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Abstract

Subsurface geophysical investigations have the potential of providing information for the long-term monitoring of geotechnical assets. This research evaluates the suitability of vertically and horizontally orientated, embedded Time Domain Reflectometry (TDR) measurements for monitoring of near-saturated, fine-grained soils under vertical loading conditions. TDR measurements were carried out regularly during vertical loading and unloading of near- and fully-saturated soil mixtures containing fine-sand, kaolinite and bentonite. The results show that TDR probe orientation, in relation to the load direction, affects the values of TDR-measured apparent permittivity (AP) and bulk electrical conductivity (BEC). The relationship between the soil void ratio and AP was found to be clearer when measured in the direction of loading whereas AP and BEC measured normal to the load application appears to reflect changes in pore-water pressure. BEC was found to be more variable and less obvious. It is concluded that monitoring relative changes in temporal AP and BEC using embedded TDR sensors can provide unique and valuable information on how a soil responds to loading under near-saturated conditions.

Keywords: Time Domain Reflectometry, geophysical monitoring, saturated soils, ground investigation, geotechnical asset, TDR probe orientation

Introduction

Geotechnical asset failures can lead to catastrophic consequences. Earth dam failures alone caused the loss of thousands of lives globally (Charles et al., 2011). Therefore, there is a pressing need for improved, long-term monitoring, management and planned interventions strategies for key infrastructure assets (Clarke et al., 2016). Long-term asset monitoring is still not common practice (Shah, 2014) as it often requires high initial investment and special technical expertise for the management of the instrumentation and data collected. Nonetheless, there has been a considerable drive in the geotechnical community to improve the nature, accuracy and cost of asset monitoring systems (Basu et al., 2013) with geophysical methods being increasing popular (McDowell et al., 2002). Geophysical monitoring has several benefits over traditional ground investigation methods as it captures the temporal changes in soil behaviour and is able to capture trends in ground deformation (Rogers et al., 2012). Given that many of the physico-chemical factors affecting the engineering behaviour of soils also affect their electrical response (Schön, 2004), non-intrusive electrical-based geophysical sensing techniques have been the focus of significant research effort in the past decade (e.g., Lambot et al., 2009; Royal et al., 2011). Ground-Penetrating Radar, Electrical Resistivity Imaging and Electromagnetic Induction are all common non-invasive geophysical techniques that utilise changes in the electrical properties of the ground (i.e., permittivity and conductivity) to infer geotechnical behaviour. To be of value for long-term geotechnical asset monitoring, it is important that the interpreted geophysical parameters are reliably and consistently related to the *in-situ* geotechnical properties, such as gravimetric water content (GWC) and dry density (ρ_d). Time Domain Reflectometry (TDR) is a relatively inexpensive sensing technique that can achieve this (Curioni et al., 2018a) and although it has been an active research area in unsaturated soil monitoring (e.g. Mojid et al., 2003; Ekblad and Isacsson, 2007; Curioni et al., 2018b), its response in saturated and near-saturated ground conditions has not been studied extensively. Nonetheless, the relationship between TDR-measured apparent permittivity (AP) and void ratio (e) measured in an oedometer (Liu, 2007), as well as its application in the prediction of ground settlement (Janik et al., 2017), show that TDR techniques can be used for the effective monitoring of saturated and near-saturated soils.

TDR probes require embedding into the medium being investigated and although probe orientation has been suggested as a factor affecting volumetric water content (VWC) estimation (Skierucha et al., 2004; Pastuszka et al., 2014), to date, no research has addressed the relationship between probe orientation and its influence on the measured AP and BEC under vertical loading conditions. As such, the purpose of this paper is to:

(i) investigate whether TDR can be used to effectively monitor temporal changes in near-saturated fine-grained soils of varying plasticity that are subject to vertical loading, and to

(ii) evaluate whether TDR probe orientation significantly affects AP and BEC readings during controlled, laboratory experiments of loading and un-loading of these soils.

The overall aim of the research is to provide, for the first time, reliable information on the sensitivity of TDR probe orientation to the observed values of measured AP and BEC in saturated materials and how this reflects changes in the geotechnical behaviour of fine-grained soils. More specifically, to show how the relationship of embedded electrical properties measured by TDR can be used to 'ground-truth' non-invasive geophysical data and improve the interpretation of time-lapse geophysical monitoring surveys for key geotechnical assets. This will be discussed on the basis of the results of experimental laboratory testing carried out during vertical loading and unloading of near- and fully-saturated soil mixtures including varied proportions of fine-sand, kaolinite and bentonite.

Background

TDR probe measurements have been known predominately for the estimation of VWC in unsaturated soils based on its relationship with AP (Topp et al., 1980). Its high accuracy (VWC within 1-2% - Jones et al., 2002), when calibrated to specific soil conditions, GWC within ± 2% and ρ_d ± 5% under laboratory conditions (Curioni et al., 2018b), in addition to the possibility of automated remote control

(Mitchell and Liu, 2006) makes TDR a reliable and accurate soil monitoring tool. Considering TDR's application in ground investigation only in the context of its VWC estimation capability, might have led to a general perception that TDR is unreliable when used in high water and high clay content soils. Whilst VWC cannot be accurately estimated in soils with GWC exceeding approximately 55% with the most commonly applied Topp's equation (Topp et al., 1980), it is possible to measure AP and BEC at higher water contents (e.g. Thomas et al., 2010). However, high clay contents, leading to high BEC values and high signal attenuation, can compromise the ability of TDR to effectively characterise soil's electrical parameters. The 'BEC threshold' is dependent on the probe length (Heimovaara, 1990), for example, waveform measurements with 45 mm long rods were found to be detrimentally attenuated at BEC values above 0.3 S/m (Mojid et al., 2003). (Further information regarding AP and BEC determination from TDR signal can be found, for example, in Jones et al., (2002), and Cassidy, (2009)). Experiments conducted by Liu, (2007) in saturated fine-grained soils, at the end of the oedometer consolidation stages, showed a positive correlation between AP and void ratio, e. Meanwhile, BEC measured at the end of subsequent consolidation stages decreased with fluid expulsion in some clays, but in others exhibited a negligible change (Liu, 2007). Furthermore, earth dam settlement prediction based on AP measurements was achieved with an accuracy of 19% (Janik et al., 2017), illustrating the potential of TDR technique for the *in-situ* investigation of saturated soils.

In fully saturated soils, the geotechnical parameters of VWC (Equation **1**), GWC (Equation 2) and ρ_d (Equation 3) can be determined from the estimated value of e.

$$VWC = \frac{e}{1+e} \quad (m^3/m^3) \quad \text{Equation 1}$$

$$GWC = VWC\frac{\rho_w}{\rho_d} \quad (kg/kg) \quad \text{Equation 2}$$

$$\rho_d = \frac{m_s}{V} \quad (kg/m^3) \quad \text{Equation 3}$$

where ρ_w is the density of water (assumed as 1000 kg/m^3 at 4°C) and ρ_d is estimated from the initial dry mass solids (m_s) and the specimen volume (V). The determination of e during 1D consolidation can then lead to estimation of soil compressibility from the compression index (C_c) based on the correlation between e and the log of effective stress (Terzaghi et al., 1996).

TDR probe orientation was indicated as an important factor in the estimation of VWC by Skierucha et al., (2004) and Pastuszka et al., (2014). In the materials having uniform porosity, grain size and shape, such as glass beads, TDR results are expected to be nearly the same in any direction, apart from minor discrepancies that can arise from the water distribution along the rods (Jones and Friedman, 2000). In layered, porous, saturated materials (where water level changes are perpendicular to a vertically orientated TDR probe) - Robinson et al., (2003) and Pastuszka et al., (2014) concluded that the vertically inserted probe represents the arithmetic mean of soil moisture for the investigated depth. Conversely, horizontally inserted probes reflect the water content of a single layer at a specific depth. Jones and Friedman (2000) reported that the vertically measured AP (AP_v) could be twice as higher as the horizontally measured AP (AP_h) in soils containing platy particles. However, this result could be affected by the particular experimental arrangement used in the study. To date, no research has attempted to link the effect of TDR probe orientation on its AP and BEC readings in fine-grained soils under a vertical loading.

Experimental Methodology

TDR in vertical loading - apparatus

A bespoke apparatus was built to test the AP and BEC response from TDR probes located in both the direction of loading and normal to it. The vertical loading test arrangement (Figure 1) included a Perspex consolidation chamber with two TDR probes and a dead-weight loading system. The TDR apparatus comprised a Campbell Scientific TDR100 operated via the proprietary PCTDR software and CS645 probes (three-rod, 75 mm long, with rod diameters and separations of 1 mm and 5 mm respectively) with a 3 m long coaxial cable. Three identical chambers were constructed, each with an inner diameter of 110 mm and height of 300 mm. The dimensions were designed to minimise the boundary effect on the consolidation process and account for the zone of influence of the TDR probes (Mojid et al., 2003). Drainage was facilitated at the top and bottom of the specimen with perforated plastic plates covered with filter paper within the chamber. Two TDR probes were installed perpendicularly to each other; one (TDR_v) mounted vertically in the direction of loading in the middle of the top drainage plate and the other (TDR_h) installed horizontally and fitted into the chamber wall at the height of 83 mm from the base, Figure 1. Additionally, one of the chambers was instrumented with external pore-water pressure sensors positioned at three depths: at the height of TDR_v (PS-t), in the middle of the specimen (PS-m) and at the same height as TDR_h (PS-b), Figure 2.

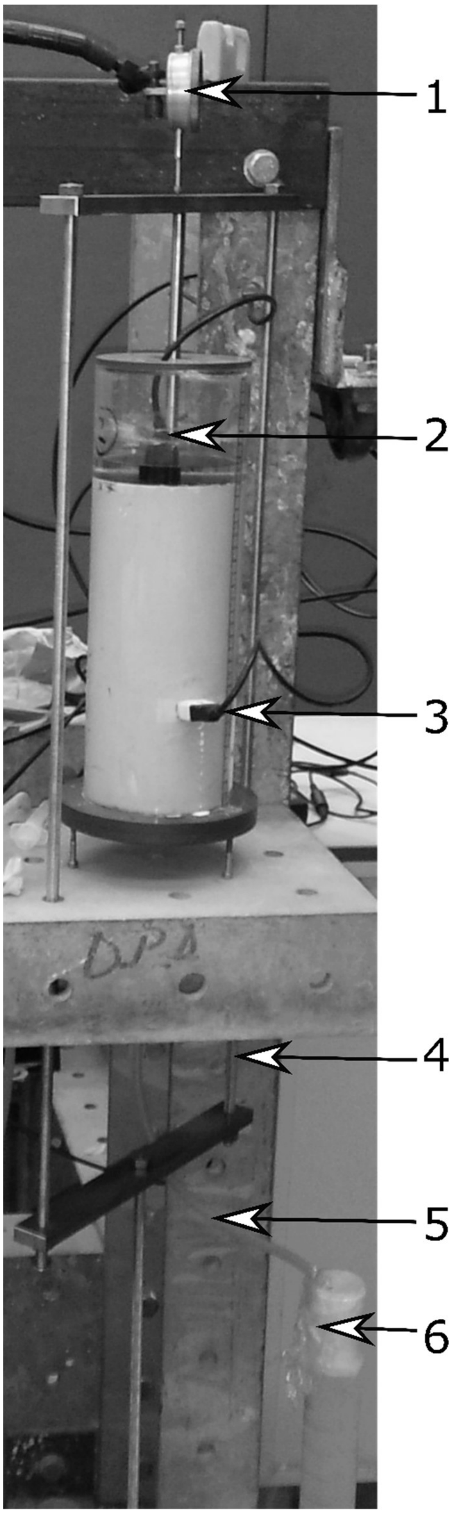

Figure 1. TDR chamber set-up under load conditions: 1 - compression gauge, 2- vertical TDR probe, 3 - horizontal TDR probe, 4 - loading frame, 5 - bottom drainage pipe, 6 - drainage container.

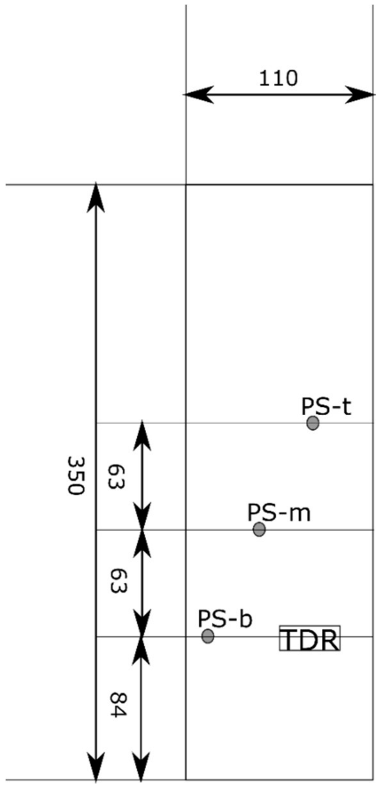

Figure 2. Schematic of the TDR chamber equipped with the pore pressure sensors (PS), positioned at the bottom (b), middle (m) and top (t) of the chamber, measurements in mm

The soil specimens were prepared at a range of water contents, between 1 to 1.8 times the liquid limit (LL), and were subjected to a gradual load increase from 5 kPa to a maximum 160 kPa and unload (the load increments varied in different samples and are provided in Table 2). The load was applied using dead weights supported on hangers that rested on the top of a metal bar mounted perpendicular to the top drainage plate (Figure 1). During each load increment, the change in the specimen height (and associated time) was recorded to calculate the time-dependant settlement parameters following the oedometer test procedure (BSI, 1990b).

In standard oedometer tests, an equal pressure head is maintained at the top and bottom of the specimen to maintain hydrostatic conditions. In the design of the TDR chambers, it was not possible to place the specimen in a water bath, due to the presence of the TDR probes. In order to equalise the pressure head, filling the bottom drainage pipe with water to the level of the top drainage plate was initially considered. However, adding water to the drainage pipe would have diluted the pore fluid and, as such, preclude the chemical and electrical investigation of its properties (which was deemed more important than maintaining hydrostatic conditions). Therefore, whilst the upper and lower drains were used in the chambers, the water in each was not at the same head. The fluid dripping out of the bottom drain was collected in a container approximately 1 m below the bottom of the chamber (suggesting that the lower head, at the base of the chamber, was equivalent to atmospheric pressure and was effectively constant). Pore fluid seeping out of the upper face of the specimen accumulated on top of the perforated loading plate, slightly increasing the magnitude of the upper head acting upon the specimen.

The physical set-up of the experiment precluded the use of a slip lining between the chamber wall and the soil. Consequently, soil located near the base of the chamber was not expected to experience a significant proportion of the vertical load applied as frictional forces between the chamber and specimen were expected to dominate with depth (Olson, 1986). The exact extent of the friction effect could not be measured directly with this chamber.

TDR data acquisition

TDR measurements were taken at a range of consolidation times. Measured signal travel time and reflection coefficient, were used to compute the AP and BEC using the tangent method and the long distance steady-state reflections respectively (Heimovaara and Bouten, 1990; Huisman et al., 2008), following the code developed by Curioni et al. (2012). The equations underlying AP and BEC estimation from TDR signal are included below for the ease of reference, nonetheless further details regarding the calibration procedure can be found in Faroqy (2018) or Curioni et al., 2018.

AP was computed using Equation 4:

$$\mathrm{AP} = \left(\frac{\mathrm{l_a}}{\mathrm{L}}\right)^2 \qquad \text{Equation 4}$$

where L is TDR probe length, ($\mathrm{l_a} = \frac{\mathrm{ct}}{2}$) - apparent length, c - the speed of light in free space (2.988 x 10^8m/s), and $\mathrm{t}/2$ - a time for the signal's travel down and back.

BEC was obtained from Equation 5:

$$BEC = \frac{K_p}{R_l - (DR_c + R_0)} \qquad \text{Equation 5}$$

Where (K_p) (1/m) is the probe constant, R_c and R_0 (Ω) – resistance corresponding to the transmission-line elements other than the probe (i.e. the TDR unit, cable and connectors), D - cable length (m), and $\mathrm{R_l}$ - load resistance (Ω),

$$R_l = Z_{out}\frac{1+\rho_\infty}{1-\rho_\infty}$$

Where Z_{out} is the output impedance of the TDR device (i.e. 50 Ω) and ρ_∞ is the reflection coefficient taken at long distances, when all the multiple reflections have attenuated and the signal has reached a steady-state level. The TDR frequency bandwidth was expected to be between 100 MHz and 500 MHz (Robinson et al., 2003).

Prior to the consolidation testing, the TDR probes were calibrated in air, water and saline solutions (0.0063-1.7960 S/m) following Heimovara (1993) and Huisman et al., (2008). To ensure that the measurements were not affected by the container and/or the localised presence of two probes, AP and BEC readings were obtained in de-ionised water (BEC~ 0.0009 S/m) within the chamber and a larger container with the vertical probe at the different heights. The results indicated that the container size and the position of the vertical probe relative to the horizontal probe in the experiment did not affect the TDR readings (Figure 3).

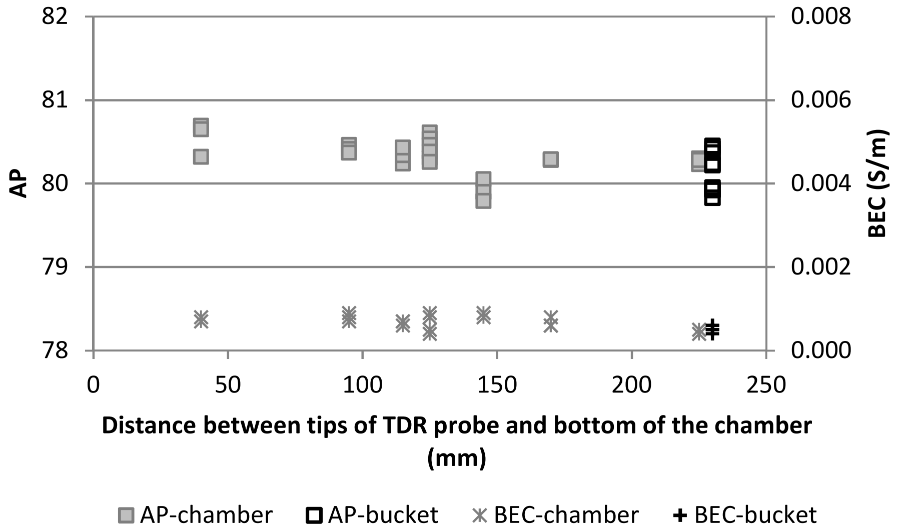

Figure 3. TDR measurements taken in DI water in the chamber and larger bucket to investigate the container effect on the measurements

Significant changes in temperature can impact upon the derived TDR data, as well as the physical properties of the soil (Mitchell and Soga, 2005). In the laboratory experiments, temperature measurements were collected every 15 minutes in air and inside each chamber with an automated LM-35 probe with an accuracy of 0.5°C (Sadeghioon et al., 2014). Conditions were generally stable at a temperature of 20°C with minimum and maximum values of 15-25°C, respectively.

Based on previous literature (Thring et al., 2014, Jung et al. 2013b), it was deemed that this range of temperatures had a negligible effect on AP, whilst its effect on the BEC was accounted for by applying a temperature correction factor according to Equation 6, (Keller and Frischknecht, 1966).

$$BEC_T = \frac{BEC_{uncor}}{1 + \alpha\,(T - T_{uncor})} \qquad \text{Equation 6}$$

where BEC_T and BEC_{uncor} are the corrected and measured BEC at a certain temperature T_{uncor}, respectively, T is the reference temperature (20°C), and α is a correction factor (in this study, 0.025, based on Abu-Hassanein et al., (1996)).

Soils used in the investigation and their geotechnical properties

The vertical loading tests were conducted on three soil mixtures prepared from commercially available English China Clay, sodium activated bentonite, and kiln dry fine sand.

Mixture proportions (Table 1) were designed to represent low, intermediate and high plasticity soils with sodium activated bentonite (a representative of the smectite family) used as it affects both the geotechnical and the electrical response of soils (Kibria, 2014). The maximum percentage of bentonite was restricted to 5% not to produce BECs greater than 0.3 S/m, compromising the ability of TDR to characterise the soil (Mojid et al., 2013). The index properties of the mixtures, tested in accordance with BSI (1990a), are presented in Table 1 . The soils were named according to their plasticity as low (CL), intermediate (CI) and high (CH) plasticity clay (BSI, 1990a). It is noted however that CI would be classed as CL in accordance with ASTM D2487 (ASTM, 2017). The initial VWC of the soil mixtures (determined from oven drying at 105°C) was found to increase with the plasticity of the soil: CL-44%, CI-55% and CH-61%.

Pore fluid analysis

In order to investigate a chemical composition of the pore fluid that seeped out during the loading, an inductively coupled plasma atomic emission spectroscopy (ICP-OES) analyses were conducted. Where the pore volume was sufficient to immerse the TDR probe, its BEC was also compared with a low frequency (11 Hz) electrical resistivity (ER) method. The ER measurements were conducted using commercial soil boxes connected to an acquisition system (Faroqy, 2018). In order to differentiate between the TDR and ER measured electrical conductivity, they are referred as BEC and EC respectively.

Results and Discussion

Initial TDR response prior to loading

Initial TDR readings were taken prior to the application of loading for all the specimens. Examples of the measured waveforms are presented in Figure 4 for soils at their LL or slightly above, deionised water and for the pore fluid collected during the vertical loading of the CI soil.

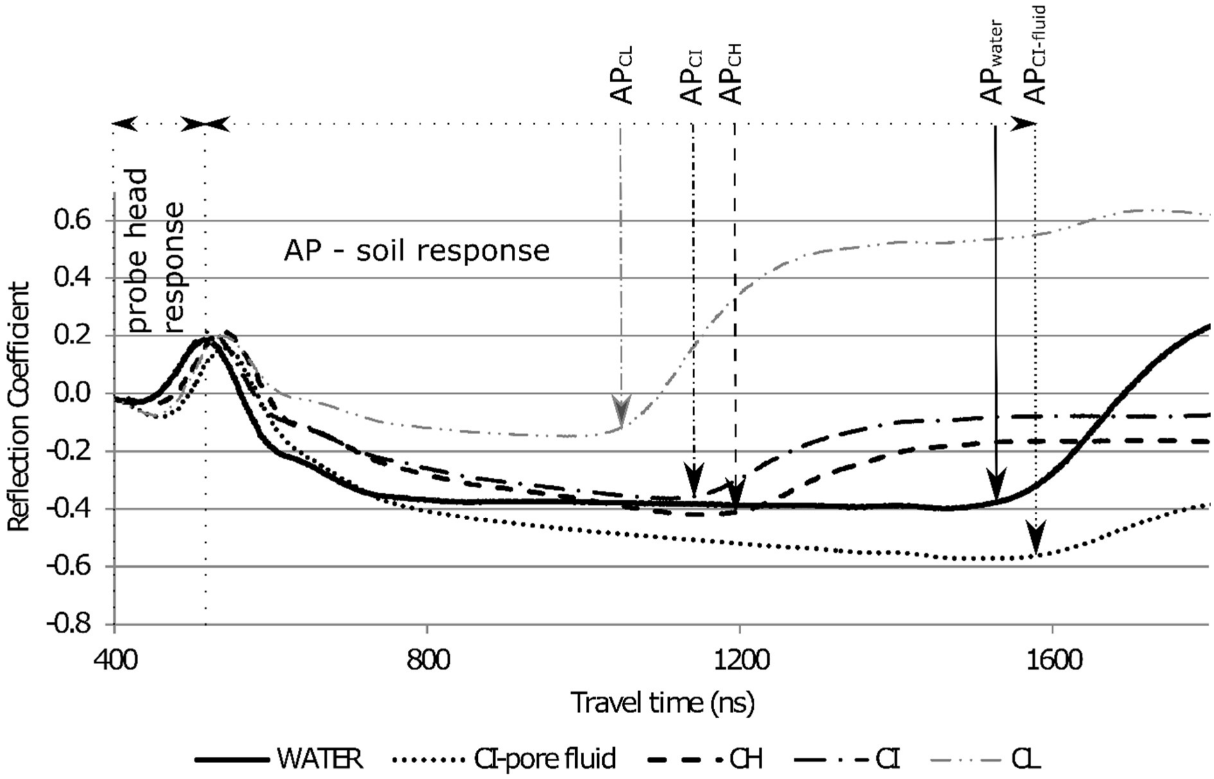

Figure 4. TDR waveforms in deionised water (WATER); in the pore fluid from the CI soil (CI-pore fluid) and representative examples of the three soil mixtures prior to loading (CH; CI and CL). The vertical arrows indicate approximate apparent permittivity (AP) magnitude (Table 3) calculated on the basis of the form of the waveform's travel time. Reflection coefficient amplitude translates to changes in the measured value of bulk electrical conductivity (BEC)

The waveforms shown in Figure 4 indicate that AP increased with the increase in the VWC and plasticity (Table 3), thus confirmed its relationship with VWC and LL in accordance with the literature (Topp et al., 1980, Thomas et al., 2010). Furthermore, higher signal attenuation due to increasing BEC was noted in those soil mixtures containing bentonite (as evidenced by the smaller magnitudes of the reflections). Despite significant differences in sand content between the CH (10% sand) and CI (50%

sand) soils mixtures, their initial AP and BEC were relatively close, Table 3. This was different than the CL soil mixture (Table 3) and suggested a dominant influence of the bentonite on the TDR response.

Variation of AP with loading in both vertical and horizontal orientations

The reduction in the specimen height with load over time results from fluid expulsion and consequential particle rearrangement (Barbour and Fredlund, 1989), which form the basis of the compressibility estimation for each soil. Given that the electrical conduction in soils takes place primarily through pore fluid electrolytes (Reynolds, 1997), it can be expected that the expulsion of pore fluid containing solutes during consolidation results in a decreasing BEC. For example, a correlation between e and EC during 1D consolidation has been found in sands (Comina et al., 2008), and in clays with low, medium and high plasticity (McCarter and Desmazes, 1997; Fukue et al., 1999; McCarter et al., 2005; Kibria, 2014) using low frequency ER measurements (0.01 Hz - 100 kHz). Simultaneously, the decrease in the volume of water during consolidation is expected to change the AP measured by TDR (Liu, 2007). This has been confirmed by the readings taken with the TDR_v probe, showing that AP decreased with the expulsion of water following the application of the vertical load. Figure 5a shows an example of the TDR_v waveforms obtained in a specimen of CI prior to the loading (L0) and under the application of a 10 kPa load (L1) at three consecutive times (L1-T1, L1-T2, L1-T3), corresponding to different consolidation stages presented on Figure 6 (T1 – 1 day, T2 – 14 days, T3 – 25 days after the load application). Whilst the start point does not change significantly with the application of the load, the signal travel time (directly related to AP) noticeably reduces, resulting in decreasing value of the measured AP. Therefore, if the soil is settling, vertical TDR measurements can potentially detect this.

In contrast, the TDR_h readings for the same soil specimen (Figure 5b) did not follow the same trend during the initial loading stages, showing an increase in travel time with drainage during the first loading stage (L1-T1). Nonetheless, during the later stages of consolidation (L1-T2 and L1-T3) the travel time reduced, resulting in a decrease in the measured AP. This response was observed also during further loading stages (L2 and L3), Figure 6.

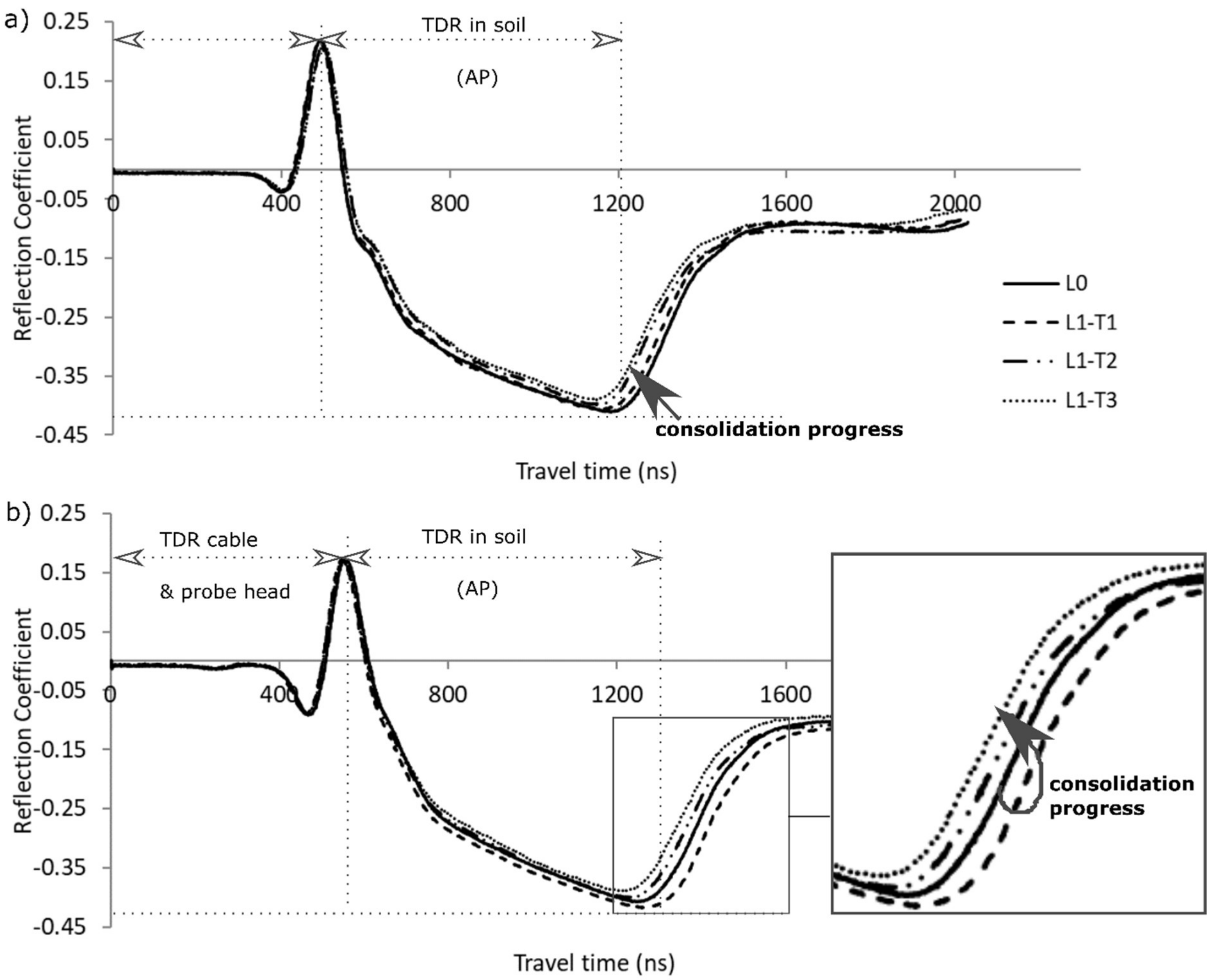

Figure 5. a) TDR waveforms collected in the CI soil mixture from TDR_v prior to load application (L0) and at three consecutive points in time (T1-T3) following the application of a 10 kPa load (L1). Note the decrease in signal travel time response with increasing load and consolidation. b) TDR waveforms collected in the CI soil mixture from TDR_h at the same intervals as TDR_v. Note again the decrease in signal travel time response with increasing load and consolidation but only at times T2 and T3.

Based on Figure 5 AP has been calculated, which is presented in Figure 6 in relation to the settlement during the consolidation time. When the results, showed on Figure 6, are analysed in view of the AP change after each loading step in relation to the settlement, 1 unit of vertical AP change corresponds to approximately 7mm change in the sample height.

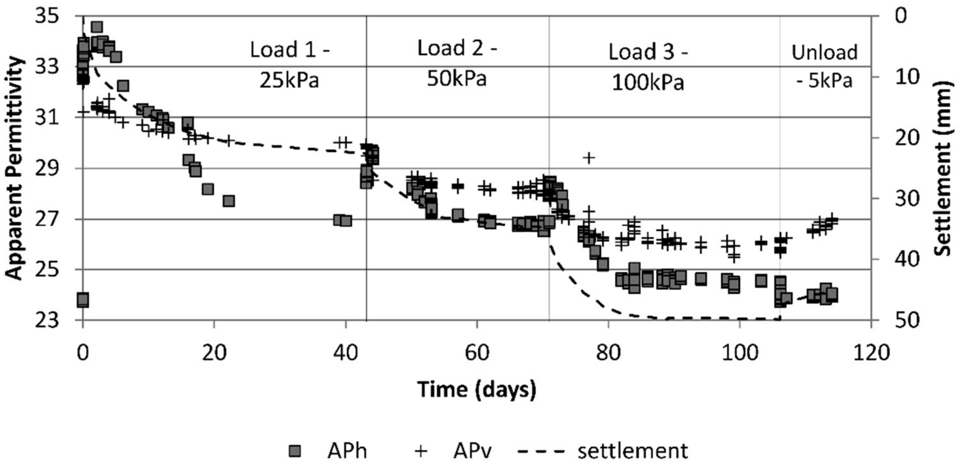

Figure 6. AP determined from the vertical (AP_v) and horizontal TDR probe (AP_h) in response to changes in settlement in CI soil mixture. AP estimation error is within 0.1, whilst settlement – 0.01mm

If the vertically loaded soil was undergoing the same changes top and bottom of the specimen, then the relative change in measured parameters from TDR_h would be expected to be less than that of TDR_v. This is because a TDR probe provides a mean value for the AP encountered in a narrow volume along the electrode rods (Nissen et al., 2003; Pastuszka et al., 2014). In case of TDR_v, the probe averages the response of 75 mm thick soil layer, whilst TDR_h reflects approximately 10 mm in thickness above and below the probe's rods. Therefore, the relative change in AP (and GWC), for a localised region of the horizontal probe's rods is likely to be much less than along the length of vertical probe in these tests.

Two factors could explain the observed TDR_h responses: (i) a localised consolidation mechanism - increased density on the top of the TDR_h probe as a result of localised consolidation, even at the reduced load experienced at this depth; and/or (ii) seepage forces - the impact of densifying forces associated with the vertically downward seepage of pore water due to hydraulic gradient increase in the specimen.

AP_h response: a localised consolidation mechanism

With TDR_h lying in a horizontal plane, localised increase in density could exist around the probe's rods. TDR rod is a rigid intrusion in the soil and therefore, as the consolidation process takes place and the soil moves past the rod, a void is created beneath that potentially fills with water (assuming that air escaped as the loading process continued). The void would only fill with soil (collapse) if the shear stress in the soil caused failure, which was unlikely to happen in this arrangement. This could not be physically verified due to the very soft consistency of the specimens at the end of the tests. Nonetheless, the visual observations during dissecting the specimen after the test indicated that the soil 'shadowed' around the upper edge of the horizontal probe during consolidation, resulting in the formation of a lower density 'pipe' underneath the rods. This 'pipe' is thought to have formed a preferential fluid pathway towards the side of the chamber and hence drained pore waters from the centre of the specimen. This localised volume would exhibit a higher water content compared to the soil zones not affected by the presence of the probe. This hypothesis appeared to be confirmed by the pore water pressure measurements (Figure 10) discussed further in the subsequent sections.

AP_h response: Hydraulic gradient considerations

Given that the chambers were 110 mm in internal diameter, and no grease was applied along the walls due to the presence of the TDR instrumentation, the vertical load distribution through the specimen was expected to be non-linear as the frictional forces between the consolidating specimen and chamber wall increased with depth. As such, the upper layers of the specimen were likely to experience a greater driver for consolidation than those lower down and the resultant flow pathways from these upper layers would be shortest vertically upward. In specimens with very low hydraulic conductivity, CH and CI, this resulted in accumulation of higher volume of water on the top than at the bottom of the sample. Therefore, increasing hydraulic gradient (maximum 0.08 in CI) could potentially impact on the consolidation process. However, it is considered to be too low, in comparison with the vertical load imposed, to significantly affect the consolidation process.

Relationship between AP and e

Soil compressibility is often estimated based on C_c, derived from the e - log σ_v correlation. Therefore, correlation between TDR-derived AP and e could potentially enable further estimation of C_c. In all the experiments, e was derived from the specimen height (h), as shown in Equation 7.

$$e = (h - h_s)/h_s$$ **Equation 7**

where h_s is the equivalent height of solids, as given by Equation 8.

$$h_s = h_0/(1 + e_0)$$ **Equation 8**

e_0 is an initial e, Equation 9, determined from GWC and G_s (the unit-less ratio of the unit weight of the solid particles to the unit weight of distilled water).

$$e_0 = GWC * G_s$$ **Equation 9**

A clear positive relationship between both vertical and horizontal measurements of AP and e was evident (Figure 7). This relationship is consistent with those previously reported in the literature for other materials (e.g., Liu, 2007; Jones and Friedman, 2000). The exact nature of the AP versus e relationship varied according to soil plasticity and water content of each specimen in the experiments and was affected by the TDR probe orientation. Whilst Jones and Friedman (2000), suggested nearly the same AP_v and AP_h values measured with TDR in glass bead mixtures, in the experiment conducted herein AP_v exhibited a stronger relationship with e, when compared to AP_h.

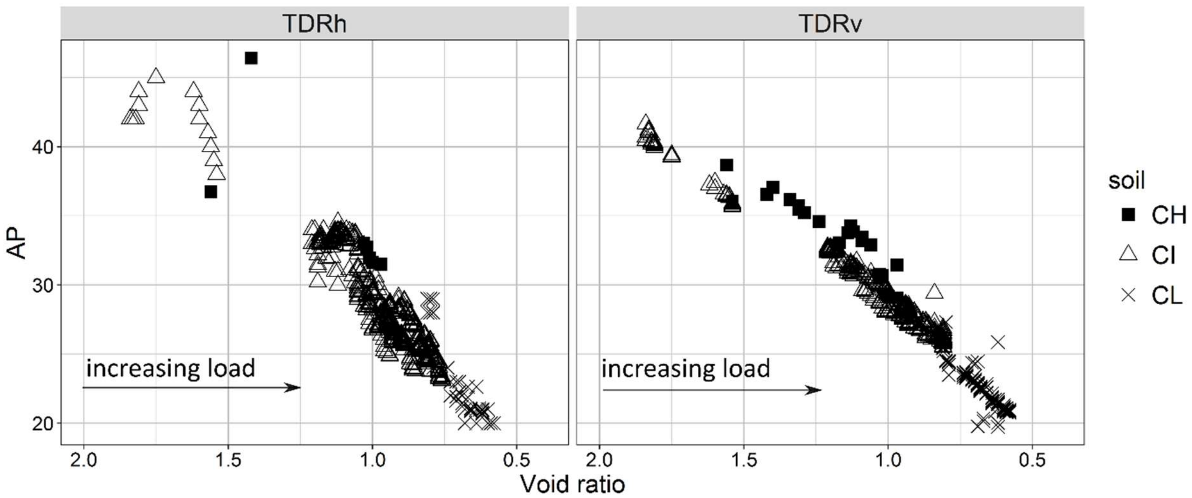

Figure 7. TDR-derived apparent permittivity (AP) relationship compared to void ratio, e for all three soil mixture during the vertical loading process (for all load steps AP measurements taken with the probes orientated horizontally (TDR_h) and vertically (TDR_v)

Given the factors described in the previous sections, the difference in the TDR_v and TDR_h response with respect to e is considered a consequence of experimental set-up and localised impact of consolidation. TDR_h was located in the bottom part of the specimen, where the acting load could be approximately 20% lower than that experienced in the top layers, hence the change in the e calculated for the whole specimen does not reflect the localised e changes in region of the TDR_h probe. It is clear, however, that all tested soils followed the same overarching trend, i.e. decreasing AP with decreasing e. Whilst the positive relationship between AP and e has been reported by other authors, based on measurements taken at the end of consolidation experiments (Liu, 2007), this research showed that the relationship can also be developed in real time during an active vertical loading process. Furthermore, the findings of the current research indicate that although the settlement could be potentially predicted based on the readings of either TDR_v or TDR_h, horizontally placed probed are more affected by the initial pore water pressure increase.

Relationship between BEC and e

Considering that the contribution of the electrolyte to BEC is restricted by the porosity of the medium (Klein and Santamarina, 2003) and the influence of the conductive particles (Waxman and Smits, 1968), in saturated soils a gradual decrease in BEC would be expected with decreasing e. This general decreasing trend can be seen in Figure 8, where the majority of the specimens show a ~10% drop in BEC with increasing load and decreasing e. However, the CL samples and vertical response from CH.S5.TDR did not display a clear trend. For CL specimens, Figure 8c, this could be attributed to the significantly lower concentration of conductive ions and therefore the relative change in BEC is less marked than in CI and CH specimens, Figure 8a. It is not obvious why the BEC response in CH.S5.TDR was not sensitive to the void ratio changes. It is noted however that the specimen was prepared at 1.5

LL, hence its initial GWC was much higher than in two other CH specimens, prepared at 1.1 LL. Potentially the conductivity of the solution did not change significantly for BEC to record the change. Similar to the AP_h trends, shown in Figure 7, BEC_h appears to also respond to the increased influx of water during initial loading. This is reflected in the 'parabolic' BEC_h - e relationship that is particularly pronounced in CI specimens and CH.TDR.S5, Figure 8b. This response is most likely affected by the increased concentration of ions available around the horizontal TDR probe. Friedman (2005) suggests that BEC is more sensitive to the pore connectivity than volume changes, which could explain why AP (sensitive to the volumetric changes) correlates better with e than BEC.

The differences between BEC_v and BEC_h response was considered to be a result of discrepancies in the density and compression of the specimens between the upper region (TDR_v) and lower (TDR_h), where the probes sit.

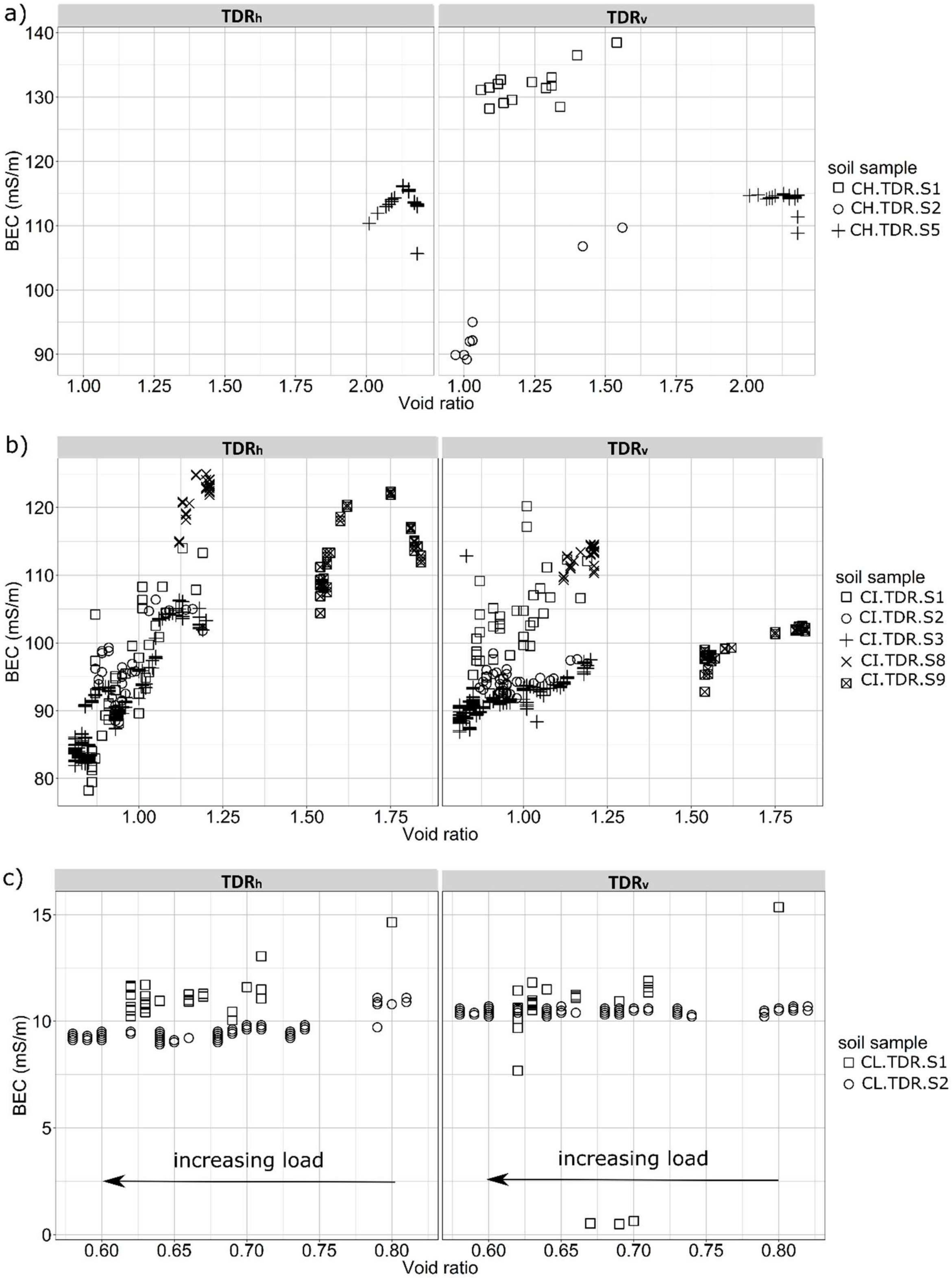

Figure 8. BEC versus void ratio for a) CH, b) CI and c) CL during consolidation with measurements taken using both TDR_v and TDR_h

Given that pore fluid conductivity is the main medium conducting the current in saturated soils (Klein and Santamarina, 2003), contribution of the pore fluid's electrical conductivity (EC_f) to the BEC of the soil specimen was investigated. The EC_f measurements of the fluid, which seeped out after the loading, were performed using the ER method (Faroqy, 2018). This approach enabled testing small volumes of fluid available (7 ml) whilst it was possible to use the remaining fluid for the ICP-OES analyses. Where the pore volume was sufficient to immerse the TDR probe, its BEC was compared with the ER method. The results indicated that the two techniques produced similar results, as the BEC of the pore fluid measured with TDR corresponded to approximately 0.288 S/m; whilst the EC_f measured with the ER was at 0.275 S/m in CI specimens.

The EC_f results (Table 4) confirmed that smectites had a dominant influence on the salt content of the pore fluid due to the much higher availability of exchangeable ions when compared to kaolinite. This was confirmed by the ICP-OES chemical results showing sodium as a dominant component in the pore fluid from sodium activated soil (Table 5) and a close EC_f range for CH and CI with values of 0.247 S/m and 0.275 S/m respectively (Table 4). Due to its high mobility, Na was found to have a significant impact on EC_f (Rinaldi and Cuestas, 2002). In contrast, CL, which contained sand and kaolinite, had an EC_f seven times smaller (approximately 0.041 S/m). Given that the BEC of soil is dominated by BEC (Cassidy, 2009; Jung et al., 2013a), BEC can be seen as an indicator of a degree to which solid particles constrain the electromagnetic response of free fluid: the BEC of the CH specimens (with 10% sand) was 50% of the EC_f value and 25% in the CI specimens (with 50% sand). In the CL soil (with 50% sand), containing no bentonite, the sand effect was even more predominant, resulting in the soil BEC being 25% of its EC_f. Following from this, the BEC/EC_f (Table 1) relationship (expressed as a percentage) reflects the LL of the samples (Table 4).

Rosenboum (1976) observed that the concentration of conductive ions in the pore fluid of soils containing montmorillonite decreased with the increasing effective stress during consolidation. In the present study, the EC_f and the chemical composition of the combined fluid were found to be very similar in several CI specimens (Table 2 and Table 5). This however, does not provide an answer to whether the EC_f was changing during consolidation. The response of BEC and EC in soils containing bentonite remains an active area of research. Using low frequency ER measurements, Fukue (1999) found that the EC of soils containing bentonite started increasing at loading stages exceeding 78 kPa, which was hypothesised to result from the diffusive double layer (DDL) deformation. Similarly, an increase in the value of BEC in a soil containing 60% montmorillonite was observed using TDR when the applied pressure exceeded 110 kPa (Liu, 2007). The latter was attributed to pore fluid salinity dependent DDL suppression, which was hypothesised (Liu, 2007) to increase BEC with a decrease in VWC in soils with a BEC of pore fluid below 0.2 S/m, however there was no experimental proof supporting this theory. The suppression of is expected with an increase in ion concentration in the pore fluid (Sridharan, 1982) and given that the long range electrical repulsive forces (DDL) resist the compression at a given external applied pressure in smectite containing soils (Sridharan and Rao, 1973), information about EC_f within the soil pores could provide further insight into the soil response to loading and unloading. Currently, TDR readings provide only a bulk response, reflecting closing of the pore spaces during loading and possible changes in the pore fluid. However, it is apparent that pore-scale changes in a soil specimen, which will result in changes in geotechnical properties, can be detected using TDR methods. This is clearly an important, and potentially far reaching finding as it provides a proxy monitoring/evaluation tool for such processes.

TDR response to unloading

During unloading, the physical and chemical bonds between the particles that are developed during the loading process break apart (Terzaghi et al., 1996). Negative porewater pressure is generated and the excess pore water pressures lead to the heave of the specimens as water is drawn back into the soil.

In kaolinite soils, the rebound (heave) is controlled only by the hydrostatic pressure deficiency developed in the undrained phase; whereas in smectite dominated soils, also DDL repulsive forces affect its magnitude (Sridharan and Rao, 1973). In the soils considered herein (where the bentonite content was limited to 5% by weight of the specimen) it is suspected that both mechanisms will be prevalent in the CI and CH specimens. Testing of the electrical response to unloading was limited to five specimens (including only CL and C soils) and a maximum of two unloading steps; nonetheless, it was interesting to note that when unloaded both AP and BEC measured in both directions rebounded in several samples as water was drawn back into the soil fabric (Figure). Although, the unloading was very limited and the magnitude of load removed differed across the samples (Table 2), it appeared that AP and BEC changes can be observed when a sufficient load is removed (unloading in small graduations did not result in observable changes). Given that the rebound was limited by the swelling properties of the CH, CI and CL soils as indicated by the C_s values of 0.08, 0.05 and 0.03 respectively, the volumes of water being drawn into the specimen are relatively small. Nonetheless, it was encouraging to observe that even these small changes can be reflected in the AP and BEC readings.

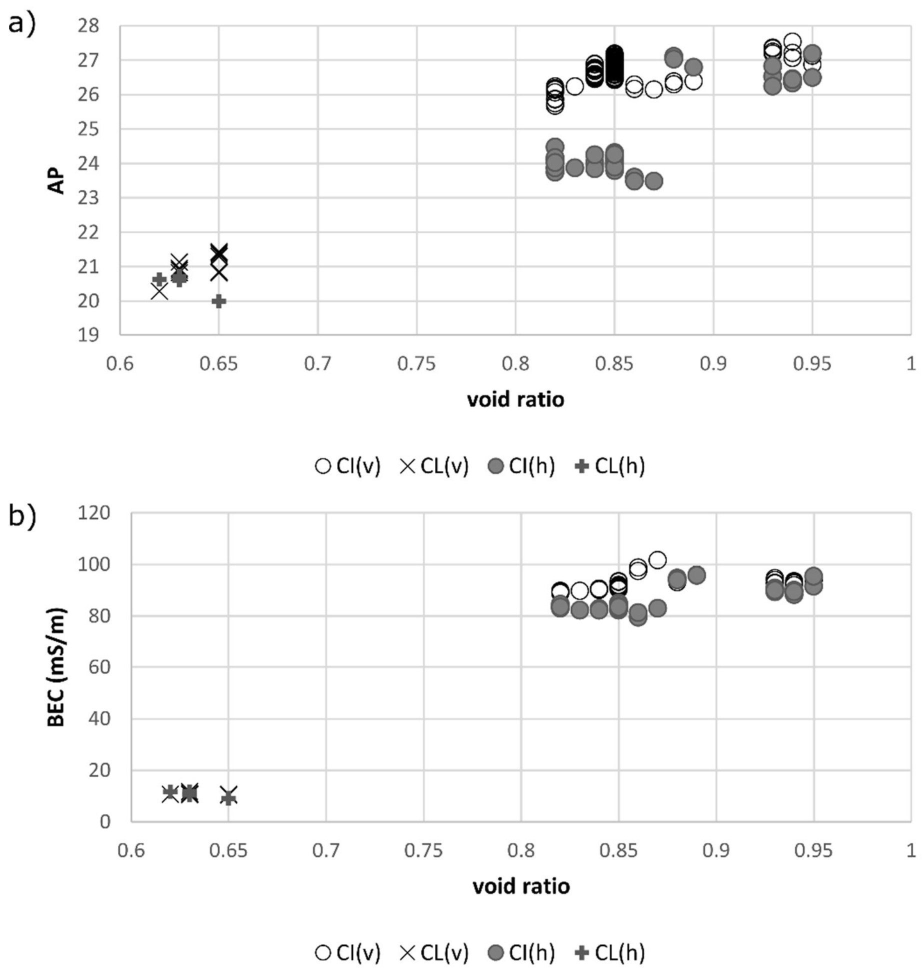

Figure 9. Relationship between void ratio, e and a) apparent permittivity (AP), b) bulk electric conductivity (BEC) measured in the direction of the load application (v) and normal to the load application (h) during unloading of three CI (CI.S01, CI.S02, CI.S3.TDR) and two CL specimens (CL.S1.TDR, CL.S2.TDR); no unloading was carried out on the CH samples

It is suggested that there is a sensitivity threshold, which is either a function of the experimental apparatus used herein, or a function of the change in void space within the soil (and the concentration of ions being drawn back into the soil), or both. It is noted that, although this rebound was observed in a laboratory setting, in field conditions the magnitude of change may lie within the sensitivity limitations of the equipment and requires further research.

TDR response to pore water pressure changes

The AP_h was noted to increase immediately after the load was applied, whilst AP_v was decreasing with the progress of settlement. In order to investigate this relationship further, pore water pressure response was monitored on selected samples. The consolidation chamber was instrumented with the external pore water pressure sensors positioned at three depths: height of TDR_v (ps-t), in the middle of the specimen (ps-m) and at the same height as TDR_h (ps-b), Figure 2. The change in the AP_v and AP_h was plotted as relative terms against consolidation time ($AP_{v(r)}$ and $AP_{h(r)}$ respectively) with the absolute values normalised to the initial values - Figure 10, indicating that the rate of the AP_h increase corresponded with that of the bottom pore water pressure response (ps-b) located at the same depth as the TDR_h. The $AP_{h(r)}$ was consistently greater than $AP_{v(r)}$, suggesting a region of higher water content near the horizontal probe. The time lag between the commencement of the settlement of the soil specimens and the decrease in the AP_h appears proportional to the plasticity and, as such, the compressibility of the soil (C_c of CH, CI and CL was in the order of 0.38, 0.32, 0.13 respectively). This effect was initially thought to be a result of the pore water pressure changes in the specimen due to the consolidation pressure. However, the additional tests in pressurised chambers (Faroqy, 2018) indicate that neither AP nor BEC responded to the pressure increase. As such, it is most likely influenced by physical changes in the soil as a response to the increased pressure. Primarily, the consolidation mechanism, which principally affected the upper layers of the soil due to the non-linear load distribution within the soil specimen, resulted in the densification of the upper layers of soil much earlier than deeper layers. Meanwhile, the emplacement of the TDR rods horizontally into the soil resulted in a small 'load-shadow' being developed directly under the rods which created a softer zone of soil below them. This may have provided a preferential pathway for water to seep out of the soil mass from the centre of the specimen, along the softer zone around the TDR rods and then down the chamber-soil interface. Given that TDR measurements are related to water content, it is believed that the initial increase in TDR_h readings seen in CH and CI, reflects the changes induced by pore water pressure with loading. This effect was not observed in CL as the pore pressure dissipated very quickly due to the higher hydraulic conductivity. Interestingly, the time at which the relative values of AP_h and AP_v begin to merge correspond with the end of the primary consolidation time, which could be used as a very useful tool to monitor the progress of consolidation.

The $AP_{v(r)}$ and $AP_{h(r)}$ results suggest that the consideration of the load direction during instrumentation of a specimen/site is of significant importance. In circumstances when a soil is subject to loading in saturated (or near-saturated) conditions, the probes normal to the loading direction (here TDR_h) appear to be responsive to the pore water pressure induced changes; whilst probes positioned parallel (TDR_v) respond to structural changes.

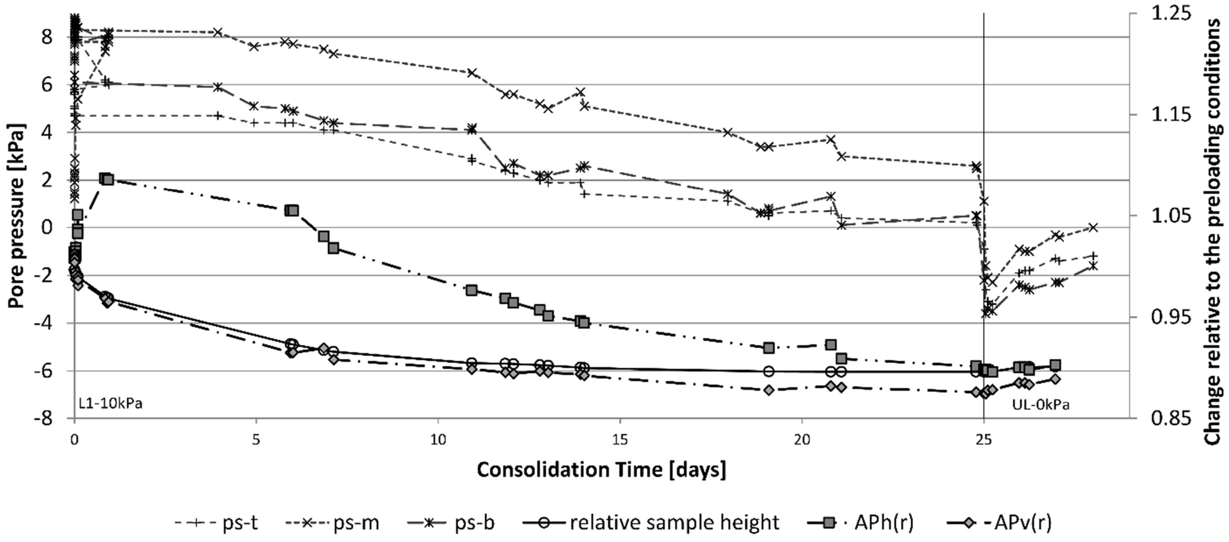

Figure 10. Relative AP_h and AP_v changes (normalised by the pre-loading measurement) in relation to the settlement and the pore pressure dissipation recorded at the top (ps-t), in the middle (ps-m) and at the height of the TDR_h (ps-b). L = loading phase, UL = unloading phase.

Conclusions and Recommendations

Regular monitoring of the AP and BEC response to the changes in saturated, fine-grained soils under vertical loading in the controlled laboratory conditions indicated a positive and clear relationship between the AP response, measured in the direction of the load application (vertically), and void ratio of soils with a range of plasticity. Changes in the geotechnical parameters were measured in terms of the bulk parameters derived from the initial and final GWC and sample-height measurements during loading and unloading. Measurements taken in two perpendicular directions allowed further insights to be gained on the initial response of the soil to the application of a load. Whilst the AP measured vertically decreased gradually with loading, horizontal probes exhibited elevated AP levels during initial loading stages and gradually decreased with the progress of consolidation. AP_v was found to correlate very well with e, whilst AP_h coincided with the increased pore water pressure dissipation. It is thought that the load application forced ingress of water locally around the horizontal probe due to excess pore water pressure in this experimental setup. Nonetheless, the same conditions are likely to take place on site. Given that the magnitude of the relative change in AP_v and AP_h began to merge at the time relating to the end of the primary consolidation stage, it is possible that this observation could be used to monitor the progress of consolidation *in-situ* before the ground movement damage is inflicted on the ground surface. Simultaneously, BEC values exhibited a tendency to mirror the AP response; however, more scatter in the results was observed. BEC was found to be correlated with e in a few samples; however, there were also cases where it plateaued whilst the structural changes continued to take place. This suggests that pore connectivity rather than the void ratio has a predominant effect on the values of BEC. Correlation of BEC with the pore fluid conductivity revealed very close relationship with LL, which could potentially be used as LL indicator depending on the soil conditions.

Most interestingly, the two-directional positioning of the TDR probes can provide insights into the spatial and temporal changes in soils during settlement. Whilst AP_v can indicate decreasing e (or VWC) with loading, the initially elevated AP_h response can indicate pore water pressure dissipation. This is a unique and novel finding, encouraging for the monitoring of saturated earthwork structures under cyclic loads. Simultaneously, this finding has an implication on the application of TDR in VWC measurements. TDR measured VWC will be overestimated if it is obtained from a probe embedded horizontally in a soil subject to vertical loading.

The unloading process was monitored with TDR for the first time. Although this aspect was investigated on a limited scale, both BEC and AP readings increased slightly with the increase in void ratio. This indicated potential applicability of TDR in monitoring the progress of unload.

Due to the observed AP_v correlation with e, AP_h correlation with the pore water induced changes, and the relationship between AP_v and AP_h, it is the authors' contention that regular, near surface-based monitoring, using TDR could be very informative for *in-situ* settlement monitoring. Relative changes could be used to inform of the comparative 'health' of the asset, with trigger levels designated when corrective action may be required. Monitoring such relative changes in AP (or similar) over time would extend our understanding of how soils respond to changes in physical conditions (environment, loading, etc.). Trigger levels for the geophysical parameters could be set where, if exceeded, additional investigations could be carried out to assess the relative stability of the asset in more detail.

Data Availability

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

Acknowledgements

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List of Symbols

Symbol	Unit	Description
AP	-	Apparent Permittivity
AP_h	-	AP measured with TDR_h
AP_v	-	AP measured with TDR_v
$AP_{(r)}$	-	AP normalised by an initial reading
BEC	S/m	Bulk Electrical Conductivity (measured with TDR)
BEC_h	S/m	BEC measured with TDR_h
BEC_v	S/m	BEC measured with TDR_v
C_c	-	Compression index
CH	-	High plasticity clay
CI	-	Intermediate plasticity clay
CL	-	Low plasticity clay
C_s	-	Swelling index
DDL	-	Diffusive double layer
e	-	Void ratio
EC_{dc}	S/m	Direct current electrical conductivity
EC_f	S/m	EC of pore fluid measured with ER method
ER	-	Electrical Resistivity method (11Hz)
G_s	Mg/m^3	particle density
GWC	g/g	Gravimetric water content
h	m	specimen height

ICP-OES	-	inductively coupled plasma optical emission spectrometry
LL	%	Liquid Limit
m_s	g	Dry mass of soil (after oven drying in 105 °C)
m_v	m^2/kN	Coefficient of volume compressibility
PI	%	Plasticity Index (PI=LL-PL)
PL	%	Plastic Limit
TDR	-	Time Domain Reflectometry
TDR_h	-	TDR probe positioned normally to the direction of loading (horizontal plane)
TDR_v	-	TDR probe positioned in the direction of loading (vertical plane)
V	m^3	volume
VWC	%	Volumetric water content
ρ_d	Mg/m^3	Dry density
σ_v	kPa	Effective stress in the vertical direction

Figure captions

Figure 1. TDR chamber set-up under load conditions: 1 - compression gauge, 2- vertical TDR probe, 3 - horizontal TDR probe, 4 - loading frame, 5 - bottom drainage pipe, 6 - drainage container.
Figure 2. Schematic of the TDR chamber equipped with the pore pressure sensors (PS), positioned at the bottom (b), middle (m) and top (t) of the chamber, measurements in mm
Figure 3. TDR measurements taken in DI water in the chamber and larger bucket to investigate the container effect on the measurements
Figure 4. TDR waveforms in deionised water (WATER); in the pore fluid from the CI soil (CI-pore fluid) and representative examples of the three soil mixtures prior to loading (CH; CI and CL). The vertical arrows indicate approximate apparent permittivity (AP) magnitude (Table 3) calculated on the basis of the form of the waveform's travel time. Reflection coefficient amplitude translates to changes in the measured value of bulk electrical conductivity (BEC)
Figure 5. a) TDR waveforms collected in the CI soil mixture from TDR_v prior to load application (L0) and at three consecutive points in time (T1-T3) following the application of a 10 kPa load (L1). Note the decrease in signal travel time response with increasing load and consolidation. b) TDR waveforms collected in the CI soil mixture from TDR_h at the same intervals as TDR_v. Note again the

decrease in signal travel time response with increasing load and consolidation but only at times T2 and T3.

Figure 6. AP determined from the vertical (AP_v) and horizontal TDR probe (AP_h) in response to changes in settlement in CI soil mixture. AP estimation error is within 0.1, whilst settlement – 0.01mm

Figure 7. TDR-derived apparent permittivity (AP) relationship compared to void ratio, **e** for all three soil mixture during the vertical loading process (for all load steps AP measurements taken with the probes orientated horizontally (TDR_h) and vertically (TDR_v)

Figure 8. BEC versus void ratio for a) CH, b) CI and c) CL during consolidation with measurements taken using both TDR_v and TDR_h

Figure 9. Relationship between void ratio, **e** and a) apparent permittivity (AP), b) bulk electric conductivity (BEC) measured in the direction of the load application (v) and normal to the load application (h) during unloading of three CI (CI.S01, CI.S02, CI.S3.TDR) and two CL specimens (CL.S1.TDR, CL.S2.TDR); no unloading was carried out on the CH samples

Figure 10. Relative AP_h and AP_v changes (normalised by the pre-loading measurement) in relation to the settlement and the pore pressure dissipation recorded at the top (ps-t), in the middle (ps-m) and at the height of the TDR_h (ps-b). L = loading phase, UL = unloading phase.

Tables

Table 1. Soil mixtures and index test results

Soil Mixture	Composition			Index Tests			Activity	Compression	
	ECC	B	S	LL	PL	PI		C_c	C_s
		%			%		%	-	
CH	85	5	10	56	26	30	0.33	0.38	0.08
CI	45	5	50	40	15	25	0.50	0.32	0.05
CL	50	0	50	30	18	12	0.24	0.13	0.03

Table 2. Specimen loading details

Specimen No	Soil	Repetition	Initial GWC	Applied Pressure (kPa)						
				L1	L2	L3	L4	L5	L6	L7
1	CH	S01	60	40	80	160	80	-	-	-
2	CH	S02	63	40	80	-	-	-	-	-
3	CH	S5	84	5	10	20	40	-	-	-
4	CI	S1	42	15	25	35	60	80	5	-
5	CI	S2	45	20	35	60	35	5	100	5
6	CI	S3	45	25	50	100	5	-	-	-
7	CI	S8	47	5	15	-	-	-	-	-
8	CI	S9	70	5	0	-	-	-	-	-
9	CL	S1	29	15	25	50	85	100	5	-
10	CL	S2	32	15	25	50	85	5	-	-

Table 3. Initial AP and BEC values (Figure 4) in relation to the plasticity and initial VWC

Soil Mixture	Index Tests			Initial	TDR response	
	LL	PL	PI	VWC	AP	BEC
		%		%	-	S/m
CH	56	26	30	61	36	0.138
CI	40	15	25	55	32	0.098
CL	30	18	12	44	26	0.015

Table 4. Conductivity of the soil mixtures measured with TDR in relation to the pore fluid conductivity - measured with low frequency (11 Hz) ER method

Soil	EC_f*	BEC**	BEC/EC_f
	S/m		%
CH	0.247	0.131	53
CI	0.275	0.099	36
CL	0.041	0.01	25

Notes: * pore fluid collected during the loading process (bulk specimen average)
** soil BEC at the end of the consolidation test (bulk specimen average)

Table 5. Cation concentrations observed in pore fluid diluted in HNO_3 (measured using ICP-OES, with detection limits of 0.5 to 200 mg/l)

Specimen	Ca	Na	Mg	K		S	Si
	mg/l						
CH.S5.TDR	5.09	>209	3.52	17.88	213.20	1.18	0.42
CI.S2.TDR	7.38	>200	4.95	21.28	307.95	2.33	1.03
CI.S3.TDR	7.37	>200	6.31	12.73	299.09	0.85	1.51
CI.S5.TDR	4.97	>252	4.91	18.96	281.80	0.14	0.99
CI.S7.TDR	5.90	>200	24.18	24.57	317.31	5.87	0.37
CL.S2.TDR	2.95	31.64	<0.5	14.19	18.24	14.14	0.35