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Boddice, Daniel; Metje, Nicole; Chapman, David

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RESEARCH ARTICLE

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Long-term monitoring to inform the geophysical detection of archaeological ditch anomalies in different climatic conditions

Daniel Boddice | **Nicole Metje** | **David Chapman**

School of Engineering, College of Engineering and Physical Sciences, University of Birmingham, Birmingham, UK

Correspondence
Daniel Boddice, School of Engineering, College of Engineering and Physical Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
Email: d.boddice@bham.ac.uk

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Abstract

Contrasts in electromagnetic properties between the target feature and surrounding soil are of importance for detection of archaeological features with Ground Penetrating Radar. These vary because of changing climatic conditions and soil type and are currently poorly understood. Long-term in situ monitoring of apparent relative dielectric permittivity, bulk electrical conductivity and soil temperature over two archaeological ditch features on sites with different soil types (one clay and one free draining) was employed to understand the detection dynamics and processes by which these properties change over time. Results were correlated with geotechnical properties of the soil for both archaeological ditchfills and the surrounding natural soil matrix and previously derived laboratory relationships between water content, temperature and geophysical properties to find the timing and reasons for the optimum geophysical contrasts. Monitoring included two distinct, relatively stable periods: one wet and one dry. In contrast to previous perception that there are significant differences in infiltration between the ditch and surrounding natural soil, time-lagged correlation analysis showed no significant differences in infiltration speed. The key differences between archaeological and natural soils were the amount of water held in a saturated state, the rates at which the different soils dried and the temperature. Thus, the optimum time for surveys was after a sustained period of several days of hot (>15°C) weather, which accentuates both water content and temperature contrasts. However, on freely draining sites that had a greater difference in the soil texture and therefore water holding capacity between the archaeological and natural soils, the timing is less critical.

KEYWORDS
conductivity, Ground Penetrating Radar performance, permittivity, seasonality, soil properties, time-domain reflectometry

1 | INTRODUCTION

Ground Penetrating Radar (GPR) is widely used to detect and map archaeological features (Conyers, 2004), which requires a contrast in the measured geophysical electromagnetic (EM) properties between the target of interest and the surrounding soil matrix. The technique is strongly seasonal in its responsiveness due to changes in climatic conditions and subsequent changes in water content (Morris et al., 2018;

Rogers et al., 2012) and temperature affecting the contrast in geophysical properties. Furthermore, the technique is traditionally thought to respond poorly on certain soils and at particular times of the year. In particular, the technique is considered to be especially poor on fine grained clay soils (David et al., 2008; Jordan, 2009) due to their high water retention capability and electrical conductivities, which limit contrast in EM properties and the depth of penetration, although some success has also been reported even in conditions thought to be detrimental for instrument performance (e.g., Weaver, 2006). The underlying mechanisms that link these soil properties and the changes to the geophysical response are poorly understood, which has made the use of the techniques and interpretation of results in these areas difficult (Williams, 2009), and often led to the abandonment of the techniques in areas containing soil types such as conductive clay. Improving the knowledge of how different soil variables affect the response will not only reduce the number of failed surveys and undetected archaeological features but also give greater confidence in the survey results and improve the quality of interpretation on the nature and former use of the archaeological features detected (Cuenca-Garcia et al., 2018).

The focus of the current work is on properties that affect GPR performance, but several of the measured properties will also display applicability to other geophysical techniques used in archaeology such as earth resistance (Schmidt, 2013) and EM conductivity mapping (Bevan, 1983; Simpson et al., 2009), which also depend on water content, albeit the results may only be indicative due to differences in the measurement frequencies.

2 | GEOPHYSICAL PERFORMANCE AND SOIL EM PROPERTIES

The key to the detectability of archaeological features using GPR is contrast in the EM properties between the archaeological features and the surrounding natural soil matrix, namely, the dielectric permittivity, electrical conductivity and magnetic permeability. These properties can be used to calculate the amplitude of the reflections (υ_r) and the rate of signal attenuation and the attenuation constant (α in Np/m), which help to determine the maximum depth of penetration and detectability using Equations (1) and (2) (derrived from Annan, 2009; Cassidy, 2009). The amount of reflected energy, υ_r, is given by the incident energy (υ_i) and the EM impedances (Z) of the different layers (Z_1 and Z_2)

$$\upsilon_r = \upsilon_i \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right),$$

where

$$Z = \sqrt{\frac{j\omega|\mu'|}{\sigma + j\omega|\varepsilon'|}}, \tag{1}$$

where υ_i is the incident amplitude, j is $\sqrt{-1}$, ω is the angular frequency (i.e., $2\pi f$), $|\mu'|$ is the absolute real magnetic permeability, $|\varepsilon'|$ is the absolute electrical permittivity and σ' is the direct current (DC) conductivity of the material. The attenuation can be determined as a function of the distance travelled (x) using the attenuation constant α.

$$\upsilon_2 = \upsilon_1 e^{-\alpha x},$$

where

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon'}{2}}\left(1 + \left(\frac{\varepsilon'' + \sigma}{\varepsilon'}\right)^2 - 1\right)^{0.5}, \tag{2}$$

where μ is the relative magnetic permeability and ε' and ε'' are the real and imaginary parts of the relative dielectric permittivity, respectively. Whilst magnetic permeability, often taken to be close to unity, is stable, changes only very slowly and is a function of the presence of iron compounds in the soil, the electrical permittivity and conductivity vary over time, mainly due to the effects of changing water content and its interaction with the soil properties. This is due to the water's ability to polarize and carry electrical charge through dissolved ions. Relationships between geophysical properties and water content are not constant in different soil types but depend strongly on the physical properties of the soil (Gong et al., 2003; Ponizovsky et al., 1999; Thring et al., 2014), temperature (Calles & Calles, 1990; Or & Wraith, 1999; Skierucha, 2009; Wraith & Or, 1999) and frequency of the applied signal (Friel & Or, 1999; Saarenketo, 1998; You et al., 2009). To investigate this, relationships between the EM properties and the water content have been tested in the laboratory over a range of different soil types, volumetric water contents (VWCs) and temperatures to determine the relationships between the apparent permittivity and water content (e.g., Bridge et al., 1996; Curtis, 2001; Topp et al., 1980). Whilst the water content is undoubtedly the most important factor, previous studies have shown strong links between the geophysical and geotechnical properties for soil including the soil particle size distribution (Gong et al., 2003; Ponizovsky et al., 1999; Thring et al., 2014), density (Gong et al., 2003; Hipp, 1974; Malicki et al., 1996), Atterberg limits and linear shrinkage (Thomas et al., 2010a, 2010b). These links have been used to create a wide range of dielectric mixing and pedotransfer models (Dobson et al., 1985; Mironov et al., 2004, 2009; van Dam et al., 2005; Wunderlich et al., 2013) and to create soil suitability maps for different techniques in average conditions (e.g., Doolittle et al., 2010, 2007).

Studies to correlate the soil properties of archaeological features to geophysical responses to validate and improve geophysical interpretations for a given survey in particular conditions are also reasonably common (Fischer et al., 2016; Garcia et al., 2017; Schneidhofer et al., 2017; Wilken et al., 2016; Wunderlich et al., 2017), occasionally also measuring geophysical properties directly (Damiata et al., 2017;

Schneidhofer et al., 2017; Verdonck et al., 2009). However, these almost always represent a single moment in time and do not account for seasonal effects. Seasonal variations in an archaeological feature's visibility and the underlying EM properties have been assessed using repeated geophysical surveys, usually using electrical resistance methods (al Chalabi & Rees, 1962; Clark, 1980; Cott, 1997; Hesse, 1966; Parkyn et al., 2011) and more rarely GPR (e.g., Rogers et al., 2012). Three main limitations exist with these approaches:

1. The temporal resolution (usually monthly) is insufficient to detect specific infiltration, drying or temperature change events, which change the ground conditions and water content contrasts between the archaeological feature and the natural soil, leading them to be inferred or assumed between surveys. From the wide range of different optimum times for survey contrast and detection shown by the different studies (with estimates spanning the entire year), it is apparent that the variation in geophysical response is more due to environmental effects on the soil properties of a particular feature rather than typical seasonal weather patterns, and so a much finer temporal resolution is needed to identify these processes.
2. Laboratory comparisons of differences in EM properties between archaeological soils and the natural soils over a wide range of water contents and temperatures are rarely used in support of these surveys to explain underlying causes of the observed changes.
3. Surveys are carried out using different instruments, configurations and frequency ranges (DC to GHz), which makes direct comparison of different studies and soil types difficult.

In order to utilize geophysical methods on archaeological sites effectively and understand the underlying processes behind geophysical responses of archaeological ditches, both the effects of the soil geotechnical properties on the geophysical response and the seasonal changes to water content and temperature need to be understood together. For the purposes of this study, the ditches used were old field boundaries, from Roman (clay site) and prehistoric (till site) periods based on pottery found during the excavations (Wilkinson, 2011). This paper provides long-term in situ measurements to monitor seasonal behaviour, explained based on laboratory measured geophysical relationships and soil properties, to provide a complete picture of the dynamic geophysical responses of archaeological features.

3 | MATERIALS AND METHODS

The field study sites used in this research were chosen as part of the ‘Detection of Archaeological Residues using remote sensing Techniques’ (DART) project (Research Councils UK, 2016) and were monitored using bespoke time domain reflectometry (TDR) monitoring stations and weather stations between 2011 and 2013 as well as having monthly geophysical surveys. All data from the project is open source (available at dartportal.leeds.ac.uk). This paper focuses on the monitoring data from the project.

3.1 | TDR monitoring stations

TDR is a technique for measuring the apparent relative dielectric permittivity (ARDP) in soils using EM signals in a coaxial transmission line, which has been widely used for experiments in geotechnical, hydrological and geophysical studies including tracking solutes (Amente et al., 2000), infiltration studies (Bachmair et al., 2009; West & Truss, 2006), contaminated land studies (Cataldo et al., 2002), monitoring the suitability of the soil for GPR (Boddice et al., 2017; Curioni et al., 2012), slope monitoring (Kim & Kim, 2007) and flood prediction (Menziani et al., 2003). The operating principles of the technique have been well described (Jones et al., 2002; Robinson et al., 2003; Topp et al., 1980) and will only be briefly described here.

TDR units consist of a high frequency pulse generator, a voltage sampling circuit with a high temporal resolution and an oscilloscope that records reflected energy from impedance changes in the transmission line as a function of time. A fast rise time broadband EM pulse is injected into a waveguide inserted into or buried in the soil, and the time required for the pulse to travel along the metal rods of the waveguide is determined by the apparent dielectric permittivity of the soil, with higher permittivity resulting in a slower wave travel time. As water is the most dielectric component in the soil, the derived values can be used to estimate the VWC of the soil using a series of empirical relationships or dielectric mixing models. Furthermore, the reflection coefficient after a long period following the pulse can be used to determine the electrical conductivity of the medium due to the signal loss (Dalton et al., 1984).

TDR allows both the long-term monitoring in field conditions and laboratory assessment of the EM properties of the soil at an effective frequency comparable to commercial GPR systems commonly used in archaeological geophysical surveys (200 MHz to 1 GHz), thus providing a direct comparison (e.g., Damiata et al., 2017; Verdonck et al., 2009). The ability to multiplex multiple probes (Evett, 1998) and to automate the collection of data (Curioni et al., 2012) allows a high spatial and temporal (hourly) resolution to be achieved, allowing infiltration and drying processes to be studied in greater detail than with repeated surveys using other geophysical techniques. These factors made it an ideal choice for long-term monitoring in the field.

The main drawback of the technique is the inability of the method to assess the frequency dependent response of these parameters and the frequency of the applied signal (Chung & Lin, 2009). Assessment of this would require the use of a vector network analyser (VNA), which is currently unsuitable for long-term field deployment, and therefore, this will remain outside of the scope of the current study, although other authors have successfully compared the results of the two methods in laboratory studies (Heimovaara et al., 1996; Lin, 2003).

For this study, monitoring stations were constructed based on the design of Curioni et al. (2012). Construction, calibration and data processing are discussed in greater detail elsewhere (Boddice et al., 2012, 2017). A similar setup using the same equipment was used to take laboratory measurements that are described in another study (Thring et al., 2014). Testing showed that the TDR had errors of less than 0.4 permittivity units and 5% of the DC bulk electrical conductivity (BEC).

3.2 | Site location, sampling and TDR installation

Two sites with suitable archaeological ditch features in Cambridgeshire have been used for this study, one on Oxford clay and the other on glacial till representing a traditionally geophysically challenging and more responsive soil environment for detection, respectively. The archaeological features were excavated and recorded using standard archaeological excavation methodologies before a mechanical digger was used to expose some of the natural soils around the ditches. During the excavation, different soil stratigraphic layers were kept on separate tarpaulins to ensure easier bulk sampling and allow reinstatement in layers as close to the previous conditions as possible after the sensors were installed. Undisturbed samples of each of the soil layers were collected using metal monolith tins, which were hammered into the trench wall and removed using a spade to cut back the trench face to give samples that preserved the soil structure, in addition to bagged bulk samples from the spoil heaps (i.e., disturbed samples). These were used to allow geotechnical characterization and laboratory testing of the soils.

The TDR and temperature probes were inserted horizontally into the section face at different depths within the archaeological and natural profile. Where possible, multiple probes were used at each depth to allow for lateral variation and heterogeneity of the soil to be estimated, as well as providing some redundancy in case of probe failure during the monitoring period of the project. The till site on a free draining gravel soil was monitored using 16 probes (8 inside and 8 outside the ditch feature). For clay, as water movement was expected to be slower and more complicated in the clay soil, 32 probes were used (16 inside and 16 outside the archaeological ditch). The final excavated section, the location of the monolith sampling tins and the probes in the section are shown in Figure 1 and summarized in Table 1. Backfilling was conducted using the separated soil stratigraphic layers, which were reinstated as close as possible to their original positions within the soil, with the backfilling in the immediate vicinity of the probes being conducted carefully by hand to avoid disturbing the probes. The layers were compacted using a vibrating compactor to try to achieve a soil density as close as field values before the excavation as possible. Comparison with commercial borehole dielectric sensors on the clay site showed similar trends throughout the monitoring period, suggesting that the disturbance of the soil had no obvious major effect on the response of the soil to infiltration and drying.

Each site was also fitted with a weather station (Vantage Pro2; Davis instruments) to record precipitation, air temperature, wind speed and direction, humidity and pressure and to estimate evapotranspiration (ET) in order to correlate the measured values to climatic conditions.

3.3 | Soil characterization

The soil from the site was subject to geotechnical testing (particle size distribution, particle and dry density, Atterberg limits and linear

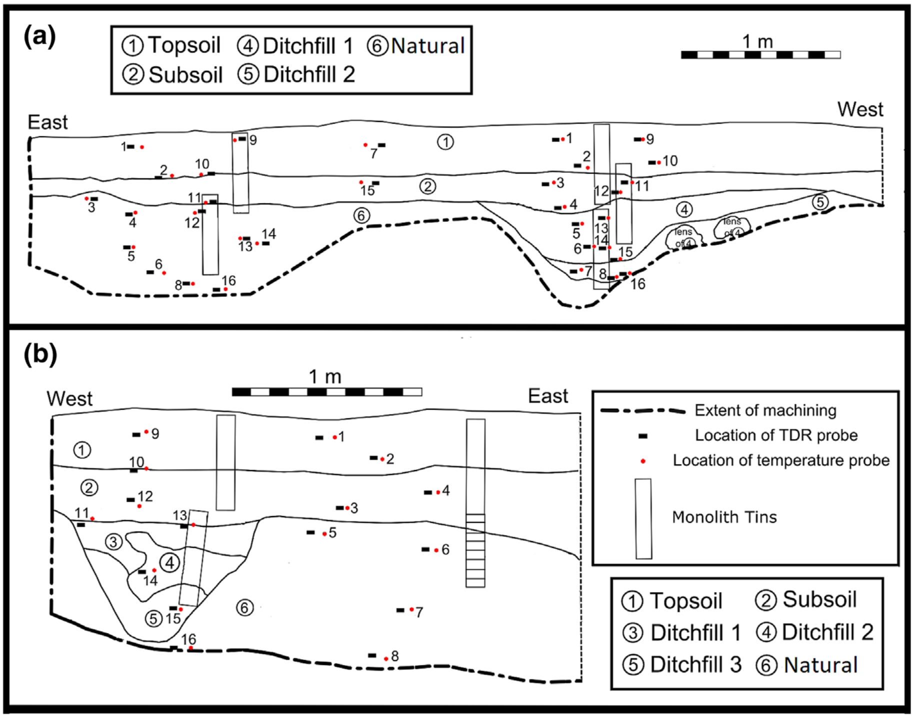

FIGURE 1 The excavated sections, location of the TDR and temperature probes and locations of the monolith sample tins for (a) the clay soil site and (b) the till site. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary of the installed probe locations.

Clay site											
Archaeology				Natural				Till site			
Probe	Approx. depth (m)	Context	Soil type	Probe	Approx. depth (m)	Context	Soil type	Probe	Approx. depth (m)	Context	Soil type
1	0.10	1 (topsoil)	Archaeology	1	0.10	1 (topsoil)	Natural	1	0.10	1 (topsoil)	Natural
2	0.20	1 (topsoil)	Archaeology	2	0.20	2 (subsoil)	Natural	2	0.20	1 (topsoil)	Natural
3	0.30	2 (subsoil)	Archaeology	3	0.40	6 (natural)	Natural	3	0.50	2 (subsoil)	Natural
4	0.50	2 (subsoil)	Archaeology	4	0.50	6 (natural)	Natural	4	0.40	2 (subsoil)	Natural
5	0.60	4 (Ditchfill1)	Archaeology	5	0.70	6 (natural)	Natural	5	0.60	9 (natural/Subsoilinterface)	Natural
6	0.80	4 (Ditchfill1)	Archaeology	6	0.90	6 (natural)	Natural	6	0.80	6 (natural)	Natural
7	0.90	5 (Ditchfill2)	Archaeology	7	0.10	1 (topsoil)	Natural	7	1.00	6 (natural)	Natural
8	1.00	5 (Ditchfill2)	Archaeology	8	1.00	6 (natural)	Natural	8	1.20	6 (natural)	Natural
9	0.10	1 (topsoil)	Archaeology	9	0.10	1 (topsoil)	Natural	9	0.10	1 (topsoil)	Archaeology
10	0.20	1 (topsoil)	Archaeology	10	0.20	2 (subsoil)	Natural	10	0.30	2 (subsoil)	Archaeology
11	0.30	2 (subsoil)	Archaeology	11	0.40	6 (natural)	Natural	11	0.60	3 (Ditchfill1)	Archaeology
12	0.40	2 (subsoil)	Archaeology	12	0.50	6 (natural)	Natural	12	0.50	2 (subsoil)	Archaeology
13	0.60	4 (Ditchfill1)	Archaeology	13	0.60	6 (natural)	Natural	13	0.60	3 (Ditchfill1)	Archaeology
14	0.80	4 (Ditchfill1)	Archaeology	14	0.70	6 (natural)	Natural	14	0.80	4 (Ditchfill2)	Archaeology
15	0.90	4 (Ditchfill1)	Archaeology	15	0.30	2 (subsoil)	Natural	15	1.00	5 (Ditchfill3)	Archaeology
16	1.00	5 (Ditchfill2)	Archaeology	16	1.00	6 (natural)	Natural	16	1.20	8 (natural below ditch)	Archaeology

TABLE 2 Geotechnical and magnetic properties of the tested soils.

			Particle size							Atterberg limits					Volume specific magnetic susceptibility			Relative magnetic permeability	
Site	Context No.	Soil name	Gravel %	Sand %	Silt %	Clay %	Particle density g/cm³	Dry density g/cm³	Calculated porosity -	Plastic limit -	Liquid limit -	Plasticity index -	Linear shrinkage %	Loss on ignition (LOI) %	χ_{lf} SI	χ_{hf} SI	χ_{fd} %	μ_r (lf) -	μ_r (hf) -
Till site	1	Topsoil	8.1	39.2	39.0	13.7	2.60	1.62	0.38	17	30	13	8.3	6.89	0.28	0.26	4.99	1.28	1.26
	2	Subsoil	11.3	33.5	41.1	14.0	2.65	1.66	0.37	15	25	10	8.4	4.91	0.19	0.17	8.29	1.19	1.17
	3	Ditchfill1	18.1	33.0	37.3	11.6	2.62	1.60	0.39	17	27	10	7.2	4.18	0.59	0.51	13.39	1.59	1.51
	4	Ditchfill2	17.4	32.9	40.9	8.8	2.65	1.31	0.51	17	27	10	7.5	4.54	1.03	0.90	13.10	2.03	1.90
	5	Ditchfill3	12.5	34.9	43.0	9.5	2.64	1.66	0.37	16	24	8	6.5	3.88	0.70	0.61	13.08	1.70	1.61
	6	Natural[a]	33.3	47.4	13.3	6.0	2.69	✘	✘	16	26	10	6.8	2.15	0.22	0.20	11.36	1.22	1.20
Clay site	1	Topsoil	6.3	22.0	49.8	21.9	2.58	1.56	0.40	22	48	26	15.2	8.26	0.21	0.21	2.91	1.21	1.21
	2	Subsoil	6.9	20.0	45.6	27.4	2.62	1.66	0.37	21	47	26	13.7	6.41	0.17	0.16	3.76	1.17	1.16
	4	Ditchfill1	8.6	16.3	52.6	22.5	2.67	1.61	0.40	19	41	22	10.8	5.53	0.14	0.13	6.74	1.14	1.13
	5	Ditchfill2[b]	6.6	15.9	36.5	41.0	2.63	1.58	0.40	21	44	23	13.3	3.72	0.12	0.12	−9.53	1.12	1.12
	6	Natural	6.5	16.3	46.3	30.9	2.83	1.90	0.33	18	40	22	10.5	4.63	0.06	0.06	2.20	1.06	1.06

[a] Undisturbed sample was unavailable as the soil was not cohesive enough.

[b] Sample size was too small to make samples for EM relationship testing.

shrinkage), conducted according to methods outlined by British Standards (BSI, 1990), and volume specific magnetic susceptibility readings (BSI, 1999) using a Bartington MS2B dual frequency sensor.

It is commonly assumed that the detection of ditches is mainly due to absolute differences in the water content (e.g., David et al., 2008), but the research highlighted above has shown that geotechnical soil properties affect the behaviour of the water and subsequent geophysical properties. To test this, further testing on relationships between VWC, ARDP and BEC at different temperatures was measured using TDR on laboratory samples. The methodology for sample preparation and measurement and results from the different soils are described in greater detail in Thring et al. (2014), who reported differences in VWC-BEC-ARDP relationships between the two sites. This paper reports on the differences between different soil layers on the same site and the potential of differences in the behaviour of the soils to generate reflections.

4 | RESULTS

4.1 | Soil characterization testing

The geotechnical properties of the soil, along with the magnetic susceptibility, are shown in Table 2 and used to explain the differences in soil EM behaviour and the results in the rest of the study. As shown, the differences in the measured properties on the same site were typically much smaller than the differences between the two sites, leading to smaller differences in the EM-water content relationships than reported for the inter site differences (Thring et al., 2014).

4.2 | Laboratory determination of EM properties

Comparing the VWC-BEC relationships of the different soils on the same site, for the clay site (Figure 2a), showed that the archaeological ditchfill soil had lower BEC values than the natural soil at low water contents but higher values at greater water contents above 25%. However, these differences were small, varying between 0% and 20% within the range of typical values in field conditions (15–40% VWC) and often within the error of the TDR for BEC determination (around 10%) across much of this range and therefore are unlikely to have a significant effect on surveying. In contrast, two of the till site (Figure 2b) archaeological ditchfill soils (1 and 2) show lower BEC values across all water contents when compared to the natural soil, with differences of between 20–40% (ditchfill 1) and 40–60% (ditchfill 2). This result seems to be the opposite to that suggested by the geotechnical properties of these soils, which indicate a slightly higher specific surface area (higher clay and organic contents) and therefore ion availability and pore fluid conductivity in the natural soils. One explanation is that measurement samples are biassed as the natural soil at the till site contained a greater number of large stones than the other samples from the site, which were sieved out here and would be excluded from field measurements due to the need to insert probes into the sample, resulting in a greater than normal prevalence of small particles with high surface areas in the till natural measurement volumes than would be typically representative. Another possibility is the greater density of these samples in comparison to the ditchfill soils, which had very low densities, as the presence of additional solid material with increasing density means that more ions are available for dissolution. The increase in BEC with increasing density was also noted by Yu and Drnevich (2004) and has been shown by varying the density of the soils from this site (Thring et al., 2014).

Comparing the VWC-ARDP (Figure 3) relationships of the different soils on the same site showed very small differences between the behaviour of the archaeological and natural soils, showing that water content rather than the physical behaviour of the water was the most important factor. The only exception to this was Ditchfill 2 on the till site, which showed significantly lower ARDP values at the same water content across most of the tested range with up to 4% difference in water content for the same ARDP value. Two possible explanations exist: (1) a lower contribution of the imaginary permittivity to the ARDP values compared to the other soils on the site, reflected in lower recorded BEC values, and (2) greater pore space in this soil reflected in its low density in comparison to other soils (1.3 mg/m3), resulting in a greater quantity of air in the measurement volume. Interestingly, the high magnetic permeability of this soil in comparison to the other soils on the site (almost double the usually assumed value of 1) does not seem to have caused an overestimation of ARDP and BEC as was suggested by other authors (Cassidy, 2007, 2008; Robinson et al., 1994), possibly due to the effects being masked by other factors such as the low density.

Various studies have shown negative relationships between temperature and ARDP (e.g., Gong et al., 2003; Ledieu et al., 1986; Menziani et al., 2003), positive relationships (Hoekstra & Delaney, 1974; Seyfried & Grant, 2007) and no temperature effects at all (Topp et al., 1980). The temperature dependence of ARDP in soil is the result of competing phenomena; the negative temperature dependence of free water and the positive effects of the release of bound water and the BEC effects as temperature increase (Gong et al., 2003; Skierucha, 2009). For the current soils, no significant effects were found with temperature for ARDP values for a given water except when the soil was over saturated. However, temperature was found to have a large positive relationship with BEC for all of the soils due to the lowered viscosity of the water and the increased ion mobility in the soil water (Calles & Calles, 1990; Campbell et al., 1948). The effect was greater on wet soils and the clay site due to the proportionality to water content and ion availability. These temperature effects may affect prospection both seasonally and at certain times of the day when temperature differences are most accentuated. Applications of electrical resistivity should be considered alongside measurements of the soil temperature and temperature corrections applied if accurate water contents are to be obtained, and soil temperature effects should be considered more widely when interpreting geophysical data using these methods as a possible cause of geophysical contrast.

The generally small differences in the VWC-ARDP relationships and the small temperature effects mean that the variation of EM

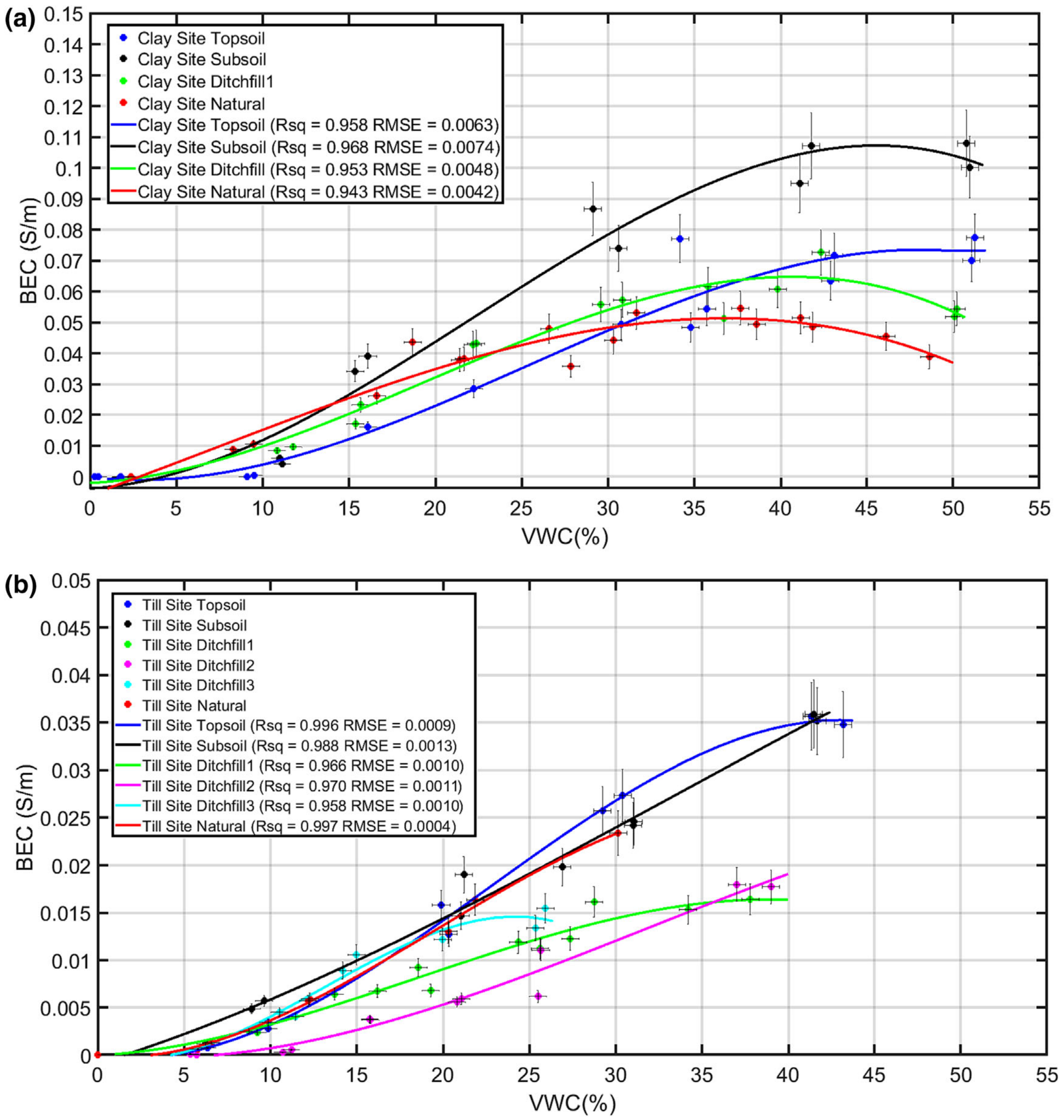

FIGURE 2 Relationships between bulk electrical conductivity and volumetric water content for (a) the clay site and (b) the till site. Curves fitted using a third order polynomial fit. [Colour figure can be viewed at wileyonlinelibrary.com]

velocity is likely to be the result of an absolute variation in water content as opposed to the behaviour of the water in the soil for both sites, making the ARDP a more reliable estimate of water content than the BEC, as it is less affected by the soil type. One common assumption is that the ARDP equals the real part of the permittivity (ε') in a TDR measurement (Robinson et al., 2005; Topp et al., 2000), whilst the BEC represents the imaginary part (ε''). Since TDR cannot separate electrical and magnetic effects due to the transverse EM mode of propagation of the signal, the magnetic effects can be taken as included within these values. Taking these assumptions, the reflection coefficients for normal incident waves between soil layers (i.e., perpendicular to a planar surface) can be calculated using Equation (1), setting the magnetic permeability to the free space value and calculating the effective frequency from the rise time of the waveform using the method suggested by Robinson et al. (2005). A common, if conservative, method for determining if a reflection from GPR is visible at the surface is that the reflection coefficient should be greater than ±0.1 (Annan, 2001), which has been used by Damiata et al. (2017) to determine which features were visible. Figure 4 shows the differences in the reflection coefficient between different soil types at the same water content for both the clay site (a) and the till site (b), which are small and rarely exceed 0.05 across the studied soils. The only notable exception is reflections between Ditchfill 2 on the till site and other soils, which generates much larger reflections (>0.1) when the soil conditions are dry, due to large differences between the model for this soil and those of the natural soil and Ditchfill 3 below it in the soil profile. However, the size of the reflections decrease as the soil becomes saturated to values similar to the

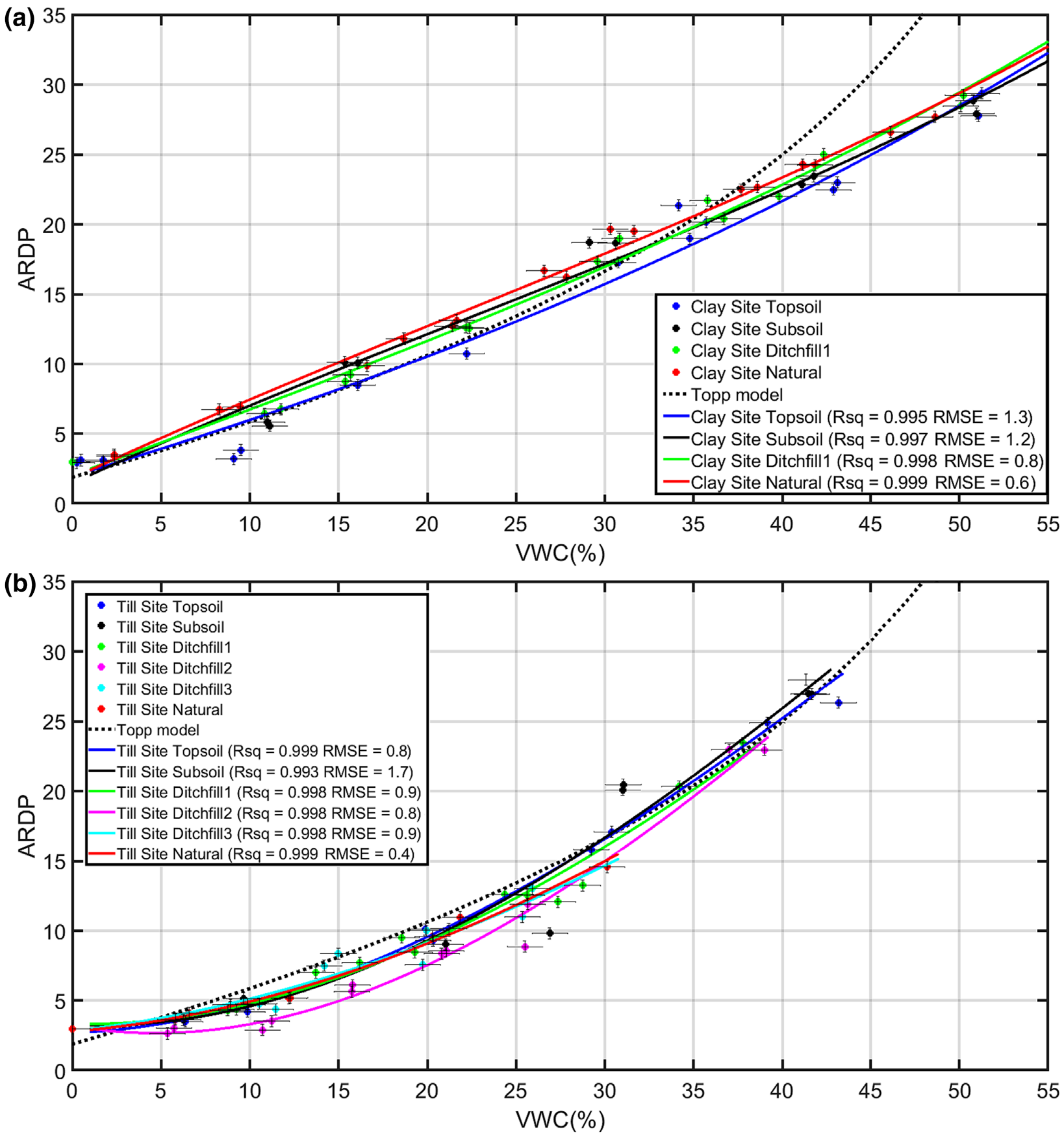

FIGURE 3 Relationships between volumetric water content and ARDP for (a) the clay site and (b) the till site. Curves fitted using a third-order polynomial fit, and the Topp model is included for comparison. [Colour figure can be viewed at wileyonlinelibrary.com]

other soils. These findings indicate that, whilst in most cases there needs to be an absolute difference in the water content between the soils for the feature to be visible, on this site, the feature may also be visible when no such large differences exist, providing the general soil conditions are dry.

4.3 | Long-term field monitoring

From the laboratory results above, it is apparent that water content is the most dominant factor for determining the ARDP and the BEC of the soil, with temperature having a significant impact on the BEC, but no large effect on the ARDP. This section draws on the knowledge of the links between water content, temperature, soil type and geophysical properties, using them to identify the behaviour of archaeological and natural soils in the field and resulting changes to geophysical contrast. Generalized seasonal signal penetration effects in the natural soil and on GPR performance were discussed in another paper by the authors (Boddice et al., 2017) and by other authors (e.g., Curioni et al., 2017), but the current work focuses on the difference in EM properties between the archaeological and natural soils. Since only small differences existed in the ARDP-VWC relationships between the archaeological and the natural soils on site and ARDP was not strongly affected by temperature, ARDP values provide a good proxy for water content, and differences in values can be mostly equated to differences in water movement and storage in the soil.

Data have been despiked by removing values outside of a viable range of values (0 and 35 for ARDP 0 and 0.15 S/m for BEC) and a

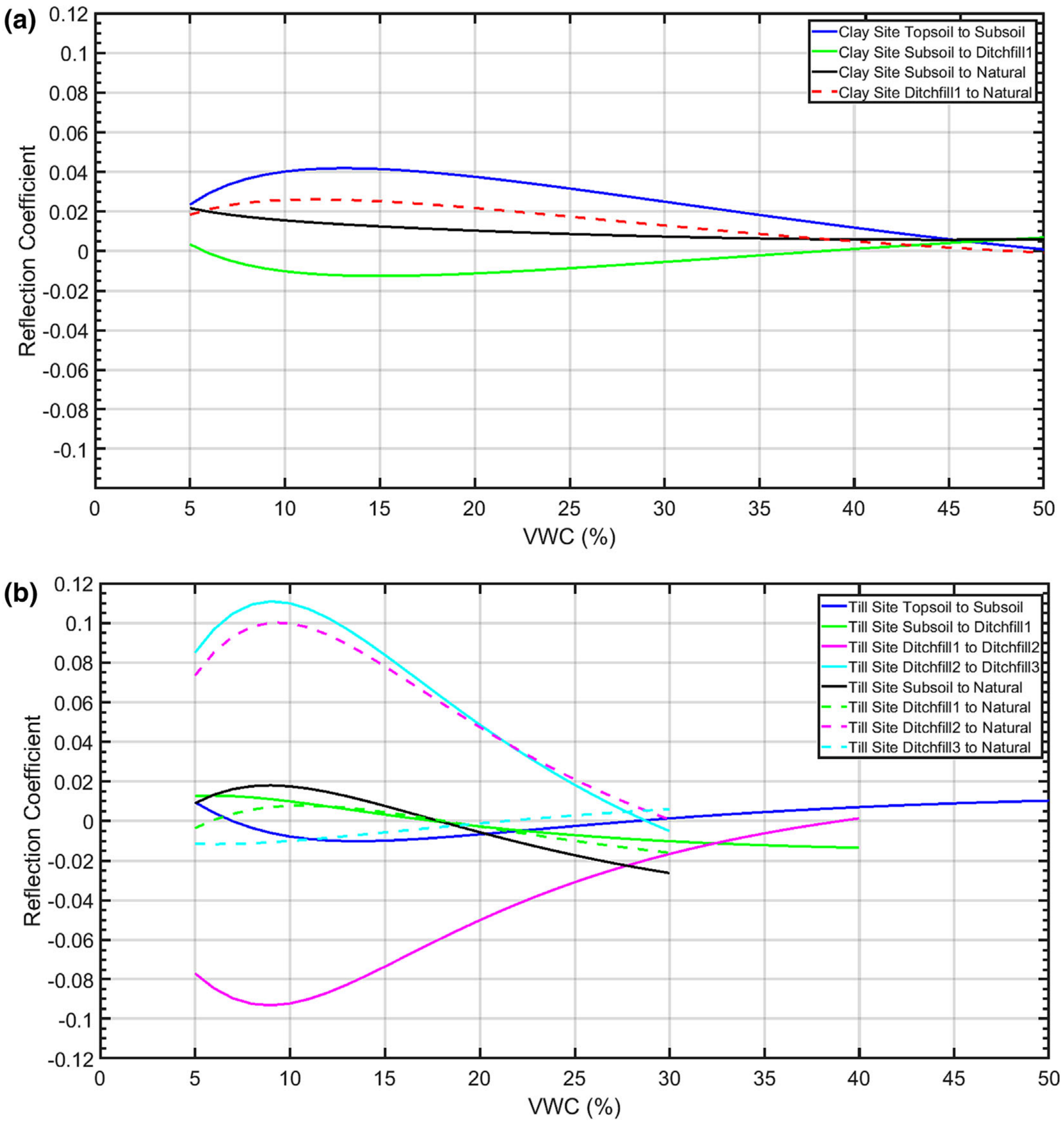

FIGURE 4 The reflection coefficients between pairs of soil types across the water content range for (a) the clay site and (b) the till site. Dotted lines show interfaces between archaeological and natural soils. [Colour figure can be viewed at wileyonlinelibrary.com]

1D median filter applied to the data to remove noise. Probes at the same depth and in the same soils were assessed for heterogeneity both inside and outside the archaeological feature and were found to show similar trends in response to weather phenomenon. The mean difference and standard deviations are shown in Table 3. Slightly larger differences were present in the near surface soils due to differences in the soil structure, which create preferential flow paths for water infiltration (Wang et al., 2006), and in drier conditions. These findings are consistent with other authors (Curioni, 2013; Herkelrath et al., 1991). Probes at the same depths and in the same soil types were averaged for the rest of the study.

4.3.1 | Seasonal trends of contrast

The weather during the study did not follow typical seasonal patterns. The winter of 2011 was the driest on record, which was followed by an equally record breaking wettest spring to summer period since records began (April–June) in 2012. These unusual weather patterns mean that whilst relating the results to seasons may be inaccurate, a full range of wet, dry and intermediate periods were captured allowing different ground conditions to be discussed. In order to produce clearer plots, data in this section have been averaged over 24 h periods to give daily values for ARDP and BEC, and rainfall and ET data have also been provided as cumulative values over 24 h periods, allowing wetting and drying patterns to be studied.

The changes in ARDP and BEC for the till site are shown in Figure 5 and for the clay site in Figure 6. The study period on both sites can be characterized by a dry period at the start of the monitoring followed by a wet period as a large wetting front moved its way down the profile between January and March 2012 after which the soils responded to subsequent rainfall. Towards the end of 2012 on the till site, a third period was noticed, consisting of a large rise in the ARDP and BEC at greater depths, which seemed to unusually affect

TABLE 3 Mean difference and standard deviation (in brackets) in geophysical properties between probes in the same soil context layers buried at the same depths on the clay site.

	ARDP			BEC (S/m)		
Site	**Till site**	**Clay site—natural**	**Clay site—archaeology**	**Till site**	**Clay site—natural**	**Clay site—archaeology**
Topsoil	-	3.3 (1.53)	2.5 (1.50)	-	0.009 (0.005)	0.005 (0.004)
Subsoil	-	1.3 (1.08)	1.3 (1.36)	-	0.007 (0.003)	0.004 (0.003)
Upper natural	-	0.9 (1.13)	-	-		-
Lower natural	-	0.6 (0.48)	-	-	0.001 (0.002)	-
Ditchfill 1	0.5 (0.44)	-	0.5 (0.43)	0.001 (0.0009)	-	0.001 (0.001)
Ditchfill 2	-	-	1.0 (0.64)	-	-	0.003 (0.001)
Ditchfill 3	-	-	-	-	-	-

Note: Multiple probes were not embedded in this context at the same depth.

the bottom layers first, contradicting the usual models of infiltration after rainfall. Excavations to remove the instruments in June 2013 showed that the water table was above the bottom of the trench (∼1.2 m), suggesting this may be caused by fluctuations in the water table but it is more likely that this shows an equipment malfunction due to the rapid changes in readings, which are not seen in the other probes at the same depth.

Throughout the whole study period, the ARDP of the soils overlying the ditch feature (Topsoil and Subsoil) responded similarly to rainfall and drying events in both the wet and dry conditions on both sites. Below these layers, there was less response to individual rainfall events, and the archaeological soils show consistently high ARDP values in comparison to the natural soil. Whilst this is in itself indicative of greater water contents, laboratory tests showed Ditchfill2 on the till site (0.8 m depth) had very low ARDP values at the same water content in comparison to the other soils on site, making these differences even greater than they appear. Previous experiments on earth resistance contrast (e.g., Clark, 1980, 1996) suggested that water can infiltrate the ditch with greater ease due to lower density in comparison to the surrounding soils, although it should be noted that the temporal resolution of these surveys was limited to monthly and so processes were inferred between measurements based on rainfall data. One key finding from this data is that neither of the studied sites appeared to show significant differences in infiltration patterns and behaviour between the archaeological and natural soils, with major wetting fronts affecting both at roughly the same time with the exception of the initial wetting fronts, which moved slower in the natural soil at greater depths, most likely due to differences in the sizes of the empty pore spaces. As all subsequent rainfall events and wetting fronts behaved more uniformly between the two soil profiles once the soil was near to holding capacity, it appears that this behaviour is only true in the case of very dry soils. A more detailed look at infiltration of individual events is examined in the next section of this paper.

Due to this similar response to rainfall events, absolute contrast in ARDP (indicative of water content) between the archaeological and natural soils remained broadly constant both during the dry and wet periods, especially at greater depths. This is indicative of the fact that the soil was either very dry (i.e., at residual water content) or near field capacity such as during the wet period. It is most likely that the most important difference for the detection of archaeological features lies in the difference in the residual and field water capacity of the archaeological soils and the natural soils. Other authors have previously identified differences in organic content as the primary factor in determining water content holding and subsequent GPR anomalies, with particle size distribution differences only visible at water contents above 5.5% (van Dam et al., 2002; Van Dam & Schlager, 2000). However, Saxton and Rawls (2006) noted that the effects of organic matter were masked in clay soils where fines dominated the relationship. As the soils here show differences in both of these, the cause is likely to be a result of a combination of these factors. The smaller size of differences in these properties on the clay site are the primary cause for the smaller contrasts between the two soils and overall challenge to surveying on fine grained soils.

One exception to this dominance of field capacity is that although infiltration was mostly constant between the archaeological and natural soils, significant differences existed in drying patterns of the two soil types during a period of hot weather (air temperature consistently >15°C) experienced in the summer of 2012. For the finer grained clay site (Figure 6), the archaeological soils dried faster and to a greater depth, shown by the ARDP values, which fell at a greater rate and to a greater extent during periods in June–September 2012. By contrast, the opposite behaviour, but a larger difference in the drying rate, can be seen on the till site (Figure 5), as the natural soils dried at a faster rate and to a greater extent in warm periods during August and September 2012. These differences in drying, which were not present in the wetting cycles, suggest different hysteresis in the soil potential between the two soil types (archaeological and natural) and are due to the greater porosity and size of pores of the lower density soil on site which allows water to escape more freely. This suggests that drying is one of the main drivers of water content differences and conducting a geophysical survey after an extended dry period, rather than immediately after wet weather may therefore provide the best time with the highest contrast.

The BEC values followed the same overall trends due to the primary dependence on the water content shown by the laboratory results. However, they also displayed a response to the temperature, with values peaking in July–August 2012 when the soil temperature

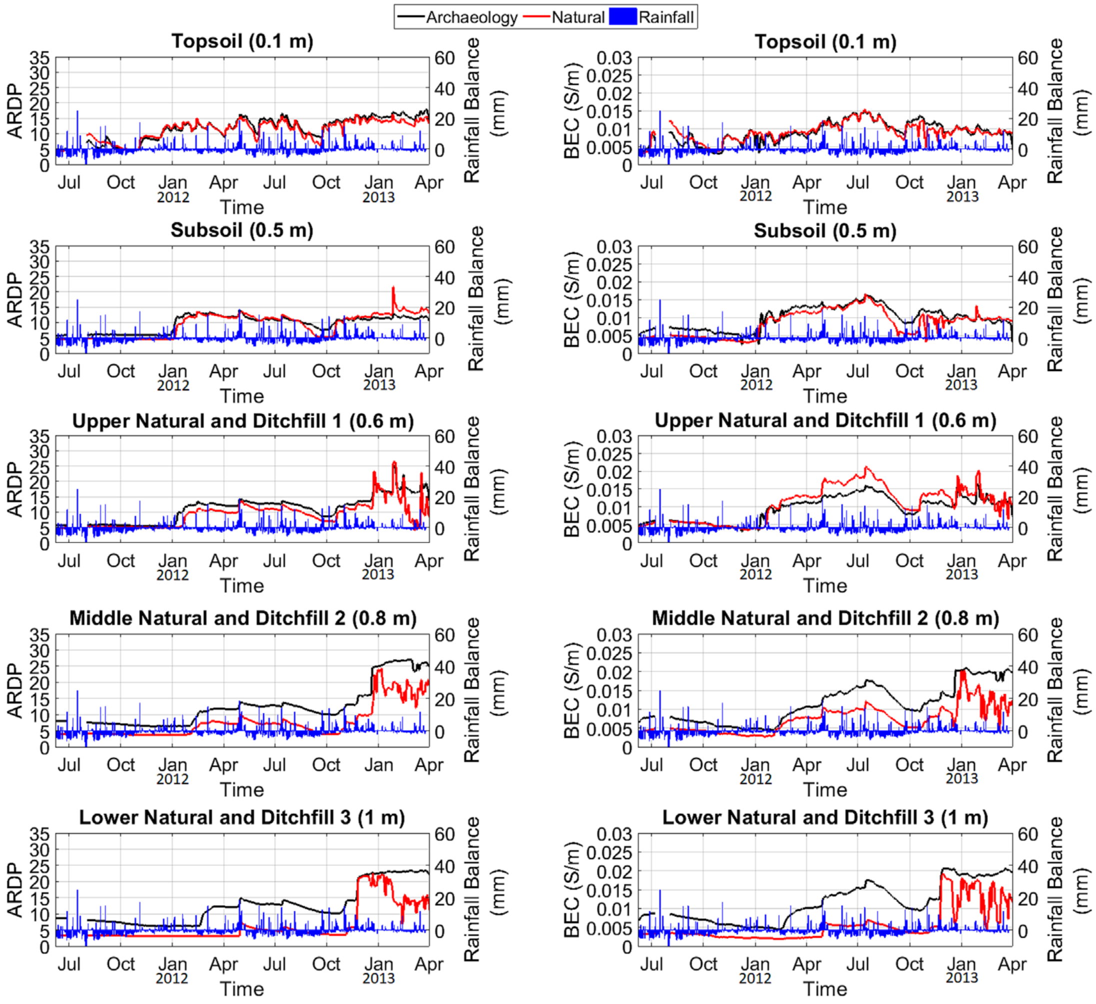

FIGURE 5 Comparison of ARDP and BEC data in different contexts and depths on the till site. [Colour figure can be viewed at wileyonlinelibrary.com]

was at its greatest (Figure 7), despite there being no corresponding rise in the ARDP. This shows that temperature is one of the major drivers of seasonal change in detection of archaeological features in saturated soils, with the best time for surveys being during a period of warm weather that accentuates the contrast in water content differences. One interesting result is that at 0.6 m depth on the till site, the Ditchfill 1 soil showed lower BEC values in comparison to the natural soil despite the ARDP data showing the opposite result. As shown in the laboratory testing, this soil had a lower BEC at the same water content than the natural soil, suggesting that its chemical composition is the main cause of this anomalous result. Nevertheless, such a reversal may have important implications for the detection of the ditch using electrical resistance or EM conductivity based methods.

4.3.2 | Infiltration

One commonly held conception about why archaeological ditches have different geophysical properties to the natural soil around them is that there are differences in the infiltration speed following rainfall events between the archaeological ditch and the natural soil profiles (i.e., water can enter the more porous soil within the ditch quicker) (e.g. Clark, 1980, 1996; Schmidt, 2013). To test this assumption and highlight differences in infiltration patterns between the archaeological soil and the SSM profiles for fine and coarse grained soils, short periods of data taken immediately after a rainfall event were chosen. In order to statistically determine the difference in infiltration lag at different depths, time domain cross correlation between the hourly rainfall and measured ARDP data from the soil was conducted. The peak of the correlation function can be used to show the lag between rainfall at the surface and the water arriving at specific depths through the soil profile. A typical event from March 2012 after a sustained rainfall event (15.4 mm in 9.5 h) has been selected, and the results are presented in Figure 8. Additional rainfall events from other times of the year were also analysed and found to produce similar results, regardless of the size of the rainfall event and preceding water content of the ground.

The time domain cross correlation analysis showed a positive correlation for both sites on the near surface probes above 0.5 m depth, confirming the findings from seasonal analysis that infiltration of

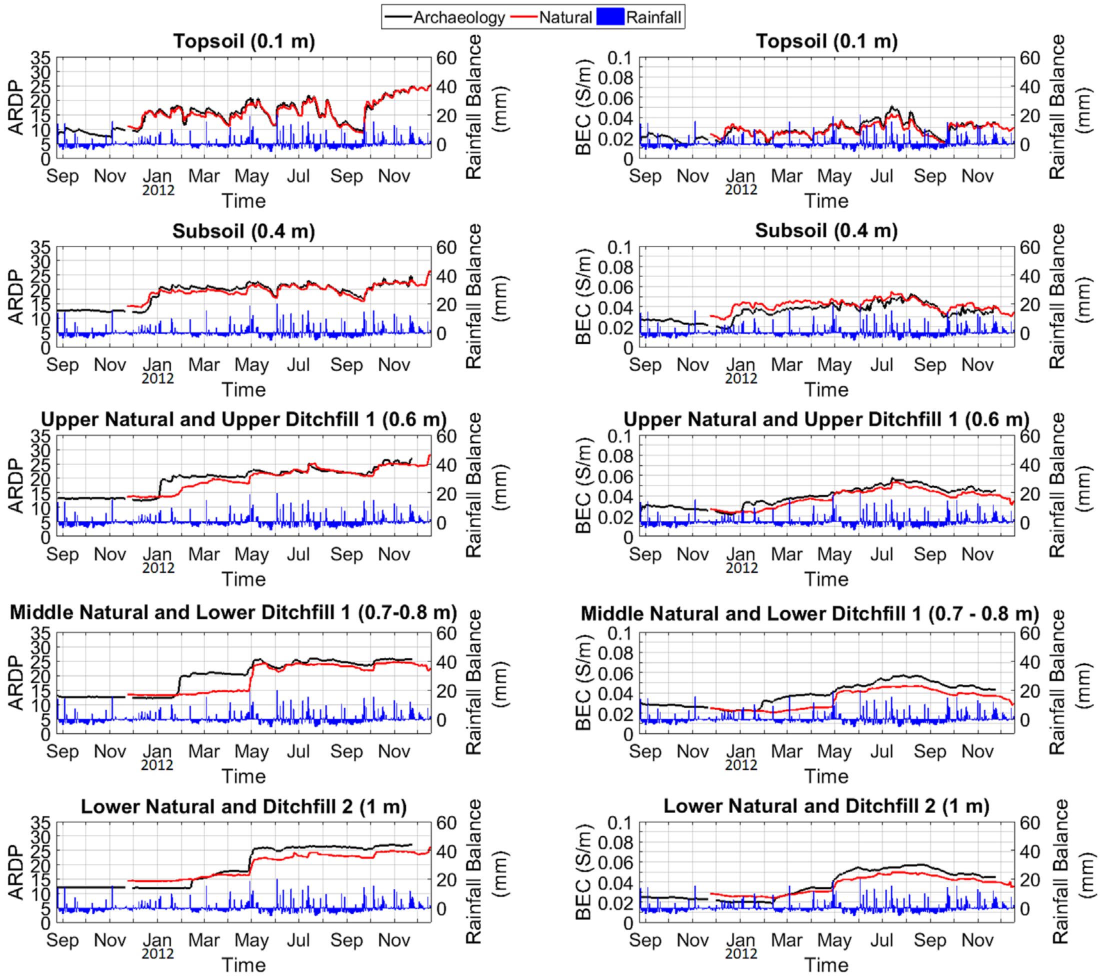

FIGURE 6 Comparison of ARDP and BEC data in different contexts and depths on the clay site. [Colour figure can be viewed at wileyonlinelibrary.com]

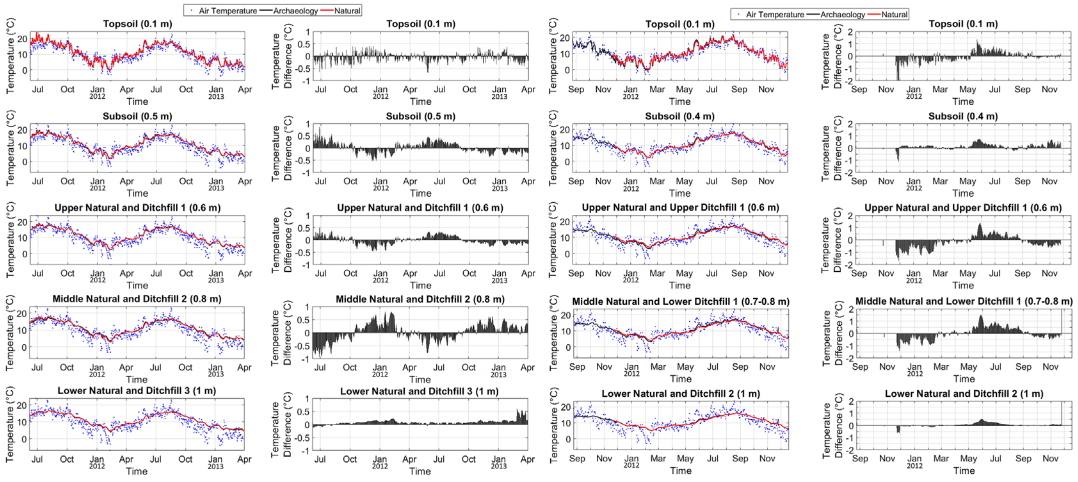

FIGURE 7 Comparison and differences in temperature between archaeological and natural soils at different depths. [Colour figure can be viewed at wileyonlinelibrary.com]

rainfall mostly affected the near surface soil, although on the till site, significant correlations after 60 h were also recorded at 0.6 and 0.8 m depth. Virtually no recordable differences were found in infiltration between the two soil types on the till site, with similar peaks recorded for the two soils at all of the studied depths. As both the archaeological and SSM soils are predominantly coarse grained, it is suggested

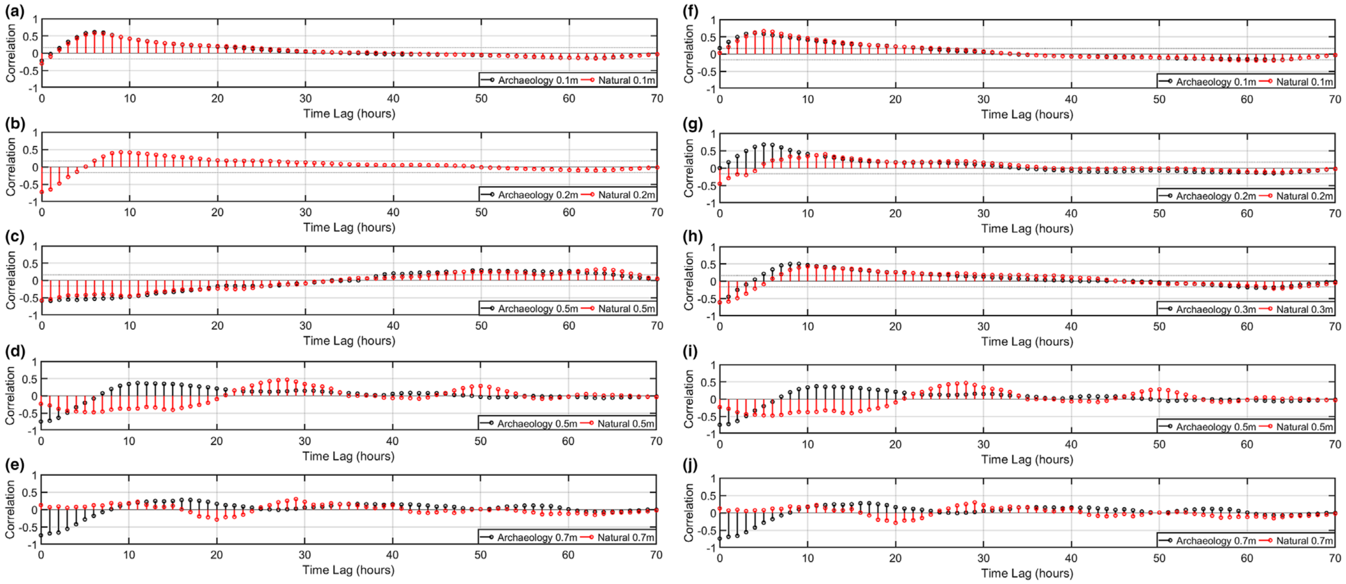

FIGURE 8 Cross correlations between a rainfall event and ARDP values at different depths for the till site (a–e) and clay site (f–j). Horizontal dashed lines represent the limits above which the absolute cross correlations are significant with a confidence level of 90%. [Colour figure can be viewed at wileyonlinelibrary.com]

that both had similar free draining properties allowing water to infiltrate at the same rate through both soils. In contrast, on the clay site, infiltration was marginally faster within the archaeological feature in comparison to the SSM, especially in the near surface, most likely due to the lower density and larger pores. However, the differences are small with a maximum of approximately 15 h at 0.5 m.

Since the difference in infiltration rates between the soils is only a few hours at most, any differences in geophysical properties are hard to exploit, as they would require implausibly good timing for the survey. These results show infiltration rates are unlikely to be the cause of significant and persistent contrasts between the archaeological and SSM soils and resulting visibility of archaeological features, with the main differences in contrast being caused by differences in the total holding capacity of the different soils.

5 | DISCUSSION OF EFFECT ON SURVEYING

5.1 | Reflections

Current guidelines suggest that surveys have the greatest potential for success when moisture contrasts are at their most accentuated (David et al., 2008), but the results presented in this paper show a complex relationship between the different properties. To examine the effect on surveying, the effective visibility of the ditch has been assessed by calculating the reflection coefficients between the SSM soil and archaeological soils at different depths, using the same method as used for the laboratory results above and a ±0.1 threshold in the reflection coefficient to assess if a reflection is visible (as used by Damiata et al., 2017). A limitation of this method is the assumption of planar linear boundaries at the interfaces between layers, which is unlikely in the real world due to bioturbation, but the results are indicative of the relative performance in different soil conditions. The results are shown in Figure 9 for the till site (a) and clay site (b).

The results from the clay site show the difficulty of surveying over clay soils in additional to the challenges of high attenuation which are discussed in Section 5.2, with the reflection coefficient between the ditchfills and the SSM being below 0.05 for most of the study period including both the dry and wet conditions, meaning it is unlikely that the ditch could be detected. The largest reflections were generated between January and May 2012 in the middle and bottom of the ditch, which correlated with the initial wetting front and subsequent difference in its movement through different soil profiles. However, these values still rarely exceeded the ±0.1 threshold, meaning the detection chance is still marginal and timing surveys to the transition period between dry and wet soils needs both an extended drought followed by heavy rain or melting snow to provide the initial wetting front which are atypical weather patterns in the UK. It is unknown if a similar difference would occur following another lengthy drought period such as the one preceding the installation, but the differential drying between the archaeological and natural soils during dry periods highlighted in the previous section suggests that this may be the case.

On the till site, a larger reflection exceeding this threshold was observable throughout the survey period between the lower two ditchfills (2 and 3) and SSM throughout the whole study period, which makes the timing of surveys less critical. Nevertheless, strong improvements to the reflection coefficients were observed after

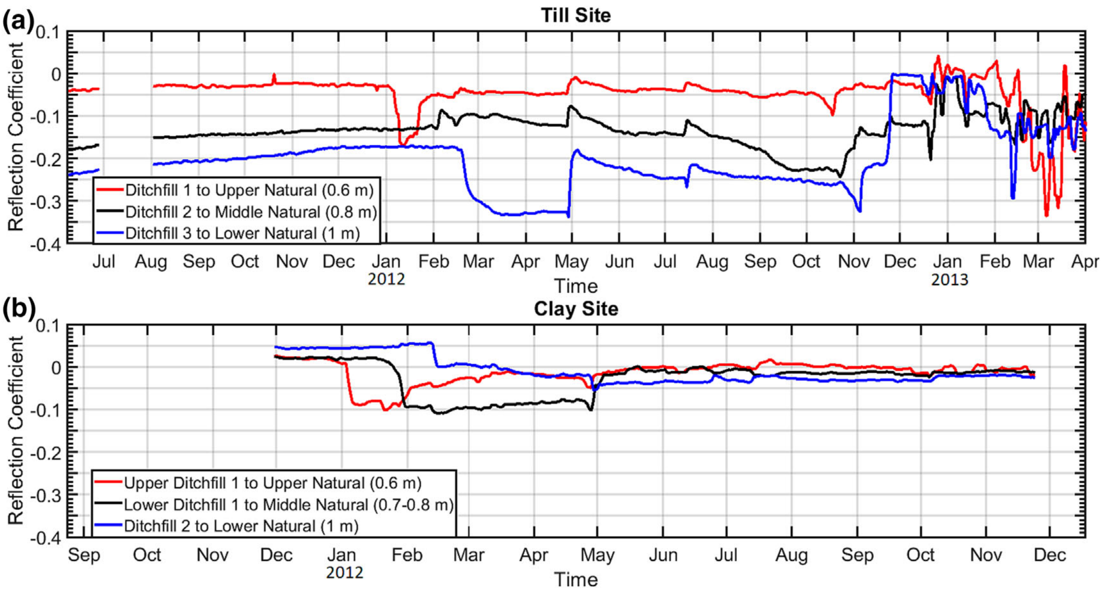

FIGURE 9 Reflection coefficients between the ditchfills and SSM for (a) the till site and (b) the clay site. [Colour figure can be viewed at wileyonlinelibrary.com]

drying events, suggesting that it is best to survey these sites after a period of drying has occurred. In contrast, the top ditchfill (ditchfill 1) rarely gave strong reflections but followed similar trends.

5.2 | Attenuation

Attenuation of the GPR waves plays a crucial role in the performance of the technique in different soil conditions as sufficient power needs to be available in the signal after passing through the uppermost soil layers to generate a reflection (Conyers, 2004). Signal loss is predominantly caused by two main factors: DC electrical conductivity and dipolar losses (Cassidy, 2009). Separating the dipolar loss component of the imaginary permittivity from a time domain waveform is challenging due to difficulties interpreting the waveform in the case of multiple reflections to identify the correct level especially in the clay soil. Furthermore, the dipolar losses are heavily dependent on the frequency of the applied signal (which can only be estimated in the broadband signal of a TDR, which means the frequency varies in different media) due to relaxation mechanisms in soil water (Robinson et al., 2005), especially bound water. For these reasons, it is assumed in this study that as the BEC is measured by using the signal loss from the TDR after a long period, this is indicative of the attenuation of the signal. Testing in the laboratory showed that the TDR derived electrical conductivity could differ from a DC value by approximately 10%, possibly due to other dipolar effects.

To give an indicative attenuation performance, the frequency of the TDR has been estimated at 500 MHz (in line with the findings of other authors; in line with the findings of other authors, e.g., Chung & Lin, 2009; Or & Rasmussen, 1999; Robinson et al., 2005), the real permittivity taken as the ARDP and the imaginary permittivity as the electrical conductivity derived from the TDR with the magnetic permeability set to 1 (as these effects are impossible to separate from the apparent measurements). These values have been used with Equation (2) to calculate the attenuation coefficient, which has been used with the thickness of each soil layer derived from the section drawings to determine the percentage signal reaching each interface. The results of this over the study period for the two sites is shown in Figure 10.

As shown, the attenuation follows similar trends across all the soil layers on each site with time. The best conditions for signal penetration for both sites are during the dry conditions at the start of the study period (before January 2012). The worst conditions on both sites were during the summer of 2012, due to a combination of wetter conditions and higher temperatures, which increased the conductivity of the soil and caused a greater signal loss throughout the soil profiles.

The differences in the attenuation across the study period are relatively small in the lower archaeological layers for each site, with the main differences in signal penetration being affected by the topsoil and subsoil layers, which show larger changes. This is perhaps unsurprising as these layers showed the greatest variation in water content, temperature and therefore their geophysical properties and the signal must also pass through these layers to reach the deeper layers. The amount of signal reaching the bottom two layers of the ditch on the clay site is small throughout the whole period (<2%), which is unlikely to be sufficient to generate a large enough signal to be detected at the surface. Similarly, small reflections can also be found on the till site during the wet period between April and October 2012. In these conditions, the best chance of detection would be to identify differences in the reflection between shallower layers such as the top of the ditchfill 1 and the surrounding natural soil. Due to their relative

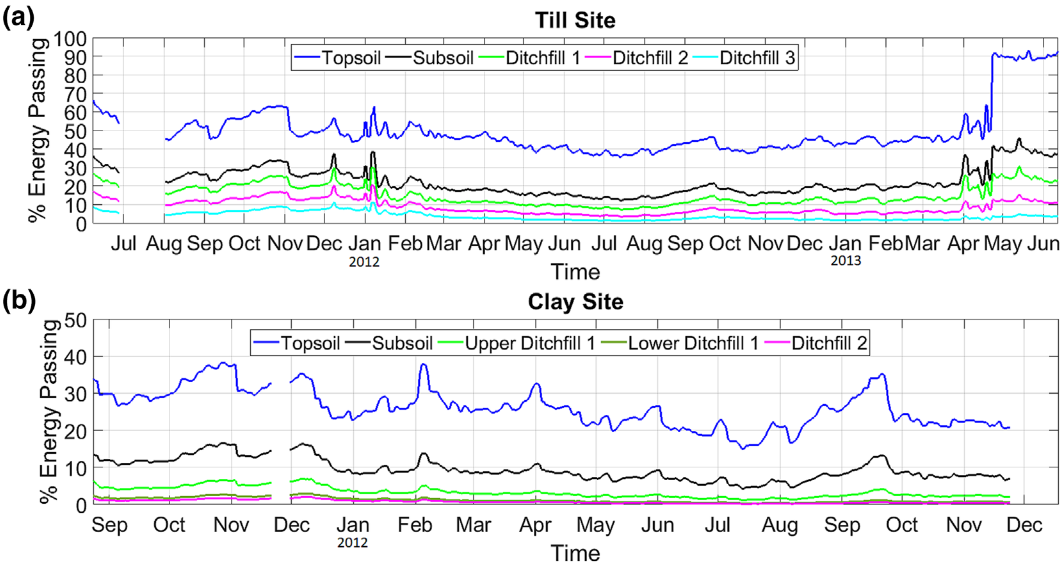

FIGURE 10 Percentage of the original signal reaching the bottom of each of the soil layers based on the TDR-derived conductivity and the thicknesses of the different layers for (a) the till site and (b) the clay site. [Colour figure can be viewed at wileyonlinelibrary.com]

importance, measurements of the water content near the surface may be used to help predict the likely signal penetration performance of GPR for a given site.

6 | CONCLUSIONS

Previous seasonality studies on archaeological features have been limited to repeated surveys predominantly using earth resistance techniques, which only considered changes in water content (ignoring temperature and differences in VWC-BEC relationships) and were limited in their ability to study soil water processes due to their coarse temporal scale and poorly defined measurement volumes due to unknown current paths in the ground. This paper addressed some of these limitations by monitoring changing geophysical contrasts between archaeological soils and the SSM using a novel TDR monitoring strategy, involving, for the first time, long-term monitoring of the soils' EM properties at a high temporal and spatial resolution, supported by laboratory investigations into the complex relationships between geophysical properties. The key findings were as follows:

- The differences in relationships between water content and the EM properties of the soil between the SSM and archaeological ditchfill soils were very small, with only ditchfill 2 on the till site showing a notable difference from the soils surrounding it, which was thought to be because of its low density. This shows that differences in the amount of water between the two soil types were more important than the soil properties and their effect on the physical behaviour of the water (e.g., how much is bound to soil particles) for a given site. Equally important, temperature was found to have a strong effect on the BEC but very little effect on ARDP, making it a far better proxy for water content than the use of DC resistivity techniques which respond to both water content and temperature.
- Field monitoring showed that there were two distinct periods: a dry period and a wet period where the ground was saturated, both of which were relatively stable in terms of short term fluctuations in the water content. Contrary to the popular model of water infiltrating the looser ditchfill soils faster, few differences in infiltration speed were observed, although some differences existed in the drying rate between the two soil profiles, with the archaeological ditchfills drying slightly quicker. Geophysical contrast between archaeological ditches and the surrounding soil was largely a function of the soils ability to hold water, meaning the overall contrasts were determined by seasonal trends rather than individual events. In terms of short term fluctuations in geophysical contrast, temperature played a much more important role as it affected the BEC, especially when the ground was fully saturated.
- The optimum time for surveying was in the transition between dry and wet periods and after periods of warm weather, which stimulated differential drying. Larger differences in the underlying soil properties between the archaeological ditchfills and SSM, which determine the water holding capacity (especially particle size and density) and therefore the resulting geophysical contrasts, were observed on coarse grained as opposed to fine grained soils explaining why these sites are considered to be more detectable and making the timing of surveys less critical on these sites.

Crucially, this study shows that although there is no such thing as a typical archaeological ditch due to differences in the formation, destruction and subsequent taphonomic processes, geotechnical properties are a useful proxy indicator for likely geophysical behaviour in different climatic conditions. Given the similarity of these tests to geoarchaeological methodologies in common use in archaeological excavations, and the availability of geotechnical databases (e.g., British Geological Survey's National Geotechnical Properties Database), which store relevant information, there is a wide range of available information that may help to improve our knowledge of geophysical responses (Pring, 2016).

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CONFLICT OF INTEREST STATEMENT

There is no perceived conflict of interest for this study for any of the authors.

DATA AVAILABILITY STATEMENT

All data from the project are open source and available at dartportal.leeds.ac.uk under a CC-BY license.

ORCID

Daniel Boddice https://orcid.org/0000-0002-3738-2327

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