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Factors affecting soil permittivity and proposals to obtain gravimetric water content from time domain reflectometry measurements

L.M. Thring, D. Boddice, N. Metje, G. Curioni, D.N. Chapman, and L. Pring

Abstract: Time domain reflectometry (TDR) measures the apparent relative dielectric permittivity (ARDP) of a soil and is commonly used to determine the volumetric water content (VWC) of the soil. ARDP is affected by several factors in addition to water content, such as the soil's electrical conductivity, temperature, and density. These relationships vary with soil type and are very soil-dependent, and despite previous research, they are still not fully understood. A multivariate statistical approach (principal component analysis, PCA) is used to describe a range of soils from two separate sites in the UK (clay and silty sand – sandy silt). The advantage of a PCA is that it considers several variables at a time, giving an immediate picture of their underlying relationships. It was found that for the studied soils, ARDP was positively correlated with VWC and bulk electrical conductivity, but did not show any dependence on some other geotechnical parameters. TDR has recently been used in geotechnical engineering for measuring the gravimetric water content (GWC) and dry density. However, the current approaches require a custom-made TDR probe and an extensive site specific empirical laboratory calibration. To extend the potential use of TDR in the geotechnical industry, three relatively simple methods are proposed to estimate the GWC from VWC (derived from the measured ARDP values) and dry density depending on the amount of information known about the soil. Examples of possible applications of these methods include continuous monitoring of consolidation adjacent to a structure, the effect of seasonal weather and climate change on ageing earthwork assets, and the shrink–swell potential adjacent to trees. All three methods performed well, with between 83% and 98% of the data lying within a $\pm 5\%$ GWC envelope, with the data for clay soils performing better than those for silty sands – sandy silts. This is partly due to the fact that the applied relationship converting ARDP to VWC performs better for clays than silty sands – sandy silts, as well as less variation of the estimated bulk density that is needed to derive the dry density.

Key words: time domain reflectometry, volumetric water content, gravimetric water content, apparent relative dielectric permittivity, principal component analysis, estimation of dry density.

Résumé : La réflectométrie dans le domaine temps (RDT) mesure la permittivité diélectrique apparente relative (PDAR) d'un sol, et est communément utilisée pour déterminer la teneur en eau volumique (TEV) de ce sol. La PDAR est affectée par plusieurs facteurs en plus de la teneur en eau, comme la conductivité électrique du sol, la température et la densité. Ces relations varient selon le type de sol, et malgré les recherches antérieures, elles ne sont pas encore bien comprises puisqu'elles dépendent beaucoup du sol. Une approche statistique multivariée (analyse en composantes principales, ACP) est utilisée pour décrire une variété de sols provenant de deux sites différents au Royaume-Uni (argile et sable silteux – silt sablonneux). L'avantage de l'ACP est qu'elle considère plusieurs variables à la fois, ce qui permet d'obtenir une image immédiate de leurs relations. Il a été déterminé que pour les sols étudiés, la PDAR est corrélée positivement avec la TEV et la conductivité électrique totale, mais ne démontre pas de dépendance sur les autres paramètres géotechniques. La TEV a été récemment utilisée en géotechnique pour mesurer la teneur en eau gravimétrique (TEG) et la densité sèche. Cependant, les approches actuelles nécessitent une sonde RDT fabriquée sur mesure et un calibrage empirique en laboratoire spécifique et détaillé. Afin d'étendre l'utilisation de la RDT dans l'industrie géotechnique, trois méthodes relativement simples sont proposées pour estimer la TEG à partir de la TEV (dérivée de valeurs de PDAR mesurées) et la densité sèche dépendamment de la quantité d'information connue à propos du sol. Des exemples d'applications possibles de ces méthodes comprennent le suivi en continu de la consolidation adjacente à une structure, l'effet du climat saisonnier et des changements climatiques sur le vieillissement d'ouvrages en terre, et le potentiel de retrait–gonflement à proximité des arbres. Les trois méthodes performant bien, avec 83 % à 98 % des données situées à l'intérieur de l'enveloppe $\pm 5\%$ TEG, avec les données pour les sols argileux offrant des meilleures performances que celles des sables silteux – silts sablonneux. Ceci est dû en partie au fait que la relation appliquée pour convertir la PDAR en TEV donne de meilleurs résultats pour les argiles que pour les sables silteux – silts sablonneux et une variation plus faible de la densité totale estimée, qui est nécessaire pour dériver la densité sèche. [Traduit par le Rédaction]

Mots-clés : réflectométrie dans le domaine temps, teneur en eau volumique, teneur en eau gravimétrique, permittivité diélectrique apparente relative, analyse en composantes principales, estimation de la densité sèche.

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L.M. Thring. Arup, The Arup Campus, Blythe Gate, Blythe Valley Park, Solihull, B90 8AE, UK.

D. Boddice, N. Metje, G. Curioni, D.N. Chapman, and L. Pring. School of Civil Engineering, College of Engineering and Physical Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.

Corresponding author: N. Metje (e-mail: n.metje@bham.ac.uk).

Introduction

Time domain reflectometry (TDR) is an electromagnetic (EM) technique commonly used to measure the soil volumetric water content (VWC). Since the development of a general calibration relationship between the TDR measured apparent relative dielectric permittivity (ARDP) and VWC by Topp et al. (1980), several other calibration equations have been presented by various authors (e.g., Ledieu et al. 1986; Roth et al. 1990; Wensink 1993; Curtis 2001). There is huge variation in the perceived significance of different soil properties on the measured ARDP (van Dam et al. 2005). ARDP has been shown to depend on the soil density (Ledieu et al. 1986; Malicki et al. 1996), temperature, (Or and Wraith 1999; Skierucha 2009) and bulk electrical conductivity (BEC) (Bittelli et al. 2008). Other authors have also found relationships between ARDP and geotechnical parameters such as liquid limit (LL) and linear shrinkage (LS) (Thomas et al. 2010a). Despite the considerable number of previous studies, the relationships between ARDP and soil parameters vary with soil type, and are still not fully understood.

A disadvantage of the TDR technique is that it often requires soil-specific calibration between ARDP and water content, requiring laboratory tests (Jacobsen and Schjonning 1993; Quinones et al. 2003). This calibration is required for every probe arrangement as the cable length and attachments have been shown to affect the measurement of ARDP (Logsdon 2000). In recent years TDR has been deployed in geotechnical engineering for measuring the gravimetric water content (GWC) and dry density (Yu and Drnevich 2004; Drnevich et al. 2005; Jung et al. 2013). However, these methods use a specifically designed probe type and also require laboratory calibration. This tends to limit the use of TDR in the geotechnical industry.

The aim of this paper is two-fold: (i) to investigate the factors affecting the measurement of ARDP by means of a multivariate statistical approach on a number of soils from the UK, and (ii) to develop rapid methodologies for measuring GWC in the field with commercial TDR without the need for laboratory tests. Furthermore, the paper uses the TDR data obtained in this research in existing empirical and semi-empirical relationships to determine the applicability of these methods to the current data set.

To fulfil these aims, laboratory testing was carried out on a range of soil types, at different water contents and temperatures, and a consistent methodology was developed to prepare uniform soil samples. Tests were performed by relatively inexpensive commercial TDR equipment using the standard travel-time analysis. The data were analyzed by means of the principal component analysis (PCA) technique, which is not commonly used in geotechnical engineering but has been demonstrated to be a useful approach to study a multivariate system such as the soil (Jolliffe 2002).

The novelty of the presented work is not in the laboratory methodology or the use of TDR probes, but the use of the data generated for two distinctly different soils at VWC between 0% and 50%, as well as three different temperatures, that also adds to the knowledge base in this field. The novelty of the presented work lies in the application of the PCA to these types of data as well as the attempt to correlate TDR measurements to GWC, as is used more commonly by the geotechnical engineering industry. The methods proposed use either existing laboratory data for dry density, or estimate the dry density using two different methods based on simple descriptions of the soil.

Theoretical background

Principles of permittivity

Relative dielectric permittivity is the ratio between the absolute permittivity of a material and the absolute permittivity of free space (ϵ_0 , 8.85×10^{-12} F/m), and expresses the ability of a material to polarize under an electric field (Ledieu et al. 1986). In this paper

the relative dielectric permittivity will simply be referred to as permittivity. To measure the ability of a material to polarize, it can be placed into an alternating EM field, and the time it takes for the wave to travel through the material is measured. This time is known as the transit time. In TDR, a probe is inserted into the soil and the transit time of an EM wave along the probe can be measured, and therefore the propagation velocity of the wave found (Ledieu et al. 1986). Propagation velocity can be used to derive a dimensionless value of the permittivity of a soil that is often referred to as ARDP in the literature (Topp et al. 1980).

Permittivity in soils

There are several factors which affect the permittivity of a soil. A soil consists of air, water, and solids. The permittivity of free water is 80.36 at 20 °C (Roth et al. 1990); much larger than the permittivity of most common soil minerals, which ranges between 3 and 5 (Roth et al. 1990). This difference is due to the high ability of the water molecules to polarize compared to that of soil particles.

As there are significant differences between the permittivity of a soil's constituent components, it stands to reason that the permittivity of a soil is highly dependent on its water content (Ledieu et al. 1986). Therefore the most important effect on the permittivity of a soil are its air:solids:water ratios. Hence the density of the soil must be significant in determining the ARDP of a soil as this will directly affect the amount of air present. However, this should have a much smaller effect than the water content because the ARDP of soil minerals is much closer to the ARDP of air (approximately unity) than that of water (Roth et al. 1990). The GWC cannot describe the volume of water surrounding a probe of finite length. However, the VWC of a soil does take this into account. Therefore, to produce a relationship relating the ARDP to the GWC, some consideration must be given as to how to take the specific volume of soil present at a particular GWC into account. This should be done without overcomplicating the proposed relationship, which would reduce its applicability. One approach adopted is to use the soil's dry density (Yu and Drnevich 2004).

There are however, additional complexities caused by bound water and temperature effects (Craig 2004). Opinions vary within the literature as to the importance of such properties. For example, Roth et al. (1990) use temperature as the secondary input into the ARDP to estimate the VWC of a soil, while Wang and Schmugge (1980) found that using sand and clay contents to estimate the amount of bound water produces a more accurate relationship. However, the amount and state of the bound water is not as simple as a relationship between the amount of clay and sand present. It has been found to be also dependent on the clay mineralogy. For example, Smectite adsorbs significantly more water than Kaolinite (Craig 2004) due to its higher specific surface area, and therefore shows a higher amount of bound water (Thomas et al. 2010a). Therefore, as part of this research, existing relationships between ARDP and VWC were tested on different soils, and investigations were conducted to shed more light into the significance of different parameters affecting ARDP, and ultimately, VWC.

Experimental methods

Soil samples

Soils from two separate sites located in Cambridgeshire, UK, were used in this study, one comprising glacially derived clay (Diddington clay field, DCF), the other comprising sand and silt of fluvial origin (Diddington pasture field, DPF). A number of soils with slightly different properties were identified from both sites and described in Table 1 according to BSI (1990). Disturbed samples were taken in bags and undisturbed samples were taken using monolith tins for geotechnical laboratory testing to characterize the soils, as per BSI (1990). The parameters measured for characterization purposes were field dry density (Mg/m^3), particle

Table 1. Brief field descriptions of the soils found on the DCF and DPF sites according to BSI (1999).

Soil	Brief description	Field dry density (Mg/m ³)
DCF Site		
Topsoil	Soft-firm brown slightly sandy slightly gravelly clay.	1.56
Subsoil	Stiff mottled light and dark brown thinly laminated slightly silty clay.	1.66
Natural	Stiff light brown slightly silty slightly gravelly clay containing chalk rockflour.	1.90
Ditchfill 1	Stiff brown slightly gravelly silty clay.	1.61
DPF Site		
Topsoil	Loose grey slightly gravelly silty sand.	1.62
Subsoil	Dense brown slightly gravelly slightly clayey sandy silt.	1.66
Ditchfill 1, 2, and 3	Loose brown slightly gravelly clayey sandy silt.	1.60; 1.31; 1.66
Natural	Uncompact sandy silt containing medium-spaced sand lenses	1.60

density (Mg/m³), particle size distribution (%), Atterberg limits (i.e. liquid limit, LL (%) and plastic limit, PL (%)), and linear shrinkage, LS (%). The range of values measured for the soils studied from both sites are reported in Table 2. Although the soils at each site varied slightly (see Table 1), the two sites can be broadly classed as “clay” (DCF) and “sandy silts – silty sands” (DPF). Therefore, for the majority of the paper, the different horizons at each site were not differentiated.

Calibration of TDR and signal processing

The TDR used to obtain the ARDP and BEC was a Campbell Scientific TDR100 in conjunction with CS645 probes. The probes had three prongs: 75 mm long and approximately 7 mm apart (centre to centre). An air–water probe calibration to find the apparent permittivity was carried out on the TDR probes, as was the BEC calibration using liquids of varying conductivities similar to Curioni et al. (2012) as outlined by Heimovaara (1993) and Huisman et al. (2008).

Sampling for permittivity testing

The samples needed to comfortably house the 75 mm long TDR probes to allow for accurate measurements and hence 100 mm by 100 mm cylindrical sample pots were used. To avoid issues with electrical interference affecting the readings, the sample pots were constructed out of plastic.

The soil samples were compacted into the cylinders in 5, 20 mm layers and left for 24 h to allow pore water to equilibrate across the sample. This is a similar approach to that recommended for British standard triaxial tests where it takes approximately 24 h to equalize sample pore pressure with cell pressure before testing (BSI 1990). Samples were sieved through a 5 mm sieve so there were no obstructions to the TDR probe. Sieving was not anticipated to compromise the results with respect to the field conditions as the probe prongs cannot fit around an obstacle larger than 5 mm. Therefore particles of this size would not be involved in any readings taken in the field. To keep soils as similar to the field as possible, the measured field dry density was used as a target for the compaction of the samples. The results are discussed later in this paper.

This still produced a large range of dry densities with values ranging between 1.3 and 1.9 Mg/m³. To check the effects of density, a laboratory sensitivity analysis was carried out, varying the dry density for two soil types from the two sites by 10%.

Working with a large set of different soil types at a large range of water contents, one particular methodology could not be applied to all samples (44 in total). Therefore two methodologies were developed. These methods deal with the tendency for very dry clays to hold water unevenly in clusters.

Method 1 was used on fine-grained and coarse-grained samples with lower target water contents. It is based on the method of starting from a dry sample outlined in Quinones et al. (2003).

Initially the sieved soil was dried in an oven at 105 °C for a minimum of 24 h. This was necessary as the soil samples were to

be prepared at the densities found in the field from where the soil was collected. All the fine-grained soils formed brick-like, sedimented chunks. These chunks were wetted to approximately 10% GWC and were placed in a mixer that broke the damp, gravel sized chunks of soil into small granules without crushing the fine gravel particles present. Breaking these by crushing the soil could have had a significant effect on the measured permittivity as it changes the specific surface area of the soil, which in turn may affect the bound water content (Craig 2004).

The granules produced (see Fig. 1) were then dried in an oven for a second time. Since the volume of the cylinders was known and the target dry density was known, using the assumption that water added was at the expense of air present in the soil, the amount of water to add to a sample was calculated.

The water was added to the sample using a plant mister to evenly distribute it through the soil. The small grains tended to have visibly different water contents at this point (Fig. 1). Therefore the sample was wrapped tightly in cling film and allowed to equalize for 24 h before being packed into cylinders.

Method 2 was developed for fine-grained soil samples tested at higher water contents. As in method 1, the soil was wet sieved and dried to form brick-like chunks of soil. This soil of known dry weight was then saturated and thoroughly mixed. This took longer if the soil was more plastic, and occasionally had to be left overnight to allow the soil chunks to absorb the water. The required mass of water for a target VWC was calculated based on the field dry density, cylinder size, and the known dry weight of soil present. Therefore, the amount of water to be removed from the sample was calculated and the target mass of the sample derived.

To achieve the target mass, the sample was dried using an oven at 105 °C for short intervals (no longer than 0.5 h) and then stirred vigorously so that no crusts of dry soil were allowed to form. This was necessary due to the practicalities associated with the amount of soil that needed to be prepared (2.5 kg for each test). However, there was often desiccated soil around the edges of the container. Therefore, as with method 1, it was vital that the soil water should be allowed to equalize before being packed into the cylinders. The entire sample was carefully removed from the container and allowed to equalize for 24 h as per method 1.

To check that both methods were producing uniform samples for testing, each sample was subject to three water content tests by removing subsamples at different stages during sample preparation and testing. One subsample was taken at the compaction stage and great care was taken to replace the removed volume of soil, and two when the sample was dismantled after testing; one from where the probe was inserted, and one using the rest of the sample. This meant that a representative VWC could be found for the entirety of the sample in the cylinder.

The cylinder was sealed with silicone to stop evaporation, and fitted with a TDR probe that was secured and remained in place throughout the duration of the testing (Fig. 2).

Table 2. Range of values for the soil geotechnical parameters of the soils studied.

	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Particle density (Mg/m ³)	Dry density (Mg/m ³)	PL (%)	LL (%)	LS (%)
DCF									
Min	6.3	16.3	45.6	21.9	2.58	1.46	18.0	40.0	10.5
Max	8.6	22.0	52.6	30.9	2.83	1.90	22.0	48.0	15.2
DPF									
Min	8.1	32.9	13.3	6.0	2.60	1.30	15.0	24.0	6.5
Max	33.3	47.4	43.0	14.0	2.69	1.86	17.0	30.0	8.4

Fig. 1. Visible variation in soil granules during sample preparation.**Fig. 2.** Completed sample with TDR probe inserted.

To examine the effects of temperature, each sample was placed in an incubator at 0, 10, and 20 °C for 24 h. Three permittivity and BEC readings were taken at each temperature, and the mean at each temperature was used for analysis. The GWC was determined after the TDR measurement for all samples.

Results

VWC results

The results in Fig. 3 show a clear difference between the silty-sandy soils and clay soils. Therefore two different empirical or soil specific relationships between the VWC and ARDP were derived (eqs. (1) and (2) in Table 3). For comparison purposes, the Topp

et al. (1980) relationship is also shown in Fig. 3. It can be seen that the Topp et al. (1980) model works reasonably well for clay soils, but underpredicts the VWC at larger ARDP, while it underpredicts the VWC for coarse-grained soils at ARDP values less than 15. Dirksen and Dasberg (1993) found that deviations from the Topp et al. (1980) equation were mainly due to variations in soil dry density. Density sensitivity testing was carried out to see if this was true for the soils studied. The dry density of two representative samples (one for each site) was varied by $\pm 10\%$ to observe the associated variation in ARDP. These variations were found to be negligible. Additionally it was found that changes in temperature produced no noticeable effect on the measured ARDP as can be seen in Fig. 4, which shows the measured VWC versus the measured ARDP for both soils and the two extreme temperatures of 0 °C and 20 °C. The scatter indicates that there was no systematic effect of the change in temperature and that the overall effects were small. However, as expected (Campbell et al. 1949), temperature had a large impact on the measured BEC (not shown in this paper).

Gravimetric results

The results obtained can also be expressed in terms of GWC. GWC is obtained by dividing the VWC by the soil dry density (eq. (7)), assuming a density of water, ρ_w , of unity (Yu and Drnevich 2004)

$$(7) \quad \text{GWC} = \frac{\text{VWC} \rho_w}{\rho_d}$$

where ρ_d is the dry density (Mg/m³). It can be seen from Fig. 5 and Table 3 that there was a loss in accuracy as a result of using the measured GWC rather than VWC (eqs. (3) and (4) in Table 3 show smaller R^2 values compared to eqs. (1) and (2)). This was expected as the GWC does not account for the volume of water the TDR probe is measuring. Therefore a more appropriate relationship is between GWC and ARDP normalized with dry density. Figure 6 shows the improved relationships (eqs. (5) and (6) in Table 3) obtained after normalizing ARDP with dry density in line with the approach taken by Thomas et al. (2010a, 2010b). However, from the density sensitivity results, dry density did not appear to significantly account for any additional variation of ARDP. Quinones et al. (2003) found that the density of a soil only affected the measured ARDP at extreme densities and the densities found here are within the commonly encountered range in natural soils (Craig 2004).

Discussion

Testing reliability

The methods used produced measureable errors in both the readings taken by the TDR and the measured water contents. The GWC was taken on 3 specimens from each sample and the measured variability was on average 0.33% GWC, with a maximum variability of 0.90% GWC, while the TDR measurement was also repeated 3 times with the probe in the same position, which resulted in a mean measurable error of 0.10, with a maximum

Fig. 3. Relationship between VWC of a soil and its measured ARDP (by TDR) shown for clay soils (DCF) and sandy silts – silty sands (DPF). Topp et al. (1980) relationship is also shown for comparison. R^2 , square of the multiple correlation coefficient.

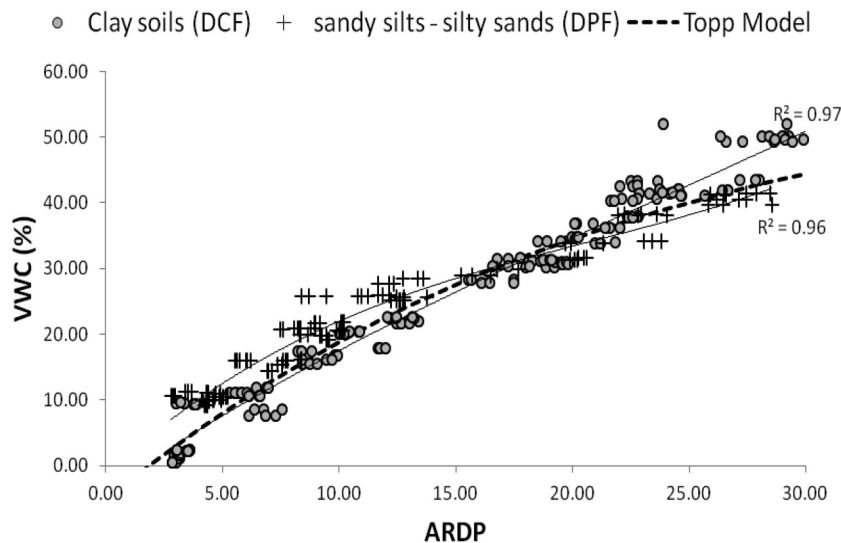


Table 3. Summary of equations derived from TDR measurements relating ARDP to VWC or GWC for different soil types.

Inputs	Outputs (%)	Soil type	Equation	R^2	Equation No.
ARDP	VWC	Silty sands – sandy silts	$VWC = 0.0019\epsilon_r^3 - 0.1169\epsilon_r^2 + 3.3208\epsilon_r - 1.4288$	0.96	(1)
		Clays	$VWC = 0.0005\epsilon_r^3 - 0.0369\epsilon_r^2 + 2.4478\epsilon_r - 3.8036$	0.97	(2)
	GWC	Silty sands – sandy silts	$GWC = 0.0007\epsilon_r^3 - 0.0913\epsilon_r^2 + 2.2737\epsilon_r - 0.8709$	0.89	(3)
		Clays	$GWC = 0.0007\epsilon_r^3 - 0.0354\epsilon_r^2 + 1.5752\epsilon_r - 2.4462$	0.94	(4)
ARDP and ρ_d (Mg/m ³)	GWC	Silty sands – sandy silts	$GWC = 0.006\frac{\epsilon_r^3}{\rho_d} - 0.2304\frac{\epsilon_r^2}{\rho_d} + 3.7823\frac{\epsilon_r}{\rho_d} + 2.0189$	0.94	(5)
		Clays	$GWC = 0.0006\frac{\epsilon_r^3}{\rho_d} - 0.038\frac{\epsilon_r^2}{\rho_d} + 2.3316\frac{\epsilon_r}{\rho_d} + 2.2181$	0.97	(6)

Note: ϵ_r , measured apparent relative dielectric permittivity; ρ_d , dry density (Mg/m³).

error of 0.50. Clearly, the variations were small and demonstrate the robustness of the experimental methodology.

Comparison with other relationships

Data from the laboratory testing have been plotted and compared to a number of different empirical and semi-empirical models developed on a large number of soils from the literature in Fig. 7. The equations used are shown in Table 4. The Roth et al. (1990) model requires additional inputs of temperature and porosity to calculate water content. In Fig. 7, the Roth et al. (1990) model is plotted for all three temperatures used in this research, with an assumed dry density value of 1.7 Mg/m³. The dry density was used to calculate a value of porosity to input in the model (equal to 1 minus the ratio of dry density divided by particle density).

The variation between different models is not large at low ARDP values with relationships varying by c. 5% VWC, although maximum variance at higher ARDP values, especially between the Wensink (1993) model and the other models, is approximately 10%–12% VWC. More significantly, however, it can be shown that none of the models provide a good fit to the collected data across the whole ARDP range for both soil types. In the DCF samples, all of the models overestimate and underestimate the water content at high and low ARDP values, respectively, with the exception of the reasonable fit of the Wensink (1993) model. The reason for this deviation is that Wensink (1993) related the VWC with the ARDP measured at 1 GHz, which is less affected by dispersion and conductive losses, and in fact provides a better fit to the clayey soils. At low ARDP values, the opposite effect is true for the DPF samples

with the models underestimating the VWC in most of the measured samples, although many of the models show a reasonable fit as the ARDP increases. These data fits highlight the need to choose a suitable model for the soil type, or if maximum accuracy is required, then a soil- and system-specific model should be developed.

It is interesting to note that the Roth et al. (1990) relationship predicts a wide variation of VWC for the three temperatures and soils investigated in this research, which is in contrast to the measurements shown in Fig. 4. Although temperature is known to have a negative dependence on ARDP (Kaatze 1989), this effect is competing with the release of bound water (Wraith and Or 1999; Skierucha 2009) and increases in bulk electrical conductivity that can contribute to an increase in ARDP. Examination of the data showed the net temperature effect on measured ARDP to be small and it is thought that this is a result of the balance between these competing effects, which largely cancel each other out. At high ARDP values on DCF and low ARDP values on DPF, these temperature deviations are less apparent due to inaccuracies in the ARDP–VWC relationship, which provide more significant errors as shown in Fig. 7.

Factors affecting soil permittivity

It is clear from the previous discussions that several parameters influence the measured ARDP, and it has been difficult to identify the various relationships. To assess which soil properties affected the measured ARDP, a principal component analysis (PCA) was carried out, which, to the knowledge of the authors, is not

Fig. 4. Relationships between VWC of a soil and its measured ARDP (by TDR) shown for clay soils (DCF) and sandy silts – silty sands (DPF) at 0 and 20 °C.

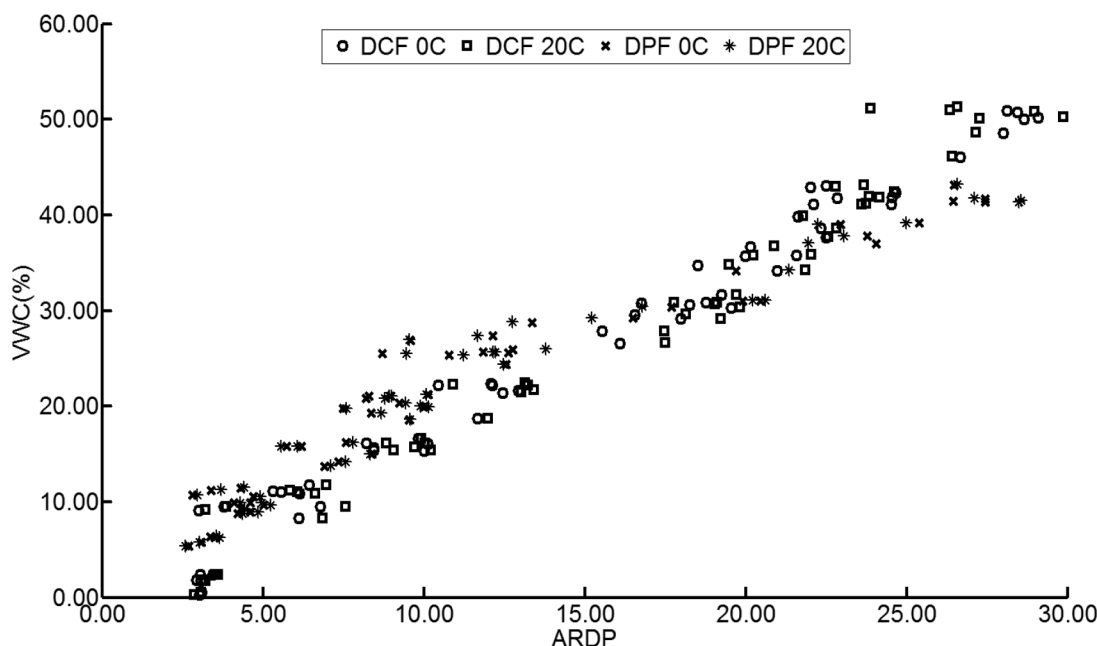
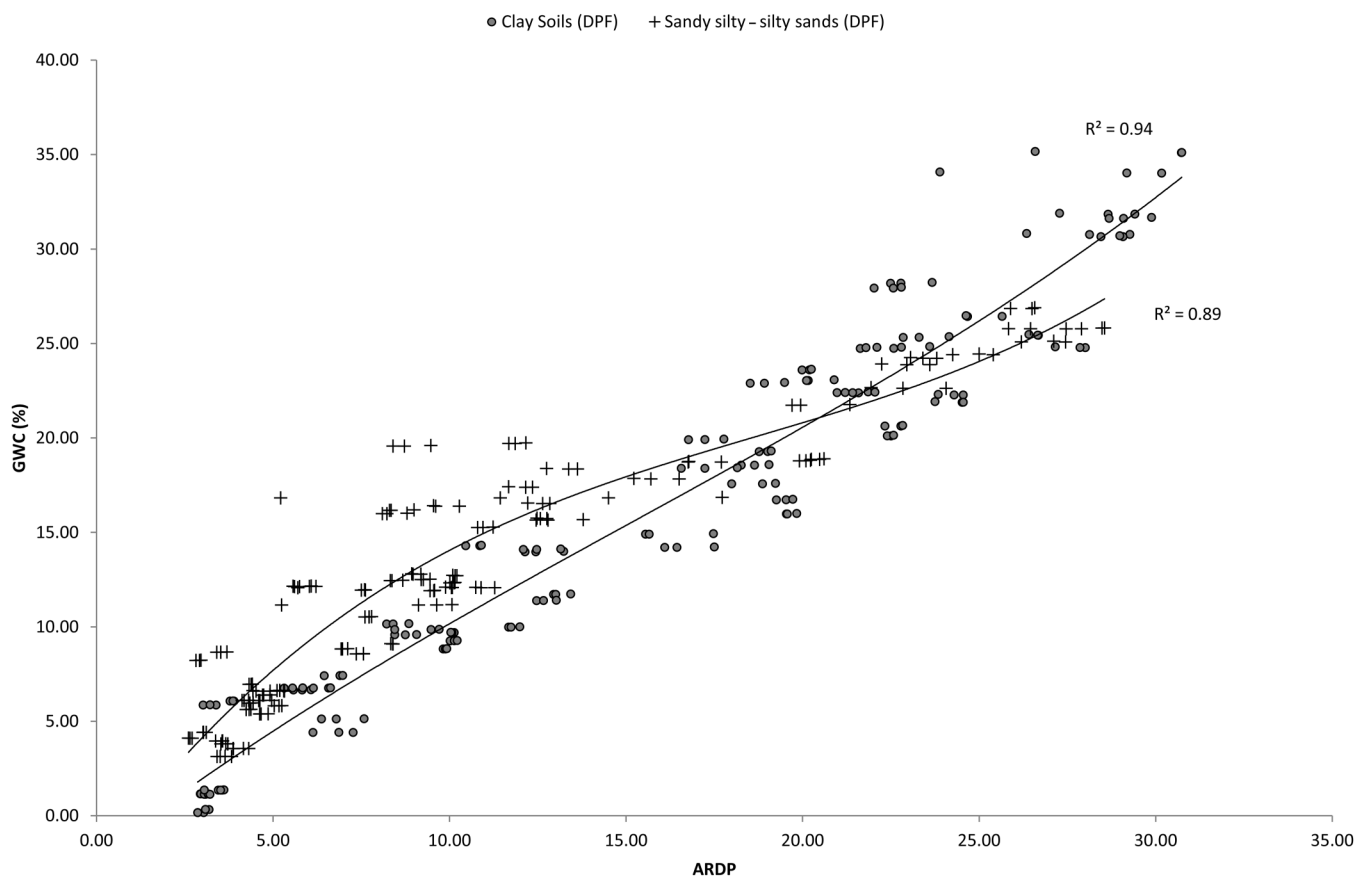
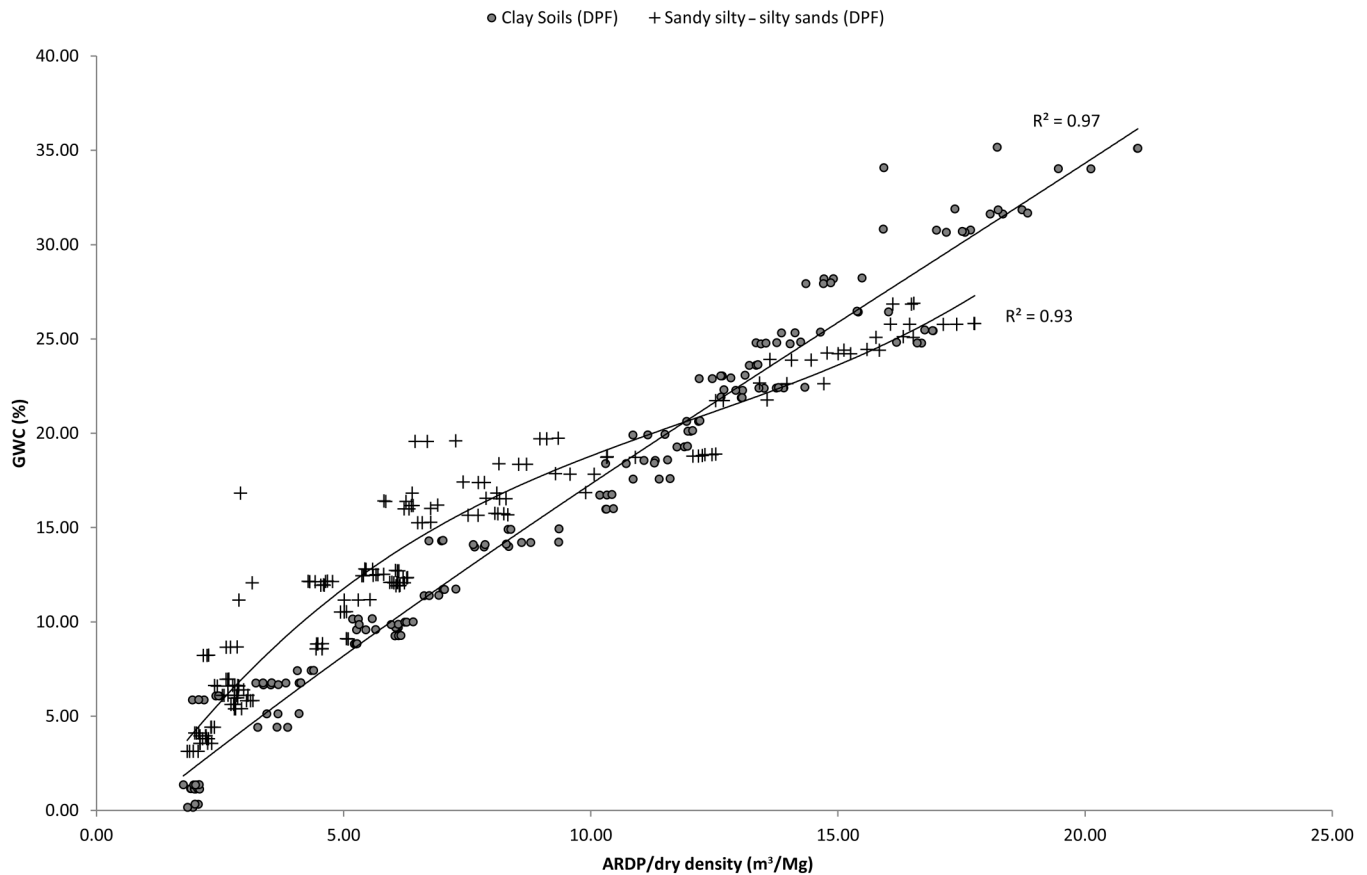
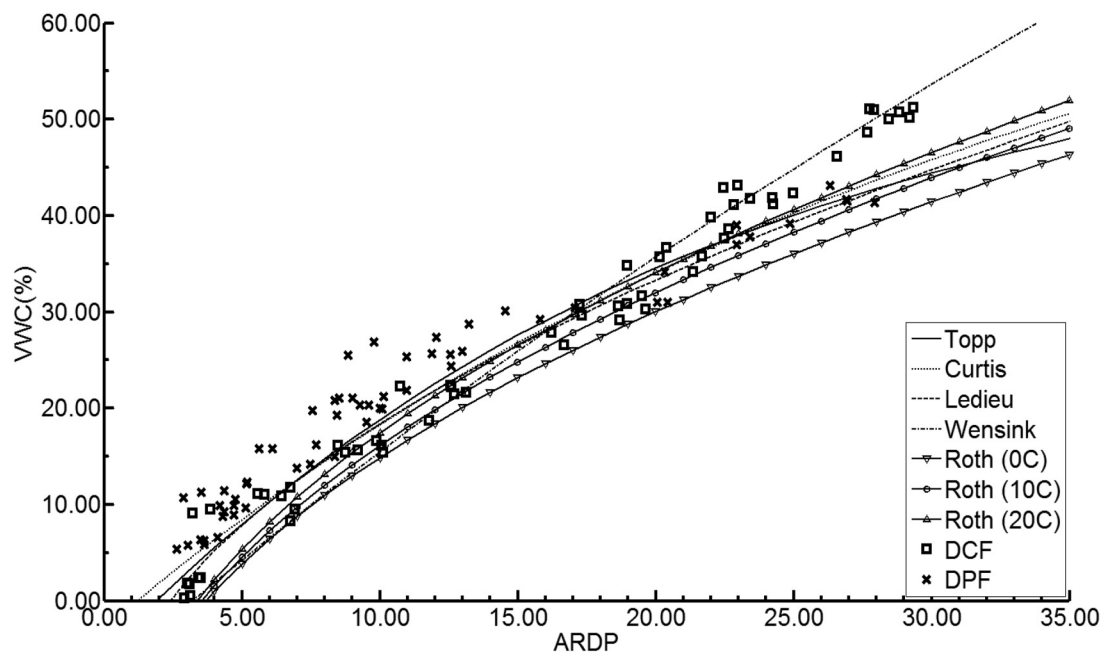


Fig. 5. Relationship between measured ARDP and GWC between clays (DCF) and sandy silts – silty sands (DPF).



common practice in geotechnical engineering. However, as the soil is a complex system characterized by a number of interrelated parameters, a PCA can be a useful way of describing this system. The advantage of the PCA is that it considers several variables at a time and gives an immediate picture of their underlying relation-

ships (i.e., correlations). This means that each parameter inputted into a PCA will be correlated with each other and the degree of correlation determined, which is then expressed in the principal components. A PCA consists of a mathematical procedure that rotates the original data, organized in an $n \times p$ matrix, where n are

Fig. 6. Relationship between measured ARDP divided by soil dry density and GWC.**Fig. 7.** Variability of VWC predictions obtained with selected empirical and semi-empirical relationships found in the literature. DCF and DPF measurements are shown for comparison.

the observations (i.e., measurements) and p the parameters, multiple times in the direction of greatest variance (Jolliffe 2002). The first rotation is along the direction of greatest variance in the data, the second rotation is along the direction of the second greatest

variance, and so forth. New orthogonal and uncorrelated variables, called principal components (PCs), are generated by this procedure and are a linear combination of the original parameters. Further details on the theory of PCA can be found in reference

Table 4. Summary of equations used for comparing relationships between VWC (%) and ARDP (ϵ_r).

Relationship	Equation(s)
Curtis (2001)	$VWC = 0.000237\epsilon_r^3 - 0.03421\epsilon_r^2 + 2.435\epsilon_r - 2.86$
Ledieu et al. (1986)	$VWC = (0.113\sqrt{\epsilon_r} - 0.1756)100$
Roth et al. (1990)	$\epsilon_w(T) = 78.54[1 - 4.579 \times 10^{-3}(T - 25) + 1.19 \times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3]$ $\zeta_c = \frac{\epsilon_r}{\epsilon_w} \quad \zeta_w = \frac{\epsilon_w}{\epsilon_w(20)} \quad \zeta_a = \frac{\epsilon_a}{\epsilon_w(20)} \quad \zeta_s = \frac{\epsilon_s}{\epsilon_w(20)} \quad \alpha = 0.45$ $VWC = \frac{\zeta_c^\alpha - (1 - \eta)\zeta_s^\alpha - \eta\zeta_a^\alpha}{\zeta_w^\alpha - \zeta_a^\alpha} 100$
Topp et al. (1980)	$VWC = (-5.3 \times 10^{-2} + 2.92 \times 10^{-2}\epsilon_r - 5.5 \times 10^{-4}\epsilon_r^2 + 4.3 \times 10^{-6}\epsilon_r^3)$
Wensink (1993)	$\epsilon_{r(1GHz)} = 3.2 + 41.4VWC + 16.0VWC^2$ $VWC = \left[\frac{-41.4 + \sqrt{41.4^2 - 64(3.2 - \epsilon_r)}}{32} \right] 100$

Note: T , temperature ($^{\circ}\text{C}$); α , empirical soil parameter; ϵ_a , RDP of air; ϵ_r , ARDP; $\epsilon_{r(1GHz)}$, ARDP at 1 GHz; ϵ_s , RDP of soil minerals; ϵ_w , RDP of free water; ζ_a , ζ_c , ζ_s , ζ_w , ratios of RDP as defined in this table; η , porosity.

manuals such as Jolliffe (2002). The input parameters used in the current analysis were: VWC, ARDP, BEC, temperature, particle density, dry density, LL, PL, LS, and clay, silt, and sand contents. Temperature, dry density, VWC, ARDP, and BEC were different for each measurement, whereas the other geotechnical parameters varied for each soil type. The variables were normalized prior to the PCA to make them comparable irrespective of their scale according to eq. (8):

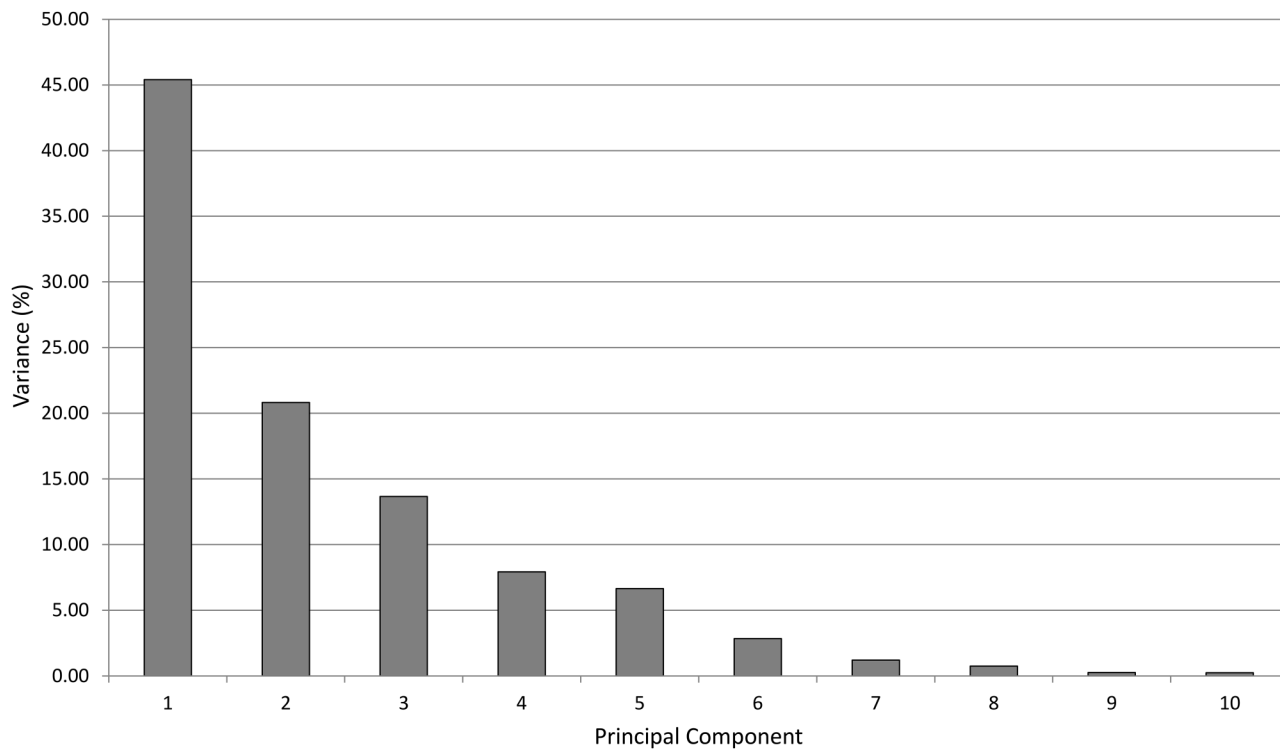
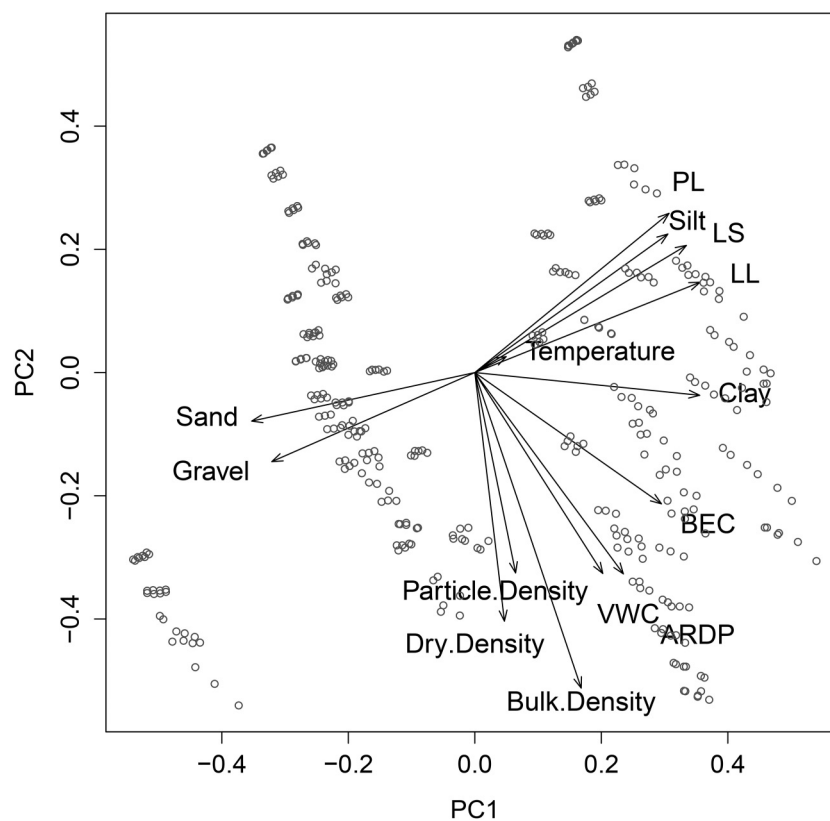
$$(8) \quad x' = \frac{x - \mu}{\sigma}$$

where x' is the normalized variable used in the PCA, x is the original variable, and μ and σ are the mean and standard deviation of the original variable, respectively. The function *prcomp* implemented in the *stats* package in the software environment R was used to perform the analysis. Table 5 shows the contribution of the original variables in the first four principal components, which are ranked according to the percentage of total variance that they explain (i.e., PC1 accounts for most of the relationships between parameters, PC2 accounts for the second most important variance and so on). Figure 8 shows the percentage variance for each PC and indicates that approximately 88% of variation was accounted for in the first four principal components. However, most of the variation was described by the first two principal components (66% of the total variance), and therefore these have been selected for further analysis. The important relationships between variables would be described by these two principal components due to their high contribution to the total variance. The typical output of a PCA, called a “biplot”, displays the contribution of the original variables and the observations in two selected principal components that represent the axes of the biplot. Variables placed close to each other are positively correlated, variables placed at 180° to each other are negatively correlated and orthogonal variables are not correlated. The size and direction of the vector indicates the contribution of the original variables in the principal components (see Table 5). Figure 9 shows the biplot of PCs 1 and 2 for the properties of all the soils tested. As expected, the ARDP appears close to VWC, indicating that the two parameters were strongly correlated. The ARDP was also correlated with BEC, confirming that BEC was predominantly caused by soluble ions in the pore water and therefore increased with water content. This is in accordance with previous literature (e.g., Hartsock et al. 2000). Figure 9 also shows that the soil density had an impact on the measurement of ARDP. This is a significant result reported

Table 5. Contribution of the original variables used in the PCA in the first four principal components.

Original variables	PC1	PC2	PC3	PC4
ARDP	0.235	-0.327	0.384	0.035
BEC	0.295	-0.213	0.282	0.015
VWC	0.202	-0.326	0.446	0.005
Temperature	0.050	0.026	0.099	0.661
Gravel	-0.321	-0.145	0.054	-0.262
Sand	-0.353	-0.079	0.201	-0.158
Silt	0.305	0.225	0.006	0.332
Clay	0.355	-0.037	-0.296	0.038
Particle density	0.064	-0.325	-0.493	0.235
Bulk density	0.168	-0.512	-0.023	-0.124
Dry density	0.047	-0.403	-0.422	-0.174
PL	0.307	0.258	0.051	-0.329
LL	0.356	0.147	-0.093	-0.251
LS	0.334	0.206	-0.011	-0.289

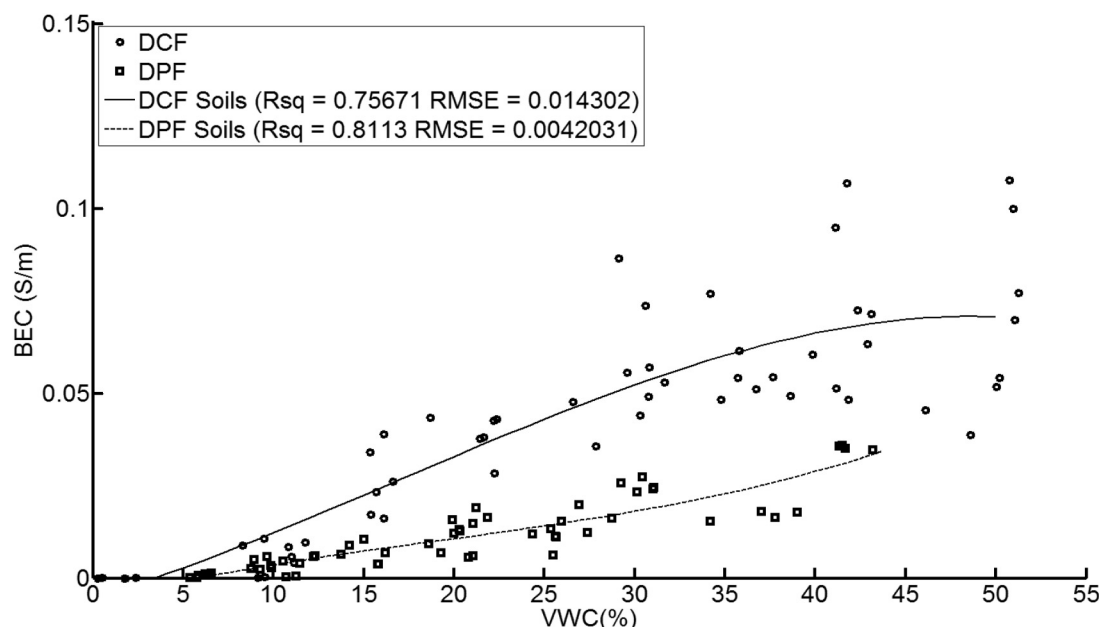
by other authors (Jacobsen and Schjonning 1993; Malicki et al. 1996) and confirms the importance of the soil solids in determining the dielectric properties of the soil. Interestingly, ARDP was slightly affected by clay content, but was not significantly influenced by any of the other geotechnical parameters measured, which are all approximately positioned orthogonally with respect to ARDP. Thomas et al. (2010a) found that ARDP measurements at 1 GHz were related to LL for a range of fine-grained soils. However, the frequency used in this study to obtain ARDP was below 500 MHz, therefore a direct comparison cannot be made. In addition, the soils tested by Thomas et al. (2010a) showed predominantly higher LL values, from 25% to 312%, compared to the limited range investigated here (24%–48%, see Table 2). Figure 9 also shows a small vector for temperature, orthogonal to ARDP, indicating that temperature was not an important parameter affecting ARDP. As mentioned above, previous authors reported conflicting relationships between ARDP and temperature, a positive one for clays due to the release of bound water, and a negative one for sands that follows a similar behaviour to free water (Or and Wraith 1999; Skierucha 2009). However, for the soils studied here, these relationships were not evident, confirming, as already mentioned above, that these competing effects cancelled each other out. A PCA was also run using the data from the two sites separately (not shown) and in both cases ARDP did not show correlations with temperature, nor did it show any different results from the ones described above. It must be pointed out that a PCA

Fig. 8. Percentage variance explained by each principal component.**Fig. 9.** Biplot of principal components 1 and 2 for properties of all of the soils tested from both sites.

analysis on each single site would not be very informative due to the limited number of soils studied, which showed limited variation of several of the geotechnical properties for each site (Table 2). In order for the PCA to be effective, it should be carried

out on a relatively large number of measurements and soil properties covering a wide range of values. Interpretation of the PCA results is important to avoid the association of parameters that in fact are not correlated, but appear correlated for a fortuitous case.

Fig. 10. Relationship between volumetric water content and bulk electrical conductivity for DCF and DPF sites measured by TDR at 10 °C. RMSE, root mean square error; Rsq (R^2), square of the multiple correlation coefficient.



This can happen if the range of values of the properties considered is not large enough or if only a small number of measurements have been made. The user must interpret the PCA results and make judgements based on existing theory. Alternatively, the PCA must be carried out on a large number of measurements over a wide range of values. When this condition is met, the PCA is a powerful tool that can describe the soil characteristics with a single plot.

From the biplot it is also possible to identify clusters of the experimental observations and determine which variables affected them more significantly (observations and variables placed close to each other). Three main clusters can be identified in Fig. 9. The two clusters on the left side portion of the plot correspond to DPF as clearly shown by the variables “sand” and “gravel” placed close to them. On the right side, centred around the variable “clay”, the cluster corresponding to DCF is visible.

The fact that two clusters form in Fig. 9 can also be explained by the fact that the DPF soils were tested at lower water contents than the DCF soils because of their lower LL; at this water content a soil can no longer be compacted. It was found that for the DPF site, BEC rose approximately linearly with water content. In the clays, however, it appeared to increase up to a certain VWC and then reach a constant level (Fig. 10). Soils appear to reach a water content threshold above which the BEC is unaffected by VWC, and this threshold has been found to vary for different soil types (Fig. 10). The sands and silts tested in this study are not expected to reach this water content threshold in normal field conditions. Hence, the fact that the two soils were tested over different ranges of water content can affect the biplot.

Estimation of GWC using TDR

Having discussed the different soil characteristics affecting ARDP and hence VWC, methods are proposed to determine GWC using TDRs as a more useful parameter for a geotechnical engineer on site. GWC is an easier parameter to derive from a site sample than a VWC, as a disturbed sample and the inexpensive and simple oven drying method (BSI 1990) can be used. Hence GWC has become the most commonly used moisture content measurement across the geotechnical industry, and is the basis of many correlations and calculations used by geotechnical engineers on a day to day basis. Small changes in GWC can create large changes in undrained shear strength, par-

ticularly in low plasticity clays (Clayton 1979). Therefore, the ability to either determine the instantaneous measurement of GWC without the need of any laboratory testing or to continuously monitor and measure GWC inexpensively with little laboratory testing would have, for example, for the continuous monitoring of consolidation adjacent to a structure; the effects of seasonal weather and climate change on ageing earthwork assets, the shrink-swell potential adjacent to trees, and trafficability and moisture variation of clay soils on haul roads.

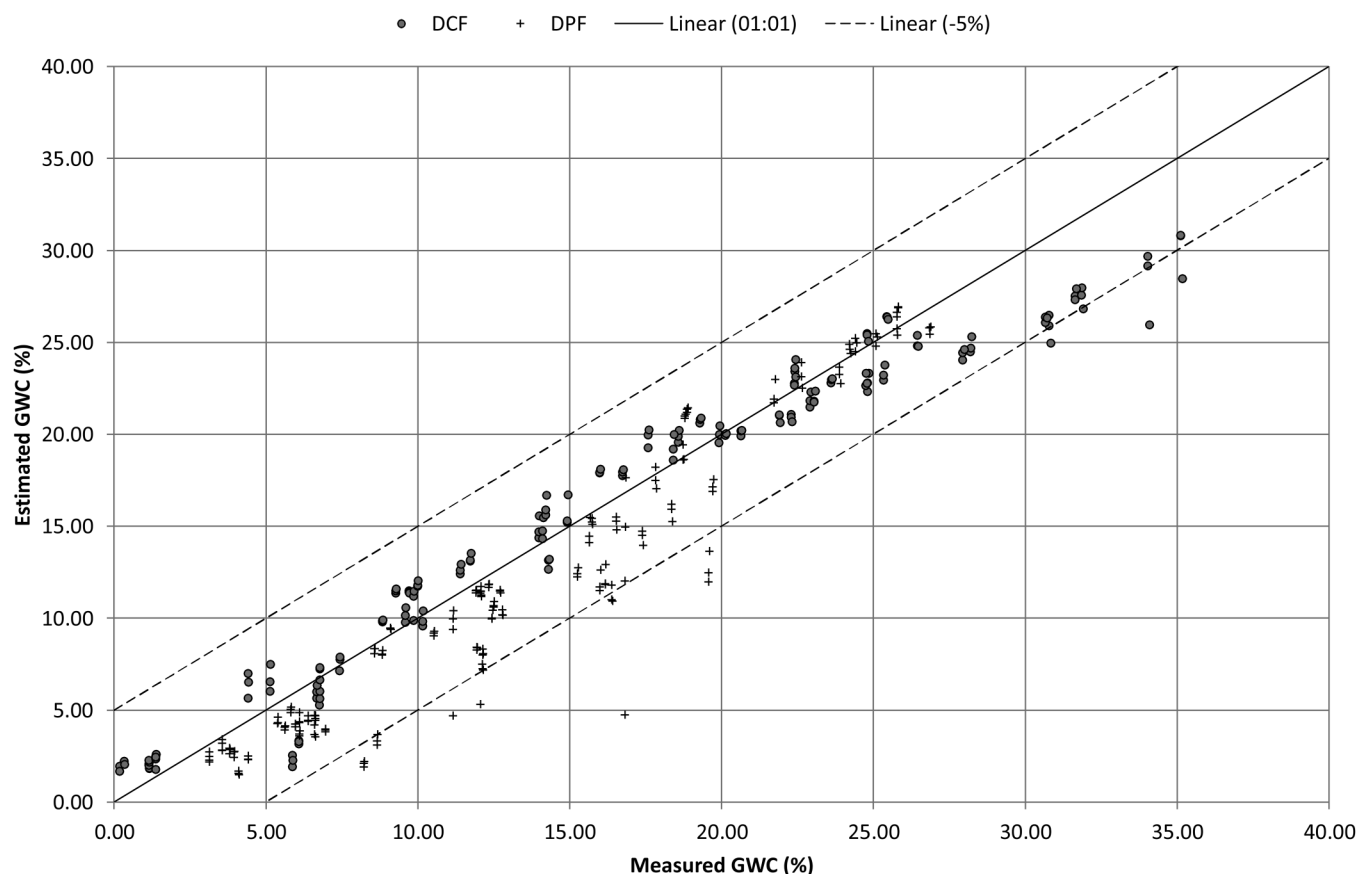
As mentioned earlier, the TDR measured ARDP can be related to VWC or alternatively to GWC if normalized by dry density. Hence, TDR has the potential for being a very useful tool to geotechnical engineers, provided that a measurement or estimation of the soil's dry density is available. Dry density is a fundamental soil property and relates directly to void ratio, making it very closely correlated to the strength and compressibility of a soil. Like GWC, it is the basis for many calculations used in geotechnical design, but unlike GWC, dry density requires more sophisticated laboratory testing to be determined directly. For example, the volume displacement method (BSI 1990) has been used on the soils in this study. For construction projects the amount of laboratory testing carried out is often constrained by budget and time. This paper proposes three methods of relating GWC to measured ARDP values based on the description of the soil, with different levels of known geotechnical properties needed. The selection of the most appropriate method depends on time, budget, and available data. The different methods are described below, followed by further details on each method, including examples.

Method A — An in-depth site investigation and undisturbed samples to carry out full laboratory testing including dry density measurement.

Method B — A basic or preliminary site investigation to obtain field soil descriptions and disturbed samples for index and classification tests.

Method C — A site walkover or desk study using published data such as those provided by the British Geological Society in the UK to obtain field soil descriptions.

All three methods rely on a measurement or estimate of the dry density, which in turn can be used to convert VWC to GWC using

Fig. 11. Estimated versus measured GWC for method A with underlying VWC based on Topp et al. (1980).

eq. (7). In all the methods, the VWC is obtained by applying empirical, semi-empirical, or soil-specific models to the ARDP values measured using TDR. For the purpose of this paper, only the Topp et al. (1980) relationship is used to obtain the VWC as this is a well-established and commonly applied relationship. The difference in the methods is thus purely based on the different ways of obtaining the dry density values. Where necessary, the method used to obtain the dry density values is explained in detail with examples provided. The results obtained from applying the different methods on the soils presented in this paper are compared and discussed.

Method A

This method requires the most laboratory work and is the least dependent on engineering judgement. The measured dry density from laboratory testing is used in eq. (7) to determine the GWV from the VWC. The results are presented in Fig. 11 showing the measured and estimated GWC using this method. Since this method uses only measured laboratory data and the Topp et al. (1980) relationship, all deviations of the predicted value from the actual value of GWC arise from experimental errors and errors in fitting Topp et al. (1980). It should be noted that only one density measurement was taken for each sample and the GWC was measured three times as discussed earlier.

Method B

This method uses the LL and LS from index testing and an estimated saturated bulk density to determine the dry density. The estimated saturated bulk density, $\rho_{b,sat}$ (Mg/m³), of a soil can be based on the standard soil description (BSI 1999) and published typical values of saturated unit weights in BSI (1994) and are shown for some soils in Table 6. Table 7 shows the saturated bulk density estimated for the soils in this paper based on the soil

description given in Table 1. Now assuming that the LL (obtained from index testing) is approximately equal to the saturation moisture content, the dry density can be calculated using eq. (9) as all the voids are water-filled.

$$(9) \quad \rho_d = \frac{\rho_{b,sat}}{1 - LL}$$

The results from this calculation are shown in Table 7. For high plasticity clay soils which shrink appreciably when dried, this will underestimate the dry density of soils at low in situ water content, as the specific volume of clay particles increases significantly between a dry state and saturation (Chertkov 2000). For soils which are expected to be at low water contents or for high plasticity clays, it is therefore recommended that this effect is accounted for by applying information on the linear shrinkage obtained from laboratory tests (BSI 1990). As the linear shrinkage represents a reduction in volume of a soil when it is dried from its LL to desiccation as a percentage it will produce an increase in dry density proportional to its volumetric shrinkage. To take account of this for clay soils, it is proposed to increase the dry density derived by eq. (9) by a percentage equal to the linear shrinkage.

Soils tested here have only been tested at moisture contents around the optimum moisture content for compaction to avoid problems of compaction at higher moisture contents. This means that these soils are close to their shrinkage limit, meaning the majority of volumetric contraction compared to saturated soil will have occurred (Chertkov 2000). However, for soils with in situ water content close to saturation, or which do not exhibit significant volumetric shrinkage with drying, this use of linear shrinkage is not required. Figure 12 shows the measured versus calculated

Table 6. Typical bulk density and saturated bulk density values for a range of soils (after BSI 1994).

Granular soil	Bulk density, ρ_b (Mg/m ³)		Saturated bulk density, $\rho_{b,sat}$ (Mg/m ³)	
	Loose	Dense	Loose	Dense
Gravel	1.60–2.00	1.80–2.10	2.00	2.10
Well graded sand and gravel	1.90–2.15	2.10–2.30	2.15	2.30
Coarse or medium sand	1.65–2.00	1.85–2.15	2.00	2.15
Well graded sand	1.80–2.05	2.10–2.25	2.05	2.25
Fine or silty sand	1.70–2.00	1.90–2.15	2.00	2.15

Cohesive soil	Bulk density, ρ_b (Mg/m ³)		Saturated bulk density, $\rho_{b,sat}$ (Mg/m ³)	
Peat (very variable)	1.20		1.20	
Organic clay	1.50		1.50	
Soft clay	1.70		1.70	
Firm clay	1.80		1.80	
Stiff clay	1.90		1.90	
Hard clay	2.00		2.00	
Stiff or hard glacial clay	2.10		2.10	

Table 7. Input parameters and derived dry densities for the three different methods proposed (values in brackets indicate the minimum and maximum values for the density based on measurements or Table 6).

Soil	Method A: Average measured dry density (Mg/m ³)	Method B		Measured linear shrinkage (%)	Est. dry density (Mg/m ³)†	Est. dry density (Mg/m ³)	Method C: Est. bulk density (Mg/m ³)*
		Measured liquid limit (%)	Est. sat density (Mg/m ³)*				
DCF topsoil	1.54 (1.46–1.59)	48.00	1.90	13.9	1.39	1.51	1.75 (1.7–1.8)
DCF subsoil	1.65 (1.65–1.65)	47.00	1.9	13.7	1.50	1.70	1.90
DCF ditchfill 1	1.59 (1.57–1.61)	41.00	1.9	10.8	1.52	1.60	1.90
DCF natural 1	1.83 (1.58–1.9)	40.00	1.9	10.5	1.53	1.69	1.90
DPF topsoil	1.62 (1.60–1.64)	30.00	2.00	—	1.57	1.57	1.85 (1.7–2.0)
DPF subsoil	1.65 (1.61–1.67)	25.00	2.15	—	1.75	1.75	1.90
DPF ditchfill 1	1.56 (1.54–1.57)	27.00	2.00	—	1.61	1.53	1.85 (1.7–2.0)
DPF ditchfill 2	1.36 (1.30–1.64)	27.00	2.00	—	1.61	1.53	1.85 (1.7–2.0)
DPF ditchfill 3	1.65 (1.65–1.66)	24.00	2.00	—	1.64	1.56	1.85 (1.7–2.0)
DPF natural	1.83 (1.79–1.86)	26.00	2.00	—	1.62	1.62	1.85 (1.7–2.0)

*From Table 6.

†Using eq. (9).

GWC using this method and Table 7 contains the relevant parameters.

If the LL is not known for eq. (9), the LL can be estimated from published geological literature and an accurate description of the soil (e.g., CIRIA 1999) or the Casagrande plasticity chart (Craig 2004) if the activity of the clay or silt is known, but clearly, this induces another level of uncertainty.

Method C

This method can be used when only the soil description from a site walkover or published geological data are available. Neglecting the mass of air, the bulk density of a soil is defined by eq. (10):

$$(10) \quad \rho_{b,m} = \frac{m_s + m_w}{V} = \rho_d + VWC\rho_w$$

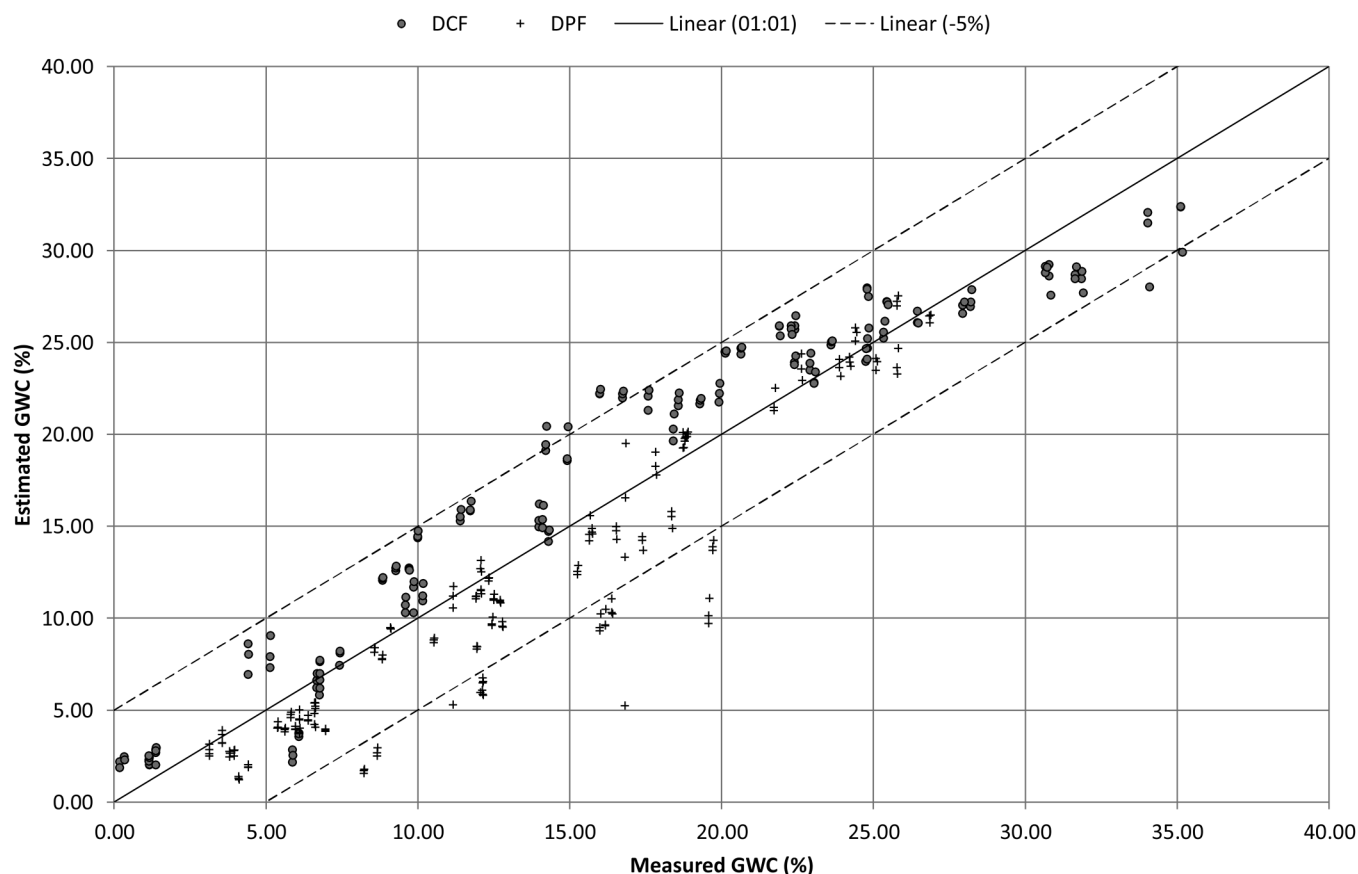
where $\rho_{b,m}$ is the moist bulk density (Mg/m³); m_s and m_w are the mass of solid particles and water (Mg), respectively; V is the volume of the sample (m³); ρ_d is the dry density (Mg/m³); and ρ_w is the density of water (Mg/m³), taken as 1. From a soil description a reasonable bulk density value can be estimated using Table 6. It should be noted though that this estimation does not take account of the change in bulk density with water content. The proposed values for the soils presented in this paper are provided in Table 7, including their ranges where appropriate. The dry density varies with water content (see eq. (10)) and hence is not constant

for the individual soils, therefore no values are provided in Table 7. Where there was a range of values, as shown in Table 6, the average bulk density value has been taken as the most appropriate estimation, but a sensitivity study has been carried out and is discussed further in the next section as well as with error bars shown in Figs. 13a and 13b.

It should be emphasized that this approach relies on having a detailed soil description to reduce inaccuracy, but does make it suitable in situations where only a desk study has been carried out. Figures 13a and 13b show the results for the measured GWC and estimated GWC using this method for DCF and DPF, respectively, with the error bars indicating the possible range depending on which value of bulk density was chosen.

Method comparison

Three different methods have been proposed to obtain GWC (from VWC derived by relating it to the measured ARDP values using TDR), based on knowing or estimating the dry density. Figures 11 to 13 show the estimated versus the measured GWC for the three methods, respectively. All the methods show reasonable agreement between the measured and calculated GWC, although it can be seen that all the methods performed less well for the DPF soils. It should be noted that errors can be induced by a number of sources, including experimental errors when measuring ARDP and GWC, the errors of using Topp et al. (1980) in contrast to

Fig. 12. Estimated versus measured GWC for method B with underlying VWC based on Topp et al. (1980).

soil-specific calibrations, and errors when obtaining the dry density either through measurements or the alternative methods proposed. The results presented in Fig. 11 are only based on laboratory measurements as well as the application of Topp et al. (1980). The errors of using Topp et al. (1980) to determine the VWC for the soils presented in this paper is also apparent in Fig. 3, and has been discussed previously. As Topp et al. (1980) performed less well for the sandy silts – silty sands (DPF), it is not surprising that the calculated GWC values for DPF (see Fig. 11) deviate further from the measured GWC in contrast to the DCF values. Overall though, 98% and 92% of the values for DCF and DPF, respectively, are within a $\pm 5\%$ GWC envelope, and the mean errors are 1.69% GWC and 2.00% GWC, respectively (see Table 8).

Methods B and C rely on the estimation of the saturated bulk density and bulk density respectively to determine the dry density. The error analysis for methods B and C (see Table 8) show that the percentage of data within the $\pm 5\%$ GWC envelope is less than method A. This is not surprising, as the dry density is based on estimation requiring engineering judgement. It can also be seen that the error increases more for DPF compared to DCF. A possible explanation is the wider possible range of bulk density values (see Table 6) for silts and sands compared to clays. This is also visible in Fig. 13b, which shows larger error bars for DPF compared to Fig. 13a for DCF.

However, it should be pointed out that all three methods performed well in determining the GWC. Not surprisingly, method A, based on only measurements, provided the best fit. The strength of methods B and C is the fact that no, or only very simple, laboratory tests are needed. Based on the accuracy required for a specific project, as well as the available soil information, the geotechnical engineer should choose the most appropriate method. It is also important to note that the accuracy can be increased by

using a soil-specific calibration to determine the VWC from ARDP measurements and the data lying within the $\pm 5\%$ GWC envelope increase to between 96% (method C) and 99% (method A). If this is obtained, the engineer will most likely have carried out extensive laboratory tests to characterize the soil, and thus should be in a position to use method A.

Furthermore, for projects that require high accuracy in the determination of GWC, soil specific empirical calibrations may be required, and more rigorous methods such as the one presented by Jung et al. (2013) should be preferred. However, this method requires the use of bespoke TDR probes together with dedicated laboratory testing specific to the soil under investigation.

Conclusions

To create a uniform soil sample from a fine-grained soil, consolidation methods can take weeks. This paper described a potentially less time consuming method using a combination of oven drying and equalization time that proved to be very successful for the TDR experiments conducted in this research, and produced a mean error of less than 0.33% GWC across a sample.

In the published literature, variations in predicted VWC is not large at low ARDP values (c. 5% VWC), but can increase to approximately 10–12% VWC at higher ARDP values. The data fits with the measurements showed that all models either overestimated or underestimated the VWC for the soils presented in the paper and that soil-specific relationships between ARDP and VWC need to be developed to increase the accuracy. In measuring the ARDP of a soil, sands and clays are expected to behave in a very different manner. This was corroborated by the derivation of two separate relationships between VWC and ARDP for the soil samples from two sites, DPF and DCF. Therefore, a relationship which has been

Fig. 13. Estimated versus measured GWC for method C with underlying VWC based on Topp et al. (1980) for (a) DCF and (b) DPF.

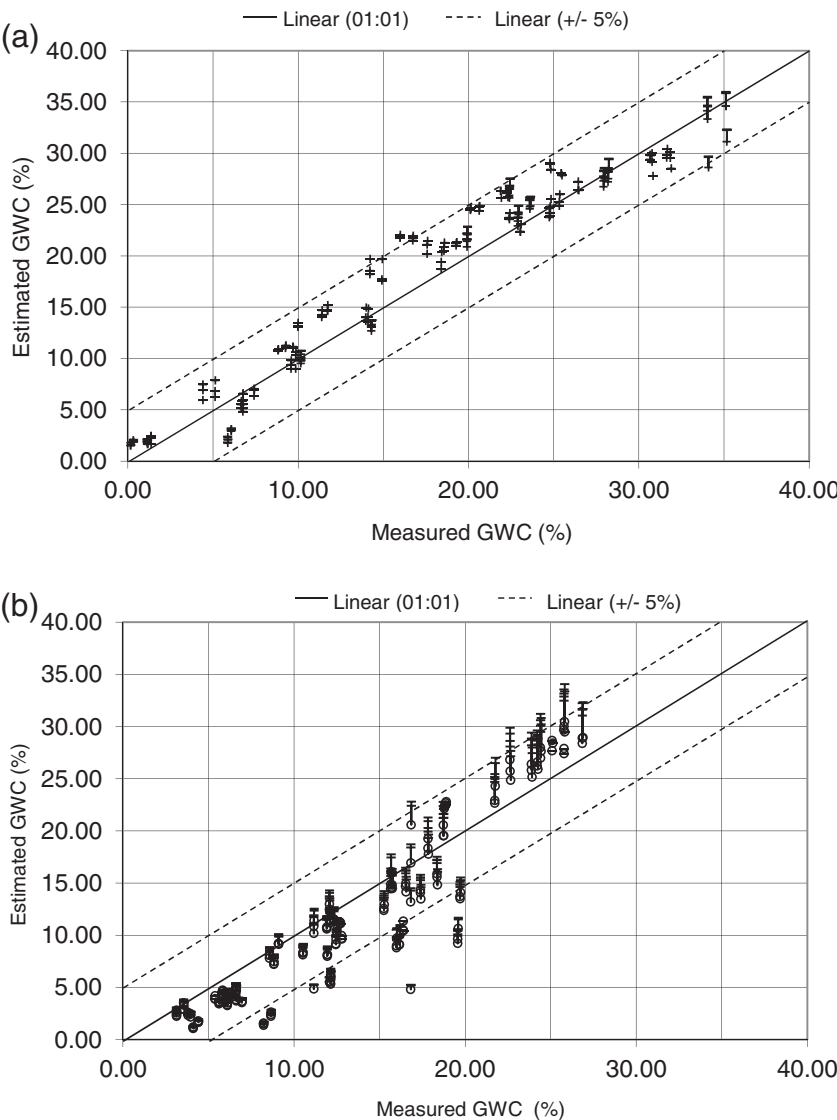


Table 8. Comparison of errors in the determination of GWC for selected models using the different estimation methods.

	Method A		Method B		Method C	
	DCF	DPF	DCF	DPF	DCF	DPF
Absolute mean error (GWC %)	1.69	2.00	2.38	2.26	1.93	2.80
Max error (GWC %)	8.12	12.09	6.45	11.58	6.05	12.02
Standard deviation error (GWC %)	1.37	1.80	1.58	2.17	1.50	2.16
Data within ±5 % GWC envelope (%)	98	92	94	84	96	84

Note: Total sample set size was 174 and 184 for DCF and DPF, respectively.

designed to apply to any soil type will be an approximation between a clay dominant and a sand dominant soil.

No measureable effect on ARDP due to temperature was found. This was confirmed by a PCA, although soil conductivity (BEC) is affected by temperature. This was in contrast to findings by other researchers, for example Roth et al. (1990). It was hypothesized that this is due to the conflicting effects of the release of bound water and the temperature dependent permittivity of water that is more important in saturated soils.

Dry density does not appear to directly affect the measured ARDP for the density range analyzed during the sensitivity analysis, but it showed some effects in the PCA analysis on all soils as

the actual dry density of the soils varied by more than the 10% used in the sensitivity analysis. The dry density can be used to add the volumetric dimension to the relationship between GWC and ARDP, improving its accuracy from an R^2 coefficient of 0.88 to 0.94 for the silty sands and sandy silts, and from 0.94 to 0.97 in the clays used in this study.

Although the results from the PCA mainly confirmed the influence of different soil parameters, the potential of this method was demonstrated and it is believed that this analysis would be even more useful for soils with a larger range of particle size distributions and Atterberg limits. The advantage of a PCA is that it con-

siders several variables at a time, giving an immediate picture of their underlying relationships.

Three different methods have been proposed to determine the GWC from the VWC, derived using Topp et al. (1980), and measured or estimated values for dry density. All three methods have a number of different error sources, but overall performed well with between 83% and 92% of data for DPF and between 95% and 98% of data for DCF lying within the $\pm 5\%$ GWC envelope, and the absolute mean errors ranging from 2.00%–2.76% for DPF and 1.69%–2.02% for DCF. Therefore, the proposed methods have the potential to extend the use of TDRs to those communities who are interested in GWC and not VWC.

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