Inference of hydraulic conductivity anisotropy through anisotropic ERT inverse modelling

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Over the past years, hydrogeophysics has proven its ability to improve the characterization of the hydraulic conductivity when used along with hydrogeological knowledge. Geophysical tools and methods provide a high density of continuous information at relative low costs and in a non-destructive way. Amongst them, the Electrical Resistivity Tomography (ERT) has been widely applied for its high spatial coverage and for the strong physical and statistical relations with key hydrogeological parameters such as porosity and hydraulic conductivity, as it has been shown in many of our past aquifer characterizations [1, 2]. ERT can therefore help improving hydraulic characterization but conventional inversions do not permit to do it in a quantitative manner. One of the reason is the fact that these algorithms consider the ground as isotropic. Recently, electrical anisotropy has been considered model-wise [3], but it is seldom considered as an interpretation tool or in the characterization process. Furthermore, in most cases, the unconsolidated aquifers in Canada reveals a strong anisotropic behavior of the hydraulic conductivity [4] and lab experiments showed a strong linear relation between electrical and hydraulic conductivity [5]. The geophysical studies could therefore play an important role in the inference of the anisotropy of hydraulic conductivity in situ. In that end, there is a need to develop anisotropic forward and inverse algorithms. Indeed, ERT numerical anisotropic algorithms have already been developed, but none implemented the full numerical finite differences scheme as we present in this paper.
Firstly is shown the numerical forward- and inverse-modelling tool we developed to quantify the electrical anisotropy, introducing the anisotropy coefficient λ. We present the theoretical basis of anisotropic ERT, and we develop the important points of its numerical implementation. A synthetic case is used to highlight the physical and numerical effects of considering or ignoring the anisotropy. It consists on an anisotropic layer resting on an anisotropic half infinite-space. The comparison between numerical and analytical solutions shows an error less than 2% (figure 1). This simple geological structure enables to show the misinterpretations that can arise when anisotropy is disregarded. Considering the forward modelling, the contact depth is over-estimated by a factor λ in the isotropic analysis. The anisotropic inverse modelling is able to reproduce well the true structure, with inversed λ coefficient close to the true λ value. Conversely, the isotropic inversion shows a lot of artifacts with a weak similarity with the true anisotropic resistivity model (figure 2). In other words, this result shows how neglecting the anisotropy can greatly affect the inversed data. Secondly, a real case study is investigated to establish the feasibility of this new integrated, trans-disciplinary anisotropic approach. The site of Saint-Lambert-de-Lauzon 35 km south-west of Quebec city is a 12 km^2 area on which numerous field campaigns have been conducted enabling to get abundant quantities of data of different natures: geological, hydrogeological and geophysical. Innovative in situ anisotropic slug-tests have revealed a strong anisotropy, with up to two magnitude orders between horizontal and vertical hydraulic conductivities. This anisotropy has also been confirmed with downhole resistivity measurements and Cone Penetration Tests CPT_r drillings. In order to confirm the link between hydraulic and electrical conductivity in situ, two new hydrogeophysical experiments were conducted at Saint-Lambert. The first consists in an electrical crosswell ERT survey, where a hydraulic tomography has already been measured. This experiment allows to quantify the correlation between hydraulic conductivity and electrical resistivity anisotropy at the field scale (metric to decametric), to complete and improve the laboratory results previously mentioned. The second experiment consists in the acquisition of horizontal and vertical resistivity profiles, along with surface-borehole measurements. Using ERT along with local true resistivities, Ground Penetrating Radar (GPR) and hydraulic conductivities, we produce an improved characterized hydraulic anisotropic section of the ground through a stochastic optimisation workflow.
Not much more resources are needed compared with conventional methods: a single borehole to perform the conventional hydraulic and the surface/borehole electrical acquisitions. We have shown that the anisotropy has a significant influence on the electrical inversion results: ignoring it when it is present leads to a high intrinsic

irreducible error. It suggests that anisotropy should be taken into account in any characterization study when its presence is presumed or known in order to produce a model closer to the true hydraulic state of the ground.

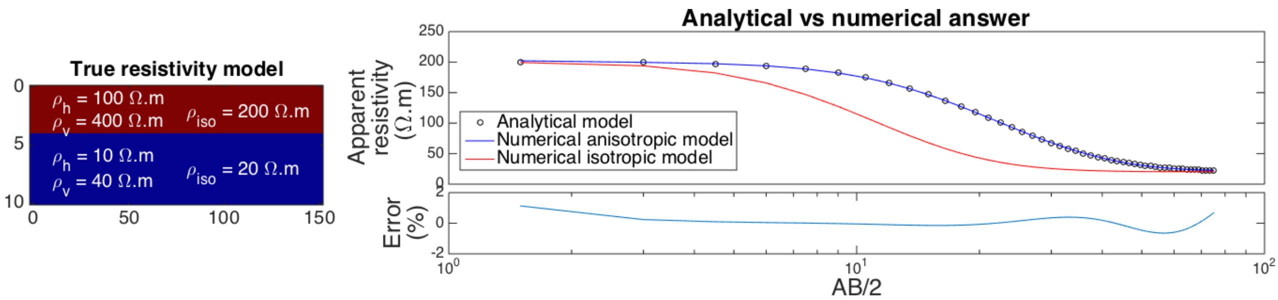

Figure 1: Forward modelling applied to a two-layers anisotropic model. Top layer has a horizontal resistivity $\rho_H = 100W.m$ and a vertical resistivity $\rho_V = 400W.m$. Bottom layer has a horizontal resistivity $\rho_H = 10W.m$ and a vertical resistivity $\rho_V = 40W.m$. Black dots are the analytical response; the fitting blue curve is the anisotropic numerical response. For comparison sake, we took an isotropic resistivity model with a $200W.m$ top resistivity and a $20W.m$ bottom resistivity to consider the isotropic resistivity response, in red. Bottom graph shows the error made by the anisotropic numerical inversion.

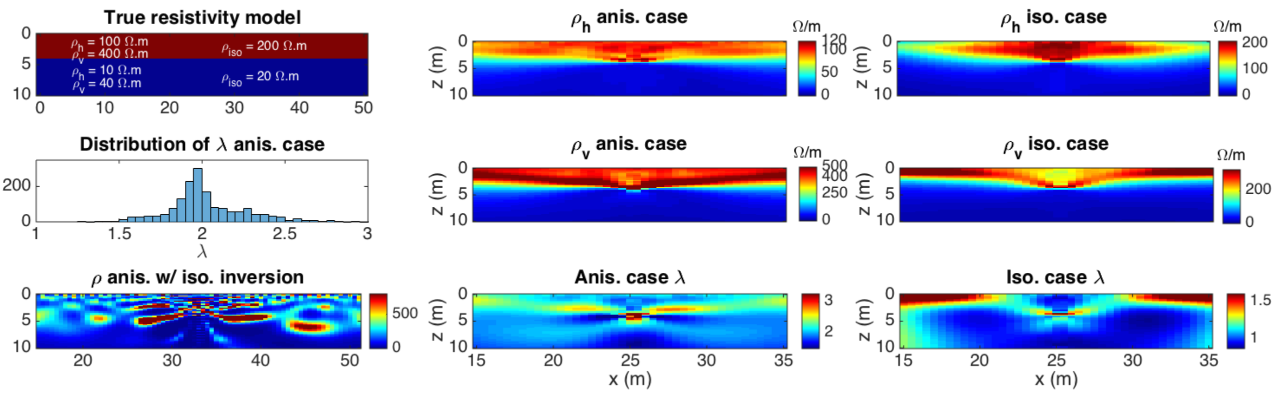

Figure 2: : Inverse modelling is applied on a synthetic true resistivity model (top bottom corner) obtained with a 50m long surface array and a 10m deep borehole array (at $x = 25m$). In this study, a surface Wenner array is used, along with a dipole-dipole borehole and a surface-borehole array. Second column displays the results in the zone of interest ($15m < x < 35m$ and $0m < z < 10m$) for the anisotropic model inversed with our anisotropic tool: ρ_H and ρ_V are respectively the horizontal and vertical components of the resistivity tensor, and $\lambda = \sqrt{\rho_H/\rho_V}$ is the inversed anisotropy coefficient distribution. Third column displays the results in the same zone of interest for the isotropic model inversed our anisotropic tool. Bottom left corner shows the anisotropic structure inversed by an isotropic algorithm.

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