Imaging spectral electrical properties of variably saturated soil columns

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Accurate knowledge about the spatial distribution of soil hydraulic parameters is highly important for modelling the movement of water and solutes in saturated and unsaturated soils on several scales. Electrical impedance tomography (EIT) is a promising technique to non-invasively acquire information on hydraulic conductivity, because the measured complex conductivity is sensitive to soil properties that also control the hydraulic properties (water saturation, porosity, specific surface and pore/grain size distribution). Even more information is available if EIT is performed in a spectral manner (i.e. performing EIT measurements over a range of frequencies), which yields information on the spatial distribution of the spectral electrical properties of the soil. Relationships between spectral electrical and hydraulic parameters have shown strong correlations in several studies. Our ability to obtain such distributions of spectral electrical parameters in an EIT inversion approach is influenced by several factors, among which data accuracy, sensitivity and regularization strength and type are typically the most important. Numerical studies of the reproducibility of spectral electrical parameters in an inversion approach showed that an effective electrical relaxation time should be less affected by these factors than chargeability or DC-conductivity. In order to investigate this finding experimentally and to test the actual reproducibility of spectral electrical properties in an imaging approach, EIT measurements were conducted on a range of packed soil columns with materials which were well defined in terms of their spectral electrical properties using effective spectroscopic measurements.

Tomographic measurements were performed for frequencies ranging from 10 mHz to 45 kHz on homogeneous sand and sand-clay mixtures and on a heterogeneous column that consisted of a sand-clay anomaly embedded within a pure sand background for frequencies ranging from 10 mHz to 45 kHz. The dry material was homogeneously mixed with 10 percent by mass tap water and compacted manually in the column. After packing the columns, they were saturated with tap water from the bottom upwards. Hydraulic states of these soil columns were varied in order to investigate the spectral electrical properties and its reproducibility in imaging as a function of saturation. This was achieved by applying a defined suction at the bottom of the column. A three-dimensional complex resistivity inversion code was used to invert the spectral measurements, whereby each single frequency was inverted independently using the same regularization strength (spatial smoothing) for all frequencies. After inversion of each frequency, the spectral results of each volume element were decomposed into a superposition of 50 logarithmically distributed Debye-terms within a range from 0.01 to 100 seconds to obtain the relaxation time distribution. Reference spectral induced polarization (SIP) measurements were performed to independently determine the spectral electrical properties of all materials. These samples were prepared in a smaller sample holder using the same packing and saturation procedure and then drained by applying air pressure to the top of the sample.

Figure 1 shows the spectral imaging results in terms of normalized total chargeability and peak relaxation time determined using Debye-decomposition of inverted spectra of complex electrical conductivity for the saturated heterogeneous column. For the normalized total chargeability, the effect of spatial smoothing is clearly visible. However, the imaging results for the peak relaxation time allow a very distinct differentiation of the two different materials in terms of their quantitative values. In addition, the peak relaxation time shows no artefacts, whereas artefacts are visible in the imaging results for the normalized total chargeability, especially near the boundaries, close to the electrodes. Spectral interpretation of the imaging results becomes more challenging with increasing drainage of the columns due to the higher contact impedances of the electrodes and the lower contrast in polarizability between the sand-clay anomaly and the sand background. Nevertheless the imaging results for the drained heterogeneous column can resolve the sand-clay inclusion as an anomaly with higher conductivity both in real and imaginary part and the inverted values are in reasonable agreement with the reference measurements. Differences from the reference data are in the range of reproducibility of the reference data itself and attributed to the packing procedure.

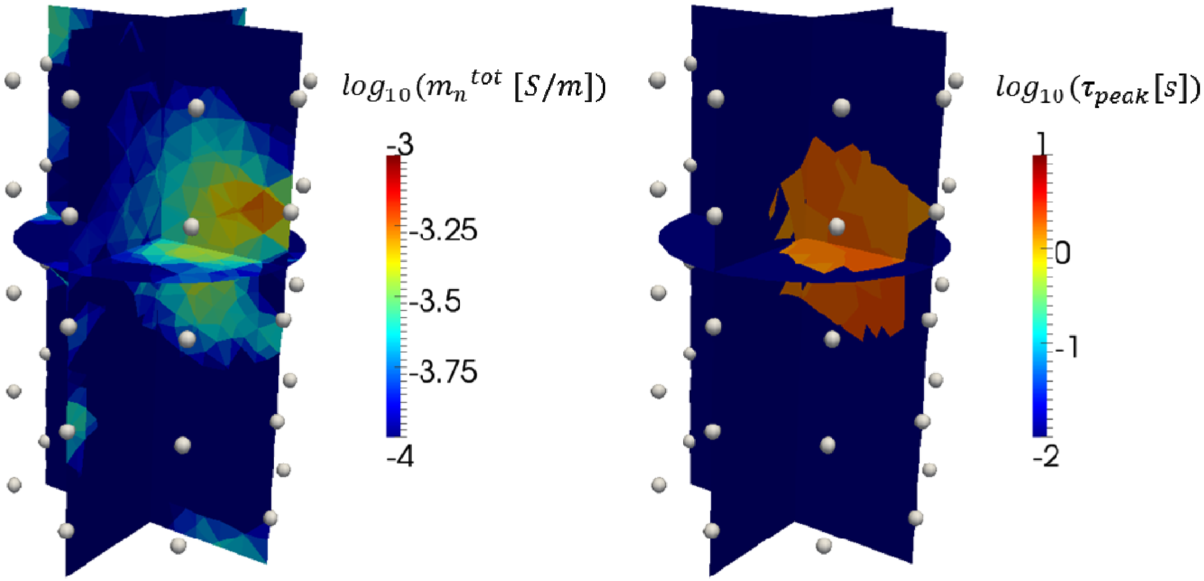

Fig. 1: Images of normalized total chargeability (left) and peak relaxation time (right) of spectral complex electrical conductivity for the sand-clay anomaly in a sand background in saturated conditions.

We conclude that the imaging results for the peak relaxation time are quantitatively much less affected by spatial smoothing than the normalized chargeability. Interpretation of the EIT measurements in the higher frequency range (> 10 Hz) was affected by phase errors that increased with increasing soil resistivity and electrode coupling impedances. This is due to the capacitive load of the electrodes which causes parasitic currents across the potential electrodes. These errors will be numerically corrected in the near future using advanced modelling of the measurement setup. The procedure of packing and saturating the columns proved to have a significant impact on the actual spectral response, which highlights the need for comparable and reasonable methodologies for sample preparation or the use of undisturbed natural soils for calibration purposes.