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Identifying unsaturated soil hydraulic parameters using integrated hydrogeophysical inversion approach on time-lapse ground-penetrating radar data

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Recently, ground-penetrating radar (GPR) has proven to have a great potential for high resolution, non-invasive mapping of the soil hydrogeophysical properties at the scale of interest. Common GPR techniques are usually based on ray-based travel time or reflection analyses to retrieve soil dielectric permittivity, which is strongly correlated to soil water content. These methods suffer, however, from two major limitations. First, only a part of the information in the GPR signal is considered (e.g., propagation time). Second, the forward model describing the radar data is subject to relatively strong simplifications with respect to electromagnetic wave propagation phenomena. These limitations typically results in errors in the reconstructed water content images and, moreover, this does not permit to exploit all information contained in the radar data.

We explored an alternative method by using full-waveform hydrogeophysical inversion of time-lapse, proximal GPR data to remotely estimate the unsaturated soil hydraulic properties. The radar system is based on international standard vector network analyzer technology and a full-waveform model is used to describe wave propagation in the antenna-air-soil system, including antenna-soil interactions. A hydrodynamic model is used to constrain the inverse electromagnetic problem in reconstructing continuous vertical water content profiles. In that case the estimated parameters reduce to the soil hydraulic properties, thereby strongly reducing the dimensionality of the inverse problem.

In this study, we present an application of the proposed method to a data set collected in a field experiment. The GPR model involves a full-waveform frequency-domain solution of Maxwell's equations for wave propagation in three-dimensional multilayered media. The hydrodynamic model used in this work is based on a one-dimensional solution of Richards equation and the hydrological simulator HYDRUS 1-D was used with a single- and dual-porosity model. To monitor the soil water content dynamics, time-lapse GPR and time domain reflectometry (TDR) measurements were performed, whereby only GPR data was used in the inversion. Significant effects of water dynamics were observed in the time-lapse GPR data and in particular precipitation and evaporation events were clearly visible. The dual porosity model provided better results compared to the single porosity model for describing the soil water dynamics, which is supported by field observations of macropores. Furthermore, the GPR derived water content profiles reconstructed from the integrated hydrogeophysical inversion were in good agreement with TDR observations. These results suggest that the proposed method is promising for non-invasive characterization of the shallow subsurface hydraulic properties and monitoring water dynamics at the field scale.