Time-lapse GPR WARR surveys during a lab-scale infiltration experiment

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Time-lapse geophysical measurements have proven to be advantageous for practitioners interested in studying dynamic hydrologic processes. Ground-penetrating radar (GPR) studies have been limited to sparse data obtained from discrete sampling in space and/or time or richer datasets with increased sampling obtained by exhausted graduate students. Time-lapse multi-offset GPR is especially valuable to the hydrologist, however, since it not only offers a non-invasive mapping of the subsurface, but also holds information regarding depth-averaged volumetric water content.

A lab-scale infiltration experiment was performed to evaluate the capability of time-lapse GPR to quantitatively monitor hydrologic changes during an infiltration event. Specifically, wide angle reflection and refraction (WARR) surveys were performed using an automated 900MHz GPR system that collected a complete set of 21 traces every 30 seconds throughout the 2 hour infiltration experiment. Organizing the transient WARR data into a cube (with axis of offset, experiment time, and travel time) allows us to perform normal move-out (NMO) analyses on the multi-offset projections of the data, as well as view changes in individual radar arrivals at a single offset through time on travel time vs. experiment time projections.

The infiltration experiments were run in a sand tank measuring 1.5m x 1.5m x 0.8m which was filled with gravel at the base (0.2m) to allow for free drainage from the tank. During the installation of the sand, 15 soil moisture probes were embedded in a central and lateral array to directly measure changes in volumetric water content at 10 second intervals. An irrigation grid constructed of parallel polyethylene tubes, each tube separated by 1cm and punctured at 1cm intervals along their length, was used in an attempt to evenly distribute the infiltrating water over the surface of the sand. Conceptualizing unsaturated flow as vertical and one dimensional, HYDRUS-1D model results were used as input into a GPR model to predict the hydrologic and geophysical response for comparison to the data.

NMO analysis of the reflection produced by the contrast between the bottom of sand and top of the gravel layer in the tank was performed to evaluate depth to the reflector and average volumetric water content of the tank through time (Figure 1a, 1b). Water content estimates from the GPR data showed good agreement with the arithmetic mean of the moisture probe readings with typical errors of 2-5%. NMO depth estimates to this reflector were also in good agreement with the true value (0.6m) with typical errors of 2-5% with the largest error (25%) occurring at early experiment times, just after the onset of irrigation. NMO analysis of the infiltration (wetting) front was also performed, which clearly showed the migration of this reflector though the tank in time. This depth vs. time relationship was found to be in good agreement with both the HYDRUS model results (Figure 1d) and in-situ moisture probe readings (Figure 1d).

Errors arising in the NMO analysis of both reflections are caused by errors in picking due to wave interference and dispersive wave guides. Wave interference between the bottom of tank reflection and wetting front reflection at early experiment times causes a significant error in the depth and velocity estimate. While at later times and larger offsets, the bottom of tank reflection is refracted as it reaches the air at the tank surface, which creates an arrival that obscures the direct arrival of the reflected energy. The same is true for the wetting front reflection and the side of tank reflection. Also contributing to errors is the presence of a dispersive wave guide at early irrigation times observed in both the model animations and through ~~Fourier~~ phase-velocity ~~transforms~~ analysis of the data. This phenomenon occurs when a low-velocity layer, with thickness comparable to radar wavelength, overlies a higher velocity layer. More interesting though is the coincidence of this phenomenon and errors in the NMO analysis of the bottom of sand reflection which indicates that methods other than travel-time analysis will be needed to determine reflector geometries at specific hydrologic conditions.

A time-lapse WARR survey was performed during an infiltration experiment in a sand tank. The data set was particularly appealing as it offered both traditional multi-offset and common offset vs. experiment time plots. Average volumetric water content and depth to the bottom of the sand were determined using NMO with good accuracy; however, errors arose from picking errors cause by wave interference and dispersive wave guides. Given a 1D conceptual model and errors in traveltime picking, the radar still does at formidable job at determining volumetric water content and depth to reflectors. However, highlighting errors in NMO analysis at specific hydrologic conditions further emphasizes the advantage and need for time-lapse monitoring and data processing that reaches beyond simple travel time analysis.

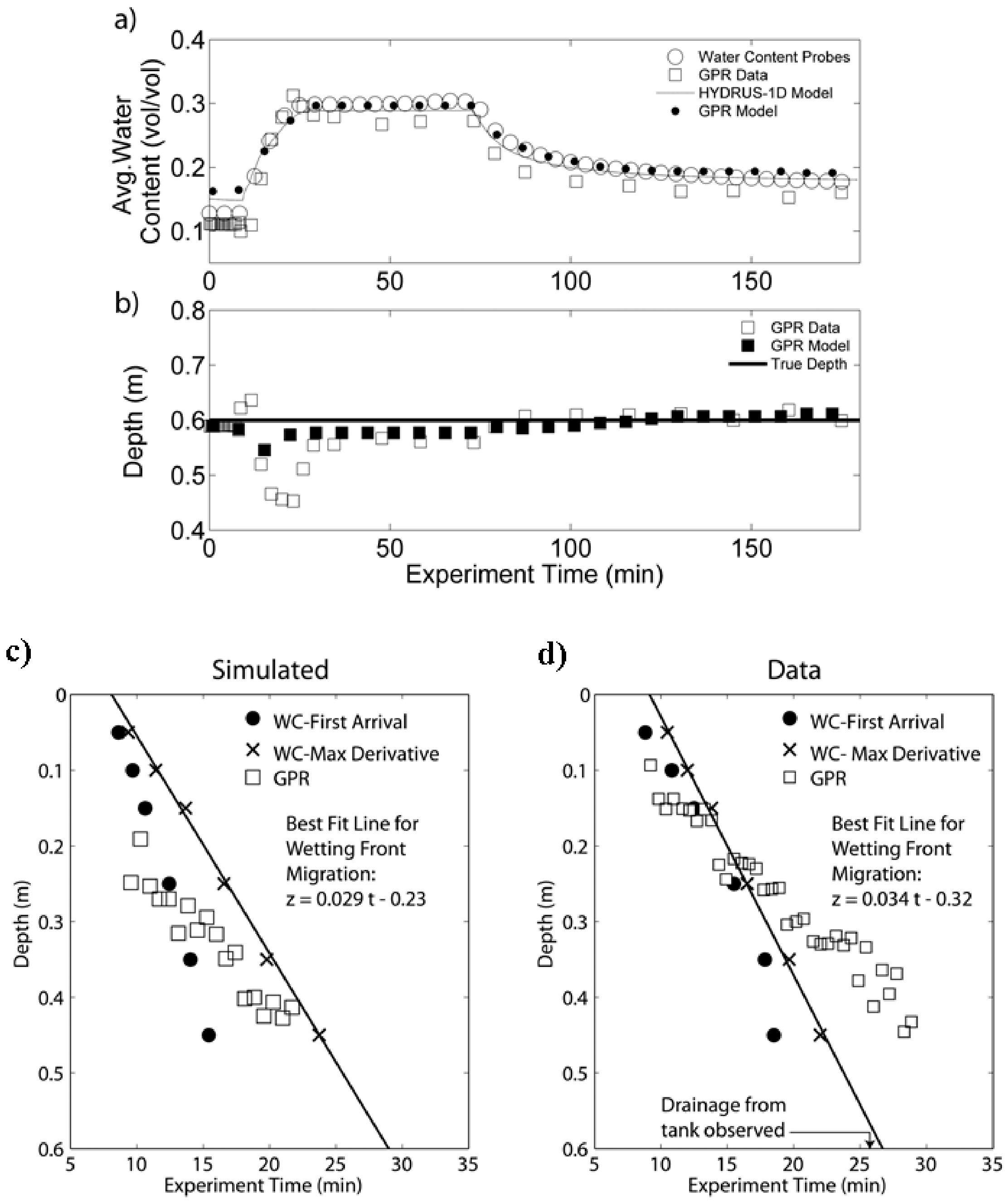

Figure 1: Results of the time-lapse WARR survey. a) Average volumetric water content determined from data and models, b) reflector depth (bottom of sand) determined from NMO analysis, wetting front depth with time from c) models and d) data.