Geophysical Research Abstracts
Vol. 13, EGU2011-8215, 2011
EGU General Assembly 2011


# High resolution imaging of the saturated and unsaturated zone of a gravel aquifer using full-waveform borehole GPR inversion

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Cross-hole ground penetrating radar is widely used in geological, hydrological and engineering investigations to map the distribution of dielectric permittivity and electrical conductivity, which are closely linked to hydrogeological parameters. Traditionally, ray-based algorithms are used to invert cross-hole GPR data using first arrival travel times and first cycle amplitudes. However, the resolution of conventional standard ray-based inversion schemes is limited, because only a fraction of the information contained in the radar data is used. Full-waveform inversion that considers the entire waveform can significantly improve imaging results of cross-hole GPR data. A 2D full-waveform finite difference time domain (FDTD) approach was recently used to invert cross-hole GPR data measured in the saturated zone of a gravel aquifer (4 -10m depth) in the Thur valley, Switzerland. The simulated traces of the final model obtained by the full-waveform inversion fit the observed traces very well in the lower part of the section and reasonably well in the upper part of the section. Due to water table refractions and reflections, the upper part of the aquifer was not reliably imaged.

Here, we extend the region of investigation by including data acquired in the unsaturated part of the aquifer. Since a high contrast of medium parameters is present between the unsaturated and saturated zone, estimating one effective wavelet was insufficient. Detailed analysis of the cross-hole data showed that the effective wavelet strongly depends on if the source and receiver antennas are present in the saturated or unsaturated medium. This indicates the need to estimate separate wavelets for the unsaturated and saturated media. The effective wavelet with the highest frequency and amplitude is obtained when source and receiver are both located in the unsaturated zone, whereas the lowest frequency and amplitude are obtained when source and receiver antennas are located in the saturated zone. When one antenna is located in the unsaturated and the other in the saturated domain, similar intermediate center frequencies and amplitudes of the effective wavelets are obtained. In the 2D FDTD full-waveform inversion code, separate effective source wavelets are used for all possible combinations of transmitter and receivers in the unsaturated and saturated domain. The full-waveform inversion returns high-resolution images throughout the model domain including the upper part of the aquifer which contains a high permittivity layer indicating a waveguide. The modelled data show a good fit with the measured data including direct, reflected and refracted waves. The measurements for the sources and receivers that were present at the depth of the waveguide layer and the modelled data show high amplitudes and elongated wave trains confirming the presence of a waveguide.