The resistivity, seismic, geotechnical and geophysical well logging measurements for road cut stability assessment

Bibiana Brixová[1], Martin Bednarik[1], René Putiška[1], Jana Lahučká[2], Vladimír Budinský[3], Marta Prekopová[4], Vincent Kultan[1] & Ivan Dostál[5]

[1] Department of Engineering Geology, Hydrogeology and Applied Geophysics, Faculty of Natural Sciences, Comenius University in Bratislava, Ilkovičova 6, 842 15 Bratislava, Slovakia
[2] Department of Environmental Geochemistry, Division of Geology, State Geological Institute of Dionýz Štúr – Bratislava, Mlynská dolina 1, 817 04 Bratislava 11, Slovakia
[3] Institute of Geosciences, Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical University of Košice, Letná 9, 040 01 Košice, Slovakia
[4] ekolive s. r. o., Americká Trieda 2430/3, Košice, Slovak Republic
[5] AEGEO Ltd., Karpatské námestie 10A, 831 06 Bratislava, Slovakia

AGEOS

Abstract: Regarding to a new highway and expressway networks construction in Slovakia, we are more often solving problems generated with stability state change, whether in natural slopes, cuts, or embankments of road bodies. In the cut of R4 expressway on the section Košice-Milhosť, after repeated anomalous precipitations slope movements leading to stability disruption of the cut were activated. As a part of and supplementary engineering geological survey, 4 inclinometric boreholes were added to the monitoring network. Further, additional laboratory tests on both undisturbed and disturbed samples, focusing primary on determining the shear parameters of the soil were realized, the functionality of the existing subhorizontal drainage elements was evaluated, and the deformations obtained from inclinometry were repeatedly measured and analysed. For the stability assessment, geophysical measurements were designed and carried out – logging measurements in boreholes, electrical resistivity tomography (ERT) and seismic refraction tomography (SRT). The obtained values of seismic velocities of P and S waves were used for the geotechnical parameters – Poisson´s ratio, Shear and Young´s modulus – determination. The stability degree calculated for the current state has a value of 0.97. This indicates an unstable slope and does not correspond with the stability degree required for permanently used structures. The stability calculation also showed the possible further development of slope movements, if the cut was not remediated.
Key words: engineering geological assessment, road cut stability, seismic refraction, logging measurements, electrical resistivity tomography, expressway Košice - Milhosť

1. INTRODUCTION

Even if the stages of orientation engineering geological survey confirms that the field planned for the infrastructure construction is inclined to landslides, often due to direction and height of the roads, it is not possible to change the route of the road. Therefore, the task of the detailed, or supplementary stage of engineering geological survey is to provide information leading to ensure the slopes stability and conceptually propose permanent remedial measures. This paper is devoted to supplementary engineering geological survey (EGS) of cut of R4 expressway on the Košice-Milhosť section (Fig. 1), where after repeated anomalous precipitation, slope movements occured.

Before the construction of the expressway R4, a detailed EGS was carried out in 2009. Based on the slope stability calculations during the road planning, static protection of the right slope with an anchored pile wall with a height approximately 5 m was recommended and carried out. The wall consists of piles with a diameter of 1200 mm and is anchored with strand anchors that were pre-tensioned to 760 kN. The axial distance between anchors is 1,5 and 3 m. Above the retaining wall, the geometry of the surface of the cut is modified by macadam, followed by surface drainage with concrete gutters, vegetation cover and another row of concrete gutters in the crest of the cut slope. Above the retaining wall, the geometry of the surface of the cut is modified by macadam, followed by surface

Fig. 1.: The route of the R4 expressway with the marked section Košice-Milhosť, where an engineering- geological survey was conducted. *(Source: https://sk.wikipedia.org/wiki/Rýchlostná_cesta_R4_(Slovensko).*

Manuscript received 2022-11-02
Revised version accepted 2022-12-08

drainage with concrete gutters, vegetation cover and another row of concrete gutters in the crest of the cut slope. 14 horizontal boreholes were built in the cut.

After construction works and commissioning of the expressway section, geotechnical monitoring consisting of geodetic measurements on the surface of the slope of the excavated cut, deformation measurements in inclinometric boreholes, regime measurements of the ground water in hydrogeological boreholes and discharge measurements from horizontal drainage boreholes between 2011–2017 were realized. The results of the geotechnical monitoring showed that there was a slight consolidation of all points (up to 40 mm), which stabilized at the level ±5 mm over the course of 5 years without identified ongoing trend. No significant movement was demonstrated, therefore in 2017 the monitoring was terminated.

In 2019, six years after the completion of the assessed section of the R4 expressway, a slope movement above the pile wall that secured the expressway, was activated. In the initial stage, open cracks and tears of up to 10 cm have developed (Fig. 2). Significant was also the subsidy from the vast field above the cut and even the seeding of the cut was not effective to eliminate it. Although the landslide did not threaten directly the expressway, it could damage or disable the upper parts of the primary protective pile wall object by damaging the gravel stabilization throw, as well as by changing the slope inclination, no least by allowing further seepage of the precipitation. Therefore, works were proposed in the assessed cut during the supplemented EGS survey, the task of which was to assess the slope stability in the area above the existing pile wall and to propose an increase of the confidence factor through structural measures.

Stability assessment requires a very detailed knowledge of the rock environment. Within this supplementary survey, standard procedures as the construction of a monitoring network consisting of four new inclinometric boreholes, soil sampling and laboratory determination of their physical-mechanical properties and shear parameters, inclinometric measurements and regime observations in boreholes were carried out. To specify the point information from supplementary EGS, geophysical measurements – seismic measurements with vertical and horizontal geophones, electric resistivity tomography (ERT) measurements and logging measurements were applied. Especially the SRT method become popular because it can map and estimate the bedrock's elastic properties and the soils that overlay it. The physical conditions of near-surface rocks strongly influence their elastic properties and stiffness. Seismic velocities usually show significant differences between the landslide mass and the underlying bedrock (Heincke et al., 2006; Donohue et al., 2012; Yamakawa et al., 2012). The problem occurs with slopes formed by similar sediments with a small velocity contrast. In such cases, it is appropriate to use the different response of P and S waves to

Fig 2.: a) The cut of the R4 expressway with a marked zone of a landslide, b) landslide above R4, c) a shear zone, d) destroyed dewatering surface element.

changes in porosity, saturation, geotechnical parameters of the environment (Gregory, 1976; Uhlemann et al., 2016; Mondol et al., 2007; Pasquet et al., 2015) and velocity gradient plots (Benjumea et al., 2011; Hinojosa-Prieto & Hinzen, 2015). The measured values of Vp and Vs waves allow to obtain additional seismic parameters (Vp/Vs, Poison ratio), which represent the texture of the rock environment along the entire profile. Hence, we can extract more geophysical information that enhances the geological understanding of the site and its geotechnical engineering implications (Hinojosa, 2020).

The results of the supplementary EGS helped to reduce the ambiguities in the construction of a mathematical calculation model of slope deformation, which ultimately led to design of effective remedial measures and helped to prevent similar situations as occurred in 2019 in this landslide area.

2. METHODOLOGY OF RESEARCH WORKS

From geological point of view, the wider area of the cut contains Quaternary slope sediments, and the basement is composed from Neogene sediments. Quaternary slope sediments are represented by clays with intermediate plasticity of class F6 Cl. Neogene sediments consists of clayey sand of class S5 SC and clay with high plasticity of class F8 CH.

To verify the engineering geological and hydrogeological conditions of the assessed cut, four core engineering geological boreholes with overall length of 80 common meter, were realized. An overview of the geological works can be seen in Fig. 3. The longitude and latitude of the boreholes was determined by GNSS TRIMBLE R4 using S-JTSK coordinate system and Baltic Vertical Datum – After Adjustment (Bpv).

Soil samples were taken from the boreholes in accordance with EN ISO 22475-1, the samples were hermetically sealed, labelled and shipped to specific laboratories within 24 hours. A total of 16 soil samples were taken, of which 10 were disturbed and 6 were intact. After drilling and cores evaluation by geologist (Fig. 4), all 4 boreholes were installed as inclinometric.

2.1. Video inspection in horizontal drainage boreholes

To video inspection of the HVK1A borehole, the complete inspection system V103288PTN for boreholes was used. A 50 mm rotating Pan Tilt camera head, AHD DVR was used.

2.2. Geophysical measurements

Surface geophysical measurements as seismic refraction for P and S waves (SRT) and 2D electric resistivity tomography (ERT) were carried out on four profiles and logging measurements were realized in boreholes. In this paper, the surface measurements are represented by profile P1 (Fig. 3), which SSW- NNE orientation correspond with the direction of the slope depression. The 70 m long profile crosses visible cracks. In the line of profile P1, drilling works were carried out, samples were taken and three inclinometric boreholes were built. This enabled to obtain more precise physical and shear parameters as inputs for stability calculations, thus having more clear predictive value and interpretation. The position of the profile was determined using a differential GPS Trimble GeoXR.

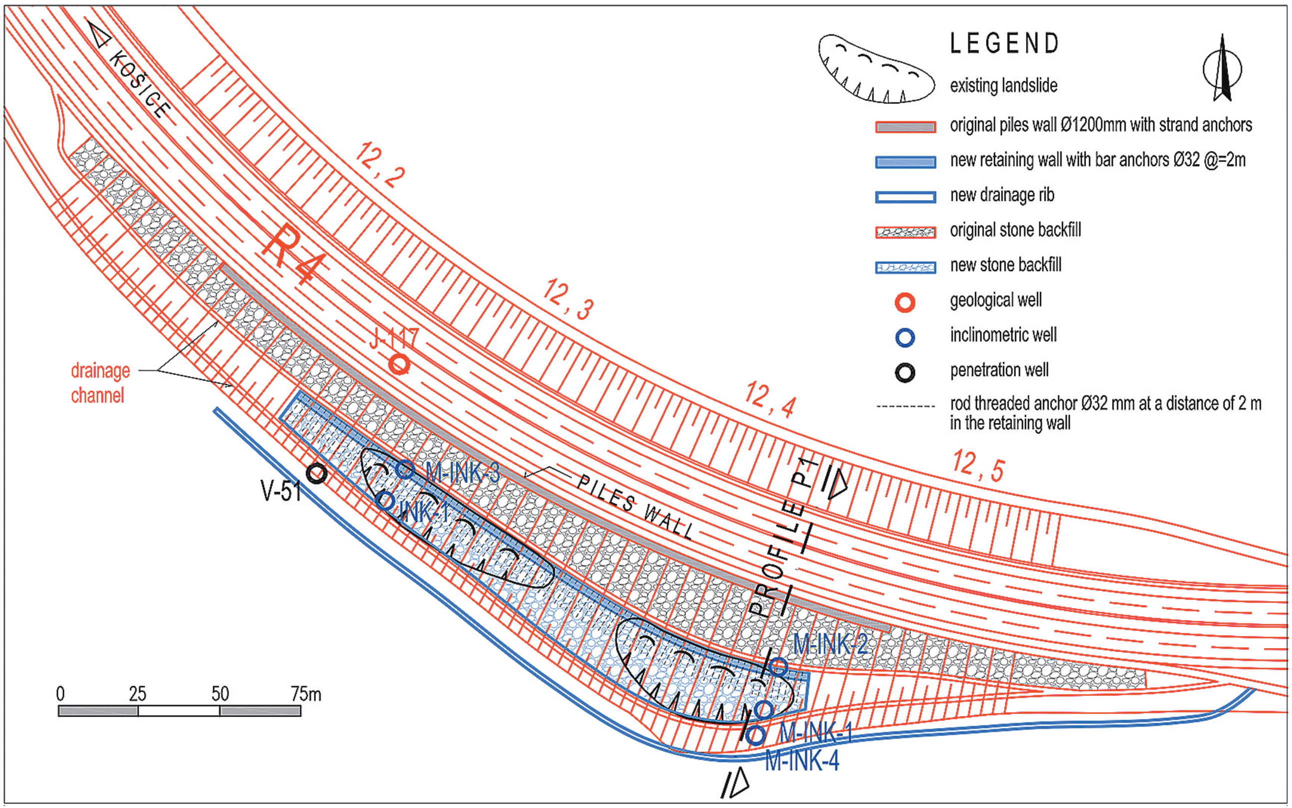

Fig. 3.: A detailed overview of geophysical works and measurements.

Fig. 4.: Cores of the borehole MI-INK-1, MI-INK-2 and MI-INK-4 in the order as they are located on the interpreted profile

2.3. Seismic refraction methods – SRT

Seismic methods belong to the geophysical methods using artificially generated seismic waves to determine the depth between seismic interfaces below the surface and the velocities of seismic waves propagation between determined interfaces (Lilie, 1999). Seismic waves propagate from the source in all directions, refract and reflect at the seismic interfaces thus creating reflected and head (critically refracted) wave. A precondition for a head wave creation is an increase in speed with depth. The arrival of each seismic waves is recorded along a line of geophones. The basic principle of seismic refraction is the measurement of the arrival time of the direct and head wave to the line of geophones. Individual hodochrones of these waves are interpreted during processing, resulting in velocity profiles with interfaces and their velocity characteristics (Reynolds, 1997). Seismic refraction tomography is an alternative to conventional interpretation methods of seismic refraction (Sheehan et al., 2005). It provides a higher resolution and record the change of velocity also in the horizontal direction.

The measurement at the Milhosť site was realized using 36 channelled seismic device M.A.E. A6000–S with 14 Hz vertical and horizontal geophones recording P as well as S waves. As a source a hammer was used, while a special pad was used during measurement with horizontal geophones, enabling to increase the energy of the transverse SH wave and initiate oppositely polarized SH+ a SH- waves (Haines, 2007). The geophone offset (distance) was 2 m for a profile P1. The source moved every 4 m. Measured data were processed by processing methods for seismic refraction and seismic refraction tomography in ReflexW software (Reflex Version 8.0 developed by Sandmeier 2016). The results are velocity cross-sections for P and S waves.

If there is not enough velocity contrast between individual interfaces, it results in a smooth velocity gradient on the SRT profiles. The consequence of such a smooth velocity gradient is that it can lead to "difficulties" in detecting or resolving the existence and position of critical geological boundaries that often indicate stratigraphic contacts or the depth to bedrock (Hinojosa, 2020). However, this challenge can be tackled using velocity gradient plots (Benjumea et al., 2011; Hinojosa-Prieto & Hinzen, 2015).

Obtained values of the seismic velocities of P and S waves (Vp, Vs) were therefore used to determine the Vp/Vs ratio and geotechnical parameters – Poisson´s ratio σ (1), shear-modulus

G (2) a Young´s modulus E (3). To calculate these following relations were used (Shebl et al., 2019):

$$\sigma = \frac{1-2\left(\frac{v_p^2}{v_p^2}\right)}{2-2\left(\frac{v_s^2}{v_p^2}\right)} \text{ (1)} \qquad G = r.v_s^2 \text{ (2)} \qquad E = 2G(1+\sigma) \text{ (3)},$$

where vp and vs are velocity propagations of longitudinal (P) and transverse (S) waves determined from seismic refraction tomography and r is the density of the environment. The values of the density of the environment used in the calculations (2650 kg/m^3) was calculated as the average value of the densities of the environment obtained from the boreholes. The calculations were carried out in the spreadsheet software Microsoft Excel. The distribution of the calculated values of all three parameters on the individual profiles was displayed through the Surfer software.

2.4. 2D electric resistivity tomography – ERT

ERT method is a system of complex resistivity measurement with higher number of electrodes. It allows to obtain information about a specific electrical resistivity distribution in a horizontal and vertical direction. The ERT survey can be realized by different electrode arrangements depending on the task specification, on the required detail and depth of the survey.

The measurement on the locality was performed by ARES II (GF Instrument) device using dipole-dipole electrode arrangement. The ERT measurement took place on the same profile as the SRT measurement. The electrode distance was 2 m on the profiles P1 to P4. On the profile P5 was the distance between electrodes 4 m. Measured data were processed in the inverse program Res2DInv. In the inverse calculation, the L2 standard was used. The results were processed into vertical inverse resistivity sections.

2.5. Logging measurements

Logging measurements represent geophysical measurements in boreholes. At the Milhosť site, two logging measurements in three boreholes were carried out, to verify and specify the thickness of geological layers and the position of sandy and clayey layers in the vicinity of the boreholes. Two logging methods were used: gamma-ray log (GL) – to measure the natural radioactivity of rocks and induction log (IL) – to measure the rocks conductivity. During GL we have noticed the degree of the rocks siltation. In general, the higher the clayey material content in the rock, the exposure power increases proportionally. During IK a change in the conductivity of the rocks along the borehole walls can be seen. As the conductivity increases, the clay content increases, and as the conductivity decreases, the sand content increases.

The measurements were provided by BLS-92H (W&R Instruments) device with continuous registration with recording step of 5 cm.

2.6. Inclinometric measurements

They are used to measure subsurface deformations in the horizontal plane and to verify movements in the slope and to assess its stability. The measurement interval was 0,5 m, while in each depth interval the inclination was recorded and converted to shift. By comparison of individual stage measurements with the basic (control) measurement, the increment of vertical deformations is obtained. Basic (control) measurements were realized in November 2019. Within the basic measurement, the currents state of the existing monitoring inclinometric boreholes on the disturbed slope was determined. The aim of inclinometric measurements is to locate the shear surface, quantify the movements on the shear surface, monitor the time evolution of the movements and determine the movement direction.

The measurements were carried out with Digitilt AT System device from DGSI company in installed inclinometric PE pipes, which are equipped with a pair of perpendicular grooves, thus ensuring the predetermined orientation of the probe.

3. RESULTS

3.1. Video inspection in horizontal drainage boreholes

The camera record of 14 horizontal drainage boreholes showed that horizontal drainage boreholes are clean without any blockage (Fig. 5) and dry along their entire length (approx. 30 m), even during prolonged rainfall. Based on this we can conclude that the horizontal boreholes were incorrectly designed and did not fulfil their function.

Fig. 5.: View from a camera record of a horizontal drainage borehole – without colmatation.

3.2. Geophysical measurements

Interpretation of seismic and electric measurements was correlated with data from boreholes MI-INK–1, MI–INK–2 a MI–INK–4, located on the interpreted profile P1.

3.2.1. Logging measurements in boreholes

The result of the logging measurements processing is the precise location of lithological boundaries in measured boreholes, seen in the Fig. 6.

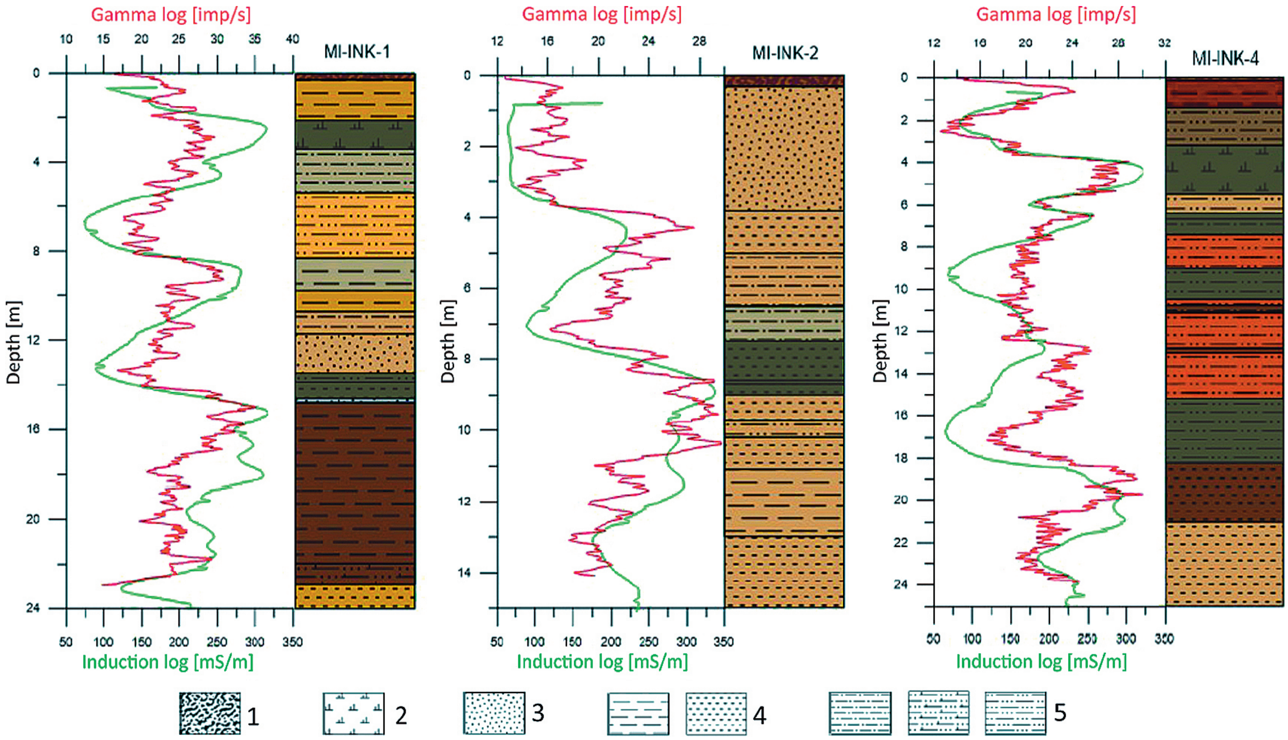

Fig. 6.: Curves from gamma logging and induction logging from boreholes MI-INK-1, MI-INK-2 and MI-INK-4 and interpreted lithological profiles. The patern corresponds to the lithological type : 1) Humouse horizon, 2) silt positions, 3) sandy positions, 4) clayey positions, 5) mixed clayey-sandy positions.

3.2.2. Electric resistivity tomography

ERT measurement on the profile P1 resulted in inverse resistivity cross-section (Fig. 7a). Based on the specific resistivity values obtained from ERT measurement, results from logging measurements and data from boreholes, it was possible distinguish two lithological units on the profile – Quaternary slope sediments in the upper part of the profile and Neogene sediments. Quaternary slope sediments are represented by clays with intermediate plasticity of class F6 Cl with specific resistivity values 15–30 Ohm.m. Neogene sediments are composed from clayey sand of class S5 SC with specific resistivity values 45–90 Ohm.m and clay with high plasticity of class F8 CH and specific resistivity values 15–25 Ohm.m. On the inverse resistivity cross-section there is a position of sand with resistivity of 85 ohm in the upper part of the profile between 10–32 m of its length, through which the surface water fed the slope and activated the slope movements.

3.2.3. Seismic refraction

Seismic refraction tomography for longitudinal waves (Vp) recorded two velocity interfaces on the profile P1 (Fig. 7b), at a depth approx. of 3 to 5 m and at a depth approx. of 6 to 10 m under the field, depending on the profile length. On the velocity profile for transverse waves are interfaces visible at a depth of 2 to 3 m and approx. 6 m (Fig. 7c). Velocity interfaces probably represent the transition of sandier locations into clayey ones. In the lower part of P1 profile, at distance of 52 m, the velocity profile Vs captured a transition of sandier positions drilled by MI-INK-2 into the macadam layer, which was demonstrated by velocity change. The thickness of macadam layer according the interpretation of the velocity profile Vs is probably around 2 m.

In Fig. 7d and Fig. 7e is graphically displayed the distribution of Poisson´s ration and Shear modulus G calculated based on the results of SRT. The values of Poisson´s ratio on the profile P1 ranged from 0,20–0,48 which according STN 72 1001 corresponds to the real values of Poisson´s ratio in soils drilled in the boreholes. Higher values (0,4–0,44) were noticed at a distance 24–48 m to a depth approx. 3 m below the surface. Lower values (0,2–0,25) in the lower part of the profile correspond to gravelly development of class G3 or G2, which can represent the used macadam fraction.

The value of the calculated Shear modulus on the P1 profile ranges between 0,07–0,16 GPa. Low Shear modulus values in the range of 0,055–0,070 GPa are found at a distance between 18 and 53 m and reach depths around 3 m below the surface. The highest Shear modulus values as well as Young´s modulus are recorded on the profile at places that were outside the slope deformation.

The value of calculated Young´s modulus ranged from 0,08 to 0,46 GPa. Also in this case were the lowest values between 0,16–0,20 GPa recorded at a distance of 20–52 m on the profile P1 with a depth range of 2–3 m.

3.2.4. Inclinometric measurements

Fig. 8 shows the measurements results of precise inclinometry in the selected borehole INK-1 from the zero measurement realized in November 2019. At a depth of approx. 2 m is visible the overall movement in the direction of the fall – approx. 75 mm for the period from 7. 4. 2020 to 2. 3. 2021. Other control measurement

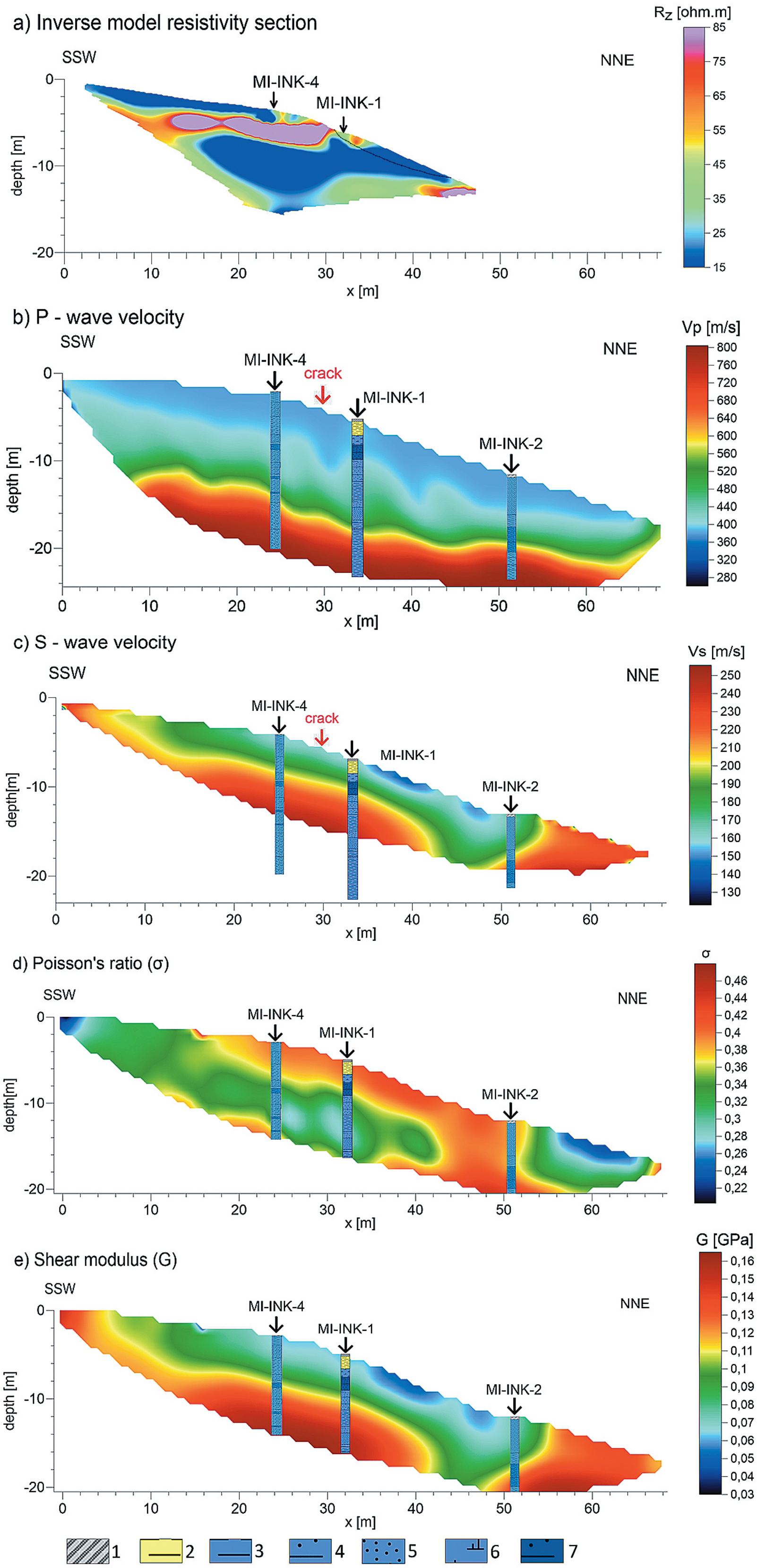

Fig. 7.: Results of geophysical measurements serving as a base for the stability assessment. a) Inverse resistivity profile, b) Vp seismic refraction tomography profile, c) Vs seismic refraction tomography profile, d) Poisson's ratio distribution calculated from the Vp and Vs, e) Shear modulus tomogram calculated from the Vp and Vs. 1) Humous horizon, 2) stiff-firm clay with medium plasticity, 3) stiff clay with medium plasticity, 4) clayey sand, 5) sand with fine-grained soil, 6) silt, 7) sandy clay.

in 2021 was not possible to carry out due to immeasurable deformation of the borehole casing.

3.3. Engineering geological assessment and stability assessment of the cut

The results of the values of geotechnical parameters distribution calculated from measured SRT on the profile P1 correspond to the stress states in the basement. Young´s modulus like shear modulus, characterizes the reaction of the rock material (slope) loaded with tensile stress (Mareš et al., 1990). Disrupted rocks are characterized by higher values of Poisson´s ratio and lower values of Young´s modulus (Shebl et al., 2019). The weakened zones of the slope of the assumed body of slope deformation were thus manifested by an increase in the values of Poisson´s ratio and a decrease in the values of Young´s and shear modulus. The distribution of shear modulus values on the P1 profile enabled to delimit the landslide body on this profile. Places with lower shear modulus values correlate well with the assumed shear surface. The highest values of shear as well as Young´s modulus are recorded on the profile at places that were outside the slope deformation, on the plane above the landslide, in places that are not stressed by tensile stress. Intact zones as the concrete base of the fence crossing the line of other measured profiles, also showed lower Poisson´s ratio values and higher stress and Young´s modulus values.

Based on the synthesis of drilling results, geophysical measurements, as well as laboratory results, it was possible to compile a mathematical model of the landslide area as a basis for stability assessment.

Stability calculations were realized on one calculation profile (Fig. 9), which is identical with geophysical profile P1. Calculation profile 1 is 70 m long. Its beginning is located at an altitude of 250 m above sea level, passes through boreholes MI-INK-4, MI-INK-1 and MI-INK-2, and ends at an elevation of 233 m above sea level.

For stability calculations were the shear planes constructed as composite (rotational-planar). They were modelled along the entire sliding body. Several dozens of hypothetical cylindrical and planar shear surfaces were recalculated.

The degree of stability (tab. 1) calculated

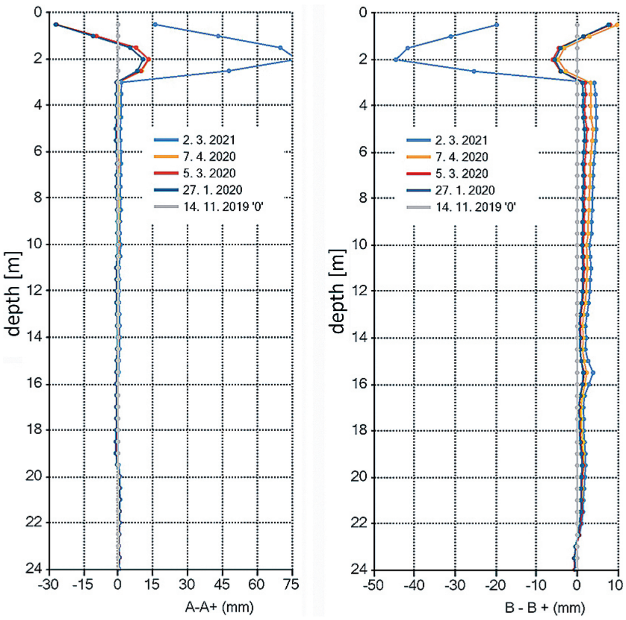

Fig. 8.: Results of inclinometry at the borehole INK – 1 for the entire monitoring period since the control measurement in November 2019.

for the current state has value of 0,97 and is represented by shear surface no. 4. Its depth range is 1,0 m. However, the stability calculation pointed to the further possible development of slope deformations demonstrated by shear surfaces 1,2 and 3, where the stability degree has values 0,65; 0,73 and 0,69. The depths of the shear surfaces are 3,70; 1,6 and 2,3 m.

Table 1 Factor of safety calculated for the slope deformations development, demonstrated by individual shear zones:

Tab. 1: Degree of stability calculated for the slope deformations development, demonstrated by individual shear zones.

shear zone	method of stability calculation	factor of safety
1	Bishop	0.65
2	Bishop	0.73
3	Bishop	0.69
4	Bishop	0.97

4. CONCLUSION

The differences in the velocities distributions on the SRT profiles Vp and Vs are related to the different propagation mechanism of longitudinal and transverse seismic waves. Therefore, P and S waves react differently to the rock material properties changes (e.g. to the filling and size of pore spaces). This is reflected by the speed of wave propagation. It can be used in interpretation in case of sufficient velocity contrasts of the interpreted positions, but also to determine the distribution of selected geotechnical parameters. Some phenomena, in this case e.g. the cracks, which did not appear on the velocity profiles, appeared on the profiles showing the distribution of geotechnical parameters values.

Disturbed rocks are represented by higher values of Poisson´s ratio. On the P1 profile were the higher values (0,4–0,44) noticed at a distance of 24–48 m, to a depth of about 3 m below the surface indicating the presence of weakened zone on the surface. During the stability calculations position and course of unfavourable shear surfaces were found in the landslide body. The modelled basal shear surface is most correlated with the spatial distribution of Poisson´s ratio determined based on the calculations from seismic measurements.

Based on the synthesis of results of the field technical works, geophysical measurements, as well as laboratory results realized within the supplemented stage of the engineering geological survey for the cut of the R4 expressway on the Košice-Milhosť section, an engineering geological profile of the assessed area was constructed, which served as a basis for the stability assessment. The stability assessment was carried out according Bishop in GEO5 software and it showed the stability conditions of the cut foot are satisfactory due to implemented anchored retaining wall. From the stability of the cut point of view, the section between the two lines of surface water drainage with concrete gutters is problematic. Therefore, in this are it is proposed to drain the slope with drainage ribs 1,0 m wide at an axial distance of 5,0 m. The depth of the drainage ribs should by according the stability calculations from 2,0 m at the edges of the cut to 4,0 m in the central part of the cut. The backfill material should be non-freezing material of fraction 32–63 mm. The outcome of the drainage ribs should be connected by a gathering drainage

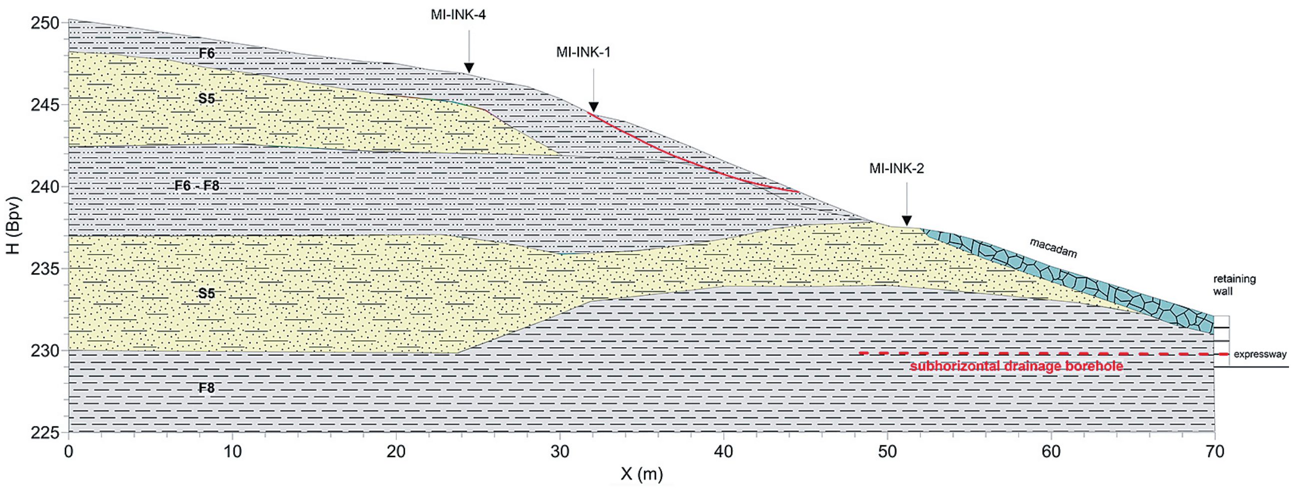

Fig. 9.: Engineering-geological profile P1 with marked shear zone no. 4.

element and should be brought out of the line of the cut. At the same time, immediate sealing of open cracks is suggested.

Determining the mechanical properties of rocks and determining the weakened zones, or even delineating the landslide based on the geotechnical parameters calculated from SRT measurements, expands the possibility of closer cooperation between geophysics and engineering geology and thus increasing the quality of the engineering geological survey.

References

Benjumea B., Macau A., Gabàs A., Bellmunt F., Figueras S. & Cirés J., 2011: Integrated geophysical profiles and H/V microtremor measurements for subsoil characterization. *Near Surface Geophysics*, 9, 413–425.

Donohue S., Long M., O'Connor P., Helle T. E., Aspmo Pfaffhuber A. & Romoen M., 2012: Multi-method geophysical mapping of quick clay. Near Surface Geophysics, 10, 3, 207–219.

Gregory A.R., 1976: Fluid saturation effects on dynamic elastic properties of sedimentary rocks. Geophysics, 41, 5, 895–921.

Haines S. S., 2007, A Hammer-impact, aluminum, shear-wave seismic source, U.S. Geological Survey. Open-File Report 2007-1406, 5 p., available only online at http://pubs.usgs.gov/of/2007/1406/. [cit. 2020-02-20]

Heincke B., Maurer H., Green A., Willenberg H., Spillmann T. & Burlini L., 2006: Characterizing an unstable mountain slope using shallow 2D and 3D seismic tomography. Geophysics, 71, 6, B241–B256.

Hinojosa H. R., 2020: The Usefulness of Body-Waves Refraction Tomography for Geotechnical Engineering in Karst Terrains. Available online at (https://www.linkedin.com/pulse/usefulness-body-waves-refraction-tomo) [cit. 2022-10-15]

Hinojosa-Prieto H. R. & Hinzen, K. G., 2015: Seismic velocity model and near-surface geology at Mycenaean Tiryns, Argive basin, Peloponnese, Greece. Near Surface Geophysics, 13, 103–113.

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

Mareš S., Gruntorád J., Hrách S., Karous M., Marek F., Matolín M. & Skopec J., 1990: Úvod do užité geofyziky [Introduction to applied geophysics]. SNTL, Praha, 677 p. [in Slovak]

Mondol N. H., Bjørlykke K., Jahren J. & Høeg K., 2007: Experimental mechanical compaction of clay mineral aggregates—Changes in physical properties of mudstones during burial. Marine and Petroleum Geology, 24, 5, 289–311.

Pasquet S., Bodet L., Dhemaied A., Mouhri A., Vitale Q., Rejiba F., Flipo N. & Guérin R., 2015: Detecting different water table levels in a shallow aquifer with combined P-, surface and SH-wave surveys: Insights from VP/VS or Poisson's ratios. Journal of Applied Geophysics, 113, 38–50.

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

Shebl S., Gemailb K.S., Attwab M., Solimana S.A., Azaba A. & Faraga M.H., 2019: Utilizing shallow seismic refraction in defining the geotechnical properties of the foundation materials: A case study at New Minia City, Nile Valley, Egypt. Egyptian Journal of Petroleum, 28, 2, 145–154.

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

Uhlemann S., Hagedorn S., Dashwood B., Maurer H., Gunn D., Dijkstra T. & Chambers J., 2016: Landslide characterization using P- and S-wave seismic refraction tomography — The importance of elastic moduli. Journal of Applied Geophysics, 134, 64–76.

Yamakawa Y., Kosugi K., Masaoka N., Sumida J., Tani M. & Mizuyama T., 2012: Combined geophysical methods for detecting soil thickness distribution on a weathered granitic hillslope. Geomorphology, 145, 56–69.

STN 72 1001 Technical standard - Classification of soil and rock

EN ISO 22475-1:2006 Geotechnical investigation and testing – Sampling methods and groundwater measurements — Part 1: Technical principles for execution