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A case study on deformation analysis of an open-pit mine using UAV photogrammetry

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Abstract

Innovative technologies, particularly photogrammetry and Unmanned Aerial Vehicles (UAVs), significantly enhance efficiency and ensure security across various domains. In open-pit mines, which are the focus of this article, continuous monitoring of the ground surface and accurate detection of deformations are crucial for operational efficiency and occupational safety. This study examines the open-pit mine near the village of Çomaklı in the Çan district of Çanakkale province, exploring the general definition of deformation analysis and measurements using the UAV-based photogrammetric method. It discusses applying deformation analysis in mining and using UAVs in deformation studies with technological advancements. It also provides detailed information about the methodology and data collected. Aerial photographs of the mine site were captured to analyze deformation over time. A 3D surface model of the terrain was generated using the Pix4D Mapper software, enabling the assessment of volume changes in a specified working area within the stripping zone and identifying these changes through cross-sections. The results demonstrated that UAV-based photogrammetry could accurately detect volumetric changes, achieving a vertical root mean square error of approximately 8 mm and an accuracy of about 99.10% in volume estimation.

1. Introduction

Today, with the advancement of camera technologies, remote sensing and geospatial analysis methods have also developed significantly. By utilizing these methods, it has become possible to save time and reduce costs related to data acquisition. Although photogrammetric methods are primarily employed for topographic mapping in the creation of three-dimensional models and spatial data, their application has become widespread across various fields, including architecture, industry, underwater research, health, and geology. As technology continues to evolve, the use of Unmanned Aerial Vehicles (UAVs) in photogrammetry has accelerated, leading to numerous studies conducted in recent years.

UAV platforms equipped with camera sensors are crucial for generating photogrammetric data today. Along with RGB cameras, ultrasonic sensors, infrared sensors, stereo cameras, laser scanners, radar, and hyperspectral sensors are utilized in producing land surface models [1]. Because of their rapid data collection capabilities, UAVs offer significant advantages in terms of time and cost. UAV Photogrammetry is essential in various studies, such as monitoring natural disasters, protecting the environment, assessing land use changes, analyzing deformations, and preserving cultural heritage.

In terms of protecting and evaluating cultural heritage, [2] examined the accuracy of three-dimensional (3D) modeling applications obtained through photographs taken by UAVs. The study used the Kanlıdivane Church as an example to investigate the production of high-accuracy 3D models by combining high-resolution images captured by UAVs. In this process, the geometric and surface features of the objects were modeled using photogrammetry techniques. In another study, efficient 3D model extraction was accomplished using UAV photogrammetry in an archaeological excavation area [3].

There are numerous applications of UAV photogrammetry. In addition to 3D modeling of cultural heritage sites, it serves as a crucial data source for flood analysis. [4] For instance, the study illustrates 3D modeling of Kocabaş Stream using UAV images in the Çan district of Çanakkale Province, followed by the generation of Digital Surface Model (DSM) and orthophotos that can be utilized in various fields, including flood management analysis.

Geomatics methods are very important for obtaining spatial information to explore and monitor mines [5]. However, classical measurement methods are often inadequate for data collection. UAV and photogrammetry techniques are currently popular advanced applications in this field. With the widespread use of UAVs, there have been significant developments in data collection and analysis processes in mining. While ground measurements in the clay field owned by the General Directorate of Etimaden Enterprises took hours in muddy and dusty conditions with multiple workers, photogrammetric measurements were completed in a very short time using a UAV, leading to results through data processing and evaluation [6].

The study by [7] discussed UAV applications in open-pit mining operations in detail and emphasized the role of these technologies in mining operations. The study discussed the potential of UAVs in many areas, such as data collection, mapping, observation, and monitoring in mining sites. This technology's advantages and innovations to open-pit mining operations are critical for work efficiency and cost management.

The use of photogrammetric methods instead of conventional techniques for volume calculations provides advantages in terms of labor and cost. [8] conducted volume measurements in the silo area using Agisoft Metashape, Pix4Dmapper, and 3DF Zephyr. The high accuracy rates raise expectations that this error rate will diminish as camera technology advances.

[9] aimed to evaluate the use of UAVs in mining regarding efficiency and accuracy. They conducted a photogrammetric assessment using UAVs in an open-pit mine and compared the results to data collected by conventional methods. The study highlights the benefits of UAVs, particularly for rapid and high-resolution data collection across large areas. Data obtained from UAVs can be utilized in critical processes such as monitoring surface deformations, detecting landslides, and overseeing slope stability at the mine site. In comparison to traditional methods, UAVs generate fast and highly accurate models.

Deformations occurring at mine sites are significant events that threaten occupational safety and adversely impact mine productivity. [10] elaborated on the effects of UAV photogrammetry and GNSS-based systems on deformation detection in detail. UAVs create high-resolution images and data, such as DEMs, enabling precise monitoring of volumetric changes and deformations in mining locations. Additionally, advanced analytics, including point clouds and 3D modeling, facilitate improved tracking of the changing processes within mining operations.

Due to the geomorphologic characteristics of Turkey, many areas experience deteriorating soil stability, such as erosion and landslides. Monitoring these areas and examining changes over time is crucial for preventing loss of life and property. The detection of erosion areas using UAV technology in the Thracian Peninsula serves as an example of these studies. The Thracian Peninsula, located in northwestern Turkey, is a region with intensive agricultural activities. Soil loss in this area negatively impacts the productivity of agricultural lands and can cause long-term damage to the ecosystem. Studies conducted in Thrace have shown that UAV technology effectively detects erosion, particularly in areas with challenging topography. [11] demonstrated that using UAVs to identify erosion areas in this region yielded valuable results. In this study, high-resolution images obtained from UAVs identified areas experiencing significant erosion and measured the amount of soil loss measured.

Challenged areas often refer to regions with steep slopes, forests, or limited human access. Conventional mapping and land surveying methods can be inefficient in these locations. In particular, steeply sloping and rugged terrains pose obstacles such as landslides, large boulders, and dense vegetation, complicating the data collection process without stable terrain features. In this context, [12] presented significant findings on the use of UAVs in challenging terrains. Additionally, [13] provided a detailed discussion on the process of photogrammetric data collection using UAVs. The study covers the determination of flight routes in mining areas, camera calibration, image acquisition, and the processing of these images through photogrammetry software.

[14] compared stockpile and dump volume determination and measurement studies using orthophoto maps and Digital Elevation Models (DEMs) produced by UAV-based mapping in the open-pit mine located in the Gökveliler district of Manisa province with classical methods. Agisoft Metashape and Virtual Surveyor achieved accuracy rates of 97.64% and 95.45%, respectively.

In open pit-mines, calculating volume, especially for stockpiles, is crucial for effective mine management and environmental audits. These calculations enable the management of key factors such as mine operations, reserve evaluation, and environmental impact monitoring. Alongside traditional methods, modern measurement technologies can today perform volume calculations more quickly, accurately, and efficiently. In this context, a study by [15] compared and analyzed GNSS/CORS and UAV measurement techniques for calculating stockpile volume in open-pit environments mines.

[16] combined traditional surveying and photogrammetric surveying using UAVs. UAVs operate over mining areas equipped with sensors, high-resolution cameras, and GPS devices. He highlighted that the data collected from UAVs can be modeled quickly in three dimensions, allowing for the measurement of large areas in significantly less time. UAVs promise to deliver highly efficient results, particularly in extensive and intricate regions. This approach greatly reduces the time required for data collection while enabling rapid scanning of larger areas efficiently.

Landslides and soil deformations are generally more prevalent in areas where groundwater emerges at the surface or where it destabilizes the soil and slopes, especially when drainage is limited. One significant reason for the deformation observed at the open pit-mine site near Çomaklı village in the Çan district of Çanakkale province, highlighted in this study, is the destabilization of the slopes caused by groundwater. The other important reason is the fault lines passing under the open mine stripping site.

2. Methods

In this study, aerial photographs were taken at three different times (initial, mid, and final) in the designated study area within the open-pit mine site (Figure 1), located in Çomaklı village in the Çan district of Çanakkale, using the UAV photogrammetry method. The resulting data were processed in Pix4D software to produce a DSM and orthophotos. These data were then transferred to the Virtual Surveyor program, where a common working area boundary was established for all flights covering the mine site, allowing for the assessment of deformation over time on a volumetric basis. Additionally, cross-sections were generated through the Netpro module in Netcad software to analyze the deformation and stability deterioration slopes visually.

The study included field studies and post-field image processing conducted to gather the data essential to the research. The steps involved in the field studies and post-field image processing are illustrated in the workflow diagram in Figure 2.

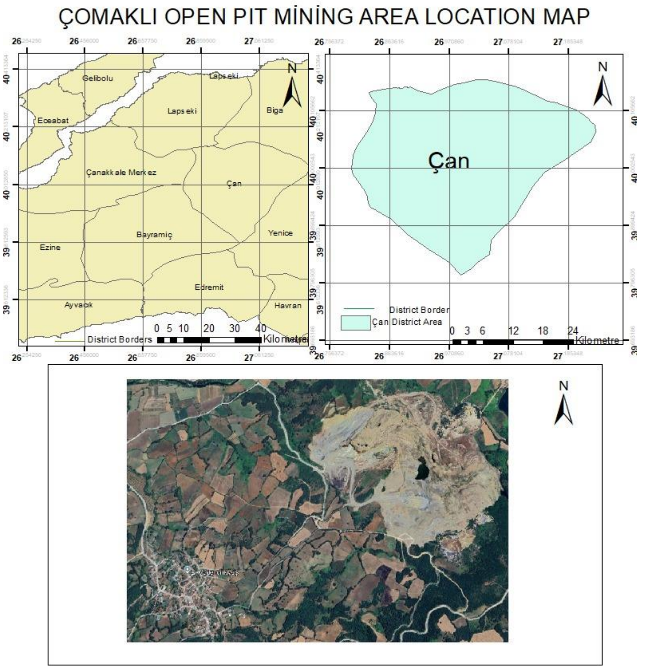

Figure 1. Çomaklı open-pit mine

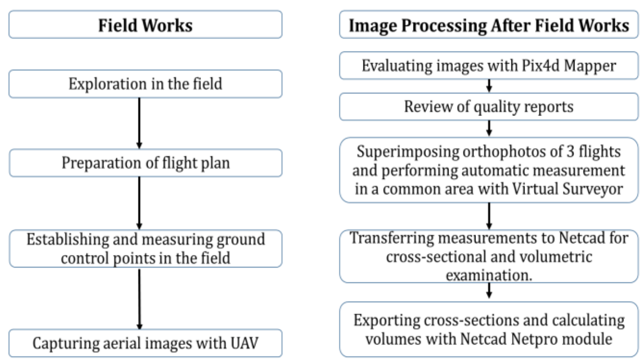

Figure 2. Workflow diagram of the method used in the study

2.1. Field Studies

A reconnaissance study was conducted in the field as part of the broader field studies. Next, based on the geographical features of the terrain, the locations of the Ground Control Points (GCPs) and Check Points (CPs) were roughly determined. Determining the optimal flight altitude and the configuration of the GCPs is essential for enhancing the accuracy of photogrammetric products [17]. The previously determined GCPs were established and epochally gathered using the Real-Time Kinematic (RTK) method in the field. A photograph of the installation of a GCP is presented in Figure 3, while the Continuously Operating Reference Station (CORS) and RTK used to measure the GCPs and CPs coordinates are illustrated in Figure 4 and Figure 5. After completing GNSS measurements at all control points, the distribution of GCPs and CPs is illustrated in Figures 6, 7, and 8. The first flight was executed with a Phantom 4 Pro, and the subsequent two flights were conducted with Mavic 3 Enterprise UAVs. The camera models employed in UAV flights are listed in Table 1.

In our study, flights were conducted on three different dates: June 2023, November 2023, and June 2024. These flights occurred in an open pit mine area near Çomaklı Village, located in the Çan district of Çanakkale province. The timing of the flights was selected to evaluate the effects of seasonal variations and the area's topographical features.

The camera resolution of the Phantom 4 Pro is 20 MP and features a 1-inch CMOS sensor. The Mavic 3 Enterprise is equipped with a 4/3 CMOS sensor and also has a resolution of 20 MP. The flights were scheduled for 10:30 am to avoid solar radiation at noon and to ensure the collection of reliable data.

Both UAV models were selected and utilized in accordance with the technical standards set by General Directorate of Mining and Petroleum Affairs (GDMPA) and General Directorate of Land Registry and Cadastre (GDLRC). While the Phantom 4 Pro V2.0 model employs a fixed focal length camera and verification with GCPs, the Mavic 3 Enterprise model provides high-accuracy positioning due to the integrated RTK module. This ultimately enhances the accuracy and reliability of the map data obtained.

The technical specifications and application processes of both models meet the precision and accuracy criteria required for map production. This indicates that the photogrammetric map production study is reliable and adheres to the relevant standards.

In this study, for the flight planning of deformation analysis using UAV photogrammetry, an 80% front-lap and a 60% side-lap were preferred as overlap ratios. In determining these ratios, the relevant technical standards and codes of practice published by both GDMPA and GDLRC were taken into account.

GDMPA's Guidelines for the Application of Photogrammetric Surveying in Mining Areas with UAVs prepare for photogrammetric surveying with UAVs in open pit mining areas and recommend an overlap ratio of at least 80% front-lap and 60% side-lap. These ratios are particularly preferred for detailed DSM production, volume calculations, and deformation analyses at mine sites. High overlap ratios minimize void formation, bonding errors, and modeling deviations. The technical instructions adopted by GDLRC in photogrammetry and map production processes and the regulations such as the Regulation on Large Scale Map and Map Information Production also emphasize that sufficient image overlap should be ensured for map and orthophoto production.

The specifications of UAVs and flight heights can be seen in Tables 1 and 2, respectively. Side and frontal overlap ratios of 60% and 80% were established, respectively, according to the terrain's structure, and flight planning was conducted using the UAV's handheld device. In the study, flight altitudes were maintained between 124 and 128 meters, and the ground sampling distances (GSD) obtained ranged from 3.43 to 3.46 cm (Table 2). These values are considered sufficient for high-precision map production.

At least five satellites with a minimum altitude of 10° were used in each measurement. A minimum of ten epochs of data were collected for one second. The first measurements were taken at 9:00 AM, and the second session measurements were conducted at 10:30 AM in accordance with the standards. In our study, TUREF/TM27 (based on ITRF96) was used as the model, and output coordinate systems and height values were expressed as orthometric. This adheres fully to the coordinate system and datum requirements set by GDMPA.

Ground Sampling Distances (GDSs) are provided in Table 3. All images in the study were taken at a nadir angle. In addition to a practical flight, the effect of oblique images on accuracy was also considered [18].

Figure 3. Installation of a GCP

Figure 4. E600 IMU GNSS RTK receiver

Figure 5. E800 IMU GNSS static receiver

Table 1. UAVs sensor specifications

Flights	UAV	Camera
1	Phantom 4 Pro	FC6310_8.8_5472x3648 (RGB)
2	Mavic 3 Enterprise	M3E_12.3_5280x3956 (RGB)
3	Mavic 3 Enterprise	M3E_12.3_5280x3956 (RGB)

Table 2. Flight dates, elevations, and GSDs

Flights	Date	Elevations (m)	GSD
1	June 2023	127	3.46
2	November 2023	124	3.43
3	June 2024	128	3.44

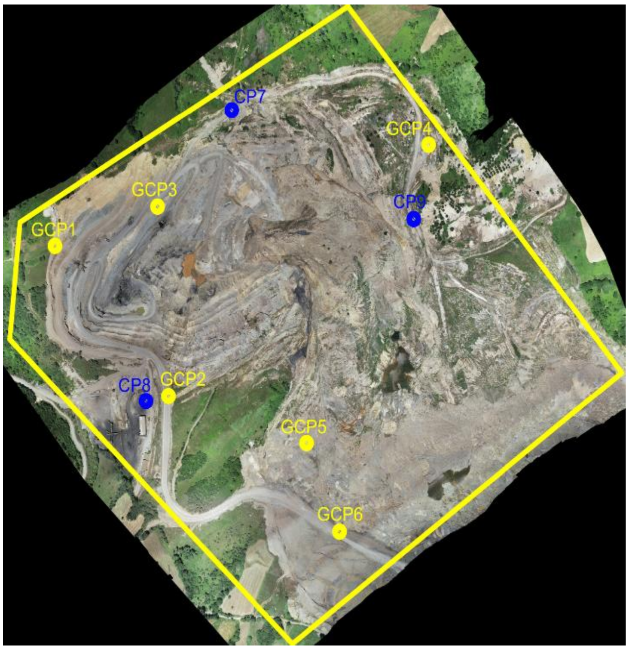

Figure 6. GCP and CP distribution during the first flight

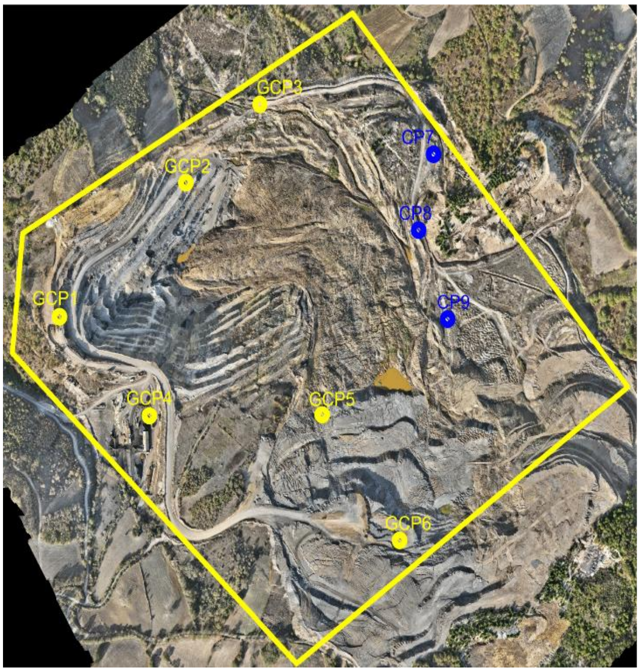

Figure 7. GCP and CP distribution during the second flight

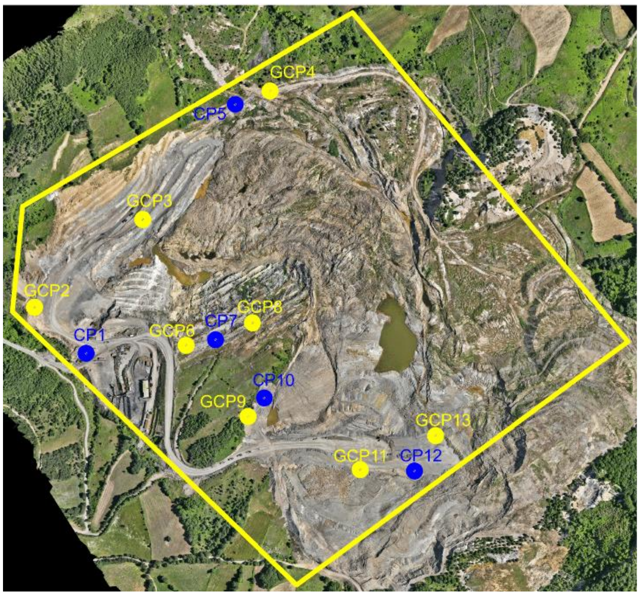

Figure 8. GCP and CP distribution during the third flight

2.2. Photogrammetric Process

The data collected from the field were transferred to the computer environment in the image processing phase following the field studies. The computer's hardware and operating system information is provided in Table 3.

Table 3. Computer specifications used in the photogrammetric process for the first, second, and third flights.

Flights	Hardware	Operating System
1, 2	AMD Ryzen 7 2700 8 Cores, 64GB, NVIDIA GeForce GTX 1660 SUPER	Windows 10 Pro, 64-bit
3	11th Gen Intel(R) Core(TM) i9-11900 @ 2.50GHz, 128GB, NVIDIA GeForce RTX 3080	Windows 10 Pro, 64-bit

The collected images were processed using Pix4D Mapper, a photogrammetric software program. First, image matching was conducted, and the position and orientation of each photograph were adjusted using the external orientation parameters obtained during flight. This process ensured that the images were accurately georeferenced. GNSS data was used to precisely geo-reference the images. Table 4 emphasizes the importance of addressing the coordinate system in the photogrammetric process.

Table 4. Coordinate systems in flight

Model Coordinate System	GCP Coordinate System	Output Coordinate System
WGS 84	TUREF/TM27	TUREF/TM27

The accuracy of the DSM and orthophoto data was assessed using GCPs and CPs. The consistency between the resulting model and these GCPs was analyzed through an accuracy assessment. Meanwhile, the CPs not included in the adjustment were evaluated for validation purposes. The mean error and root mean squared error (RMSE) of GCPs and CPs resulting from the validation process are presented in Tables 5-10. On the other hand, Figures 9-14 present the DSM and orthophotos achieved from the flights.

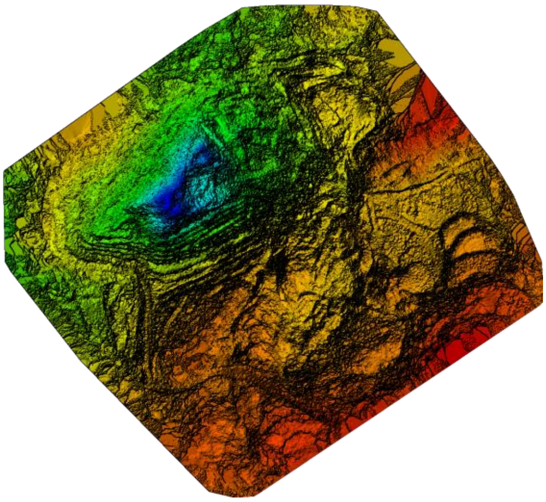

Figure 9. DSM acquired from the first flight

Figure 10. Orthophoto obtained from the first flight

Table 5. First flight GCPs error table

Point no	Error X (m)	Error Y (m)	Error Z (m)
1-1	-0.000	0.001	0.000
1-2	-0.001	-0.001	0.001
1-3	0.000	-0.003	-0.001
1-4	0.001	0.000	0.001
1-5	0.000	0.003	0.000
1-6	0.000	-0.001	-0.000
Mean	-0.000002	-0.000011	0.000189
RMSE	0.000527	0.001723	0.000505

Table 6 . First flight CPs error table

Point no	Error X (m)	Error Y (m)	Error Z (m)
1-7	-0.000	0.002	-0.001
1-8	-0.002	-0.001	0.002
1-9	0.001	-0.003	-0.001
Mean	-0.000333	-0.000667	0.000
RMSE	0.001291	0.002160	0.001414

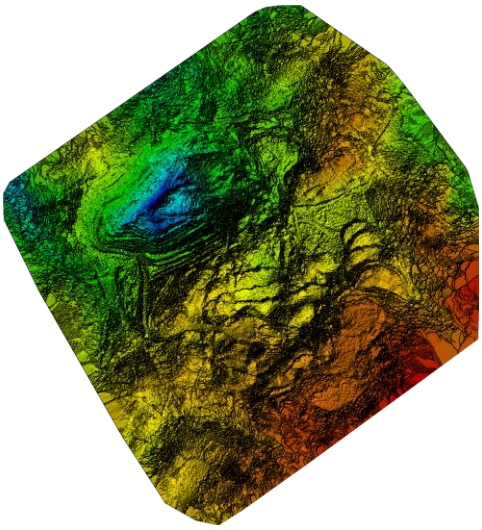

Figure 11. DSM acquired from the second flight

Figure 12. Orthophoto obtained from the second flight

Table 7. Second flight GCPs error table

Point no	Error X (m)	Error Y (m)	Error Z (m)
2-1	0.003	0.004	0.003
2-2	-0.002	0.004	-0.006
2-3	-0.007	-0.005	-0.010
2-4	0.004	-0.003	-0.012
2-5	-0.012	0.006	0.019
2-6	0.012	-0.005	0.006
Mean	-0.000135	0.000054	0.000140
RMSE	0.007792	0.004657	0.010511

Table 8 . Second flight CPs error table

Point no	Error X (m)	Error Y (m)	Error Z (m)
2-7	0.002	-0.001	0.000
2-8	-0.001	0.000	0.001
2-9	0.001	0.002	-0.001
Mean	0.00067	0.00033	0.000
RMSE	0.00141	0.00129	0.00082

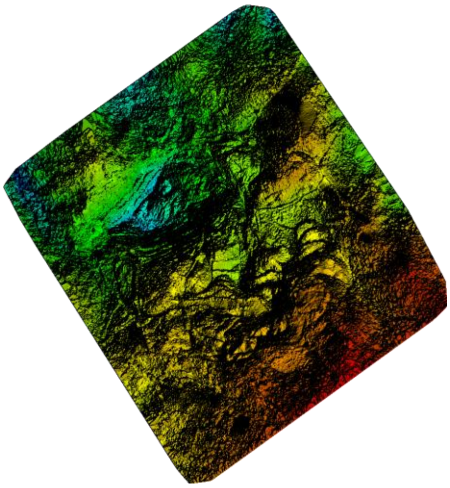

Figure 13. DSM acquired from the third flight

Figure 14. Orthophoto obtained from the third flight

Table 9. Third flight GCPs error table

Point no	Error X (m)	Error Y (m)	Error Z (m)
3-2	-0.005	-0.009	0.012
3-3	0.012	0.003	0.028
3-4	0.002	0.002	-0.000
3-6	0.001	-0.008	-0.019
3-8	-0.001	0.003	-0.006
3-9	-0.006	0.001	-0.011
3-11	-0.002	0.002	-0.003
3-13	-0.001	0.003	-0.004
Mean	0.000033	-0.000148	-0.000534
RMSE	0.005104	0.004680	0.013632

Table 10. Third flight CPs error table

Point no	Error X (m)	Error Y (m)	Error Z (m)
3-1	0.0034	-0.0002	0.0947
3-5	0.0345	0.0276	0.0285
3-7	-0.0154	0.0074	0.0247
3-10	-0.0062	0.0118	-0.0294
3-12	-0.0302	0.0486	-0.0329
Mean	-0.002772	0.019055	0.017130
RMSE	0.021851	0.025777	0.049650

The error values presented in Table 5-10 illustrate the model errors at each ground control point. These errors denote the differences between the coordinates derived from the photogrammetric modeling and the actual coordinates. Most of the error values are quite small, suggesting that the model was constructed with high accuracy. The RMSE in the X, Y, and Z coordinates reflects the overall accuracy of the model, implying that the accuracy of the model is high.

These values are well below the error limits established by GDMPA. Specifically, the maximum error in the Z direction is approximately 5 cm, which provides adequate sensitivity for detecting small deformations. The RMSE Z value obtained in Flight 1 is 0.05 cm, indicating a very high level of accuracy according to GDMPA and GDLRC standards. The RMSE Z value obtained in Flight 2 was measured at 1.05 cm, which offers sufficient accuracy for identifying small-scale deformations. The RMSE Z value obtained in Flight 3 was determined to be 1.36 cm, representing an acceptable level of accuracy for detecting small-scale deformations. Overall, the Z-error values obtained from the three flights align with the general accuracy standards set by GDMPA and GDLRC, providing adequate accuracy for detecting small-scale deformations and for precise terrain modeling.

Virtual Surveyor software was utilized to define the study area accurately. Within this software, the boundaries of the area to be cropped were outlined using multiple lines (Figure 15). These boundaries, established in the virtual environment, were marked on the digital map in an orthogonal manner, clarifying the exact limits of the area. After delineating the study area, these boundaries were exported in Shapefile (shp) vector format. This process was conducted for all three flights.

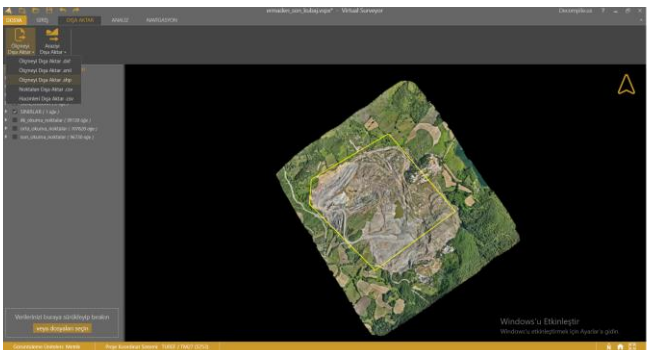

Figure. 15 Study boundaries in Virtual Surveyor

The exported SHP file was imported into ArcMap 10.8. The Clip Management tool in ArcMap 10.8 was utilized. To focus the obtained models on a specific region within the study area, the data was made more manageable by clipping. At the same time, the cropped study area served as a base for creating an elevation map.

Elevation maps were created for all three flights using the cropped DSM data. An elevation map is a colored representation that visually illustrates the topography of the land surface, showing elevation values with specific color ranges. These maps were created using the same color scale for each flight, which makes them comparable.

In ArcMap 10.8, elevation ranges were established based on the DSM data, and a unified color palette was chosen for these ranges. Using a consistent color scale ensured coherent visualization of the height values from the DSMs acquired during the three flights. As a result, the height differences between each flight could be analyzed more effectively, and temporal changes were clearly observed. Figures 16, 17, and 18 display the height maps from the three flights, respectively.

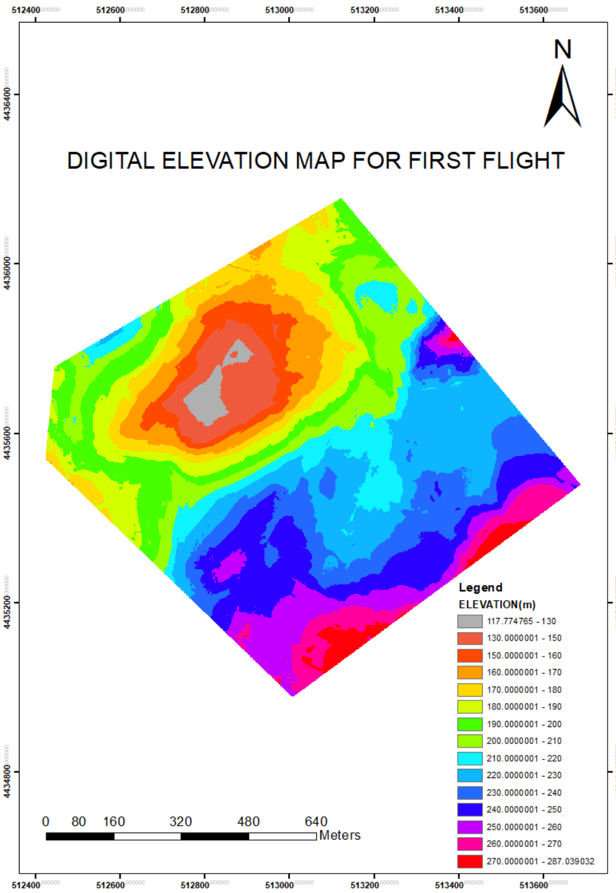

Figure 16. Elevation map of the first flight

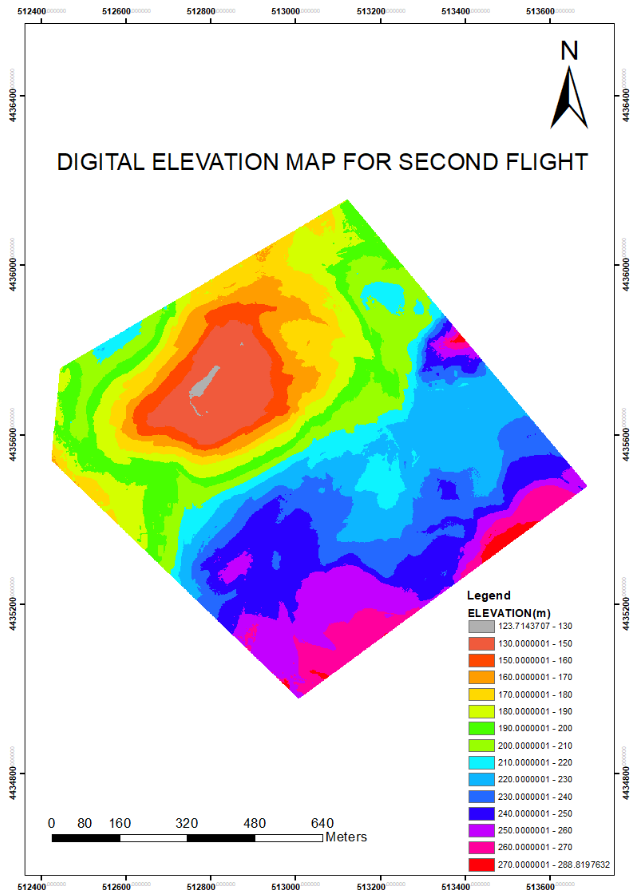

Figure 17. Elevation map of the second flight

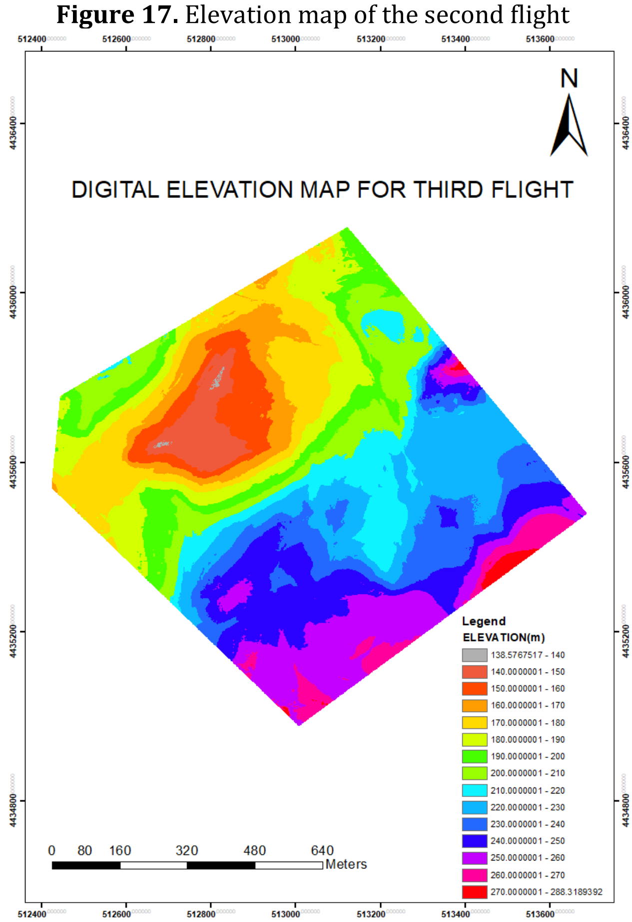

Figure 18. Elevation map of the third flight

3. Results

In this study, the DSM, orthophoto, and 3D models created in the Pix4D application as a result of three flights at different times in the open-pit mine near Çomaklı Village in the Çan district of Çanakkale province demonstrate the significance of UAV photogrammetry in obtaining essential data.

Virtual Surveyor allows users to work interactively with photogrammetric data, particularly DSM and orthophotos. Operations such as pointing, profile drawing, and volume calculation can be performed using a user-friendly interface. Visualizing volumetric differences through regular gridding, especially with the Q-point method, proves to be very practical. It enables faster processing than other CAD-based programs and facilitates visual analysis of data.

Using the DSM data, the Virtual Surveyor program automatically acquired information within the study boundary by employing the Q Point method with a 0.50m margin of flexibility (Figure 19).

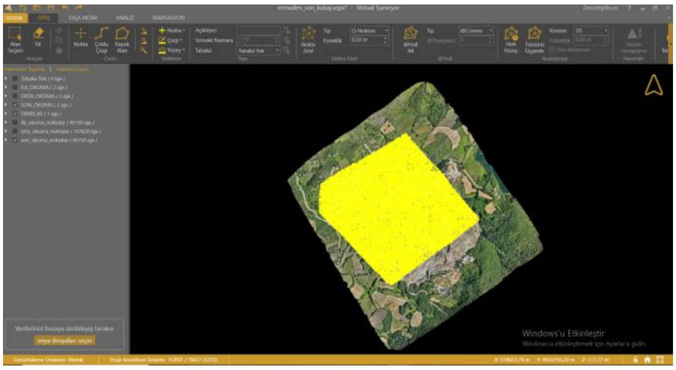

Figure. 19 Virtual Surveyor automatic Q Point retrieval

DSMs obtained with UAVs inherently include trees and other surface elements. For this reason, particularly in areas with vegetation that obstructs accurate representation of the land surface, these areas were visually detected using high-resolution orthophotos, and DSM comparisons were made, with manual interventions occurring thereafter. In these interventions, heights attributed to vegetation were removed, and points were corrected so that the vegetation remained unaffected, preserving the structure of the terrain to create a model closely resembling the actual land surface. Although this process is not automated, these manual corrections produced a terrain model that accurately represents the ground surface for deformation and volume change analysis in the mine.

These acquisitions were transferred to the Netcad environment, and a project was created in the Netpro module to calculate the volumes between three different time flights in the study area; the route was also determined, as shown in Figure 20. The route kilometer coordinate table is provided in Table 11.

Table 11. Route kilometer-coordinate table

Point	Kilometer	Y (m)	X (m)
Start point	0+000.00	512645.586	4435326.586
End point	0+903.71	513404.842	4435816.713

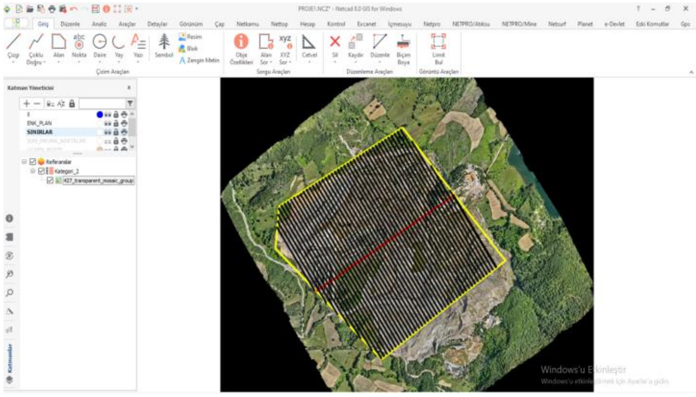

Figure 20. Study area, route, and cross-sections

Cross-sections were determined along the route, and the volumes were calculated. In the Netcad - Netpro module, routes passing through areas of intense deformation were identified, and cross-sections were taken every 20 meters. This interval was determined with a balance that allowed the deformation to be visually clear but did not overwhelm the data. More frequent intervals, such as 5 meters, can produce a lot of detail but may complicate graphical readability. Twenty meters was appropriate for both ease of analysis and a clear view of the topography. The volume calculations are presented in Table 12. Figures 21-28 illustrate cross-sections along the route line of the study area, spanning from 280 to 420 meters.

Table 12. Cumulative volume table between the flights

Flights	Cutting (m3)	Filling (m3)	Bruckner (m3)
1-2	781727.535	1174098.828	- 392371.293
2-3	843727.982	1184062.891	-340334.909
1-3	1175917.456	1907112.003	-731194.546

The accuracy of volume calculations is directly related to the RMSE values, particularly on the Z-axis, which represents vertical position errors. The RMSE value is a critical parameter for determining the accuracy of DSMs. High RMSE values can introduce vertical bias in surface models, leading to errors in volume calculations. This is especially significant in areas such as mining sites, where such deviations can result in inaccurate estimates of material amounts. A low RMSE value is also crucial in deformation monitoring studies. Deformation typically occurs in the vertical direction, and accurately detecting these changes is vital for structural safety and risk management. The RMSE values of the GCPs and CPs in the study are provided in Table 13. In our study area, with an average RMSE value of 8mm in the Z direction, this results in an error rate of 99.10%, calculated using Equations 1 and 2. In equations 1 and 2, Vol stands for Volumetric, and Avg stands for Average.

Table13. Z Errors and RMSE Values

Flights	GCPs (Z RMSE)	CP (Z RMSE)
1	0.05 cm	1.4 cm
2	1.05 cm	0.82 cm
3	1.36 cm	4.96 cm

$$Vol.Error = Avg.RMSE\_in\_Z \times Area \quad (1)$$

$$Vol.Accuracy = (1 - \frac{Vol.Error}{Total\ Vol.Change} \quad (2)$$

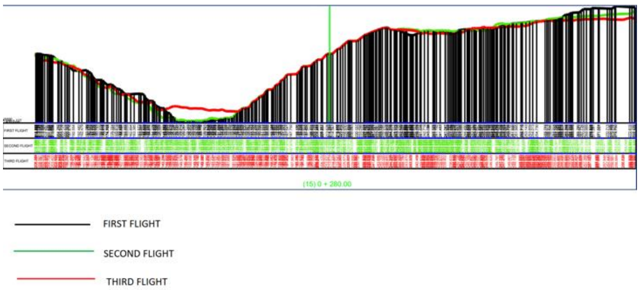

Figure 21. Cross-section at route kilometer 0+280.00

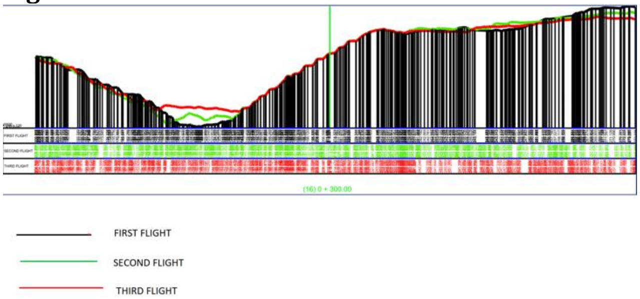

Figure 22. Cross-section at route kilometer 0+300.00

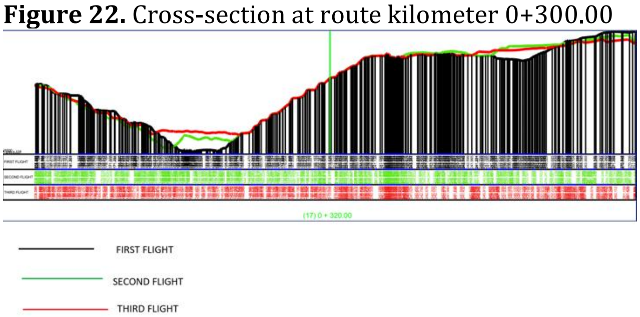

Figure 23. Cross-section at route kilometer 0+320.00

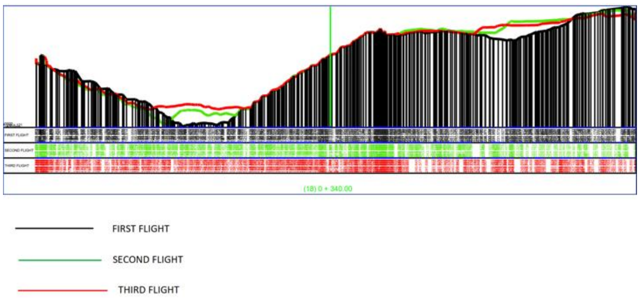

Figure 24. Cross-section at route kilometer 0+340.00

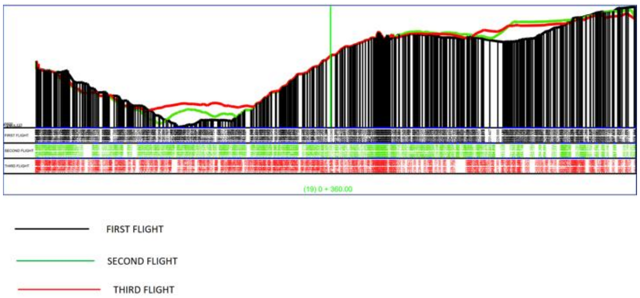

Figure 25. Cross-section at route kilometer 0+360.00

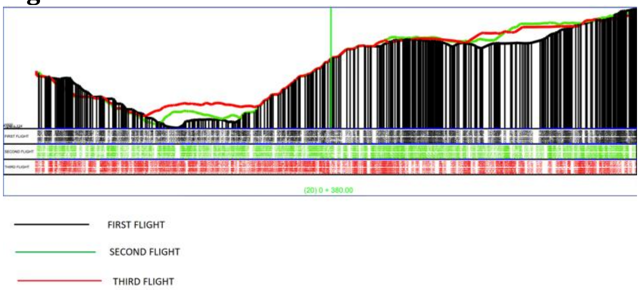

Figure 26. Cross-section at route kilometer 0+380.00

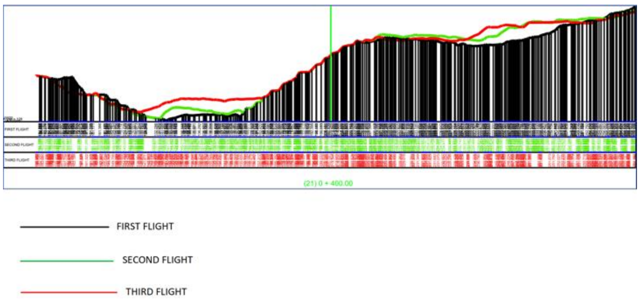

Figure 27. Cross-section at route kilometer 0+400.00

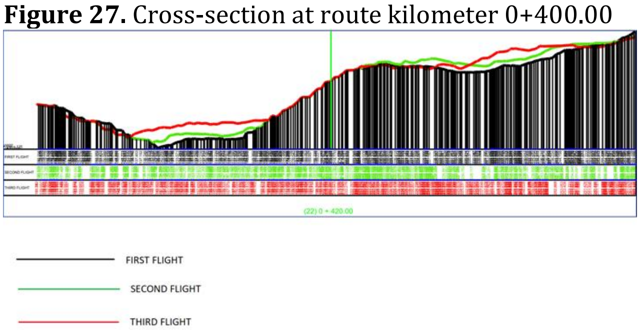

Figure 28. Cross-section at route kilometer 0+420.00

The cross-section method enables visual and numerical comparison of slope stability over time. With cross-sections taken from the same routes at three different periods, sliding, sedimentation, or accretion on the surface can be analyzed clearly. It is one of the most effective methods for detecting minor deformations.

Cross-sectional analyses clearly showed that the upper part of the mine has deformed downwards, particularly after 280 meters along the route line. This finding indicates that the excavation and extraction operations at the open-pit mine site have caused displacement and deformation of the soil and rock structures in the upper part of the mine. Such deformations directly impact the topography and surface structure in the vicinity of the mine, significantly affecting the sustainability and environmental safety of the site. The Çan district of Çanakkale province serves as the study area, is also significant because it is a transit route for fault lines.

Surface deformations were correlated with geological ground features, groundwater status, and fault zones to determine whether only surface deformation existed. Simultaneously, areas consistent with field observations were viewed as indicative of permanent deformation. If a deeper analysis was necessary, it could be supported by systems such as InSAR or ground penetrating radar. A comparison of the three periods of UAV flights in the study revealed that most deformation occurred in the dumping areas. However, this deformation manifests as landslides due to natural factors rather than volume changes caused by excavation or filling activities in the classical context.

The main reasons for the observed deformation in the dumping areas are the lack of drainage and proximity to fault lines. Due to the random and uncontrolled piling of dump material, surface and groundwater drainage is inadequate in these areas. This leads to water accumulation in the dump material, especially during rainy periods, which reduces the soil's bearing capacity. As the soil becomes saturated, slip surfaces form, and the soil mass begins to slide. On the other hand, the investigated area is situated within active tectonic zones, and analysis of the local geological data reveals that a fault zone passes close to the study area. This fault line undermines the natural stability of the site, particularly destabilizing the sloping piles of rubble. Alongside the weak soil conditions, this is another factor that amplifies the magnitude of deformation.

Fault lines and drainage issues pose a major threat to the environmental safety of the mine and increase the likelihood of such problems escalating future.

DSM, orthophotos, and point clouds obtained from GNSS receivers and UAV photogrammetry in open-pit mines are vital data for mining. With these data, changes in mine sites can be detected precisely and efficiently, allowing appropriate measures to be taken accordingly. Natural processes or human activities, such as slope failure, soil destabilization, and the expansion of the mine stripping area, may drive these changes. Early and on-site detection is crucial for enhancing the productivity of mines and preventing potential hazards and risks.

Photogrammetric data allows for continuous monitoring of the mine site, while the accuracy of the data obtained through integrating the RTK method and GCPs is significantly enhanced. Despite the significant contributions of GCPs to accuracy, UAV photogrammetry can also achieve relatively high-accuracy volume calculations without using GCPs, particularly in flat terrain [19]. The combined use of GNSS and UAVs improves positional accuracy, enabling a more precise analysis of changes in mines. While the RTK method offers highly accurate location data, this information becomes even more reliable and precise with the integration of the GCPs. Thus, the measurements taken are accurate and can be updated in real time, allowing for the quick identification of potential hazards.

In conclusion, integrating UAV photogrammetry and GNSS-based methods in open-pit mines enables more efficient, safer, and more sustainable management of mine sites. The combination of these technologies is essential for the future of the mining industry. Deformation detection, early warning systems, and advanced data analysis at mine sites will foster a healthier approach to both occupational safety and economic efficiency. Further development of such systems will enhance mine safety and help minimize environmental impacts.

4. Discussion

In this study, the UAV photogrammetry method was used to analyze deformations with aerial photographs taken at three different times at the open-pit mine in Çomaklı village, located in the Çan district of Çanakkale province. Changes over time were measured on a volumetric basis, and visual changes in slope stability were assessed using Netcad software by overlaying cross-sections on the route. The findings demonstrate UAV photogrammetry's high accuracy and effectiveness for monitoring deformations and managing sites in dynamic environments such as mine sites.

Seasonal changes can affect the accuracy of the data obtained from UAV photogrammetry. In our study, various measures were implemented to minimize these effects. In particular, careful planning was undertaken to reduce the seasonal impact of the flights. Climatic conditions such as brightness, temperature, wind speed and direction, and solar radiation are among the factors affecting photogrammetric accuracy. For example, lower error rates were observed for flights during the morning hours. In our study, flights were conducted in June 2023, November 2023, and June 2024. These dates were chosen to ensure that climatic conditions in the region would not affect photogrammetric accuracy. During the flights, GCPs and CPs point acquisitions were taken at 09:00 in the morning, with the second session acquisitions occurring at 10:30, maintaining at least one hour between sessions. We avoided high brightness and temperature values at midday.

Accurate implementation of field studies and image processing processes is crucial for obtaining data that underpins the study. During the field surveys, the locations of the GCPs were determined and verified using high-precision measurements. Measurements taken with the RTK method enhanced data accuracy and ensured the quality of the photogrammetric processes. In this context, the precise placement of GCPs is critical for DSM and orthophoto production.

The resulting orthophotos and DSMs clearly illustrate the deformation of the mine site over time. Analyzing the differences between three flights at various times offers a powerful method to assess the extent and shape of terrain deformations. Calculating deformations on a volumetric basis is especially useful for applications in large areas such as mines. Volume calculations identify land changes and present these alterations in a more tangible manner. However, due to the small scale of some deformations, detecting them through volume calculations alone can be challenging. Therefore, methods supported by visual analysis, such as the cross-sectional representations in this study, provide more effective monitoring of deformations.

On the other hand, the UAV photogrammetry method employed in this study has certain limitations. For instance, weather and lighting conditions can significantly impact data quality during flights. Overcast weather or low light levels may diminish the resolution and clarity of the photos. Thus, conducting flights in optimal weather conditions will enhance data accuracy. Additionally, the accuracy of the acquired data relies not only on the UAVs' quality but also on the software algorithms. The advanced algorithms found in software like Pix4D Mapper, ArcGIS, Virtual Surveyor, and Netcad play a crucial role in accurately processing and analyzing the data.

LIDAR is particularly advantageous in forested areas, as it can penetrate through vegetation. It also provides more precise height data on steep slopes. However, its cost is high. In this study, photogrammetry is an effective and cost-efficient method, especially in an open mine site where it is primarily applied to bare soil. In future studies, integrating various sensor technologies, like LiDAR, may enable more precise detection of deformations. LiDAR data can deliver topographic information with greater accuracy, especially in challenging terrain, allowing for more detailed insights into slope stability. Additionally, precise monitoring of deformations through long-term studies can yield critical information for managing mine sites. Ongoing routine monitoring can aid in identifying immediate changes, making it easier to implement preventive measures.

5. Conclusions

This study revealed that UAV photogrammetry saves time, manpower, and costs compared to traditional methods. DEM and orthophotos obtained from UAV data can be utilized across various disciplines. Integrating the positioning accuracy of the GCPs and the positioning accuracy within the UAV-RTK method can yield more reliable and precise spatial data.

With the advancement of technology, the sensitivity and accuracy of deformation methods in flight are expected to continue to improve. These developments are particularly crucial for monitoring hazardous areas and identifying deformed regions. Detecting and analyzing risks caused by natural disasters or human activities, such as shifting soils or structural changes, will enable more precise and dependable planning. UAV-based photogrammetric techniques play a vital role in the early detection of such situations and in the implementation of safety measures. Furthermore, these technologies facilitate real-time data collection and monitoring, immediately identifying changes in hazardous areas.

High-resolution data from UAVs will help achieve long-term sustainability goals by facilitating accurate monitoring of environmental changes, structural deformations, and other critical factors. Furthermore, artificial intelligence and machine learning techniques will enhance the processing and analysis of data obtained through these technologies, leading to the development of more effective and proactive management strategies. Such innovative approaches will boost the success rates of future projects while reducing environmental and economic risks across the sector and society at large.

In conclusion, UAV photogrammetry provides faster, more efficient, and more reliable data collection methods, particularly in mining sites and environmental monitoring areas. As these technologies are integrated and advanced software solutions are developed, it is anticipated that even more precise, rapid, and cost-effective solutions will emerge in the future. Additionally, the diversity and accuracy of data provided by UAVs will facilitate the development of more effective project management and risk management strategies.

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Author contributions

Mehmet Ünlü: Conceptualization, Writing, Data curation, Formal analysis, Methodology. **Özgün Akçay:** Editing, Writing and Supervision.

Conflicts of interest

The authors declare no conflicts of interest.

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