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Void ratio determination in soil using time domain reflectometry

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ABSTRACT

In geotechnical engineering, the void ratio stands out as a critical parameter that is closely related to several essential soil properties, including permeability, compressibility, settlement and bearing capacity. Accurate and rapid determination of this key parameter is therefore essential. Traditional methods involve assessing the properties of soil samples taken from the field using simple laboratory techniques. However, determining the void ratio requires the determination of parameters such as soil water content and specific gravity. Whilst these parameters can be determined using straightforward methods, their determination in civil engineering typically takes place over an extended period. Consequently, there is a tendency to explore alternative methods for delineating specific physical properties of soils. While some methods provide direct results, such as nuclear methods, others provide results indirectly through correlations using techniques such as drilling. Due to technological advances and the increased importance of time as a critical economic parameter, there is an increasing demand for fast and reliable methods. Accordingly, Time Domain Reflectometry (TDR), which is widely used in electrical engineering, has begun to find application in civil engineering. In this study, research is carried out to determine the void ratio, a key parameter in soil mechanics, using the TDR method. Experiments were therefore carried out on samples prepared in the laboratory with different void ratios, and the void ratios of the soils were then determined using the TDR method. The results of this study suggest that the TDR method could serve as an alternative approach for determining the void ratio of soils.

I. INTRODUCTION

The void ratio, as an index property of soil, is one of the basic parameters in many important engineering problems such as bearing capacity, consolidation, stability and permeability of soil [1-3]. Therefore, it is very important to determine the void ratio of a soil accurately and quickly. Traditionally, the preferred method for determining the void ratio is to subject the field boring samples to a series of tests in geotechnical laboratories and then determine the void ratio by simple calculations. However, in cohesive soils this method can easily be used to take undisturbed soil samples, whereas in granular soils it can be very laborious and costly. Therefore, the void ratio of granular soils is generally estimated using empirical relationships established from in-situ measurements and measurements obtained from tests such as SPT, CPT, etc.. However, these methods are affected by changes in the soil grain diameter and may occasionally give inaccurate results [4-6]. Another method can be listed as geophysical methods. According to geophysical methods, void ratio can be estimated by using shear wave velocity and surface wave velocity [7-13].

As these methods are in some cases inadequate, new methods need to be developed. To this end, it is considered appropriate to investigate the applicability of TDR, which uses radar logic to locate the points where cable damage occurs. It first became an accepted technique for cable testing in the 1930s. The physical principles are simple. The electromagnetic signal sent along a known transmission line will not be reflected if there is no change in

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impedance. If there is an impedance difference on the line, i.e. if there is a discontinuity in the transmission line, part of the signal will be reflected from that point. By using the reflected signal, this technique can be used to find the location and extent of the damage [14]. The method is currently used in a wide range of applications in fields such as geotechnics, hydrology, construction, agriculture, materials testing and aviation [15]. TDR is effective for monitoring landslides by detecting shear planes in slopes [16-17], as well as for scour monitoring [18-19], monitoring of stream and drainage stages [20], monitoring ballast fouling [21], measuring water content in railway subgrades [22], assessing compaction quality by measuring soil saturation [23], and measuring water content during continuous desiccation and intact conditions [24].

The TDR method has been used in geotechnical engineering for the last 30 years as a method of indirectly determining water content from the dielectric properties of soils. Apart from the TDR method, there are other methods such as Amplitude Domain Reflectometry (ADR) and Frequency Domain Reflectometry (FDR), whose basic approach is to determine the dielectric coefficient of the soil [25]. Among these methods, only TDR directly determines the velocity of the signal, while ADR solely measures the amplitude of the reflected signal. The basic logic of these methods is based on the determination of the velocity of an electromagnetic wave passing through the soil by means of metal rods buried in the soil. The speed at which the electromagnetic wave travels through the soil depends on the dielectric coefficient of the soil. As the dielectric coefficient increases, the speed of transmission slows down [26]. Soil is a composite structure consisting of air, minerals, organic particles and water. Soil components have different dielectric coefficients, air has a value of 1, water has a value of 80 and grains have a value between 2 and 4. The fact that the dielectric coefficient of water is considerably higher than the others means that the dielectric coefficient measured in soil, which is actually a soil-water-air mixture, is largely related to the amount of water. The water content of soils can be determined using empirical relations established by laboratory studies of the soil whose dielectric coefficient is being determined [27].

Jones et al. (2002) highlighted TDR as an accurate and automated technique for assessing water content and electrical conductivity in porous media. They explained how water content is determined from dielectric permittivity, while electrical conductivity is inferred from TDR signal attenuation. The influence of clay and organic matter on water binding and the need for individual calibration were discussed. It also highlighted the versatility of TDR probe configurations for specific site and media requirements. It also highlighted advances in TDR technology and other dielectric methods, suggesting the potential for cost-effective and accurate determination of various properties beyond water and solute content in porous media [28].

Soil moisture content and density have a significant effect on pavement performance, particularly under cyclic traffic loads. TDR provides a non-destructive approach to assessing both moisture content and density. Byuhan et al (2020) performed laboratory TDR measurements under varying conditions and developed theoretical formulations correlating voltage drop and electrical conductivity. These formulations were validated against field data, demonstrating satisfactory accuracy. The calibrated models facilitate routine performance monitoring and contribute to a better understanding of material behavior, such as road rutting [29].

Bittelli et al. (2021) introduced a novel algorithm integrated into TDR software to effectively measure soil bulk density. Their method, tested on samples with different textural properties, showed an accuracy between 1 and 3%. The algorithm allows the simultaneous measurement of density and soil water content, using automated methodology and non-linear least-squares optimization to analyze multiple waveforms. Dielectric mixing models gave the most accurate results for deriving soil water content from electrical permittivity. The robustness of the method makes it suitable for field monitoring applications [30].

Fu et al. (2021) developed a method for estimating soil water retention curves (SWRCs) using bulk soil electrical conductivity (σ) as a proxy for water content. Their approach uses the van Genuchten model parameters m and α, which are derived from σ measurements at saturated and residual water contents, together with intermediate water content measurements. Thermo-time domain reflectometry sensors were used to measure σ and water content (θ) simultaneously. SWRCs were estimated for different soils and compared favorably with direct SWRC measurements, demonstrating the accuracy of the σ-based method [31].

Yu and Drnevich (2004) proposed a novel method for assessing soil water content and dry density using a single TDR test, offering improvements over ASTM D6780. Their method involves the simultaneous measurement of apparent dielectric constant and bulk electrical conductivity on the same soil sample, with calibration equations correlating these parameters with gravimetric soil water content and dry density. This approach compensates for temperature effects and provides a fast, automated test of about 3 minutes, making it suitable for both laboratory and in-situ applications, providing an efficient tool for construction quality control [32].

Zhang et al. (2023) investigated the shrink-swell behavior of clayey soils, which is crucial for understanding their impact on agricultural and engineering projects. They introduced a thermo-time domain reflectometry technique for in-situ monitoring of soil shrinkage-swelling dynamics and hydrothermal regimes during wet-dry cycles. Field experiments on two clayey soils showed significant volume changes, with the thermo-TDR method providing accurate bulk density measurements compared to independent core sampling and ruler image processing methods. The technique also allowed consistent monitoring of soil shrinkage curves and water retention areas, demonstrating its reliability for continuous in-situ assessment of soil shrinkage-swell processes, with implications for future comprehensive soil transport models [33].

Leao et al. (2020) conducted a study focusing on water management in agricultural areas of tropical savannas, where low rainfall and prolonged droughts necessitate efficient irrigation practices. TDR sensors evaluated for estimation of soil water content in different soil types commonly found in the Brazilian savannah. The study investigated different calibration equations considering soil properties such as bulk density, organic matter, clay content and magnetic materials. The results showed that a single logarithmic calibration equation performed best across all soils, with no significant influence of bulk density, clay content, organic matter or magnetic permeability on the calibration equations [34].

Lee and Yoon (2020) presented a novel method for measuring hydraulic conductivity using TDR. They established a theoretical relationship between the dielectric constant obtained from TDR and hydraulic conductivity, demonstrating its potential as an alternative approach to conventional methods. Their method, validated by various experiments, showed a high similarity to results obtained from traditional constant head experiments, confirming its reliability and effectiveness in determining hydraulic conductivity by TDR [35].

Yoon and Lee (2010) conducted a study aimed at estimating elastic moduli and void ratios using compressional and shear wave velocities and electrical resistivity measured by a field velocity resistivity probe (FVRP). They used piezoelectric and bending elements installed on the tip of the FVRP frame to measure waves and electrical resistivity. Tests were carried out in various soil mixtures in both controlled and field conditions. The data collected was used to determine Young's moduli and void ratios, showing promising potential for the FVRP to accurately assess soil properties [36].

The importance of accurate and rapid determination of void ratio under field conditions is obvious. Given the varying advantages and disadvantages of existing methods, it is essential to estimate void ratio quickly and innovatively. This study aims to investigate the potential of using TDR, which has previously been used for a variety of purposes, as a rapid and reliable tool for determining void ratio in soil. Experiments were carried out on two different soil samples to assess the feasibility of the TDR method. The void ratios of the soils were determined using both conventional methods and TDR. The values obtained were then compared to evaluate the effectiveness of the method.

II. MATERIALS AND METHOD

2.1 Materials

As part of the experimental study, soil samples from two different quarries in Kocaeli are used. The proportions of gravel, sand and fine grains in the soil are determined by sieve analysis tests carried out on the materials brought to the laboratory and are presented in Table 1. As seen in Table 1, three of the soil samples are classified as poorly graded sand (SP), while the other soil sample is classified as silty sand (SM).

Table 1. Percentages of gravel, sand, and clay+silt in utilized soils

Soil Classification	Gravel (%)	Sand (%)	Clay + Silt (%)
SP	9	86	5
SM	0	90	10

2.2 Methods

The study began with the procurement of soil samples to be used in the experimental study. The relationship between the dielectric constant - volumetric water content - void ratio of the soil was then established theoretically. The accuracy of this theoretical relationship was investigated experimentally. The flow chart of the study is shown in Figure 1.

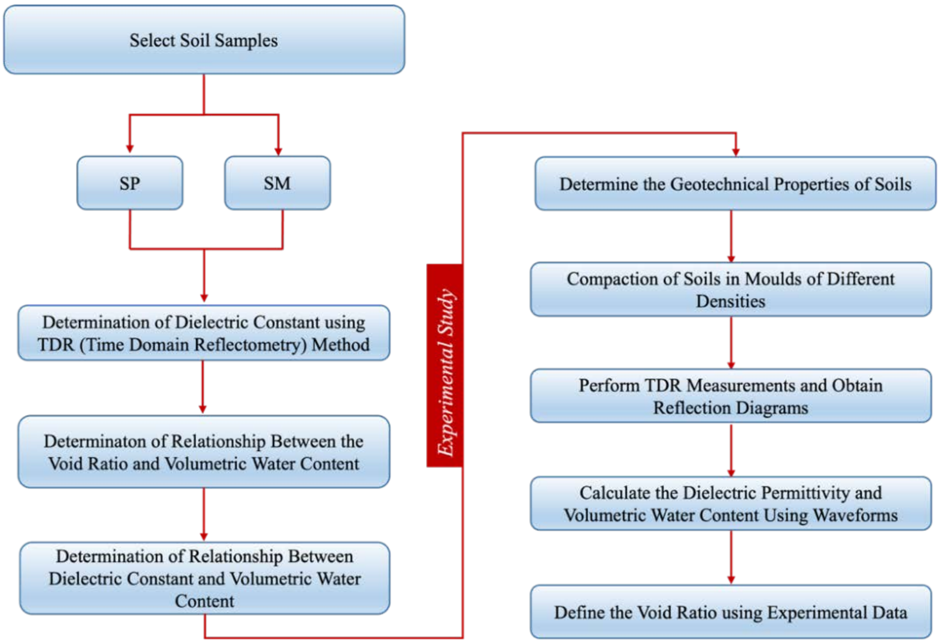


Figure 1. Flow diagram of the study

2.2.1. Determination of the dielectric constant of soils using the TDR method

In TDR reflection forms, two different reflections occur. The first reflection occurs at the air-soil interface and the second reflection occurs at the end of the TDR probe [32]. Topp et al (1980) showed that the apparent permittivity is related to the velocity of an electromagnetic wave along the transmission line. The relationship between the apparent velocity of the electromagnetic wave and the dielectric constant is given by equation (1) [37].

$$v = \left(\frac{c}{\sqrt{K_a}} \right) \tag{1}$$

Where v is the apparent velocity of propagation and c is the speed of light. The apparent velocity of propagation is related to the travel time between the reflection points. This relationship is given in equation (2).

$$v = \left(\frac{2L}{t} \right) \tag{2}$$

Where t is the time taken for the reflected signal to travel between the start and end points of the probe in the soil and L is the length of the probe in the soil. Combining equations (1) and (2), the dielectric constant can be expressed as in equation (3).

$$K_a = \left(\frac{ct}{2L} \right)^2 \tag{3}$$

In this equation, the term $\left(\frac{ct}{2}\right)$ is defined as the apparent length (L_a) (Baker and Allmaras, 1990) [38]. Therefore, equation 3 can be defined as follows:

$$K_a = \left(\frac{L_a}{L_p}\right)^2 \tag{4}$$

The dielectric constant is defined as the ratio of the apparent length (L_a) to the actual length (L_p) of the probe, where L_a is the measured length and L_p is the physical length of the probe. The apparent length is determined using the TDR reflection form. For this method to be effective, it is essential that the start and end points of the probe are identified in the reflection form. Two different techniques have been proposed to identify these critical points. The first, introduced by Topp et al (1982), is the tangent method, while the second, introduced by Baker and Allmaras (1990), is the derivative method [38-39].

According to the "tangent" method proposed by Topp et al. (1982) for determining the positions of the points considered as the beginning and end of the probe, the beginning point is defined as the intersection of the tangents drawn on the horizontal and vertical arms before and after the first diffraction of the reflection curve. The end point is defined as the intersection of the tangents drawn on the horizontal and vertical arms before and after the diffraction occurring at the end of the reflection curve. These determined start and end points are interpreted as the points where the probe contacts the ground and the end point of the probe respectively. In addition, the time elapsed between these two points is considered as the time "*t*" [39]. Figure 2 shows graphically how the Tangent method can be used.

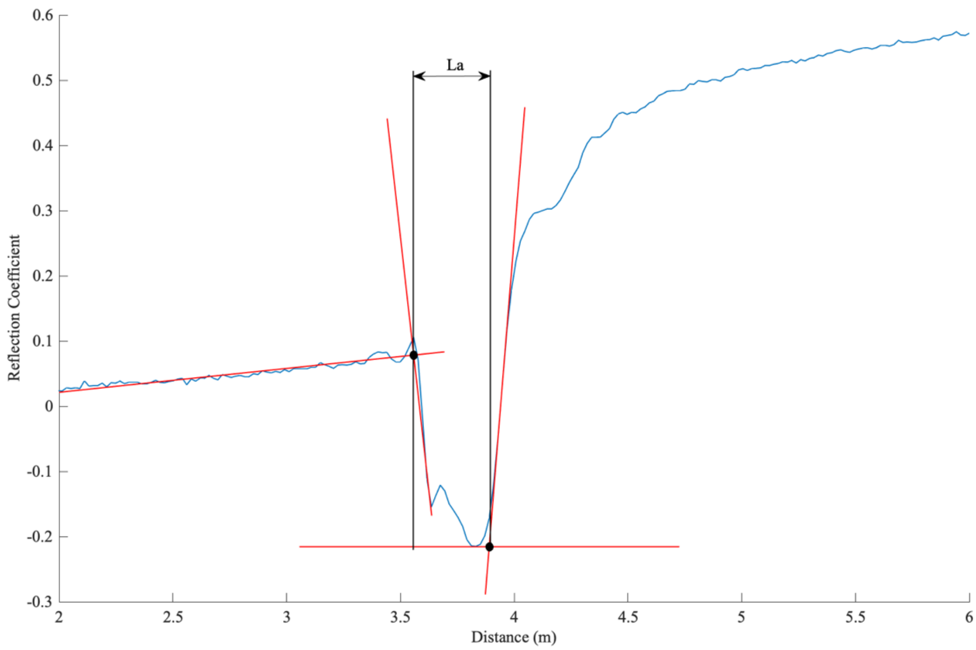


Figure 2. Graphical representation of the tangent method

Another method, known as the "derivative method", was developed by Baker and Allmaras (1990). In this approach, the derivative of the TDR record with respect to time is taken. Two tangents are then drawn from two points on the TDR record corresponding to the maximum and minimum values of the derivative, with the slopes of these tangents representing the values of the derivative at those specific points. Horizontal tangents passing through the maximum and minimum values of the TDR record are then intersected with the two tangents previously drawn. This process determines the start and end points of the probe [38]. Figure 3 shows graphically how the derivative method can be used.

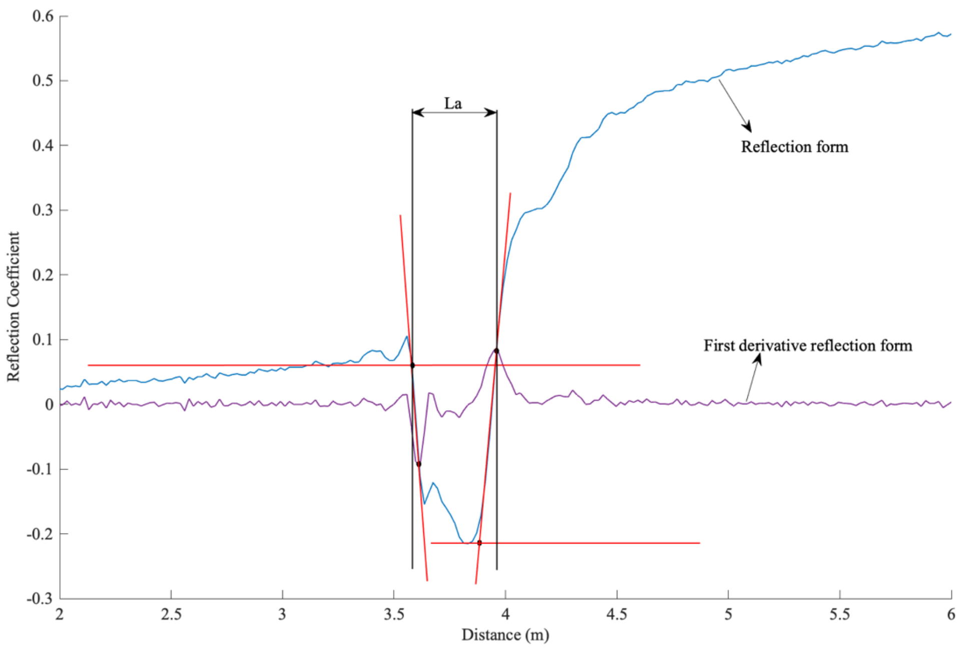


Figure 3. Graphical representation of the derivative method

2.2.2. Relationship between dielectric constant and volumetric water content

While the measurement of dielectric constant and the subsequent calculation of water content from this value has become common in recent years, the earliest studies on the subject date back to 1939, as noted by Patterson and Smith (1980) [40]. Despite numerous attempts to determine water content from the dielectric constant during the 1960s and 1970s, no significant results were obtained, as reported by Davis and Annan (1977) [41].

The frequency range of the TDR device, originally designed for cable testing, is significant due to the frequency dependence of the dielectric constant. Topp et al. (1980) demonstrated that the dielectric constant can be accurately determined in the low-frequency range (1-1000 MHz) [37].

The dielectric constant is composed of two components: the real part and the imaginary part. The imaginary part is referred to as the dielectric loss, which occurs along the transmission line, as noted by Davis and Annan (1977) [41]. Topp et al. (1980) have demonstrated that the dielectric loss, representing the imaginary part of the dielectric constant, is negligible when measuring water content [37].

According to Topp et al. (1980), there is a third-order relationship between volumetric water content and dielectric constant, which is expressed in Equation (5) [37].

$$\theta = 4.3x10^{-6} K_a^3 - 5.5x10^{-4} K_a^2 + 2.92x10^{-2} K_a - 5.3x10^{-2} \quad (5)$$

In this context, θ represents the volumetric water content and Ka denotes the dielectric constant. The correlation established by Topp et al. (1980) has been corroborated by various studies conducted by Dasberg and Dalton (1985), Heimovaara (1994), Roth et al. (1992), and Zeglin et al. (1992) [42-45].

Equation (6) defines volumetric water content as the proportion of water volume within the soil to the total soil volume.

$$\theta = \frac{V_w}{V} \quad (6)$$

Topp et al.'s (1980) equation is generally accurate, but some studies indicate that it may produce inaccurate results for organic soils and clayey soils with a high proportion of fine materials. Roth et al. (1992), Dobson et al. (1985), and Dirksen and Dasberg (1993) have all suggested this [44,46,47].

Ledieu et al. (1986) and Alharti and Lange (1987) presented findings that demonstrate a linear correlation between volumetric water content and the square root of the dielectric constant, as expressed in Equation (7) [48-49].

$$\theta = a + b\sqrt{K_a} \quad (7)$$

In this context, the calibration coefficients, *a* and *b*, are specified by Ledieu et al. (1986) as *a*=1.545 and *b*=8.787, and by Alharti and Lange (1987) as *a*=1.59 and *b*=7.83 [48-49].

Furthermore, Ledieu et al. (1986) introduced a new equation that considers the dry density of the soil, which affects the water content. The proposed equation is outlined in Equation (8) [48].

$$\sqrt{K_a} = a\rho + b\theta + c \quad (8)$$

The equation (9) details the calibration coefficients *a*=0.297, *b*=8.79, and *c*=1.344, where ρ represents the dry density of the soil.

Ferre et al. (1996), Malicki et al. (1996), and Yu et al. (1997) have introduced a similar linear equation to Equation (8) in their respective studies [50-52].

$$\theta = b^{'}\sqrt{K_a} + a^{'} \quad (9)$$

The calibration coefficients a' and b' are determined through regression analysis, as shown in Equation (10). Malicki et al. (1996) argued that combining the dielectric constant and the dry density of the soil improves accuracy in determining water content, rather than relying solely on the dielectric constant [51].

$$\theta = \frac{K_a^{0.5} - 0.819 - 0.618\rho + 0.159\rho}{7.17 + 1.18\rho} \tag{10}$$

Arsoy et al. (2013) investigated the suitability of these methods using 17 different sand samples. The study showed that the models perform well when calibrated for specific soil types [53].

2.2.3. Relationship between volumetric water content and void ratio

Equation (11) defines the void ratio as the ratio of the volume of voids to the volume of solids in the soil.

$$e = \frac{V_w + V_a}{V_s} \tag{11}$$

Equation (12) defines porosity as the ratio of the volume of voids to the total volume.

$$n = \frac{V_w + V_a}{V} \tag{12}$$

Using the equations given in Equation 11 and Equation 12, it is possible to write the void ratio and porosity values in terms of each other. Equations for void ratio and porosity in terms of each other are given in Equations 13 and 14 respectively.

$$e = \frac{n}{1 - n} \tag{13}$$

$$n = \frac{e}{1 + e} \tag{14}$$

Equations 15 and 16 outline how to express the void ratio and porosity of fully saturated soil, which occurs when all voids are filled with water, corresponding to 100% saturation.

$$e = \frac{V_w}{V_s} \tag{15}$$

$$n = \frac{V_w}{V} \tag{16}$$

The volumetric water content is defined as the ratio of the volume of water in the soil to the entire volume of the soil. Since porosity is the ratio of the voids in the soil to the entire volume of the soil, 100% water saturation of the soil means that all voids in the soil are filled with water. Consequently, this establishes an equivalence between the porosity of the soil in a water-saturated state and the volumetric water content of the same soil under saturated conditions. This correlation becomes evident upon examination of Equation 6 and Equation 16. Therefore, when the soil is saturated with water, it is appropriate to assert the following expressions as given by Equation 17 and Equation 18.

$$\theta = n \tag{17}$$

$$\theta = \frac{e}{1+e} \tag{18}$$

Writing the void ratio in terms of volumetric water content in the above equation yields Equation 19.

$$e = \frac{\theta}{1-\theta} \tag{19}$$

2.2.4. Experimental Study

The relationships between the dielectric constant and the volumetric water content of the soil samples were investigated using the TDR reflection form. For this purpose, all soil samples were mixed homogeneously by adding water in certain proportions. The homogenously mixed soil samples were compacted in standard compaction molds by applying standard compaction energy. In order to find the water content of the compacted samples, two test samples were taken from the samples compacted in the molds and the water contents were calculated with the help of an oven. In addition, in order to find the weight of the soil sample compacted in the mold, the compaction mold was weighed before and after the soil sample was compacted in the mold.

The reflection-distance graphs for the soil samples were obtained using a probe inserted into the soil, connected to a TDR 100 device, and analyzed with the PCTDR program on a computer. Figure 4 provides a schematic of the measurement system.

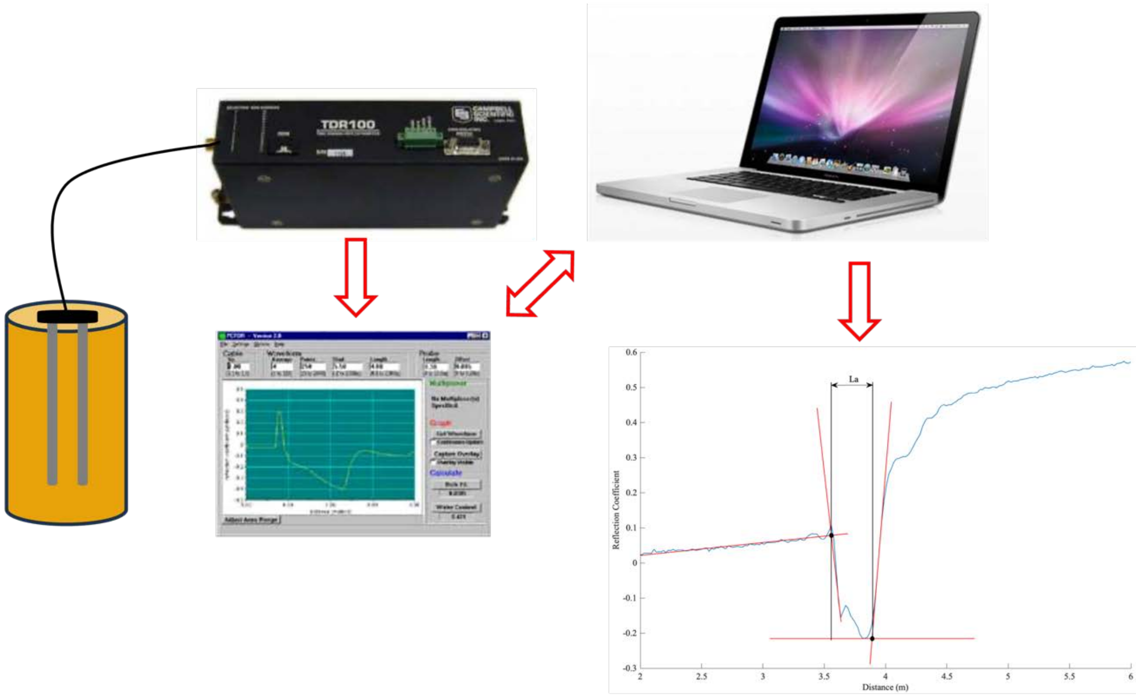


Figure 4. Schematic diagram of the measurement system

A Campbell Scientific TDR100 was used for the measurements. After the signal sent by the TDR100 device was reflected from the soil, it was transmitted to the computer via an RS232 cable and the reflection form was displayed using the PCTDR software. The reflection form displayed in the PCTDR program was taken as digital data and processed using a Matlab code developed as part of the study.

As part of the study, the start and end points of the probe placed in the ground were determined using the tangent and derivative methods. After determining the distance between the start and end points of the probe, i.e. the apparent length of the probe, the dielectric coefficient was calculated using equation 4. The dielectric coefficients were calculated using both methods and the relationship between the dielectric coefficients and the volumetric water content was analyzed using the models of Topp et al. (1980) and Leideu et al. (1986).

Void ratios of soils were determined using dielectric constants and volumetric water content values calculated using TDR reflection forms. The determined void ratios were compared with those calculated by the classical method and the accuracy of the method was investigated.

III. RESULTS AND DISCUSSIONS

3.1 Determination of Geotechnical Properties of Soils

Sieve analysis experiments were carried out to determine the particle size distribution curves of the soil samples. The resulting curves, obtained from three replicates of sieve analysis experiments carried out on both SP and SM samples, are shown in Figure 5. Figure 5(a) shows the grain distribution curves for the SP sample, while Figure 5(b) shows the grain distribution curves for the SM sample.

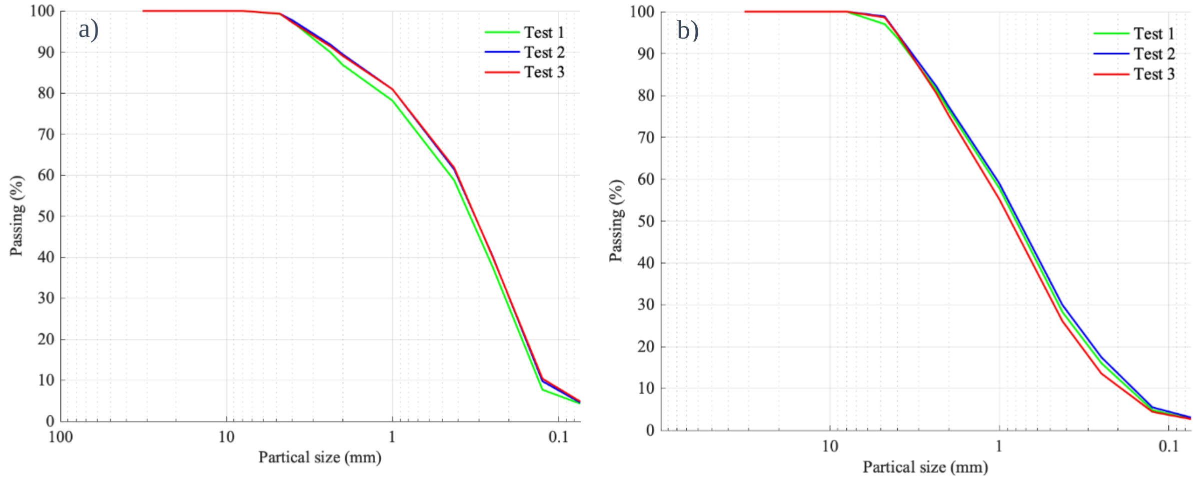


Figure 5. Sieve analysis test results **(a)** for SP sample **(b)** for SM sample

The specific gravity test was repeated five times to determine the specific gravity values of the SP and SM soils. The test results showed that the specific gravity of the SP and SM soil samples was 2.69. Detailed results of the specific gravity test are given in Table 2.

Table 2. Specific gravity values obtained for SP and SM samples

Soil Type	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	Average
SP	2.69	2.69	2.69	2.70	2.69	2.69
SM	2.69	2.69	2.70	2.69	2.69	2.69

Furthermore, the organic matter determination test results for these samples showed the presence of 0.08% and 0.09% organic matter in the SP and SM soil samples respectively. The SP sample had maximum and minimum void ratio values of 0.77 and 0.51, while the SM sample had values of 0.64 and 0.42.

The results of the sieve analysis, specific gravity test, maximum-minimum void ratio and experiments to assess the amount of organic matter on the soil samples used in the experimental study are presented in Table 3.

Table 3. Some geotechnical properties of the soils used in the study

Soil Type	d_{10}	d_{30}	d_{60}	C_u	C_c	GS	e_{min}	e_{max}	OM (%)
SP-1	0.13	0.22	0.45	3.46	0.83	2.69	0.51	0.77	0.08
SM	0.08	0.60	1.70	21.25	2.65	2.68	0.42	0.64	0.09

3.2 Determination of Dielectric Constant

A total of 22 soil samples were prepared, 11 for each soil type (SP and SM) with different water content values. Reflection forms were obtained because of TDR measurements on the prepared soil samples. Dielectric constants were determined from the reflection forms of the samples using tangent and derivative methods. Figure 6 shows a reflection form used in the tangent method for SP and SM samples and Figure 7 shows the reflection form used in the derivative method and examples of the first derivative of the reflection form.

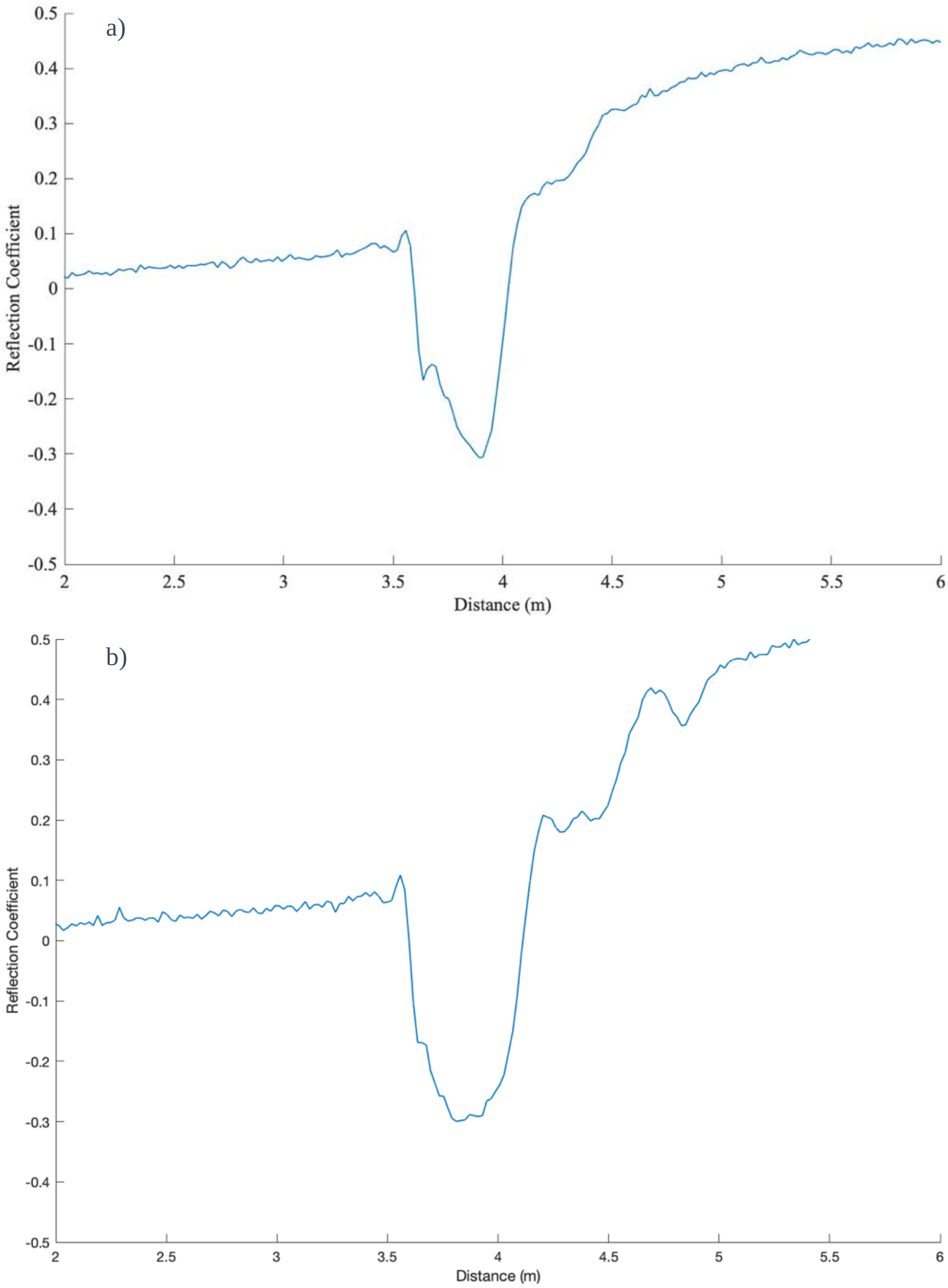
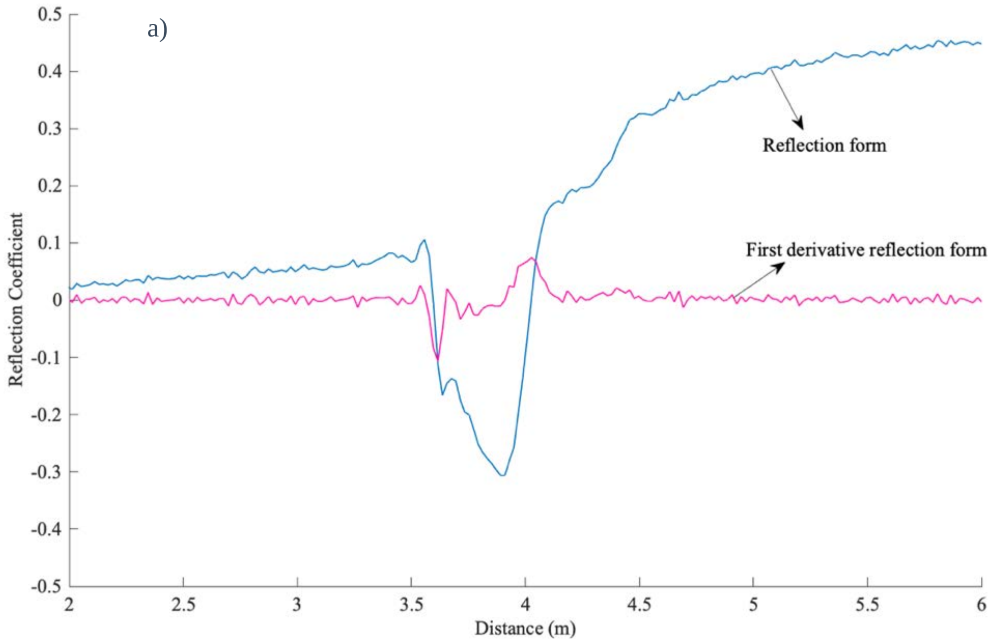


Figure 6. Reflection forms measured by TDR for SP and SM samples **(a)** for SP sample **(b)** for SM sample

Figure 6(a) shows the TDR reflection form plots for the SP soil sample with a volumetric water content of 15.11%, while Figure 6(b) shows the TDR reflection form plots for the SM soil sample with a volumetric water content of 24.53%. The start and end points of the probe were determined using the tangent method for both soil samples and the distance between these points gave the apparent probe length (La). The apparent probe length was 0.409 m for the SP sample and 0.443 m for the SM sample, whereas the actual probe length was 0.093 m. Using these data, the dielectric constant was calculated using the equation given in equation (4). The calculations gave a dielectric constant of 19.34 for the SP sample with a water content of 15.11% by volume and 22.67 for the SM sample with a water content of 24.53% by volume.



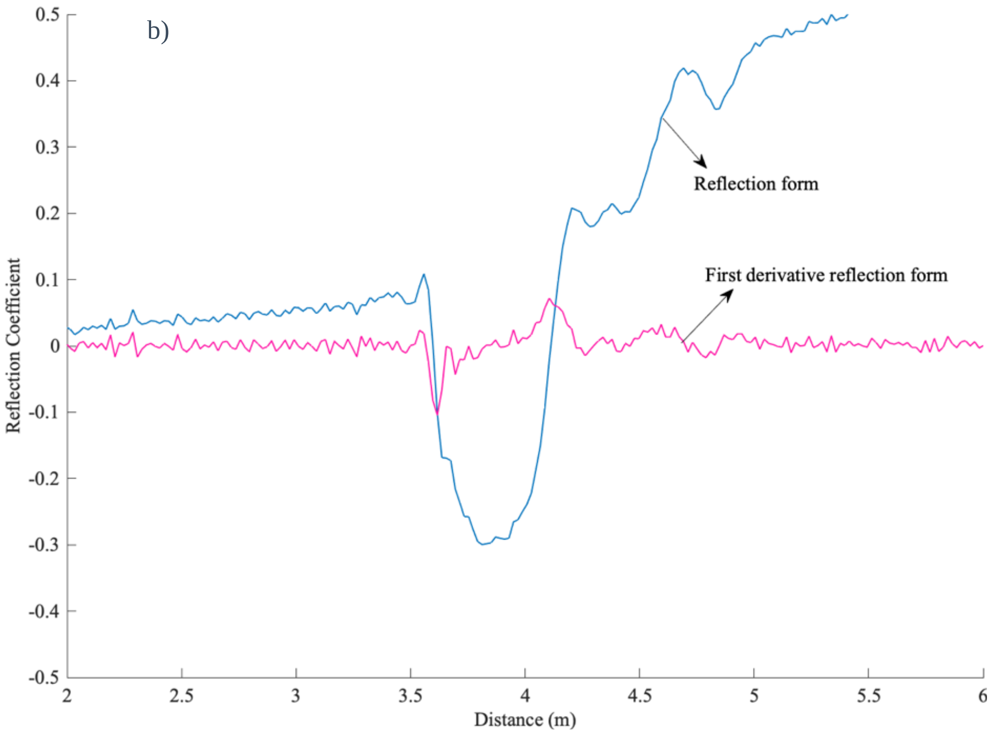


Figure 7. Reflection forms measured by TDR for SP and SM samples and 1st derivatives of reflection forms **(a)** for SP sample **(b)** for SM sample

Figure 7(a) shows plots obtained by taking the first derivative of the TDR reflection form for the SP soil sample with a volumetric water content of 15.11%, while Figure 7(b) shows similar plots for the SM soil sample with a volumetric water content of 24.53%. Using the derivative method to determine the start and end points of the probe, an apparent probe length of 0.430 m was obtained for the SP sample and 0.452 m for the SM sample. Consequently, the dielectric constants were calculated using the equation given in equation (4), giving values of 21.39 for the SP sample and 23.62 for the SM sample.

These procedures were carried out separately on 22 soil samples. The dielectric constants obtained by both methods for SP and SM soil samples are compared in Figures 8a and 8b. Analyzing the figures, it can be seen that the dielectric constants calculated by both methods for both soil samples are within acceptable error rates. As a result of the regression analysis, the regression coefficient was found to be 0.997 for the SP soil sample and 0.989 for the SM soil sample.

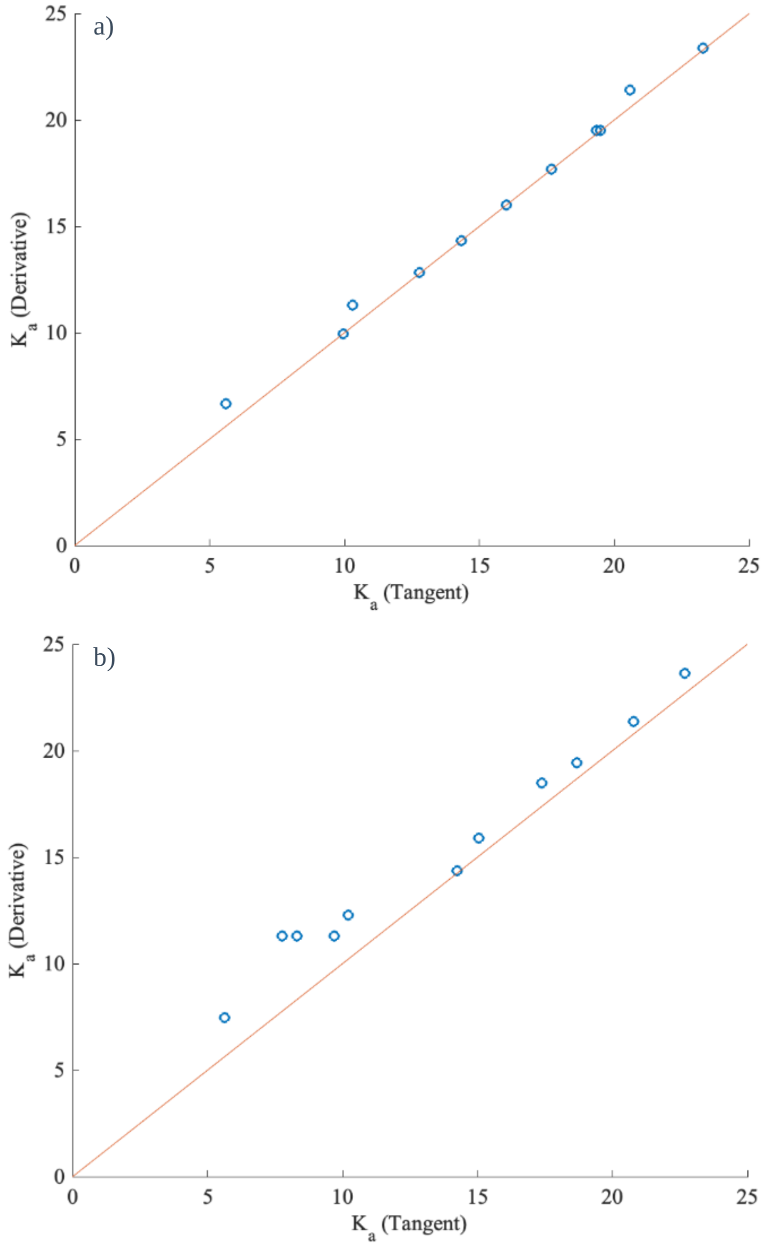


Figure 8. Comparison of dielectric constant determined by the tangent and derivative methods **(a)** for SP sample **(b)** for SM sample

3.3 Determination of Volumetric Water Content

The relationship between the volumetric water content and the dielectric constant is described by Topp et al. (1980) and Ledieu et al. (1986) in equation 5 and equation 7 respectively. Soil specific calibration is required to apply these equations. Calibrations were performed for both soil samples and then the volumetric water contents were calculated using the dielectric constants determined by both the tangent and derivative methods according to the respective equations. The accuracy of the calculated volumetric water contents was verified by comparison with values obtained using the traditional oven method. The volumetric water contents obtained by experiment and calculation are compared in Figure 9.

The calculated volumetric water content values for SP and SM soils are presented in Figure 9 and Figure 10, respectively. In Figure 9a and Figure 10a, the volumetric water content values were calculated using the equations proposed by Topp et al. (1980), while in Figure 9b and Figure 10b, they were calculated using the equations proposed by Leideu et al. Both tangent and derivative methods were employed to determine the dielectric constants used in the calculations. The x-axis of the graph represents the volumetric water content values obtained via the oven method, while the y-axis represents the water content values determined by the models proposed by Topp et al. (1980) and Leideu et al. (1986).

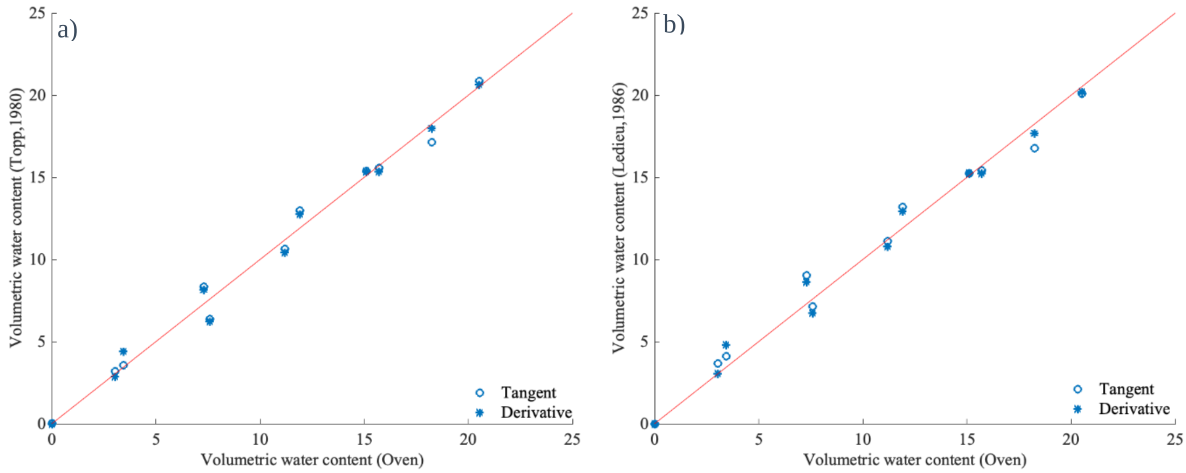


Figure 9. Volumetric water contents calculated with the models proposed by Topp et al. (1980) and Leideu et al. (1986) for SP soil samples (a) Topp et al. 1980 (b) Leideu et al. 1986

Upon examination of the volumetric water content values presented in Figures 9 and 10, it becomes evident that the values derived through traditional methods align closely with those calculated using the equations proposed by Topp et al. (1980) and Leideu et al. (1996).

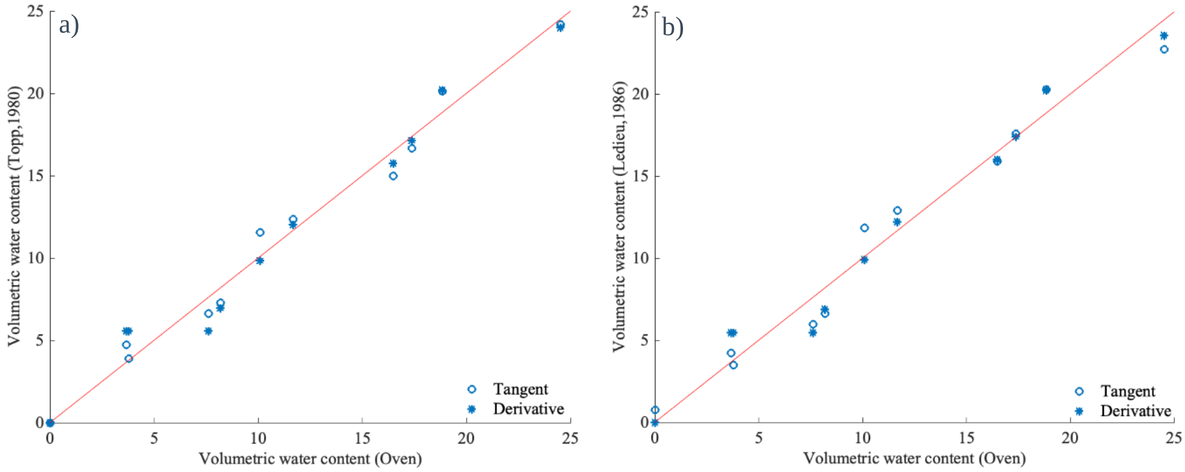


Figure 10. Volumetric water contents calculated with the models proposed by Topp et al. (1980) and Leideu et al. (1986) for SM soil samples (a) Topp et al. 1980 (b) Leideu et al. 1986

Regression analysis was performed on the values presented in Figure 9 and Figure 10 and the regression coefficients obtained because of this analysis are presented in Table 4.

Table 4. Regression coefficients of SP and SM sand samples

	Topp ve ark. (1980)		Ledieu ve ark.(1986)	
	Tangent	Derivative	Tangent	Derivative
R^2 (SP sample)	0.995	0.994	0.982	0.986
R^2 (SM sample)	0.991	0.986	0.985	0.991

3.4 Determination of Void Ratio

The void ratio of the soil was calculated using both the conventional method, using the water content obtained from the oven, and the volumetric water content value obtained from the TDR waveform.

As a result of the calculations, the void ratio values obtained from both the classical method and the TDR method were found to be very close to each other. Figure 11a shows the void ratio values obtained for the SP soil type and Figure 11b shows the void ratio values for the SM soil type.

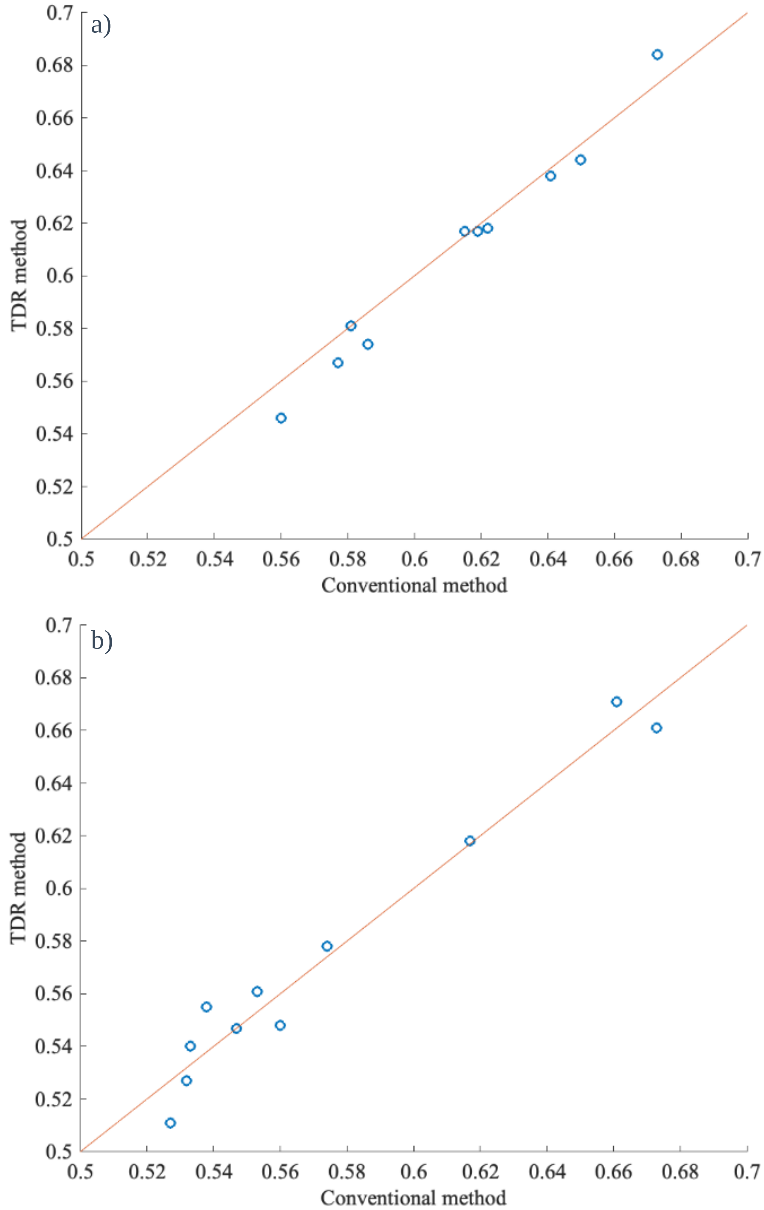


Figure 11. Void ratio values calculated by TDR and conventional methods (a) for SP sample (b) for SM sample

These graphs provide a comparative representation of the void ratio values obtained by both methods. On the graphs, the x-axis represents the void ratio values obtained by the conventional method, while the y-axis represents the void ratio values obtained by the TDR method. The void ratio values range from 0.546 to 0.684 for the SP sample and from 0.527 to 0.671 for the SM sample. When comparing the void ratios, the largest absolute error obtained for the SP sample is 0.0140 and the smallest error is 0. For the SM sample, the largest absolute error is 0.017 and the smallest error is 0.

The relationship given in equation 20 was used to determine the error rates of the void ratio values determined by the TDR method compared to the void ratio values calculated by the conventional method.

$$ER(\%) = \left(\frac{e_{TDR} - e_{con}}{e_{con}}\right) * 100 \quad (20)$$

In this equation, *ER* is the error rate, e_{TDR} is the gap ratio obtained by the TDR method and e_{con} is the gap ratio value calculated by the conventional method. The error rates calculated using Equation 20 are shown graphically in Figure 12. The y-axis represents the error rates and the x-axis represents the void ratio values calculated using conventional methods.

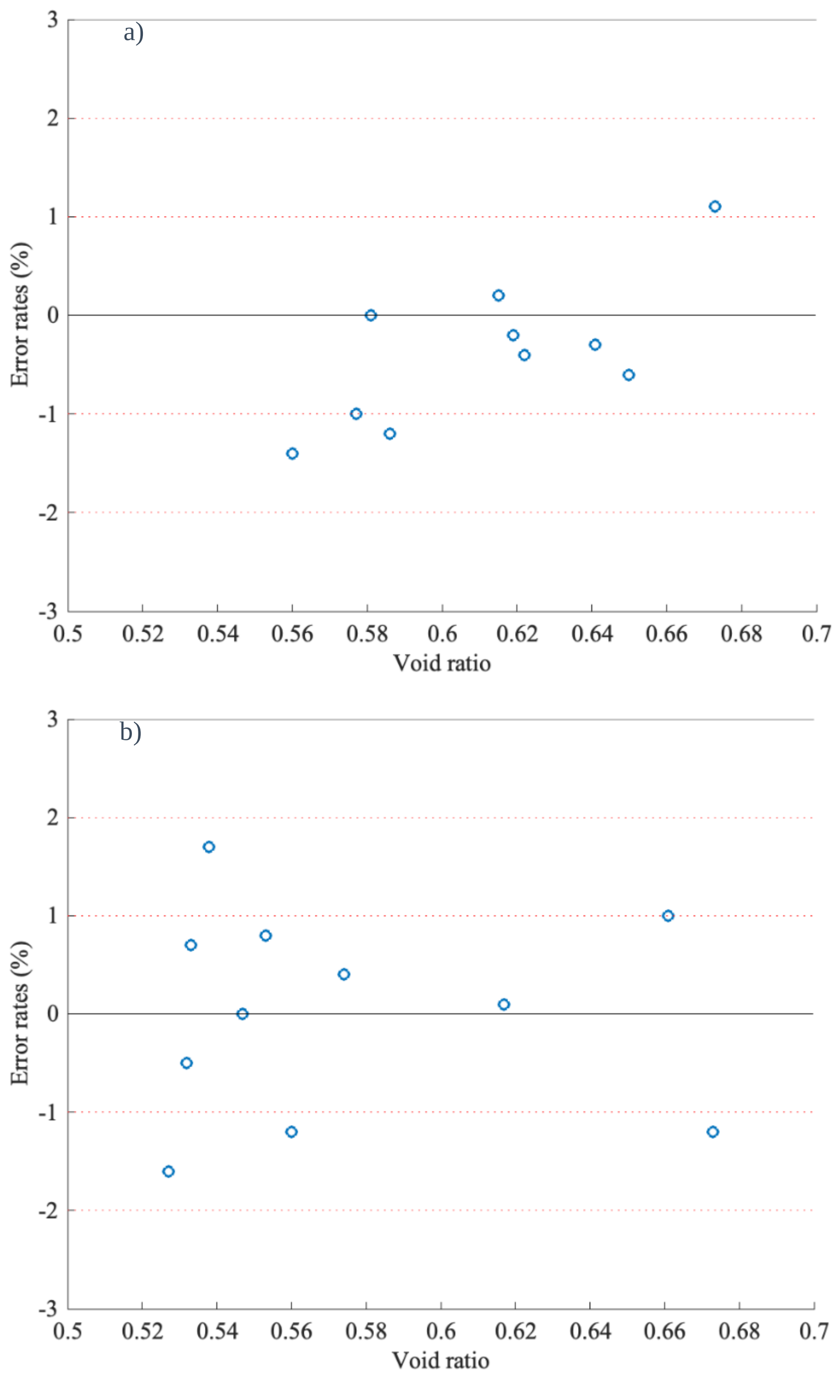


Figure 12. Error rates of void ratio values calculated by the TDR method (a) for SP sample (b) for SM sample

Figure 12 shows that 70% of the samples for SP samples and 65% of the samples for SM samples have an error rate between -1% and 1%. The remaining soil samples were within the error rate between -2% and 2%.

IV. CONCLUSIONS

As part of the study, experimental studies were carried out on SP and SM sand samples prepared at different densities. The results of the study are presented below.

- It has been shown that both the tangent and derivative methods can be used to determine the soil dielectric constant. It has been found that the dielectric constants calculated by these methods give very close values. In addition, both methods were found to be effective in determining the dielectric constant from the reflection forms.
- Volumetric water content values were calculated using the tangent and derivative methods. Calculations using the relationships proposed by Topp et al. (1980) and Leideu et al. (1996) showed good agreement with the volumetric water content values calculated by conventional methods. These results confirm that both methods give accurate results.
- The use of TDR reflection forms for the determination of void ratios, which was the main objective of the study, gave very favorable results. The studies show that this method is effective in predicting the void ratio. These results highlight the potential of TDR, particularly in the determination of soil properties.
- The error rates in the void ratio values obtained for the SP soil type are lower than the error rates obtained for the SM soil type. However, the void ratio values for both soil samples were estimated within acceptable error limits. The reason for the slightly higher error rates in the SM soil sample is thought to be the higher proportion of fine material in the soil sample.

As a result of all these studies, it was concluded that the TDR method can be used quickly and safely to determine the void ratio of soils in the laboratory or in situ. With a few small software programs to be written, it has been shown that the void ratio of the soil can be determined in situ as soon as the TDR measurement is taken.

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