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Rapid 2D Inversion of Boreheole Electromagnetic Data to Determine Anisotropic Resistivity Using Fréchet Derivatives with the Reciprocity Theorem

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1. Extended Abstract

Downhole well logging data acquired by modern electromagnetic (EM) tools enables determining not only resistivity, but also resistivity anisotropy of reservoirs. The most popular anisotropic model for EM data interpretation is a horizontally layered model with transverse isotropic (TI) resistivity anisotropy in each layer. The TI resistivity anisotropy is described by horizontal resistivity (R_h) in the direction parallel to the bedding planes, and vertical resistivity (R_v) in that normal to the planes. This one-dimensional (1D) model is widely used in the oil industry to retrieve anisotropic resistivity from borehole EM measurements. Such a model, however, ignores the resistivity change caused by the mud filtrate invasion that often occurs in a permeable layer. The invasion effect can be so strong that the anisotropic resistivity derived based on the 1D model can be substantially affected. It is crucial to include the invasion in the forward model in order to properly handle the invasion effect on anisotropic resistivity in the inversion.

A 2D inversion approach was developed previously to automatically correct for the invasion effect on the estimation of anisotropic resistivity [1]. Results of the 2D inversion have demonstrated that determining anisotropic resistivity is highly feasible when an invasion is developed in the formation. Good results have been obtained in a broad range of resistivity and a variety of geometric complexity with the 2D inversion. The ability is largely attributed to the richness of data provided by modern EM tools that often employs a multi-array and multi-axis configuration for data acquisition. On the other hand, it is observed that the efficiency of the inversion can deteriorate significantly in complex formations with a large number of layers. The increase in the computational overhead can be so large that the inversion becomes prohibitively time-consuming from a practical point of view.

Considering that sedimentary formations are generally reciprocal, we resort to the reciprocity theorem to find Fréchet derivatives rapidly based on a novel 2D forward solver. The forward solver starts with a Fourier series expansion for electric field in the azimuthal direction. The ρ and z dependences of each harmonic in the expansion are expressed in terms of numerical eigenmodes in the radial direction and exponential functions in the vertical direction. Physically, the latter describes a set of plane waves propagating in the vertical direction. This property allows for using reflection and transmission matrices to couple EM fields from layer to layer. The use of reflection and transmission matrices makes it highly efficient to simulate EM logging response as the two matrices are computed only once for all logging points.

Fréchet derivatives with respect to conductivity are found with the distorted Born approximation [2] in the cylindrical coordinate system. Those with respect to invasion radii and bed boundaries are obtained afterwards by using the chain rule. The semi-analytical property of the forward solver makes it possible to perform integration in three dimensions separately. A closed form solution is first found for the integration in the azimuthal and vertical directions. The integration over ρ is then found separately once an interpolation function is properly defined for the ρ dependence of electric field. Numerical experiments have shown that using the reciprocity theorem leads to a factor of three speedup for an EM tool with one triaxial transmitter and six triaxial receivers. In most cases, three receivers have been to be sufficient for formations with a piston-type invasion, and therefore an additional factor of two can be achieved.

The inversion is based on a Gauss-Newton approach with the L_2-norm regularization technique that not only ensures the stability of the inversion, but also greatly enhances the resolution of reconstructed model in thinly-layered formations. Results show that it takes approximately one hour to solve the inversion in a complex formation of 28 layers on a laptop computer with a 2.5G CPU and an 8GB RAM.

2. References

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