D-43 AN ILLUSTRATIVE APPROACH TO ESTIMATING THE NEAR-SURFACE TEM SYSTEM POTENTIALITIES

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SUMMARY

The paper discusses potentialities and limitations of the TEM sounding method when applied to the near-surface investigations. It is shown that decreasing effective sounding depth below 10m results in the necessity to measure TEM response at very early times and dramatic decrease in the level of transient signals.

INTRODUCTION

The TEM method is making rapid strides among other methods of electromagnetic prospection. Today, the TEM method is finding increasing use in solving groundwater, engineering, environmental, and geotechnical problems. Although many excellent articles on the application of the TEM method to the near-surface problems were published during the last decade, there are only a limited number of works discussing actual potentialities and limitations of the TEM method in the near-surface studies. In this paper we try, on the basis of simple, illustrative approach, to some degree to compensate for a deficiency in the near-surface TEM system analysis.

METHODOLOGY AND RESULTS

The effective sounding depth of an TDEM system (in m) can be estimated as (Matveev, 1990):

$$h = k_1 \sqrt{\rho\, t}\,, \qquad (1)$$

where ρ is the earth's resistivity (in Ω·m); t is time (in s) elapsed after transmitter current turn-off; k_1 is a coefficient, the value of which lies somewhere between 400 and 700, averaging at about 500.

Designate the desired minimum sounding depth as $h_{\min}$. It follows from (1) that the earliest time after the transmitter current turn-off have to be as small as

$$t_{min} = \frac{h_{min}^2}{k_1^2 \rho}\,. \qquad (2)$$

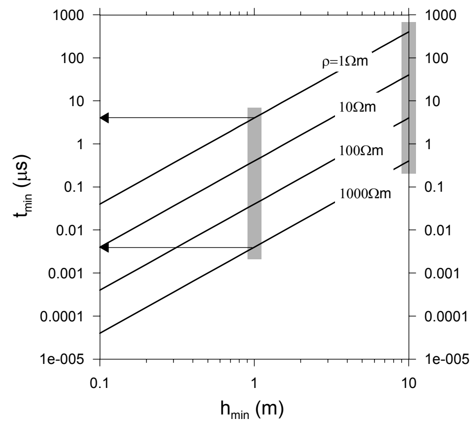

Figure 1: The $t_{\min}$ versus $h_{\min}$ graphs plotted for the earth resistivities from 1 to 10^3 Ωm. Grey vertical bars show $t_{\min}$ range at $h_{\min}$=1m and 10m.

Figure 1 represents $t_{\min}$ versus $h_{\min}$ graphs plotted for the earth resistivities of 1, 10, 10^2, and 10^3 Ω·m. Since $t_{\min}$ decreases as the square of $h_{\min}$, reducing the desired minimum sounding depth necessitates measurements to be done at very early times. Thus, in the case of $h_{\min}$=10m, the earliest measurement time falls in the range from few tenths to few hundreds of microsecond. Measuring transient response of the ground at times of about few microseconds and later is reported to become common in the today's

TEM prospection method. So, a TEM sounding starting from a depth of about 10m, especially in conductive ($\rho<10^2$ Ω·m) environment, can be regarded as a practicable one.

A decrease in $h_{\min}$ by an order of magnitude (up to 1m, in our case) would result in $t_{\min}$ ranging from few ns to several μs. In practice, measuring transient earth response at such early times presents a challenge to the professionals, particularly if $t_{\min}$ is smaller than 1 μs. In the case discussed such extremely early times are needed to sound the earth with resistivities of 10-10^3 Ω·m to a depth of about 1m. All other things being equal, the more resistive is the earth the less is $t_{\min}$ (see Figure 1).

Figure 2 shows a schematic sketch of a TEM system that includes transmitter, transmitter coil , the earth, receiver coil , and receiver (Zakharkin, 1981). The above elements are connected in series, and their individual responses convolve resulting in the overall transient response of the TEM system. The earth transient response is the signal that should be separated out the overall transient response. As for the transient responses of all other elements, they govern the inertia of the TEM system. The shorter is the overall transient response of these elements as compared to that of the earth, the earlier is the starting measurement time, $t_{\min}$, and, respectively, the smaller the minimum depth of investigation, $h_{\min}$.

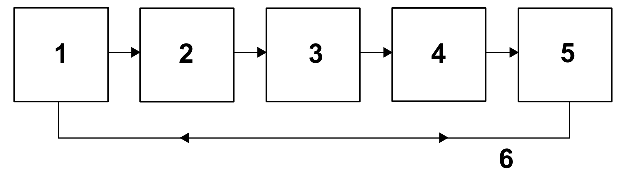

Figure 2: Schematic sketch of a TEM system: (1) transmitter (2) transmitter coil;(3) the earth; (4) receiver coil, (5) receiver; (6) reference cable.

Suppose that transmitter and receiver coincident coils (loops) are circular and their radius is *a*. For the sake of simplicity assume that the overall transient performance of the TEM system is determined predominately by the transmitter coil inertia. This assumption, apparently being too optimistic, may hold some validity as a starting point for the further consideration. It is a practice to evaluate the coil's EM inertia by its natural resonance frequency:

$$f_0(in\ Hz) = \frac{1}{2\pi\sqrt{LC}}\ , \quad (3)$$

where *L* is the coil inductance, in H; *C* is the coil capacitance, in F. For a single wire turn, both *L* and *C* are directly proportional to the coil's characteristic size, *l*: $L=l\cdot k_L$, $C=l\cdot k_C$, where k_L and k_C are coefficients.

For a circular wire turn, *L* (in H) and C (in F) are given by (Panin and Stepanov, 1987):

$$L = \mu_0 a\left(ln\frac{8a}{d} - 2\right), \qquad C = 2\varepsilon_0 a\left(ln\frac{8a}{d} - 2\right)^{-1},$$

where *a* is the coil radius, *d* is the wire radius, μ_0 is magnetic permeability of free space, ε_0 is dielectric permittivity of free space. It is suggested that $d<<a$, the condition that is certainly met for the coils that are practically used. Substituting these formulae into (3) results in

$$f_0 = \frac{1}{4\pi a\sqrt{\frac{1}{2}\varepsilon_0\mu_0}} \approx \frac{10^8}{\pi a}. \quad (3)$$

Obviously, the more is the coil radius, the lower is its resonance frequency and the more the time starting which from accurate measurements of the earth's transient response are possible. According to Zakharkin (1981), $t_{\min}$ and f_0 are related by

$$t_{min} = \frac{k_2}{f_0}, \quad (4)$$

where the coefficient k_2 is governed by the acceptable relative measurement error. In our calculations we used k_2=10, the value recommended by Zakharkin (1981).

Combining (1), (3), and (4) gives the formula for calculating the coil radius that is as small as to assure the starting effective sounding depth to be no more than $h_{\min}$:

$$a_{min} = \frac{10^8}{\pi k_1^2 k_2} \cdot \frac{h_{min}^2}{\rho}, \qquad (5)$$

In Figure 3 the equation (5) is represented graphically. As it is easily seen, to investigate the near-surface geology starting from a depth of about 10m, the coils' radius is allowed to be 1m and more. If the wanted $h_{\min}$ shouldn't exceed few meters, coils would have to be too small that measuring transient signal were practicable, especially in the case of the resistive earth. First and foremost, the measuring problem is that of decrease in the level of transient signal.

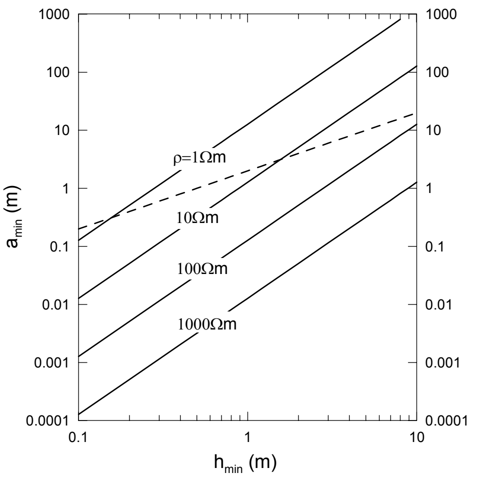

Figure 3: a_{min} versus h_{min} graphs plotted for different earth resistivities. The dashed line graph illustrates the "near-zone" condition (8).

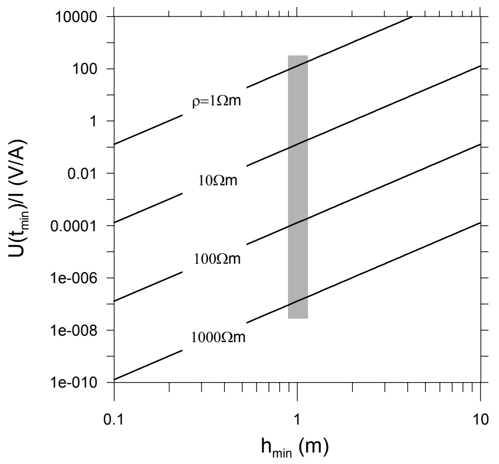

Figure 4: $U(t_{min})/I$ versus h_{min} graphs plotted for the earth resistivities in the range 1 - 1000 Ωm. Grey vertical bar shows the range of the $U(t_{min})/I$ values for h_{min}=1m.

Recall that at the late stage electromotive force, $e(t)$, induced in the receiver coil and normalized to the current I in the transmitter one, is given by (Kaufman and Keller, 1983)

$$\frac{e(t)}{I} = \frac{\sqrt{\pi}}{20} \cdot \frac{\mu_0^{5/2} a^4}{\rho^{3/2} t^{5/2}}. \qquad (6)$$

Inserting into (6) $t_{\min}$ and $a_{\min}$ given by (1) and (5), i.e. expressed in terms of $h_{\min}$ and ρ, gives normalized emf induced in the receiver coil at the earliest measuring time:

$$\frac{e(t_{min})}{I} = \frac{\sqrt{\pi}}{20} \cdot \frac{\mu_0^{5/2}}{k_1^3} \cdot \left(\frac{10^8}{\pi k_2}\right)^4 \cdot \frac{h_{min}^2}{\rho^3}. \qquad (7)$$

At any time later than $t_{\min}$, emf will be less than $e(t_{\min})/I$. Figure 4 represents $e(t_{\min})/I$ versus $h_{\min}$ graphs plotted for ρ=1, 10, 10^2, and 10^3 Ω·m. It is easily seen that decreasing the desired minimum sounding depth to few meters results in a significant decrease of the earth's transient response. It should be recalled that in the above analysis of the near-surface TEM system inertia only transient response of the transmitter coil was taken into consideration. Accounting also for the receiver coil early-time transient response would result in a further decrease of the (earth response/system response) ratio (Qian, 1985).

Each of the graphs represented in Figures 1, 3, and 4 defines an upper boundary of the parameter under discussion. For example, consider $a_{\min}$ versus $h_{\min}$ graph plotted for ρ=1Ω·m (see Figure 3). On this graph $a_{\min}$, that corresponds to $h_{\min}$=10m, exceeds 10^3m. It doesn't mean yet that in practice measurement of the earth's transient response has to be done with transmitter coil having radius of 1 km! It means only that using transmitter coil with radius more than 1km would result in resonance frequency of the coil insufficiently high for accurate measurements at times allowing $h_{\min}$=10m.

One should keep in mind that, according to the conventional theory of the TEM sounding method, the radius of a transmitter coil or loop is usually governed also by the "near zone" condition:

$$a \leq 2h_{min} \ . \qquad (8)$$

The graph representing (8) is shown in Figure 3 by the dashed line. From the two equations for estimating $a_{\min}$, we have to use that one which, with ρ and $h_{\min}$ given, imposes on $a_{\min}$ more strict limitation. As Figure 3 shows, in the near-surface TEM studies the determining factor is given by (1). Decreasing ρ and/or increasing $h_{\min}$ results in equation (8) becoming decisive.

In conclusion, it should be stressed that in measuring near-surface transient signals we have to realize that our possibilities to control the current and primary magnetic field waveform are limited. At very early times, transmitter and receiver coils interact not only due to the inductive, but also due to the capacitive coupling. The latter, depending dramatically on the coils' environment (near-surface structures and sometimes geophysicist himself included!), is difficult to control. In the case that coils or loops laid out immediately on the earth surface are significant in their size, they and the near-surface are integrated into a system with distributive rather than with lumped parameters (Kozhevnikov and Nikiforov, 1998, 2000). Even simplified study of this system, not to mention its accurate analysis, represents a hard problem. Resonance frequency of this system, unlike that of a coil placed above the earth, is given by (Kozhevnikov and Nikiforov, 1998)

$$f_0(in\ Hz) = \frac{1}{2p\sqrt{L'C'}} ,$$

where p is the loop perimeter (in m), L' is linear inductance (in H/m) of loop wire, and C' is its linear capacitance (in F/m).

CONCLUSION REMARCS

The results we represent in this paper have been obtained on the basis of simple assumptions and models. Numerous in-the-field experiments have shown that, in the general way, the above approach to estimating parameters of the near-surface TEM system does work. Its main idea is illustrated graphically in Figure 5, which doesn't need any special comments.

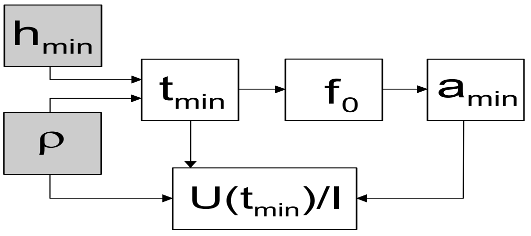

Figure 5: Graphical presentation of the approach to estimating performance of the very-early-time TEM system.

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