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ΙΔΡΥΜΑ ΤΕΧΝΟΛΟΓΙΑΣ ΚΑΙ ΕΡΕΥΝΑΣ

Έργο ΠΕΦΥΚΑ: Περιβάλλον και Φυσικές Καταστροφές: Νέες μέθοδοι για τη μέτρηση και βελτίωση της ποιότητας του περιβάλλοντος και για την αντιμετώπιση φυσικών καταστροφών

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Dey, A. and **Morisson**, H.F. (1979). Resistivity Modelling for Arbitrarily Shaped Three-Dimensional Structures. *Geophysics*, **44**, 753-780.

A numerical technique has been developed to solve the three-dimensional (3-D) potential distribution about a point source of current located in or on the surface of a half-space containing an arbitrary 3-D conductivity distribution. Self-adjoint difference equations are obtained for Poisson's equation using finite-difference approximations in conjunction with an elemental volume discretization of the lower half-space. Potential distribution at all points in the set defining the subsurface are simultaneously solved for multiple point sources of current. A comparison of the 2-D and 3-D simple block-shaped models, for the collinear dipole-dipole array, indicates substantially lower anomaly indices for inhomogeneities of finite strike-extent. In general, the strike-extents of inhomogeneities have to be approximately 10 times the dipole lengths before the response becomes 2-D. A downhole-to-surface configuration of electrodes produces diagnostic total field apparent resistivity maps for 3-D buried inhomogeneities. Experiments with various lateral and depth locations of the current pole indicate that mise-àla-masse surveys give the largest anomaly if a current pole is located asymmetrically and, preferably, near the top surface of the burried conductor.

Petrick, W.R. Jr., **Sill**, W.R. and **Ward**, S.H.(1981). Three-dimensional Resistivity Inversion using Alpha Centers. *Geophysics*, **46**, 1148-1162.

The method of alpha centers represents a class of solutions to the three dimensional (3-D) DC conduction equation based on certain nonlinear substitutions for electric potential and earth conductivity. The inversion routine results in a conductivity distribution defined by 'α' centers which simultaneously fits the data from several parallel or perpendicular dipole dipole profiles. This method is useful for in field data interpretation to site drilling locations or to guide further exploration and for obtaining a good initial guess for more sophisticated and costly multidimensional inversion schemes.

Shima, H. (1990). Two Dimensional Automatic Resistivity Inversion Technique Using Alpha Centers. *Geophysics*, **55**, 682-694.

A method is proposed that uses alpha centers for two-dimensional automatic analysis of dc electrical exploration data. The appropriateness of using negative C parameters in the alpha centers method is demonstrated by considering the resistivity and electric potential distribution expressed by the alpha centers. Using a network of fixed alpha centers both stabilizes the analysis and makes it possible to employ a large number of alpha centers (more than 100). The combination of these improvements, compensation for topography, and application of a nonlinear least-squares method, which has good convergence throughout the iteration process, makes automatic analysis possible. The experiments show that this method has high resolution. The fact that one of the experiments shows the alpha centers method to be effective for cross-borehole data analysis suggests its wide applicability.

Park, S.K. and **Van**, G.P. (1991). Inversion of Pole-Pole Data for 3-D Resistivity Structures Beneath Arrays of Electrodes. *Geophysics*, **56**, 951-960.

In this work a practical algorithm is developed for inverting gridded resistivity data for three-dimensional structure and it is applied to data from an experiment design in order to detect leaks from ponds. The best results are obtained when transmitting electrodes are located directly above the suspected leak. Application to

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real data yields results which are consistent with drilling data and an adjacent Schlumberger sounding.

Li, Y. and **Oldenburg**, D.W. (1994). Inversion of 3-D DC Resistivity Data using an Approximate Inverse Mapping. *Geophys. J. Int.*, **116**, 527-537.

This study presents an iterative algorithm for inverting 3-D pole-pole DC resistivity data. The algorithm utilizes an AIM (approximate inverse mapping) formalism and iterative inversions are carried out by performing updates in both model space (AIM—MS) and data space (AIM—DS) by using an approximate inverse mapping with an exact forward mapping. Fourier transforming the data equation decouples wavenumber components and the Fourier transform of the conductivity anomaly is recovered by performing 1-D linear inversions at each wavenumber. Inverse Fourier transforming the 1-D inversion results produces the sought conductivity. The AIM methodology avoids the generation and inversion of a full 3-D sensitivity matrix and is consequently fast and efficient. Only one forward modelling is performed at each iteration.

Sasaki, Y. (1994). 3D Inversion using the Finite Element Method. *Geophysics*, **59**, 1839- 1848.

With the increased availability of faster computers, it is now practical to employ numerical modeling techniques to invert resistivity data for 3-D structure. Full and approximate 3-D inversion methods using the finite-element solution for the forward problem have been developed. Both methods use reciprocity for efficient evaluations of the partial derivatives of apparent resistivity with respect to model resistivities. In the approximate method, the partial derivatives are approximated by those for a homogeneous half-space, and thus the computation time and memory requirement are further reduced. The methods are applied to synthetic data sets from 3-D models to illustrate their effectiveness. They give a good approximation of the actual 3-D structure after several iterations in practical situations where the effects of model inadequacy and topography exist. Comparisons of numerical examples show that the full inversion method gives a better resolution, particularly for the near-surface features, than does the approximate method. Since the full derivatives are more sensitive to local features of resistivity variations than are the approximate derivatives, the resolution of the full method may be further improved when the finite-element solutions are performed more accurately and more efficiently.

Ellis, R.G. and **Oldenburg**, D.W. (1994a). Applied Geophysical Inversion. *Geophys. J. Int.* **116**, 5-11.

Using the 2-D DC-resistivity tomography experiment as an example, some of the difficulties inherently associated with constructing a single maximally smooth model are examined as a solution to a geophysical inverse problem. It is argued that this conventional approach yields at best only a single model from a myriad of possible models and at worst produces a model which, although having minimum structure, frequently has little useful relation to the earth that gave rise to the observed data. In applied geophysics it is usual to have significant prior information which is to be supplemented by further geophysical experiments. With this perspective, an alternate approach is suggested to geophysical inverse problems which emphasizes the prior information and includes the data from the geophysical experiment as a supplementary constraint. To this end, all available prior information is examined and an inversion algorithm is constructed which, given an arbitrary starting model and the absence of any data, will produce a preconceived earth model and then introduce the observed data into the inversion to determine how the prior earth model is influenced by the supplementary geophysical data.

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Ellis, R.G. and **Oldenburg**, D.W. (1994b). The Pole-Pole 3D DC-Resistivity Inverse Problem: A Conjugate Gradient Approach. *Geophys. J. Int.* **119**, 187-194.

The pole-pole 3-D DC-resistivity inverse problem is solved by converting the inverse problem into an objective-function optimization problem, using the adjoint equation to compute the gradient of the objective function, and using a conjugate gradient minimization. Two examples of the application of the resulting inversion algorithm are given. First, a large synthetic data set is inverted, and second, the inversion algorithm is used to invert E-SCAN field data of relevance to mineral exploration

Zhang, J., **Randall**, L.M. and **Madden**, T. (1995). 3D Resistivity Forward Modelling and Inversion using Conjugate Gradients. *Geophysics*, **60**, 1313-1325.

Rapid 3-D dc resistivity forward modeling and inversion algorithms are developed that use conjugate gradient relaxation techniques. In the forward network modeling calculation, an incomplete Cholesky decomposition for preconditioning and sparse matrix routines are combined to produce a fast and efficient algorithm. The side and bottom boundary conditions are scaled impedance conditions that take into account the local current flow at the boundaries as a result of any configuration of current sources. For the inversion, conjugate gradient relaxation is used to solve the maximum likelihood inverse equations.

Loke, M.H. and **Barker**, R.D. (1996a). Rapid Least-Squares Inversion of Apparent Resistivity Pseudo-Sections using Quasi-Newton method. *Geophysical Prospecting*, **48**, 152-181.

A fast inversion technique for the interpretation of data from resistivity tomography surveys has been developed for operation on a microcomputer. This technique is based on the smoothness-constrained least-squares method and it produces a two-dimensional subsurface model from the apparent resistivity pseudosection. Tests with a variety of computer models and data from field surveys show that this technique is insensitive to random noise and converges rapidly.

Loke, M.H. and **Barker**, R.D. (1996b). Practical Techniques for 3D Resistivity Surveys and Data Inversion. *Geophysical Prospecting*, **44**, 499-523.

Techniques to reduce the time needed to carry out 3D resistivity surveys with a moderate number of electrodes and the computing time required to interpret the data have been developed. The computing time required by this technique can be greatly reduced by using a homogeneous half-space as the starting model so that the Jacobian matrix of partial derivatives can be calculated analytically. A quasi-Newton updating method is then used to estimate the partial derivatives for subsequent iterations.

Mauriello, P and **Patella**, D. (1999). Resistivity Anomaly Imaging by Probability Tomography. *Geophysical Prospecting*, **47**, 411-429.

Probability tomography is a new concept reflecting the inherently uncertain nature of any geophysical interpretation. The rationale of the new procedure is based on the fact that a measurable anomalous field, representing the response of a buried feature to a physical stimulation, can be approximated by a set of partial anomaly source contributions. These may be given a multiplicity of configurations to generate cumulative responses, which are all compatible with the observed data within the accuracy of measurement. The purpose of the new imaging procedure is the design of an occurrence probability space of elementary anomaly sources,

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located anywhere inside an explored underground volume. The typical tomography is a diffuse image of the resistivity difference probability pattern, that is quite different from the usual modelled geometry derived from standard inversion.

Lesur, V., **Cuer**, M. and **Straub**, A. (1999a). 2D and 3D Interpretation of Electrical Tomography Measurements, Part 1: The Forward Problem. *Geophysics*, **64**, 386-395.

A computer code is developed to model the electrical potential field for borehole-to-borehole measurements. This scheme supports a large class of model geometries including 2-D and 3-D structures embedded in a homogeneous half-space. It enables the computation of the electrical potential at any point due to a direct current injection at any source point within the model. A new boundary integral formulation is used that generates a sparse linear system. The sparsity is exploited in order to optimize the memory size and the computation time needed to solve the forward problem. This formulation is new because two unknown quantities—the electrical potential and a current-related quantity—are solved for each interface. Simulations of a simple model geometry are used to gain insight on when 3-D phenomena differ from those of 2-D models.

Lesur, V., **Cuer**, M. and **Straub**, A. (1999b). 2D and 3D Interpretation of Electrical Tomography Measurements, Part 2: The Inverse Problem. *Geophysics*, **64**, 396-402.

The interpretation of borehole-to-borehole electrical measurements requires solving an inverse problem for a given class of model geometries. The usual approach to an inverse problem includes a model dependent task (i.e., forward modeling) and a generic task (i.e., an optimization scheme). An optimization algorithm is developed using a nonlinear inversion technique. This algorithm allows recovery of a possible resistivity distribution in an investigated zone between two boreholes or in the vicinity of them. This resistivity distribution is defined as a set of 2-D or 3-D volumes of constant resistivity. The inversion procedure minimizes a least-squares term plus a damping term. This latter term seeks to minimize the roughness of the solution. An improved form of this smoothness term may enhance the spatial resolution of the resistivity image, assuming that the resistivity contrast is known a priori.

Tsourlos P. and **Ogilvy** R. (1999). An algorithm for the 3-D inversion of tomographic resistivity and induced polarization data: Preliminary results. *Journal of the Balkan Geophysical Society*, **2**, 30–45.

An algorithm for the 3-D inversion of dc-resistivity and induced polarization cross-borehole data is presented. The procedure is fully automated and is based on a 3-D finite element forward modelling algorithm. The inversion is achieved by a smoothness-constrained algorithm and uses sophisticated data error treatment. The features of the algorithm are presented in detail. Tests of the algorithm with synthetic data are presented as well. The preliminary results indicate that the algorithm is robust, noise insensitive and it produces good quality inversions. Further testing of the algorithm with real data is necessary in order to prove its full potential.

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Yi. M.J., **Kim**, J.H., **Song**, Y., **Cho**, S.J., **Chung**, S.H. and **Suh**, J.H. (2001). Three-Dimensional Imaging of Subsurface Structures using Resistivity Data, *Geophysical Prospecting*, **49**, 483-497.

A three-dimensional inverse scheme is developed for carrying out DC resistivity surveys, incorporating complicated topography as well as arbitrary electrode arrays. The algorithm is based on the finite-element approximation to the forward problem, so that the effect of topographic variation on the resistivity data is effectively evaluated and incorporated in the inversion. Numerical verifications show that a correct earth image can be derived even when complicated topographic variation exists.

Pain, C.C., **Herwanger**, J.V., **Worthington**, M.H. and de **Oliveira**, C.R.E. (2002). Effective Multidimensional Resistivity Inversion using Finite Element Techniques. *Geophysics J. Int.*, **151**, 710-728.

This paper describes the development of a multidimensional resistivity inversion method that is validated using two- and three-dimensional synthetic pole–pole data. We use a finite-element basis to represent both the electric potentials of each source problem and the conductivities describing the model. Using a least-squares method rather than a lower-order method such as non-linear conjugate gradients, has the advantage that quadratic terms in the functional to be optimized are treated implicitly allowing for a near minimum to be found after a single iteration in problems where quadratic terms dominate. Both the source problem for a potential field and the least-squares problem are solved using (linear) pre-conditioned conjugate gradients. Coupled with the use of parallel domain decomposition solution methods, this provides the numerical tools necessary for efficient inversion of multidimensional problems. Since the electrical inverse problem is ill-conditioned, special attention is given to the use of model-covariance matrices and data weighting to assist the inversion process to arrive at a physically plausible result. The model-covariance used allows for preferential model regularization in arbitrary directions and the application of spatially varying regularization.

Loke, M.H. and **Dahlin**, T. (2002). A Comparison of the Gauss-Newton and quasi-Newton Methods in Resistivity Imaging Inversion. *Journal of Applied Geophysics*, **49**, 149-162.

In this method, the Jacobian matrix for a homogeneous earth model is used for the first iteration, and the Jacobian matrices for subsequent iterations are estimated by an updating technique. Since the Gauss-Newton method uses the exact partial derivatives, it should require fewer iterations to converge. However, for many data sets, the quasi-Newton method can be significantly faster than the Gauss-Newton method. The effectiveness of a third method that is a combination of the Gauss-Newton and quasi-Newton methods is also examined. In this combined inversion method, the partial derivatives are directly recalculated for the first two or three iterations, and then estimated by a quasi-Newton updating technique for the later iterations. As the combined inversion method is faster than the Gauss-Newton method, it represents a satisfactory compromise between speed and accuracy for many data sets.

Yi, M.J., **Kim**, J.H. and **Chung**, S.H. (2003). Enhancing the Resolving Power of Least-Squares Inversion with Active Constraint Balancing. *Geophysics*, **68**, 931-941.

A new regularization approach is presented in which the Lagragnian multiplier is set as a spatial variable at each parameterized block and automatically determined via the parameter resolution matrix and spread

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function analysis. For highly resolvable parameters, a small value of the Lagragnian multiplier is assigned, and vice versa. This approach, named “active constraint balancing” (ACB), tries to balance the constraints of the least-squares inversion according to sensitivity for a given problem so that it enhances the resolution as well as the stability of the inversion process.

Gunther, T., **Rucker**, C. and **Spitzer**, K. (2004). Three-dimensional Modelling and Inversion of DC Resistivity Data Incorporating Topography-II. Inversion. *Geophysics J. Int.*, **166**, 506-517.

A novel technique is presented for the determination of resistivity structures associated with arbitrary surface topography. The approach represents a triple-grid inversion technique that is based on unstructured tetrahedral meshes and finite-element forward calculation. A Gauss–Newton method is used with inexact line search to fit the data within error bounds. A global regularization scheme using special smoothness constraints is applied. The regularization parameter compromising data misfit and model roughness is determined by an L-curve method and finally evaluated by the discrepancy principle. To solve the inverse subproblem efficiently, a least-squares solver is presented. The technique is applied to synthetic data from a burial mound to demonstrate its effectiveness. A resolution-dependent parametrization helps to keep the inverse problem small to cope with memory limitations of today's standard PCs. Furthermore, the SP calculation reduces the computation time significantly. This is a crucial issue since the forward calculation is generally very time consuming. Thus, the approach can be applied to large-scale 3-D problems as encountered in practice, which is finally proved on field data.

Pidlisecky A., **Haber** E. and **Knight** R. (2007). RESINVM3-D: A MATLAB 3-D resistivity inversion package. *Geophysics*, **72**, H1–H10.

An open source 3D, MATLAB based, resistivity inversion package is developed. The forward solution to the governing partial differential equation is efficiently computed using a second-order finite volume discretization coupled with a preconditioned, biconjugate, stabilized gradient algorithm. Using the analytical solution to a potential field in a homogeneous half space, the accuracy of the numerical forward solution is evaluated and, subsequently, a source correction factor is developed that reduces forward modeling errors associated with boundary effects and source electrode singularities.

Marescot L., **Lopes** S.P., **Rigobert** S. and **Green** A.G. (2008). Nonlinear inversion of geoelectric data acquired across 3-D objects using a finite-element approach. *Geophysics*, **73**, F121–F133.

A new finite-element-based scheme is introduced for the fast nonlinear inversion of large 3D geoelectric data sets acquired around isolated objects or across the earth’s surface. The principal novelty of this scheme is the combination of a versatile finite-element approach with (1) a method involving minimization of an objective function using a conjugate-gradient algorithm that includes an adjoint-field technique for efficiently establishing the objective-function gradient and (2) parabolic interpolation for estimating suitable inversion step lengths. Computation of the Jacobian matrix, which might require computers with a large amount of memory, is not necessary.

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Papadopoulos, N.G, P. **Tsourlos**, C. **Papazachos**, G.N. **Tsokas,** A. **Sarris** and J. H. **Kim** (2011) An Algorithm for the Fast 3-D Resistivity Inversion of Surface Electrical Resistivity Data: Application on Imaging Buried Antiquities. Geophysical Prospection, 59, 557-575.

In this work a new algorithm for the fast and efficient three-dimensional (3-D) inversion of conventional two-dimensional (2-D) surface Electrical Resistivity Tomography (ERT) lines,, is presented. The proposed approach lies on the assumption that for every surface measurement there is a large number of 3-D parameters with very small absolute Jacobian matrix values, that can be excluded in advance from the Jacobian matrix calculation. A sensitivity analysis for both homogeneous and inhomogeneous earth models showed that each measurement has a specific region of influence. Application of the proposed algorithm accelerated almost three times the Jacobian (sensitivity) matrix calculation for the data-sets tested in this work. Moreover, application of the Least SQuares Regression (LSQR) iterative inversion technique, resulted in a new 3-D resistivity inversion algorithm more than 2.7 times faster and with computer memory requirements less than half compared to the original algorithm. The efficiency and accuracy of the algorithm was verified using synthetic models representing typical archaeological structures, as well as field data collected from two archaeological sites in Greece, employing different electrode configurations.

Plattner, A., **Maurer**, H. R., **Vorloeper**, J. and **Blome**, M. (2012), 3-D electrical resistivity tomography using adaptive wavelet parameter grids. *Geophysical Journal International*, **189**, 317–330.

A novel adaptive model parametrization strategy is presented for the 3-D electrical resistivity tomography problem and demonstrate its capabilities with a series of numerical examples. In contrast to traditional parametrization schemes, which are based on fixed disjoint blocks, the subsurface is discretized in terms of Haar wavelets and adaptively adjust the parametrization as the iterative inversion proceeds.

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