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Evaluation of limitations of the transient electromagnetic method in shallow-depth studies: numerical experiment

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Abstract

Based on a proposed electrical model of a system for subsurface sensing by an induction transient electromagnetic method, a numerical experiment was performed to evaluate the limitations of the method in shallow-depth studies. During the experiment, the theoretical and pseudoexperimental emf curves are compared. Based on the degree of their convergence, the capability of the system to adequately record the response from the excited space at depth is determined. The experimental results are used to plot dependences of the measured parameters of the system on its geometrical dimensions. Recommendations on the use of small-size systems are given.

Keywords: transient electromagnetic method; shallow depth; model experiment; interference

Introduction

The limitations of the method in shallow-depth studies were considered in a paper (Kozhevnikov and Plotnikov, 2004) using analytical methods and graphic illustrations.

In the present work, the limitations are studied in numerical experiments using training software by calculating response curves with imposed interference. The capabilities of the transient electromagnetic method (TEM) at shallow depths are determined from the results of comparison of the theoretical and pseudoexperimental curves of the electromotive force (emf). This approach reveals new details in the assessment of limitations and is more informative.

For a particular geophysical system, the concept of shallow depth means that the response curve recorded by this system ceases to adequately reflect actual heterogeneities in the resistivity profile. When this happens but information on this subsurface region is still needed, it is common to use a smaller system. In this case, the magnitude of the useful signal against the noise of the associated harmful transients is significantly reduced. If we make several such transitions, the concept of shallow depth becomes associated with the inability to extract useful information from the recorded signals because of the prevalence of interference. In this case, it may be reasonable to use small-size systems. Hence, the objective of the present numerical experiment is to evaluate the limitations of the method at shallow depths.

As is known, a signal recorded by electromagnetic induction sounding techniques is a convolution of the useful response from the subsurface with various measurement noises that do not carry information about the subsurface structure. Since, in practice, the accompanying noise cannot be completely removed, they are analyzed by performing numerous field experiments which allow some components of the received signal to be emphasized and others to be weakened. Numerical experiments allow solution of this problem without equipment, only with its basic parameters taken into account. Furthermore, this approach offers additional opportunities because it allows one to divide the received signal into components and analyze their role in the distortion of the useful response independently from each other.

Signal components and experiment model

In order to obtain subsurface information, the earth is excited by current pulses in a transmitter loop placed on the surface. When the current is switched off, eddy currents are formed in the conducting earth (in accordance with the law of electromagnetic induction), which propagate into the depth of the earth to produce a varying electromagnetic field. This process is called the transient. On the earth's surface there is

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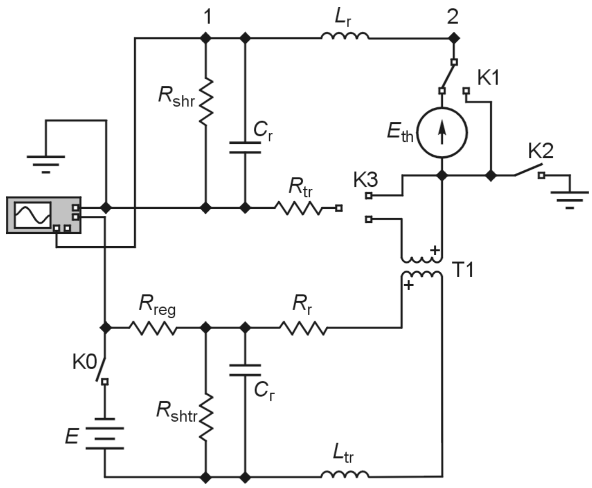

Fig. 1. Equivalent electrical circuit of the transmitter-receiver system for transient electromagnetic sounding. R_{tr}, R_{shtr}, L_{tr}, and C_{tr} are the elements of the transmitter loop; R_r, R_{shr}, L_r, and C_r are the elements of the receiver loop; T1 is an air-core transformer; E_{th} is the theoretical earth-response signal; K0–K3 are the switches of the measurement modes; 1 and 2 are the signal measurement points.

a receiver loop in which an emf is induced due to the electromagnetic field of the eddy currents forming in the earth. The induced emf in the form of a transient signal which carries useful information is called the response, and its value is calculated by well-known formulas, e.g., (Kozhevnikov and Antonov, 2007). Usually, in the analysis of electromagnetic induction measuring systems, its components are treated as a sequence of linear lumped-parameter two-port networks (Zaharkin, 1981). It is also assumed that the parameters of the two-port networks are mutually independent and constant in time.

In another technique (Kozhevnikov, 2006), the transmitter and receiver loops, together with the underlying near-surface section, form a lamped-parameter system whose components interact with each other. It is emphasized that it is the near-surface that integrates the components of the system into a whole unit with properties not reducible to the simple sum of the properties of the individual components. Kozhevnikov (2012) rightly points out that the existing similarity criteria between laboratory and field data do not include the specifics of the transmitter-receiver unit as a complex lamped-parameter system. This gap in the theory of similarity of electromagnetic systems needs to be filled.

For the above reasons, in the numerical experiment, the transmitter and receiver loop were simulated in the form of equivalent lumped-parameter circuits, and the electromagnetic coupling between them was implemented via a transformer used to convert currents and voltages. In a simple case, the transformer consists of two galvanically uncoupled and fixed coils without a ferromagnetic core. This transformer is a linear element since it is described by linear equations, has linear characteristics and is called an air-core transformer. In fact, it is this transformer that is formed on the earth's surface by the system of a transmitter and receiver loops during sounding by the TEM method. This configuration allows us, as a first approximation, to take into account the response time of the loops and, simultaneously, simulate the significant overvoltage surges occurring in the receiver loop due to the interruption of the current in the transmitter loop. This process, called direct induction, is actually more complex since it depends on the subsurface (Kozhevnikov, 2012). Nevertheless, the proposed equivalent electrical circuit (Fig. 1) allows laboratory modeling of the basic relationships present in a real geophysical system and provides an understanding of the processes occurring in it.

It should be noted that earth sounding by the geophysical system is carried out at low and high excitation currents. The transmitter loop circuit current drops differently in these cases. This is because the switching elements of the commutator operating with the inductive circuit are protected from overvoltage by the developers using special units. Typically, these parts of the circuit come into operation starting at a certain average switching current. The low-current measurement mode is the basic one in our case since it is maximally responsible for the shallow part of the subsurface studied. The switching-off process for low current occurs in the idle mode with a time constant $\tau = L_{tr}/(R_{tr} + R_{sh})$, which reflects the proposed equivalent circuit.

It is known that in the design of circuits with a transformer, use is made of equivalent circuits in which the actual electromagnetic transformer couplings are replaced by electrical ones. These circuits are convenient for analytical studies of established and transitional modes in the transformer. The circuits are designed so that their currents and voltages are described by the same equations as in the real transformer and this makes possible their use in different programs. One of these, the Electronics Workbench systems (Chernyshev and Chernysheva, 2005), specifically designed for modeling and analysis of electrical circuits was used in the present numerical experiment.

As follows from the above, the receiver output signal is the result of at least three impacts. This is the transient characteristic from the excited earth, the direct induction from the switched-off current in the transmitter loop, and the signal distortion due to the response time of the receiver loop. The proposed equivalent circuit can be used to analyze the contribution of each of them depending on the varying parameters of the geophysical system and the surveyed subsurface under the above simplifications.

The circuit consists of two parts with linear elements R, L, and C representing the transmitter and receiver loops. The air-core transformer T1 simulates the coupling between them, which is controlled via the mutual induction. The parameters of all elements are calculated taking into account the sizes of the loops and the wire used. The circuit includes the shunt resistances of the R_{sh}, chosen so that the loops operate in a mode close to the critical. All calculations in the experiment are carried out at an excitation current of 1 A, which is set by the battery voltage E and the regulating resistor R_{reg}. The theoretical signal—the undistorted response signal from the excited earth—is calculated using the Unv QQ program (developed by E. Yu. Antonov, IPGG SB RAS) (Kozhevnikov and Antonov, 2007) and is implemented in the circuit via a voltage source E_{th}. In the circuit shown in Fig. 1, the connection point of the input of the software oscilloscope and the switches used to record the necessary data.

Conditions of solution of the problem

The notation of the systems corresponds to the side dimension of the transmitter loops. For the numerical experiment, we used data of coaxial geophysical systems with the same ratio of the sides of the transmitter and receiver loops ($L_{tr}/L_r = 2$) with dimensions of 2000, 200, 20, and 2 m. The first two are used in practice. The last systems are included in the experiment to verify the possibility of using induction electric survey in shallow-depth studies.

The earth model was a homogeneous conducting half-space with a resistivity of 1, 10, 100, and 1000 Ohm·m.

The applicability of the TEM method to shallow-depth geoelectric studies was determined by calculating the theoretical emf signal $E_{th}(t)$ and the pseudoexperimental emf signal $E_e(t)$ for the chosen earth model and geophysical system. The relative difference between the obtained signal values calculated by the formula

$$\delta(t) = 100 \cdot \frac{E_e(t) - E_{th}(t)}{E_e(t)} \% \quad (1)$$

was used to determine the time point t_1 starting from which the discrepancy between the curves was within the conventionally accepted 10%.

As is known, the limitation of the recording time of the response signal depends on the ratio of the received signal to the recorded interference due to the properties of the measuring system and external noise. This parameter is important for high-quality measurements and is controlled by the dimensions of the system and the transmitter loop current. Under favorable conditions, modern TEM systems are capable of detecting a signal of up to 100–10 nV. In this work, signals are free from noise, although this could be done fairly easily by adding random signals to the electrical circuit of the transmitter. Therefore, the time limit t_2 to which it was reasonable to record the transient characteristic was conventionally assumed to be the moment the signal reaches a level of 1 μV. The mark is fixed in order to monitor its movement as a result of change in the parameters of the system, and it does not necessarily imply a signal after the mark carries no information about the subsurface.

Numerical experiments

Figure 2 shows an example of calculated theoretical and pseudoexperimental emf curves for a system with a 200 × 200 m transmitter loop and a 100 × 100 m receiver loop at a an earth resistivity of 1 to 1000 Ohm·m.

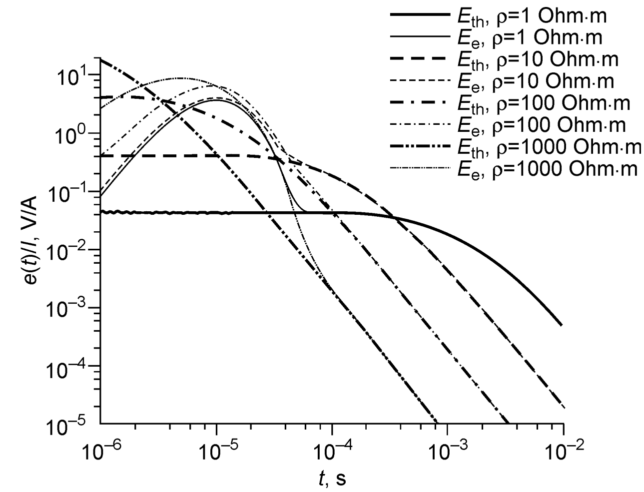

Fig. 2. Theoretical (E_{th}) and pseudoexperimental emf signals (E_e) from different sections calculated for the 200 m system.

We proceed as follows. The values of the equivalent parameters of the transmitter and receiver loops and air-core transformer T1 corresponding to the chosen system are entered into the experimental circuit (see Fig. 1). The theoretical response curve $e_{th}(t)/I$ is calculated for the chosen half-space model using the Unv_QQ software. This function is substituted into the emf source E_{th}. At point 1, a pseudoexperimental emf curve is recorded by a software oscilloscope. The starting point for the measurement is the moment of opening of switch K0.

The switching-off current of the transmitter loop flowing through the air-core transformer T1 produces an emf in the receiver loop, which serves as a simulation of direct induction without the influence of the underlying section. Simultaneously, the emf of the theoretical signal $E_{th}(t)$ acts in the receiver loop circuit. The emf signal recorded at point 1 is a convolution of both signals distorted due to the response time of the receiver loop. The pseudoexperimental emf signals for all sections are calculated in the same way.

Figure 2 shows the difference between the pseudoexperimental emf signals and theoretical signals. Obviously, their interpretation makes no sense before a certain time from the beginning of recording. Therefore, one objective of the numerical experiment was to calculate these values of t_1 to determine the possibility of operation of the systems at shallow depth.

It is known that the response time of the measurement circuit introduces a distortion in the form of a time delay in the recorded signal (Zakharkin, 1981). Shifting the experimental signal by a certain magnitude allows one to partially recover the response signal and move the boundary of convergence of the theoretical and experimental curves to earlier times. In the experiment, the magnitude of the shift Δt is easily determined by gradual imposition of the practical curve on the theoretical curve and calculation of the relative difference between the curves by formula (1). When the shift

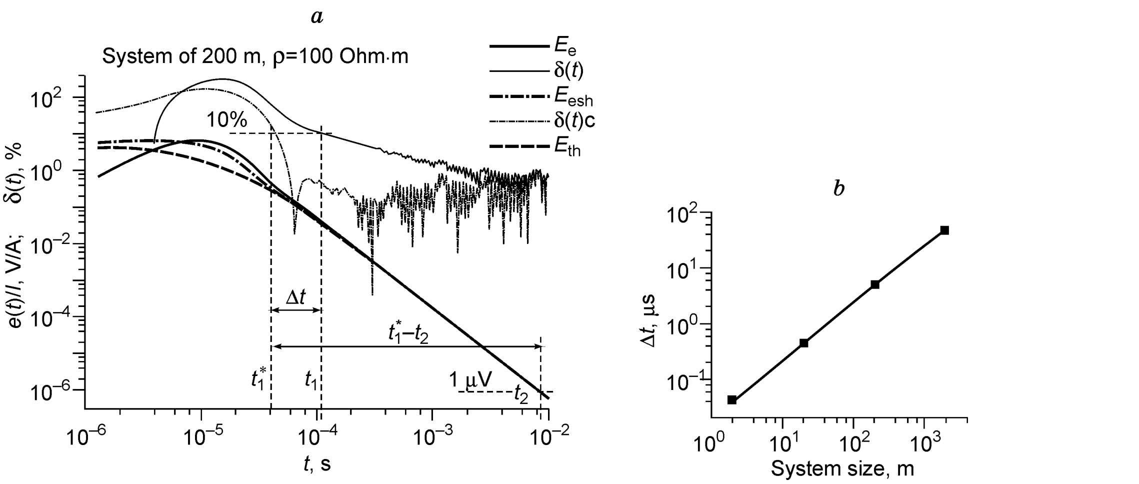

Fig. 3. Example of determining the time shift of the signal Δt and the confidence limits t_1 and t_2 (*a*) and a curve of the shift versus the size of the system (*b*).

is optimal, most of the difference curve takes a typical horizontal shape and the point of the maximum allowable mismatch t_1 moves to the left on the time scale (Fig. 3). During the experiment, it was confirmed that the magnitude of the shift were determined by the parameters of the loops and that for a particular system, it was the same for all sections. Since the shift is a recoverable signal distortion, correction of the shift was performed each time before comparing theoretical and experimental signal curves.

In Fig. 3, the portion [t_1, t_2] of the pseudoexperimental curve corrected in time is characterized by the fact that at early times, it differs from the theoretical curve by not more than 10%; in the middle part, it is the most similar to this curve; and at the time mark t_2, it loses its information properties due to possible dominance of noise.

As an example, Fig. 4 shows a pseudoexperimental signal and its components obtained by numerical experiments on the 200 m system. The theoretical signal was calculated using the Unv_QQ software. The theoretical signal distorted only due to the response time of the receiver loop was recorded at point 1 with commutation of switch K3. The distortion due to the response time of the receiver loop was obtained by subtracting the theoretical signal from the last curve. The direct induction signal was recorded at point 1 with commutation of switch K1. Summation of the signal components, as expected, forms a pseudoexperimental signal, which is entirely recorded at point 1, and separation into components allows evaluating the contribution of each of them.

As is known, the size of the system can be reduced to reliably track the dynamics of the recorded signal at an early stage and, thus, reduce the minimum sounding depth. This is

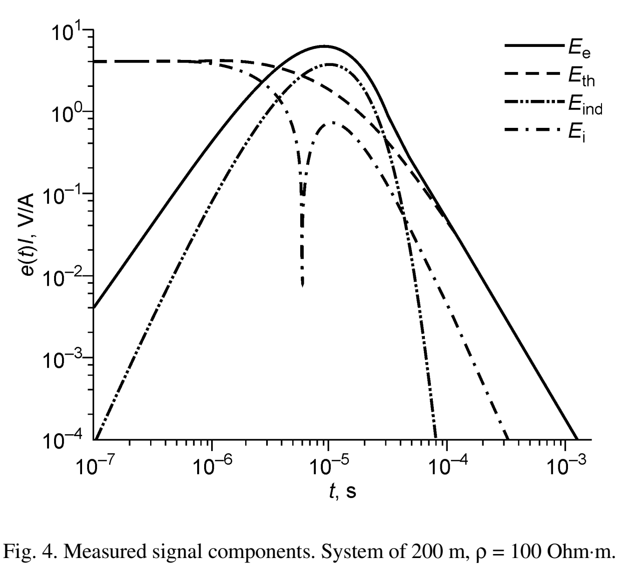

Fig. 4. Measured signal components. System of 200 m, ρ = 100 Ohm·m.

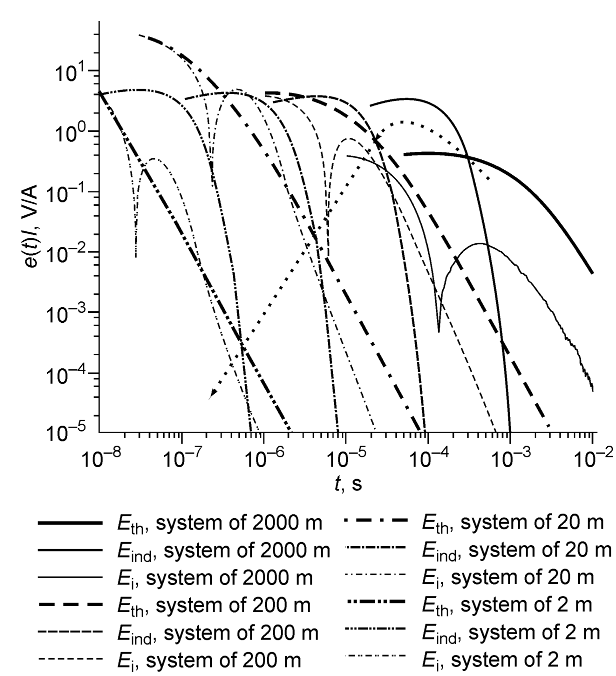

Fig. 5. Graphs the theoretical signal, direct induction, and inertial interference of systems of different size for a section with a resistivity ρ = 100 Ohm·m.

justified by the fact that the smaller the size of the loop, the smaller its response time, which in a first approximation, is inversely proportional to the linear dimension of the loop.

The loop receives not only the useful response signal but also the direct induction from the switching-off of the transmitter loop current. The two signals depend differently on the geometrical dimensions of the system. For example, a proportional factor of *k* decrease in the linear dimensions of the system increases the speed of response of the transmitter and receiver loops by approximately a factor of *k* and simultaneously leads to a proportional decrease in the coefficient of mutual induction. Due to the joint action of these factors, the total change in the direct induction signal in the graph with a bilogarithmic scale looks like a shift to the left on the timeline without changes in the amplitude and shape. This indicates an acceleration of the process of its rise and fall. The same is observed for the useful response signal.

Analysis of the data in Fig. 5 suggests that as the size of the system is decreased by three orders of magnitude, the direct induction signal is compressed/accelerated by the same amount, and the useful signal response by five orders of magnitude. Simultaneously, according to the graphs in the figure, this leads to a reduction of the useful signal at the same time mark by twelve orders of magnitude. In other words, reducing the size of the system for the purpose of earlier recording of the signal at point t_1 leads to a significant increase in the requirements for the measuring equipment. Thus, due to the acceleration of the transient process, it is necessary to reduce the time sampling, and due to the reduction in the signal level, it is necessary to increase the resolving power, and the increase must be several orders of magnitude rather than a factor of several times.

Results

The results of the numerical experiment are shown in graphical form in Figs. 6–10 It is seen from Fig. 6*a* that by changing the size of the system, it is possible to proportionately reduce the initial time of high-quality recording of the signal t_1 and reduce the minimal sounding depth by a factor of $\sqrt{t_1}$ (Kozhevnikov and Plotnikov, 2004). Reducing the size

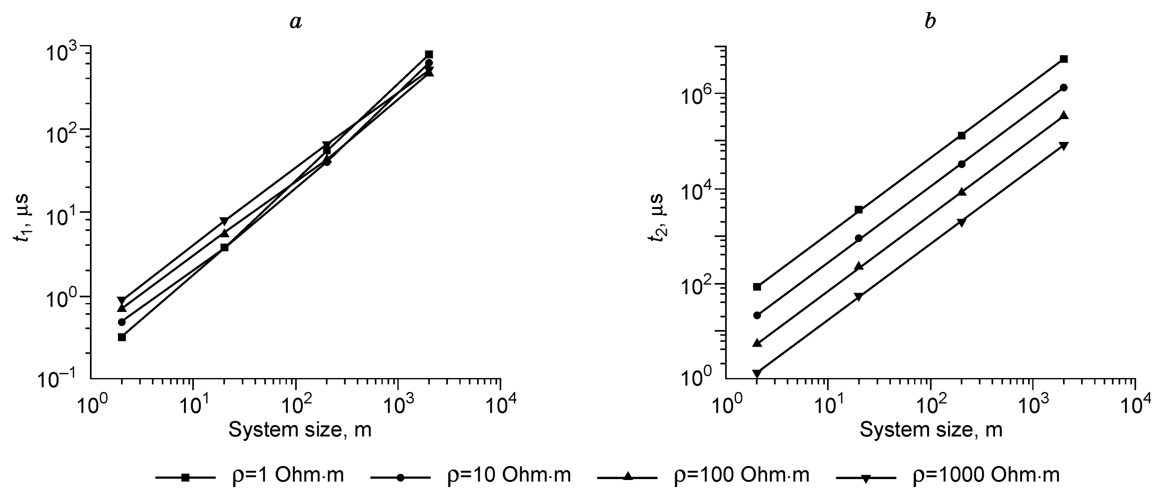

Fig. 6. Parameters t_1 *(a)* and t_2 *(b)* versus size of the system and subsurface resistivity.

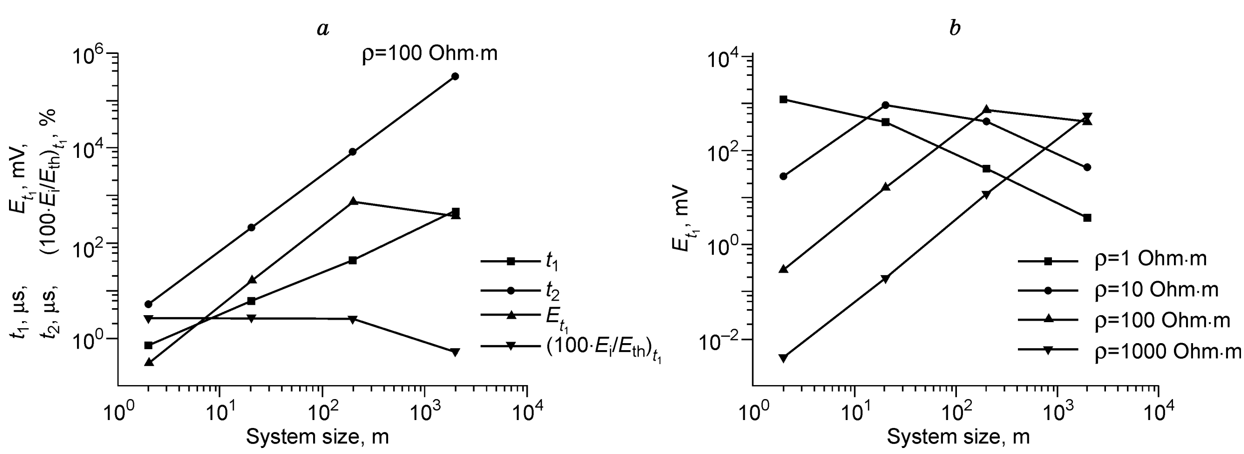

Fig. 7. Parameters depending on the size of the system *(a)* and plots of the signal level at point t_1 versus size of the system in different sections *(b)*.

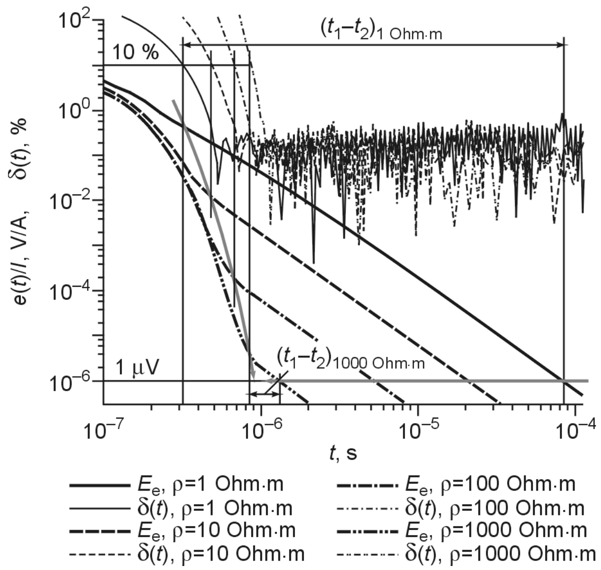

Fig. 8. Confidence interval for pseudoexperimental signals from different sections for the 2 m system.

of the system by an order of magnitude leads to a decrease of one and a half order of magnitude in the duration of high-quality measurement of the response signal (t_2) (see Fig. 6*b*).

Signal recording at early times involves certain difficulties. Evaluation of the parameters of the system for obtaining correct measurements at early times of the process is presented in Fig. 7. Curve t_1 in it shows the time from which one should expect high-quality results of measurement for the selected size of the system. The plot of E_i/E_e shows the portion of the inertial noise in the time-corrected signal recorded at point t_1. The curve of E_{t_1} defines the initial level of the measured signal, and the curve t_2 the minimum measurement time.

It should be added that as the conductivity of the earth reduces by an order of magnitude, the response signal decreases by one and a half order of magnitude (see Fig. 8). Consequently, the duration of the useful signal from the poorly conducting earth is shortened, which complicates noise control and interpretation. Reducing the size of the system further aggravates the situation since an order of magnitude decrease in the size leads to a four orders of magnitude decrease in the signal responsible for the same sounding depth. Therefore, reducing the size of the system primarily affects high-resistivity sections.

From the foregoing, it follows that it is not sufficient to have a portion of the response curve within the confidence interval. It is necessary that its length be sufficient. Considering that researchers are interested primarily in subsurface heterogeneities, it becomes clear that for numerical determi-

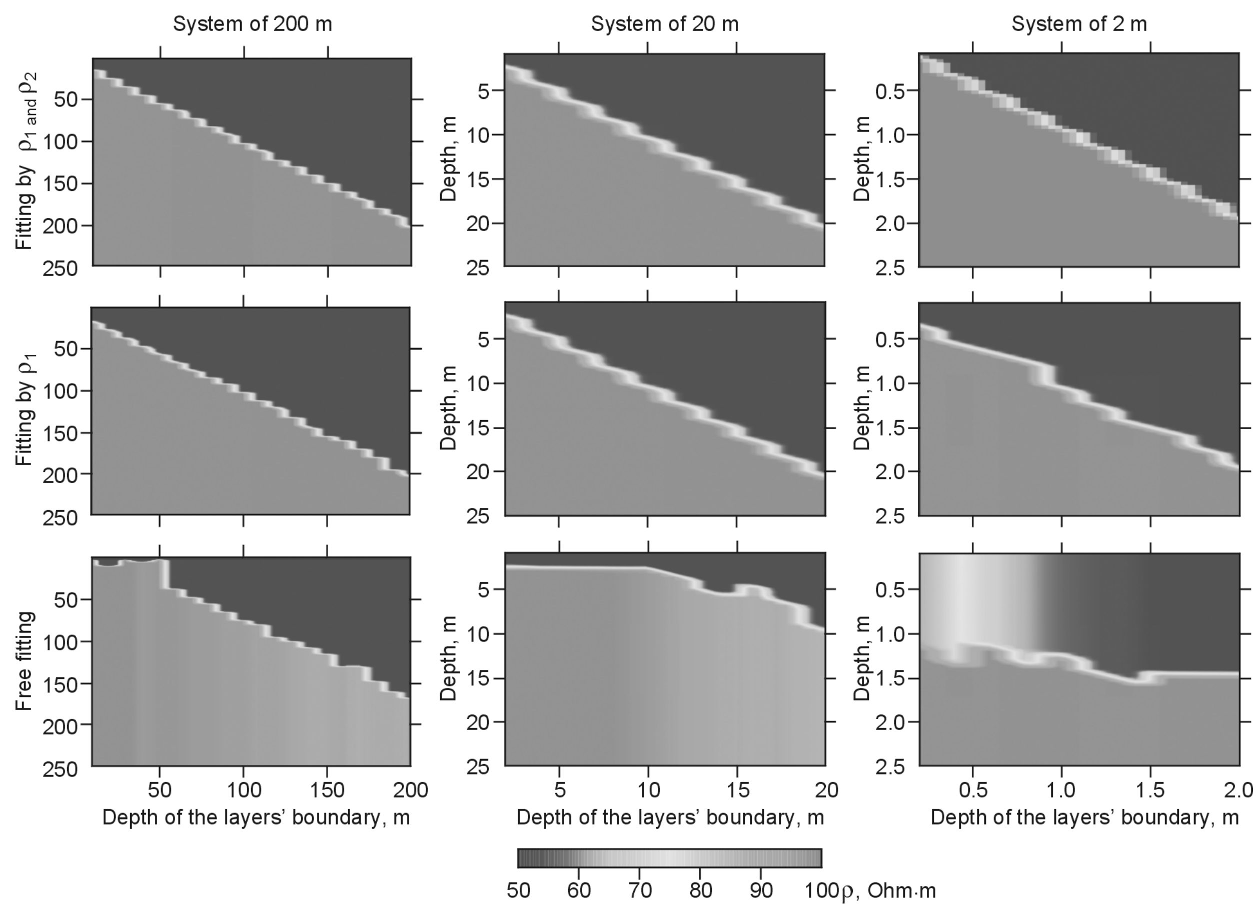

Fig. 9. Two-layer resistivity sections with a uniformly dipping basement.

nation of the performance of the system at shallow depths, complication of the subsurface model is necessary. Therefore, it was decided to use a two-layer subsurface model with horizontal layers. Calculating experimental signals for a sequence of sections with different depths of the boundary between the layers, and, thereby, repeatedly moving the conditional point of inflection on the recorded transient response curve away from the beginning of the reliable reception of a high-quality signal t_1, and using these data to solve the inverse problem, we can determine upper limit of sensitivity of the system to the sounding depth from the stability of the interpretation results.

The experiment is performed as follows.

1. For the chosen two-layer subsurface model and geophysical system, theoretical curves are calculated for a resistivity profile with a dipping basement.

2. The theoretical signals are used to produce an independent emf source in the equivalent circuit of the geophysical system (see Fig. 1) and calculate the corresponding pseudo-experimental emf signal.

3. The obtained curves corrected by a shift in time (in accordance with the graph in Fig. 3*b*).

4. The portions [t_1, t_2] containing information suitable for interpretation are cut from the calculated curves according to the graphs in Fig. 6.

5. The prepared emf curves are used as input data for the program for solution of the inverse problem. The thicknesses of the layers are calculated for each point of the profile. This is first done using full a priori information. Then, the information is limited to the near-surface resistivity, and then is completely removed.

6. Resistivity sections are constructed from the obtained data and are analyzed.

Figure 9 shows sample calculation for systems of size 200, 20, and 2 m and resistivities of the geoelectric section layers of 50 and 100 Ohm·m. Analysis of the data suggests that the system with a transmitter loop size of 200 m and receiver loop of 100 m is capable, without any a priori information, to determine the boundary of a two-layer section, starting from a depth of about 1/4 the size of the transmitter side. For the system reduced by an order of magnitude and, especially, for the system of size 2 m, a successful solution of the same problem will require a priori information about the near-surface.

Obviously, the above calculation will not stop prying experimenters from trying to use small systems. We can help them in this by citing the data of a numerical experiment showing how spatial separation of the receiver loop from the transmitter reduces the time of direct induction and thereby improves the performance of the system at shallow depth (see Fig. 10). This method holds the possibility of high-quality interpretation of the obtained material, but leads to some negative effects: reduction in the useful signal at an early stage, zero crossing, and positioning uncertainty. Despite this, measurements using a spatially separated system definitely lead to positive results due to the smoothening of transients in the system. For comparison, in addition to using graphs of

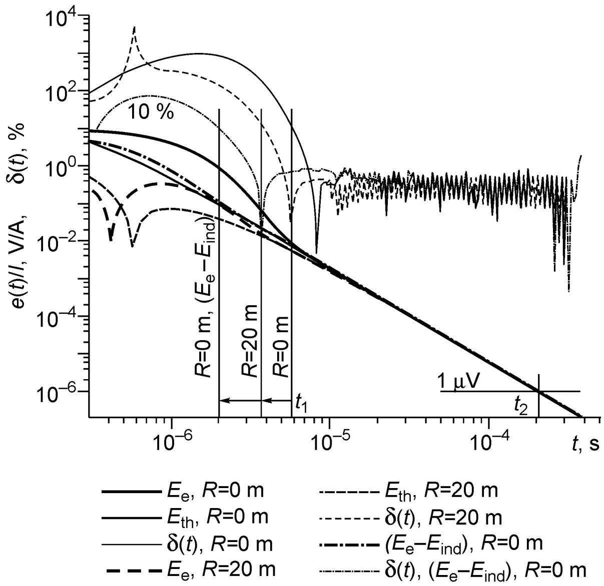

Fig. 10. Reducing the direct induction by spatial separation of the receiver from the transmitter. System of 20 m, ρ = 100 Ohm·m.

the coaxial system, use is made of the capabilities of numerical experiments and data for the imaginary case in the absence of direct induction.

Theoretically, direct induction can be completely eliminated by using various kinds of differential systems. A significant disadvantage of such measurements is the absence of the possibility of high-quality interpretation. However, this sounding method has good sensitivity to heterogeneities at depths commensurate with the size of the system and may be the only possible for certain types of survey, such as delineation of search objects at low depth.

Conclusions

The results obtained in this study are consistent with the general calculations presented in (Kozhevnikov and Plotnikov, 2004) and supplement them. It is shown which loops should be used in induction electrical survey at shallow depths and what physical processes prevent this. Dependences of the sounding depth on the receiver size, its frequency response, and initial recording time at different geophysical sections were derived. It is noted that at early times, the transmitter and receiver loops are connected not only by the magnetic field of the eddy currents decaying in the earth, but also through the direct inductive and capacitive couplings. This effect imposes a restriction on the formulas derived. In the study, these restrictions were identified, together with the inertial properties of the loops, in the form of time marks starting from which the recorded signal carries accurate subsurface information.

In general, the results of the numerical experiment suggest the use of small-size systems to reduce the sounding depth is quite possible under certain favorable conditions such as increased electrical conductivity of the earth at the measurement point and the presence of a priori information.

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