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Imaging weak zones in the foundation using frequency domain attenuation tomography

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ABSTRACT

Cross-hole imaging method using Time Domain (TD) and Frequency Domain (FD) parts of cross-hole radar tomography data acquired using Step Frequency Ground Penetrating Radar (SFGPR) was implemented. This method was adopted for imaging foundation of a dam to check if the foundation was free of geological weak zones. The dam site is characterised by massive and jointed-phyllites associated with major and minor shears. The cross-hole radar tomography data was acquired in the frequency bandwidth of 250 MHz, from the deepest level gallery up to a depth of 40 m in the foundation. In TD, first arrival time and amplitudes of radio waves were inverted using Simultaneous Iterative Reconstruction Technique (SIRT) resulting in velocity and attenuation tomograms. The tomograms showed nearly uniform velocity or attenuation structure in the respective tomographic plane. Subsequently, cross-hole radar tomography data was analysed in FD for a variation of spectrum-amplitude at different frequencies. Amplitudes picked at each single frequency were then inverted using SIRT for obtaining frequency domain attenuation tomogram (FDAT). The FDAT clearly showed presence of anomalous high attenuation zones in the depth range of 23–33 m of the tomographic plane. The anomalous zones in the attenuation tomogram are weak zones in the foundation. To validate the above observations, cross-hole seismic tomography was also done in the same boreholes. Cross-hole seismic tomography results showed low velocity (p-wave) zones around the same location corresponding to the high attenuation zone in FDAT, bringing the dormant weak zone to light. This enabled fine-tuning of the reinforcement design and strengthening the weak zone. This paper discusses the cross-hole radar tomography imaging method, the results of its application in imaging weak zones in the foundation and the comparison of cross-hole radar tomography results (in TD and FD) with the cross-hole seismic tomography results.

1. Introduction

Cross-hole tomography is one of the high resolution imaging techniques adopted for imaging subsurface targets, when the depth and size of target are beyond the resolving power of near surface geophysical techniques. Different near surface geophysical techniques can be found in literature (Butler, 2007; Dahlin, 1996; Everett, 2012; Hinze, 1990; Pellerin, 2002; Steeples, 2001; Woolery, 2002; Yule et al., 1998). Cross-hole tomography is preferred as it is a viable alternative geophysical imaging technique, where surface survey is not possible due to limited area of interest for investigation. There are different cross-hole geophysical techniques based on seismic, electrical and electromagnetic methods (Angioni et al., 2003; Deceuster et al., 2006; Deidda and Ranieri, 2005; Jung and Kim, 1999; Saito et al., 1990; Wadhwa et al., 2009). Among such techniques, cross-hole radar tomography is generally preferred owing to its high resolving power enabled by the use of very high frequency ranges (microwaves), for the given probing depth and non-destructive imaging capability (Davis and Annan, 1989; Jha et al., 2002; Valle et al., 1999).

Cross-hole radar tomography has been applied for a variety of objectives for imaging targets of size ranging from few millimetres to few metres using various techniques based on data acquisition, processing and analysis for imaging targets (Holliger et al., 2001; Klotzsche et al., 2010; Valle et al., 1999; Vasco et al., 1997; Wänstedt et al., 2000). Each of those studies has been successful in imaging subsurface targets to a different degree of resolution and accuracy and majority of the cross-hole radar studies involve treating the tomography data in Time Domain (TD). In TD, time and amplitude of radar waves in the media are generally used for imaging the rockmass and other targets. The cross-hole radar tomography images obtained by inversion of time and amplitude are useful in quickly reconstructing the image of the subsurface medium in terms of its velocity and attenuation structures. For most geological materials, the dielectric permittivity varies between 3–40 F/m. Presence of water or air influences the dielectric permittivity of the rock mass and thereby the travel time of propagation in the geological material (Nuzzo et al., 2008). However, in geological materials

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the radar wave velocity does not generally vary significantly as to enable deciphering subtle variation in rock mass conditions. Hence, poor velocity contrast reduces resolving power. The resolving power of such TD technique is also influenced by size of the target, separation of boreholes, ray path coverage, and sensitivity of EM waves to the change in electrical properties between the target and the host medium. For a medium characterised by poor dielectric permittivity contrast, variation in conductivity of the medium can be a useful alternative as conductivity strongly influences the amplitude along the path of propagation of radio waves (Hinz and Bradford, 2010; Holliger et al., 2001; Zhou and Fullagar, 2001). Higher conductivity is well known to impart higher attenuation of radio wave amplitudes. However, amplitude variations are not always commensurate with the conductivity as amplitude is also influenced by geometric spreading, multiple scattering or diffraction, antenna radiation pattern and transmission (Quan and Harris, 1997). Therefore, it is often difficult to obtain reliable attenuation estimates always from the amplitude decay method. Moreover, in order to resolve subsurface features based on attenuation structure, a sufficient contrast in conductivity is essential.

In FD, studies based on transmission and measurement of mono-frequency (Cote et al., 1995), estimating attenuation (Quan and Harris, 1997), studying pulse broadening by centroid frequency down shift (Liu et al., 1998), material–signal interaction (Grandjean et al., 2000), mapping conductive zones in the subsurface (Zhou et al., 2001) and imaging media heterogeneity using phase and amplitude inversion (Ellefsen et al., 2011) have demonstrated the effectiveness of the FD approach in tomographic imaging. However, since most of such studies have been conducted using impulse GPR (IGPR), they have predominantly relied on data transformed from TD. Analysing target responses as acquired in raw and pre-transformed data is one of the possibilities for better resolution of the subsurface targets, which is made possible in frequency domain radars. Moreover, frequency of signal holds some additional clues for understanding the nature of the medium or target under study (Annan and Cosway, 1992; Bradford, 2007; Reynolds, 2000). FD processing and analysis of data can help bring out such important information and help improve the resolution of the target. Hence, as an alternative approach to understanding the attenuation, we analysed the Step Frequency GPR (SFGPR) signal in FD. Details about various works with SFGPR can be found in literature (Iizuka et al., 1984; Kong and By, 1995; Langman and Inggs, 2001; Leckebusch, 2011; Noon et al., 1994; Stickley et al., 2000).

In this study, we have adopted cross-hole imaging method using cross-hole radar tomography in which SFGPR data has been analysed separately in TD and FD. While time and amplitude were inverted in TD for velocity and attenuation structures, amplitude at different frequencies was inverted in FD for obtaining frequency domain attenuation. The tomographic imaging method has been applied for imaging the foundation of a dam site with encouraging results. To validate the above observations, cross-hole seismic tomography was also done in the same boreholes.

The organisation of the paper is as follows: Section 2 provides the details of the cross-hole imaging method. Section 3 describes the case study wherein the site of cross-hole-tomography survey, data acquisition and implementation of the imaging method. Section 4 discusses the results of the cross-hole imaging and finally Section 5 gives the conclusion of the study.

2. Cross-hole imaging method

Cross-hole radar tomography is an inverse problem in which image of the subsurface target and the medium between a pair of boreholes is reconstructed based on the influence rendered by electrical conductivity and dielectric permittivity of the medium through which the wave propagates (Annan, 2005). For inversion, waves transmitted through the medium between a pair of boreholes are measured at constant intervals throughout the depth of the boreholes over a dense network of ray paths between N_T number of transmitter (T_x) locations and N_R number of receiver (R_x) locations. This results in collection of $N_T \times N_R$ data set. The entire set of data is then inverted using Simultaneous Iterative Reconstruction Technique (SIRT) to generate a 2D tomographic image called tomogram. The tomogram is interpreted in the light of the geological setting in the study area. Details of SIRT are given in Section 2.3.

Cross-hole radar tomography is a robust method (Clement, 2006) as measurements are reliable for closely spaced boreholes and denser acquisition ray paths. In cross-hole radar tomography, the EM waves travel with different velocities influenced by relative dielectric permittivity (ε_r) and are subjected to attenuation due to conductivity (Hinz and Bradford, 2010) and propagation losses (Reynolds, 2000). While velocity is a time domain factor, the attenuation of signal can be studied in time domain as well as in frequency domain.

2.1. Time domain tomography

Travel time and amplitude of the TD signal are commonly used to reconstruct velocity tomogram and attenuation tomograms, as it is relatively easier and quicker to get these values from the measured data. Since velocity and attenuation are related to two different electrical properties (electrical conductivity and dielectric permittivity) of the media (Zhou et al., 2001), it is useful to obtain both the tomograms as they can provide complementary information.

Cross-hole velocity tomography is a technique to obtain distribution of velocity in the medium between a pair of boreholes. Velocity tomography is useful in getting a high-resolution image of the medium. The resolution depends on the contrast in the dielectric permittivity in the medium, size of the target and the separation between the T_x and R_x boreholes. In order to reconstruct the velocity structure, an $N_T \times N_R$ matrix of travel times are obtained before inversion using SIRT (Section 2.3). The resulting velocity image, known as cross-hole radar Velocity Tomogram (VT), is the distribution of wave velocity in the plane separating the boreholes. VT enables identification of anomalous velocity zones lying between the boreholes as well as imaging individual velocity layers.

In attenuation tomography, the amplitude of the signal recorded at the receiver positions throughout the length of the borehole is used for generating attenuation tomogram (Holliger et al., 2001; Zhou and Fullagar, 2001). In situations, where the contrast in dielectric permittivity of the target and the host medium is poor and the medium or target is conductive, the attenuation tomogram holds better information than its velocity counterpart on the property of the medium as the propagation of radar wave amplitude is highly influenced by conductivity (Annan, 2005; Zhou et al., 2001). In order to reconstruct the attenuation structure, $N_T \times N_R$ matrix of amplitudes are obtained and inverted using SIRT (Section 2.3). The resulting attenuation structure in the plane separating the boreholes is called as cross-hole radar Attenuation Tomogram (RAT).

2.2. Frequency domain tomography

When radar wave velocity in a medium does not vary significantly, the radar wave attenuation becomes a crucial factor to understand the properties of the medium. Such situations arise when the medium is a complex geological setting, characterised by poor electrical contrasts and high conductivity or attenuation. It is well known that, small fault zones or fractures are normally more conductive compared to the surrounding media and affect the propagation of EM waves (Haeni et al., 2002; Lane et al., 1994; Stolarczyk and Fry, 1990). Therefore, studying the amplitude variations at different frequencies could yield more information on the subsurface medium. This is because, variation in the amplitude with frequency is quite significant (Jha et al., 2003, 2004; Neto and de Medeiros, 2005) even for low to moderate conductive losses in the media. Hence, an attempt was made to study the variation