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Electromagnetic properties of the ground: Part I – Fine-grained soils at the Liquid Limit

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ABSTRACT

Knowledge of the geotechnical properties of soils when engineering shallow underground spaces is of obvious importance, as it provides information, for instance, on the susceptibility of their strength to water content changes. It also indicates the degree to which they are likely to shrink or swell with variations in water content, and so whether later displacement of buried infrastructure may occur. Trenchless installations, however, are often undertaken without full knowledge of obstructions and ground conditions along their route, and so increasingly rely on electromagnetic geophysical methods to 'see' into the ground. Interpretation of such geophysical data requires full knowledge of the electromagnetic properties of materials, particularly for fine-grained soils. It is less widely appreciated, however, that these electromagnetic properties can be directly related to geotechnical properties, and so additional data could be obtained from geophysical surveys in terms of potential ground conditions and their variations over long installation lengths. Therefore, the aim of this paper is to consider links between these two sets of soil properties as a pre-cursor to investigating the properties of individual soils. The Liquid Limit was considered an important water content at which to test the electromagnetic properties of fine-grained soils, as it provides an immediate opportunity to determine whether any related geophysical correlations exist between soils. In the study described herein the apparent permittivity of a number of fine-grained soils was measured at the Liquid Limit and it was found that at higher frequencies, ca. 1 GHz, good correlation exists between the two. However, at lower frequencies this relationship was not apparent due to significant variations in electromagnetic dispersion. By considering the differences between high and low frequency data to be based on differences in inter-sheet and inter-particle water, however, this discrepancy is explained. It is therefore concluded that, under laboratory conditions, the frequency-dependent nature of apparent permittivity in fine-grained soils can be explained, and even predicted, using the Liquid Limit of a soil, its dry density, and the percentage linear shrinkage it exhibits.

1. Introduction

Trenchless installations involve undertaking work within a complex environment (e.g. pipes, cables, soil, aggregates, concrete, voids) the properties of which are often not known in advance with certainty. Given the congested nature of many urban underground spaces, it is therefore not surprising that the potential for collision with underground features such as utilities, in directional drilling, has been recognised and look-ahead ground penetrating radar (GPR) methods developed in mitigation (ORFEUS, 2009). Geophysical methods, particularly GPR, are now commonly used in an attempt to 'see' through the ground and they are considered a useful and cost effective means by which to improve geotechnical investigations (Anderson et al., 2008). Much recent research has focussed on improved methods and equipment (Metje et al., 2008), as well as combining them to improve performance (Metje et al., 2007). Such work can be considered important to mitigate the estimated £7 billion spent annually in the UK on direct and social costs associated with street works (McMahon et al., 2005). However, knowledge of the effects of these materials on GPR signals is of significant benefit in terms of interpreting remotely located buried infrastructure (Thomas et al., 2007), which often requires location within tight tolerances (Thomas et al., 2008a). The study described herein aims to further knowledge on the fine-grained soil aspect of the underground, as the dominant material found in the shallow subsurface, within the UK in terms of electromagnetic signal velocities. In so doing it is intended to inform future mapping and monitoring of the underground, including for the purpose of trenchless installation where advance knowledge of potential effects of soils

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on GPR systems could also be gained from any available geotechnical data.

Relationships are known to exist between geotechnical and electromagnetic properties of fine-grained soils (Thomas et al., 2008b), generally defined for geotechnical purposes as those with grain sizes of 425 μm and below, which are the dominant soil types beneath urban areas in the UK (Rogers et al., 2009). Therefore, a greater understanding of their electromagnetic properties can be gained by considering the nature of these relationships. As the Liquid Limit of soils is a widely tested geotechnical property, and of wide practical relevance, the study described herein considers the links between it and electromagnetic signal velocities. In its simplest sense, the Liquid Limit provides a useful indicator of the maximum possible water content under normal field conditions (Craig, 1997) and the water content at which the soil will begin to flow as a fluid. However, the Liquid Limit can also be considered representative of the specific surface area of a soil (Farrar and Coleman, 1967), and relates to a similarity in properties for a wide range of soils (Mitchell and Soga, 2005). Therefore, it was considered instructive to compare the Liquid Limits of a wide range of fine-grained soil samples to the apparent permittivity (a proxy for electromagnetic signal velocity) they exhibit over a wide range of electromagnetic signal frequencies.

Shrink/swell properties of fine-grained soils are also of significant geotechnical interest in terms of volume changes in the ground, and potentially subsequent displacement of underground infrastructure and utilities within the first few metres of the subsurface (Waltham, 1994). Therefore, this study also included measurement of linear shrinkage, as the ability to remotely identify the potential magnitude of soil shrink/swell properties could be of significant usefulness. For that reason, the magnitude of changes in apparent permittivity with frequency (known as electromagnetic dispersion) have been compared to standard linear shrinkage tests. The rationale behind this is that both could be considered related to the quantity of inter-sheet pore water associated with hydration of the spaces between sheet mineral surfaces in fine-grained soils, and so this may be detectable due to differences in electromagnetic properties of such water. This would imply that differences between inter-sheet and inter-grain water may relate to the more commonly termed 'bound' and 'free' water described in geophysical literature.

It should also be noted that the research described herein allows commencement of a database of the electromagnetic properties of all materials commonly encountered in underground space development work. In conjunction with future research, this will also allow initial development of expert-system software for prediction of soil electromagnetic properties from geotechnical data. Together with geotechnical databases such as those held by the British Geological Survey in the UK, geospatial mapping of the potential effects of soils on GPR could, therefore, also be achieved (Rogers et al., 2009), so providing more informed planning and interpretation of trenchless installation electromagnetic surveys. Additional data may be obtainable from the literature for use in such databases, although it should be noted that relatively little research is available that covers all water content states relevant to geotechnical engineering, and accompanied by all relevant geotechnical index test data.

Having considered the relationships between electromagnetic signal velocities in fine-grained soils, and standard Liquid Limit and shrinkage tests, these relationships will be investigated further in Part II of this paper. In contrast to Part I of this paper, which considers soils mostly at a single water content (in order to relate the data to specific geotechnical parameters), Part II will apply the knowledge gained in considering two of the selected fine-grained soils over a very wide range of water contents.

2. Materials and methods

2.1. Measurement of electromagnetic signal velocities

Measurement of soil electromagnetic properties was undertaken using a method developed specifically for use as part of routine geotechnical laboratory and field testing (Thomas et al., 2008c), as well as the more widely used Time-Domain Reflectometry (TDR) system employing the commonly used tangent line method of determining signal velocity (see Topp et al., 1980). In a soil, the propagation velocity of an electromagnetic signal can be determined from knowledge of the permittivity and magnetic permeability, both of which are complex parameters respectively describing charge storage and loss mechanisms (see Thomas et al., 2006). As most soils are considered to have low, and non-complex, magnetic permeabilities, the signal velocity can be calculated using Eq. (1) (after Hayt and Buck, 2006).

$$V = \frac{\omega}{\beta} = \frac{1}{\sqrt{\frac{\mu\varepsilon'}{2}}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right)^{\frac{1}{2}}} \quad (1)$$

where V is the velocity (ms^{-1}), ω is the radian frequency ($\omega = 2\pi f$ where f is the frequency in Hertz), β is the phase constant (i.e. the phase change per unit distance expressed in radians m^{-1}), μ is the magnetic permeability and ε' and ε'' are, respectively, the real and imaginary parts of the permittivity (i.e. the electromagnetic charge storage and loss mechanisms) that together form the complex permittivity.

Loss mechanisms in soils are generally considered to comprise those associated with electromagnetic dispersion: i.e. dipolar losses associated with the inability of water molecules to rotate in time with the applied electromagnetic field (Debye, 1929) and those associated with the conductivity. Therefore, for the purposes of Eq. (1), losses are often included through use of Eq. (2).

$$\varepsilon'' = \varepsilon''_P + \frac{\sigma_{DC}}{\omega} \quad (2)$$

where σ_{DC} is the static (direct current) conductivity of the material ($\mathrm{S\,m}^{-1}$) and ε''_p represents dipolar losses.

The measurement of apparent permittivity (ε_r^*) has become widespread due to the popularity of TDR and provides a single value to describe all of the electromagnetic parameters. It is based on calculation of the real relative permittivity of a lossless material, as calculated from Eq. (3), that corresponds to the velocity obtained in Eq. (1). From this, it can be seen that the apparent permittivity is a representation of a number of parameters in one simple value.

$$\varepsilon_r^* = \left(\frac{c}{V}\right)^2 \quad (3)$$

where c is the velocity of light in a vacuum (2.9979E8 ms^{-1}).

When a sinusoidal signal (generated by a Vector Network Analyzer – VNA), is injected into a coaxial measurement cell, the voltage magnitude of the reflected signal returning to the analyzer will be the summation of two signals. These are the signal reflected at the cable/cell interface, due to a characteristic impedance, and a second signal associated with multiple reflections within the cell. The voltage magnitude associated with the multiple reflections will therefore be a function of two sinusoidal voltages: the inward moving signal and the signal reflected from the end of the cell. These interfere, either constructively or destructively, to create maxima and minima in the measured voltage and the frequencies at which they occur can be used to determine apparent permittivity at discrete frequencies using Eq. (4) (after Heimovaara et al., 1996).