INFLUENCE OF WATER CONTENT ON THE ELECTRICAL CONDUCTIVITY OF PEAT

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ABSTRACT

Organic layers are heterogeneous in space and their composition changes over time. This poses challenges to ecohydrologists, subsurface hydrologists, and ground engineers to characterize subsurface peat structures and to predict their behavior over time. A better characterization of peat deposits in terms of hydraulic properties can be achieved by performing multi-frequency electrical surveys provided the complex conductivity of peat is understood and connected to its index and geo-mechanical properties. For this purpose, the relationship between water content, pore-fluid conductivity and the bulk conductivity of peat was investigated using a PVC compression cell equipped with two couples of electrodes placed at the top and bottom of the sample. This set-up allows measurements of electrical resistivity and induced polarization at different levels of compression, and thus water contents, of the peat.

Broadband frequency measurements (10^{-1} to 10^6 Hz) of complex electrical conductivity were carried out on peat samples saturated with water at different salinity in the range 0.001 to 1 S/m. The results were interpreted with an empirical model which shows a positive correlation between water content and the peat conductivity when the pore-fluid conductivity is higher than the conductivity of the solid material, whereas the correlation is found to be negative when the pore-fluid conductivity is lower than the conductivity of the solid material. The results indicate that the water content of peat can be predicted by low-frequency electrical measurement when the value of the pore-fluid conductivity is known. This study presents results that can provide a better understanding of the low-frequency electrical properties of organic soils.

Keywords:*Electrical Conductivity, Peat, Water Content, Laboratory Testing*

1. INTRODUCTION

Peat is a soil with high organic content formed in wetlands after the deposition and partial decay of vegetation matter. It covers large areas of Dutch subsurface. It is characterized by strong compressibility and creep, anisotropy, sensitivity to chemical processes (like oxidation), high water content and organic content (Hobbs

[1]). These properties require paying special attention to the behavior of organic layers, in order to guarantee, for example, the long term stability of secondary dikes.

In order to improve the characterization of peat layers and to gain further information about the near surface, several geophysical methods (e.g. dc resistivity, time domain electromagnetic and ground penetrating radar) can be used for non-destructive in-situ investigations. Particularly, electrical resistivity imaging (ERI) has been successfully used to investigate stratigraphy of peatlands (Slater and Reeve [2]) and to predict pore-fluid conductivity (Mansoor and Slater [3]). Field observations of the electrical conductivity of peat present very diverse values, from few to hundreds mS/m (e.g. Siegel [4]; Theimer et al. [5]). The electrical conductivity of peat depends on both the fluid saturating the peat and the surface of the solid grains in contact with the fluid (Comas and Slater [6]) and it is linearly correlated to the concentration of total dissolved solids in the pore water (Theimer et al. [5]). Conductivity is also strongly controlled by temperature and affected by other properties of peat like cation exchange capacity (CEC), organic content, structure, heterogeneity pH and water content. Also a change of porosity has an influence on the conductivity of peat, as pore-throat diameters and pore geometry of water-saturated geo-materials contribute significantly to both in-phase and out-of-phase conduction at low-frequency (Scott [7]). In clays, the conductivity decreases slowly as the moisture content decreases, and for moisture content values lower than 10-15% it decreases rapidly (Russell and Barker [8]).

Therefore, a better characterization of peat deposits can be obtained knowing the influence of pore-fluid conductivity and water content on the electrical properties of organic materials for a broad spectrum of frequencies, providing a useful tool for ground investigation and soil classification. This can be achieved performing multi-frequency electrical measurements, under different degrees of compression of the peat and conductivities of the pore-fluid.For this purpose, a new laboratory prototype cell has been developed. It combines vertical hydraulic compression and a four-electrode measurement system. This system allows studying the electrical response of peat samples during their compression and consolidation.

2. LABORATORY SET-UP AND METHOD

Laboratory tests were conducted using a new prototype cell (Fig.1), which allows for simultaneous electrical and compression tests. The cell consists of a hydraulic loading and electric measurements system, achieved by a four electrodes configuration. A PVC ring, with an internal diameter of 148 mm and a height of 140 mm, hosts the sample and electrically insulates it along its lateral area from the top to the bottom surface.
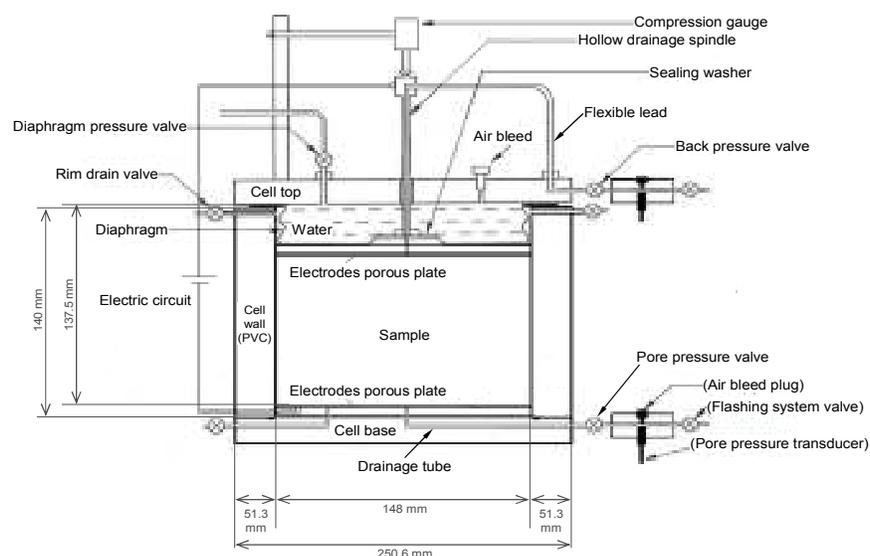

Fig.1 Schematic diagram of prototype cell for electrical-mechanical combined tests

The vertical one-dimensional loading is carried out by a hydraulic system under lateral confinement. In order to perform electrical measurements between the extremities of the sample and to allow at the same time a vertical drainage, two special glass porous plates have been mounted, on which two couples of copper electrodes are printed. The four-electrode configuration was chosen to reduce electrode polarization at low frequencies.

Moreover, the vertical settlement and the pore pressures at the top and bottom of the sample can be acquired, with a compression gauge and two pore pressure transducers.
This configuration allows performing hydraulic consolidation tests and measuring simultaneously the impedance phase and amplitude of the sample, as the cell acts as a capacitor in which the sample is the dielectric. The electrical impedance between the extremities of the sample is acquired with two different systems. At high frequencies with a precision component analyzer, working in the broadband frequency range of 20Hz – 3MHz. At low frequencies, with a two-channel dynamic signal analyzer (35665A), which operates over a frequency range from 16 mHz to 51 kHz. Two electrodes are used for current injection, while the other pair to measure the electric potential.

The sample between the electrodes is represented as resistor in parallel with a capacitor. The impedance amplitude ($|Z|$) and phase (θ) are measured over the frequency range of the instrument and determine the complex impedance that is related to the capacitance (c) and the resistance (R):

$$Z^* = H + iX = \frac{R}{1 + R^2\omega^2 c^2} - i\frac{R^2\omega c}{1 + R^2\omega^2 c^2}$$

(1)

Consequently, the complex conductivity σ^* can be derived according to the geometrical factor (d/A):

$$\sigma^* = \frac{1}{Z^*}\frac{d}{A} = \frac{H}{(H^2 + X^2)}\frac{d}{A} + i\frac{X}{-(H^2 + X^2)}\frac{d}{A} = \frac{1}{R}\frac{d}{A} + i\omega c\frac{d}{A}$$

(2)

The complex conductivity represents two parallel conduction paths: the electrolytic conductivity, σ^*_{bulk}, through the bulk pore fluid, and the surface conductivity, σ^*_{surf} through the electrical double layer formed at the grain-fluid interface (Lesmes and Frye [9]):

$$\sigma^* = \sigma^*_{bulk} + \sigma^*_{surf} = [\sigma_{bulk} + i\omega\varepsilon'_\infty] + [\sigma'_{surf}(\omega) + i\sigma''_{surf}(\omega)]$$

(3)

where σ_{bulk} and ε_∞ represent the low-frequency conductivity and the high-frequency dielectric constant of the bulk sample. A modified Archie's law, accounting for the electrical double layer (EDL) surface conductivity, is typically used for saturated inorganic sediments:

$$\sigma^* = \frac{1}{F}\sigma_w + \sigma'_{surf}(\sigma_w) + i\sigma''_{surf}(\sigma_w)$$

(4)

where F is the formation factor and σ_w the conductivity of the pore fluid.
The imaginary part of the surface conductivity is higher and more σ_w-dependent in peat than in inorganic soils and it is assumed linearly dependent on the real part of the surface conductivity (Börner and Schön [10]).
A low-frequency empirical model for peat proposed by Comas and Slater [6] relates the real part of conductivity and the induced polarization measurements to the conductivity of the pore fluid, through the fitting parameter A, b and C:

$$\sigma'_{peat} = A\sigma_w^b + C\sigma''_{surf}(\sigma_w)$$

(5)

The reliability of the electrical measurements for the described set-up configuration has been studied with tests on distilled water at different electrode spacing. The range of reliability for the high frequency set-up was found to be from 5 kHz to 600 kHz. At low-frequencies, the real conductivity is measured correctly below the electromagnetic coupling effect (1 kHz), whereas the imaginary conductivity is affected by the electrode polarization, and thus was not considered in this study.

3. RESULTS AND DISCUSSION

For the measurements at high frequencies, three remolded samples were prepared mixing peat (obtained in IJkdijk, Netherlands) with distilled water for an average water content of 90%. Each sample was flushed inside the cell with saline water, until the conductivity of the outflow σ_w reached a stable value. Progressive steps were performed over the range of conductivity 0.00244 to 0.545 S/m, with a fixed distance of 6.5 cm between the electrodes. The complex conductivity was calculated with eq. (2) and compared with the conductivity of the saturating fluid in the reliable frequency range. The real part of the peat conductivity increases with the conductivity of the pore fluid, while the imaginary part shows more scatter in the data, with a peak around 0.1 S/m, with a similar trend observed in previous studies on organic (Comas and Slater [6]) and inorganic materials (Vinegar and Waxman [11]).

Data were interpolated with eq.(4) and eq.(5), as shown in Fig.2 for the frequency of 50 kHz. Both model fit the data, with a smaller error for the modified Archie's law (rmsep = 0.084 vs. 0.092). The results suggest that these two low-frequency conductivity models (<1kHz) can be used to predict the peat conductivity also at higher frequencies.
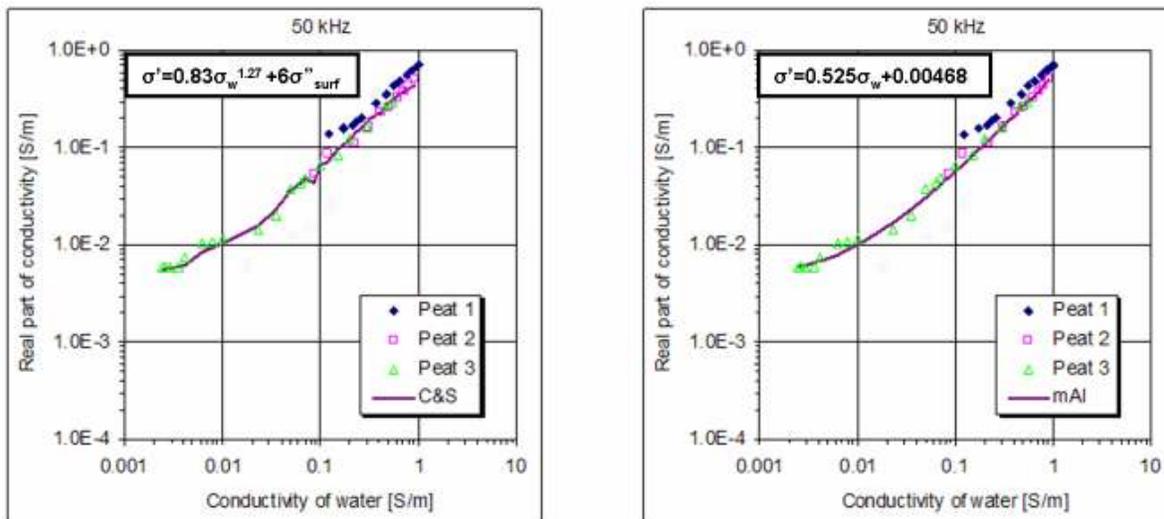

Fig.2 Curve fitting of peat conductivity with Comas and Slater model (left) and modified Archie's law

Similar experiments were carried out at low frequencies with the same type of peat saturated at different pore-fluid conductivities, with the aim of studying the peat conductivity response as a function of water content and conductivity of the fluid saturating the peat. In these measurements, the vertical loading system was used to compress the saturated peat samples and to measure the complex conductivity at different water contents. In the reliable frequency range of the set-up (<1 kHz), the real part of peat conductivity is constant. Results measured for the frequency of 1 Hz and corrected at the temperature of 20ºC are illustrated in Fig.3. For all samples, the conductivity of peat strongly increases with the conductivity of the pore fluid – the same trend was found for the higher frequencies. For high values of σ_w, a decrease of water content clearly induces a reduction of the peat conductivity. However, there is a threshold value for σ_w (=10 mS/m) below which the conductivity of peat increases as the water content of the sample is reduced. The threshold value can be identified as the conductivity of the solid phase (σ_m), because it has the same value of σ_w for all water contents. Therefore, the peat conductivity is mainly controlled by σ_w and the influence of the water content depends on the value of σ_m.
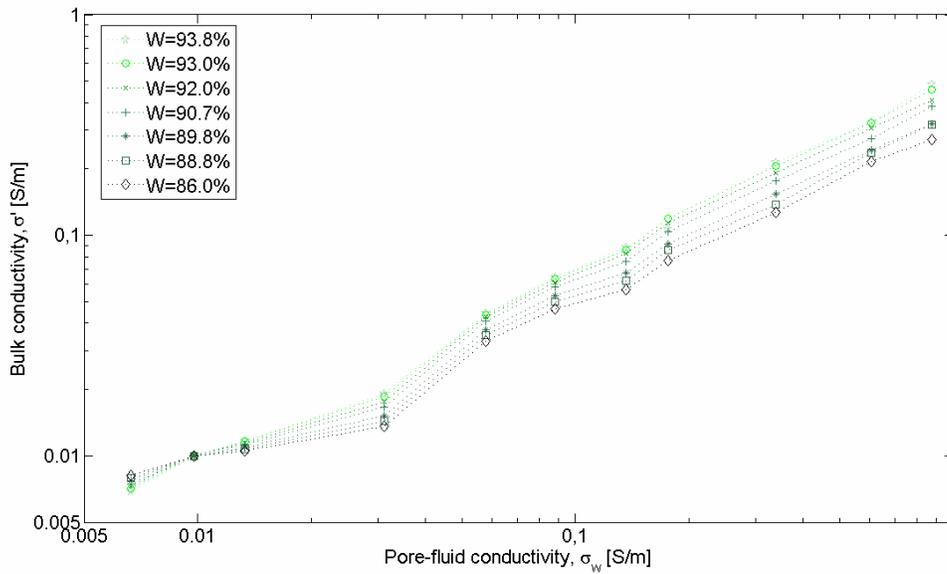
Fig.3 Peat conductivity as a function of water content and of pore-fluid conductivity

. We can try a different and more general approach than eq.(5) to model the experimental data, without expressing the electrolyte and surface conductivity acting in parallel, but relating peat and pore-fluid conductivity through a function α which depends on the conducting properties of both the solid and the fluid phase:

$$\sigma'_{peat} = \alpha \sigma_w \tag{6}$$

From the experimental results we can assume that α is equal to 1 when $\sigma_w = \sigma_m$ and that the water content (W) controls the ratio solid/fluid phase. Therefore eq.(6) can be written in the following way:

$$\sigma'_{peat} = \left(\frac{\sigma_w}{\sigma_m}\right)^\beta \sigma_w \tag{7}$$

Where β is a parameter which accounts for the non linear dependence of the water content on σ_w and for the geometry of the sample (tortuosity and cementation), as the formation factor in eq.(4). The model expressed by eq.(7) was used to reproduce the data of the peat-conductivity tests, with σ_m and β as fitting parameters. Fig.4 shows the low part of the curves around the threshold value of 10mS/m, and the curves obtained from eq. (7). The least squares regression lines were obtained through the Levenberg-Marquandt algorithm, with a root mean square error of prediction (rmsep) ranging from 0.0155 to 0.0275. The output parameter σ_m is similar for all the curves and as expected it has a mean value of 10.04 mS/m, which is the value that was empirically found as the point $\sigma_w = \sigma_m$ in Figure 3
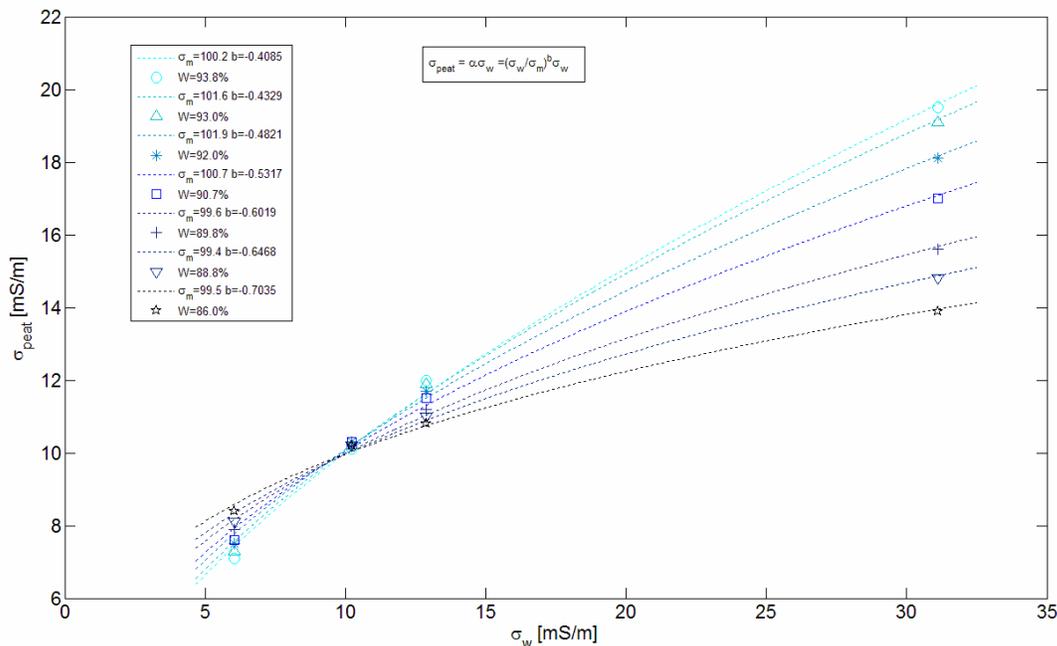
Fig.4Least squares regression for peat samples

On the contrary, the output parameter β shows a linear correlation with the water content (Figure5) and it increases when the water content is higher. These results are promising in the determination of a model that can describe the electrical behaviour of peat as a function of pore-fluid conductivity and water content. The peat water content may be estimated from electrical conductivity measurements if the conductivity of the ground-water is known and it is sufficiently different from the conductivity of the solid phase. Further investigations are needed to confirm these results and to study the variation of the model for different types of peat. In fact, the botanical composition and the degree of humification of peat have a strong influence on the structure of the material. This means that the parameter β may be associated to different peat types.
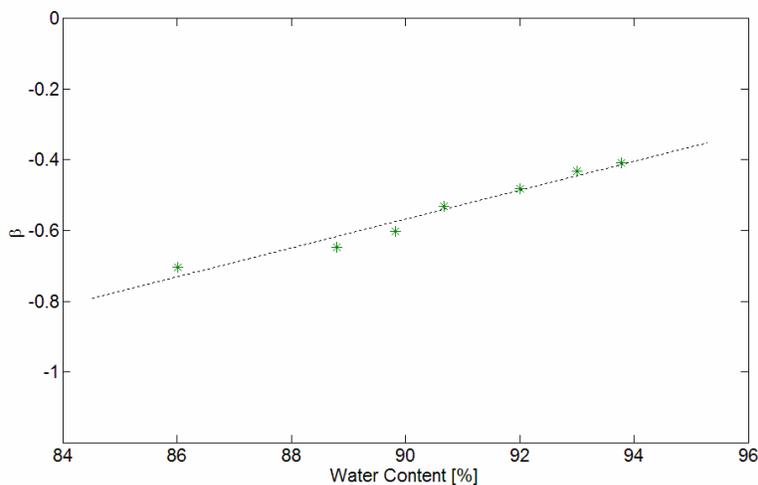

Figure5. Linear correlation between β and W (rmsep=0.0319)

5. CONCLUSIONS

Electrical conductivity measurements are a powerful tool to map the near surface and to investigate soil properties. However, there is a lack of knowledge in the electrical properties of organic soils to improve the interpretation of field tests with quantitative descriptions of peat properties. The electrical conductivity response

of peat is mainly dependent on the conductivity of the fluid saturating the sample. The influence of a change in water content on the peat conductivity response was studied using a new prototype cell for simultaneous testing of electrical and geo-mechanical properties of organic soils. Two different set-ups were used in order to measure the complex conductivity at high and low frequencies. High frequency data fits both the low-frequency model for peat and the modified form of the Archie's law for inorganic sediments. At low frequencies, the conductivity of peat shows a different dependence on water content below or above the pore fluid conductivity value of 10 S/m. A new model in which the conductivity of peat is determined by the conductivity of the solid and fluid phase has been proposed. In this model, the key parameter β accounts for the non-linear dependence on σ_w. As shown by the experimental results, β is linearly correlated to the water content of the saturated peat. Therefore, the electrical resistivity measurements showed considerable promise in being able to characterize peat properties such as water content, even if further investigations are needed to establish the variation of the electrical conductivity response with different peat types. These results have general implications for the application of broadband frequency electrical measurements to field-scale studies of organic soils.

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