A QUICK METHOD OF SOLVING THE INVERSE PROBLEM OF ELECTROMETRY IN OIL AND GAS WELLS

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***Abstract**: The effective iterative method for the inverse problem of oil and gas wells electrometry rapid solution was considered. Author proposed to use a high-effective full currents method to solve the direct problem of electrical and induction logging at each step of the inverse problem iterative solution. It was demonstrated that when structure model changes, only the coefficients in the equations of system of linear algebraic equations change too. In this connection, their number is not change. The possibility of taking into account the quantative measure of each sonde influence to overall result was used to increase the efficiency of the inverse problem solution. That opportunity allows taking into account firstly the sondes which are the most sensitive to selected section model parameters changing, with minimizing of discrepancy. That attitude significantly accelerates the speed and accuracy of the inverse problem solution. This article is a generalization of long-term work for development of highly effective algorithms to solve direct and inverse problems of well logging.*

***Keywords**: Numerical modeling, electrometry in wells, direct problem, inverse problem*

***ACM Classification Keywords**: G1.8. Partial Differential Equations, J.2 Physical Sciences and Engineering*

Introduction

Unless and until the only way to extract oil and gas will be drilling of wells, until then the well logging (WL) will not lose its relevance both from scientific and practical points of view. Among the number of methods, WL-electrometry takes the main place because it gives the answer to the key question: “Where is the useful fluid, how much it can be extracted totally and per day?” [Pirson, 1996;

Anderson, 2001]. The answer to these questions is not hidden among measured averaged values of the apparent resistivity (AR), but among the values of section model geoelectrical parameters. This model describes the spatial distribution of differential value of specific resistivity (SR). Such parameters can be determined in solving the inverse problem of electrical logging (IL) of induction logging (EL). However, it should be understood the necessity of direct problem solving (Fig. 1).

Also, as a lot of geophysical problems, answer to these questions requires a numerical solution of complex and unstable Hadamard mathematical inverse problem [Strahov, 1967; Tikhonov etc., 1979; Tikhonov etc., 1990].

Note that in addition to volatility naturally factored in a lot of geophysical inverse problems, electrometry inverse problem solution is often enhanced by complex start conditions.

In practice, geoelectrical parameters of researched objects (reservoir beds) are often comparable with equipment spatial and/or measurement resolution value.

A lot of researches are on the problem of creating the effective method to solve direct problem (and its using in the iterative solution of the inverse problem). However, there are still no method with no possibility of improving. Therefore, the purpose of this research was to develop a method of solving the direct and inverse problems which have an advantage over existing methods in implementation simplicity and calculation speed, other factors being equal. In this paper quantitative assessment of the calculation speed using the proposed methods in comparison with widely used other was realized.

Direct problem

What do we mean under EL [Ilinsky, 1971] direct problem or IL [Kaufman, 1965; Plyusnin, 1968] direct problem?

Firstly, we mean some way of value obtaining which corresponds to a measurement of value by a particular sonde, of specific physical measurement principle, for the particular well section.

We need to formalize some concepts to describe the improving of this method.

In this method, the measurement is the physical law, its mathematical description and their possibility of modelling in convenient way.

From a mathematical point of view, we need to solve the equation of divergence in the area with no current sources, and with variable coefficients:

$$div\vec{j} = div\left(\sigma\vec{E}\right) = 0\,. \tag{1}$$

In terms of modeling, it means to improve the numerical solution of such equation in any convenient way, but without error, which can exceed the predetermined (preferably small enough) value. For example, finite difference or finite element methods can be used [Samarsky, 1971; Samarsky etc., 1989; Bakhova etc., 1999].

In this research, we will use the method of integral currents [Myrontsov, 2012e; 2019a]. To do it, we replace the structure with a discrete model, which describes by a non-uniform system of linear algebraistic equations (SLAE). This SLAE describes the “electrical integrator” [Alpin, 1953; 1962; Myrontsov, 2007b; 2009b].

In each node we record the Second Kirchhoff law. It is the integral analogy of current density vector equation of continuity (1):

$$\frac{U_i^{j+1} - U_i^j}{R_{j,i}^{j+1,i}} - \frac{U_i^j - U_i^{j-1}}{R_{j-1,i}^{j,i}} + \frac{U_{i+1}^j - U_i^j}{R_{j,i}^{j,i+1}} - \frac{U_i^j - U_{i-1}^j}{R_{j,i-1}^{j,i}} = 0\,,\, i = \overline{1,n},\; j = \overline{1,m}\,, \tag{2}$$

where U_i^j – potential in the node j,i ; n – nodes number on z-direction; m – nodes number on r-direction; $R_{j,i}^{j+1,i}$, $R_{j,i}^{j,i+1}$ – resistances between nodes $(j+1,i)$, (j,i) and $(j,i+1)$, (j,i) appropriate (for nodes on z-direction we need to make a change to the appropriate step change to the denominator):

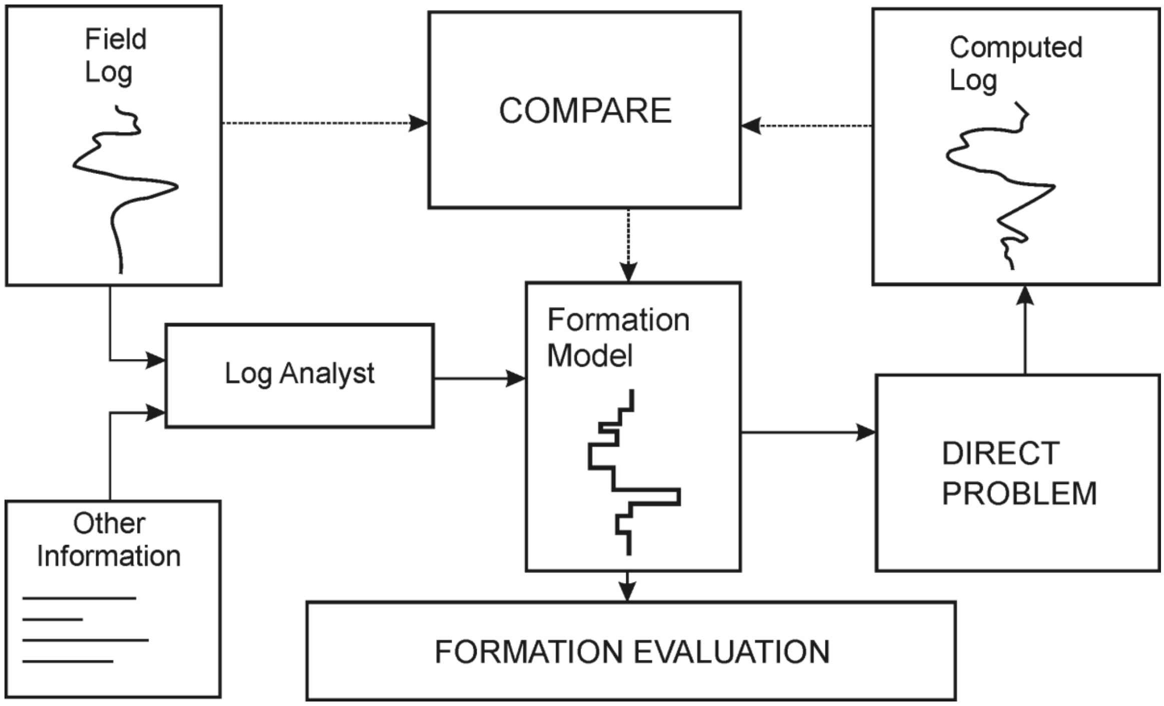

Figure 1. Scheme of the inverse problem effective solution

$$R_{j,i}^{j+1,i} = \int_{\Delta r} \rho \frac{dr}{2\pi\Delta z\left(r_0 + (j-0.5)\Delta r\right)}, \tag{3.1}$$

$$R_{j,i}^{j,i+1} = \int_{\Delta Z} \rho \frac{dz}{\pi\left[\left(r_0 + (i+0.5)\Delta r\right)^2 - \left(r_0 + (i-0.5)\Delta r\right)^2\right]}. \tag{3.2}$$

In (3.1), (3.2) – approximation step in the coordinates r, z appropriate, r_0 – sonde radius.

We note that the system (2) will not change (type and number of equations) for any number and any location of coaxial boundaries with coordinates $i \cdot \Delta r$ or for boundaries which are normal to the well axis with coordinates $j \cdot \Delta z$ in the model with plane-parallel arrangement. Only (3.1) and (3.2) will change, because change in the model will only result in the calculation of the corresponding integrals (coefficients of the system).

The variant when $\rho = \rho(z,r)$ a change with its derivative continuously also does not require changes of number or equations of system type.

That’s why, solving of EL direct problem is that:

– the problem of rectangular grid (discrete model of structure);

– system (2) solution for homogenous structure with SR, equal to 1 for sonde (or sondes) coefficient calculating;

– coefficient (3.1), (3.2) calculation for system (2) and it solution for a given model of structure.

Boundary conditions for the derivative functions (Neumann condition) on the infinity and on insulator surfaces of the device are performing automatically. Grid is limited, that’s why the current cannot spread in the direction with absent grid.

The non-zero boundary conditions on the electrodes surfaces are performing by adding to the equations (2) right side the magnitude of the current flowing from the electrode.

By this means, we have a non-homogenous SLAE with a single solution. This solution also can be expressed through the determinant of the system (according to Kramer formula). Therefore, for a given geometry of the sonde (specified boundary conditions), the direct problem solution for any 2D-spatial distribution of SR does not require changes in system of equations, but only changes of coefficients.

System without generality limitation accepts the use of grid with an irregular pitch.

Now let substantiate the proposed method for EL direct problem solving. Transition from the differential equation (1) to its integral analogue (2) by choice (3.1) and (3.2) is proved. Transition from integral form to a differential transforms the system (2) into a finite difference system with orthographic grid. It allows to use all the theorems about convergence and stability of the method (in a homogenous structure).

Relation (2) and (1) follows from equation of continuity, which has that form in cylindrical coordinate system (CCS):

$$\frac{j_r}{r} + \frac{\partial j_r}{\partial r} + \frac{\partial j_z}{\partial z} = 0 .$$

Elements I_r , I_z of the full current are related with its density:

$$I_r = j_n \cdot r \cdot 2\pi \cdot \Delta z ,$$

$$I_z = j_z \cdot ((r + \Delta r/2)^2 - (r - \Delta r/2)^2) \cdot \pi \cdot \Delta r = j_z \cdot r \cdot \Delta r \cdot 2\pi .$$

Then let's use the transformation:

$$\frac{j_r}{r} + \frac{\partial j_r}{\partial r} = \frac{I_r}{r^2 \cdot 2\pi \cdot \Delta z} + \frac{\partial I_r}{\partial r} \cdot \frac{1}{r \cdot 2\pi \cdot \Delta z} - \frac{I_r}{r^2 \cdot 2\pi \cdot \Delta z} = \frac{\partial I_r}{\partial r} \cdot \frac{1}{r \cdot 2\pi \cdot \Delta z} ,$$

$$\frac{\partial j_z}{\partial z} = \frac{\partial I_z}{\partial z} \cdot \frac{1}{r \cdot \Delta r \cdot 2\pi} .$$

And finally will get:

$$\frac{j_r}{r} + \frac{\partial j_r}{\partial r} + \frac{\partial j_z}{\partial z} = \frac{1}{\Delta r} \cdot \left(\frac{\partial I_r}{\partial r} + \frac{\partial I_z}{\partial z} \right) = 0 ,$$

or:

$$\frac{\partial I_r}{\partial r} + \frac{\partial I_z}{\partial z} = 0 ,$$

which is equivalent to the equation (2) that describe our discrete model.

To verify the numerical method for EL direct problem solving, we can compare the calculated values of the sondes coefficients with calculated ones by analysis [Myrontsov, 2003].

There are a number of numerical methods for exact solution of IL direct problem. For example, author proposed and implemented method [Myrontsov, 2004, 2007a, 2009], which is based on structure performance as an integration of elementary rings under additional conditions:

- considering coils contours as elementary rings, with taking into account their geometric (diameter, cross section etc.) and physical (conductivity) features;
- taking into account currents interaction as a mutual induction of all elementary rings in the system.

In general form, change of current in generator coil k : $I = I^k_{\text{Re}} e^{i\omega t} + i I^k_{\text{Im}} e^{i\omega t}$, (where I^k_{Re}, I^k_{Im} – active and reactive components) is provided by applied electromotive force (EMF):

$$\varepsilon = \varepsilon^k_{\text{Re}} e^{i\omega t} + i\varepsilon^k_{\text{Im}} e^{i\omega t},$$

where

$$\varepsilon^k_{\text{Re}} = A^k = const,$$

$$\varepsilon^S_{\text{Im}} = B^k = const.$$

Let's see the principle of mutual induction: on change of current I^j in the elementary ring j EMF ε^{ij} emerges in elementary ring i :

$$\varepsilon^{ij} = -M_{ij} \frac{dI^j}{dt},$$

where M_{ij} – coefficient of mutual induction.

Full EMF ε^i emerges in elementary ring i , and is sum of EMF, which induced in other rings by separate currents:

$$\varepsilon^i = \sum_j \varepsilon^{ij} = -\sum_j M_{ij} \frac{dI^j}{dt}.$$

To obtain the final systems of equations, we use:

1. Ohm's law in integral form:

$$\varepsilon^i = I^i R_i,$$

where R_i – resistivity of elementary ring. Because of axial symmetry: $R_i = \oint_{C_i} \langle\rho\rangle \frac{dl_i}{dS_i}$ ($\langle\rho\rangle$ – is SR, which averaged on the section of the elementary ring;

2. The formula for derivative in time of constant frequency alternating current:

$$\frac{dI^i}{dt} = i\omega I^i_{\mathrm{Re}} e^{i\omega t} - i\omega I^i_{\mathrm{Im}} e^{i\omega t}.$$

3. So that:

$$M_{ij} = M_{ji}.$$

Finally we obtain:

$$I^i_{\mathrm{Re}} R_i - \omega \sum_j M_{ij} I^j_{\mathrm{Im}} = 0, \tag{4.1}$$

$$I^i_{\mathrm{Im}} R_i + \omega \sum_j M_{ij} I^j_{\mathrm{Re}} = 0. \tag{4.2}$$

These equations corresponds to changes in active and reactive components of generator coils EMF A^k or B^k. By adding to right parts of these equations right parts of equations (4.1) and (4.2), we will obtain a non-homogenous and regular SLAE with number of variables N and number of equations equality.

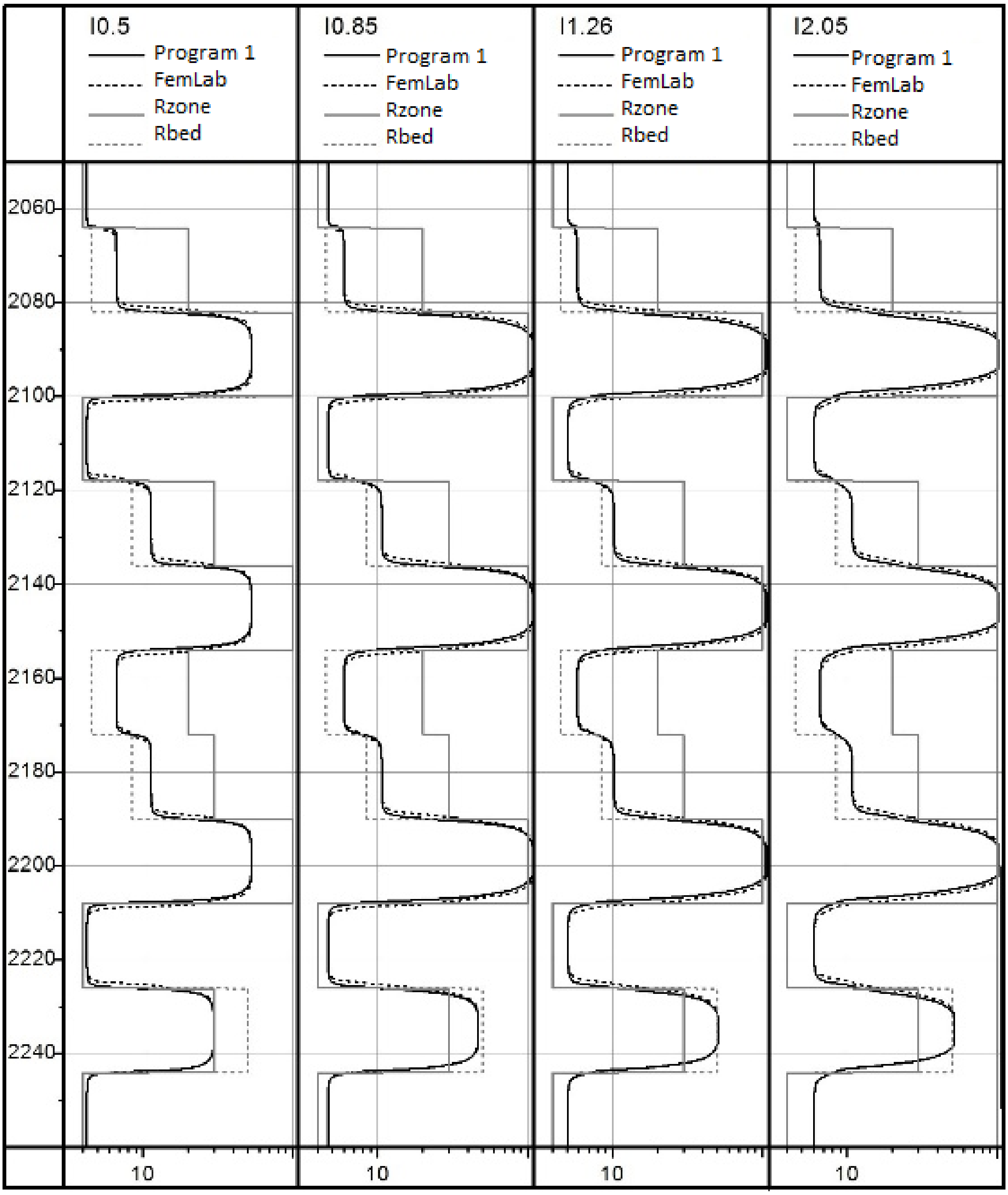

Figure 2. An example of comparing IL direct method solving results with different software

Comparison of various methods accuracy and speed for direct problem solving

Let's make comparison with other methods to evaluate the effectiveness and accuracy of the proposed solution.

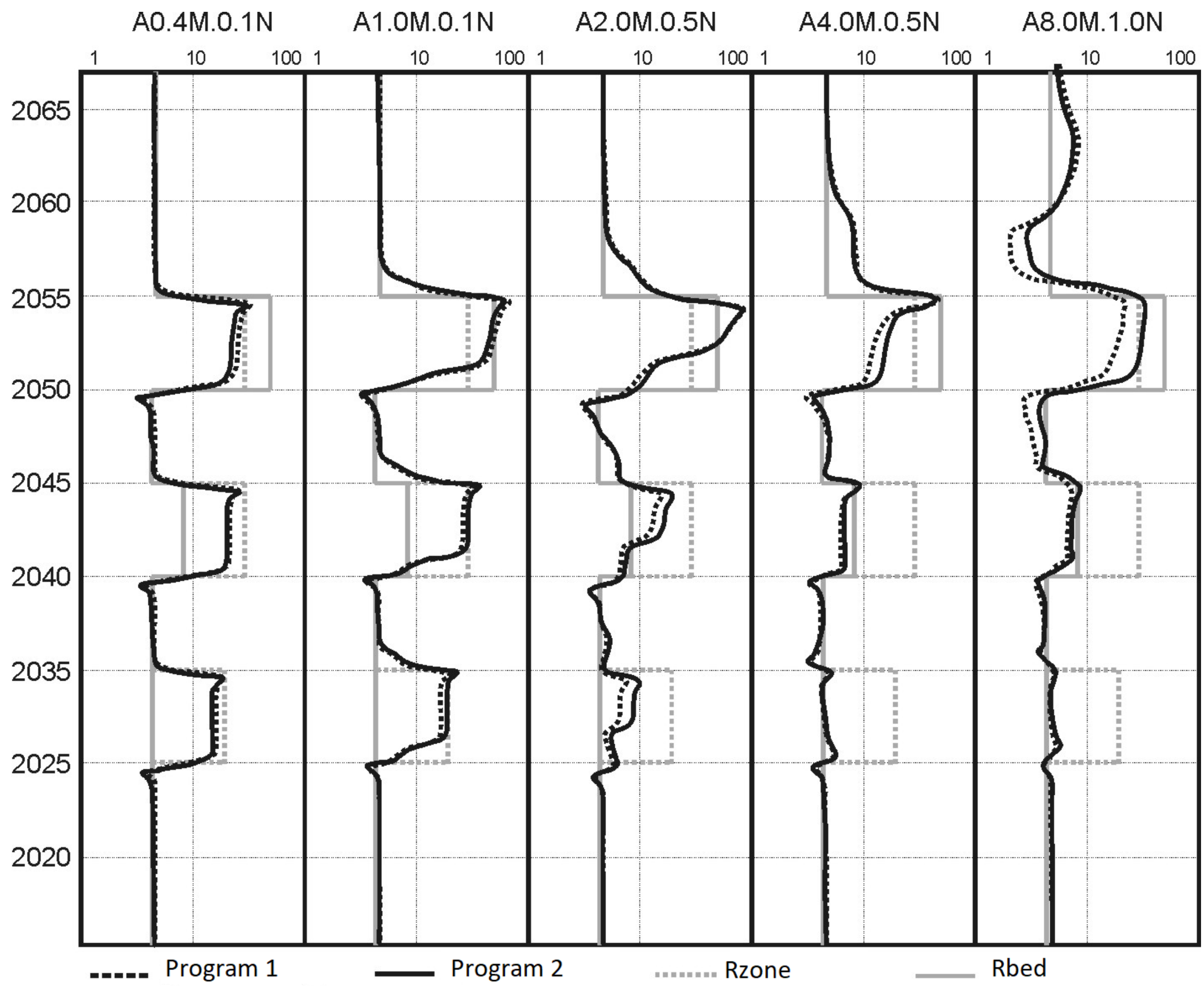

Figure 3. An example of comparing direct 2D problem by different software for the section with three-layer horizons (ρ_C = 2 ohm·m; r_C =0.1 m)

Firstly, let's compare IL direct problem solution for IL four-probe equipment using the proposed method with the result of modelling by FemLab software (University of Florida).

Fig. 2 shows the log graphs 4IL [Myrontsov, 2012e; 2019a] complex for a bench. It contains different models of the horizons in different sequence which corresponds to water-saturated, petroleum-saturated, gas-saturated, clay and consolidated. Log graphs were obtained using proposed method (codenamed as “program 1”) and using FemLab (codenamed as “FemLab”). The agreement of results is obvious, but solution using proposed method was almost 20 times less than FemLab (University of Florida) program.

Let’s assess the effectiveness of the proposed method for EL [Technical…, 2002] direct problem solving (“program 1” in Fig. 3) by comparing its results with results of software developed in Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences (“program 2” in Fig. 3) for side logging sound equipment [Myrontsov2019a].

In addition to the results agreement, proposed method solves the problem almost 100 times faster than software of colleagues from Novosibirsk. Unfortunately, author cannot name neither software authors nor its name without allowance.

During the discussion about comparison results, it was establishing the facts that some differences may occur due to different representations during reversed current electrode modelling. In author’s software it is presented not as point electrode but as conducting braid of a logging cable as a finite distance from the direct electrode. Other divergences are the results of the approximation in any numerical calculation, they are objectively reflecting values of real error. Author leaves visual assessment of results convergence behind the reader.

Inverse problem

The answer to the question about location and amount of useful fluid, about possible daily amount of its extraction is not in the area of measured AR (or apparent conductivity (AC) imaginary quantities. It is in the area of geoelecrtrical parameters of a model describing the spatial distribution of SR or specific conductivity (SC).

Therefore, geophysical characteristics of the equipment are the ability of particular algorithm (and its implementation) to solve the inverse problem: to allocate certain objects and to recognize their geoelectrical parameters with define accuracy.

Consequently, from the WL point of view, equipment with more accurate measurement is less good than equipment with more precise inverse problem solution. The effectiveness of any inverse problem solving method depends on such factors: way to determine the sondes measurement data for the define structure parameters; choice of “proximity” of sonde and real indications parameter; choosing for model parameters selecting for selected proximity parameter.

These questions can be paraphrased as:

– choice of direct problem solution method (finite difference, finite elements, full currents, semi-linear solution etc.);

– choice of a functional which will be minimized during inverse problem solving;

– choice of iteration process method for inverse problem solving.

We can consider minimization of the functional as a criterion for proximity of the solution with desired true value:

$$F\left(\rho_1^T,...,\rho_n^T\right)=\frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{\rho_i^T-\rho_i^E}{\rho_i^T}\right)^2}, \qquad (5)$$

where n – number of sondes; ρ_i^T – AR calculated values for model; ρ_i^E – AR obtained values.

There are some variations of functional representation, which will be minimized during inverse problem solving.

For example, as:

$$F\left(\rho_1^T,...,\rho_n^T\right)=\frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{\rho_i^T-\rho_i^E}{\delta_i\rho_i^T}\right)^2}, \qquad (6)$$

where δ_i – relative error for sonde i.

Or:

$$F\left(\rho_1^T,...,\rho_n^T\right)=\frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{\rho_i^T-\rho_i^E}{\delta_i\rho_i^T+\chi_i}\right)^2}, \qquad (7)$$

where χ_i – absolute error for sonde i.

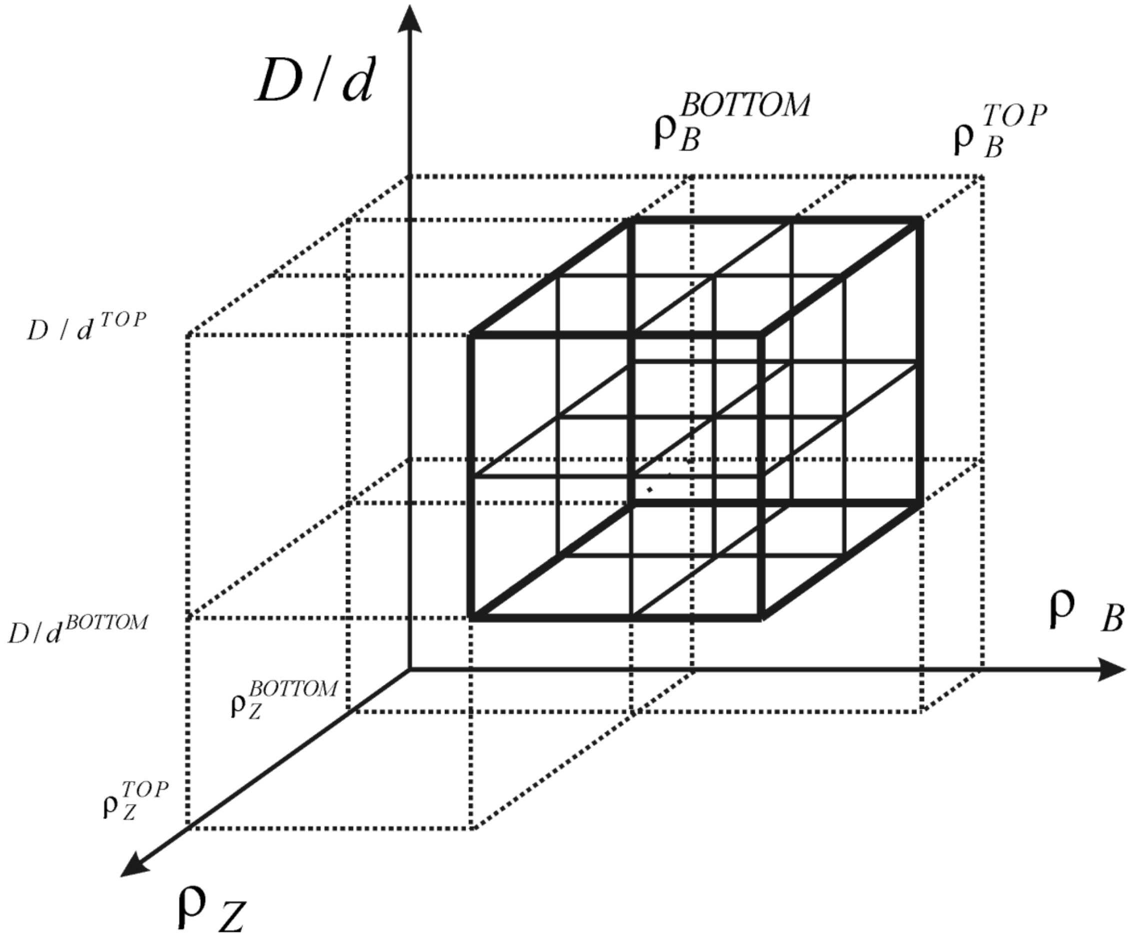

Figure 4. Illustration of reservoir parameters shredding. For allocated points direct problem was solved on the n+1-step of iteration

Let's consider such type of functional:

$$F\left(\rho_1^T,\ldots,\rho_n^T\right)=\sqrt{\sum_{i=1}^{n}K_i\left(\frac{\rho_i^T-\rho_i^E}{\rho_i^T}\right)^2}, \quad (8)$$

where K_i are weight coefficients of each sonde of the complex which can be changed by the interpreter.

During calculation of functional (5)-(8) we can take both values ρ_i^T and ρ_i^E in denominator. Values ρ_i^E, at which minimum is achieved, do not depend on this. But this may depend on the functional minimizing speed which may be important during real inverse task solving. Different speed of minimization (depending on chosen method) can be explained by different form of the dependence of expression under radical sign and the denominator (argument or constant number).

The first step of inverse problem solving is formalization of requirements to the correspondent algorithm.

The requirement of accuracy is clear. Its ability to be executed depends on the accuracy of the available algorithm

of direct problem solving. Let's assume that accuracy is not in doubt, then focus on another requirement, which is the speed of calculation process. Practically, this is the speed of non-compliance functional minimization (8).

Let's consider the three-layer model as the model of reservoir-collector [Myrontsov, 2013]: well (SR of drilling mud $-\rho_W$, well diameter – d) + zones encircling the borehole flushed by the borehole mud (invaded zone) (SR of zone – ρ_Z, zone diameter – D) + uninvaded zone of bed (SR – ρ_B).

To begin, let's construct a table that associates the values of vectors components in the area of geoelectrical model parameters with vectors components from the measurement data area.

In the case of three-layer model, the associate table ρ_Z/ρ_W, D/d, ρ_B/ρ_W with number of AR ρ_i/ρ_W, $i=\overline{1,n}$, where n – quantity of sondes in the complex (for convenience and without generality limitation $\rho_W=1$ ohm·m). Practically, the construction of each row in the table:

$$\rho_Z^j,\ (D/d)^j,\ \rho_B^j,\ \rho_{A0.4M0.1M}^j,...,\ \rho_1^j,\ \rho_2^j,\ ...\rho_n^j.$$

requires to solve at least one direct problem.

Usually, table has to be made in bi-logarithmic scale. After making a table, it is actually possible to implement the algorithm of simplest solution of inverse problem.

During row of the table selecting, we choose the one for which the AR of selected logging complex is most closely identical with measured. Parameters $\rho_Z^j, (D/d)^j$, ρ_B^j from that row will be selected as the required model parameters. Search can be realized automatically, criterion of "the most accurate coincidence" will look like minimizing the functional (8).

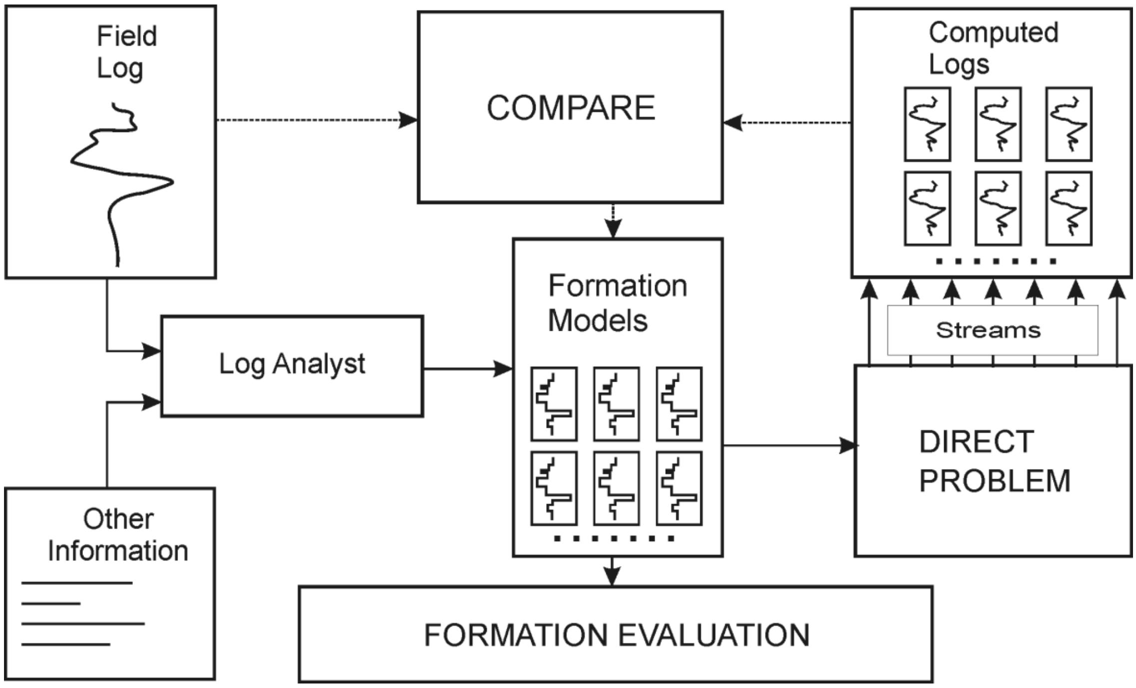

Figure 5. Scheme of inverse problem solving

That method is implemented in a lot of software for electrometer data interpretation. With a dense filling of the table, it shows a good results with error comparable with error of logging.

Modern development of hardware technologies and presence of pre-calculated table make possible solve inverse problem for interval of 1000 m along well axis in the split second. However, such algorithm has several drawbacks.

First: its accuracy is limited by the step of sweeping the parameters ρ_Z, D/d, ρ_B. Second: a large size of the table requires significant computing resources and prolongs the time of solving.

For three parameters, during the sweeping ρ_Z, ρ_B in 1000 values, and D/d – twenty, we will have 20000000 rows in the table. This can be considered for three-layer model, but this method are irrational and too difficult in implementation for four-layer model.

However, we will use such table. Even a table with 5 values for D/d and in 50 for ρ_Z, ρ_B(1250 rows in table) can simplify and accelerate further solution (for a four-layer model, with number of possible variations of washed zone parameters (5 for diameter and 50 for its SR) we will have a table with only 312500 lines).

This table will necessary to build the first approximation in the subsequent iteration minimization (8).

For iteration we will select the first approximation of the required parameters in the form of range [Myrontsov, 2019b]:

$$\rho_Z^{BOTTOM} < \rho_Z < \rho_Z^{TOP}, \tag{9.1}$$

$$D/d^{BOTTOM} < D/d < D/d^{TOP}, \tag{9.2}$$

$$\rho_B^{BOTTOM} < \rho_B < \rho_B^{TOP}. \tag{9.3}$$

On the next step, we divide the area (9.1)-(9.3) into flats (Fig. 4):

$$\rho_Z = \rho_z^{BOTTOM} + 0.5\cdot(\rho_z^{TOP} - \rho_z^{BOTTOM}), \tag{10.1}$$

$$D/d = D/d^{BOTTOM} + 0.5\cdot(D/d^{TOP} - D/d^{BOTTOM}), \tag{10.2}$$

$$\rho_B = \rho_B^{BOTTOM} + 0.5\cdot(\rho_B^{TOP} - \rho_B^{BOTTOM}), \tag{10.3}$$

on eight areas. Now we solve the direct problems in the vertices of formed parallelepiped (9.1)-(9.3); at the points of flats intersection (10.1)-(10.3) only 13 of the points on the sides of parallelepiped. At one point we have a solution from the previous iteration.

Each of the eight areas creates a monotone area in the value space $\tilde{\rho}_i^T$. We select the one the value $\tilde{\rho}_i^E$ belongs to. Next step is to select the vertices of the area as the boundaries of intervals (9.1)-(9.3) of the next iteration: $\rho_Z^{BOTTOM}, \rho_Z^{TOP}$, $D/d^{BOTTOM}, D/d^{TOP}$, $\rho_B^{BOTOM}, \rho_B^{TOP}$.

We need to continue this process until satisfaction the condition for the pre-determined value of the misfit ε:

$$F\left(\rho_1^T, ..., \rho_n^T\right) = \sqrt{\sum_{i=1}^{n} K_i \left(\frac{\rho_i^T - \rho_i^E}{\rho_i^T}\right)^2} < \varepsilon,$$

or if the value of the functional does not stop decreasing. Decreasing is possible because the minimum of functional does not necessarily equal zero during task redefining.

For the first iteration we construct area (9.1)-(9.3) from our pre-calculated table, taking the closest but not equal model parameters from rows with smallest values as boundary values (8).

For solving such a number of direct problems, it is appropriate to use so-called streams (for example with TThread object in Delphi). Possibility of solving several mathematical problems simultaneously is widely available now. Use of streams leads to solve several direct problems instead one (Fig. 5) in the same time. Number of direct problems depends, of course, from parameters of hardware.

Author uses know-how, which allows to significantly reducing the number of points in which direct task solved.

It should be said about another possible method to increase the accuracy of inverse problem solution. The described method can be effectively applied to measured values of layers AR. The values of layers AR are not influence by the value of shoulder beds SR. So, before using described method of solving the inverse problem for each bed, we need to exclude the influence of shoulder beds to measurement.

In the case of EL inverse problem is non-linear. Then it is proposed to reduce the influence of shoulder beds to measurement using equipment with high vertically (along the axis z) spatial resolution [Myrontsov, 2010a; 2010d; 2010e; 2018a; 2018b].

Such equipment proved to be more effective in such complicated geological conditions in which the complex used in Ukraine is not effective [Yegurnova etc., 2005; Myrontsov, 2012a; 2012b; 2012c; 2012d].

In the case of IL, inverse problem is linear. In this context an effective factorization method developed and implemented by author can be used to exclude the influence of shoulder beds [Myrontsov, 2009a; 2010b]. This method also can be used for pulsed IL [Myrontsov, 2010c].

Conclusion

It was being shown that the use of integral currents method for EL and IL direct problem solving has such advantages over the use of the finite difference or finite element method:

- unlike the finite difference or finite element method, it is not necessary to change the number or type of SLAE during model around well environment changing. It is only necessary to change the values of system coefficients;
- implementation of the proposed method gives the preference to the calculation speed (for IL almost 20 times, for EL almost 100 times in comparison with finite element method).

It was being shown that the inverse problem solution based on the method of desired parameters space half-separating (by analogy with bisection method or half-partition division method for non-linear equations solution) has higher accuracy in comparison with calculated table-based methods. It connects the values of horizon with values of measurement. Obviously, this follows inaccuracy of method based on such table using due to discreteness of the possible solution values in the table.

In addition, the proposed method of inverse problem solving has one more advantage. It is ability to change the weight number values for each probe of the complex. Thus, user has an opportunity to exclude unserviceable probes or amplify an effect of probes with better geophysical parameters for selected model of the cut to solve the inverse problem.

Proposed and implemented method of solving inverse problems of EL and IL is currently on the technical tests by industrial geophysical companies of Ukraine.

Author plans to continue theoretical researches firstly in the scientific area of equivalent solutions for inverse problem with measurement error [Myrontsov, 2012f; 2019c].

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