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Analysis of coupled hydraulic and dielectric material properties of soils: a multivariate approach

Norman Wagner
Institute of Material Research and Testing
at the Bauhaus-University Weimar
Coudraystr. 4, 99423 Weimar, Germany

Frank Daschner
Microwave Group
Faculty of Engineering
University of Kiel, Germany

Alexander Scheuermann and Moritz Schwing
Geotechnical Engineering Centre
The University of Queensland
Brisbane, Australia

***Abstract*—The frequency dependence of dielectric material properties of porous mineral materials such as soil are not only disturbing in applications with high frequency electromagnetic (HF-EM) techniques but also contain valuable information of the material due to strong contributions by interactions between an aqueous pore solution and mineral phases. This circumstance opens the possibility to estimate physico-chemical parameters such as water content, texture, mineralogy and matric potential with broadband HF-EM measurement techniques. In this context, a multivariate approach was applied to analyse coupled hydraulic and dielectric material properties of a silty clay soil.**

I. Introduction

The success of water content estimation in porous media with high frequency (radio and microwave) non and minimal invasive electromagnetic (HF-EM) measurement techniques is caused by the dipolar character of the water molecules resulting in a high permittivity in comparison to other phases. However, interactions between an aqueous pore solution and solid phases lead to strong contributions to the electromagnetic material properties due to interphase processes [1], [2]. Therefore, the broadband dielectric spectrum contains valuable information about porous media and it can be used for an estimation of physico-chemical parameters besides free pore water such as texture, structure, mineralogy and matric potential as important hydraulic property with broadband HF-EM measurement techniques. In this context, a multivariate (MV) approach according to Daschner et al. (2003) [3] is applied for the simultaneously determination of soil water content, porosity and matric potential from measured frequency dependent dielectric material properties.

II. Material and experimental methods

A slightly plastic clay soil was investigated (for soil details see [4]). The soil sample was saturated with deionized water, prepared at liquid limit with gravimetric water content w = 0.267 g/g (volumetric water content θ = 0.45 m^3/m^3) and placed in a rod based transmission line (R-TML, see [4]). Then the sample was stepwise dried isothermal at 23 °C under atmospheric conditions at defined humidities and equilibrated. Appropriate mass loss and sample volume change were estimated during the drying process to obtain appropriate volumetric water content θ.

The frequency dependent complex permittivity was determined in the frequency range from 1 MHz to 10 GHz with network analyzer technique according to Wagner et al. (2011) [4] by means of quasi-analytical or numerical inversion of measured four complex S-parameters (Fig. 1).

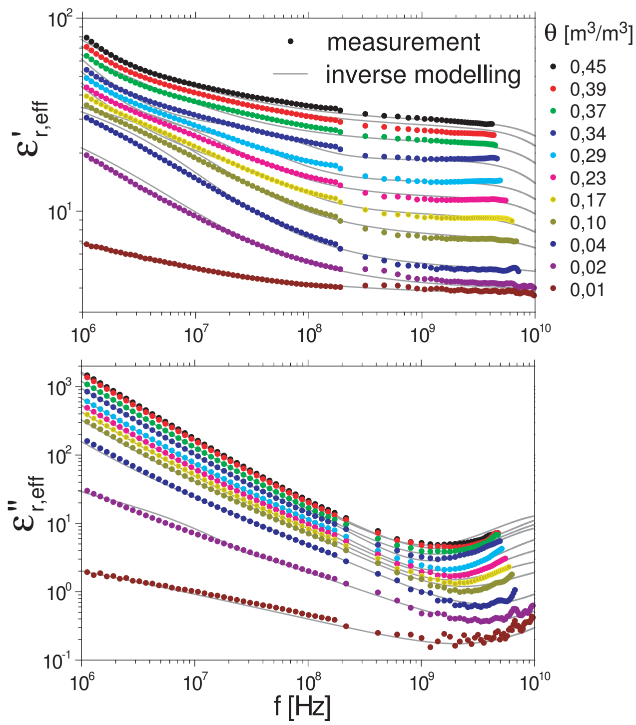

Fig. 1. Real part $\varepsilon'_{r,\text{eff}}$ and imaginary part $\varepsilon''_{r,\text{eff}}$ of the experimental determined complex relative effective permittivity $\varepsilon^{\star}_{r,\text{eff}}$ as a function of frequency for different volumetric water contents θ.

Soil water characteristic curve (SWCC- relationship between volumetric water content θ and matric potential Ψ) as well as shrinkage behavior (changes in porosity n as a function of volumetric water content θ) were determined in separate experimental investigation (for details see [5], Fig. 2). SWCC was parameterized with a trimodal van Genuchten equation according to Priesack and Durner (2011) [6] using a shuffled complex evolution metropolis algorithm (SCEM-UA, [7]) and shrinkage behavior was parameterized with an empirical equation to determine appropriate matric potential and porosity at defined volumetric water contents.

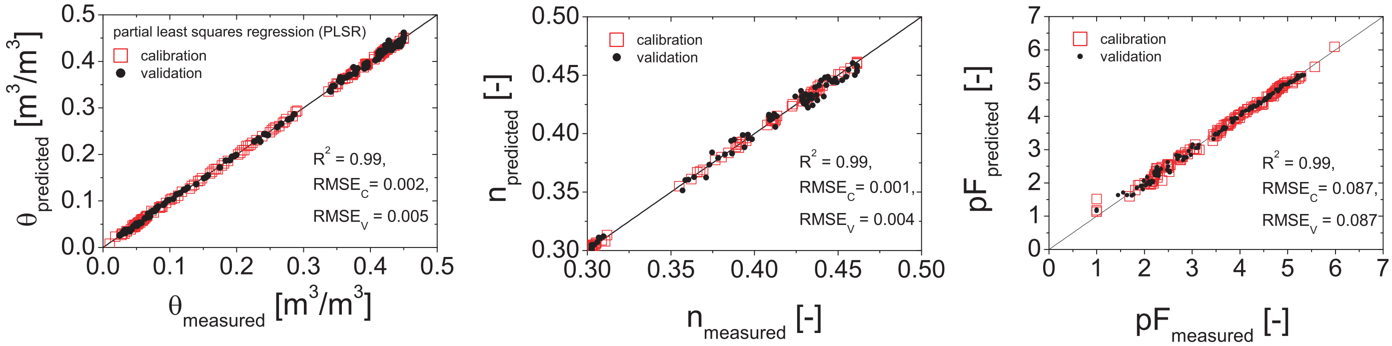

Fig. 3. Experimental determined parameters (volumetric water content θ, porosity n, matric potential Ψ expressed in terms of pF=log($|\Psi|[hPa]$)) versus predicted results from the dielectric spectra based on PCLR.

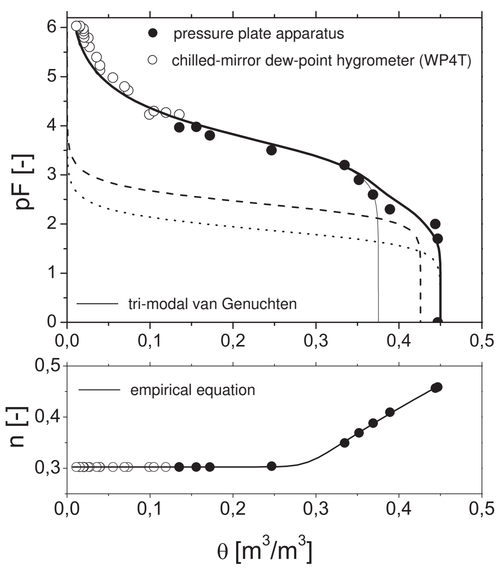

Fig. 2. (top) Matric potential Ψ expressed in terms of pF=log($|\Psi|[hPa]$) and (bottom) porosity n as a function of volumetric water content θ.

III. Results and Conclusion

Measured dielectric spectra were reduced to 81 frequency points in the frequency range from 1 MHz to 5 GHz. The following multivariate methods were applied to quantitatively relate the spectra to soil physical properties such as water saturation S_W and porosity n or volumetric water content $\theta = S_W \cdot n$ as well as matric potential Ψ: principal component analysis (PCA) with principal component regression (PCR), partial least squares regression (PLSR) as well as artificial neural networks (ANN) (for details see [3], [8], [9]). The complete dataset of 266 measured spectra were randomisely divided into two sets with each 133 groups. One set is used for calibration and one set for validation. In Table I the results of the different approaches are summarized. The PLSR-technique presented in Figure 3 gives the best results with lowest RMSEs.

The applied MV approach gives evidence, (i) of a physical relationship between frequency dependent dielectric properties and soil matric potential as important hydraulic material

TABLE I
RESULTS OF THE USED MULTIVARIATE METHODS (R^2=0.99 FOR ALL PROPERTIES AND METHODS) AND ROOT MEAN SQUARE ERROR ESTIMATE FOR CALIBRATION $RMSE_C$ OR VALIDATION $RMSE_V$, RESPECTIVELY.

	PCR	PLSR	ANN
θ [%]	0.4 / 0.5	0.2 / 0.5	0.3 / 0.3
n [%]	0.4 / 0.6	0.1 / 0.4	0.3 / 0.4
Ψ [pF]	0.12 / 0.12	0.09 / 0.09	0.12 / 0.12

property and (ii) the applicability of multivariate methods for estimation of physico-chemical parameters of porous media from broadband measured dielectric spectra.

Acknowledgment

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