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PLENARY PAPER
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High-Precision Landslide Monitoring Using Laser Scanning Technology

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Abstract Landslides represent geological phenomena that pose significant threats to infrastructure safety. In response to the need for more advanced monitoring techniques in terms of accuracy and reliability of spatial data, this paper undertakes an examination of recent advancements in geodetic technologies, specifically focusing on the application of state-of-the-art laser scanning (LS) techniques. This article deals with laser scanning techniques capable of providing a high-quality point cloud necessary for more advanced landslide analysis. Paper explores Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS) and Unmanned Aerial Vehicles Laser Scanning (UAVLS), emphasizing their potential in achieving optimal quality of spatial data for landslide analysis.

Recent developments in LS technologies have improved the field of geodetic monitoring, enabling surveyors to measure detailed three-dimensional data with high accuracy and in the same time with high spatial resolution and low data noise. TLS, conducted from ground-based stations, MLS from ground moving vehicles and UAVLS provide complementary perspectives, facilitating a better understanding of landslide dynamics.

The approach employed in rockfall monitoring using LS techniques is multifaceted. The paper underscores the significance of achieving millimetre-level precision of a single point and in the same time high spatial resolution and low data noise typical for LS. Data processing techniques include advanced point cloud registration, georeferencing, 3D modelling and analysis,

The application of laser scanning is demonstrated through two case studies. The first involves a seven-year monitoring campaign of a rocky slope near Ljig, Serbia, utilizing TLS technology. This method ensures precise and detailed three-dimensional surveying for a reliable assessment of rockfall dynamics. In the second case study, erosion monitoring at Devils' Town in southern Serbia employs an approach integrating TLS and UAV photogrammetry. This strategy provides overall and targeted insights into erosional processes, showcasing the versatility of 3D surveying in terrain monitoring.

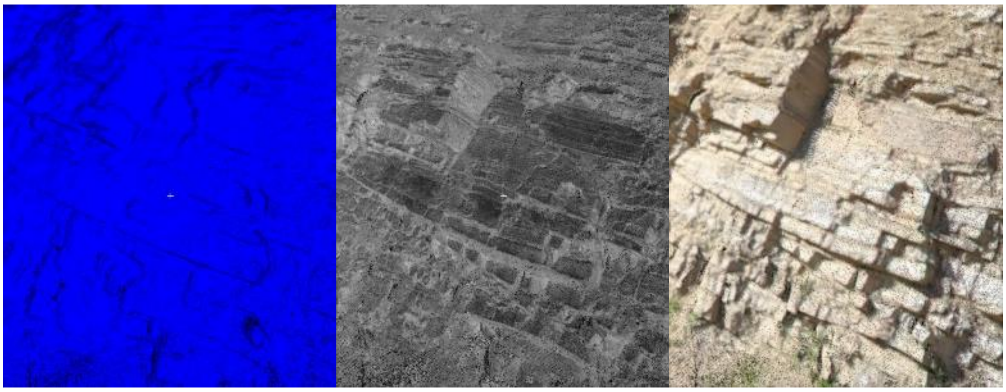
Keywords Landslide Monitoring, Geodetic Techniques, Laser Scanning (LS), Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), Unmanned Aerial Vehicles Laser Scanning (UAVLS), Rockfall Dynamics.

Introduction

Enhancing the functional characteristics of laser scanners and developing corresponding software algorithms have created the essential prerequisites to meet two basic quality requirements within a comprehensive process of measurement and data processing. The first requirement pertains to point accuracy from the measurement sample, representing the positional accuracy of each point in the measurement sample commonly referred to as a point cloud. The second requirement concerns the ability to interpret the recorded object as a whole, often associated with the spatial resolution of the point cloud. In the context of LS technology, both requirements are largely satisfied, marking a significant improvement in overall data quality compared to traditional geodetic observation methods (Pejić, 2022).

The optimal surveying method in geotechnics should be applied in accordance with the characteristics and composition of the object being surveyed, considering the dynamics of potential movements. When it comes to landslides as objects of geodetic measurement, optimal geodetic methods are often those offering greater potential for territorial coverage in a short time, consequently resulting in higher spatial uncertainty. This primarily pertains to landslides such as debris flow, mudflow, earthflow, etc. Geodetic methods like aerial photogrammetry, satellite imagery, and similar approaches can be employed in such cases. However, high-precision laser scanning technology, primarily utilizing TLS, finds its place for rocky formations that require geotechnical analysis of scanned rock surfaces and rockfall monitoring (Abellán at all). Therefore, this study will focus on objects of that specific nature. The primary objective of geodesy in rock formation surveying and monitoring is to provide geometric information essential for subsequent geotechnical analyses.

LS devices conduct measurements with a certain measurement uncertainty, and the scanned data is three-dimensional (3D), referred to as a point cloud (Figure 1a.). An additional attribute, in the form of return intensity for each point, can be associated with the point cloud (Figure 1b). This intensity value mostly depends on the object's reflectivity and such attribute is part of the laser measurement system. In practice, it is common for each scanned point to be associated with RGB (Red Green Blue) values based on an integrated CCD (Charged Coupled Device) sensor and corresponding optics, which can be integral or external component of LS instrument (Figure 1c) (Pejić, 2022).



a b c

Figure 1 Point cloud. Lacking additional attributes (a.), accompanied by the attribute of backscattered radiation intensity (b.), and incorporating the attribute of RGB values (c.).

Considering that light travels at an almost constant speed through a medium, the distance can be determined based on the time it takes for light to return to the detector. These systems are known as Time of Flight (TOF) systems. TOF measurements can also be achieved indirectly through phase measurements of continuous waves by amplitude modulation of the continuous wave (AMCW – Amplitude-Modulated Continuous Wave) or frequency modulation of the continuous wave (FMCW – Frequency-Modulated Continuous Wave).

The triangulation method involves forming a triangle using two known angles (exit and entrance) and a constant baseline, from which the distance to the object can be determined. The range and accuracy of LS largely depend on the methodology of distance determination. The triangulation method is used for very close distances, the phase measurement methods for measurements from close to medium distances, and the pulsed TOF measurement method for medium to large distances. Figure 2 illustrates the uncertainty and working range of laser rangefinders in LS systems, classifying them based on their application areas.

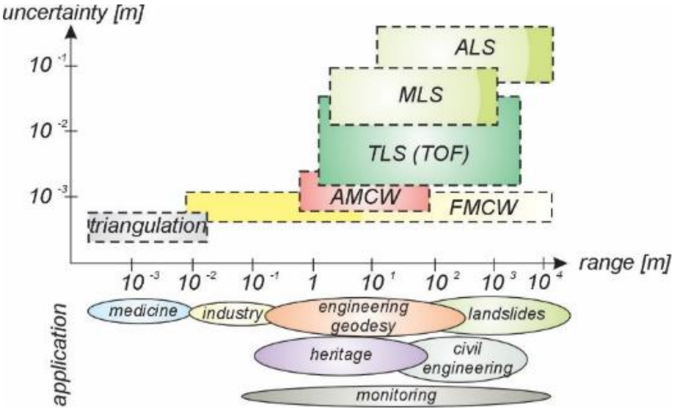


Figure 2 Distance determination, application, working range, and uncertainty of LS systems (after Schulz, 2007)

When it comes to LS technology, it is important to mention that this term can include devices that are stationary (TLS) or placed on mobile platforms such are MLS and ALS (airborne LS) devices. As these instrument moves during measurements, the system must have additional devices which define the positions and inclinations of the instrument in real-time. However, due to the fact that the instrument is on an unstable platform, despite the use of complex sensors, the quality of scanning data with respect to positional accuracy and data noise is typically lower for such instruments. These instruments are usually oriented towards applications where positional accuracy is not the primary priority.

A Mobile Laser Scanning (MLS) system integrates a laser scanner unit for three-dimensional point cloud acquisition, Global Navigation Satellite System (GNSS) for precise positioning, an Inertial Measurement Unit (IMU) to sense and record angular rate and acceleration, cameras for synchronized high-resolution imaging, a dedicated data storage and processing unit to manage acquired data, a reliable power supply for uninterrupted operation, a control and navigation system for overall system management, and communication Interfaces to facilitate data transfer and system control. The synchronized integration of these components enables MLS systems to dynamically acquire precise geospatial information during motion, making them essential for applications such as topographic mapping and geohazard assessment (Singh at all, 2021). MLS are often mounted on a vehicle moving along roads or terrain.

Unmanned Aerial Vehicle (UAV) mapping, a rapidly advancing field in geospatial sciences, involves the use of drones equipped with remote sensing instruments to capture data for mapping applications. These drones, acting as aerial platforms, carry a variety of sensors such as RGB or multispectral cameras or LiDAR scanners, GNSS and IMU. The workflow includes planning, data acquisition, and post-processing, resulting in data essential for environmental monitoring. Very recent technological developments have enabled UAV to integrate laser scanners, achieving flight durations and measurement precision suitable for engineering applications (Liu at all, 2019.)

The accuracy and reliability of data acquired by MLS or UAVLS is still far from the level achieved by TLS. Nevertheless, the spatial coverage that can be scanned in a short time is very large (Guisado-Pintado at all, 2019.). Additionally, inaccessible areas for humans are not a challenge especially for UAV systems.

Laser Scanning Method in Geodetic Engineering

Surveying measurements, such as tachymetry, GNSS, photogrammetry, and precise leveling, have traditionally been widely used in engineering. Precise leveling is extensively employed for height transfers and will not be further discussed in the context of LS.

In engineering applications, tachymetry, photogrammetry, and GNSS can be considered compatible methods compared to LS. These methods can provide 3D data of complex objects. Additionally, radar interferometry holds a significant place in modern engineering geodesy for determining digital elevation models, scanning, or deformation monitoring at large distances from the observed object (Zogg, 2008).

Tachymetry is a polar method for determining the 3D coordinates of a predefined point on an object using a total station (TS). Measurement accuracy is typically high only when targeting a standard prism, while measurement frequency is low. The range of TS in engineering varies from a few centimeters to several hundred meters. Tachymetry enables transferring and marking the horizontal and vertical positions of points on the ground (staking out).

GNSS measurements in geodesy provide 3D position, time, and receiver movement speed as results. In engineering, selected points on the object are measured using this method, along with vectors between two or more receivers in relative positioning procedures.

Photogrammetry is a method that determines the position of points on an object based on one or more images. It is an indirect measurement method, where data on the radiation intensity of the object are collected using a passive sensor (CCD camera), usually in the visible part of the spectrum. The fundamental data is the pixel, and the record is a digital image. Typical accuracy ranges from less than one millimetre to several decimetres, with a range from several centimetres to several hundred meters (Zogg, 2008). A photogrammetric camera can be stationary or mounted on a moving platform. Given that the image acquisition occurs within a brief exposure period, the geometric reconstruction of pixel positions in space may obviate the need for camera integration with inertial and positional systems. This characteristic renders photogrammetry a cost-effective.

Terrestrial radar interferometry (ground-based interferometric synthetic aperture radar – GB-InSAR) is a modern polar measurement method based on radar technology. It measures distance based on electromagnetic waves in the microwave part of the spectrum. Measurements are realized on a grid or profile by linear movement of the radar interferometer along a track and/or rotation around the vertical axis. It is applied in terrain deformation monitoring. Temporal resolution is measured in minutes, making this method suitable for early warning systems. The range is up to several kilometres, with submillimetre-level precision. Terrestrial radar interferometry effectively detects surface changes related to mass movement, detecting slow and fast displacements in rock walls, and assessing qualitatively fast and episodic processes like rockfall (Caduff at all, 2015). The drawback of radar interferometry is relatively poor spatial resolution compared to LS systems. The spaceborne aspect of InSAR involves the deployment of radar-equipped satellites in orbit around the Earth. These satellites emit radar signals towards the Earth's surface, and the signals are reflected back to the satellite's antenna.

The LS method does not completely belong to polar measurement methods, photogrammetric methods, or any other method. It can be considered a distinct method of geodetic measurement, and LS represents a specialized discipline within geodetic surveying.

Photogrammetry and laser scanning share common characteristics in terms of high detail (density) of collected geometric data and additional information about the intensity of the reflected radiation. If the reflection intensity is a result of the object's own reflectivity, it can be a parameter in content classification processes. Often, an RGB value can be assigned to a scanned point for easier interpretation of content. This information is collected by a digital camera, which is an integrated or additional part of most TLS devices, although it is not inherently part of LS technology. This visual information is usually not accessed for measurement purposes, primarily serving visual interpretation of point clouds.

The basic principle of determining coordinates using TLS technology does not differ from the principle that has been used in geodesy for a long time thanks to classical instruments. TLS instrument has a similar technical solution to total station instrument, regarding certain components, such as the main instrumental axes, collimation, compensators, etc. Coordinates are determined using a polar geodetic method, with the measurement of the slope distance, horizontal and vertical direction of individual points on the object.

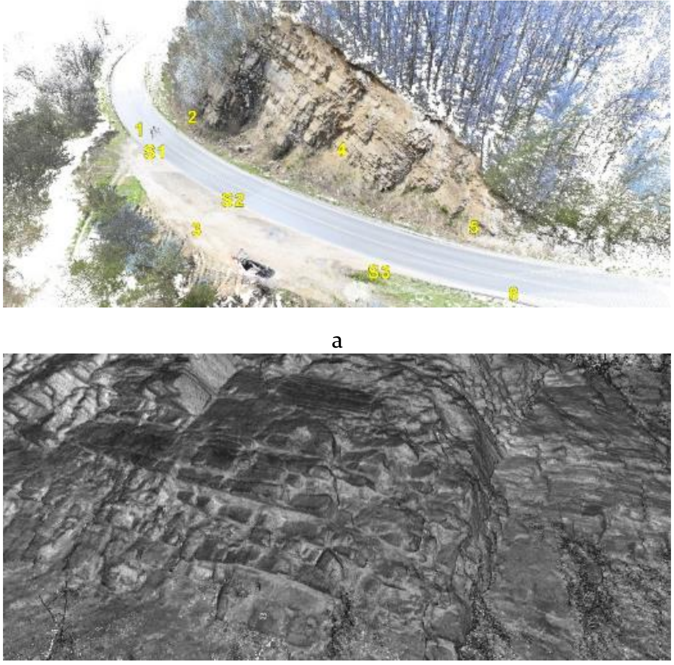
LS, photogrammetry, and radar interferometry represent post-processing methods, meaning measurement results must be processed and interpreted after measurement realization. These methods are also called indirect methods, unlike direct methods such as tachymetry or GNSS, which can provide real-time results without the obligatory need for post-data processing. Direct measurement methods enable surveying procedures such is staking out. (Zogg, 2008).

LS in precise landslide monitoring and analysis - examples

In this section, the practical value of laser scanning data in geotechnical analyses of landslides will be demonstrated. Special emphasis will be placed on techniques capable of providing high-reliability data for geometric interpretation. This is particularly crucial when observing rocky structures adjacent to infrastructure elements, as their stability often demands thorough analysis and monitoring.

Rock slope Ljig monitoring and analysis

LS monitoring systems, particularly TLS, can be employed to observe suspicious rock faces over extended periods, either seasonally, annually, or even daily. This approach yields systematic data that enhances comprehension of the prefailure and failure stages and facilitates the correlation of these stages with triggering conditions. The research focuses on these precursory indicators, advocating for the standardization of monitoring parameters in rockfall management. While this study presents a singular example of isolated rockfall, entire rock slope will be analysed in greater depth in the near future (Marjanovic et al, 2021).



a

b

Figure 3 TLS point cloud of experimental site. a: S1, S2 and S3 represent scanner station. Objects 1 to 6 represents scanning targets (a). Detail of a rock slope with an associated attribute of radiation intensity value

The site of interest is located along IB22 highway, a corridor with high traffic frequency near Ljig in Serbia (44° 12′ 02′′ N; 20° 14′ 35′′ E), featuring a height of 30 m and a length of 60 m, with an approximate 60° slope (Figure 3). Originally engineered as a road cut, the exposed rock face has undergone significant deformations. Despite its relatively active slope, the insignificant rockfall volume and runout led to the slope being left unprotected.

Comprising a flysch complex dominated by brittle sandstone banks and marly-shales, the slope poses stability concerns. Over seven years of TLS monitoring (from 2013. to 2019.) source areas are identified, but runouts were unrecorded due to swift clean-ups by the Public Enterprise Roads of Serbia. Back-analysis involved comparing TLS scanning epochs, determining block size, and assessing rock properties. Results indicate one source area as potentially critical, with trajectories reaching the road. Calculations show manageable energies and forces, suggesting feasible remediation measures. Rock bouncing and fragmentation effects are mitigated by the slope's characteristics (Marjanovic et al, 2021).

The primary acquisition technique involves the Leica Scan Station P20, a TOF TLS scanner with a laser beam width of 2.6 mm and a single-point 3D uncertainty of up to 3 mm/50 m. It collects points within a range up to 100-120 m, providing 3D coordinates and intensity values (I) for each point. Colour information is obtained either from the internal scanner camera or external high-definition camera for enhanced results.

The initial years of rockslope monitoring were experimental, marked by irregular and less systematic data acquisition. This experience aided in optimizing the long-term TLS observation procedure. The main goal was to ensure nearly identical measurement conditions and establish a standard procedure, determining spatial and temporal resolution, timing, and other crucial acquisition parameters. Procedures are standardized with an annual frequency. The optimal acquisition time is early spring on a cloudy but dry day for consistent lighting and minimal vegetation interference. Three scanning stations are used for near-full data coverage, with 5-8 evenly distributed scanner targets for reliable registration. Scanning parameters are set for a spatial resolution of at least 3 cm over the entire rock face. Additionally, a full 360°/270° field of view enables reliable cloud-to-cloud data registration. (Marjanovic et al, 2021).

The georeferencing of registered point clouds from all epochs is performed using surface matching algorithms, with the reference epoch being 2013. The standard deviation of the coordinate transformation in registration and georeferencing procedures is up to 3 mm. Leica Cyclone software is used for data processing, segmentation, and point cloud resolution unifying. The CloudCompare software plug-in CANUPO classifier eliminates remaining vegetation points for each epoch. Deformation analysis involves calculating cloud-to-cloud differences between successive scanning epochs and the "zero-2013" point cloud.

Over the period from 2013 to 2019, a total of seven scanning epochs were performed and analysed in accordance with the described procedure.

The Figure 4 shows an example illustrating the quantities and locations of rockfalls between spring 2013 and 2016. The analysis was conducted using Leica Cyclone 3DR software.

For a more comprehensive geotechnical analysis of landslides and the cause-and-effect mechanisms, refer to (Marjanovic et al, 2021).

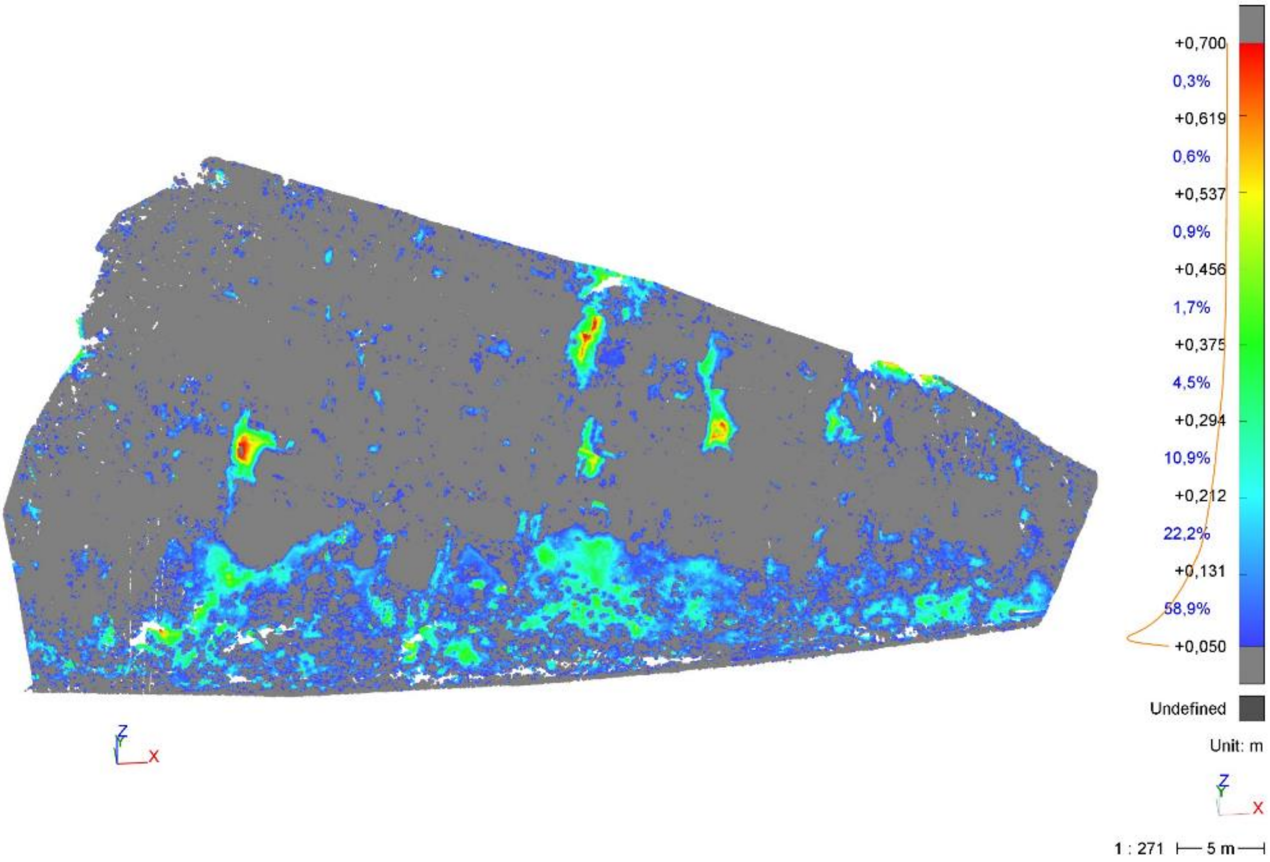


Figure 4 Example Cloud-to-cloud difference computed using Leica Cyclone 3DR software. Epoch 2016-2013.

Devils' town erosion monitoring

The erosion monitoring focuses on Devils' Town, a unique natural site in southern Serbia, shaped by water and wind over millennia. It is a UNESCO-listed protected heritage site managed by Planinka, the Municipality of Kuršumlija, and the Institute for Nature Conservation of Serbia. Increased human interest and activity on the site have led to observed erosional changes in the pillars, highlighting the need for a comprehensive understanding.

The Devils' Town site is part of the larger Lece volcanic complex in southern Serbia, spanning about 700 km². Formed over millions of years, this extensive stratovolcano experienced both violent and peaceful eruptions, leaving geological evidence of calderas and volcanic activity. The area, now featuring hot springs like Prolom Spa, Kuršumlija Spa, and Sijarinjska Spa, showcases the aftermath of extensive volcanic history. Erosional processes have obscured the once-visible calderas, but the geological legacy persists. Notably, violent eruptions produced lahars and pyroclastic flows, crucial for understanding the authenticity of the Devils' Town site.

The project titled DEMONITOR, which specifically deals with the erosion of these rocky formations, has been approved as a three-year grant by the Ministry of Science of the Republic of Serbia. It utilizes advanced surveying methods such as TLS, UAV photogrammetry and satellite InSAR, as well as geophysical techniques, to quantify erosion dynamics, rockfall occurrences, weathering rates, and ground subsidence. Building on a successful 1-year pilot, the project aims to not only depict changes but predict rates and trends, facilitating the design of preventive measures for the permanent conservation of the site.

Figure 5 A point cloud generated through UAV photogrammetry at the Devils' Town site. Epoch 2017-2018.

The complex interplay of erosional processes and volcanic rock has yielded a diverse array of noteworthy landforms, colloquially termed "the Devils" and scientifically acknowledged as the "badlands" (Figure 5). The host rock represents a vestige of an ancient pyroclastic flow, characterized by loose and friable material prone to erosion. Over extended periods of time, the cumulative effects of weathering and erosion have intricately carved nearly 200 pillar-like structures, reaching heights of up to 15 meters and diameters spanning 6 meters.

During the pilot monitoring project, two measurement epochs were conducted in the autumns of 2017 and 2018. Data for the broader area of the Devils' Town site were collected using UAV photogrammetry, providing an overview of the general terrain morphology beyond the pillar-like forms. For a detailed analysis of the erosion of the figures themselves, TLS data were utilized. Measurements were performed using the Leica ScanStation P20 scanner, based on a pre-defined surveying methodology. The objective was to optimize all measurement parameters to ensure the necessary resolution, measurement uncertainty, and a consistent coordinate system for all future measurements. The achieved accuracy of the point cloud is within a few millimetres in absolute terms for TLS and in the order of centimetres for the photogrammetric method.

The pivotal outcomes of the aforementioned pilot project indicate ability to identify annual changes specifically between 2017 and 2018, quantifying and illustrating them (see Fig. 6). The annual change rate is concerning, encompassing detached small rock fragments from the pillar bodies and incisions at their bases caused by linear erosion (red areas indicate changes > 14 cm). Some preliminary findings have been partially published in Đurić et al, 2018.

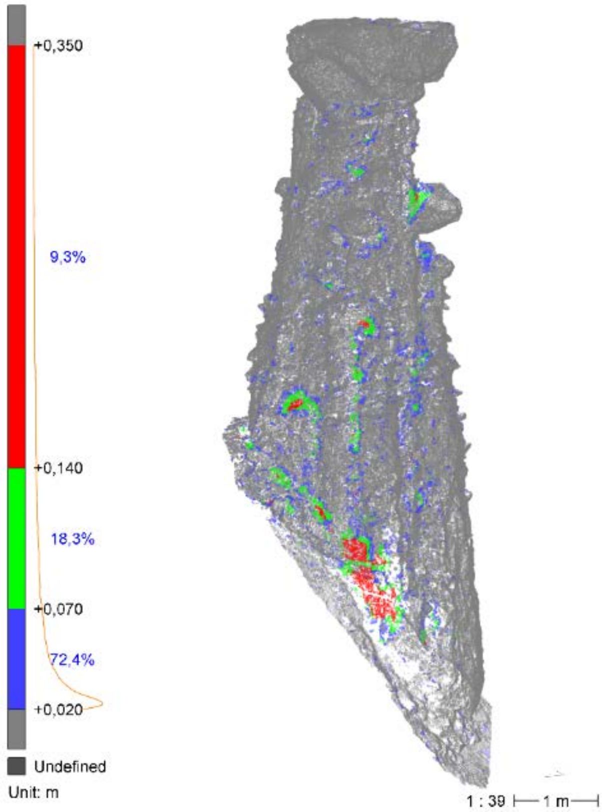


Figure 6 Identified erosion in the landform known as "Barjaktar" between the years 2017 and 2018. Computed in Leica Cyclone 3DR software.

Preliminary analyses of the point cloud of the earth feature known as "Barjaktar" (Figure 7) have indicated that its andesite cap (Figure 7b) has a mass of approximately 3,4 tons, significantly larger than the mass estimated based on visual observation.

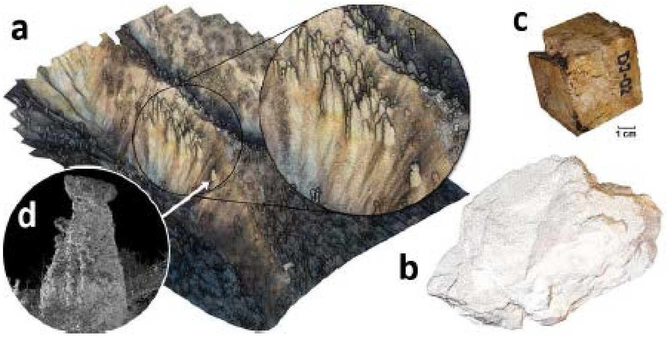


Figure 7 A point cloud from the wider area, b) a point cloud of the andesite cap of the "Barjaktar" figure obtained by TLS, c) a sample of the andesite rock taken from an accessible location (with similar properties to the rock cap) near the "Barjaktar," used for measuring bulk density, required for the estimation of the cap mass, d) the "Barjaktar" scanned by TLS (Đurić et al, 2018).

Conclusion

LS has integral role in geodetic engineering, specifically for the high-precision landslide monitoring. The demand for precise and reliable spatial data in the analysis of geological phenomena, especially in the context of landslides is a critical imperative. The examination of recent developments in laser scanning techniques reveals their potential to provide detailed three-dimensional data marked by notable precision, high spatial resolution, and low data noise.

The practical applications of laser scanning in rockfall monitoring, as exemplified through case studies such as the seven-year rock slope monitoring near Ljig, Serbia, demonstrate the efficacy of laser scanning in capturing the progression of rockfalls. Furthermore, the erosion monitoring of Devils' Town exemplifies the integration of other surveying methods, such as UAV photogrammetry or UAV LS, providing a comprehensive approach to quantify erosion dynamics, predict rates, and enhance conservation.

In essence, LS emerges as a powerful tool in geodetic engineering, providing a reliable spatial data source that contributes to the broader understanding of landslide dynamics. Designing parameters of scanning experiment, their processing, and analysis, with the aim of reaching reliable conclusions during rockfall monitoring and analysis, represents a crucial step.

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