GEOPHYSICAL TRANSACTIONS 1991
Vol. 36 No. 1-2. pp. 93–102

IP METHOD AS A MEANS OF IMPROVING THE SITING OF WATER WELLS

Heinrich AIGNER* and Pál DRASKOVITS**

In order to determine the optimum sites for drilling water wells, the IP method was used combined with a resistivity survey. Initially resistivity and polarizability characteristics of recent river sediments of different grain size were studied by laboratory model measurements. Interpretation of field data was based on these laboratory results. In order to support the interpretation of field measurements, in-hole resistivity and IP measurements (both in the time- and frequency domain) were carried out. For this purpose the instruments had to be adapted to borehole conditions. In a water prospecting project in SE-Hungary, the quantity and distribution of porous formations were determined qualitatively. These data were later checked by test pumping. On this basis in alluvial basins the best water-bearing formations can be expected in areas characterized by high resistivity and low or medium polarizability.

Keywords: IP-method, water prospecting, water wells, resistivity, polarizability, sand reservoir

1. Introduction

In hydrogeologic investigations of clastic sediments the sand/shale ratio is of prime importance as high permeability zones can only be expected in areas of high sand content. In water supply projects the various resistivity methods are generally used as the leading geophysical method. The limitations of the dc methods become obvious when sand and different sand–clay mixtures have similar resistivities. Therefore it is necessary to find another geoelectric method which, without considerably increasing the costs, might help to solve the problems. Judging from the technical literature, induced polarization might be the method sought [Aigner 1986, Bertin and Loeb 1976, Bodmer et al. 1968, Niesner and Weber 1985].

In sedimentary rocks, at the phase boundary between the matrix and the electrolyte, there is a state of equilibrium (electric neutrality). If a current is turned on (or off), this equilibrium of charges breaks down and polarization phenomena occur. The amplitude, frequency and phase characteristics of this polarization are utilized in the induced polarization method [Aigner 1986, Keller and Frishknecht 1970].

There are two ways to measure the IP effects. In time-domain measurements, direct current is passed into the ground and in a certain time it is interrupted. The current can be turned off practically instantaneously whereas the decay of potential between the electrodes is a relatively long process. Time-domain IP measurements mean the analysis of this decaying potential.

* Forschungsgesellschaft Joanneum, Roseggerstrasse 17, A–8700 Leoben, Austria
** Eötvös Loránd Geophysical Institute of Hungary, Budapest, POB 35, H–1440, Hungary
Revised version of a paper presented at the 49th EAEG Meeting in Belgrade, 1987

In frequency-domain measurements, charging is effected by ac current and the resistivity of the rocks (the amplitude of the potential) and the phase shift between the charging current and the measured potential will be studied as a function of the frequency.

The work was carried out co-operatively, the basis for co-operation — between Joanneum (Leoben, Austria) and ELGI (Budapest, Hungary) — being provided by the former's expertise in frequency-domain IP, while the latter's in time-domain IP. ELGI had, in 1982, completed a large water supply project when the idea for co-operation in using the IP method in hydrogeological problems arose. In that the results were available of a 4-year systematic VES + IP (time-domain) survey together with the pumping tests of the subsequent drilling project [Draskovits et al. 1990], an ideal test area was at hand for comparing different methods.

2. Instrumentation

Induced polarization has been the leading method in ore prospecting for about 25 years. The possibility of using the method for other purposes was opened up by the development of the instruments [Keller and Frishknecht 1970, Sumner 1976, Vacquier et al. 1957] increasing their accuracy significantly, first of all by introducing the microprocessor technique. In the 1980s a large amount of IP measurements were carried out both in the field and in the laboratory [Draskovits 1986, Keller and Frishknecht 1970, Lipskaya and Ryapolova 1970, Roy— Elliott 1980]. Several attempts were made to extend the method to in-hole measurements which resulted in further problems mainly of a technical nature (e.g. electromagnetic coupling through the cable, or limitations caused by the small hole diameter and large depths, etc.) [Draskovits 1986, Webster 1986]. In the first stage of Austrian–Hungarian co-operation, field and laboratory measurements were carried out in the time domain, and in-hole measurements were performed both in the time and frequency domains.

For time domain measurements the DIAPIR–18 resistivity and polarizability equipment (ELGI, Budapest) was used. It samples the first 1.5 s of the decay curve in 100 ms steps, and uses longer sampling intervals for the time range up to 30–40 s. The length of the current pulses can be varied in accordance with the formula $T = 1.6 \times 2^k$ s where $k = 0, 1, 2, \ldots, 9$.

For frequency domain measurements the instrument (Joanneum, Austria) contains a sine generator which produces current pulses of varying frequency; these pulses are converted to dc by a potential-to-current transformer. The measured potentials reach a two-phase lock-in analyser where the potential synchronized to the frequency is filtered and its amplitude and phase related to the charging current are determined. The instrument operates in the 0.1–10,000 Hz frequency range.

It must be underlined that the above instruments are not well loggers.

Either the standard field units are connected to the sondes or they are modified to some extent (e.g. built-in preamplifier), and standard well-logging winches, depth indicators, etc. are used.

3. Model studies

For model measurements Danube sand was used. By passing the sand through a series of sieves, different grain size samples were obtained (0.63–0.32 mm, 0.32–0.20 mm, 0.2–0.1 mm, 0.1–0.06 mm). They were saturated with fresh water and with a solution of NaCl of various concentrations. The resistivity and polarizability curves (100 ms after turn-off) for fresh and brackish water (0.01 n NaCl) saturation are presented in *Fig. 1*. This shows, in agreement with published data, that

— whereas resistivities of different grain size fractions differ slightly, their polarizabilities show considerable differences;

— the best conditions for high polarizability (first of all for electrolytic polarization) occur in the grain size fraction below 0.1 mm.

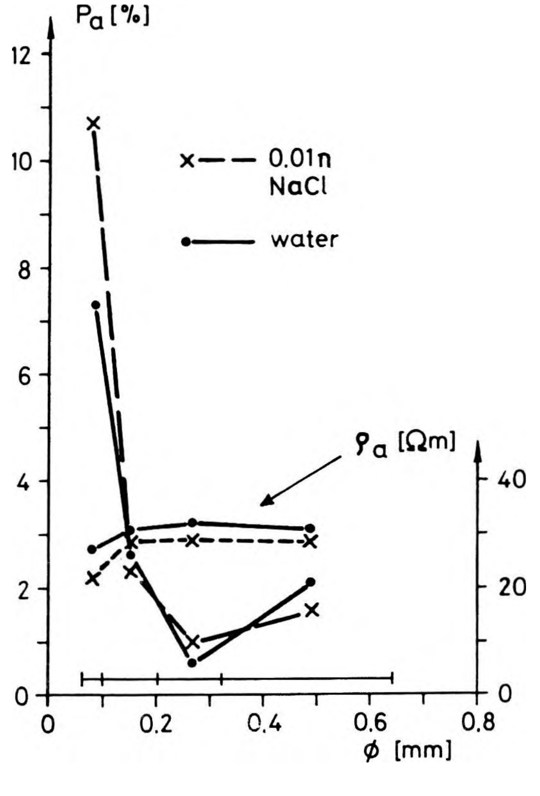


Fig. 1. Resistivity and polarizability measured in sands of different grain size

1. ábra. Különböző szemcseméretű homokban mért ellenállás és polarizálhatóság adatok

Рис. 1. Значения сопротивления и поляризуемости, полученных в песках различной зернистости

These results of laboratory measurements prove that the induced polarization method provides valuable additional information for water prospecting in a sand/shale sequence.

4. Field measurements

The next step in the co-operation was field work with the frequency-domain instrument of the Austrian team in an area which had formerly been prospected by ELGI. The test area chosen was an alluvial fan of the river Maros (SE Hungary). The task was to search for the coarse sediments of paleo-rivers running in Upper Pliocene and Pleistocene times. The whole alluvial fan is located on Pannonian clays of considerable thickness. An integrated geoelectric survey was carried out in 1978–82 over an area of 1500 km^2. Two promising depth intervals could be traced between the surface and near-surface formations of extremely variable resistivity and the low-resistivity Pannonian clays, named upper and lower water-bearing horizons. The areal resistivity and polarizability distribution of the upper water-bearing horizon are presented in *Fig. 2.* Depth to this horizon varies between 5 and 30 m — while the thickness of the water-bearing sequence between 100 and 300 m, decreasing from E to W. On the resistivity map there are definite highs of similar resistivity (Fig. 2a), interpreted as local accumulation of the coarse-grain fraction (areas marked by 1–2–3). So on the basis of this single parameter the hydrological value of these areas can be taken as near to equal. Anomaly No 1 can be judged more favourable because of its large extent.

The polarizability distribution of the same depth interval (Fig. 2b) shows a totally different character: areas having identical or similar resistivity show different polarizability.

5. In-hole measurements

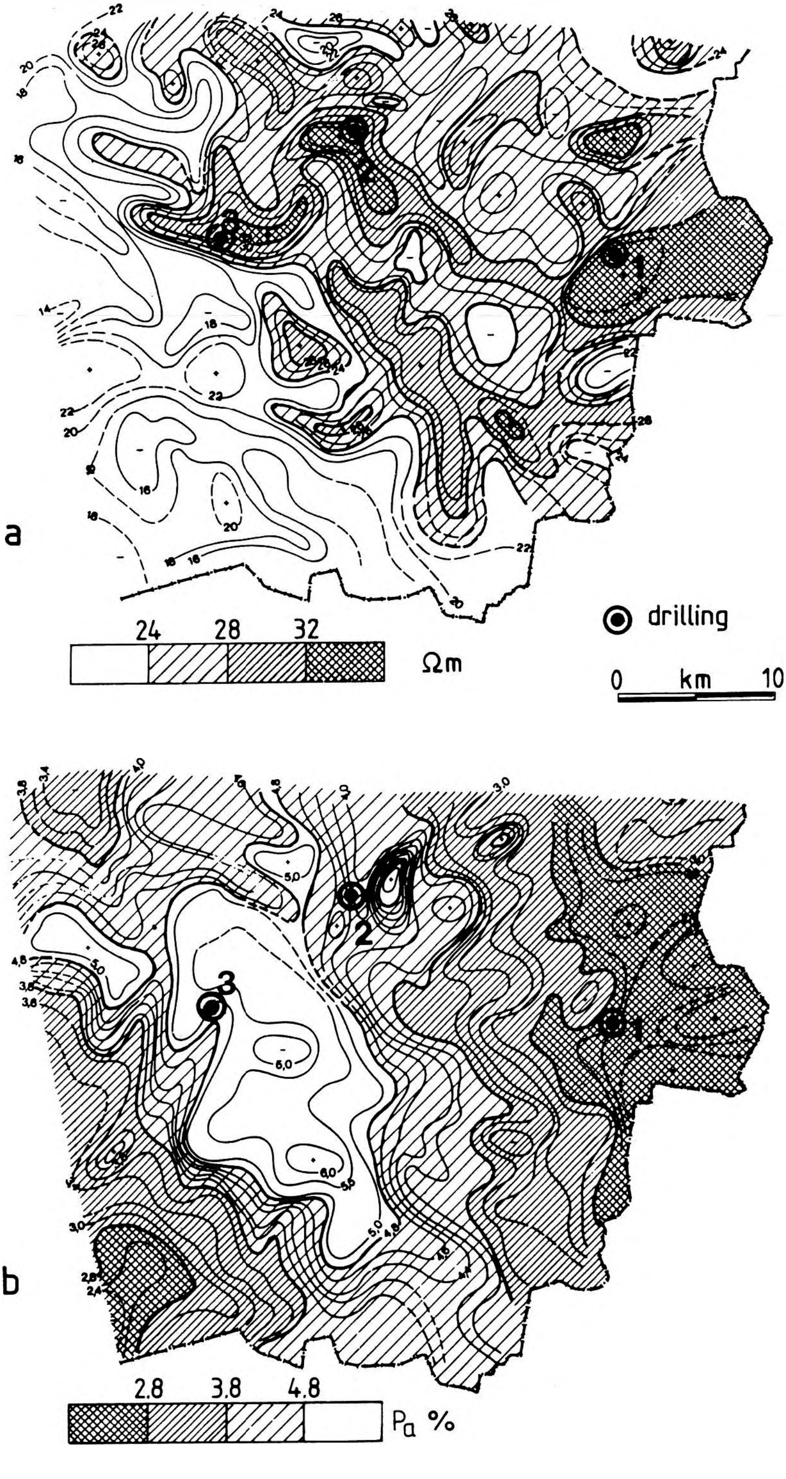
Figure 3. shows a comparison between point-like in-hole measurements performed with a 40 cm Wenner probe attached to a time-domain surface instrument and the resistivity log obtained with a 40 cm potential probe on drilling 1. The two resistivity curves match perfectly and enable us to construct the sand/clay variation in the lithologic column. The polarizability values are

— small (below 4%) in clays (e.g. 50–56 m);
— medium (4–6%) in clean sands (62–68 m);
— high (8–11%) at sand/clay boundaries (60 m, 70 m, 91 m, 98 m).

Fig. 2. Resistivity (a) and apparent polarizability (b) maps of the alluvial fan of river Maros

2. ábra. A Maros hordalékkúpjának ellenállás- (a) és látszólagos polarizálhatóság- (b) térképe

Рис. 2. Карты сопротивления (а) и кажущейся поляризуемости (в) по конусу выноса р. Марош


a
24 28 32
Ωm
drilling
0 km 10
b
2
3
2.8 3.8 4.8
Pa %

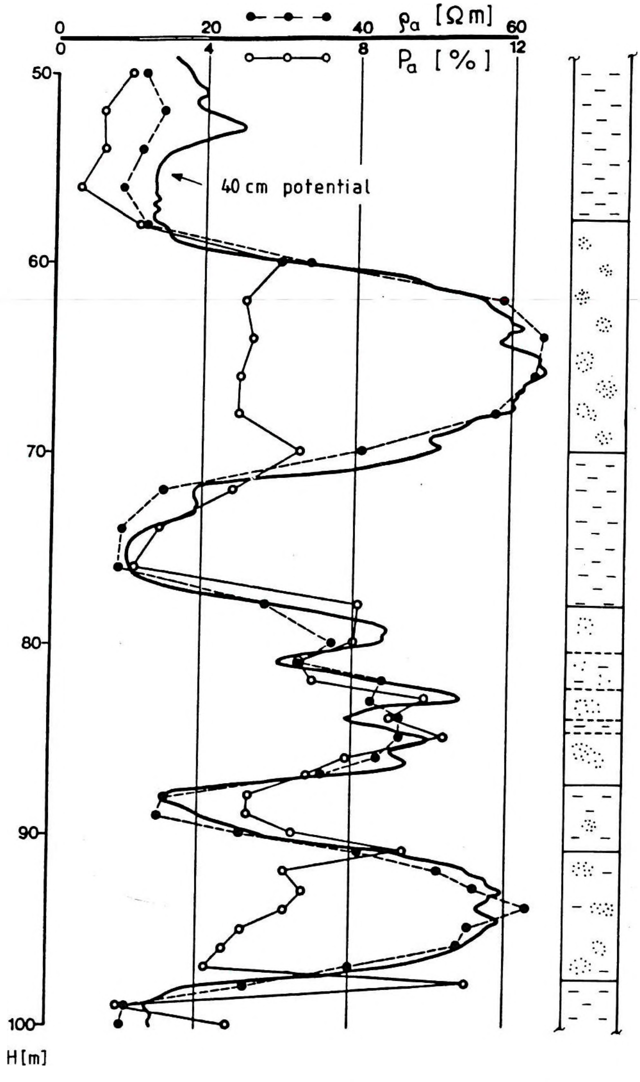


Fig. 3. In-hole resistivity and polarizability values measured in SE-Hungary

3. ábra. DK-Magyarországon mért fúrólyukbeli ellenállás- és polarizálhatóság értékek

Рис. 3. Значения сопротивления и поляризуемости, измеренных в скважинах юго-восточной Венгрии

These results suggest that induced polarization takes place mostly at sand/clay boundaries. Therefore the average level of polarizability becomes high where thin individual sand and shale layers alternate (e.g. between 78 and 86 m).

At the same time, the average resistivity level is only slightly lower than in the case of a clean sand layer (between 62 and 68 m). From these data it may be suggested that the resistivity value determined by surface measurements is linked with the total quantity of sand in the depth interval studied, while the polarizability value is linked with the distribution of this sand. Thus thick clean sand layers may be expected in areas of high resistivity and low polarizability, i.e. in our case in the eastern anomaly marked by 1. In areas of similarly high resistivity but high polarizability (anomalies marked by 2 and 3), variation of thin sand and clay layers are to be expected. This conclusion is supported by borehole data and pumping tests.

Time domain and frequency domain in-hole measurements were compared in the framework of another water supply project (Western Hungary). Frequency domain measurements were carried out in the frequency range of 0.1 to 1000 Hz, at 11 discrete frequencies. One point in clean clay (24 m) was taken as reference, and measurements at other points were normalized to this value. Normalized resistivity and phase curves obtained in clay *(Fig. 4a)* differ both for shape and amplitude from the respective curves obtained in sand (Fig. 4b).

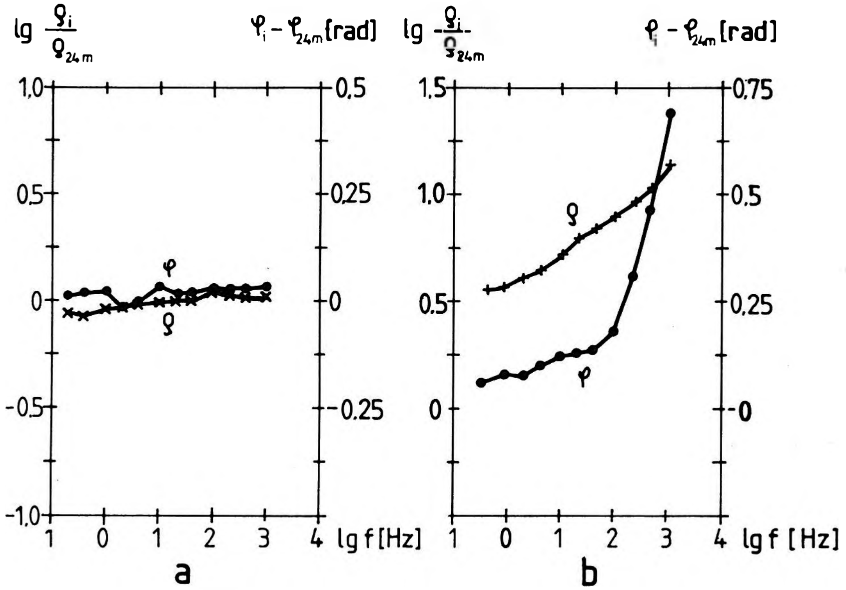


Fig. 4. Normalized resistivity ($\varrho_1/\varrho_{24\ m}$) and phase shift ($\varphi_1-\varphi_{24\ m}$) values versus frequency
a) Sonde in 25 m, clay; b) Sonde in 30 m, sand

4. ábra. Normalizált ellenállás ($\varrho_1/\varrho_{24\ m}$) és fáziseltolás ($\varphi_1-\varphi_{24\ m}$) értékek a frekvencia függvényében
a) 25 m mélyen lévő szonda, agyag; b) 30 m mélyen lévő szonda, homok

Рис. 4. Значения нормированного сопротивления ($\varrho_1/\varrho_{24\ м}$) и фазовых смещений ($\varphi_1-\varphi_{24\ м}$) как функции частот
а) зонд на глубине 25 м, глина; b) зонд на глубине 30 м, песок

Although the experiment comprises a short section of the well, it includes the boundary of a layer of dominating sand fraction around 28–29 m. This is reliably indicated both by dc and ac resistivity measurements *(Fig. 5c)* and the time-domain polarizability measurements indicate the same boundary (Fig. 5a). Figure 5b shows the phase shift as a function of depth and frequency. Sand appears with high phase shift and the contrast between sand and clay increases with increasing frequency. This is favourable from the viewpoint of both time demand and economy of measurements. In the middle part of the section it is interesting that ac and dc resistivity correlate well with the phase shift. A local polarizability maximum at a depth of 28 m indicates the same boundary.

Summarizing, we found that clay and sand can be separated by other methods (well-logging) more quickly and more accurately than by in-hole resistivity and IP measurements. However, our experiments were aimed not at accurate separation of clay and sand but as a means of contributing to the interpretation of combined resistivity and IP surveys. In this respect our results are of help in explaining IP phenomena in sand/clay sequences.

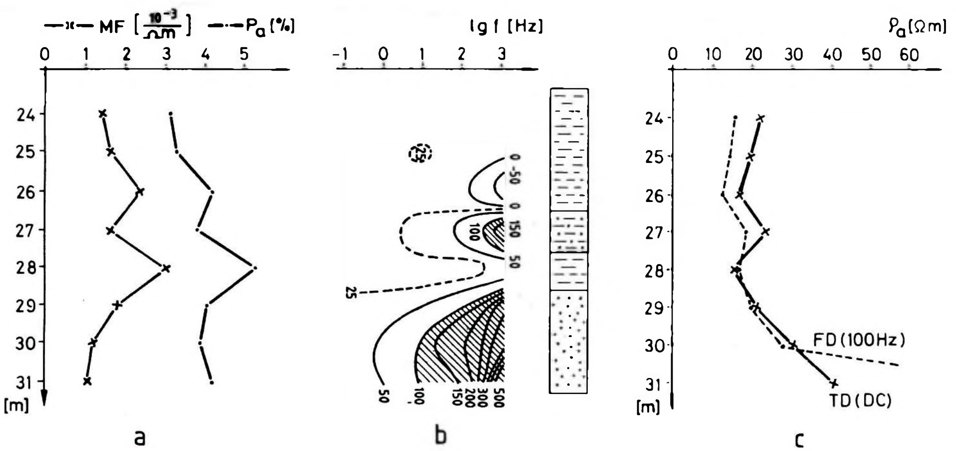


Fig. 5. In-hole resistivity, time and frequency domain polarizability measurements
a) Apparent polarizability in time domain (P_a) and frequency domain (*MF*)
b) Phase shift in mrad versus depth and frequency
c) ac and dc resistivity values

5. ábra. Fúrólyukbeli ellenállásmérések összehasonlítása idő- és frekvenciatartománybeli polarizálhatóság mérésekkel
a) Látszólagos polarizálhatóság az idő- (P_a) és frekvenciatartományban (*MF*)
b) Fázistolás mrad-ban a mélység és frekvencia függvényében
c) Váltóáramú és egyenáramú ellenállás értékek

Рис. 5. Сопоставление результатов скважинных измерений сопротивления с измерениями поляризуемости во временнóм и частотном диапазонах
a) Кажущаяся поляризуемость во временнóм (P_a) и частотном диапазонах (*MF*)
b) Фазовое смещение в мрад как функция глубин и частот
c) Значения сопротивления постоянного у перененного тока

6. Conclusion

In hydrogeologic prospecting of basins filled with young clastic sediments the use of the IP method is found to be a good means of complementing resistivity surveys. Anomalies of similar resistivity can be distinguished or even classified with the help of their apparent polarizability. The best water-bearing layers occur in areas characterized by high resistivity and low or medium polarizability judging from our results in several water-prospecting projects. This conclusion is supported by laboratory and in-hole resistivity and IP measurements, and by pumping tests.

REFERENCES

Aigner H. 1986: Methode der Induzierten Polarisation. Angewandte Geophysik, Bd. II., Springer Verlag Wien, Akademie Verlag Berlin, pp. 186–207

Bertin J., Loeb J. 1976: Experimental and theoretical aspects of induced polarisation. Bd. II, Gebrüder Borntrager, Berlin,

Bodmer R., Ward S. H., Morrison H. F. 1968: On induced polarisation and ground water. Geophysics **33**, 5, pp. 805–821

Draskovits P. 1986: Study on hydrogeological application of the induced polarization method. (in Hungarian) Project report, ELGI, Budapest (manuscript) 10 p.

Draskovits P., Hobot J., Smith B. D., Verő L. 1990: Induced polarization surveys applied to evaluation of ground water resources, Pannonian Basin, Hungary. *in:* Induced polarization: Application and Case Histories, Society of Exploration Geophysicists, Tulsa

Keller G. V., Frishknecht F. C. 1970: Electrical methods in geoelectric prospecting. Pergamon Press, New York

Lipskaya, A. E., Ryapolova, V. A. 1970: Application of induced polarization method in engineering geologic studies (in Russian). *in:* Application of geophysical methods in hydrogeologic and engineering geologic investigations, Moscow, pp. 30–37

Niesner E., Weber F. 1985: Anwendung der induzierten Polarization auf nichtmetallische Materialien, Projectbericht StA-60/84 und StA-60/85, Forschungsgesellschaft Joanneum, Leoben

Roy K. K., Elliot M. M. 1980: Model studies on some aspects of resistivity and membrane polarization behaviour over a layered earth. Geophysical Prospecting **28**, 5, pp. 759–775

Sumner J. S. 1976: Principles of induced polarization for geophysical exploration. Elsevier, Amsterdam

Vacquier V., Holmes C. R., Kintzinger P. R. and Lavergne M. 1957: Prospecting for ground water by induced electrical polarization. Geophysics **22**, pp. 660–687

Webster B. 1986: Time domain IP borehole logging. *in:* Borehole geophysics for mining and geotechnical applications, ed. P. G. Killeen, Geological Survey of Canada, Paper 85–27, pp. 107–118

VÍZKUTAK TELEPÍTÉSÉNEK OPTIMALIZÁLÁSA A GERJESZTETT POLARIZÁCIÓS MÓDSZER ALKALMAZÁSÁVAL

Heinrich AIGNER, DRASKOVITS Pál

Vízkutak optimális telepítése céljából az ellenállás méréseket gerjesztett polarizációs mérésekkel kombináltuk. Először laboratóriumi modellmérésekkel meghatároztuk a különböző szemcseméretű folyóvízi üledékek ellenállás- és polarizálhatóság jellemzőit. A terepi adatok értelmezése a laboratóriumi mérések eredményein alapul. A felszíni mérések értelmezésének alátámasztása céljából fúrólyukbeli ellenállás- és GP méréseket végeztünk az idő- és a frekvenciatartományban. E célból a mérőműszereket alkalmassá kellett tenni a fúrólyukbeli viszonyokra. Egy DK-magyarországi vízkutatás során kvalitatíve meghatároztuk a porózus képződmények mennyiségét és eloszlását. Ezeket az adatokat később próbaszivattyúzásokkal ellenőrizték. Mindezek eredményeképp megállapítható, hogy alluviális medencékben a legjobb víztároló képződmények a nagy ellenállással és kicsi, vagy közepes polarizálhatósággal jellemezhető körzetekben várhatók.

ОПТИМАЛИЗАЦИЯ ВЫБОРА ПУНКТОВ ПОД ГИДРОГЕОЛОГИЧЕСКИЕ СКВАЖИНЫ С ПРИМЕНЕНИЕМ МЕТОДА ВЫЗВАННОЙ ПОЛЯРИЗАЦИИ

Гейнрих АИГНЕР, Пал ДРАШКОВИЧ

С целью выбора оптимальных пунктов для гидрогеологических скважин электроразведка методом сопротивлений была поставлена в комплексе с методом вызванной поляризации. При этом на лабораторных моделях были определены параметры сопротивления и поляризуемости аллювиальных отложений различной зернистости. Интерпретация данных полевых работ основана на результатах лабораторных измерений. Для подтверждения интерпретации наземных данных были выполнены измерения сопротивления и поляризуемости в скважинах в частотном и временном диапазонах. Для этой цели измерительная аппаратура была приспособлена к скважинным измерениям.

В ходе гидрогеологических работ в Юговосточной Венгрии были качественно определены количество и распределение пористых пород. Эти данные впоследствии были проверены путем испытательных откачек. В результате проведенных работ можно установить, что в аллювиальных бассейнах отложения, наиболее насыщенные водой, можно ожидать на участках высокого сопротивления и малой до средней поляризуемости.