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Investigation and mapping of the temporary dynamics of the highest Lithuanian outcrop using ground-based measurements and UAV imagery

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Abstract. The main goal of the study is to evaluate changes that have occurred in the Pūčkoriai outcrop surface over the 2014–2019 period and to compare the accuracy of ground-based measurements with that of UAV aerial image models. Ground-based measurements were performed applying the original methodology, which involves comparison of the first one and subsequent beam direction. For surface change surveys, we used repeated terrestrial geodetic measurements and UAV imagery. Ground-based measurements were performed using a Trimble M3 Total Station (with RTK); aerial images were captured using UAV INSPIRE1 with a ZENMUSE X3 camera. Pix4D photogrammetric software was used to create a DEM. The comparison of repeated terrestrial measurements and UAV aerial imagery revealed that the average change in the outcrop surface altitude over the period 2014–2019 amounted to 8.3 cm, with a maximum of 24.23 cm and a minimum of 0.33 cm. Contactless remote sensing allows obtaining data without affecting or altering the surface of the exposed deposits. The difference between terrestrial geodetic measurements and the UAV-based DEM did not exceed the following values: ΔX and $\Delta Y \leq 68$ mm; $\Delta Z \leq 21$ mm. Previous research has shown that the use of UAV aerial photography images for assessing changes in outcrops consisting of loose sediment layers yields sufficiently accurate results. The present study focuses on the determination of quantitative indicators of seasonal changes in the outcrop surface. Quantitative surface changes of the outcrop were mapped based on dynamic signs, surface comparison and a formal choropleth map (10 × 10 m); dynamic zones of the outcrop were distinguished based on the results obtained employing these methods. The data obtained can be extrapolated to other Lithuanian river outcrops, which are characterized by a variety of sediments.

Keywords: *high-precision GPS; remote sensing; UAV; geomorphological mapping*

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INTRODUCTION

The use of unmanned aerial vehicles (UAVs) in geomorphologic research provides a wide range of detailed mapping capabilities. This method proves particularly effective in investigating hard-to-reach or dynamic objects. In addition, it is very important when evaluating the accuracy of the measurement results obtained from UAV images. The accuracy of aerial imagery depends on several important factors, including optical capabilities of the camera, flight altitude, flight path (manual or designed) and meteorological conditions. If all these conditions are favourable, high-quality aerial images can be attained and photogrammetrically processed, and a 3D terrestrial digital relief model (DRM) or a digital elevation model (DEM) can be created. The effectiveness of this technique is highly dependent on the accuracy of the obtained aerial imagery data. To determine accuracy, ground-based terrestrial geodetic measurements can be used to record the X, Y and Z coordinates of exceptional points (benchmarks). However, ground-based surveying requires additional equipment, is time-consuming, is difficult to implement (especially on steep surfaces) and may destroy the surface (in the case of loose deposits). Recent research in different countries has shown that the use of global navigation satellite systems (GNSS) alone is not sufficient: they need to be used in combination with ground-based measurements (Bemis *et al.* 2014; Vasuki *et al.* 2017). Czech researchers have pointed out that the use of aerometric methods alone poses problems in mapping the low-height (up to 1.5 m) terrain roughness of quarries or landslides (Patikova 2004). This problem has been extensively studied by Slovak researchers, who found that the mismatch between surface geodetic measurements and UAV image models mounts to 4 m (Pukanská *et al*. 2014). The combined use of global navigation satellite systems and ground control points makes it possible to develop a much more accurate DRM, where the accuracy of the vertical positioning of points equals 0.7 cm (Blistan *et al.* 2016). Research carried out in Australia (Turner *et al.* 2012; Harvin *et al.* 2015), Great Britain (Westoby *et al.* 2012; James *et al.* 2017), Canada (Hugenholtz *et al.* 2013, 2016; Mian *et al.* 2016; Shahbazi *et al.* 2015; Whitehead, Hugenholtz 2015; Nesbit *et al*. 2018), Italy (Mancini *et al.* 2013; Benassi *et al*. 2017; Forlani *et al.* 2018), China (Wu *et al*. 2013), New Zealand (Javernick *et al.* 2014), Spain (Labourdette, Jones 2007; Calvo, Ramos 2015), Denmark (Sørensen *et al.* 2015), the USA (Chesley *et al.* 2017), Saudi Arabia (Mezghani *et al.* 2018) and Slovakia (Blistan *et al.* 2016) showed that the combined application of ground-based methods and UAV images makes it possible to significantly increase the accuracy of measurement results.

The aim of this research is to compare the accuracy of aerial imagery and that of ground-based measurements and to determine the efficiency of their combined use in investigating loose sediment outcrops.

The exploration of riverbank outcrops in Lithuania dates back to the 19th century (Geology of Lithuania 1994). Riverbank outcrops represent excellent research objects for analysing the material composition and structure of surface sediments. Several periods can be distinguished in the history of outcrop investigations in Lithuania, differing in the objectives pursued and the methods and technologies employed to achieve them. The investigations performed in the first period (the mid-19th century) were mainly focused on fossils found in the Jurassic outcrop deposits on the banks of the Venta, Neris and Nemunas rivers. The second period (the end of the 19th century) of investigations was marked by detailed studies of the Quaternary and Pleistocene deposits on the banks of the Neris, Vilnia, Nemunas, Jiesia and Mūša rivers (Česnulevičius *et al.* 2011). The focus of the studies performed in the first half of the 20th century (third period) was on the correlation between outcrop sediments and sparse, deep Devonian, Neogene and Pleistocene boreholes. The fourth period of outcrop studies in Lithuania was noted for the use of modern methods: photogrammetric methods were applied in investigating the outcrops of the Neris River and Kaunas reservoir (Gaigalas, Molodkov 2002; Gaigalas, Hütt 1995), paleobotanical, paleozoological, carbon and heavy metal isotope, electronic resonance spectroscopy (ERS) and optical stimulation (OSL) methods being employed in outcrop sediment studies (Gaigalas *et al.* 2005; Šeirienė *et al.* 2011; Stančikaitė 2006; Baltrūnas *et al*. 2013a, b; Satkūnas *et al.* 2008; Satkūnas, Hüt 1999). The fifth period of outcrop investigations in Lithuania was marked by precise terrestrial geodetic measurements and the use of aerial photographs captured by unmanned aerial vehicles (UAVs). Local aerial images provide detailed quantitative information on the morphometric characteristics of outcrops and their dynamics as well as the absolute height of sedimentary layers.

STUDY AREA

Pūčkoriai is the highest outcrop in Lithuania, with the relative height of 63.2 m. The outcrop is 260 m long, and its maximum altitude is 208.2 m a. s. l. The outcrop is located on the right bank of the Vilnia River (a tributary of the Neris River), 8 km away from its mouth (Fig. 1).

The outcrop was formed in the Late-Glacial and Holocene periods, when the Vilnia River was deepening its valley and draining the limnoglacial basin of the Mickūnai glacial depression. However, the present shape of the outcrop is rather young, as slope processes here are very rapid (Guobytė, Satkūnas 2011; Morkūnaitė *et al.* 2014; Petrošius *et al.* 2017, 2019). Indeed, over a short geological time span (less than 10,000 years), the Vilnia River eroded a deep valley, forming an outcrop exposing sediments formed 20,000 years ago.

The inner structure of the Pūčkoriai outcrop is typical of the northernmost spur of the Medininkai Heights (part of the Ašmena Upland) forming the topography of Vilnius. The outcrop is outside the limits of the Last Glaciation, and its structure has not been affected by either accumulation or erosion of the Weichselian ice sheet (Guobytė, Satkūnas 2011). The outcrop is permanently changing the slope of the Vilnia River valley. The lateral erosion of the Vilnia River stimulates its instability, although lately the Vilnia River has been unable to clean off the abundant colluvium from the outcrop foot. Therefore, vegetation is beginning to grow here.

MATERIALS AND METHODS

Accurate terrestrial geodetic observations of the ongoing outcrop dynamics can be conducted apply-

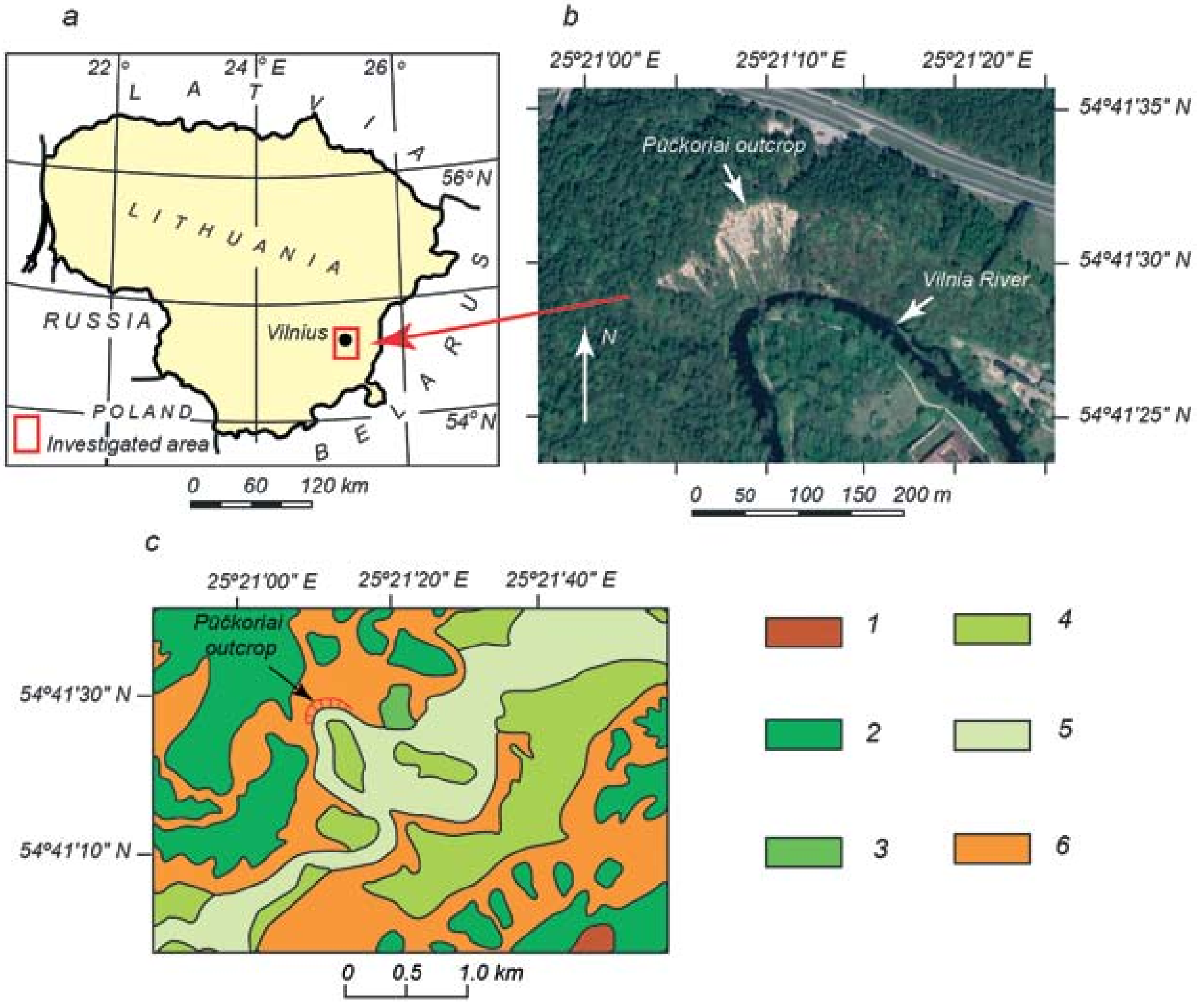

Fig. 1 The investigated area (a and b) and geological map (c) of the Pūčkoriai environment: 1 – Middle Pleistocene marginal moraine deposits, 2 – Middle Pleistocene marginal fluvioglacial deposits, 3 – Middle Pleistocene fluvioglacial deposits, 4 – Upper Pleistocene (Grūda Stage) fluvioglacial deposits, 5 – Upper Pleistocene (Baltija Stage) fluvioglacial deposits; 6 – Holocene deluvial deposits

ing geodetic measurements. The classical method using such measurements is based on permanent signs (benchmarks) installed in the area of observation. The spatial coordinates of such benchmarks are determined from the measurement stations installed in a stable zone applying geodetic resection methods.

Through repeated measurements at a given time interval Δ_t (1) and by determining the spatial coordinates of the established benchmarks on the surface of the outcrop (x, y, z), the changes in the outcrop surface were assessed as:

$$\Delta_t = (t_0 - t_n) \quad (1)$$

where Δ_t is the time interval between measurements, t_0 is the first measurement of the whole surface and t_n is the repeated (n^{th}) measurement of the whole surface.

This method, however, is appropriate only to small areas, as it allows identifying changes solely within the zone of the installed sign. In order to evaluate changes in the area under observation more precisely, there should be many benchmarks installed. As demonstrated by the data reported from other investigations (Patikova 2004; Pukanská *et al.* 2014; Blistan *et al.* 2016), the outcrops we measured were small, so the installation of such permanent signs was certainly not cost-effective.

Taking into account the fact that during measurements the surfaces of riverbank outcrops can be destabilized, in our research, we performed measurements using an electronic tacheometer with a GPS function. For measurement of points location were used different techniques: 1) comprehensive repetitive measures were made when the quantity of measured points were little (10–20 points), 2) when the quantity of measured points were large, repeatedly measured only a part of them. The timing of the full re-measurement of the points was decided depending on the partial measurement results.

The time interval Δ_t between repeated measurements should not be long, because in the case of long measurement intervals (e.g., half a year), the first signs of considerable changes can be overlooked. Intermediate measurements must be frequent, quick and sufficiently accurate.

Measuring equipment and methods. The measurements of outcrop surface points were performed using a Trimble M3 Total Station and applying the laser system single-image spatial resection method. The laser beam was directed to the selected outcrop surface points rather than to benchmarks (Figs 2 and 3, Table 1). Horizontal and vertical angles were measured with an accuracy of ± 5″ and distances with an accuracy of ± 3 mm. As mentioned above, permanent signs cannot be installed on the surface of the outcrop, and frequent mapping of the entire outcrop surface is rather complicated and too costly. Hence, there is a need for a method that would allow taking control measurements promptly and at short time intervals, allow assessing the ongoing processes in the outcrop and deciding on the necessity to perform another full mapping of the studied surface.

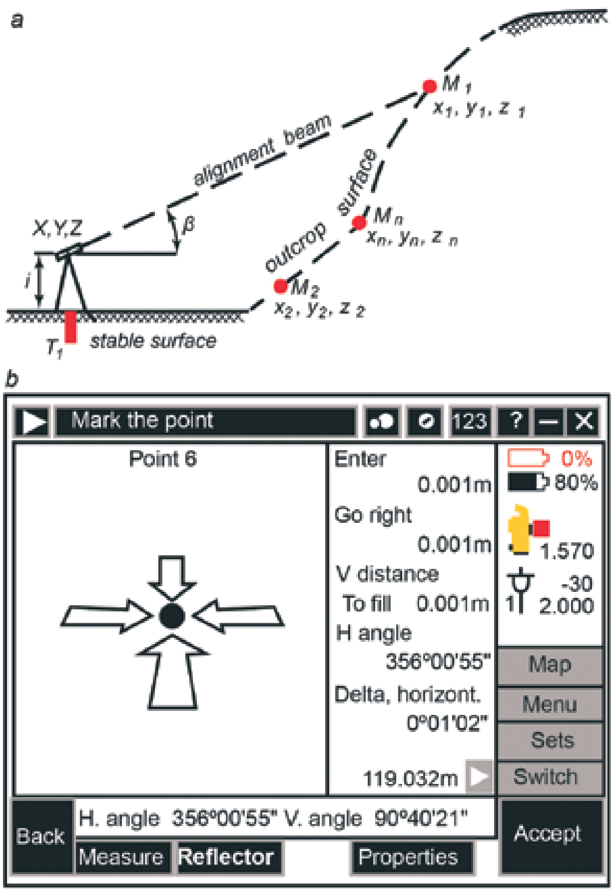

Fig. 2 Measurement by Trimble M3 Total Station: a – measuring of surface points applying single-image spatial resection method, b – marking of spatial points

Table 1 Reference point coordinates of the Pūčkoriai outcrop

Point No.	Coordinate system	X_m	Y_m	Z_m
P1000	LKS94	6062492,464 m	587227,472 m	121,295 m
	WGS	54°41′28.64434″	25°21′10.80252″	
P2000	LKS94	6062487,930 m	587209,075 m	121,310 m
	WGS	54°41′28.50916″	25°21′09.77066″	

In this study, intermediate (control) measurements were taken applying for the first time the method, which is provisionally called the virtual reference point (VRP) method. This method is based on the ability of the Trimble M3 Total Station device to measure directions from a fixed point and to enter the desired directions into the device memory. This allows it to determine the direction of the primary measurement during subsequent measurements and

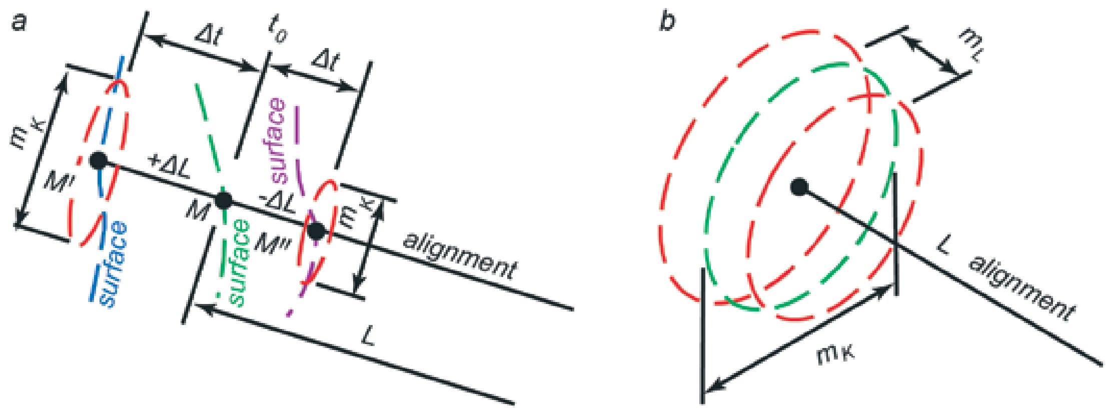

Fig. 3 Measurement of reference points when applying the AVT method: a – spatial change of the virtual point, b – accuracy of the position determined by repeated measurement

to show the point location of the primary measurement. When these data are entered, the location of the marked point is visualized, and the accuracy of fixation is established (Fig. 2).

During the initial measurement (t_0), the position of the point M is accurately determined (Fig. 3A). During the next measurement, which is performed after a certain time interval (Δ_t), the position of the point M changes. The former surface may have changed, i.e. it may have fallen down due to the removal of sediment, or it may have been overlapped by the sediment that slipped from above. The Trimble M3 Total Station device makes it possible to determine the alignment beam direction of the first measurement and accurately measure the distance to the changed surface. The change in planar distances ($\pm\Delta_L$) will indicate the surface change (Fig. 4). We can state that by aiming the device at the earlier position of the point M, i.e., by entering the calculated orientation angles and only then measuring the distance L_n, the new position of the point M (M′ ($X_{M'}$, $Y_{M'}$, $Z_{M'}$) or M″ ($X_{M''}$, $Y_{M''}$, $Z_{M''}$)) will be determined. With such data, it is possible to estimate changes in the outcrop surface (2):

$$t_n = t_0 + \Delta_t;\ \ \Delta_X = X_0 - X_n;\ \ \Delta_Y = Y_0 - Y_n;\ \ \Delta_Z = Z_0 - Z_n;$$

$$\Delta_L = L - L_n = \sqrt{\Delta_X^2 + \Delta_Y^2 + \Delta_Z^2} \quad (2)$$

where t_n represents the repeated measurement data; t_0 represents the initial measurement data; Δ_t is the time interval until the repeated measurement; Δ_X, Δ_Y, Δ_Z are the changes in the point position measured; X_0, Y_0, Z_0 are the initial coordinates of the point measured; X_n, Y_n, Z_n are the coordinates of the repeated measurement of the point; Δ_L is the change in the distance to the point; L is the initial distance to the point; and L_n is the distance to the point after the time interval Δ_t.

The value of the change in distance Δ_L allows estimating the magnitude of the change, and the mark (±) indicates the direction of change (Fig. 4).

Accuracy of measurements. When applying such a measurement methodology, it is important to take into consideration measurement errors and exactly determine how much the position of the previously measured point has changed. For this purpose, the AVT (applied vehicle technology) method is the most appropriate. The ATV method let enhance precision of point location for moving vehicles (drones) and ground-based measurements.

It can be assumed that when taking repeated measurements from the same initial point T1 (Fig. 3), i.e., trying to precisely aim at the spatial point M, due to measurement errors, the sighting beam of the device creates a specific cylindrical cone-shaped zone of inaccurate fixing around the actual position of the point M (Fig. 3). The size of this zone, i.e., a precise hitting error, depends on angular measurement errors (m_K) and the distance (m_L). As mentioned above, the angular measurement error of our device (horizontal and vertical) was ± 5″, and the maximum distance measured by a laser rangefinder was 400 m. While using 3 formula it is possible to determine a mistake of beam device which is directed to the point M:

$$m_K = \pm\left(L_{max} \times sin(5")\right) \approx \pm 10.0\ mm\ ; \quad (3)$$
$$m_{K_h} = m_{K_v} = m_K$$

where m_K is the angular measurement error; m_{Kh}, m_{Kv} are the horizontal and vertical angle measurement errors; L_{max} is the maximum distance measured by a laser rangefinder (400 m in our case); and 5″ is the angular measurement error of the device.

A laser rangefinder can measure distances with an accuracy of ±3 mm, but it is necessary to take into consideration the fact that the spatial distance L to the point can be affected by the height (i) of the device (Fig. 3A). The change in the inclination angle (*β*) when aiming at the initial position of the virtual point M also depends on this value. If during repeated measurements, the height of the device was the

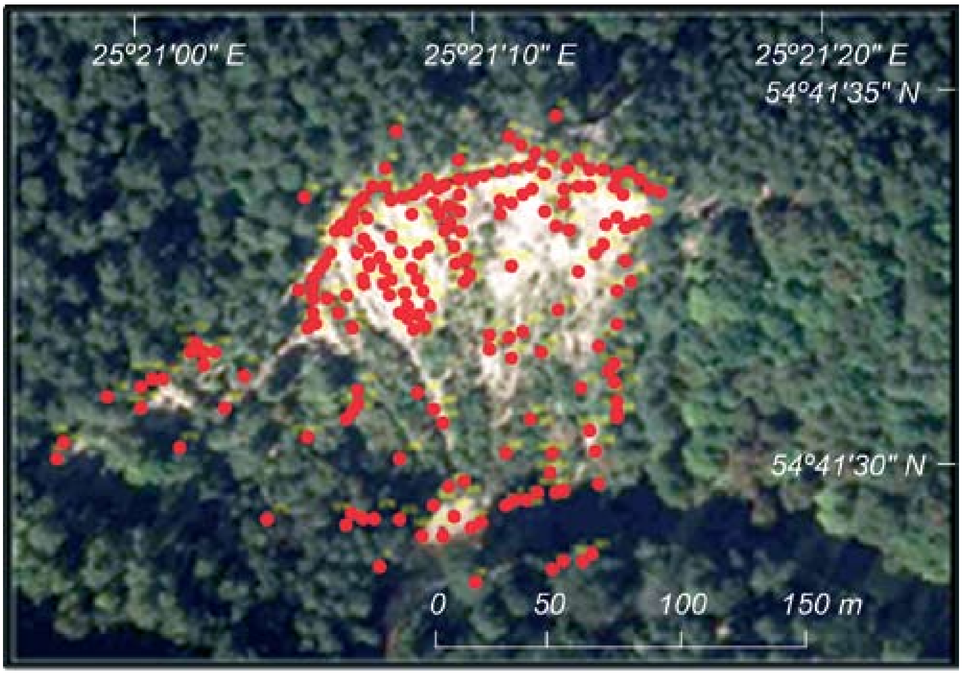

Fig. 4 The "cloud" of points measured at the Pūčkoriai outcrop in the LKS-94 coordinate system

same as during the initial measurement, it is possible to calculate Δ_L (2) immediately and thereby estimate changes, but this is not the case here. The horizontal alignment error of the device hardly ever exceeds several millimetres above the installed sign whereas the height of the device might significantly differ from the initial height, because it directly depends on, e.g., the measurer's height. Such a change in the device height Δ_i should be considered when taking each repeated measurement. As we can see from the analysis of the measurements performed, this change hardly ever exceeds ±10 cm, so we can calculate the spatial distance measurement error m_L that can be expected if we measure at a maximum (400 m) distance:

$$\Delta\beta = \pm\left(arctg\left(\frac{i_{max}}{L_{max}}\right)\right) \approx \pm 52'' \; ;$$
$$m_L = \pm\left(\frac{L_{max}}{cos(\Delta\beta) - (L_{max}) + 3\ mm}\right) \approx \pm 3.013\ mm \quad (4)$$

Here we can see that the effect of the change in device height on the measured distance is negligible; therefore, the spatial distance will be measured with the device's measuring accuracy, i.e., ± 3 mm. The change in device height most strongly affects the angle of inclination to the measured spatial point, but this does not deserve great attention either, because when the spatial coordinates of the device change, all of the orientation angles necessary for marking the spatial point are automatically corrected.

All possible measurement errors were calculated for the maximally possible distance that the laser rangefinder could measure. It is obvious that if spatial distances to the virtual reference points become shorter, the measurement accuracy increases. Therefore, we can state that the points whose change in spatial coordinates does not exceed the maximum measurement error of the point m_M (5) are stable:

$$m_M = \sqrt{m_{K_h^2} + m_{K_v^2} + m_L^2} \quad (5)$$

Another very important factor affecting the accuracy of the observation of dynamic processes is the frequency of the measurement of control points, i.e., the time interval Δ_t between control measurements. Obviously, such an interval can be stable only when no anthropogenic activities or extreme climatic changes occur in the place of observation. Given that this control points measuring method is used for the first time and because – as previous research has shown – repeated measurements of a small number of spatial reference points take a very short time, we decided to take control measurements every two weeks or immediately after abundant precipitation.

UAV photo fixation. Photo fixation of aero images was conducted using the unmanned aerial vehicle (UAV) INSPIRE 1. Automatic flight routing was used for the exposure of the images that were photographed. The UAV route was designed so that aerial views would have 80% longitudinal and 70% transverse overlap. Such an overlap allowed us to create an accurate 3D model of the terrain from which the image of the contour lines was generated.

This study assessed discrepancies between the elevation isoline positions obtained from the ground-based geodetic measurements and from the aerial images of UAVs. The associate professor of the Department of Cartography and Geoinformatics, Artūras Bautrėnas, designed a computer program “Circle_3p”, which employs the classical Delaunay method and ensures a consistent systemic selection of points (Česnulevičius *et al.* 2019). Using the Delaunay triangulation method, the altitude interpolation of ground measurement points was performed and an isoline view was generated.

Dynamic maps of the outcrop were created based on the data describing spatial changes in the surface. The thickness of the altered surface layer was used as the main change classification criterion. Quantitative change estimates were mapped using three methods:

Surface comparison method: during the measurements, the positions of the points (x, y, z) were fixed, and interpolation between neighbouring points was applied.

Quantitative dynamic sign method: the outcrop space was divided into formal grids (10 × 10 m), the surface change was estimated and was mapped in individual grids using quantitative vectors (arrows).

Choropleth map method: the outcrop space was divided into formal grids (10 × 10 m), and the average surface change in each grid was estimated. The extent of erosion and accumulation is reflected in the intensity of bluish (erosion) and yellowish-pink (accumulation) colours.

To ensure the accuracy not only of the initial but also of the repeated measurements, a coordinated reference (base) line was created near the outcrop, the ends of which were fixed by temporary signs. The coordinates of the installed points (X, Y, Z) were determined using a Trimble 5800 GPS (with RTK) device, whose accuracy of determining coordinates in good measurement conditions was ±5 mm. The reference points were installed at the place providing the best view of the large Pūčkoriai outcrop surface, i.e., on the left bank of the Vilnia River. As the measurement conditions were complicated, i.e., the riverbank was overgrown with high trees and most of the visible horizon (for observation by satellites) was blocked by the outcrop itself, multiple measurements of the coordinates of reference points were taken, and their mean values (X_m, Y_m, Z_m) were calculated in an attempt to achieve higher accuracy. For the altitude, Z_m, a ± 1.5 mm tolerance was applied.

The spatial coordinates x_n, y_n, z_n of 341 points (n is the point number) were recorded when performing the first measurements (May 2014) (Fig. 4).

To reduce the impact of vegetation cover on aerial imagery, the images underwent colour correction, which was performed using Photoshop software. As a result, the green colour contrast in the images was increased.

Creation of 3D model. It is obvious that for creating the 3D model of the outcrop surface, some of the points (i.e., those inaccurately measured or outside the limits of the main outcrop area) had to be rejected. To ascertain as accurately as possible which points are not applicable, the photo panoramic image of the outcrop was created from five separate (overlapping) digital photographic images.

The points on the outcrop surface were measured in the LKS94 coordinate system, and the photo panorama was created in a free coordinate system. In order to transfer the measured points onto the photo panorama, it was necessary to transform the coordinates of all the points into the coordinate system and scale of the photo panorama. To automate this transformation, the computer program *DXFtoFotoXY* was created (author Bautrėnas) (Fig. 5). An automated horizontal generation and interpolation program was used to create the 2D terrain model, which made it possible to calculate the exact horizontal surfaces of the relief, i.e., to interpolate heights.

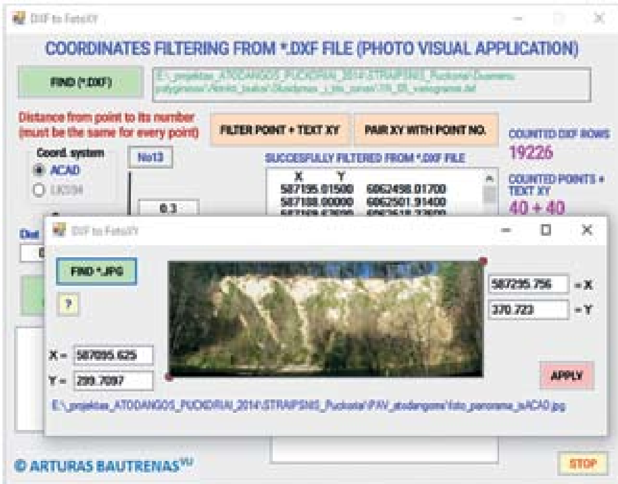

Fig. 5 The window of the computer program *DXFtoFotoXY*, which was used to transform the measured points into a photo panorama

The Delaunay triangulation method was selected for the interpolation of the heights (Fang, Piegl 1999; Česnulevičius *et al.* 2019). A 2D relief model and a scheme of inclination vectors were developed from the 310 points that were selected for further analysis (Fig. 6). Horizontal lines were drawn every 1 m in the Baltic height system (BAS77). As the outcrop surface inclinations were distributed irregularly, a scheme of inclination vectors was created, and the average inclination angles of separate parts of the outcrop slope were calculated.

Ground-based measurement data were used to develop a 2D terrain model. The Delauney triangulation method was applied to perform the interpolation of the horizontal planar position and its height. The 3D terrain model was created from aerial imagery using Pix4D software (Pix4Dmapper 4.1 User Manual).

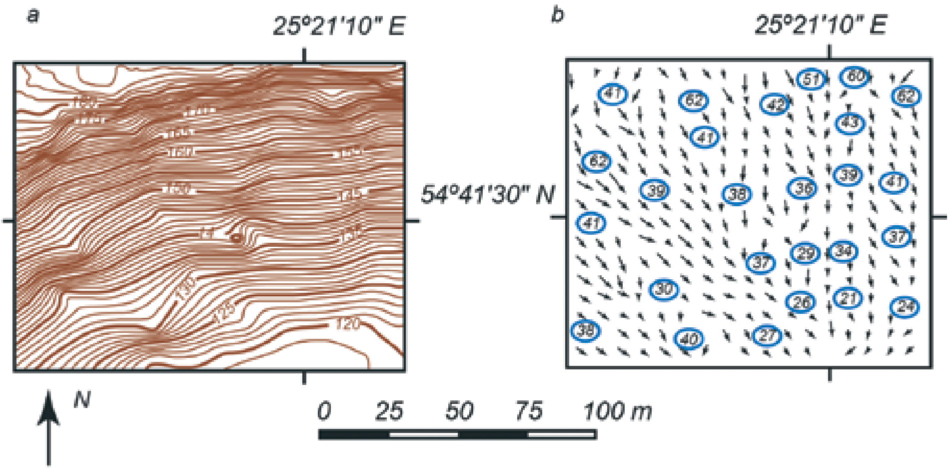

Fig. 6 Outcrop surface generated by the *DXFtoFotoXY* program: a – 2D relief model, b – scheme of inclination vectors with average inclinations of separate surface parts

RESULTS

The comparison of the 2D and 3D horizontal positions revealed the following:

1. The smallest discrepancy between the ground-based and UAV data on the planar and height positions of the contour line was found in the highest and steepest (up to 62°) parts of the outcrop (165–175 m a.s.l.). The maximum bias of the horizontal X and Y positions was 33 mm and the mean absolute deviation 18 mm. The maximum height (Z) position disagreement was 18 mm and the mean absolute deviation was 7 mm.

2. In the middle part of the outcrop (135–165 m a.s.l.), where the surface inclination reached 41°, the maximum discrepancy between the ground-based and UAV data on the planar position of the contour line reached 48 mm and the mean absolute deviation 23 mm. This part of the outcrop showed a higher absolute maximum height discrepancy reaching up to 38 mm (the mean absolute deviation was 13 mm).

3. In the lower part of the outcrop (120–135 m a.s.l.), where the surface inclination was the smallest (up to 37°), the maximum values of contour line disagreement reached up to 64 mm (the mean absolute deviation was 31 mm), and the maximum height mismatch errors up to 54 mm (the mean absolute deviation up to 21 mm) (Fig. 7).

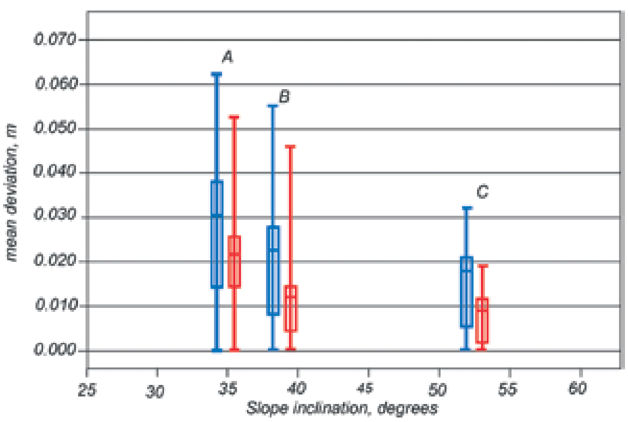

Fig. 7 Differences between 2D and 3D models in different inclination parts of the outcrop (blue – planar place, red – height)

Analogous models were also constructed through interpolation using simple kriging of the height points measured at the Pūčkoriai outcrop at different times. Two DRMs were obtained: one was constructed from the data measured in May 2014, and another was based on the data of the measurements performed in October 2014. The second comparison of outcrop surface changes included data of the measurements performed in May–October 2019. Figure 8 shows the outcrop altitudes measured in May 2014, changes in the outcrop surface over the period May–October 2014, the outcrop altitudes recorded in May 2019 and changes in the outcrop surface over the period May–October 2019.

To assess the relief changes that have occurred over a half-year period (May–October 2014 and May–October 2019), two DRMs of the Pūčkoriai outcrop, constructed based on the same modelling parameters, were compared.

The average change in the Pūčkoriai outcrop relief over the half-year period reached the value of -0.23 cm. The greatest landslide vertical displacement reached -24.23 cm, and accretion +19.57 cm. The standard deviation was +5.28 cm. The performed detailed analysis of outcrop relief changes in 2014 revealed that most (35%) of the relief had changed from +0.33 cm to +2.56 cm, and 22% of the relief had changed from -2.24 cm to -0.33 cm. The relief changes recorded in 2019 were similar: the lowered surfaces (from -5.0 to -2.5 cm) and the slightly changed (from -2.5 to +2.5 cm) surfaces covered the largest area. The changes are presented in Table 2.

To visualize the Pūčkoriai outcrop relief changes, we made calculations showing the permanent downs-

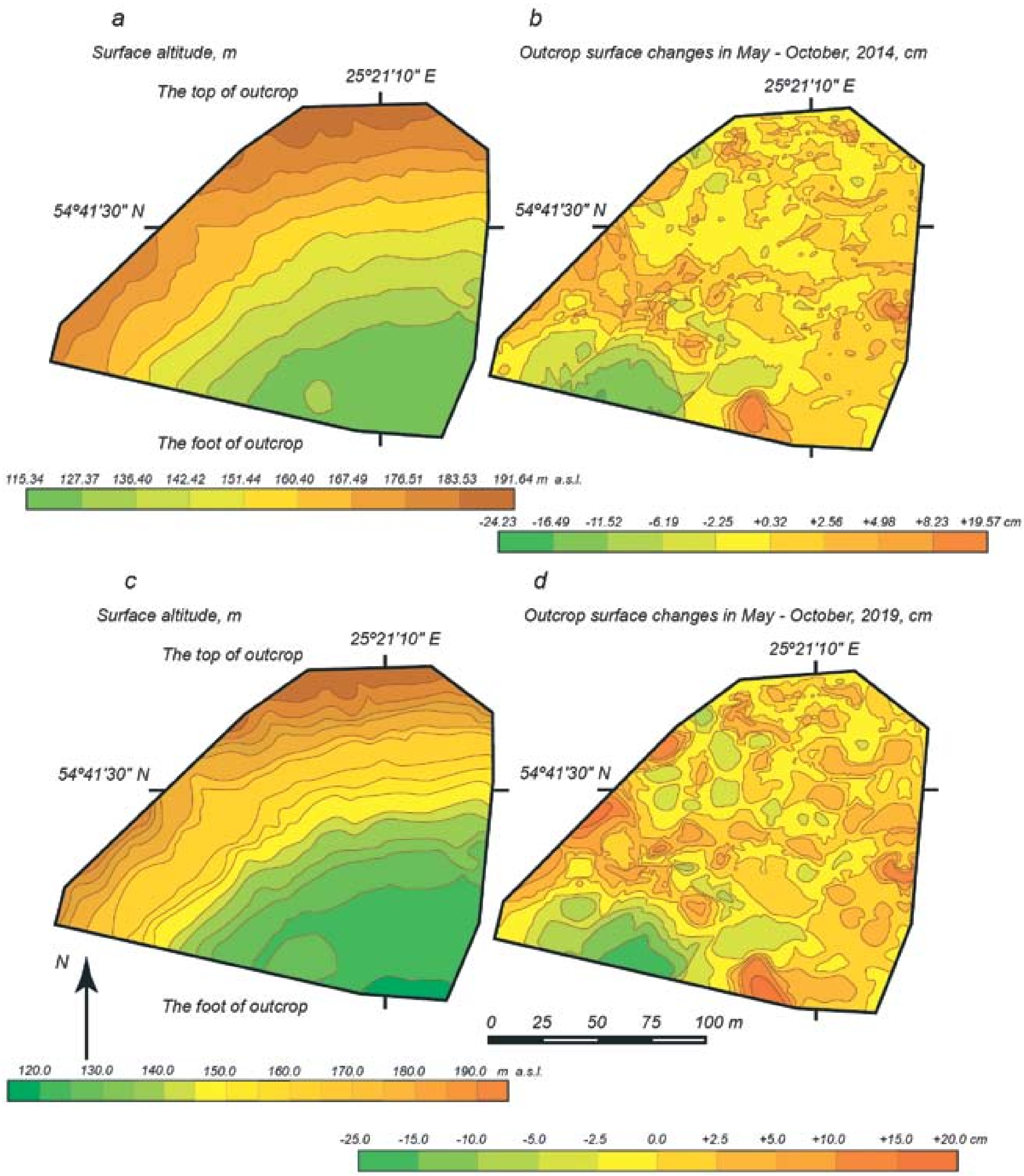

Fig. 8 DRM of the Pūčkoriai outcrop: a – surface altitudes in May, 2014, b – outcrop relief changes from May to October 2014, c – surface altitudes in May, 2019, d – outcrop relief changes from May to October 2019

lope movement of the sediment mass on the outcrop slope, characterized by considerable amounts of outcrop foot sediments.

The intense segmentation of sediments and the fall of detached small blocks taking place in the upper part of the outcrop, where a solid moraine loam layer lies, are due to climatic effects. The middle part of the outcrop, where various-grained sand lies, is characterized by free crumbling of sediments, and the surface erosion in the lower part of the outcrop is caused by rainwater. Using different mapping methods, we succeeded in identifying several different erosion-accumulation sections in the Pūčkoriai outcrop. The upper part of the outcrop is dominated by gentle erosion (up to 2 cm per year) associated with the crumbling and retreat of the outcrop edge. In the middle part of the outcrop, separate areas show different intensities of erosion (up to 5 cm per year) and accumulation

Table 2 Surface changes of the Pūčkoriai outcrop (May–October 2014 and May–October 2019)

Surface change			
2014		2019	
in cm	area, in percent	in cm	area, in percent
-24.23 – -16.50	0.8	-25.0 – -15.0	1.9
-16.49 – -11.52	4.2	-15.0 – -10.0	2.1
-11.51 – -6.19	2.2	-10.0 – -5.0	2.3
-6.19 – -2.24	10.7	-5.0 – 0.0	24.7
-2.24 – -0.33	29.9	-2.5 – 0.0	26.6
+0.33 – +2.56	32.3	0.0 – +2.5	21.6
+2.57 – +4.97	15.4	+2.5 – +5.0	13.1
+4.97 – +8.23	3.0	+5.0 – +10.0	4.8
+8.23– +19.57	1.5	+10.0 – +15.0	1.8
		+15.0 – +20.0	1.1

(2–10 cm per year). The lower part of the outcrop is characterized by intense erosion (10–25 cm per year) (Fig. 9), which is caused by the water level rise in the Vilnia River during spring floods.

DISCUSSION

Outcrops have undoubtedly been the key to the science of geology. However, traditional field work has always been associated with challenges. Different technologies are now widely used in geosciences to model outcrops in 3D. The technology used for 3D modelling is usually based on LIDAR, but photogrammetry represents an alternative methodology (Blistan *et al.* 2012; Thurmond *et al.* 2014; Trinks *et al.* 2005; Baltsavias 1999; Brihla 2016; Casas *et al.* 2006; Chandler 1999; Rotnicka *et al.* 2020).

The performed comparison of ground-based geodetic measurements and UAV aerial images showed that the aerometric methods used to investigate the outcrop surface yielded sufficiently accurate results. The discrepancy in the planar position of the contour line obtained employing ground-based and aerial methods did not exceed 70 mm, and that in the altitudinal position of the contour line 60 mm (Fig. 8). Given that the identified seasonal and annual changes in the exposure surface were several times bigger (up to 250 mm), the accuracy of the UAV aerial images fully met the objectives of this research.

The smallest discrepancy in the planar and altitudinal positions of the contour line, found in the upper, steepest part of the outcrop, may have been due to its large altitudinal range, reaching 65 m: the height of the outcrop increases by 65 m from the foot to the top. The UAV flight altitude was 130 m from the foot of the outcrop (altitude = 270 m), which was only 60 m above the outcrop top. It is likely that smaller vertical distances resulted in a more accurate 3D model, which was reflected in the planar and altitudinal positions of the contour line.

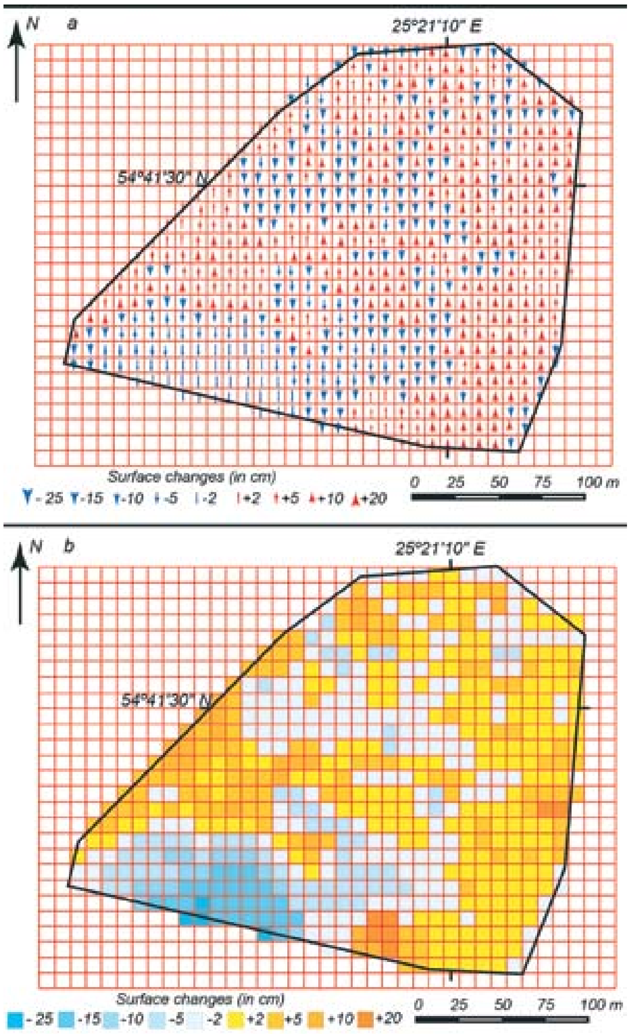

Fig. 9 Erosion and accumulation zones on the Pūčkoriai outcrop during May–October 2019: a – quantitative dynamic sign method, b – choropleth method

Oksanen, Sarjakoski (2006) found quite large discrepancies when comparing ground-based measurements with the data of the Finnish National Land Service (NLS) and LIDAR DEMs. Discrepancies between the ground-based measurements and the LIDAR DEM data were found to range from 0.01 to 0.03 m, while discrepancies between the ground-based measurements and the Finnish NLS DEM data reached several meters. Comparative studies of the accuracy of ground-based measurements and UAV aerial imagery performed in the Polish coastal dunes yielded findings similar to those of our study: horizontal discrepancies in the position of isolines reached 0.04–0.12 m, and vertical discrepancies 0.01–0.07 m (Laporte-Fauret *et al.* 2019). Similar results were reported by French scientists, studying dunes in southwestern France: vertical position discrepancies were found to range from 0.02 to 0.05 m (Gomez-Heras *et al.* 2014).

Vegetation cover (tree leaves and needles, grass) distorts the 3D surface model, concurrently distorting the spatial position of contour lines. In our study, the influence of the vegetation cover could not be completely avoided, but wherever the leafage was sparser, the exposure of the surface in the model was highlighted.

Assessment of minimum measurement errors was of great importance when comparing the Pūčkoriai outcrop dynamics in spring with that in autumn. For example, the construction of a 3D model using UAV images – as mentioned by Turner *et al.* (2012) – encountered such a restriction, and the proper DEM was not created: a DRM was created instead. The techniques we applied relied on optical sensors, so the failure to record vegetation changes might have resulted in erroneously measured heights compared with those recorded using the tachometer laser system. Using optical sensors, it is possible to visualize a point cloud as a simple point data or, alternatively, as triangulated surfaces (Godt *et al*. 2012). The advantage of a solid surface presentation over point cloud visualization is that there are no visible gaps between scanned data points.

In the future, continuous measurements and regular data compilation might reveal cycles in outcrop dynamics. Fig. 4 shows when it is appropriate to perform extensive repeated measurements and how accurate the measurement results are expected to be. The computer program *DXFtoFotoXY* control window (Fig. 5A) indicates that 310 points were used for the creation of a 3D model for the Pūčkoriai outcrop. Moreover, the outcrop photo panorama (Fig. 5B) presents recalculated measurement points and the point selection technique used for all the other outcrops.

We can debate about which of the following models is more significant for outcrop dynamics disclosure: a model of relief changes measured in meters, or a model of volume changes presented conventionally (increased, did not change or decreased). However, according to Turner *et al.* (2012), where areas of change are large, an erroneous image could be obtained concerning volumes constituting a small percentage part, i.e., the absolute error is lower, but the relative error is high.

Discrepancy between the spatial contour line data derived from ground-based measurements and the UAV-based 3D models showed that the slope inclination has the greatest influence. In steep parts of the slope (50–60º), discrepancies in the spatial position of contour lines were the smallest, which is due to very small gaps between different values of the contour lines in the 3D aerial image model and in ground-based measurements. At lower surface inclinations, the gaps between the isolines are larger, which directly leads to a great discrepancy in the position of contour.

Mapping of local changes in the outcrop surface is highly problematic. Eroded outcrop surface sediments are transported downslope along concentrated paths, where surface changes are very dynamic. The most appropriate method for mapping such sediment transport would be vectors (arrows), whose widths would express the velocity of sediment transport.

However, the routes of the paths in unstable outcrop sediments are constantly changing. Thus, the mapping of local sediment transport over several periods employing the vector (arrow) method would yield an image of highly intertwined lines. For this reason, the authors believe that the choropleth map method is more suitable for mapping local changes in the outcrop surface. In addition, the area of the grids must be small: 10 × 10 m or 5 × 5 m.

The summarized data on outcrop relief changes are presented in Table 2. They allow indicating active outcrop areas as well as more accurately identifying the causative factors behind the identified outcrop changes, i.e., precipitation, morphometry, river erosion etc. In this article, we have presented results of the performed geodetic measurements; however, we assume that the comparison of our data with those on other neighboring outcrops on the banks of the Vilnia River would deepen the understanding of the main causes of the outcrop surface dynamics. In this research we used some of the surface change models, created remotely. They can be related with plenty of rainfall data. It could let predict formation of landslides. Therefore, in this study, a greater number of digital models have been developed. Furthermore, dynamics curves such as varvograms could be also used. The illustrations accompanying this study deepen the understanding of the composition of outcrops.

Rivers also exist within a complicated geomorphic context (Wohl 2018; Skuodis, Ng 2018). The geological bodies present in river catchments play a significant role in predetermining river channels and catchment geometry, the inclination of river valleys slopes in different sections as well as other catchment features. Thus, it is obvious that investigation methods must be precise, complex and universal. The recalculation of altitudes according to regular coordinate systems also requires considerable routine work. Thus, this study represents just a fragment of the complex geodetic investigations of the Pūčkoriai outcrop, the highest outcrop in Lithuania. The Pūčkoriai outcrop is a suitable object for complex investigation as it is composed of lithologically and morphometrically diverse parts. Its stability is strongly affected by the unevenness of sediment layers (loam, silt, sand with gravel). The thick layer of the moraine loam in the upper part of the outcrop is more resistant to the atmospheric effects However, when soaked, it breaks into large clumps, which fall down forming slopes of less inclination in the middle part of the outcrop

(Fig. 9B). The outcrop is of great value for recreation and for the Vilnia River, the flow and banks of which might change due to the outcrop collapse (Mikšys *et al.* 2002; Baum, Godt 2010).

Similar complex investigations are applicable and valuable where landslide processes affect the economies of urban areas and the banks of artificial reservoirs of hydropower plants (Mardosienė 1991).

CONCLUSION

The surface of the outcrop was measured using a Trimble M3 Total Station and applying the laser system single-image spatial resection method. These methods facilitated the performance of control measurements at short time intervals, making it possible to evaluate the ongoing changes and to determine when to conduct repeated measurements.

The photo of the outcrop was taken using an INSPIRE 1 UAV with a Zenmuse X3 camera. The aerial images were used for 3D modelling. The photogrammetric software Pix4Dmapper, which was used to analyse the performed measurements, allowed minimizing the measurement errors arising due to external factors. The methodology applied will allow us to accumulate long-term data sequences and to build up suitable databases for the quantitative analysis of outcrop degradation processes.

In this study, the maximum surface descents reached 24–25 cm. However, the changes that occurred in different parts of the outcrop surface were heterogeneous: in the lower part, there was a sediment slide (surface lowering) observed, while in the middle part, due to the sediments falling from above, there was a rise in the surface recorded.

The accuracy of the aerial images was greatly dependent on the relative height of the exposed parts of the outcrop. In the upper part of the outcrop, above which the UAV had risen 60 m, discrepancies between the surface positions, determined by ground-based geodetic measurements and those determined by the photogrammetric interpretation of aerial photographs, were the smallest. In the lower part of the outcrop, above which the UAV had risen 120 m, discrepancies in the positions of the surfaces were the largest. This was due to the large altitudinal difference between the foot and the top of the outcrop, which affected the accuracy of the 3D terrain model.

The choropleth map method seems to be the most suitable for mapping surface changes of the unstable outcrop. It can be used to reveal qualitative changes (surface lowering or elevation) as well as the quantitative values of these changes.

The performed research allowed the quantification of the erosion processes taking place on the surface of the Pūčkoriai outcrop. Research showed, that the multi-layered structure of outcrop has influence on dynamics of individual parts of the outcrop.

In addition, the obtained data can be extrapolated to other Lithuanian river outcrops, which are characterized by a variety of sediments.

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