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Variogram-based inversion of time-lapse electrical resistivity data: development and application to a thermal tracing experiment

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Electrical resistivity tomography (ERT) has become a popular imaging methodology in a broad range of applications given its large sensitivity to subsurface parameters and its relative simplicity to implement. More particularly, time-lapse ERT is now increasingly used for monitoring purposes in many contexts such as water content, permafrost, landslide, seawater intrusion, solute transport or heat transport experiments.

Specific inversion schemes have been developed for time-lapse data sets. However, in contrast with static inversions for which many techniques including geostatistical, minimum support or structural inversion are commonly applied, most of the methodologies for time-lapse inversion still rely on non-physically based spatial and/or temporal smoothing of the parameters or parameter changes.

In this work, we propose a time-lapse ERT inversion scheme based on the difference inversion scheme. We replace the standard smoothness-constraint regularization operator by the parameter change covariance matrix. The objective function can be expressed as

$$\psi_{diff}(\Delta m) = \|W_d[d - d_0 + f(m_0) - f(m)]\|^2 + \lambda \left\|C_{\Delta \mathrm{m}}^{-0.5} \Delta \mathrm{m}\right\|^2$$

where W_d is the data weighting matrix, d and d_0 are the data sets corresponding to the considered time-step and to the background, $f()$ is the forward operator, m and m_0 are the models corresponding to the considered time-step and to the background, Δm is the parameter change (resistivity), $C_{\Delta m}$ is the parameter change covariance matrix and λ the regularization parameter. This operator takes into account the correlation between changes in resistivity at different locations through a variogram computed using independent data (e.g., electromagnetic logs). It may vary for subsequent time-steps if the correlation length is time-dependent.

The methodology is first validated and compared to the standard smoothness-constraint inversion using a synthetic benchmark simulating the injection of a conductive tracer into a homogeneous aquifer inducing changes in resistivity values of known correlation length. We analyze the influence of the assumed correlation length on inversion results. Globally, the method yields better results than the traditional smoothness constraint inversion. Even if a wrong correlation length is assumed, the method performs as well as the smoothness constraint since the regularization operator balances the weight given to the model constraint functional in the objective function.

Then the methodology is successfully applied to a heat injection and pumping experiment in an alluvial aquifer. The comparison with direct measurements in boreholes (temperature loggers and distributed temperature sensing optic fibres) shows that ERT-derived temperatures and breakthrough curves image reliably the heat plume through time (increasing part of the curve, maximum and tail are correctly retrieved) and space (lateral variations of temperature are observed) with less spatial smoothing than standard methods.

The development of new regularization operators for time-lapse inversion of ERT data is necessary given the broad range of applications where ERT monitoring is used. In many studies, independent data are available to derive geostatistical parameters that can be subsequently used to regularize geophysical inversions. In the future, the integration of spatio-temporal variograms into existing 4D inversion schemes should further improve ERT time-lapse imaging.