because of the dielectric permittivity of materials. The Later are the waves that reflected and refracted at the surface layer of different materials.

Rx records pulses over a period of time called a trace that includes all of ray paths, as shown in figure 2.3. Color or gray scale can be applied to the amplitude values for investigating that is called a scan.

Table 2.1 The relative dielectric permittivity of materials and radiowave velocities (Reynolds, 2011).

Material	ε_r	v (mm.ns^{-1})
Air	1	300
Water (fresh)	81	33
Sand (dry)	3 - 6	122 - 173
Sand (wet)	10 - 32	53 - 95
Silt (unsaturated)	2.5 - 5	134 - 190
Silt (saturated)	22 - 30	55 - 64
Clay (dry)	2 - 5	134 - 212
Clay (wet)	8 - 40	47 - 106
Agricultural Land	15	77
Average Soil	16	75
Granite	5 - 8	106 - 120
Basalt (wet)	8	106
Concrete	4 - 30	55 - 150
Asphalt	3 - 5	134 - 173
PVC, Epoxy, Polyesters	3	173

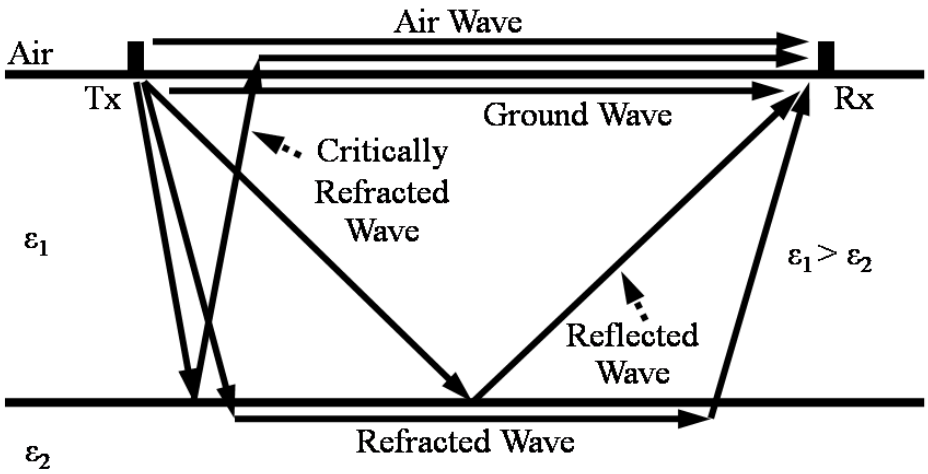
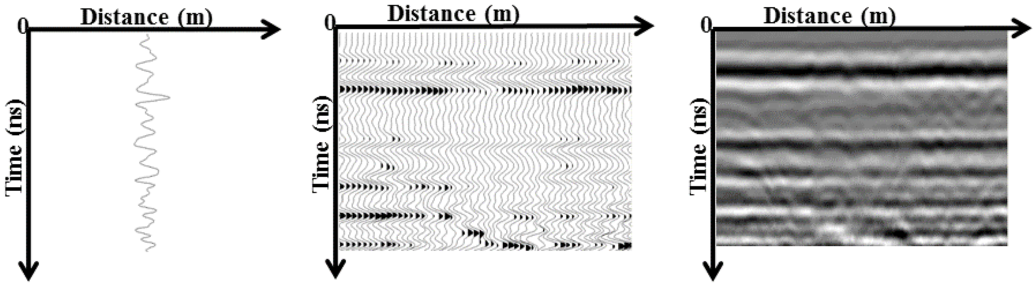


Figure 2.2 Ray paths of EMW travel from Tx to Rx along two layers of soil with contrast dielectric constants (Modified from (Huisman et al., 2003).



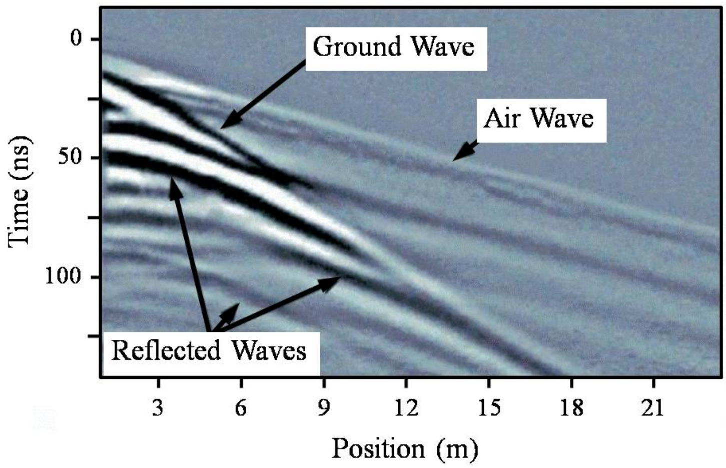
(a) (b) (c)

Figure 2.3 (a) a single trace. (b) multiple traces along the survey distance. (c) multiple traces with gray scale applied.

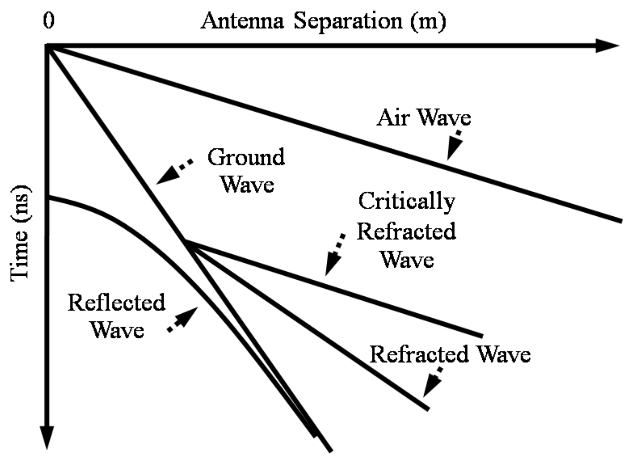
Graphs between travel time of wave and antenna separation are shown in figure 2.4 which (a) is signal display and (b) is schematic display. Figure 2.4 (b) shows that air wave come to Rx earlier than ground wave because it propagates in air, and both waves have straight line graph with different slope. Reflected wave is shown as hyperbola which does not use in this research.

To estimate the VSWC from GPR data, variable such as travel time, speed, amplitude of GPR signal are calculated to find the relative dielectric permittivity of soil, and then convert it to VSWC by using Topp's equation. There are many configurations of surveying with different advantages and conditions depend on each of variation, including: frequency, such as 100 450 or 900 MHz. The depth penetration of GPR signal depends on its frequency. In general, higher frequency gives higher resolution of data but lower depth of penetration.

Configuration of equipment affects speed of surveying and results. Many researchers used ground wave with different configuration depends on soil type and their instruments, such as on-ground surveying (Grote et al., 2003; Huisman et al., 2002), off-ground surveying (Ardekani, 2013; Weihermuller et al., 2007), or borehole surveying (Wijewardana and Galagedara, 2010), etc. In 2003, Huisman et al. reviewed four methods of GPR estimating VSWC namely 1) reflected wave, 2) ground wave, 3) transmitted wave, 4) surface reflection coefficient. Choosing appropriate methods depends on the survey objectives. There were many hypothesis, for example, consideration on time variation of VSWC (Grote et al., 2005), horizontal or vertical spatial variation (Grote et al., 2010; Grote et al., 2003; Huisman et al., 2002; Weihermuller et al., 2007), soil type or climate influence (Steelman and Endres, 2009), drainage and irrigation influence (Galagedara et al., 2003; Galagedara et al., 2005; Wijewardana and Galagedara, 2010), etc.



(a)



(b)

Figure 2.4 Display of EMW ray paths that propagate to Rx. (a) Signal display. (b) Schematic display (Modified from (Huisman et al., 2003).

All four methods have some pros and cons. For reflected wave, detecting the reflection of wave from contrast medium with different dielectric constant to read time travel and calculate wave speed in each medium, and then convert to dielectric constant. It cannot valid for vertical heterogeneous medium because of variation of speed. Besides, configuration called multi offset use so much time. For transmitted wave, Tx and Rx are installed in boreholes and propagates wave through medium between them. Like reflected wave, time travel are used to calculated dielectric constant, and this method can build the tomographic by analyzed many results. Disadvantages are the effect of reflected and refracted wave which make hardly wave classified, and making borehole is very tedious and time consuming. For surface reflection coefficient, GPR are lifted above ground liked remote sensing, and detect changed amplitude from surface reflection. The instruments can attached to vehicle and mobile along field, but quality of signal will be reduced by rough surface. This research chooses ground wave technique which using time travel of ground wave to calculate the dielectric constant of the ground. Tx and Rx offset is fixed at constant separation, as shown if figure 2.5 (a). To find dielectric constant, time travel of air wave and ground wave, assumed that travel in straight line between antennas, are required as an input in the equation (2.4) of EMW velocity and dielectric constant (Weihermuller et al., 2007).

$$\varepsilon_{Soil} = \left(\frac{c}{v}\right)^2 = \left(\frac{c(t_{GW} - t_{AW}) + x}{x}\right)^2 \qquad (2.4)$$

which ε_{Soil} is relative dielectric permittivity of soil (dimensionless)

c is speed of light in free space (299,792,458 m.s^{-1})

t_{GW} is ground wave travel time (s)

t_{AW} is air wave travel time (s)

x is travel displacement of air and ground wave that is equal to antenna separation (m)

Then dielectric constant will be converted to VSWC by an appropriate petrophysical relationship which can be determined by using the GPR field-calibration or by previous relationship. It's not easy to perform an accuracy calibration at study area due to the amount of auxiliary measurement. Despite it may be the most accurate because of the specific of site. So, previous established petrophysical relationship is often used to estimate VSWC from GPR measurements; e.g., Topp's equation (Galagedara et al., 2005; Weihermuller et al., 2007).

The main disadvantages in using ground wave are: 1) it attenuates faster than other waves (Du and Rummel, 1994). 2) It does not suit for soil with dominant silt and clay because of high electric conductivity that strongly attenuate EMW (Weihermuller et al., 2007). 3) The difficulty of observing the separation between ground wave and air wave. From figure 2.4 (b), air wave and ground wave are straight line with same origin. At short antenna separation, or in dry soil (ground wave velocity is fast), their signal may too close so that the interference is occurred and hard to identify (Grote et al., 2003; Hubbard et al., 2002). At large antenna separation, ringing effect of air wave may be appeared in the data. Consequently, proper antenna separation is important for this surveying technique. By using surveying called wide angle reflection and refraction (WARR), i.e. multi offset reflected wave method, Tx is fixed and Rx is moved away with signal transmitted every move, as shown in figure 2.5 (b), and the result shown in figure 2.4 (a). From this graph, properly antenna separation can be chosen. Besides, WARR can approximate an influent depth of GPR. Du (1996) suggested that the influent depth of GPR is about half of wavelength, as shown in equation below.

$$\lambda = \frac{v}{f} \tag{2.5}$$

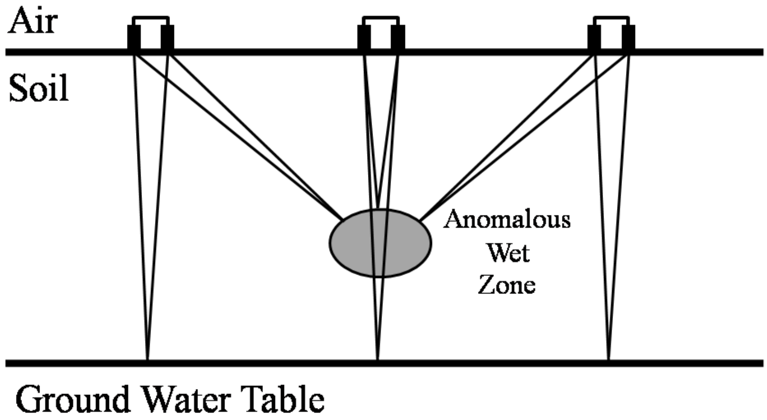
which λ is wavelength of ground wave (m)

v is speed of ground wave in soil ($m.s^{-1}$)

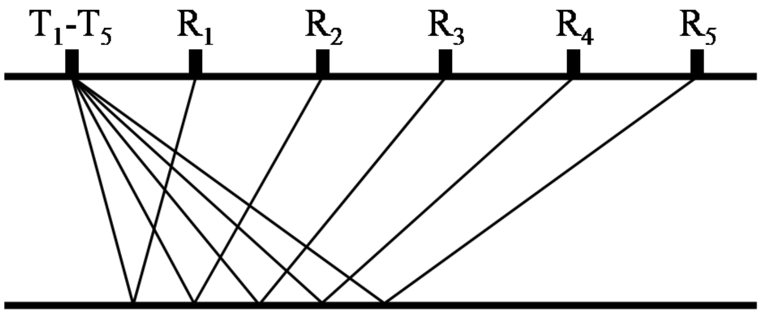
f is central frequency of GPR (Hz or s^{-1})

As seen that the wavelength is a function of ground wave speed which depends on dielectric permittivity of medium. So, the influent depth of GPR also depends on dielectric permittivity of soil (i.e. the amount of VSWC).

In this research, ground wave fixed-offset (FO) technique is used with central frequency of 400 and 900 MHz compared to gravimetric and capacitance probe, and also consider in time variation of three events with different rainfall. The interesting of this research is there are many researches in many countries but never happened in Thailand before.



(a)



(b)

Figure 2.5 (a) FO acquisition, (b) WARR acquisition, where T is transmitter and R is receiver (Modified from Huisman et al., 2003).

CHAPTER 3
METHODOLOGY

3.1 Study Area

The study area is located in the center of learning network for the region (CLNR), Chulalongkorn University, Changwat Saraburi, central of Thailand (Figure 3.1). The experimental field has dimension of 10 m width and 20 m length which align on north-south direction. The south-west corner is at latitude 14° 31′ 14.5″ north and longitude 101° 2′ 7.1″ east, and altitude is 43 m above mean sea level. Geography of the experimental field is foot hill plain which has hill at the east. The rocks in the area are volcanic rocks such as rhyolite, andesite and volcanic breccia (Department of Mineral Resource, 2007). Soil series is slope complex. Climate is tropical savanna with average temperature of 28 to 29°C. Maximum rainfall has occurred on May to October. Land use is agriculture such as grass or corn.

Before the experiment, there was 50 cm tall grass in the field that is not comfortable for GPR method. So, tractor was used to clear the grass about 1 day before the data aquisition. Then stretched ropes with sticks were used to create 11 GPR lines, as illustrated in figure 3.2 and 3.3. There were 9 soil sampling points for determining the VSWC by gravimetric and capacitance sensor method. At each point, soil was sampled at each 10 cm depth to 30 cm. So, total soil samples are 27.

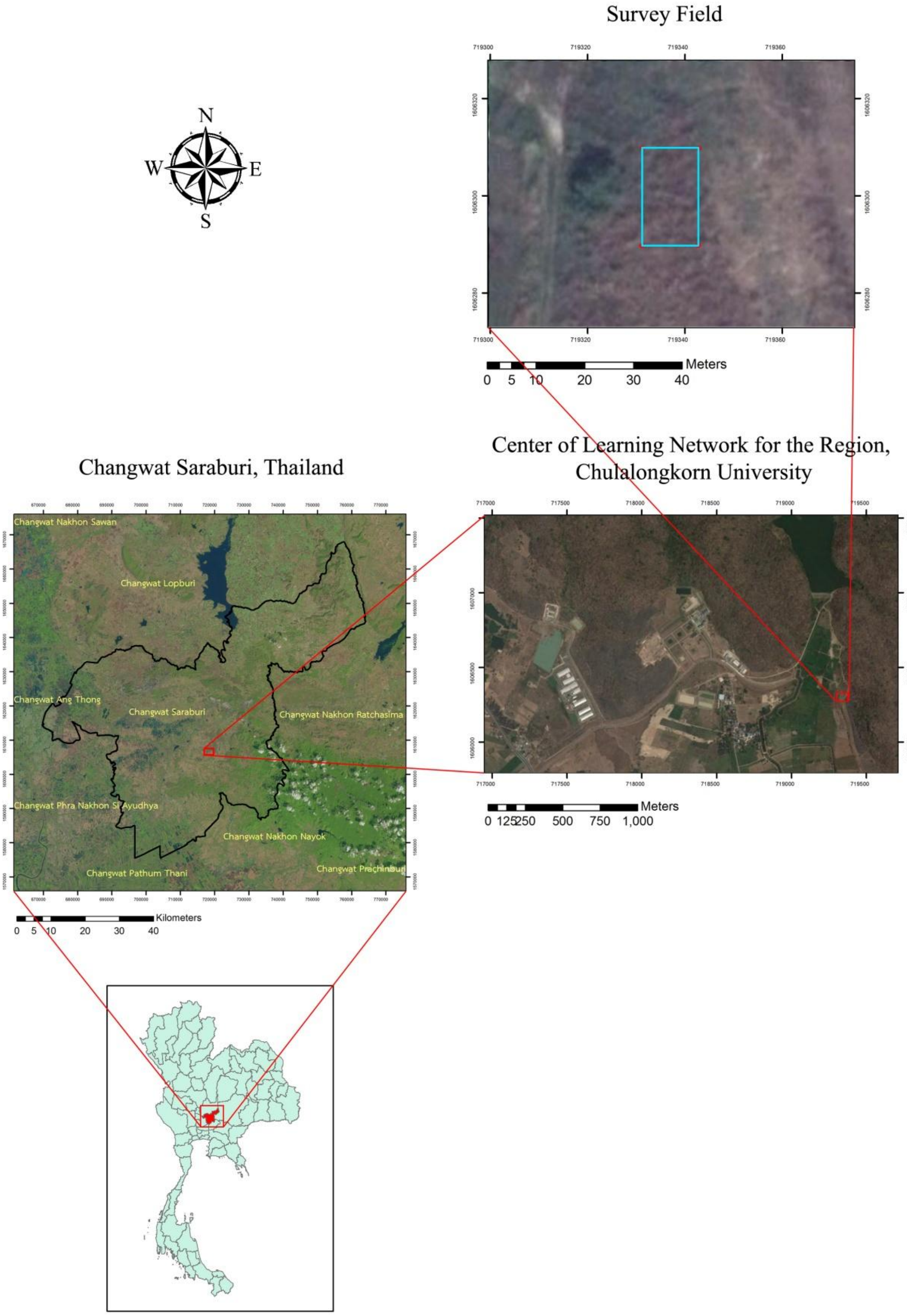


Figure 3.1 Blue rectangular shown a survey field in CLNR, Chulalongkorn University, Changwat Saraburi, Thailand.

Figure 3.2 Photo of survey field. Ropes stretched with sticks are survey guideline.

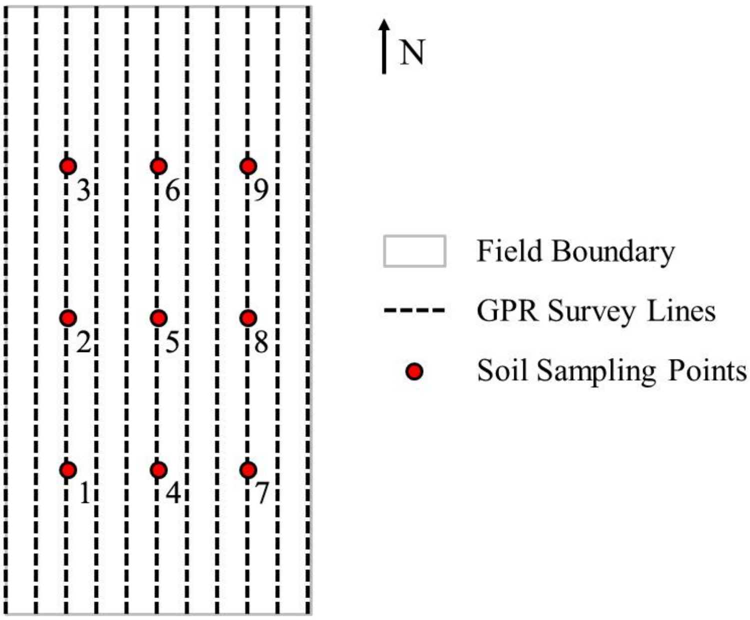


Figure 3.3 Schematic of GPR survey lines and soil sampling points.

Each soil sampling point had 3 samples with different depth (10, 20, and 30 cm). These samples were collected to estimate VSWC by conventional method. Some samples were sent to the Agricultural Production Science Research and Development Division, Department of Agriculture for soil texture classification using hydrometer method. Table 3.1 presents the percentage of sand, silt, and clay of soil at depth 10 20 and 30 cm. By using the standard of United States Department of Agriculture (USDA) as shown in figure 3.4, soil texture classification of all depth is a loamy soil which the sand particle decreases with depth, but silt and clay increase with depth. Density of soil is about 1.43 $g.cm^{-3}$ which estimated from mass of dry soil divided by volume. Because of the limitation of apparatus, soil samples were disturbed collected. So the bulk density which used to converted gravimetric soil water content to VSWC as equation (2.2) would not be accurately determined.

To see how GPR can detect variation of water content with times, three data acquisitions were conducted in different times in order to compare the derived water contents. The first experiment was on 29th July 2014 (rainy season), the second was on 23rd November 2014 (end of rainy season), and the third was on 10th February 2015 (winter). Every experiment day has no rainfall, but total rainfall of one month prior to the data acquisition day was shown in table 3.2, measured at S.9 (5445) station, Amphoe KaengKhoi, Changwat Saraburi (Royal Irrigation Department, 2015).

Table 3.1 Percentage of sand, silt, and clay of soil at depth 10 20 and 30 cm.

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

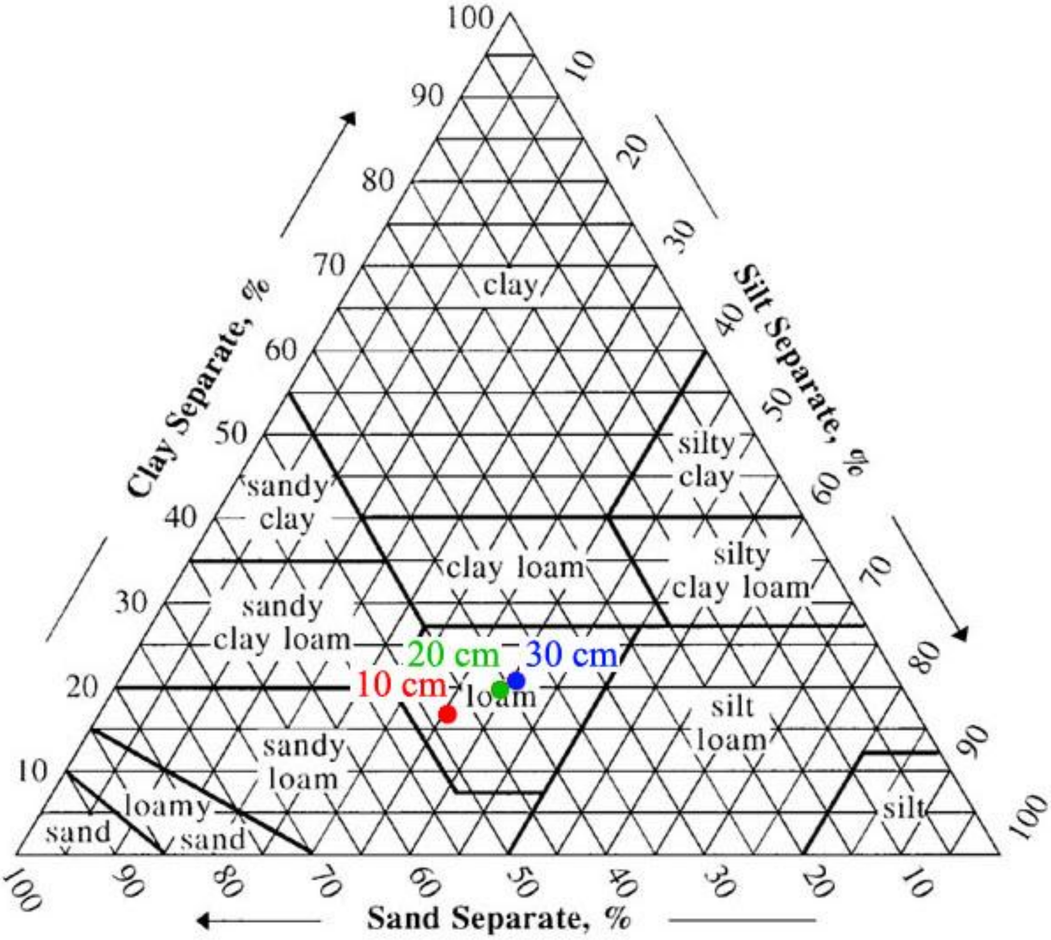


Figure 3.4 Soil classifications of 3 depth samples on the USDA soil texture classification triangle (red, green, blue dots). All three samples were plotted in the loamy soil type.

Table 3.2 Total rainfall for one month before experiment day, measured at S.9 (5445) station, Amphoe KaengKhoi, Changwat Saraburi (Royal Irrigation Department 2015).

Duration	Total Rainfall (mm)
29th June to 29th July 2014	107.4
22nd October to 23rd November 2014	94.6
9th January to 10th February 2015	0

3.2 Materials and Methods

3.2.1 Ground Penetrating Radar System

This research uses GSSI system with ground coupled antenna. This type of antenna contains both Tx and Rx within the same box and the housing or shield can be effectively protect noise from environment. Central frequency of 400 and 900 MHz are used which each frequency has two boxes because antenna separation of ground wave fixed offset technique is greater than GPR housing. So the front box is set to be Rx only, and the back is Tx only. To find properly antenna separation, results of WARR are required and will be explained in next chapter.

After getting the appropriate antenna separation from WARR data analysis, sledge was built by connecting two plastic boxes with wooden sticks, as shown in figure 3.5. There is towline in front of sledge and connect with distance calibrated survey-wheel in the back. At the front and back of the edges of sledge, the two curved PVC were installed to be a bumper. The plastic boxes should be firmly attached to the ground for reducing the effect of air and; making signal to be stable. Try to avoid using metal instruments because of the disturbance of signal. Wood, plastic and PVC have small dielectric constant approximately about 2 to 6 for wood, 2 to 3 for plastic, and 3 for PVC, so they are less disturbance.

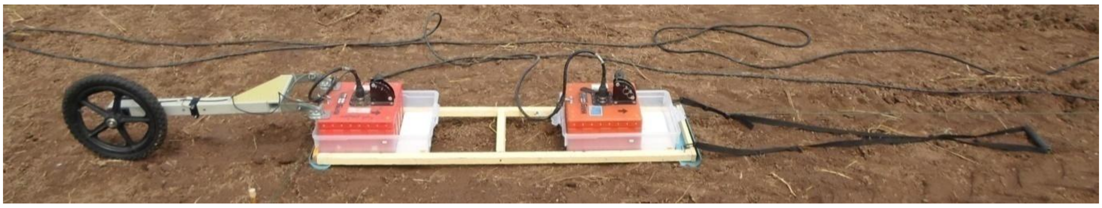


Figure 3.5 GPR 400 MHz on sledge. The separation of the Tx and Rx is 1 meter.

Software used for data collecting is SIR 20 with survey wheel data collection mode. Survey wheel at the back of sledge is used to calibrate distance by electronics device, e.g. encoder. When the wheel start rotating, Tx is trigged and send EMW pulse continually along the distance until the wheel stop. This research set the number of scan per distance about 100 scans per meter. Antenna on sledge in FO method was towed along eleven survey lines with walking speed (approximately 1.5

m.s^{-1}), as shown in figure 3.6. Then the data would be analyzed for the air wave and ground wave by processing software called RADAN 6.6.

Figure 3.6 GPR with FO method was towed along survey line for data collecting.

3.2.2 Gravimetric and Capacitance Probe

The results of GPR data were compared with gravimetric results of nine sampling points, and also capacitance probe. Soil samples were collected every 10 cm depth by hand auger immediately after GPR surveying. Because of the limitation of facilities, soil samples were disturbed collected and contained in plastic container for gravimetric in laboratory. But before that, the capacitance probe was inserted in the soil sample for estimating the VSWC right after collected with the auger, as figure 3.7.

Capacitance probe used in this study is EC-5 model. The probe is two prongs with dimension of 8.9 cm × 1.8 cm, connected to the ProCheck handheld reader of Decagon Devices (Figure 3.8) with manufacturer's calibration which has an accuracy at least 3% VSWC.

(a) (b)

Figure 3.7 (a) Soil samples were collected by hand auger.
(b) Using capacitance probe.

Figure 3.8 EC-5 sensor probe and ProCheck handheld reader
(Decagon Devices, 2015).

Every 27 soil samples were brought to laboratory to estimate VSWC by gravimetric technique. First of all, the soil samples were weight to find mass of wet soil. Then be baked in the oven (figure 3.9) with temperature of 105°C for 24 hrs. After cool down, they were weight again to find mass of dry soil. Gravimetric soil water content can be calculated by equation (2.1) and then converted them to VSWC by equation (2.1). The bulk density of soil is about 1.43 $g.cm^{-3}$, and the density of water is about 1 $g.cm^{-3}$.

(a) (b) (c)

Figure 3.9 Materials and apparatus used for gravimetric. (a) 27 of soil samples. (b) Scientific weighting scale. (b) Oven.

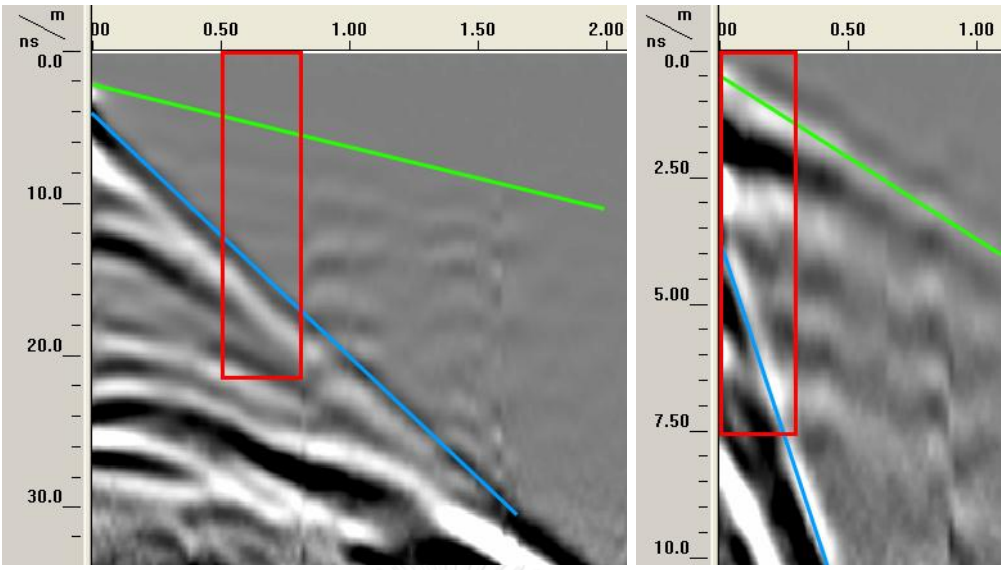
CHAPTER 4
RESULTS

4.1 Wide Angle Reflection and Refraction

Antenna separation is a key for ground wave fixed-offset technique because air wave and ground wave will be accurately identified. By using WARR, Tx is fixed at midpoint of study area and discretely moves Rx. For 400 and 900 MHz, moving distance of Rx is 2 cm and 1 cm respectively, and total distance is 4 and 2 m.

The result of WARR is shown in figure 4.1. For GPR 400 MHz (figure 4.1a), red rectangular shows the position of ground wave that clearly separated from air wave, which has antenna separation about 50 to 80 cm. In this study, antenna separation at 70 cm was selected, and then combined with size of GPR housing about 30 cm that is the nearest distance of two GPR boxes (Notice that signal line of air wave and ground wave do not convergent to origin). So a separation between Tx and Rx is 100 cm. For GPR 900 MHz (figure 4.1b), antenna separation of 8 cm was used. When combined with GPR housing about 32.5 cm, the final distance is 40.5 cm.

Besides, the results from WARR can be used to calculate the ground wave velocity and used to find the influent depth from equation 2.5. The approximately ground wave velocity of both frequency is 6.45×10^{7} $m.s^{-1}$. So, the influent depth of GPR 400 MHz and 900 MHz is about 0.08 m and 0.04 m, respectively.

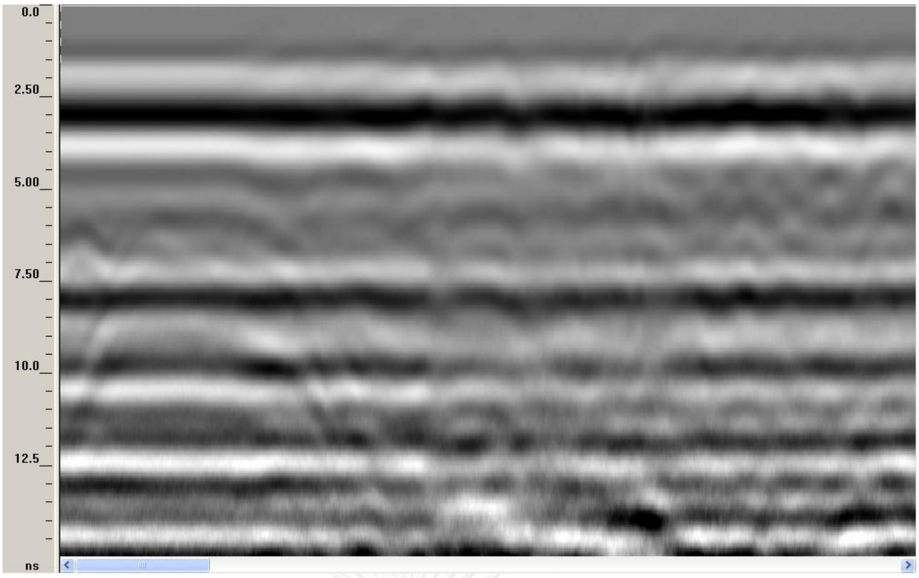


(a) (b)

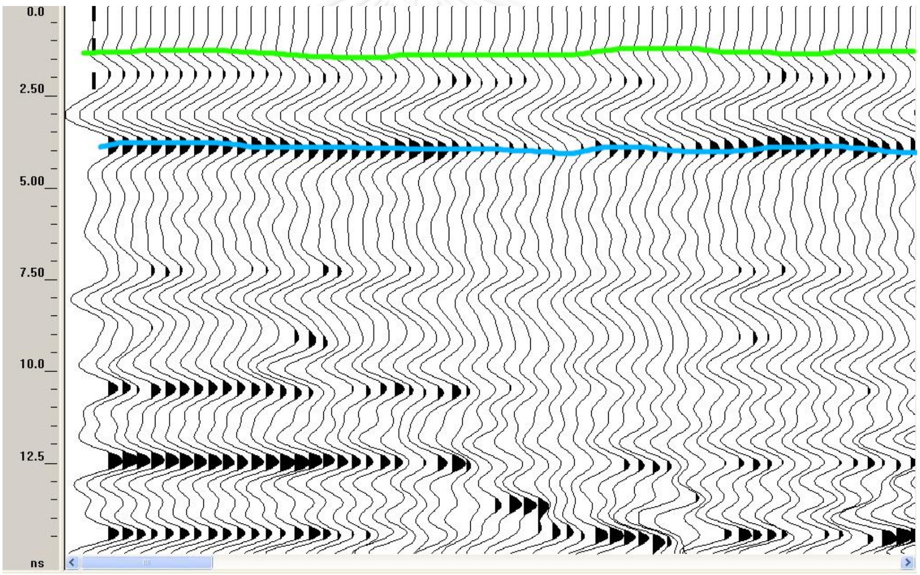
Figure 4.1 The results from WARR, red rectangular shown proper antenna separation that ground wave (blue line) separates from air wave (green line). (a) The result of GPR 400 MHz. (b) The result of GPR 900 MHz.

4.2 GPR Data Processing for Calculating VSWC

The example results, from 900 MHz, are shown in figure 4.2a is a gray scale display of signal, and figure 4.2b shows wiggle display that is the continually of signal traces. Green line is signal of air wave, and blue line is signal of ground wave. Different of travel time at each distance is required as an input to equation (2.4). By using EZ Tracker command in RADAN 6.6, the highest amplitude of interested signal (i.e. picked by researcher) will be identified, shown as dot lines in figure 4.3. Because the pulses of EMW of GPR are sent in a rate of about 100 scan per meter, each survey line contain many GPR sampling points. So, estimating VSWC by GPR contain many points of data and it can be acquired faster than conventional point-measurement methods. EZ Tracker is set up to track signal every 10 cm, so there are possibly 2,200 VSWC data at one survey.

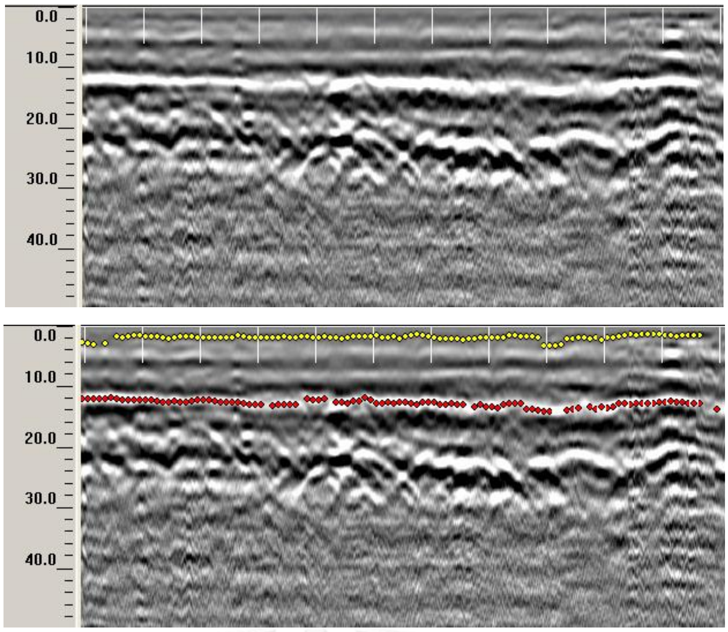


(a)

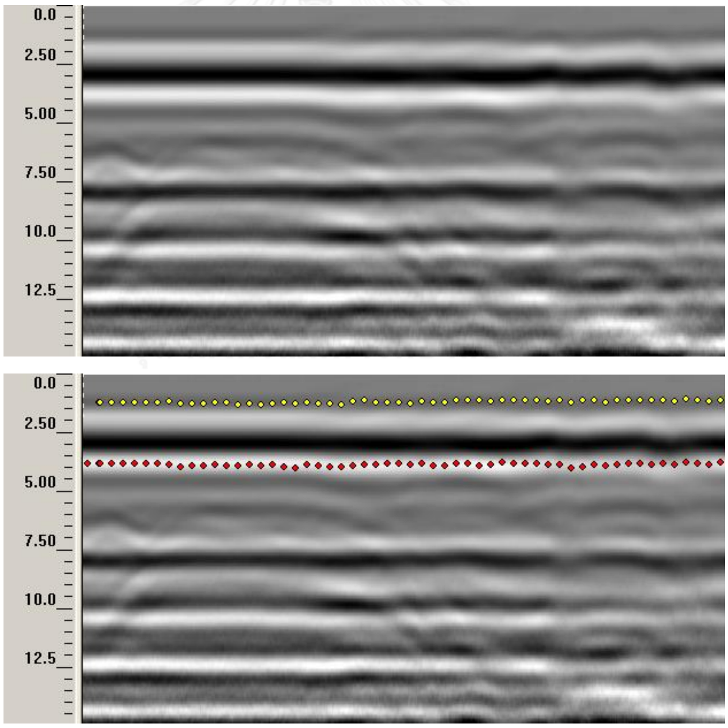


(b)

Figure 4.2 Signal from GPR 900 MHz with (a) gray scale display and (b) wiggle display. Green line shows amplitude of airwave and blue line shows ground wave.



(a)



(b)

Figure 4.3 Example of signal before and after process by EZ Tracker command. (a) is an example of GPR 400 MHz and (b) is an example of GPR 900 MHz.

4.3 The Results of VSWC

4.3.1 The First Experiment (29th July 2014)

The first experiment (29th July 2014) was performed at the rainy season. The results of gravimetric by %VSWC [$cm^3.cm^{-3}$], shown in table 4.1, at depth 10 cm is about 28.87 to 32.98 (Average is 30.30), at depth 20 cm is about 25.28 to 35.07 (Average is 29.63), and at depth 30 cm is about 23.68 to 34.46 (Average is 30.10). The raw data of weight is shown in the appendix. The tendency of VSWC with depth is not seem to be any pattern.

The results of EC-5 is less than half of gravimetric, i.e. at depth 10 cm is about 13.07 to 20.79 (Average is 16.21), at depth 20 cm is about 12.28 to 17.47 (Average is 14.76), and at depth 30 cm is about 13.35 to 20.79 (Average is 16.61). Like gravimetric, the trend of VSWC has no pattern with depth.

The results of GPR 400 MHz is about 18.16 to 39.78 (Average is 30.98), and GPR 900 MHz is about 12.82 to 19.74 (Average is 15.80), which can be illustrated as a color contour map in figure 4.4. Interpolated VSWC contour map was obtained by krigging technique with 10 cm grid. The range of VSWC is about 0% to 50% that is shown with the range of rainbow color from red (The driest; 0%) to purple (The wettest; 50%). For GPR 400 MHz, the tendency of VSWC has high at north-west (i.e. blue) and gradually decreases to south-east (i.e. green with some yellow). For GPR 900 MHz, the result is rather different from GPR 400 MHz. First, VSWC value is about half of GPR 400 MHz which can be seen from map with orange and yellow color. Second, the pattern is quite different that has more dry area about the center of the field in north-south orientation.

Table 4.1 VSWC (% $cm^3.cm^{-3}$) from gravimetric, EC-5 and GPR of total 9 soil samples at each depth of the first experiment. Note that the results of GPR were picked at the nearest points as soil samples.

Soil Sample	Gravimetric			Average Gravimetric			EC-5			GPR	GPR
	10 cm	20 cm	30 cm	0 - 10 cm	0 - 20 cm	0 - 30 cm	10 cm	20 cm	30 cm	400 MHz	900 MHz
1	28.88	28.32	28.05	28.88	28.60	28.42	16.07	13.21	15.63	29.98	16.25
2	29.47	31.22	34.46	29.47	30.34	31.71	15.87	16.53	17.23	29.29	16.25
3	32.40	35.07	27.49	32.40	33.74	31.65	17.39	17.47	13.35	32.03	16.24
4	29.58	27.03	30.28	29.58	28.30	28.96	16.47	13.76	17.00	29.63	15.72
5	30.46	25.28	31.30	30.46	27.87	29.01	18.77	15.19	20.79	31.69	15.98
6	32.98	32.05	30.30	32.98	32.51	31.78	20.79	12.61	16.91	31.69	15.20
7	28.87	29.00	33.72	28.87	28.93	30.53	13.71	15.44	19.39	26.11	15.98
8	30.06	31.27	31.60	30.06	30.66	30.98	13.07	16.36	15.33	30.32	16.51
9	29.98	27.42	23.68	29.98	28.70	27.03	13.74	12.28	13.88	30.32	17.31
Average	30.30	29.63	30.10	30.30	29.96	30.01	16.21	14.76	16.61	30.12	16.16

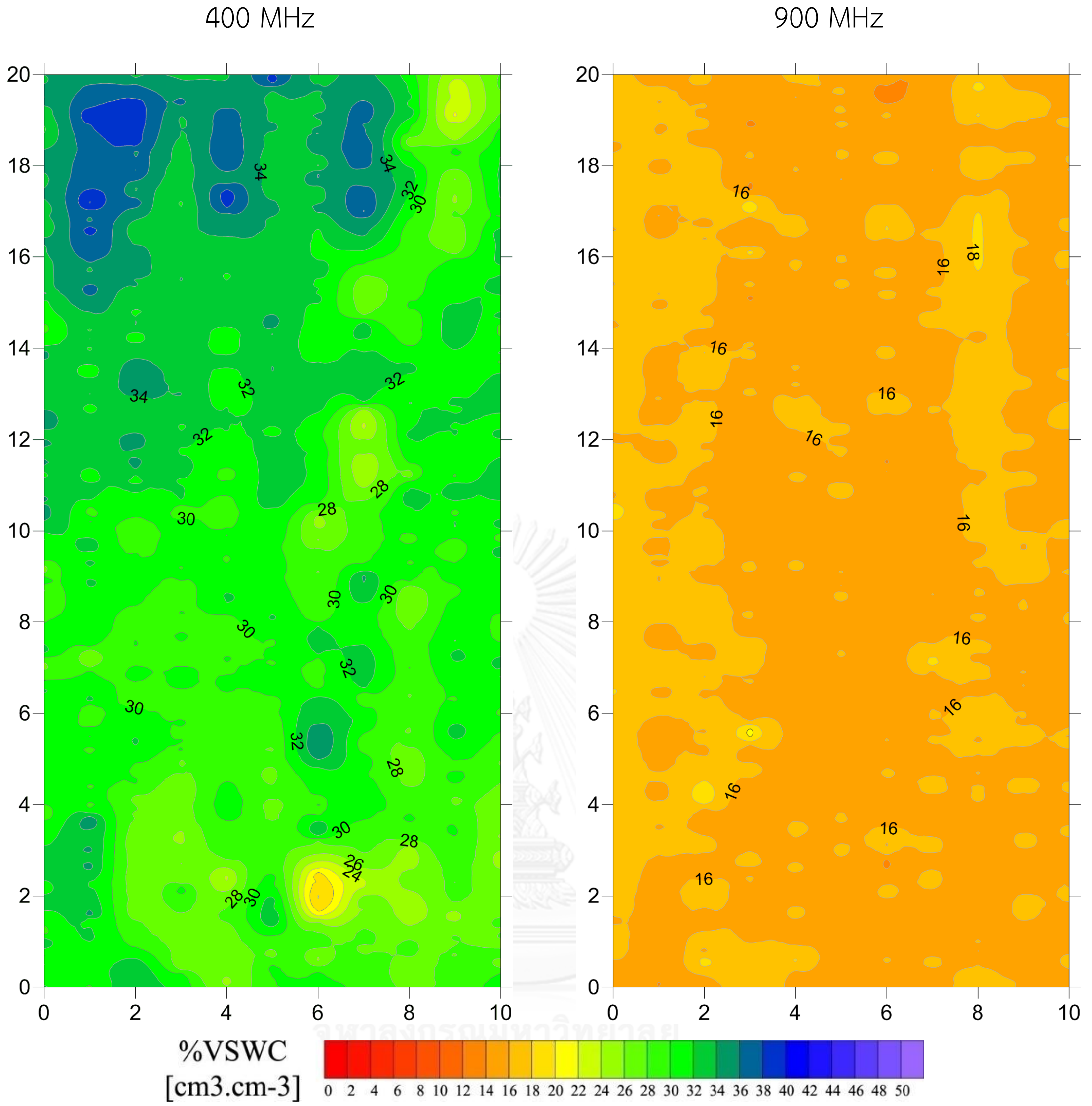


Figure 4.4 Contour maps of VSWC from GPR of the first experiment.

4.3.2 The Second Experiment (23rd November 2014)

The second experiment (23rd November 2014) was performed at the end of rainy season that expecting of the higher VSWC than the first experiment. The results of gravimetric by %VSWC [$cm^3.cm^{-3}$], shown in table 4.2, at depth 10 cm is about 26.52 to 34.16 (Average is 30.29), at depth 20 cm is about 26.82 to 34.35 (Average is 31.37), and at depth 30 cm is about 26.32 to 38.00 (Average is 31.52). The tendency of VSWC with depth is not seem to be any pattern.

The results of EC-5 is about half of gravimetric, i.e. at depth 10 cm is about 9.89 to 15.56 (Average is 12.41), at depth 20 cm is about 11.64 to 17.03 (Average is 14.33), and at depth 30 cm is about 13.90 to 23.07 (Average is 18.15). Like gravimetric, the trend of VSWC has no pattern with depth.

The results of GPR 400 MHz is about 26.97 to 41.96 (Average is 34.82), and GPR 900 MHz is about 16.47 to 19.13 (Average is 18.04). Contour maps are shown in figure 4.5 which are quite different from the first experiment. For GPR 400 MHz, the tendency of VSWC has high at west area in north-south orientation (i.e. deep blue) and sharply decreases at east (i.e. green). For GPR 900 MHz, the VSWC is higher than the first but still lower than gravimetric and GPR 400 MHz. The pattern of moist area is also not similar to GPR 400 MHz.

Table 4.2 VSWC (% $cm^3.cm^{-3}$) from gravimetric, EC-5 and GPR of total 9 soil samples at each depth of the second experiment. Note that the results of GPR were picked at the nearest points as soil samples.

Soil Sample	Gravimetric			Average Gravimetric			EC-5			GPR	GPR
	10 cm	20 cm	30 cm	0 - 10 cm	0 - 20 cm	0 - 30 cm	10 cm	20 cm	30 cm	400 MHz	900 MHz
1	29.05	31.92	26.32	29.05	30.48	29.10	11.20	12.61	13.90	40.58	19.13
2	32.48	34.35	27.79	32.48	33.41	31.54	9.89	11.64	14.54	39.15	17.53
3	34.16	33.59	38.00	34.16	33.88	35.25	13.83	13.42	21.55	41.96	16.47
4	26.52	30.68	35.35	26.52	28.60	30.85	10.83	12.37	14.68	34.15	18.65
5	27.89	32.62	27.66	27.89	30.25	29.39	11.79	17.03	17.70	34.80	18.90
6	30.43	31.98	35.01	30.43	31.20	32.47	13.28	16.34	20.38	34.80	18.65
7	30.51	30.96	33.81	30.51	30.74	31.76	12.15	15.30	23.07	31.16	17.04
8	31.53	29.39	32.97	31.53	30.46	31.30	15.56	14.46	21.46	29.78	17.85
9	30.07	26.82	26.80	30.07	28.44	27.90	13.14	15.86	16.09	26.97	18.11
Average	30.29	31.37	31.52	30.29	30.83	31.06	12.41	14.33	18.15	34.82	18.04

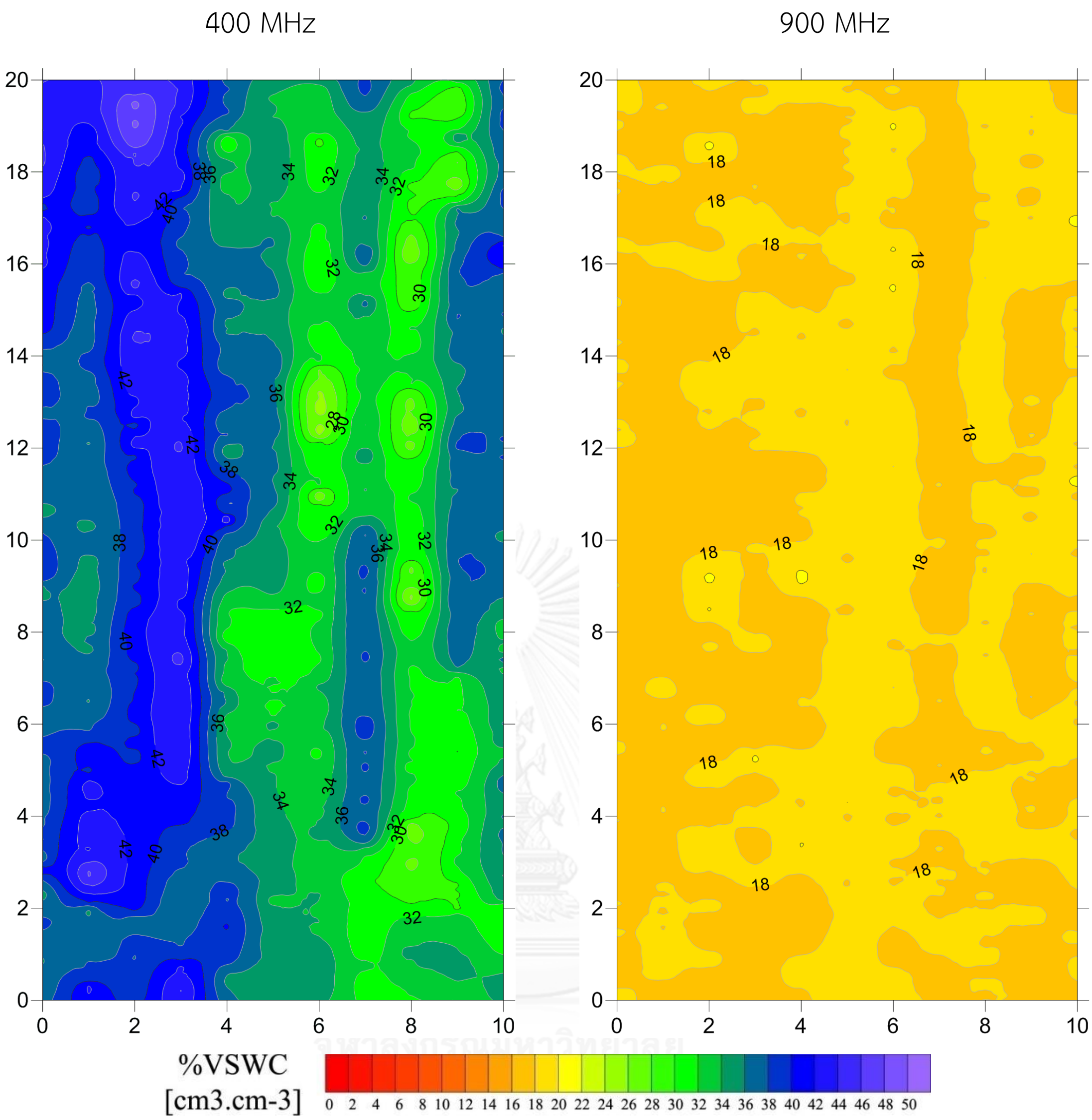


Figure 4.5 Contour maps of VSWC from GPR of the second experiment.

4.3.3 The Third Experiment (10th February 2015)

The third experiment (10th February 2015) was performed in the dry season that expecting of the lower VSWC than early experiments. The results of gravimetric by %VSWC [$cm^3.cm^{-3}$], shown in table 4.3, at depth 10 cm is about 6.75 to 15.53 (Average is 10.58), at depth 20 cm is about 11.02 to 18.68 (Average is 13.51), and at depth 30 cm is about 12.00 to 21.38 (Average is 15.36). Now the tendency of VSWC is increase with depth.

The results of EC-5 are less than gravimetric, i.e. at depth 10 cm is about 6.58 to 9.00 (Average is 7.74), at depth 20 cm is about 6.19 to 9.15 (Average is 7.82), and at depth 30 cm is about 6.07 to 9.23 (Average is 7.78). The trend of VSWC has no pattern with depth.

The results of GPR 400 MHz is about 14.95 to 23.49 (Average is 19.51), and GPR 900 MHz is about 13.65 to 17.85 (Average is 15.65). Contour maps are shown in figure 4.6. For GPR 400 MHz, the tendency of VSWC is low at north-west area (i.e. orange) high at east (i.e. yellow and green). For GPR 900 MHz, the VSWC is lower than early experiments but still lower than gravimetric and GPR 400 MHz. The pattern of VSWC is not clear and not similar to GPR 400 MHz.

Table 4.3 VSWC (% $cm^3.cm^{-3}$) from gravimetric, EC-5 and GPR of total 9 soil samples at each depth of the third experiment. Note that the results of GPR were picked at the nearest points as soil samples.

Soil Sample	Gravimetric			Average Gravimetric			EC-5			GPR	GPR
	10 cm	20 cm	30 cm	0 - 10 cm	0 - 20 cm	0 - 30 cm	10 cm	20 cm	30 cm	400 MHz	900 MHz
1	9.59	13.10	12.00	9.59	11.34	11.56	7.08	6.78	8.15	22.14	15.73
2	6.75	11.02	13.02	6.75	8.88	10.26	6.58	7.61	6.96	14.95	17.85
3	10.56	12.25	12.79	10.56	11.40	11.87	7.18	6.19	6.07	14.95	15.46
4	15.53	18.68	21.38	15.53	17.11	18.53	9.00	8.60	9.23	23.49	17.05
5	7.69	11.64	13.28	7.69	9.66	10.87	7.69	7.41	7.11	15.21	13.65
6	9.92	14.12	18.39	9.92	12.02	14.14	7.63	8.18	8.31	19.86	13.90
7	11.80	15.25	18.07	11.80	13.53	15.04	8.07	8.32	8.86	21.78	15.98
8	11.20	12.69	13.73	11.20	11.94	12.54	8.26	8.16	7.50	21.78	15.73
9	12.16	12.88	15.56	12.16	12.52	13.53	8.18	9.15	7.82	21.41	15.45
Average	10.58	13.51	15.36	10.58	12.05	13.15	7.74	7.82	7.78	19.51	15.65

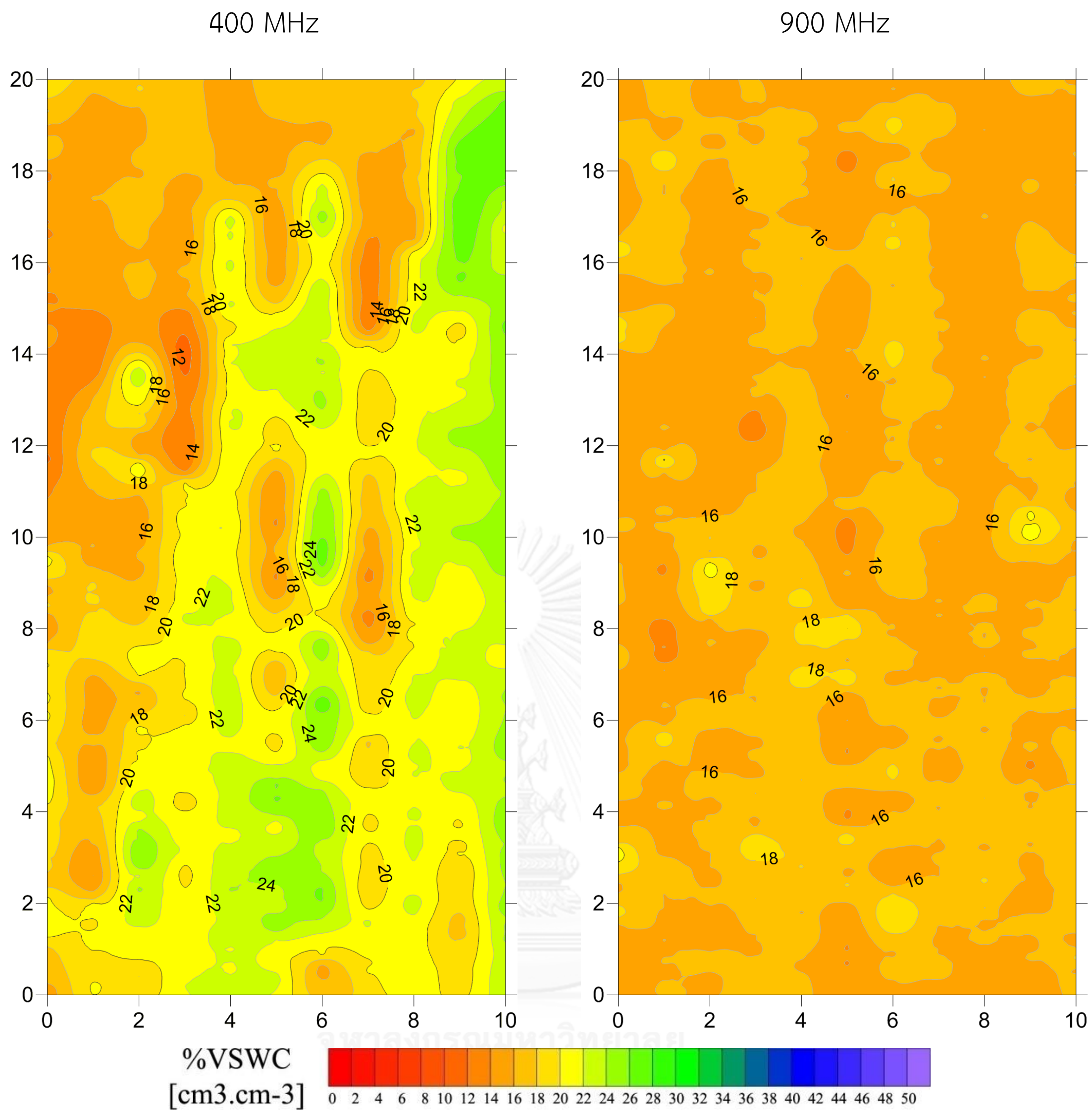


Figure 4.6 Contour maps of VSWC from GPR of the third experiment.

CHAPTER 5
DISCUSSION

5.1 Validation of GPR Method

The data of GPR at the same position as gravimetric, i.e. 9 sampling points with 3 different depths, will be analyzed by linear regression model and correlation. If they have good relation, the result of gravimetric which is used as reference compared with GPR should be the same. So, versus graph should be a 1:1 straight line with R squared value approach to 1. R squared is a number that indicated how well the data fit to the model. And if they have strong correlation, correlation value should be a positive and approached to 1. Correlation indicates the fluctuation of variables. A positive correlation indicates that the variables increase or decrease by each other, and a negative correlation indicates that one variable increases as the other decreases (which does not proper in this experiment).

5.1.1 The Relation of the First Experiment (29th July 2014)

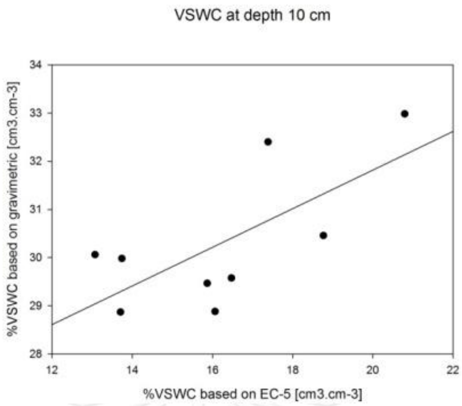
The relations of gravimetric and EC-5 of all three depths have medium correlation (about 0.5 to 0.7), as shown in figure 5.1. The results from EC-5 are underestimated about half of gravimetric. So, the results of EC-5 in this first experiment are not valid to gravimetric.

For VSWC of gravimetric compared with GPR 400 MHz, only at depth 10 cm has a good positive correlation about 0.732 (figure 5.2). For GPR 900 MHz (figure 5.3), all three depths have a negative correlation.

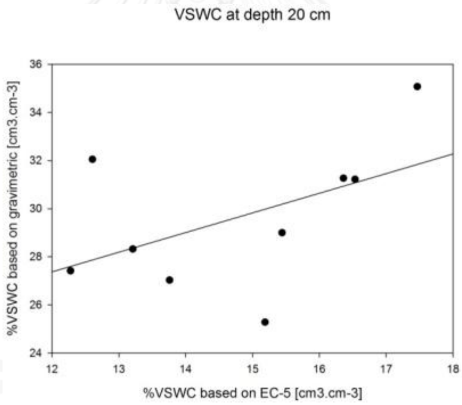
Considering when GPR send EMW into subsurface, the wave passes through whole medium. So, the comparison between GPR and gravimetric data at each depth is not quite right, and should perform at average depth rather than at specific depth.

For average VSWC by gravimetric, GPR 400 MHz has better positive correlation than comparison to gravimetric at each depth but the value is still weak (figure 5.4), and GPR 900 MHz still has a negative correlation (figure 5.5). For all result, the best relationship between GPR 400 MHz and gravimetric is at depth 10 cm, that is according to influent depth about 8 cm. GPR 900 MHz does not relate with gravimetric at any depths.

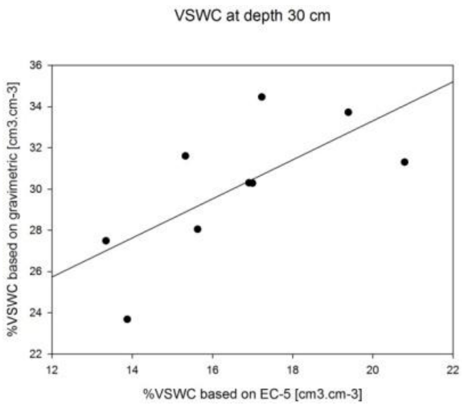
Gravimetric vs EC-5



Y = 0.4009X + 23.80 R^2 = 0.483499 Correlation = 0.695341



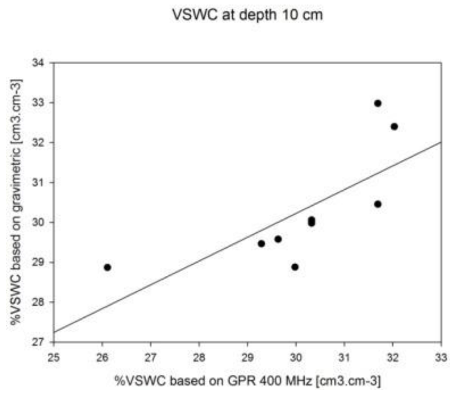
Y = 0.8172X + 17.57 R^2 = 0.253988 Correlation = 0.503972



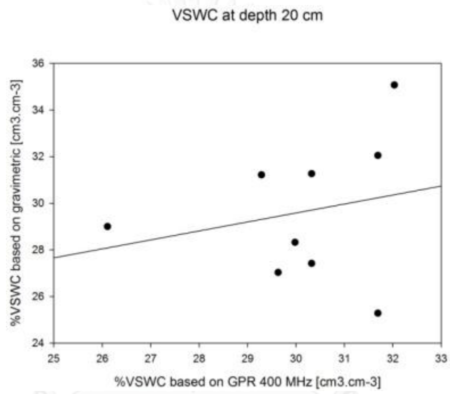
Y = 0.9468X + 14.37 R^2 = 0.473826 Correlation = 0.68835

Figure 5.1 Relation of gravimetric and EC-5 of the first experiments.

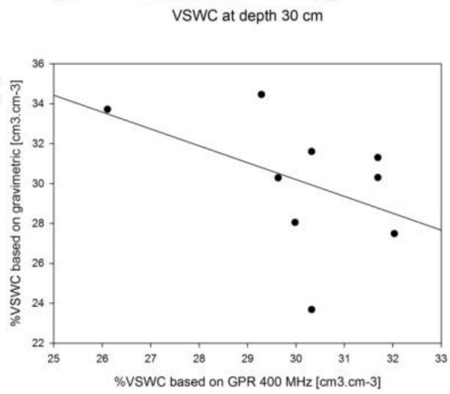
Gravimetric vs GPR 400 MHz



Y = 0.5966X + 12.33 R^2 = 0.536377 Correlation = 0.732377



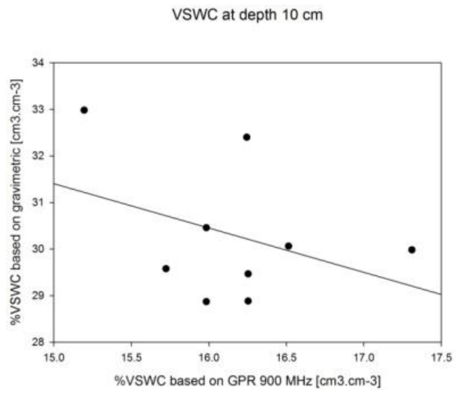
Y = 0.3851X + 18.03 R^2 = 0.051996 Correlation = 0.228026



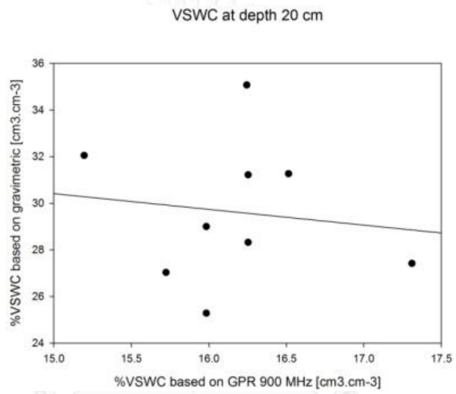
Y = -0.8452X + 55.55 R^2 = 0.208475 Correlation = -0.45659

Figure 5.2 Relation of gravimetric and GPR 400 MHz of the first experiment.

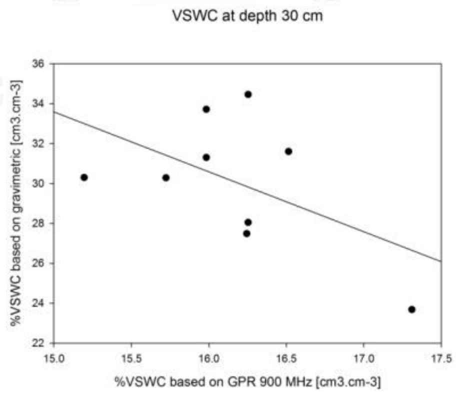
Gravimetric vs GPR 900 MHz



Y = -0.9523X + 45.69 R^2 = 0.208475 Correlation = -0.37568



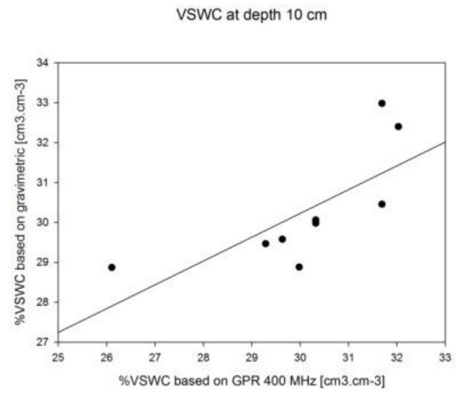
Y = -0.6772X + 40.57 R^2 = 0.016607 Correlation = -0.12887



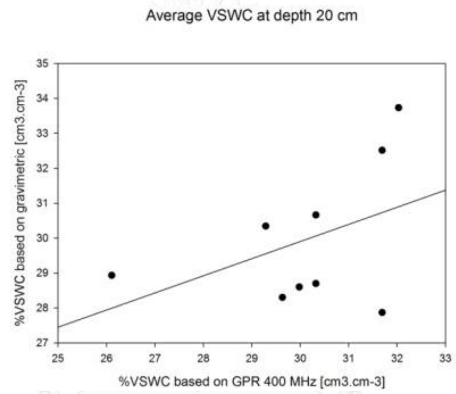
Y = -0.3004X + 78.64 R^2 = 0.271888 Correlation = -0.52143

Figure 5.3 Relation of gravimetric and GPR 900 MHz of the first experiment.

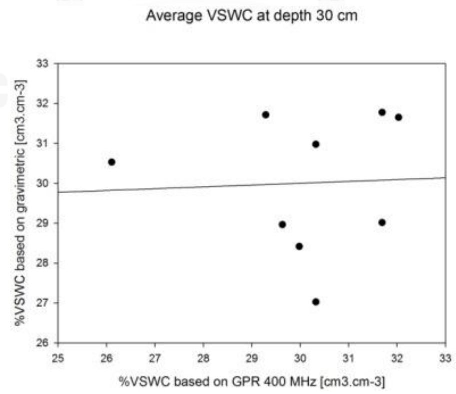
Average Gravimetric vs GPR 400 MHz



Y = 0.5966X + 12.33 R^2 = 0.536377 Correlation = 0.732377



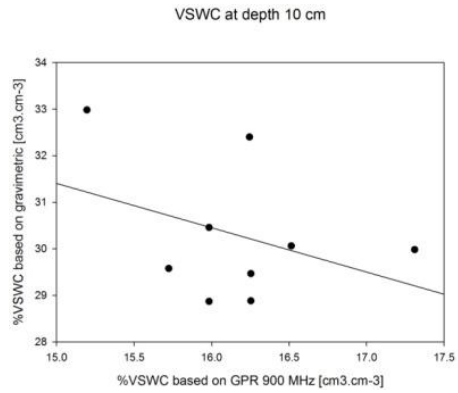
Y = 0.4908X + 15.18 R^2 = 0.18756 Correlation = 0.433082



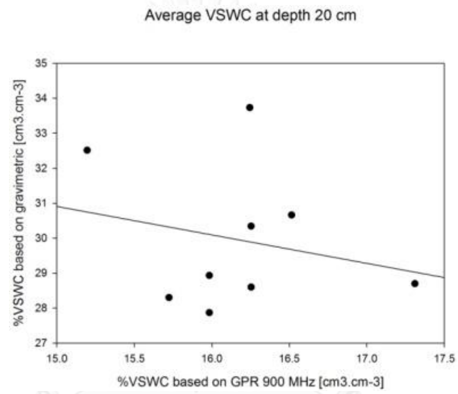
Y = 0.04548X + 28.64 R^2 = 0.002267011 Correlation = 0.047613

Figure 5.4 Relation of gravimetric (average) and GPR 400 MHz of the first experiment.

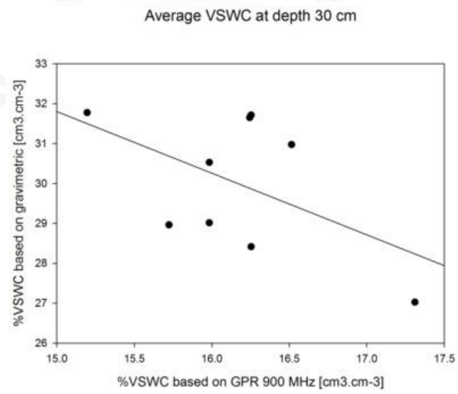
Average Gravimetric vs GPR 900 MHz



Y = -0.9523X + 45.69 R^2 = 0.208475 Correlation = -0.37568



Y = -0.8147X + 43.13 R^2 = 0.05337 Correlation = -0.23102



Y = -1.544X + 54.97 R^2 = 0.270014 Correlation = -0.51963

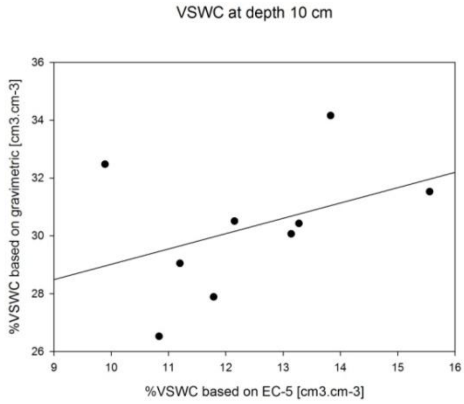
Figure 5.5 Relation of gravimetric (average) and GPR 900 MHz of the first experiment.

5.1.2 The Relation of the Second Experiment (23rd November 2014)

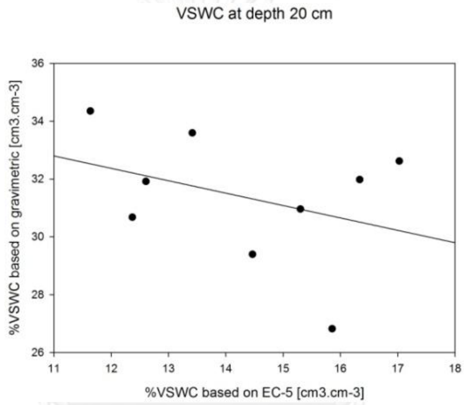
The relations of gravimetric and EC-5 of 10 cm depth has low correlation, at 20 cm depth has a negative correlation, and at 30 cm depth has medium positive correlation (about 0.6), as shown in figure 5.6. The results from EC-5 are underestimated as the first experiment.

For the relation of average gravimetric versus GPR 400 MHz (figure 5.7), the result at 20 cm depth has medium correlation (about 0.7), but the average depth of 10 cm and 30 cm have low correlation (about 0.3 and 0.5). So, the best relationship is at average depth of 20 cm that is not according to influent depth about 8 cm and the results of the first experiment that have the best positive correlation at 10 cm depth. For GPR 900 MHz (figure 5.8), all three depths have negative correlation that are not relate with gravimetric.

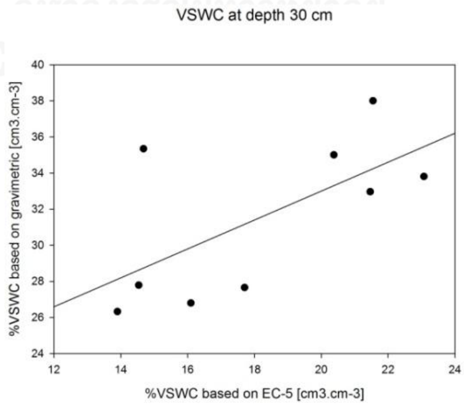
Gravimetric vs EC-5



Y = 0.5305X + 23.71 R^2 = 0.157170 Correlation = 0.396446



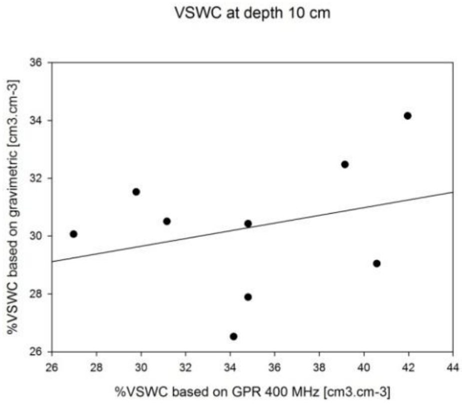
Y = -0.429X + 37.52 R^2 = 0.131551 Correlation = -0.362700



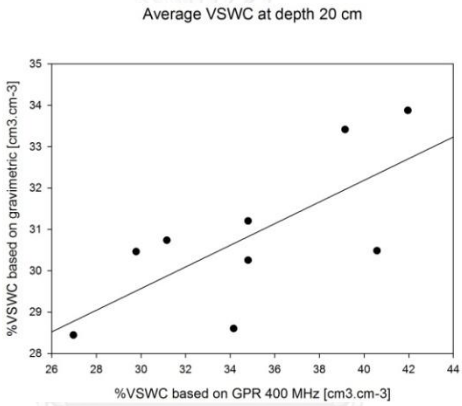
Y = 0.8016X + 16.97 R^2 = 0.413393 Correlation = 0.642956

Figure 5.6 Relation of gravimetric and EC-5 of the second experiment.

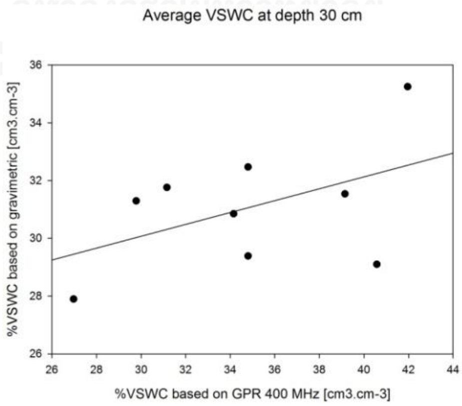
Average Gravimetric vs GPR 400 MHz



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



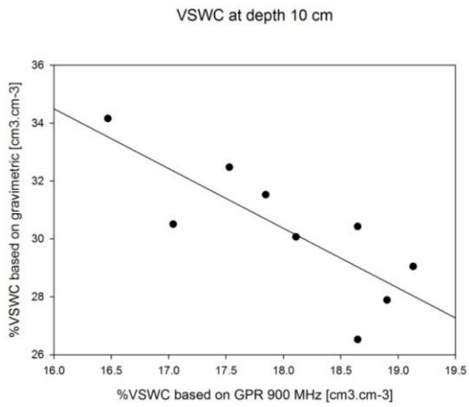
Y = 0.2619X + 21.71 R^2 = 0.510925 Correlation = 0.714790



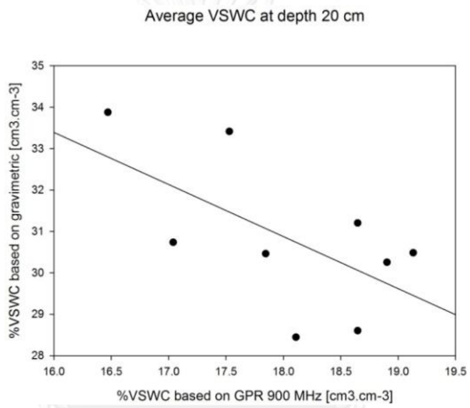
Y = 0.2057X + 23.9 R^2 = 0.232723 Correlation = 0.482414

Figure 5.7 Relation of gravimetric (average) and GPR 400 MHz of the second experiment.

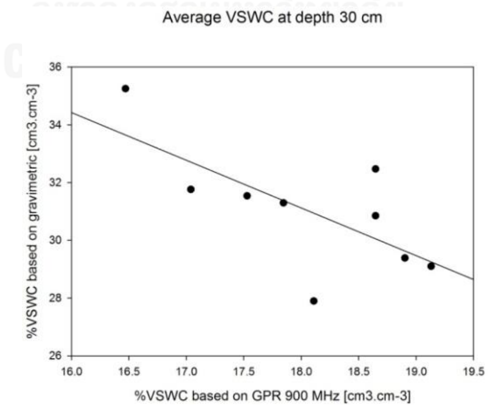
Average Gravimetric vs GPR 900 MHz



Y = -2.065X + 67.53 R^2 = 0.640172 Correlation = -0.800108



Y = -1.259X + 53.53 R^2 = 0.373161 Correlation = -0.610869



Y = -1.653X + 60.87 R^2 = 0.475212 Correlation = -0.689356

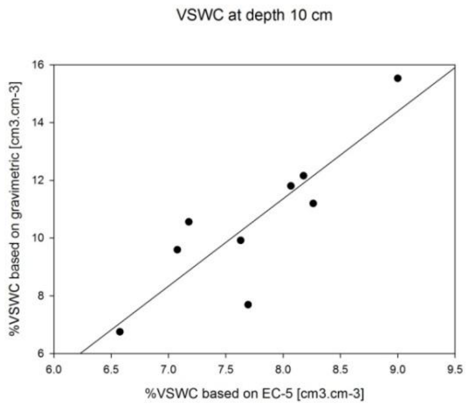
Figure 5.8 Relation of gravimetric (average) and GPR 900 MHz of the second experiment.

5.1.3 The Relation of the Third Experiment (10th February 2015)

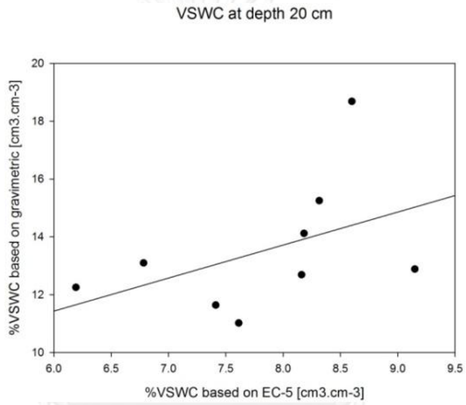
The relations of gravimetric and EC-5 of all three depth have better positive correlation than early experiments about medium-high correlation (about 0.4 - 0.8), as shown in figure 5.9. The best correlation is at 10 cm depth. But the results from EC-5 are still underestimated.

For the relation of average gravimetric versus GPR 400 MHz (figure 5.10), all three depths have good positive correlation about 0.7 which 20 cm depth is the best. And again, it is not according to influent depth about 8 cm. For GPR 900 MHz (figure 5.11), all three depths are now turned to positive correlation but they are still weak correlation.

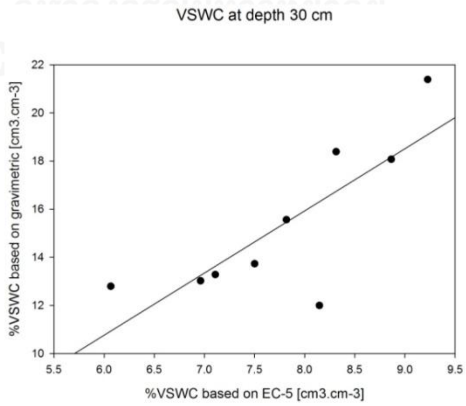
Gravimetric vs EC-5



Y = 3.026X −12.85 R^2 = 0.737617 Correlation = 0.858846



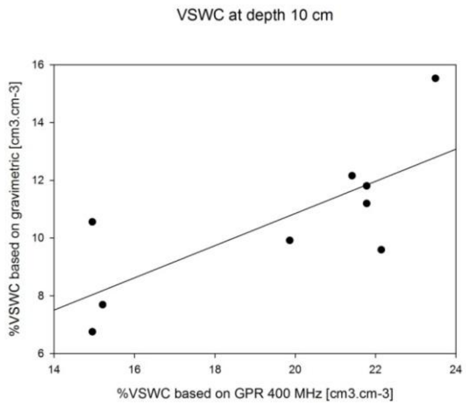
Y = 1.141X + 4.585 R^2 = 0.207684 Correlation = 0.455723



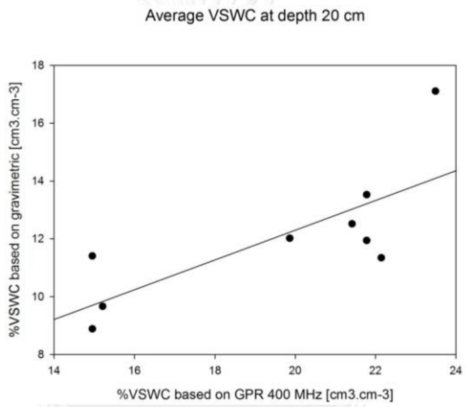
Y = 2.583X − 4.736 R^2 = 0.627257 Correlation = 0.791996

Figure 5.9 Relation of gravimetric and EC-5 of the third experiment.

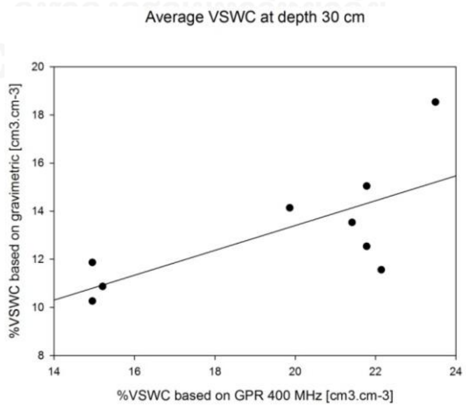
Average Gravimetric vs GPR 400 MHz



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



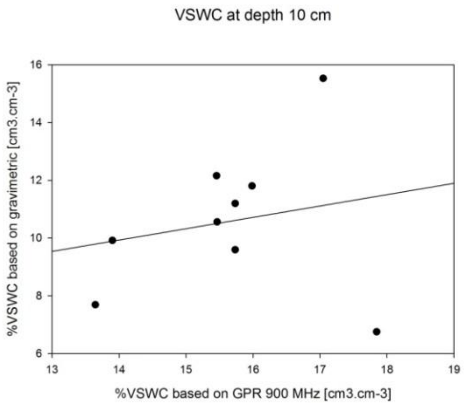
Y = 0.5148X + 2.002 R^2 = 0.575682 Correlation = 0.758737



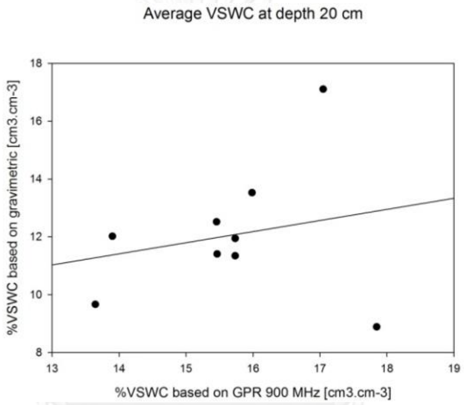
Y = 0.5164X + 3.075 R^2 = 0.499249 Correlation = 0.706575

Figure 5.10 Relation of gravimetric (average) and GPR 400 MHz of the third experiment.

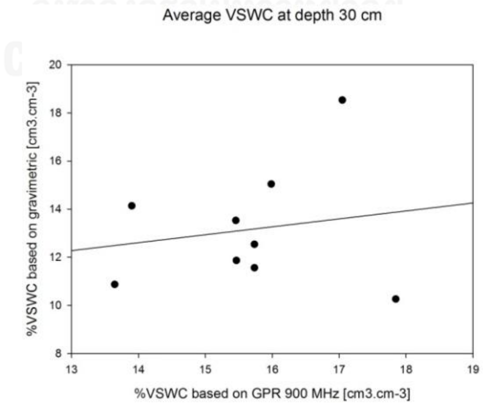
Average Gravimetric vs GPR 900 MHz



Y = 0.394X + 4.412 R^2 = 0.04094 Correlation = 0.202336



Y = 0.385X + 6.022 R^2 = 0.046681 Correlation = 0.216059



Y = 0.33X + 7.987 R^2 = 0.029551 Correlation = 0.171903

Figure 5.11 Relation of gravimetric (average) and GPR 900 MHz of the third experiment.

5.1.4 The Validation of All Experiments

From all experiments, EC-5 and GPR have different relationship with gravimetric at different depth. Table 5.1 shows the correlation value and the percentage of RMSE of all results. Note that GPR is compared with gravimetric results at average depth, and bold values mean the best value of each experiment.

Table 5.1 RMSE and correlation of all experiments. Note that GPR is compared with gravimetric results at average depth. Bold values mean the best value of each experiment.

Experiment	Gravimetric at depth	Capacitance Probe: EC-5		GPR 400 MHz		GPR 900 MHz	
		%RMSE	Correlation	%RMSE	Correlation	%RMSE	Correlation
The First (20^{th} Jul 2014)	10 cm	14.195	**0.695341**	**1.173**	**0.732377**	14.231	-0.37568
	20 cm	15.074	0.503972	1.936	0.433082	13.960	-0.23102
	30 cm	**13.677**	0.68835	2.284	0.047613	**13.982**	-0.51963
The Second (23^{rd} Nov 2014)	10 cm	18.013	0.396446	6.468	0.291077	**12.596**	-0.800108
	20 cm	17.345	-0.362700	**5.451**	**0.714790**	13.010	-0.610869
	30 cm	**13.758**	**0.642956**	5.617	0.482414	13.299	-0.689356
The Third (10^{th} Feb 2015)	10 cm	**3.400**	**0.858846**	9.190	0.751697	5.651	0.202336
	20 cm	6.013	0.455723	7.768	**0.758737**	4.275	**0.216059**
	30 cm	7.942	0.791996	**6.770**	0.706575	**3.537**	0.171903

All results of EC-5 show that the third experiment (i.e. the driest) have the highest correlation and the lowest RMSE. The second experiment has lower correlation and higher RMSE than the first (which has slightly lower of moisture) at all depth. This can conclude that EC-5 has higher efficiency in drier area. Considering about depth, bold values of each experiment are scattered and not seem to be in any pattern. So, the relation about the depth does not obvious. As described before from section 3.2.2, the soil samples were disturbed collected so the results of EC-5 would be significantly incorrect. The assumption may be that; the contact between EC-5 and soil would be very poor. Disturbed soil samples with loose compaction may create much air gap between probe and soil compared with the small size of probes (i.e. about decimeter). This is a significant impact to decrease the dielectric constant of samples. Then, the measurement of VSWC is underestimated (Francesca et al., 2010). And this research used manufacturer's calibration which can be poorly fitted to this site. Besides, disturb soil samples also dominated to the density of soil. Then the VSWC estimated from gravimetric water content (as equation (2.2)) would be moderately incorrect.

The first result of GPR 400 MHz has the highest correlation and the lowest RMSE at average 10 cm depth. The second experiment has the best result at 20 cm depth. And the third has good relation at all depth which is the best correlation at average 20 cm and the lowest RMSE at average 30 cm. These can approximately conclude that GPR 400 MHz has well results at depth about 10 to 20 cm in wet condition, and can be more capable at deeper soil in dry condition. This can be described by the amount of moisture (e.g. rainfall) in soil that is affect to the propagation of EMW. In EMW principle, another significant variable beyond the dielectric permittivity is the electric conductivity. The electric conductivity of soil has much effect to attenuate the signal (i.e. energy) of EMW, especially in high frequency. Soil water content has many free ions that make wet soil to has higher of electric conductivity than dry soil, and higher of attenuation. So, the dry condition in the third experiment makes the deeper results.

Some interesting is that the bold texts of GPR 400 MHz in table 5.1 are not at the same depth. From section 4.1, influence depth is proportional to wavelength of EMW in soil, i.e. velocity. So, different in VSWC (proportional to ε_r or velocity of soil) make different of influence depth. It could be calculated from WARR acquisition which is also given the information of antenna offset. This research used offset and influence depth data from the first experiment to use in later experiments. The results show that the highest of correlation of later experiments are at different depth. It means that the same configuration cannot be used in any different specific site. WARR acquisition is needed to perform at every different site of experiment before using FO method to receive the appropriate offset and influent depth expecting. So, the results of the first experiment are strong according to the influent depth and have low RMSE. Besides, sledge should be modified to be able to change the offset.

The first and second results of GPR 900 MHz are negative correlations which are not related to gravimetric method. The third experiment has better correlation with positive value but still weak. The reason should be same as GPR 400 MHz from electric conductivity issue. But the underestimate results of GPR 900 MHz may come from the miss-choosing of antenna offset. At close offset, the interference of air wave and ground wave may occur. Superposition of wave caused air wave appears later than it would and caused ground wave appears earlier (Grote et al., 2003). So the time different (i.e. input to equation (2.4)) is lower than it would be and makes the lower of VSWC.

Beside of electric conductivity from rainfall, soil texture has significant to GPR surveying. Soil texture of study area is loamy soil with large amount of silt and clay which are not rather suitable for GPR surveying (Weihermuller et al., 2007). Because of pore water, electric conductivity of soil is high and makes the great attenuation of EMW. So, the soil texture is affect to all experiments.

The conclusions are; 1) GPR 400 MHz has high correlation at dry condition at depth of 10 to 30 cm with VSWC about 10 to 15%. And at wet condition, the result is reasonable at depth 10 to 20 cm with VSWC around 30%. 2) GPR 900 MHz is not related to gravimetric method but the results are looked well in dry condition. 3) Capacitance probe EC-5 is not related to gravimetric method due to the misused and the limitation of experiment.

5.2 Time Variation Monitoring

The results of GPR of all experiments are illustrated as contour map of VSWC with the same color range scale and shown in figure 5.12. The first experiment, performed in rainy season, has VSWC about 18.16 to 39.73 (Average is 30.98) with the highest VSWC at north-west corner. The later experiments were used the same configuration of GPR as the first, i.e. same offset, to determine the changing of VSWC with time. The second experiment, performed in the end of rainy season, has higher

VSWC than the first experiment, about 24.72 to 48.54 (Average is 36.32). As seen that most area has blue color with the lower VSWC as green color in the east. The third experiment was performed in the dry season with zero rainfall for one month earlier and has the lowest VSWC about 10.83 to 27.88 (Average is 19.62). The west and the northwestern of the area have the medium water content and show in color of yellow and green. The driest area is at the north-west as shown in orange color. It is clearly seen that three experiments have different VSWC according to season and rainfall, so GPR 400 MHz can respond to the change of VSWC with time.

For GPR 900 MHz (figure 5.4.1), the first experiment has VSWC about 12.82 to 19.74 (Average is 15.80), the second is 15.46 to 22.34 (Average is 17.98), and the third is 12.37 to 21.59 (Average is 16.06). All three experiments have VSWC lower than gravimetric and the distribution of VSWC has different pattern from the results of GPR 400 MHz. From section 5.1.4, the results of GPR 900 MHz are not according to gravimetric method. So, GPR 900 MHz cannot be claimed to detect the variation of VSWC with time in this study.

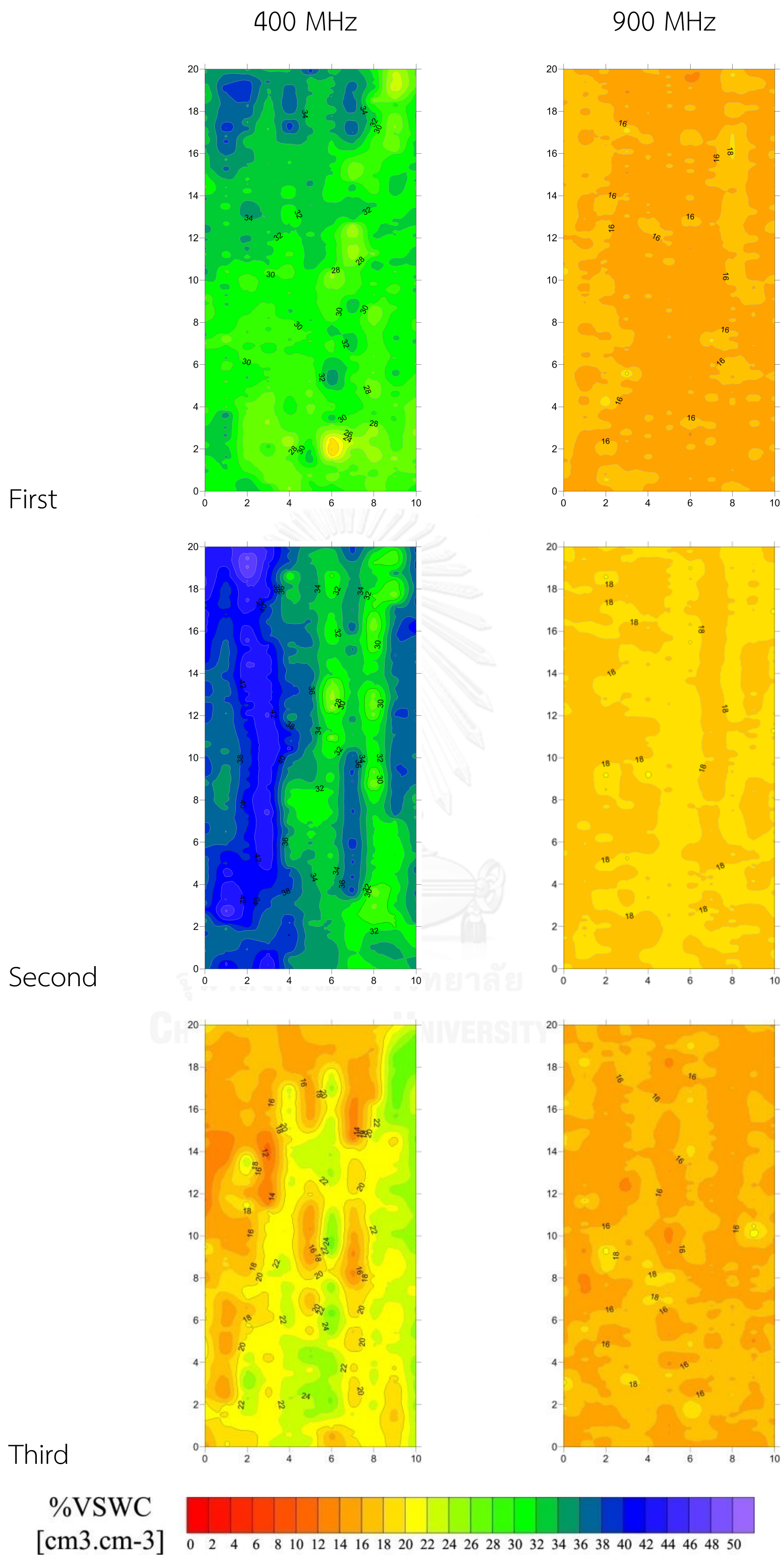


Figure 5.12 Contour maps of average VSWC using GPR of three experiments.

CHAPTER 6
CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Determination of VSWC at the field scale of loamy soil in CLNR, Chulalongkorn University, Changwat Saraburi was determined by using GPR ground wave fixed-offset technique. It can be concluded that GPR method is appropriate for estimating VSWC due to the easy of data acquisition and processing. GPR 400 MHz has high correlation at dry condition at depth of 10 to 30 cm with VSWC about 10 to 15%. And at wet condition, the result is reasonable at depth 10 to 20 cm with VSWC around 30%. GPR 900 MHz is not related to gravimetric method but the results are looked well in dry condition. Capacitance probe EC-5 is not related to gravimetric method due to the misused and the limitation of experiment.

In the time monitoring of VSWC, the results of GPR 400 MHz in three experiments changed with time, but not for GPR 900 MHz. The GPR 400 MHz can be effectively used to determine VSWC at 10 to 20 cm at this site but GPR 900 MHz is not. This is probably due to the high amount of clay and silt content of soil that is limited the depth penetration of GPR signal. This technique can be used in many types of soils but with different in GPR frequency and offset; but it need specialist for the operation and data processing. However this method needs to be study further in a larger scale in order to evaluate the effectiveness of the GPR technique in helping to determine VSWC in planning and managing agricultural field.

6.2 Limitation

The major limitation in this research is the disturbed soil sampling. Gravimetric method was used as reference for comparisons. It required an accurate data such as density of bulk soil that is needed some accurate specific apparatus. Disturbed soil sampling also impacted to capacitance probe measurement because of the poor contact between probe and soil. So, these are affected to the reliability of reference data.

The another limitation is about the experiment field. It was hard to acquire the desired location in the boundary of University. So, the experiment field described in section 3.1 was used with some uncontrollable such as crop cover, field size, or soil type.

6.3 Recommendation

In the future research, it is necessary to have the additional investigation to solve the limitations. For instance, the appropriated soil sampling techniques are needed for quality controls. The larger experiment field with different soil types in many geographic areas may also need to study in order to accurately evaluate the effectives of GPR method. GPR data acquisition and configuration have to be improved for more accuracy and for the convenient of surveying such as using some gadget to faster the WARR acquisition or using adjustable sledge for the properly offset in FO method. Different GPR data acquisition might be used in the same field or scenario to compare for the best solution. Finding petrophysical relationship of specific area is challenged and interested for comparing to Topp's equation.

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APPENDIX

APPENDIX A
PRIMARY DATA

Table A-1, A-2, and A-3 show the data of gravimetric method of all three experiments. After soil was collected in field surveying, they were brought to the laboratory of the department of geology, faculty of science, Chulalongkorn University. Soil samples were contained in the container for baking which were weighted for the mass of moist soil with container in gram. Before that, all of containers were weighted for the mass of container. Then soil samples were baked in the oven with temperature of 105°C for 24 hrs. After cooled down, they were weighted again for the mass of dry soil with container. All of mass data would be calculated as a following equation which modified from equation (2.1).

$$\theta_m = \frac{m_w}{m_s} = \frac{m_2 - m_1}{m_3 - m_1} \quad \text{(A-1)}$$

which θ_m is gravimetric soil water content (dimensionless)

m_w is mass of soil water (g)

m_s is mass of dry soil (g)

m_1 is mass of container (g)

m_2 is mass of wet soil (g)

m_3 is mass of dry soil (g)

The results of gravimetric soil water content would be converted to VSWC by equation (2.2) with the density of soil and water. Density of soil was evaluated from mass divided by volume of dry soil samples. The bulk density of dry soil is 1.43 g.cm^{-3} and the density of water used an approximate value of 1 g.cm^{-3}. All of soil water content data were multiplied by 100 to be a percentage.

Table A-1 Raw data of soil water content from gravimetric method of the first experiment.

Soil Sampling Point	Soil Water Content														
	10 cm Depth					20 cm Depth					30 cm Depth				
	m_1	m_2	m_3	%GSWC	%VSWC	m_1	m_2	m_3	%GSWC	%VSWC	m_1	m_2	m_3	%GSWC	%VSWC
1	42.240	96.862	87.684	20.196	28.881	41.646	108.265	97.253	19.803	28.319	40.165	104.403	93.870	19.613	28.046
2	52.070	111.977	101.742	20.605	29.465	50.225	127.258	113.454	21.832	31.219	40.081	125.558	108.960	24.097	34.459
3	41.116	102.651	91.284	22.658	32.401	36.515	93.947	82.636	24.525	35.070	40.343	109.045	97.969	19.220	27.485
4	41.338	118.505	105.280	20.683	29.576	41.728	127.572	113.926	18.901	27.028	50.339	117.792	106.004	21.177	30.283
5	41.950	128.044	112.927	21.298	30.457	45.162	128.729	116.174	17.680	25.283	51.960	147.770	130.563	21.891	31.304
6	39.999	128.420	111.849	23.063	32.981	44.156	126.104	111.101	22.411	32.048	42.497	125.841	111.269	21.189	30.300
7	35.461	117.129	103.411	20.188	28.869	45.015	124.103	110.769	20.279	28.998	39.688	124.777	108.542	23.579	33.718
8	34.927	93.661	83.459	21.021	30.060	42.478	119.891	106.002	21.864	31.266	51.226	129.297	115.166	22.100	31.604
9	51.102	123.286	110.775	20.966	29.981	44.377	122.368	109.821	19.172	27.416	44.259	114.903	104.866	16.561	23.682

Note: The density of soil is 1.43 $g.cm^{-3}$, The density of water is 1 $g.cm^{-3}$

m_1 = Mass of container (g), m_2 = Mass of wet soil (g), m_3 = Mass of dry soil (g)

GSWC = Gravimetric Soil Water Content [$g.g^{-1}$]

VSWC = Volumetric Soil Water Content [$cm^3.cm^{-3}$]

Table A-2 Raw data of soil water content from gravimetric method of the second experiment.

Soil Sampling Point	Soil Water Content														
	10 cm Depth					20 cm Depth					30 cm Depth				
	m_1	m_2	m_3	%GSWC	%VSWC	m_1	m_2	m_3	%GSWC	%VSWC	m_1	m_2	m_3	%GSWC	%VSWC
1	28.463	123.310	107.297	20.312	29.047	37.913	125.476	109.498	22.320	31.918	26.850	143.974	125.765	18.409	26.324
2	28.500	116.252	100.011	22.711	32.477	28.002	119.697	101.937	24.021	34.350	38.040	159.334	139.600	19.431	27.786
3	29.726	125.548	107.072	23.887	34.159	37.198	127.805	110.569	23.492	33.593	26.220	118.523	99.144	26.574	38.001
4	30.501	127.609	112.415	18.549	26.525	27.718	128.760	110.912	21.453	30.678	26.103	148.069	123.896	24.719	35.348
5	30.360	125.657	110.106	19.501	27.886	27.335	127.810	109.148	22.811	32.619	27.699	141.563	123.111	19.339	27.655
6	26.576	109.370	94.844	21.278	30.427	36.334	125.957	109.578	22.362	31.978	31.275	134.760	114.409	24.480	35.006
7	27.314	117.834	101.917	21.336	30.510	25.979	106.584	92.238	21.651	30.961	27.491	130.777	111.025	23.645	33.813
8	32.049	119.487	103.692	22.047	31.527	26.232	117.501	101.939	20.556	29.394	26.794	123.409	105.308	23.054	32.968
9	31.439	107.695	94.447	21.026	30.067	22.035	101.504	88.953	18.756	26.821	27.983	115.940	102.058	18.740	26.799

Note: The density of soil is 1.43 $g.cm^{-3}$, The density of water is 1 $g.cm^{-3}$

m_1 = Mass of container (g), m_2 = Mass of wet soil (g), m_3 = Mass of dry soil (g)

GSWC = Gravimetric Soil Water Content [$g.g^{-1}$]

VSWC = Volumetric Soil Water Content [$cm^3.cm^{-3}$]

Table A-3 Raw data of soil water content from gravimetric method of the third experiment.

Soil Sampling Point	Soil Water Content														
	10 cm Depth					20 cm Depth					30 cm Depth				
	m_1	m_2	m_3	%GSWC	%VSWC	m_1	m_2	m_3	%GSWC	%VSWC	m_1	m_2	m_3	%GSWC	%VSWC
1	30.476	114.609	109.321	6.707	9.591	22.007	87.746	82.231	9.157	13.095	26.760	95.198	89.901	8.389	11.996
2	28.469	105.462	101.991	4.721	6.751	31.247	111.587	105.840	7.704	11.017	37.171	107.093	101.258	9.105	13.020
3	36.302	107.789	102.873	7.385	10.560	26.544	93.410	88.134	8.566	12.250	38.007	105.009	99.507	8.946	12.793
4	27.951	97.661	90.833	10.858	15.528	29.698	101.784	93.454	13.065	18.684	26.193	89.037	80.862	14.954	21.384
5	27.459	105.315	101.342	5.377	7.690	32.016	109.789	103.935	8.140	11.640	26.821	88.202	82.986	9.287	13.280
6	31.405	108.215	103.234	6.935	9.916	26.073	104.707	97.642	9.872	14.116	26.203	83.907	77.333	12.857	18.386
7	27.286	100.657	95.062	8.255	11.805	27.692	110.605	102.615	10.664	15.250	28.441	100.700	92.592	12.639	18.074
8	27.282	112.339	106.163	7.830	11.196	37.886	108.678	102.909	8.872	12.687	25.950	93.073	87.193	9.601	13.730
9	27.976	104.417	98.428	8.501	12.156	27.675	109.404	102.649	9.010	12.884	30.329	103.986	96.757	10.882	15.562

Note: The density of soil is 1.43 $g.cm^{-3}$, The density of water is 1 $g.cm^{-3}$

m_1 = Mass of container (g), m_2 = Mass of wet soil (g), m_3 = Mass of dry soil (g)

GSWC = Gravimetric Soil Water Content $[g.g^{-1}]$

VSWC = Volumetric Soil Water Content $[cm^3.cm^{-3}]$

APPENDIX B
SECONDARY DATA

Rainfall data is used from the nearest station from the experiment field about 20 km at north, as shown in table B1. The station is Station S.9 Ban Pa (Code 5445), Amphoe KaengKhoi, Changwat Saraburi, Thailand. Which is in the organization of Hydrology Irrigation Center for Central Region, Office of Water Management and Hydrology, Royal Irrigation Department, Thailand.

Table B-1 The Daily Rainfall of Station S.9 Ban Pa (Code 5445), Amphoe KaengKhoi, Changwat Saraburi, Thailand in WaterYear: 2014 (April 2014 – March 2015). Three underlines in data are the data on the experiment days.

Date	Month												Annual
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
1	0.0	0.0	0.0	0.0	6.8	12.2	0.0	0.0	0.0	0.0	0.0	8.5	
2	0.0	0.0	0.0	0.0	0.0	28.3	17.8	0.0	0.0	0.0	0.0	0.0	
3	0.0	0.0	49.3	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	
4	0.0	0.0	0.0	0.0	0.0	4.1	0.0	41.2	0.0	0.0	0.0	0.0	
5	0.0	0.0	3.3	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
6	0.0	12.0	4.3	0.0	12.8	22.8	11.0	0.0	0.0	2.5	0.0	0.0	
7	0.0	0.0	0.0	0.0	56.2	0.0	0.0	0.0	0.0	5.0	0.0	0.0	
8	0.0	0.0	0.0	0.0	3.5	0.0	29.3	13.6	0.0	0.0	0.0	0.0	
9	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
10	0.0	0.0	0.0	0.0	0.0	0.0	25.2	0.0	0.0	0.0	0.0	10.5	
11	0.0	0.0	0.0	0.0	1.9	0.0	7.5	0.0	0.0	0.0	0.0	0.0	
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
13	5.2	0.0	0.0	28.4	19.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
14	12.0	0.0	12.8	5.3	62.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
15	0.0	0.0	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
16	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
17	5.8	12.3	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18	0.0	7.0	0.0	0.0	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	5.7	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	3.0	0.0	56.3	0.0	4.0	0.0	10.8	0.0	0.0	0.0	0.0	0.0	
21	0.0	0.0	0.0	0.0	0.0	5.8	11.7	0.0	0.0	0.0	0.0	25.8	
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
23	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
24	0.0	0.0	0.0	37.2	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	
25	0.0	0.0	27.5	0.0	0.0	7.2	15.3	0.0	0.0	0.0	0.0	15.2	
26	0.0	0.0	2.7	10.3	0.0	8.9	0.0	0.0	0.0	0.0	0.0	0.0	
27	0.0	53.5	0.0	0.0	0.0	0.0	0.0	45.8	0.0	0.0	0.0	5.8	
28	0.0	23.2	0.0	0.0	33.5	7.8	14.8	0.0	0.0	0.0	36.5	0.0	
29	13.5	0.0	20.7	0.0	1.5	24.8	0.0	0.0	0.0	0.0		4.0	
30	0.0	31.8	5.5	5.3	5.3	3.8	9.7	0.0	0.0	0.0		0.0	
31		0.0		0.0	0.0		0.0		0.0	0.0		0.0	
Total	45.2	139.8	199.2	86.5	218.9	135.5	153.1	100.6	0.0	7.5	36.5	69.8	1,192.6
Mean	1.5	4.5	6.6	2.8	7.1	4.5	4.9	3.4	0.0	0.2	1.3	2.3	
Rain/Day	6	6	13	5	15	12	10	3	0	2	1	6	79
Max Rain/day	13.5	53.5	56.3	37.2	62.5	28.3	29.3	45.8	0.0	5.0	36.5	25.8	
Maximum 1 Day Rainfall = 62.5 mm [14 Aug 2014]													

VITA

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