EAGE
CONFERENCE & EXHIBITION
NEAR SURFACE GEOSCIENCE'21

Resolving hydrogeological parameters through joint inversion of seismic and electric data considering surface conductivity

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Summary

Geophysical methods have proven to overcome the spatial limitations of direct investigations by providing spatio-temporal information about subsurface properties with an adequate resolution in a non-invasive manner. However, the resolved models remain qualitative unless subsequently transformed to the quantitative estimates of the parameters of interest based on a petrophysical model. Petrophysical joint inversion (PJI) approaches permit an improved quantitative estimation of hydrogeological parameters by simultaneously inverting complementary geophysical datasets, e.g., seismic and electric data, related through a common petrophysical parameter. Subsurface models resolved for data collected in fine-grained environments might still be biased if the petrophysical model underlying the PJI framework does not consider the conduction of electric current along the grain-fluid interface. In this study, we present a PJI framework that implicitly takes into account the surface conductivity based DC and instantaneous resistivity data. We apply this PJI approach to data collected in the Hydrological Open Air Laboratory (HOAL; Petzenkirchen, Austria) to solve for hydrogeological parameters relevant for the understanding of surface-groundwater interactions. We discuss the resolved subsurface models with respect to models obtained through a PJI approach neglecting the surface conductivity, demonstrate the good agreement with available direct information and provide an interpretation of the subsurface conditions.

Introduction

The Hydrological Open Air Laboratory (HOAL) located in Petzenkirchen (Austria) aims at understanding the interaction between surface water and groundwater. In particular, understanding the stream-aquifer interaction and monitoring of the associated spatio-temporal evolution related to other environmental processes are of vital interest for the interdisciplinary research activities (Blöschl et al., 2016). Hydrogeological modeling requires a detailed characterization of soil parameters controlling the infiltration and groundwater recharge. Subsurface investigations are commonly conducted as direct measurements at spatially confined sampling points, e.g., boreholes. Although the collected datasets provide direct information with high temporal resolution the required spatial interpolation might bias the interpretation of the corresponding results. Geophysical methods have proven to overcome this limitation considering their ability to provide spatio-temporal information regarding subsurface properties with adequate resolution in a non-invasive manner (e.g., Flores Orozco et al., 2018). However, the interpretation of geophysical imaging results remains qualitative unless the resolved models are transformed to estimates of the parameters of interest through the application of a petrophysical model (see Binley et al., 2015, for an overview). Commonly, geophysical investigations rely on two or more complementary methods that are independently processed and inverted, and subsequently the results are joined for the interpretation. For permafrost investigations, Wagner et al. (2019) highlight that the simultaneous transformation of complementary geophysical imaging results can result in physically implausible estimates, e.g., negative values. Based on the well-established four-phase model (4PM; Hauck et al., 2011), Wagner et al. (2019) present the petrophysically coupled joint inversion of different geophysical data sets to allow for an improved estimation of the parameters of interest. Considering the successful application of this petrophysical joint inversion (PJI) framework in recent studies (Mollaret et al., 2020; Steiner et al., 2021), we propose to extend its scope to hydrogeological studies in unfrozen environments to quantitatively solve for relevant hydrogeological parameters (e.g., water content, porosity) based on electric and seismic data. To this end, we change the 4PM underlying the PJI framework to a three-phase model (3PM), i.e., we remove the frozen water content from the set of equations, and also implement the dynamic stern layer model (DSLM; e.g., Revil et al., 2020) model taking into account not only electrolytic conduction but also surface conduction. We then use both PJI schemes to invert data collected at the HOAL in March 2021 to demonstrate the estimation of physically plausible models for the hydrogeological parameters which we consider a first step towards the quantification of the hydraulic conductivity.

Joint inversion of electric and seismic data solving for hydrogeological parameters

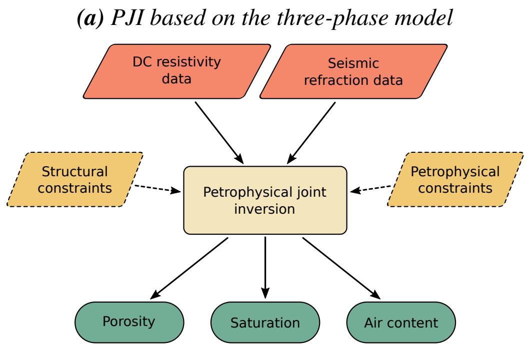

Figure 1 *Schematic illustration of the petrophysical joint inversion (PJI) schemes used in this study. (a) PJI of single frequency resistivities and seismic traveltimes to solve for porosity* Φ*, saturation* Θ_w*, and air content. (b) To take into account the surface conductivity, DC and instantaneous resistivity data have to be considered in the PJI.*

The proposed modification of the PJI framework assumes the soil to be composed by three phases that are related by a volume conservation constraint

$$f_r + f_w + f_a = 1\,, \tag{1}$$

where f_r denotes the volumetric rock content, and f_w and f_a denote the volumetric water and air content, respectively, filling the pore space. Considering only three phases is the crucial modification required to make the PJI framework developed by Wagner et al. (2019) applicable for studies in non-frozen conditions. Following the approach used by Hauck et al. (2011) we describe the seismic slowness s through a modification of the time-averaging Timur (1968) equation that sums up the seismic velocities of the three phases weighted by the respective volumetric fraction (e.g., Hauck et al., 2011)

$$s = \frac{1}{v} = \frac{f_w}{v_w} + \frac{f_a}{v_a} + \frac{f_r}{v_r}. \tag{2}$$

In the 4PM the bulk electrical conductivity is linked to the pore water content f_w, i.e., the saturation θ_w, through Archie's second law (Archie, 1942)

$$\sigma = \sigma_w (1 - f_r)^m \left(\frac{f_w}{1 - f_r} \right)^n, \tag{3}$$

where m, n and σ_w denote the cementation exponent, the saturation exponent and the pore water conductivity, respectively. As illustrated in Figure 1a the input data are the electrical resistivity as obtained through DC resistivity measurements and seismic refraction data, i.e., traveltimes of seismic waves propagating through the subsurface. Archie's second law, however, does not consider the contribution of the surface conductivity. Hence, incorrect estimates for the water content have to be expected due to the assumption that conductive anomalies are solely controlled by electrolytic conduction and neglecting the conduction along the grain-fluid interface. The surface conduction is, in particular, relevant for fine grains, e.g., clays, characterized by high surface area and surface charge, and thus, needs to be taken into account in areas with a high content in fine grains such as the HOAL (Flores Orozco et al., 2020). To address this shortcoming we consider the DSLM used by Revil et al. (2020) to estimate the water content based on DC conductivity σ^0 and instantaneous conductivity σ^∞ data, i.e., data measured at a low and high frequency, respectively. Such datasets are collected through the induced polarization (IP) method, which is an extension of the electrical resistivity tomography (ERT) that can be conducted in the frequency (FDIP) and in the time domain (TDIP). Figure 1b shows that the proposed PJI scheme requires a third input data set and provides also an estimate for the cation exchange capacity (CEC). Although not used in this study both PJI schemes provide the means to incorporate structural and petrophysical constraints obtained from complementary data sources (e.g., Steiner et al., 2021). As described by Wagner et al. (2019) the PJI minimizes the objective function Φ where the data fit is quantified by the error-weighted chi-squared fit χ^2, where $\chi^2 = 1$ indicates that the resolved models describe the observed data within their respective error bounds (Günther et al., 2006).

PJI of data collected at the Hydrological Open Air Laboratory (Austria)

In March 2021, we collected seismic and electric data along a 126 m long profile crossing a small stream meandering within a streambed of approximately 9 m width (the natural surface water outlet from the HOAL catchment; Blöschl et al., 2016). For the seismic refraction survey we used the DMT Summit data acquisition system with 64 vertical geophones (30 Hz corner frequency) deployed at the surface with 2 m spacing. The shot positions were located between the geophone positions and the seismic waves were generated by hitting a plastic plate with a 7.5 kg sledgehammer; to improve the signal-to-noise ratio we stacked four hammer blows at each shot position. FDIP data were collected with the Multi-Phase Technologies DAS-1 using a square waveform with a pulse length of 0.125 s and a 50 % duty cycle. Stainless steel electrodes were deployed with 2 m spacing with the first electrode being co-located with the first geophone.

Regularization		Data error		
λ	*zWeight*	ρ^0 (0.5 Hz)	ρ^∞ (25 Hz)	s
100	0.5	3 %	12 %	2 ms

Table 1 *Inversion parameters considered for the application of both PJI schemes proposed in this study*

For the application of both PJI schemes we used the inversion parameters summarized in Table 1, where λ denotes the regularization parameter and the value for *zWeight* corresponds to a two times stronger smoothing in the horizontal direction. As indicated in Table 1, ρ^0 refers to electrical data collected at 0.5 Hz whereas data collected at 25 Hz are considered as ρ^∞. Based on the model by Hauck et al. (2011) and the model by Revil et al. (2020) the PJI finished with $\chi^2 = 1.4$ and $\chi^2 = 2.2$, respectively.

Discussion of the resolved subsurface models

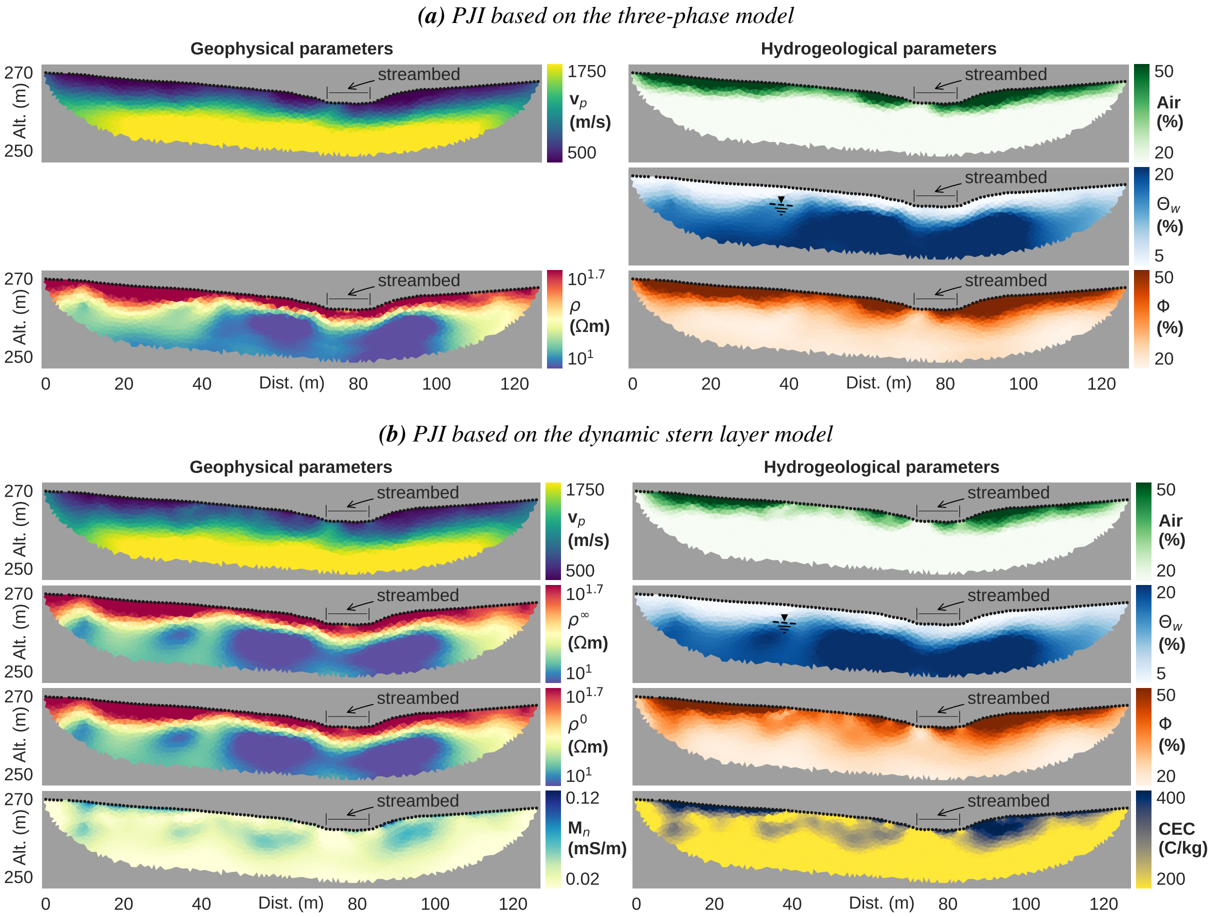

Figure 2 Subsurface models resolved through the proposed PJI schemes. The black dots indicate the sensor/shot positions. The groundwater level observed in a borehole nearby is indicated in the resolved saturation model. (a) Subsurface air content, saturation and porosity. (b) Estimation of both ρ^∞ and ρ^0 permits the computation of the normalized chargeability M_n. Additionally, the CEC is obtained through the application of this PJI scheme.

The models for the subsurface seismic velocity and the electrical resistivity resolved through both PJI schemes show similar patterns and value ranges suggesting that the corresponding χ^2 data fit is acceptable. Low seismic velocities (< 1000 m/s) are confined to near-surface areas (depths < 5 m) and coincide with subsurface areas characterized by high electrical resistivities. At depth (below 5 m) we observe substantially lower resistivities and spatially confined low resistivity anomalies. The normalized chargeability $M_n = \sigma^\infty - \sigma^0$ refers to the ability of porous materials to store electrical charges in presence of an external electrical field and directly related to the surface area and surface charge, which are quantified by the CEC (Revil et al., 2020). Accordingly, the resolved CEC may be used as a proxy to delineate areas with high clay content. To facilitate the interpretation of the resolved petrophysical subsurface models we indicate the streambed in Figure 2. The embankments on both sides of the stream are characterized by high values in the air content and the porosity corresponding with the loose materials observed in these areas during the field work. Both PJI schemes correspondingly solve for substantial lateral variations in the air content and the porosity in near-surface areas. Similarly, both PJI schemes resolve corresponding saturation models. The groundwater level observed in a nearby borehole is in agreement with the groundwater level indicated by the saturation models. Furthermore, both saturation models illustrate a high saturation in the vicinity of the streambed. The high saturation zone beneath the stream does not reach the surface, possibly indicating a lack of resolution in the geophysical data hindering a detailed assessment of near-surface stream-aquifer interactions.

Conclusions and Outlook

We presented the application of two PJI schemes relying on different petrophysical models describing the relationship between the electrical resistivity and the subsurface water content. Our results demonstrate that the PJI facilitates the estimation of petrophysical parameters relevant in hydrological studies (e.g., saturation and porosity). Moreover, we showed that both PJI schemes solved for similar subsurface models suggesting that the influence of the surface conductivity is not as large as initially expected. Considering the promising results obtained in this study we propose to conduct further geophysical surveys in the same area (along lines parallel and perpendicular to the presented profile) to provide subsurface models with high spatial resolution, which in turn might improve the understanding of the stream-aquifer interactions. Further measurements at sites where direct information is available (e.g., boreholes) could help in the interpretation of models resolved through the PJI, and permit the incorporation of constraints in the PJI. The collection of data in an extended frequency bandwidth both in-situ and in laboratory samples might enhance the parameterization of the surface conductivity in the PJI scheme and thus, the estimates for the hydrogeological parameters of interest.

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