One port large coaxial cell for dielectric characterization of compacted partly saturated coarse grained materials

Cellule de mesure coaxiale en réflexion pour la caractérisation dielectrique. Application aux matériaux compacts partiellement saturés.

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ABSTRACT: Precise knowledge of the frequency dependent electromagnetic properties of coarse grained materials is imperative for the successful application of high frequency electromagnetic measurement techniques for near and subsurface monitoring. For example, ground penetrating radar (GPR) needs the perfect knowledge of electromagnetic properties to localize in space rather than in time. The main challenge for characterizing the dielectric behavior of materials with large heterogeneities is the minimum size of samples with respect to the Representative Elementary Volume (REV). Material sample dimensions need to be at least three times greater than the maximum dimensions of the major aggregate. In the presented framework, we aim at developing a laboratory measurement device that allows the broadband characterization of compacted partly saturated coarse grained materials under controlled boundary conditions. The main goal of our research is to develop inverse analysis of frequency dependent dielectric characteristics to simultaneously estimate moisture content, electrical conductivity and density for the in situ monitoring of road.

RéSUMÉ : La connaissance précise des propriétés électromagnétiques des matériaux à larges hétérogénéités en fonction de la fréquence est imperative pour l'usage des méthodes hautes fréquences pour la surveillance des sols. Par exemple, l’utilisation d’un radar nécessite la connaissance des propriétés électromagnétiques pour localiser un défaut dans l’espace plutôt que dans le temps. Le principal défi lors de la caractérisation de matériaux avec de larges hétérogénéités est de respecter le critère de volume élémentaire représentatif. Ainsi, les dimensions du matériau sous test doivent être au moins trois fois supérieures à la dimension du plus large agrégat. Dans ce papier, nous présentons une cellule de mesure permettant la caractérisation dielectrique de matériaux à larges hétérogénéités compacts et partiellement saturés. L’objectif principal de notre recherche est de développer à partir de mesures de caractéristiques dielectriques des méthodes inverses pour l’estimation simultanée de la teneur en eau, densité et conductivité électrique.

KEYWORDS: one port large coaxial cell, coarse grain soils, dielectric spectroscopy, compaction test, relaxation model

1 INTRODUCTION

The water content of base or sub-base materials of pavements greatly influences the performance of the overall pavement. The increase of water content can for example cause severe deterioration of the pavement structure by the expansion of clay minerals with consequently decrease in its bearing capacity. In coastal regions, soil water salinity causes corrosion and alters the properties of the road materials and the bituminous surface layer. According to a study implemented by the Queensland Government, salinity causes huge decreases in the lifespan of road pavements when saline groundwater levels rise to within 2 meters of the pavement surface. Moreover, capillary action supported by evaporation and the cyclic mechanical loading due to bypassing vehicles assist to drive the salt-laden water to the surface of the pavement. Concentration of salts within unbound granular road pavements has been shown to cause damage to thin bituminous surfacing resulting in debonding, cracking and blistering of the surfacing (CARTERET et al. 2010). It is also recommended that salt damage mechanisms are influenced by climate, hydrogeology, geology, material characteristics, and pavement surfacing design including the construction practice (Obika 2001). Salt concentrations in surplus of 500 – 1,500 µS/cm are commonly considered to be necessary to cause damage to thin bituminous surfacing, depending on the type of surfacing. In this context, it is mandatory to develop monitoring system of road. Due to their capability of automation and remote sensing, geophysical electromagnetic method have been gained increasing importance.

In (Yu & Drnevich 2004) a new method was presented for determining moisture content and density using a single Time Domain Reflectometry (TDR). This new method is based on the simultaneous measurement of apparent dielectric permeability and bulk electrical conductivity with the same soil sample taking into account temperature effects. A further development of the method was presented in (Drnevich et al. 2005). A straight line soil-dependent calibration relationship was developed to calculate moisture content and density. In this method, moisture and density can be determined by obtaining only two calibration constants without determining the electrical conductivity as it was required for the method presented in (Yu & Drnevich 2004). However, crushed rock materials, as they are usually used as road base material, have not been considered in determining the required calibration constants. In (Jung et al. 2013) a new methodology for measuring moisture and density was introduced. The methods takes advantage from the voltage drop, which occurs during the passage of electromagnetic wave along the transmission line at the transition from coaxial cable to sensor and at the sensor’s end. Voltage drop and density are normalized against dielectric permittivity, and a calibration function was developed to determine dry density directly. The calibration equation is independent of compaction energy. Following that, gravimetric moisture content was calculated using method presented in (Drnevich et al. 2005).

The methods developed so far for simultaneously quantifying water content and density were only based on effective parameters describing the dielectric permittivity and electrical conductivity measured using TDR. However,
previous study (Heimovaara 1994) has shown that apparent permittivity from travel time analysis is closely related to the real part of the frequency dependent dielectric permittivity at high frequencies (roughly between 1 and 1.5 GHz). At this frequency, it is well known that dielectric permittivity is almost insensitive to soil texture or bulk conductivity (Schwartz & Evett 2009). On the contrary, at lower frequency (below 200 MHz), the dielectric permittivity is much more sensitive to the soil structure and the pore water phase and solid phase interaction (Schwing et al. 2016). Thus, the determination of dielectric permittivity over a broad frequency range seems to be fundamental to develop robust model to estimate soil parameters other than free pore water content. Moreover, the extensive use of electromagnetic sensors in civil or geo-environmental engineering requires the knowledge of dielectric permittivity over broad frequency range. For example, the analysis of measurements using ground penetrating radar needs the perfect knowledge of electromagnetic properties to localize disturbances in space rather than in time (Loewer et al. 2016).

In the presented framework, we aim at developing a laboratory measurement device that allows the broadband characterization of compacted partly saturated coarse grained materials under controlled boundary conditions. The main goal of our research is to develop inverse analysis of frequency dependent dielectric characteristics to simultaneously estimate moisture content, electrical conductivity and density.

2 METHOD

2.1 Design of the large coaxial cell

The main challenge for characterising the dielectric behaviour of materials with large heterogeneities is the minimum size of samples with respect to the Representative Elementary Volume (REV). According to (Robert 1998), material sample dimensions need to be at least three times greater than the maximum dimensions of the major aggregate. The materials targeted for our application can present a large particle size of up to 25 mm. In this configuration, the design of a large coaxial cell is required. The second main design constraints consist in having the possibility to compact the soil directly in the measurement device. In order to comply with existing compaction tests from geotechnical engineering, at least three layers of compacted material need to be placed in the cell with the height of the layers being approx. 3 times the maximum particle size. To allow compaction of the soil and to simplify the overall design, a one port measurement cell was selected. The measurement were made directly in frequency domain with vector network analyzer (VNA) rather than measuring in time domain and applying inverse discrete fast Fourier transform (DFFT). This choice was motivated by the results presented in (Huisman 2004) where both approaches have been compared. It is interesting to note that, as far as the authors know, no studies have been undertaken with coarse grained soils in the frequency domain. The large coaxial cell was made with three different coaxial line sections: a feeding section (which is mainly a commercial connector), a sealing system and the probe section where the materials to be characterized is inserted (see figure 1 for illustration). The probe section present the following transversal dimensions: diameter of inner conductor 66 mm, diameter of inner conductor 151.9 mm; whereas the length is 207.5 mm. Measurements were performed over the 1 MHz – 860 MHz frequency range. The upper frequency was set when the propagation of electromagnetic wave within the cell is no more pure Transverse Electromagnetic mode. Figure 1 represents an illustration of the cell connected to the VNA.

2.2 Calibration

Dielectric spectroscopy in such a non-uniform transmission line requires a wave propagation model that accounts for multiple reflections. Impedance transformation in combination with layer peeling algorithm was used to develop such a model. Each section can be modeled by 4 parameters: it’s geometric impedance $Z_0$, physical length $d$, resistance loss factor $\alpha_R$ and its relative complex permittivity $\varepsilon_r$. Finally, the forward model compute the scattering function $S_{11}(\omega)$ as a function of frequency and the 12 parameters of the line. The calibration step consist in determining the unknowns of the model using measurement in perfectly known materials. Measurements in air and deionized water were used. For air, a value of 1 was used for the complex permittivity, for deionized water tabulated values from literature were used (Kaatz 2007) to describe the variation of relative complex permittivity with frequency. Please note that in this configurations we aims at determining 11 parameters since the relative complex permittivity of calibrations materials are known. This was achieved by minimizing the cost function between the measured and modeled scattering function. A Monte Carlo Markov Chain (MCMC) algorithm was used to obtain the best fit. The quality of this step was validated with a good Root Mean Square Error (RMSE).

3 MATERIALS

The performance of the cell was tested with a coarse grained material collected from the Civil Engineering Laboratory of the University of Queensland. Gravel of several different sizes ranging particle size from 0.075 mm to 20 mm were mixed to make a particle size distribution similar to typical road base material of Queensland. The gravel mix has an OMC of 5.5% and maximum dry density 2260 kg/m$^3$.

In this study, sample with three different water content with almost constant dry density was investigated. Target moisture content was mixed properly with the soil sample. Soil was poured carefully and compacted in between the outer and inner co-axial tube in three layers where each layer was compacted having equal number of temping with a view to maintain constant density over the whole tube. Roughly the target density was 85% of maximum dry density. Moisture content was increased in the same sample and compaction was done.
accordingly. The complete state parameters of the samples were determined after the electromagnetic measurement: material was poured out and classical gravimetric measurement were performed. Table 1 gives the state parameters of the 3 samples under investigation.

Table 1. State parameters of the samples under investigation.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Volumetric water content θ (%)</th>
<th>Porosity n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Gravel 1</td>
<td>8</td>
<td>22.2</td>
</tr>
<tr>
<td>Mixed Gravel 2</td>
<td>12.2</td>
<td>20.2</td>
</tr>
<tr>
<td>Mixed Gravel 3</td>
<td>17.6</td>
<td>17.9</td>
</tr>
</tbody>
</table>

4 RESULTS

In order to compute the relative complex permittivity from the measured scattering function, a model of frequency dependence of the permittivity was used. Generalized Dielectric Relaxation (GDR) model (Wagner et al. 2013) with 2 relaxations processes was used (equation 1). Generally for high frequency measurement on porous medias, three relaxation process are expected (Bore et al. 2016): free water relaxation, and 2 relaxations mechanism which are related to interactions between the aqueous phases and solid particles (absorbed water, Maxwell Wagner effect and counter ion relaxation). Since free water relaxation occurs at frequency around 20 GHz, we used a 2-models which includes a 2 Cole-Cole terms to account for the interfaces process.

\[
\varepsilon'(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon_{IF}}{1 + (j\omega\tau_{IF})^{\beta_{IF}}} + \frac{\Delta\varepsilon_{LF}}{1 + (j\omega\tau_{LF})^{\beta_{LF}}} - j\frac{\sigma_{DC}}{\omega\varepsilon_0}
\]

with \(\omega = 2\pi f\) the angular frequency, high frequency limit of permittivity \(\varepsilon_\infty\), relaxation strength \(\Delta\varepsilon\), relaxation time \(\tau\) and stretching exponents \(0 \leq \beta \leq 1\) of the \(k\)th process and apparent direct current electrical conductivity \(\sigma_{DC}\). Here, the highest frequency process will be denoted as IF (as intermediate process) whereas the lowest frequency will be denoted as LF (low frequency process). Please note that in this configuration, the term \(\varepsilon_{\infty}\) should include some contributions of the free water relaxation (which could be considered as the high frequency process if the frequency ranger was broader).

The parameters obtained during the calibration were using as input in the scatter function model. The permittivity of the material in the probe will be now computed according to GDR model. In this framework, the 8 unknowns parameters of the models were computed by fitting the scatter function in an optimization scheme using MCMC algorithm.

In Figure 2, the comparison between the measured scattering function \(S_{11}(\omega)\) and the best fit obtained with GDR is presented for each sample for Mixed Gravel soil. Please note that we only represents the modulus part of the data (i.e. the results obtained for the phase is not given here). The RMSE obtained is given in the picture. As it can be seen, the optimized model matched closely the measured scattering function \(S_{11}(\omega)\). The quality of the results can be judged in term of RMSE. Finally, the relative complex permittivity can be computed from the obtained parameters with equation 1. The results are presented on Figure 3 and 4 in terms of real and imaginary part.
expected, higher permittivity values are observed for higher water contents (see Table 1). Much higher values can be observed for the imaginary part, which can be explained by the contribution of the direct current conductivity $\sigma_{DC}$ towards the low frequency range.

The presented method gives the opportunity to determine the frequency dependent relative complex permittivity of coarse grained materials. Moreover, the used model gives an estimation of the bulk conductivity of the samples. In next step, mixing equation (Bore et al. 2017) will be used to simultaneously determine water content and density.

5 CONCLUSIONS

This paper reports the design of a large coaxial cell built in order to measure the frequency dependent relative complex permittivity of coarse grained materials. The dimension of the probe section offers the opportunity to measure heterogeneous materials with large aggregate dimensions (up to 28 mm) over the 1 MHz – 860 MHz frequency range. The first step consists in calibrating the cell. A model based on impedance transformation in combination with layer peeling algorithm was used to take into account the discontinuities within the cell. Two measurements in perfectly known media behavior with a dispersion along the frequency range for processes, one high frequency limit of permittivity and one mixing equation (Bore et al. 2017) will be used to simultaneously determine water content and density.

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A materials with heterogeneity up to 20 mm was selected for this study. Three samples with different water contents and almost constant dry density have been characterized. State parameters of the samples were determined after the electromagnetic measurement based on classical gravimetric water content measurement. The spectra were computed assuming a dielectric dispersion model and using the calibration parameters as an input in a fitting process. The model used consists in a relaxation model. This model involves 8 parameters considering two relaxations linked with interfaces processes, one high frequency limit of permittivity and one direct current contribution. The results have shown a good agreement between modelled and measured data with very low RMSE. The computed spectrum have shown a classical porous media behavior with a dispersion along the frequency range for both real and imaginary part.

The next study will focus on the use of mixing equation, such as complex refractive index model (CRIM) to simultaneously estimate water content and density. In this framework, by combining relaxation model and mixing equation, the simultaneous estimation of water content, density and electrical conductivity should be possible with one measurement. In a final stage, our approach will be tested on the field with appropriate sensors to monitor the evolution of this quantities in time.

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REFERENCES