EUREKA innovation across borders

ISSN 2464-4595

GEOtest

BRNO UNIVERSITY OF TECHNOLOGY

E!7614 APPL–EIS

EUREKA 2016

4th conference and working session

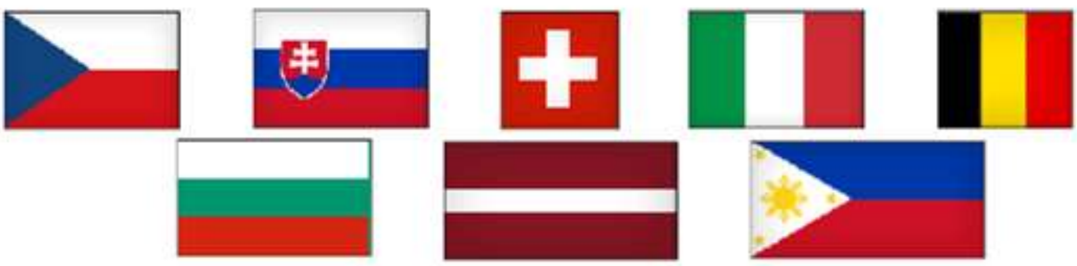
SCHEDULE

PROCEEDINGS

October 13th – 14th, 2016

GEO*test*, Inc., Brno University of Technology

Lednice, CZ



Responsible editor: Assoc. Prof. Dr. Ing. Jana Pařílková
RNDr. Lubomír Procházka

Proceedings design: Assoc. Prof. Dr. Ing. Jana Pařílková

Issued: Publisher VUTIUM
Brno University of Technology
Antonínská 1, 601 90 Brno, Czech Republic

Proceedings printing: Copy General, s.r.o.
Dvořákova 13, 602 00 Brno, Czech Republic

Edition: first

Year of issue: 2016

ISBN 978-80-214-5338-8
ISSN 2464-4595

EUREKA 2016

4th Conference and Working Session Within the frame of the International Program EUREKA

Project No.: E!7614

A System of Monitoring of Selected Parameters of Porous Substances Using the EIS Method in a Wide Range of Applications

Systém sledování vybraných parametrů porézních látek metodou EIS v širokém spektru aplikací

E!7614 APPL–EIS

October 13th – 14th, 2016
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THE MAPPING OF A WATER INRUSH AREA USING THE EIS METHOD

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Abstract **–** Seepage of water through bodies of earth-fill dams and processes connected with it are the second most frequent cause leading even to their failure, not only in the cases of their extreme hydrodynamic stress, e.g. during floods. This paper presents the issue of mapping of a water inrush area on the earth-fill dam of the Hornický Fishpond under different weather effects using the method of electrical impedance spectrometry.

Keywords **–** earth-fill dam, seepage, water inrush area, electrical impedance spectrometry

1 Introduction

Water is a condition of life on the one hand, but it can become its destroyer and significantly damage material values on the other. Water in civil engineering is an essential part of many technological processes leading to the creation of values. It would be impossible to carry out some construction work without water. Yet, water can complicate construction work (e.g. inflow of water to construction pits or underground structures), or damage finished constructions (e.g. if water serves as a transport medium for contaminants or if it contains substances corrosive to concrete or reinforced-concrete parts of constructions). Water can act in many ways on a construction or on the rock environment (Bruthans et al., 2012) that forms a single functional unit with the construction (Rozsypal, 2009).

Water in soils and rocks is a natural part of the very complex natural environment that is more or less influenced by human activity. The behaviour of the system "water – construction – rock environment" is very hard to predict on the basis of deterministic mathematical models, and therefore it is

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necessary to work with a probability approach. This approach has been proved in the long term, e.g. in hydrotechnical engineering when designing earth-fill dams and ensuring their safety to extreme discharges (Yen, 1995; Říha, 2010). However, it is still necessary to consider that the construction of a dam and its operation also implies a potential risk of the inundation of the area below the dam caused by its possible failure (MacDonald, Langridge-Monopolis, 1984; Serafim, Coutinho-Rodrigues, 1989; Singh, Scarlatos, 1988, Novak et al., 2007), while even the current era of advanced technologies of construction and monitoring techniques (Aldorf, Kořínek, 1994) does not know the term “absolute safety” of any work. The basic factors determining the goals of the monitoring of earth-fill embankment dams include the formation of fractures of a different character and the rise of pore pressures in the body of the dam emerging as a result of the uneven settlement of different parts of the dam filled with materials of different deformation properties. This particularly concerns the difference in the settlement of the stabilising and sealing parts of the dam. In addition, the problems are caused by water seeping through the dam and by fluctuating water in the reservoir.

Failure of an earth-fill dam can be caused by natural or anthropogenic factors. Natural factors include earthquakes, landslides, filter deformation, overtopping, drifting of ice, action of animals and vegetation. Anthropogenic factors are, e.g, a bad design of the structure, unsuitable siting, errors during construction, unsuitable or insufficient maintenance and operation, or sabotage. This often concerns a combination of several causes. The aim of the design, construction and operation of dams is to tackle the above-given factors at the level of the current knowledge and to reduce the danger of failure of water-retaining structures to a generally acceptable measure, with the priority being to reduce damage to property and lives of inhabitants in the protected area. Causes of fatal failures of dams can generally be classified in different ways (Floods and Reservoir Safety, 1996; National Science Foundation, 2013; Pilarczyk, 1998; Říha, 2010).

2 Water in the Body of an Earth-Fill Dam

Water in civil engineering is particularly manifested as a force, e.g. by hydrostatic pressure, flow pressure, pore pressure, the pressure of ice and the pressure acting in discontinuities of the rock mass. Damp soil has a higher unit weight than dry soil, and so an increasing amount of water in soil can change the equilibrium of forces. The action of water is bound to soil porosity, the size and velocity of change in the loading of an earthen construction, etc. The principle of effective stresses in soils (effective and total shear strength of soils) is derived from the conditions mentioned above. Or, water can directly change the properties of soils. In soils with an increasing degree of water saturation of pores, strength decreases and plasticity increases. Water accelerates the process of weathering and the overall degradation of the physical properties of rocks. It directly influences also some of the technological properties of soils and rocks, which are important for their processing into earthen constructions, for example binding power, workability and compactibility. An excess of water in soil can cause its slaking and unworkability (Šimek et al., 1990; Stanek, Kořínek, 1991).

Water can manifest by the following basic processes in the body of an earth-fill dam and in its basement (Rozsypal, 2009; Říha, 2010; Hošková, 2015)

- Seepage;
- Internal erosion (washing out, piping, suffosion);
- Disturbance by pore pressure (hydraulic fracturing);
- A decrease in shear strength by pore pressure; and
- Consolidation as a result of the dying-out of pore pressure by an additional load or by lightening.

The processes above usually occur if the individual parts of an earthen body are unsuitably designed, or if the technology of their implementation is not followed (e.g. unsuitable compaction) or some part is missing (e.g. sand filters). Dam failures can cause all of the processes above.

2.1 Water seepage

The character of water seepage through the body of a dam or its basement is governed by hydraulic head (i.e. the difference of the water levels at the input and at the output) and by the length of the seepage pathway. Another important factor is hydraulic conductivity that is a function of the grain size composition and the current porosity of soil. To prevent unacceptable seeping is the fundamental task for the design of every dam. To reduce seepage can be done by lengthening the seepage pathway, or by lessening the value of the hydraulic conductivity of the sealing element, or by their combination. The sealing element is placed into the dam or on its upstream face. The seepage pathway can be lengthened, e.g., by a sealing curtain, an installed sealing mat, etc. It is possible to move farther the seepage curve from the dam surface using suitably placed filters.

At the present time it is possible in the earthen dam body to calculate both the velocity of seeping water and pore pressure, and thus the total seepage as well. Therefore, it is no problem to design artificial earthen structures (such as protective flood-control dykes and dams) so that seepage can be acceptable and cannot cause undesirable filter deformations which could even lead to dam failure.

It is necessary for the calculations of velocity, pressure and seepage to know the hydraulic conductivity of soils that occur in the earthen body, the geometry of the dam body, and the boundary and initial conditions. It is necessary to carry out the designs of dams so that:

- The surface of seeping water in the dam can be at a sufficient distance from the dam surface;
- The velocity of seeping water below or in the dam is so low to avoid filter deformations; and
- Seepage below and through the dam is sufficiently small, i.e. so that compaction and the material used are such that the hydraulic conductivity of the material of the sealing of the dam body is sufficiently low.

A pilot project is to verify the method of electrical impedance spectrometry in mapping a water inrush area on the downstream face of the earth-fill dam of the Hornice water reservoir.

2.2 Failure by pore pressure

Failure of an earthen dam body by the pore pressure of water occurs if the sum of the least main stress and the tensile strength of soil in the assessed place of the dam is lower than pore pressure. When such a case occurs, fractures are formed being oriented perpendicular to the direction of the least main stress. This mechanism is known as hydraulic fracturing and is used for detecting the original state of stress of the rock mass by a water blasting pressure test. It has been observed in the sealing parts of earthen dams.

2.3 Internal erosion (suffosion)

Internal erosion is meant to be the washing-out of fine parts of soils with the formation of pathways predetermined for seepage. There are four conditions for the formation of the given type of failure, which must be met at the same time:

- Flowing water in soil – the existence of a certain size of flow pressure;
- Cohesionless soils;
- A possibility of outflow of washed-out material; and
- Sufficient strength of the soil skeleton.

In addition, the formation of erosion pathways in an earthen body can be supported by a number of natural or artificial factors, for instance:

- The inhomogeneity of the basement and the dam body in terms of permeability and grain size, which thus contributes to the concentration of seepage to certain places;
- The loosening of soils along the excavations for underground structures;
- Imperfectly compacted soil of the dam close to the walls of building structures; and

- Places with a lower state of stress beneath the arch effect shown at the contact of the basement with the walls of underground building structures, or above slightly compacted areas or on vertical boundaries between compressible and uncompressible soils.

Internal erosion generally takes place in the following way (Rozsypal, 2009): Specific discharge concentrates, as a consequence of hydraulic head, to predisposed places. There, the carrying force of seeping water increases, and if it is sufficiently strong, begins to wash out the finest particles of soil. The specific discharge of water as well as its velocity increases with gradual wash-out and the whole process thus accelerates. Internal erosion moves against water flow. Thus the pathway of seepage is shortened. The hydraulic gradient is thus increased and the whole process further rapidly accelerates. Internal erosion is facilitated where water seeps through places with a significantly lower state of stress and where compaction is lesser. There, intergranular forces between soil grains are smaller and therefore such soil undergoes erosion more easily. If the size of water pressure approaches the size of soil strength (intergranular forces of soil material), tensile stress will appear at the contact of certain grains and such grains will be eroded. With the progressive growth of flow pressure this stress can exceed the tensile strength of soil and such soil is then disturbed. In this way internal erosion is accelerated. If total stress in soil at the contact with a concrete structure or with the soil of the basement is lower than the flow pressure of water in this place, the soil can separate from the concrete structure. This separation will cause an enlargement of the specific discharge and the formation of another erosion pathway. At the moment when the erosion tunnel reaches the upstream side, the water flow becomes continuous and the velocities as well as the carrying forces will begin to increase progressively. The consequence of it is usually breach of the dam.

3 Description of the Site

The Hornice dam (Fig. 1) was constructed to accumulate water for agricultural use and is located close to the municipality of the same name lying in the Třebíč District. It is constructed on the Kojatický Brook, fitted with an auxiliary emergency spillway in the form of a concrete trough, a side main emergency spillway, a spillway channel of the emergency spillway, a roughened chute excavated in the rock and a stilling basin. Its available parameters are given in the paper by Pařílková and Pařílek (2015) and in a detailed situation in Hejtman (2012). The water reservoir has an earth-fill embankment dam.

Fig. 1 Aerial view of the Hornice dam and water reservoir (www.mapy.cz)

A road runs along the dam crest; its average width is 4.25 m (at its beginning it is 4.30 m, above the place of the observed seepage 3.80 m and at the railing securing the roughened chute 4.65 m). Soil in the place of the road was consolidated with gravel that is currently locally visible in grass cover. According to the project, the dam at its toe is 46.80 m wide; the upstream face has a gradient of 1:2.5 and is fortified with stone packing; the downstream face of the dam has a designed slope of 1:2.5 as well, but during the mounting of the EIS monitoring system a change in the slope gradient was surveyed, which is probably due to the deformation of the downstream face caused by the emerging water inrush area. The downstream face is covered with grass maintained by an inhabitant of the municipality of Hornice. The height of the dam above the original ground surface is 8.22 m and the height of the dam above the base of the footing is 11.0 m. The water inrush area on the downstream face of the dam is visible in Fig. 2.

Fig. 2 Water inrush area on the downstream face of the dam

4 EIS Measuring Apparatus

Measurement was carried out using a mobile fork probe and a Z-meter IV device. The fork probe (Fig. 3) is constructed as pair one with a single sensor formed by two electrodes. The electrodes are designed as rods made of stainless steel, with a diameter of 0.012 m and a length of 0.040 m. For easier installation into soil, the electrodes are terminated with a tip. The axial spacing between the tips of the electrodes forming the sensor is 0.060 m. The sensor can be gradually installed to a maximum depth of 0.340 m. The surface of the steel rods is fitted with insulation material 0.300 m long so that the diameter of the exposed measuring part of the electrode is flush with the part of the electrode with insulation material. The head of the sensor is built into a robust handle made of PVC with dimensions of 0.205 m × 0.147 m × 0.020 m, with an opening of 0.114 m × 0.085 m × 0.020 m in dimensions for enabling handling with the probe. Cables are welded in the lower part of the probe handle, interconnecting the electrodes with the Z-meter IV device. The cables are 1.5 m long and their free end is fitted with a 25-pin CANON connector.

The installation set includes a hammer and two stainless steel rods of 0.012 m in diameter and 1 m in length, through which it is possible, if necessary, to prepare openings for placing the electrodes. Another item facilitating handling in field conditions is a wooden prism, in the axis of which two holes are drilled, spaced the same distance as the electrodes, and their dimensions being 0.020 m × 0.010 m × 0.045 m enable easy control of depth, at which the sensor is found in measurement. The parameters of the measuring Z-meter IV device are given in the manual of the device (Pařílková et al., 2015) and in the technical sheet (www.eureka3838.com).

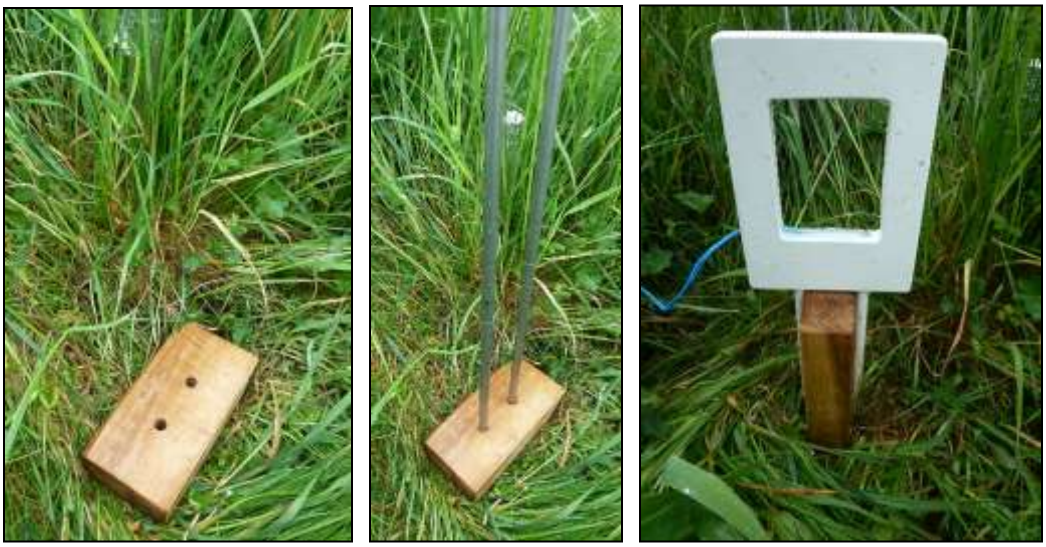


Fig. 3 Mobile fork probe and its installation in measurement

5 Measurement

The mapping of the water inrush area took place in a raster as shown in Fig. 4. Measurement was carried out in a square network with individual points spaced 2.5 m × 2.5 m apart, i.e. in a total of 25 points; the total measured area was 100 m^2. The position of the point on the axis x is in the direction of the length of the dam crest and the position of the point on the axis y is on the downstream face of the dam. The values of electrical impedance were measured at four depths, namely at -0.02 m, -0.12 m, -0.22 m and -0.32 m. Measurement is evaluated as measurement in points because the distance of the electrodes of the sensor to the size of the measured area represents an uncertainty of 0.6%.

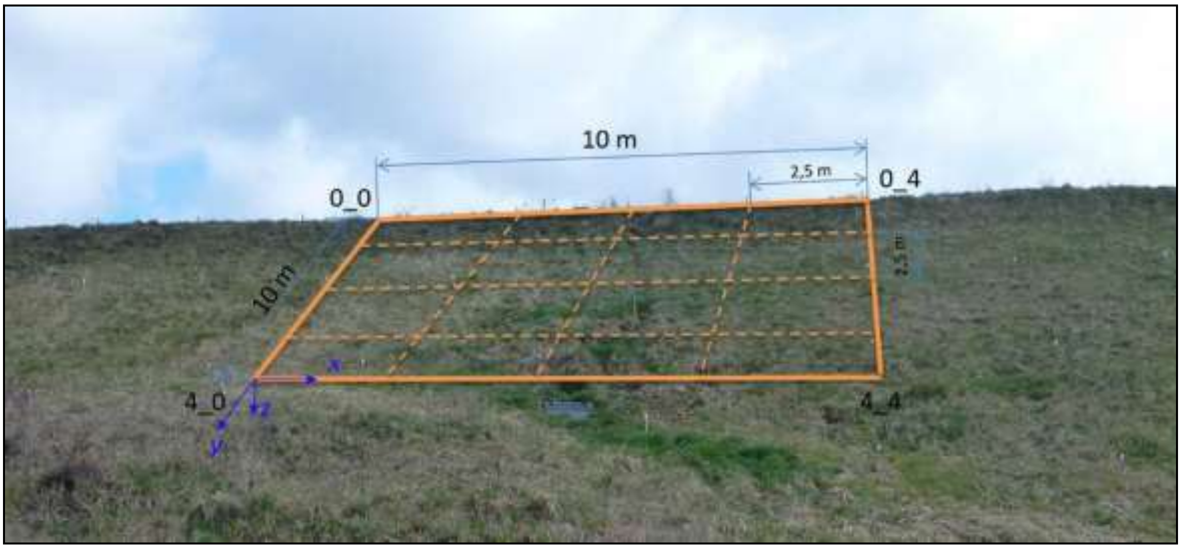


Fig. 4 Layout plan of the measured tract of the water inrush area

Measurement was carried out at the frequency f = 2,000 Hz, the value being chosen on the basis of the results of a frequency analysis of the dam soil, with the time of switching between measurements being t = 0.100 s and the number of repetition on one sensor n = 5. Two-terminal connection of electrodes was used on the probe.

The mapping of the water inrush area was carried out through electrical variables based on the principle of the method of measurement (Pařílková, 2010). The real component (the electrical resistance R) and the imaginary component (the reactance X – apparent electrical resistance) of the electrical impedance **Z** are measured separately:

$$\mathbf{Z} = R + jX \quad , \tag{1}$$

or the admittance:

$$\mathbf{Y} = \frac{1}{\mathbf{Z}} = G + jB \quad . \tag{2}$$

where Y is admittance, G is electrical conductance, and B is susceptance (Berka, 2010). The electrical conductance G gives information about the content of water in soil. The higher the value G, the higher the content of water in soil provided that the chemical and mechanical properties of soil are constant. The electrical admittance **Y** takes account of not only the effect of water content in the measured profile of soil, but it also covers other effects such as the structure, grain size, density, etc., through the apparent conductance B.

Measurement took place on two dates, namely on 19.05.2016 and 22.06.2016 because of the documentation of the effect of weather conditions and the water level in the reservoir (Fig. 5, Tab. 1). Because there is no meteorological station in the place of measurement – the municipality of Hornice, the data are obtained from the Czech Hydrometeorological Institute from the nearest-located stations – discharges of the watercourse Želetavka from the limnigraph station Jemnice, and because the station does not measure precipitation, information about precipitation is taken from the station in Moravské Budějovice. The company GEO*test*, a.s. has equipped the monitoring system of the earth-fill dam, among others, with sensors of soil temperature (used are data from sensor S2 placed above the inrush of water), and Brno University of Technology installed a sensor of the altitude of the water level in the reservoir on 09.05.2016. The temperature of air is taken from the web site http://www.meteocentrum.cz/ predpoved-pocasi/cz/1669/hornice and http://www.e-pocasi.cz/archiv-pocasi/ 2016/.

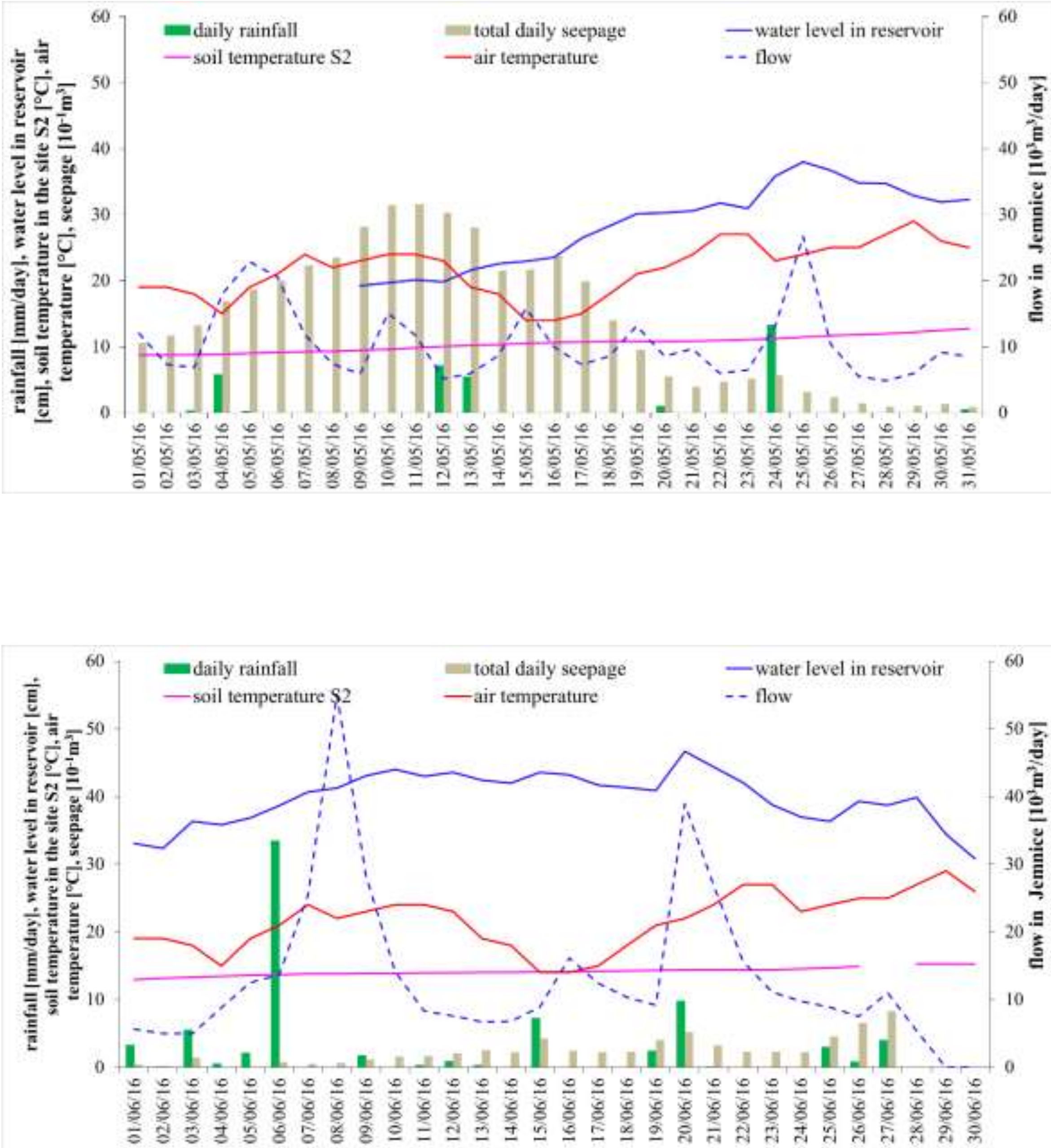


Fig. 5 Patterns of the monitored variables

Although the discharge measured at the limnigraph station shows a slightly descending tendency in both the months, the water level in the Hornice reservoir rises. The above-given processes are not in conflict. Not only precipitation is involved in the increase of the water level (Fig. 5), but also the artificial closing of the auxiliary safety spillway made as a concrete trough carried out for the application of the BioSealing method to seal the seepage through the dam body. The closure was done in two steps, namely on 06.05.2016 and on 02.06.2016; on 29.06.2016 the gate of the spillway was lowered by 0.10 m, resulting in a decrease of the water level in the reservoir because zero precipitation had been recorded. The temperature of air and soil measured in the place of the water inrush show an ascending trend in both the months.

Tab. 1 Measured parameters

Date	Discharge	Seepage	Precipitation	Water level in reservoir	Air temp.	Soil temp.
dd.mm.rr	$10^3 m^3$/day	m^3/day	mm	m a.s.l.	°C	°C
19.05.16	13,2	0,951	0	447,40	21	10,8
22.06.16	15,6	0,233	0	447,52	28	14,4

6 Data Processing

The processing of the measured data was carried out using the MS Excel program. According to the established Cartesian system of coordinates, the patterns of the electrical conductance *G* determined as the arithmetic average of the values from the number of repetitions $n = 5$ were plotted for the individual points, as well as the average value of the admittance $\bar{Y}$ determined as the arithmetic average of the values of the admittance **Y** measured in the individual points at all depths (Fig. 6).

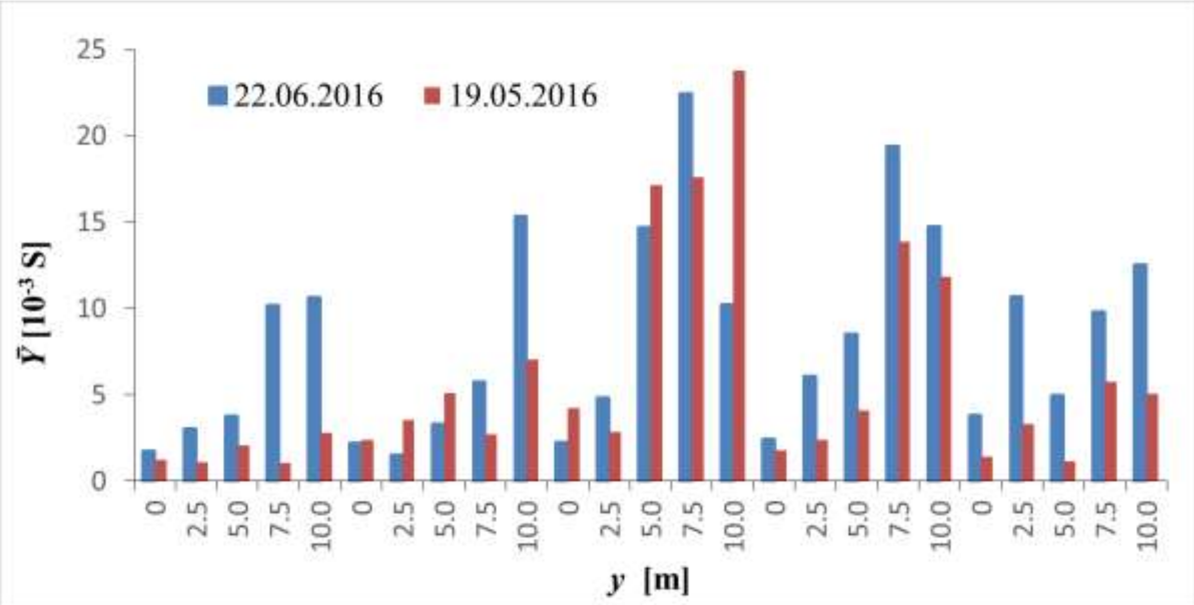


Fig. 6 Admittance of the soil

7 Evaluation of the Measurement

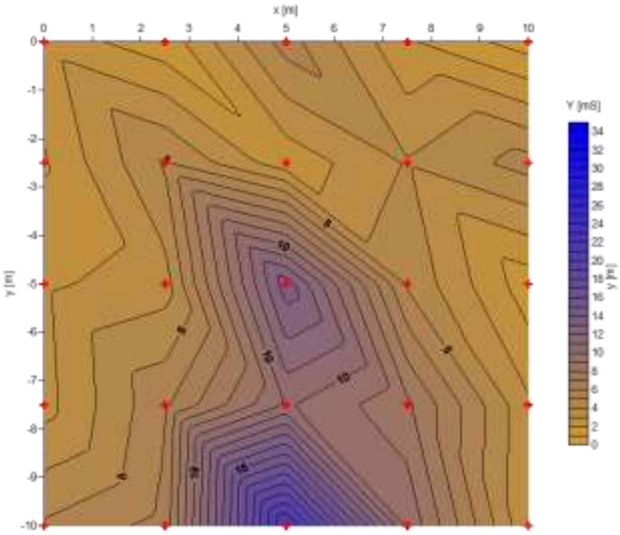
On 22.06.2016, recorded was an increase in the discharge by 18.2 %, in the water level in the reservoir by 39.6 %, in air temperature by 33.3 % and in soil temperature by 33.3 %. Probably due to the application of the method of BioSealing, a decrease in the total daily seepage by 75.5% was recorded. Although precipitation was zero on both of the days of measurement, in June precipitation was recorded before measurement, whereas in May a drought lasting for several days preceded measurement. Particularly due to precipitation and the seepage of water through the dam body, the content of water in the measured layers was higher by 27.1% (according to the measured electrical conductance). Because the evaluated average value of admittance changed by 40.9%, it can also be judged that the character of soil changed (the effect of chemical and mechanical parameters).

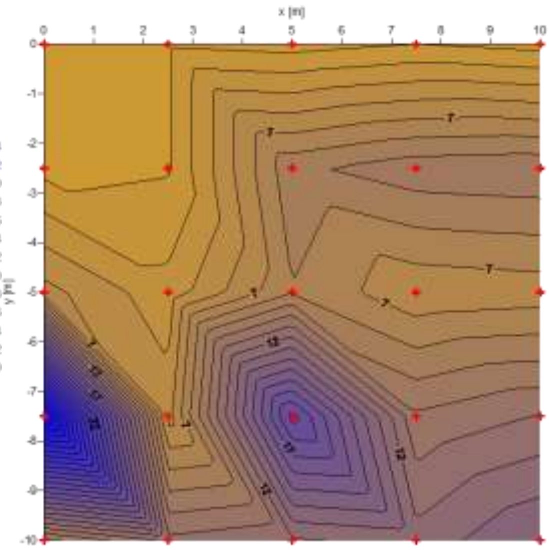
These findings are also supported by visual observations – the vegetation in the place of the water inrush area is still noticeably more vital (Fig. 7).

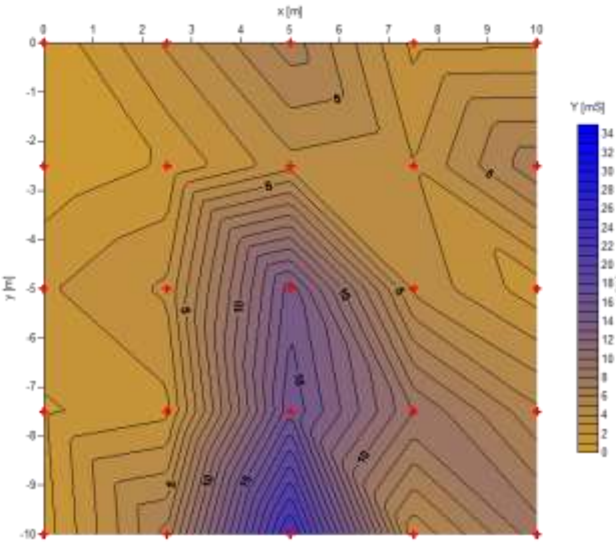
Fig. 7 Grass cover on the water inrush area

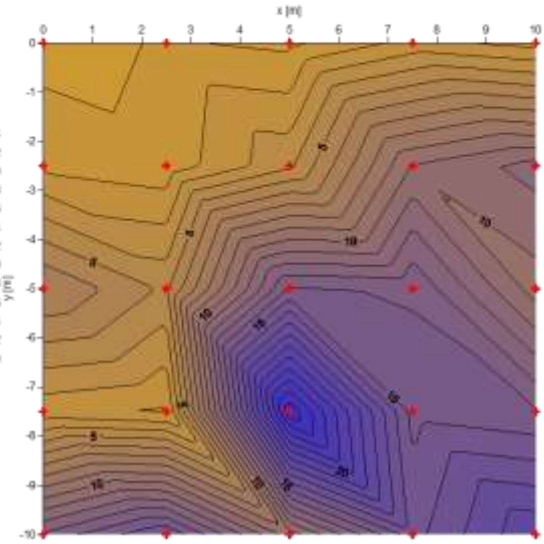
The values processed in the MS Excel program were loaded into the Surfer 8 program. In it the triangulation of the area was made with defined points, and contours documenting the water inrush area were plotted (Fig. 8). The colour scale of admittance is uniform for all evaluations; the individual depths are depicted in the direction of gravitational acceleration.

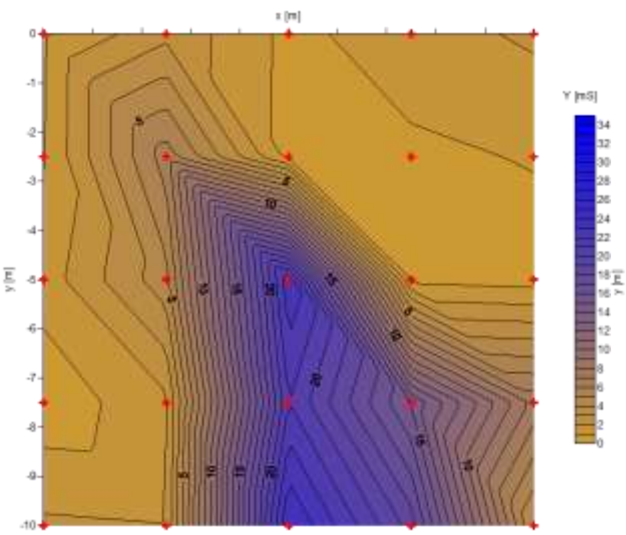
19.05.2016 22.06.2016

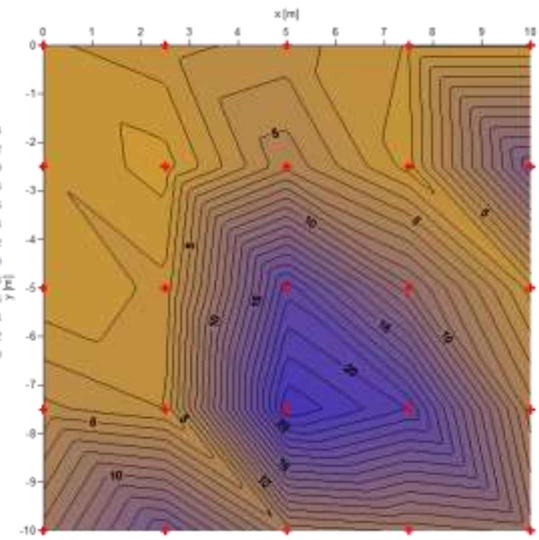












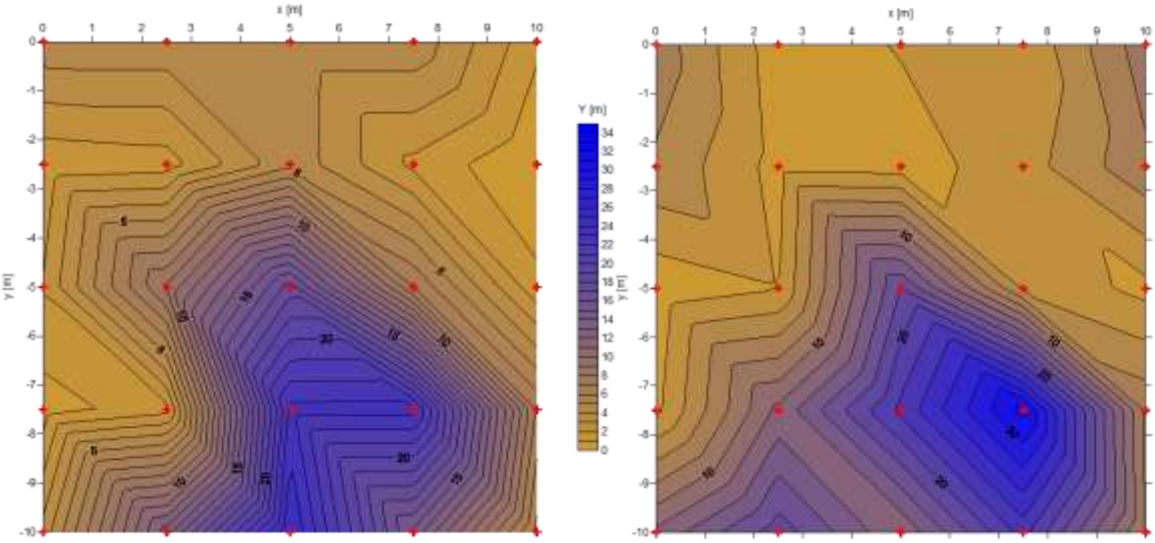


Fig. 8 Maps of electrical conductance

8 Conclusion

The achieved results prove the suitability of the EIS method and the constructed apparatus with a mobile probe attached to the Z-meter IV device for monitoring changes in the soil characteristics, caused by a variable water load (water infiltrated from precipitation and seepage water from the reservoir). Measurement by the described mobile probe can be carried out to a depth of 0.34 m. This depth and the construction of the probe were evaluated as the most suitable, at which no deformation of the probe should occur, e.g. in its installation into a hard soil or a soil containing stones.

It can also be stated that a good agreement was achieved with the processes which had preceded or had been recorded on the days of measurement. A percentage-identical agreement was recorded on the days of measurement during changes in air and soil temperature measured close to the inrush of water. The evaluated results in the other measured variables correlate with the processes which took place or began to occur at the time of measurement. This particularly concerns the change in the water level in the reservoir, the effect of rain precipitation and the ongoing process of the application of the method of BioSealing for sealing the earth-fill dam. It is evident that due to the processes mentioned above, new seepage pathways are sealed or, in contrast, are formed in the soil. The above-given conclusions assume that the individual elements do not influence the measured components of electrical impedance and hence the evaluated electrical conductance or admittance.

Acknowledgements

This paper has been created within the solution of the projects LF13019, which is part of the international projects E!7614 and LO1408 AdMaS UP - "Advanced Construction Materials, Structures and Technologies" supported by the Ministry of Education, Youth and Sports within the purpose-specific support of EUREKA programmes and the National Sustainability Programme I.

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Fig. 9 Monitoring at June 22nd, 2016