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EFFECT OF LATERAL INHOMOGENEITIES ON THE FREQUENCY SOUNDING CURVES OBTAINED FROM THE VERTICAL ELECTRIC COMPONENT OF A BURIED VERTICAL CURRENT DIPOLE

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The paper discusses how the effect of lateral inhomogeneities manifests itself in underground frequency soundings carried out using vertical electric transmitter and receiver dipoles in an equatorial array.

The simplified models are:

- a vertically infinite interface and sheet perpendicular and parallel to the axis connecting the transmitter and receiver dipoles;
- a break in the horizontal high resistivity layer perpendicular to the axis connecting the transmitter and receiver dipoles.

The former case was studied numerically, the latter one by physical modelling.

Keywords: frequency, electrical sounding, dipole, lateral inhomogeneity, in-mine geoelectric methods, models

1. Introduction

In an earlier paper [TAKÁCS et al. 1986] the characteristics of a vertical electric field of a buried vertical electric dipole in horizontally layered medium were analysed. Survey tasks solved by applying underground transmitter and receiver are, however, rather associated with detection of

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lateral inhomogeneities either between the transmitter and receiver or in their vicinity. It is essential to study the nature of the effect of such inhomogeneities because observed deviations from the response of horizontally layered models suggest the presence of inhomogeneities.

The approved methods for studying lateral inhomogeneities are seismic and electromagnetic tomography or dc reconstruction. These types of measurements can be carried out only if the relative position of transmitter and receiver can be changed in a sufficiently wide range to obtain as many crossing transilluminating radii as possible. It may happen, however, that this kind of measurement is unaccomplishable and the space between or in the vicinity of the dipoles can only be studied using a given fixed array. The question arises whether frequency sounding might have a role in detecting lateral inhomogeneities in such cases.

To deal with the problem I have carried out physical and numerical modelling for a variety of situations. The models chosen are simplified; they are, however, suitable for recognizing, as a first step, the basic characteristics. The conclusions obtained can be used as a basis for extending the study to more complicated cases.

In every discussed case vertical electric (grounded) transmitter and receiver dipoles in an equatorial array are considered.

The complex shape of frequency sounding curves — quasi-stationary part, possibly a maximum, then a steeply descending branch — makes the visual recognition of the effects of both horizontal stratification and lateral inhomogeneities difficult. The introduction of an apparent resistivity that at any frequency is equal to the resistivity of that homogeneous space which substitutes the inhomogeneous space considering its effect is of help. This apparent resistivity — $\rho_a^*(f)$— can be obtained from measurement of amplitude, phase or in-phase or out-of-phase components. To derive it the dependence of the quantity in question on the induction number — transmitter-receiver separation normalized to the skin depth — in a homogeneous medium should be known. In addition, values of the actual transmitter-receiver separation — R — and frequency will be used. Thus, $\rho_a^*(f)$ can be derived not from the actual field strength value but from the position of characteristic points on the frequency sounding curve along the frequency axis [TAKÁCS et al. 1986].

The other parameter used later is the effective resistivity (ρ_{eff}^*) of the 'rock-slab' containing the transmitter and receiver dipoles. This can be given knowing the resistivity ρ_a calculated using the factor of the geometric sounding on the quasi-stationary part of the curve and $\rho_a^{\bullet}$ (f_{max}) calculated at the maximum of the amplitude curve. In a continuous layer this is a very good approximation of the actual resistivity. In the case of discontinuity it reflects the degree of discontinuity [TAKÁCS et al. 1986].

In view of the fundamental behaviour of $\rho_a^{\bullet}$ (f) it can be expected that at lower frequencies the effect of the more distant environment of the dipoles manifests itself as well; then, with increasing frequency, it reflects more and more the resistivity distribution in the closer vicinity of the transmitter.

2. Effect of infinite vertical interface

In one of the cases studied, 20 and 250 Ωm media can be found at two sides of the interface. The measuring array with a constant transmitter-receiver separation — R=100 m — has different positions related to the interface. The direction of R is perpendicular to the interface. The amplitude curves are shown in *Fig.1,* the phase curves in *Fig.2.*

Amplitude curves corresponding to the different positions obviously lie between the curves of 20 and 250 Ωm homogeneous space, respectively. As long as the transmitter and receiver are in a medium of the same resistivity the high frequency asymptotes of the curves coincide. It means that an increase in frequency causes a decrease in the effect of the adjacent halfspace. With decreasing frequency, on the other hand, its effect increases. This is the reason why the maximum becomes more enhanced on approaching the low resistivity halfspace from the higher resistivity one. At the same time, the amplitude of the maximum related to the quasi-stationary part of the curve decreases when both the transmitter and receiver are in the halfspace of lower resistivity and they approach the halfspace of higher resistivity.

When the interface lies between the transmitter and receiver, the quasi-stationary field strength remains the same at different positions of the array, and it depends only on the transmitter-receiver separation. In our case it is constant. Location and value level of maxima and descending branches, on the other hand, depend on the effective resistivity of the rock volume determined by the current field developing at the corresponding frequen-

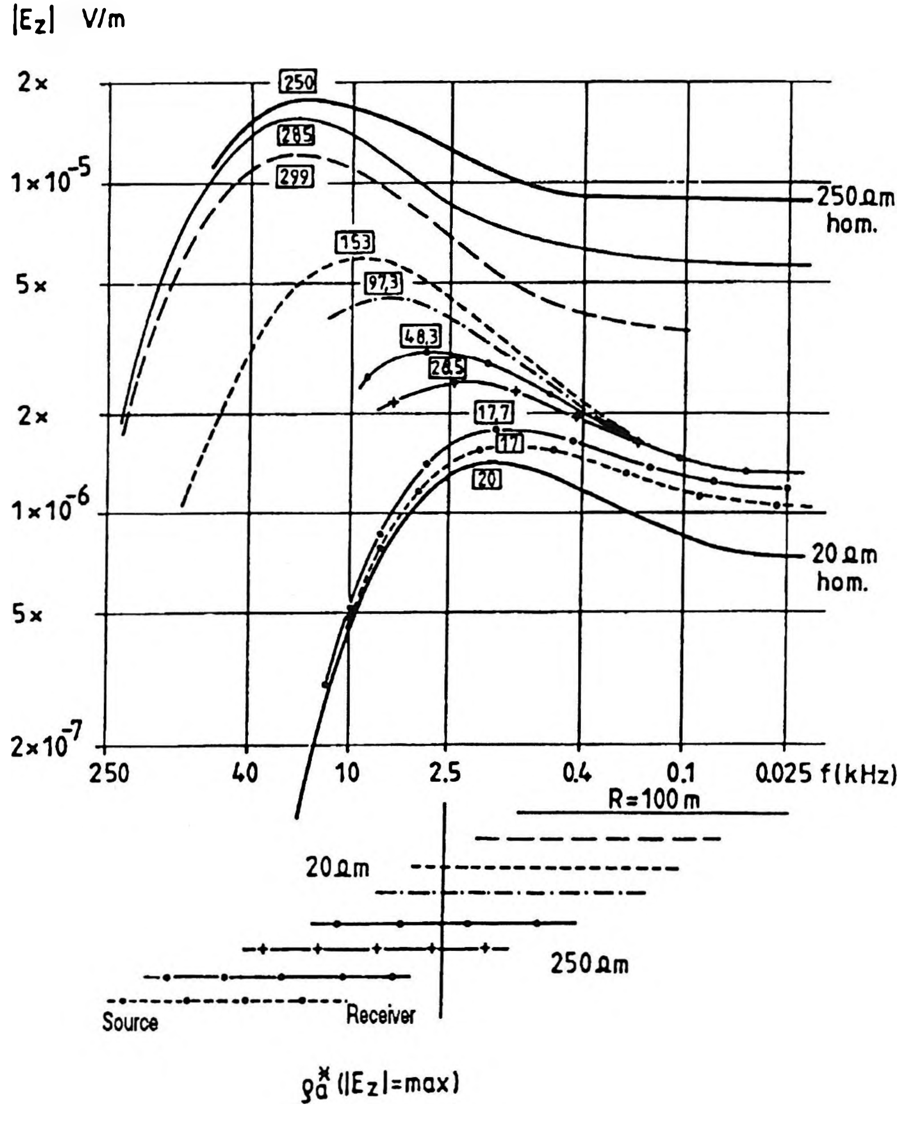

Fig. 1. Amplitude-frequency curves for vertical interface perpendicular to the axis connecting the vertical transmitter and receiver dipoles in an equatorial array, for different positions of the array

1. ábra. Az amplitúdó görbéi az ekvatoriális helyzetű vertikális adó- és vevő-dipólust összekötő tengelyre merőleges vertikális határfelület esetén különböző felállások melett

Рис. 1. Амплитудные кривые частотного зондирования при перемещении установки вертикальных экваториальных диполей вкрест простирания вертикального контакта двух сред

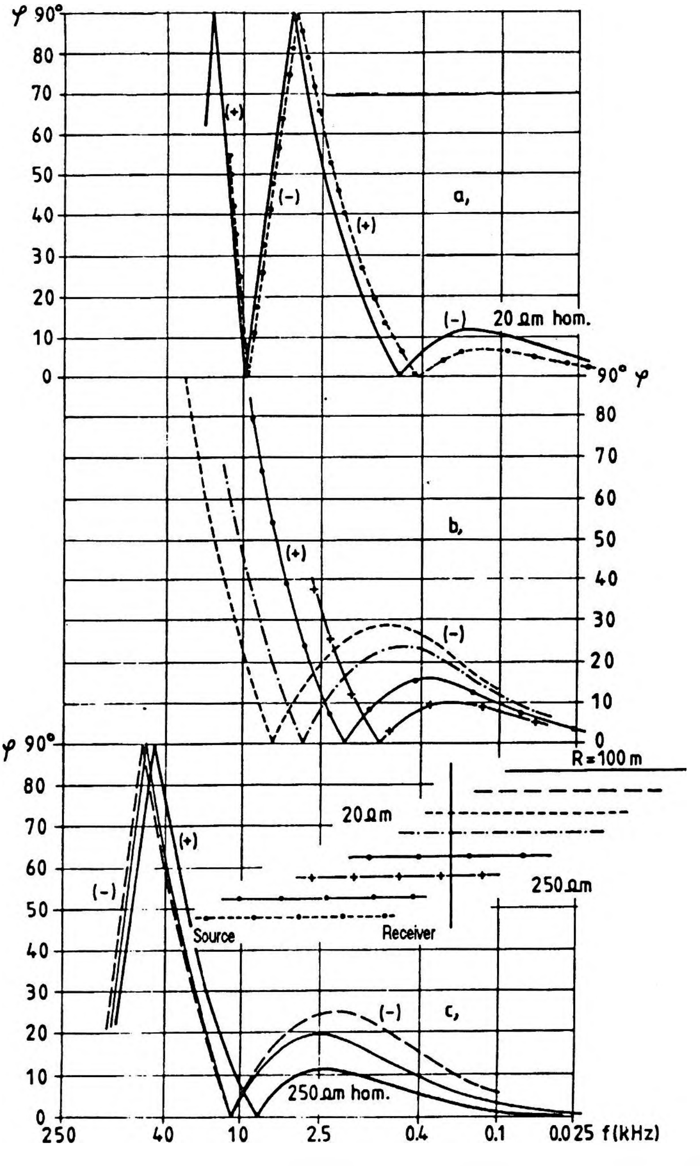

Fig. 2. Phase-frequency curves for vertical interface perpendicular to the axis connecting the transmitter and receiver dipoles in an equatorial array, for different positions of the array

2. ábra. A fázis frekvenciaszondázási görbéi az ekvatoriális helyzetű adó- és vevő-dipólust összekötő tengelyre merőleges vertikális határfelület esetén különböző felállások mellett

Рис. 2. Фазовые кривые частотного зондирования при перемещении установки вертикальных экваториальных диполей вкрест простирания вертикального контакта двух сред cies. The position of the interface between the transmitter and receiver influences this effective resistivity. The shorter that part of separation *R* which lies in the lower resistivity halfspace is, the higher the amplitude and the frequency where the maximum can be found will be.

Consequently, frequency sounding curves reflect the position of the dividing, vertical interface between the transmitter and receiver in every case.

The trend of ρ_a^* apparent resistivity values belonging to the maxima — framed numbers in Figure 1 — shows that when the larger part of separation *R* gets into the halfspace of higher resistivity, sensitivity to the position of vertical interface increases.

The phase curves in Fig. 2 are arranged in three groups according to their position related to the interface; the array lies completely within one of the halfspaces or it intersects the vertical interface. At curves of arrays lying in one or the other halfspace, the curves for the homogeneous space having the resistivity of the corresponding halfspace can also be seen for comparison. In the figure the sign of the phase is indicated at each curve section. In a homogeneous space, in the innermost, low frequency current field the value of the phase minimum — negative phase angles — is independent of resistivity. On the other hand, when the resistivity of the homogeneous space is higher the minimum develops at higher frequencies. With an array further from the interface a curve obviously corresponding to the homogeneous space is obtained. Approaching the vertical interface both value and position of the minimum change; their trend can be seen in the figure. For the same shift changes in phase angle are larger when the array is in the higher resistivity part.

When the vertical interface lies between the transmitter and receiver, the transmitter is in the 20 Ωm halfspace and it gradually moves towards the interface starting from 75 m to 12.5 m the position of the minimum shifts more and more towards higher frequencies as a result of increasing effective resistivity; the amplitude of the minimum also increases. With increasing frequency the potential dipole gets into the second current system of positive phase angles. When the transmitter and receiver are in the same halfspace the phase curves hardly separate in the second current system at different positions of the array. On the other hand, when the interface lies between the transmitter and receiver, the position of characteristic parts and branches of the phase curves along the phase axis is very sensitive to the position of the interface.

In the other case, the vertical interface is parallel to the axis connecting the vertical transmitter and receiver dipoles; the separation between this axis and the interface varies (x=10, 20, 30 and 50 m). Both the transmitter and receiver dipoles are in the halfspace of 250 Ωm. The amplitude curves in *Fig. 3* show that the lateral inhomogeneity causes a deviation from the curve of the homogeneous 250 Ωm space when the frequency decreases; it results in a lower field strength. The closer the interface is to the array the higher the frequency where the deviation begins. Moving from the maximum towards the quasi-stationary section the decrease in amplitude is stronger than for the curve of the 250 Ωm space. The maximum becomes wider with decreasing x.

With increasing frequency, on the other hand, that part of the space which is close to the axis of the array has more and more effect on the field strength. This can primarily be seen from the frequency dependence of resistivity $\rho_a^*(f)$, which was calculated on the basis of phase angle. Its behaviour for the two cases studied up to now is shown in *Fig.4*. For the interface perpendicular to the axis of the array — part b — that part of the transmitter-receiver separation can be seen at the individual curves in parenthesis that falls into the halfspace of resistivity indicated. When the array is in only one of the halfspaces the resistivity of this halfspace and the separation x between the interface and the closest electrodes are indicated. For a vertical interface parallel to the transmitter-receiver axis — part a — the parameter of the curves is the separation x between the interface and the parallel array in the 250 Ωm medium.

When the array is in only one of the halfspaces — parallel array and some perpendicular arrays — the high frequency asymptote is the resistivity of the host medium. At lower frequencies the effect of the other halfspace prevails more and more. At intermediate frequencies, however, 'overshoots' also appear.

3. Effect of vertical infinite sheet

An interesting case in practice is when the transmitter and receiver are situated in the same rock and information on the homogeneity or inhomo-

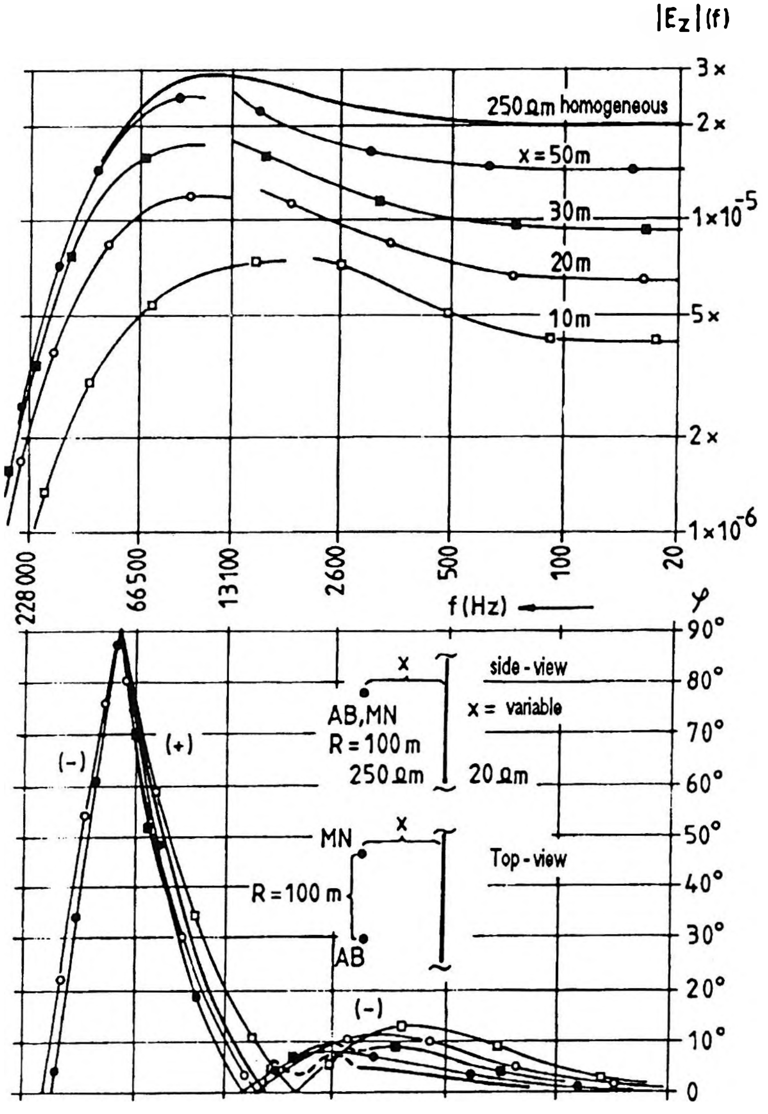

Fig. 3. Amplitude-frequency and phase-frequency curves for interface parallel to the axis connecting the vertical transmitter and receiver dipoles in an equatorial array, for different positions of the array

3. ábra. Az amplitúdó és fázis frekvenciaszondázási görbéi az ekvatoriális helyzetű vertikális adó- és vevő-dipólust összekötő tengellyel párhuzamos határfelület esetén különböző felállások mellett

Рис. 3. Амплитудные и фазовые кривые частотного зондирования при перемещении установки вертикальных экваториальных диполей по простиранию вертикального контакта двух сред

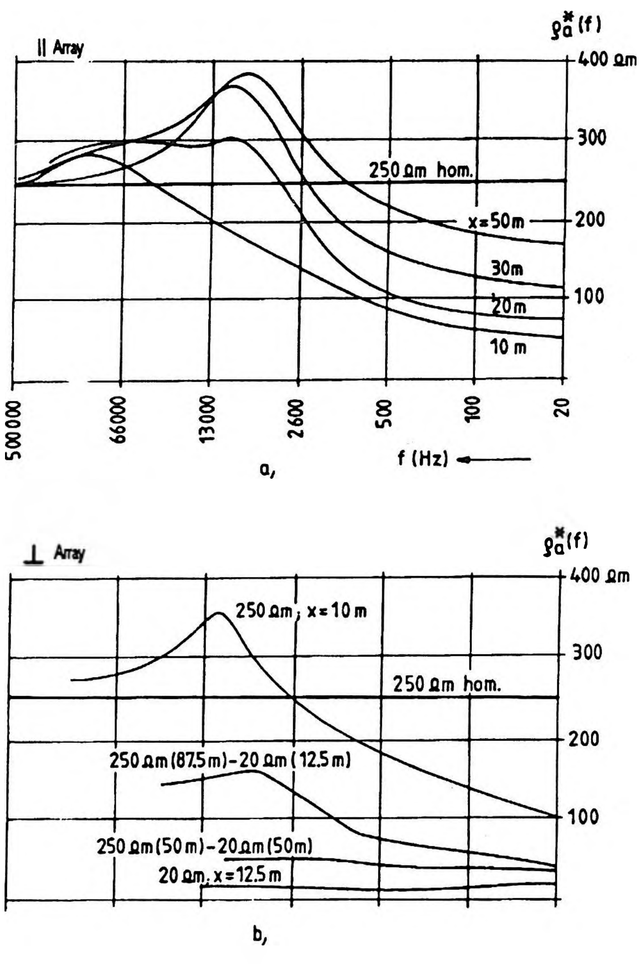

Fig. 4. Curves of apparent resistivity ρ_a^* (f) for an array parallel and perpendicular to the vertical interface (model of Figs. 1. and 3)

4. ábra. A ρ_a^* (f) látszólagos fajlagos ellenállás görbéi a vertikális határfelülettel párhuzamos és rá merőleges felállásnál (Az 1. és 3. ábra modellje)

Рис. 4. Кривые кажущихся сопротивлений ρ_a^* (f) для установок, параллельных и перпендикулярных вертикальному контакту двух сред (Модели рис 1. и 3.)

geneity of the space between them needs to be obtained by means of frequency sounding.

To study this potential application a vertically infinite, 20 m wide sheet of 20 Ωm embedded in a homogeneous space of 50 Ωm was considered.

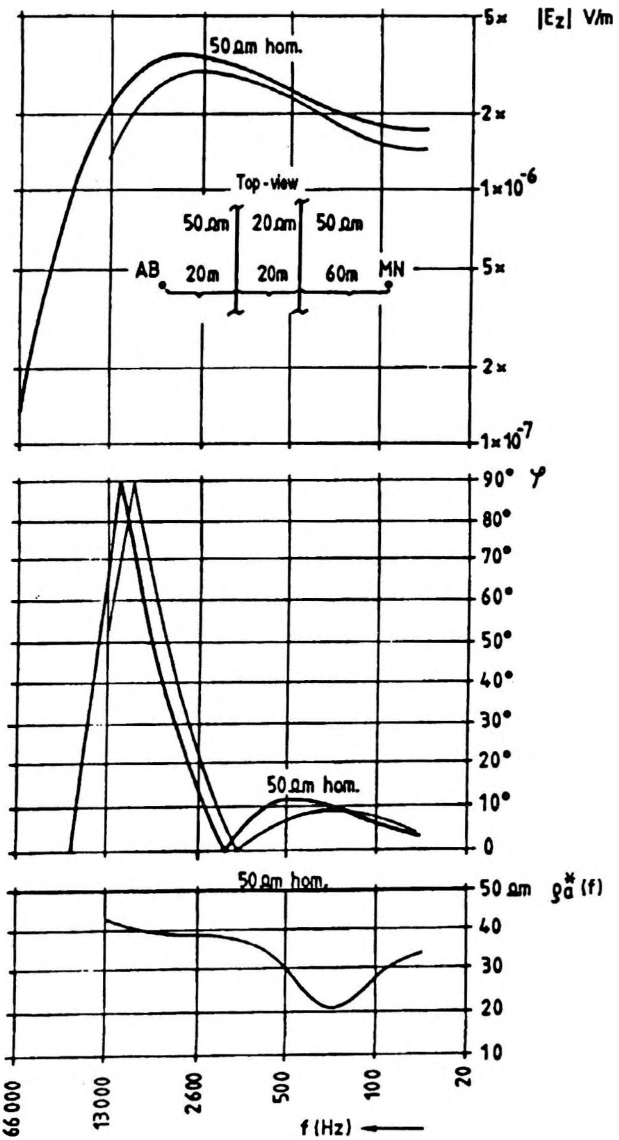

Fig. 5. Amplitude-frequency, phase-frequency and apparent resistivity ($\rho_a^*(f)$)- frequency curves for array passing through the vertical sheet

5. ábra. Az amplitúdó, a fázis és a $\rho_a^*(f)$ látszólagos fajlagos ellenállás frekvenciaszondázási görbéi a vertikális lemezt közrefogó felállásnál

Рис. 5. Кривые кажущихся сопротивлений ($\rho_a^*(f)$), а также амплитудные и фазовые при частотном зондировании для установки, внутри которой находится вертикальная пластина

The transmitter and receiver dipoles are vertical, their separation is 100 m, the array axis is perpendicular to the sheet and its position is asymmetrical to the sheet. The top-view of the geometric arrangement, together with the amplitude and phase curves for the homogeneous and inhomogeneous cases, respectively, can be seen in *Fig. 5*.

It is obvious that because of the lower effective resistivity in the inhomogeneous case the maximum of the corresponding curve is shifted towards lower frequencies. Details, however, should appear in the shape of the curves. To enhance them, from the phases apparent resistivities $\rho_a^*(f)$ were calculated which are shown in the lower part of the figure. For the homogeneous 50 Ωm space $\rho_a^*(f)$ = 50 Ωm = const. On the other hand, the effect of the embedded 20 Ωm sheed, can clearly be seen on the apparent resistivity curve at frequencies between 100 and 500 Hz. This example is remarkable from the aspect of investigation of inhomogeneities located between the transmitter and receiver. Of course, other models that more closely approximate reality should also be studied.

The lateral zone, which has an effect on the underground measurements can be investigated when a 60 m wide, 250 Ωm vertical slab is embedded into a medium of 20 Ωm; and the array of 100 m transmitter-receiver separation is in a horizontal plane, in the middle of the slab. The amplitude curves for the 250 Ωm homogeneous medium, and for the inhomogeneous model are shown in *Fig. 6*. At the highest frequencies the curves for homogeneous and inhomogeneous cases coincide or lie close to each other because, as a result of the lateral contraction of the current system, the low resistivity part of the space has no effect on the field strength. In practice, at frequencies higher than about 200 kHz the electromagnetic field concentrates in the higher resistivity slab. At a given frequency the width of the lateral zone having an effect on the measurement becomes wider with increasing transmitter-receiver separation and slab resistivity.

In the model of *Fig. 7* the 10 m wide vertical sheet of 5 Ωm is parallel to the axis of the dipole equatorial array located in the 50 Ωm homogeneous space.

The distance from the sheet and the transmitter-receiver separation are also taken as variables. The lower resistivity sheet causes a distortion in the amplitude curves at the maximum and at the beginning of the descending branch of the curves — which may not occur in horizontally

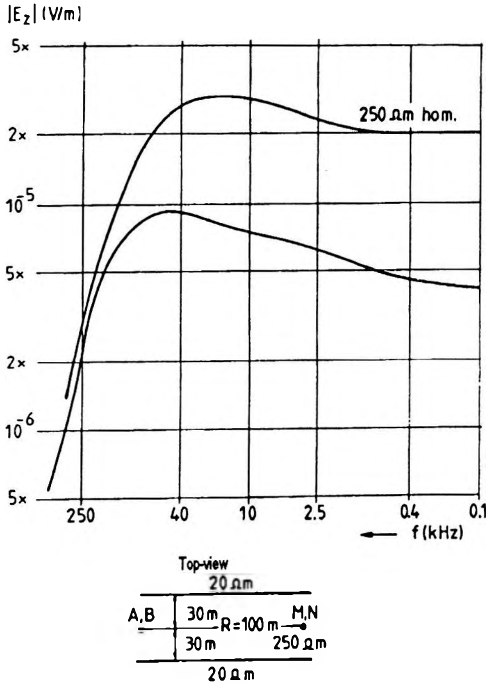

Fig. 6. Amplitude-frequency curves for vertical transmitter and receiver dipoles in an equatorial array within the vertical slab

6. ábra. Az amplitúdó frekvencia-szondázási görbéi a vertikális lemezen belüli ekvatoriális helyzetű vertikális adó- és vevő-dipólus esetében

Рис. 6. Амплитудные кривые частотного зондирования при положении установки вертикальных экваториальных диполей внутри вертикальной пластины

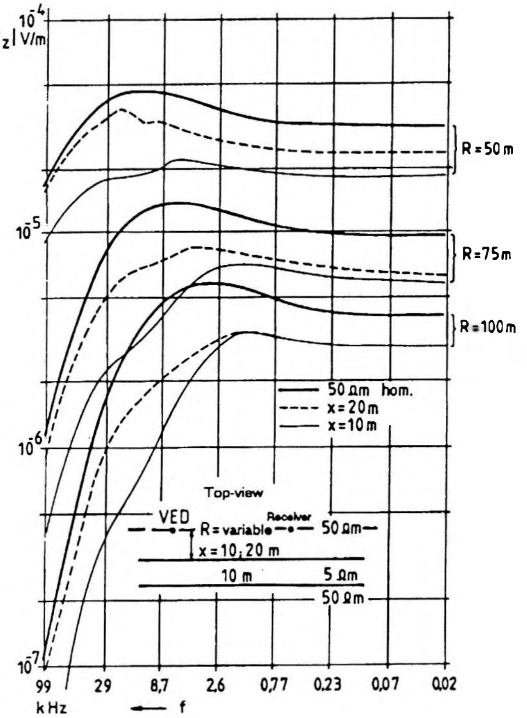

Fig. 7. Amplitude-frequency curves for a lower resistivity vertical sheet parallel to the axis connecting the vertical transmitter and receiver dipoles in an equatorial array

7. ábra. Az amplitúdó frekvenciaszondázási görbéi az ekvatoriális helyzetű vertikális adó- és vevődipólust összekötő tengellyel párhuzamos kisebb fajlagos ellenállású vertikális lemez esetén

Рис. 7. Амплитудные кривые частотного зондирования при наличии вертикальной пластины пониженного сопротивления параллельно установки вертикальных экваториальных диполей layered models. The presence of a relative minimum between the frequencies 2.6 and 29 kHz is connected with the phenomenon that the current system contracting towards the transmitter and receiver gradually leaves the 50 Ωm medium on the other side of the sheet; and the effect of the sheet gradually ceases to exist above 29 kHz.

In *Fig. 8* frequency dependence of apparent resistivity ρ_a^* (*f*) calculated from the curves of amplitude, phase, in-phase and out-of-phase components is plotted together with the curve of geometric sounding. ρ_a^* (*f*) has a value

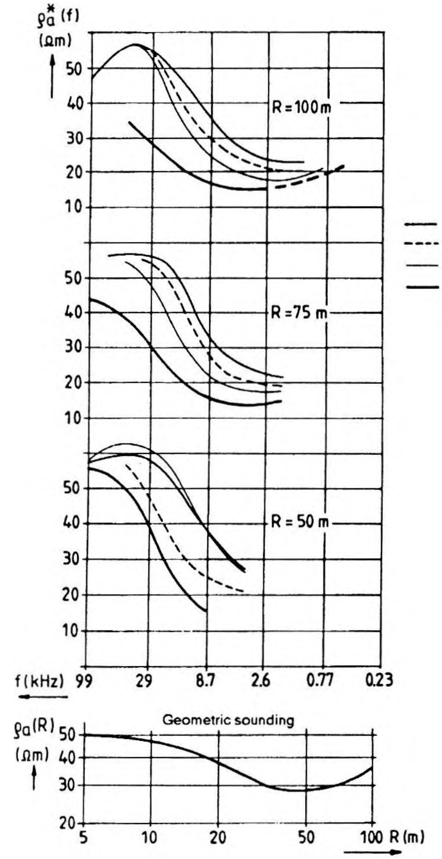

Fig. 8. Frequency dependence of apparent resistivity ρ_a^* (*f*) calculated from in-phase, out-of-phase components, phase and amplitude for a vertical sheet parallel to the array

8. ábra. A valós és képzetes összetevőből, a fázisból és amplitúdóból számított ρ_a^* (*f*) látszólagos fajlagos ellenállás frekvenciaszondázási görbéi a terítéssel párhuzamos vertikális lemez esetében

Рис. 8. Кривые кажущихся сопротивлений ρ_a^* (*f*) частотного зондирования, рассчитанные по реальной и мнимой компонентам, а также по фазе и амплитудам для установки, параллельной вертикальной пластине

close to 50 Ωm at the highest frequency for each *R*, and it decreases towards lower frequencies. The effect of the 50 Ωm part of the space on the other side of the sheet begins to appear only at *R*=75 and 100 m, and rather in the out-of-phase component. This figure demonstrates the fact — that can be observed in other cases too — that in-phase and out-of-phase components of the field strength reflect geologic conditions of different surroundings of the transmitter dipole. Both of them are transferred into the summarized geologic information of amplitude and phase.

4. Effect of a break in the high resistivity horizontal layer

At our request the effect of a break in the high resistivity plate was studied by physical modelling in the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences. The structure of the model, its data and the frequency sounding curves can be seen in *Fig. 9.* Moving

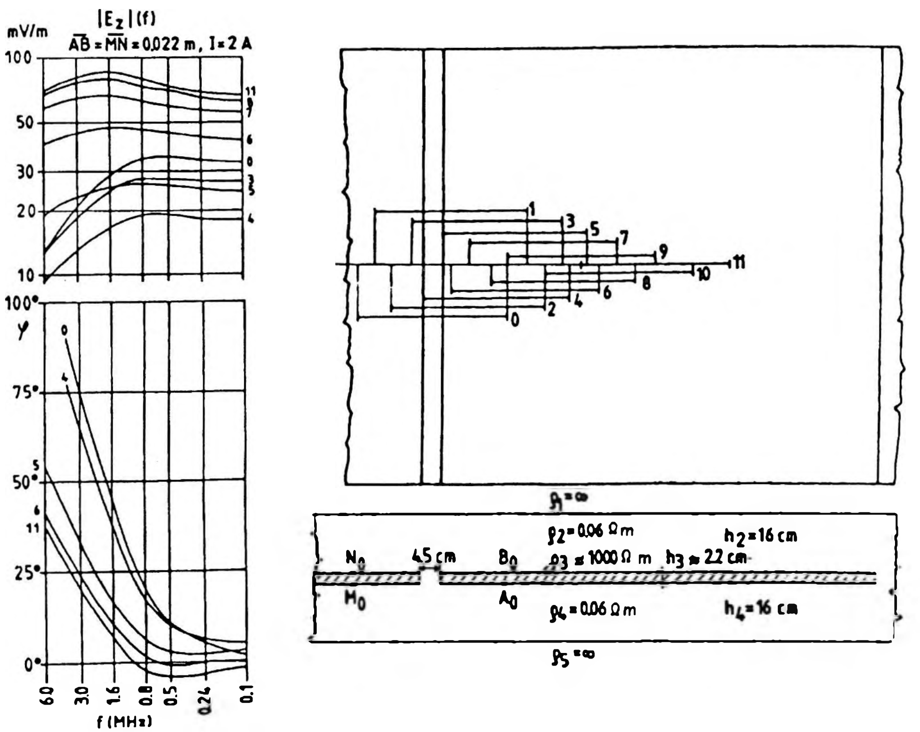

Fig. 9. Amplitude and phase curves obtained by physical modelling using constant vertical transmitter-receiver dipole separation for a break in the high resistivity plate

9. ábra. Konstans távolságú vertikális adó- és vevő-dipólussal végzett fizikai modellezéssel kapott amplitúdó- és fázisgörbék a nagy fajlagos ellnállású lemez megszakadása esetén from the middle of the plate — station 11— towards the break a strong decrease in the field strength can be observed starting from station 8. A definite change in the position of maximum along the frequency axis takes place only if one of the electrode pairs — either transmitter or receiver dipole — gets into contact with the break.

For arrays passing through the break — stations 4 to 0 — the maximum gets to lower frequencies because of the reduced effective resistivity. The field strength is lowest at station 4 when one of the electrode pairs falls into the break. On crossing the break the field strength increases.

A break in the high resistivity plate has a drastic effect on the phase as well, particularly at high frequencies. Phase curves reflect location better than amplitude curves. Their shape and position depend less on the place of break in the case of an array passing through the break.

Profile curves belonging to a constant frequency are informative too. Profiles for the lowest and highest frequencies are shown in *Fig. 10.* In the

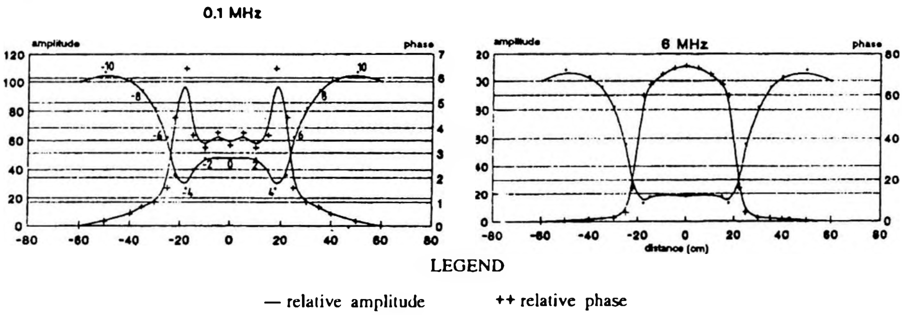

Fig.10. Amplitude and phase profiles for highest and lowest frequencies used in physical modelling

10.ábra. Az amplitúdó és fázis szelvény menti alakulása a fizikai modellezésnél használt legkisebb és legnagyobb frekvencián

Рис. 10. Амплитудные и фазовые кривые при наименьших и наибольших частотах, использовавшихся при физическом моделировании

Рис. 9. Амплитудные и фазовые кривые, полученные при физическом моделировании с постоянным расстоянием между вертикальными передающим и приемным диполями при разрыве в пластине высокого сопротивления curve for 0.1 MHz reference points of the plotted values are indicated as well. It can be seen that changes caused by the break are larger both in amplitude and phase at high frequency. At the same time the lateral effect is smaller than at lower frequency. For arrays passing through the break, the shape of the curves is different too.

REFERENCES

TAKÁCS E., NAGY J., MÁDAI F. 1986 : Field of vertical alternating current, electric elementary dipole in a layered medium. Geophysical Transactions **32,** 1, pp. 43-56

TAKÁCS E. 1988: In-mine sounding with a buried grounded dipole source. Geophysical Transactions **34**, 4, pp. 343-359

LATERÁLIS INHOMOGENITÁSOK HATÁSA A FELSZÍN ALATTI VERTIKÁLIS ÁRAMDIPÓLUS VERTIKÁLIS ELEKTROMOS ÖSSZETEVŐJÉNEK FREKVENCIASZONDÁZÁSI GÖRBÉIRE

TAKÁCS Ernő

A tanulmány azt mutatja be, hogy az ekvatoriális elrendezésű vertikális elektromos adó- és vevő-dipólussal végzett földalatti frekvenciaszondázásnál hogyan jelentkezik a laterális inhomogenitások hatása.

Az egyszerűsített modellek az alábbiak:

— az adó- és vevő-dipólust összekötő tengelyre merőleges és vele párhuzamos vertikálisan végtelen kiterjedésű réteghatár és lemez,

— a nagy fajlagos ellenállású vízszintes réteg megszakadása az adó- és vevő-dipólust összekötő tengelyre merőlegesen.

Az előbbi esetet numerikus, az utóbbit fizikai modellezéssel vizsgáljuk.

ВЛИЯНИЕ ЛАТЕРАЛЬНЫХ НЕОДНОРОДНОСТЕЙ НА КРИВЫЕ ЧАСТОТНОГО ЗОНДИРОВАНИЯ, ПОЛУЧЕННЫХ ПО ВЕРТИКАЛЬНОЙ ЭЛЕКТРИЧЕСКОЙ КОМПОНЕНТЕ ПОДЗЕМНОГО ВЕРТИКАЛЬНОГО ТОКОВОГО ДИПОЛЯ

Эрнё ТАКАЧ

В работе рассматривается эффект от латеральных неоднородностей в подземном частотном зондировании, выполненном вертикальными экваториальными диполями.

Упрощенными моделями являлись следующие:

— установка направлена вкрест простирания и по простиранию бесконечного вертикального контакта двух сред и такой же пластины,

— разрыв в горизонтальной пластине высокого сопротивления перпендикулярно оси установки.

Первый случай исследуется путем численного, а второй — физического моделирования.