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Effectiveness of Electrical Capacitance Volume Tomography Method in Soil Water Content Measurement

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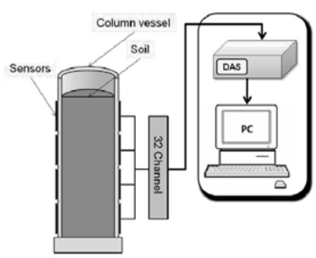
Graphical abstract



Abstract

Many researchers, in the recent years have developed various techniques for determining water content of the soils. Electrical Capacitance Volume Tomography (ECVT) is one of the techniques developed by using various types of sensors to improve the quality and effectiveness in the determination of water content in the soil. The technology is based on the capacitance measurement generated from a whole volumetric image of the region which is surrounded by three-dimensional geometry capacitance sensor. This study was carried out to determine the effectiveness of ECVT in measuring soil water contents in fine sand and silty sand to compared with the gravimetric method. Results analysis show that the correlations of the water content measurement R^2 using ECVT and gravimetric methods for fine sand and silty sand are very good, about 0.978 and 0.988, respectively. These suggest that ECVT method has a good potential in determining the soil water content in this respective soil type.

Keywords: Soil water content; electrical capacitance volume tomography (ECVT); gravimetric method

1.0 INTRODUCTION

Soil water content is one of the soils physical properties that are very important in defining the relationship between physical qualities with the specific function of soil (Arshad *et al*. 1996). The study of soil water content is useful for many discipline area. For example in agriculture area, where the soil water content is important to guarantee the quality of crops. In land activity area, the study about slope stability also includes the soil water content (Mukhlisin *et al*. 2011a and Mukhlisin *et al*. 2011b).

Several methods for measuring soil water content has been reported in many literatures (Kutflek and Nielsen 1994). The methods are including gravimetric method, dielectric method, electromagnetic method, etc. The advantages and limitations of each method also have been presented (Tarantino *et al*. 2008). Recently, a new tomography tool called Electrical Capacitance Volume Tomography (ECVT) is used to monitor and measure soil volumetric water content (Mukhlisin *et al*. 2012). The advantage of ECVT application is that the capacitance sensors can do a real-time 3D volume imaging (Wang *et al*. 2010). The relationship between relative permittivity and water content have been discussed in Wu *et al*. 2010, where relative permittivity measurement widely used to calculate water content. Therefore ECVT should be a potential tool to calculate volumetric water content with the real-time measurement. This paper objective is to study the potential of ECVT in determining the soil volumetric water content by comparisons with the laboratory gravimetric method. This is to measure the reliability of ECVT method when comparing it to the gravimetric method.

2.0 ELECTRICAL CAPACITANCE VOLUME TOMOGRAPHY (ECVT)

2.1 ECVT System

ECVT is a non-invasive tomography that measures capacitance then generates of whole volumetric image from permittivity distribution (Warsito *et al*. 2007a; Warsito *et al*. 2007b). ECVT employed capacitance modality to measure the distribution of permittivity based on Poisson's equation (Mukhlisin *et al.* 2012):

$$\nabla.(\varepsilon(x,y,z)\nabla\emptyset(x,y,z) = -\rho(x,y,z)) \tag{1}$$

where ε is the relative permittivity, $\emptyset$ is the potential electric, and ρ is the charge distribution. The capacitance value is defined as

$$C = \frac{1}{\nabla V} \oint \varepsilon(x, y, z) \nabla \emptyset(x, y, z).n\, dl \quad (2)$$

where C is the capacitance and V is the potential difference. The approximation of Eq. 2 can be written as matrix expression

$$C = SG \quad (3)$$

where C is capacitance matrix, S is the sensitivity matrix, and G is permittivity distribution matrix.

The inverse problem is defined as the way to generate value of permittivity. This can be obtained as S^T is the transpose of sensitivity matrix.

$$C = S^T G \quad (4)$$

The value of G produces image that are prepared on the basis of voxels. Each voxel has the information of permittivity from each specific location on the geometry of the system.

2.2 Normalized Volumetric Water Content

Normalized volumetric water content is the dimensionless of volumetric water content. The normalized volumetric water content, Θ can be expressed as

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (5)$$

where θ is the volumetric water content, θ_r is the residual volumetric water content, and θ_s is the saturated volumetric water content. The value of normalized volumetric water content ranges from 0 to 1. The relative permittivity of air, dry soil, saturated soil and water are 1, 2 to 4, 23 to 28, and 80, respectively (Mukhlisin *et al*. 2012). In ECVT system, relative permittivity is obtained in the form of a normalized permittivity. Thus, the range of permittivity value is between 0 (normalized permittivity of air) and 1 (normalized permittivity of water).

2.3 Soil Water Content and Relative Permittivity Relationship

The relationship between relative permittivity and volumetric water content has been used by previous researchers to determine the volumetric water content. In this study, the common-well empirical relationship between relative permittivity and volumetric water content proposed by Topp *et al*. (1980) is used. The equation is shown below:

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

■3.0 METHODOLOGY

In this study, the fine sand and silty sand water contents were measured using gravimetric and ECVT methods. According to USDA Soil Taxonomy System, the diameter size of the sand soil particle (Figure 1a) is around 0.10 to 0.25 mm while the silty sand is around 0.002 to 0.05 mm (Figure 1b). The bulk densities of sand soil and silty sand used in this study are 1747 kg/m^3 and 1534 kg/m^3. Every test for both types of soil was repeated 3 times to get the average data.

Figure 1a Fine sand

Figure 1b Silty sand

3.1 ECVT Method

The sketch of ECVT system with soil in a column vessel with diameter 11.5 cm and high 27 cm is shown in Figure 2. Before the experiment started, the first step to perform is the calibration process. The purpose of this step is to normalize the data so that the capacitance value is within 0 and 1. Low permittivity value (air) is denoted as 0, while high permittivity value (water) is denoted as 1. Permittivity value depends on the object (in this case is the soil) in the experiment as it does not necessarily specific to the water, air or soil. The example figure of unsaturated soil compared to the saturated soil by ECVT system is shown in Figure 3a and 3b, respectively. As expected, many parts of water saturated soil will have permittivity value of 1 (blue colour) while the unsaturated soil will have a combination of other colours (red to blue). About 3000 g weight of soil is used for this experiment. Water is added to the soil from 5% until 25% of soil mass. Then, the water and the soil are mixed until well-blended before the mix is transferred into the column vessel. For each measurement, the total interval times was set to be 100 times per second. Matlab software is used to operate this system and the capacitance data will be measured by the data acquisition system (DAS). Subsequently, the data will be transferred to the computer. After that, the volumetric water content can be calculated using Eq. 6.

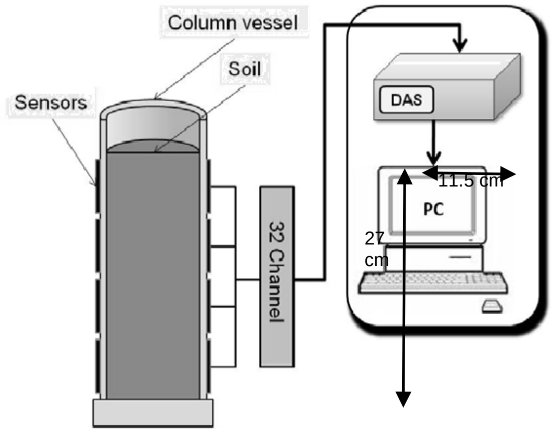


Figure 2 Sketch of an ECVT system (Source: Mukhlisin *et al.* 2012)

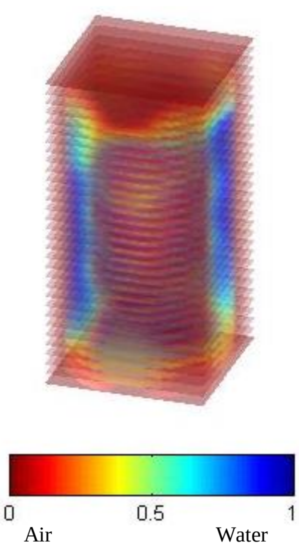


Figure 3a Unsaturated soil

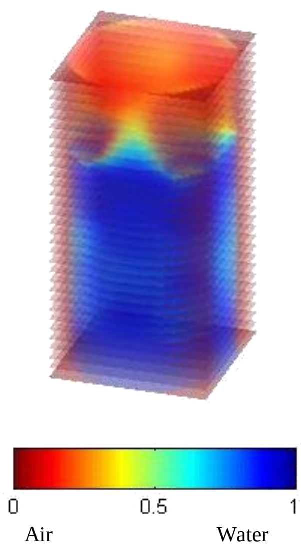


Figure 3b Saturated soil

3.2 Gravimetric Method

For gravimetric method, 4000 g of soil weight is used and the percentage of water was added to the soil. The percentage of water is about 5% until 25% of bulk soil mass, with the addition of 5% per run. After water is mixed well with soil, 400 g of wet soil will be taken. The soil will then is transferred and compacted into the core ring before labelling. These steps are repeated until the soil is saturated. The samples will be dried out in the oven for at least 24 hours.
Gravimetric water content, *w* value can be obtained from

$$w = \frac{\text{Weight of soil prior to dry} - \text{Weight of soil after drying}}{\text{Weight of soil after drying}} \quad (7)$$

Therefore, the expression for volumetric water content, θ can be obtained, viz.

$$\theta = w \times (\rho_b / \rho_w) \quad (8)$$

where ρ_b, and ρ_w are the bulk density of soil and water density, respectively.

■4.0 RESULTS AND DISCUSSION

Figures 4 and 5 present the volumetric soil water content against percentage of water added to the bulk fine sand and silty sand, respectively. The gravimetric method plotted as blue colour and ECVT plotted as red colour. These figures show that the value of soil water content keeps increasing due to the additional water added. At 10% of additional water, the value measured by ECVT almost similar with the value of by gravimetric method for both types of soil.

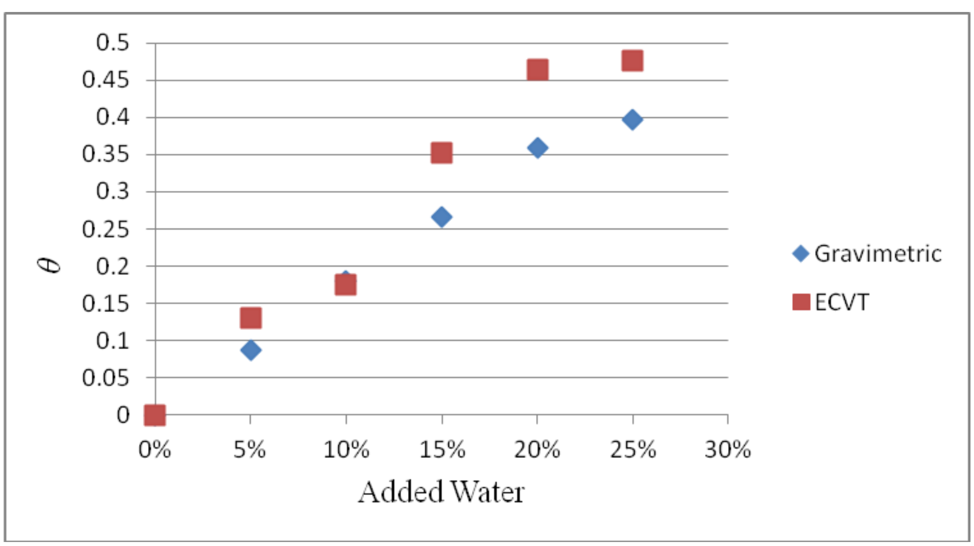


Figure 4 Average fine sand water content against percentage of added water for both methods

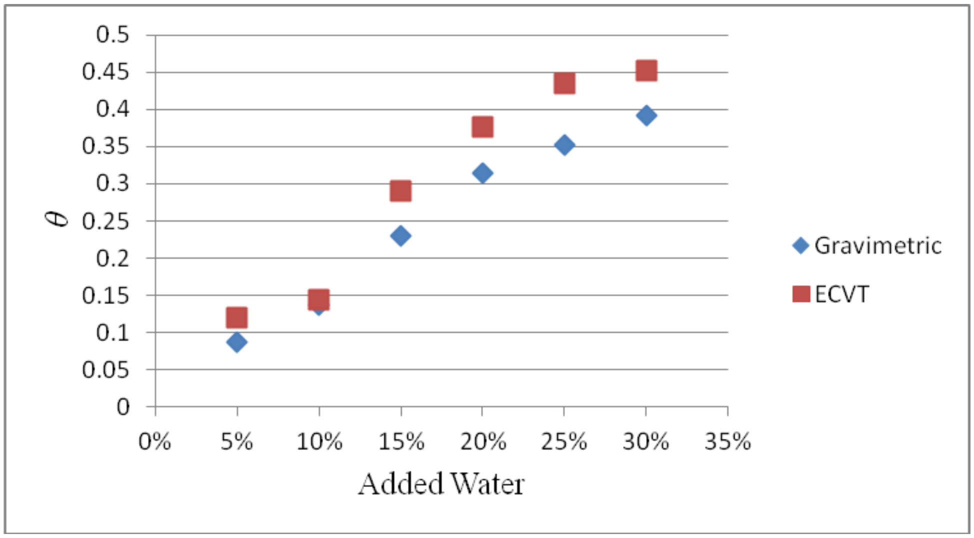


Figure 5 Average silty sand water content against percentage of added water for both methods

Figure 6 shows that the regression line for the result soil water content value. The coefficient of determination, R^2 is defined by

$$R^2 = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (9)$$

where $f_i = a + bx$, linear equation of the line and $\bar{y} = 1/n \sum_{i=1}^{n} y_i$. The linear regression line has the coefficient of determination, R^2 value of 0.978 that shows good correlation of the water content measurement using ECVT and gravimetric methods. The result is quite similar with that of silty sand with R^2 is 0.988 a shown in Figure 7. As the R^2 values for both soils are almost to 1, these results suggest that the volumetric water content by Topp *et al*. (1980) equation using capacitance measurement of ECVT method is comparable and have a good correlation with that of gravimetric method, especially when added water is below 10% . Standard deviations of differences between ECVT and gravimetric values were from 0.004 to 0.06 and 0.005 to 0.07 for silty sand and fine sand, respectively. Therefore, it can be concluded that ECVT may be useable in determining the soil water content in these respective soil types.

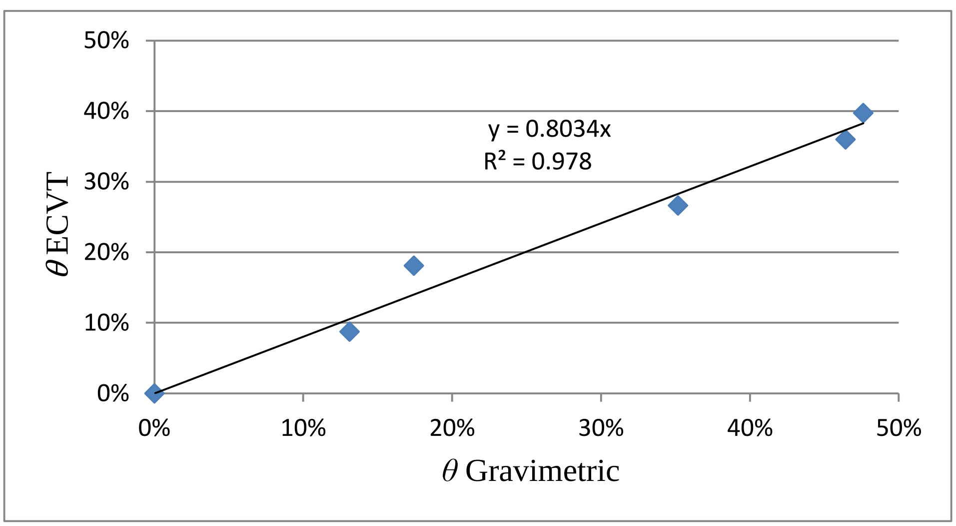


Figure 6 Comparison of both techniques for fine sand water content

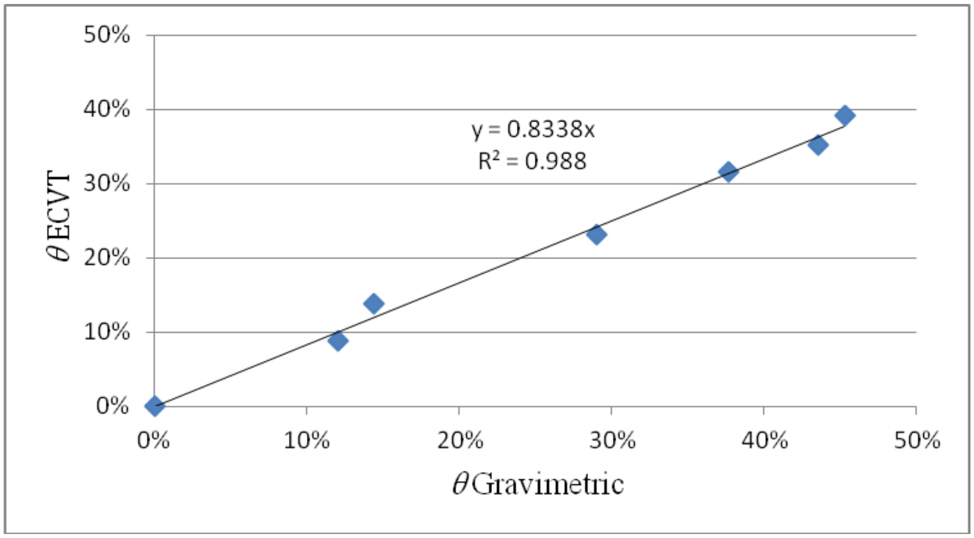


Figure 7 Comparison of both techniques for silty sand water content

5.0 CONCLUSIONS

This study presents an investigation of measuring volumetric soil water content by employing ECVT and gravimetric techniques on fine sand and silty sand. From the comparisons for both methods, ECVT technique is well acceptable for measuring soil water content. The value of volumetric water content measured by this technique is reliable and efficient.

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