BOREHOLE GROUND PENETRATING RADAR SURVEYS OF FRACTURED LIMESTONE

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Abstract

Two Borehole Ground Penetrating Radar (GPR) surveys were conducted to evaluate fractured limestone bedrock formations. One survey was conducted at the proposed location for a bridge pylon and one at a limestone quarry. The objective for both surveys was to identify small voids and fractures in the limestone. At the proposed pylon site, the voids and fractures were mapped to evaluate the limestone's bearing capacity and to design a grouting program. At the quarry site, the voids and fractures were mapped to help identifying permeable layers. Borehole GPR is the only geophysical technique capable of imaging individual small voids and fractures that do not intersect a borehole.

Nine boreholes were drilled into the limestone formation at the footprint of the proposed pylon. All nine boreholes were surveyed in reflection mode using 100 MHz and 250 MHz borehole GPR antennas. Two cross-hole tomographic surveys were also conducted at the site. The reflection surveys identified multiple layers that indicated voids and fractures of varying intensity. The tomography data provided information regarding the bulk characteristics of geological units and identified smaller areas with anomalous high porosity that could indicate high density of voids or fractures.

At the quarry site, two boreholes were drilled into the limestone formation. The boreholes were logged using 100 MHz and 250 MHz reflection borehole GPR, electric, temperature and natural gamma techniques. The electric and gamma logs identified sand, clay, and limestone layers, but only the borehole GPR could identify small fractures and voids not intersecting the borehole.

Introduction

Based on its proven capability to map fractures, United States Geological Survey (USGS), universities, and research centers have been advocating the use of borehole GPR for several years to the environmental and engineering communities. Applications include mapping fractures ahead of tunnel walls; better evaluate how the ground will react to loads and how contaminants may migrate through fracture systems. Still, the tool has not found wide acceptance outside the research world and the technology remains largely unknown.

Figure : Assembling a 250 MHz borehole GPR tool for tomography survey.

Borehole GPR is based on the same principles as surface GPR, but instead of scanning the material beneath the antenna, as surface GPR does, borehole GPR scans the material surrounding the borehole. Borehole GPR can be deployed in two different configurations; reflection

mode where the transmitter and the receiver are positioned in the same borehole and tomography mode where the transmitter and the receiver are in neighboring boreholes (Figure 1). In reflection mode objects surrounding the borehole, such as voids, fractures, and rocks will reflect the GPR signal back to the receiver. The GPR travel time is converted to distance from the borehole wall. The most commonly used models can not determine what direction the reflection is coming from, only how far it is from the borehole. However, by analyzing the data from several neighboring boreholes, it is often possible to determine an object's exact location.

In tomography mode, the transmitter and the receiver are positioned in two different boreholes (usually neighboring boreholes). The receiver detects the wave that travels straight across from the transmitter to the receiver. By shooting and receiving in different locations, it is possible to build a tomographic model showing bulk variations in velocity and attenuation in the geologic section between the boreholes.

Analogous to surface GPR, borehole GPR signal penetration distance is highly site-specific and is limited by signal attenuation (absorption) in the subsurface materials. Signal attenuation is dependent upon the electrical conductivity of the subsurface material and is greatest in materials with relatively high electrical conductivity such as clays, brackish groundwater, or groundwater with a high dissolved solid content from natural or manmade sources. Signal attenuation is lowest in relatively low-conductivity materials such as dry sand or rock.

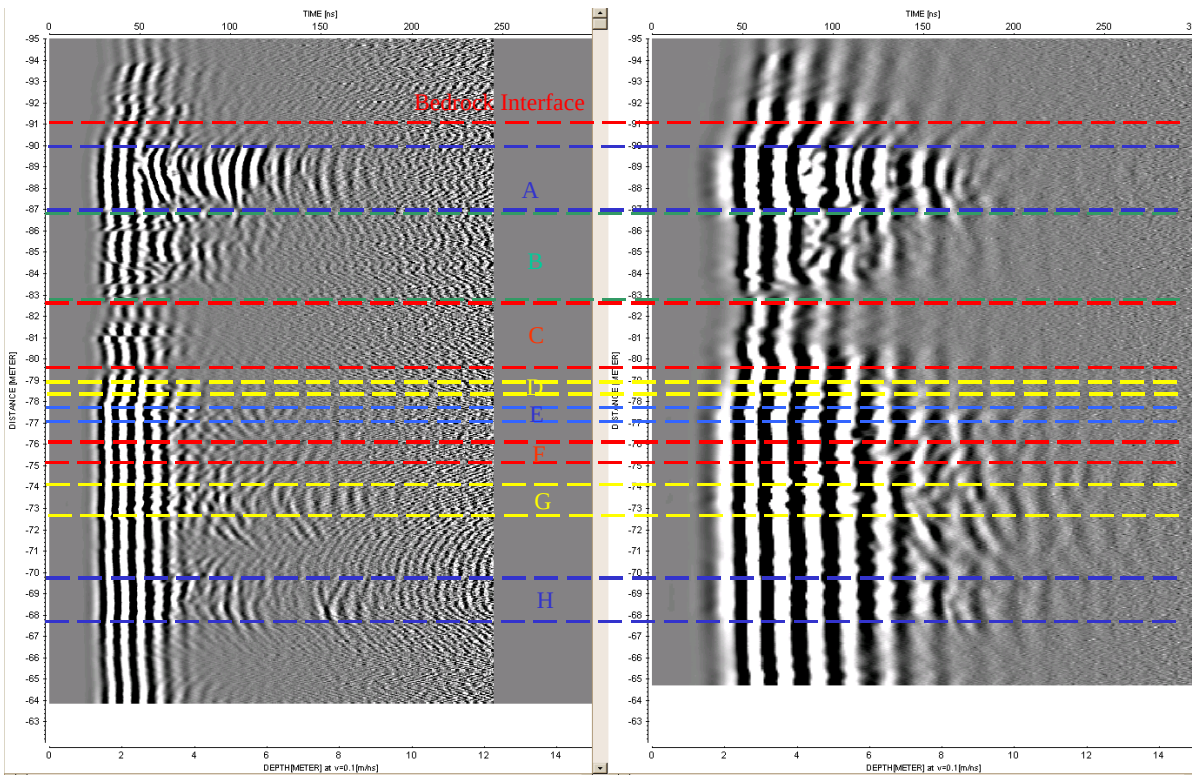

Figure 2: Borehole GPR Reflection survey using 250 MHz (left) and 100 MHz borehole antennas. The GPR data reveals zones that contain fractures and voids, imbedded between zones of more competent rock. Vertical axes show elevation above sea level in meters.

Case Study I – Assessing ground conditions under a proposed bridge pylon

During exploratory drilling for the foundation of a bridge pylon small (1-2 inch) voids and high angle fractures were discovered in the upper section of the limestone bedrock. At the site, the bedrock is

overlain by approximately 100-120 feet of unconsolidated sediments. Since the voids and fractures may affect the competency of the limestone to support the pylon, borehole GPR was used to assess the extent of the voids and fractures and their interconnectivity. This information will be used to design a grouting program to increase the structural integrity of the foundation material. All nine boreholes were drilled into the limestone and all were surveyed in reflection mode using 100 MHz and 250 MHz borehole GPR antennas. Two tomographic surveys were also conducted at the site.

The borehole GPR reflection surveys identified nine zones that appear to contain voids and fractures (Figure 2). The most severe fracturing was found at the top 13 feet of the bedrock. Below this zone, several fine zones were detected. The zones, which are interpreted to contain fractures and voids, range in thickness from 2 to 7 feet. The tomography data confirmed the existence of zones more likely to contain voids and fractures and identified local high porosity areas (Figure 3).

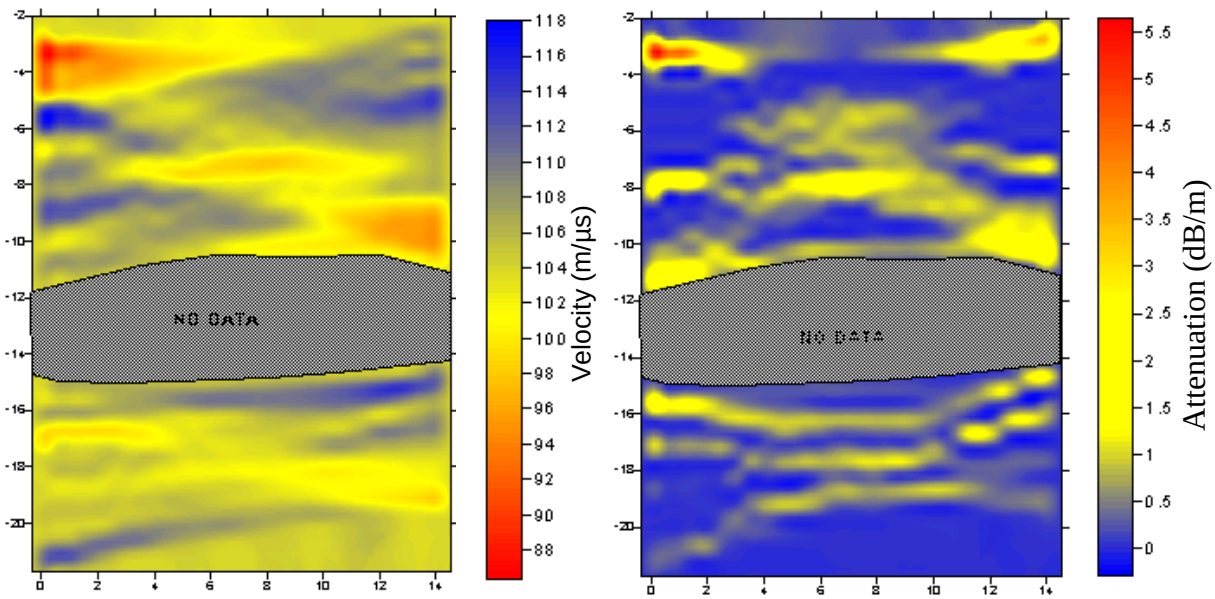

Figure 3: Velocity (left) and Attenuation tomograms. The velocity is measured in m/µs and the attenuation in dB/m. Competent limestone with low porosity will exhibit higher GPR velocities (blue) than porous limestone (red). High attenuation (red) indicates higher clay content or higher porosity. The data set was collected with 250 MHz antennas.

Case Study II – Assessing fracture density and location of permeable layers at a quarry site

A limestone formation that is being quarried lies below the natural groundwater table. In order to mine the limestone, deep trenches are excavated around blocks of limestone to stop the inflow of groundwater to the block. The block is then drained by collecting water from the trenches. This process is costly, slow and inefficient. If possible, a more cost effective approach would be to lower the groundwater table locally using wells. In order to assess the effectiveness of this method, two test holes were drilled into the limestone formation. The two holes were logged using a wide range of geophysical logs, including resistivity, temperature, natural gamma and borehole GPR (Figure 4). The object of the geophysical survey was to identify natural permeable layers that would be targeted for draining the limestone. Fractures and voids in the limestone were of special importance since they were considered to be of high importance for groundwater flow.

A combination of natural gamma, resistivity and borehole GPR was found to be very effective for identifying sand, clay and limestone layers. However, only borehole GPR was found to be a successful method for mapping fracture systems and the occurrence of voids in the limestone.

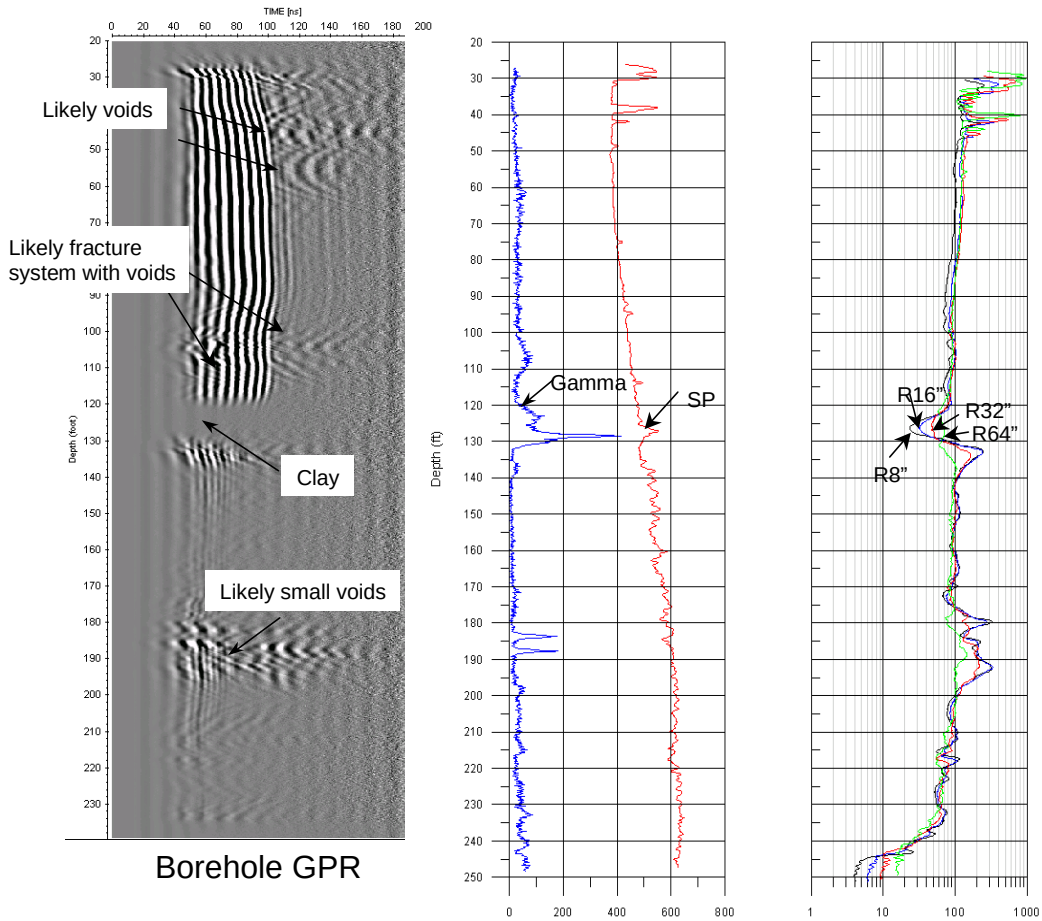

Figure 4: Comparison of 100 MHz Borehole GPR, Natural Gamma, Self Potential and Resistivity logs. Fine fracture systems and voids can only be detected in the GPR data. The detected voids are up to 20 feet from the borehole.

Conclusions

The presented case studies show that borehole GPR has unique capabilities of detecting fractures and voids, even if they do not intersect the borehole. Borehole GPR can be used as a stand-alone tool or in combination with other geophysical methods to evaluate subsurface conditions. Borehole GPR tomography is a powerful method for investigating a geological cross-section between two boreholes. Velocity tomograms can be used to discriminate between competent limestone and porous limestone. Attenuation tomograms can be used to map porous zones and clay layers. As with surface GPR, borehole GPR signal penetration is limited in electrically conductive materials such as clays.