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RECONSTRUCTION OF ELECTRIC IMPEDANCE FIELD OF SOIL WITH CLAY ANOMALY

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Electrical impedance characterizes the properties of the examined environment when passing through an alternating electric current. The paper is based on the dependence of the course of real and imaginary components of electrical impedance on the humidity of the porous environment. Different soil environments have various water retention capacities under the same hydrometeorological conditions. This hydrophysical characteristic is used in the presented paper to study the inhomogeneity of the porous environment. The contribution is beneficial in that it proposes a method which, based on simple measurements, allows to evaluate the homogeneity of the porous environment. The method is widely used in water management (e.g. determination of failures of sealing cores in earth dams and dams) but also in hydrological survey and monitoring (e.g. determination of volume humidity).

KEY WORDS: clay, soil, probe, electrical impedance, Z-meter device

Introduction

Electrical impedance (EI) extends the concept of electrical resistance to situations where alternating electrical current passes through the environment. It is a quantity whose value depends on many factors of which is used in various fields of science and applications (Barbiero and Miracapillo, 2008). The EI of the measured environment can be detected across the frequency spectrum. Therefore it can provide a broader picture of its layout – impedance spectrometry (IS). It is consequently used to characterize or detect solid, liquid and gaseous substances and their properties. IS has become a relatively convenient method in the research and development of materials because it requires relatively simple electrical measurements, in most cases, non-destructive, which can be easily automated. Generally, three basic measurement methods are used in IS, namely transient phenomenon measurement, measurement response at white noise and EI measurement on each frequency of the required spectrum separately (Barsoukov and MacDonald, 2005).
In practical terms, the most commonly used method of measuring EI at each frequency of the desired spectrum is separately. Generally speaking, a harmonic signal of constant frequency and amplitude is input, and the phase shift and amplitude in the desired frequency range are monitored. The advantage of this measurement principle over the other two approaches is a good signal-to-noise ratio and the ability to measure (depending on the meter's instrumentation) in the frequency range from mHz to MHz. However, since it is necessary to perform measurements in the selected frequency spectrum for each frequency separately, it is required to take into account the time consuming of the measure, which may be a limiting factor when monitoring dynamic phenomena.
Because of their predictive ability, electrical resistance or electrical impedance methods have been included. They are also used as geoelectric research methods (Gruntorád, 1985; Karous, 1989; Vogelsang, 1994) or in hydrogeology (Mareš, 1983). The most common field electrical geophysical methods used for monitoring processes occurring in bodies of earth dams due to their hydrodynamic loading include methods using conductivity, capacitance, microwave and resistive measurement principles. Their basis is the dependence of parameters that characterize soil in an electric field on the change of water content in soil.
In the paper, a modified third EI measurement method was chosen for the measurement of electrical impedance for the detection of anomalies occurring in the ground environment. An alternating electric field was used to assess the soils. The EI measurement method was implemented by implementing the multi-electrode resistance method (MRM) IS with extension to electrical impedance tomography (EIT). The physical principle of the electrical resistive method using direct current, which is based on Ohm's relationship, has been known and used in archaeology and geology since the early 20th century. In this case, the modification of the IS measurement

method and the EI measurement method is based on the fact that an initial measurement is performed in the selected frequency spectrum. From the measured characteristics of the measured ground environment (output that monitors the EI components), one measurement frequency is chosen for the experiment at which the most positive signal response was detected in both EI components measured.

The experiment aimed to verify whether the above mentioned EIT diagnostic method and the apparatus with the Z-meter device can be used for the detection and mapping of soil failure sites, respectively places with anomalies. In practice, this involves revealing layers of deposits, gravel, the level of the bedrock, places saturated with water, cracks or larger veins in rocks. MRM has excellent results in searching for underground cavities, galleries, buried wells or excavations for utilities. In the field of water management, from the stability of the building structure and the safety of its operation, it is primarily the detection and monitoring of sites with higher water content.

Because of the water load, it is seepage through the dam can be detected, including possible catastrophic consequences leading to its total destruction (Cunningham, 1986; Dean et al., 1987).

The detection of anomalies occurring in the earth environment (subsoil of hydro-technical structures, earth dams, etc.) by electric impedance tomography (EIT) is, therefore, a topical topic.

Electrical impedance spectrometry and Z-meter device

The method of electrical impedance spectrometry belongs to a group of indirect measurement methods (Barbiero and Miracapillo, 2008), which represents a sensitive instrument and an experimental technique designed to determine the parameters of the observed hydrodynamic effect. It is based on a periodic harmonic signal of a small amplitude providing minimal concentration changes at the surface of the electrode associated with the measured environment (Pařílková, 2010).

The basic principle of the electrical impedance spectrometry method is the measuring of the frequency characteristic of the electrical impedance Z of the environment. Electrical impedance is a complex quantity that describes the apparent resistance of a porous medium and the phase shift of an electric voltage against an electric current when a harmonic alternating electric current of a given frequency passes through the environment. In the DC circuit, the electrical resistance R [Ω] of the resistor characterizes the soil properties (water content, porosity, humidity, ion content, temperature, etc.). The electrical impedance $\mathbf{Z}$ [Ω] characterizes the features of the soils in the AC circuits (the characteristics of the soils, which can be described above by the apparent resistance X [Ω], such as texture, grain size, ease, etc.).

The frequency response of the electrical impedance of the soils $\mathbf{Z}$ can be expressed in the form

$$\mathbf{Z} = R + \mathrm{j} \cdot X \tag{1}$$

where R [Ω] is the resistance forming the real part of the electrical impedance (generally independent of frequency) and X [Ω] is the reactance forming the imaginary part of the electrical impedance (varies with frequency). When expressing the reactance, which is predominantly capacitive in the case of soils, the angular velocity ω [Hz], which is given by

$$\omega = 2 \cdot \pi \cdot f_M, \tag{2}$$

where f_M [Hz] is the measuring frequency.

The EI measurement of soils is based on the consideration that two electrodes, which form one EIS sensor, are installed in the distance L [m]. The electrically defined monitored space of the soil will always have the character of a resistor, that is, there will always be a real part R of the EI of the soil and the capacitor represented by the resistance X_C [Ω]

$$X_C = \frac{1}{\omega \cdot C} = \frac{1}{2 \cdot \pi \cdot f \cdot C}. \tag{3}$$

The electric conductor delimited in this way may have the shape of a cylinder or a prism with a cross-sectional area A [m^2] and a length l [m]. Therefore, it is possible to express the resistance value (resistivity) ρ [Ω m] resp. conductivity (specific conductivity)

$$\sigma = \rho^{-1} \tag{4}$$

which are used most frequently to describe the electrical properties of soil, as they are closely dependent on hydrogeological parameters of soil and rock environment.

$$\rho = R \frac{A}{l} \tag{5}$$

The complexity of monitoring the environment is documented by the nomogram of electrical resistances (Fig. 1), resp. the conductivity of the earth (Pande, 1975). For electrical impedance of soil measurement was used apparatus with Z-meter IV device. The apparatus consists of a Z-meter device, measuring probes with cables and an AC power source. The basic parameters of the used Z- meter IV device are given in Table 1.

Materials

For the experiment were used a sample of sand and three samples of clay. It is of sand (Fig. 2) mined near village Bratčice (designation sand Bratčice) was used.

The sand formed a homogeneous environment, so only a material with an effective grain size of 1.0 mm was used, which was separated by sieving through standard sieves.

As clay samples (Fig. 2) were used clays with different chemical composition (designation B01, GEM and GEP) were provided by LB Minerals. These samples were used to created inhomogeneity of the environment. The chemical composition of clays are given in Table 2.

A density test (Fig. 3), (ČSN EN ISO 14688-1, 2018), (ČSN EN ISO 14688-2, 2018) was used to characterize the clay samples. The result is a graph where the horizontal axe shows the grain diameters, and the vertical axe cumulatively show the weight percentages of soil particles. The results are shown in Fig. 4.

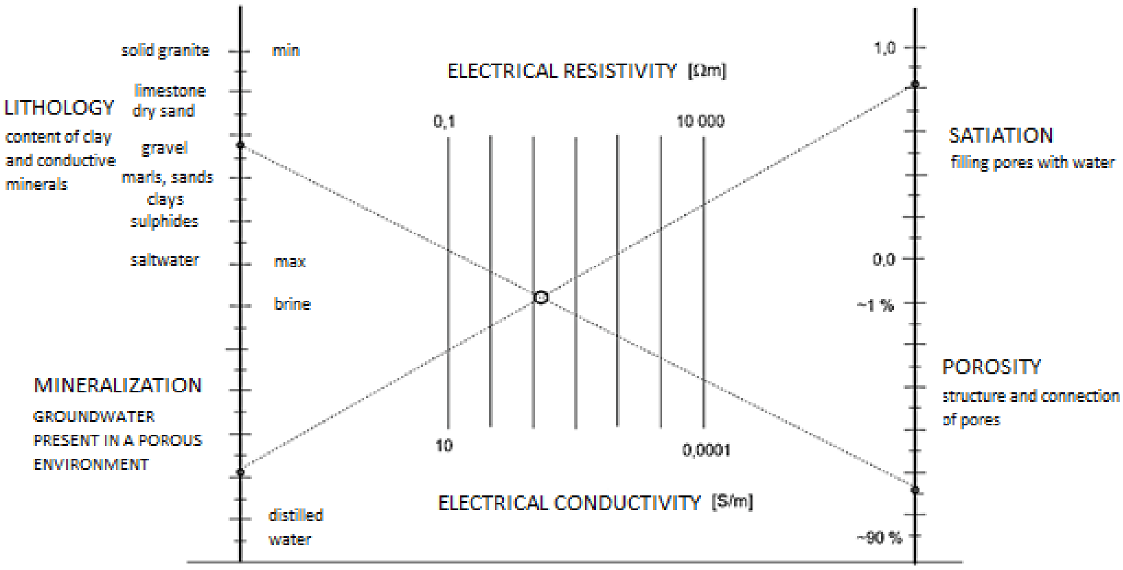

Fig. 1. Nomogram for estimating the impact of changes in basic factors on the resistivity assessment respectively conductivity of the natural environment.

Table 1. Parameters of the Z-meter IV device

Parameter	Z-meter IV
Impedance range	10 Ω - 1 MΩ
Frequency range	100 Hz – 200 kHz
Measuring Voltage	0.2 V and 1.0 V
Accuracy of module Z measurement	± 2 % from range
Accuracy of phase measurement	± 2 °
Communication interface	USB, SD card, Ethernet, Bluetooth
Numbere of measurement points	1, 8, 16, 32, 64, 128, 256
Switcher	internal, external
Power	battery, net

Table 2. Parameters of the Z-meter IV device

TITLE	*SiO2* [%]	*Al2O3* [%]	*Fe2O3* [%]	*TiO2* [%]	*CaO* [%]	*MgO* [%]	*Na2O* [%]	*K2O* [%]
B01	48 – 52	32.0 – 34.0	2.3 – 2.7	0.8 – 1.2	0.2 – 0.4	0.2 – 0.4	0.0 – 0.2	2.3 – 2.8
GEM	54 – 58	16.5 – 18.5	10.0 – 12.0	1.0 – 1.3	1.0 – 1.3	2.5 – 3.5	0.1 – 0.3	3.0 – 3.7
GEP	54 – 58	18.0 – 20.0	7.5 – 9.5	1.3 – 1.8	1.2 – 1.5	2.2 – 3.2	0.1 – 0.3	2.7 – 3.5

Fig. 2. Samples of soils (sand Bratčice, B01, GEM, GEP – designation from left to right).

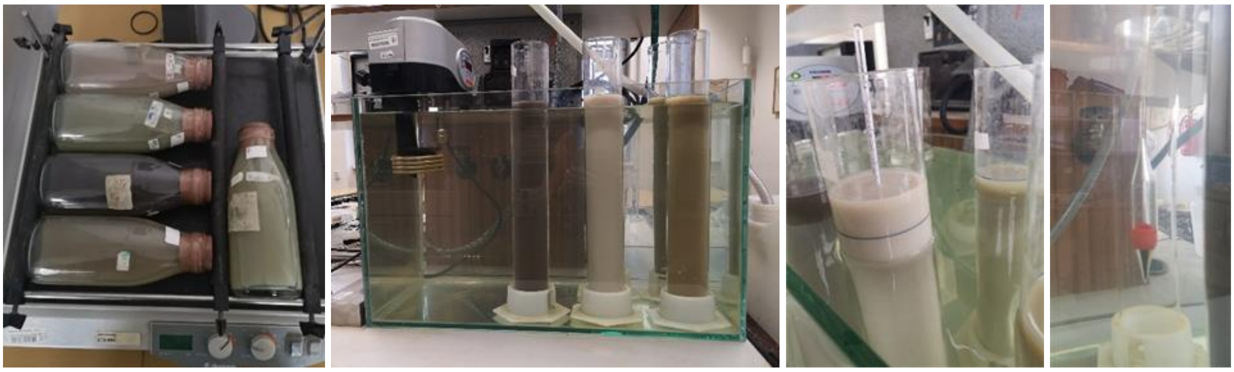

Fig. 3. Density test.

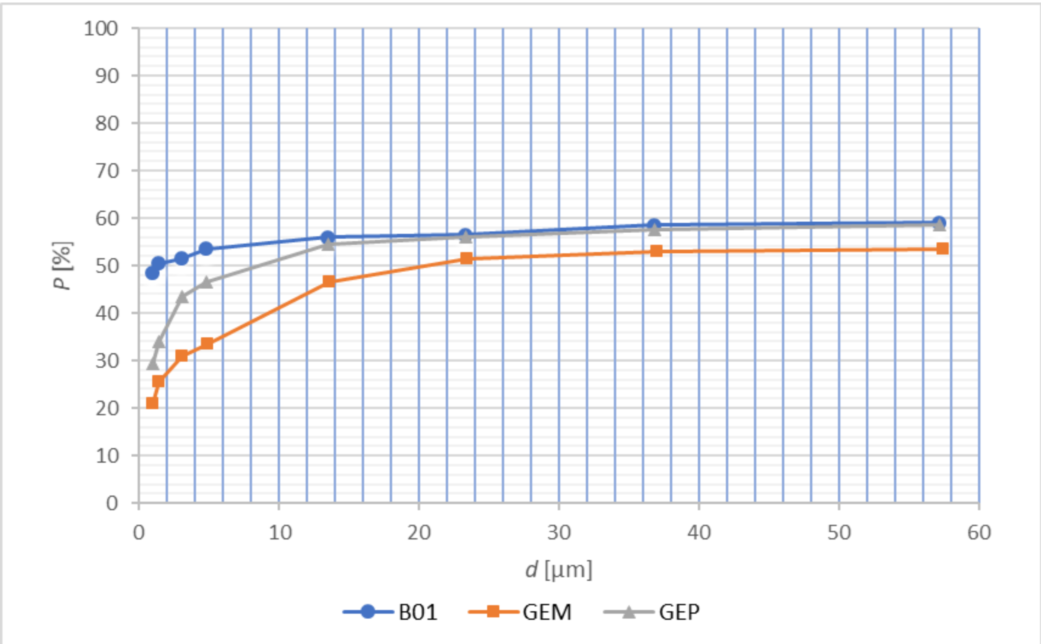

Fig. 4. Results of the density test.

Experiment

The experiment was carried out in laboratory conditions at the laboratory of Water Management Research at the Faculty of Civil engineering in Brno. It was based on the measurement of the components (real *R* and imaginary *X*) of the electrical impedance using the Z-meter IV device. (Pařílková and Radkovský, 2016). For the measurement of electrical impedance was used a model (Fig. 5 – left) consisting of a particular cylindrical organic glass container with an inner diameter D=0.19 m, a height h=0.29 m and a wall thickness t=0.004 m.

A carrier was placed in the model, which divided the model into a measurement space containing soil (upper part) and space for accumulating infiltrated water with an output outside the model (lower part). The measuring area of the cylindrical model was fitted with 16 stainless steel electrodes on the circumference at three „colours" levels (yellow, red and black) of the model (Fig. 5 – left). The electrodes were realized screws with a round head with a diameter of 0.01 m, whose mutual distance was constant L=0.037 m (Fig. 5 – left). Conductors with a constant length of 1.5 m were connected to the electrodes. To ensure stability and prevent leaching of fine particles of the soil sample in the modified cylindrical model, PE mesh-work was placed on the carrier (Fig. 5 – right). The mesh-work is inert to the adherence of possible impurity impurities of the salt type and has a mesh size sufficient to permeate water while preventing the elimination of soil particles.

The electrodes and the free conductor ends were numbered because of the gradual connection of the individual sensors to the Z-meter device. The EI measurement was carried out in such a way that each of the connection electrodes gradually formed a sensor with all the remaining electrodes in one surface section. Probes used in laboratory conditions were passive because they did not contain any active element (signal generator, voltage source, etc.) in their design. During the measurements, the sensed length of the examined environment was determined by the area of measuring electrode in contact with ground and distance between electrodes. The evaluated point of this conductor was placed in the geometric centre of the conductor for the further processing. The measurement of electrical characteristics (real R and imaginary X components) was realized with the Z-meter IV device. The device was connected to the measuring electrodes by cables. Switching of individual sensors (Fig. 6) was realized manually, since this is a static task, using KSS AC-3RD crocodile clips, which were equipped with insulating PVC material.

The experiments were designed in such a way that a sample of sand Bratčice's with an effective grain size of 0.001 m separated by sieving through standard sieves was gradually poured into the cylinder (Fig. 7 – right). The sample was compacted by shaking in layers and pierced. After the model was filled with a soil sample, the sample was loaded with distilled water 0.01 m above the soil sample level and was subsequently punctured again to eliminate air bubbles in the sample. Since free ions (e.g. Na +, Cl-) cause electrical conductivity in wet, porous soils, distilled water has been used to minimize the physicochemical properties of the water. At this time was done the first measurement of the field of electrical impedance. After the measurement, a portion of the soil was asymmetrically removed from the model, and a clay sample (Fig. 7 – left) was placed at this place, representing an anomaly in the ground environment. The anomaly was represented by a clay-shaped clay with a diameter of 0.04 m (Fig. 7 – in the middle). The clay sample was then backfilled with a sampled soil. The soil sample was again compacted with weights, pierced and loaded with water. Three samples of different clays were used in succession and were always placed in the same place.

The changes of ambient conditions were monitored during the whole experiments. The temperature and humidity of air in the room and the temperature and humidity of the environment were monitored. The changes in the measured ambient conditions during the experiments were negligible. In the place, the temperature was 22°C ± 0.2°C and air humidity was 60.0% with a deviation of ± 0.5%. The temperature of the soil samples measured varied by a maximum of 0.5°C.

Before starting the experiment, the parameters of the measuring device were set up (Table 3). The parameters of the measuring instrument were the same for all measured experiments. The location of the clay sample in the model is schematically shown on Fig. 8.

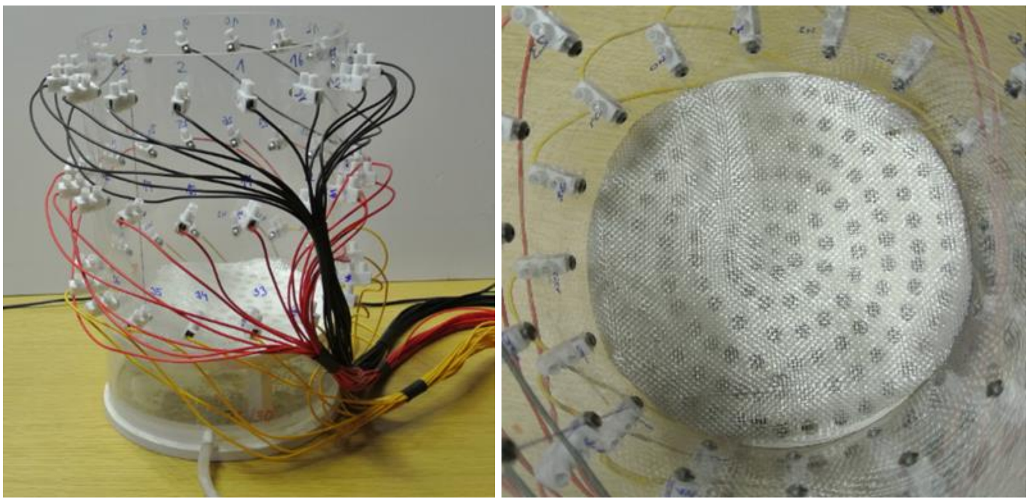

Fig. 5. A cylinder model – left, PE mesh-work – right.

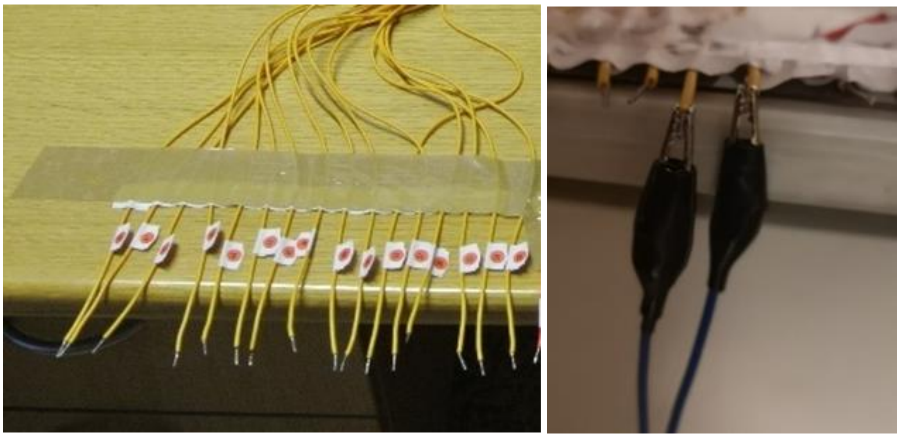

Fig. 6. *Switching between individual sensors.*

Fig. 7. *A model with a sample of sand – left, a sample of clay – in the middle, sample of clay inside the environment – right.*

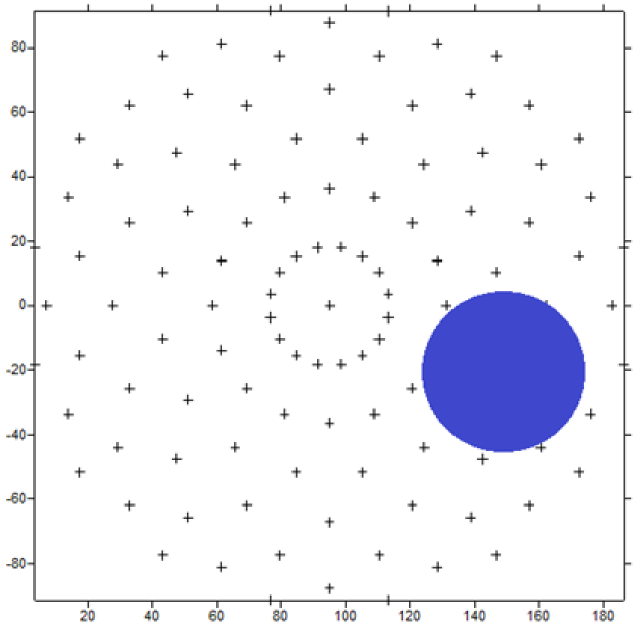

Fig. 8. *Schematic design of the experiment (blue circuit presents clay position).*

Table 3. Parameters of the Z-meter IV device

Measuring regime	1 probe pair	-	**Measuring frequency**	8 000	Hz
Number of channels	1	-	**Number of repetitions**	1	-
Sampling time (sensing the value)	100	ms	**Time lag between measurements**	10	ms

Results and discussion

Data were processed using an MS Excel program. Then the results were evaluated in the program Surfer 8 (Surfer, 2002). Triangulation with Linear interpolation was used for evaluation results.

This method uses the optimal Delaunay triangulation, which means that the algorithm creates triangles by drawing lines between data points. The original points are connected in such a way that no triangle edges are intersected by other triangles. The result is a patchwork of triangular faces over the extent of the grid. The accuracy of the method is determined by the positioning of the electrodes; it means the number of measured data (Surfer, 2002).

It was measured both components of the EI between each pair of electrodes total number of which is 16 in one level. After this measured was calculated model EI and phase shift. Resistance maps have been created from the EI model for better presentation of results. Resistivity was calculated according to formula (5). The implementation of resistivity values was done as relative. It means that was calculated and evaluated the difference of resistivity between the values of the initial environment and environment with an anomaly.

The results of the measured individual environments are shown in Fig. 9 – Fig. 11

From these results (Fig. 9 – Fig. 11) it is possible to detect the location of the "anomaly" in the given environment in individual experiments, resp. the changes of the monitored environment. However, the differences between the measurements are insignificant, as the clay samples used are very similar, which is also evident from the specified curves of grain size (Fig. 4).

The results also show the significant surrounding environmental changes near anomaly due to manipulation of the environment (removal, replacement and backfilling) between individual experiments.

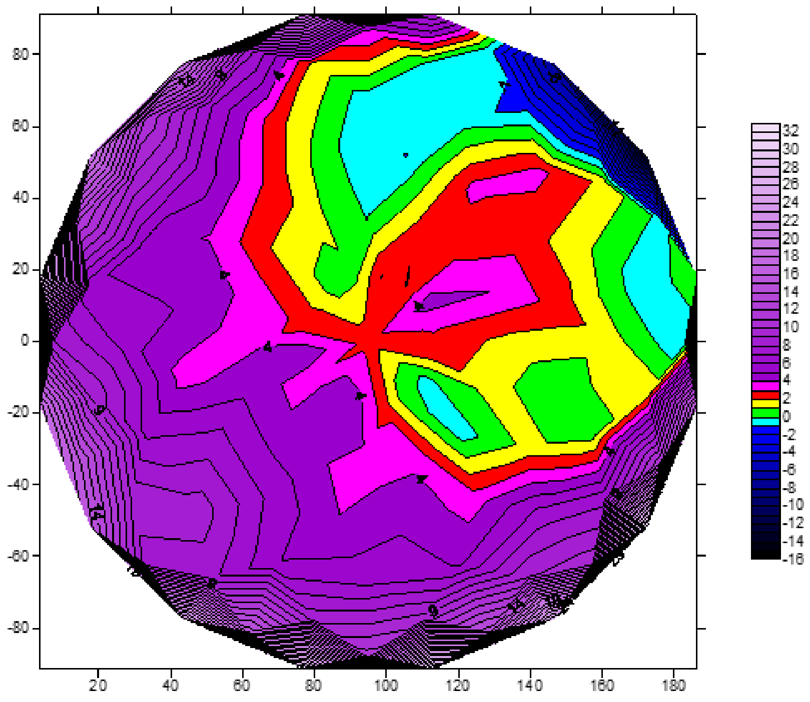

Fig. 9. Evaluation of resistivity in Surfer 8 for clay designation "B01".

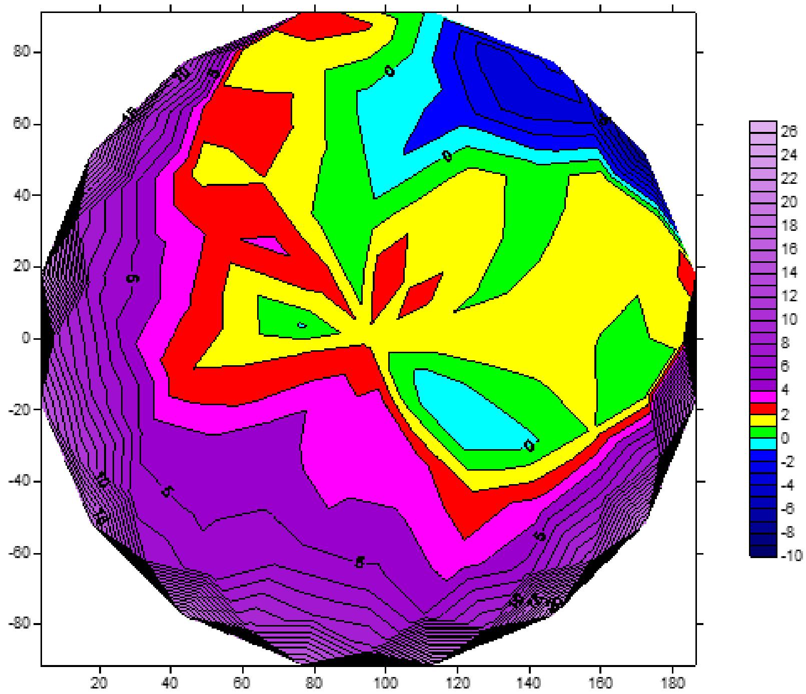

Fig. 10. Evaluation of resistivity in Surfer 8 for clay designation "GEM".

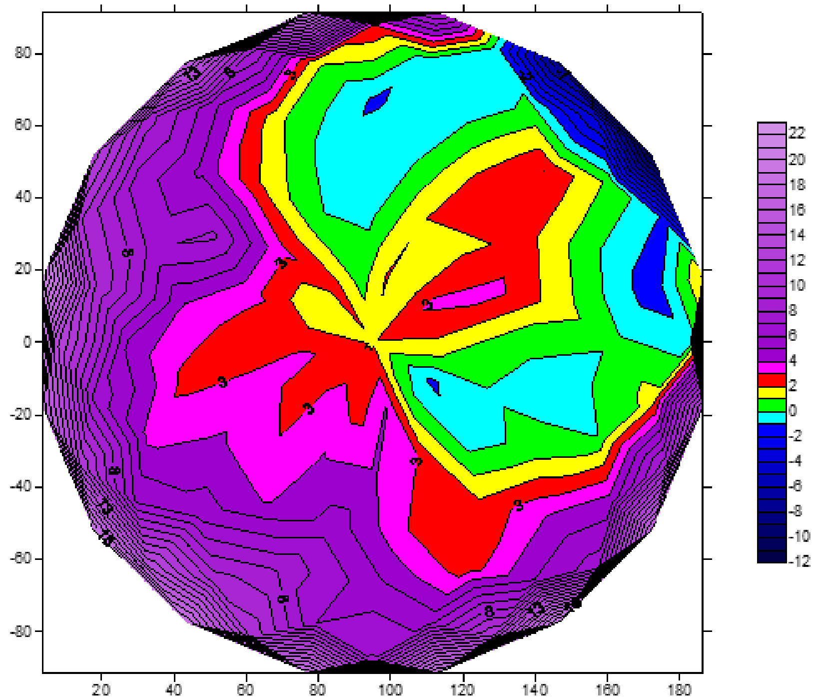

Fig. 11. Evaluation of resistivity in Surfer 8 for clay designation "GEP".

Conclusion

In laboratory conditions, experiments were performed using an apparatus with Z-meter device. The components of the electrical impedance of soils with an artificial clay anomaly were measured.

The results shows that the given modified EIS method with measuring apparatus and Z-meter IV device can be used for measurement and EI image reconstruction. Using the technique of EIS, it is possible to detect the location of the anomaly in the examined environment. Experiments were done in laboratory conditions. The advantage of this method is the relatively simple measuring procedure and manipulation with the measuring apparatus. The disadvantage can be its interpretation of the measurement results should be carried out by an expert with knowledge and practical experience of the method used.

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