Journal of Applied Geophysics 73 (2011) 305–314

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Inversion of multiple intersecting high-resolution crosshole GPR profiles for hydrological characterization at the Boise Hydrogeophysical Research Site

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ARTICLE INFO

Article history:
Received 25 August 2010
Accepted 3 February 2011
Available online 12 February 2011

Keywords:
GPR
Hydrogeophysics
Crosshole tomography
Inversion

ABSTRACT

The integration of geophysical data into the subsurface characterization problem has been shown in many cases to significantly improve hydrological knowledge by providing information at spatial scales and locations that is unattainable using conventional hydrological measurement techniques. In particular, crosshole ground-penetrating radar (GPR) tomography has shown much promise in hydrology because of its ability to provide highly detailed images of subsurface radar wave velocity, which is strongly linked to soil water content. Here, we develop and demonstrate a procedure for inverting together multiple crosshole GPR data sets in order to characterize the spatial distribution of radar wave velocity below the water table at the Boise Hydrogeophysical Research Site (BHRS) near Boise, Idaho, USA. Specifically, we jointly invert 31 intersecting crosshole GPR profiles to obtain a highly resolved and consistent radar velocity model along the various profile directions. The model is found to be strongly correlated with complementary neutron porosity-log data and is further corroborated by larger-scale structural information at the BHRS. This work is an important prerequisite to using crosshole GPR data together with existing hydrological measurements for improved groundwater flow and contaminant transport modeling.

1. Introduction

Knowledge regarding spatial heterogeneity in hydrological properties is required for effective modeling of subsurface contaminant transport (e.g., Gelhar, 1993; Hubbard and Rubin, 2005). To this end, geophysical methods offer much potential because they provide a scale of spatial resolution and degree of subsurface coverage not available with traditional hydrological measurement techniques such as borehole log and core analyses and pumping and tracer tests (e.g., Hubbard et al., 2001; Hyndman and Gorelick, 1996). Initially, the use of geophysical methods in hydrology was geared towards the qualitative delineation of larger-scale subsurface features such as facies boundaries and unconformities (e.g., Beres and Haeni, 1991; Keller and Frischknecht, 1966). More recently, however, the goal has been to extract detailed quantitative information regarding the spatial distribution of hydrological properties from these data (e.g., Chen et al., 2001; Dafflon et al., 2009; Harp et al., 2008; Hyndman et al., 2000; Kowalsky et al., 2005; Linde et al., 2006b; Tronicke et al., 2004). Such information has the potential to greatly improve hydrological models and thus predictions of groundwater flow and contaminant transport (e.g., Dafflon et al., 2010; Hubbard et al., 2001; Hyndman and Gorelick, 1996; McKenna and Poeter, 1995; Scheibe and Chien, 2003).

Two of the most important hydrological parameters controlling flow and transport in the subsurface are the hydraulic conductivity and the porosity. Although the spatial distribution of hydraulic conductivity remains generally much more difficult to estimate than that of porosity, both parameters are often seen to exhibit a significant degree of similarity with regard to their spatial variability and/or spatial correlation. For example, a large number of studies have shown that, for the sand- and gravel-type unconsolidated sediments commonly seen in near-surface studies, changes in the porosity are often linked to corresponding changes in the hydraulic conductivity and can play an important role in transport behavior (e.g., Chen et al., 2001; Hu et al., 2009; Hubbard et al., 2001; Kowalsky et al., 2005; Linde et al., 2006b; Scheibe and Chien, 2003). In this regard, a number of geophysical measurements are sensitive to the subsurface porosity distribution. In particular, crosshole ground-penetrating radar (GPR) tomography is of much interest because of its ability to provide images of porosity in saturated environments with unsurpassed spatial resolution. This is possible because of the strong relationship that exists between radar wave velocity and soil water content.

In recent years, a wide variety of approaches have been developed to generate crosshole GPR tomograms (e.g., Ernst et al., 2007; Giroux et al., 2007; Gloaguen et al., 2007; Hansen and Mosegaard, 2008; Irving et al., 2007; Johnson et al., 2007; Paasche and Tronicke, 2007). Each of these approaches differs in the way that the crosshole data are modeled and/or inverted, and has advantages and limitations depending on the data quality, nature of the subsurface environment, and particular objectives

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0926-9851/$ – see front matter
doi:10.1016/j.jappgeo.2011.02.001

of the study. In each case, however, and in the vast majority of crosshole GPR studies to date, research efforts have focused on the inversion of data from a single well-to-well profile, and on getting the maximum amount of information along that single profile. This is despite the fact that, at an increasing number of hydrological field sites, crosshole GPR data are collected between multiple pairs of boreholes where the profiles intersect and/or overlap. Indeed, although a number of previous studies have investigated the joint inversion of multiple collocated data sets acquired using different geophysical methods (e.g., Gallardo and Meju, 2004; Kowalsky et al., 2005; Linde et al., 2006a), little work has been done regarding the joint inversion of several intersecting crosshole data sets acquired using the same geophysical technique. Given that such inversions have the potential to provide models of the subsurface with excellent spatial resolution and coverage that can be highly valuable for the 3-D estimation or simulation of hydrological properties, this is a topic that warrants further investigation.

In this paper, we develop and demonstrate a robust procedure for jointly inverting 31 intersecting crosshole GPR data sets that were collected between 1998 and 2000 at the Boise Hydrogeophysical Research Site (BHRS) near Boise, Idaho, USA. The goal of our work is to obtain a single, high-resolution, subsurface velocity model for the site that honors all of the available data and is internally consistent. This is an important step towards 3-D hydrological characterization and modeling at the BHRS, which are primary long-term objectives. Because of the large amount of data involved and the significant variability in their quality due to surveys being performed by multiple researchers under different conditions and over many years, development of the inversion strategy posed many challenges. We begin by presenting some general information about the BHRS and the crosshole GPR data that were acquired there. We then describe the developed joint inversion methodology and show its application to the BHRS profiles. The final velocity model obtained is evaluated through comparison with porosity-log measurements and other available structural information. Lastly, we assess the advantages and limitations of jointly inverting different numbers of crosshole GPR profiles with regard to the quality and coherency of the results.

2. BHRS field site and measurements

The BHRS is a hydrological and geophysical field research site located near Boise, Idaho, USA. The subsurface at the site is characterized by an approximately 20-m-thick layer of sediments consisting of coarse, unconsolidated, fluvial deposits (Barrash and Clemo, 2002) with minimal fractions of silt and clay, which is underlain by a layer of red clay. A total of 18 wells have been emplaced at the site, all of which were carefully completed in order to minimize the disturbance of the surrounding formation. The wells were cased with 4-inch PVC well screen. The well field consists of 13 wells in a central area (~20 m in diameter) and five boundary wells at 10 to 35 m from this central area. Fig. 1 shows the configuration of the central area wells. The center well (A1) is surrounded by two concentric rings of 6 wells (B1–B6 and C1–C6). The distances between the different well pairs vary between 2.6 and 8.6 m. The depths of the wells are between 18.2 and 20 m below the land surface which is situated between 849.32 and 849.64 masl.

Key information regarding the hydrogeological structure at the BHRS has been obtained from neutron porosity-log data that were collected every 0.06 m in each of the boreholes in Fig. 1 (Barrash and Clemo, 2002). The porosity values were obtained from the measured count rate through a petrophysical transform (Hearst and Nelson, 1985) that was calibrated using porosity measurements in similar environments (Barrash and Clemo, 2002). Based on the neutron porosity logs, Barrash and Clemo (2002) have identified 5 units and their geostatistical behaviors at the BHRS. Four of these five units (i.e., Units 1–4) have been defined in the depth interval discussed in this paper. More recently, electrical capacitive conductivity measurements have identified a

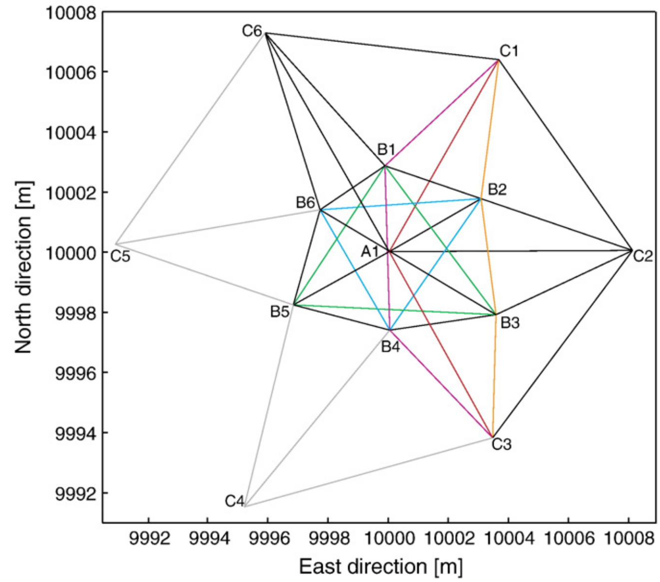

Fig. 1. Detailed map of the central area wells at the BHRS with lines to indicate where crosshole GPR data have been acquired. For the joint inversion, all of the profiles except the ones in gray were considered. The various colors represent the profiles shown in Figs. 5a (orange), b (red), c (violet), **6**a (green), and b (blue).

Subunit 2b, which is present in all of the wells shown in Fig. 1 except B1, B3, C1 and C2 (Mwenifumbo et al., 2009).

A total of 38 crosshole GPR data sets were acquired from 1998 to 2000 at the BHRS (Fig. 1). The GPR data were collected using a Mala Ramac GPR system with antennas having a nominal center frequency in air of 250 MHz. All of the data sets were acquired using the same survey parameters, but several were gathered in two or more sessions. For the joint inversion presented in the next section, we considered all of the available data with the exception of measurements involving wells C4 and C5, most of which were found to be of notably poor quality. This means that 31 crosshole data sets were considered. To conduct each GPR survey, a walkaway test was first performed by firing the antennas in air to determine the system sampling frequency and transmitter fire time. Common-receiver gathers were then collected. To do this, the receiver antenna was lowered every 0.2 m in one well and the transmitter antenna was fired approximately every 0.05 m in the other well. Because such non-symmetrical data acquisition can result in undesirable variable resolution in the resulting tomograms, we considered every fourth trace to achieve a common depth-sampling interval in the transmitter and receiver boreholes of approximately 0.2 m. In addition, we consider only those traces where both the transmitter and receiver antenna elements were submerged entirely below the water table, which was located between 1.5 and 2.5 m depth during the times of data acquisition. The antenna positions were corrected to account for borehole deviations based on magnetic deviation logging tool measurements conducted in early 2010.

3. Inversion methodology

To develop a single, consistent model of GPR velocity at the BHRS, our general strategy is to invert together the data from the 31 intersecting crosshole GPR profiles shown in Fig. 1, while maintaining every data set in its original 2-D coordinate system. Having consistency in the estimated velocity values where the profiles intersect is critically important and must be enforced in the inversion procedure. We perform the tomography within a ray-based traveltime inversion framework because it has been proven to be robust, computationally efficient, and flexible for handling large amounts of data of varying quality. Although significant developments have been made recently