AQUIFER CHARACTERIZATION USING ELASTIC FULL-WAVEFORM INVERSION

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ABSTRACT

This study exploits the benefits of elastic full-waveform inversion (FWI) as an effort to improve aquifer characterization for better understanding of their properties and delineating their structure. Conventional methods (e.g. boreholes, pumping tests) have usually one-dimensional nature and cannot provide information concerning the lateral heterogeneities of such complex subsurface environments. In the past, many studies were conducted using ground-penetrating radar (GPR), electrical resistivity tomography and seismics which result in two-dimensional tomographic images and provide spatially highly resolved mapping of aquifer heterogeneities. In this research, we focus in the seismic method and in particular we apply FWI to seismic data acquired at the Krauthausen test site. We compare our findings with borehole data and GPR FWI from previous studies. We conclude that combining the results of FWI with additional geophysical techniques can provide more reliable subsurface models and reduce uncertainties on reconstructing the aquifer architecture with higher spatial resolution.

INTRODUCTION

A detailed characterization of aquifers strives to improve the prediction of groundwater flow and to evaluate possible contaminant hazards. Conventional methods (Döring, 2002) either have limited spatial sampling volume but high resolution (e.g. boreholes), or they record an average response over a large volume (e.g. pumping tests). The inherently one-dimensional nature of these methods cannot provide information concerning the lateral heterogeneities of such subsurface environments. Doetsch et al. (2010) and Klotzsche et al. (2015) studied the use of ground penetrating radar (GPR) and electrical resistivity tomography (ERT) methods to obtain spatially highly resolved mapping of aquifer heterogeneities, taking advantage of the two-dimensionality of the tomographic images provided by these methods. Along with GPR and ERT, shallow seismic applications are also important for hydrogeological site characterization. In particular full-waveform inversion (FWI; Tarantola, 1984) allows us to derive information of the elastic parameters and reconstruct accurate subsurface models that describe our measured data. Several studies revealed the applicability of FWI in the case of near-surface applications (Köhn et al., 2012, Athanasopoulos and Bohlen, 2017b, Groos et al., 2017 andWittkamp et al., 2019). In this study, we demonstrate the value of using elastic FWI of seismic data acquired at the Krauthausen test site for improved aquifer characterization. We conclude that combining the results of FWI with additional geophysical techniques can provide more reliable results and reduce uncertainties on reconstructing the aquifer architecture with higher spatial resolution.

STUDY AREA

The location of the survey is the Krauthausen test site, situated in the North-West Germany between the cities of Jülich and Düren (figure 1a). A detailed description of the test site, which was set up in 1993 by the research center Jülich is given by Döring (2002). According to Döring (2002) the subsurface on top of the aquifer can be divided into three layers (figure 2, right column): (a) a bottom layer composed of sandy to gravelly grain size (from 6 to 11.5 m depth), (b) a well sorted sand layer (from 4 to 6 m depth), and (c) a poorly sorted gravel layer (from 1 to 4 m depth). The base of the aquifer is formed by thin layers of clay and sand, at approximately 12 m depth. The groundwater level shows variations from 1 to 3 m depth depending on the annual season. The aquifer material is composed of alluvial terrace sediments, deposited by the river Rur. Numerous studies were performed in the area (Döring, 2002; Klotzsche et al., 2015; Gueting et al., 2015) with the goal to study the spatial distribution of aquifer parameters. The true aquifer architecture exhibits lateral variations in layer thickness and properties and additional information from various geophysical methods is necessary for the adequate characterization of these spatial distributions. Klotzsche et al. (2015) studied the area extensively by applying GPR full-waveform inversion and revealed the heterogenous nature of the subsurface (figure 1c). The focus of our study lies on characterizing the aquifer by applying elastic FWI (seismic) and reconstruct the P-wave velocity (v_p), S-wave velocity (v_s) and density (ρ) models of the subsurface. The seismic line was choosen in the center of the profile crossing several borehole and GPR transects (figure 1b), in order to allow a further qualitative comparison between the various methods.

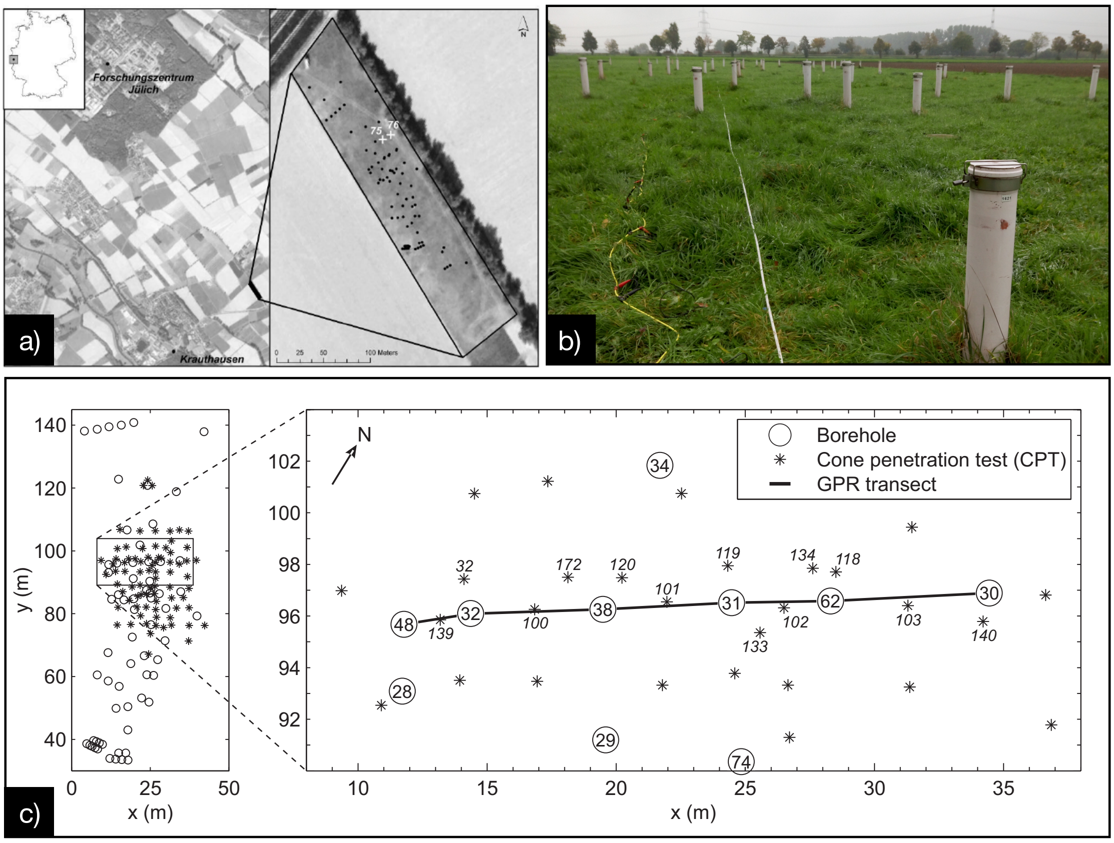

Figure 1: a) Location of the Krauthausen test-site. b) Seismic survey line. c) Map of the Krauthausen test site with the location of boreholes (open circles) and cone penetration tests (asterixes). The black solid line in the close-up (right) shows the location of the acquired seimic profile in the central part of the test site. Selected cone penetration tests located close to the seismic transect are labeled with italic numbers.

METHOD AND THEORY

Both the forward modelling (Bohlen, 2002) and inversion process (Köhn et al., 2012) of the 2D elastic full-waveform inversion are performed in the time domain with finite differences on a standard staggered grid. The optimization we use to solve the inversion problem consists of a preconditioned conjugate gradient technique. The gradients are computed in the time domain using the adjoint-state method. As objective function, we define the least-squares misfit between the normalized synthetic and observed seismograms. To precondition FWI we apply: (1) a semi-circular source tapering around the respective source position, (2) a multi-scale step-wise inversion of seismic signals in which we increase the frequency band of the data set gradually from 10 to 100 Hz by lifting the corner frequency of a low-pass filter, and (3) an approximation to the diagonal elements of the Hessian (Groos et al., 2017). We apply a three-parameter FWI using the total wavefield in order to reconstruct the v_p, v_s and ρ.

FIELD DATA AND FWI PARAMETRIZATION

The acquisition geometry of the field measurements consists of a linear profile of 23 vertical component geophones with an equidistant spacing of 1 m. The sources are vertical hammer blows on a steel plate (6 in total) with an equidistant spacing of 4 m. A source-time function correction is applied to correct for the unknown source contributions. The model space consists of 336 grid points in the horizontal direction and 144 grid points in the vertical direction, resulting in model space of approximately 35 m x 15 m (grid spacing is 0.105 m). The seismograms were normalized trace by trace. The initial v_p, v_s and ρ models are calculated from the arrival times of the refracted waves, dispersion curve analysis, and through Gardner's relationship, respectively. In all three models the values of velocity and density increase with a smooth gradient until the depth of 12.6 m, followed by an homogenous half space, while their values vary only in depth and not laterally. Specifically, the initial model of v_p and v_s are given values from 250 to 2300 m/s and 140 to 450 m/s, respectively, while the density varies from 1700 to 2600 kg/m^3. To account for anelastic damping we estimate and apply a passive attenuation model (Groos et al., 2017) with three relaxation mechanisms and a Q value of 15, which was found as optimal after a line-search.

RESULTS

In this section we present the models obtained from the multi-parameter FWI along with the results obtained from boreholes in the area (Döring, 2002). Figure 2 shows the reconstructed v_p (top) and v_s (bottom) models obtained from FWI. The red asterisks represent the shot locations, while dashed vertical lines mark the locations and depths of the boreholes. The geology of the area is also shown here (right) as interpreted by Döring (2002).

To avoid artifacts in the vicinity of the shot locations we applied 1.5 m semi-circular tapering and therefore the discontinuity due to the groundwater table is not visible in the v_p or v_s models. There appears to be a distinct sedimentologic boundary in the aquifer material at a depth of 4 m, where according to the borehole information the soil changes from gravel to sand. Another observation is that at depth below 6.5 m another layer could be distinguished which would fit to the sandy gravel layer. However, since the refracted wave could not be perfectly resolved (figure 3, right) the reliability of the v_p model is not high enough to draw conclusions.

The structure of the S-wave velocity reveals more accurate information, since the modes of the Rayleigh wave could be accurately resolved (figure 3). Once more excluding the top 2 meters, we observe a low velocity layer around 4 to 6.5 meters, right after a slightly higher velocity layer from 2 to 4 m. The S-wave velocity of sand typically exhibits values lower than gravel under the same weathering/pressure conditions (overburden and below the groundwater table). This matches the reconstructed v_s model from FWI. From a depth of 6.5 to around 11 m the velocity increases which can be correlated to the layer of sandy gravel from the borehole data. At the deepest part of both the v_s and v_p models the velocities are high, possibly indicating the beginning of the bedrock. The vertical extension of the boreholes (figure 2, dashed lines) reveal some corelation with the v_s model, especially boreholes B48, B32, B38 and B30. However, due to the limited amount of ray-coverage at depths deeper than 8 meters and at the edges of the domain, the reliability of the seismic velocity models is much lower than in the center. The reconstructed density models did not provide valuable information, apart from the fact that higher density values are revealed compared to our initial model. However, from previous studies we know that the reconstruction of density suffers from significant cross-talk leaking from the v_s and v_p models.

Apart from the model space we compare the results in the data space. Figure 3 shows the comparison between the velocity seismograms of the observed and synthetic data and frequencies up to 100 Hz for every shot-gather. In general, both the residuals between observed and synthetic seismograms and the misfit function were minimized. The inversion fitted the fundamental and higher Rayleigh modes sufficiently well. The first arrivals corresponding to the refracted wave show a rather weak correlation. This is a

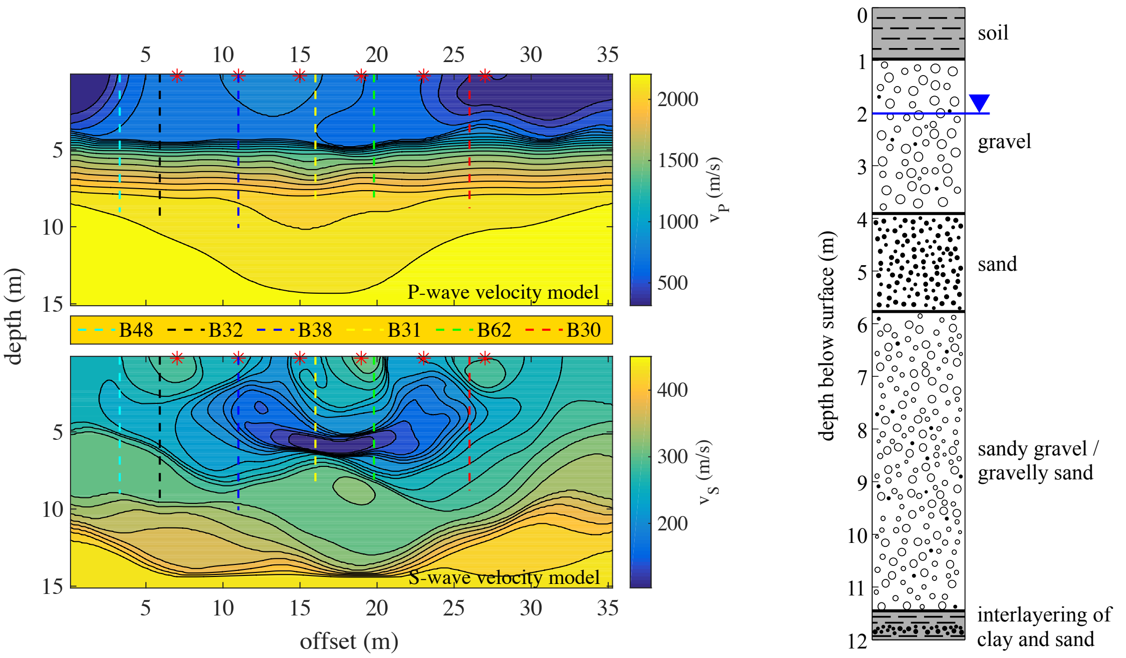

Figure 2: P-wave (top, left) and S-wave (bottom, left) velocity models reconstructed from FWI. The location of the shots (red asterisks) and the 6 boreholes (dashed vertical lines) are indicated. The corrsesponding geology as studied by Döring (2002) is shown on the right along with the estimate depth of the groundwater table (blue line).

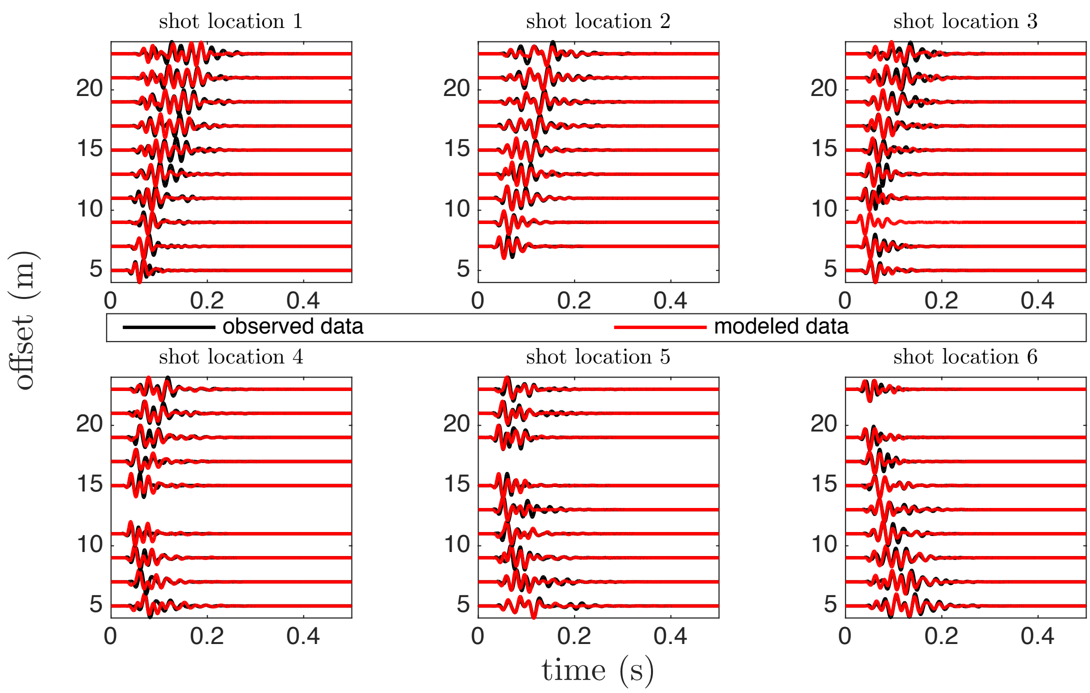

Figure 3: Normalized displacement seismograms for different offsets, calculated from the observed data (black) and the synthetic data from FWI (red) for all the shots.

common issue since the amplitudes of the Rayleigh waves in shallow seismics are often much higher than the amplitudes of the compressional P-waves and therefore the small energy of the refracted waves is not well resolved by the FWI (Athanasopoulos and Bohlen, 2016, 2017b).

DISCUSSION AND COMPARIZON WITH GPR FWI

We compare the v_s model with the findings of Klotzsche et al. (2015) where they used the same profile and applied FWI of crosshole GPR data. We observe high correlation of mainly the four individual layers below the groundwater table. Four different depth levels were determined from the seismic FWI: 2-4 m, 4-6.5 m, 6.5-11 m and below 11 m, where for each layer the seismic velocities varied between 170-290 m/s, 110-260 m/s, 280-440 m/s and higher than 440 m/s, respectively. Approximately the same layers were shown in the GPR FWI, with electrical permittivity (ϵ) decreasing for each layer (but the first) over depth. Since this property (ϵ) is inversely proportional to the squared wavespeed, there seems to be a strong correlation between these two geophysical methods. In other words, by including additional information from borehole data we can better characterize the general architecture of the aquifer.

CONCLUSIONS

We performed an elastic multi-parameter FWI on seismic data acquired at the Krauthausen test site, with the aim to characterize the architecture of the aquifer. The inversion was successful as both the residuals between observed and synthetic seismograms and the misfit function were minimized. The v_s model was the most reliable due to the accurate fit of the Rayleigh way and its higher modes. In order to overcome the uncertainties of the reconstructed models, due to the inherent non-uniqueness of the method, we compared our results with borehole data and crosshole GPR FWI results from previous studies. All methods revealed high correlation between one another, showing the applicability of seismics in aquifer characterization. This study suggests the joint FWI between seismic and GPR data to obtain high spatial-resolution mapping of the aquifer architecture.

PUBLICATIONS

Detailed results were published by Athanasopoulos and Bohlen (2016), Athanasopoulos and Bohlen (2017b), Athanasopoulos and Bohlen (2017a) and Athanasopoulos et al. (2018).

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