GEOPHYSICAL TRANSACTIONS 1997
Vol 40. No. 3-4. pp. 175–189

Vertical steel casing as a monopole transmitter antenna for electromagnetic prospecting

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A vertical steel casing excited as a monopole antenna could potentially be used as a source for electromagnetic investigation of the surroundings of a borehole. In this respect the behaviour of the current distribution along the casing and the surface electric field due to it is treated. Special emphasis is laid on the frequency dependence, which seems to be of good use in interpretation. Numerical models developed to simulate the casing response — although considerably simplified — match the experimental data very well.

Keywords: frequency sounding, E-field excited casing, casing as antenna, surface electric field of a casing

1. Introduction

The steel casings of two drill-holes used as vertical input electrodes — line sources — produce a higher current density with increasing depth than point sources located at the ground surface [ROCROI, KOULIKOV 1985]. This procedure (called Tubel) was developed to delineate a partially known hydrocarbon deposit overlain by resistive layers. HAGREY [1994] presented a case history for investigating electric anisotropy in a granite basement by applying the mise-à-la-masse technique. One of the two fixed current electrodes was connected to a fracture via the metal casing of a borehole. Similar measurements were carried out in Hungary to determine the main directions

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Manuscript received (revised version): 30 August, 1995

of large karstic water-filled cavities inside the limestone bedrock of the coal seam in Lencsehegy MiningWorks [TAKÁCS 1989].

Otherwise, in recent years several papers have been published in the geophysical literature in connection with borehole casing, discussing questions such as

— the effect of well casings on electrical surveys [e.g. JOHNSTON et al. 1992],
— communication capability of a casing or a drillstring for measurement-while-drilling (MWD) [e.g. XIA et al. 1993],
— electrical resistivity measurement through metal casing [e.g. SCHENKEL et al. 1994],
— DC resistivity imaging from a steel cased well [SCHENKEL 1994].

This paper investigates whether the electromagnetic field of the vertical steel casing of a single well excited by an alternating voltage applied to an isolation gap that divides the casing into two parts near the top or bottom end could be used for the exploration of the surroundings of the well. Frequency domain measurements offer an opportunity to govern the penetration depth and transform the measured voltages into apparent resistivities.

2. Surface radial electric field of an E-field excited casing in a homogeneous half-space

If a voltage is applied to an isolation gap near the top or bottom of an E-field excited casing a complex $I(z)$ current-distribution will arise along its length. The maximum value of $I(z)$ will be at the gap, and at the ends of the casing its value becomes zero. With increasing frequency $I(z)$ concentrates itself towards the gap. Taking the casing as an "antenna" the current distribution along its axis can be determined by procedures known from antenna theory [KING, SMITH 1981; XIA et al. 1993].

In practice, E-field excitation can be more or less accomplished if the top of the casing and surface electrodes around it, or an electrode located beneath the casing shoe are taken as points of current supply.

A computer program was developed to determine the current distribution by the method of moments if the casing has perfect electrical contact with the homogeneous half-space [VARGA 1994].

In *Fig. 1* current distributions along a casing can be seen. The casing is in a homogeneous half-space with specific conductivities of 0.04 and 0.07 S, and the frequencies are 3.5 and 3500 Hz. *Im I(z)* values at 3.5 Hz are negligibly small. They could not be plotted on this scale. The casing emits radial currents towards the formation in the vicinity that are proportional to the partial derivative of *I(z)* with respect to the vertical direction. Elemental currents along the casing can be considered as elementary vertical electric dipoles with real and imaginary currents. Their superposed field can be measured at the earth's surface. The contribution of an elementary section of the casing to the surface field depends on both the current and the relative positions of the elementary sections with respect to the observation point.

Amplitude and phase frequency sounding curves are presented in *Fig. 2* for the half-spaces considered above. The frequency dependence of the surface radial electric field is similar to the field of a vertical electric dipole placed in the middle part of the casing.

3. Geometrical sounding over a horizontally layered half-space

It is well known that the electromagnetic field generated by a vertical electric dipole is weaker by a factor of at least 100 for a given separation and frequency, and that this attenuates more rapidly with the separation than those fields due to a horizontal dipole with the same source strength [GOLDMAN 1990]. At the same time, the rock volume between the source and observation point has a larger effect on the field than the section below the source [TAKÁCS 1988].

Owing to the similiarity between the electromagnetic fields of the casing and a buried vertical electric dipole the rules mentioned above will probably apply to our case. It is therefore advisable to examine the attenuation of the surface electric field and the effect of the layering below the casing.

In *Figs. 3* and *4* surface amplitude and phase values of the radial electric field are shown along a profile above a homogeneous and a layered half-space for 5 Hz and for the top and bottom excitation respectively. In the layered section a resistive layer —1000 Ωm — is embedded into the homogeneous half-space below the casing.

The surface field is rather sensitive to the presence of the 1000 Ωm layer — which lies close to the termination of the casing — already at relatively small offset. At $R< 3.5h_1$ — h_1 is the thickness of the first layer — the field

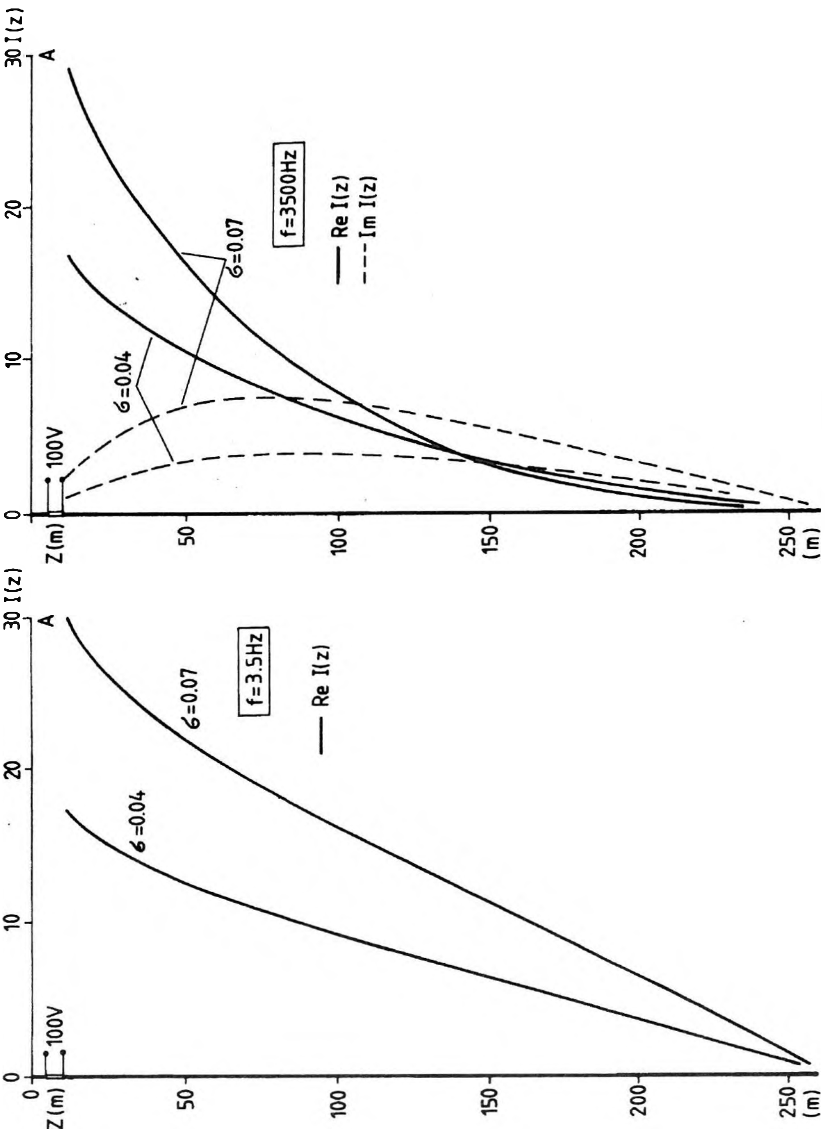

Fig. 1. Real and imaginary parts of current distributions along a vertical casing in homogeneous half-space

1. ábra. A valós és képzetes áramok eloszlása a homogén féltérben levő függőleges béléscső mentén

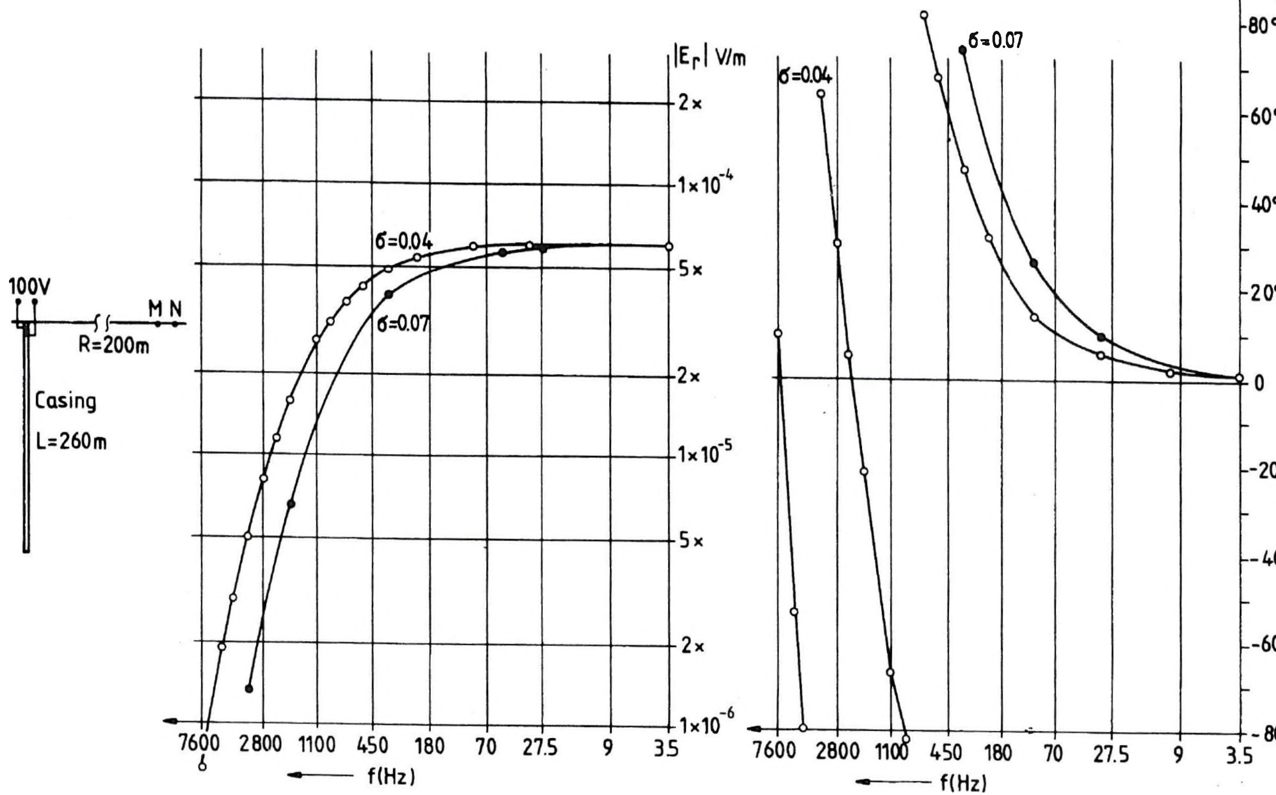

Fig. 2. Amplitude and phase frequency sounding curves of the radial electric field on the surface of homogeneous half-space
2. *ábra.* A radiális elektromos térerősség amplitúdó és fázis frekvenciaszondázási görbéi homogén féltér felszínén

is lower than for the homogeneous case, at $R > 3.5h_1$, on the other hand, the values are higher for the layered model. Even at this low frequency — 5 Hz — the phase grows dynamically with offset and the effect of the 1000 Ωm layer is an unambiguous decrease at $R > h_1$.

The difference is more pronounced in the case of the bottom excitations, and the amplitudes are larger owing to the geometry and to the fact that from the bottom end of the casing more current dissipates at a given voltage than it does at top excitation.

The effect of the resistive layer is more clearly indicated by the ρ_a apparent resistivity curve calculated from the ratio of the amplitude in the layered earth to the amplitude in a half-space having the resistivity of the uppermost layer. The ρ_a apparent resistivity curves have a false minimum. At the same time the practical application of this apparent resistivity definition is not so straightforward as for point electrodes.

Another apparent resistivity determination — ρ_a^*— can be made based on the homogeneous half-space electric number phase characteristic, i.e. phase curve versus offset normalized to the skin-depth [Takács 1988]. ρ_a^* values are also given in Figs. 3 and 4. It can be seen, that they have a direct relation to the section without any "undershoot".

Geometrical sounding data for large offset are needed to obtain reliable information about the section. It should not be forgotten, however, that the low signal sets limits to the separation.

Owing to the fact that the effect of the lower 1000 Ωm layer appears at rather small separation it is expected that frequency domain soundings could have advantages in the exploration of the immediate vicinity of the well.

4. Frequency sounding over a layered half-space

Amplitude and phase frequency sounding curves are presented in *Figs. 5* and *6* for the homogeneous and layered half-spaces in the case of a top and a bottom excitation. The separations are 250 and 500 m, both in the range where amplitudes respond with a decrease due to the presence of the resistive layer. The effect of the 1000 Ωm layer for both excitations increases with the offset. However, it is more pronounced in the case of bottom excitation.

So far as the amplitudes are concerned the difference between the curves for layered and homogeneous half-space is the gratest at the lowest frequency as a result of the larger penetration depth. On the other hand, the phase

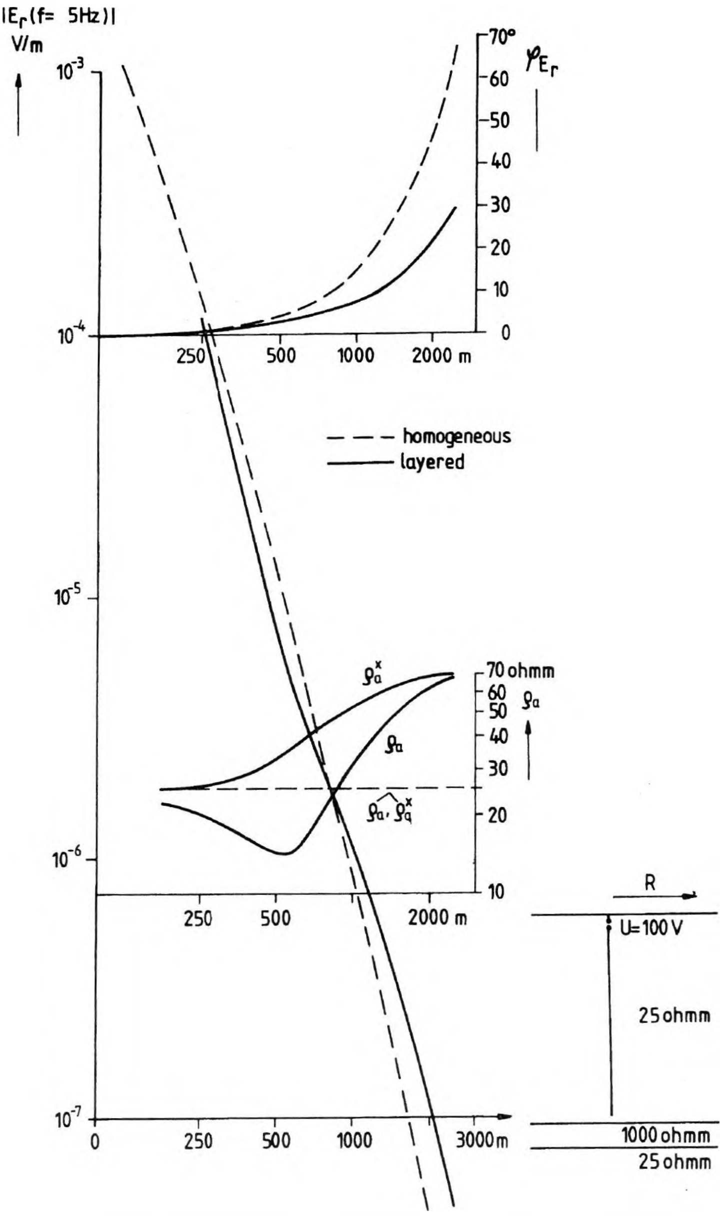

Fig. 3. Amplitudes, phases of the 5 Hz radial electric field and apparent resistivities (ρ_a, ρ_a^*) on the surface of a homogeneous — 25 Ωm — and a layered — 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm — half-space (top excitation)

3. ábra. Az 5 Hz-es radiális elektromos térerősség amplitúdó-, fázis-, és látszólagos fajlagos ellenállás (ρ_a, ρ_a^*) szelvényei a 25 Ωm-es homogén és a 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm paraméterű rétegzett féltér felszínén (felszíni árambevezetés)

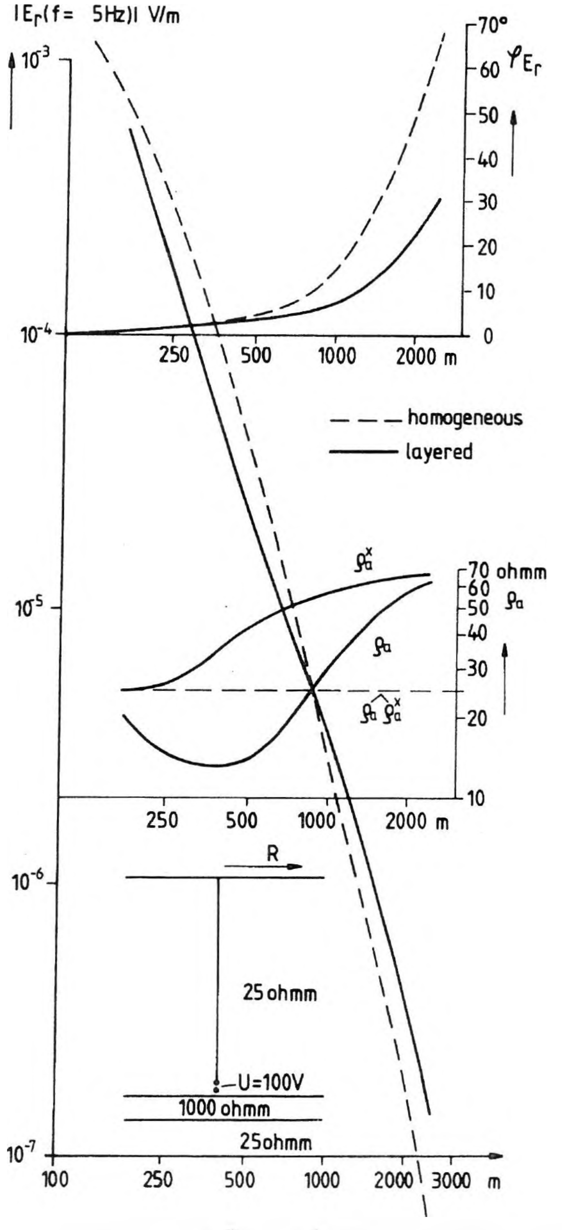

Fig. 4. Amplitudes, phases of the 5 Hz radial electric field and apparent resistivities (ρ_a, ρ_a^*) on the surface of a homogeneous — 25 Ωm — and a layered — 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm — half-space (bottom excitation)

4. ábra. Az 5 Hz-es radiális elektromos térerősség amplitúdó-, fázis- és látszólagos fajlagos ellenállás (ρ_a, ρ_a^*) szelvényei a 25 Ωm-es homogén és a 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm paraméterű rétegzett féltér felszínén (alsó árambevezetés)

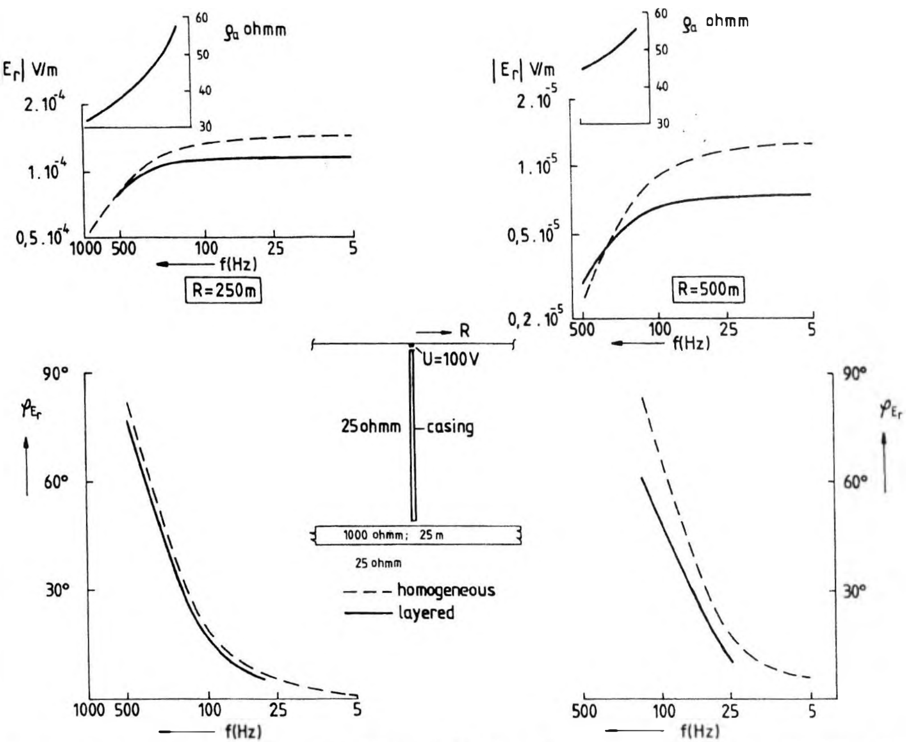

Fig. 5. Amplitude and phase frequency sounding curves of the radial electric field and ρ_a apparent resistivities derived from amplitudes on the surface of a homogeneous — 25 Ωm — and a layered — 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm — half-space at separations R = 250 m (*a*) and R = 500 m (*b*) (top excitation)

5. ábra. A radiális elektromos térerősség amplitúdó és fázis frekvenciaszondázási görbéi és az amplitúdóból származtatott ρ_a látszólagos fajlagos ellenállások a 25 Ωm-es homogén és a 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm paraméterű rétegzett féltér felszínén R = 250 m (*a*) és R = 500 m (*b*) távolságban (felső árambevezetés)

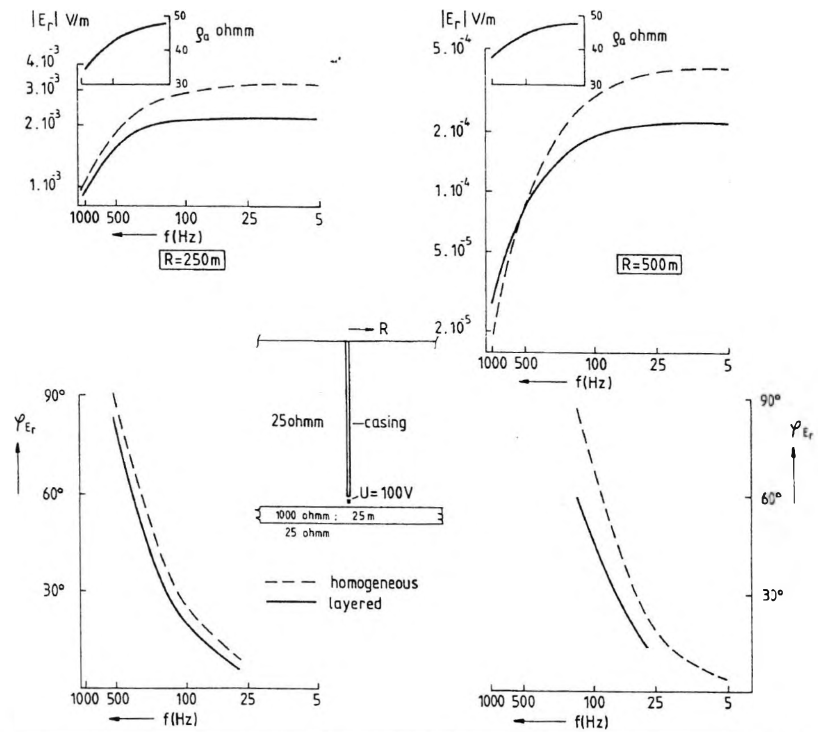

Fig. 6. Amplitude and phase frequency sounding curves of the radial electric field and ρ_a apparent resistivities derived from amplitudes on the surface of a homogeneous — 25 Ωm — and a layered — 1000 Ωm, 25 m; 25 Ωm — half space at separations R = 250 m (*a*) and R = 500 m (*b*) (bottom excitation)

6. ábra. A radiális elektromos térerősség amplitúdó és fázis frekvenciaszondázási görbéi és az amplitúdóból származtatott ρ_a látszólagos fajlagos ellenállások a 25 Ωm-es homogén és a 25 Ωm, 250 m; 1000 Ωm, 25 m; 25 Ωm paraméterű rétegzett féltér felszínén R = 250 m (*a*) és R = 500 m (*b*) távolságban (alsó árambevezetés) difference has an opposite tendency which is connected mainly with the changes of the lateral extension of the current systems of changing sign around the casing. Otherwise, the phase values are represented only for the inner current system around the casing. After the first sign-change they rapidly change.

The monotonic character of the frequency sounding curves conceals the information about the layering. However, it will clearly appear in the apparent resistivity curves calculated by the use of the characteristics of the electric number over a homogeneous half-space [Takács 1988]. Such characteristics can be seen in *Fig. 7* for top excitation, where phases and normalized amplitudes to the DC field are represented as a function of the separation normalized to the skin-depth (δ). Similar characteristics can be given for the bottom excitation.

For given separation and frequency, knowing the measured phase — or the amplitudes at the frequency considered and at DC — ρ_a values can be calculated.

ρ_a values determined for the descending branches of the amplitude curves — where the rate of change is well defined — clearly show the presence of the 1000 Ωm layer near the bottom of the casing. The apparent resistivity decreases significantly with increasing frequency from 150 Hz to 1000 Hz, this means that it does not remain constant as it does in the case of a homogeneous half-space.

5. Field experiment

Numerical models developed above to simulate the casing response match the experimental data very well.

There is a cased borehole at the Miskolc University campus, which has offered us a possibility to check the theoretical considerations. The length of the steel casing is 261 m. Immediately below the casing shoe — from 267 m downwards — highly resistive Mesozoic limestone basement can be found. Overlying formations containing the casing are mostly argillaceous sediments of low resistivity. Apparent resistivities measured in the borehole exceed 20 Ωm only in the depth interval 70–132 m.

Phase curve and apparent resistivities deduced from it measured at a separation $R = 250$ m are shown in *Fig. 8*.

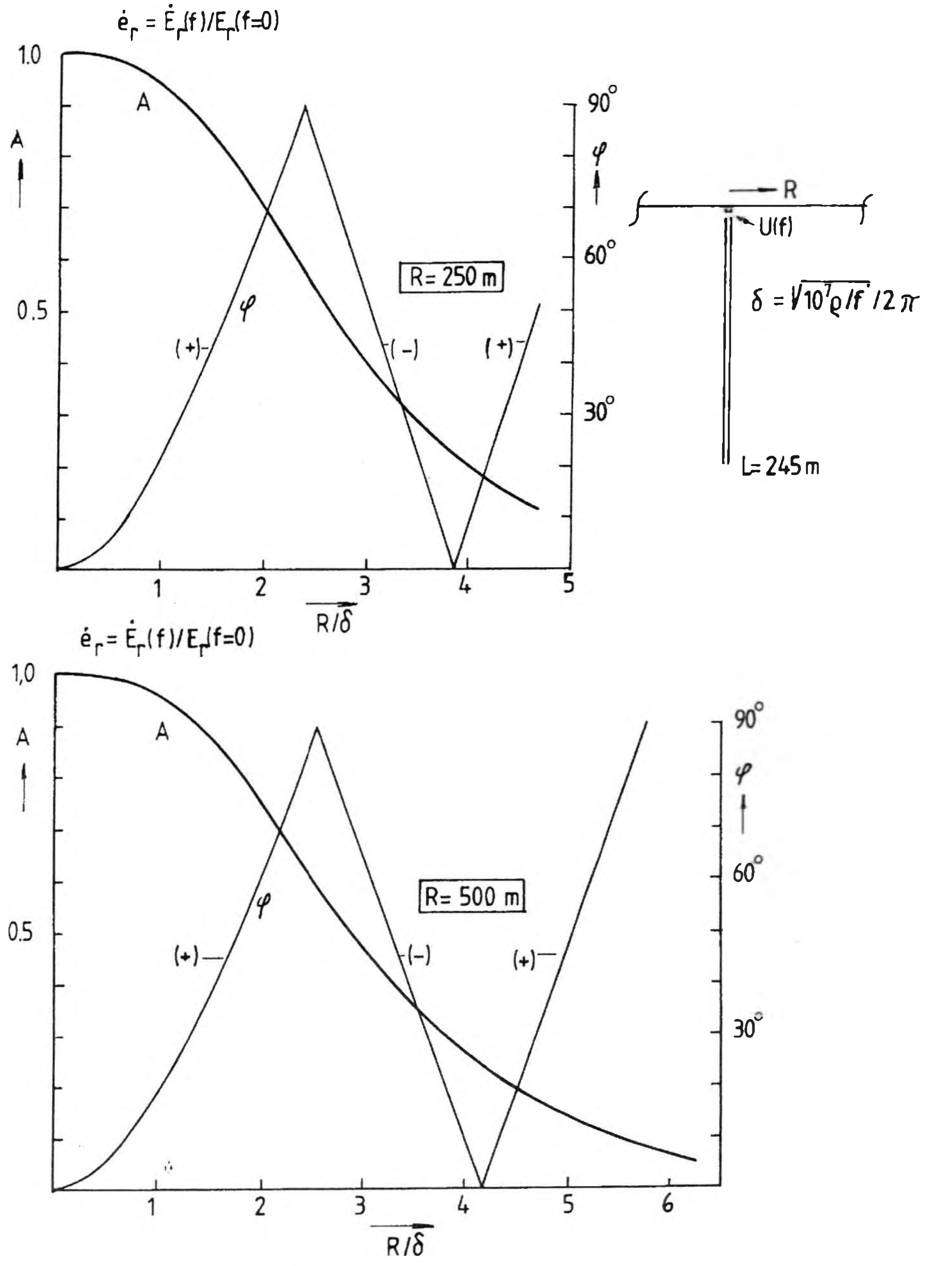

Fig. 7. Amplitudes and phases of the radial electric number ($\dot{e}_r$) as a function of the induction number R/δ (top excitation)

7. ábra. A radiális elektromos szám ($\dot{e}_r$) amplitúdó és fázisgörbéje az R/δ indukciós szám függvényében (felső árambevezetés)

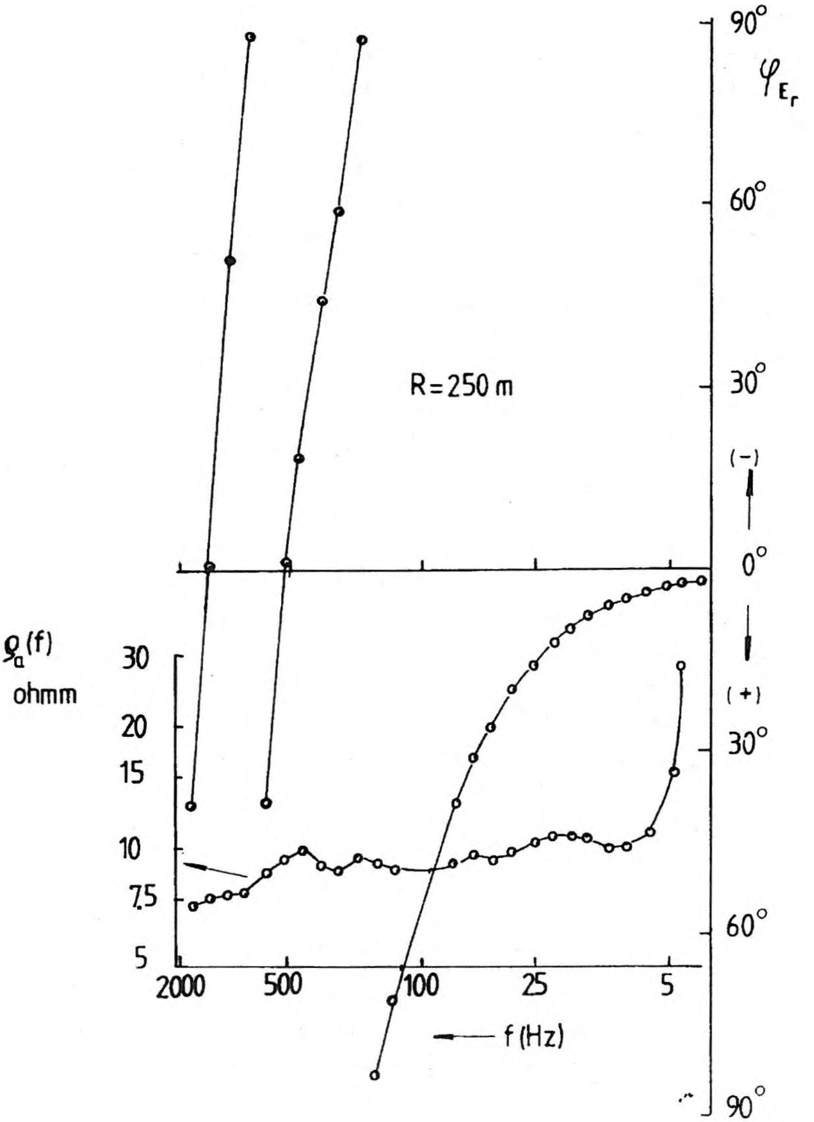

Fig. 8. Results of a field test obtained by the top excitation of a casing 261 m in length. Frequency dependence of the phase and apparent resistivities (ρ_a) derived from it are shown. 50 V voltage was applied between the casing and short-circuited electrodes around a circle with 10 m radius

8. ábra. Egy 261 m hosszúságú béléscső felső megtáplálásával kapott kísérleti mérés eredményei. A fázis frekvenciafüggése és a belőle levezetett ρ_a látszólagos fajlagos ellenállások láthatók. Az 50 V-os feszültséget a béléscső teteje és a körülötte 10 m sugarú körön levő rövidre zárt elektródákhoz csatlakoztatták

The author's opinion is that the aim of such measurements is not so much the quantitative interpretation for layering, but the location of the possible lateral inhomogeneities in the neighbourhood of the borehole. For that purpose several measurements have to be made around the borehole on the circumference of a series of concentric circles.

In our case the signs of human activity prevented us from making more measurements. Therefore our single test measurement proves only that the $\rho_a(f)$ curve has such characteristic features, that can be used for correlation between stations with the same separation around the borehole to detect lateral inhomogeneities.

6. Conclusions

This study has shown that the steel casing of a borehole may be used as a transmitter antenna. The *E*-excitation mode — applying a voltage to an isolation gap that divides the casing into two parts — was selected. Based on numerical simulations and a test measurement it is to be expected that the changes of the surface radial electric field around the circumference of a circle whose centre is the borehole will reflect inhomogeneities in the neighbourhood of the borehole. Additional work needs to be done since in reality there are other factors — e.g. contact impedance, dip — that could bias the results.

Acknowledgement

This work was supported by the Hungarian Scientific Research Fund (OTKA) — contract number 2383 and CO216.

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A béléscsőnek, mint adó- és vevőantennának használata az elektromágneses kutatásban

TAKÁCS Ernő

A monopol-antennaként megtáplált acél béléscső elvileg az elektromágneses tér forrása lehet a fúrás közvetlen környezetének kutatásához. A tanulmány ilyen célzattal vizsgálja a béléscsőmenti árameloszlást és az általa létrehozott felszíni elektromos térerősséget. Különös figyelmet szentel a frekvenciafüggésnek, ami az értelmezésben jól használható. A béléscső elektromágneses terét leíró modell — bár sok közelítést tartalmaz — a kísérleti méréssel jól egyező eredményt ad.