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13. ABSTRACT *(Maximum 200 words)*
This is the final report on a field and modeling study aimed at developing methods to map permeability by combining hydrologic and surface geophysical data. Results include: recognizing variation in cobble-and-sand units with principal components analysis based on borehole geophysical logs; demonstrating a method for recovery of core from these coarse deposits; determining stiffness and damping coefficients by jointly inverting velocity dispersion and attenuation data from vertical seismic profiles (VSPs); recognizing variation below the water table with VSPs, transient electromagnetic soundings, and ground penetrating radar; demonstrating a method for modeling hydrologic responses at a well with MODFLOW; generating program developments in MODFLOW and MODFLOWP to facilitate modeling 3-D heterogeneous aquifer systems. Also, findings from this project were the basis for a follow-on, five-year URISP project to develop a field-scale control volume (research wellfield) to continue research to develop methods for mapping permeability with non-invasive surface geophysical methods.

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JOINT INVERSION OF HYDROLOGIC AND GEOPHYSICAL DATA
FOR PERMEABILITY DISTRIBUTION OF AN ALLUVIAL AQUIFER

FINAL PROGRESS REPORT

WARREN BARRASH

NOVEMBER 24, 1998

U.S. ARMY RESEARCH OFFICE

GRANT NUMBER DAAH04-94-G-0271

BOISE STATE UNIVERSITY

STATEMENT OF PROBLEM STUDIED

This project addresses the need for non-invasive techniques for characterizing subsurface stratigraphy and the three-dimensional (3-D) distribution of permeability in natural shallow, alluvial aquifers to improve groundwater flow and contaminant transport modeling and remediation of groundwater contamination in these aquifers. It is widely acknowledged that permeability is the most important parameter influencing groundwater flow, contaminant transport and the design and performance of remediation systems. However, direct information on the distribution of permeability usually is too sparse to adequately describe the variation in permeability in alluvial aquifers because well costs limit the number of wells that can be placed at a given site, and current methods for interpolating and extrapolating the distribution of permeability away from wells have high degrees of uncertainty. The problem then, is to develop methods of using surface geophysical (non-invasive) methods which can rapidly and inexpensively provide information about physical properties in the subsurface to supplement sparse direct information on permeability at wells. The particular alluvial aquifer for study in Boise, Idaho is comprised of very coarse (cobble-and-sand), braided stream deposits - a generic class of sedimentary aquifers which, due to the large clast sizes, pose additional problems for subsurface control because (a) lithology and facies cannot be determined directly from conventional drilling or coring, and (b) borehole samples are not representative and so cannot be used for laboratory measurements of physical or hydrologic properties.

SUMMARY OF MOST IMPORTANT RESULTS

The goal of this project is to develop a method for mapping variations in permeability in a shallow, heterogeneous, very coarse (cobble-and-sand) alluvial aquifer with non-invasive surface geophysical techniques by jointly inverting geophysical and hydrologic data. Achievement of this goal requires: (1) accurate measurement of subsurface geological, geophysical and hydrologic parameters at control locations (in wells) in order to determine relationships between permeability and parameters measurable with geophysic at the surface, (2) the "tuning" of surface geophysical techniques for measurement of these parameters with sufficient resolution and certainty to recognize subsurface property changes that can be related to permeability variations in the shallow subsurface, and (3) determining the 3-D distribution of permeability independently of geophysical methods to test the validity of permeability mapping techniques based on geophysical methods. Project field activities were conducted at the Capital Station groundwater remediation site in downtown Boise, Idaho where the Center for Geophysical Investigation of the Shallow Subsurface at Boise State University was provided access to the site including pre-existing wells, and was permitted to emplace an addition well to experiment with coring methods.

This project has made significant progress in the component steps necessary for achieving the project goal by: (1) demonstrating a method for high-percentage recovery of core in unconsolidated, very coarse, conglomeratic sediment (i.e., >80% recovery including cobbles with associated sand matrix) for direct information on lithologic units in this highly variable medium (Barrash et al., 1997a, 1997b); (2) demonstrating a method for distinguishing between different types of cobble-dominated facies in wells in these deposits with multivariate statistical analysis (principal components analysis) on data from three types of borehole geophysical logs: neutron, natural gamma, and induction resistivity or conductivity (Barrash and Morin, 1996, 1997); (3) demonstrating the capability of recognizing vertical variations of geophysical properties in the upper 20 meters of the shallow subsurface in boreholes or 1-D vertical soundings with three accessible geophysical methods: seismic reflection, ground penetrating radar (GPR), and time-domain electromagnetics (TEM) (Barrash et al., 1995, 1997a); (4) demonstrating methods for measuring permeability variations: (a) confirming flowmeter and pumping method for determining permeability profiles in wells (where other borehole data sets are available for developing relationships to permeability), and (b) demonstrating a discretization scheme in MODFLOW that permits accurate simulation of transient responses at partially penetrating pumping wells in 3-D heterogeneous systems (Barrash and Dougherty, 1995, 1997) - thereby providing a means to conduct a series of such tests with multiple observation points at discrete intervals in multiple observation wells and determine the 3-D distribution of permeability with measured hydrologic response information ("hydrologic tomography") independent of geophysical measurements; and (5) developing program modifications in MODFLOW and MODFLOWP to facilitate modeling transient hydrologic conditions in 3-D heterogeneous systems (Huang et al., 1998). In addition, (6) responses to SH seismic waves in vertical seismic profiling (VSP) experiments were modeled using the Voigt model for soil particle motion to determine damping and stiffness coefficients (useful engineering parameters, also related to permeability and storativity respectively) from joint inversion of SH-wave attenuation and velocity dispersion Michaels and Barrash, 1996, 1997; Michaels, 1998). And (7) findings from this study (which was conducted at a contaminated groundwater site undergoing remediation) were the basis for a follow-on proposal to the URISP program; this proposal was funded (ARO Project 38502-RT-RS) and the Center for Geophysical Investigation of the Shallow Subsurface at Boise State University currently is developing a research wellfield and conducting a testing program there to provide the necessary subsurface control to achieve the goal of developing methods for mapping variations in permeability in a shallow, heterogeneous, coarse (cobble-and-sand) alluvial aquifer with non-invasive surface geophysical techniques by jointly inverting or combining geophysical and hydrologic data (Barrash and Knoll, 1997, in press).

References cited in this section are the publications and technical reports produced as part of this project. Full citations are given in the following section.

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In addition, Boise State University graduate students and undergraduate students are employed on an irregular help basis to assist with geophysical field experiments associated with the site selection process.

REPORT OF INVENTIONS: N/A