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GEOPHYSICAL AND GEOTECHNICAL SURVEY OF THE WATER STORAGE TANK FOR SNOWMAKING

GEOFYZIKÁLNY A GEOTECHNICKÝ PRIESKUM AKUMULAČNEJ NÁDRŽE NA ZASNEŽOVANIE

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Abstract

Aim of this paper is to show the results of a combination of engineering-geological survey with geophysical measurements, which were realized in order to solve the emergency state of the snow storage tank in the ski resort close to Králiky village (Banská Bystrica district, Slovakia). Suffosion resulted in the disturbance of the dam body associated with the leakage of the entire volume of water and following disfunction of the dam. Within additional survey focused to determine the extent of the disturbance, core engineering-geological wells, dynamic penetration tests, infiltration tests in wells as well as geophysical profile measurements using methods ERT and SRT were performed. The areas damaged by suffosion were displayed on the geophysical measurements as zones of anomalies with decreased resistivity on the ERT profiles and decreased seismic velocities on the SRT profiles. These signs allowed assessing the areal extent of the suffosion in the area and vicinity of the dam.

Abstrakt

Cieľom tohto príspevku je ukázať výsledky kombinácie klasického inžiniersko-geologického prieskumu s geofyzikálnymi meraniami, ktoré boli realizované za účelom riešenia havarijného stavu akumulačnej nádrže pre zasnežovanie v lyžiarskom stredisku pri obci Králiky (okres Banská Bystrica, Slovensko). V dôsledku sufózie došlo k porušeniu telasa hrádze nádrže spojené s únikom celého objemu vôd s nádrže a tým k jej následnému znefunkčneniu. V rámci doplnkového prieskumu na zistenia rozsahu poškodenia boli v oblasti nádrže realizované jadrové inžiniersko-geologické vrty, dynamické penetračné skúšky, nalievacie skúšky vo vrtoch a geofyzikálne profilové merania metódou ERT a SRT. Sufóziou poškodené oblasti sa na geofyzikálnych meraniach v okolí hrádze nádrže prejavili ako anomálne zóny so zníženou hodnotou merného odporu na ERT profiloch a znížením seizmických rýchlostí na SRT profiloch. Tieto prejavy umožnili posúdiť priebeh sufózie a plošné rozšírenie sufózie v oblasti nádrže a jej okolí.

Keywords
geophysical measurement, electric resistivity tomography, engineering-geological survey, suffosion

Kľúčové slová
geofyzikálne meranie, elektrická odporová tomografia inžiniersko-geologický prieskum, sufózia

1. Introduction

Suffosion processes, as well as the subsurface erosion of water, results in soil parts degradation thus causing surface subsidence, or its deformation (Petránek, 2007; Wan and Fell, 2008; Richards and Reddy, 2014; Moffat et al., 2011). Suffosion is a geohazard, which result can be represented by damage of communication infrastructure (Lavrusevich et al., 2017), or slope stability disturbance. It is one of the most common causes of dam disturbation (Xiong et. al, 2021; Wan and Fell, 2008; Horikoshi and Takahashi, 2015, Ferdos et al., 2018). Suffosion caused the damage of the dam body of the snow making water tank in the ski resort close to Králiky village.

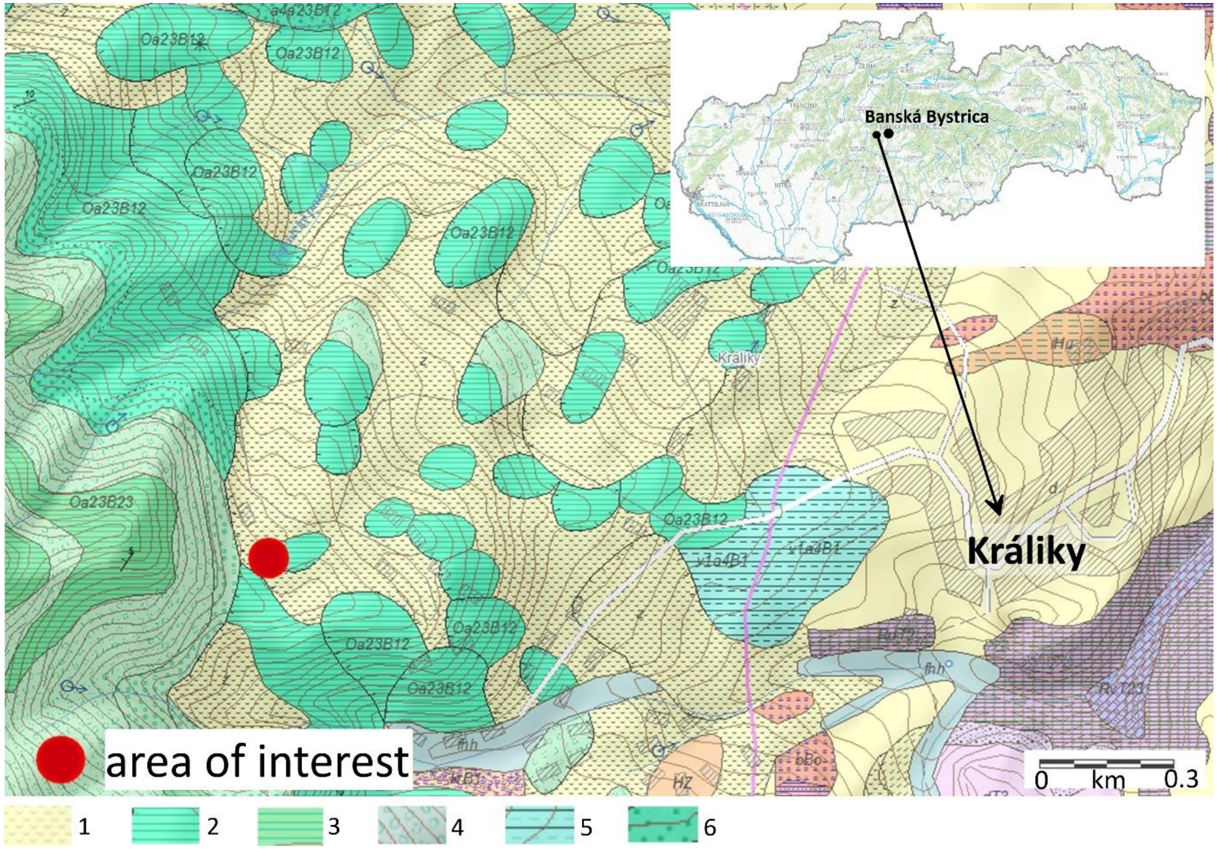
The dam remediation required complex information regarding the engineering-geological conditions in the area of the dam, especially the extension of the disturbance caused by suffosion, in order to prevent further possible water leakage. Therefore, classical methods of engineering-geological survey were carried out, as core engineering-geological wells, soil and water sampling, dynamic penetration tests and infiltration tests in wells. These methods were supplemented by geophysical profile measurements. Geophysical methods are able non-invasively indicate the state of erosion processes in the rock environments and enable the interpolation of the state of the rock environment between individual wells. They are gradually becoming a common part of engineering-geological surveys (for example: Colombo et al., 2014; Gołębiowski et al., 2021). Also, in the case of the Králiky storage tank, these provided a comprehensive view of the extent of object disturbance.

2. Geology

The area of interest can be found in the middle Slovakia (Fig. 1), close to Banská Bystrica, approximately 1,5 km west of Králiky village. It belongs to unit of eastern margin of the Kremnica Mountaina, on the border of Kordícka brázda and Malachovské predhorie (Atlas Krajiny, 2002).

From the geological point of view, the wider surrounding of the assessed area is composed from Mesozoic, Tertiary and Quaternary rocks (Fig. 1). The Mesozoic is represented by limestone-dolomitic complex. Tertiary sediments are Neogene as well Paleogene age. The Neogene is formed by pyroxenic andesites of Zlatostudňa Formation and epiclastic volcanic breccias and conglomerates. The Paleogene is represented by the basal complex of Paleocene conglomerates. The Quaternary sediments consist of deluvial sediments - stony clayey deposits of blockfields and clayey stony materials of landslides and soil flows.

The Kremnica Mountains represent a volcanic relief in a high degree of deformation. The foothill is affected large-scale slope deformations, block-, flow- and areal-type as well. Most slope deformations are stabilized at the present.



1) landslides,
2) lava flows of pyroxenic andesites,
3) lava flows of pyroxenic andesites,
4) epiclastic volcanic breccias to conglomerates pf pyroxenic andesites,
5) tuffaceous siltstone and sandstones of acid andesites locally with redeposited tuffs, claystones and lignites,
6) thick redeposited hyaloclastic breccias of pyroxenic andesites

Fig. 1 The geological composition of the assessed area (zdroj: portál Geology.sk)

3. Methods

The aim of the survey was to provide complex view of the engineering-geological characteristics of the studied area. Therefore 9 core engineering-geological wells were drilled, from which samples of soil were taken for classification and determination of geotechnical parameters entering into geotechnical calculations for geotechnical constructions design. Further 5 dynamic penetration tests and infiltration tests in 7 wells were carried out. These were the basis for filtration coefficient calculation of the tested section of the geological environment.

In order to gain information regarding the rock state of the reservoir and close surrounding of the dam, geophysical profile measurements were realized on the 8 profiles (GF-1 to GF-8) using electric resistivity tomography (ERT) and on 2 profiles (GF-1, GF-2) using also seismic refraction tomography method (SRT). Three profile measurements were performed on the dam body (profiles GF-1 to GF-3), three profile measurements through the bottom of the storage tank (GF-5, GF-6 and GF-7) and two profile measurements in the vicinity of the storage tank (GF-4 and GF-8). In the results the profiles are not presented as usually from GF-1 to GF-8. The order of profiles' presentation is based on appearance of the suffosion. Interpretation starts with profile GF-3, which passes through the area affected by suffosion.

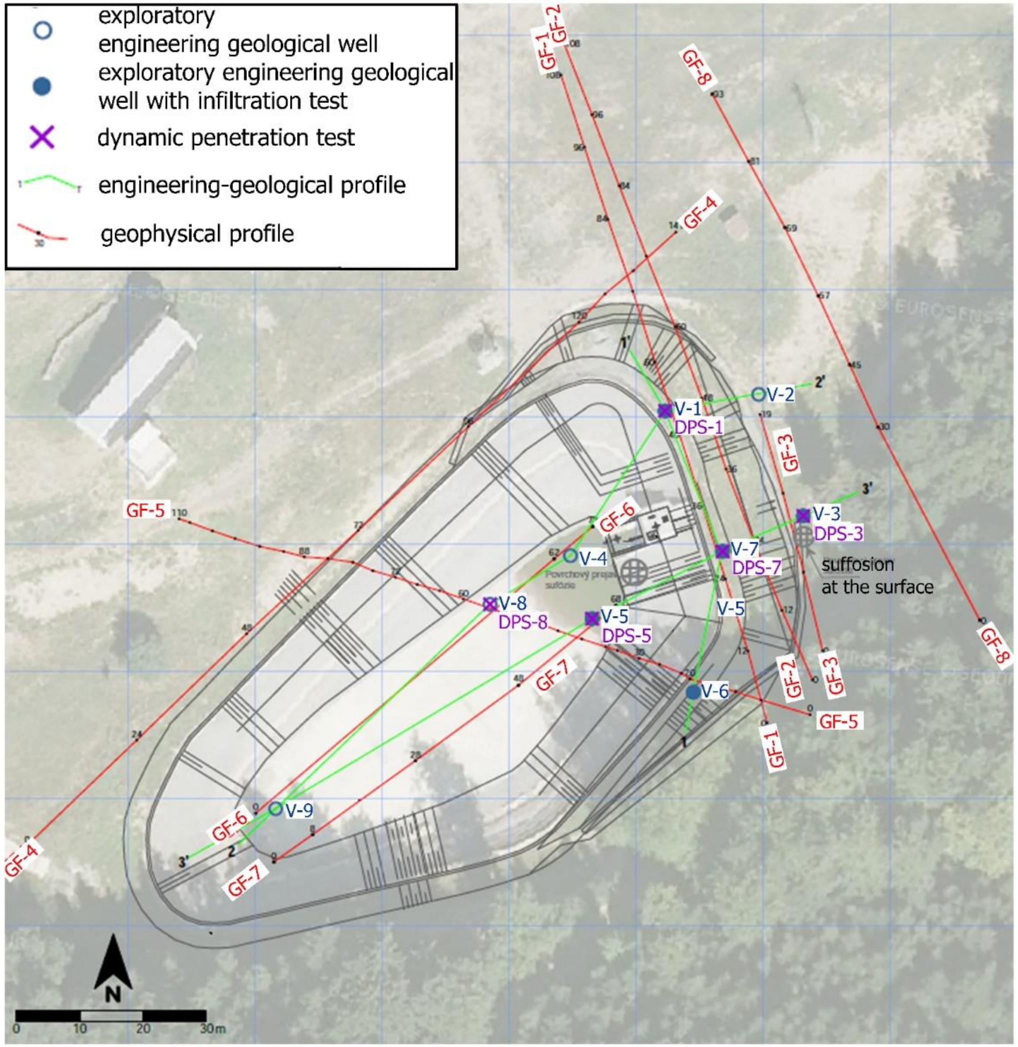


Fig. 2 Situation of the individual survey works in the area of the storage tank

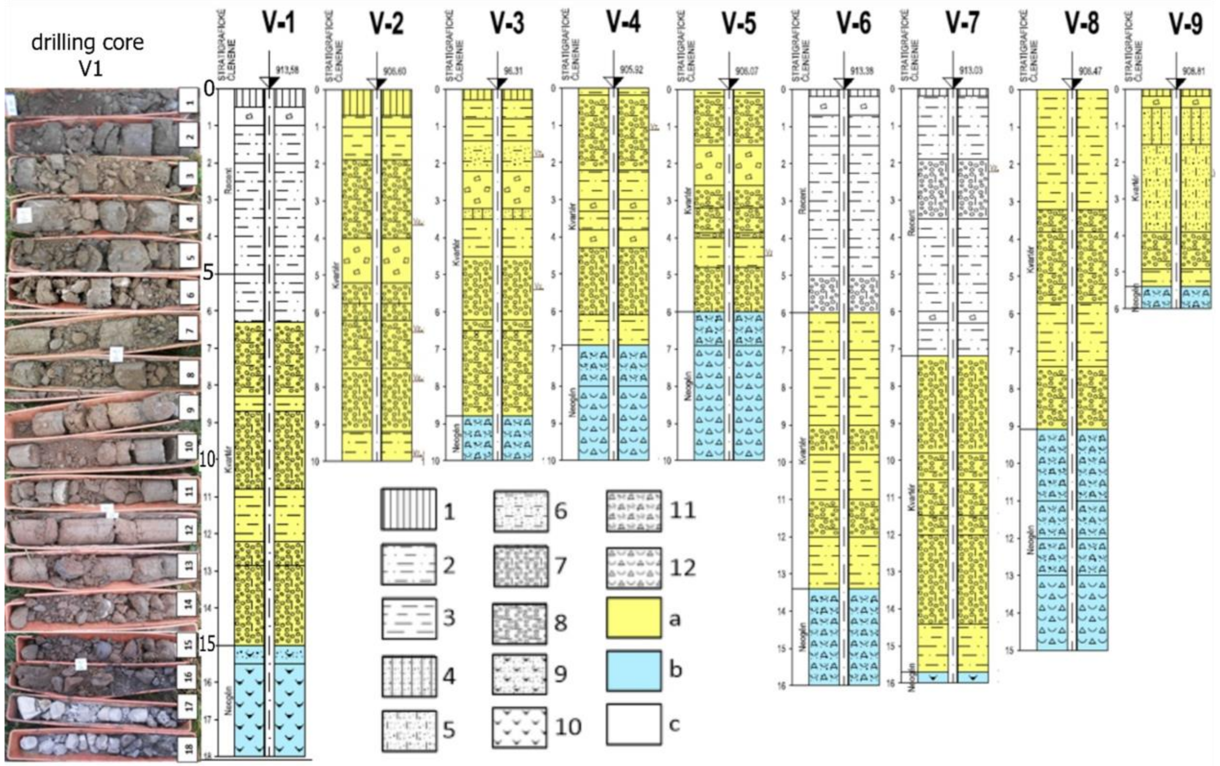
Tab. 1: The length of individual GF profiles and the distance between electrodes for ERT measurements

Profile	ED [m]	length [m]	Profile	ED [m]	length [m]
GF-1	2.0	110	GF-5	2.0	110
GF-2	2.0	110	GF-6	2.0	70
GF-3	1.0	39	GF-7	2.0	68
GF-4	3.0	141	GF-8	3.0	93

The measurements location and height were set using Trimble GeoXR device with an accuracy of up to 2 cm using GNSS technology (RTK method with SKPOS service). The altitude of the points was determined in the Bpv binding system. The layout of the individual survey works in the area of the storage tank is shown in Fig. 2.

Electric resistivity tomography (ERT)

ERT is geophysical method, which provide information about the value of the resistivity in the underground in vertical, as well in horizontal direction. The ERT survey can be performed by various arrangements of electrodes depending on the specific task requirement. The choice of the proper electrode arrangement depends mainly on the type of required information, the measurement density and the presence of noise. In this case, a dipole-dipole arrangement was



1) Sandy silt with humus content silt,
2) sandy clay,
3) clay with intermediate plasticity,
4) sandy silt,
5) silty sand,
6) clayey sand,
7) silty gravel,
8) clayey gravel,
9) andesite-completely weathered,
10) andesite-weakly weathered,
11) volcanic complex-completely weathered,
12) volcanic complex-strongly to intermediately weathered,

a) Quaternary,
b) Neogene,
c) Recent (dam body)

Fig. 3 Lithological classification

chosen. Due to assumption of horizontal setting of the layers of the dam body, a possible disturbance of the compactness should be visible on the resistivity section as isometric anomaly.

To interpret the measured values of apparent resistivity program Res2DInv for calculation of the inverse problem was used. For the inverse calculation itself L1 norm of the smoothed optimization method was used. The measurements were realized by ARES device (GF Instruments, Brno, ČR). The electrode distance (ED), determining the detail of the survey and its depth range, differs for individual profiles and is displayed together with the profile lengths in Tab. 1, the direction of the profile is shown in Fig. 2.

Seismic refraction tomography (SRT)

Seismic methods are geophysical methods using artificially induced seismic waves to determine the seismic interfaces below the surface and velocity of the seismic waves propagation between the given interfaces (Lilie, 1999). Seismic waves propagate from the source and the arrival of each wave is detected along the line of geophones. Seismic refraction uses direct wave and head waves arising at individual interfaces. The precondition for the head wave creation is the increasing velocity with depth. During processing, the individual hodochrons of these waves are interpreted and the result are velocity profiles with interfaces and velocity characteristics (Raynolds, 1997). Seismic refraction tomography is an alternative to conventional methods of refraction seismic (Sheehan et al., 2005). It provides higher resolution and record velocity changes also in a horizontal direction.

SRT measurement was performed using 36-channeled M.A.E device with 14 Hz vertical geophones with 2 m of geophone offset and hammer as a source. At each source position, the record was stacked from 4 impulses. Measured data were processed by methods for refraction seismic tomography (program Reflex Version 8.0 developed by Sandmeier 2016). The result of the processing is a velocity profile showing the changes in the velocity parameter of the studed environment.

4. Results

Well works, sampling and dynamic penetration tests were used for lithological classification (Fig. 3) and for geotechnical parameters determination, which are entering the geotechnical calculations for geotechnical constructions design.

Based on the filtration tests, the hydrogeological conditions and hydraulic properties of the environment were evaluated and the permeability of the selected sections was verified. The results show that the volcanoclastic rocks are composed from two different

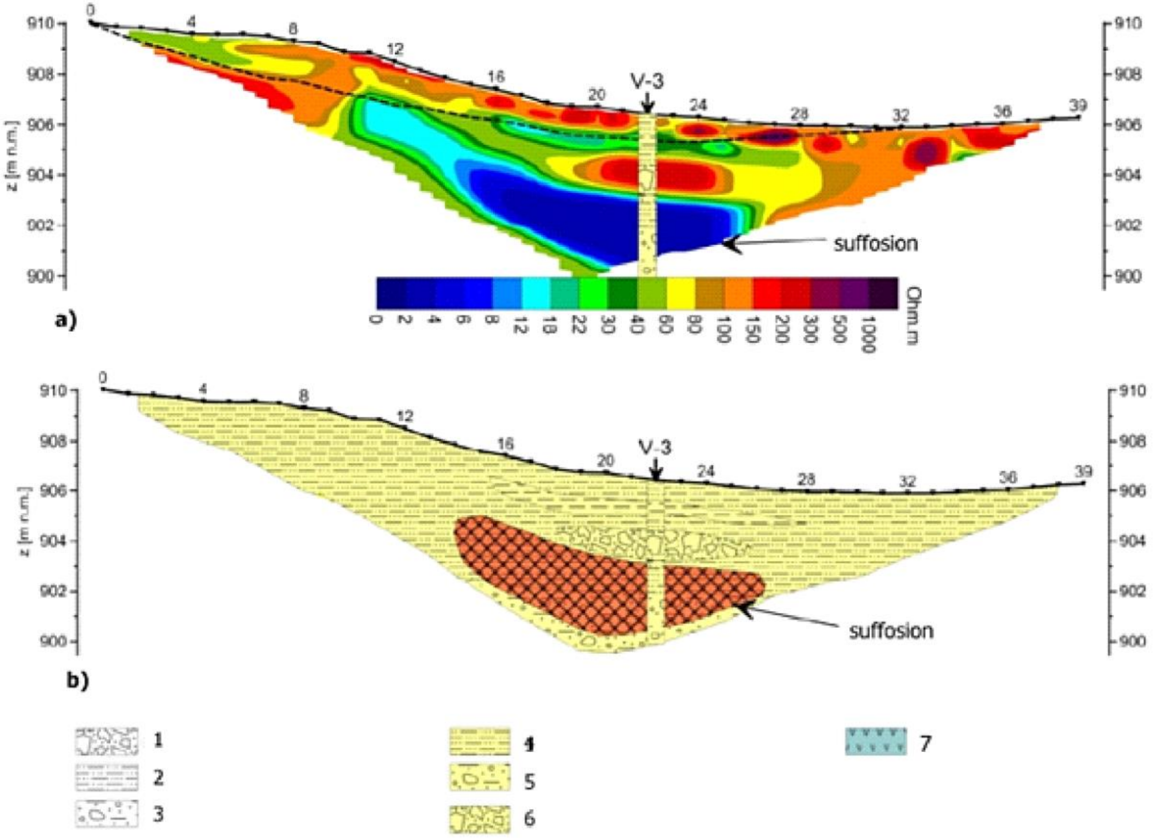


Fig. 4 Geophysical profile GF3
a) Inverse resistivity profile and
b) interpreted geological cross-section

1) macadam, andesite debris,
2) sandy silt, sandy clay,
3) silty gravel,
4) sandy clay, sandy silt,
5) debris of silty (clayey) gravel nature,
6) derbis composed from andesite boulders,
7) andesite and volcanic conglomerates with different level of weathering

hydrogeological types on the studied area. These are completely weathered andesite having gravelly nature (wells V-1 and V-7) with dual, very strong fissure intergranular permeability and intermediate to completely weathered volcanoclastic breccia (wells V-3 to V-5) with very weak intergranular permeability with filtration coefficient k = 1,32.10^{-7} m.s^{-1} to 1,47.10^{-5} m.s^{-1}.

Geophysical works

Profile GF-3 is situated immediately next to the surface demonstration of the suffosion process under the dam (Fig. 2). The purpose of the ERT measurement was to visualize the suffosion area (through which the water leaked from the tank) on the resistivity profile. The measurement results (Fig. 4a) show that the suffosion area lies in the original environment, which was not affected by the dam construction,

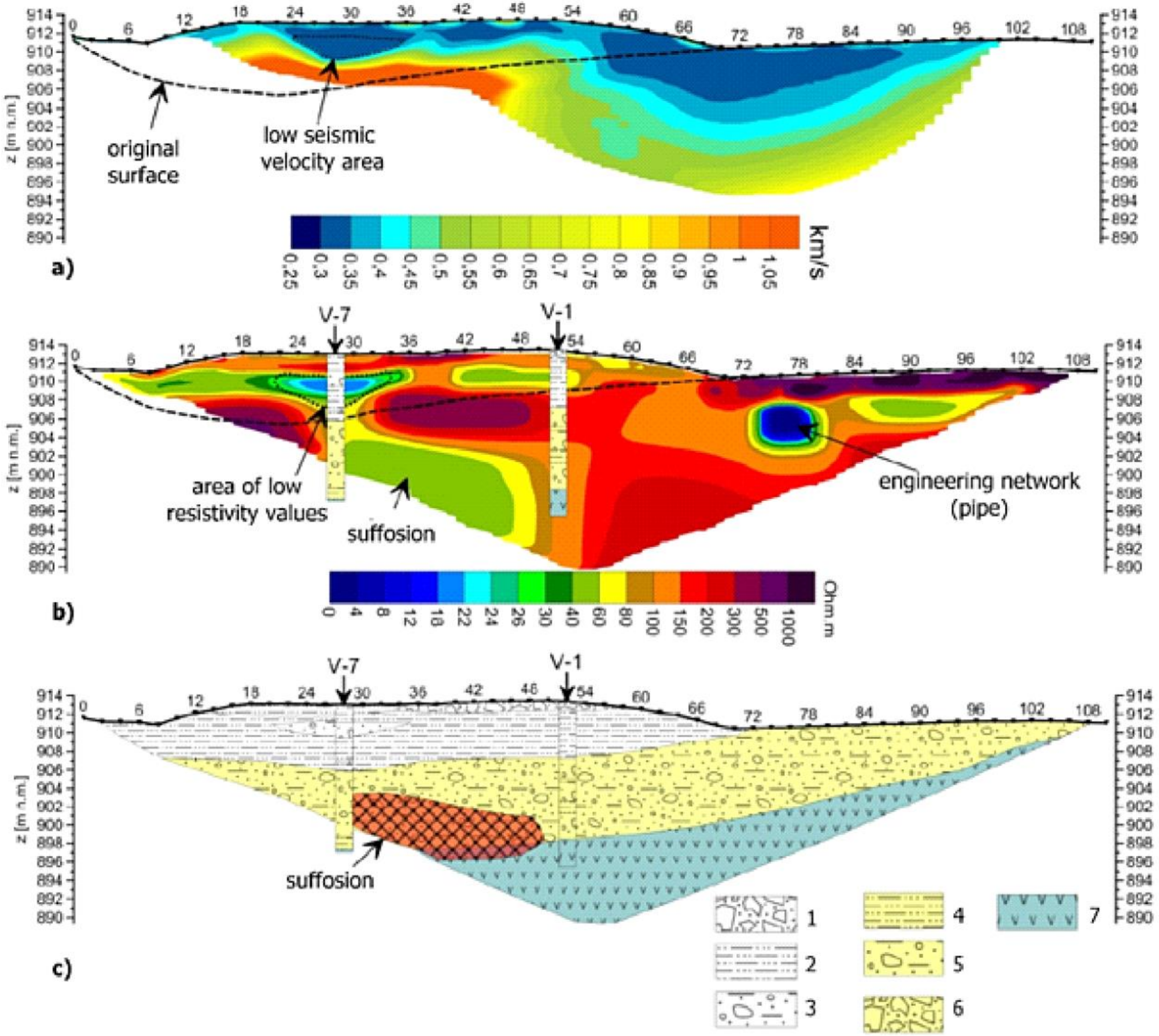


Fig. 5 Geophysical profile GF1
a) Seismic velocity cross-section,
b) inverse resistivity profile,
c) interpreted geological profile

1) macadam, andesite debris,
2) sandy silt, sandy clay,
3) silty gravel,
4) sandy clay, sandy silt,
5) debris of silty (clayey) gravel nature,
6) derbis composed from andesite boulders,
7) andesite and volcanic conglomerates with different level of weathering

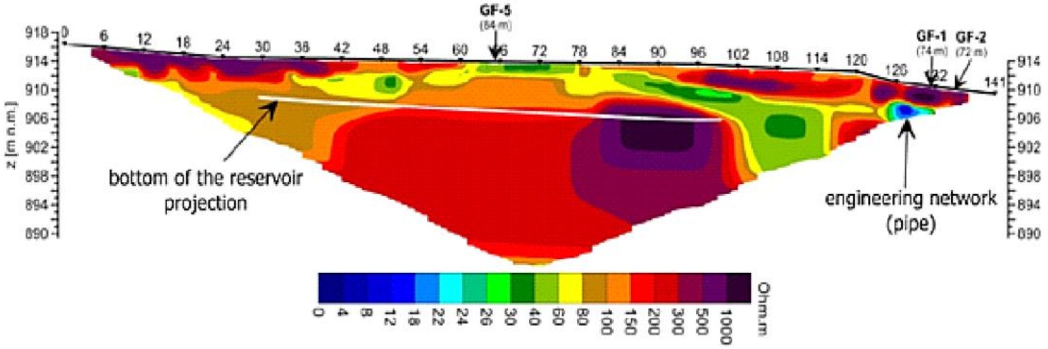


Fig. 6 Geophysical profile GF4. Inverse resistivity cross-section with marked projection of the dam bottom

at the depth of 3 to 6 m under the current terrain. In the resistivity section is it seen as marked conductive anomaly. High conductivity (low resistivity values) is probably caused by the presence of fine-grained sediments. Based on the ERT measurement interpretation, an interpreted geological profile with marked area affected by suffosion was created (Fig. 4b).

Profile GF-1 is oriented through the crown of the dam from the forest and overlap the original terrain of the ski slope (Fig. 2). The overlap of the profile was necessary to achieve the depth range of the measurement. The original surface course was found from the project documentation for the reservoir construction (Fig. 5, dashed line). The dam body (environment above the line of the original terrain) is located at the 0 – 70 m of the profile GF-1. According the project documentation, the dam was to be built in layers of 80 – 100 cm thickness with gradual compaction of each layer. From geophysical point of view, the dam body should consist of homogenous or layered environment, depending on the level of compaction. However an anomalous area was found in the dam body on the 22nd – 36th m of profile. This area lies above the area of water leakage and is demonstrated on the SRT profile (Fig. 5a) by decreased velocity

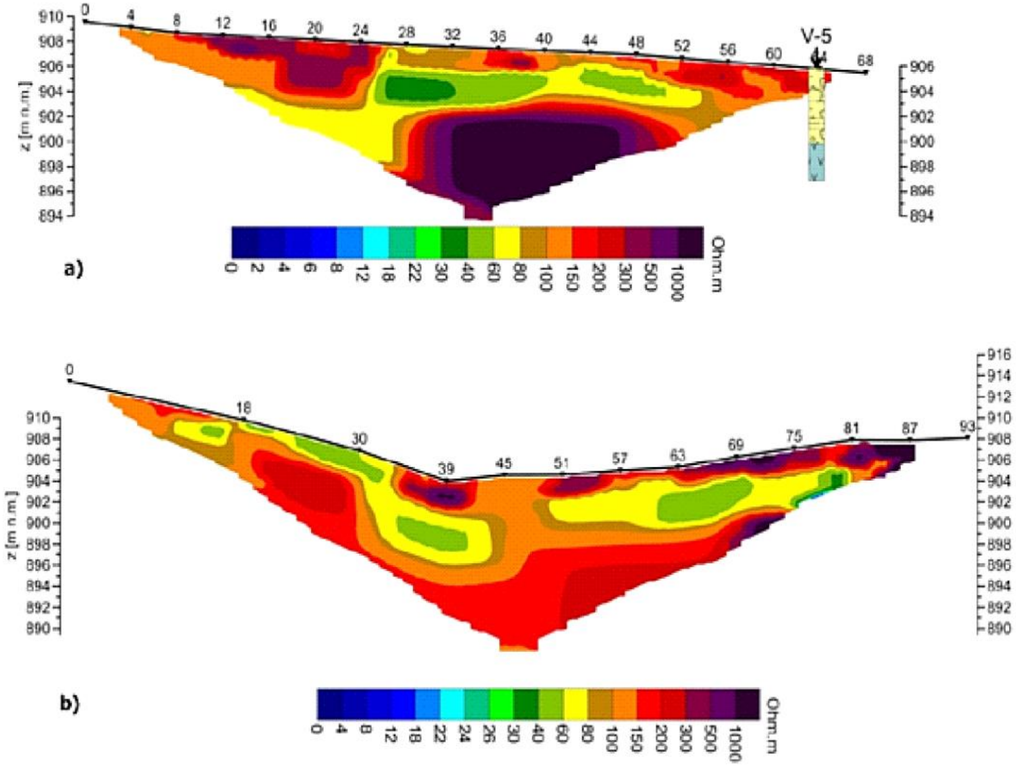


Fig. 7 a) Inverse resistivity cross-section GF7, b) inverse resistivity cross-section GF8

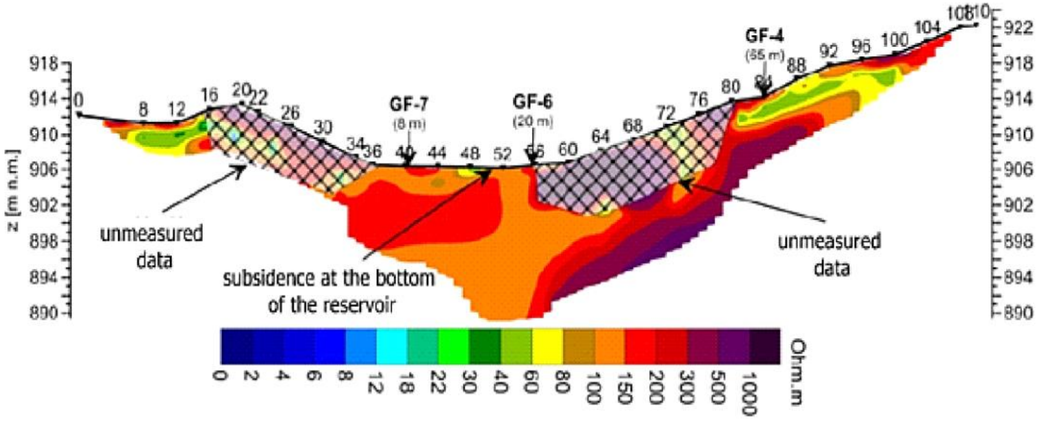
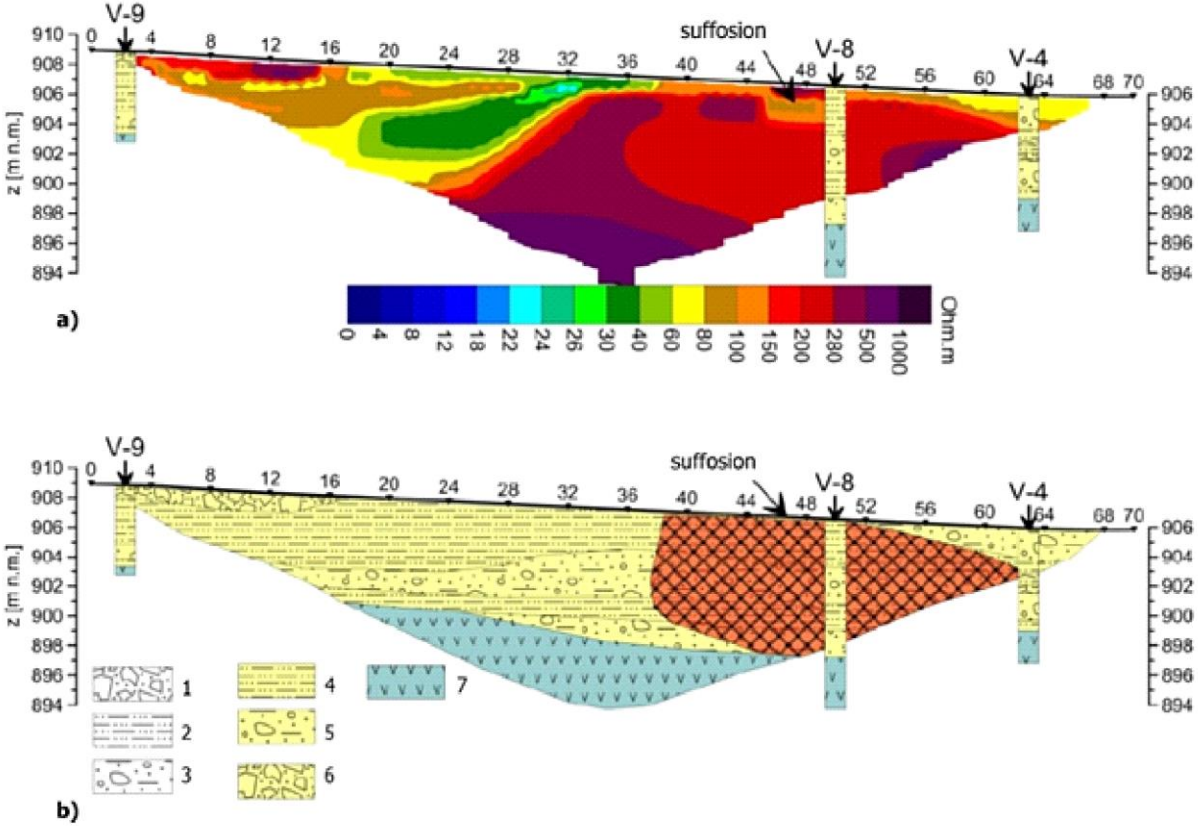


Fig. 8 Geophysical profile GF5 - Inverse resistivity profile

values (0.25-0.3 km/s) and on the ERT profile by decreased resistivity values (18-26 Ohm.m). The anomalous area is in depth connected with the suffosion area below the dam body (Fig. 5c), which is manifested in a resistivity section with resistivity values between 40 and 60 Ohm.m (Fig. 5b). In the same way demonstrated itself the suffosion area on the profile GF-2, as a direct continuation of the zone recorded on the profile GF-1. In seismic tomography, a useful signal was lost under the dam body due to presence of significantly heterogeneous environment (suffosion area), and this resulted in decreased depth range and therefore is the mentioned area of suffosion not recorded on SRT profiles (Fig. 5a).

Profile GF-4 was led from SW to NE along the NW margin of the reservoir and *profile GF-8* was situated under the dam body approximately 15 m from the dam foot with SE – NW orientation (Fig. 2). The purpose of these measurements was to determine the possible continuation of the area of suffosion to the west and east. On the profile GF-4, the environment at the depth level below the bottom of the reservoir appears as solid, composed from hard rocks with resistivity values above 200 Ohm.m (Fig. 6). The field of decreased values of resistivity on the 102nd – 114th m of the profile is probably a demonstration of strongly weathered hard rock at the basement. The continuation



a) Inverse resistivity profile and
b) interpreted geological cross-section

1) macadam, andesite debris,
2) sandy silt, sandy clay,
3) silty gravel,
4) sandy clay, sandy silt,
5) debris of silty (clayey) gravel nature,
6) derbis composed from andesite boulders,
7) andesite and volcanic conglomerates with different level of weathering

Fig. 9 Geophysical profile GF6

of the suffosion area was on the profile GF-4 below the projection of the bottom of the storage tank not detected. Similarly, the sign of suffosion was also not found on the ERT measurement of profile GF-8 (Fig. 7b).

Evident manifestation of the suffosion below the bottom of the dam can not be seen also on the profile GF-7, which was measured at the bottom of the tank. Deluvial sediments have resistivity values between 30-300 Ohm.m (Fig. 7a), according the grain composition found in well V-5. The resistivity values of deluvial sediments correspond to the grain composition found in well V-5.

Profile GF-5 was oriented from SE to NW through the reservoir (Fig. 2) to record the possible anomalous areas, which have parallel course with the botom of the dam. Signs of the dam bottom sinking can be visible only close to the surface (48th – 56th m of the profile) on the inverse resistivity profile (Fig. 8). The resistivity values on the shaded sections were obtained by interpolation in the inverse calculation. In these areas we miss the measured data, because here the profile was led over the slopes of the dam, where the electrodes could not be grounded to not disturb the insulating foil.

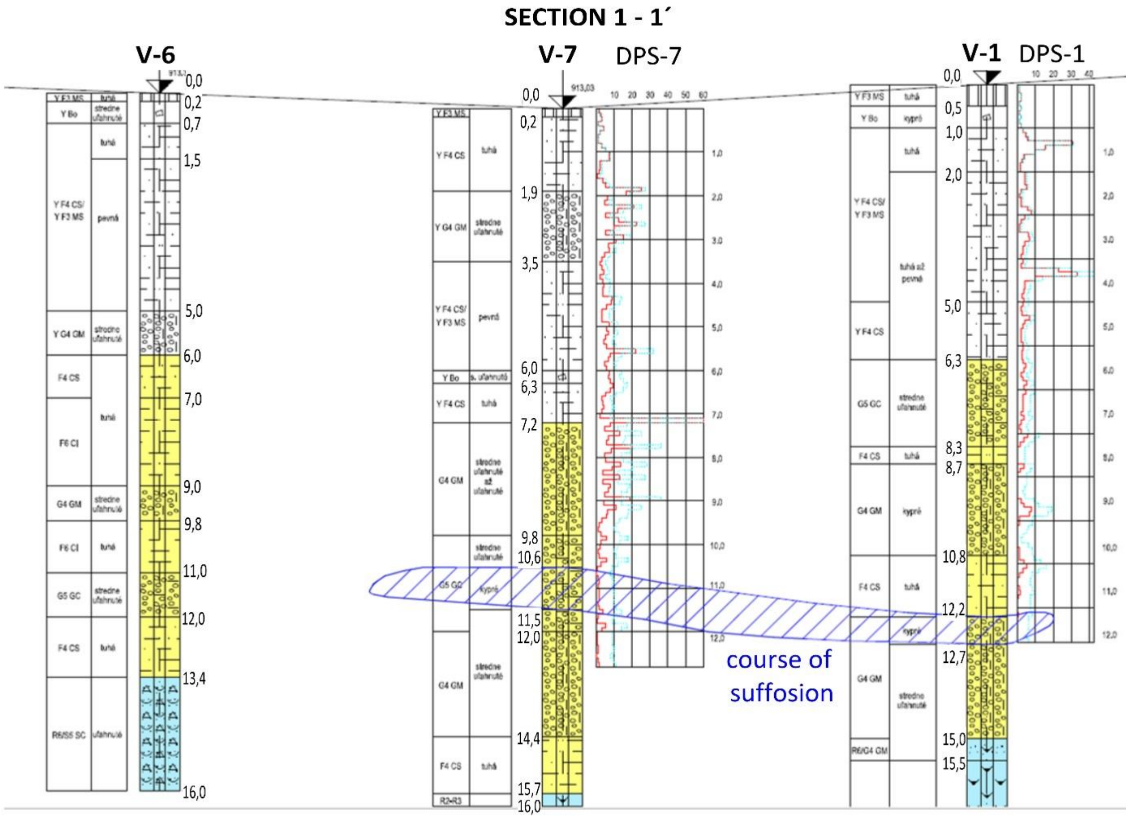


***Fig. 10** Engineering-geological profile EG 1-1´ with marked course of the suffosion*

Profile GF-6 passes through the sink part of the dam bottom (surface manifestation of suffosion) from SW to NE (Fig. 2). The area of suffosion is interpreted from the 38th m of the profile to its end in deluvial sediments environment (Fig. 9b). The deluvial sediments have between 32nd to 64th m higher resistivity values (150 -300 Ohm.m, Fig. 9a) than in case of the anomaly on profiles GF-1 to GF-3, what is caused by loose consistency of sediments found in well V-8.

5. Evaluation of results

The field works led to construction of three engineering-geological (EG) profiles. Profile 1-1´ is constructed through the dam crown of the storage tank, and profiles 2-2´ and 3-3´ through the bottom of the tank (Fig. 2). Based on the results of drilling and sampling works, dynamic penetration and infiltration tests, the course of suffosion was marked in the EG profiles (Fig. 10).

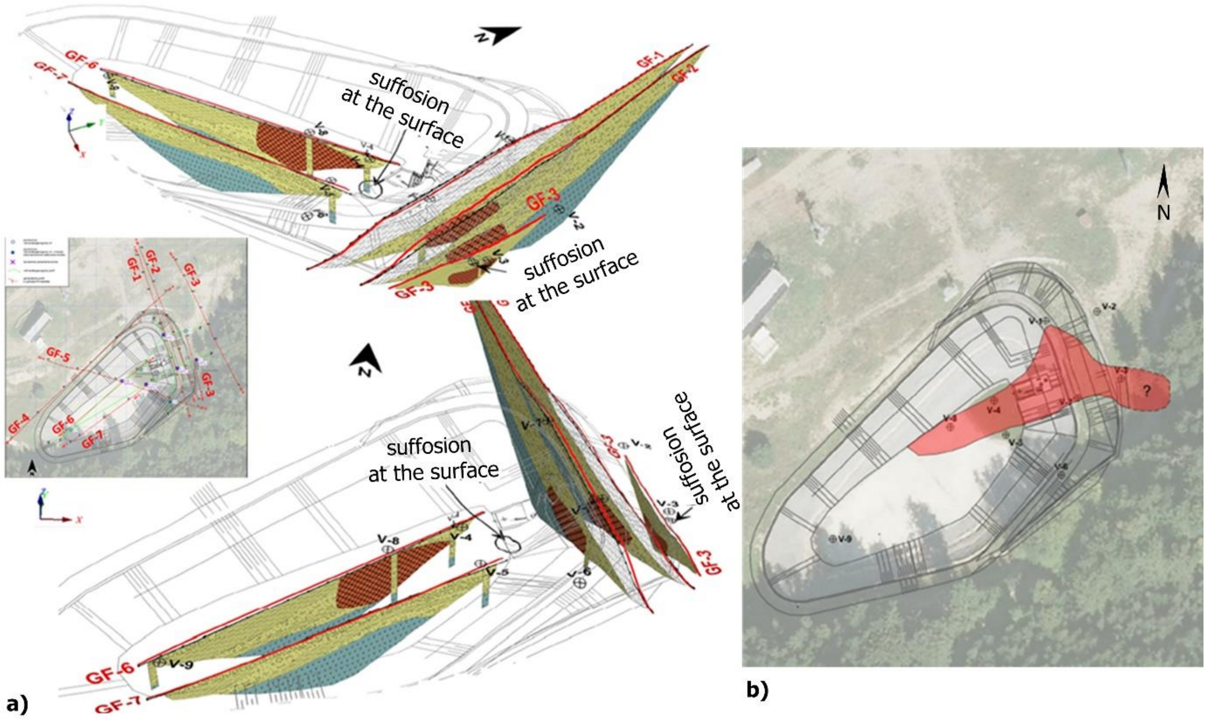


Fig. 11 a) 3D model of the reservoir with displayed interpreted geological cross-sections, marked suffosion area, b) surface projection (areal extent) of the area affected by suffosion

After correlation of results from drilling and sampling works with geophysical profiles, interpreted geological profiles were created, in which based on the physical signs was also marked the area of suffosion (Fig. 5, 4, 9). Subsequently, the interpreted geological cross-sections were displayed within 3D model of the reservoir (Fig. 11a), where we it can noticed that the marked suffosion areas are located under the reservoir body and dam. On the Fig. 11b is marked the surface projection (areal extent) of the area affected by suffosion.

The obtained results (Fig. 11a) show that in the area of the dam the suffosion takes place between wells V-7 (in depth 10,6 – 11,5 m) and V-1 (in depth 12,2 – 12,7 m), where the infiltration tests confirmed high permeability of sediments under the dam. In the area of the storage tank, the water loss was in well V-8 and continued towards the dam to well V-4 and under the dam in permeable Quaternary sediments. In the area of storage tank is the suffosion most pronounced in the vicinity of wells V-8 to a depth of 9,10 m; well V-4 at the level of 6,20 - 6,90 m. In well V-5 in the interval from 6,9 - 10,00 m, where infiltration test was realized, a low permeability environment is indicated on its basis.

6. Conclusion

This paper evaluates in detail the engineering-geological and hydrogeological conditions of the studied area of storage tank in the cadastral area of Králiky in terms of filtration stability. To analyse the problem, complex geophysical works, drilling and sampling works, dynamic penetration tests and infiltration tests in vicinity of damaged reservoir Králiky were used, which allowed to record the course of sufossion causing the damage of the reservoir dam and to map the areal extent of the area affected by sufossion. Suffosion is an internal filtration erosion occurring when the water flow from less permeable environment to environment with higher permeability and transports fine-grained particles with itself. Based on a comprehensive analysis of the results it can be concluded that in the area of the storage tank the water loss occurs at well V-8 and continued towards the dam to the well V-4 and below the dam in permeable Quaternary sediments. In the area of the water tank was suffosion marked significantly mainly close to well V-8 to a depth of 9,10 m; close to well V-4 at the level of 6,20 - 6,90 m. In the area of well V-1 at the depth of 12,20 to 12,70 m and in the area of well V-2 at the depth level 5,80 - 6,20 m. The essential results are an areal interpretation of changes in consistency – density and the course of suffosion, which enable to design the remediation measures.

Acknowledgment

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References

COLOMBO, L., GATTINONI, P., FRANCANI, V. Suffosion hazard for building and infrastructure in the high lombardy plain (northern Italy). *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, 2014, 2, p. 869 – 875.

FERDOS, F., DARGAHI, B., SOLARI, L. Mechanism of Suffusion Erosion Phenomenon In Porous Media. *J Geol Geosci* 2, 2018, 001-018.

LILIE R.J. *Whole Earth Geophysics.* Prentice Hall, New Jersey,1999, 361 p.

MOFFAT, R., FANNIN R. J., GARNER, S. J. Spatial and temporal progression of internal erosion in cohesionless soil Can. *Geotech. J.*, 2011, 48 (3), pp. 399-412.

REYNOLDS, J. M. *An Introduction to Applied and Environmental Geophysics*. John Wiley and Sons Ltd, Chichester, first edition, 1997, 796 pp.

RICHARDS, K.S., REDDY, K.R. Kinetic Energy Method for predicting initiation of backward erosion in earthen dams and levees Environ. *Eng. Geosci*., 2014, 20 (1), pp. 85-97.

SHEEHAN, J. R., DOLL, W. E., MANDELL, W. A. An Evaluation of Methods and Available Software for Seismic Refraction Tomography Analysis. *Journal of Environmental and Engineering,* 2005, 10 (1), p. 21-34.

WAN, C. F., FELL, R.: Assessing the Potential of Internal Instability and Suffusion in Embankment Dams and Their Foundations. *J. Geotech. Eng., ASCE*, 2008, Vol. 134, No. 3, pp. 401–407.

XIONG, H., YIN, Z. Y., ZHAO, J., YANG, Y. Investigating the effect of flow direction on suffusion and its impacts on gap-graded granular soils. *Acta Geotech*., 2021, 16, 399–419.

Atlas krajiny: Atlas krajiny Slovenskej republiky. 2002, [cit. 2022-05-05]. Available on: https://app.sazp.sk/atlassr/

GOŁĘBIOWSKI, T., PIWAKOWSKI, B., ĆWIKLIK, M., BOJARSKI, A., Application of Combined Geophysical Methods for the Examination of a Water Dam Subsoil. *Water* 2021, 13(21):2981 [cit. 2022-05-05]. Available on: https:// doi.org/10.3390/w13212981

HORIKOSHI, T., TAKAHASHI, A. Suffusion-induced change in spatial distribution of fine fractions in embankment subjected to seepage flow. *Soils and Foundations*, 2015, Volume 55, Issue 5, 1293-1304 [cit. 2022-05-05]. Available on: https://doi.org/10.1016/j.sandf.2015.09.027

LAVRUSEVICH, I., PODLESNYKH, A., LAVRUSEVICH, A. Some geoecological aspects of suffosion danger in the road infrastructure using. *MATEC Web of Conferences*, 2017, 106, 02010 [cit. 2022-05-05]. Available on: https://www.matec-conferences.org/articles/matecconf/abs/2017/20/matecconf_spbw2017_02010/matecconf_spbw2017_02010.html

PETRÁNEK, J. Sufoze, *On-line geologická encyklopedie geology.cz*, 2007, [cit. 2011-06-12]. Available on: http://www.geology.cz/aplikace/encyklopedie/term.pl?sufoze

SANDMEIER, K. J. Reflexw - GPR and seismic processing software [software]. ©Sandmeier geophysical research 2016 [cit. 2018-01-04]. Available on: http://www.sandmeier-geo.de/reflexw.html

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