Project Title: The Use of Radar Methods to Determine Moisture Content in the Vadose Zone
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Research Group: This research project currently involves two graduate students (James Irving, Stephen Moysey) and one research scientist (Paulette Tercier).

Research Objective

Moisture content is a critical parameter affecting both liquid-phase and vapor-phase contaminant transport in the vadose zone. The objective of our three-year research project is to determine the optimal way to use radar methods as a non-invasive means of determining *in situ* moisture content.

Research Progress and Implications

This report describes the progress that has been made in the fourth year of our 4-year research project. We had a one-year no-cost extension to the original 3-year project.

Determining the large-scale facies structure of the subsurface is of first-order importance for predicting contaminant fate and transport at sites like Hanford. Our efforts in this regard have focused on using neural networks to interpret facies from radar data. We have focused on investigating approaches that result in probabilistic or 'fuzzy' facies interpretations, which allow us to account for uncertainty in the interpretation of the radar data.

A major success over the past year has been the integration of our radar facies analysis with geostatistics allowing for the generation of conditional facies realizations constrained to both radar and well log (or core) data (Moysey et al., 2003). Developing an approach that merges multiple data types is a critical step in improving the prediction of contaminant transport. Additionally, building groundwater models that are conditioned to the most data possible results in the lowest uncertainty in flow and transport predictions. Although this concludes this line of investigation under the current DOE grant, we have obtained further funding from the National Science Foundation for continued research on this topic.

One approach in the use of radar methods to characterize the vadose zone is to determine the dielectric constant of sampled volumes of the subsurface and then use rock physics relationships to obtain estimates of water content. We have been able to show that in complex geologic environments, however, choosing the appropriate rock physics relationship to make this transformation to water content is not clear-cut (Moysey and Knight, 2002b); the relationship selected must apply at the field-scale, where GPR measurements are relevant, but can typically only be calibrated using core-scale information. By accounting for the scaling behavior of both the water content and dielectric constant, we have developed a methodology to derive the needed field-scale rock physics relationships from measurable core-scale relationships. Additionally, using geostatistical media as a starting point, we have derived analytical solutions that account for the transformation between scales in terms of commonly available geostatistical parameters (e.g., mean, correlation length, anisotropy, etc.).

In the past year we completed another study also focused on the use of radar data to determine subsurface moisture content. In collaboration with Chris Murray, Mark Rockhold and Gene Freeman at Pacific Northwest National Lab we assessed the usefulness of GPR data as a means of characterizing the spatial variation in water content at Hanford. Available for our study were GPR data and neutron probe data from the Sisson and Lu test site. The comparison of probe-derived water content data, synthetic radar data, and the acquired radar data indicated a good correspondence between the changes in water content and the location of reflections in the radar data. Geostatistical analysis was conducted of the two sets of water content values and the amplitudes of the reflections in the radar section. The experimental semivariograms for the three data sets were similar in form and were assessed in terms of the scales (sampling, extent and support) of the two forms of measurement. We have concluded that surface and borehole radar measurements can provide valuable information about subsurface water content at Hanford. The ideal way to use radar measurements would be to acquire radar data in boreholes, to determine the relationship between radar data and water content, and then use surface radar measurements to provide information between or away from borehole locations.

Our geostatistical analysis of the radar and neutron probe data has led to further investigation of the affect of the support volume of a measurement on the determined correlation structure. To better understand how support volume affects correlation length we are in the process of examining a number of different digital photographs of both the natural world and man-made structures. The original images, 1024 x 1024 pixels in size are first analyzed for their "true" (i.e. best resolution) correlation lengths. To understand how increasing support volume affects the determined correlation length of these images we increased the resolution of the images using three different block-averaging schemes: horizontal block averaging, vertical block averaging, 2D block averaging. The first method involves averaging pixels within a set rectangle size along each row in the image; (e.g. 32 x 1 pixel block), the second averages pixels within a set rectangle size along each column, (e.g. 1 x 32 pixel block), and in the third scheme the number of row and column pixels averaged are equal thus the averaging is over a block with square dimensions, (e.g. 32 x 32 pixel block). In general, as the size of the averaging block increases so does the determined correlation length. This is similar to what we have found with the analysis of multi-frequency GPR data; as the frequency is decreased the support volume is increased and thus the determined correlation length increases.

Another focus over the past year has been the investigation of how surface and crosshole radar data can be used together to quantify the distribution of water content in the vadose zone. We are currently working on an effective methodology for integrating these two forms of data for electromagnetic (EM) wave velocity tomography. This will improve our ability to quantify the distribution of moisture content in the vadose zone at the sub-meter scale, through providing more accurate and higher-resolution velocity tomograms of the subsurface.

Related to this, we have spent considerable time over the past year investigating the significance of saturation-dependent EM wave velocity anisotropy in the subsurface. Numerical models that we have developed indicate that, in the saturated zone, EM wave velocity anisotropy due to fine-scale layering of sediments can usually be ignored. In the vadose zone, however, our models (which are based on the assumptions of effective medium theory and capillary equilibrium between layers) indicate that significant EM wave velocity anisotropy can exist due to the strong dependence of velocity upon saturation, and the pronounced saturation heterogeneity that can exist between layers. During the summer of 2002, crosshole radar data were collected at a site near Abbotsford, British Columbia in order to investigate these results. These data were acquired between two wells located 5.89 m apart and 25 m deep, and the water table at the time of the survey was 17.5 m below the surface. Analysis of the data indicates that, in the vadose zone, anisotropy is significant. We are currently in the process of developing a bent-ray anisotropic inversion code so that this vadose zone anisotropy can be compared with the amount of anisotropy present in the saturated zone.

An important contribution to our GPR research was the development, over the past year, of 2-D numerical models for both crosshole and surface-based GPR using the finite-difference time-domain (FDTD) technique. These forward models will play a key role in our research by allowing us to create synthetic data sets on which we can test and evaluate processing and inversion methodologies before applying them to field data.

Planned Activities

The summer will be spent completing the research and publications related to the remaining three studies underway related to this research project. We are currently completing a paper on the scaling of the dielectric constant-water content relationship, which is to be submitted for publication in the summer of 2003. The paper describing the study of the use of GPR data for characterizing water content at Hanford is close to completion and will be submitted in the near-future to Water Resources Research. In the time period between June and August, 2003, we plan to finish a 1-D anisotropic inversion code that incorporates ray bending, so that the crosshole radar data collected last summer at the Abbotsford test site can be inverted for anisotropy both in the vadose and saturated zones. Our goal is to be able to compare the degree of EM wave velocity anisotropy above and below the water table, in order to validate our numerical results.

Information Access: (Publications related to this research)

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Knight, R., Ground Penetrating Radar for Environmental Applications, Annual Review of Earth and Planetary Sciences, 29, 229-255, 2001.

Knight, R. J., Irving, J., Freeman, E., and Tercier, P., The use of ground penetrating radar for site characterization at Hanford, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6-10, 2003, San Antonio, TX,

Moysey, S., R.J. Knight, R.M. Allen-King and J. Caers, The construction of stochastic facies-based models conditioned to ground penetrating radar images, 4th International Conference on Calibration and Reliability in Groundwater Modelling, Universita Karlova, Prague, Czech Republic, June 2002.

Moysey S. & R.J. Knight, 2002b, The effect of change in scale on water content estimates derived from ground penetrating radar data, *EOS Trans. AGU*, 83(47), Fall Meet. Suppl., Abstract T22B-1148.

Moysey S., J. Caers, R.J. Knight, R.M. Allen-King, Stochastic estimation of facies using ground penetrating radar data. Accepted for publication in *Stochastic Environmental Research and Risk Assessment,* May 2003.