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Crosshole GPR full-waveform inversion and amplitude analysis of waveguides for 3D characterization of a gravel aquifer

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For an accurate characterization of aquifers, high resolution 3D visualization with a high resolution can greatly improve the understanding of the interior process of flow and transport. Over the last decades crosshole ground penetrating radar showed to be a powerful tool for the characterization of aquifers due to the possibility of providing high resolution images and the strong connection to porosity and soil water content. The full-waveform inversion of GPR, that incorporates the entire waveform, can significantly improve the model resolution compared to standard ray-based techniques that uses only a small fraction of the signal. Here, the 2D full-waveform inversion is applied to a gravel aquifer in Switzerland and analyzed in 3D by inverting six crosshole GPR planes acquired between four wells. The permittivity and conductivity results obtained by the full-waveform inversion for the saturated aquifer between 4m–10m depth showed sub-wavelength resolution images with mainly similar layering at the intersection of the planes and the borehole locations. In all the conductivity images the underlying lacustrine sediments (high clay content) are clearly identified. Additionally a high permittivity zone is resolved between 5m–6m depth in all the six GPR planes which indicates a high porosity zone that is possible acting as a zone of preferential flow. Due to the high contrast to the surrounding medium this layer is acting as an electromagnetic waveguide and causes high amplitude late arrival elongated wave trains with at least one order of magnitude higher trace energy in the GPR data for transmitters-receiver combinations in this zone. For the same receivers when the transmitter is located outside this zone a distinct minimum in the trace energy can be observed. Using these maxima and minima positions of the trace energy spectra, we developed a novel amplitude analysis approach that is able to identify waveguides and their boundaries already in the measured GPR data. This method was applied to the six crosshole GPR planes and the detected waveguide boundaries were confirmed by the full-waveform inversion. Nevertheless, the full-waveform inversion is necessary for a detailed characterization of waveguides. Porosities converted from the full-waveform permittivity show a good agreement with Neutron-Neutron porosity logging data at the intersecting diagonal planes. Moreover, permeability estimates measured in the same wells indicated zones of preferential flow between 5m–6m depth which is in a good agreement with the high permittivity/ high porosity zone obtained by the full-waveform inversion. This work shows the potential of the full-waveform method and the novel amplitude analysis approach for a semi-3D high resolution characterization of the sub-surface which can be applied to a wide range of applications.