Shallow geophysical survey as a tool for compactness verification of the underground sealing wall

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Abstract: The aim of this paper is to assess the compactness of the underground sealing wall through selected geophysical methods as a part of the engineering geological research. Underground wall was realised by grouting concrete mixture through series of two parallel lines of grouting boreholes. The injected environment is represented by the Quaternary sediments, mainly by anthropogenic sediments and soils - weathered rock material of silt composition, clayey sand to clayey gravel with rock fragments up to 10 cm in size, and remains of concrete wall at a depth of 0.3 – 1 m. Under anthropogenic sediments, granite subsoil rocks were to be interposed by grouting boreholes. Electrical resistivity tomography (ERT), shallow seismic measurements (SRT), and georadar (GPR) were used to verify the compactness of the underground wall. Measurements were made on one profile of a total length of 94 m in the middle between individual grouting boreholes. The measurement results were confronted with geological documentation of boreholes. On one of the boreholes, an electrical resistivity measurement was made on the core sample, which showed that values up to 100 ohm.m represent an injection-free environment and the presence of the injection mixture is displayed by an increase in apparent electrical resistivity. The results of the ERT on the measured profile showed that the individual grouting boreholes behave discreetly, and neither in the vertical nor in the horizontal direction doesn't form the pre-injected continuous homogeneous layer. Under the groundwater level, the injection mixture did not appear in the electrical resistivity tomography. The mixture was probably washed away in the groundwater flow. The building object was evaluated as non-compact in both horizontal and vertical directions. This result was confirmed also by borehole cores sampling and hydrodynamic testing in boreholes on the assessed section of the staunching wall.

Keywords: geophysical methods, ERT, GPR, SRT, underground sealing wall, flood protection line, Danube River

1. INTRODUCTION

The aim of this paper is to point out the possibilities of geophysical methods application for assessment of underground sealing wall (USW) compactness. The underground sealing wall assessment belongs to extensive tasks of engineering geology. Except common methods used in engineering geology, also geophysical methods can be applied to deal with this topic. Determining the strength, homogeneity and tightness of USW is mainly a part of tasks focused on the landfill's remediation (Matys et al., 2008; Rickertsen & Jacob, 2019), or on the dam walls integrity control (detection of covered faults, and zones of weakness; Llopis et al., 1995; Panagiotis & Sentenac, 2021). Unlike methods that are invasive to the study environment (boreholes, core sampling, current tests), the geophysical methods were carried out on the surface and displayed a continuous image over the entire length of the measured profile. The non-destructive nature of these methods is the main advantage in providing subsurface information for the assessment of the underground engineering objects as USW are.

The assessed building object is part of a flood protection line built on the left bank of the Danube River in Bratislava city. USW was built by classic high-pressure concrete mixture grouting. Injection wells were designed in two parallel rows with 0.75 m distance between them, with a step of 1.5 m and 0.75 m shift. The depth of the wells was 9 – 14 m. USW was designed to seal the already existing flood protection line (FP). It represents a vertical sealing element inserted into the permeable subsoil from the level of the crown of the wall base with a tight connection to the concrete foundation of the wall construction and concrete foundation of the mobile wall. The permeability of the sealing element was proposed with respect to the requirement of the the maximal allowed leakage –0,1 $l.s^{-1}$ per running meter. The lower level of the sealing was suggested to the 9, or 7 m, respectively of the pre-injected depth from the current terrain high. At the same time, also the boundary condition is defined here, according to which the injection should finished min. 0.5 m in the massive rock. Crucial criterion for the sealing wall building was the allowed gradient of the materials. For the designed thickness of the sealing approximately 2.25 and 3 m (grouting), max. water level difference of 3.5 m and allowed seepage 0.1 $l.s^{-1}$ on running meter, a sufficient required maximal permeability of the injected object in order of $10^{-7} m.s^{-1}$ was determined. Seepage calculations below the line were based on the basement permeability that was characterised by the permeability parameter $k = 10^{-4} m.s^{-1}$.

After the sealing wall building, five new wells for hydrodynamic tests were realised. These were geologically documented, and their cores were recorded by photos. Geological documentation of the core drills was confronted with the results of the geophysical measurements.

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The injected environment consists of Quaternary sediments represented mainly by anthropogenic and fluvial sediments. These are weathered rock materials of muddy nature, clayey sand to clayey gravel with rock fragments up to 10 cm and remnants of a concrete wall at the 0.3 – 1 m depth. More detailed composition of this complex of anthropogenic deposits lying on the granite basement are documented by core of the wells V1 – V5 (Fig. 1).

2. METHODS

To verify the compactness of the underground sealing wall, geophysical measurements – electrical resistivity tomography (ERT), shallow seismics and georadar (GPR) were applied. Each method measured 94 m long profile. At the section 0 to 23 m, the line of the profile was outside the injected line. At 23 m, it passed through a compact concrete wall of a flood protection line emerging to the surface and continued in the middle among the individual injection wells (Fig. 2).

The position and altitude of the applied geophysical measurements were performed by Trimble GeoXR device, with accuracy up to 2 cm using GNSS technology (RTK method using SKPOS service). The altitude of the points was determined in the obligatory system Bpv (Balt after settlement).

2.1. Electrical resistivity tomography

The method of 2D electrical resistivity tomography (ERT) is a system of complex resistivity measurement with larger number of electrodes, allowing to obtain information regarding the distribution of specific electrical resistivity in the horizontal and vertical direction. The distance between the electrodes is determined depending on the required detail and depth range of the survey. The measurement was carried out with ARES II (GF Instrument) device using a dipole-dipole electrode arrangement with electrode distance of 2 m. Gained data were processed by inverse software Res2DInv. The inverse calculation allows the transformation of the measured data into a set of values of the actual resistivity of the environment and on their basis to obtain a view of the real structure of the investigated rock environment. The results of ERT measurements were processed to the vertical inverse resistivity profile.

In addition to ERT, electrical resistivity measurements on the well cores were performed, using the Wenner-alpha electrode arrangement with distance between the electrodes of 5 cm.

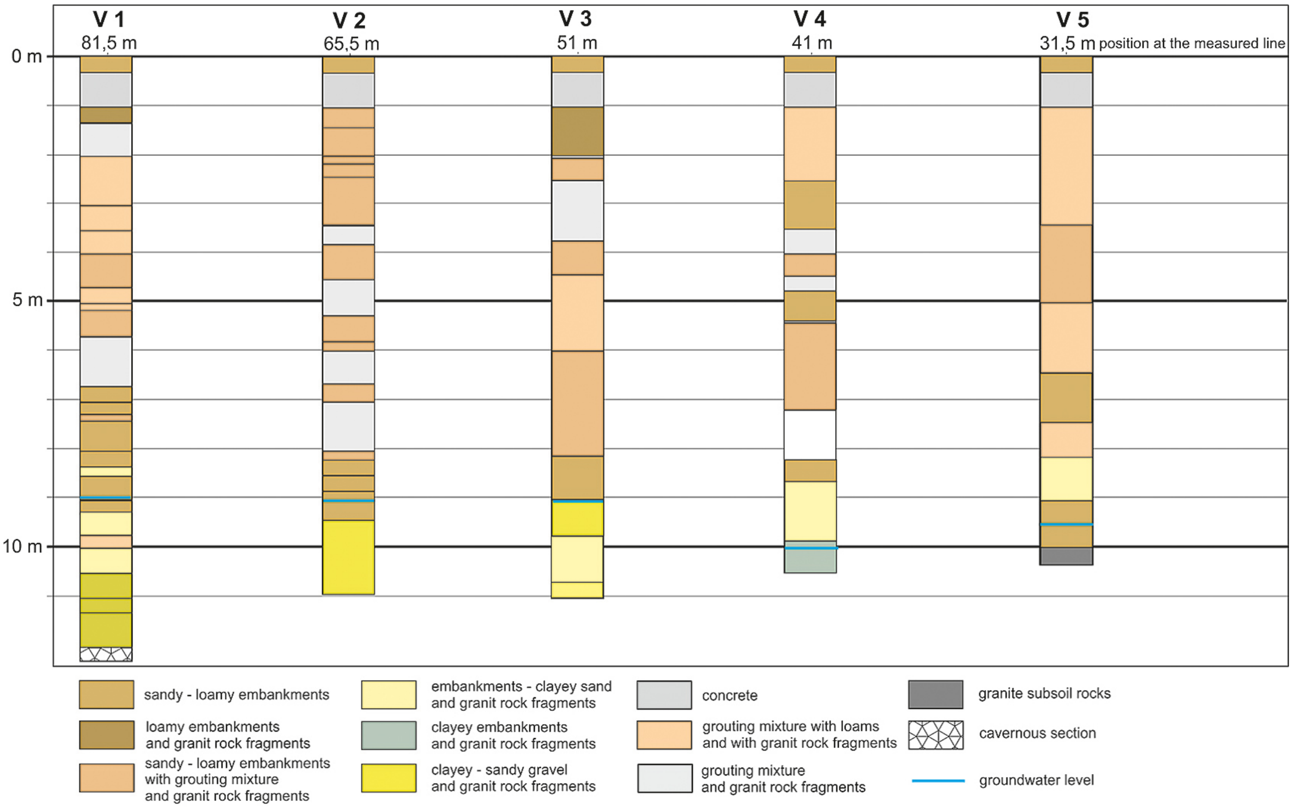

Fig. 1. Logs of wells V1 – V5 interpreted based on the drilled cores.

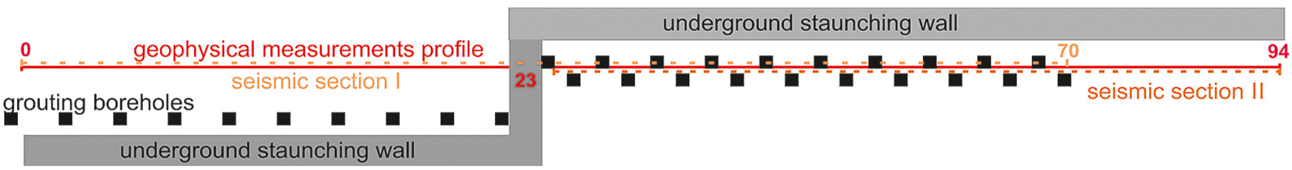

Fig. 2. Schematic location of the profiles.

2.2. Ground penetrating radar

Georadar (GPR, Ground Penetrating Radar) is geophysical method using radar pulses to map subsurface structures and objects. The transmitted waves pass through the environment, while the envelope curve of the electromagnetic waves is cone shaped and widens to the depth. When the wave passes through interface of two layers with different dielectric parameters, the part of the energy reflects to the surface and the rest propagates further through the environment. The reflected energy is recorded and displayed in the form of time course, where amplitudes and time of the passage through the individual layers can be seen. Based on the parameters of the recorded reflected waves (size and frequency, time shift between their initiation and recording), information regarding the state of the diagnosed environment is obtained. By passage through the individual layers, the velocity of the waves is changing, and their intensity decreases due to the reflection of a part of the energy at the interface of different materials (signal attenuation to the depth). The measurement was performed with SIR3000 (GSSI) device with a 400 MHz antenna and MALA device with 350 and 500 MHz antenna. The depth range was from 2.5 to 4.5 m depending on the frequency of the used antenna.

To determine the depth of individual interfaces, the analysis of the wave's velocity propagation was done during the measurement processing, and this was followed by these steps: suppression of the direct wave evidence ("wow-effect"), correction of the first signal onset, correction of the length of the profiles, amplification of the signal in areas of interest, bandpass filtering of the signal and background noise removal.

2.3. Shallow seismic methods

Shallow seismic methods are geophysical methods using artificially initiated seismic waves to determine the depth of seismic interfaces under the surface and the velocity of the propagating seismic waves between these 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 a direct wave and head waves arising at individual interfaces. The precondition to head wave creation is the increasing velocity with depth. The processing includes interpretation of individual hodochrones of waves and results in velocity profiles with interfaces and velocity characteristics (Reynolds, 1997). Seismic refraction tomography represents an alternative to the conventional interpretative methods of seismic refraction (Sheehan et al., 2005).

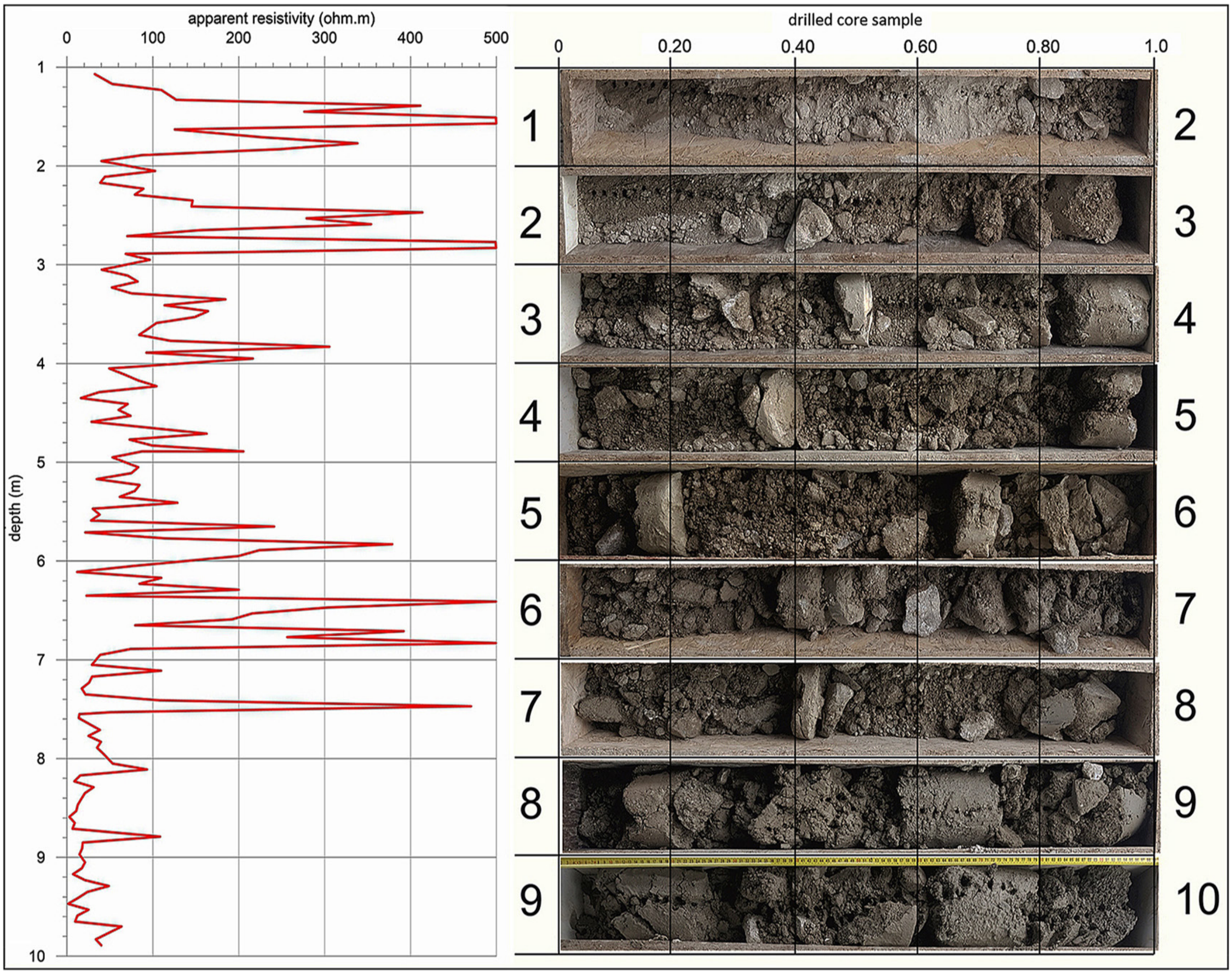

Fig. 3. The result of electrical resistivity measurement on the core sample; left - measured resistivity, right - drilled core sample.

It provides higher resolution and records velocity changes also in horizontal direction. Reflection seismic uses reflected waves. The results are time profiles (vertical axis indicating two-way time – TWT), or depth profiles (vertical axis indicating depth, calculated from the TWT after velocity analysis) with reflection interfaces corresponding to interfaces with certain acoustic impedance contrast.

Seismic measurement was performed by 36-channeled M.A.E device with 14 Hz vertical geophones and hammer as a source. Coverage of the entire measured profile was ensured by two overlapping layouts, each with a length of 72 m and with 12 overlapping geophones. Geophone offset was 2 m at each line and the source position shift was 4 m, while the first shot was 3 m before the first geophone, and the last position of the shot was 3 m after the last geophone. The record was summed from 4 to 6 pulses at each position. The measured data were processed by processing methods for refraction seismic and refraction seismic tomography (Reflex Version 8.0 developed by Sandmeier, 2016 and ZondST2D) and for reflection seismic (Reflex Version 8.0).

3. RESULTS

3.1. Electrical resistivity measurement

Electrical resistivity measurement (SOP) on the core sample

The result of electrical resistivity measurement on the core sample is at the Fig. 3. Values up to 100 ohm.m represent an injection-free environment and the presence of the injection mixture is displayed by an increase in apparent electrical resistivity. Based on these measurements of apparent electrical resistivity by SOP method, the results from ERT were correlated.

Electrical resistivity tomography

The measurement of electrical resistivity tomography is displayed in a resistivity section (Fig. 4a), where we can observe the change in resistance. Values with higher apparent resistance (red to purple colour) represent environment in which the injection mixture related to the surrounding environment – in terms of the geological documentation consisting of anthropogenic deposits. The results of ERT measurements show that the individual grouting wells are discreet and neither in vertical, nor in the horizontal direction

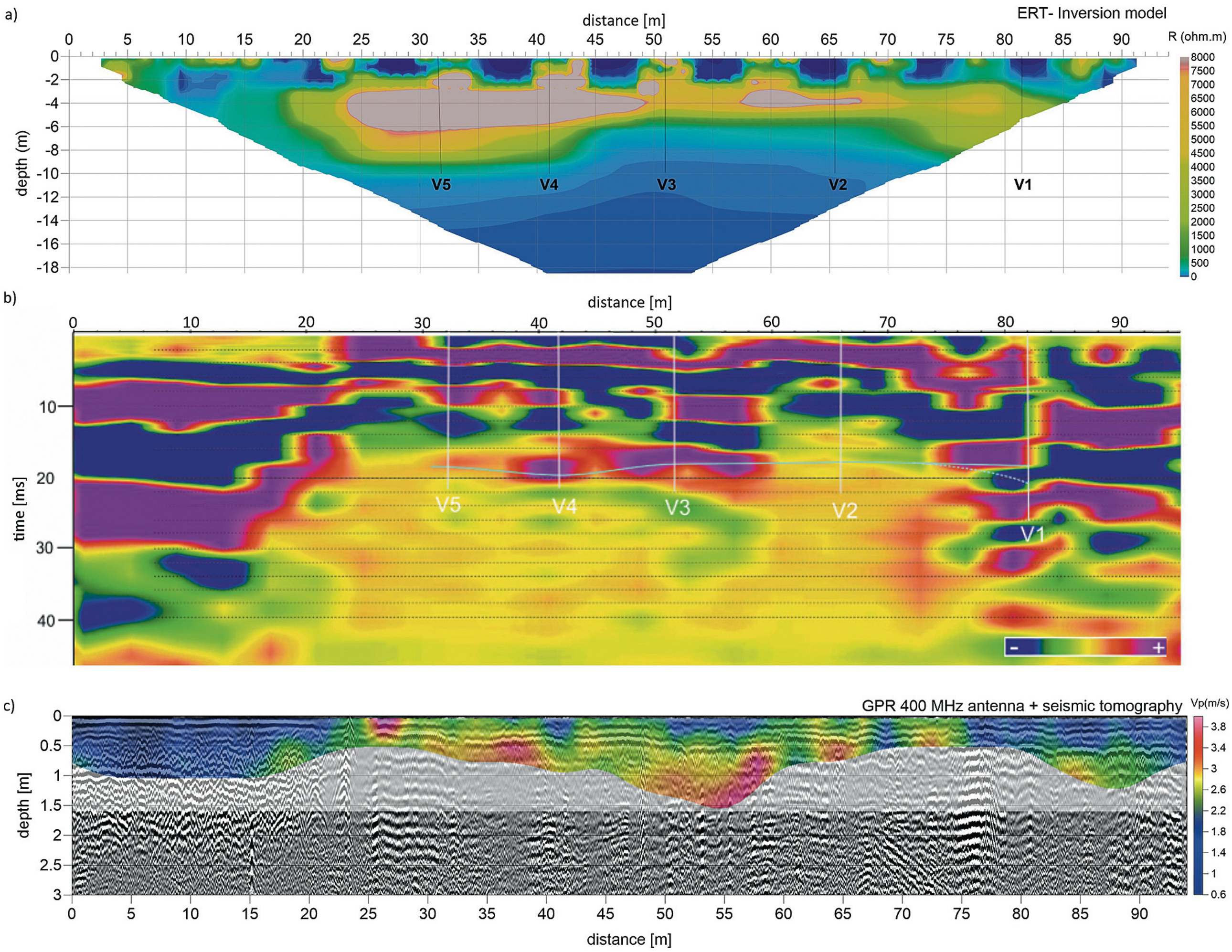

Fig. 4. The results of geophysical measurements: a) inverse resistivity profile ERT with position of wells, b) seismic reflection profile (time profile with wells position, c) combined results of GPR measurement and SRT measurements.

the grouting does not form a continuous homogeneous layer – the effect of isolated islands. Below the groundwater level, about 8 m below the surface, the injection mixture was not indicated in the measurement of electrical resistivity tomography.

3.2. Reflection seismic

First 23 m of the profile lies outside the injected line, what was reflected also in the reflection section (Fig. 4b), differing significantly from the rest of the profile. Up to 25 m depth is this sector formed by thick, continuous reflections. At the depth about 10 m under the surface, marked reflection interface can be seen, which could correspond to the groundwater level. Up to 2 m under the surface no reflections are visible. Contrary to the second part of the profile, where the zone between 23 and 82 m at the depth around 1 m under the terrain, a contact of older concrete wall fragments with clayey – sandy anthropogenic deposits is reflected. Here the contact is manifested by continuous intact reflex. Below this reflective element up to a depth of approximately 10 m, the reflection picture is discontinuous, what corresponds to the inhomogeneity of the environment consisting of layers of anthropogenic deposits permeated to a various degree by injection mixture. The selected measurement parameters do not provide sufficient measurement resolution and together with a small velocity contrast between the individual layers do not allow to divide the seismic image into a more detailed part. A significant reflection interface at a depth of approximately 10 m can represent the ground water level, or the contact of the sandy-clayey anthropogenic deposits with the bedrock. Deeper is the seismic image in the injected part without reflections, thus probably indicating the presence of the bedrock. Crossing of the profile at 23 m with a compact concrete wall of a flood protection line is also visible on the seismic image (Fig. 4b).

3.3. Seismic refraction

Despite the sufficient measured profile length, the depth range of the seismic refraction measurement was very small, only 2 – 3 m (Fig. 4c, 5). Seismic refraction tomography was not able

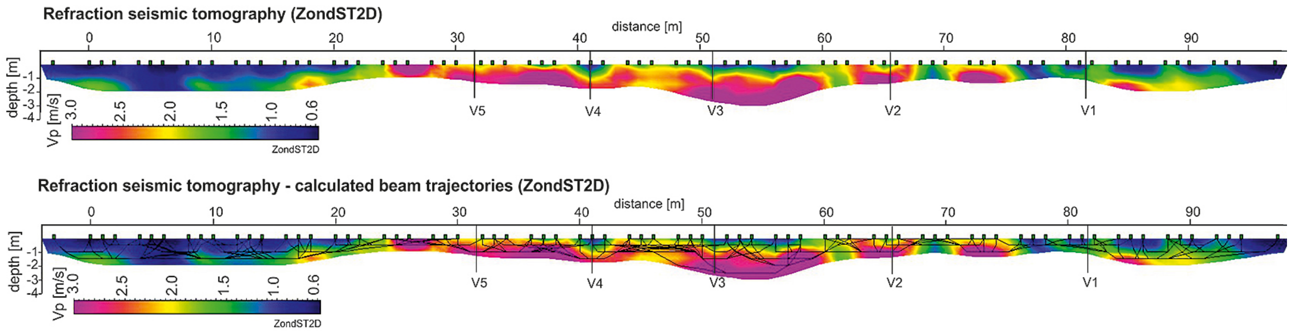

Fig. 5. Final velocity model of the seismic refraction tomography.

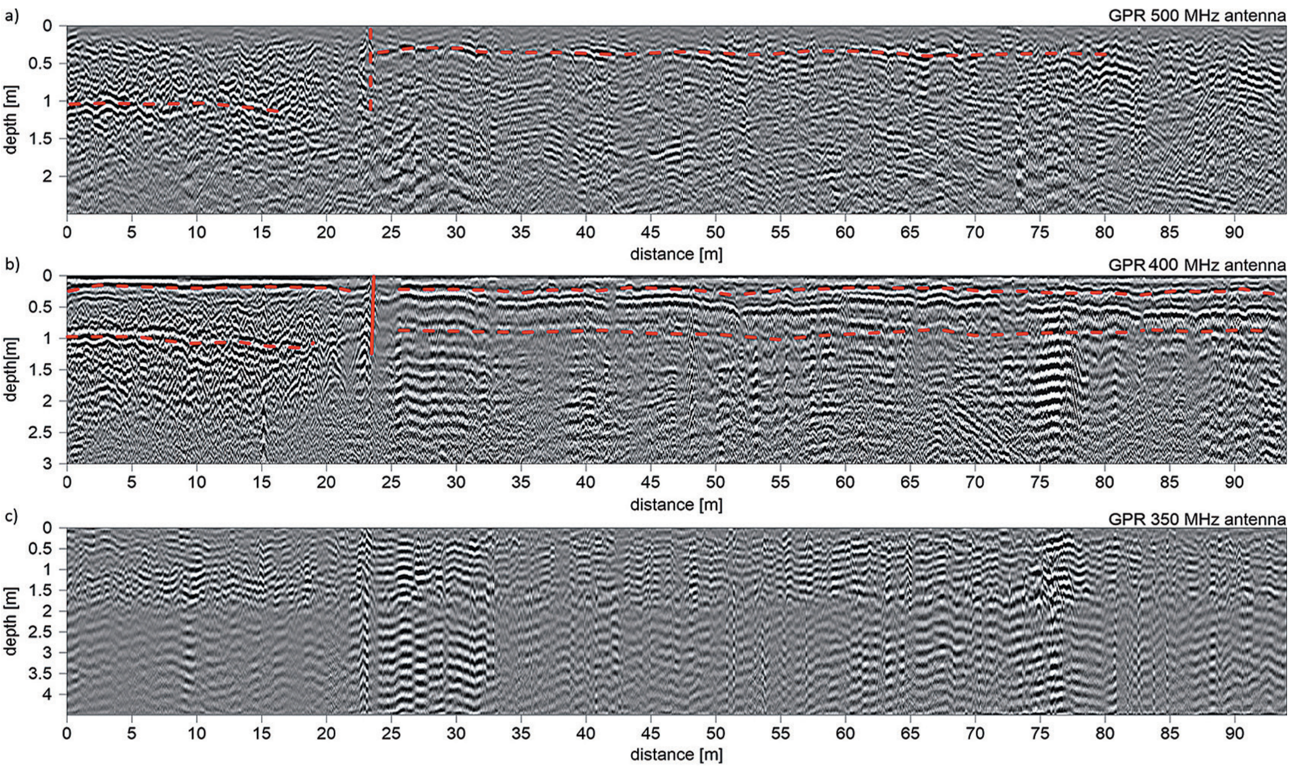

Fig. 6. Radargram: a) antenna 500 MHz, b) antenna 400 MHz, c) antenna 350 MHz.

to record the interface at a depth about 1 m, representing the passage of the remains of the concrete wall into the material of the anthropogenic deposits. There is no head wave formation at this interface because the environment under the interface (anthropogenic deposit) is typical by lower velocity of seismic waves propagation, and thus the basic precondition of the head wave formation is not fulfilled. The velocity interface representing the groundwater level, or the beginning of the bedrock, recorded on the seismic reflection profile at a depth around 10 m (Fig. 4b), was not displayed on the seismic refraction tomography profile. However, the velocity changes of the environment around the 23rd m of the profile, where the profile passes from the anthropogenic deposits into the line of grouting wells with remains of the concrete wall, was recorded. The transition was manifested by a large velocity jump from Vp around 600 m/s (environment of the anthropogenic deposits) to values in the range 1600 – 3000 m/s (concrete mixture in various stage of disruption).

Ground penetrating radar

GPR measurement was processed in the form of vertical radargrams (Fig. 6a-c). The best result was provided by SIR 3000 device with 400 MHz antenna (Fig. 6b). The radargrams shows vertical interface at around 23 m of the profile, representing the passage of the profile through the wall and two distinct horizontal interfaces. The first at a depth of about 0.3 m, representing the upper boundary of the concrete wall and the second at a depth of about 1 m, representing the lower boundary of the same wall (Fig. 6a, b). The visualisation did not indicate anything under this significant anomaly.

CONCLUSIONS

Based on the obtained results of the used geophysical methods we can conclude that as the most appropriate geophysical method for the given task appears to be the ERT or shallow seismic reflection. For a more comprehensive assessment of the valued structure using shallow seismic reflection, it would be necessary to choose smaller geophone offset and thus improve the resolution of the method. However, because of the given technical equipment compromise between the horizontal resolution of seismic methods and their depth range was chosen. Seismic refraction was not suitable for the present environment. The velocity profile of seismic refraction tomography recorded only the beginning of the injected section at 23rd m of the profile, in the form of significant velocity increase. Also, GPR measurement recorded only the course of the older concrete wall of the flood protection line at a depth of about 1 m. The image under this significant anomaly did indicate nothing.

A significant change of the environment from transition outside the injection line is marked also on the reflection image, where the injection section is manifested by discontinuous reflexes. The compact concrete wall of the flood protection line and the remnants of the older concrete wall in close proximity below the surface have significant reflection effect. The reflex at a depth of approximately 10 m under the surface indicates the onset of the groundwater level, eventually the beginning of the bedrock at some parts of the profile.

The essential method for the final evaluation of the compactness of the underground wall was ERT measurement in this case. ERT results on the measured profile show that the individual grouting wells are discreet, and neither in the vertical nor in the horizontal direction does the grouting form continuous homogeneous layer. Below the groundwater level, the injection mixture did not display at all in the measurement of electrical resistivity tomography. Based on these results, we assume that most of the injection mixture was washed away in the direction of groundwater flow. This result was also confirmed by samples of drill cores and evaluation of hydrodynamic tests in wells on the assessed section of the sealing wall.

Control wells V1–V5 showed that the final permeability after injection does not correspond to the required value of 10^{-7} m.s^{-1}, but achieves a value of the order of 10^{-2} m.s^{-1}. Only in the case of well V-5 was the measured value of the order of 10^{-5} m.s^{-1}, but even that does not reach the required value of 10^{-7} m.s^{-1}. This means that this environment (with filtration coefficient of the order of 10^{-2} m.s^{-1}) seems to be unsuitable for the application of the chosen technological procedure.

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References

Lilie R.-J., 1999: Whole Earth Geophysics. Prentice Hall, New Jersey, 361 p.

Llopis J.-L., Sharp M.- K., Butler Dwain K.- B. & Yule D.- E., 1995: Applied geophysical techniques to evaluate earth dams and foundations. *Proceedings Volume 2457, Nondestructive Evaluation of Aging Structures and Dams. Event: Nondestructive Evaluation of Aging Infrastructure, 1995, Oakland, CA, United States,* https://doi.org/10.1117/12.209402

Matys M., Gajdoš V. & Rozimant K., 2008: Kontrola podzemnej tesniacej injekčnej steny okolo skládky v Šali. (Inspection of the underground sealing injection wall around the landfill in Šala). http://fast10.vsb.cz/science/seminar2008/pics/10.pdf (in Slovak)

Panagiotis M. & Sentenac P., 2021: Subsurface condition assessment of critical dam infrastructure with non-invasive geophysical sensing. *Environmental Earth Sciences, 80, 17,* Springer, DOI: 10.1007/s12665-021-09841-x

Reynolds J.-M., 1997: An Introduction to Applied and Environmental Geophysics, John Wiley and Sons Ltd, Chichester, first edition, 796 p.

Rickertsen H. & Jacob R., 2019: Ground Penetrating Radar and Electrical Resistivity Methods to Characterize Soil-Bentonite Slurry Cutoff Wall and Detect Defects. *AGU 2018 Fall Meeting, Washington, DC.* https://www.essoar.org/doi/abs/10.1002/essoar.10500758.1

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

Sheehan J.-R., Doll W.-E. & Mandell W.-A., 2005: An Evaluation of Methods and Available Software for Seismic Refraction Tomography Analysis. *Journal of Environmental and Engineering*, 10, 1, 21–34.