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Joint Use of Seismic and Electromagnetic Methods in Geophysical Surveys

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Abstract
Multi-channel Analysis of Surface Waves (MASW) is a seismic wave propagation method which involves the measurement of Rayleigh waves propagating along the surface of a medium. The method is non-intrusive, fast and practical and it has been successfully utilized for the *in-situ* evaluation of shear modulus and layer thicknesses of soils and, more recently, pavement systems. The method is also widely utilized as a tool for monitoring stiffness during construction, for maintenance inspections and even for the detection of voids and sinkholes. Time Domain Reflectometry (TDR) is an electromagnetic method based on the measurement of the propagation velocity of a step voltage pulse along a probe inserted in the soil. Electrical properties of the soil, i.e. dielectric permittivity and bulk electrical conductivity, are determined and can be related to some geotechnical properties, e.g. the volumetric water content and potentially the soil density. Seismic wave propagation methods such as MASW are sometimes used in conjunction with electromagnetic methods, in an attempt to reduce the uncertainty associated with each individual method, and to provide an enhanced characterization of the investigated soil. It is still unknown however, whether they are mostly complementary methods or whether they share the assessment of common mechanical/geotechnical properties. In this work the potential and the limitations of the joint use of the MASW and TDR techniques were investigated through an *in-situ* near-surface programme measurement at two different soil sites, up to a depth of 1 metre. A Dynamic Cone Penetrometer test was performed and the Particle Size Distribution curve determined to extend the soil characterization, and where possible soil samples were taken at various depths in order to measure the dry density and the volumetric water content. The two techniques measured similar trends, augmenting the results obtained by each method and showing the potential for an enhanced and more complete assessment of the soil properties. In addition, bulk electrical conductivity was shown to be related to the shear modulus for the soils studied.

Keywords: Multichannel Analysis of Seismic Waves (MASW), Time Domain Reflectometry (TDR), dry density, volumetric water content (VWC), Dynamic Cone Penetrometer (DCP), phase velocity, shear wave velocity, dielectric permittivity, bulk electrical conductivity.

1. Introduction

Shallow geophysical techniques such as seismic methods and electromagnetic methods are used in a range of applications to assess the condition of the ground. Seismic methods are typically used to determine soil mechanical properties such as stiffness and density [1, 2]. Electromagnetic methods are suited to measuring soil water content, clay content and to some extent, soil density [3, 4]. As with all geophysical techniques, each method has limitations and potentially suffers from non-uniqueness issues. The combined use of different shallow geophysical methods has proved useful in order to obtain more robust inversions by adding more *a-priori* information [5]. Many efforts have been put in during the past few decades in searching for good correlations between seismic wave velocities and geotechnical parameters of soils and rocks, i.e. their mechanical properties. Many empirical correlations have been proposed between P-wave velocity and dry density of rocks, with decent correlation coefficients [6]. Kulkarni and co-workers found good relationships between geotechnical parameters and S-wave velocity of clays from coastal regions. In particular, it has been shown that the shear wave velocity in soils can be employed for estimating void ratio, bulk density, undrained shear strength and to some extent, gravimetric water content, with a certain degree of confidence. This investigation was based on the assessment of the shear velocity and geotechnical properties by means of laboratory tests on disturbed specimens [7]. Research by

other authors [8] led to similar empirical relationship between shear strength and natural water content of soils, depending on their natural physical composition. Parks [9] jointly used electromagnetic and seismic reflection method to evaluate the groundwater table in soil deposits, i.e. to identify the shallow water surface.
The present study shows the results of the combined application of a seismic and an electromagnetic method at two field test sites in the UK with the aim of comparing the two methods and identifying the potential and limitations of their joint use. This preliminary study also claims to understand the potential of surface wave methods and electromagnetic methods in assessing some geotechnical properties and in reducing the uncertainty of a geophysical survey.

2. Multichannel Analysis of Surface Waves

MASW is a seismic method that exploits the dispersive behaviour of surface waves to determine the dynamic shear modulus and thicknesses of shallow soil layers. The method consists of monitoring the propagation of Rayleigh waves over a wide range of wavelengths, at specified distances from the source. The vertical motion induced by the Rayleigh wave is recorded at different distances from the source, and each data in the time domain is then transformed into the frequency domain using a Fourier Transform. The Rayleigh velocity and shear velocity are closely linked through the Poisson's ratio of the medium; the shear velocity is linked to the shear modulus through constitutive relationships [1, 10].
The set-up configuration consists of a source of seismic energy and multiple receivers (typically 24, but also up to 48 or more) placed on the ground surface with an equal spacing along a survey line [11, 12]. The source offset x_1 and the spacing D between receivers are chosen according to the wavelength and hence the depth of investigation (Figure 1).

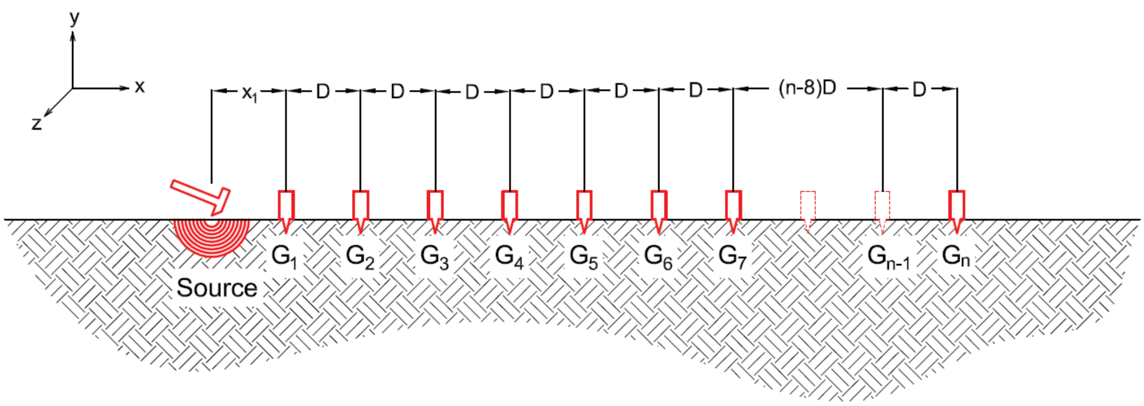


Figure 1. Typical MASW configuration, where X_1 is the source offset, G refers to a geophone, D is the receiver spacing and n is the number of receivers.

The seismic energy is recorded simultaneously by all the receivers. MASW typically uses a continuous source like a vibrator or an impulsive source like a sledgehammer [13]. When the MASW is used to determine the shear wave profile, the soil is assumed to behave as a horizontal layered model with no lateral variation in elastic properties [14]. The shear wave velocity profile is usually obtained through a numerical inversion of the experimental dispersion curve, and so is the shear modulus.

Surface Wave Spectral Method for Dispersion Calculation

With the Surface Wave Spectral Method the data collected with the surface wave method are used to construct the dispersion curve of a soil site, i.e. a depth-velocity curve. For each sensor spacing D, the phase velocity, or apparent velocity, is calculated as follows:

$$V_{ph} = \frac{D}{t(f)} = \frac{D \cdot 2\pi \cdot f}{\phi(f)} \tag{1}$$

Where $\phi(f)$ is the phase difference between two signals, i.e. the phase of the cross-power spectrum between two signals. Repeating the same procedure for each possible receiver distance adds a contribution to the dispersion curve.

The definition of apparent or phase velocity is that of a velocity which does not necessarily correspond to the velocity of one mode of propagation or one wave, but is rather an average value among different types.

In this work data points with low coherence value (i.e. lower than 0.9) and with frequency value under the natural frequency of the geophones (i.e. 35Hz), are identified and discarded from the survey. To reduce the inclusion of ambient noise, 5 or more measurements are averaged (stacking).

It is clear that this technique is unable to discern different type of waves and different modes of propagation of Rayleigh waves. Rather the dispersion measurement is an average dispersion that takes into account all the phenomena occurring in the surveyed medium and hence a superposition of different modes of propagation. Therefore it is a reliable method for Rayleigh wave velocity measurement provided the first fundamental Rayleigh wave mode is dominant among all the other modes and waves in terms of energy; this is likely to be the case in homogeneous soils, when the stiffness does not vary abruptly with depth [15-17].

Seismic data are directly inverted into phase depth-velocity curves considering the effective depth of investigation equal to one third of the wavelength, from dispersion curves obtained through the spectral method. In fact for the vertical component of the wave motion the energy is more concentrated toward the surface, at a depth approximately equal to one third of the wavelength, suggesting that the measured wave velocity corresponds to the properties of material at this depth. A direct approximate inversion based on the effective depth of propagation of the Rayleigh wave is acceptable as a first approximation for the shallow subsurface, i.e. for the highest frequencies [1, 18, 19]. For the purposes of this work a more accurate inversion of the seismic data was not accomplished since the focus was on a preliminary comparison between MASW and TDR results.

3. Time Domain Reflectometry

TDR is a method for the determination of the relative apparent dielectric permittivity (k_a) and bulk electrical conductivity (EC_b) of soils [20, 21]. These electrical properties are known to be related to a number of soil properties, thus TDR is typically used in a variety of applications including agriculture, soil science and geotechnical engineering.

k_a (herein referred to as simply called permittivity) is a measure of the ability of a material to polarise when subject to an electric field. It is commonly used to measure the volumetric water content (VWC) of soil through empirical relationships, such as the widely used Topp model [21]. EC_b is a measure of the ability of a material to conduct electric current and can be used to estimate the attenuation of electromagnetic signals propagating through the soil.

TDR injects a short electromagnetic pulse into a coaxial cable and a multi-rod probe filled with or embedded in the material under test, and measures the reflected signals at the start and the end of the probe. Reflections occur in the presence of discontinuities such as a change in impedance, according to the following equation:

$$\rho = \frac{Z_s - Z_{out}}{Z_s + Z_{out}} \tag{2}$$

where Z_{out} is the impedance of the TDR unit and Z_s is the impedance of the soil sample. The TDR output is a waveform showing the reflection coefficient versus time. An example is given in Figure 2.

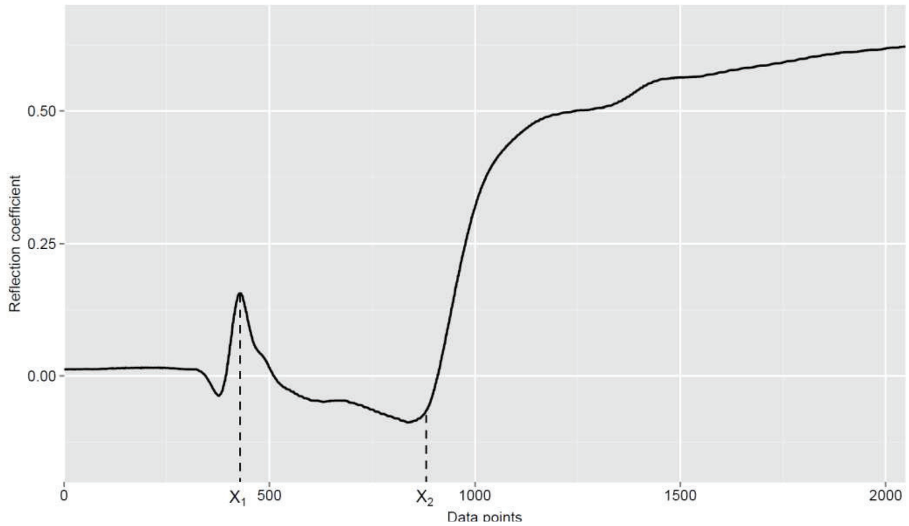


Figure 2. Typical waveform from a TDR measurement.

The propagation velocity of the electromagnetic signal propagating along the probe rods (transmitted and reflected) is proportional to the travel time for the pulse to traverse the length of the embedded waveguide (down and back) and to the length L of the waveguide (the probe rods). The travel time along the probe can be calculated from the reflections occurring at the start and at the end of the probe, x_1 and x_2 respectively. In practice, k_a is calculated by:

$$k_a = \left(\frac{x_2 - x_1}{P_P \cdot L} \right)^2 \tag{5}$$

where P_P is a relative propagation velocity, usually set equal to unity.

EC_b is measured with the method proposed by Giese and Tiemann [22] which uses the attenuation of the reflection coefficient at long apparent distances (i.e. at long reflection times). EC_b is calculated using the following expression, according to [23]:

$$EC_b = \frac{\varepsilon_0 \cdot c \cdot Z_0}{L \cdot (R_L - (L_1 \cdot R_c + R_0))} \tag{6}$$

where:

ε_0 is the absolute permittivity of free space
Z_0 is the characteristic impedance of the probe
R_L is the resistance of the sample, or load resistance
L_1 is the cable length
R_c is the cable resistance per unit length
R_0 is the extra resistance caused by the TDR device, the connectors, multiplexers and probe head
R_L is determined as follows:

$$R_L = Z_{out} \frac{1+\rho_\infty}{1-\rho_\infty} \tag{10}$$

where ρ_∞ is the reflection coefficient at long apparent distances.

4. Experimental Investigation

Experimental measurements were carried out at two different test sites up to a depth of one metre using the MASW and TDR techniques with the purpose of comparing the two methods. The test sites consisted of one predominantly clayey and of one predominantly sandy soil deposits with stiffness generally increasing with depth. A Dynamic Cone Penetrometer (DCP) test [24] was performed and Particle Size Distribution (PSD) curves determined for soil characterization purposes. When possible, dry density and VWC were measured at various depths from soil cylindrical samples of known volume taken on site, up to a depth of one metre. The PSD tests were conducted in accordance with B.S.1377.

4.1 Experimental Procedure Case Study 1

Case study 1 was located at Chilworth (UK), a few kilometres from Southampton University main campus. The experimental set-up for case study 1 consisted of a source and an array of 7 tri-axial geophones, arranged as shown in Figure 3. The data was acquired using a ProSig P8020 data acquisition unit and a laptop. The source consisted of an inertial shaker with a nominal moving mass of 1.21kg , vertically attached to one rectangular L-shaped aluminium platform, consisting of a horizontal 16.0x16.0xl.5cm plate and a vertical 10.0x16.0xl.5cm plate. The time extended signal was white noise, with a unit variance and low pass filtered at 4kHz .

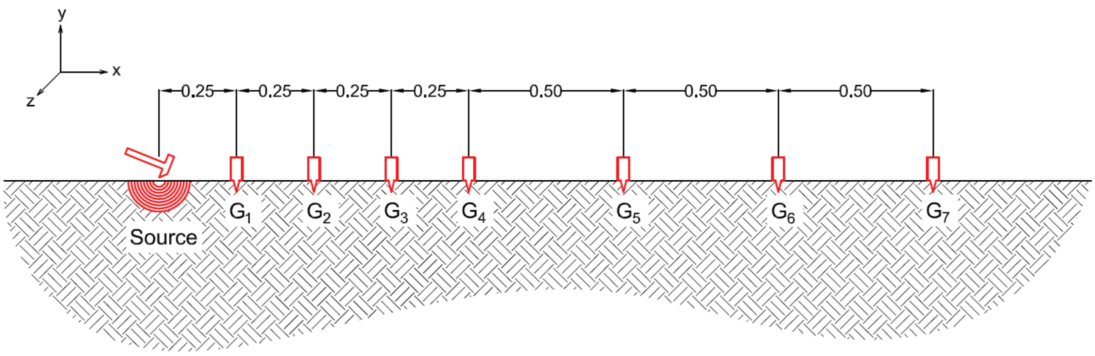
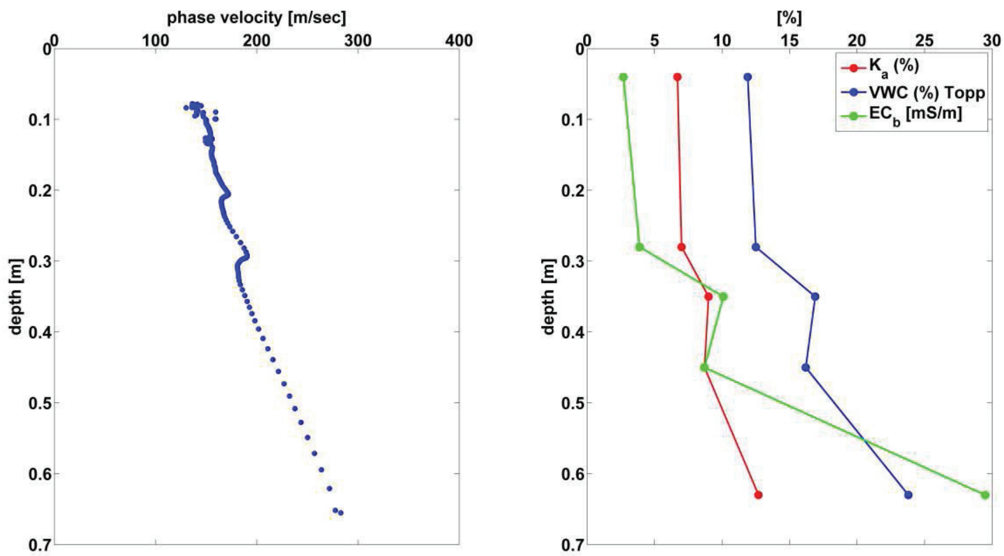


Figure 3. Experimental set-up for case study 1, G refers to a geophone and the number identifies the position. Distances are shown in metres.

TDR measurements were taken using a TDR100 device (Campbell Scientific, Logan, UT) and by inserting a TDR probe horizontally at the following depths into a shallow excavation: 0.04m, 0.28m, 0.35m, 0.45m, 0.63m. A Campbell Scientific CS635 150mm probe was used in the topsoil. However, due to the presence of large amounts of gravel and cobbles it was only possible to insert a smaller probe (model CS645, 75mm) in the subsoil. For the same reason it was not possible to collect soil samples of known volume from this site. The excavation was approximately 0.50m from the survey line in the proximity of geophone 3.
The DCP investigation was executed along the survey line, between geophone 3 and geophone 4 (see Figure 3).

4.2 Experimental results case study 1

Figure 4a depicts the phase velocity-depth curve for case study 1 obtained with a direct inversion of the dispersion curve, considering the depth of investigation of a Rayleigh wave equal to one third of its wavelength.
The phase velocity progressively increased with depth, as it is expected to behave in the presence of a regular soil profile due to increasing stiffness. It is also possible to observe two humps in the phase velocity trend, at depths of approximately 0.20m and 0.30m.
Figure 4b shows the electrical parameters measured with the TDR, i.e. k_a and EC_b, and the VWC calculated from the permittivity using the Topp model.
Both k_a and EC_b were related to the phase velocity, showing a similar trend with depth: they increased with depth and they also showed a clear hump at a depth between 0.30m and 0.40m. It should be noted that a TDR probe was not inserted at a depth of 0.20m and therefore it was not possible to confirm the presence of the hump identified by the MASW survey.

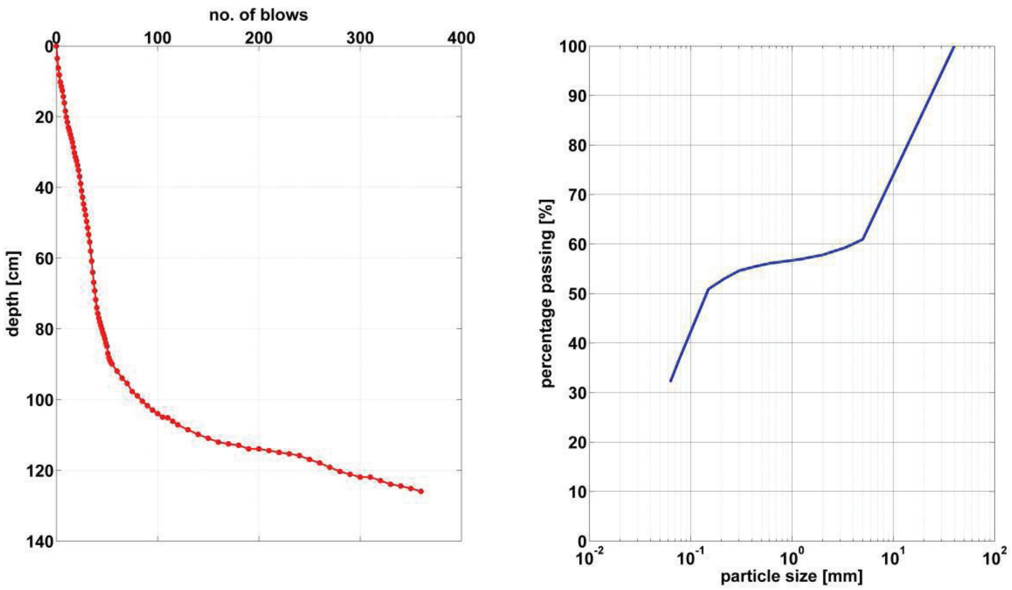


(a) (b)

Figure 4. Phase velocity-depth curve for case study 1 (a). Outputs from the TDR investigation for case study 1, with VWC calculated through the Topp model. Each marker denotes the depth at which the test is executed (b).

The DCP investigation as depicted in Figure 5a clearly showed the presence of a two-layered homogeneous soil, with a change in the slope of the DCP field test curve at a depth of approximately 1.00m , corresponding to a change in the material stiffness. However, the DCP was not sensitive enough to slight changes in the stiffness in the first metre of depth.

The PSD curve for a soil sample taken at a depth of approximately 0.50m is shown in Figure 5b. The soil was a gravelly clay, with a percentage of fines (i.e. particles smaller than 0.063mm) of 32.



(a) (b)

Figure 5. DCP field test curve for case study 1 (a). PSD curve for case study 1 (b). The tests suggest gravelly clay and a two-layered system with a clear change in the stiffness at around one metre of depth.

4.3 Experimental procedure case study 2

Case study 2 was located at the University of Birmingham campus (UK). The experimental set-up consisted of a source and an array of 21 tri-axial geophones, as shown in Figure 6, covering a length L of 5.00m. The data was again acquired using a ProSig P8020 data acquisition unit and a laptop. The source consisted of a 4-oz metallic mallet striking a circular aluminium plate of 0.15m diameter and 1.5cm thickness. The data acquisition was triggered with respect to the hammer impact.

TDR measurements were taken by inserting a CS635 150mm probe at the following depths into a shallow excavation: 0.05m, 0.10m, 0.15m, 0.30m, 0.35m, 0.40m, 0.50m, 0.60m, 0.70m, 0.82m, 0.97m. The excavation was located approximately 1.00m far from the survey line in the proximity of geophone 8. The DCP investigation was executed along the survey line, corresponding to the position of geophone 6 (see Figure 6). In addition, soil samples of known volume were taken at different depths into the ground.

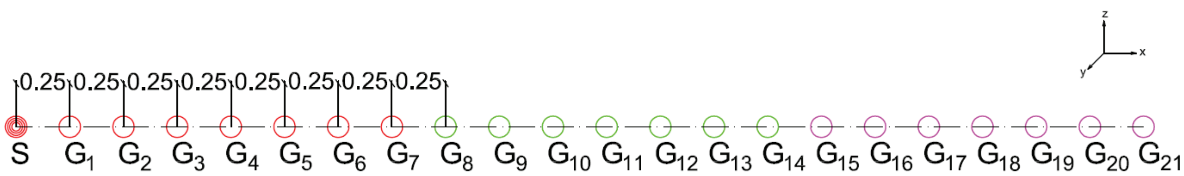


Figure 6. Experimental set-up for case study 2, G refers to a geophone, S refers to source and the number identifies the position. Distances are shown in metres (top view).

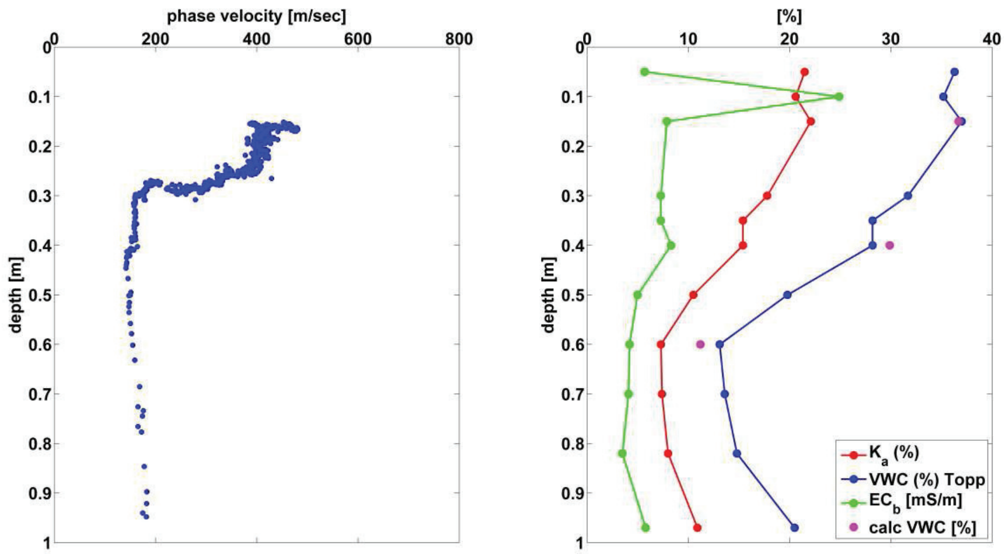
4.4 Experimental results case study 2

Figure 7a depicts the phase velocity-depth curve for case study 2 obtained with a direct inversion of the dispersion curve, considering the depth of investigation of a Rayleigh wave equal to one third of its wavelength.

The phase velocity was quite high near the surface, peaking at the depth of approximately 0.15m (probably due to a thin hard layer), followed by a sharp decrease and a slight increase at greater depths. A less noticeable peak was also present at a depth of approximately 0.40m.

Figure 7b shows the parameters measured with the TDR, i.e. k_a and EC_b, and the VWC calculated from the permittivity using the Topp model. The VWC calculated from the soil samples of known volume are also shown on Figure 7b.

The EC_b trend was consistent with the trend of the phase velocity, showing high values close to the surface, peaking at a depth of approximately 0.15m, and followed by a sharp decrease and a small increase at greater depths. A hump at a depth of 0.40m can also be seen. The k_a trend with depth was to some extent different from that of the phase velocity. In addition, the VWC computed with the Topp model did not differ significantly from the VWC measured in the laboratory.

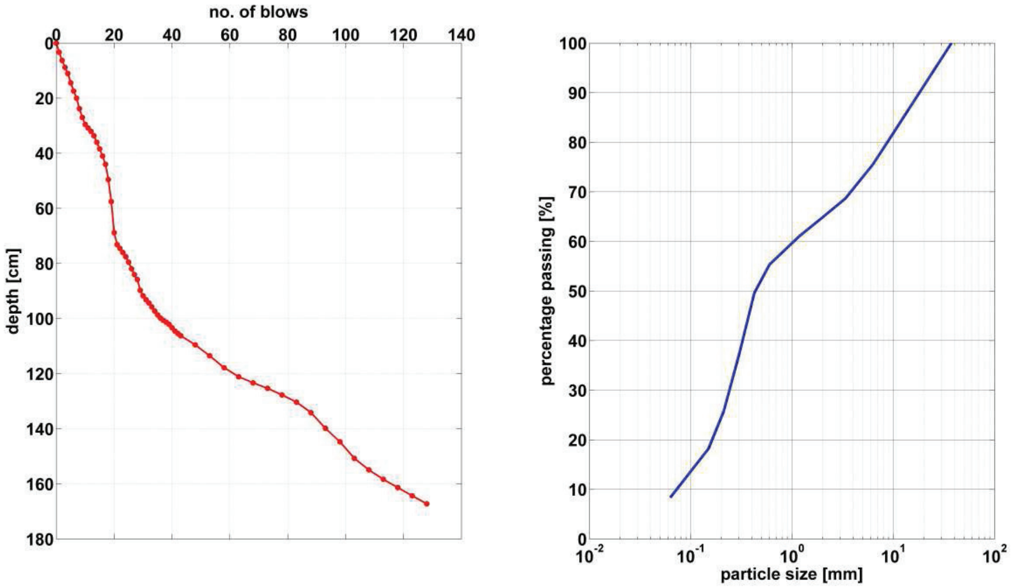


(a) (b)

Figure 7. Phase velocity-depth curve for case study 2 (a). Outputs of TDR investigation for case study 2, with VWC calculated through the Topp model and VWC measured with laboratory tests. Each marker denotes the depth at which the test is executed (b).

The DCP investigation as depicted in Figure 8a shows a soil profile with stiffness generally increasing with depth. Interestingly, a hump in the stiffness profile at a depth of approximately 0.40m was visible, which is in accordance with both the phase velocity and the EC_b profiles (Figure 7).

The PSD curve of a soil sample taken at the depth of approximately 0.60m, obtained in accordance with B.S. 1377, is shown in Figure 8b. The soil consisted of gravelly sand, with a percentage of fines below 10.



(a) (b)

Figure 8. DCP field test curve for case study 2 (a). PSD curve for case study 2 (b). The tests suggest gravelly sand and a two-layered system with a change in the stiffness at around one metre of depth.

5. Conclusions

This study has shown the joint application of a seismic (MASW) and an electromagnetic (TDR) method at two different field test sites in the UK consisting of a predominantly sandy soil and a predominantly clayey soil. The results from both investigations showed similar trends. In particular, EC_b was found to show a very similar behaviour with depth to the phase velocity, which can be assumed to equal the Rayleigh wave velocity of the fundamental mode in typical soil profiles. As the phase velocity in the soil increased, the EC_b increased, and viceversa, showing a strong positive correlation.

This agreement could be nonlinear, site and material dependent, so further investigations are needed to help better understand the relationships between shear modulus and bulk electrical conductivity of soils emerging from this preliminary study.

The positive relationship between k_a and the phase velocity, although noticeable in most cases, was slightly less evident compared to the relationship between EC_b and phase velocity.

In the case of the sandy soil (case study 2) where it was possible to collect samples of known volume, the values of VWC measured from the laboratory tests were consistent with the values calculated with TDR using the Topp model, showing only minor discrepancies. Thus, TDR was confirmed to be a reliable tool for the evaluation of *in-situ* VWC of sandy soils.

Therefore this preliminary study has shown that a joint test investigation on soil deposits using both seismic and electromagnetic techniques has the potential to improve the confidence in the data and the accuracy of shallow field surveys. In addition, this preliminary study had shown the possibility of relating the EC_b to the shear modulus of soils and, to some extent, to link the shear modulus of soils to their *in-situ* VWC. Since the comparison at this stage is qualitative, the physical meanings of these relationships, as well as their trends and limitations, are still unknown and further investigations are needed.

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