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SOME APPLICATIONS OF FREQUENCY DOMAIN 2.5-DEM NUMERICAL MODELLING USING HED SOURCES

MATHEMATICAL AND COMPUTATIONAL BACKROUND

If the conductivity structure is a 2-D one which is excited with a 3-D source the problem is named as 2.5-D problem. The geoeletric or electromagnetic (EM) response of elongated conductivity structures (2-D) due to 3-D source is usually determined in the along-strike wavenumber domain, because of the relative simplicity of the equations in that domain. The spatial field response then is calculated by inverse Fourier transform. These steps can be followed in the papers listed here where solutions can be found to 2.5-D direct current (DC), 2.5-D frequency domain electromagnetic (FEM), 2.5-D time domain electromagnetic (TEM) numerical modelling. Resistivity modelling for arbitrarily shaped two-dimensional structures due to a point source was done by Dey and Morrison (1979). Stoyer and Greenfield (1976) developed a finite-difference solution using a coupled transmission sheets analogy for determining the frequency domain electromagnetic fields due to a magnetic source as a point source in the presence of two-dimensional conductivity structures. Unsworth, Travis and Chave (1993) developed a finite-element method to solve the frequency domain electromagnetic response of a 2-D earth under the excitation of a 3-D current source. The 2.5-D finite-element solution for the fields induced by a magnetic dipole has been addressed by Lee and Morrison (1985). The increasing interest in marine controlled-source systems led Everett and Edwards (1993) to solve the 2.5-D forward problem of transient marine electromagnetics.

As far as the frequency domain EM responses of 2-D conductivity structures excited with horizontal electric dipole sources are concerned similar way can be followed. The starting point is the Maxwell's equations with electric source terms. After Fourier transform of Maxwell's equations from the space domain to the along-strike wavenumber domain the electromagnetic problem can be defined in a form of second order partial differential equations. These are very similar to those of two coupled transmission sheets and this analogy makes it possible to fulfil the interior boundary conditions. In order to model 2-D inhomogeneities the structures and their surroundings are covered with a finite rectangular grid. Each rectangular grid element and any part of the conductivity cross section can be characterized with distributed parameters (which are constant within each rectangular grid element) and any part of the conductivity cross section with distributed parameters can be replaced by a grid section consisting of lumped circuit elements. The electric sources are treated in the way as the magnetic sources were considered by Stoyer (1974) and Takács (1979). They are assumed to have no extension in the structural strike direction, and constant distributed parameters are supposed in their vicinity. This transformation results in that the original three-dimensional problem is derived to a set of two-dimensional ones. The chosen numerical procedure is a finite-difference method in the along-strike wavenumber domain. The applied method to solve the linear set of equations is the block tridiagonal LU decomposition in which the order of the greatest real matrix to be inverted was 16 times the square of number of rows. Additional details are given by Pethő (1987). After solving the linear set of equations at different along-strike wavenumbers the next step is the determination of the spatial electromagnetic field components which is done by numerical inverse Fourier transforms. These transforms are made for the plane which is perpendicular to the strike and contains the source. In this way EM numerical modelling can be done both the broadside (TE mode) and collinear (TM mode) configurations. During the numerical modelling emphasis is put on the grid discretization, the selection of the range and distribution of discrete along-strike wavenumbers depending on the frequency and transmitter-receiver range and the conductivity distribution. In the beginning the shortage of suitable computer facilities hindered the modellings. The use of an IBM ES/9121-260 computer at the Oulu University gave an impulse in 1992 (Pethő and Kaikkonen, 1993) and since that time some numerical problems have been solved at the University of Miskolc due to additional code development and improving computer facilities. At first computation was done with CDC 3300, after that MicroVAX 3000, IBM RISC/6000/320 and at present IBM AIX RISC/6000 R20 computer (Pethő and Ficsór (1997), Ficsór and Pethő (1998)).

SOME PROBLEMS SOLVED

In the next a short summary is given on the applications of the forward numerical modelling on the basis of papers presented earlier. The common feature of the applications is the determination of the EM responses of elongated conductivity structures due to horizontal electric dipole sources. The main difference can be found in the position of the electric dipole sources (which are placed on the surface or on the seafloor) besides the aim of investigations. Additional characteristics of the modellings are the different transmitter receiver and the varying frequency ranges resulting in modelling near the far field zone, in the transition zone and close to the near field zone. In order to support Controlled Source Audio Frequency Magnetotelluric (CSAMT) measurements' interpretation plane wave assumption is frequently applied. However, a lot of CSAMT measurements are carried out not in the far field zone rather in the transition zone neighbouring far and near field zones. The procedure makes it possible to make difference between zones on the basis of the proper selection of along-strike wavenumber domain.

Pethő (1994) dealt with the numerical modelling of CSAMT for thermal EOR monitoring assuming strike directional (x) electric dipole source placed on the surface over different 2-D conductivity structures representing thermal zones with different widths at two different depths. In case of fire flood or steam injection thermal enhanced oil recovery procedure the resistivity of the thermal zone decreases as compared with that of the reservoir before injection or flooding. The change in the reservoir resistivity can make it possible to follow the dislocation of the thermal front from the surface with Controlled-Source Audio Frequency Magnetotellurics (CSAMT) method. This kind of monitoring has practical importance in planning or modifying production systems. The first experience was gained by Wayland, Lee, Cabe (1987) in this field. In the late eighties CSAMT measurements were used by Hungarian Geophysical Exploration Co. for thermal EOR monitoring in Hungary as well. The reservoir of Demjén-East situated at the depth of 200 m under the surface and the normalized E_x contour maps in the frequency range of 16-64 Hz were found to be the most suitable for monitoring according to Beke, T. Nagy, Z. Nagy, Péterfai (1989). The real problem is always a 3-D one and the most effective solution to the problem can be achieved by EM analogue modelling available also in Hungary. However, the 2-D situation can be interesting for interpretational point of view and 2-D modelling can be applied to moderate resistivity contrasts, too. Six 2-D models were computed at frequencies of 8 Hz and 32 Hz. The thermal zone as a 2-D inhomogeneity was directly placed along the layer boundary of the two-layer horizontally stratified halfspace with $\rho_1 = 10$ Ωm, $\rho_2 = 100$ Ωm, $h_1 = 250$ m. The thermal zone with constant resistivity ($\rho = 1$ Ωm) and thickness ($h = 12{,}5$ m) was put over and in the second case under the layer boundary, and its width was varied as 50 m, 100 m and finally 250 m at both depths. The E_x, Z_{xy}, H_z responses of 2-D thermal zones were computed in the transmitter-receiver range of 600 m = *r* = 1200 m. We applied a grid with 24 rows and 35 columns and we experienced that 15 along-strike wavenumbers had to be used. In order to enhance the response of the 2D thermal zones normalized amplitudes and relative phases were computed with respect to the two-layer horizontally stratified halsfpace. In this way the values presented along the profile were free from the effect of transmitter-receiver offset as well. On the basis of numerical modelling it was concluded that the effect of the 2-D thermal zone on the EM components depends upon its resistivity, geometry (width, thickness), depth and the frequency at which the measurements are carried out. Besides measurement of E_x both Z_{xy} and H_z measurements are suggested. In the situation presented there the dynamics and the relative changes of H_z and Z_{xy} is greater than those of E_x. However, they did not exceed 15 % and 18 % respectively, even for the largest thermal zone. The smallest thermal zone (12,5 m x 50 m) could not be detected and this surface EM arrangement could not cope with the depth location of the thermal zone.

Other application can be the determination of EM fields in case of marine controlled-source EM systems. These systems for the exploration of seafloor operate in either frequency or time domain. Pethő, Kaikkonen and Vanyan (1995) presented the effect of a 2-D seafloor trench on sea-bottom EM measurements in the frequency domain. Numerical modelling was done at two frequencies ($f = 0{,}1$ Hz and $f = 1$ Hz) with transmitter-receiver range of 14,5 km = *R* = 19,5 km over the trench with a cross-section 1 km x 0,6 km. It was concluded that due to the horizontal skin effect in case of marine FEM measurements the far zone features could be observed at relatively smaller transmitter-receiver distances to compare with on-land EM frequency soundings. The normalized EM field responses of a 2-D trench to dipole equatorial (TE mode) and to dipole axial arrays were presented along a horizontal in-line profile on the sea-bottom at two frequencies. The electric field responses of the dipole axial arrays have better resolution than those of the dipole equatorial ones, similarly TM and TE modes in MT due to the electric charge accumulation along the boundaries. E_z and H_z responses are particularly sensitive to the topographic changes. The E_z response is due to the galvanic effect and H_z is induced by the current flow in strike direction within the trench. The numerical modellings proved that all EM components were influenced by the varying topography of the seafloor but in a different degree. In general, it can be stated that the topographical effects have to be taken into account in order to avoid the misinterpretation of frequency domain EM responses. In this situation the galvanic effect could be considered as a distortion effect.

Just like seafloor topographical changes, elongated surface conductivity inhomogeneities can also result in distortion effect on on-land CSAMT measurements. In a frequency range of 0,1 Hz-100 Hz the EM responses for the two source polarizations (TM and TE mode) were determined by Pethő and Ficsór (1998) over elongated surface conductivity inhomogeneities. 27 along-strike wavenumbers were needed to determine the spatial EM field components by a numerical inverse Fourier transform. The EM modelling in this frequency range required three grid geometries. The shift of impedances for TM mode is dominant at lower frequencies with a strong edge effect opposite the TE mode where current channelling can be observed. Having the same geometry and fixed moderate resistivity contrasts between the inhomogeneity and the host the conductive inhomogeneity embedded in a two-layer half-space with resistive basement resulted in greater distortion effect than the resistive one and in opposite sense in both broadside and collinear configuration. Besides the well known galvanic effect in TM mode the tuning effect can also be significant. It can be observed when the effect of a conductive layer on a resistive basement is masked by a transitional notch. The measure of this effect depends upon the type of configuration, too. The change of the position of transition notch can also be experienced when transmitter-receiver range changes. The tuning effect and the change in the position of transition notch can be observed in case of both 1-D and 2-D conductivity structures.

Usually the task of CSAMT measurements is to provide information on faults, structural elements at greater depths. The authors are convinced that tandem multireceiver CSAMT can be the most effective tool to cope with these problems. However, the CSAMT measurements data usually are influenced by the EM effects of near-surface conductivity inhomogeneities. It would be desirable to get rid of their effects (just like in MT of static shift). In order to do it the first step can be to analyse the resultant EM responses due to structures at different depths. Pethő and Ficsór (1999) presented numerical modelling results over complex conductivity structures in the frequency range of 268,3 Hz = f = 0,1 Hz. To increase the accuracy 29 discrete along-strike wavenumber and finer grid (249 x 50) were applied. It was experienced that the resultant EM responses can not be considered as a simple superposition of the EM responses of separate conductivity structures. Additional investigations are needed to be clear about the development of combined EM responses in the different zones.

CONCLUSIONS

In order to make numerical modelling over 2-D conductivity structures excited with horizontal electric dipole sources a finite-difference method was developed to formulate the Fourier transform of Maxwell's equations in the along-strike wavenumber domain. Spatial EM fields were determined for broadside and collinear configurations. The numerical procedure was applied to model on-land and seafloor controlled source EM measurements. At the beginning relatively simple conductivity structures were investigated, but lately soundings for three decades in frequency were computed over complex conductivity structures. Current channelling, galvanic effects (including static shift), tuning effect, horizontal and vertical skin effect could be observed. The numerical modeling over a relatively wide frequency range made it possible to investigate the characteristics of the different zones including transition zone.

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