Monitoring slope stability in surface mines: are low-cost UAVs used for excavated rock volume calculations capable of early detection of displacements?

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Abstract. This paper tries to assess the ability of UAVs equipped with RGB cameras to monitor the stability of the specific slopes in the surface lignite mines of Ptolemaida basin. For this purpose, the results of high measurement accuracy surveying, which was applied based on a series of target prisms placed on the crests of mine benches, are compared with the displacements detected by subtracting successive digital terrain models produced using UAVs equipped with RGB cameras in combination with RTK processing.

1 Introduction

Geotechnical failures in surface mines pose potential threats to the safety of personnel and equipment, the achievement of production targets and the mitigation of environmental impacts. For this reason, monitoring the stability of slopes in surface mines is a primary concern for any extraction company [1]. The development of an early warning system in cases where an instability phenomenon is in an early stage is also one of the objectives of every monitoring system [1, 2].

Traditional slope stability monitoring methods include visual observation, monitoring of the displacement of target prisms placed at selected points and drilling of inclinometers [1, 2]. However, mainly due to their cost and the continuously changing topography resulting from massive excavations and dumping works, permanent constructions are usually placed only in areas that have already been classified as high risk. Such areas may concern slopes that have previously failed or exhibit unfavourable tectonic characteristics.

For the above reasons and especially in large-scale surface extraction works developed in multiple long benches, it is necessary to find an alternative methodology for the regular monitoring of the stability of all active faces, permanent slopes, as well as the slopes of the waste heaps [3-5]. In this context, it was considered appropriate to investigate under what conditions the common surveying equipment present in a surface mine for determining the

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volumes of excavations could be used to monitor slope displacement as well. The equipment that may now be available in surface mines for topographic measurements includes terrestrial, Unmanned Aerial Vehicles (UAVs) and satellite systems that have high accuracy and probably can detect three-dimensional soil movements that may be associated with the start or development of an instability phenomenon [6-10].

2 Study area description

The surface mines of the Ptolemaida-Amynteon basin have been in operation since the late 1950s and, to date, have produced more than 1.7 billion tons of lignite and have excavated 8.5 billion cubic metres of rocks. Nowadays, they are developed in six pits applying the area mining method, while at the same time, waste rock dumping is carried out in both internal and external heaps. The total area occupied by mining activities exceeds 17,000 ha, including tens of kilometres of excavation and waste heaps slopes, which demand systematic monitoring to prevent landslides.

In the study area, there have been two significant landslides in terms of the volume of earthy materials that were moved but fortunately without loss of human life and with limited economic damage mainly associated with the loss of production. The first of these landslides occurred in 2004 and involved the displacement of excavated rocks that had been dumped in an external waste heap, while the second occurred in 2017 and concerned the failure of the mining face of a mine, which were developed in many successive benches. In addition to large-scale failures, mines are more often called upon to deal with local-scale phenomena that may also prove detrimental to the productivity of the project [11, 12]. It is worth noting that the risk of equipment loss is greater because, in these mines, a continuous system of materials excavation, transport and spreading has been installed. This system is characterized by limited flexibility.

For the purposes of this work, the lignite mine of Mavropigi (Figure 1) was chosen to be studied and, more precisely, the permanent slope of the pit to the western side, where a minor scale landslide occurred a few months ago, and high displacement figures have been occasionally measured since then. The stability of this slope is critical for the exploitation of the deeper part of the lignite deposit with non-continuous mining equipment.

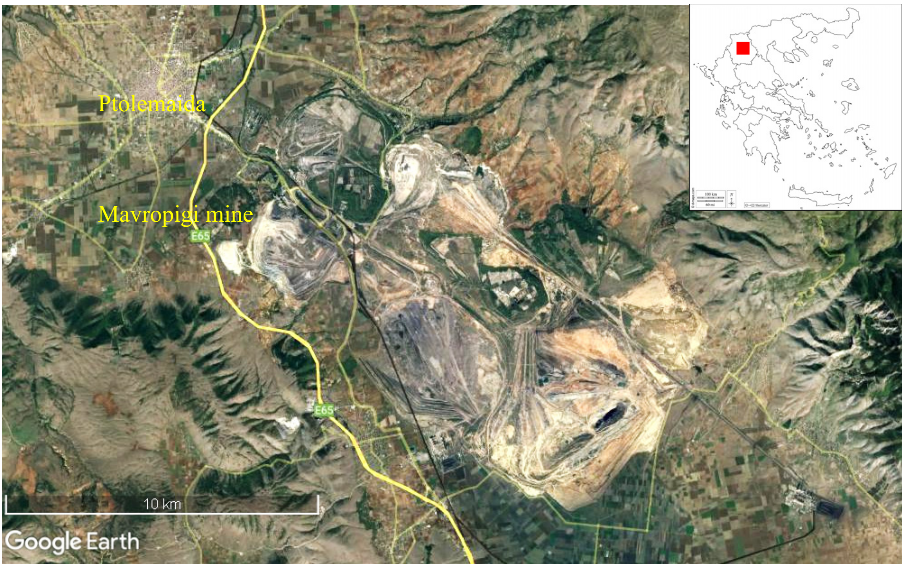

Fig. 1. Map of the lignite mines in the Ptolemaida basin and location of the Mavropigi mine.

3 Equipment and methods

3.1 Equipment Description

3.1.1 Total Station and Target Prisms

Four target prisms were placed on the crests of mine benches in the study area to achieve high accuracy measurements of displacements. The prisms were standard GPR1 prism reflectors, which were solidly placed (Table 1).

Table 1. Maximum range of prism concerning weather conditions [13].

Reflector	Range A		Range B		Range C	
	m	*ft*	*m*	*ft*	*m*	*ft*
Standar Prism (GPR1)	1,800	6,000	3,000	10,000	3,500	12,000
Range A: Strong haze, visibility 5 km; or strong sunlight, severe heat shimmer						
Range B: Light haze, visibility about 20 km; or moderate sunlight, slight heat shimmer						
Range C: Overcast, no haze, visibility about 40 km; no heat shimmer						

The prisms were measured multiple times in the months following installation using conventional surveying methods. Specifically, a Leica TS30/TM30 high accuracy measurement total station was used. The precise mode and angular accuracy of the equipment are presented in Tables 2 and 3, respectively.

Table 2. Precise mode of Leica TS30/TM30 total station [13].

EDM Measuring Mode	Standard Prism Accuracy	Measurement Time, typical [s]
Precise	0.6mm + 1ppm*	7

*Atmospheric conditions type C, range up to 1000 m, GPH1P reflector

Table 3. Angular accuracy of Leica TS30/TM30 total station [13].

Type	std. dev. Hz, V, ISO 17123-3		Display least count	
	["]	*[mgon]*	*["]*	*[mgon]*
TS30	0.5	0.15	0.01	0.01
TM30	0.5 1.0	0.15 0.30	0.01 0.01	0.01 0.01

3.1.2 Digital Terrain Models

The digital terrain models were created using UAVs and RTK technology. The UAV used was the SenseFly eBee RTK, a fully autonomous survey grade-mapping drone equipped with a GNSS/RTK antenna (Table 4).

Table 4. Drone accuracy specifications for surveying [14].

Characteristic	Accuracy
GSD (per pixel)	< 5cm (2.0 in)
Absolute Horizontal	< 3cm (1.2 in)
Absolute Vertical	< 5cm (2.0 in)
Relative Orthomosaic 3D model	1-3 times GSD

The accuracy of the 3D terrain model was improved significantly using photogrammetric methods and ground control points (GCPs). The software used for the point cloud process was the PIX4DMapper. In addition, the software Quick Terrain Modeler was used to assess geospatial information and data extraction from the 3D terrain model.

3.2 Methodology

3.2.1 Target Prism Measurements

The accurate observation of the displacements occurring in the study area required a careful selection of the prism positioning. The number and exact position of the prisms that were finally installed resulted after a thorough examination of alternative scenarios, taking into consideration the following factors:

- Visibility of prisms from the surveying base.
- Interfering of prisms locations with any ongoing mining procedures.
- Prisms must be placed strategically to points of interest so that the measurements reflect the realistic scale of the displacements.
- Indications of instability phenomena reported by the mining personnel (e.g., crevices, road subsidence, rock falls).

The study team finally selected the prism positions shown in Figure 2. ASV1 prism is located close to the crest of the pit slope, ASV2 and ASV4 within the landslide that occurred a few months ago and ASV3 on a bench just outside of the landslide.

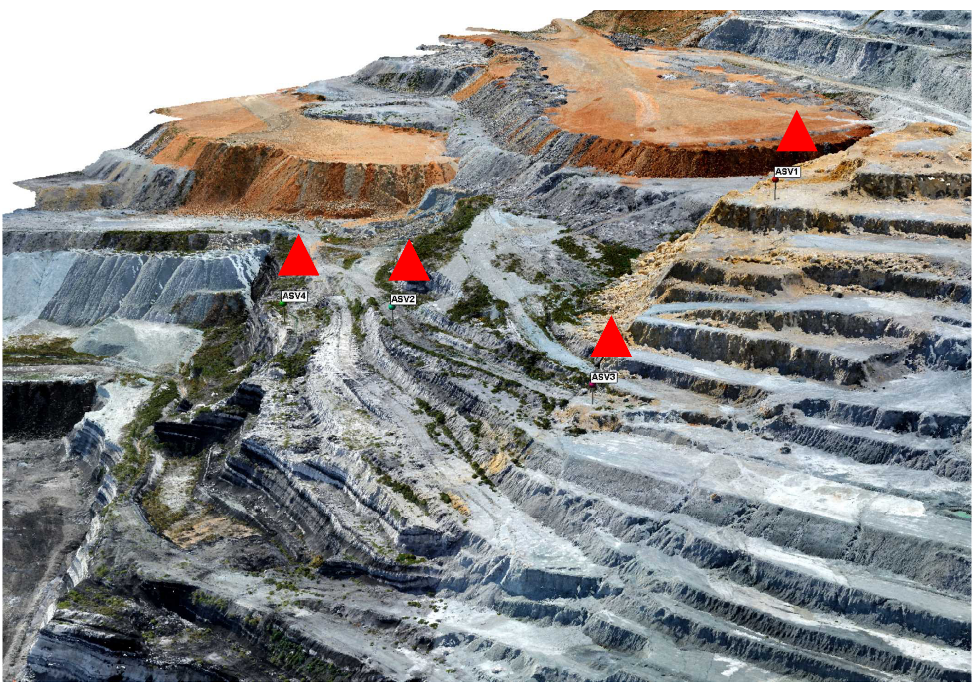

Fig. 2. Prisms positioning in the monitored area of the pit slope.

The frequency of the prism measurements was decided to be high in order to gather an extensive series of data, which was considered necessary for checking the reliability of the results. In this frame, the average number of measurements carried out on a weekly basis

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ranged between 4-5, while the total duration of the measurements campaign was six months (July 2021 – December 2021). Moreover, to reduce probable systematic errors, it was decided all the measurements to be conducted by the same experienced observant, supervised by the surveyor of the mine.

Some basic parameters of the measurements were the following:

- Each prism was measured periodically over ten times per measuring session.
- The precise mode on the total station was selected.
- The prisms and base positions were statically reviewed periodically, using GPS/GNSS surveying to verify the total station measurements.

Weather factors were evaluated during every measurement session, using real-time data gathered by a local meteorological station [15]. In addition, this data was cross-checked with relevant data from neighbouring meteorological stations [16]. The surveying total station settings were adjusted to the specific weather conditions of the day. In particular, the following weather factors were considered significant: temperature, humidity, atmospheric pressure and visibility conditions.

Finally, a statistical analysis of the results using the normal distribution model was conducted to detect and exclude fault observations from further data processing.

3.2.2 Digital Terrain Models

For the purpose of the digital terrain model creation, the UAV was flown three times over the six months period, thus creating three representative terrain 3D models for further investigation. The flight settings were carefully chosen for maximum accuracy of the digitized study area, including parameters such as flight height (as low as possible), drone speed, camera settings and weather factors (Figure 3).

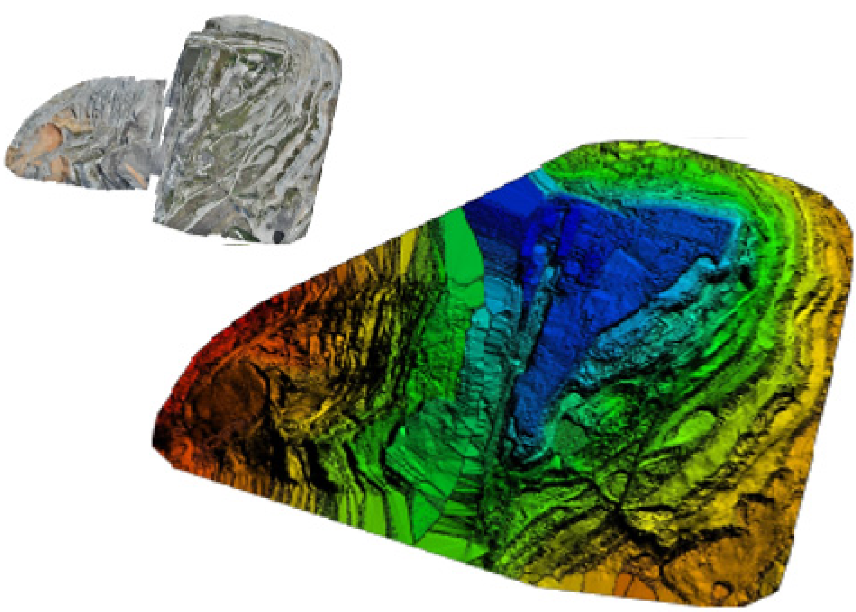

Fig. 3. Orthomosaic of the digital terrain model created: the reddish colours correspond to higher elevations at the pit perimeter (West) and on the waste heaps (East), and the bluish colours to lower elevation in the pit (Centre).

The point cloud software process's accuracy was strongly enhanced by using ground control points (GCPs), which were added to the analysis as a photogrammetric method for terrain model creation. Their usage proved of vast importance to the analysis accuracy, which reached the levels required for the cross-comparison of the two methods. The reported accuracy was acceptable and within the desirable range in every case.

The software used for the cloud point resolution, and the quality control, was PIX4Dmapper. The relative geolocation variance reported for each flight session is presented in Table 5.

Table 5. Relative geolocation variance reported for each flight session.

- July 2021 Flight Session:

Relative geolocation error	Images X[%]	Images Y[%]	Images [%]
[-1.00, 1.00]	99.38	99.84	95.65
[-2.00, 2.00]	100.00	99.84	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	0.025432	0.025432	0.030427
Sigma of Geolocation Accuracy [m]	0.028294	0.028294	0.039661

- September 2021 Flight Session:

Relative geolocation error	Images X[%]	Images Y[%]	Images [%]
[-1.00, 1.00]	89.03	90.52	92.77
[-2.00, 2.00]	98.00	97.76	100.00
[-3.00, 3.00]	99.75	98.75	100.00
Mean of Geolocation Accuracy [m]	0.024707	0.024707	0.028652
Sigma of Geolocation Accuracy [m]	0.002186	0.002186	0.003314

- December 2021 Flight Session:

Relative geolocation error	Images X[%]	Images Y[%]	Images [%]
[-1.00, 1.00]	100.00	99.40	90.42
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	0.023818	0.023818	0.031726
Sigma of Geolocation Accuracy [m]	0.000988	0.000988	0.002692

4 Results

4.1 Displacement Calculation

The study area was measured and digitized using the two above-described methods based on target prism measurements and UAV measurements. First, three digital terrain 3D models were created, corresponding to specific days of July, September, and December 2021 (Figure 4). Next, the digital terrain modelling outcome was assessed by using the target prisms' positions as control points for the digital measurement. Then, the cross-comparison of the two different measuring approaches was carried out.

The digital 3D models were created, and their accuracy was evaluated as statistically acceptable.

Finally, successive digital terrains were subtracted to create a map that visualizes the displacement measured for each pixel of the study area (Figure 5).

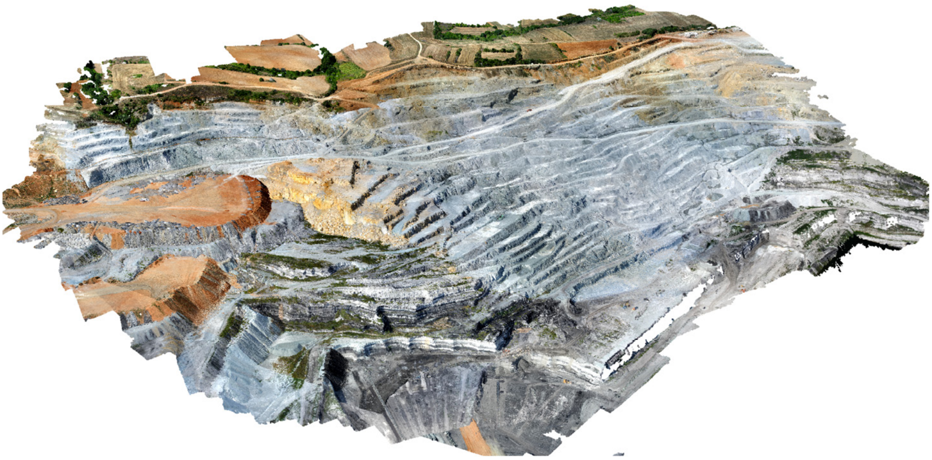

Fig. 4. Digital terrain model of the study area (July 2021).

Fig. 5. Colourized visualization of the displacements calculated by the subtraction of different digital terrain 3D models (July – December 2021).

4.2 Slope Profile Analysis

For better visualization of points displacement recorded in the digital terrain 3D models, slope profiles were created on three different dates corresponding to the measurement campaigns carried out in July, September, and December 2021. For reasons of comparison, the sloped terrain intersections were illustrated in the same diagram with different colours for each of the three measurement periods, so that the magnitude of the gradual displacement over time could be easily determined. Each profile's starting and ending points coincide with the positions of two prisms. Figure 6 presents the intersection of the sloped terrain with the level determined by the prisms ASV1 and ASV3. It is obvious that the horizontal parts of the slope are moved downwards while the old excavation faces are moved gradually to the right.

To this end, displacements of the terrain, which were gradually created over a period of four months, were tracked by simple processing techniques of the 3D terrain models. Also, the user of this specific software can calculate the displacements throughout the overlapping terrain models with the statistical accuracy of the point cloud processing solution reported.

Fig. 6. View of the terrain intersection between points ASV1 – ASV3 (Grey: July 2021 - Green: September 2021 – Red: December 2021).

4.3 Comparison of Target Prism Measurements (TPM) and 3D terrain models

The results of target prism measurements with the traditional surveying methods and the 3D terrain model measurements were compared and reviewed. Table 6 compares the elevations determined for the four target prisms. Although there was a significant difference between the absolute elevation values for all the prism positions, the same direction of movement (downward) was measured by both the compared methods.

In addition, Table 7 presents the displacements rate (%) between the successive measurements campaigns (July-September and September-December). Again, the compliance between the two compared methods is confirmed.

Table 6: Comparison of elevations calculated using TPM and 3D terrain models.

	ASV1		ASV2		ASV3		ASV4	
	TPM	3D Models	TPM	3D Models	TPM	3D Models	TPM	3D Models
July 2021	661,893	660,115	615,205	*N/A*	612,500	*N/A*	602,968	*N/A*
Sept 2021	661,635	659,840	615,221	613,337	612,266	611,181	602,974	601,673
Dec 2021	660,332	658,561	615,239	613,319	612,051	610,999	602,969	601,496

Table 7. Displacement rate (%) between successive measurement campaigns using TPM and 3D terrain models.

	ASV1		ASV2		ASV3		ASV4	
	TPM	3D Models	TPM	3D Models	TPM	3D Models	TPM	3D Models
Jul/Sep 2021	-0,039	-0,042	0,003	-	-0,038	-	0,001	-
Sep/Dec 2021	-0,197	-0,194	0,003	-0,003	-0,035	-0,030	-0,001	-0,029

Based on the results presented in Tables 6 and 7, it can be assessed that both methods provide complying results in terms of point displacement, which are also within the range of statistical accuracy of the 3D models created. This indication encourages further examination of the usage of UAVs in mapping the mining fields and creating a surveillance tool for terrain displacements and landslides.

5 Discussion and conclusions

The present contribution investigated some critical aspects regarding the potential of effectively using UAVs for carrying out surveillance campaigns in large surface mines aiming at an early warning of slope failure phenomena. Based on the presented results, the following remarks are worth to be noticed:

- UAVs and up-to-date drone mapping and surveying techniques can be applied for accurate and reliable surveillance of numerous mining activities and terrain observation, including those related to stability monitoring of slopes where mining activities were not carried out for the examined period.
- Using stable and unmovable ground points or installing permanent Ground Control Points (GCPs) is highly recommended for simplifying the in-pit work with UAVs and reducing the probability of inaccuracies introduced due to the change of GCPs every day of measurements. In this case, the profiles of the terrain created will have a stable starting and ending point throughout the entire measurement procedure.
- The combination of traditional surveying methods with the use of UAVs provides an alternative hybrid method for fast mapping large areas, which demands fewer working hours and, consequently, less cost. Additionally, drones have the potential to map areas difficult to be accessed by the personnel of the mines, such as steep slopes and waste heap surfaces that have not been contoured yet.
- It is advised to cross-compare the techniques for a more reliable evaluation of the mining landslides and displacements. Moreover, the supervising team should be adequately trained in the field of UAVs piloting and data processing with special software and mining management procedures.
- The measurements campaign conducted in this study's frame is not considered adequate for claiming that UAVs are ready to replace traditional surveying methods in surface mines' mapping projects. Nevertheless, the obtained results encourage further research.
- In this direction, additional field tests should be conducted under various conditions, such as varying environmental factors and a wide range of weather conditions. In this case, the total duration of measurements is suggested to be at least 12 months.
- The proposed ground surveillance and mapping method can be applied in various types of earth-moving works and in large areas where natural phenomena cause displacement of land surfaces. For instance, the method can be applied for monitoring soil erosion – deposition that goes on with high rates in waste heaps, prior to developing a permanent vegetative cover. In this case, the time intervals between successive measurements must be longer.

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