

Integrated monitoring techniques for landslide hazard assessment in Ruská Nová Ves (Eastern Slovakia)

Vladimir Greif¹, Martin Maľa¹, Jaroslav Buša², Martin Bednarik¹, Rudolf Tornyai¹, David Kušnirák¹, Ivan Dostál¹, René Putiška¹ & Ivan Zvara¹

Department of Engineering Geology, Hydrogeology and Applied Geophysics, Faculty of Natural Sciences, Comenius University Bratislava, Ilkovičova 6, 842 15 Bratislava, Slovakia; vladimir.greif@uniba.sk

Department of Geosciences, BERG Faculty, Technical University of Košice, Comenius Park 15, 042 00 Košice, Slovakia

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Abstract: The presented research deals with a multidisciplinary approach to the monitoring of an active landslide in Ruská Nová Ves, Slanské Vrchy Mountains (Eastern Slovakia). The kinematic activity of the landslide was studied by classical geotechnical methods - inclinometric measurements and groundwater level monitoring in combination with remote sensing method - Radar Satellite Interferometry (PS InSAR) and shallow geophysical methods - Electrical Resistivity Tomography (ERT) and Electro Magnetic Radiation Method (EMR). The results showed that the detection and determination of the most active parts within the studied landslide using ERT and EMR measurements is consistent with engineering geological investigations. The slope deformation in Ruská Nová Ves was formed on two polygonal shear surfaces at depths of 6.5 m and 11.5 m below the surface with an average displacement rate of 25.0 mm/year for the level 0-6 m below the surface and 18.0 mm/year for the level 6-11 below the surface and determined azimuth of 275°. The shallower shear surface was confirmed by both ERT and EMR methods in contrast to the deeper shear plane located in Neogene clay sediments due to significantly lower resistivity values (ERT) and continuous plastic deformation (EMR). The PS InSAR technique was used for the evolution of landslide displacement permanent scatterers within the landslide area, indicating displacement rates in the satellite line of sight (LOS) direction ($V_{LOS} = 24.5$ mm/year) and slope direction ($K_{SLOPE} = -23.25$ mm/year). The results were obtained using borehole inclinometric data series. The results demonstrate how interdisciplinary studies of landslide kinematics contribute to a better understanding of possible landslide trends, especially with significant positive impacts on urbanized areas.

Key words: monitoring, landslide, satellite radar interferometry, borehole inclinometry, EMR

1 INTRODUCTION

Slope movements are major geological hazards in Slovakia that, along with floods, are the most frequently occurring phenomena that affect human infrastructure, land use, and human life in general.

The study and analysis of landslides cover several fields of geosciences, among which landslide monitoring plays an important role. In addition to traditional techniques such as geotechnical and topographic methods, it can benefit from exploiting timely and high-quality information derived from remote sensing observations. Examples of these observations include Airborne Light Detection and Ranging (LiDAR), Terrestrial Laser Scanners (TLSs), photogrammetric techniques that utilize air photographs or high-resolution satellite images, Differential Interferometry using radar images (DInSAR), or computer vision techniques that employ data from Unmanned Aerial Vehicles (UAVs). Apart from remote sensing observations shallow geophysical techniques have evolved and are being used in the study of temporal variations of geological structures and landslides characterization (Jongmans and Garambois, 2007).

The main goal of presented study is to combine of different types of monitoring methods, namely: Differential Synthetic Aperture Radar Technique (DInSAR), two geophysical techniques- Electrical Resistivity Tomography (ERT) and Electro Magnetic Radiation method (EMR), with traditional methods

(inclinometric measurements, groundwater monitoring and field investigation), to effectively determine the electrical characteristics, spatial structure and velocity field of the Ruská Nová Ves landslide.

In the study of landslide hazards, it is essential to ascertain the spatial distribution characteristics of the sliding surface, and the geological stratification (Liu et al. 2022). A wide range of techniques are available for the identification and monitoring of landslides. However, conventional geophysical exploration methods and geological surveys suffer from drawbacks such as high costs, limited data acquisition, and low efficiency (McCann and Foster 1990). Geophysical exploration, which relies on the indirect observation of known ore rock specimens and established relationships (mathematical or physical models), offers a means to interpret field data and deduce subsurface structural information through inversion algorithms. Recent years have witnessed an increased application of geophysical methods in landslide research, particularly for studying complex geological settings in shallow landslide-prone areas (Popescu et al. 2016).

In order to comprehensively acquire information about the subsurface structure of landslides and address the challenges associated with interpreting results from a single method, it is crucial to employ multiple techniques. This approach not only enhances the efficiency of the research but also improves the accuracy of the obtained results. That's why we decided to

choose two Electromagnetic methods (EM) – ERT and EMR.

The aforementioned methods have several advantages in landslide studies. The ERT method has found extensive application in studying landslides across different geological settings (Dahlin 2001; Jongmans and Garambois 2007). This method is sensitive to changes in resistivity and allows for the determination of resistivity distribution in subsurface materials. The subsurface medium exhibits a wide range of resistivity variations, influenced by factors like mineral composition, soil porosity, and water content. ERT effectively captures differences in electrical conductivity within the medium (Colangelo et al. 2008; Falae et al. 2019; Wang et al. 2021), making it a valuable tool in landslide research.

The EMR method, according to Krumbholz (2010), is a tool that provides the opportunity to investigate geological structures and related stress configuration in a fast and low-cost way. The method is based on the property of brittle materials to emit electromagnetic waves when subjected to mechanical stresses. With the development of the portable electromagnetic radiation instrument Cerescope, the EMR method has become more applicable for field studies, especially for the mapping of faults (Mallik et al. 2008), but less in studying of potential or active landslides (Lauterbach 2005; Morgounov and Zdorov 2007). This method is based on the registration of electromagnetic emissions which are produced in a rock environment by using a ferrite antenna. The measured parameter is the magnitude of the voltage (U [mV]) induced in the antenna coil by the radiated EM wave. The source of electromagnetic emissions are geodynamic processes which take place in the rock environment, but this process mechanism is still under discussion. According to Krumbholz (2010) the most frequently discussed sources of electromagnetic emissions in the rock environment are: piezoelectric effects (originating from oriented pressure on mineral crystals), “positive holes” (these are defects in crystal lattices of oxygen ions of igneous and metamorphic rocks), electro kinetic effect interaction of the liquid with the solid phase, triggering an osmotic effect and generates a Zeta-potential) and micro (nano) cracking (this cracking occurs in every brittle material). Orientation of these cracks is not random but depends on the direction of the stress field.

The monitoring of landslide displacement and understanding the characteristics of structures in the area necessitate a comprehensive understanding of the surface morphology. This is crucial because it directly impacts the stability conditions. Traditionally, such data has been collected using tools on the ground, like total stations, and more recently, laser scanners. However, in recent years, there has been a growing trend in using remote sensing tools mounted on aircraft and satellites, which provide a different method of gathering spatial data.

Satellite-based remote sensing techniques have become standard in the field of landslide mapping and monitoring. Optical imagery and GPS techniques are commonly used methods for studying different types of slope deformations. The use of radar techniques in landslide studies began in 1989 with the introduction of the differential interferometric synthetic aperture radar technique (DInSAR) described by Gabriel et al. (1989). Early attempts at DInSAR used a limited

number of interferograms, allowing for the assessment of ground deformations even with limited SAR data availability. However, these early DInSAR techniques had inherent errors related to atmospheric variations affecting radar wave phase delay and inaccuracies in the digital elevation model used to cancel out topography created by signal interference. To overcome these limitations, Ferretti et al. (2001) proposed the concept of using longer acquisition sequences, known as Permanent Scatterers (PS), which mitigated atmospheric phase delay through statistical filtering of long-term radar sequences. This technique provided highly accurate residual topography estimates on stable targets. Subsequent research and development focused on algorithms and procedures for PS analysis. (Berardino et al. 2002; Mora et al. 2003; Wegmüller et al. 2005; Kampes and Adam 2006; Fornaro et al. 2007; Monti-Guarnieri and Tebaldini, 2008). The scientific literature offers detailed descriptions of the DInSAR technique (Rott and Nagler, 2006; Colesanti and Wasowski 2006). The first applications of DInSAR in landslide studies were reported in France (Fruneau et al. 1996), Canada (Singhroy et al. 1998), Austria (Rott et al. 1999), and other regions (Vietmeier et al. 2000; Crosetto et al. 2005). The improved PS-InSAR technique has proven particularly useful in landslide monitoring when the deformation rates are less than approximately 1.4 cm/month and long-term series of SAR data are available. PS-InSAR can detect deformations of individual objects, ranging from small houses to objects as small as one square meter. To achieve accurate correction of atmospheric phase delay, a certain density of stable objects (about 5 per km²) is necessary (Singhroy 2009).

2 LANDSLIDE AREA CHARACTERIZATION

Landslide area is situated in the north-east part of the Kosice basin, in the cadastral area of a small village- Ruská Nová Ves, on the western border of Slanské vrchy Mts. in Eastern Slovakia (Fig.1).

Climatic conditions of study area vary from moderately warm and very humid to moderately cold. The 30-year mean annual precipitation is 700-800 mm (Lapin et al. 2002). The wider surroundings of the study area fall into the northern part of neo-volcanic mountains - Slanské vrchy and Kosice basin (Neogene). The Kosice Basin from geological viewpoint represents north-eastern promontory of the Pannonian Basin. The geological structure of the site under study consists mainly of sediments of the Quaternary age-fragments of the landslide slope sediments with a variable thickness (1-12 m). From the granulometric analysis, these sediments are mainly clayey-gravel soils with a very variable content of solid and semi-solid volcanic rocks- mostly andesites and rhyolites with a variable content of sand fraction. Subsoil is mainly represented by marine clays and claystones.

From the point of the slope stability almost the entire edge of the volcanic mountain range Slanské vrchy is disturbed by extensive slope deformations, mainly landslides and block slope deformations. Within the endangered area, a several

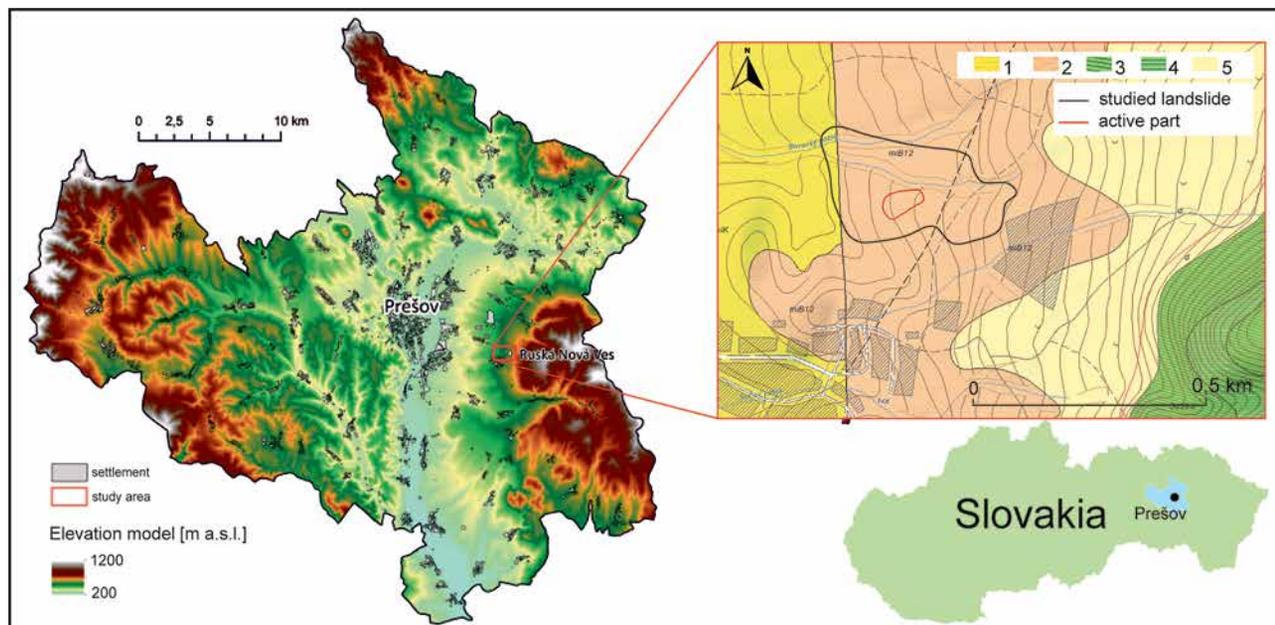


Fig. 1: Geographical and geological conditions of the study area (1 – colored claystones, sandstones, anhydrites, halite (Kladzany formation — Karpatian); 2 – claystones (Mirkov formation – Badenian); 3 – lava flows of augitic-hyperstenic andesite (volcanic rocks – Sarmatian); 4 – lava flows of pyroxenic andesite (volcanic rocks – Sarmatian); 5 – slope sediments (lithofacial undifferentiated sediments and debris)

cottages, local football playground, third-class road, and high voltage lattice tower can be found. The whole area which is located on the east from the Ruska Nova Ves, has the character of a large landslide with dimensions of about 400 m in length and 250 m in width. The depth of the shear plane was verified by boreholes at the level of 12-15 m below the surface. After heavy rainfalls in 2010, the minor slope deformation within landslide body was activated. The main reason of the landslide activation was a significant saturation of the Quaternary clayey-gravelly sediments and subsequent wetting of Neogene clays located in the subgrade. Degradation of their shear strength properties was associated with this process. This factors with cooperation with buoyancy effects of groundwater were the main reason for activation, respectively reactivation of the

landslide. The dimensions of active part of slope deformation are 150 x 80 m in size. The main scarp of the landslide body is significant and reaches height of 0.7- 1.5 m. The accumulation part of the landslide body is undulating with several elevations and depressions. The frontal part of the landslide is not well marked. The depth of the shear plane was verified by boreholes at levels- 6-7 m and 11-12 m below the surface (Fig.2).

A set of monitoring boreholes proposed in 2012 (Spišák et al. 2012; Grech 2012) and 2016 (Fig. 3), oriented on subsurface drainage system, and five inclinometric boreholes (INR-1; INR-2; INR-3; INR-4, INR-4a) and four piezometric boreholes (PR-1, PR-3, PR-4 and RNV2- H1) were installed. Long-term monitoring proved subsurface drainage system, as originally projected and build, is not sufficient.

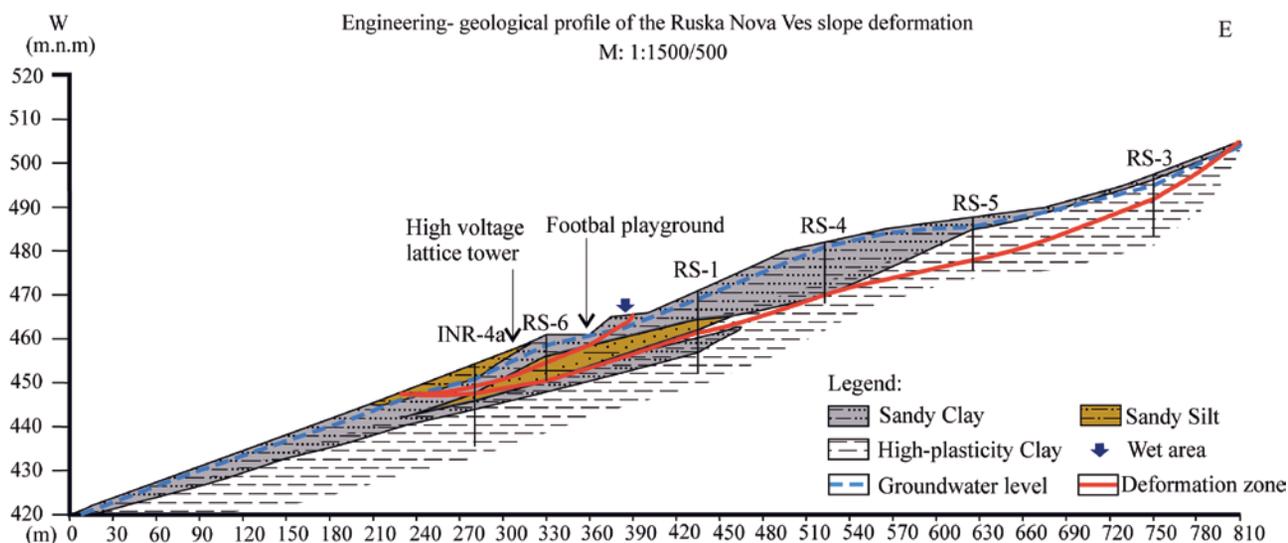


Fig. 2: Engineering-geological cross section of active part of the landslide

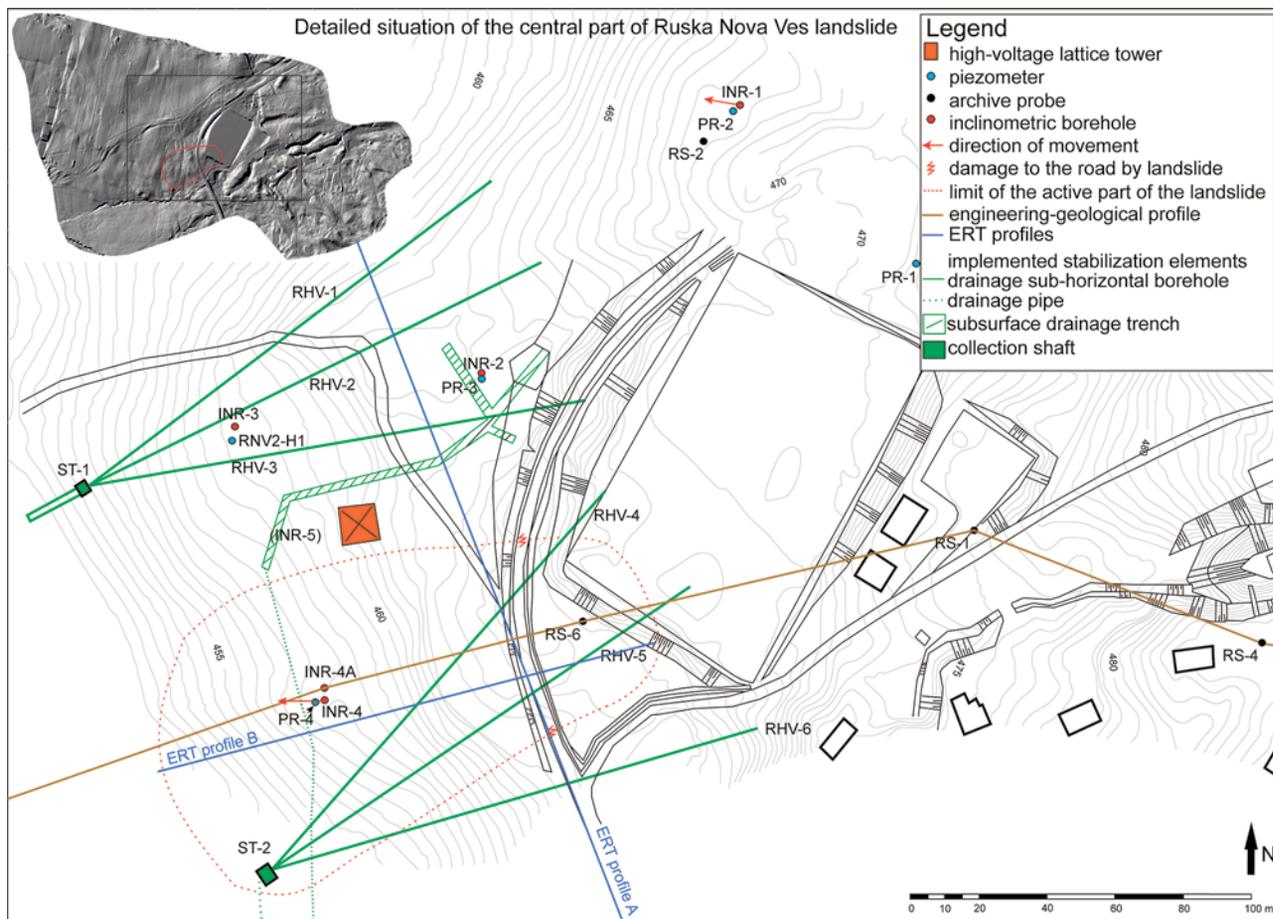


Fig. 3: Detailed situation of the studied area showing remediation works realized in 2013 and 2016 (adapted from Stercz et al., 2013)

3 METHODS APPLIED

Geotechnical investigation of landslide stability usually considers three following issues: 1.) the definition of the 3D geometry of the landslide body with determination of deformation zone or failure surface; 2.) the determination of ground water regime; 3.) the detection and characterization of subsurface movements (McCann and Foster 1990)

3.1 Landslide body lithology and deformation zone geometry definition

Landslide geometry was determined by Electrical Resistivity Tomography method (ERT) and subsequent verification its results from boreholes logs and field mapping. According to Griffiths and Barker (1993) Electrical resistivity tomography (ERT) can be widely applied to obtain 2D and 3D high-resolution images of resistivity subsurface patterns in areas with complex geological structure. The in-field procedure includes the use of multi-electrode cable and the use of a multi-electrode cable laid out on the ground, to which a number of steel electrodes are connected with fixed spacing according to a specific electrode configuration. The electrodes are used both for the injection of the current (I) in the soil and the measurement of the voltage (V). Knowing the I and V values and the geometrical coefficient depending on the electrode configuration

used, the apparent resistivity values characterizing the subsoil investigated can be calculated. These values are positioned at pseudo-depths according to geometrical reconstruction (Edwards 1977), which results in a pseudo-section representing an approximate image of the true subsurface resistivity distribution (Hack 2000).

Measurements herein were performed by ARES GF Instrument and the RES2DINV 2-D inversion program (Loke and Barker 1996) for an interpretation of measured resistivity. Interpreting of data obtained from ERT requires inversion transformation into an actual electrical resistivity value, which can provide an image of the real structure of the investigated geological environment (Bednarik et al. 2012). This typical 2D task defines that the resistors vary only in the X-axis profile direction and are constant for Y-axis and Z-axis directions. Root Mean Square Error (RMSE) was calculated as percentage difference between the logarithms of the measured and calculated apparent resistivity values. The Trimble's GNSS station R4 was adopted to create the two ERT (Profile A=258.5 m and Profile B=140.1 m) profiles with dipole-dipole electrode arrays at 5.5 and 3.0 m intervals. We used the dipole-dipole electrode configuration to increase the depth of penetration. This configuration ensures good resolution for identifying lateral heterogeneities. Both profiles (A and B) were situated in the accumulation of the deformation area near the pole of high voltage VVN 400 kV.

3.2 Monitoring of groundwater level

Regime observations of the groundwater were measured since May 2014 till November 2017. A total 8 measurements were performed by using a water-stage indicator. Another monitored element was the monitoring of the yield of the drainage elements. Their purpose is to control the effectiveness of drainage measures, specifically the outlets of sub-horizontal boreholes. Abundance in the sub-horizontal boreholes was measured by calibrated sampling vessels.

3.3 Inclinometric measurements

Inclinometer measurements were taken using a Geokon inclinometer probe with a measurement interval of 0.5 m within the boreholes INR-1, INR-3, INR-4 and INR-4A (replacement for the original INR-4 borehole, which was malfunctioned in 2017 due to the high rate of slope movement and destruction of the inclinometric borehole). The full inclinometric equipment consisted of the probe itself a 50-m cable wound on a reel equipped with a Bluetooth interface that communicates with a portable handheld computer. The inclinometer system comprised the inclinometer casings, the probe, the control cable and a reader unit. The PVC inclinometer casings (diameter 67 mm) had longitudinal grooves in two perpendicular directions to ensure the probe remains oriented in the predetermined direction. They were installed directly at a near vertical angle in a construction element or borehole (the space between the casing and the wall of the borehole and the borehole wall is filled with a bentonite-cement mixture). The grooves of the guide casings were oriented in the expected direction of movement. Technical parameters were as follows: measuring base 500 mm, measuring range $\pm 53^\circ$, resolution 0.02 to 500 mm, working temperature -20 to 50°C . After the completion of in situ measurements, the results were transferred electronically to a computer and evaluated in the program DigiPro2 from the US company DGSI (Durham Geo Slope Indicator).

3.4 Satellite radar interferometry

In order to achieve the goal of assessing the landslide activity the data processing was divided into two stages. The first stage involved application of PS InSAR algorithm for radar data processing in order to obtain the velocities of ground deformation. In the second stage resulting line of sight velocities V_{los} were manipulated about the slope orientation and subsequently compared to existing landslide inventory database in the GIS environment. Results were compared to data obtained from inclinometric measurements.

The input radar data consisted of 67 ascending acquisitions of Sentinel-1A satellite from orbit no. 102 and 57 descending acquisitions from orbit no.153. The radar Interferometric Wide Swath mode (IWS) SLC images were acquired between December 2014 and May 2017. The data processing was carried out by stacking interferometric images creating 66 interferograms from ascending orbits with master image from March 11th 2016 and 56 interferograms from descending orbits with

master image from May 2nd 2016, ensuring lowest possible dispersion of the perpendicular baseline and maximum coherence of interferometric stack. A Goldstein filter was applied to radar images before “phase unwrapping” (Goldstein and Werner 1998). In order to eliminate topographic and atmospheric artefacts and for the purpose of georeferencing of resulting PS a DEM (digital elevation model) from Shuttle Radar Topography Mission with 90m resolution was used (Jarvis et al. 2008). Coherence threshold value for resulting PS was set at 0.75 (Ferretti et al. 2001).

The procedure used for the vector transformation was similar to the one used by Colesanti and Wasowski (2006), Cascini et al. (2010) or more recently by Greif and Vlcko (2012). For the transformation of the 1D line of sight displacement rates to the orientation of the landslide movement K_{SLOPE} it was necessary to know the geometry of the data acquisition and slope orientation parameters obtained from the DEM (Fig.4).

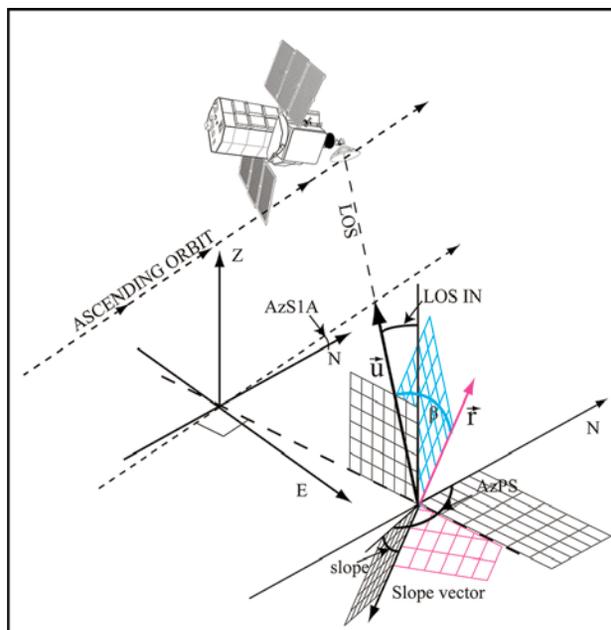


Fig. 4: Acquisition geometry for ascending satellite orbits (modified after Greif and Vlčko, 2012)

The angles of incidence in this context refer to the angle between the vertical direction and the line of sight (LOS) direction θ (LOS In), as well as the azimuth angles of the radar orbit α_s (Az PS). The sensitivity versor values (\vec{r}) (Massonnet and Feigl 1998), which represent the opposite of the LOS unit vector and are composed of rE , rN , and rZ , are utilized. The translation movement of the landslide occurs along the direction of the unit motion slope vector (\hat{u}), which is composed of uE , uN , and uZ . This vector is calculated based on the slope aspect (Φ). The slope was determined using map data of the area in a scale of 1:10,000 with a cell size of 1x1m. To establish acceptable projected displacement rate values, a scaling factor of $1/\cos\beta$ threshold of 15 (equivalent to $\beta = 86.2^\circ$) was adopted as suggested by Cascini et al. (2010). The KSLOPE (slope vector) value was determined using the vectors u and r , considering $\cos\beta$ and VLOS.

4 RESULTS

4.1 Geological structure and geometry of landslide body by ERT method

The results of ERT measurements provided information about changes in slope sediments between exploration boreholes, confirming the polygonal shape of the shallowest shear plane (Fig. 5). Slope sediments are characterized with wide range of resistivity values. This indicates the heterogeneity of the accumulation zone. Position of the deeper deformation zone cannot be identified by this method, because the Neogene sediments generally showed significantly low resistivity values.

4.2 Monitoring of groundwater level

Four piezometric boreholes marked as PR-1, PR-3, PR-4 and RNV2-H1 were monitored. The groundwater level is closely linked to the total precipitation (Fig. 6a) A total of 11 measurements on PR-1, PR-3 and PR-4 and 6 measurements on RNV2-H1 were performed. The individual measurements are shown in Fig. 6b.

The development of groundwater levels is closely related to precipitation, and this relationship is reflected in individual measurements. Based on the information provided, it can be concluded that groundwater circulation is relatively shallow, resulting in a quick response to rainfall as rainwater infiltrates

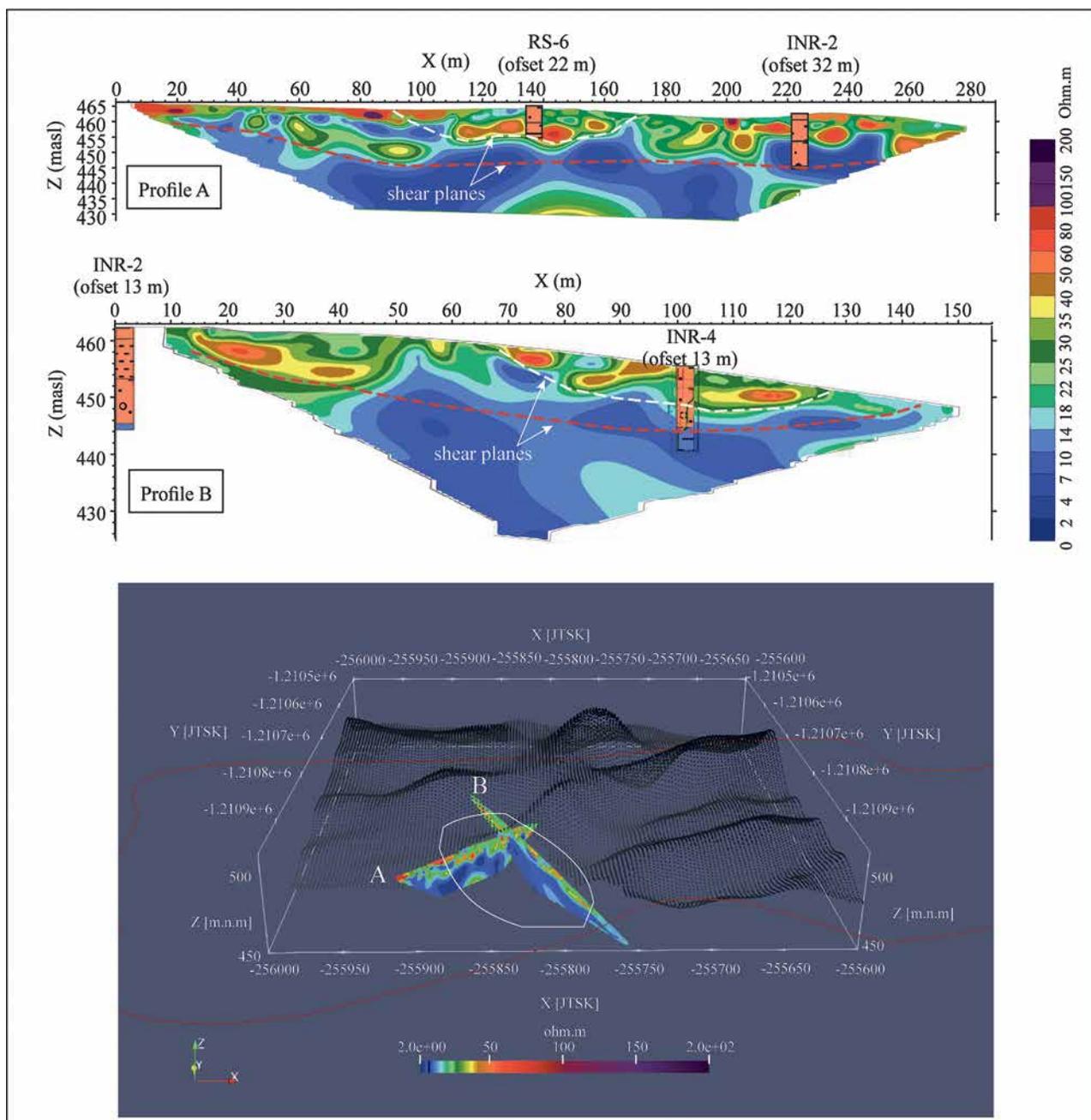


Fig. 5: 3D model of the landslide generated from orthophoto images and the DMR obtained from Lidar with ERT cut profiles A and B across the landslide body showing interpreted engineering geological structure based on borehole data

rapidly. This can mainly be attributed to unfavorable hydrogeological conditions, as the terrain consists of slope sediments characterized by a high proportion of permeable sandy and gravel materials, containing sharp-edged to sub-rounded fragments of volcanic rocks such as andesites and rhyolites. These fragments typically have a diameter of up to 20 cm, although larger boulders and blocks measuring 50-100 cm in diameter can also be found.

These hydrogeological conditions pose challenges for groundwater management and extraction. Due to the high proportion of sand and the presence of fragmented volcanic rocks,

the permeability of the aquifer is relatively high, allowing for rapid infiltration of rainwater. The study identified two levels of shear surfaces. The first is a shallower, partial shear surface with a polygonal shape, located at a depth of 5.0-6.5 m below the terrain. The second shear surface is found at a deeper depth of 10 m. These shear surfaces play a significant role in landslide movements, particularly during periods of increased precipitation or after the melting of the snow cover.

Landslide activation primarily occurs due to unfavorable hydrogeological conditions, characterized by a significant rise

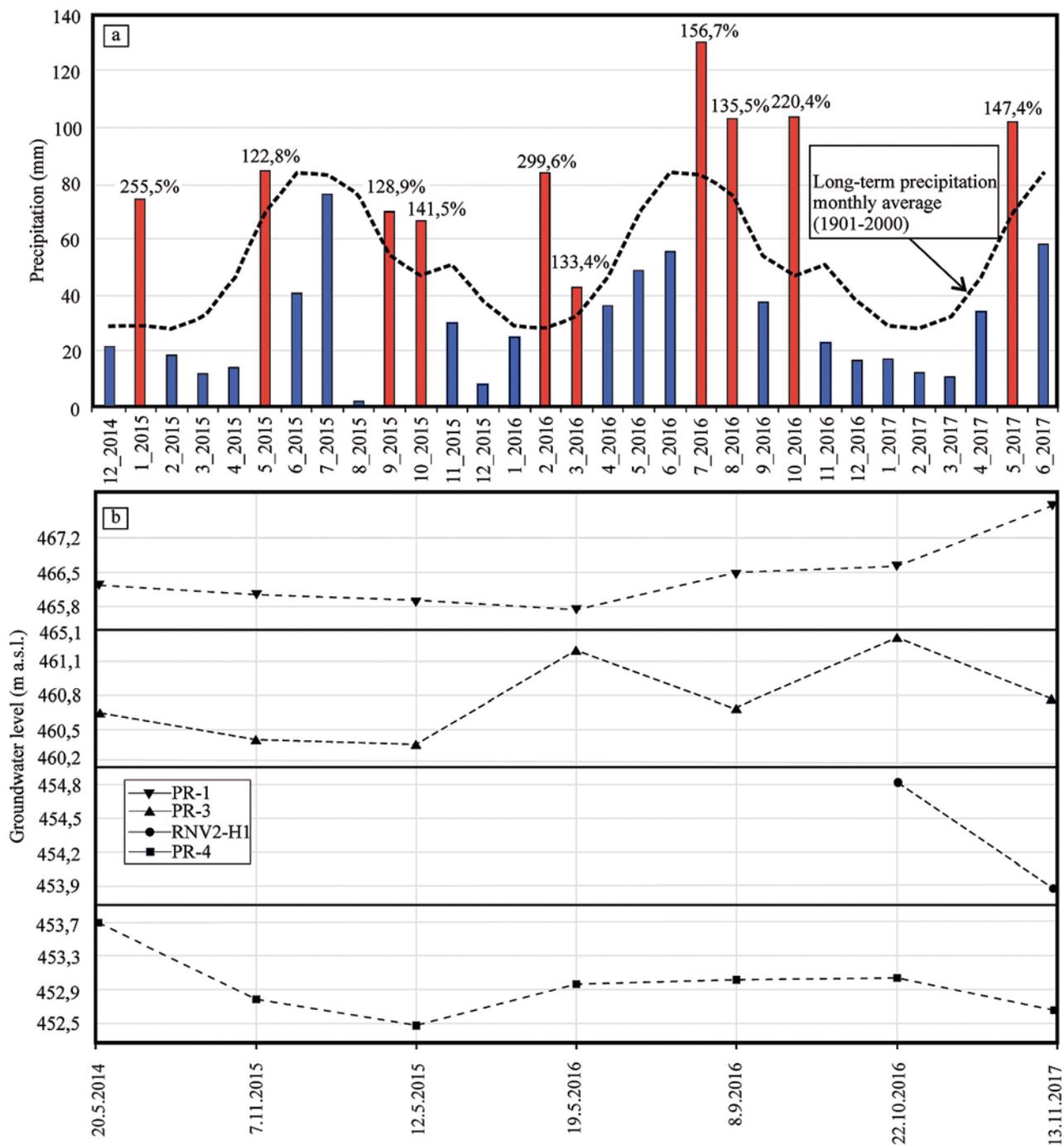


Fig. 6: Plot of average monthly precipitation totals during the monitored period from December 2014 to June 2017 at the meteorological station SHMÚ Prešov - planetarium (Source: SHMÚ). The monthly average totals that exceed the long-term precipitation average (1901–2000) by a given percentage point are shown in red. (5a); Groundwater levels measured on Ruská Nová Ves landslide (5b)

in water levels and an increase in pore pressures. The presence of these conditions leads to accelerated movement along the shear surfaces. It is important to note that the interaction between precipitation, snowmelt, and pore pressures influences the timing and intensity of landslide events.

Understanding the relationship between hydrogeological conditions and landslide activation is crucial for effective landslide hazard assessment and mitigation strategies in the area. By monitoring water levels and pore pressures, it is possible to identify periods of increased landslide susceptibility and take appropriate measures to minimize potential risks.

4.3 Inclinometric measurements

As part of the inclinometric measurements carried out on the landslide at Ruska Nova Ves, we monitored 3 inclinometric

boreholes: INR-1, INR-3 and INR-4. Borehole INR-4 was damaged due to strong deformation activity and was replaced by INR-4A in 2016.

Based on results from holes: INR-1, INR-3, we can state that there are only minimal movements, so the landslide can be considered as stabilized in these parts. The situation was different in borehole INR-4 (Fig. 7) and its replacement INR-4A (Fig. 8), which showed relatively large changes during the monitoring period.

Zero measurement in INR-4 borehole was performed on 31.10.2013. The depth of the borehole is 15 m and the orientation A0 is 266°. Based on the measured data we were able to determine the shear surfaces which were located in two depth levels. 6-6.5 m and 11-12 m below ground level. At a depth of 6.5 m below ground level, the accumulated movements were 88.34 mm, and the azimuth was 225°. At a depth of 11.5 m below

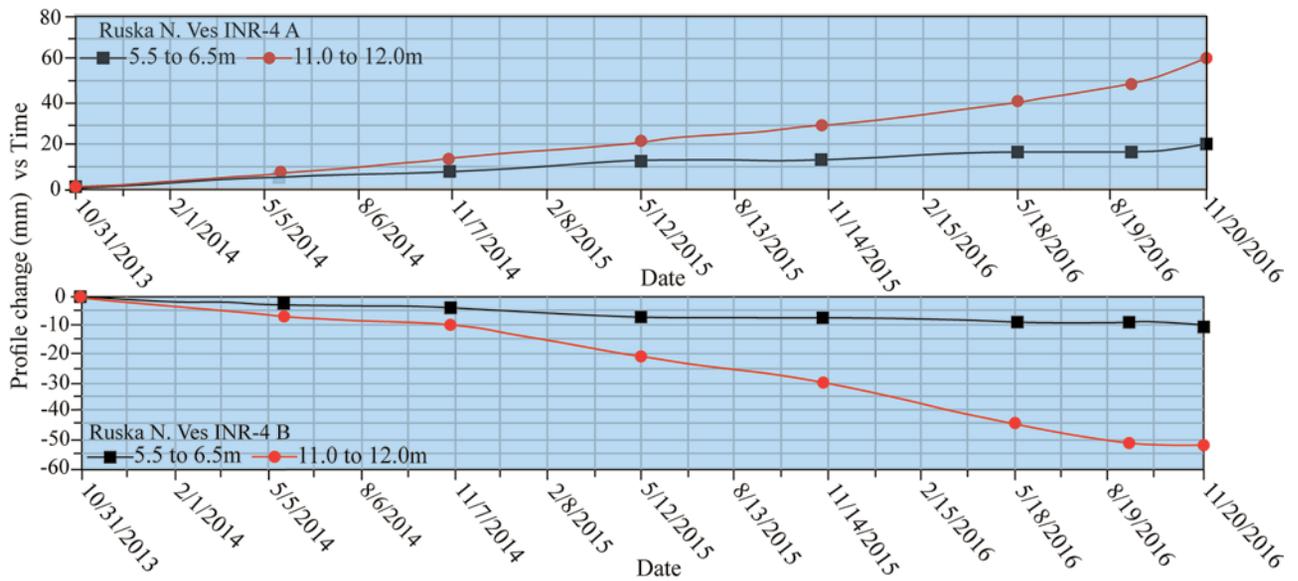


Fig. 7: Time evolution of deformations on two sliding surfaces at INR-4 borehole in the slope direction (upper) and in perpendicular direction (lower)

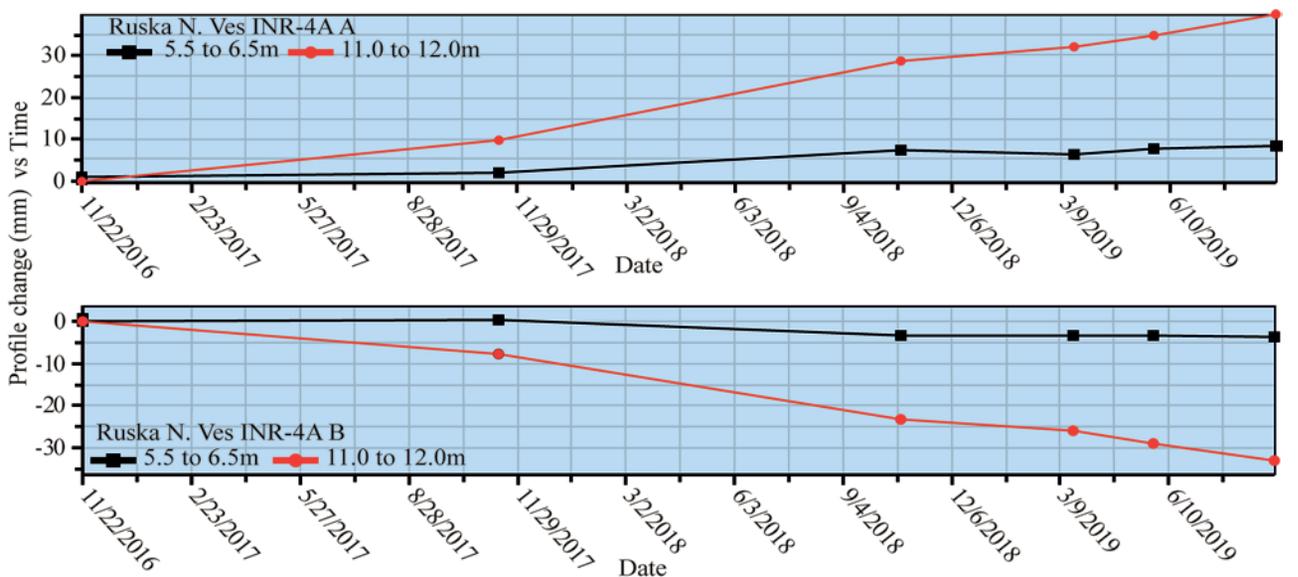


Fig. 8: Time evolution of deformations on two sliding surfaces at INR-4A borehole in the slope direction (upper) and in perpendicular direction (lower). Inclinometric borehole INR-4A was installed as a replacement for sheared off borehole INR-4 in November 2016

ground level, the size of the movements was 35.59 mm, and the azimuth was 225°.

The reference measurement on the INR-4A hole was carried out on 22.11.2016, followed by 5 monitoring campaigns, the last of which was carried out on 9.9.2019. As in INR-4, two different shear surfaces can be identified at 6.5 and 11.5 m below surface. The accumulated displacement is 75 mm for a depth of 6.5 m below ground level at an azimuth of 275°. Monitoring data shows an average rate of movement of 25.0 mm/year for a level of 0-6 m below ground level and 18.0 mm/year for a level of 6-11 m below ground level.

4.4 Satellite radar interferometry

After processing of acquired images one PS point with object (ID 15807) from ascending orbit was detected inside the landslide body, while no PS from descending orbit were detected inside the landslide. The overall rate of displacement in the line-of-sight direction of the satellite (V_{LOS}) was determined to be equal to 8.95 mm/year (Fig.9).

In Table 1 the acquisition geometry and the LOS vector r consisting of the components rE, rN, rZ is shown together with the resulting motion slope vector u with the unit vector components uE, uN and uZ .

The K_{SLOPE} value was determined from the vectors u and r , which was based on $\cos \beta$ and V_{LOS} . The magnitude of the angle

Tab. 1: Parameters of scanning geometry and vector component, direction of view r and parameters of slope and orientation of PS and vector component of slope direction u used during the calculation for PS point No. 15807.

ID PS	Orbit	Az S1A [°]	Los IN [°]	rE	rN	rZ
		349,97	40,47	-0,639	-0,113	0,761
15807	Asc	Slope [°]	Az PS [°]	uE	uN	uZ
		10	224	0,684	0,708	0,174

β in the case of PS (ID 15807) was 112.7°. The resulting rate of the movement in the direction of K_{SLOPE} was 23.25 mm/year.

Based on the data from the INR-4A (INR-4) the values of the motion vector amplitude V (mm) and the azimuth orientation Az (°) were determined. The rate of displacement in the direction of sliding V_{SLOPE} (mm/year) was also calculated and are presented in Table 2.

Tab. 2: Inclinomeric borehole parameters for INR-4A and INR-4 (Az (°) – azimuth of inclinometric boreholes; V_{slope} – the rate of displacement of the landslide in mm/year; V – total deformation in mm).

Borehole	Az [°]	VSLOPE [mm/year]	Monitoring period			V [mm]
			From	Till	Days	
INR-4A	275	24,5	22.11.2016	21.3.2019	850	57
INR-4	275	37,2	21.10.2013	2.11.2016	1129	114

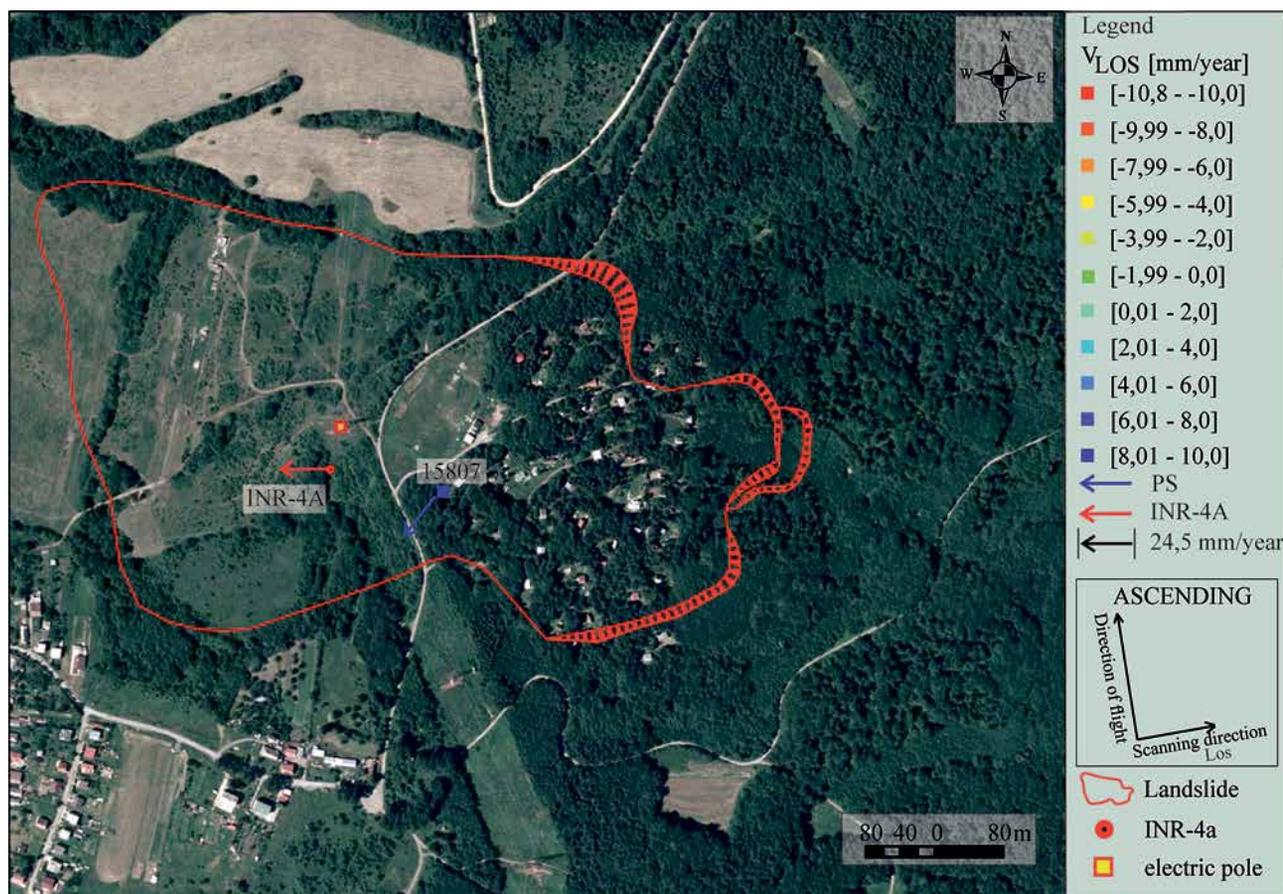


Fig. 9: Orthophoto map of the Ruská Nová Ves landslide showing with rate of movement in the V_{los} direction at the point scatterer No. 15807 in mm/year and V_{slope} vector obtained from inclinometric borehole INR-4A

The deformation map of Ruská Nová Ves landslide created from PS and inclinometric boreholes data is shown in Fig. 9. Fig.10 shows the partial deformations V (mm) obtained from the measured borehole INR-4 and INR-4A data compared to deformations in the scanning direction D_{LOS} of the satellite at the PS point (ID 15807).

4.5 EMR method

Repeated EMR measurements on three boreholes provide interesting information on spatial and temporal changes of deformation stresses in the landslide body. Borehole INR-1 is located in the transport part of the landslide body. From the point of inclinometric measurements, the movements are minimal, at the limit of the accuracy of the inclinometric

probe. Anomalous zones (local maxima) in the EMR field are located at the depth of 3-4 m. Their fluctuation is closely related to the culmination of the groundwater level, and the whole EMR field in this borehole reaches values from 400-800 mV. INR-3 is located in the accumulation part of the landslide body. Inclinometric measurements show that movements are minimal, and the shear plane can be assumed at a depth of 3.5 m (Fig.11). A small maximum in the EMR field was also recorded at this level. The total EMR field in this hole reaches values of 800-1500 mV. INR-4, like INR-3, is in the accumulation part of the landslide body. We can identify two shear planes at the depth of 5.5 and 11.0 m. The local maximum in the EMR field was recorded at the depth of 4-6 m and its fluctuation is related to the maximum groundwater level. At the depth of the second slide surface no increased values in the EMR field

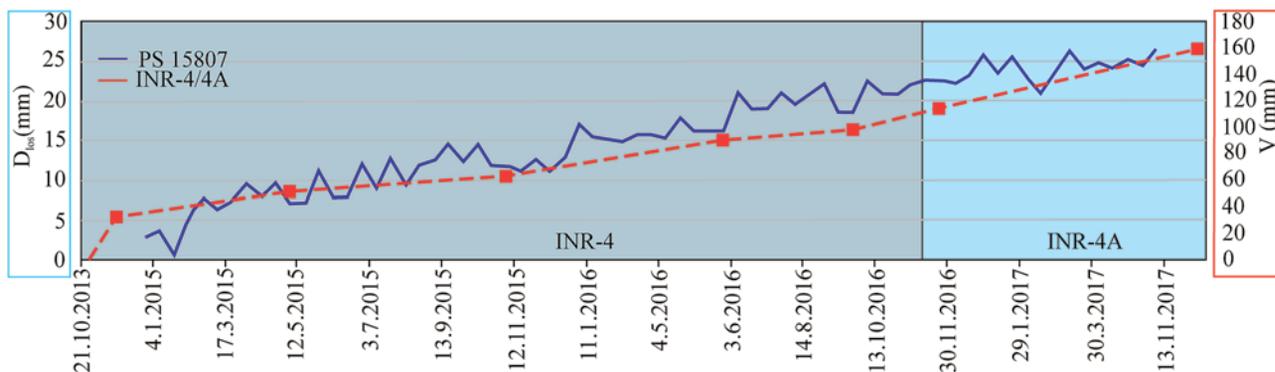


Fig. 10: Displacement plot of D_{LOS} (mm) and V (mm) inclinometric measurements. The blue line represents the deformation in the scanning direction D_{LOS} (mm) of PS (ID 15807- ascending orbit during monitoring period from December 2014 to May 2017). The red line depicts the deformation V (mm) at a depth of 1.5 m below the surface from INR- 4 and INR-4A during the monitoring period from 21.10.2013 to 21.3.2018

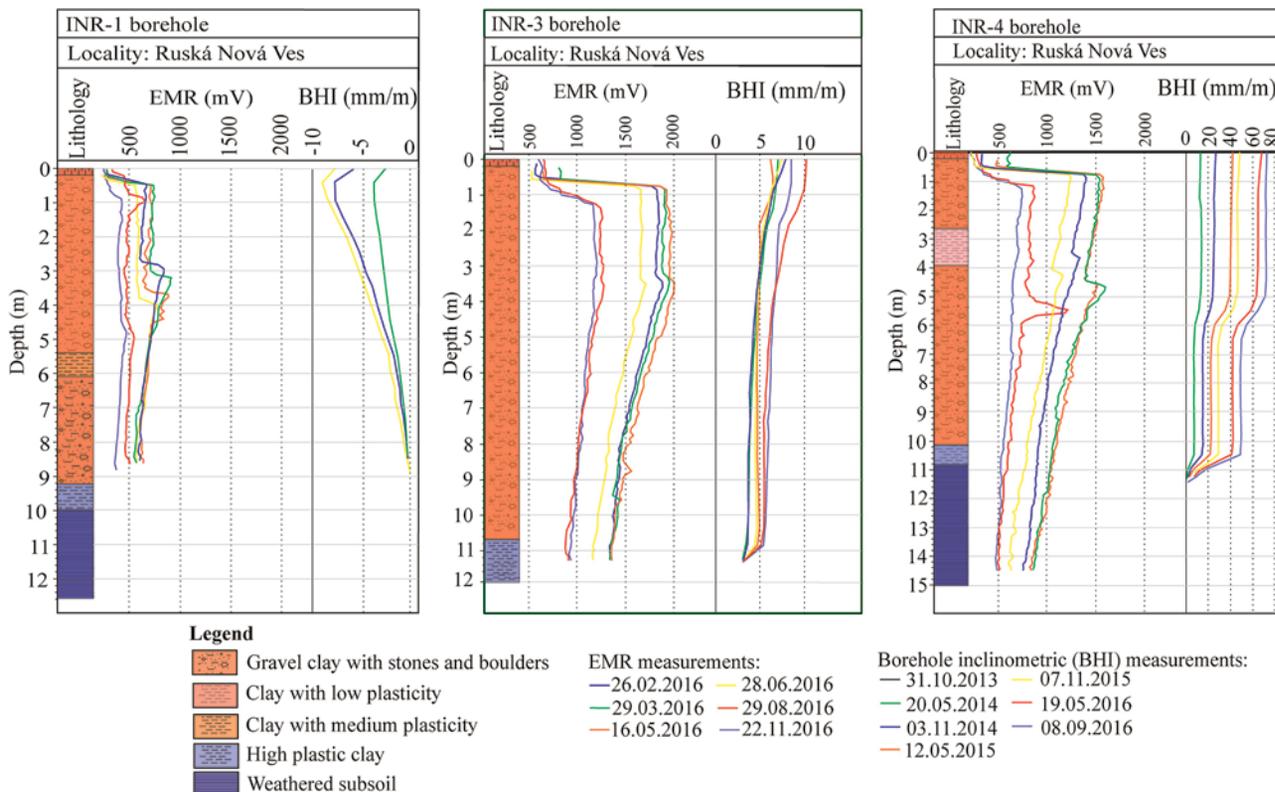


Fig. 11: Results of EMR method compared to inclinometric measurements on INR-1, INR-3 and INR-4 boreholes

were recorded. The total EMR field in this borehole reaches values from 700 to 1300 mV.

5 DISCUSSION AND CONCLUSIONS

This manuscript deals with a multidisciplinary approach to the monitoring of landslide area in Ruská Nová Ves. There are several methods that can be adopted to perform landslide monitoring. Obviously, each monitoring method has some limitations and thus integrated system of several methods contributes to achieve more realistic features as e.g., the size, direction of the landslide movements as well as geometry and depth of the shear zone.

To clarify the characteristics of the slope movements the classical geotechnical monitoring technique compared with modern remote sensing methods, electrical resistivity method and electromagnetic method were performed.

Based on results it can be stated that landslide in Ruská Nová Ves presents a typical planar landslide with polygonal shear planes. Its lithology and geometry have been determined by ERT method and verified by boreholes situated in the landslide body. Based on data from inclinometric measurements namely INR-4 and INR-4a boreholes, two deformation zones were determined at the levels of 6-7 m and 11-12 m below the surface with an average rate of movement 25.0 mm/year at the depth of 0-6 m 18.0 mm/year at the depth 6-11 with the azimuth of 275°.

Monitoring of landslide displacements using radar satellite interferometry is one of the state-of-the-art monitoring methods (Raspini et al. 2018; Shahabi and Hashim 2015). The European Space Agency (ESA), through its COPERNICUS program, has been significantly involved in the development and widespread use of radar satellite interferometry, most recently through the Sentinel-1A and 1B satellites (Buša et al. 2019). The assessment of landslide activity monitoring using PS was based on the velocity of movement in the direction of V_{LOS} satellite scanning, from which the velocity of landslide movement in the direction of K_{SLOPE} was estimated. The main problem with the recalculation was that the values needed for the recalculation - azimuth and slope at the point of reflection - were derived from a digital relief model based on a 1:10,000 topographic map from vectorized contours. The solution to this problem may be the use of LIDAR systems or drones, which can map large (or local) areas with relatively high resolution (Rusnák et al. 2016). In the case of the Ruská Nová Ves landslide, there are significant movements, which were confirmed by the velocity of V_{SLOPE} 24.5 mm/year from the INR-4A borehole, which was relatively well approximated by the recalculated velocity in the direction of K_{SLOPE} from the PS with a value of -23.25 mm/year. From the inclinometer data it can be concluded that the landslide at Ruska Nova Ves shows significant activity based on the average and median values in the direction of the V_{LOS} satellite scan and in the direction of K_{SLOPE} .

With the development of the mobile Cerescope, the EMR method has become more applicable to the monitoring and mapping of active landslides (Lauterbach 2005). According to the results of Lauterbach (2005), EMR is a well-functioning method for investigating the structural inhomogeneity of landslides

under considerable stress. Electromagnetic radiation occurring in a landslide is associated with the mechanical stresses and frictions resulting from the displacement of landslide layers under downward sliding forces (Pralat et al. 2005). Our results show that the most active are near-surface layers of slope sediments, which consists mainly of gravel clay with stones and boulders, and in a layer near the shallower shear surface, which is also manifested by a high intensity in the EMR field. Near a deeper shear plane, found in clay sediments, no enhanced EMR field values were registered, confirming the assumption of continuous plastic deformation. The total EMR field varies during the year, with values higher from February to June than from June to November. We assume that in the first period, water infiltrates into the landslide due to melting snow and spring precipitation, which causes an increase in deformation stress in the landslide body. In the second period, we consider a lower water saturation of the landslide body (lower total precipitation, evapotranspiration by vegetation) as the cause of the decrease in the values of the EMR field intensity. Our results show that the highest differential deformations in the INR-4 borehole were recorded in the period from November 2015 to May 2016. The highest total EMR values were also recorded during this period. The minimum deformations found by inclinometric measurements in the period from May to September 2016 also correlate well with the minimum values of the EMR field. Different values of total EMR intensity in individual boreholes indicate changes in the spatial distribution of deformation stresses in the landslide body.

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