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Development of Engineering and Analytical Models of Pulsed Electromagnetic Field and Magnetic Fluxes of Horizontally Inhomogeneous Flat Geological Structure

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Abstract. The development of multicomponent engineering and analytical model of magnetic flux of a pulsed electromagnetic field of horizontally inhomogeneous electrically conductive structure using the dynamic method of images, solutions of the Laplace and Helmholtz equations, the Fourier spectral method, numerical experiment, and modelling is considered. The most simple but distinctive electrically conductive geological structure in the form of known inclined plane — the contact model of two media, ore-controlling tectonic zones, the boundaries of oil and gas deposits and other stratiform objects, was adopted as horizontal heterogeneity. Since rigorous methods for solving problems of electrodynamics on horizontally heterogeneous bodies are quite complicated and time-consuming, the technology of pulsed electrical exploration in the study of such structures is mainly based on the results of physical modelling and technologies of "related" methods based on measurements of low-frequency harmonic fields. The design and modelling of an engineering and analytical model of pulsed electromagnetic field of horizontally heterogeneous structure are shown. In order to increase the depth of the study and more efficiently assess the horizontal heterogeneity of the section, analytical models of multicomponent fields of the flux of magnetic induction of an inclined conductive structure are presented.

1. Introduction

The problem of studying horizontally heterogeneous media to the depth of development of mineral deposits in solving ore, oil and gas, structural, tectonic and similar problems has significant practical and scientific significance.

In solving these issues, one of the leading places is currently occupied by pulsed electrical exploration, but its technological basis, due to the known difficulties of rigorous solutions to such electrodynamic problems, is based mainly on the results of physical modeling and "related" technologies based on the study of harmonic electromagnetic fields . In this regard, it is of interest to consider the construction and modeling of engineering and analytical models that provide technological schemes for electric sounding and electric profiling of deeply lying horizontally heterogeneous geological structures.

2. Methodology for vertical seam modeling

The S plane (parent model) is placed vertically on the drawing plane. We apply method of images to this model of electrically conductive vertical seam [1,5,10,19,20], taking for the plane of symmetry the earth's surface, which divides the S plane into two equal vertical (relative to the earth's surface) half-planes S (daughter model) excited by a horizontal magnetic dipole with a moment Mx. Moreover, the validity of the application of method of images follows from the equality of the boundary conditions on the parent and daughter models [10,14,16,18].

Components of an unsteady electromagnetic field of horizontal magnetic dipole above the S plane:

$$\dot{B}_{1r}^{1x}(t) = \frac{3M_x}{2\pi S} cos\varphi a \frac{4r^2 - a^2}{(a^2 + r)^{7/2}} \quad (1)$$

$$\dot{B}_{2r}^{1x}(t) = \frac{3M_x}{2\pi S} cos\varphi a_1 \frac{4r^2 - {a_1}^2}{({a_1}^2 + r)^{7/2}} \quad (2)$$

$$\dot{B}_{2r}^{11x}(t) = \frac{3M_x}{2\pi S} rcos\varphi a_2 \frac{r^2 - 4{a_2}^2}{({a_2}^2 + r)^{7/2}} \quad (3)$$

where $a = \frac{2t}{\mu S} + 2h + z$, $a_1 = \frac{2t}{\mu S} - z$, $a_2 = \frac{2t}{\mu S} + 2h - z$, S – seam longitudinal conductivity, $\dot{B}_r^x(t)$ – components of horizontal magnetic dipole above the S plane [13], M – magnetic dipole moment, t – observation time, μ - magnetic permeability, h – distance from the S plane to the field source.

The components of transient electromagnetic field of vertical magnetic dipole above the S plane:

$$\dot{B}_{1z}^{1z}(t) = -\frac{3M_z}{2\pi S r^4} \frac{a(2a^2 - 3)}{(a^2 + 1)^{7/2}} \quad (4)$$

$$\dot{B}_{2z}^{1z}(t) = -\frac{3M_z}{2\pi S} \frac{a_1({a_1}^2 - 3r^2)}{(a^2 + r^2)^{7/2}} \quad (5)$$

$$\dot{B}_{2z}^{11z}(t) = -\frac{3M_z}{2\pi S} \frac{a_2({a_2}^2 - 3r^2)}{({a_2}^2 + r^2)^{7/2}} \quad (6)$$

where $a = \frac{2t}{\mu S} + 2h + z$, $a_1 = \frac{2t}{\mu S} - z$, $a_2 = \frac{2t}{\mu S} + 2h - z$.

According to the method of images, doubled unsteady field of horizontal magnetic dipole above the vertical S plane is transformed into field of vertical magnetic dipole when electric profiling by the transient method along the z axis.

Figure 1 shows graphs of the electric profiling of an unsteady electromagnetic field, for the combined version of the transient method, calculated by the equations (1) and (3) and for the dipole version, calculated by the equations (1) and (2).

a) b)

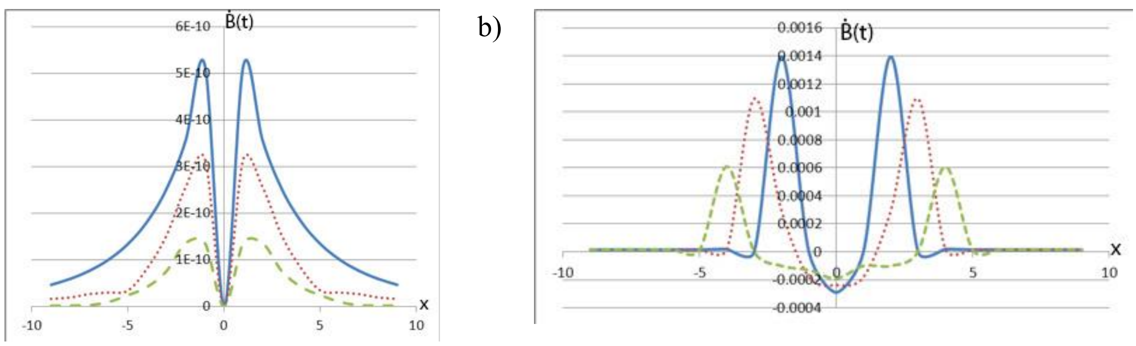

Figure 1. Components of unsteady electromagnetic field in (a) combined version, (b) dipole version.

Comparison of given electric profiling graphs with the known results of physical modeling shows their qualitative identity, i.e. the presented analytical models of electric profiling over the vertical S plane are adequate.

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The fluxes of magnetic induction for this model are presented in the form [12, 14]. Figure 2 shows graphs of electric profiling of vertical and horizontal components of magnetic induction for the technology of combined and dipole variants [2,4,6,11].

The components of the magnetic induction of horizontal and vertical magnetic dipoles are determined by the integration over time of equations (1-6) [9,12,14,17].

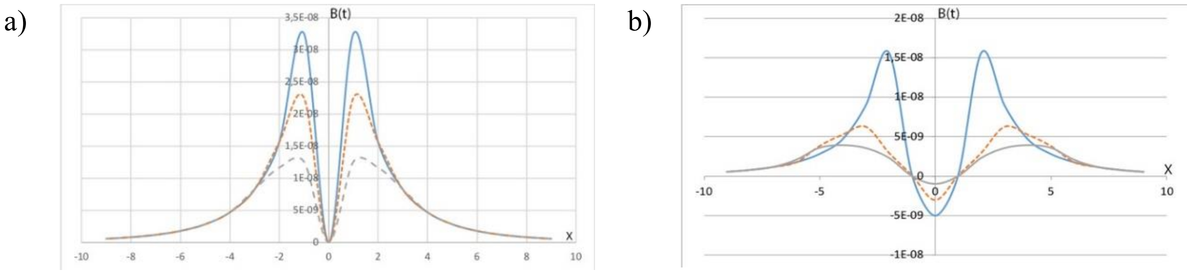

Figure 2. Magnetic induction components in (a) combined version, (b) dipole version.

3. Steep seam construction methodology

Considering the result of applying the method of images to the modeling of electrical conductive vertical seam in this analysis, we believe that the unsteady field of steep seam quantitatively is determined by known models [3,7,15] considering the flat boundary of the day surface.

The moment of the vertical magnetic dipole is determined to define the pulsed electromagnetic field of the steep seam S, lying at an angle γ to the horizontal boundary of the earth's surface. We decompose it into two components: one of which is parallel and the other is perpendicular to the interface [15].

The unsteady electromagnetic field of an inclined plane is determined through the vector potentials of the vertical and horizontal magnetic dipoles in the corresponding regions, and then they are transferred to the original coordinates. Then, by differentiating along the corresponding coordinates, there are vertical and horizontal components that describe the electromagnetic fields of the steep seam [12,14].

Thus, the task is reduced to finding the components of the horizontal and vertical dipoles and their addition. The vertical magnetic moment has a $M cos\gamma$ moment above the S plane, and the horizontal magnetic dipole has $M sin\gamma$ moment. Electromotive forces of vertical and horizontal magnetic dipoles are the same as for the vertical plane but considering the angle of inclination γ [3,15].

Figure 3 shows the graphs of electric profiling of components of an unsteady electromagnetic seam in combined and dipole versions.

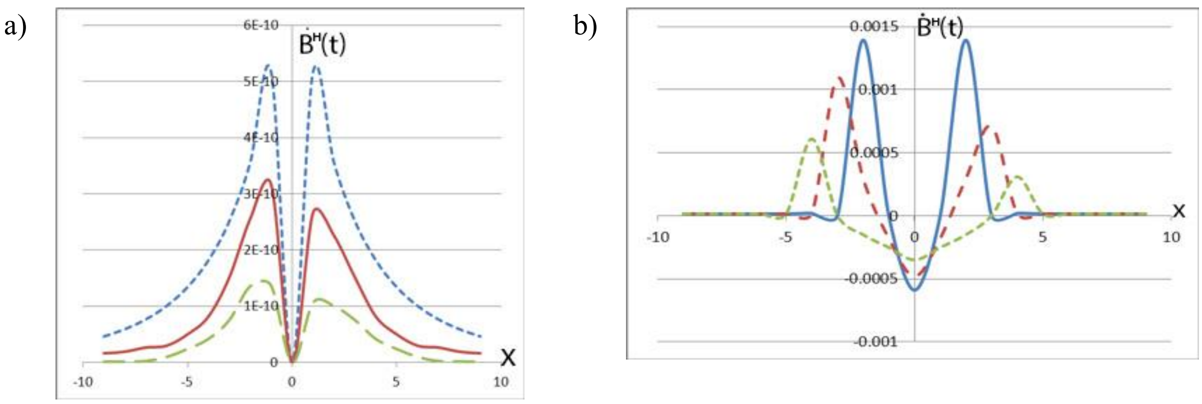

Figure 3. Components of unsteady electromagnetic field of steep seam in (a) combined version, (b) dipole version.

Figures 4 and 5 show graphs of the components of the magnetic induction B_z and B_r of the steep seam in the combined and dipole versions.

a)

b)

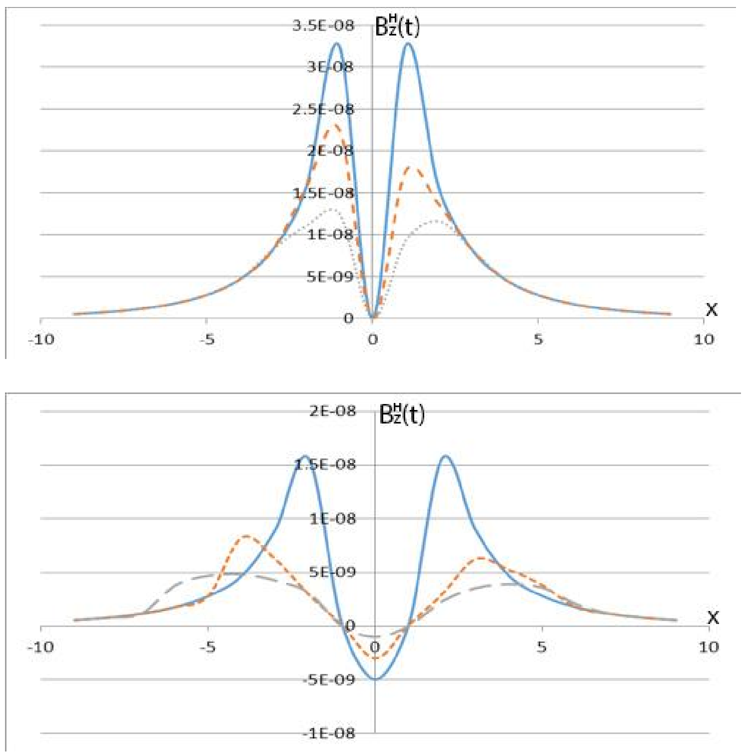

Figure 4. Components of magnetic induction B_z of steep seam in (a) combined version, (b) dipole version.

a)

b)

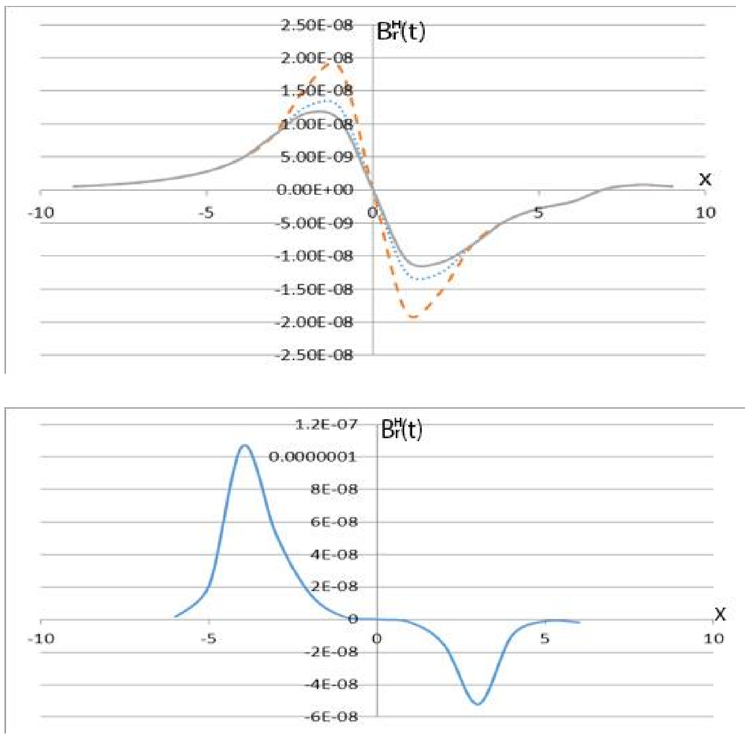

Figure 5. Components of magnetic induction B_r steep seam in (a) combined version, b) dipole version.

The unsteady field of an inclined magnetic dipole is determined by the superposition of the fields of vertical and horizontal dipoles, whose moments are equal to the projections of the vertical magnetic dipole moment M on the new coordinate axes OZ_1 and OX_1 [15].

The components B_r and B_z of the steep seam are determined through the vector potentials of the vertical magnetic dipole of the steep seam, followed by differentiation according to the corresponding coordinates when determining the vertical and horizontal components of magnetic induction [8,9,12,14, 21].

$$B_{1z}^{\mathrm{Hz}}(t) = -\frac{3\mu M_{x1}^{\mathrm{H}} sin\gamma cos\gamma}{4\pi} r_1 cos\varphi \frac{a_1}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} + \frac{\mu M_{z1}^{\mathrm{H}} cos\gamma sin\gamma}{4\pi} \frac{2a_1 - {r_1}^2}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} - \frac{3\mu M_{x1}^{\mathrm{H}} sin\gamma sin\gamma}{4\pi} r_1 cos\varphi \frac{a_1}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} + \frac{\mu M_{z1}^{\mathrm{H}} cos\gamma cos\gamma}{4\pi} \frac{2a_1 - {r_1}^2}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} \quad (7)$$

$$B_{1r}^{\mathrm{H}z}(t) = \frac{\mu M_{x1}^{\mathrm{H}} sin\gamma cos\gamma}{2\pi} cos\varphi \frac{a_1({a_1}^2 - 2{r_1}^2)}{({a_1}^2+2{r_1}^2)^{\frac{5}{2}}} - \frac{3\mu M_{z1}^{\mathrm{H}} cos\gamma sin\gamma}{4\pi} \frac{a_1}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} + \frac{\mu M_{x1}^{\mathrm{H}} sin\gamma sin\gamma}{2\pi} cos\varphi \frac{a_1({a_1}^2 - 2{r_1}^2)}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} + \frac{3\mu M_{z1}^{\mathrm{H}} cos\gamma cos\gamma}{4\pi} \frac{a_1}{({a_1}^2+{r_1}^2)^{\frac{5}{2}}} \quad (8)$$

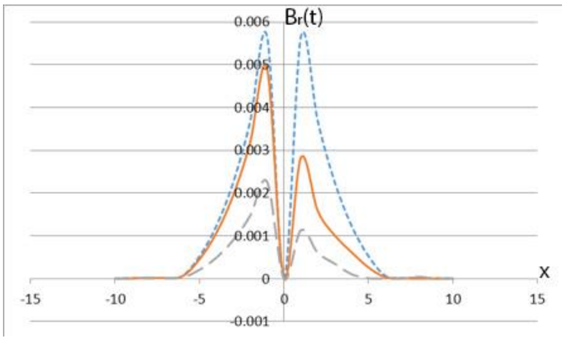

Figure 6. Graphs of electric profiling B_z over steep seam.

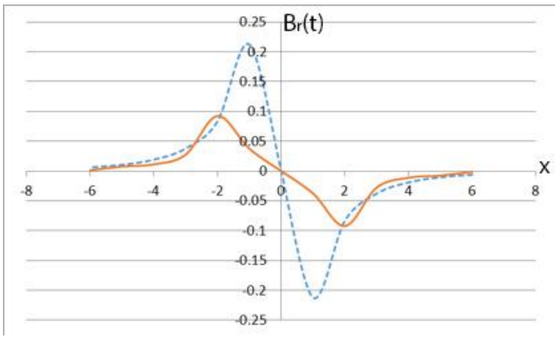

Figure 7. Graphs of electric profiling B_r over steep seam.

4. Conclusion

We propose a method of engineering and analytical analysis of pulsed electromagnetic fields of horizontally heterogeneous reservoir structures using the method of images.

Considering the result of applying the method of images, combination of experimental-numerical analysis and graphical constructions, adequate engineering and analytical models have been obtained: magnetic induction components for the technology of combined and dipole versions of pulsed electrical exploration in the study of vertical and steep seams.

The results of the study expand and strengthen the theoretical base of pulsed electrical exploration and can be used in prospecting-mapping, structural-tectonic and predictive assessments of geological structures.

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