Modelling unfrozen water content in a silty clay permafrost deposit

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ABSTRACT: The mechanical properties of both unfrozen soils and permafrost soils are influenced by the amount of unfrozen water in the pore space. When dealing with foundation engineering in permafrost areas it is essential to estimate the unfrozen water content (w_u). This paper deals with the establishing of a calibration equation for determining the unfrozen water content of a Greenlandic silty clay permafrost deposit. Calibration experiments have been conducted for water contents in the interval 0 – 10 % at both 5 °C and 22 °C. Calibration equations are verified against permittivity data from a permafrost core of properties material similar to the test soil. The calibration for 5°C is seen to make a good fit to the permafrost core data. Further experiments should be performed in order to extend the range of water contents tested and hence the range of validity of the calibration equation.

RÉSUMÉ : Les propriétés mécaniques des sols gelés et le pergélisol sont influencés par la quantité d'eau non gelée dans l'espace poreux. Lorsqu'il s'agit de travaux de fondation dans les zones de pergélisol, il est essentiel pour estimer la teneur en eau non gelée (w_u). Cet article traite de la mise en place d'une équation de calibration pour déterminer la teneur en eau non gelée d'un dépôt de pergélisol limono-argileux du Groenland. Expériences d'étalonnage ont été réalisées pour les teneurs en eau dans l'intervalle de 0 à 10% à des températures 5 °C et 22 °C. Équations d'étalonnage sont vérifiées par rapport aux données de permittivité d'un échantillon de pergélisol de matériau des propriétés similaires au sol analysé. L'étalonnage de 5 °C est vu faire un bon ajustement aux données sur l'échantillon pergélisol. Des expériences complémentaires doivent être effectuées afin d'étendre l'intervalle des teneurs en eau et donc augmenter l'intervalle de validité de l'équation d'étalonnage.

1 INTRODUCTION

The strength and deformation properties of both unfrozen soils and permafrost soils are influenced by the amount of unfrozen water in the pore space. Thus, when dealing with foundation engineering in permafrost areas it is essential to estimate the unfrozen water content (w_u). In fine-grained sediments, water molecules are bound to the electrically charged surfaces of the sediment grains. This effectively lowers the freezing point of parts of the water phase. Even at low temperatures (≤5°C), there may therefore still be significant (≥10% vol (Anderson and Morgenstern 1973)) amounts of unfrozen water present in the sediment.

Table 1. Typical permittivities of some geomaterials and permafrost soil constituents. (Reynolds 1997).

Material	Permittivity ε_R
Air	1
Water (fresh)	81[1]
Freshwater ice	4
Clay soil (dry)	3
Sand (dry)	3-6

[1] Permittivity at 20°C. At 0°C the permittivity of freshwater is 88.

One approach is based on the measurement of the bulk soil relative permittivity, ε_R. The relative permittivities of different soil constituents are listed in Table 1. The extremely large relative permittivity of water compared to air and ice, allows the quantification of the water content through measurements of the relative permittivity. Most commercial sensors are not built for application in the sub-zero temperature regime, but are applied under the assumption, that the measured permittivity adheres to the unfrozen water phase alone.

Yoshikawa and Overduin (2005) compared unfrozen water contents measured with a number of commercial sensors based on both Frequency Domain Reflectometry (FDR) and Time Domain Transmissometry (TDT) technologies. The results were compared to moisture contents determined by Nuclear Magnetic Resonance (NMR), which were considered true values. A field test reported only small errors for the applied FDR sensor compared to a TDT sensor. They found that manufacturer supplied calibration equations generally produce water contents twice the water content found using NMR, and that more accurate calibration equations should be developed.

The focus of this study is to establish such a calibration equation, based on a commercial permittivity sensor applying the FDR technology, specifically targeted at a Greenlandic silty clay sediment. Thus, the resulting calibration equation will serve as an augmentation to the existing library of calibration functions.

2 METHODOLOGY AND MATERIALS

Figure 1. The samples used for this study was collected near Kangerlussuaq International Airport, Western Greenland.

This study consisted of a series of different tests building the study data basis. Initially the testing cell was calibrated and the permittivity sensor was tested for bias due to choice of logging interval or stacking routine. From this basis, permittivity tests were conducted on remoulded soil samples with known water content and temperature. The permittivity data and the measured water contents were then used to establish a calibration equation for the specific silty clay soil. Specifics on procedures are presented along with the results for enhanced readability.

The permittivity sensor used for this study is the Steven's Hydra Probe II SD-12 employing the FDR technology. This sensor is a descendant of the FDR sensor used in the field test mentioned by Yoshikawa and Overduin (2005).

2.1 Silty clay material properties

The marine silty clay used for the calibration, was collected from the plains approximately 3 km west of the Kangerlussuaq International Airport, Western Greenland. See Figure 1. The saline pore water originally present in the deposit has been leached out of the material used for these experiments. Thus the salinity of the tested soil has been shown to be less than 100 mg/L (Skels 2010). The Atterberg limits and other soil classification properties are presented in Table 2.

3 PROCEDURE AND RESULTS

The results below are presented as mean values along with measurement uncertainties in terms of ± 1 standard deviation unless otherwise specified.

3.1 Measurement setup

Table 2. Soil properties of the silty clay used for the calibration experiments in this study (Ekstrand 2008, Larsen et al. 2001, Morelli and Bennedsen 2005, Skels 2010).

Property	Value	Unit
Sand > 63 µm	5	%
Silt 2-63 µm	47	%
Clay < 2 µm	48	%
D_{50}	1.9	µm
U	13.3	-
w_L	26.6	%
w_P	20.2	%
$w_{natural}$	24	%

Permittivity measurements were performed in an acrylic glass cylindrical cell of diameter Ø = 80 mm. The permittivity sensor was installed through holes in the bottom plate. As the cylinder base plate slightly disturbs the permittivity measurements, a calibration was established linking permittivities measured using the cell to values measured with the sensor fully submerged. For this purpose corresponding measurements of air, ethanol and tap water were performed. During measurements, a thermistor installed in the medium monitored the temperature.

Temperatures during measurements were at 6.6±0.70 °C and 22.1±0.51 °C which deviated slightly from the intended 5°C and 22°C. The derived conversion equations are shown in figure 2. No bias of the sensor measurements were identified as the measured permittivities were within the precision of ±1% specified by the manufacturer (Steven's Water Monitoring Systems, 2008).

3.2 Sample preparation

Dried soil was mixed to match the target water content and then set aside for acclimatising at the test

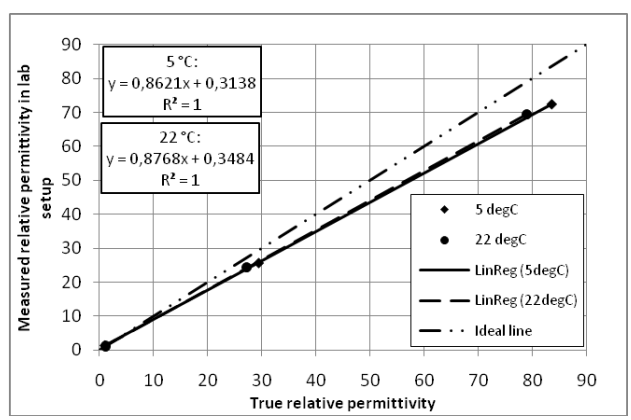

Figure 2. Conversion of permittivities measured in the test cell to true permittivities for 5°C and 22°C.

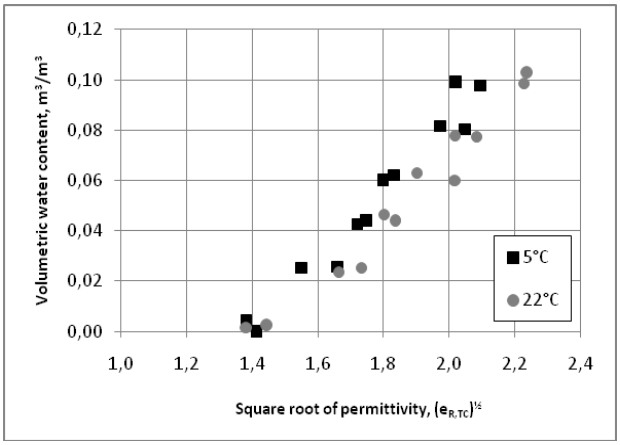

Figure 3. Data basis for establishment of calibration equations for a Greenlandic silty clay deposit.

temperature prior to testing. The water content of the mixed soil was determined by triple sampling just after mixing and just prior to sample installation.

A sample was build into the test cell in two steps. First the cell was filled to about half the sample height and then compacted by placing a proctor punner gently on the soil surface 3 times. This was repeated when the cell was filled to full sample height and subsequently the permittivity sensor and the thermistor were installed into the sample. Before the sample was left to acclimatise, plastic film was mounted on top of the cell to avoid evaporation. The temperature was logged during acclimatisation. Water content of the sample was measured before and after testing.

The actual water content deviated from the target water content for all samples. A meat mincer was used for the sample mixing resulting in a large sample surface area during preparation. Evaporation is expected to have caused the observed deviations, which are considered unimportant for the results of the study, as actual measured water contents were used in the analysis.

The mean dry density of all the prepared samples was calculated to be 1.07±0.04 g/cm^3 based on the water content after testing. This indicates that the installation was performed consistently for all samples.

3.3 Test procedure

Prior to testing the soil, the sample temperature was monitored via the thermistor to ensure complete acclimatisation. Permittivities were measured at water contents w = [0, 2, 4, 6, 8, 10] %. For each water content, two replications were conducted at room temperature and two replications were performed in a refrigerator at 5°C. The permittivity was logged every 5 seconds and the tests were run for at least 5 minutes. The soil sample temperature and ambient temperature were logged once pr. minute during testing.

The recorded data were converted to true permittivity values using the cell-specific conversion previously described, and corrected for temperature influence as specified by the manufacturer (Bellingham, 2007).

Corrected true permittivities were averaged for 5 min periods, and datasets of corresponding permittivities and calculated volumetric water content were fitted with a linear regression, using the square root of the permittivity as the independent variable. Thus the calibration equation takes the form

$$w_{vol} = a \cdot (\varepsilon_{R,TC})^{½} + b \qquad [1]$$

The obtained datasets can be seen in Figure 3. The calibration coefficients are presented in Table 3.

3.4 Verification

Agergaard and Ingeman-Nielsen (2010) measured the relative permittivity of a permafrost core retrieved from the Kangerlussuaq area. This core had similar properties to the material used for the present study, and permittivities were measured during a controlled thaw-experiment over a full thaw-freeze-thaw cycle, see Figure 4. The gravimetric water content of the core material was measured at the end of the experiment to be w = 34.1%.

For verification of the calibration equations obtained here, we have applied the 5°C calibration equation to the permafrost core data set. We would expect the permittivity based water content at room temperature to equal the reported gravimetric water content. In order to overcome too crude extrapolation outside the range of water contents applied in the calibration, the permittivity measured at 5°C/w = 34.3% from Agergaard and Ingeman-Nielsen (2010) was added to the calibration data basis. This yields a calibration equation of

$$w_{vol} = 0.165 \cdot (\varepsilon_{R,TC})^{½} - 0.239 \qquad [2]$$

where the correlation is R^2 = 0.994.
For comparison, we also applied previously published calibration equations (Bellingham, 2007) to the data set. The predicted gravimetric water contents are seen in

Figure 5. Table 3. Calibration coefficients and temperature regime for the obtained calibration equations.

Quantity	5°C	22°C	Unit
a	0.139	0.122	-
b	-0.194	-0.175	-
R^2	0.962	0.964	-
Mean temperature	5.18	21.88	°C
Standard deviation, temperature	0.15	0.44	-

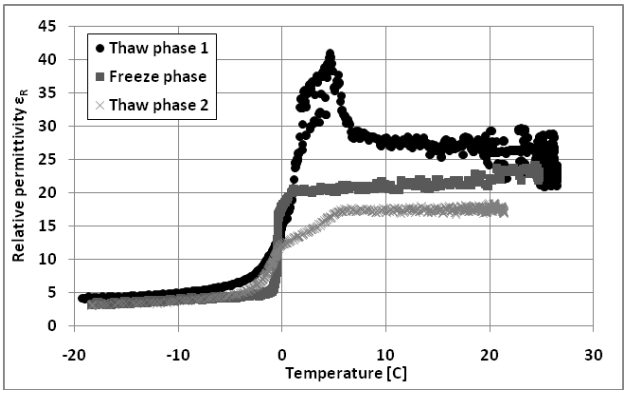

Figure 4. Permittivity during a controlled thaw experiment (Agergaard and Ingeman-Nielsen 2010).

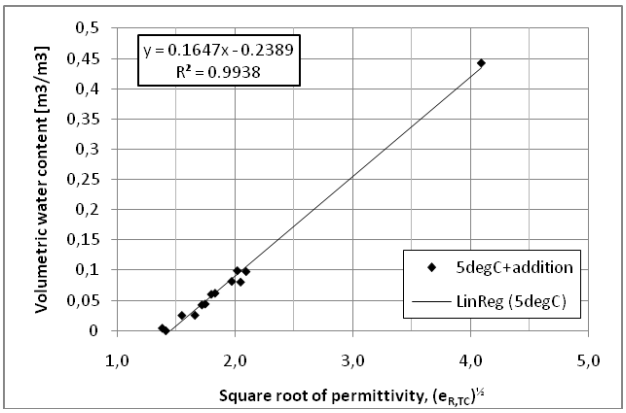

Figure 5. The data point for w = 34.3% at 5.1°C fits in a good linear regression with the obtained calibration data. This new extended range calibration equation was used for the verification against the core material permittivity data.

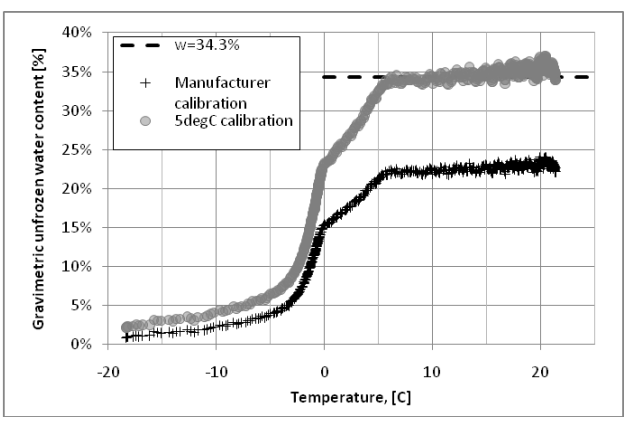

Figure 6. Gravimetric water contents predicted by the best fitting manufacturer supplied calibration equation and the extended 5°C calibration equation from this study. The calibration equation obtained in this study models the measured gravimetric water content nicely.

4 DISCUSSION

Some assumptions are related to the concept of measuring unfrozen water content based on permittivity. Most commercial permittivity sensors are not designed specifically for measuring under frozen conditions (Yoshikawa and Overduin 2005), but are applied within the field of permafrost research anyway. In order to do so, it is widely accepted, that permittivities, and hence water contents, measured under frozen conditions are assumed to equal permittivities and water contents measured at positive temperatures, since most manufacturer's calibration equations are valid for this temperature regime only. This phenomenon is further promoted due to the relative inexpensiveness and in-field versatility of permittivity sensors compared to other means of soil moisture measurements, say NMR.

The calibration equations established in the previous section inherits their properties from the test conditions of the calibrations experiments performed. As it can be noted from Table 1, the permittivity of water changes with varying temperatures, hence it is important to control and monitor the temperature of the test medium. Apart from this exception, all temperature corrections and calibration temperatures presented, e.g. in Table 3, are acquired via the thermistor installed in the soil sample. Thus, the temperature measurements are in general considered to be reliable.

During the calibration of the measurement cell performed initially, the temperatures recorded for the calibration at room temperature were less precise (0.5°C) than those for the cooled calibration (0.01°C) due to a change of temperature logger in between tests. In order to attain the most smooth and reliable temperature correction of the permittivities, temperature data recorded by the permittivity sensor were used instead. In addition, the temperature employed in the actual calibration experiments, e.g. approximately 5°C and 22°C, was not fully attained for the former. Thus, the conversion from measured permittivities in the test cell to true permittivities at this temperature is not fully valid and should be repeated. This is likely to lead to a more clear distinction between the two temperature levels than what can be observed from Figure 3. The correlation of replicated experiments are reasonably good, but could be improved by improved control of the ambient temperature, as the differences mainly reflects variation in sample temperature in between experiments.

The obtained calibration equations presented in Table 3 are consistent with the generally anticipated increase of water's permittivity with decreasing temperatures. However, the range of water, contents within which the calibration equations are valid, are rather narrow considering the actual natural water content of the deposit as stated in Table 2. Hence, more experiments are needed to extend the data basis, and subsequently eliminate the need for adoption of data points obtained under different conditions. Nevertheless, the inclusion of the extra data point mentioned in section 3.4 seems reasonable, the correlation coefficient taken into account, and the final prediction of water content is very good

related to the measured gravimetric water content. If this was left out, and the calibration coefficients from Table 3 were applied instead of Eq. 2, the predicted water content delineated by the grey circles in Figure 6 would only have reached a gravimetric water content level of approximately w = 28 %.

The good fit of the established calibration equation to the permafrost core data seen in Figure 6 is in contrast to the conlusion of Yoshikawa and Overduin (2005) mentioned in the Introduction, namely that manufacturer calibration equation generally overestimates the water content by a factor 2. In this case the water content calculated from the calibration equations established in this study exceeds the water content predicted by the manufacturer equation. This dichotomy appears odd, when the consistency of the collected data is considered, and should be further investigated to avoid ambuiguity

5 CONCLUSION

This paper deals with the establishing of an improved calibration equation for determining the unfrozen water content of a Greenlandic silty clay permafrost deposit based on the assumption, that the calibration equation is equally valid above and below 0°C.

Calibration experiments have been conducted for water contents in the interval 0 – 10 %. Based on the very small variation of sample dry densities, and the good correlation of replicated measurements, the experiments are considered a consistent basis for establishing a calibration equation.

Calibration equations are established for both 5°C and 22°C and are verified against permittivity data from a permafrost core, of material properties similar to the test soil, subjected to a thaw-experiment, previously performed by the authors. Using a simple extension of the data basis to enhance quality of extrapolation, the calibration for 5°C is seen to make a good fit to the permafrost core data. However, further experiments should be performed in order to extend the range of water contents tested and hence the range of validity.

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