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EXPERIENCES OF UAS PHOTOGRAMMETRIC ROCKSLIDE MONITORING IN THE ALPINE TERRAIN IN HIGH TATRAS, SLOVAKIA

Abstract: The development of surveying methods and equipment has moved from conventional surveying methods to modern technologies such as Unmanned Aerial Systems (UAS) aerial photogrammetry or Terrestrial Laser Scanning (TLS). These methods were used to monitor the rockslide of the Tatranská magistrála hiking trail in the High Tatras, where a rockslide occurred as a result of its washing away. This research is devoted to a detailed comparison of the results obtained using different measurement methods based on the minimum distance of point clouds. During the research, TLS technology, UAS photogrammetry using DJI Phantom 4 RTK UAS and DJI Matrice 30T UAS were used, and freely available data from Airborne Laser Scanning (ALS) was also downloaded for comparison. The rockslide in the area of the hiking trail occurred by 2.32 m, which is confirmed by the method based on determining the minimum distance of points.

Keywords: UAS, SfM photogrammetry, TLS, rockslide, geohazard, High Tatras

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Introduction

The alpine environment of the High Tatras is one of the most popular tourist destinations in Slovakia. One of the most popular place is Hrebienok, which serves as the gateway to the Tatra valleys and at the same time as the starting point for many hiking trails (Hrebienok, 2024). However, this sought-after location also faces challenges associated with the natural conditions of the alpine terrain. One of the serious problems that threatens the safety of tourists is the rockslide that occurred on the Tatranská magistrála hiking trail (Kovanič et al., 2020). This natural phenomenon reveals the vulnerability of the alpine environment to climate change and unpredictable geological processes (Kovanič et al., 2024; Nguyen et al., 2024). Such a disturbed area can be dangerous for tourists as there can be repeated uncontrollable movement of soil and rocks at any time, which can cause injuries in some situations (Rugg et al., 2020; Jovančević et al., 2016; Mavroulis et al., 2022). In response to the challenges associated with natural conditions and the danger of rockslides in the Hrebienok area, it is important to implement accurate and efficient modern geodetic technologies for monitoring and analyzing the terrain, which mainly include UAS photogrammetry, TLS, LiDAR (Light Detection And Ranging) and many others advanced mapping technologies (Chang et al., 2018). It is also not necessary to forget the chosen methodology of applying these technologies, which simultaneously determines the optimal process of analyzing the terrain.

UAS photogrammetry represents a fast and efficient technology for obtaining detailed aerial images and creating three-dimensional terrain models in a short time. Such a method of mapping the terrain from the air has the advantage of better access to hard-to-reach locations and is therefore considered an ideal tool for monitoring changes in the terrain and detecting potential risks of rockslides (Miřijovský et al., 2015; Yaprak et al., 2017). Surveying using UAS technology has been applied in various fields and disciplines such as mining (Park & Choi, 2020; Ćwiąkała et al., 2020), cadastre (Šafář et al., 2021; Fetai et al., 2019), industry (Ajayi et al., 2021; Kovanič et al., 2020), geology (Blišťan et al., 2016; Jacko et al., 2021), archaeology (Fiz et al., 2022; Schroder et al., 2021; Marčiš et al., 2023), architecture (Lin & Sang, 2022; Germanese et al., 2019), agriculture (Lambertini et al., 2022; Marín-Buzón et al., 2020) or for monitoring natural processes in the landscape such as slope stability (Migliazza et al., 2021; Junaid et al., 2022), geohazards (Kovanič et al., 2020; Urban et al., 2019) or landslides (Kyriou et al., 2021; Gantimurova et al., 2021). Another modern mapping method is TLS, which provides highly accurate and detailed 3D terrain models using laser scanners placed directly in the terrain. Scanning captures fine details and topographical features, which is key in assessing slope stability and identifying areas at risk of rockslides (Tyszkowski et al., 2023). The application of TLS is in the fields of structural design (Bariczová et al., 2021; Erdélyi et al., 2020), engineering and industry (Sofranko & Zeman, 2014; Wittenberger & Sofranko, 2015; Kovanič et al., 2020; Kovanič et al., 2023) or mapping (Pukanská et al., 2020). The most accurate and newest technology for mapping is currently LiDAR, which can be placed on a different carrier. It uses laser pulses to measure distances and create accurate 3D surface models.

This approach provides detailed information on elevation, topography and vegetation that is important in analyzing soil stability and predicting potential rockslides (Gomez et al., 2014; Darvasi et al., 2024; Albanwan et al., 2024). The implementation of these modern technologies enables effective monitoring and analysis of terrain, provides early warnings of potential dangers and supports decision-making in the planning and implementation of preventive measures. In this way, safety and security in risk areas are increased.

Procedures and techniques used in data collection and processing will be presented, as well as the results obtained from these measurements. The spatio-temporal development of this geohazard can be documented using geodetic and photogrammetric measurements. Using these methods, results will be obtained in the form of point clouds and 3D models – digital terrain model (DTM), digital surface model (DSM), which will provide a detailed structure of the mapped area and will serve as a basis for the restoration and repair of the part of the hiking trail where the landslide occurred. The basic stage of monitoring of this geohazard took place in November 2023, further monitoring will take place in at least two more stages in 2024.

Material and methods

Hrebienok is a popular tourist location located in the High Tatras in the north of Slovakia. Hrebienok is a tourist center located above Starý Smokovec at the foot of Slavkovský štít (Hrebienok, 2024; Hrebienok Center, 2024). The rockslide on the Tatranská magistrála hiking trail (Fig. 1) occurred as a result of its being washed away near the study area at an altitude of 1.285 m above sea level. The rockslide occurred on the thirteenth kilometer of this hiking trail in the section between Hrebienok and Rainerová cottage.

This hiking trail is located in an alpine environment with a high degree of nature protection, it is one of the most frequented and popular hiking routes, and its damage can threaten the safe movement of tourists, so we can mark it as a geohazard (Mrázik, 2019; Po tatranskej magistrále, 2024). The rockslide occurred approximately on a 10-meter-long section in hard-to-reach terrain.

Work on monitoring the hiking trail was carried out in the field according to the following procedure:

- Terrain reconnaissance.
- Surveying Ground Control Points (GCP) for photogrammetry and TLS.
- Photogrammetric measurement.
- TLS measurement.

Surveying equipment. GNSS rover Trimble R12i. Nowadays, thanks to GNSS technology, high-precision positioning anywhere on Earth is already available. Its simple real-time operation is widely used in surveying, mapping and other applications. The Trimble R12i (Fig. 2) is currently among the most powerful GNSS receivers in the world. Thanks to IMU Tilt technologies, there is no need to adjust the stake during measurement and stakeout, so it uses unlimited measurement with tilt. Other specific GNSS parameters of the Trimble R12i assembly are listed in Table 1 (Trimble R12i, 2024).

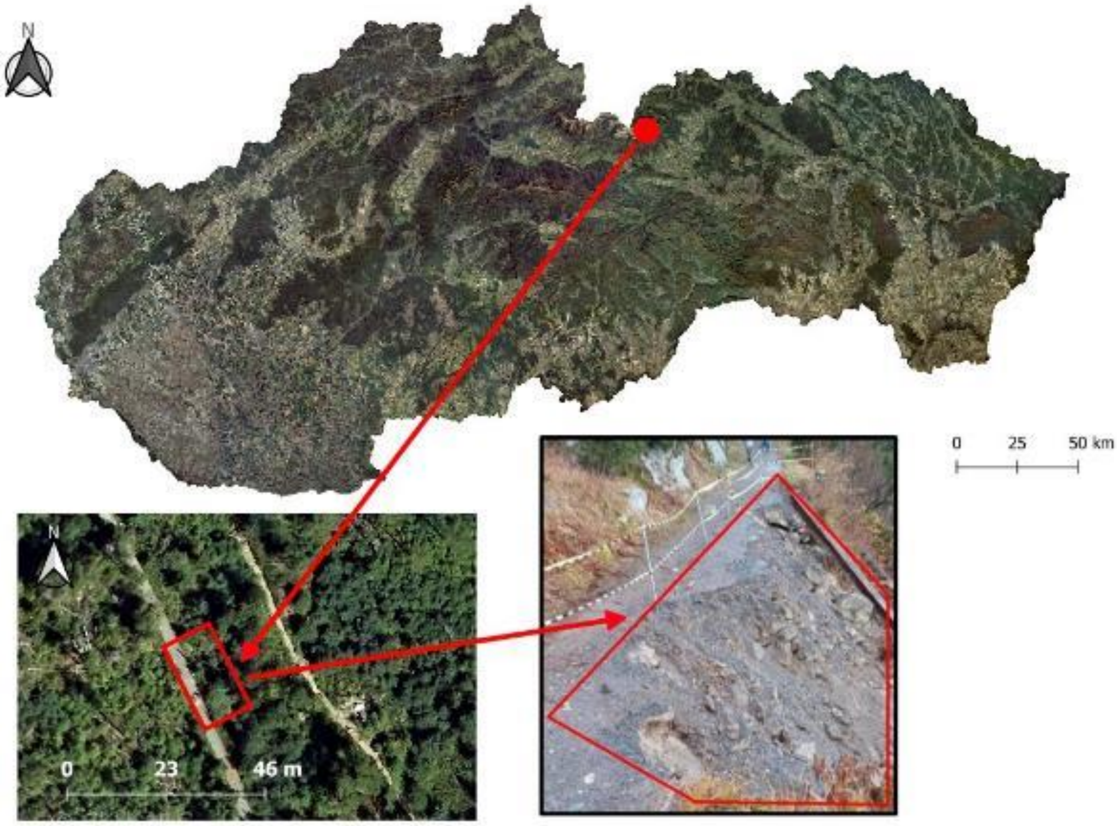

Fig. 1. The location of the rockslide of the Tatranská magistrála hiking trail in the study area Hrebienok
Source: Own elaboration

Fig. 2. GNSS rover Trimble R12i
Source: Own elaboration

Table 1. Specification of GNSS rover Trimble R12i

Technology	Trimble ProPoint GNSS technology	
Weight	3.95 kg	
Channels	672	
TIP Compensated Surveying	RTK + 5 mm + 0.4 mm/° tilt (up to 30°) RMS	
RTK surveying	Single baseline	Horizontal: 8 mm + 1 ppm
		Vertical: 15 mm + 1 ppm
	Network RTK	Horizontal: 8 mm + 0.5 ppm
		Vertical: 15 mm + 0.5 ppm
Static GNSS surveying	High-Precision Static	Horizontal: 3 mm + 0.1 ppm
		Vertical: 3.5 mm + 0.4 ppm
	Static and fast static	Horizontal: 3 mm + 0.5 ppm
		Vertical: 5 mm + 0.5 ppm

Source: Own elaboration based on: Trimble R12i, 2024

Surveying equipment. Terrestrial laser scanner Leica RTC 360. The Leica RTC360 laser scanner (Fig. 3) is a mobile, automated and efficient 3D laser scanner with a range of up to 130 m. It can reliably and accurately scan surroundings of instrument in a short time. As a result, a colored point cloud of millions of points is obtained. Automatic registration in the field using VIS technology is also a significant advance, reducing processing time. Specifications and technical parameters are shown in Table 2. During the measurement, the laser scanner is placed on a fixed-head carbon tripod consisting of three telescopic legs (Geotech s.r.o., 2023).

Fig. 3. Terrestrial laser scanner Leica RTC 360
Source: Own elaboration

A helpful feature is double scanning, enabling removing of moving objects, whether indoors or outdoors. An integrated large color touchscreen or tablet can be used to control the device in the field. The Leica Cyclone FIELD 360 app, designed to view and control the data acquired by the laser scanner, works quickly and easily. The practical application of the device is versatile, whether in industry, surveying, or the civil sector (Geotech s.r.o., 2023).

Table 2. Specifications and technical parameters of Terrestrial laser scanner Leica RTC360

<table>
<tr><td>Technology</td><td colspan="3">3D laser scanner with integrated system for capturing HDR panoramic images and VIS (Visual Inertial System) for real-time cloud data registration</td></tr>
<tr><td>Data acquisition</td><td colspan="3">< 2 minutes for full scan and HDR panoramic image at 6mm @ 10m scan resolution</td></tr>
<tr><td>Weight</td><td colspan="3">5.35 kg (without batteries)</td></tr>
<tr><td rowspan="2">Scanning</td><td colspan="2">Double scanning</td><td>Automatic removal of moving objects</td></tr>
<tr><td colspan="2">Scanning speed</td><td>2 000 000 points/sec</td></tr>
<tr><td rowspan="5">Accuracy</td><td>Angle</td><td colspan="2">18"</td></tr>
<tr><td>Distance</td><td colspan="2">1.0 mm + 10 ppm</td></tr>
<tr><td rowspan="3">3D point</td><td colspan="2">1.9 mm @ 10 m</td></tr>
<tr><td colspan="2">2.9 mm @ 20 m</td></tr>
<tr><td colspan="2">5.3 mm @ 40 m</td></tr>
<tr><td rowspan="3">Camera</td><td rowspan="2">Quality</td><td>36 MPx</td><td>3-camera system</td></tr>
<tr><td>432 MPx</td><td>Raw data for calibrated 360° x 300° panoramic image</td></tr>
<tr><td>Capturing speed</td><td colspan="2">1 minute for 360° HDR panoramic image in any lighting conditions</td></tr>
<tr><td>Range</td><td colspan="3">0.5 m – 130 m</td></tr>
<tr><td>Resilience</td><td colspan="3">IP54</td></tr>
<tr><td>Working temperature</td><td colspan="3">- 5°C až + 40°C</td></tr>
<tr><td>Storage temperature</td><td colspan="3">- 40°C až + 70°C</td></tr>
</table>

Source: Geotech s.r.o., 2023

Surveying equipment. UAS DJI Phantom 4 RTK. Thanks to modern and constantly evolving times, it is possible to collect large amounts of data even from the air in the required quality and in a short time interval. The DJI Phantom 4 RTK (Fig. 4) is a compact, precise, fast UAS operating at low altitudes. The DJI Phantom 4 RTK is controlled using a controller with an integrated display by the DJI GS RTK app. The device is controlled by a trained pilot safely on the ground. Using an integrated RTK module, this UAS provides centimetre accuracy in the flight. Precise coordinates are used in post-processing. At the bottom, a 20 MPx camera mounted on a gimbal captures images or video. Further specifications of the device can be seen in Table 3. With these features, the manufacturer provides a spatial resolution (GSD) of only 2.74 cm at a flight height of 100 m at high-resolution imaging. Combining RTK image files and proper georeferencing using the SfM processing method allows detailed three-dimensional (3D) models and point clouds to be reconstructed with centimetre-level accuracy (DJI, 2023).

Fig. 4. UAV DJI Phantom 4 RTK
Source: Own elaboration

Table 3. Technical parameters of UAS DJI Phantom 4 RTK

Aircraft	Weight	1391 g	
	Max. speed	Ascending	6 m/s
		Descending	3 m/s
		Flight	50 km/h (mode P) 58 km/h (mode A)
	Max. time of flight	cca 30 min	
Accuracy	active RTK	Horizontal	± 0.1 m
		Vertical	± 0.1 m
	Non-active RTK	Horizontal	± 0.3 m
		Vertical	± 0.1 m
Camera	Senzor	1" CMOS	
	Quality	20 MPx	
	Size of image	4864 × 3648 (4:3)	
	Angle	- 90° to + 30°	
GNSS	GPS, BeiDou, Galileo, GLONASS		
Batteries	Type	LiPo 2S	
	Kapacity	4920 mAh	
	Voltage	17.5 V	

Source: Own elaboration based on: DJI, 2023

Surveying equipment. UAS DJI Matrice 30T. The DJI Matrice 30 (Fig. 5) offers multiple high-performance sensors in one compact camera. Controlled is by an ingeniously designed remote control, and runs on the improved Pilot 2 software, which significantly improves the experience of flying and using the UAS. The 30T offers much more power, durability and capabilities for demanding professional use, while its size makes it easy to transport and set up quickly. The 30T integrates a 48-megapixel 1/2'' sensor CMOS zoom camera with 5x – 16x optical and 200x digital zoom and a 12-megapixel wide-angle camera. Selected technical parameters are listed in Table 4 (DJI Matrice 30T, 2024).

Fig. 5. UAS DJI Matrice 30T
Source: Own elaboration

Table 4. Technical parameters of UAS DJI Matrice 30T

Aircraft	Weight	3770 g	
	Max. speed	Ascending	6 m/s
		Descending	5 m/s
		Horizontal	23 m/s
	Max. Flight time	41 min	
Accuracy	active RTK	Horizontal	± 0.1 m
		Vertical	± 0.1 m
	Non-active RTK	Horizontal	± 0.3 m
		Vertical	± 0.1 m
Camera	Senzor	1/2" CMOS	
	Quality	48 MPx	
	Size of image	4000 × 3000 (4:3)	
	Angle	- 120° to + 45°	
GNSS	GPS, BeiDou, Galileo		
Batteries	Type	Li – ion 6S	
	Kapacity	5880 mAh	
	Voltage	26.1 V	

Source: Own elaboration based on: DJI Matrice 30T, 2024

Fieldwork. GCP for UAS photogrammetry. After reconnaissance of the terrain in the study area, 8 GCPs for photogrammetry were evenly distributed around the rockslide of the hiking trail. These GCPs were temporarily stabilized using black-and-white 12-bit targets, 0.3 × 0.3 m in size, marked on the sides with a red frame for better visibility in difficult terrain. Their type and location can be seen in Fig. 6. Thus, the GCPs uniformly placed throughout the area play an essential role in the survey, as they are used to georeference the point clouds to a reference coordinate system or check (CP) RTK/PPK georeferencing.

Fig. 6. GCP for UAS photogrammetry
Source: Own elaboration

Fieldwork. GCP for TLS surveying. GCPs for TLS in hiking trail monitoring were temporarily stabilized by black and white circular scanning targets (Fig. 7). At every second position, 3 GCPs (CPs) for TLS were placed around the scanner. Targets were subsequently scanned and used to connect the TLS measurement to a common coordinate system. In total, 84 scanning targets were used in the monitoring of the Tatranská magistrála hiking trail. GCPs for photogrammetry and TLS were determined by the fast static method using Trimble R12i GNSS set with TSC5 controller using RTN method with connection to SKPOS (Slovak RTN service). The estimated accuracy of determining the GCPs coordinates was 0.02 m in position and 0.04 m in height.

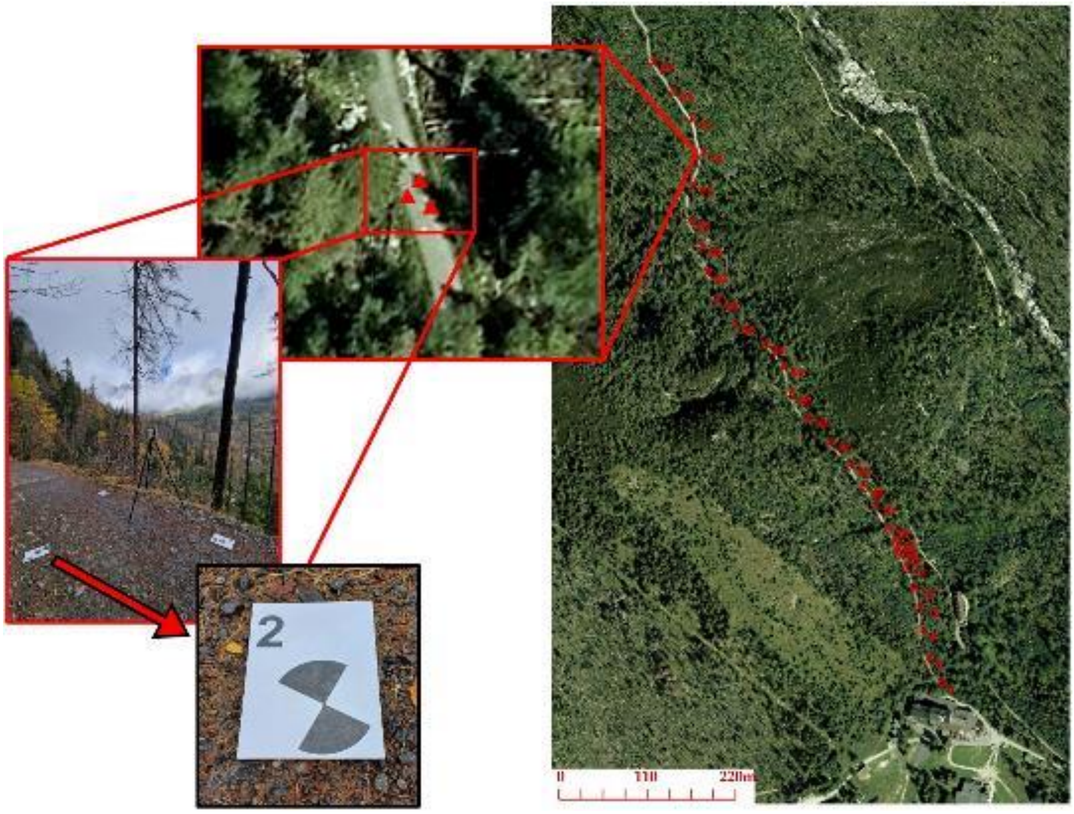

Fig. 7. GCP for TLS surveying
Source: Own elaboration

Fieldwork. UAS photogrammetric surveying. The hiking trail was measured using a DJI Phantom 4 RTK UAS with a 20Mpx CMOS sensor with a resolution of 5472 x 3648 pixels and set to automatic mode with a fixed ISO (100). The flight plan was controlled by the DJI GS RTK application, which allows it to maintain a constant height above terrain with different slopes or shapes. The flight trajectory was designed over a generalized DTM (source: ÚGKK SR by CC-BY 4.0) provided by Geoportal.sk (Geoportál, 2024). The entire process involved 8 separate flights with partial overlap, lasting approximately 2 hours and providing 975 images for further processing. A double-grid flight pattern was used for all flights, where the first flight line is perpendicular to the slope and second flight line is oriented in the direction of the slope.

The hiking trail was also surveyed by a UAS DJI Matrice 30T equipped with a 1/2" CMOS 48Mpx camera. A total of 6 flights were made, which were made based on a flight plan created using the DJI FlightHub 2 application, which is part of the integrated UAV controller. This application allows you to plan and manage a flight mission, while the Terrain Follow function is used to maintain a constant height above the terrain, based on a DTM. The first 2 flights were conducted based on a single-grid flight pattern, where the flight trajectory is in one direction only. Another 4 flights were carried out by measuring a line directly above the area of the hiking trail at a flight height of 90 m above ground level (AGL). A total of 687 images were obtained using the DJI Matrice 30T, and the flight parameters of the DJI Phantom 4 RTK UAS and the DJI Matrice 30T were shown in Table 5.

Table 5. Comparison of technical parameters used by UASs

	DJI Phantom 4 RTK UAS	UAS DJI Matrice 30T
Number of images	975	687
Number of GCP	8	8
Flight height [m]	63	90
GSD [cm/px]	2.00	3.19
Overlap of the image [%]	70	80
Pitch value of the gimbal [°]	80	90
Total flight time [h]	2	2

Source: Own elaboration

Fieldwork. TLS surveying. TLS measurement during rockslide monitoring of the hiking trail was carried out using a Leica RTC360 laser scanner. This method was used to monitor not only the site of the rockslide but also a significant part of the hiking trail in the section between Hrebienok and Rainerová cottage. The hiking trail was captured from 55 positions at a scanning resolution of 6 mm/10 m with a range of 130 m. Three temporary black and white circular scanning targets were scanned separately at every second station to serve as GCPs for the TLS method. The measurement with this method took approximately 3 hours.

Data processing. SfM Processing of UAS Photogrammetry. UAS photogrammetry and TLS methods were used to monitor the Tatranská magistrála hiking trail in the study area Hrebienok. Agisoft Metashape Professional software was used for processing data from photogrammetric measurements, and Leica Cyclone Register 360 software was used for TLS data processing. Data classification was performed in the Trimble Realworks 12.2. and Leica Cyclone 3DR software. The comparison of the resulting point clouds was performed in the CloudCompare 2.13 program and Leica Cyclone 3DR.

Photogrammetric data obtained using the DJI Phantom 4 RTK UAS were processed in Agisoft Metashape Professional 1.8.0 software using the standard SfM-MVS workflow. A total of 975 images were used in the processing, and after block aerotriangulation in high quality, a sparse point cloud was created, containing 704,208 points. The dense point cloud was generated in high quality with depth filtering set to mild. The generation of the dense point cloud took nearly 2 hours and resulted in 170,590,665 points. Additional parameters of the point cloud obtained using the DJI Phantom 4 RTK UAS are presented in Table 6.

The monitoring of the hiking trail was also conducted using the UAS DJI Matrice 30T, which captured 687 images. These images were subsequently processed in Agisoft Metashape Professional 1.8.0 software. After importing and after block aerotriangulation with high-quality setting, a sparse point cloud containing 666,589 points was generated. The dense point cloud with high quality and mild depth filtering was created in 10 minutes and contained 157,667,823 points. Detailed information about the point cloud obtained using the UAS DJI Matrice 30T is described in Table 6.

Table 6. Comparison of technical parameters used by UASs

	Point cloud from DJI Phantom 4 RTK UAS	Point cloud from UAS DJI Matrice 30T
The number of tie points	704,208	666,589
The number of points of a dense point cloud	170,590,665	157,667,823
Point density [points/m²]	622	303
Error in the X coordinate [mm]	10.1	34.4
Error in the Y coordinate [mm]	29.0	40.8
Error in the Z coordinate [mm]	24.6	40.8
RMSE on GCPs [mm]	39.3	67.2

Source: Own elaboration

Data processing. TLS data processing. Using the Leica RTC360 laser scanner, 55 positions were used to scan the hiking trail in the study area Hrebienok. Data were processed in the Leica Cyclone Register 360 software. Point clouds from individual scans were registered and georeferenced based on mutual overlap and 84 GCPs (CPs). The resulting dense point cloud consisted of 1,120,382,469 points. The average root mean square error (RMSE) of scan registration reaches value of 0.012 m, the Bundle error accuracy was 0.015 m, and the Cloud to Cloud value was 0.015 m. The total overlap of the point clouds was 58%, and the strength of the final point cloud reached 45%. Data classification was carried out using Trimble Realworks 12.2 and Leica Cyclone 3DR.

Results and discussion

This section focuses on a detailed comparison of the results obtained using various measurement methods based on the minimum distance of point clouds and cross-sections. During the research, TLS technology, UAS photogrammetry using DJI Phantom 4 RTK UAS, and UAS DJI Matrice 30T were used. Available data from ALS (source: ÚGKK SR by CC-BY 4.0) (Geoportal, 2024) were also used for comparison. The resulting point cloud (Fig. 8), trimmed to the area of the specific rockslide obtained by the TLS method, contained 19,891,783 points, the DJI Phantom 4 RTK UAS point cloud consisted of 655,984 points, UAS DJI Matrice 30T point cloud 307,172 points, and ALS point cloud 9,826 points.

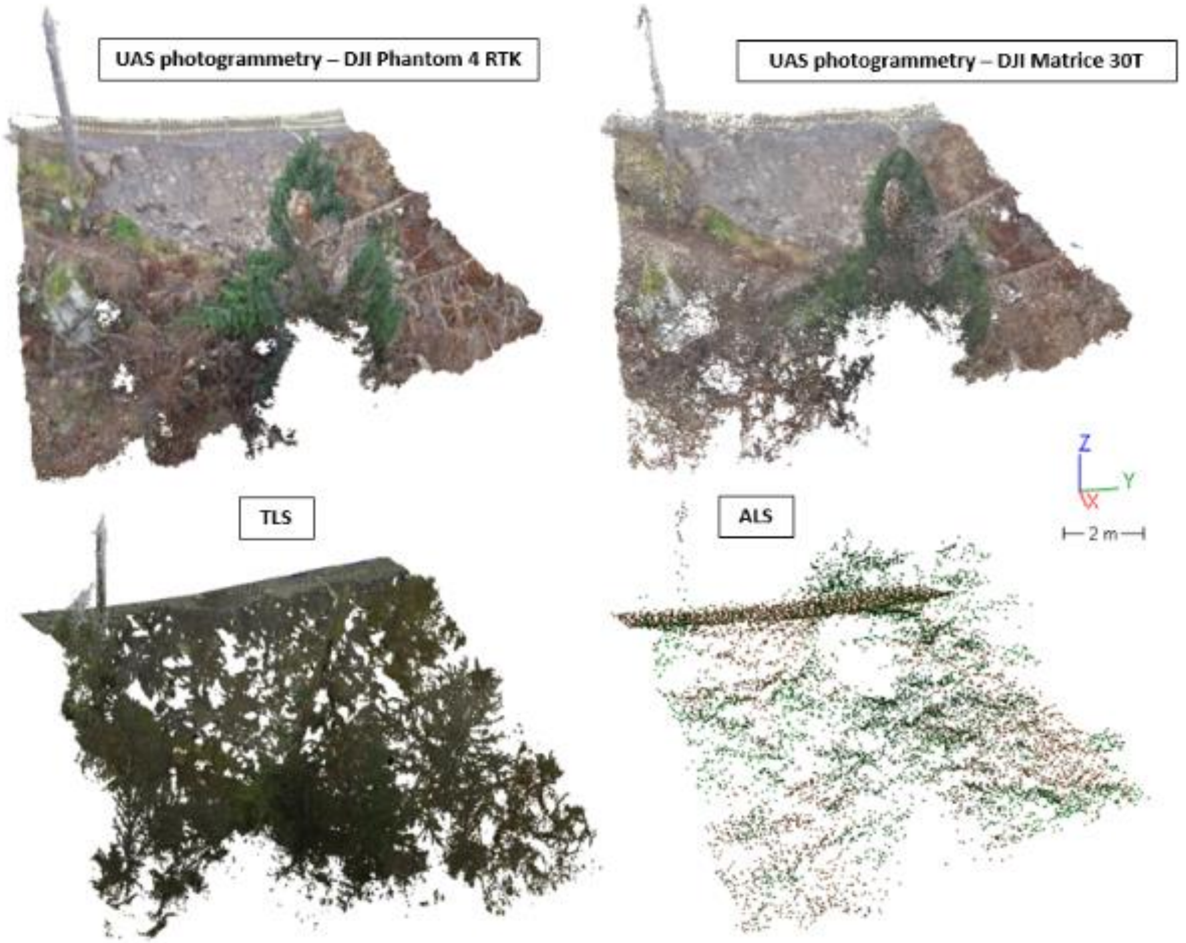

Fig. 8. Point clouds obtained by UAS photogrammetry, ALS and TLS
Source: Own elaboration

The resulting point clouds were then classified to remove vegetation, noise and unnecessary points. The classified cloud of points can be seen in Fig. 9. In Table 7 clearly shows the values of individual point clouds. Only the classification class Ground was included in the next comparison.

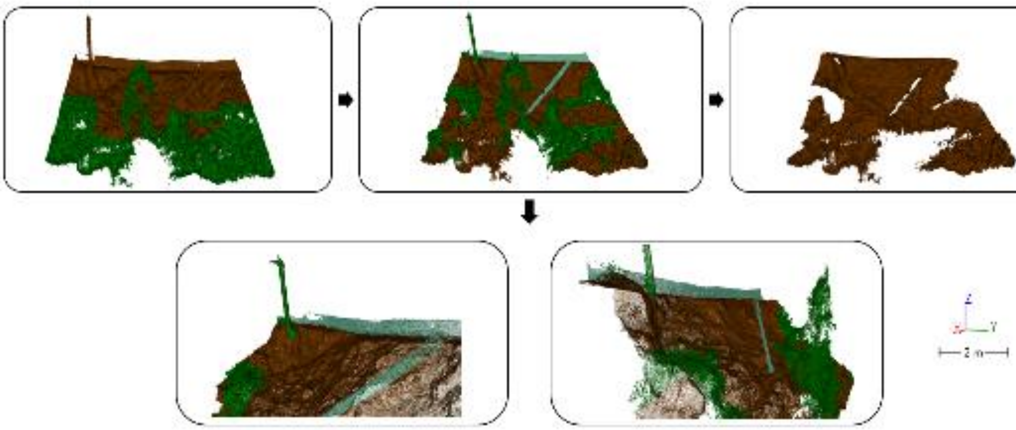

Fig. 9. Classified point cloud of the Tatranská magistrála hiking trail
Source: Own elaboration

Table 7. Parameters of classified point clouds

	DJI Phantom 4 RTK UAS	UAS DJI Matrice 30T	TLS	ALS
The number of points	655,984	307,172	19,891,783	9,826
The number of points of the Ground class	416,704	175,248	8,194,340	5,057
Point density [points/m^2]	2,925	1,334	190,155	95

Source: Own elaboration

Figure 10 shows minimum distance between points between two UAS carriers that mapped terrain using the UAS photogrammetry method. Only part of the territory with an area of 110 m^2 from the entire mapped location was analyzed. This part represents the most important and suitable place because it was affected by the rockslide. In this comparison, the resulting point clouds from both UAS were analyzed based on the minimum distance between points that was limited to 10 cm. The largest representation of points was represented by points up to a distance of 1.3 cm (25.7%), which are marked in blue. In total, the fewest points were in the range of 8.7 cm – 10 cm (2.9%). The total number of points that were compared in these methods is 66,208. Figure 11 shows the statistical analysis of the comparison of both UAS carriers based on the minimum distance. In this analysis, the average distance between points was determined to be 3 cm. A standard deviation of 2 cm was also determined.

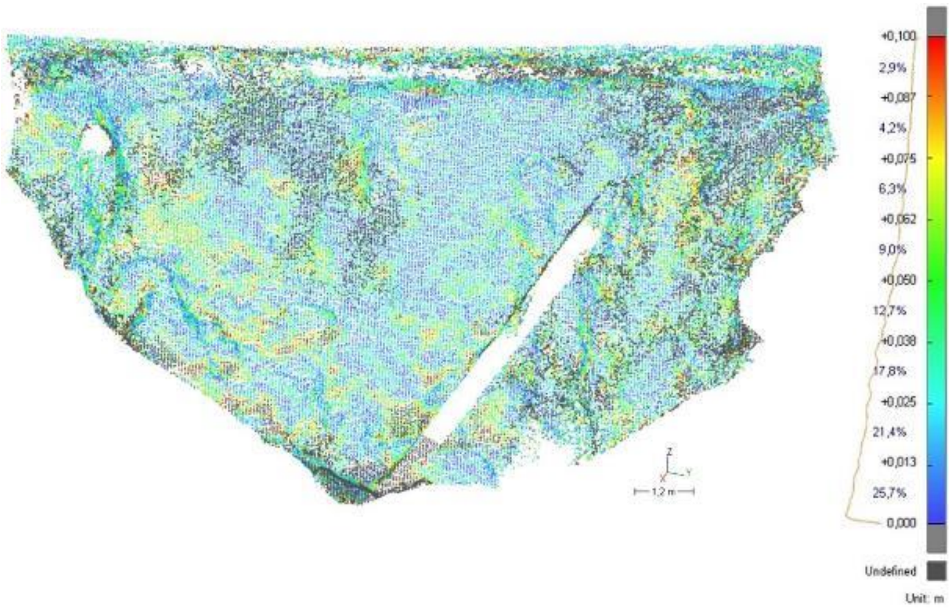

Fig. 10. Comparison of the UAS photogrammetry DJI Phantom 4 RTK and UAS photogrammetry DJI Matrice 30T
Source: Own elaboration

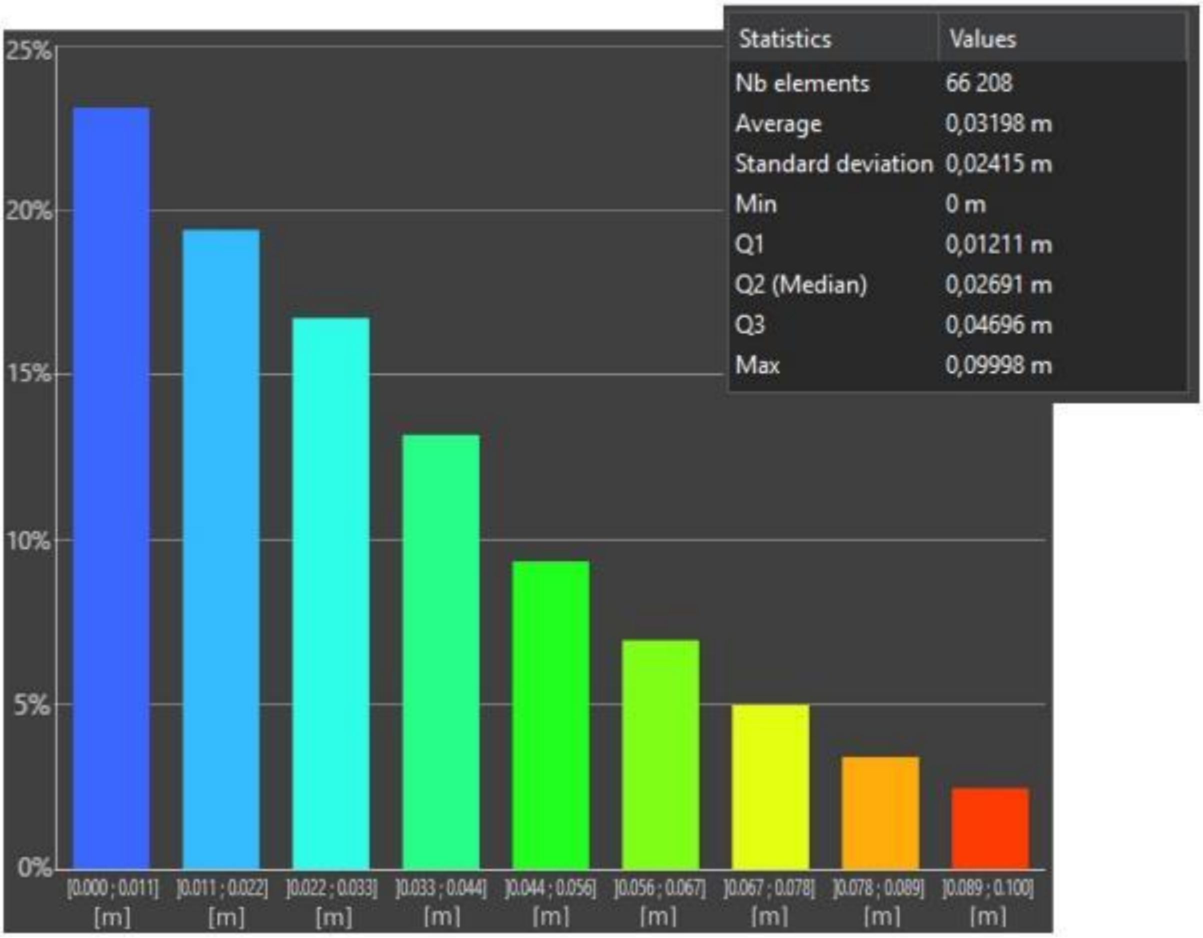

Fig. 11. Statistical analysis of the comparison of the UAS photogrammetry DJI Phantom 4 RTK and UAS photogrammetry DJI Matrice 30T
Source: Own elaboration

In further analyses, we considered UAS photogrammetry using the DJI Phantom 4 RTK as a reference method because, while the DJI Phantom 4 RTK UAS is directly intended for photogrammetric mapping of the landscape, the DJI Matrice 30T UAS is more intended for search operations in difficult terrain. Figure 12 illustrates the comparison between UAS photogrammetry from DJI Phantom 4 RTK and TLS, conducted after the rockslide, where the largest deviations occur in areas with insufficient point overlap. The average distance between the points was 0.8 cm, the standard deviation reached the value of 0.5 cm and maximum distance was 2 cm (Fig. 13).

In the last case, the comparison point cloud was from ALS. The ALS point cloud was obtained before the rockslide of the hiking trail, so based on this comparison, we can say that the rockslide in the upper parts of the trail reached a value of up to 2.32 meters, as shown in Fig. 14.

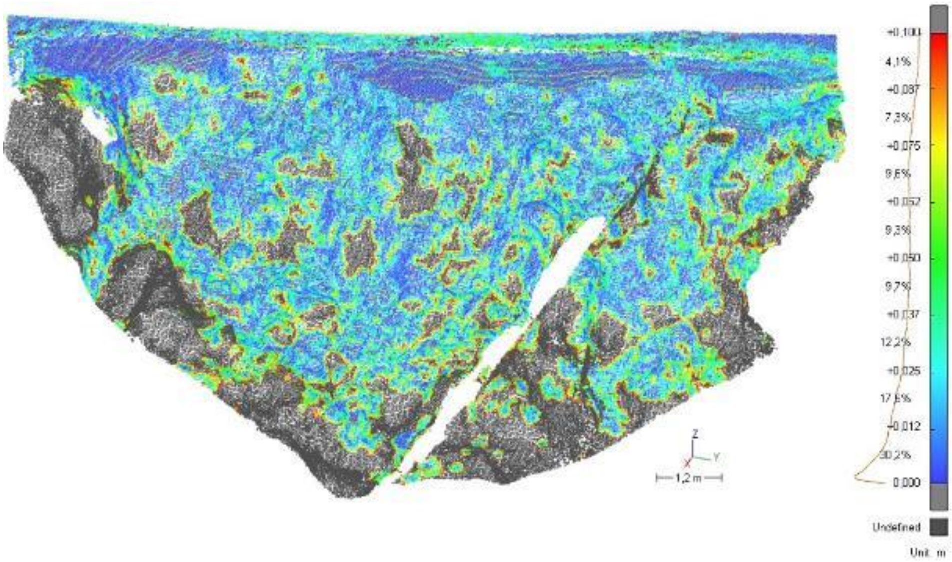

Fig. 12. Comparison of the UAS photogrammetry DJI Phantom 4 RTK and TLS point clouds
Source: Own elaboration

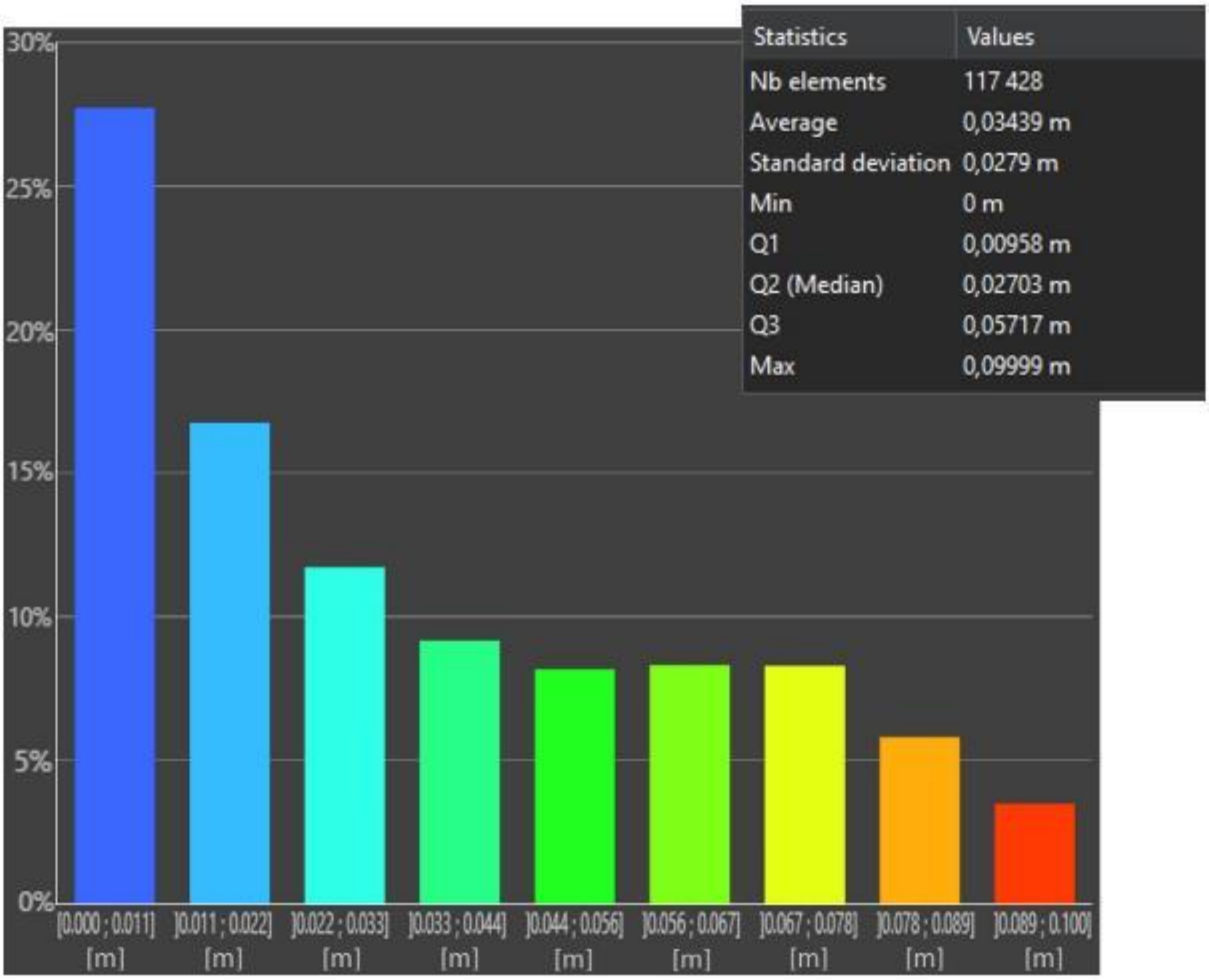

Fig. 13. Statistical analysis of the comparison of the UAS photogrammetry DJI Phantom 4 RTK and TLS point clouds
Source: Own elaboration

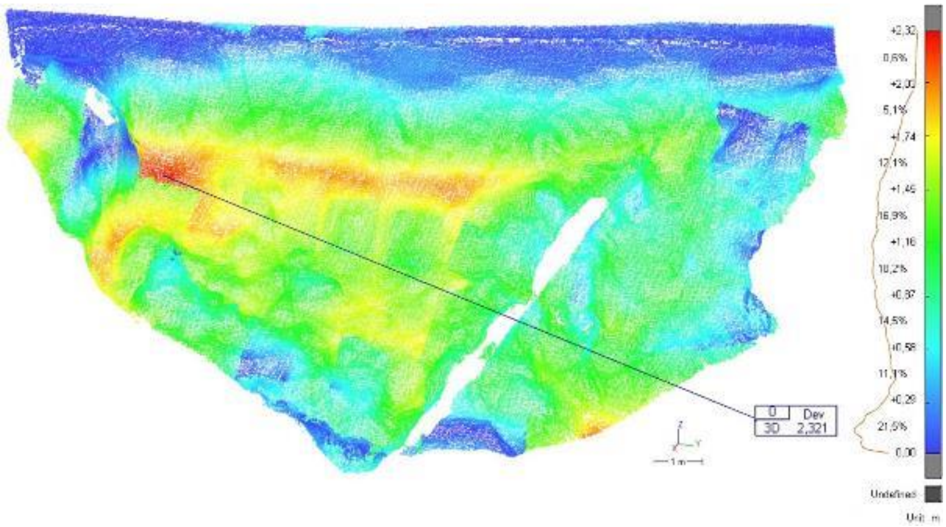

Fig. 14. Comparison of maximum distance of UAS photogrammetry (current terrain) and ALS point cloud (original terrain)
Source: Own elaboration

Conclusions

Based on our results, it is appropriate to state that the point cloud parameters obtained by photogrammetric methods are qualitatively and accurately comparable to the point cloud parameters obtained by terrestrial laser scanning. Both methods are thus considered suitable and can be used as a basis for systematic monitoring of such natural objects. However, the photogrammetric method is preferable due to the ease of data acquisition, flexibility and quick use, cheap acquisition and equipment cost, and high point cloud density. Combining TLS and photogrammetric measurements can be considered mutually compatible and recommended as a suitable solution for documenting spatial objects. The presented results of this research contribute to a better understanding of the dynamics of alpine geohazards and provide valuable tools and methodologies for their monitoring. The application of modern technologies, such as TLS, ALS, and UAS photogrammetry, demonstrates high potential in the field of environmental monitoring and risk management.

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