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Joint Inversion of Geophysical Data for Site Characterization and Restoration Monitoring

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Research Objective

The purpose of this project is to develop a computer code for joint inversion of seismic and electrical data, to improve underground imaging for site characterization and remediation monitoring. The computer code developed in this project will invert geophysical data to obtain direct estimates of porosity and saturation underground, rather than inverting for seismic velocity and electrical resistivity or other geophysical properties. This is intended to be a significant improvement in the state-of-the-art of underground imaging, since interpretation of data collected at a contaminated site would become much less subjective. Potential users include DOE scientists and engineers responsible for characterizing contaminated sites and monitoring remediation of contaminated sites. In this three-year project, we use a multi-phase approach consisting of theoretical and numerical code development, laboratory investigations, testing on available laboratory and borehole geophysics data sets, and a controlled field experiment, to develop practical tools for joint electrical and seismic data interpretation.

Research Progress and Implications

This report summarizes work after about 1.7 years of a 3-year project. Progress on laboratory measurements is described first, followed by progress on developing algorithms for the inversion code to relate geophysical data to porosity and saturation.

Since limited information is available for unconsolidated sediments at low pressures appropriate for the near-surface, particularly for sediments containing clays, we have made our own laboratory measurements for unconsolidated sand-clay mixtures and are in the process of reducing and interpreting both elastic and electrical properties data. We have been conducting a series of electrical and elastic properties measurements on sand-clay mixtures containing 0%, 3%, and 10% clay, using filtered, deionized water, tap water, and $CaCl_2$ brines having a range of different salinities for the saturating fluids. The conductivity of the solutions ranged from about 0.002 mS/cm to 64 mS/cm. Fully saturated samples were used for electrical conductivity measurements. Dry and fully saturated samples were used for the velocity measurements since partial saturation introduces a significant degree of complexity to the problem. We have been investigating the effects of different clays such as kaolinite, bentonite, and a natural clay-rich soil called Alligator clay. We have used various mixing techniques to construct the sand-clay samples, since the microgeometry is a critical factor affecting measured elastic and electrical properties. We measured porosities and permeabilities as well as geophysical properties. This provides the needed information for developing relationships between geophysical properties and the hydrogeologic parameters that are most useful for environmental applications. Our laboratory measurement results suggest that microstructure controls the geophysical properties. Thus microstructure assumptions used in empirical or theoretical methods may be the determining factor for which methods are most successful in relating geophysical properties to porosity and saturation.

The results of velocity measurements on samples containing swelling clays are described in the Bonner et al. (1997) reference listed in the Additional Information section of the Web version of this report. The major implication of these results is that the wave amplitudes are critical data, as well as the wave velocities, and that the vadose zone may have more complex behavior than deeper regions.

Results of electrical conductivity measurements showed that the bulk sample conductivity ranged from approximately 0.023 to 14.3 mS/cm for pure sand; 0.1 to 6.4 mS/cm for 3% clay; and 0.4 to 3.5 mS/cm for 10% clay. The bulk sample conductivity varies linearly with the fluid conductivity according to the equation

$$sbulk = sfluid/F + 2Ss/LF$$

where F is the formation factor, Ss the surface conductance, and L is a geometrical parameter related to dynamically connected pore sizes. Estimates of the formation factor F range from ~4.5 for the pure sand sample to ~12.8 for the 10% clay sample. More details on these results are in the Additional Information section of this report.

We are developing the necessary algorithms for the inversion code using a flexible approach that allows us to assess the relative usefulness of geostatistical methods, empirical techniques commonly used in borehole geophysics interpretation, and rock physics theories that describe how elastic wave velocities and electrical conductivities depend on porosity and saturation in porous materials having different microgeometries. For testing geostatistical methods, we have made an exhaustive search of the marine geophysics, civil engineering, soil mechanics, exploration geophysics, and environmental geophysics literature to find available information on rock properties measurements for unconsolidated sands and clays at low pressures (i.e. shallow depths). We have compiled a database containing elastic properties data for unconsolidated sediments that we are using to modify and test the necessary algorithms for relating elastic properties to porosity and saturation for dry and fully saturated sediments. We found that laboratory data for very low pressures appropriate to shallow depths (e.g., the top 50 m of the subsurface) are sparce and contain large amounts of uncertainty. Our own laboratory measurements greatly augment the available database for elastic properties, particularly since we were able to obtain reliable shear wave measurements at very low pressures. For the rock physics approach, we have selected theories that are appropriate for the microstructures typically found in shallow sediments, including the self-consistent theory developed by Berryman and theories that provide bounds on rock properties, particularly the lower bound for an unconsolidated medium. Additional work on effective medium theories is described in the Berryman and Pride (1997), Dvorkin et al. (1997), and Pride et al. (1998) References listed in the Additional Information section. Existing effective medium theory methods commonly used with consolidated materials at moderately high pressure conditions, such as the differential effective medium theory algorithm that Berge developed for modeling velocities of volcanic rocks and cemented sandstones, are not appropriate for application to the near surface environment. One early implication of our work is that codes typically used in the oil industry cannot be applied to environmental applications if they rely on theoretical methods such as the differential effective medium theory.

Planned Activities

The schedule of this project is as follows: In the first year, investigators perform laboratory measurements of elastic and electrical properties of sand-clay mixtures containing various fluids. Investigators also develop methods of relating measurable geophysical properties to porosity and saturation by using rock physics theories, geostatistical, and empirical techniques together with available laboratory measurements. In the second year, investigators finish any necessary laboratory measurements and apply the methods developed in the first year to invert available borehole log data to predict measured properties of cores and sediments from a borehole. Investigators refine the inversion code in the third year and carry out a field experiment to collect seismic and electrical data. Investigators then use the inversion code to invert the field data to produce estimates of porosity and saturation in the field area where the data were collected.

Other Access To Information

Additional Information

This section provides additional detail on the laboratory measurement results and a list of the publications that were produced as part of this EMSP project.

Additional Details of Laboratory Results

We found that small amounts (3%) of swelling clay affect the pressure (depth) dependence of elastic wave velocities at low pressures (below 0.1 MPa, i.e. top few m), and the ratio of amplitudes for compressional and shear waves depends on clay content even for small amounts of clay. Saturated samples behaved like mechanical suspensions, as expected. Experiments with imbibition and with drained samples showed that minor residual gas in saturated samples and residual fluid retained by the clay in a drained sample strongly affect wave amplitudes. We are working on determining the surface conductance term and L parameter for each sample. The surface conductance contribution is apparent in plots of log bulk sample conductivity versus log solution conductivity where two distinct regions are indicated: one where the log bulk sample conductivity is nearly independent of log solution conductivity (fluid conductivities less than ~ 1 mS/cm), and another region where the log sample conductivity varies directly with log fluid conductivity (fluid conductivities greater than ~1 mS/cm). We observe that the pure sand sample does not display the above described flat region indicating no surface conduction component exists in the absence of clay. The greater the clay content, the greater the surface conduction contribution to bulk sample conduction. Measurements are currently being performed on samples containing ~10% clay in layers or distributed as discrete domains as a test of effective medium models.

Publications

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