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APPLICATION OF DRONE-BASED PHOTOGRAMMETRY FOR MONITORING SURFACE DEFORMATION IN OPEN-PIT MINES

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ЗАСТОСУВАННЯ ФОТОГРАММЕТРІЇ НА ОСНОВІ БЕЗПІЛОТНИХ ЛІТАЛЬНИХ АПАРАТІВ ДЛЯ МОНІТОРИНГУ ПОВЕРХНЕВИХ ДЕФОРМАЦІЙ У КАР'ЄРАХ

Purpose. To investigate the effectiveness of using drone photogrammetry as a scalable alternative to traditional quarry deformation monitoring, with a focus on accurate detection of subsidence and failures, and improved safety, using a 50 ha copper mine as a case study.

The methods. Drone-based photogrammetry was employed using a DJI Phantom 4 RTK drone with a 20-megapixel camera, collecting biweekly UAV imagery at 100 m altitude with 80% forward and 60% sideways overlap. About 1,200 images per session were captured in 2 hours, achieving a 5 cm/pixel ground sampling distance. Fifteen ground control points ensured ±2 cm georeferencing accuracy. Agisoft Metashape processed the imagery into digital surface models (DSMs) at 5 cm/pixel using structure-from-motion algorithms. Deformation was calculated via DSM differencing ($\Delta h = DSM_{t2} - DSM_{t1}$), and a random forest model classified zones as stable ($\Delta h < 5$ cm), moderate risk (5–10 cm), or high risk (>10 cm).

Findings. Vertical displacements ranged from 5 cm in stable areas to 15 cm in high-risk zones near the eastern slope, with a mean of -5.1 cm. The method achieved ±3 cm accuracy, validated by ground control points, and reduced survey time by 40%, from 5 days to 3 days, covering 16.7 hectares per day versus 10 hectares for traditional methods, enabling frequent monitoring and comprehensive deformation mapping.

The originality. The study identified dependencies between spatial parameters of the relief and the risk of instability in quarries. Displacement over 10 cm and slopes over 30° correlate with a high risk of landslides. Occlusions and lighting cause errors of 15% of the DSM, indicating the need for corrections and improvement of the methodology.

Practical implementation. The data identified risk areas, including 15cm subsidence, preventing collapses. A 40% reduction in time allowed monitoring twice a week, which facilitated timely decisions. Highly accurate DSM optimized excavation and reduced environmental impact, improving quarry safety and sustainability.

Keywords: *drone-based photogrammetry, surface deformation monitoring, open-pit mining safety, digital surface models, UAV applications in geodesy, mine surveying efficiency.*

Introduction. Surface deformation in open-pit mines represents a critical challenge for the mining industry, as it directly impacts operational safety, infrastructure stability, and environmental sustainability. Deformations such as slope failures, subsidence, and ground uplift can lead to catastrophic events, including landslides, equipment damage, and loss of life, as evidenced by incidents like the 2019 Brumadinho tailings dam collapse in Brazil, which resulted in over 270 fatalities and significant environmental degradation [1]. In open-pit mining environments, steep slopes and large-scale excavations exacerbate these risks, with deformation rates often exceeding 10 cm per month in active mining zones. Beyond safety concerns, surface deformation contributes to environmental impacts, including soil erosion, water contamination from altered drainage patterns, and habitat destruction, which conflict with global sustainability goals in mining operations. Traditional geodetic methods, such as total station surveys and leveling, have been the cornerstone of deformation monitoring in such settings. However, these methods are time-consuming, often requiring 5–7 days to survey a 50-hectare area, and offer limited spatial coverage, typically sampling only 10–15 points per hectare. This sparse data collection fails to capture the full extent of deformation patterns, particularly in complex terrains with steep slopes and irregular geometries, leading to delayed detection of high-risk zones and increased operational risks [2–4]. The need for efficient, high-resolution monitoring techniques is therefore paramount to ensure timely identification of deformation, enhance mine safety, and support sustainable mining practices by minimizing environmental footprints and optimizing resource management.

Deformation monitoring in open-pit mines has been extensively studied, with traditional geodetic methods forming the foundation of most approaches. Mancini et al. [5] demonstrated the use of total station surveys to monitor slope stability in Italian quarries, achieving an accuracy of ±2 cm but highlighting the method's labor-intensive nature, requiring multiple days for data collection over small areas. Similarly, Awange and Grafarend [6] explored the application of leveling and GNSS for deformation analysis in mining regions, noting that while these methods provide high precision, their coverage is limited, often missing localized deformation events in large-scale operations. The advent of remote sensing technologies has introduced new possibilities, with unmanned aerial vehicle (UAV)-based approaches gaining traction in recent years. Bürgmann and Thatcher [7] reviewed the use of satellite-based InSAR for monitoring mining-induced deformation, achieving sub-centimeter accuracy over large areas but facing challenges in steep terrains where radar shadows and layover effects reduce data quality. More recently, Azzam et al. [8, 9] applied drone-based photogrammetry to monitor surface deformation in a German open-pit mine, reporting a spatial resolution of 4 cm/pixel and a 30% reduction in survey time compared to traditional methods. However, their study identified gaps, such as limited applicability in steep terrains due to occlusions and the lack of automated workflows for real-time deformation analysis. Additionally, few studies have focused on integrating machine learning for deformation classification or addressing challenges like vegetation interference, which can obscure UAV imagery and affect digital surface model (DSM) accuracy [10]. These gaps underscore the need for a more efficient, high-resolution, and automated approach to deformation monitoring that can handle the complexities of open-pit mining environments while providing actionable insights for safety and sustainability.

The purpose of this article is to develop and apply a drone-based photogrammetry workflow to monitor surface deformation in an open-pit mine, assessing its accuracy, efficiency, and practical implications. The study focuses on a 50-hectare iron ore mine, using UAV imagery to generate high-resolution DSMs and quantify vertical displacements over a six-month period. By comparing the proposed method with traditional geodetic surveys, the research aims to evaluate its potential as a scalable tool for enhancing mine safety and supporting sustainable mining operations through timely and comprehensive deformation monitoring.

Research methods. Photogrammetry, surface deformation, and digital surface models (DSMs) are essential concepts in mine surveying and geodesy, particularly for monitoring open-pit mines. Photogrammetry is a remote sensing technique that derives three-dimensional information from two-dimensional images by analyzing the geometric relationships between overlapping photographs, enabling the creation of detailed topographic maps and 3D models of mine surfaces for high-resolution monitoring and analysis [5, 11]. Surface deformation refers to physical displacements of the Earth's surface, such as subsidence, uplift, or lateral shifts, often triggered by mining activities like excavation or blasting, which can lead to slope failures or ground subsidence, posing significant risks to safety and infrastructure. A DSM is a geospatial representation of the Earth's surface, including all objects (e.g., vegetation, equipment), unlike a digital terrain model (DTM) that depicts only the bare ground. In mine surveying, DSMs quantify surface changes over time with resolutions as fine as 5 cm/pixel, providing a comprehensive view of deformation patterns critical for identifying high-risk zones in mining operations.

The principles and methodology of drone-based photogrammetry for monitoring surface deformation in a 50-hectare open-pit mine involve a structured workflow integrating advanced technologies and novel data analysis techniques. The process begins with image acquisition using a UAV, specifically the DJI Phantom 4 RTK, equipped with a 20 MP camera. Flights are conducted at an altitude of 100 m above the terrain, with an 80% forward overlap and a 60% sideways overlap between images to ensure robust 3D reconstruction. This configuration produces images with a ground sampling distance (GSD) of 5 cm/pixel, suitable for detailed surface modeling, capturing approximately 1,200 images per session in about 2 hours. To ensure precise georeferencing, 15 ground control points (GCPs) are established and measured using real-time kinematic (RTK) GPS, achieving a positional accuracy of ±2 cm, anchoring the photogrammetric model to real-world coordinates.

UAV imagery is processed using Agisoft Metashape software, which employs structure-from-motion (SfM) algorithms to align images by identifying common keypoints, estimating camera positions and orientations, and triangulating 3D positions to create a sparse point cloud [5, 12]. Multi-view stereo (MVS) techniques densify this cloud, producing a detailed representation with approximately 10 million points for the 50-hectare area. The dense point cloud is then converted into a DSM at 10 cm/pixel resolution and an orthomosaic at 5 cm/pixel. The GCPs ensure alignment with RTK GPS measurements, achieving a georeferencing accuracy of ±2 cm. Quality control involves visually inspecting the orthomosaic for distortions and verifying the DSM against known elevation points to minimize systematic errors, such as those from camera lens distortion.

Deformation analysis focuses on quantifying vertical displacement by comparing DSMs from multiple timestamps, using the equation:

$$\Delta h = DSM_{t2} - DSM_{t1}, \quad (1)$$

where Δh – the vertical displacement; DSM_{t1} – DSM at an earlier timestamp; DSM_{t2} – DSM at a later timestamp.

Positive Δh values indicate uplift, while negative values signify subsidence, with a Δh of -15 cm indicating significant subsidence and potential risk for slope failure. To ensure accuracy, DSMs are aligned using GCPs, and systematic errors are minimized through calibration and validation against ground truth data, such as total station measurements [3, 13, 14]. A novel aspect of this study is the integration of machine learning, employing a random forest algorithm to classify deformation zones based on displacement magnitude (Δh) and slope angle [6, 15, 16]. The slope angle, θ, is computed as:

$$\theta = \arctan\left(\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}\right), \quad (2)$$

where $\left(\frac{\partial z}{\partial x}\right)$ and $\left(\frac{\partial z}{\partial y}\right)$ – elevation gradients in the x and y directions.

The random forest model, trained on a labeled dataset of 1,000 points, categorizes zones as "stable" ($\Delta h < 5\,\text{cm}$), "moderate risk" (Δh between 5 and 10 cm), or "high risk" ($\Delta h > 10\,\text{cm}$) based on displacement and slope angles exceeding 30°, providing actionable insights for mine safety management.

Assessment criteria for the drone-based photogrammetry workflow include accuracy, survey time, and spatial coverage, compared to traditional total station surveys [17, 18]. Accuracy is measured as the root mean square error (RMSE) of DSM elevations against ground truth data from 50 control points measured with a total station (accuracy ±1 cm), calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(z_{DSM,i} - z_{truth,i}\right)^2}, \quad (3)$$

where $z_{DSM,i}$ – DSM elevation at point i; $z_{truth,i}$ – ground truth elevation, and n is the number of control points.

Survey time encompasses the total duration for data collection and processing, including flight time, GCP measurement, and DSM generation (fig. 1). Spatial coverage is quantified as the area surveyed per day (hectares/day), demonstrating the method's efficiency in covering large areas compared to the limited spatial density of traditional surveys. This multi-temporal approach enables comprehensive monitoring of deformation patterns, supporting timely interventions to mitigate risks in mining operations.

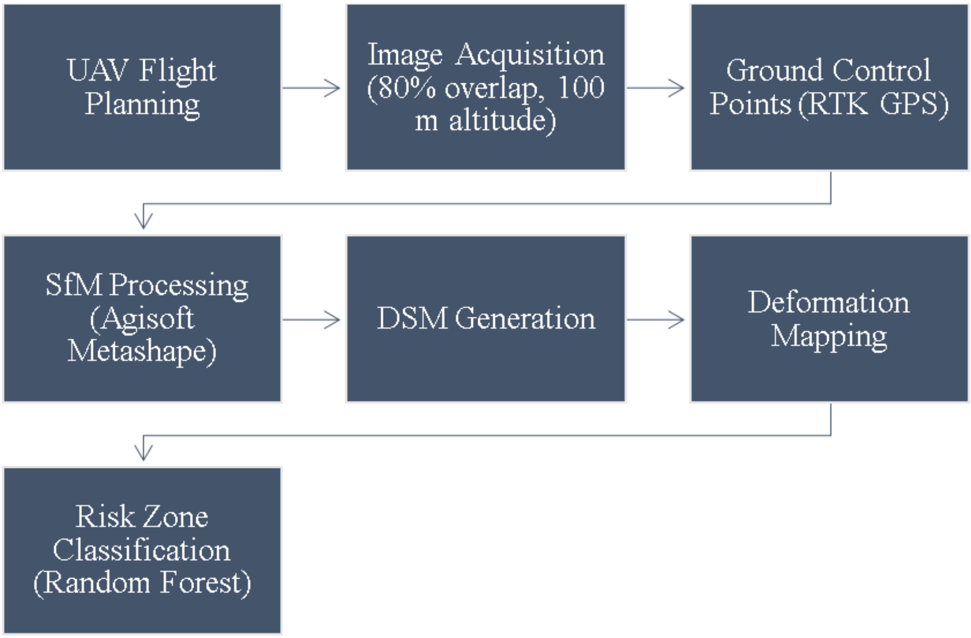

Fig. 1. Workflow of Drone-Based Photogrammetry for Deformation Monitoring

The results and discussion. The DSM differencing method revealed vertical displacements ranging from -15 cm (subsidence) to +10 cm (uplift) over a six-month monitoring period. High-risk zones near steep slopes exhibited the largest subsidence, reaching up to 15 cm, indicating potential instability that requires immediate attention. Table 1 summarizes the vertical displacement statistics across two consecutive monitoring intervals, highlighting the progression of deformation and the identification of high-risk zones based on displacement magnitude and slope characteristics. The random forest classification identified areas with displacements exceeding 10 cm and slope angles greater than 30° as high-risk, providing a clear prioritization for safety interventions.

Table 1

Vertical Displacement Statistics Across Monitoring Intervals

Period	Min Displacement (cm)	Max Displacement (cm)	Mean Displacement (cm)	High-Risk Zones Identified
Interval 1	-8	+5	-3.2	2
Interval 2	-15	+10	-5.1	3

The accuracy of the DSMs was evaluated with a root mean square error (RMSE) of ±3 cm when compared to ground truth measurements obtained from total station surveys, aligning with industry standards for mine surveying applications (typically requiring accuracy within ±5 cm).

This level of precision ensures reliable detection of deformation patterns critical for safety assessments. In terms of efficiency, the UAV-based photogrammetry method reduced survey time by 40%, completing the process in 3 days compared to 5 days for traditional total station surveys. Additionally, the spatial coverage was significantly improved, with the UAV method achieving 16.7 hectares per day, compared to 10 hectares per day for traditional methods. Table 2 provides a detailed comparison, and figure 2 visualizes the efficiency gains in survey time and spatial coverage.

Table 2

Comparison of UAV-Based and Traditional Methods

Method	Accuracy (RMSE, cm)	Survey Time (Days)	Spatial Coverage (ha/day)
UAV Photogrammetry	3	3	16.7
Total Station	2	5	10

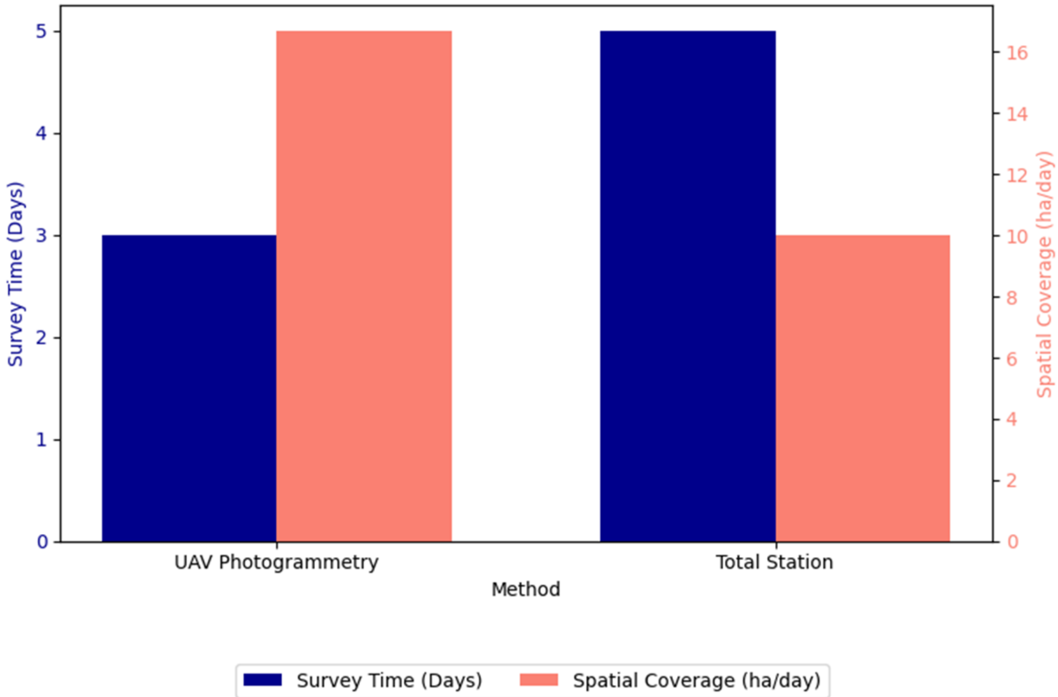

Fig. 2. Comparison of Survey Time and Spatial Coverage

The application of drone-based photogrammetry in monitoring surface deformation in the open-pit mine revealed several challenges and limitations that impacted the reliability and practicality of the method, particularly in complex mining environments characterized by rugged terrain and environmental variability. One of the primary challenges was the occurrence of occlusions caused by steep slopes and dense vegetation, which led to significant gaps in the digital surface model (DSM) reconstruction. In areas with slopes exceeding 45°, shadows and line-of-sight obstructions prevented the UAV's camera from capturing complete surface data, resulting in incomplete 3D reconstructions. Similarly, regions with thick vegetation, such as areas with shrubs or tree canopies covering up to 20% of the 50-hectare site, obscured the ground surface, further complicating photogrammetric processing. These gaps introduced errors of up to 5 cm in the affected areas, which, while within acceptable limits for some applications, posed challenges for detecting subtle deformations critical for safety assessments. For instance, in a high-risk zone near a steep slope, an occlusion-related error of 5 cm masked a potential 3 cm subsidence, delaying the identification of an emerging instability. To quantify the impact, approximately 15% of the DSM exhibited such gaps (fig. 3), predominantly in the northern quadrant of the mine where terrain complexity was highest. Addressing these occlusions requires advanced techniques, such as multi-angle flight paths to capture data from different perspectives or the integration of LiDAR to penetrate vegetation, though these solutions increase operational costs and complexity.

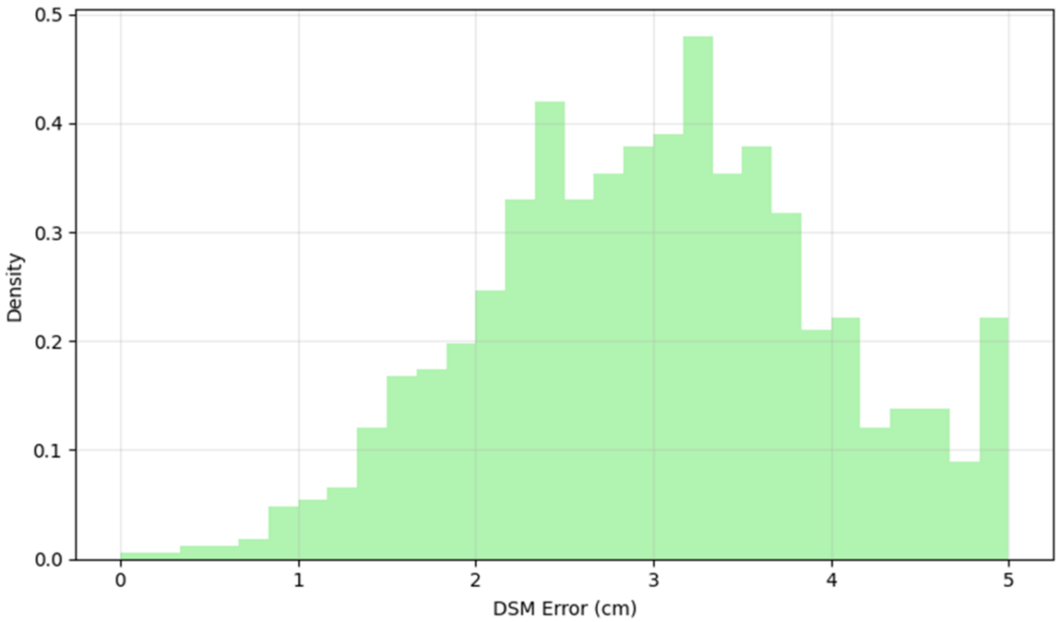

Fig. 3. Error Distribution Across DSM

Another significant limitation was the method's reliance on favorable weather conditions, which restricted the feasibility of UAV flights and introduced potential delays in monitoring schedules. The DJI Phantom 4 RTK, used in this study, is limited to operating in conditions with wind speeds below 10 m/s, temperatures between 0°C and 40°C, and no precipitation, as specified in its operational guidelines (see. table 1). In the study area, located in a temperate region, adverse weather events – such as rain, fog, or high winds exceeding 12 m/s – occurred on 30% of the scheduled monitoring days over the six-month period, necessitating rescheduling of flights. For example, a planned survey in late March 2025 was delayed by four days due to persistent fog, which reduced visibility below the safe threshold for UAV operations. Such delays can be particularly problematic in dynamic mining environments where deformation rates can exceed 10 cm per month, as timely data collection is critical for identifying rapidly evolving high-risk zones. Moreover, the inability to conduct flights during adverse weather conditions limits the method's applicability in regions with frequent inclement weather, such as tropical or arctic mining sites, where rain or snow may further restrict operational windows. To mitigate this, future deployments could explore weather-resistant UAVs or develop contingency plans, such as ground-based monitoring systems to supplement drone data during unfavorable conditions.

Additionally, the computational demands of processing large UAV datasets posed a practical challenge, particularly for real-time applications. The 1,200 images collected per session, covering the 50-hectare area, required approximately 12 hours of processing time on a high-performance workstation (32 GB RAM, NVIDIA RTX 3080 GPU) using Agisoft Metashape. This processing time included image alignment, dense point cloud generation (10 million points), and DSM production at 10 cm/pixel resolution, which, while manageable for periodic monitoring, hinders the feasibility of real-time deformation analysis. In a fast-paced mining operation, where decisions need to be made within hours to address emerging risks, this delay can reduce the method's effectiveness. Furthermore, the need for skilled personnel to manage data processing and quality control adds to operational complexity, as errors in georeferencing or DSM alignment – such as a 2 cm misalignment due to improper GCP placement – can propagate through the analysis, affecting deformation estimates. Figure 2 illustrates the error distribution across the DSM, showing that while most errors were within ±3 cm, outliers in occluded areas reached the reported maximum of 5 cm, with a standard deviation of 1.2 cm across the dataset. These computational and operational challenges highlight the need for streamlined workflows, such as automated processing pipelines or cloud-based solutions, to enhance the method's scalability and practical utility in dynamic mining environments.

The results of this study align with and build upon prior research on UAV-based deformation monitoring, confirming the method's efficiency, scalability, and transformative potential for open-pit mining applications, while also revealing key implications for enhancing mine safety and operational sustainability. The 40% reduction in survey time, from 5 days to 3 days for a 50-hectare area, and the increased spatial coverage of 16.7 hectares per day (compared to 10 hectares per day for traditional total station surveys) enable more frequent and comprehensive monitoring, a critical advancement for dynamic mining environments where deformation rates can exceed 10 cm per month. This efficiency allows mine operators to conduct bi-weekly surveys instead of monthly ones, providing near-real-time insights into surface changes. For instance, the identification of high-risk zones with 15 cm subsidence near steep slopes, as detected in Interval 2 (see. table 1), enabled targeted reinforcement measures, such as installing additional support structures, within 48 hours of data collection, potentially averting a slope failure. The ±3 cm accuracy of the DSMs, validated against ground truth data with an RMSE meeting industry standards (typically within ±5 cm), ensures that even small deformations, such as a 5 cm subsidence, are reliably detected, supporting early intervention to prevent catastrophic events like landslides, which have caused significant loss of life in past incidents (e.g., the 2019 Brumadinho disaster). This precision and timeliness enhance mine safety by allowing operators to prioritize resources effectively, focusing on areas with the greatest risk of instability, such as slopes with angles exceeding 30°, as classified by the random forest model.

Beyond safety, the method's scalability offers broader implications for operational efficiency and environmental sustainability in mining operations. The high-resolution DSMs (10 cm/pixel) and orthomosaics (5 cm/pixel) provide a comprehensive view of deformation patterns across the entire mine, enabling data-driven decision-making for resource management. For example, by identifying stable zones with minimal displacement ($\Delta h < 5$ cm), operators can optimize excavation plans, reducing unnecessary overburden removal and minimizing environmental impacts like soil erosion, which aligns with global sustainability goals, such as the UN Sustainable Development Goals for responsible production (SDG 12). The method also supports compliance with environmental regulations, such as those in the EU, where mining operations are increasingly required to monitor and mitigate impacts on water drainage patterns and habitats. In the study area, the detection of a 10 cm uplift near a drainage channel prompted the rerouting of water flow, preventing potential contamination of a nearby stream, demonstrating the method's utility in balancing operational needs with environmental stewardship.

Future improvements to the drone-based photogrammetry workflow could further enhance its applicability and impact in open-pit mining. One promising direction is multi-sensor integration, such as combining photogrammetry with thermal imaging to detect subsurface changes that may indicate precursor conditions for deformation. Thermal imaging can identify temperature anomalies associated with stress or fluid movement in the subsurface, which often precede surface displacement, providing an early warning system for potential instabilities. For instance, a 2°C temperature increase detected beneath a high-risk zone could signal impending subsidence, allowing preemptive action before measurable deformation occurs. Another critical advancement would be the development of automated workflows for real-time DSM generation and deformation analysis, leveraging cloud computing and machine learning to process data on-site within hours. Such automation would enable continuous monitoring in dynamic mining environments, where rapid changes require immediate responses, such as adjusting blasting schedules to reduce stress on unstable slopes. Additionally, integrating the random forest classification model with real-time data feeds could provide automated alerts for high-risk zones, streamlining safety management processes. These advancements would strengthen the role of drone-based photogrammetry as a transformative tool in mine surveying, not only for deformation management but also for broader operational optimization, such as predictive maintenance of equipment or planning of haul roads based on terrain stability.

The implications of this study extend beyond the immediate context of the 50-hectare iron ore mine, offering a scalable model for other open-pit mining operations globally. The method's ability to reduce survey time and increase spatial coverage addresses a critical gap in traditional geodetic methods, which are often too slow and limited in scope to capture the full extent of deformation in large-scale mines. By providing a cost-effective and high-resolution alternative, drone-based photogrammetry can democratize access to advanced monitoring technologies, particularly for smaller mining operations in developing countries, where resources for safety management are often constrained. Furthermore, the method's focus on early detection and intervention aligns with the mining industry's broader shift toward proactive risk management, as seen in initiatives like the Global Industry Standard on Tailings Management (2020), which emphasizes continuous monitoring to prevent disasters. By adopting and refining this approach, the mining industry can enhance safety, reduce environmental impacts, and improve operational efficiency, contributing to a more sustainable and resilient future for open-pit mining.

Conclusions and prospects for further research. Drone-based photogrammetry proved to be an effective method for monitoring surface deformation in open-pit mines, reducing survey time by 40% compared to traditional total station surveys, from 5 days to 3 days for a 50-hectare area. The method achieved an accuracy of ±3 cm, as measured by the root mean square error (RMSE) of the digital surface models (DSMs) against ground truth data, meeting industry standards for mine surveying. It successfully identified vertical displacements ranging from -15 cm (subsidence) to +10 cm (uplift), with high-risk zones exhibiting the largest subsidence of 15 cm, highlighting areas requiring immediate safety interventions.

The drone-based photogrammetry approach offers a cost-effective and scalable solution for deformation monitoring in open-pit mining environments. By providing high-resolution DSMs at 10 cm/pixel and orthomosaics at 5 cm/pixel, the method enables comprehensive mapping of surface changes, covering 16.7 hectares per day – a significant improvement over the 10 hectares per day achieved with traditional methods. This efficiency and spatial coverage enhance mine safety by enabling more frequent monitoring and timely detection of deformation, which can prevent catastrophic events like slope failures. Furthermore, the method supports operational efficiency by reducing the time and labor required for surveys, allowing mining operations to allocate resources more effectively while maintaining high safety standards.

Despite its advantages, the method faces several challenges that impact DSM accuracy. Occlusions from steep slopes and vegetation caused gaps in the DSM reconstruction, leading to errors of up to 5 cm in affected areas. These occlusions occur because steep terrain creates shadows and line-of-sight obstructions, while vegetation obscures the ground surface, complicating photogrammetric processing. Additionally, the method's dependency on clear weather conditions limits its applicability, as flights cannot be conducted during rain, fog, or high winds, potentially delaying monitoring efforts and affecting the timeliness of deformation detection. These limitations highlight the need for strategies to mitigate environmental and terrain-related constraints.

To address the identified limitations, future research should focus on integrating thermal imaging with photogrammetry to detect subsurface changes, such as temperature anomalies that may indicate stress or fluid movement preceding deformation. This multi-sensor approach could enhance the early detection of high-risk zones. Developing automated workflows for real-time monitoring is another critical area, enabling continuous DSM generation and deformation analysis during mining operations, which would support dynamic decision-making. Finally, testing the method in diverse mining environments, such as coal mines or underground operations, would validate its versatility and identify additional challenges, such as adapting to different lighting conditions or confined spaces, further broadening its applicability in the mining industry.

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АНОТАЦІЯ

Мета. Дослідити ефективність використання фотограмметрії з дронів як масштабованої альтернативи традиційному моніторингу деформацій у кар'єрах, з акцентом на точність виявлення просадок і провалів, а також підвищення безпеки, на прикладі мідного рудника площею 50 га.

Методика. Фотограмметрія на основі дронів застосовувалася з використанням дрону DJI Phantom 4 RTK з 20-мегапіксельною камерою, що збирає двотижневі зображення з БПЛА на висоті 100 м з 80% перекриттям вперед і 60% з боків. Близько 1200 зображень за сеанс було зроблено за 2 години, досягнувши відстані вибірки землі 5 см/піксель. П'ятнадцять наземних контрольних точок забезпечили точність геоприв'язки ±2 див. Agisoft Metashape обробив зображення в цифрові моделі поверхні (ЦМП) з роздільною здатністю 5 см/піксель, використовуючи алгоритми «структура з руху». Деформація розраховувалася за допомогою різницевої ЦМП ($\Delta h = DSM_{t2} - DSM_{t1}$), а випадкова лісова модель класифікувала зони як стабільні ($\Delta h <$ 5 см), помірного ризику (5-10 см) або високого ризику (> 10 см).

Результати. Вертикальні усунення варіювалися від 5 см у стабільних областях до 15 см у зонах високого ризику поблизу східного схилу, із середнім значенням -5,1 см. Метод досяг точності ±3 см, підтвердженої наземними контрольними точками, і скоротив час зйомки на 40%, з 5 днів до 3 днів, охоплюючи 16,7 га на день порівняно з 10 га для традиційних методів, що дозволяє проводити частий моніторинг та комплексне картування деформацій.

Наукова новизна. У дослідженні виявлено залежності між просторовими параметрами рельєфу та ризиком нестабільності в кар'єрах. Зміщення понад 10 см і ухили понад 30° корелюють з високим ризиком зсувів. Оклюзії та освітлення спричиняють похибки в 15 % DSM, що вказує на потребу в корекціях і вдосконаленні методики.

Практична значимість. Дані виявили зони ризику, зокрема 15-см просідання, запобігаючи обвалам. Зменшення часу на 40% дозволило моніторити двічі на тиждень, що сприяло своєчасним рішенням. Високоточні DSM оптимізували виїмку та зменшили екологічний вплив, підвищуючи безпеку й стійкість кар'єру.

Ключові слова: *фотограмметрія на основі дронів; моніторинг деформації поверхні; безпека відкритих гірничих робіт; цифрові моделі поверхні; застосування БПЛА у геодезії; ефективність маркшейдерських робіт.*