Detection and Mapping of Fractures and Cavities using Borehole Radar

F. P. Haeni, Geophysical Consulting (860-227-0643, fphaeni@snet.net)
Lucien Halleux, G-Tec (+32 87 79 52 22, l.halleux@gtec.be)
Carole D. Johnson, U.S. Geological Survey (860-487-7402, cjohnson@usgs.gov)
John W. Lane, Jr., U.S. Geological Survey (860-487-7402, jwlane@usgs.gov

Abstract

Borehole radar can be used in a single-hole reflection mode or in a cross-hole tomography mode. In the reflection mode, radar provides an image of discontinuities in the bedrock surrounding a borehole, including bedding planes, lithologic contacts, fractures, and cavities. The measurements are either directional or omni-directional, depending upon the type of equipment and antennas. In the tomography mode, where the transmitter and receiver are in separate boreholes, radar provides an image of the planar section between the boreholes. The radius of investigation depends on the antenna frequency and the electrical conductivity of the bedrock. For a central frequency of 100 megahertz, in the reflection mode the ranges are typically 10 to 40 meters in resistive solid rock and less than 5 meters in conductive, clay-rich, or silty rock.

Single-hole and cross-hole radar also have been used for water-supply investigations in the northeastern United States. Borehole radar was used to investigate crystalline bedrock in two rapidly developing communities that rely on water resources in the bedrock. The surveys were conducted and interpreted along with data from other borehole geophysical tools. The borehole radar surveys were used to identify the location and orientation of reflectors, locate the primary pathways of flow to the supply wells, and identify aquifer characteristics that may be useful in siting a production well and protecting high-yielding wells in crystalline rocks.

Borehole radar has been used to investigate fractures, cavities, and lithologic changes at several sites in Europe. The radar data has been interpreted in conjuction with the results of modeling of borehole-radar response. At the Grimsel nuclear waste laboratory in Switzerland, single-hole reflection and tomography methods were used to characterize the rock in inclined boreholes. At numerous geotechnical sites in Belgium, France, and the Netherlands, borehole radar has been used to characterize the rock and identify fractures and cavities.

Introduction

Subsurface radar techniques were developed in the early 1970s. They are based upon the propagation of electromagnetic (EM) waves in a frequency range from 10 to 2000 megahertz (Mhz). For borehole radar, the antennas are lowered in boreholes and they may be operated either in the cross-hole tomography mode or in the reflection mode. The surface ground-penetrating radar method is typically operated in the reflection mode only.

The petrophysical properties that influence the propagation of EM waves in the ground are the conductivity, which determines the attenuation of the wave, and the permittivity, which determines its propagation velocity (the "radar velocity"). The conductivity, or its inverse, the resisitivity, is one of the best known petrophysical parameters. It is measured by conventional resistivity and electromagnetic techniques. In normal rocks and soils, the conductivity is mainly influenced by the porosity, the saturation, and the conductivity of the fluid. Archie's law and other similar mixing laws describe the relation between these parameters. In the frequency range used by radar, the frequency dependence of the conductivity plays a major role: the effective conductivity increases significantly with the frequency, mainly due to the dipole relaxation of the water molecule. As a direct consequence, the range of radar techniques decreases with an increase in frequency. The permittivity or the relative permittivity is not widely used in geophysical techniques other than radar. The relative permittivity of common minerals ranges from 4 to 9 and freshwater has a relative permittivity of 81. Empirical mixing laws are available for estimating the permittivity of rocks and soils. Thus, the water content has a major influence on the permittivity, or, conversely, the permittivity deduced from a borehole radar survey is a good indicator of water content.

The use of surface radar often is precluded by the presence of a conductive topsoil that limits the penetration to a few meters (m). This problem does not exist for borehole radar, which is a major advantage. Compared to conventional logging techniques, which have a very short range (<0.3 m), borehole radar is characterized by a radius of investigation ranging from 1 meter to more than 50 meters, depending upon the conductivity

Citation: Haeni, F.P., Halleux, Lucien, Johnson, C.D., and Lane, J.W., Jr., 2002, Detection and mapping of fractures and cavities using borehole radar, *in* Fractured Rock 2002, Denver, Colorado, March 13-15, 2002, Proceedings: Westerville, Ohio, National Ground Water Association, 4p.

of the rockmass, the frequency, and the operating mode. The borehole radar method is complementary to conventional logging techniques.

In rocks, single-hole borehole radar is mainly used to provide high resolution information on the location, orientation, and lateral extent of individual fractures, cavities, and other discontinuities which are, or are not, intersected by the drilling. In the tomography mode, borehole radar is used to provide an image of the rock mass between two boreholes. The major limitation of this method is the attenuation of the signal in rocks or soils containing clay, silt, or conductive fluids.

Borehole radar in the reflection mode

The principles of borehole-radar reflection logging are similar to those of surface-radar profiling, except that the antennas are connected together and lowered as a single unit down an open or polyvinyl chloride-cased borehole (fig. 1). A radar pulse is transmitted into the bedrock surrounding the borehole. The transmitted pulse moves away from the borehole until it encounters material with different electromagnetic properties, such as at a fracture zone, or change in rock-type, or void. At this location, some of the energy in the radar pulse is reflected back towards the receiver, and some of it is transmitted further into the rock. A radar reflection profile along the borehole is created by taking a radar scan at each position as the antennas are moved in 0.1 to 1.0-m steps up or down the borehole. The typical reflection patterns from planar and point reflectors are shown in figure 1.

Radar-reflection logging can be conducted with omni-directional or directional receiving antennas. Omni-directional antennas are useful for rapidly identifying the location, dip, and lateral continuity of fracture zones, but directional antennas are required to determine the strike of planar reflectors or the azimuth to point reflectors. Because directional antennas are less efficient than omni-directional antennas, and cannot "see" as far into the surrounding rock as the omni-directional antennas, logging runs that use both omni-directional and directional receivers are often conducted. Even without a directional antenna, it is often possible to provide a partial directional interpretation by using information from other logs (dipmeter, optical imaging, borehole televiewer) or from the local geology (e.g. strike and dip).

In Seabrook, New Hampshire, borehole radar was used in a municipal supply well completed in fractured phyllite and quartzite that has a sustained yield of 2120 liters per minute (Lpm) (Johnson et al., 1999). Borehole radar was used in single-hole reflection mode to locate and determine the orientation of reflections in the bedrock surrounding the production well and the observation well. Cross-hole radar tomography was used to identify the complex hydraulic connections between the production well and a nearby observation well.

In Rye, New Hampshire, six wells in schist and gneiss were logged with single-hole reflection radar methods. Zones in the radar logs characterized by low velocity and high attenuation correlated with known water-bearing fractures and fracture zones. Borehole radar was used to identify extensively fractured sections of the bedrock. A subsequent production well drilled in a zone of intensely fractured rock was reported to yield more than 2600 Lpm (Mack et al., 1998).

Numerous borehole-radar logs have been recorded in the Grimsel underground site (Switzerland), which is used as an *in situ* laboratory for future nuclear repositories. The rock mainly consists of granite and borehole radar is used to map fractures and other structural or lithologic features. A typical example recorded with a 100 MHz antenna in an inclined hole is shown in figure 2. Many planar reflectors are identified. The investigation range around the borehole is excellent (>50 m) due to the high resistivity of the granite. Considering the local geology, the reflectors may be interpreted either as thin (0.3 to 1 m) lamprophyre dykes that have low permeability or as thin fractures with a high permeability. An innovative processing technique, developed at the University of Leuven (Grégoire, 2001) and based on the spectral analysis of the reflection coefficient, has been applied

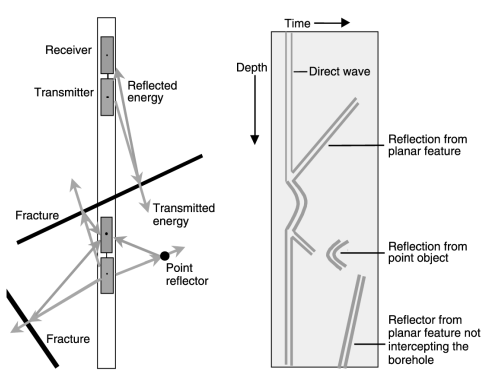

Figure 1. Orientation of transmitter and receiver in a single borehole and the resultant radar record from a fracture and a point reflector

to the data to determine the thickness of the fracture and the permittivity of the filling material. Using this technique, the lamprophyre dykes and the fractures could be clearly differentiated.

Borehole radar in the tomographic mode

Cross-hole tomography is the process by which a two-dimensional model is made of physical properties in the plane between two boreholes. For tomography surveys, the transmitter antenna is in one borehole, and the receiver antenna is in the other borehole. Numerous radar scans are made for each transmitter position by moving the receiver along the borehole at regular intervals. A typical cross-hole scanning geometry is shown in figure 3. Hundreds or thousands of different combinations of transmitter and receiver locations are required for a survey. For each scan, the travel-time and amplitude of a radar pulse is measured as it travels from the transmitting antenna to the receiving antenna. These data are used to create tomograms of the radar propagation velocity and attenuation properties of bedrock between two boreholes. Variations in velocity and attenuation can be interpreted to identify fracture zones, lithologic contacts, and voids in the image plane.

An application of borehole-radar tomography for the imaging of karstic features in fractured limestone is illustrated in figure 4. The measurements were carried out for a foundation study in Belgium (Corin et al., 1997). The carboniferous limestone is strongly fractured and karstified. A survey in the reflection mode would have a range of a few meters due to the high conductivity of the fractured rock. In the tomographic mode, the range is increased by about a factor of 3 because the radar pulse travels in one direction only and the direct arrival is detected instead of a reflection.

A radar velocity tomogram is shown in figure 4. The radar-pulse velocity ranges from 60 to 100 meters per microsecond. The lower velocities correspond to karst zones filled with water-saturated silty to sandy material. The higher velocities correspond to competent limestone. The intermediate velocities represent fractured limestone. The velocity is determined by the porosity due to the presence of fractures. The survey shows rapid lateral variations that are typical of this type of karst. Such variations are nearly impossible to map using conventional techniques.

Current developments

Use of downhole borehole radar is a fairly recent technique and many developments are taking place. Time lapse tomographic surveys (or differential tomography) are an important tool for the monitoring of hydro-

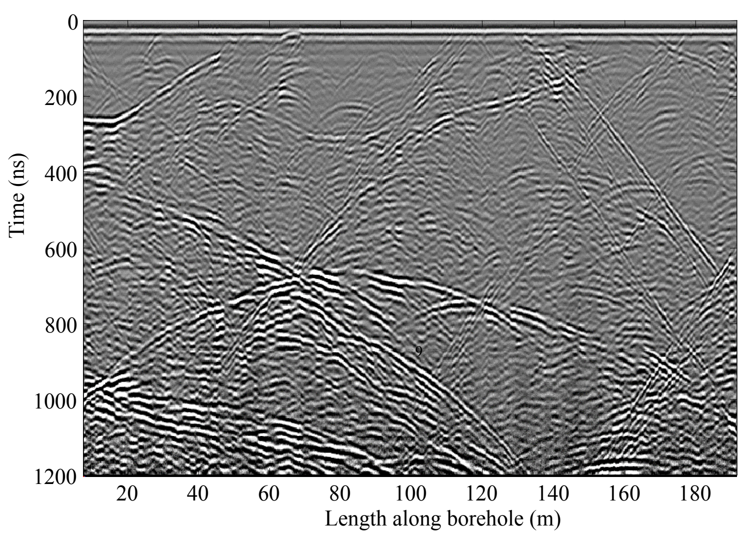

Figure 2. Borehole radar in an inclined borehole, using 100 MHZ antennas. The reflectors are due to thin dykes and to fractures.

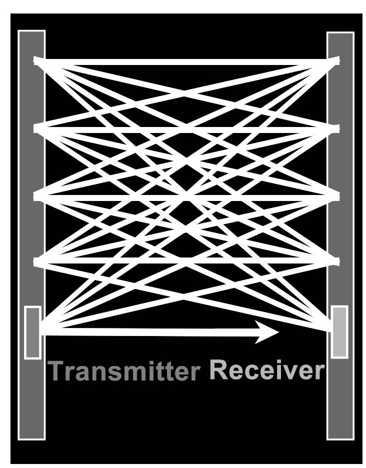

Figure 3. Ray coverage of cross-hole tomography.

geological processes (e.g. tracer test, displacement of a contamination plume) (Lane et al., 1999) or the control of *in situ* remedial works (Lane et al., 1996, 2001). Another active field of research is the quantitative interpretation of reflected signals (e.g. amplitude versus offset and spectral analysis of the reflection coefficient) (Yaramanci and Fechner, 1996).

Conclusion

Borehole radar logging, used in either the reflection or the tomography mode, has the unique ability to provide structural, petrophysical, and hydrological information about the rock mass around a borehole, within a radius of 10 to 40 m in resistive rock. Water-bearing fractures, cavities, and other features that are not intersected by the borehole can be detected and mapped. Features intersected by the hole can be traced laterally. The most important limitation is the attenuation of the EM signal. In a conductive environment (e.g. conductive water, silty or clayey material, etc.), the investigation radius may be reduced to less than a meter and the method would then become useless.

References

Corin, L., Couchard, I., Dethy, B., Halleux, L., Monjoie, A., Richter, T., and Wauters, J.P., 1997, *Radar tomography applied to foundation design in a karstic environment*: London, Geological Society, Engineering Geology Special Publication, no. 12, p. 167-173.

Grégoire, C., 2001, *Fracture characterization by ground penetrating radar*: Published Ph. D thesis, KU Leuven, Civil Engineering Dept., D/2001/7515/32, Belgium.

Johnson, C.D., Dunstan, A.H., Mack, T.J., and Lane, J.W., Jr., 1999, *Borehole-geophysical characterization of a fractured-bedrock aquifer, Rye, New Hampshire*: U.S. Geological Survey Open-File Report 98-558, 61 p.

Lane, J.W., Jr., Haeni, F.P., Soloyanis, Susan, Placzek, Gary, Williams, J.H., Johnson, C.D., Buursink, M.L., Joesten, P.K., and Knudson, K.D., 1996, *Geophysical characterization of a fractured-bedrock aquifer and blast-fractured contaminant-recovery trench*, in Bell, R.S., and Cramer, M.H., eds., Symposium on the Application of Geophysics to Engineering and Environmental Problems, Keysone, Colo., Proceedings: Wheat Ridge, Colo., Environmental and Engineering Geophysical Society, p. 429-441.

Lane, J.W., Jr., Joesten, P.K., and Savoie, J.G., 2001, Cross-hole radar scanning of two vertical, permeable, reactive-iron walls at the Massachusetts Military Reservation, Cape Cod, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 00-4145, 17 p.

Lane, J.W., Jr., Wright, D.L., and Haeni, F.P., 1999, *Borehole radar tomography using saline tracer injections to image fluid flow in fractured rock*, in Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program – Proceedings of the Technical Meeting, Charleston, S.C., 1999: U.S. Geological Survey Water-Resources Investigations Report 99-4018 v. 3, p. 747-756.

Mack, T.J., Johnson, C.D., and Lane, J.W., Jr., 1998, *Geophysical characterization of a high-yield fractured-bedrock well, Seabrook, New Hampshire*: U.S. Geological Survey Open-File Report 98-176, 22 p.

Yaramanci, U., and Fechner, T., 1996, *Influence of complex dielectric properties on the characteristics of radar reflection*: European Journal of Eng. and Env. Geophysics, v. 1 of 3, p. 287-301.

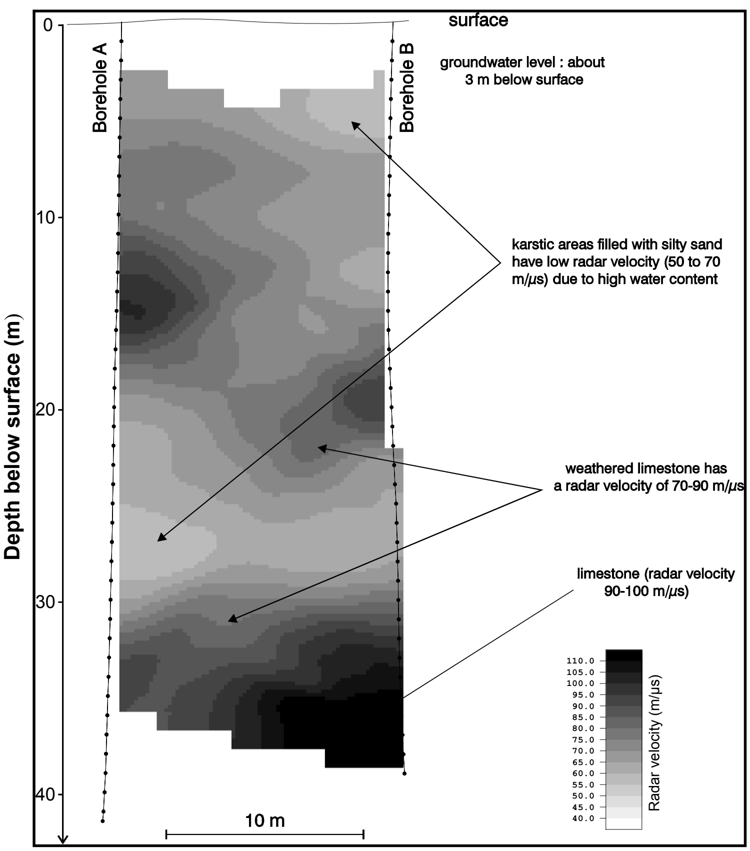

Figure 4. Borehole radar velocity tomogram showing karstic features in limestone (from Corin et al., 1997). [m/µs is meter per microsecond.]