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Effects of borehole casing on TEM response

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Abstract

The effect the metal casing of a vertical borehole may exert on transient electromagnetic (TEM) responses has been studied in a field experiment. Eddy currents in the casing affect transients only slightly at early times, but the casing effect predominates at late times. Therefore, early-time TEM response measured near a borehole can provide information on shallow subsurface. The late-time TEM signals induced by the eddy currents in the casing show exponential behavior $b \cdot \exp(-t/\tau)$. The time constant τ refers to the rate of eddy current decay in the casing; the amplitude b is $M_{12} \cdot M_{23} \cdot L^{-1} \cdot \tau^{-1}$, where L is the casing self-inductance, and M_{12} and M_{23} are the mutual inductances between the transmitter loop and the borehole and between the borehole and the receiver, respectively. Both M_{12} and M_{23} are controllable, while M_{23} is especially important for survey applications: by reducing it, one can reduce the casing effect on the TEM data.

Keywords: transient electromagnetic sounding; transient response; borehole; casing; model; loop; inductance; time constant

Introduction

Transient electromagnetic (TEM) surveys are often run in the vicinity of boreholes with metal casing which can strongly affect the acquired response. Thus it is important to study these effects and possible ways of reducing them in order to better design the surveys and interpret the data.

However, this issue has received very little attention in the literature. We found a single publication by Mauldin-Mayerle et al. (1998) from *Zonge Engineering & Research Organization, Inc* who reported near-surface TEM soundings with a *NanoTem* instrument for environmental applications. Among other objectives, they searched a piece of a casing pipe, 15 cm in diameter, buried at a depth of 0.84 m. Mauldin-Mayerle et al. (1998) presented a single figure with horizontal loop responses of the earth above and off the pipe (the loop size was not indicated). As the figure shows, the early-time response is from the near-surface ground while the late-time one is dominated by the casing effect. The authors fail to estimate or interpret the casing effect; neither they suggest any ways of eliminating it.

We expect to somehow bridge the gap by investigating the effects of casing on transient responses in a field experiment. Before reporting the method and the experiment results, we briefly describe the survey area, the borehole, and the local resistivity pattern. The employed model of the borehole as a local conductor inductively coupled to the transmitter and receiver loops allows us to interpret the results and to suggest practical recommendations for reducing the casing effect in real TEM surveys.

Actually, they are rather eddy currents in the metal casing that cause effects on TEM data and not the borehole itself. In the paper we refer either to the borehole or to the casing meaning always the eddy current effect from the latter.

Survey area and borehole description

The survey area is located in a forest-steppe hilly plain within the Biya–Barnaul basin of the West Siberian plain (Maslyanino district, Novosibirsk region). According to drilling evidence, the upper 37 m of sediments are alternated clay silt and clay lying over the 37–65 m interval of brown dense clay (weathered shale). The interval between 65 and 97.2 m consists of fractured semiconsolidated water-saturated yellow

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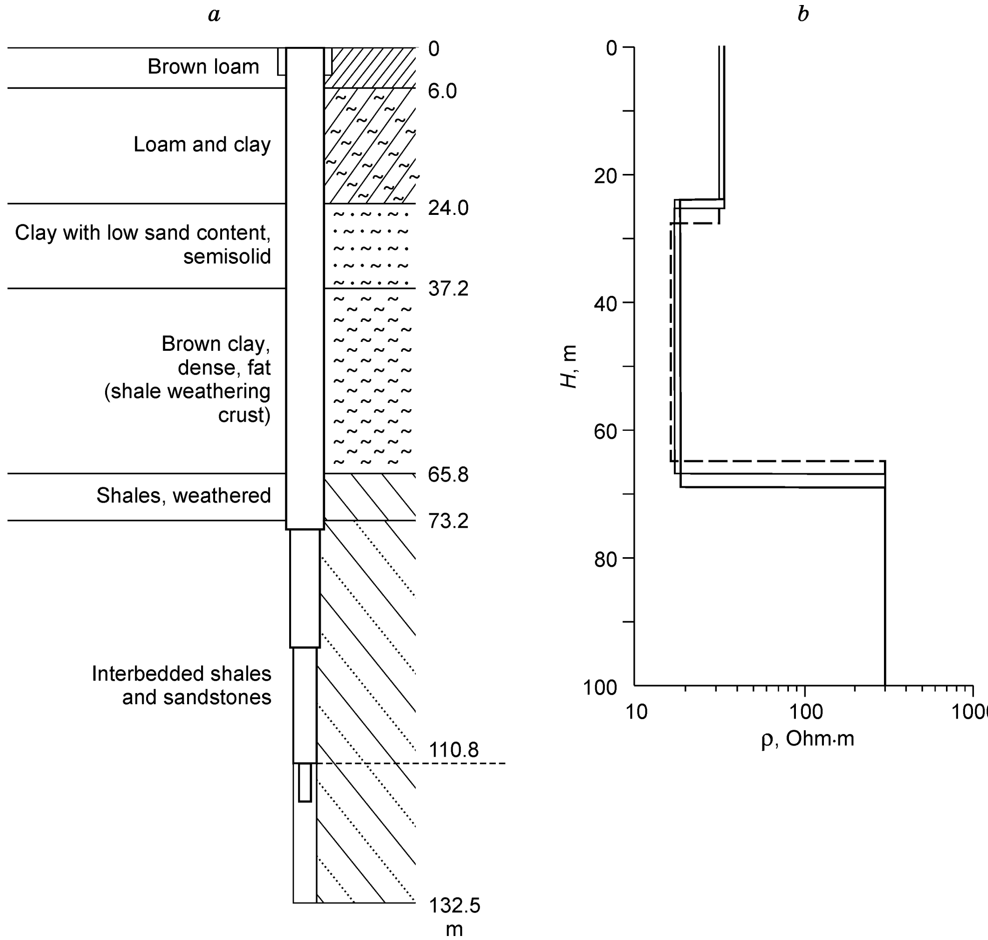

Fig. 1. Borehole, geological section (*a*) and ρ(*H*) curves obtained by individual (solid line) and joint (dashed line) inversion of TEM responses (*b*).

coaly shale, with steep (15° to the core axis) schistosity; the fractured shale includes an aquifer in the 65–135 m interval.

The borehole is 132.5 m deep (Fig. 1*a*) and cased to 110.8 m. The casing pipes have a diameter of 325 mm at the depths from 0 to 4 m, 219 mm from 4 to 74.6 m, 168 mm from 74.6 to 93 m, and 133 mm from 93 to 110.8 m; below 110.8 m, the hole is noncased and is 112 mm in diameter.

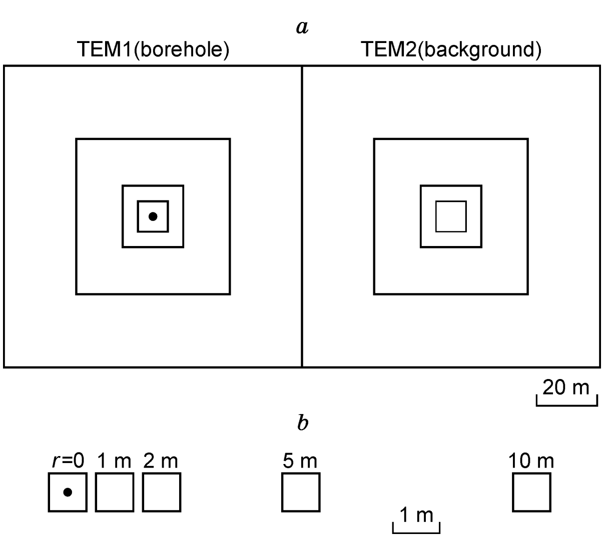

Fig. 2. Experiment layout: stages 1 (*a*) and 2 (*b*). Bold circle marks borehole. See text for details.

Experiment

The experiment consisted of two stages. *First*, we studied the borehole effect on central-loop responses, with two 100 m × 100 m transmitter loops (Fig. 2*a*). One loop (TEM1, point 1) was centered on the borehole head and the other (TEM2, point 2) had its center 100 m away from the borehole and one side coinciding with a side of TEM1. The transmitter size (100 m × 100 m) was chosen to be commensurate with that used most often in mineral and groundwater exploration, geological mapping, engineering geology, etc.

The site of measurements was located on a survey line where TEM soundings were done previously for groundwater exploration. The survey showed a laterally uniform resistivity pattern, and the TEM responses measured at point 2 were thus suitable as reference in estimating the casing effect.

In order to see how the casing effect on the TEM voltage decay may depend on the receiver loop size, we used loops of three sizes (10 m × 10 m, 20 m × 20 m, and 50 m × 50 m), with their centers at the center of the transmitter loop.

The TEM responses measured at point 2 were inverted, separately and jointly (Fig. 1*b*), using the *TEM-IP* software

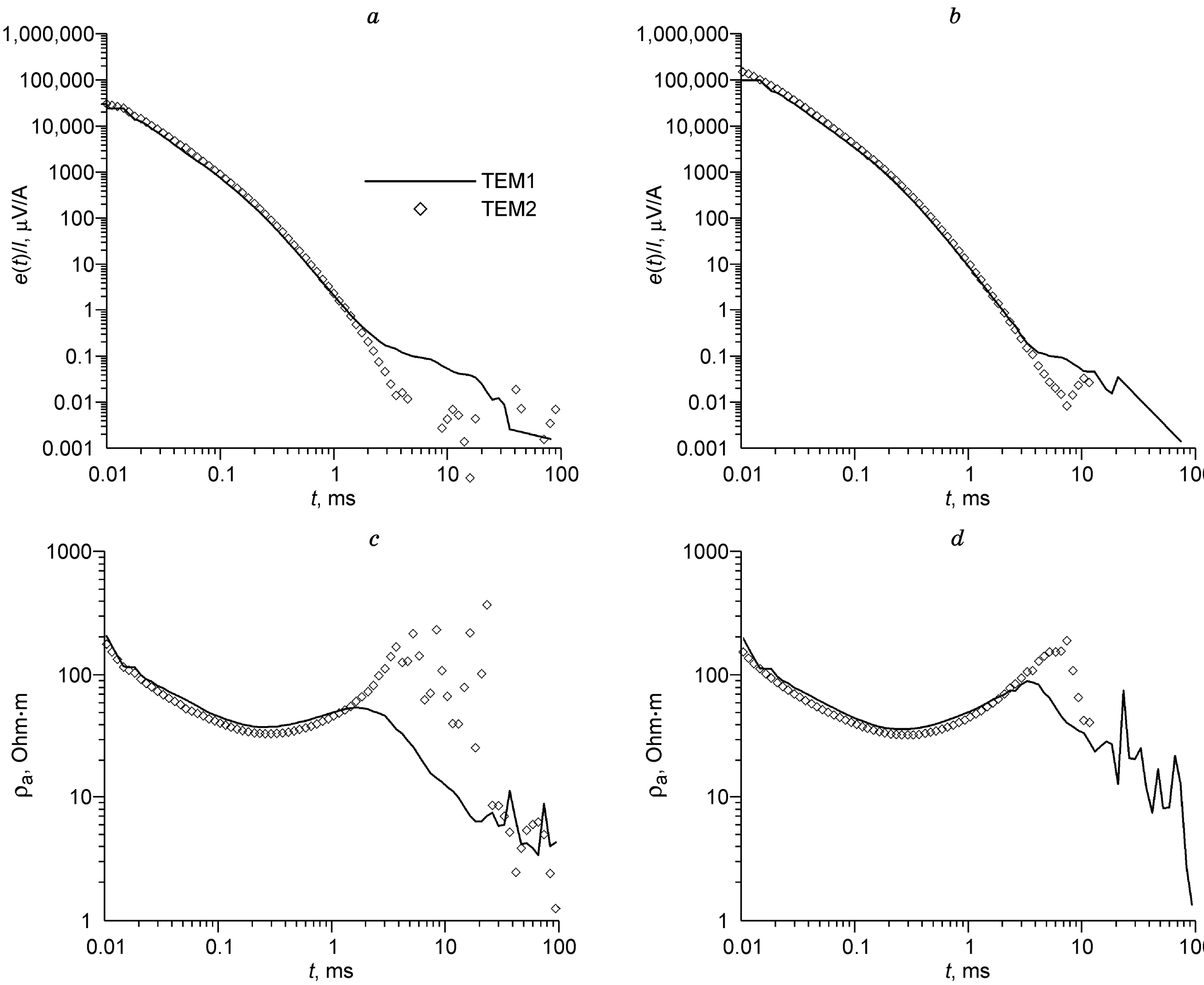

Fig. 3. TEM1 (borehole) and TEM2 (background) voltage decay (*a*, *b*) and apparent resistivity (*c*, *d*) curves. Receiver loop size: 10 m × 10 m (*a*, *c*) and 20 m × 20 m (*b*, *d*).

(Antonov et al., 2014), with a layered-earth assumption. The inversion indicated three layers: 30 Ohm·m clay silt and clay on the top, 17 Ohm·m clay in the middle, and 300 Ohm·m shale and sand at the base. The geoelectrical boundaries match the geological ones based on well-log data (Figs. 1*a* and *b*).

At the *second stage*, soundings were done with the first transmitter only. The TEM responses were acquired by a small multiturn induction coil with an amplifier, of 10,000 m^2 effective area, designed by A. Zakharkin (Fig. 2*b*). The spacing between the transmitter and the receiver centers was varied (five offsets were tried: $r = 0$, 1, 2, 5 and 10 m) to check the effect of the receiver position on TEM data.

All measurements were run with the *FastSnap* TEM instrument (Sharlov et al., 2010).

Results

Stage 1. The TEM1 and TEM2 current-normalized voltage responses, emf ($e(t)/I$), measured with 10 m × 10 m receiver (Fig. 3*a*) are almost identical at early times (0.01 to 2 ms). The casing effect shows up between 2 and 40 ms, where TEM1 voltage exceeds the TEM2 one which falls to the noise level (≈ 0.01 μV/A) already after 2 ms.

The respective TEM2 apparent resistivity curve (ρ_a) likewise becomes fuzzy at times later than 2 ms (Fig. 3*c*), meaning that the late-time voltage is commensurate with or below the noise. The TEM2 ρ_a curve (borehole point) has a descending right branch, i.e., resistivity gradually decreases with time to a few Ohm·m.

The 20 m × 20 m loop response (Fig. 3*b*, *d*) is similar to that of the 10 m × 10 m loop: both voltage and apparent resistivity curves coincide at early times and differ at $t > 2$ ms because of the borehole effect.

However, the 50 m × 50 m loop response produces a different pattern (Fig. 4). Namely, the TEM1 and TEM2 emf curves coincide at early times, i.e., the casing effect remains insignificant, but both ρ_a curves become noisy at $t > 3$ ms. Therefore, unlike the cases of smaller loops, there is no reason to speak about the difference between the TEM1 (borehole) and TEM2 (background) responses.

Figure 4 shows only the ρ_a curves, because the voltage polarity behaves chaotically in the region where the signal

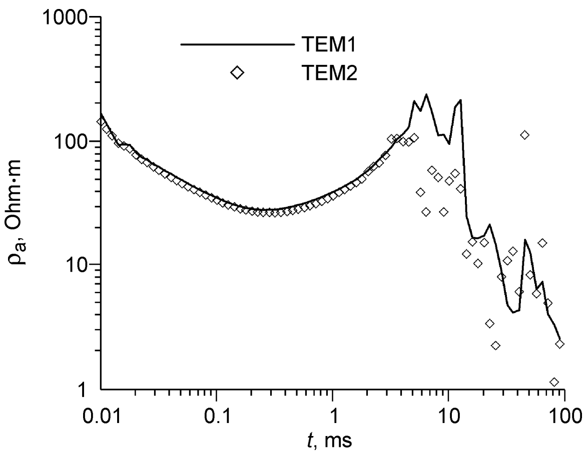

Fig. 4. TEM1 (borehole) and TEM2 (background) apparent resistivity curves. Receiver loop size: 50 m × 50 m.

reduces to the noise. Plotting negative voltage in the log–log coordinates is problematic, while no problem arises with ρ_a which is calculated from absolute voltage values.

The 10 m × 10 m and 20 m × 20 m loop responses at TEM1 show exponential voltage decay at late times:

$$e(t)/I = b\exp(-t/\tau), \quad (1)$$

where b is the initial value (amplitude) and τ is the time constant.

Small triangles in Fig. 5 show the TEM1 voltage responses measured with 10 m × 10 m and 20 m × 20 m receivers. Dash line shows an exponentially decaying voltage response fitting the measured voltage in the (t_1–t_2) interval (see Table 1 for the exponent parameters). The obtained estimates are $b \approx 0.2$ μV/A and $\tau = 7$–10 ms.

Stage 2. Measurements with the small receiver coil (Fig. 6) show slow, monotonically decaying voltage of the positive polarity at $r = 0$ (the coil center at the borehole). As the coil center is set 1 m off the borehole, the voltage experiences double polarity reversal: from positive to negative at $t = 1.5$ ms and back at 10.6 ms. As the offset increases to $r = 10$ m, the voltage induced in the receiver becomes as low as the noise at $t > 4$ or 5 ms.

The voltage curves measured at offsets 2 and 5 m lie between those at $r = 1$ m and $r = 10$ m (not shown in the figure for simplicity). These curves likewise exhibit polarity reversal, while the time interval of negative voltage is narrower than that of $r = 1$ m data.

At $t \geq 5$ ms and $r = 0$, the voltage decays exponentially, and the log–log voltage curve is a straight line with a negative slope (Fig. 7). Dash line in Fig. 7 is the exponent ($b = 1740$ μV/A, $\tau = 10.3$ ms) providing the best fit to the observations at late times from 5 to 80 ms.

All b and τ values found by fitting the exponents to the late-time (tail) parts of the measured responses are given in Table 1.

Discussion

We discuss the results using a simple model, which proved to be workable when we studied the applicability of horizontal closed loop responses to test the TEM system (Kozhevnikov, 2012). The model consists of a transmitter loop, a borehole casing with eddy current induced in it, and a receiver loop, all coupled inductively to one another. The eddy currents arising both in the earth and in the casing once the transmitter current has been turned off induce voltage in the receiver loop, which is recorded by the acquisition unit of the TEM system.

Figure 8 shows the subsurface, the borehole, and the receivers of the secondary field (loops or induction coil). Let $e_1(t)/I$ and $e_2(t)/I$ be, respectively, the current-normalized voltages induced in the receiver due to the decaying eddy currents induce in the earth and in the borehole. Strictly

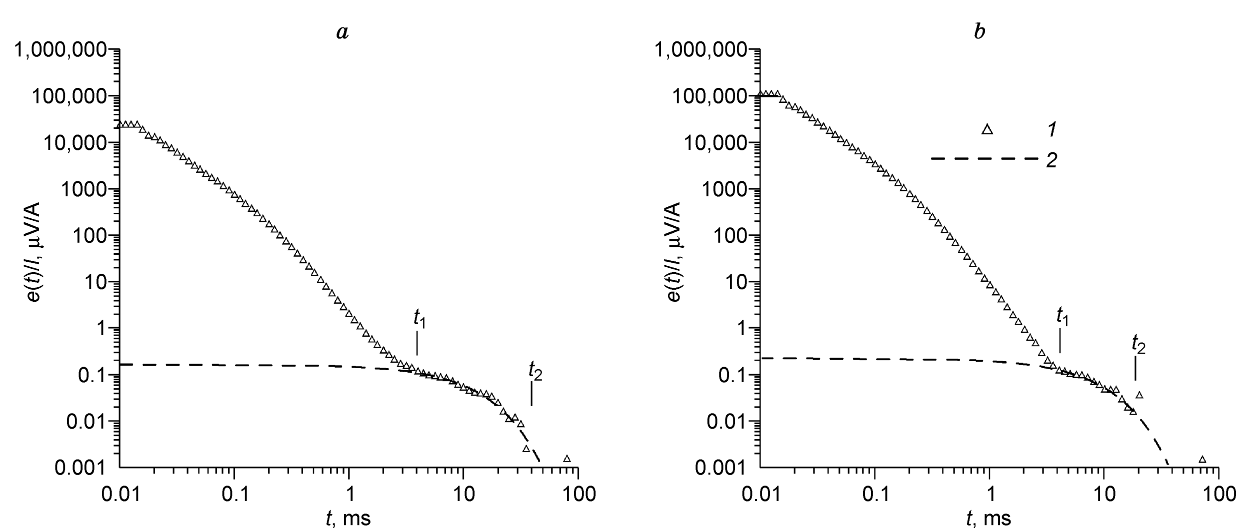

Fig. 5. TEM1 (borehole) voltage decay curves. Receiver loop size: 10 × 10 m (*a*) and 20 m × 20 m (*b*). See exponential voltage decay at later times. *1* is measured voltage and *2* is exponent.

Table 1. Approximation of TEM1 (borehole) voltage response "tails" by exponent $e(t)/I = b\cdot\exp(-t/\tau)$

Receiver	$(t_1–t_2)$, ms	b, μV/A	τ, ms	R^2
Loop 10 m × 10 m	4–40	0.17	9.6	0.97
Loop 20 m × 20 m	4–40	0.18	8.5	0.84
Loop 20 m × 20 m	4–18	0.22	6.8	0.98
Induction coil, S_{eff} = 10,000 m^2	5–80	1740	10	0.999

Note. $(t_1–t_2)$ is the time interval of approximation; R^2 is the coefficient of determination.

speaking, $e_1(t)/I$ and $e_2(t)/I$ are not fully independent, but within quite a large time interval (Kozhevnikov, 2012) the total transient response $e_{12}(t)/I$ may be written as

$$e_{12}(t)/I = e_1(t)/I + e_2(t)/I.$$

A homogeneous conductive half-space is the simplest fundamental earth model. Its TEM voltage response can be approximated by the power decay function (Sidorov, 1985; Spies and Frischknecht, 1991):

$$e_1(t)/I = a\cdot t^{-5/2},$$

where a is the time-independent coefficient that accounts for the loop configuration and the earth resistivity.

The casing is a confined conductor showing exponentially decaying transient responses (1) (Kaufman, 1974; McNeill, 1980):

$$e_2(t)/I = b\exp(-t/\tau).$$

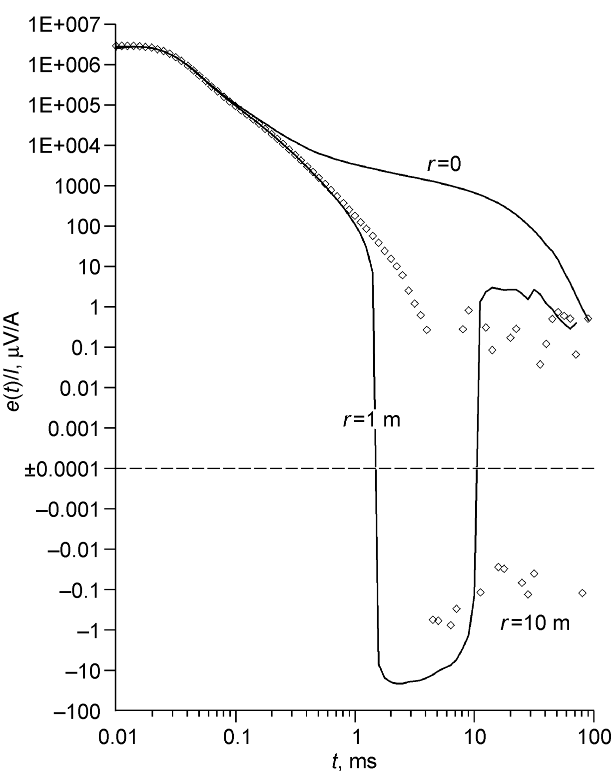

Fig. 6. TEM voltage responses measured with a small induction coil.

The time constant τ is known (Kaufman, 1974; McNeill, 1980) to be proportional to $\mu\sigma l^2$, where μ is the absolute magnetic permeability, σ is the conductivity, l is the conductor's characteristic size. It is of diagnostic importance as it characterizes the "quality" of the conductor in the integral form.

The transmitter turn-off time may be assumed to be very short with respect to the time constant (τ). In this case, the b coefficient is given by (Kozhevnikov, 2012)

$$b = \frac{M_{12}M_{23}}{\tau L}, \qquad (2)$$

where M_{12} and M_{23} are, respectively, the mutual inductances between the transmitter and the borehole (M_{12}) and the borehole and the receiver (M_{23}), and L is the casing self inductance.

The idealized voltage responses are shown on the log–log scale in Fig. 9. One is the voltage induced in the receiver by eddy currents decaying in the homogeneous conductive earth, with its log–log plot looking as a straight line with the slope –5/2. The same figure shows two curves of exponential voltage decay induced by eddy currents in the casing. If the borehole head is within the receiver loop, the borehole-receiver inductance M_{23} is positive, the voltage induced in the receiver by eddy currents both in the earth and in the borehole has the same polarity, and the total response looks as in Fig. 5. Otherwise, when the receiver loop lies off the borehole head (Fig. 8), $M_{23} < 0$, the voltage the borehole eddy currents induce in the receiver has its polarity opposite to that induced by eddy currents in the earth, and the total response is equal to their difference.

In the latter case ($M_{23} < 0$), the total responses may look different depending on relation between the absolute values of $e_1(t)/I$ and $e_2(t)/I$. The response is nonmonotonic, without polarity reversal, at $|e_2(t)/I| \le |e_1(t)/I|$ over the whole time range (curve *1* in Fig. 9). Or, it may show a double polarity reversal (Fig. 6) if $|e_2(t)/I| > |e_1(t)/I|$ within some $(t_1–t_2)$ interval (curve *2* in Fig. 9).

The response ($e_1(t)/I$) is controlled by the earth's resistivity and by the parameters of the TEM system. Unlike $e_1(t)/I$, the voltage $e_2(t)/I$ has no relation to geology and thus is noise to be attenuated as far as possible. In this respect, the question arises which parameters from (2) are controllable for reducing the borehole effect. The time constant τ and the inductance L obviously cannot be changed being the intrinsic casing

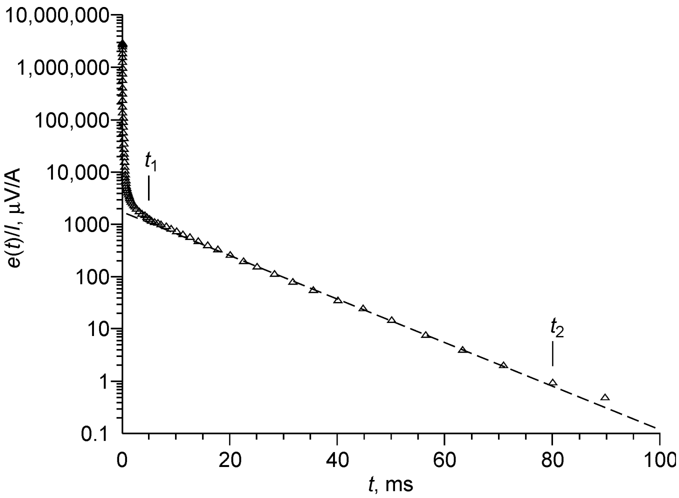

Fig. 7. TEM voltage responses measured with a small induction coil at $r = 0$ (borehole). The log-log voltage response looks like a straight line at the (t_1–t_2) interval indicating that eddy current in the borehole casing decays exponentially (McNeill, 1980). *1* and *2* are as in Fig. 5.

parameters, but one can control the inductance M_{12} between the transmitter and the casing via the transmitter's size and position. The real possibility to reduce the casing effect on TEM data by decreasing M_{12} is limited because the transmitter size and configuration depend on the geological objectives (e.g., the desired depth penetration, resolution, etc.). There remains the inductance M_{23} between the borehole and the receiver, which can be reduced either by increasing the receiver loop size or by setting the induction coil far off the borehole: both ways reduce the borehole-receiver inductive coupling.

This conclusion seems to be at odds with the comparison of TEM1 responses measured by the 10 m × 10 m and 20 m × 20 m receivers. The amplitude *b* for both loops turned out to be almost identical (Table 1), though the magnetic coupling and, correspondingly, the M_{23} inductance were expected to be lower for the 20 m × 20 m receiver than for the 10 m × 10 m loop. The controversy may be explained as follows. Unlike the inductance between the wire loops, which can be represented as a lumped circuit at times later than a few tens of microseconds (Kozhevnikov, 2006), the borehole-receiver inductance is essentially a distributed parameter. Perhaps, the larger size of the 20 m × 20 m loop relative to the 10 m × 10 m one is compensated by its greater sensitivity to the magnetic field of the current circulating in the deeper parts of the borehole.

On the contrary, the TEM1 and TEM2 50 m × 50 m loop responses are almost identical (Fig. 4), which is evidence of a very weak coupling between the borehole and the receiver loop. Thus, the inductance M_{23} between the borehole and the 50 m × 50 m receiver is so small that the eddy currents in the casing cause no effect on the total response.

The experiment results for small receiver coils agree with the idea of inductive coupling between the borehole and the receiver. Namely, the experiment showed that M_{23} becomes negative at large offset because in this case the magnetic field of eddy currents in the casing is directed opposite the field trough the coil placed at the borehole head (Fig. 8). Furthermore, M_{23} decreases rapidly away from the borehole.

In conclusion, we comment on the fact that the effect of an ungrounded receiver loop, even centered on the borehole, appears no earlier than after 2–3 ms (Fig. 3). This means that the left branches of the transient response curves can be

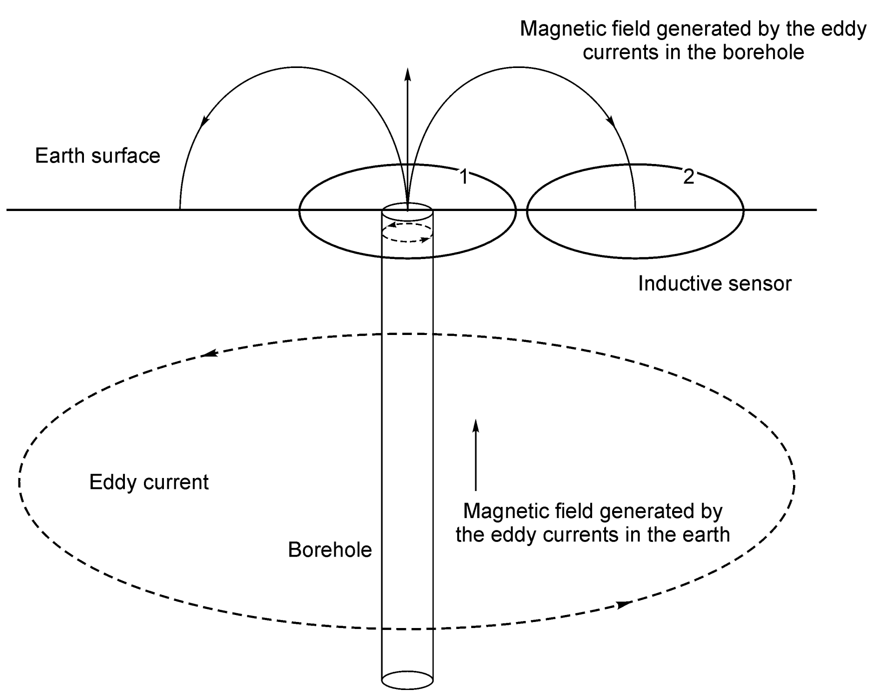

Fig. 8. Induction coil placed at the borehole head (1) and away from it (2). Dash line shows eddy current in the earth and in the casing.

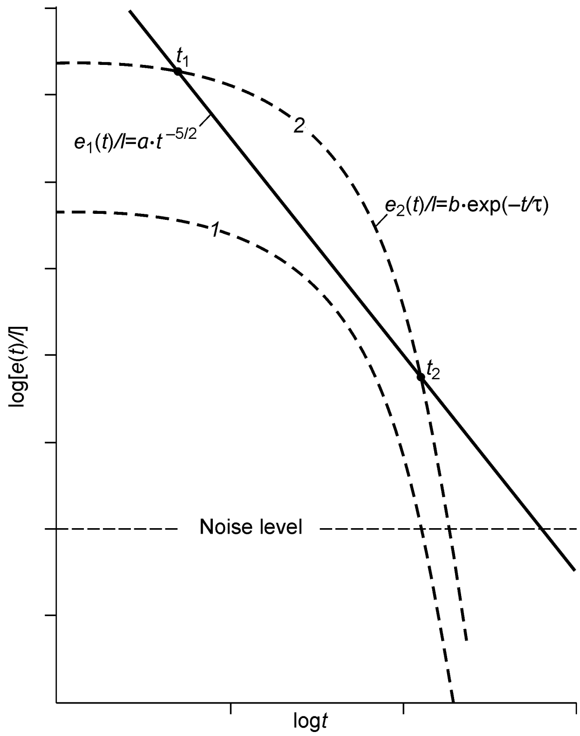

Fig. 9. Transient voltage responses of a homogeneous conductive earth and a borehole casing. *1* and *2* are explained in text.

interpreted in terms of a horizontally layered earth model. In the reproted case, TEM soundings can resolve the earth structure to the depths of about 100 m.

Why the casing effect is vanishing at early times? If the casing is considered as a confined conductor, the reason may be that the secondary magnetic field induced by the eddy current in the casing which decays exponentially with the time constant τ about 10 ms (Table 1) changes much slower than that induced in the receiver by eddy currents in the earth within the 1–2 ms interval. Correspondingly, the casing-related induced voltage is much lower than that caused by the earth eddy currents. Apparently, the larger the time constant τ and the lower the earth resistivity, the later the time at which the total response becomes notably different from the earth response.

However, the strong inductive coupling between the casing and the small receiver coil placed at the borehole head makes its effect notable as early as at $t \approx 100$ μs (Fig. 6). The amplitude of b in the case of a small multiturn induction coil is almost four orders of magnitude greater than with the 10 m × 10 m and 20 m × 20 m loops (Table 1), while the casing effect decreases away from the borehole. Already at $r = 10$ m, the voltage induced in the receiver coil reduces to the noise at times later than 2–3 ms (Fig. 6).

Note that we have failed to fit the modeled 1D TEM responses computed with the layered-earth assumption to the observations over the whole time range. Because of the casing effect, there exists no 1D resistivity model to account for the measured late-time ($t > 3$–5 ms) transients.

Conclusions

At early times, the eddy currents induced in the metal borehole casing cause a much lower effect on the TEM response than those induced in the earth. Therefore, early-time transients can provide reliable information on the near-surface resistivity distribution. At late times, however, the casing effect predominates, and the respective late-time loop responses show exponential behavior $b \cdot \exp(-t/\tau)$.

The relaxation time τ refers to the rate of eddy current decay in the borehole; the amplitude b is directly proportional to M_{12} and M_{23} and inversely proportional to L and τ (where L is the casing self inductance, and M_{12}, M_{23} are the transmitter-borehole and borehole-receiver mutual inductances, respectively). The parameters M_{12} and M_{23} are controllable, while M_{23} is especially important for survey applications: by decreasing it one can reduce the casing effect on TEM data.

There are two ways to weaken the inductance between a borehole and an ungrounded receiver loop: either increase the loop size or, in the case of a small receiver coil, place it far enough from the borehole.

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