Geophysical methods in groundwater prospecting and environmental protection

Pál DRASKOVITS*, Balázs MAGYAR*, Miklós PATTANTYÚS-Á.*
* Eötvös Loránd Geophysical Institute of Hungary
1145 Budapest, Columbus str. 17-23, Hungary

RESUMEN

En principio, el abastecimiento de agua potable puede tener su origen en depósitos superficiales o subterráneos. Sin embargo, la cuantía de los primeros experimenta fuertes variaciones temporales y su calidad puede cambiar a menudo. Por ello únicamente los acuíferos subterráneos pueden ser considerados como recursos estables y duraderos para el próximo siglo.

En las depresiones rellenadas con sedimentos jóvenes (Cuaternarios) la principal tarea de la prospección acuífera es encontrar capas porosas portadoras de agua. Por ello, los métodos geoeléctricos juegan un papel decisivo en la solución de problemas de este tipo.

La prospección hidrológica y la protección ambiental son discutidas conjuntamente en este artículo porque, muchas veces, ambas tareas son muy similares desde el punto de vista geofísico; se trata de distinguir formaciones porosas e impermeables. Muchos contaminantes (pero no todos) se propagan principalmente por medio de las aguas subterráneas, disueltos o flotando sobre ellas. Así mismo, en este trabajo se mencionan otros problemas ambientales (por ejemplo la detección de oquedades) y se presentan distintas tareas:

– problemas sencillos que pueden ser resueltos con métodos convencionales;
– casos en los que es necesaria la aplicación integrada de diferentes métodos geofísicos (principalmente geoeléctricos);
– situaciones variadas en las que, junto con otros métodos geofísicos, se presenta la utilización de un procedimiento desarrollado especialmente y conocido con el nombre de Sondeo Eléctrico Ingenieril;
– problemas pocos comunes; nuevos tipos de trabajos de ingeniería o de geofísica ambiental que demandan soluciones diferentes (prospección electromagnética, radar, tomografía sísmica, etc.).

Si se aplican diferentes métodos simultáneamente en un mismo emplazamiento, el caso más favorable se presenta cuando los parámetros medidos o interpretados muestran distribuciones distintas y las diferencias pueden ser explicadas razonablemente por causas geológicas.

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Las tareas y las soluciones se ilustran con más de 10 casos. Todas las mediciones comentadas fueron realizadas por expertos del Instituto Geofísico Eötvos Loránd de Hungría (ELGI). Algunos de los métodos, y la mayor parte de los equipos y de las técnicas de procesado, han sido desarrollados en este Instituto. Se considera muy ventajosa la integración de una amplia variedad de científicos, equipamiento y programas de cálculo porque ello permite una investigación más efectiva, tanto desde el punto de vista geofísico como económico.

Palabras clave: Agua subterránea, protección medio-ambiental, sedimentos incoherentes, resistividad, polarizabilidad, sondeos geofísicos para ingeniería, georradar, tomografía sísmica.

ABSTRACT

In principle, drinkwater supply has two sources: Surface and subsurface water. The amount of surface water courses, however, shows heavy variations in time and their quality may also change frequently. Therefore only the subsurface aquifers can be considered as stable and long-term potential drinkwater resources for the next century.

In basins filled up with young (Quaternary) sediments the main task of water prospecting is to find porous water-bearing layers. Therefore geoelectric methods play leading role in solving problems of this kind.

Groundwater prospecting and environmental protection are discussed in one and the same paper because in many cases the two tasks are very similar from geophysical point of view: Porous and impermeable formations should be distinguished. Many (but not all) contaminants spread namely by means of groundwater; either solved in it or floating on it. Other environmental problems (e.g. void detection) are also mentioned. Various tasks will be discussed:

* simple tasks which can easily be solved with the help of conventional method(s);
* cases where integrated application of different (mostly geoelectric) geophysical methods is necessary;
* a wide variety of cases where the use of a specially developed method, the socalled engineering geophysical sounding (EGS) will be demonstrated (applied together with other geophysical methods);
* unusual problems, new types of engineering or environmental geophysical tasks which require new solutions (electromagnetics, radar, seismic tomography, etc.).

If different methods are applied at the same site, the most favourable case is when the measured or interpreted parameters exhibit various distributions and the differences can be explained by reasonable geological reasons.

The tasks and solutions are illustrated with more than 10 case histories (numberized). All the measurements mentioned were carried out by experts from the Eötvös Loránd Geophysical Institute of Hungary (ELGI) alone. Some of the methods, most of the instruments and processing procedures have been developed in ELGI. It is very advantageous if a wide variety of scientists, equipment and computer programs can be integrated, because in this case a survey is much more effective, both from geophysical and economical points of view.

Key words: Groundwater, environmental protection, loose sediments, resistivity, polarizability, engineering geophysical sounding, ground penetrating radar, seismic tomography.

INTRODUCTION

Drinkwater and environmental problems are primarily of local character (except for the areas of large river systems or border regions). Thus, their solution should also be local. As a consequence, a very wide variety of tasks and solutions exists. Therefore presentation of different case histories is very useful for geophysicists because it may widen their horizon. And it is probably even more useful for non-geophysicist experts because they may get an impression on the possibilities and limitations of geophysical methods in solving groundwater and environmental problems.

It should be underlined that in most cases we do not detect directly water or contamination, but geological formations which allow or prevent spreading of groundwater or any solution.

To estimate the vulnerability of detected aquifers is a task of similar importance - or even more important - than to search for new subsurface water resources.

CLASSICAL WATER PROSPECTING EXAMPLES

1. A groundwater prospecting project (a «simple task») was implemented in the Lenti basin, SW-Hungary, which has been filled up with fluvial sediments. High resistivity porous formations were looked for, thus the vertical electrical sounding was applied. Figure 1 shows a principal cross section of the basin (sure, it was constructed not before but after the prospecting). It clearly shows the thin (0 to 2 m) Holocene overburden (1) and below it a near-surface Pleistocene coarse-grained clastic sequence (2). Although the overburden

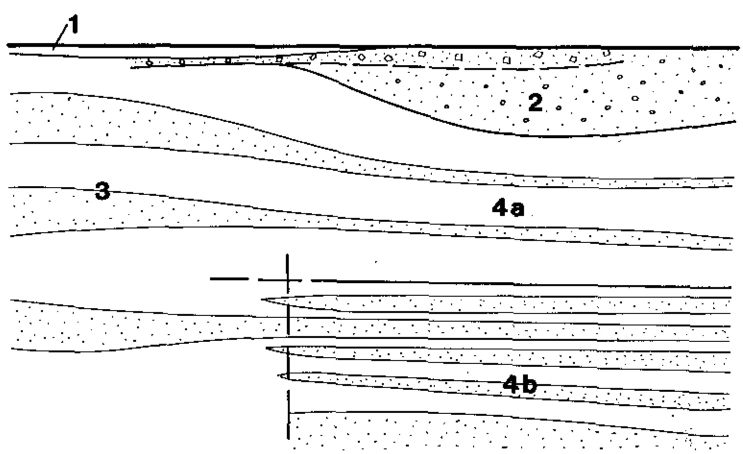


Fig. 1. Principal cross section for the Lenti basin, SW-Hungary. 1 - Holocene overburden; 2 - near-surface coarse-grained Pleistocene sequence; 3 - one-layer type structure; 4a and 4b - two-layer type structure.

consists mainly of clayey, fine-grained formations, it practically does not protect the underlaying layers against surface pollution because of its thinness. Thus, although the thick Pleistocene sequence bears a lot of water, it cannot be considered as a safe aquifer because it is completely unprotected. Therefore the deeper lying Upper Pannonian formations had to be investigated.

The Upper Pannonian sequence consists of relatively thin sand and clay layers (and their mixtures). As a consequence of the alternation periodicity and relative thickness of these individual layers, the sequence seems to be a thick, more or less homogeneous geoelectric layer at some places (3), while definitely splits into two layers in other parts of the area (4a and 4b). A characteristic VES curve of the so-called «one-layer type» structure and its 1D inversion can be seen in Fig. 2 and those of the «two-layer type» structure in Fig. 3. One-layer type and two-layer type curves do not occur randomly, they can be found on separated sub-areas. It is emphasized that the two-layer type structure does not mean a sharp, considerable change in resistivity at the boundary. In the survey area there are no sharp horizontal, even less vertical boundaries. The whole sequence is a clay-sand-gravel alluvial deposit, the internal differences can be interpreted as lithological changes. The more resistive lower layer reflects the change in the sand/clay ratio within the given depth interval. The fact that the average resistivity of the one-layer type structure lies generally between the resistivity values of the two layers of the two-layer type suggests that both types consist of the same individual layers but in different shares. The vertical dotted line in Fig. 1 symbolizes the connection of the two types but it is clear that there is a continuous transition between the sub-areas, without sharp boundary (e.g. the individual layers obviously do not finish exactly below each other).

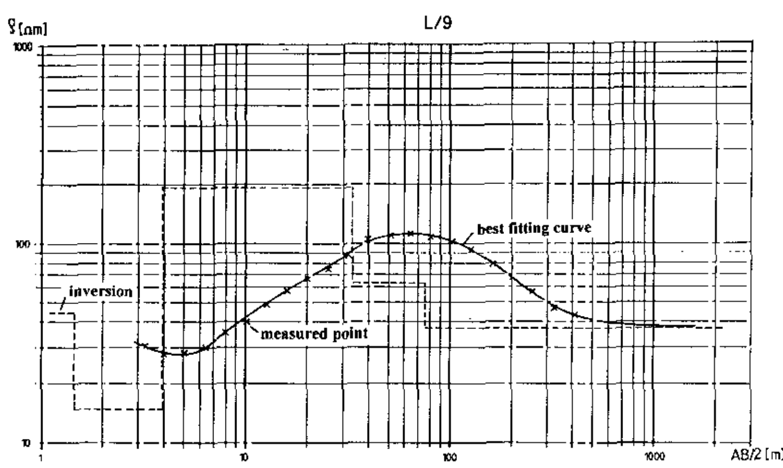


Fig. 2. Characteristic VES curve and its interpretation for the one-layer type structure.

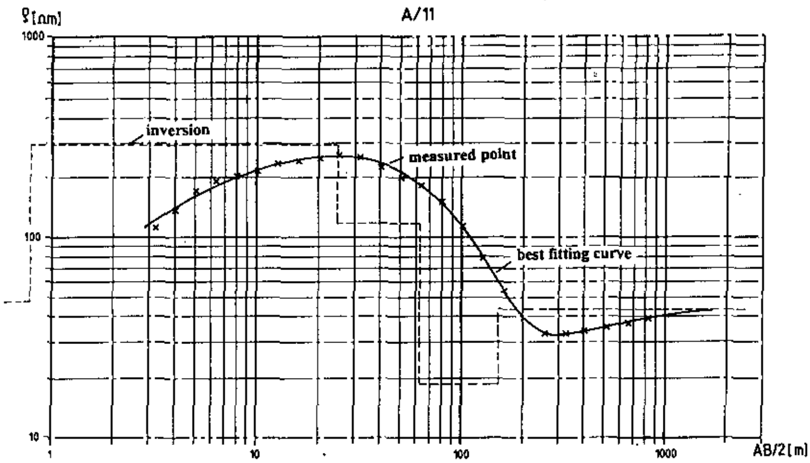


Fig. 3. Characteristic VES curve and its interpretation for the two-layer type structure.

The more resistive lower section of the Pannonian sequence is of high hydrological value. Its higher resistivity suggests increased quantity of porous formations, moreover, the less resistive upper part of the two-layer type means higher share of clayey formations, that is some protection against the surface pollution. The one-layer type areas are however of considerable importance as well. Resistivity highs of this «homogeneous» layer indicate sites where the relatively highest sand content might be expected. Especially the deeper parts of these sites can be considered as potential drinkwater reservoirs because the relatively long filtration path probably prevents the water contamination. Drillholes and test pumpings supported this interpretation in areas of both types.

2. The supposed alluvial cone of a paleo-river system was investigated in the Békés basin, SE-Hungary [1]. Here traditional VES and time domain induced polarization were applied. The resistivity measurements (about 700 VES points in an area of 1500 km^2) gave the expected results:

– in the whole survey area four layers (or sequences) occur, from top to bottom: overburden of variable resistivity; so-called upper aquifer (20 to 40 Ohmm); lower aquifer (8 to 18 Ohmm) underlain by a conductive (less than 6 Ohmm) clay layer. Therefore mapping of resistivity and/or thickness of the above sequences is a reasonable task;

– resistivity highs of the upper aquifer indicate the most promising parts of the area having the highest percentage of sandy formations (Fig. 4).

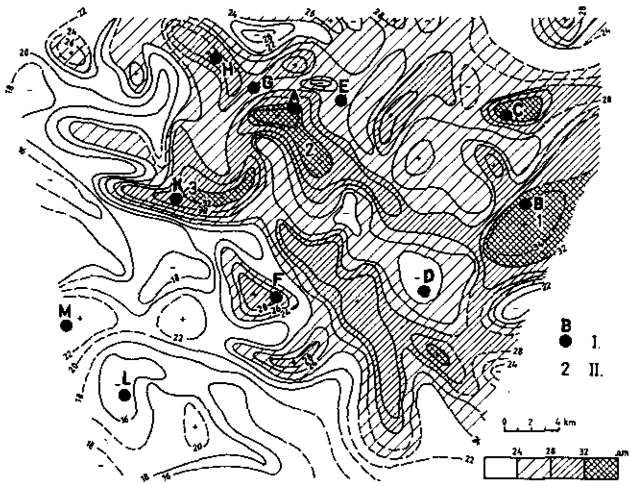


Fig. 4. Resistivity of the upper aquifer, Békés basin, SE-Hungary. I - drillings; II - distinguished sub-areas.

There are several subareas of about the same resistivity. They could be distinguished using a second parameter only which may be the polarizability. The map of apparent polarizability for AB = 640 m, that is for a penetration depth everywhere within the upper aquifer (Fig. 5) completely differs from the re-

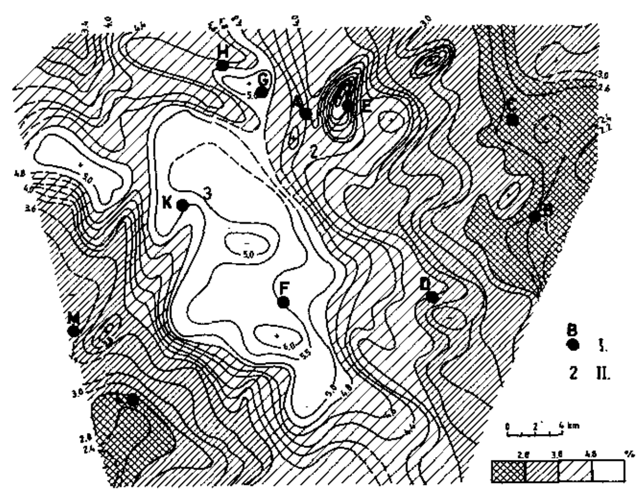


Fig. 5. Apparent polarizability map for AB = 640 m, Békés basin, SE-Hungary. I - drillings; II - distinguished sub-areas.

sistivity map. It means that there exist areas of similar resistivity but of strongly different polarizability. The joint interpretation is based on the results of in-hole resistivity and polarizability measurements carried out with ground instrument. Below the water table the resistivity is influenced first of all by the proportion of sand in a given depth interval. The logs show that the source of higher polarizability is the sand-clay transition itself (Fig. 6). Therefore areas

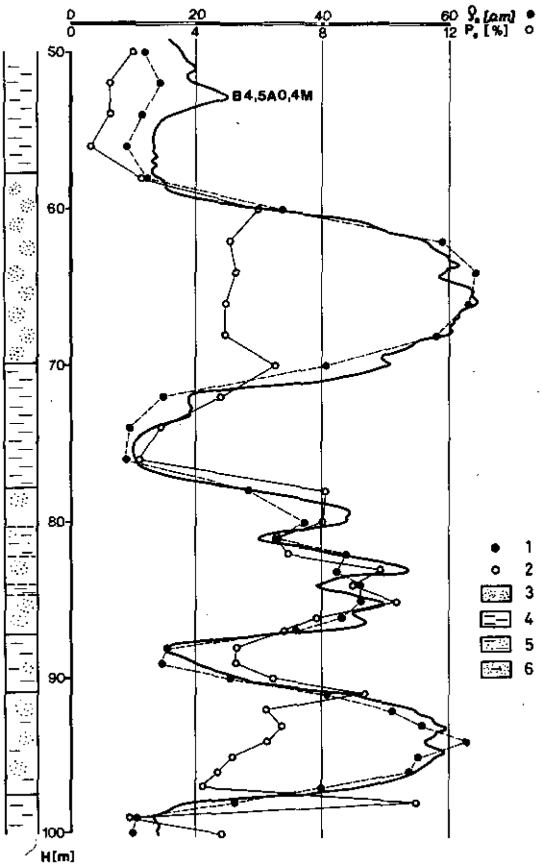


Fig. 6. In-hole resistivity and polarizability measurements, Békés basin, SE-Hungary. 1 - point-like resistivity data; 2 - point-like polarizability data; 3 - sand; 4 - clay; 5 - sandy clay; 6 - clayey sand.

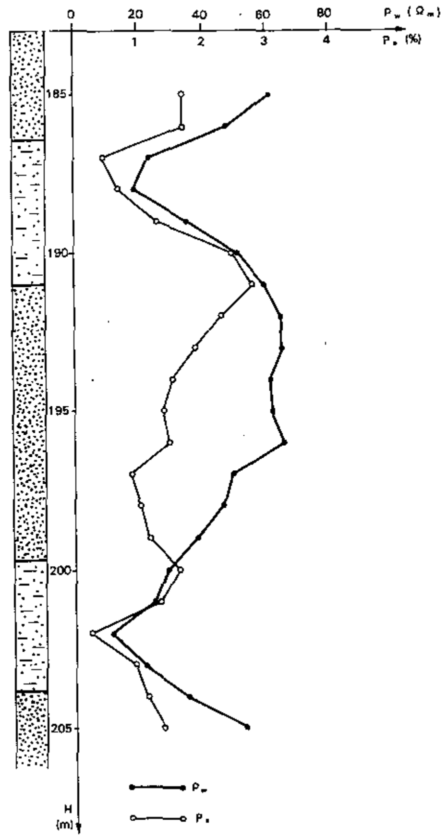


Fig. 7. In-hole resistivity and polarizability measurements, Lenti basin, SW-Hungary.

consisting of few thick layers (a few boundaries => low polarizability) or many thin layers (many boundaries => high polarizability) can be distinguished. Based on this areas characterized by high resistivity and low to medium polarizability can be considered as most promising for water production. Wells drilled in the most promising eastern part marked with 1 in Fig. 4 resulted in about three times higher water yield than wells in the area marked with 2 (about the same resistivity but much higher polarizability). It should be mentioned that the above behaviour of polarizability is probably not a specific phenomenon. In another project area (several hundred km away from the previous one) in-hole measurements provided similar results (Fig. 7).

TRADITIONAL EXAMPLES FOR ENVIRONMENTAL PROTECTION

In many cases environmental problems mean that we would like to avoid the harmful consequences of human activities (waste disposal, transport, construction, shallow mining, use of chemicals in agriculture, etc). These problems are very diverse and numerous, therefore in a relatively short paper only an incomplete review can be given.

3. It frequently occurs that an illegal waste deposit has been covered with soil and no indications can be seen on the surface. In such cases (sure, if some suspicion arises) ground geophysical methods can help. As an example, a shallow (2-5 m penetration depth) electromagnetic resistivity profile is presented (Fig. 8) running over a buried waste deposit (covered by soil). The figure requires no explanation: the undisturbed vicinity of the deposit (A) and the deposit itself (B) can clearly be distinguished.

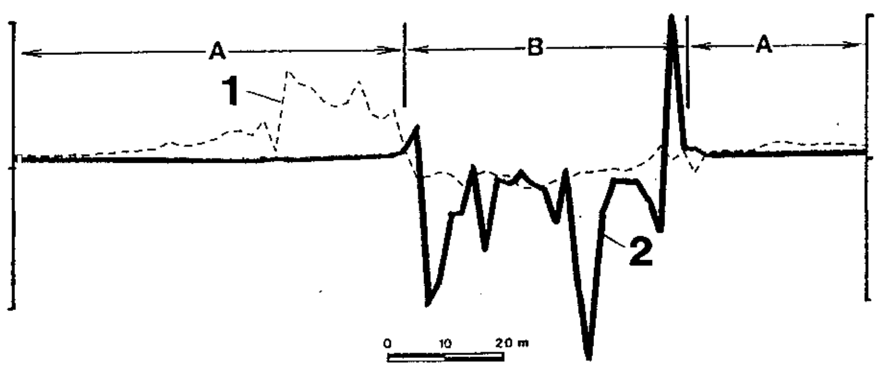


Fig. 8. Electromagnetic resistivity profile over a buried waste deposit. 1 - phase; 2 - resistivity.

4. Before establishing waterworks, the stability of water quality should be examined (or at least estimated). The uppermost several meters plays a decisive role in spreading of surface contaminants. Therefore the detailed knowledge on the structure of the upper 10-20 m is necessary. Around waterworks one of the most important features is the so-called travel time (the time until a today pollution reaches the filter of the water well). Surface points of the same travel time form the isochrone diagrams for 5 years, for 20 years, etc. In many cases these diagrams are of exactly circular shape. In our opinion the circles mean that only unsatisfactory information on the geological structure was available and this information was extrapolated for larger distances. This must not be done in some sites where the geological structure is not of circular symmetry as the example below shows.

In the vicinity of a waterworks in Hungary with shallow wells resistivity sounding/profiling was carried out. The results clearly show that there are significant changes at a depth of several m (Fig. 9). The change in the structure can very clearly be seen in three neighbouring sounding curves (Fig. 10). The near-surface clay layer (point C-190) and sand layer (point C-210) are very characteristic; between them a characterless curve (point C-200) can be seen where the model is surely not horizontally layered. Extent of the unconsolidated porous formations can be determined by a dense mapping only. The small step between the measuring points is necessary because the structure may change even within 20-30 m.

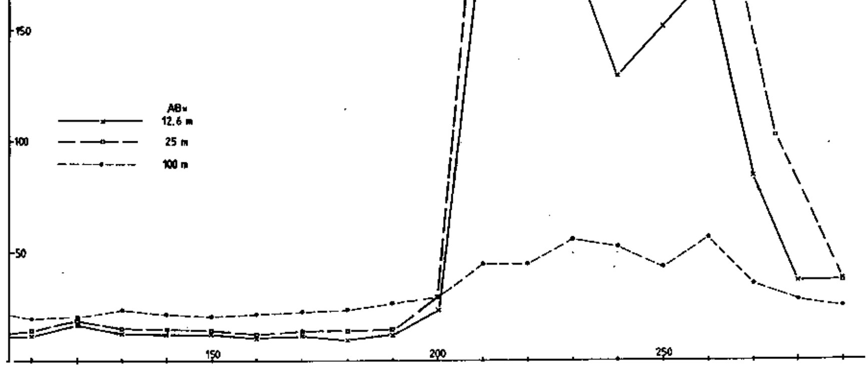


Fig. 9. Apparent resistivity profiles near a waterworks.

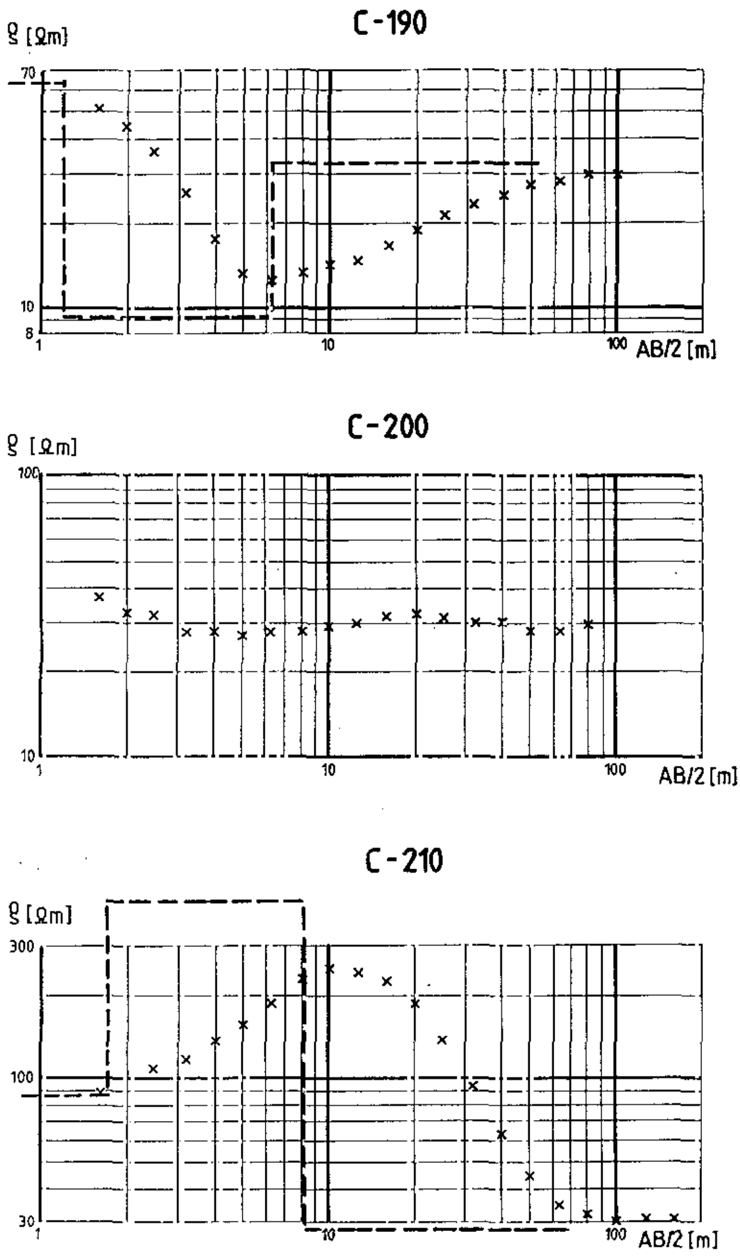


Fig. 10. Characteristic VES curves and their inversion.

These examples were quite simple illustrating only that a lot of environmental tasks can be solved relatively easily. In such cases no technical developments but rather promotion or public relations activity is necessary. As an example, a little more complicated task will be shown below.

5. Increasingly important environmental task has been in recent years to determine the location, extent and movement of contaminated subsurface waters. Its traditional method is to create a network of monitoring wells and then to analyse the water samples taken periodically. In several cases the network of monitoring wells should be completed with other, e.g. geophysical investigations, mainly because of financial, timing or scientific reasons. In the following case history the question was not if there was contamination or not; the task was to determine its extent, location and temporal change [2].

At a municipal and industrial waste deposit in Germany the moving groundwater practically washes through the waste, due to the insufficient isolation from the subsoil. Highly contaminated groundwater flows out from the deposit as indicated by anomalously high conductivity (over 100 000 S/cm) of water samples taken from the monitoring wells. Where the polluted water leaves the deposit, parallel dc resistivity-polarizability profiles were measured suggested by Professor G.-P. Merkler (Karlsruhe University, Germany) as an early initiator of application of IP method in solving tasks associated with waste deposits. The measurements were carried out in pole-dipole arrangement (a = 10 m, n = 1 to 5, distance between profiles = 10 m; Fig. 11). The results are shown as pseudo-sections (Figs. 12 and 13).

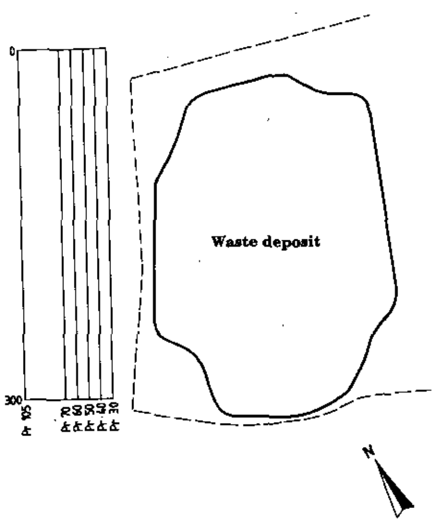


Fig. 11. Location of geophysical profiles at a waste deposit, Germany.

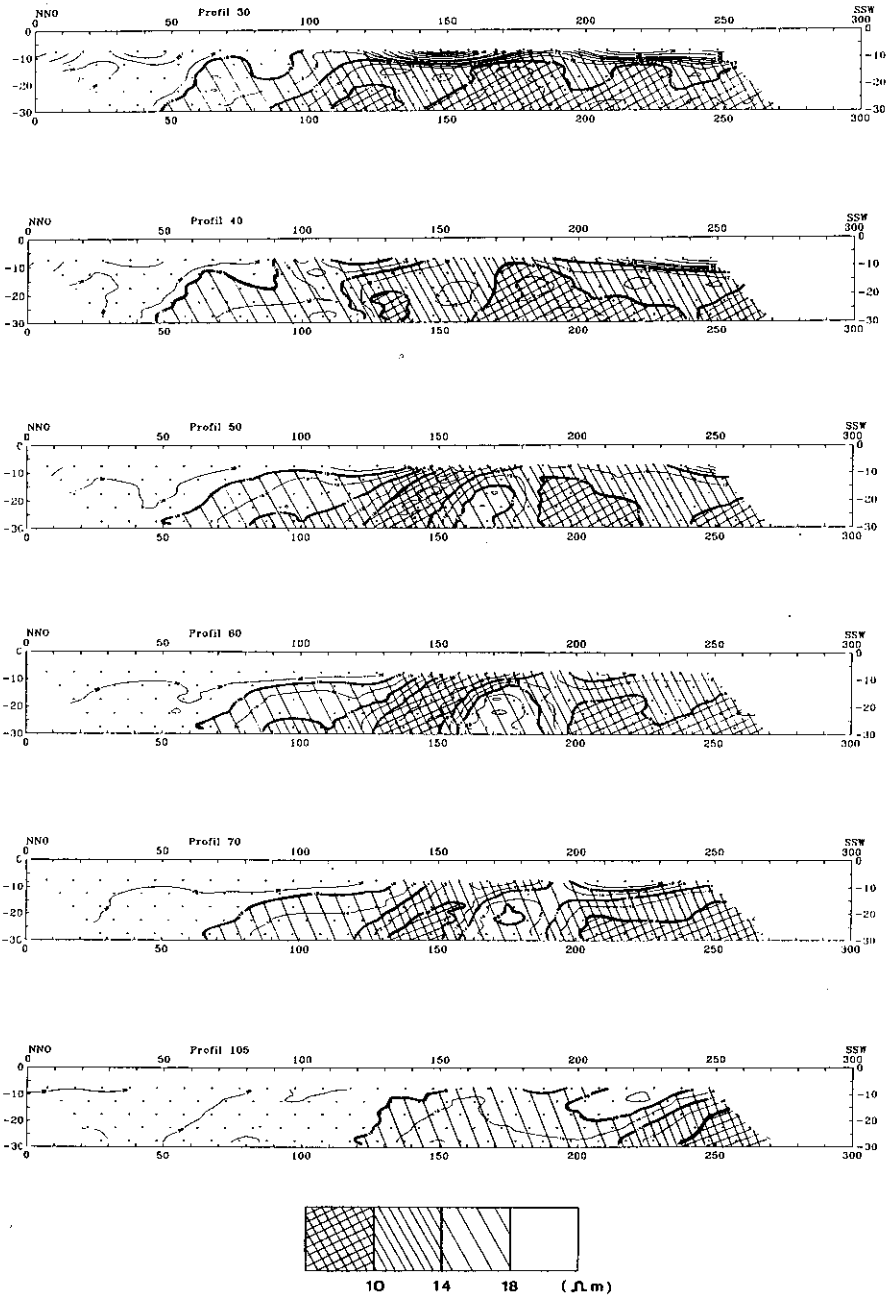


Fig. 12. Resistivity pseudo-sections.

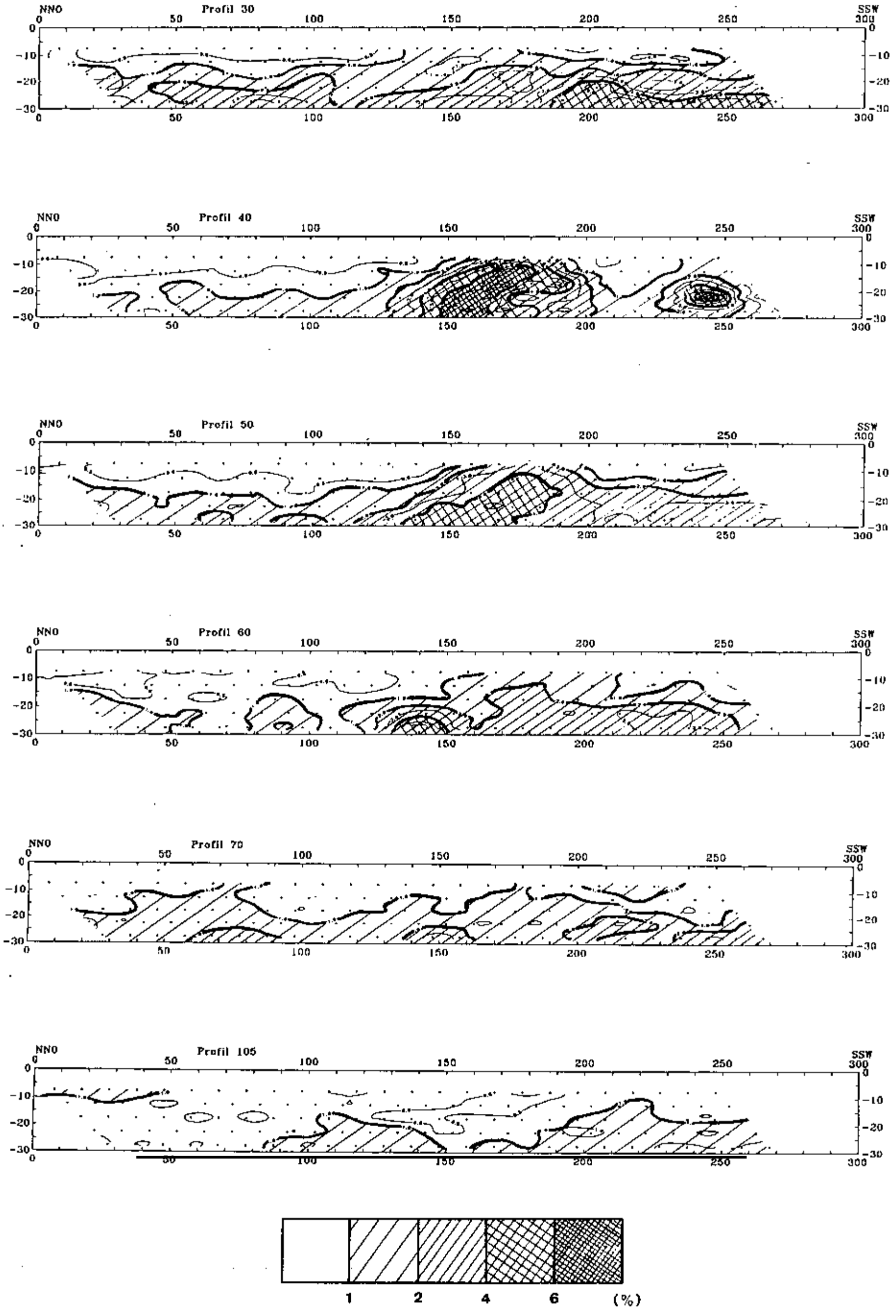


Fig. 13. Polarizability pseudo-sections.

In general, left-hand side (northern) part of the sections is of higher resistivity. It means that the polluted groundwater (a weak electrolyte) has affected mainly the southern 50-60 % of the profiles. There is a very characteristic low resistivity zone in the middle of the profiles 50, 60, 70 and it can be recognized in profile 40, too. It is very difficult to obtain a geometric model from the non-symmetric anomalies. It is sure, however, that about the middle of profiles a low resistivity zone nearly perpendicular to the profiles can be traced, at least from profile 40 to profile 70. It is close to a fault which was approximately located by geology. Moreover, the anomaly is so sharp and narrow that it obviously suggests a fault and through its fractured zone solutions move easier. It seems that this fault (or its northern edge) stopped the pollution spreading to the north. In the direction of groundwater flow the behaviour of contamination seems to be as expected: Strongest pollution can be supposed in the profile closest to the deposit (largest area of resistivities below 10 Ohmm). In further profiles the contamination will be weaker and weaker; the difference between the northern and southern parts is characteristic for each profile.

Simultaneous examination of resistivity and polarizability sections shows that the two parameters are not independent (the highest IP anomalies lie at the edge of the resistivity low) but the correlation is not close. In the left-hand 40% of the profiles there are practically no IP anomalies and the highest resistivities can be observed here, too. These sections are considered to be the least (or not at all) affected by contamination. The IP highs in the middle of the profiles coincide quite well with the conductivity highs of water samples. It means there is a direct connection between the parameters (conductivity => salinity => ion concentration => polarizability).

The highest IP values (in profile 40) may indicate the outflow of groundwater of highest salinity. This is approximately the crossing of the deposit and a fault assumed from geology and exploratory wells. Further away from the deposit, the peak value of IP anomalies decreases (along the last profile no IP anomaly can be observed) while their extent increases. All these correspond to the assumed spreading of a contamination plume in groundwater: in the flow direction lower and lower concentrations may be expected over larger and larger areas. Based on this assumption the highest IP values should occur in the profile closest to the source. But it is not true, the highest values were obtained along the second profile. An acceptable explanation for the phenomenon is that the salinity of groundwater at the outflow point is higher than optimal for the development of IP processes. Other researchers have reported on similar experience; in our case analysis of water samples taken from the monitoring wells supports our explanation. It would require, however, experimental evidence, too. In this respect the first results have already been obtained. In a similar project in Hungary a very close correlation between the total dissolved salt content and resistivity was found. Thus the resistivity - polarizability diagrams of Fig. 14 can be considered as salt concentration - polarizability crossplots. They show that in that case of very strong contamination the polarizability is very low and increases with decreasing concentration. Since in non-polluted areas the polarizability is low again, there must be a medium contamination resulting in maximum IP response.

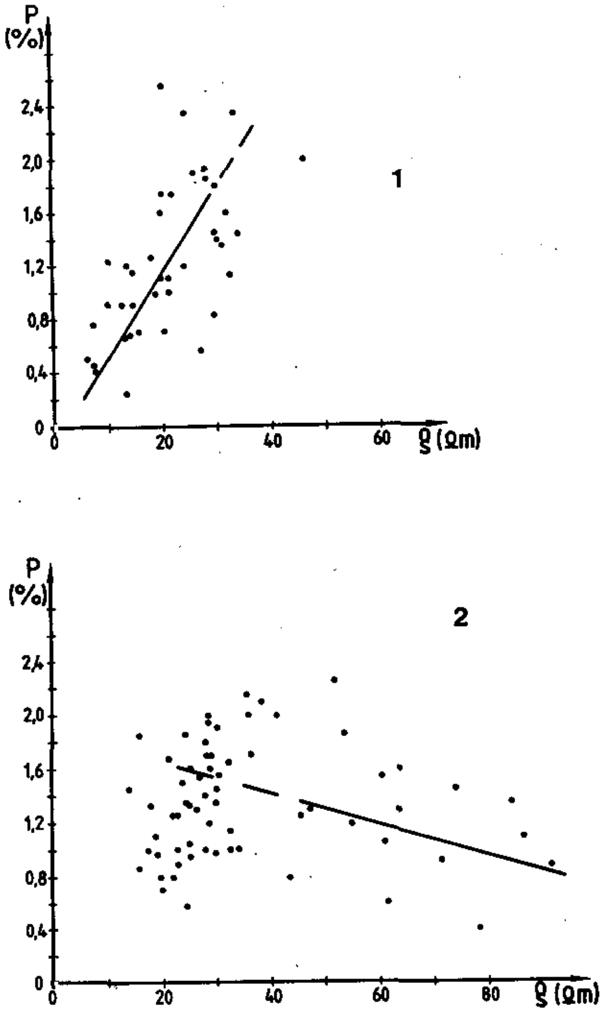


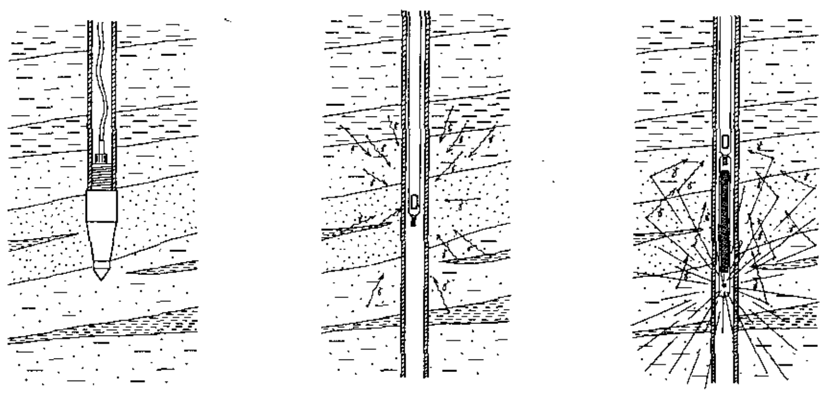
Fig. 14. Resistivity vs polarizability around a tailing pond, Hungary. 1 - heavily contaminated area; 2 - area of moderate contamination.

All the above tasks were solved by traditional geophysical methods. Now some non-conventional methods, instruments and case histories will be presented.

ENGINEERING GEOPHYSICAL SOUNDING (EGS)

Principles of EGS

This survey method has been developed in Hungary especially for investigating unconsolidated near-surface formations. Although its main principles were published in the early nineties [3], a short summary completed with the developments in recent years may be useful.



a b c

Fig. 15. Data sets measured in engineering geophysical sounding, reflecting independent properties of penetrated layers. a - cone pressure => breaking strength; b - natural gamma activity => clay content; c - gamma-gamma activity => bulk density.

A small diameter tube ending in a standardized cone is pressed into the soil with the help of a hydraulic system (non-destructive penetration). During the penetration mechanical, after reaching the required (or technically possible) depth nuclear parameters are measured (Fig. 15). The penetration disturbs the original conditions only slightly, therefore the method provides in situ parameters. These are:

– total pressure, that is the oil pressure in the hydraulic cylinders. This is the sum of the force necessary to penetrate the given formation and the friction along the wall of the tube;

– cone pressure, that is the pressure appearing at the cone while moving downwards into the layer. This pressure is proportional to the breaking strength of the material;

– natural gamma activity, an integrated quantity measured within the tube. Since the absorption of natural radioactive elements on the grains is proportional to the specific surface, this parameter indicates the clay content;

– gamma-gamma activity, the measurement of the Compton-scattering of the gamma particles in the layer. With the help of calibration cpm can be converted into bulk density data;

– *neutron-neutron activity:* a neutron source radiates quick neutrons and a detector detect those which slow down to the thermic state as a result of interaction primarily with hydrogen ions. Thus the hydrogen content (practically water or hydrocarbon content) can be estimated.

In addition, the static water level can be measured, soil and water samples can be taken and the k hydraulic conductivity can be determined. Location of EGS points is usually planned after performing and evaluating other ground geophysical - mainly geoelectrical - methods of integrating character.

The data set of a sounding point characterizes the penetrated layers with very high resolution (Fig. 16). Each penetrated layer can be characterized by average

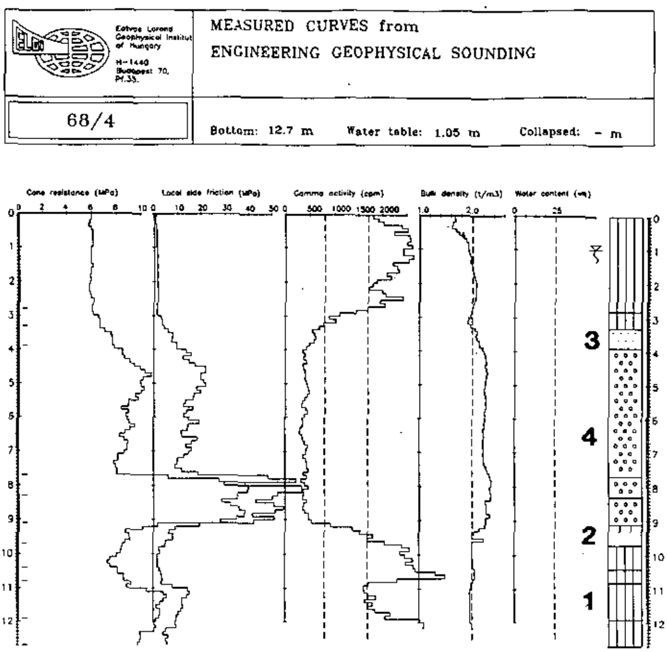


Fig. 16. Measured data of engineering geophysical sounding. 1 - impermeable; 2 - semi-impermeable; 3 - poorly permeable; 4 - highly permeable.

values of the measured parameters. If the three main of them (cone pressure, natural gamma activity and bulk density) are plotted on the axes of an orthogonal coordinate system, then they determine a spatial point characteristic for the given layer. As the comparison with the material of shallow drillings shows, the most important sediment types are characterized by a more or less wide interval of parameters (a compartment) in the coordinate system. This diagram is the basis for interpretation of measured data: The interpretation program examines the location of the spatial point related to the centre of the individual compartments. The diagram of Fig. 17 shows the characteristics of alluvial sediments. For peat-lignite-type young coals or various bauxites different spatial diagrams can be constructed on the same basis (Figs. 18 and 19, respectively).

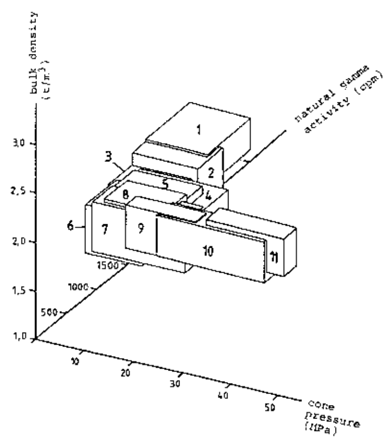


Fig. 17. Interpretation diagram of engineering geophysical sounding in alluvial sediments. 1 - clay; 2 - lean clay, silty clay; 3 - silt, clayey silt; 4 - silt with fine sand; 5 - fine sand with silt; 6 - fine sand; 7 - silty sand; 8 - sand; 9 - coarse sand; 10 - sand with gravel, coarse sand with gravel; 11 - sandy gravel, gravel.

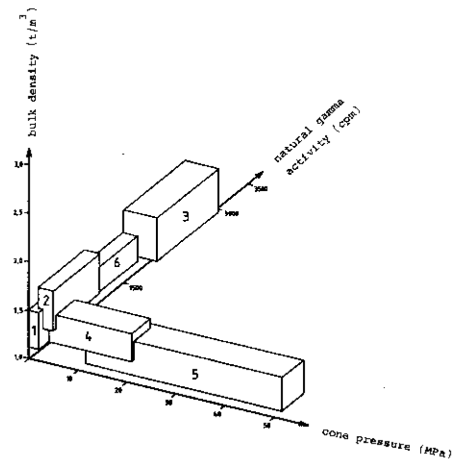


Fig. 18. Interpretation diagram of engineering geophysical sounding in prospecting for very young coals. 1 - peat; 2 - sand containing organic material; 3 - clay containing organic material; 4 - lignite; 5 - woody lignite, low degree of coalification; 6 - coal slurry.

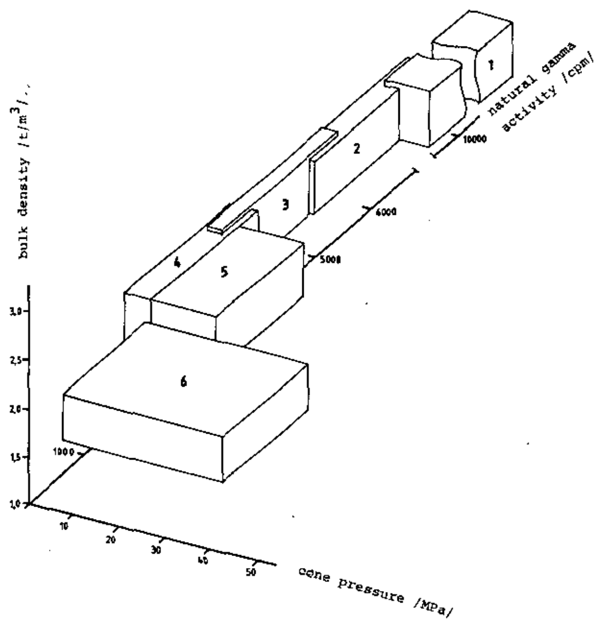


Fig. 19. Interpretation diagram of engineering geophysical sounding in prospecting for bauxites. 1 - bauxite; 2 - clayey bauxite; 3 - clay with bauxite; 4 - clay; 5 - clay with detritus; 6 - detritus.

6. Examination of the stability of waste dumps.

The Mátra Thermal Power Station (near the town of Gyöngyös, N-Hungary) uses lignite exploited from open-pit workings. Depth of the pit reaches, several times exceeds 75 m. The waste material - consisting mainly of Oligocene-Pleistocene blue clay - is deposited in the worked out area. Volume of the waste deposited since years exceeds 30 000 000 m³. On the other side of the pit there is a continuous mining, therefore the stability of the waste dump is especially important; its examination by traditional drilling methods is very complicated.

Using the EGS a critical layer could be detected, studying the correlation between several parameters. Figure 20 demonstrates the studied parameters of the upper 30 m of the waste, and the layers determined on the basis of the parameters. In case of normal, consolidated layer the bulk density increases with increasing water saturation. Above a certain critical value, increase in water content results in decrease of bulk density and running of the layer. Figure 21 shows water saturation - bulk density cross-plots for two layers of different depths. One of them - marked by D - caused the slip of about 4 million cubic meter of waste.

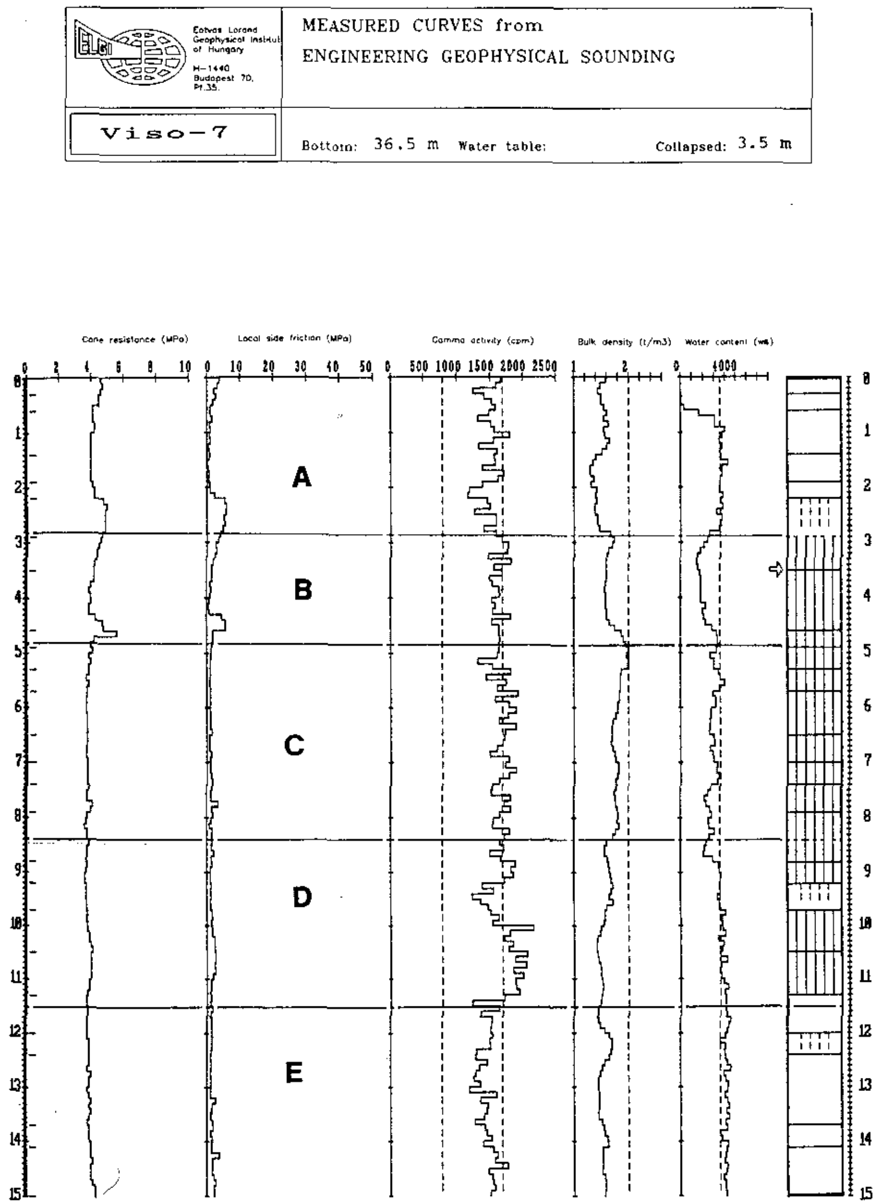


Fig. 20. Engineering geophysical sounding curves, investigation of waste dumps.

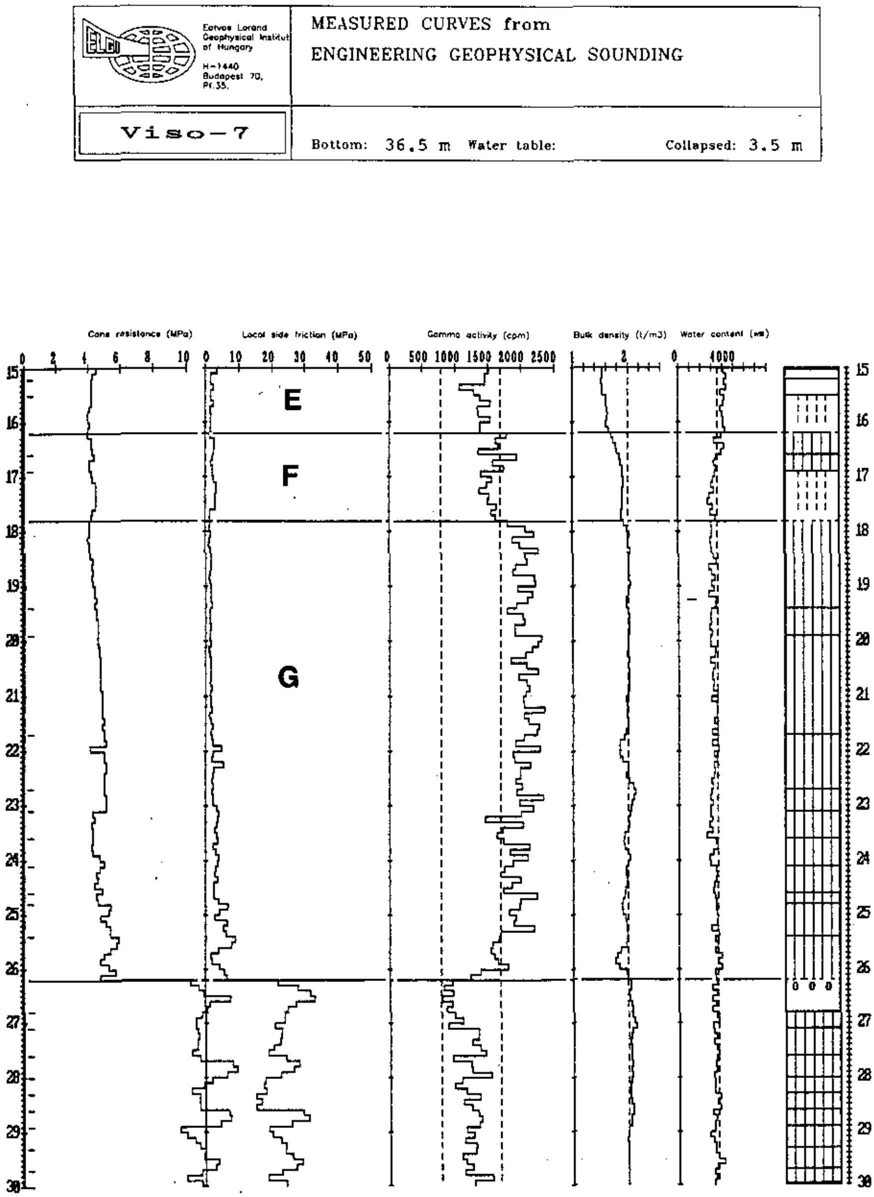


Fig. 20. (Continuation).

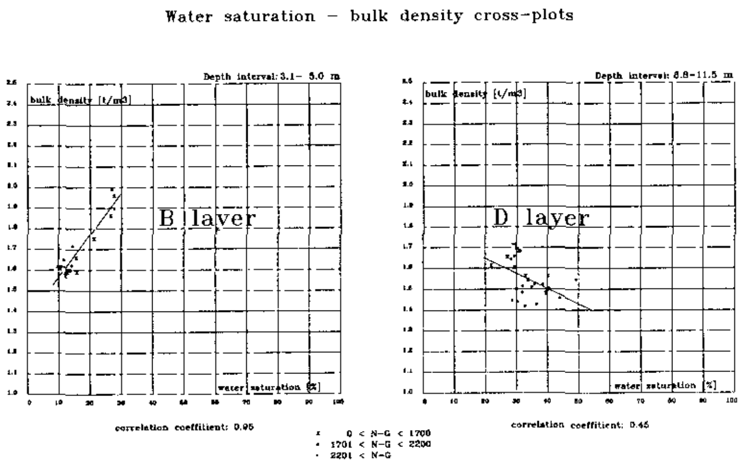


Fig. 21. Water saturation - bulk density cross-plots for two different layers. B - direct proportionality, D - inverse proportionality.

7. Waste deposition.

In Hungary, a considerable part of waste deposits was created without proper artificial or natural (geological) protection in the past decades. If municipal and industrial waste is deposited directly onto a permeable layer, close to the water table, then the risk of pollution of groundwater and of subsurface reservoirs in the direction of groundwater flow considerably increases. Figure 22 shows the waste deposited directly onto the gravel in an abandoned

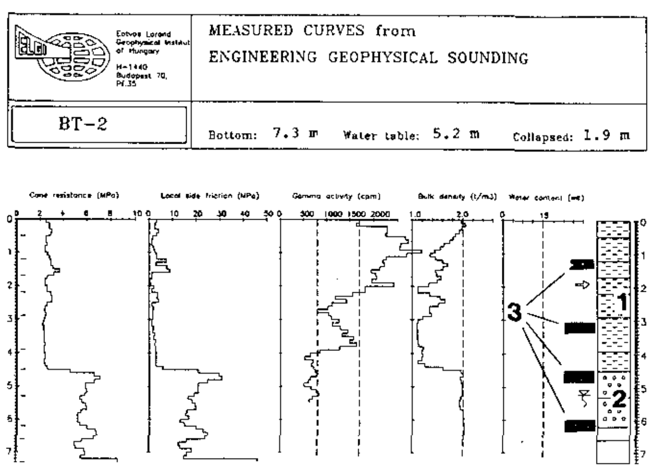


Fig. 22. Engineering geophysical sounding over a waste deposit. 1 - waste; 2 - coarse sand, sand with gravel; 3 - sampling places.

gravel pit in a thickness of 4.5 m. The water table is at a depth of about 3 m; analysis of groundwater and soil samples taken at the site indicated in the figure revealed contamination caused by dangerous industrial waste (leaded dyestuff) in a concentration exceeding many times the environmenal treshold. And moreover: although a 0.4 m thick so-called «recultivation layer» has been deposited over the waste, besides the possibility of groundwater pollution, the site is not suitable even for the planned «one-family house development method». The stability of the loose unconsolidated material is too low for construction what is indicated by the very low (1.15 to 1.25 T/m^3) density of the waste.

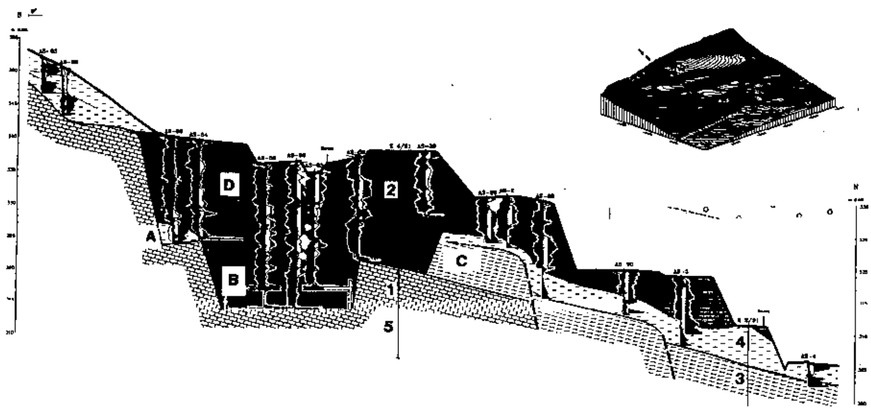


Fig. 23. Engineering geophysical soundings along a profile crossing a waste deposit. From EGS: A - laminated limestone; B - waste; C - marl; D - traceable waste layers; from drillings: 1 - laminated limestone; 2 - waste; 3 - marl; 4 - soil (holocene), slide rock (Pleistocene); 5 - alternating marl and limestone beds.

In Fig. 23 a similar example –a waste deposit without artificial protection– is shown along a profile. The figure undoubtedly shows that the marl layer left as geological barrier has been either cut several times in the course of waste deposition or considerably thinned or has been affected by faults. Consequently, it is not suitable for natural protection, thus the contamination washed out from the waste may pollute the water stored in the laminated limestone below the marl (the drinkwater supply of a nearby country town is based on the limestone). Sampling of layers differentiated on the basis of bulk density and natural gamma intensity rendered possible the identification of waste layers of unknown origin and the estimation of danger.

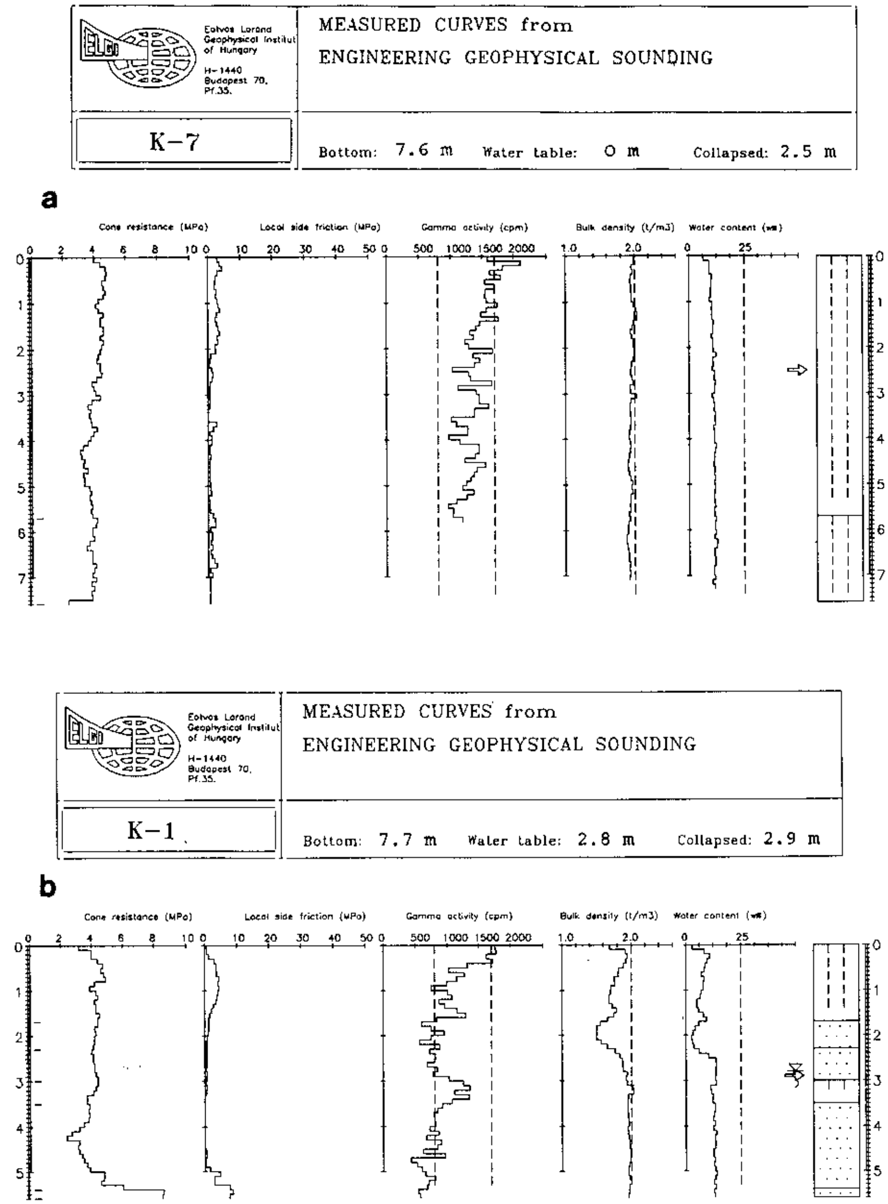


Fig. 24. Detection of kerosene by EGS in an abandoned Soviet air base, Kalocsa, Central Hungary. a - not contaminated site; b - presence of kerosene.

8. Hydrocarbon contamination.

The neutron-neutron sonde (so-called zero length probe) with an Am-Be source, can be applied very effectively in localizing hydrocarbon contamination of the soil, a consequence of technical trouble, human negligence, etc. Figure 24 illustrates determination of free phase kerosene (about 1.5 m thick) in an abandoned Soviet air base. In normal circumstances the zone of capillarity is indicated by a slow, continuous decrease of the water content curve above the water table (a). A sharp minimum both in water saturation and bulk density just above the groundwater level indicates the sudden increase of hydrogen content that is the presence of kerosene (b).

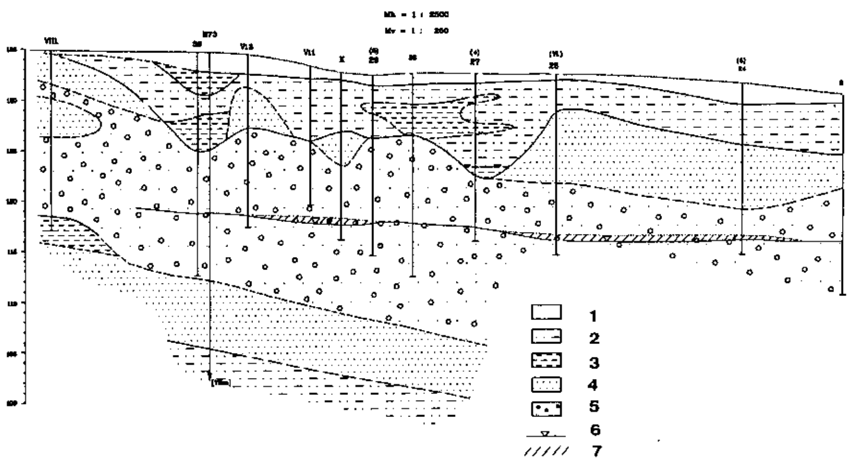


Fig. 25. Results of engineering geophysical sounding in detailed geological mapping. 1 - soil; 2 - silty clay, silty fine sand; 3 - clay; 4 - sand; 5 - gravel, sand with gravel; 6 - groundwater level; 7 - kerosene.

9. EGS for detailed geological mapping.

Application of EGS in geological mapping, in shallow geological survey is shown in Fig. 25. Revealing the complicated structure of the alluvial cross-bedded sequence allowed to plan an effective environmental protection work.

10. Application in soil mechanics.

The last example (Fig. 26) shows the advantages of EGS in comparison with the conventional Cone Penetration Test (CPT) method. The advantages come from the nuclear measurements, better said from the parameters calculated from them. In a construction area the side friction in the upper 4 m was extremely low. Examining other parameters, the bulk density and water content showed anomalous values; the latter was extremely low (below 5 %). Cone pressure of this layer was over 20 MPa in dry condition which suggested

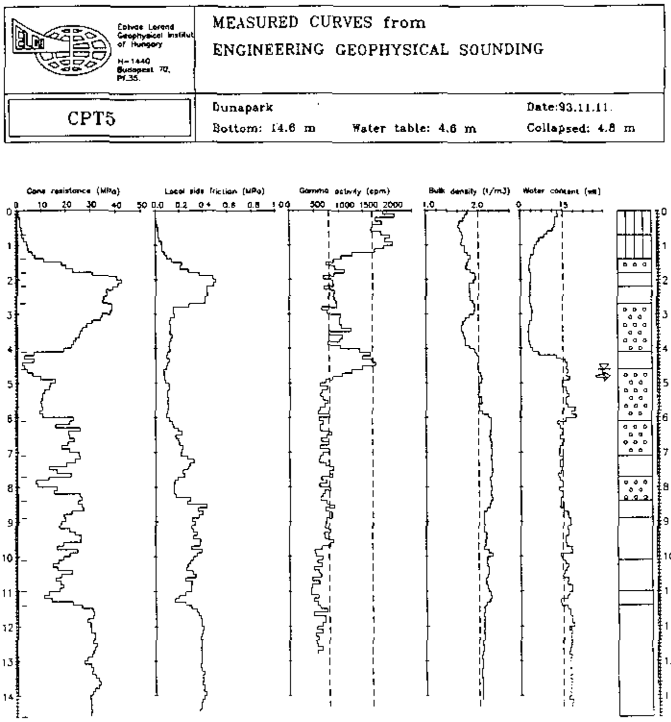


Fig. 26. Engineering geophysical sounding in soil mechanics. Drying up and loss of plasticity.

the presence of a layer of high loadability. The extremely low side friction and water content call however the attention: It is very likely that the penetrated material has lost its plasticity because of drying up. This is, however, a reversible process. In case of high water saturation the breaking strength of the same material can fall down to zero. This is indicated by cone pressure values less than 1 MPa measured near the water table (about 4 m).

APPLICATION OF GROUND PENETRATING RADAR (GPR) AND SEISMICS FOR ENVIRONMENTAL PROBLEMS

The GPR Method

GPR works by radiating a series of high-frequency (20-1000 MHz) electromagnetic impulses into the ground via a surface contact transmitting antenna. As this signal passes through the earth it may encounter subsurface materials of varying electrical properties. At these electrical interfaces, the signal is reflected and diffracted, being more or less attenuated or dissipated in the material. The reflected signal is detected on the surface by the receiving antenna wich is near the transmitter. Reflections come back from all geological inhomogeneities so the effect of layers, geological structures and other buried objects can be recognized on the time-sections of radar profiling. The essence of the method is the exact measurement of the signal delay time (10-2000 nanoseconds), which depends on the velocity of the signal in the subsurface as it passes through the material, then it is reflected and travels back to the receiving antenna (two way travel time: TWT). The time-section of radar measurements can be converted into a depth-section by calculating this wave propagation velocity [4].

In GPR survey, soil conductivity and dielectric properties are the main parameters that influence the detectability of the subsurface features [5]. High conductivity causes high attenuation of the signals and therefore the penetration depth is smaller. Dielectric permittivity controls the wave propagation velocity, and the dielectric contrast between the target and its surroundings determines the reflectivity of the object. The investigation depth can be controlled by the frequency applied: lower frequency (25-100 MHz) results in a higher penetration (25-10 m) but poorer resolution, and the application of a higher frequency (300-1000 MHz) results in excellent resolution but only down to small depths (5-1 m).

The principle of the operation of the GPR is illustrated in Fig. 27 [6]. The inhomogeneity can be detected as a characteristic reflection, and the boundary of a deeper layer can also be traced on the time/depth section.

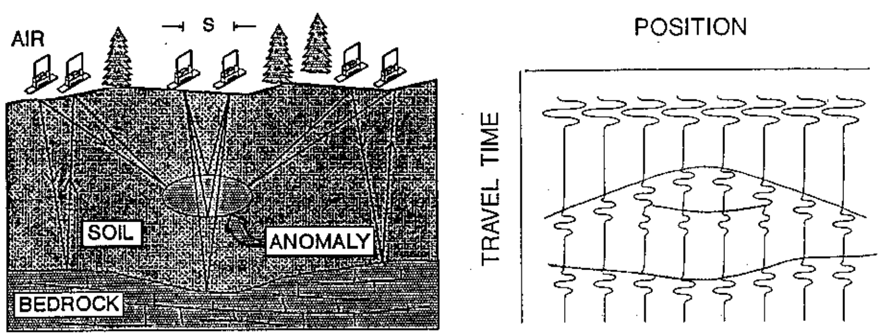


Fig. 27. Schematic illustration of GPR field survey procedure and the resulting reflection section.

As it was already mentioned, high conductivity is the most significant limiting factor in radar applications. Water saturation or the presence of highly conductive clay beds will cause high attenuation and a decrease in signal velocity and energy, consequently a decrease in depth penetration or observable reflections. Another disturbing factor may be the objects above the ground surface which cause reflections on the radar profile and interference with the subsurface reflections [7]. This latter problem can be lessened by careful planning of measuring lines and by thorough and accurate observation of such effects and taking them into account during the interpretation.

INSTRUMENTATION

The instrument we use with great success for near surface investigations is pulseEKKO IV system, with frequencies of 25, 50, 100 and 200 MHz depending on the task to be solved. This system is a lightweight, modular and fully battery powered instrument, controlled by a computer. Operation is digital with data transfer by fibre optic cables thereby ensuring high performance and resolution and avoiding the noises picked up by wires. The multiple signal averaging effectively improves the signal/noise ratio. Computer-based data acquisition makes possible the on-site presentation of the sections or pre-processing before interpretation. The digital data storage means that further processing can be carried out by applying seismic processing techniques [8].

11. Prospecting for voids.

Caves.

Many known and unknown caves and cavities can be found in Budapest, particularly in the Buda hills where more and more houses and buildings are to be constructed. Everywhere at this area, the site must be investigated from the point of view of caves. In order to demonstrate the suitability of GPR for this task, we measured a 160 m long profile above known caves. This record is shown in Fig. 28. The easily detectable hyperbolic reflections on the record are caused by cavities the top of which are located at different depths. The sketch-map of the cave-gallery is also shown below the record, together with the survey line. The places where cavities were detected on the record are marked on this line. The excellent correlation between the interpretation and the site-map is evident.

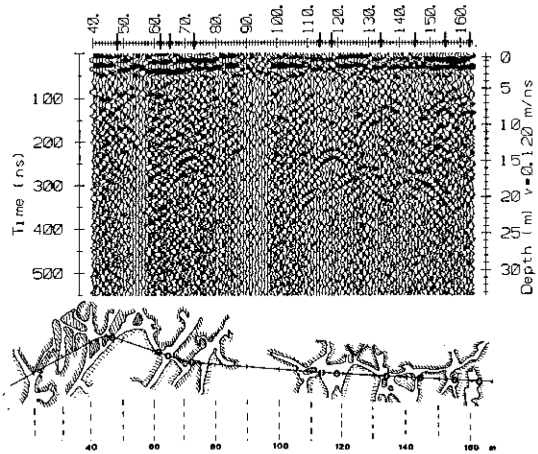


Fig. 28. Detection of caves by GPR (100 MHz). Characteristic reflections are marked both on the record and on the site map below.

Cellars.

As the collapse of unknown or forgotten cellars that are in bad condition often causes damages to buildings, their investigation is a very important task if a new building is to be constructed. GPR is suitable for detecting cellars, as it is shown in Fig. 29. This test measurement was carried out using 100 MHz antennas. Cellars were excavated in a loessy soil at a depth of about 1-2 m. The reflections from them could be enhanced by frequency filtering.

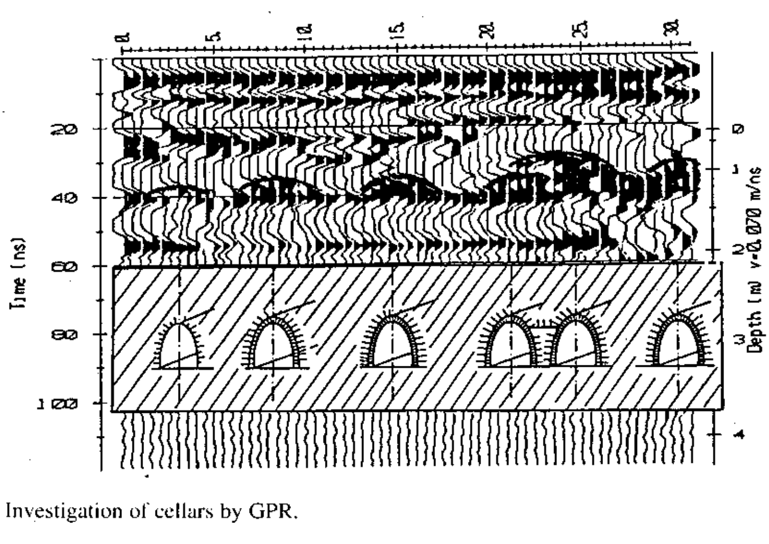


Fig. 29. Investigation of cellars by GPR.

12. Prospecting the area of an old mine.

An integrated geophysical survey was carried out over an old mine. The site is to be built up but problems arose due to the unconsolidated zones and improperly backfilled shafts of the mine. The methods used were GPR, EM conductivity and DC resistivity profiling for detecting near surface features; and seismics for detecting unconsolidated zones.

Detection of shafts.

On the basis of an old mining map we pegged out the potential hazardous areas of the former shafts of the mine. In the vicinity of these areas we measured some profiles by GPR, by electromagnetic conductivity meter (type EM-31, Geonics, Canada), and by DC resistivity referring to different depths. Anomalous zones were found mainly on the basis of the radar sections. Other methods either supported the interpretation or gave additional information to radar reflections. The application of this integrated survey was necessary because of the many cultural noises such as fences, cottages and utilities (pipes, cables). The anomalies were checked by shallow drillings. Figure 30 shows one of the most characteristic cases where typical GPR section can be seen together with the corresponding conductivity and resistivity profiles. Sites of test drillings are also shown in the figure. Five similar objects could be identified in the same way in this area.

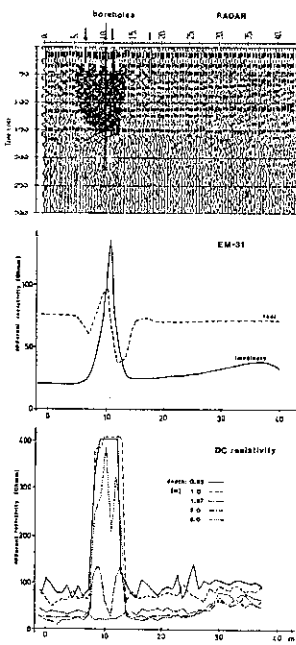


Fig. 30. Radar record, EM conductivity and DC resistivity profiles above an improperly refilled shaft of an old mine. The places of the control drillings are marked with arrows on the radar record.

Investigation of critical zones.

For mapping the potentially endangered areas above abandoned mines, combined application of reflection and refraction seismic methods might be appropriate. The change in signal intensity (or the attenuation of seismic waves) in the reflection time-section is caused by the changes in rock properties. On the velocity profile calculated from refraction measurements, high seismic velocity could be interpreted as rocks under stress, whereas low velocity reflects subsided, loose layers. In this way, undisturbed and loose zones, as well as rock stresses can be identified.

Seismic reflection and refraction measurements were carried out along three lines over the old mine mentioned above, in order to locate the geotechnically dangerous zones. Figure 31. shows a seismic reflection time section where the zone of the mine working is marked. At the bottom, the velocity diagram of refraction measurements, in the middle, the interpretation is shown.

The undisturbed zone does not cause any problem; the zone under stress is the most dangerous because of the likely collapse or subsidence of rocks; in consolidated zones only slow (not dangerous) subsidence of soil may be expected. These results are important for reinforcing the existing buildings or for the planning of new houses at this site.

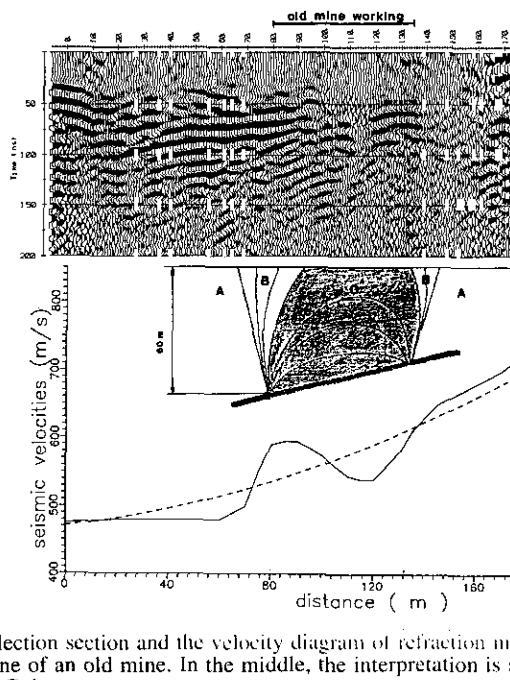


Fig. 31. Seismic reflection section and the velocity diagram of refraction measurements carried out above the critical zone of an old mine. In the middle, the interpretation is shown. A: undisturbed; B: critical (stressed); C: loose zones.

METHOD OF SEISMIC TOMOGRAPHY

There are many areas of science in which the distribution of some physical quantity inside a «body» has to be determined from its line integrals measured on the perimeter of the body. These tasks can be solved by tomographic methods. The principles of the seismic transmission - as one type of tomography - can be found in [9].

Applying the tomography in seismic prospecting we measure the travel times of elastic waves between the source points - located on one side of a body - and the receiver points - that are located on the other side. This method is called seismic transmission. For determination of the wave propagation velocity map the input data are the geometry and arrival times, i.e. the first breaks picked out on the recorded time series.

For processing of acquired data we use our own, curved ray velocity tomography software. The essence of this procedure is that the values of travel times calculated from the velocity field of an initial model are compared with the measured arrival times. As a next step, the algorithm makes a correction on the velocity field for decreasing the differences in the time values. This procedure is repeated many times by iteration. Since this process is convergent, after some modifications, the calculated velocity field will be more and more similar to the real velocity distribution.

The basis for the interpretation of the velocity maps is as follows: The loose (cavity) zones have lower seismic velocity but hardrock and consolidated formations have a high propagation velocity.

13. Investigation of a bastion by seismic tomography.

Method of seismic tomography was applied to investigate one of the corner-bastions of the Buda Castle called «Esztergomi Rondella» [10]. This rondella has a diameter of about 40 m and a height of 11 m. A thick brick-wall has been built around it and the surface is almost free: there are only some sitting-places and a high flag-pole with an enormous underground concrete basement. The aim of measurements was to investigate the inner structure: ancient walls and cavities were supposed to be at a depth of 5 to 10 m.

A combined geophysical investigation was carried out here: GPR measurements for prospecting the near-surface zone, seismic refraction profiling for tracing the bedrock relief and seismic tomographic measurements between boreholes and between the wall-face and the boreholes (Fig. 32 shows the sketch of this procedure). For these measurements two boreholes were drilled in the middle of the bastion, the logs of which gave also useful information on the subsurface conditions. Results of seismic tomography will be discussed here in detail.

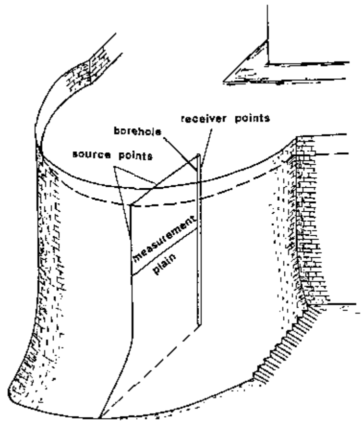


Fig. 32. Sketch of the seismic transmission measurement carried out between the wall-face of the rondella and one borehole.

Measurements were carried out in the following way: seismic receivers (geophones/hydrophones) were located in the boreholes one after the other, and the source of elastic waves was many of hammerings in every half meters along eight vertical lines on the outer part of the wall.

Figure 33 shows the ray tracing of the initial model (A) and the final velocity field (B) of a wall-borehole tomogram calculated by this type of iteration. The result of these measurements was that the velocity field in some planes shows a clearly distinguishable high velocity zone (see Fig. 33, B) that could be due to the Middle Age wall; while velocity maps of other planes do not contain this type of anomaly. In this way the presence of the wall could be demonstrated.

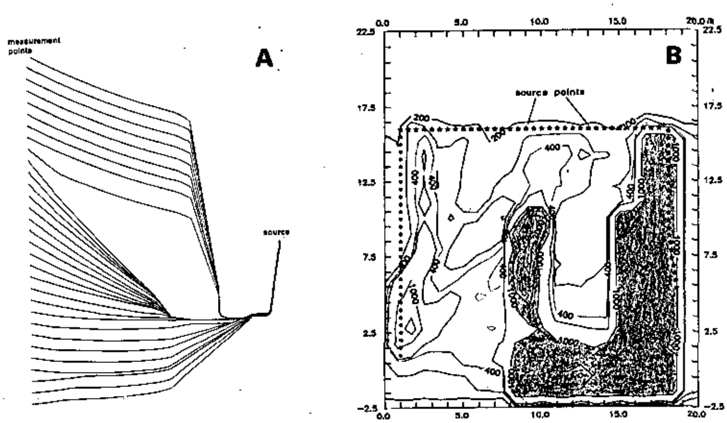


Fig. 33. The initial ray tracing (A) and the final velocity field (B) of the iteration.

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