USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Relationship Between the Properties of Seismic Shear-Wave Reflections and the Hydraulic Conductivity Contrast Across a Shallow Subsurface Interface

Focus Categories: GW, SED, MET

Keywords: Hydraulic Conductivity, Seismic Methods, Shear-Wave Reflection

Duration: March 1, 1999 – February 28, 2002

FY 2000 Federal Funds: $9,672

FY 2000 Non-Federal Funds: $19,344

Principal Investigators: Dr. John R. Pelton, Geology, Boise State University

Congressional District: Second

Statement of Critical Regional or State Water Problems

Shallow heterogeneous alluvial aquifers are vulnerable to contamination from a wide variety of sources in the Treasure Valley and throughout Idaho. In the Boise area, examples of recent contamination problems include sites in Garden City, downtown Boise, the Curtis Road area, and near the Boise Town Square mall. Contamination at shallow depths cannot be overlooked because it may impact water quality in the deeper aquifer system which is the source of nearly all of the water supply for Canyon County and northern Ada County. The proper design of remediation systems for shallow contaminated aquifers is heavily dependent on knowledge of the three-dimensional distribution of hydraulic conductivity. Since direct measurements of hydraulic conductivity are expensive and are almost never acquired on a sufficiently dense grid, there is widespread (regional, national, and international) interest in developing more economical indirect methods of measurement.

Statement of Results or Benefits

For relatively little cost, the research proposed here will provide the necessary scientific basis to pursue a possible new seismic method for indirect estimation of hydraulic conductivity in shallow heterogeneous alluvial aquifers. Specifically, we will learn whether or not (and under what conditions) changes in the amplitude and phase spectra of reflected shear waves can be linked theoretically and experimentally to the contrast in hydraulic conductivity across a reflecting interface in saturated shallow sediments. Because of the comprehensiveness and high quality of the data to be supplied to this project (from the Boise Hydrogeophysical Research Site), the probability is very high that the results will provide unambiguous answers and a solid foundation for future development work.

Nature, Scope and Objectives of the Research

It is well accepted that the ability of hydrogeologists to model groundwater flow and contaminant transport far exceeds their ability to adequately parameterize the subsurface. Of particular concern is the difficulty of defining the three-dimensional distribution of hydraulic conductivity (K) in complex aquifers where the bulk of the water movement is commonly restricted to one or more highly conductive paths. Research on this problem is proceeding internationally on numerous fronts including the development of new hydrologic techniques for direct measurement of K (e.g., Barrash and Knoll, 1998), the use of geophysical effects that depend on a physical connection between certain geophysical parameters and K (e.g., Hyndman and Gorelick, 1996), and the fusion of different data types to take advantage of as many constraints on K as possible (e.g., McKenna and Poeter, 1995). The work proposed here provides the necessary basis for a possible new geophysical contribution to the problem of estimating K at shallow depths in saturated sediments. This proposal seeks support to investigate a frequency-dependent effect associated with the reflection of seismic shear waves from an interface between two near-surface saturated sedimentary materials of contrasting hydraulic conductivity. Recent theoretical work predicts that the reflection of horizontally polarized shear waves under these conditions will be accompanied by a change in amplitude and phase that is a function of frequency (Pelton, 1999). The frequency-dependent change in amplitude is small and probably not useful because of the many factors that affect the amplitude of seismic waves. However, the frequency-dependent change in phase in the 10-100 Hz bandwidth is quite significant and potentially useful for deducing the relative change in K across the interface. The next logical step, and the basic objective of the proposed research, is to confirm the existence of the frequency-dependent phase effect using real data acquired at a research site where K is known. If this effect can be confirmed, then future work can focus on the inverse problem of estimating K from shallow shear-wave reflections recorded in boreholes or from the surface.

Note: A brief description of previous research that is the basis for this proposal is provided in item 14. References for all citations are given after item 16.

Method, Procedures and Facilities

The Boise Hydrogeophysical Research Site (BHRS) provides an ideal facility for the proposed research (Barrash et al., 1999). It consists of 18 specially designed and instrumented boreholes developed in a coarse near-surface alluvial aquifer about 15 km east of downtown Boise. The central cluster of 13 wells spans an area of approximately 320 m^2 and penetrates to a depth of about 25 m. All wells have been cored and have complete lithologic descriptions. A full range of hydrologic and geophysical tests are completed or are underway at the site, including experiments with sources and receivers located at the surface, within boreholes, and between boreholes. Of particular importance are 3-component vertical seismic profiles (used to study properties of seismic wave transmission and reflection), EM-flowmeter measurements that provide hydraulic conductivity vertical profiles in all of the wells, and gamma- gamma logs that give mass density vertical profiles. The research proposed here will be carried out using these data according to the following procedure:

> A. Vertical seismic profile (VSP) data will be processed to accentuate horizontally polarized shear-wave (SH) reflections. Existing BHRS seismic data show several reflecting interfaces that span the central wellfield. At least one reflecting interface will be chosen for analysis.
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> B. Processing of the SH-VSP attenuation and dispersion data using the procedure of Michaels (1998) will independently determine Kelvin-Voigt stiffness and damping parameters assignable to either side of the reflecting interface. These results, together with the gamma-gamma density profiles, provide the data needed to compute SH reflection coefficients according to expressions developed by Pelton (1999).
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> C. Amplitude and phase spectra will be computed from records of incident (downgoing) and reflected (upgoing) SH waves arriving at a common receiver located slightly above the reflecting interface. Small corrections are anticipated because of small differences in the length of the travel path between the incident and reflected waves arriving at the common receiver. Comparisons between the incident and reflected spectra should be consistent with the Pelton (1999) reflection coefficients, thereby confirming the theoretical basis of the coefficients.
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> D. Using the hydraulic conductivity data, investigate the relationships, both theoretically and empirically, between the amplitude and phase spectra of the reflected SH waves and the hydraulic conductivity contrast across the reflecting interface.

All data used for the proposed research (SH-VSP, EM-flowmeter, and gamma-gamma density) are acquired as a result of very high-quality characterization efforts at the BHRS and are provided at no cost to the project. All data processing will be done using CGISS computational facilities which includes approximately 10 workstations (Linux, MacOS, Windows), comprehensive peripheral devices (printers, plotters, scanners, tape drives, CD read/write, massive hard drive storage), and extensive geophysical and general-purpose computational and scientific software.

Results will be presented at a national professional conference such as the Symposium for the Application of Geophysics to Environmental and Engineering Problems (SAGEEP) at no cost to the project. Page charges have been included to pay for publication in a refereed journal.

Related Research

Barrash, W., and M. D. Knoll, Design of research wellfield for calibrating geophysical methods against hydrologic parameters, *Proceedings of the 1998 Conference on Hazardous Waste Research* (Snowbird, UT), Great Plains/Rocky Mountain Hazardous Substance Research Center, Kansas State University, Manhattan, KS, 296-318, 1998. Barrash, Warren, Clemo, Tom, and Michael D. Knoll, Boise Hydrogeophysical Research Site (BHRS): objectives, design, initial geostatistical results, *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems* (SAGEEP99- Oakland, CA), Environmental and Engineering Geophysical Society, Wheat Ridge, CO, 389- 398, 1999. Biot, M. A., Theory of elastic waves in a fluid-saturated porous solid. I. low frequency range, *J. Acoust. Soc. Am.*, 28, 168-178, 1956a. Biot, M. A., Theory of elastic waves in a fluid-saturated porous solid. II. higher frequency range, *J. Acoust. Soc. Am.*, 28, 179-191, 1956b. Biot, M. A., Mechanics of deformation and acoustic propagation in porous media, *J. Appl. Phys.*, 33, 1482-1498, 1962a. Biot, M. A., Generalized theory of acoustic propagation in porous dissipative media, *J. Acoust. Soc. Am.*, 34, 1254-1264, 1962b. Hyndman, D. W., and S. M. Gorelick, Estimating lithologic and transport properties in three dimensions using seismic and tracer data: the Kesterson aquifer, *Water Res. Res.,* 32, 2659- 2670, 1996. Kramer, S. L., *Geotechnical Earthquake Engineering*, Prentice-Hall, Englewood Cliffs, NJ, 1996. Malvern, Lawrence E., *Introduction to the Mechanics of a Continuous Medium*, Prentice-Hall, Englewood Cliffs, NJ, 1969. McKenna, S. A., and E. P. Poeter, Field example of data fusion in site characterization, *Water Res. Res.*, 31, 3229-3240, 1995. Michaels, P., In situ determination of soil stiffness and damping, *Journal of Geotechnical and Geoenvironmental Engineering*, 124, 709-719, 1998.

Pelton, J. R., Amplitude and phase effects of SH reflection at a near-surface contrast in hydraulic conductivity, *Expanded Abstracts of the Technical Program*, 70th Annual International Meeting and Exposition of the Society of Exploration Geophysicists (Tulsa, OK), Calgary, Canada, in preparation for submission, 1999.

Although linear elasticity theory can describe many features of seismic wave propagation, it cannot account for the observed intrinsic attenuation and dispersion of body waves (P and S) because the elastic constitutive equation does not include a dissipative mechanism. Of the many dissipative mechanisms that have been proposed, viscous interaction of pore water with the granular frame of an aquifer is the primary interest in hydrogeological applications. Theoretical analysis of seismic wave propagation featuring this dissipative mechanism was carried out by Biot in a classic series of papers (1956a, b; 1962a, b) that provided the basis for many subsequent theoretical and experimental investigations. The results of this large body of work, when applied to near-surface water-saturated sediments and seismic frequencies, indicate that in fine-grained materials with low permeability, dissipation of wave energy occurs mostly at the interfaces between grains (friction and other inelastic effects), whereas in coarser-grained sediments of relatively high permeability, dissipation is dominated by viscous interaction between the pore water and the frame. Furthermore, it has been shown that these different dissipative mechanisms give rise to fundamental differences in the attenuation and dispersion of body waves. We may conclude that attenuation and dispersion of seismic waves propagating in a shallow granular aquifer are linked to grain-size and permeability, and thus to hydraulic conductivity. The characteristics of other features of seismic wave propagation, such as reflection, should be similarly linked to hydraulic conductivity.

A common way to incorporate a dissipative mechanism in the theory of seismic wave propagation is by modeling the subsurface as a linear viscoelastic solid. Perhaps the simplest case is the Kelvin-Voigt model for which the mechanical analog is a spring in parallel with a dashpot (Malvern, 1969). The “strength” of the dashpot may be chosen to represent the degree of viscous damping in saturated permeable sediments. Although the deficiencies of the Kelvin-Voigt model are well known, it is commonly used in geotechnical engineering to represent the dynamic properties of soils (Kramer, 1996). Recently, Michaels (1998) has shown that the attenuation and dispersion of horizontally polarized shear waves (SH) in water-saturated near-surface sediments in the Boise area are consistent with the Kelvin-Voigt model in the frequency range of 10-100 Hz. Using this finding as justification for proceeding with the Kelvin-Voigt formulation (at least initially), Pelton (1999) has derived the reflection coefficient for a plane harmonic SH-wave incident on a plane interface separating two different Kelvin-Voigt solids. The work proposed here builds on the foregoing results by investigating the properties of SH-reflections at the Boise Hydrogeophysical Research Site in conjunction with borehole measurements of Kelvin-Voigt parameters, hydraulic conductivity, and mass density.