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INTERPRETATION PROBLEMS OF ELECTRIC SOUNDING AND PROFILING IN REGIONS OF COMPLICATED GEOLOGY AND RUGGED TERRAIN

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Electric soundings in zones of complicated geology and rugged terrain (e.g. in the folded mountainous belt of the Albanids), have shown the existence of electric field scattering. The lateral changes of resistivity, the limited extension of geologic structures, the existence of several structures close to each other, and rugged terrain are characteristic features of this complicated geoelectrical medium.

Electric field scattering distorts the apparent resistivity values; if the apparent resistivity curves were interpreted without regard to the above phenomena and without performing correction for their effect, an unreliable view would be taken. Therefore the electric field scattering of the direct current was studied in a heterogeneous medium with curved boundaries and in rugged terrain. Potential response was computed with the aid of the quasi-harmonic equation (two- and three-dimensional) for boundary conditions of Neumann type. To solve the quasi-harmonic equation in a trapezoidal zone, in the lower half-space it was replaced by the corresponding variational problem, which can be solved by the finite-element method, giving an approximate representation of the electric field scattering. We have developed two computer programs in Fortran programming language for 2-D and 3-D modelling.

Results of some geoelectric models are given. In these models the electrical soundings are taken over the interface of different types of rocks and flexures, or above horsts and grabens. The programs are also used to correct different effects, including terrain effects.

Keywords: electric sounding, Albania, resistivity, finite-element analysis

1. Introduction

The widespread use of shallow electric soundings for engineering studies and in mineral prospecting and the use of deep electrical soundings in the search

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for oil and gas, have brought forth some problems related to the interpretation of the electric soundings in cases of complicated geology and rugged terrain in some regions of Albania. The experience gained and the theoretical analysis of the phenomena observed create possibilities for their solution and the overcoming of their influence.

Electric soundings are interpreted by comparing them with theoretical models of simplified geoelectrical sections (horizontal, sometimes inclined layers which are always flat and have infinite extent, without horizontal changes of the resistivity). In practice the use of electric sounding involves a number of aspects related to the surface geology and terrain:

— the relief is rugged in many areas;
— lateral (abrupt or gradual) changes of resistivity exist due to the presence of different types of rocks. The contact between them may be outcropped or may be covered by overburden;
— the geological structures have smaller extent than their depth, so the geoelectric boundaries are limited;
— various types of geological structures are often situated close to each other, at the same or different depths.

The above mentioned factors influence the scattering of the electric field and consequently the values of the apparent resistivity measured during the electric soundings.

2. Terrain effect in resistivity surveys

Rugged terrain causes deformations on the sounding and the resistivity profiles [DAHNOV 1953, KOEFOED 1979, FRASHËRI et al. 1984] due to the changes of the subsurface current distribution. For example when the current line configuration is perpendicular to the strike of a crest, the apparent resistivity at first begins to decrease, because of the decrease of the current density in the region where the potential electrodes are placed. The opposite is the case when the centre of the sounding is located over a valley. A more complicated influence appears on the resistivity curve when the centre of the sounding is located over the foot, or a crest, or over the side of a valley. If these deformations are not taken into consideration they may lead to a wrong interpretation. Evaluation of terrain effects can be made in two ways: firstly, taking into consideration not only the sounding to be interpreted but the neighbouring curves as well. At the same time information about the resistivity of the outcropped rocks in the sounding area must be provided. Secondly, correction of apparent resistivity with respect to the terrain effects is carried out.

For terrain correction we use the finite-element method to solve numerically the Laplace's equation in order to study the electric field behavior in a heterogeneous medium with curved boundaries of any configuration (*Fig. 1*). The finite-element modelling procedures are treated mathematically in several

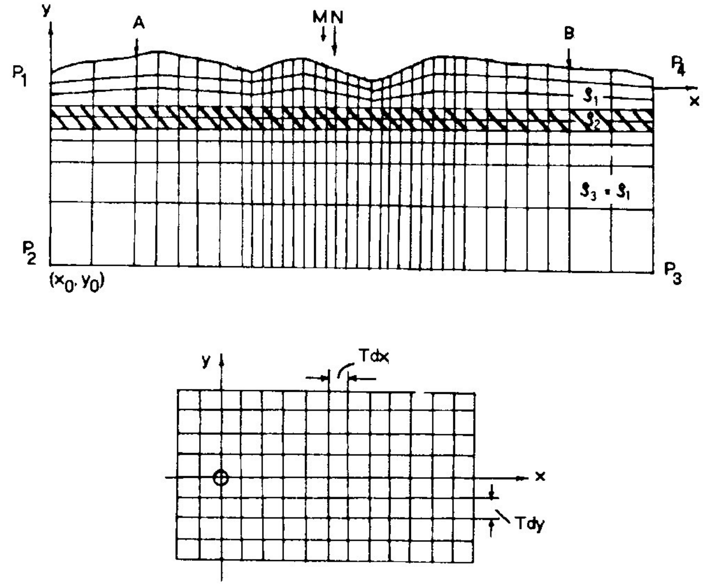

Fig. 1. Three-layer geoelectric model for finite-element method to compute two-dimensional terrain correction

1. ábra. Háromréteges geoelektromos modell kétdimenziós terrén korrekció számításához

Рис. 1. Двухмерная трехслойная геоэлектрическая модель для расчета поправки за влияние рельефа методом конечных элементов

publications [e.g. HOLCOMBE, JIRACEK 1984, FOX et al. 1980 or PRIDMORE et al. 1981]. For the calculation of terrain effect along two-dimensional structure a special algorithm was used, the mathematical elements of which are presented in earlier works of the author [FRASHËRI 1987, FRASHËRI et al. 1984].

In accordance with this algorithm a program, ELTRON-3, in Fortran-77 programming language was developed. This algorithm is different from those of many other authors [FOX et al. 1980, HOLCOMBE, JIRACEK 1984, MUNDRY 1984, SCRIBA 1981, PRIDMORE et al. 1981, GYIMESI, SIMON 1989]. We use the ordinary variational problem for elliptic differential equations as described by AMES [1977] and ZIENKIEWICZ [1977]. During the tests carried out on a BULL DPS7 computer with models consisting of a thousand nodes, the computer time ranged from 5 minutes (for profiling) to 30 minutes (for soundings). Correction of the terrain effects [FRASHËRI et al. 1984] and construction of synthetic curves of the apparent resistivity with arbitrarily curved layer boundaries for both sounding and profiling [FRASHËRI 1987] were performed by this program.

In *Fig.* 2 the correction of the terrain effects is presented when the relief is broken by a crest and a valley; the geological section has two half-layers divided by a vertical plane. Apparent resistivities, measured with fixed-source gradient and Schlumberger arrays, present minima over the crest and maxima in the valley, accompanied by smaller anomalies on both sides. After terrain correction, the profiles of the apparent resistivity assume their normal view.

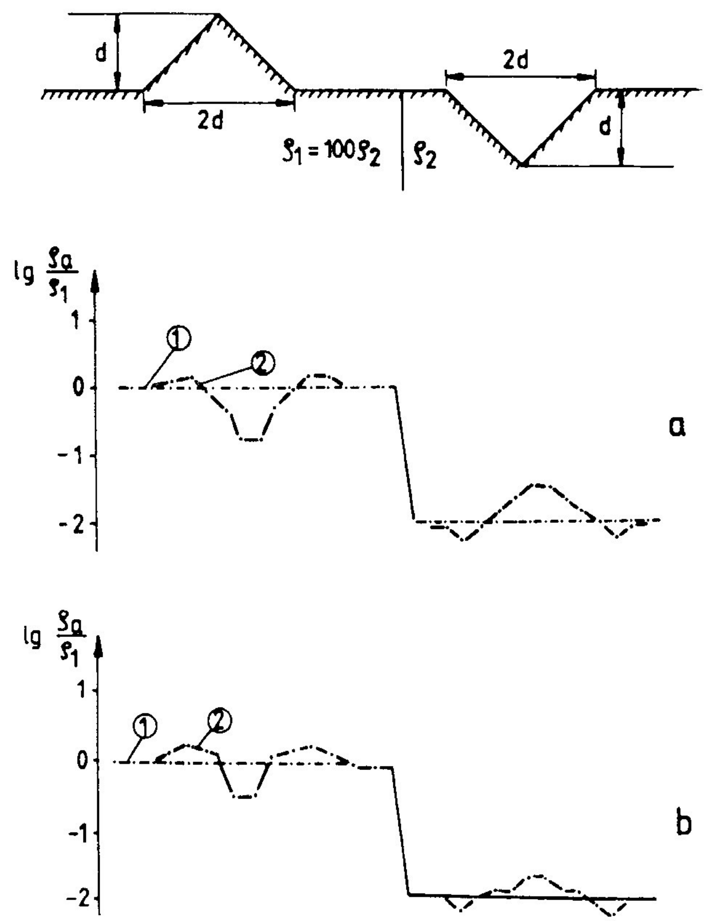

Fig. 2. Terrain corrections of resistivity profiling over a vertical contact, computed with ELTRON-3 program. a—fixed-source gradient array (MN=Δx=1/50 AB); b—on-line Schlumberger array (AB=6Δx=6 MN) 1—corrected curve; 2 —curve with terrain effects

2. ábra. Az ELTRON-3 programmal számított terrén korrekció értékek függőleges határfelület feletti ellenállás szelvényezéshez. a—gradiens elrendezés (MN=Δx=1/50 AB); b—Schlumberger elrendezés (AB=6Δx=6 MN) 1—korrigált görbe; 2— terrén hatást tartalmazó görbe

Рис. 2. Поправка данных электрического профилирования над вертикальным контактом, расчитанная программой ELTRON-3. а– по установке срединных градиентов при MN=Δx=1/50 AB; b–для симметричной установки AB=6Δx=6 MN 1–поправленный график; 2–исходный график с влиянием рельефа

In *Fig. 3* synthetic AMNB soundings carried out on a mountain crest and over a valley formed in homogeneous half-space are presented. For the soundings carried out over the valley or on the top of the crest, curves with similar appearance to the two-layer curves are obtained, the right flanks ascending and descending respectively. The interpretation of these curves may lead to a fictious two-layer section. When the soundings are carried out at the border of the crest or the valley, the curves have other three-layer configurations of the types K and H, respectively.

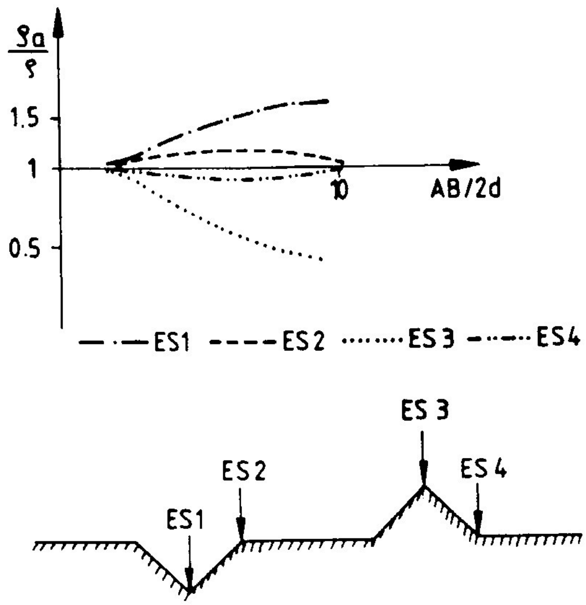

Fig. 3. Synthetic AMNB sounding curves over an isotropic homogeneous medium. Array parallel to the profile. ES1—in a valley; ES2—on the margin of a valley; ES3—at the top of a crest; ES4—on the margin of a crest

3. ábra. Szintetikus AMNB szondázási görbe izotróp homogén közeg felett. A terítés párhuzamos a szelvénnyel. ES1—egy völgyben; ES2—egy völgy szegélyén; ES3—egy hegygerinc tetején; ES4—egy gerinc szegélyén

Рис. 3. Теоретические кривые ВЭЗ над однородной изотропной средой. Точка ES1–размещена в долине; ES2–на крае долины; ES3–на хребте; ES4–на крае хребта

In *Fig. 4* apparent resistivity profiles of the fixed-source gradient array are presented over a section with 80 m level difference. Profile '1' is calculated in an analytical way with the above mentioned algorithm; profile '2' gained through physical modelling with electrical conductive paper is given for comparison. The shapes of these profiles are similar, although the absolute values of the apparent resistivity are different because the physical modelling does not possess the same conductivity as the mathematical model. The profiles reveal that the hills and the valleys cause anomalies of the apparent resistivity which amounts to some thousand ohmm above a medium of 1000 Ωm resistivity.

In all cases shown above, in the 2-D geoelectrical models the current sources A and B are point sources. All the soundings and the profilings are carried out parallel with the profile drawn in the figures.

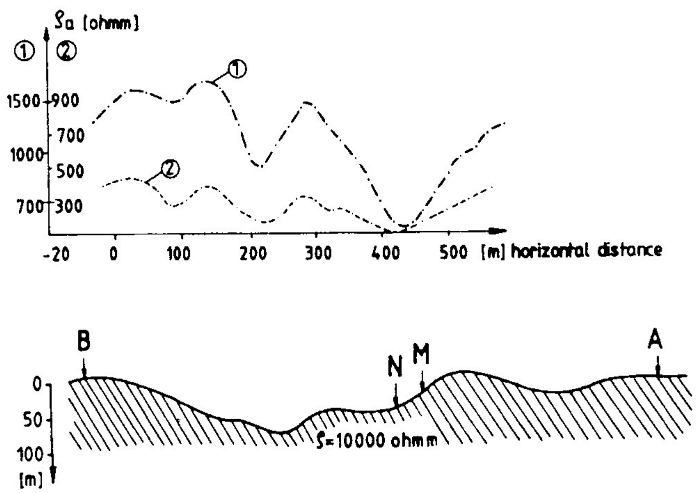

Fig. 4. Comparison of apparent resistivity profiles based on mathematical and physical modelling. Fixed source gradient array. 1—mathematical modelling; 2—physical modelling

4. ábra. Matematikai és fizikai modellezésen alapuló látszólagos ellenállás szelvényezés összehasonlítása. 1—matematikai modellezés; 2—fizikai modellezés

Рис. 4. Сопоставление графиков, полученных по данным математического и физического моделирования, для схемы срединных градиентов. 1—по данным математического моделирования; 2—по данным физического моделирования

3. Influence of buried and outcropped boundaries

Interfaces between rocks with different resistivity (for example limestones, flysch or halitic deposits in Albania) influence the scattering of the electric field; as a consequence the measured resistivity curve is deformed. The effect of outcropped, vertical contact was analysed by well-known authors [e.g. DAHNOV 1953]. Nomograms were constructed to correct the contact effect, when the position and the reflection coefficient of the contact are known. Evaluation of this influence is especially indispensable in the neighbourhood of resistive salt diapirs in Albania.

In *Fig. 5* a sounding observed near a salt diapir (1) is presented together with the corrected curve (2) for the influence of the vertical contact of the salts. The sounding is situated over flysch deposits with a resistivity of about 20 Ωm, covered by alluviums. The contact caused an increase in the resistivity of the second electric layer (flysch) to 50 Ωm and at the same time there are signs of a nonexistant third layer of high resistivity. After correction, these false phenomena could be avoided.

The study of the influence of more complicated boundary was possible by the ELTRON-3 program for 2-D models and ELTRONHA for 3-D models [FRASHËRI 1987]. In F*ig. 6* electric soundings are presented over two-layer models with a buried vertical contact. Interpreting the curves deformed by the

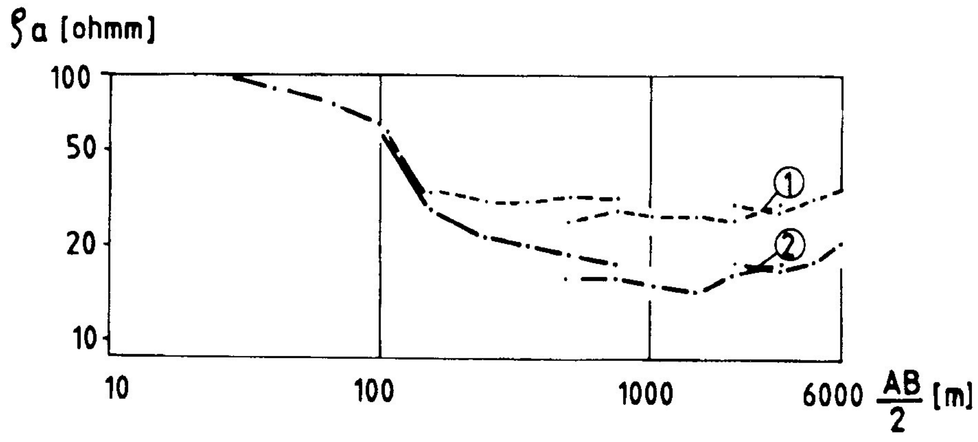

Fig. 5. Deformation of the apparent resistivity curve from the vertical contact and correction
1—uncorrected; 2—corrected

5. ábra. Látszólagos ellenállás görbe függőleges határfelület által okozott torzulása, és korrekció
1—nem korrigált görbe; 2—korrigált görbe

Рис. 5. Наблюденные искаженные и поправленные кривые при наличии вертикального контакта 1—наблюденная кривая; 2—поправленная кривая

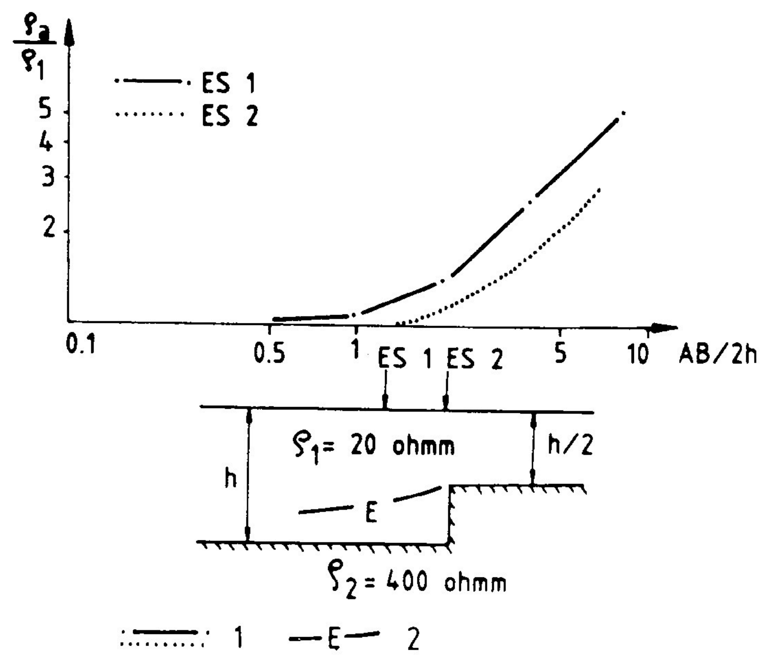

Fig. 6. Effect of a buried vertical contact. 1—sounding curves modelled with ELTRONHA program; 2—interpreted (false) boundary without the influence of vertical contact

6. ábra. Eltemetett függőleges határfelület hatása. 1—az ELTRONHA programmal modellezett szondázási görbe; 2—értelmezett (hamis) határfelület a függőleges érintkezés hatása nélkül

Рис. 6. Влияние флексуры. 1–кривая ВЭЗ, расчитанная по программе ELTRONHA; 2– ложный геоэлектрический горизонт, полученный при интерпретации непоправленной кривой influence of the contact, the top of the basement is defined as being at a shallower depth than it really is. The impression of the existence of a right-hand structural flank is also created.

From the results of this modelling it can be concluded that precise determination of the thickness of the first layer can be carried out only when this thickness (i.e. the basement depth) is at least ten times smaller than the sounding distance from the vertical contact. For smaller distances the effect is not negligible and the curves need to be corrected. In order to do this, we should previously know the position of the near-vertical contact. The presence of the vertical (even buried) contact of high resistivity causes a more distinct increase of the apparent resistivity in the right flank of the curve than in the case of horizontal layers. This peculiarity creates the possibility of detecting (in some cases) the vertical contact of high resistivity.

4. Influence of lateral resistivity changes in the geoelectrical horizons

Geophysical prospecting has revealed that there are facial changes, which in some regions of Albania are accompanied by great lateral resistivity changes. For example, the calcareous core of an anticline with limited (as small as 1-2 km) dimensions and the terrigenous deposits around it represents an extraordinarily great lateral change in the layer resistivity.

In order to study the influence of the lateral change of the layer resistivity for this type of anticline, we modelled — exploiting the ELTRON-3 program — the case when the structure is slightly wider than its depth (see *Fig. 7*). Analysing the calculated curves, it is obvious that the side effects of the resistive basement is felt even at long distances from the edge of the horst, and it is expressed by an increase in the apparent resistivity.

Two-layer curves of the apparent resistivity do not have regular configuration, they are much more similiar to the curves of inclined layers with considerable dip angle to the side vertical contact. If the electric soundings are carried out with a shorter array than is needed for the whole curve, only the beginning of the upward left flank will be obtained. Observing these short curves it can be supposed that the top of the limestone becomes deeper the further it is from the horst centre, belonging to a wide anticlinal structure. Over structures that have comparable dimensions and layering depth, the apparent resistivity is reduced as a consequence of current deviation because the electric current flows alongside the structure. This causes the top of the structure to appear as if it is at a greater depth than it really is.

Sounding carried out in grabens filled with conductive overburden and bordered by rocks of high resistivity (e.g. limestone), displays a deformed curve as well, when the width of the graben is smaller then the length of the electrical sounding array. To avoid the influence of the above analysed phenomenon and the misleading interpretation the following measures should be taken:

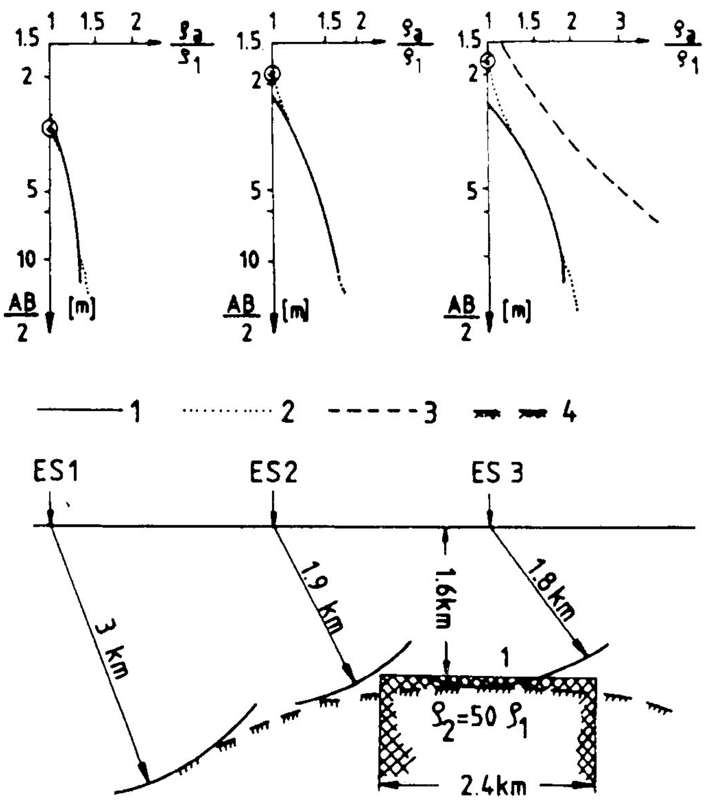

Fig. 7. Apparent resistivity curves placed across a horst. 1—synthetic curves computed with ELTRON-3 program; 2—analytical curves that fit to the synthetic curves; 3—analytical curve assuming the horst to be horizontally infinite; 4—geoelectric horizon after interpretation which does not consider the horst limited in the horizontal direction

7. ábra. Látszólagos ellenállás görbék egy sasbércen keresztül. 1—az ELTRON-3 programmal számított szintetikus görbék; 2—a szintetikus görbére illesztendő analitikus görbék; 3—analitikus görbék a sasbérc oldalirányú végtelen kiterjedését feltételezve; 4— geoelektromos szint értelmezés után, nem véve figyelembe a sasbérc korlátozott oldalirányú kiterjedését

Рис. 7. Кривые ВЭЗ по профилю, расположенному вкрест горста.1—Синтетические кривые, расчитанные по программе ELTRON-3; 2—Теоретические кривые, совпадающие с синтетическими; 3—теоретические кривые при горизонтальном положении кровли бесконечного горста; 4—Ложный геоэлектрический горизонт, полученный при интерпретации без учета влияния ограниченности горста в боковом направлении

— field and regular surveys should be carried out, to detect as clearly and surely as possible the structures. When interpreting the soundings, structures may turn out to be different in form and dimensions from the surrounding structures and may not correspond to the recognized tectonics of the region. In such cases the side effects of the soundings should be thoroughly studied;

— study of the structural form should be carried out together with a study of the lateral resistivity changes in the layers constituting the section over the geoelectric horizon as well as the horizon itself;
— sounding should be carried out with long array, so that the sounding curve to be as complete as possible; this allows us to carry out some sort of classification of the distortion effects;
— interpretation of the curves carried out in the regions of complicated geology should not be carried out solely by comparing the theoretical models for horizontal layers. Interpretation should begin with a comparison of the curve of the parametric soundings on boreholes with the synthetic curves calculated from the data of electrical well logging. These synthetic curves should be computed for simple models with horizontal layers as well as for the supposed geoelectrical structures in the region applying the ELTRON-3 program.

5. Conclusions

The apparent resistivity values measured during electric soundings in geologically disturbed (tectonized, folded, mountainous) zones reveal the influence of lateral contacts, gradual lateral changes of resistivity, and of the rugged terrain. The influences can add up to 50% of the resistivity values. Hence the curves of the electrical sounding are deformed, thereby influencing the geoelectrical interpretation as well. To analyse the above mentioned effects it is necessary to implement a regular grid of soundings and it is advisable to keep the length of the arrays sufficiently long. Correction of the apparent resistivity values is needed. The finite-element method is suitable for computing the apparent resistivity of soundings or profilings in a heterogeneous environment. The programs ELTRON-3 for 2-D models and ELTRONHA for 3-D models can be utilized for this purpose. These models are of great value for qualitative interpretation.

To avoid the terrain effects, the effects of the buried vertical contact, and the lateral structures parallel to the array, it is essential to use 3-D finite-element modelling.

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ELEKTROMOS SZONDÁZÁS ÉS SZELVÉNYEZÉS ÉRTELMEZÉSI PROBLÉMÁI BONYOLULT FÖLDTANI SZERKEZTŰ ÉS EGYENETLEN FELSZÍNŰ TERÜLETEKEN

Alfred FRASHËRI

Komplikált geológiájú és egyenetlen felszínű területeken (pl. Albanidák gyűrt hegyláncai) végzett elektromos szondázások az elektromos tér szóródását mutatták. A bonyolult geoelektromos közeg jellemzői az ellenállás oldalirányú változásai, a geológiai szerkezetek véges kiterjedése, számos, egymáshoz közel fekvő szerkezet és az egyenetlen felszín.

Mivel az elektromostér szóródása torzítja a látszólagos ellenállás értékeket, az ellenállás görbék kiértékelése e jelenség figyelembevétele és hatásainak korrigálása nélkül megbízhatatlan kép kialakulásához vezethet. Ezért egyenáram elektromos terének szóródását vizsgáltuk heterogén közegben, törött határfelületek és egyenetlen terepviszonyok mellett. A potenciál válaszokat kváziharmonikus potenciálegyenlet (két- és háromdimenziós) segítségével határoztuk meg, Neumann-féle határfeltételek figyelembevételével. A kváziharmonikus egyenlet trapezoid alakzatra való megoldásához az alsó féltérben a megfelelő variációs problémával helyettesítettük azt. Így a véges elemes módszerrel előállítható a megoldás, az elektromos tér szóródásának egy közelítő leírását biztosítva. Két számítógépes programot készítettünk Fortran nyelven, kétdimenziós és háromdimenziós modellezéshez.

Bemutatjuk néhány geoelektromos modell eredményét. A modellekben az elektromos szondázásokat különböző típusú kőzetek határfelületei, vagy sasbércek és árkok fölé helyeztük. A programok különböző hatások korrekcióinak végrehajtására is szolgálnak, beleértve a terén korrekciót is.