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Russian Geology and Geophysics 58 (2017) 1263–1269

RUSSIAN GEOLOGY AND GEOPHYSICS

www.elsevier.com/locate/rgg

Subsurface geoelectric array with two transmitters for petroleum exploration in offshore areas

A.V. Marinenko [a,*], M.I. Epov [a,b]

[a] *A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*
[b] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090, Russia*

Received 16 August 2016; accepted 6 December 2016

Abstract

At present, sounding methods based on the effect of electromagnetic pulses on the environment are widely used for marine exploration of hydrocarbon deposits. The exploration is performed using research systems with special equipment fixed in the water column. The goal of this work is to develop equipment and methods for marine electrical prospecting that would allow reliable predictions of petroleum fields in the underlying environment with reduced labor intensity of the necessary surveys. For this purpose, a subsurface array for marine electrical prospecting during vessel movement is proposed. The effective frequencies, current strengths in cables, and the size and efficiency of the array are determined using both the theoretical knowledge of the operation of similar arrays in similar environments and numerical simulation of the developed array. The 3D finite element method is used for mathematical modeling.

Keywords: marine geophysics; electric array; finite element method; electric field; electrical conductivity; electric charge

Introduction and problem statement

The main problem of marine geoelectrical exploration is the screening effect of the highly conducting seawater layer. The easiest way to eliminate this effect is to place the entire array or its parts (measuring probes) near the seabed (Davydycheva and Rykhlinski, 2011). This approach is obvious, but the corresponding technologies require very complex and costly technical solutions. Because of the strong influence of the conductive seawater layer on the measured signals, the arrays commonly used in surface electrical exploration are brought nearer to target objects by placing them at the bottom or at a small distance from it. This is of course a forced decision, which leads to major difficulties in practice, such as transportation of the array along the uneven seabed, its inaccurate positioning, etc. The use of subsurface arrays is possible if they have low sensitivity to the seawater layer and if the measured signal provides a sufficient amount of information to identify petroleum deposits and determine their structure, distribution, and specific electrical conductivity (SEC).

A similar problem, associated with the wide use of highly conductive biopolymer salt-based drilling muds, was encountered in borehole geophysics (Epov and Antonov, 2000). The logging unit (probe) is in a penetrating borehole filled with a highly conductive homogeneous drilling mud. For such models, approximate expressions describing the electromotive force (EMF) of a current turn of short radius (but comparable to the length of the probe) were obtained as early as in the 1970s. It was assumed that the borehole is in a homogeneous conductive medium.

$$\xi^{(2)}(k_1 r_1, k_2 L) \approx \frac{\xi^{(1)}(k_2 L)}{I_0^2(k_1 r_1)}. \qquad (1)$$

Here $\xi^{(2)}$ is the EMF in the two-layer nonmagnetic medium [V]; $\xi^{(1)}$ is the EMF in the homogeneous nonmagnetic external environment [V]; r_1 is the radius of the borehole [m]; k_1 and k_2 are the wavenumbers in the external and borehole environments; I_0 is a modified Bessel function of zero order. In the quasi-stationary approximation, we assume that the influence of the bias currents is small:

$$k_j^2 = -i\omega\mu_0\sigma_j, \quad j = 1, 2,$$

* Corresponding author.
E-mail address: arkadiy@reqip.net (A.V. Marinenko)

1068-7971/$ - see front matter
http://dx.doi.org/10.1016/j.rgg.2016.12.011

where σ_1 is the SEC of the drilling fluid; σ_2 is the SEC of the external environment; $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability of vacuum; ω is the cyclic frequency [s^{-1}]; L is the distance between the transmitter and the measured point (probe length) [m]. Comparative analysis of calculations using accurate expressions and approximate formulas has shown that relation (1) is sufficiently accurate for practice if $|k_1L|$, $|k_2L| > 1$. Furthermore, the accuracy increases if $\sigma_1 > \sigma_2$.

The second condition necessary for the signal to be well approximated by relation (1) is $\frac{L}{r_1} \geq 5$, i.e., the length of the probe should be several times the radius of the borehole.

Note an important feature of relation (1): on the logarithmic scale, the EMF in the two-layer medium is the sum of two contributions—from the borehole and the external environment:

$$\ln \bar{\xi}^{(2)}(k_1r_1, k_2L) = \ln \bar{\xi}^{(1)}(k_2L) + \ln I_0^2(k_1r_1), \quad (2)$$

where $\xi^{(1)}$ and $\xi^{(2)}$ are the nondimensionalized EMFs.

In relation (2), the second term depends only on the parameters of the borehole and is independent of the separation L. We consider the expression for the EMF at two separations, L_1 and L_2:

$$\ln \left|\bar{\xi}^{(2)}(k_1r_1, k_2L_1)\right| = \ln \left|\bar{\xi}^{(1)}(k_2L_1)\right| + \ln I_0^2(k_1r_1),$$

$$\ln \left|\bar{\xi}^{(2)}(k_1r_1, k_2L_2)\right| = \ln \left|\bar{\xi}^{(1)}(k_2L_2)\right| + \ln I_0^2(k_1r_1).$$

Subtracting one equality from the other, we obtain:

$$\ln \left|\bar{\xi}^{(2)}(k_1r_1, k_2L_1)\right| - \ln \left|\bar{\xi}^{(2)}(k_1r_1, k_2L_2)\right| = \ln \left|\bar{\xi}^{(1)}(k_2L_1)\right| - \ln \left|\bar{\xi}^{(1)}(k_2L_2)\right|. \quad (3)$$

It is seen from relation (3) that the difference between the logarithms of the normalized EMFs in this approximation is independent of the borehole radius and the SEC of the drilling fluid.

The measured quantities can be represented in terms of the amplitudes $|\bar{\xi}|$ and the phases φ:

$$\bar{\xi} = |\xi|\, e^{i\varphi}. \quad (4)$$

Then relation (3) can be rewritten as

$$\begin{aligned} &\ln \left|\bar{\xi}^{(2)}(k_1r_1, k_2L_1)\right| - \ln \left|\bar{\xi}^{(2)}(k_1r_1, k_2L_2)\right| = \ln \left|\bar{\xi}^{(1)}(k_2L_1)\right| - \ln \left|\bar{\xi}^{(1)}(k_2L_2)\right|, \\ &\ln \left|\frac{\ln \bar{\xi}^{(2)}(k_1r_1, k_2L_2)}{\ln \bar{\xi}^{(2)}(k_1r_1, k_2L_1)}\right| = \ln \left|\frac{\bar{\xi}^{(1)}(k_2L_2)}{\bar{\xi}^{(1)}(k_2L_1)}\right|, \end{aligned} \quad (5)$$

$$\varphi^{(2)}(k_1r_1, k_2L_2) - \varphi^{(2)}(k_1r_1, k_2L_1) = \varphi^{(1)}(k_2L_2) - \varphi^{(1)}(k_2L_1). \quad (6)$$

Thus, in this approximation, the ratios of the EMF amplitudes and the phase differences measured at two distances from the transmitter depend only on the parameters of the homogeneous external environment.

Methodology of the study

Now let us return to the problem of marine geoelectrical exploration. We consider a three-layer geoelectrical model with two plane-parallel boundaries. The top layer is nonconducting, the middle layer is highly conductive seawater, and the bottom layer is the underlying conductive space (earth). We introduce a Cartesian system of coordinates in which the plane $x0y$ coincides with the boundary between the first and second layer, and the z axis is directed perpendicularly downward (Fig. 1). The position of the boundary between the first and second layer is described by the equation $\bar{Z} = 0$, and that between the second and third layer, by the equation $\bar{Z} = h$. The top and bottom boundaries will be considered so remote that they virtually do not affect the calculated fields.

Using the analogy with the logging problem and the method of obtaining the approximate expression (1), we can write the following expression for the EMF ξ on the surface of the laterally homogeneous seawater layer underlain by the conducting half-space:

$$\xi(k_1, k_2, h, L) \approx \xi(k_2, L) \cdot e^{-2k_1h}, \quad (7)$$

where k_1 and k_2 are the wavenumbers, h is the thickness of the seawater layer, L is the distance between the transmitter and receiver (separation).

Taking the natural logarithm of expression (7) and using the nondimensionalized EMFs, we obtain:

$$\ln\left(\xi(k_1, k_2, r, L)\right) \approx \ln\left(\xi(k_2, L)\right) - 2k_1h. \quad (8)$$

Thus, the influence of the seawater layer can be weakened by calculating the following quantity:

$$\ln\left(\xi(k_1, k_2, h, L_1)\right) - \ln\left(\xi(k_1, k_2, h, L_2)\right) \approx \ln\left(\xi(k_2, L_1)\right) - \ln\left(\xi(k_2, L_2)\right). \quad (9)$$

As shown above, this quantity can be converted into the phase difference (6). By setting the separation in the array and calculating the phase difference between the measurement electrodes, it is possible to significantly reduce the effect of seawater layer.

However, this approach does not account for the unique property of the seawater layer that its physical properties such as salinity and temperature are inhomogeneous with depth (Luz and Regis, 2009). In measurements of seawater temperature at different depths, the water column is conditionally divided into three layers (Fig. 2, left): a surface layer, a layer with an abrupt temperature change (thermocline), and a deep-water layer. The temperature changes in the surface and deep-water layers are less significant than the temperature jumps in the thermocline. This is due to the fact that the upper layer of seawater is well mixed by the winds, and sunlight does not penetrate into the deep-water layer.