Chapter 7
Subsurface Permeability for Groundwater Study Using Electrokinetic Phenomenon

Alexander K. Manstein and Mikhail I. Epov

Abstract Electric parameters of rocks and soils are valuable and important information for the purpose of groundwater management. The existing methods for the study of electric parameters are able to give exact information about the structure of any media saturated with a fluid, even in noisy urban and industrial areas. The presented work is devoted to the interaction between a geological structure saturated with groundwater and its electrical parameters. The Near-surface Electro-Magnetic Frequency Induction Sensor (NEMFIS) has a narrower sensing volume with respect to Electric Resistance Tomography (ERT), does not require a direct contact with the ground and exhibits an high immunity to noise. In addition, NEMFIS is able to work with 14 frequencies in every station, providing a vertical resolution of 0.5–0.7 m. This sensor has been successfully used for groundwater contamination mapping in the past. The electroosmosis is a well known phenomenon used for dehydration of porous media and for impregnation. Such phenomenon has been used to study the electrokinetic features of rock samples. The sustainable filtration process of fluid through sandstone was observed, and the volumetric velocity of the fluid current was measured. The interaction between direct electric current and specific electric resistance was studied experimentally. The presented results show the possibility to create the electroosmosis process and control the transport on a large volume of groundwater. The analysis of electric conductivity changes measured by NEMFIS, allows us to assess the relative water permeability of the media.

Keywords Electrokinetics • Frequency induction

A.K. Manstein (✉) • M.I. Epov
Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of Russian
Academy of Science, Bld. 3, Koptyuga street, Novosibirsk 630090, Russia
e-mail: MansteinYA@ipgg.nsc.ru

7.1   Introduction

Development of new methods for the improvement of soils and rocks features for various tasks, e.g. building construction and exploitation, is one of the task of geophysical engineering. This work proposes the use of mass transport phenomena due to the injection of a direct electric current where the transport velocity can be measured using geoelectric methods. The measurement of rocks and soils electric conductivity is very important in view of it. Such a parameter is very sensitive to the water saturation and is applicable for a media soaked in electrolytes of any kind.

Features used to characterize solutions in physical chemistry can be divided in two groups of parameters: (i) parameters that can be studied by equilibrium system analysis; (ii) parameters that can be studied by non-equilibrium system analysis. The second group is formed by those parameters that can be assessed by diffusion, electric conductivity and viscosity [3]. Porous geological media soaked with fluids, mainly with electrolytes, are divided into sandy and argillaceous rocks [5]. Electrokinetic potential in water saturated clay layers is higher than in sands. The range of potential values is 10–80 mV for any alluvial sediments [1].

The electric field affects the electric conductivity of solutions, as it is well known. For instance, M. Win (Materials of 90-th convention of German Medical Doctors and Naturalists, 1928 [7]) has discovered that the electric conductivity of electrolytes is not a constant parameter, and increases with the intensity and frequency of an electric field imposed. He also showed that the increase is a function of concentration, valency and origin of the solution.

The electric conductivity of a porous geological media is determined by the presence of attenuated electrolyte ions in the rock matrix. The electric potential for such current carriers under the hypothesis of constant concentration (c) is:

$$\varphi = (\frac{d\Phi}{dn})c \tag{7.1}$$

where: Φ is the thermodynamic potential; n is the amount of ion charges in a unit of solution volume (see [4], pp. 151).

Considering the chemical potential gradient ($\nabla\xi$) the current density should include the additional part:

$$j = \sigma(E - \beta \cdot \nabla\xi). \tag{7.2}$$

Here β is the additional electric parameter of the media, which is describing the diffusion and electric processes. For the electroosmosis it is the electrokinetic potential [2]. The chemical potential gradient exists close to metal electrodes of grounded power lines. Chemical potential ξ is the derivative of the thermodynamic potential of a mass unit of solution by its concentration, at given P and T conditions. Concentration here is the ratio between the electrolyte mass and the total fluid mass in a given volume. Constancy of the chemical potential, as well as pressure and temperature constancy are the conditions for thermodynamic equilibrium.

Direct electric current in porous geologic media saturated by fluid at constant temperature causes a flux of electrolyte mass. Flux density of electrolyte mass, transported by macroscopic fluid movement is equal to the product of speed, solution density and concentration. Another component of the total flux density is the electrolyte transport by molecular diffusion. The above mentioned flux is proportional to the product of the electric current density and an additional electric parameter of the media. Let us designate the flux density of mass of electrolytes with the fluid in general as:

$$\rho c v \tag{7.3}$$

here v is the speed and ρ is the density of the solution. Given I as the diffusion flux density, the full electrolyte mass flux density is:

$$\rho c v + i \tag{7.4}$$

Irreversible diffusion leads to the increase of entropy. The entropy change speed is:

$$\frac{dL}{dt} = \int \frac{E \cdot j}{T} \, dV - \int \frac{i \cdot \nabla \xi}{T} \, dV \tag{7.5}$$

The diffusion flux, as well as the electric current density, can be expressed as a linear combination of j and $\tilde{N}\xi$. The diffusion flux density is:

$$i = -\frac{\rho D}{\left(\dfrac{d\xi}{dc}\right)_{P,T}} \nabla \xi + \beta \, j \tag{7.6}$$

here D is the electric field induction. When there's no electric current, and pressure and temperature are constant, the flux is due only to diffusion:

$$i = -\rho D \nabla c \tag{7.7}$$

All the electric-diffusion processes of porous media saturated with electro-lyte under thermodynamic equilibrium are described in the Eqs. 7.2 and 7.6.

The experimentally measured electric conductivity, diffusion and viscosity values that are needed to describe the non-equilibrium state of open system will be obviously depend on time. The instantaneous values of electric conductivity with gradient of electrolyte concentration are not able to describe the system. The speed of values change must be measured too. Equations 7.3 and 7.6 show that the diffusion flux density is small in comparison to macroscopic fluid flux in the media. Under the hypothesis of constant viscosity in the porous media under a low density of electric current, the electric conductivity and electroosmosis fluid volume flux speed are the values to be measured to describe the porous media.

The experiments described were performed to record the change of electric conductivity in time under direct electric current.

Taking into account that the total electrolyte mass flux density is proportional to the amount of current densities of the various origins, the authors made experiments

to discover the influence of a direct current from an external transmitter on the signal of two electromagnetic sounding devices. The direct current density from external transmitter was essentially higher than the density of sounding currents of both devices.

The modern instrumentation for the measurement of specific electric conductivity have an improved spatial resolution with respect to older methods, featuring better local measurements, that are very important for the study of small objects. For instance, the multielectrode DC sounding systems are able to perform profiling down to h meters depth using $3h$ transmitting line length, where h can be as short as 1 m. Such a multielectrode system can be used to monitor the groundwater flow.

The near surface electromagnetic induction sounding device (NEMFIS) features a particularly good spatial resolution, with respect to other methods of nowadays [6]. The NEMFIS does not require galvanic contact with the media and is very immune to noise. The device is a TD-EM three-coils sensor controlled by a wireless remote control. The total length is 2.75 m (1.4 m when transported), weighting 8 kg. Data visualization is in the form of maps and cross-sections, that is now under development for a real time data representation together with GPS data binding.

7.2   Core Samples Electroosmosis

The widely known electrokinetic phenomena – electroosmosis is using for porous media dehydration, impregnation etc. The electrokinetic parameters of cemented sandstone samples were measured in the Institute. The permanent process of fluid flux was observed.

The aim of the work (assessment of the flux speed of a fluid volume in porous samples due to electroosmosis) was obtained by measuring:

– The transported fluid volume (ml)
– The elapsed process time (s)
– The electric field intensity (V/cm)
– The current in the sample (mA).

The fluid used was distilled water was used as the fluid. The temperature 22 °C, pressure 740 mm mercury, air moisture 30–40%. The sample cylinders were 38 ± 0.5 mm in diameter, 12 ± 0.5 mm in length.

For the averaged macroscopic section of capillary-porous media the basic electroosmosis equation [2] is:

$$\frac{V_{eo}}{I} = \frac{\varepsilon \cdot \beta}{4\pi \cdot \eta \cdot \sigma} \qquad (7.8)$$

where V_{eo} is the volumetric speed of electroosmosis flux under electric current I, ε is the dielectric permittivity of the fluid, β the electrokinetic potential including double layer potential ξ, η the viscosity and σ the specific electric conductivity of the electrolyte.
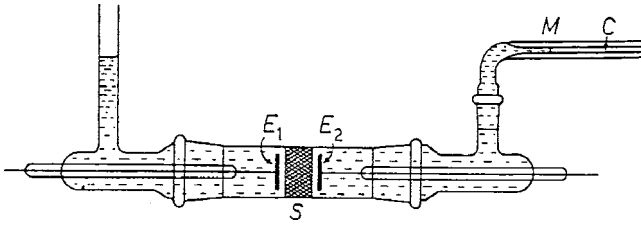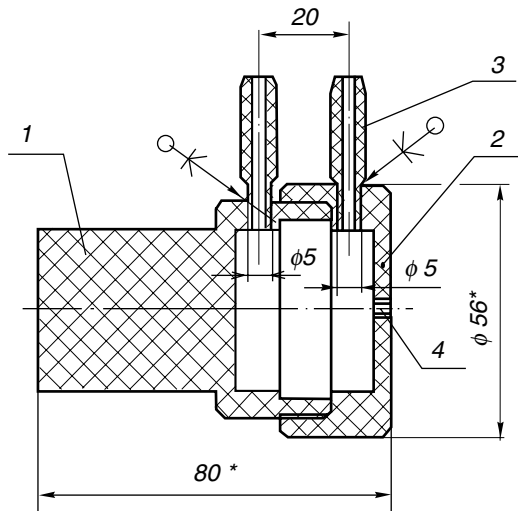
Fig. 7.1 Conventional device for the study of electroosmosis

Fig. 7.2 The device specifically built

The V_{eo}/I ratio is the electroosmosis transportation. It can be experimentally measured and includes information about β [2].

The sketch of a conventional electroosmosis study device is shown in Fig. 7.1. Such device is not suitable for water based solutions, because of the influence of gases produced by the electrolysis, as a consequence, a specific device has been built by the authors (see Fig. 7.2).

The sample is inserted in the holder (pos. 1) with the screw cap (pos. 2). The fluid is fed through the hose connectors (pos. 3). The electrodes are located inside the connectors. Thus, the gases are not able to reach the measuring capillary, that is connected by a flexible hose to the hole in the center of the cap (pos. 4). Our device is equipped with a feed tank and measuring capillary installed higher than the holder, as well as the device shown in Fig. 7.1.

It must be noted that bases, i.e. KOH, are preferable than salts, such as NaCl, because they do not form the chlorine gels nearby the anode.

The experiments show a permanent fluid flux through the cemented sandstone. The ratios between the averaged water transportation (ml) due to electroosmosis

Table 7.1 Ratio between electroosmosis water transportation (ml) and electric charge (mA·s) for the presented experiments

Sample #	Electroosmosis	Potential, V
1660–93	$0.169 \cdot 10^{-4}$ ml/mA·s	$260 \div 360$
5138–92	$0.250 \cdot 10^{-4}$ ml/mA·s	$200 \div 240$
1812–93	$0.100m \cdot 10^{-3}$ ml/mA·s	$80 \div 200$
1796–93	$0.074 \cdot 10^{-3}$ ml/mA·s	$160 \div 200$

Table 7.2 Dried and water saturated weighing of the samples

Sample #	Water saturated weight, kg (m)	Dry weight, kg	Water weight in the sample, kg (m_B)	$n = m_B/m \cdot 100$, %
1660–93	0.033	0.0328	0.0002	0.6
5138–92	0.0316	0.0306	0.001	3.2
1812–93	0.0336	0.0314	0.0022	6.55
1796–93	0.0358	0.034	0.0018	5.03

and the electric charge (mA·s), obtained in the presented experiments, are shown in Table 7.1.

The porosity of samples was assessed by their dried and water-saturated weighing (see Table 7.2).

7.3 Electroosmosis and Permeability Index

Let us apply the Darcy law for our experiment. The fluid flux volumetric speed through a porous sample can be expressed as follows:

$$V_0 = k_{por} \frac{\Delta PS}{l\eta} \tag{7.9}$$

where S is the section of the sample (m²), l is the sample length (m), ΔP is the difference of pressure at the sample edges (Pa), η is the fluid viscosity (Pa·s) and kpor is the porosity index.

The acting pressure of the fluid is:

$$P = \frac{F}{S} = \frac{mg}{S} = \frac{mg \cdot l}{S \cdot l} = \frac{W}{V_{sample}} \tag{7.10}$$

where F is the acting force (N), m is the fluid mass (kg), g is the acceleration of gravity (m·s⁻²), W is the potential energy (J) and V_{sample} is the sample volume (m³). Expressing the difference of pressure in terms of energy, the Darcy law can be written as:

$$V_0 = k_{por} \frac{\frac{W}{Sl}}{l\eta} S = k_{por} \frac{W}{l^2 \eta} \tag{7.11}$$

To express the potential energy by electric parameters we can use the mechanical power as a function of the energy $P = W/t$ (J/s) and electrical power $P = U \cdot I$ (V·A). Thus, the energy is $W = U \cdot I \cdot t$ (J), where t is the time of fluid flux. Considering the energy conservation law we can now write the Darcy law in terms of electric energy:

$$V_0 = k_{por} \frac{U \cdot I \cdot t}{l^2 \eta} \tag{7.12}$$

So, the basic equation of electroosmosis becomes:

$$\frac{V_0}{I} = k_{por} \frac{U \cdot t}{l^2 \cdot \eta} \tag{7.13}$$

Here, the volume of electroosmosis water flux is connected to the permeability index.

Since the energy is an additive physical parameter, the heating energy can be easily discriminated. The heat quantity that is needed to warm up the water is proportional to the water mass m and the temperature increment ΔT:

$$Q = c \cdot m \cdot \Delta T \tag{7.14}$$

where c is the specific heat, with $c = 4.19 \cdot J/(g \cdot K)$ for water. Considering the heating energy, the connection between electroosmosis and permeability is:

$$V_0 = k_{por} \frac{U \cdot I \cdot t - 4.19 \cdot m \cdot \Delta T}{l^2 \cdot \eta} \tag{7.15}$$

This relationship is essential for samples, while for in-situ works the heating energy can be neglected, being of insignificant value.

7.4   Electrometric Soundings and Electroosmosis

The influence of direct electric current on the results of electric and elec-tromagnetic soundings was studied. A direct current of 10 A was imposed between the casings of two wells. The distance between wells was 200 m and the water table was 2.5 m. All the measurements were made nearby the negative pole. The current flow time has been 80 min.

The apparent specific electric resistivity diagram measured by the NEMFIS sensor is shown in Fig. 7.3. The direct current makes the apparent resistivity decrease.

The apparent resistivity gradient is equal to the fluid flux speed. The speed can be assessed as an average resistivity decrease speed and media relaxation speed after the direct current cut off. The time of formation of a steady-flow process is the time of equalization of the electric energy with the potential energy and is equal to the fluid flux time.
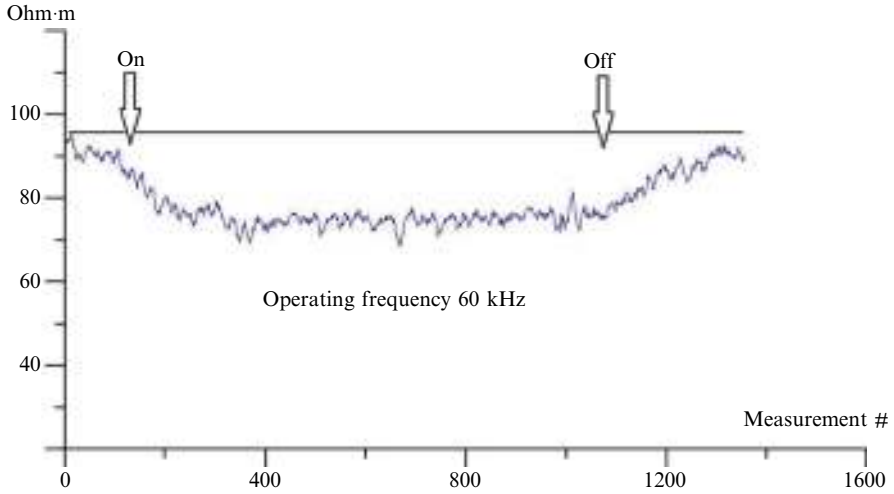
Ohm·m

Fig. 7.3 Apparent specific electric resistivity diagram measured by NEMFIS
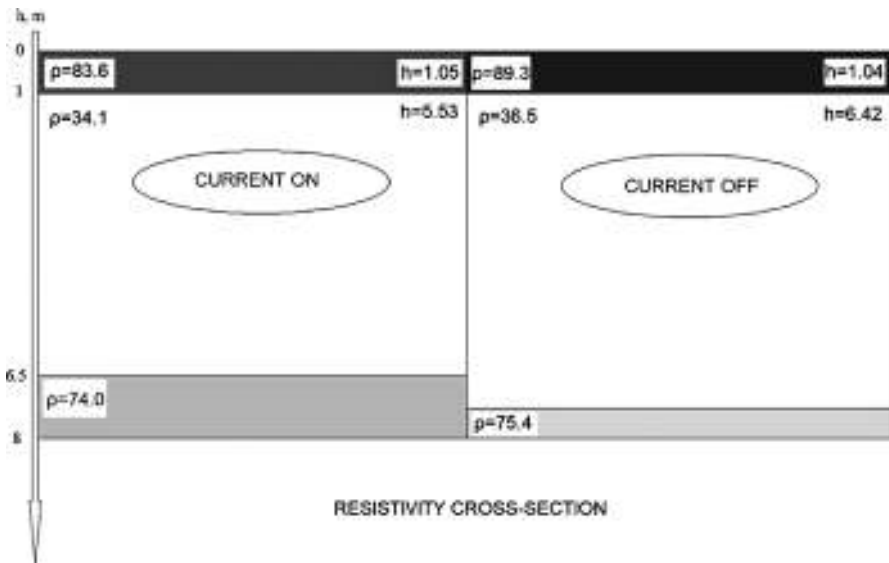

Fig. 7.4 Resistivity cross-section after 50 min of DC action

The DC electrical vertical sounding was performed before the direct cur-rent flow and during the steady-flow process (see Fig. 7.4). The data inversion in an horizontally layered model was performed. It is ascertained that after 50 min of direct current flow the soil becomes more conductive at the depth up to 6.5 m. The electric conductivity, as per S parameter which is the ratio of layer thickness to his specific resistivity, was increased up to 7%.

The increase of fluid volume in the system is the only one cause of the electric resistivity increase. Thus, both the experiments show the electric conductivity increase caused by electroosmosis fluid flux.

7.5 Results

The presented work shows the possibility of organization and control of the electroosmosis processes for large groundwater mass transportation. The electric conductivity change and the measurement of the volumetric speed of the fluid flux allow us to assess the water permeability of the media and permitted to introduce a new electric parameter: the electrokinetic potential.

References

1. Dobos D (1980) Electrochemical constants. Russian edition. Mir, Moscow, 365
2. Dukhin SS, Deryagin BM (1976) Electrophoresis. Nauka, Moscow, 332
3. Harned G, Owen B (1952) Physical chemistry off electrolytic solutions, Russian edition. Moscow, Izdatinlit, 628
4. Landau LD, Lifshiz EM (1982) Electrodynamics of continuum. Nauka, Moscow
5. Manstein AK, Epov MI et al (1999) Seismic velocities change under direct electric current. Geol I geofizika 40(3):465–473
6. Manstein AK, Epov MI et al (2000) Patent of Russian Federation No. 2152058 C1, G 01 V 3/10, dated 24.06.98. Method of induction frequency sounding. Russian patent agency, vol 18, p 1
7. Materials of 90-th convention of German Medical Doctors and Naturalists, Hamburg, September, 1928 Phys. Z. S. 29 751, 1928: I. M.Win (Jien). About digression of electrolytes from Ohm law; II. H. Ioos (Jien). Theoretic explanation of electrolytic conductivity from electric current voltage and frequency; III. E. Lange (Munich). New thermochemical and refractometry studies of strong electrolytes. http://www.ufn.ru/ru/articles/1929/3/e/