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Collaborative Research: Hydrogeological-Geophysical Methods for Subsurface Site Characterization

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Research Objective

The general purpose is the subsurface characterization of LLNL superfund site. The goal is to get the most accurate map of the hydrogeological parameters, necessary for modeling and designing the cleanup efforts at the site, using well log data and remote sensing geophysical techniques.

Research Progress and Implications

In the second year of the project progress has been made in several areas: gathering and interpreting Vertical Seismic Profile (VSP) and Electromagnetic (EM) surveys; investigating the impact of various seismic measurements on upscaling of rock physics relations between sediment properties; and developing a new approach to integrate geophysical and hydrological data using state of the art methods to characterize the subsurface lithology.

Vertical Seismic Profile data has been gathered from selected wells at the Treatment Facility D (TFD) during April 1996 and April 1998. The most striking finding here is the detection of anomalies related to saturation conditions. Preliminary results have revealed three anomalously low acoustic velocity zones with velocities below 1000 m/s; this is lower than the natural acoustic velocity in saturated media by pure water (1500 m/s).

These three zones appear to be associated with HSUs 3a, 3b and 5. Velocities below 600 m/s have been revealed in the 3a and 3b HSUs (**http://www.ce.Berkeley.edu/~ezzedine/DOE/paul.html**). We believe that these anomalies are indicative of partial saturation. This explanation is supported by the water samples taken from pumping stations near the VSP well sites which appears to contain air bubbles. A gas analysis of water samples has not yet been performed. We hypothesize that this gas can be either air being sucked-in from the vadose zone above the water table, or from some chemical reaction. As a matter of fact, the natural water table level at this site was around 20m below ground surface before any large scale pumping began, and had dropped to 25.5m, in April 98. Furthermore, some of these low velocity zones are occurring not only in the major free-flowing sand or gravel parts of the HSU, but in boundary layers of silty sand either above or below the main HSU conductor.

An electromagnetic survey was conducted at the site during June 4-25, 1997, and we worked on its interpretation. Seven cross well EM data sets were collected. Both 1D and 2D simulations, approximating the actual site and survey setup, were conducted. The 1D simulations were conducted using the code EM1D for one data set. Newman and Alumbaugh's 3D forward code was used to simulate the response of both a resistive layer (representing HSU 4) and a conductive layer at the same location. Three separate inversion algorithms were applied to the data: Newman and Alumbaugh's 2.5D finite difference and integral solution algorithm, Alumbaugh's iterative Born approximation with a cylindrical symmetry, and Tseng's 3D extended born approximation. The field EM data are still being analyzed.

A synthetic model consistent with the shallow unconsolidated nature of the sediments at the site was built, to investigate the impact of various seismic measurements on upscaling petrophysical relations such as velocity-porosity and velocity-clay relations. The available well logs were used to assign distributions of physical properties to different facies. Care was taken to build the model self-consistently by taking into account relations between facies type, clay content, porosity, resistivity, and velocity in unconsolidated media. Once a consistent earth model was built, we simulated a surface seismic image using a single scattering, frequency domain, and the Born filter approximation

methods, which allowed us to estimate the impact of various measurement geometries and bandwidths on the spatial distribution of the imaged seismic velocity. Cross section of the 'true' fine scale velocity model, and the synthetic surface seismic image reveal a smoothing effect caused by the limited frequency bandwidth and aperture of the simulated seismic measurement (**http://water.stanford.edu/doe/**).

Velocity-porosity and velocity-clay relations which may be perfectly correlated at a fine scale appear to have large scatter when imaged at a coarser scale. We used the Born filter approximation as well as traveltime algebraic reconstruction tomography to explore the scatter introduced by the imaging in the bilinear velocity-clay relation for a dispersed binary mixture model of shaly sand sediments. We built a simple filter in the frequency domain to estimate the seismic response of various measurement scenarios. The filter response was designed to match a tomographic image obtained by numerically simulating wave propagation for a cross-well geometry, picking the synthetic seismograms, and inverting the traveltime pick using an ART algorithm. The frequency domain filter provides a very fast and efficient way to explore multiple stochastic realizations and scenarios such as varying saturations, pressures, and clay content, without having to do a full finite-difference wave propagation and inversion. This tool can be used to map out the space of uncertainty by applying it to large numbers of stochastic simulations of the random velocity field.

One of the important issues in using rock physics to interpret seismic and VSP velocities at the site is to understand the variations of velocity with lithology and clay content relative to the velocity sensitivity to pore fluid saturations. Therefore, we compared the VSP velocities for different lithologies to laboratory data on loose sediments. The VSP velocities are comparable to the laboratory data, suggesting that laboratory derived velocity models may be applicable at this site. The velocities do not show a strong dependence on lithotype.

A conceptual data-driven approach for hydrogeological mapping based on the well logs, and cross well geophysical data has been developed (**http://www.ce.Berkeley.edu/~ezzedine/DOE/**). The general framework is hierarchical stochastic, and it consists of three major steps, starting from mapping lithofacies, and ending in high resolution hydrogeological mapping: (1) the unknown image of the sand/silt cross-section is developed as a particular realization of a two or three-dimensional, statistically homogeneous binary random field. Sequential Indicator Simulation for lithology estimation is employed for that purpose. The indicator is defined by its unconditional univariate probability distribution function (pdf), or can be made conditional to binary-valued observations of lithology at the wells, and can be further updated if geophysical data is available and is informative. The outcome of this step is a complete stochastic characterization of the spatial distribution of sand and silt, and a series of lithology images; (2) each of the lithology images generated are overlain with an image of the shaliness generated using facies-specific pdf. The spatial correlation structure of the shaliness is determined by its variograms facies specific. The outcome of this step is a serious of shaliness images, which will be converted to resistivity images. Our focus on shaliness stems from the observation that it displays a well defined spatial correlation structure, it correlates well with resistivity, and can be used to infer other hydrogeological properties; (3) a prior non stationary pdf is assigned to each point over a regular grid. These pdfs are obtained from the petrophysical relationship, once a location is identified as being as either in the sand or silt facies and a measurement or generated value of the shaliness is specified. Unless additional information becomes available, prior resistivity pdf's can be used for generating resistivity values. To further update the pdf's of the resistivity, we adopted a Bayesian framework where the prior resistivity pdf's are combined with the pdfs of the likelihood resistivity image obtained from Electromagnetic (EM) surveying to get an updated resistivity image.

These concepts were implemented to one HSU using all available well data at TFD at LLNL superfund site. Extension to all HSUs is straightforward. Statistical analysis of the updating procedure showed the tremendous improvement in the estimation of the posterior resistivity image.

Planned Activities

Several activities are planned in all areas for the third year of the project:

(1) more VSP data acquisition has to be done to get an adequate areal coverage of low velocity zones to map them. Also, an adequate hydrostratigraphic and/or chemical model will have to

be worked out to explain these low velocity zones. If this model directly links pumping activity with the areal spread of these low velocity zones, then perhaps continuous (time lapse) VSP surveys may be performed to help control and direct which wells to pump from, and at what rates;

(2) EM cross well surveys will be analyzed and compared with the VSP surveys;

(3) results of VSP and EM will be integrated in the Bayesian stochastic hydrogeological-geophysical subsurface characterization model; and

(4) the integration between EM and VSP will be further investigated using synthetic studies.