https://doi.org/10.18485/resylab.2024.6.ch16

Detection and monitoring of slope movement by using point cloud derived from the SfM technique

Igor Ivanovski[(1)*], Natasha Nedelkovska[(2)], Gose Petrov[(3)], Milorad Jovanovski[(4)], Toni Nikolovski[(1)], Igor Peshevski[(4)]

1) Strabag AG, Skopje, Mirče Acev 2, MK-1000 Skopje, Republic of North Macedonia, igor.ivanovski@strabag.com

2) Geohydroconsulting Ltd., Skopje, Manapo

3) Faculty of Natural and Technical Sciences, “Goce Delčev” University in Štip

4) Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering, Skopje, blvd. Partizanski odredi 24

Abstract The paper presents an example of the detection and monitoring of slope movements by using a 3D point cloud obtained from the low-cost, remote, and precise SfM (Structure from Motion) technique. SfM is a photogrammetric range imaging technique for estimating three-dimensional structures from two-dimensional image sequences that may be coupled with local motion signals. Its algorithm detects common feature points in multiple images and uses them to reconstruct the movement of those points throughout the image sequence. The analysed instability represents one part of the cut 4 at km 11+620 to km 12+244 on A2 Expressway Kriva Palanka-Stracin, section Dlabochica-Chatal (Republic of Macedonia). The rockslide developed at the beginning of the cut 4 excavation, in a medium of albite-epidote-chlorite schists. The surveying was performed with a low-altitude camera drone - Phantom 4 RTK, the Pix4D software was used for processing the SfM recordings, while the analyses were done in the CloudCompare software. Four point cloud sets were analyzed in relation to the initial (the reference) one acquired before the detected movements. Multi-temporal geomorphic changes in the rockslide area were identified by comparing the SfM-derived point clouds in pairs. 3D distances were estimated with the multi-scale model-to-model cloud comparison for each pair of point clouds. The results show that the displacements on the slope range up to 70 cm. Also, the 5-month observation period shows that the rockslide is not settled and there are certain movements, especially in its upper part. The obtained results show that the application of SfM for the detection and monitoring of displacements seems to be a beneficial technique for such purposes because of its swiftness, the high detail of prospecting, and the possibility of determining minimal movements.

Keywords SfM technique, displacement, rockslide, point cloud

Introduction

Among the many geological hazards, landslides have the widest distribution and cause considerable losses to the national economy and property. The stability of the road cuts directly affects the local traffic and the safety of life and property of the surrounding residents (Montgomery 1994, Harabinova 2017, Shariati et al. 2021).

Monitoring of loose rocky slopes along the roads is quite important. This aspect is relevant for Macedonia during the construction, reconstruction, and exploitation of the roads, especially since many roads are built in mountainous areas.

In terms of in-situ measurement and monitoring, many scholars have used monitoring devices such as displacement sensors, inclinometers, and pore water pressure sensors, combined with IoT technology and GNSS technology to monitor slopes (Moradi et al. 2021). These monitoring devices improve monitoring efficiency (Olabode et al. 2022). However, this type of sensor equipment is point-based monitoring and cannot achieve comprehensive coverage of the slope. The monitoring data comes from various scattered sensors, and there is little relevant monitoring information for non-sensor installation points (Zhou et al. 2020).

SfM (Structure-from-Motion) (Westoby et al. 2012), is now a powerful method for 3D reconstruction and point-cloud generation. SfM applications, such as Smart3DCapture, PhotoScan, and Pix4D, are popular for professional and/or non-professional operators of photogrammetry. These systems directly process a sequence of images and generate point clouds. Each point has a colour index originating from the colour of an original image pixel. By photographing loose rock and the surrounding environment, SfM software can calculate a point cloud which can realize a quantitative estimation of rock movement (Kazuo et al. 2016).

Here we present an example of monitoring slope failure mechanisms during the construction of A2 Expressway Kriva Palanka-Stracin, by using Unmanned Aerial Vehicles (UAV) and SfM photogrammetry. UAVs are an effective tool in landslide risk management, allowing rapid collection of imagery and production of high-resolution photomosaics to safely evaluate rockslide deformation and activity. UAVs combined with SfM photogrammetry have emerged as a new approach in recent studies for landslide monitoring (Brook et al.2020). The efficiency of SfM algorithms has been demonstrated in multiple studies for landslide monitoring (Lucieer et al. 2014).

Various papers have been published elaborating examples of predicting rockfall assessments using point clouds (Marjanović et al. 2021), (Rosser et al. 2007), Janeras et al. 2017), (Xiao et al. 2023). Systematic application of these methods can provide excellent information for managing rockfall-prone slopes.

This research aims to implement already available datasets that were obtained for another purpose for this site, here processed in the context of monitoring and predicting the movement of a rockslide during road construction. The goal is to present a low-cost and fast new approach that replaces the classic field surveying. Considering that the known methods are used for monitoring already occurred instabilities, the application of SfM represents the earliest form of constant monitoring and detection of possible rockslides.

Study area

The study area represents one part of the cut at chainage km 11+635 to km 12+191 on the A2 Expressway Kriva Palanka-Stracin, section Dlabochica-Chatal, close to village Petralica. The rocks in this part of the alignment by their mineralogical composition can be distinguished in different lithological units, depending on the dominant minerals. However, according to the similar structural, textural, and physico-mechanical characteristics all rocks are classified as green schists. During the field geological mapping, the schists were further distinguished as albite-epidote-chlorite schists, which are characterized by a schistose structure, at some parts quite fractured, folded, and tectonized especially at the contact parts with fresher and stronger albite-epidote-chlorite schists.

With the start of the construction activities, a major rockslide occurred on the right side, at the beginning of the cut (Fig. 1). After the remediation of this part, another local rockslide occurred in the approximate same area, which is the subject of this paper (Fig. 2). The monitoring of this part of the cut using drone surveillance and the SfM technique enabled comparison and estimation of the scale of movement of the rockslide.

The processes of surface weathering of the rocks change the composition and setting of the rock mass and lead to the destruction of the rock into fine debris and larger rock fragments. These engineering geological processes are anthropologically caused, i.e. they occurred after undertaking construction activities for the alignment of the road and construction of the cut.

Figure 1 Aerial view of the cut: the studied area before the rockslide occurrence is marked with a red circle.

Figure 2 The initial stage of the rockslide (01.02.2023).

On the other hand, the morphology of the terrain, precipitation, oxygen, CO_2, temperature oscillations, ice, and the steep inclination of the slopes also contribute to the occurrence of rockslides. The surface weathering of the rocks is expressed along the entire length of the cut slope and is most pronounced on the contact parts between the schists and the fault structures. At the currently constructed slopes, the first two are made with an inclination of 1:2 (26.6°), and the third (the one where the rockslide occurred) is excavated with an inclination of 1:1.5 (33.7°). Because of the gravitational conditions, there is the occurrence of falling of small rock fragments and in some instances of larger quantities of rock material. The unfavourable dip elements of the foliation on the right side of the cut, tectonic fracturing, intersection of fault structures with the foliation, and perpendicular fractures to the foliation, as well as precipitation, are significant factors for the creation of this state.

In the subsequent period, the dimensions of this rockslide increased, as a result of which additional amounts of material were falling off the slope (Fig. 3).

Figure 3 Rockslide state on 27.09.2023.

Used methods, hardware, and software

The traditional methods are based on physical access to the rock surface. Since the 2000s, remote sensing techniques have been applied to several fields, particularly to the characterization of rocky slopes (Riquelme et al 2021). The scientific community has shown a growing interest in the extraction of information on discontinuities from remote sensing-derived datasets (Ivanovski et al. 2023).

Structure from Motion introduced by Ullman (1979), is a photogrammetric range imaging technique for estimating three-dimensional structures from two-dimensional image sequences that may be coupled with local motion signals. It requires a digital camera and, if needed, a Remotely Piloted Aircraft System (RPAS). It can provide a 3D point cloud (3DPC) that can be further analyzed by appropriate software.

In our case, this technique has been performed using a low-altitude camera drone - Phantom 4 RTK (enterprise.dji.com). It belongs to Low-Altitude Unmanned Aerial Vehicles which is employed to capture the ortho and oblique images during the flight. (Fig. 4a). The photo size is 5742 x 3648 pixels with horizontal and vertical resolution of 72 dpi.

Before scanning the area with the camera mounted on the drone, at least four reference points should be visibly marked which are surveyed with high precision GPS device. In our case, when using the drone, it is connected in real-time with NTRIP MAKPOS reference stations in Macedonia that send corrections to the drone. Due to the operating range that is specially intended for our alignment, it is necessary to set control points to obtain the necessary accuracy, whereby the model would correspond to the project on which the expressway is being worked.

With the SfM technique using the drone, the entire area was recorded by navigating the drone to take pictures and record all visible surfaces (Fig. 4b). When recording, the drone positions itself using its coordinates.

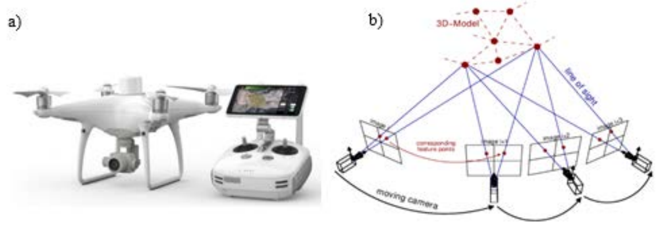

Figure 4 a) Drone b) Principles of SfM method.

There are several approaches and algorithms to reconstruct camera orientation and geometry from images. Currently, one of the most used methods is based on the employment of Structure-from-Motion (SfM) algorithms. These algorithms belong to the computer vision research field and together with stereo-reconstruction techniques provide the opportunity to create accurate 3D models from images without prior information about the location of image acquisition, or about the camera parameters used to perform the acquisition (Verhoeven 2013).

With the SfM method, the 3D scene geometry and camera motion are reconstructed from a sequence of 2D images which are taken by a camera that moves around the scene. The SfM algorithm detects common feature points in multiple images and uses them to reconstruct the movement of those points throughout the image sequence. With this information, the locations of those points can be calculated and visualized as a 3D point cloud.

Four different surveys are made and four point cloud sets are prepared for this research: The point cloud acquired before detected movement is the reference point cloud. During five months, four photogrammetric surveys were made on 13.12.2022, 20.01.2023, 21.02.2023, and 16.05.2023.

Multitemporal geomorphic changes in the rockslide area were identified by comparing the SfM-derived point clouds in pairs. 3D distances were estimated with the multiscale model-to-model cloud comparison for each pair of point clouds.

Two different software were applied. Pix4D mapper version 4.8.3 is commercial software specialized for photogrammetry (pix4d.com). It was used for the photos received from drone imaging to be turned into a point cloud. CloudCompare version 2.11.0 is an open-source software that was used for the processing of 3D point clouds.

During the processing of the obtained images in Pix4D, a visualization of the exact positions of the camera while the photos were taken is obtained (Fig. 5).

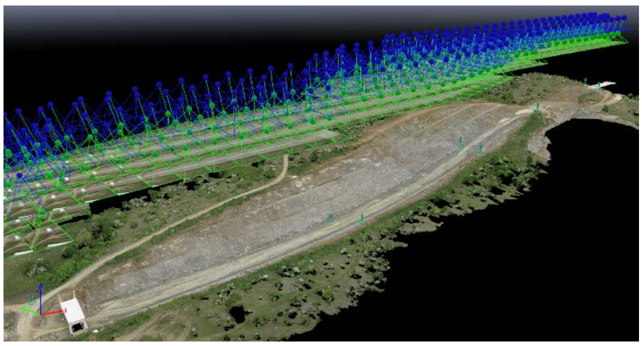

Figure 5 Positions of the camera while surveying.

Very high-density point clouds can be extracted from these photos, but to be able to work properly, an optimal point density number was chosen. In this case point cloud density is set to 5-7cm. With the complete processing, the model is obtained, i.e., four different point clouds (Fig. 6). The resulting model was saved in. xyz, extension. The number of points for these four surveys is between 510.034 to 655.834 depending on the conditions when the survey was done.

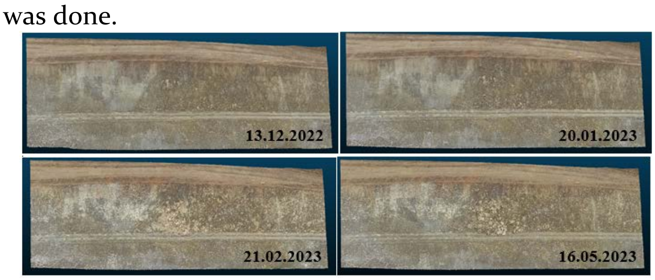

Figure 6 Point clouds derived from four different surveys.

Results

The study area represents a small part of the entire cut 4, i.e. area of 100m by 60m.

The CloudCompare tool Cloud-to-Cloud (C2C) Distance is used to compute the distances between two selected point clouds. Before displaying the tool dialog, it is necessary to select the reference cloud, and the comparative one. The older cloud would always be the reference one (www.cloudcompare.org).

For each C2C distance computation method, CloudCompare software computes four values for the distance, which are: the maximum distance, average distance, mean distance, and the standard deviation. In this case, that data are not used because of the changes due to cut excavation in the surrounding parts of the rockslide, a factor that influences the complete statistics. The detection of the largest differences is done manually using the tool *Point picking*. The entire visible area that shows changes due to the comparison doesn't represent the real positions of the material that has been moved (the size of the rockslide). Choosing bulk data for C2C distances can gain false information due to redepositing of some material, i.e., changes of a type that some part that showed differences in one time of surveying, in other time can be redeposited and with that to falsely represent that there is no movement. So manual point picking addresses the positions that in reality suffered the most changes.

The bright colours in the middle of the image indicate that there are some changes when comparing the first two surveys. The bright colours at the edges of the area indicate differences due to excavation that was done in the surrounding area between the two surveys (Fig. 7). The rockslide was detected first time on 01.02.2023. When using the surveys from the period before the rockslide, i.e. surveys 1 and 2, and using survey 1 as a reference, it can be easily detected that there was some kind of movement before the visual detection of the rockslide.

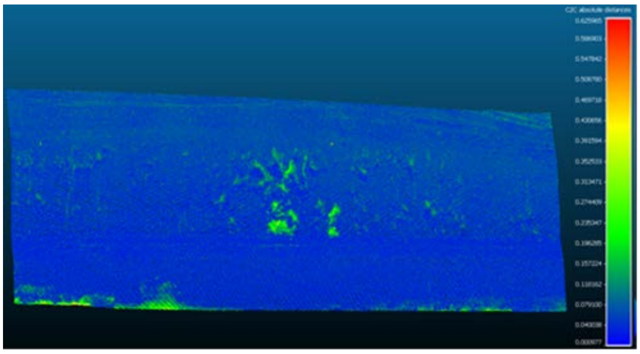

Figure 7 Comparison between the first and second surveys.

The biggest change in positions between the first two surveys is 28 cm, and mostly in the range of 0-8 cm (Fig. 8a). It can be noticed that there are small differences around the study area, because of the small difference in positioning of the two point clouds (up to 3 cm) and from the erosion that was present at the cut. Apart from the fact that this type of rockslide is already observed, using Cloudcompare, displacements can be measured in different places of the rockslide, with the largest displacement being 59 centimetres (Fig. 8b).

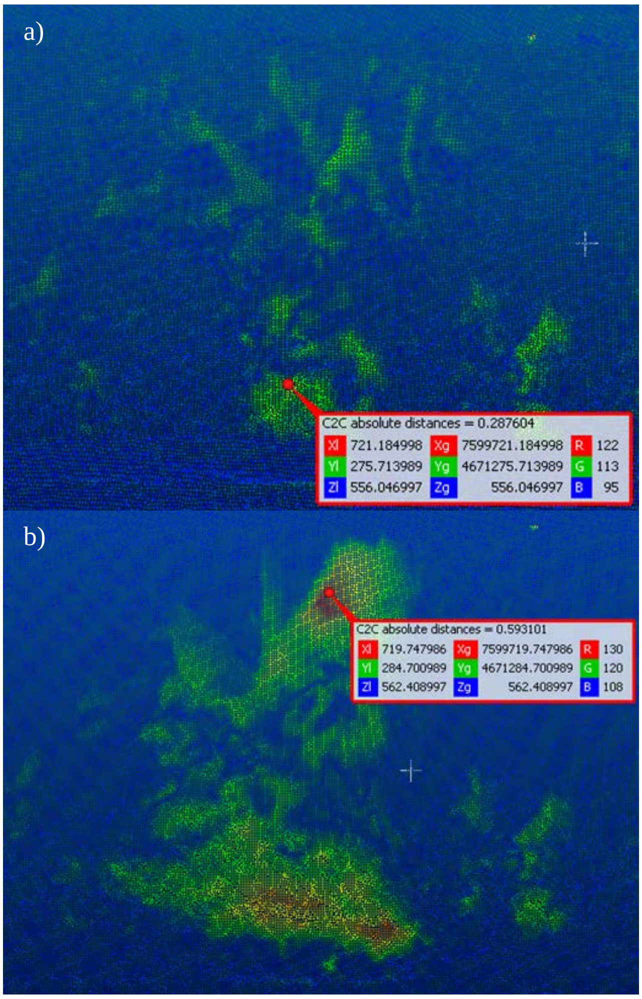

Figure 8 a) Absolute distances between first and second survey (up) b) Absolute distances between first and third survey.

When comparing the first survey with the survey that was taken after the occurrence of the rockslide (the third survey), it can be said that the greater difference between the two clouds of points in the part of the researched area is already noticeable (Fig. 9). When comparing the first with the last survey (Fig. 10), it can be noticed that the differences between the two point clouds are larger and that they are spread over a larger area.

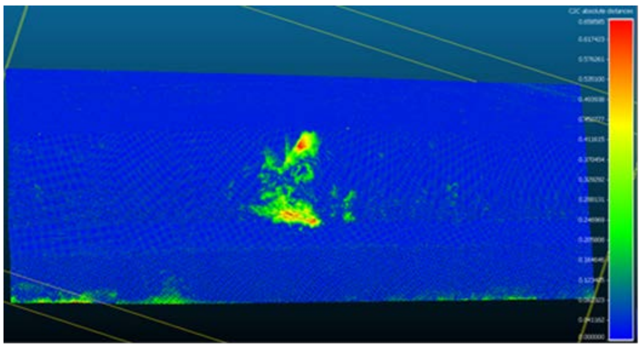

Figure 9 Comparison between the first and third survey

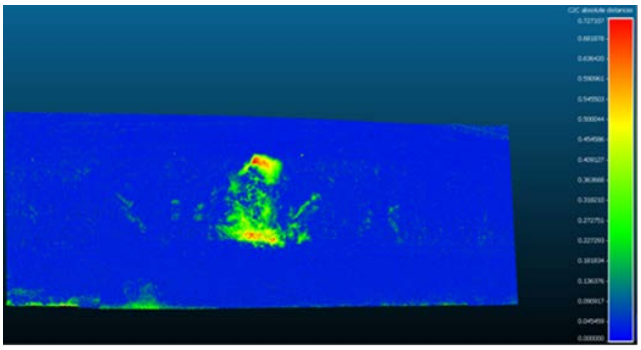

Figure 10 Comparison between the first and fourth surveys.

The maximum observed distance is 70 cm (Fig. 11a).

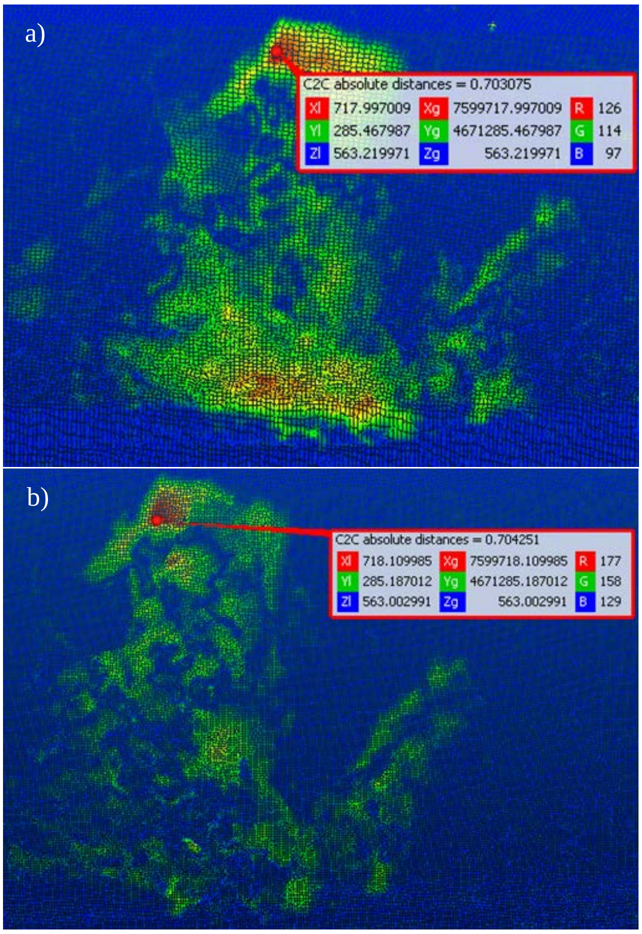

Figure 11 a) Absolute distances between first and fourth survey; b) Absolute distances between third and fourth survey.

It is noticeable that the absolute maximum distance of the two point clouds is increasing but it is also noticeable that the shape of the rockslide is changing especially in the upper part of the area. This is because of the permanent erosion and rockslides throughout the cut and redeposition of the rocky material. The real activity of the rockslide is in the upper part.

From this comparison, it can be noted that by comparing two images taken after the occurrence of the rockslide, in 5 months from one survey to the other, it is not settled and there are still certain movements, especially in its upper half. For this period, the largest distance between these two recordings is 70 cm (Fig. 10b).

It is clear that the maximum distance is the same as comparing the changes from the initiation of the rockslide. However, it can be seen that due to constant erosion and rockslides, there is redepositing of the rocky material on the slope, which is changing the shape of the rockslide. The part with maximum absolute change has narrowed its gap due to redeposition and erosion.

After the analysis, it can be concluded that movements are greatest in the part where the actual sliding occurred (along the foliation of the schist), i.e. in the upper part of the slope. The lower part of the rockslide endures changes mostly due to redepositing the rocky material from the upper parts.

Because this comparison provides reliable data that there is still movement on that part of the slope, the same technique can be applied to the entire cut where periodic recordings can be used for a quick and constant insight into the possible dangers of slope instabilities.

Figure 12 shows the differences between the recordings done on 13.12.2022 and 16.05.2023. In blue are the parts where there were no changes during that period. In red are the parts of the cut where changes have occurred.

It is most noticeable in the part of the rehabilitation of the slopes and the part of the road construction, positions where excavation was carried out in the meantime, as well as in the periphery where there is a change in the vegetation. In the part of the slopes and berms, it can be noticed the occurred change, the rockslide on the third slope on the right side of the cut (marked with the white arrow).

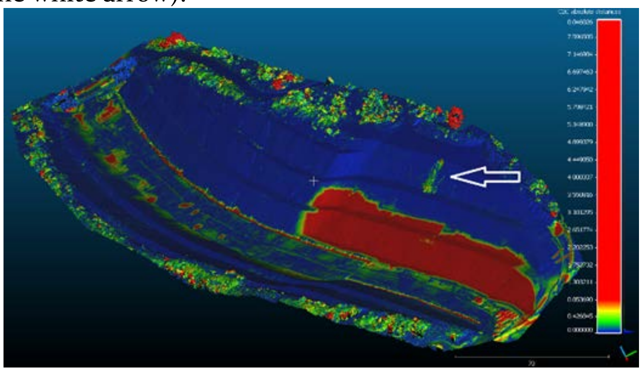

Figure 12 Terrain changes for 5 months.

With constant monitoring of the entire cut, early detection of any unwanted occurrences of slopes is possible.

Conclusions

The example presented in this paper is about a small local rockslide, but it should be taken into account that the same methodology can quite well give information about the occurrence of other types of movement, or the initiation of planar or wedge-shaped failures.

This methodology does not represent an implementation of the latest innovations in technology, but rather the application of several software and hardware solutions that have been used in engineering for years. However, this is a practical example of the application of this methodology on site and its direct engagement during the construction of civil structures, such as an expressway. Using this type of prospecting/monitoring, there is a possibility to determine the occurrence of rockslides at an early stage, and thus to undertake appropriate measures, which would increase the safety of labour and machinery operating in a certain area, as well as during exploitation of the road.

There are several procedures for detecting this kind of phenomenon, all of which give similar results in terms of dimensions and the speed of the changes. The most standard is the visual one, where almost always, after the occurrence of a certain hazard, the solution to the problem is approached. From the presented in this paper, it is obvious that even before the visual detection, there are ways to determine possible minor or major changes, and thus the possibility of preventing or minimizing major damage and increasing the safety of the area.

This can be an example of introducing a procedure for slope monitoring using recordings that are used for other purposes in the construction process as in this case for the calculation of quantities for performed earthworks. This does not incur new costs, it increases the detail of prospecting, replaces the slow in-situ inspection with computer processing, and finally gains greater reliability because it is proven that this method can determine even the smallest processes during the occurrence of rockslides.

However, it should be borne in mind that the use of this method should be approached carefully. Changes in vegetation, or advances in excavation, should be considered before accessing analyses of this type. Also, a good knowledge of geological predisposition and processes combined with a strong geotechnical background is crucial for proper result interpretation.

References

Brook M, Tunnicliffe J, (2020). Rapid, cost-effective 3D monitoring of urban landslide displacements using UAV-Structure from Motion (SfM) (3714483), Research report for www.eqc.govt.nz, paper number 3809 (EQC 18/762).

Harabinova S (2017) Assessment of slope stability on the road. Procedia Eng 190:390–397.

Ivanovski I, Nedelkovska N, Petrov G., Jovanovski M., Nikolovski T. (2023) Comparison between traditional and contemporary methods for data recording in structural geology. Journal Geologica Macedonica (37):119-133.

Janeras M, Jara J A, Royán M J, Vilaplana J M, Aguasca A, Fàbregas X, Gili J, and Buxó P, (2017) Multi-technique approach to rockfall monitoring in the Montserrat massif (Catalonia, NE Spain). Eng. Geol. (219):4–20.

Kazuo O, Satoko H, Toko T, (2016) Detection of slope movement by comparing point clouds created. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B5, 2016 XXIII ISPRS Congress, 12–19 July 2016, Prague, Czech Republic

Lucieer A, Jong SMD, Turner D, (2014) Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. Progress in Physical Geography 38:97-116.

Marjanović M, Abolmasov B, Berisavljević Z, Pejić M, Vranić P, (2021) Pre-failure deformation monitoring as rockfall prediction tool. IOP Conf. Series: Earth and Environmental Science 833 (2021) 012197.

Montgomery DR, (1994) Road surface drainage, channel initiation, and slope instability. Water Resour Res 30:1925–1932.

Moradi S, Heinze T, Budler J, et al (2021) Combining site characterization, monitoring and hydromechanical modeling for assessing slope stability. Land 10:423.

Olabode OP, San LH, Ramli MH, (2022) Geophysical and geotechnical evaluation of landslide slip surface in a residual soil for monitoring of slope instability. Earth and Space Science, 9, e2022EA002248.

Riquelme A, Tomás R, Cano M, Pastor JL, and Jordá-Bordehore L, (2021) Extraction of dis-continuity sets of rocky slopes using iPhone-12 derived 3DPC and comparison to TLS and SfM datasets. IOP Conf. Ser.: Earth Environ. Sci. 833 012056

Rosser N, Lim M, Petley D, Dunning S and Allison R 2007 Patterns of precursory rockfall prior to slope failure. Jour. of Geoph. res. 112 F04014

Shariati M, Fereidooni D, (2021) Rock slope stability evaluation using kinematic and kinetic methods along the Kamyaran-Marivan road, west of Iran. J. Mt. Sci. (2021) 18(3): 779-793

Ullman S, (1979) The interpretation of structure from motion. Proceedings of the Royal Society of London. 203(1153): 405–426.

Verhoeven G, Sevara C, Karel W, Ressl C, Doneus M, Briese C, (2013) Undistorting the Past: New Techniques for Orthorectifica-tion of Archaeological Aerial Frame Imagery. In: C. Corsi, B. Slapsak and F. Vermeulen, ed., Good Practice in Ar-chaeological Diagnostics, 1st ed. Springer International Publishing Switzerland, pp.31-67.

Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM, (2012) Structure-from-Motion Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications. Geomorphology 179: 300–314.

Xiao G, & Nie, Wen & Geng, Jiabo & Yuan, Canming & Zhu, Tianqiang & Zheng, Shilai (2023) Road slope monitoring and early warning system integrating numerical simulation and image recognition: a case study of Nanping, Fujian, China. Stochastic Environmental Research and Risk Assessment 37:1-17.

Zhou X, Xu Q, Zhao K et al, (2020) Research on calibration method of discrete element mesoscopic parameters based on neural network andslide in Heifangtai, Gansu as an example. Chinese J Rock Mech Eng 39:2837–2847.

https://enterprise.dji.com/phantom-4-rtk/specs [Last accessed: 16.01.2024].

École Polytechnique Fédérale de Lausanne (EPFL) Com-puter Vision Lab in Switzerland – Pix4D mapper. Available online: pix4d.com [Last accessed: 16.01.2024].

https://www.cloudcompare.org/doc/wiki/index.php/Cloud-to-Cloud_Distance [Last accessed: 16.01.2024].