MINE SURVEYING VERIFICATION MEASUREMENTS USING THE UNIFIED DIGITAL MODEL METHOD

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Abstract

The introduction of modern equipment and software by the mine surveying departments of mining enterprises contributes to the improvement of mine surveying methods, enhances the efficiency of the entire mineral extraction and processing cycle, and reduces the cost per tonne of raw material.

The aim of this study is to develop a method for conducting verification surveys of the volume of rock mass extracted during a reporting period, based on current practices in aerial surveying and data processing. The methodology is based on the analysis of the results obtained from the photogrammetric processing of open-pit mine imagery acquired using an unmanned aerial vehicle on different dates. An accuracy assessment of the resulting rock-mass volume estimates made it possible to establish requirements for the number and geometric configuration of ground control points, as well as for the software and hardware employed. The determined surface changes over specified time intervals demonstrated sufficiently high accuracy and complied with the requirements of the relevant regulatory guidelines and technical instructions.

The scientific novelty of the study lies in the development and validation of a method for conducting verification surveys of rock-mass volumes based on the processing of aerial survey data acquired over an open-pit mine. Particular attention was paid to selecting optimal survey conditions; determining the number and geometric configuration of ground control and check points; and selecting the appropriate characteristics of digital models generated for the open-pit mine on different dates.

The findings confirmed the effectiveness of the proposed verification survey method, which enables the operational data provided by the technical department of an open-pit mine to be verified and refined within a short time frame and with the required accuracy. The practical significance of the study lies in the development of an effective method that can be implemented by the mine surveying departments of mining enterprises.

Keywords*: quarry, aerial survey, control measurement, digital model*

1. Introduction

Issues related to the improvement of mine surveying support for mining operations remain highly relevant today, as they have always been [1-3], since the introduction of new technologies into production contributes to increasing the efficiency of the entire mineral extraction process and influences production costs. The implementation of modern technologies enables mine surveying activities to be carried out at a significantly higher level throughout all stages of mineral deposit development [4-6]. One of the key tasks of the mine surveying service at a mining enterprise is the determination of the volumes of extracted rock mass. Numerous studies have analyzed the transition from traditional surveying methods based on GNSS and total station surveys to modern photogrammetric approaches employing unmanned aerial vehicles (UAVs) and Structure from Motion (SfM) techniques [7-8]. Remote sensing methods are indispensable for such objects as open-pit mines, waste dumps, and subsidence zones [9-11]. Consequently, most contemporary studies focus on the use of aerial surveying from various platforms equipped with different types of cameras, with particular emphasis on the application of low-cost UAVs [12, 13].

Mine surveying support of open-pit mining operations at iron ore deposits includes the performance of control surveys [14]. Control surveys are conducted to improve the accuracy of rock mass volume determination in open-pit mines, particularly for material extracted and subsequently delivered to customers or stockpiled. The introduction of modern instruments and technologies into mine surveying practice has resulted in a substantial increase in the volume of surveying data, which requires significant storage capacity

and high-performance computer systems. At the same time, the requirements for the accurate processing of large datasets have become increasingly stringent. Today, in order to improve the accuracy of operational rock mass accounting at iron ore mining enterprises, weighing systems together with modern and efficient methods of instrumental measurements and mathematical computations are employed. However, control surveys make it possible to verify the results obtained over a specific period, prevent the accumulation of errors and inaccuracies, and refine both the calculated volumes and the swell factor.

Since the second half of the twentieth century, aerial surveying has been recognized as one of the most effective methods for conducting control surveys of rock mass volumes, as it provides the most complete and detailed information at a single point in time compared with other methods, such as electronic tacheometry and RTK surveying [15-17]. Numerous studies have investigated the effectiveness of various camera systems used for aerial data acquisition, enabling image capture in different regions of the electromagnetic spectrum [18-21]. However, for the majority of tasks performed by the mine surveying departments of mining enterprises, digital cameras have proven to be the most efficient solution.

As is well known, when aerial surveying is employed, volume calculations are performed by comparing digital surface models of mine workings generated for different observation dates. Research findings indicate that, for the Kryvbas open-pit mines, whose depths range from 170 m to 800 m, the accuracy of volume calculations is significantly affected by both the geometry of the ground control point distribution and their number. This issue has been extensively discussed by numerous researchers [22-25]. Modern open-pit mines are characterized by the presence of multiple areas where intensive mining activities are carried out. Such activities often lead to the destruction of ground control and check points, making it impossible to ensure the stability of reference areas during the period between surveys used for volume determination. Moreover, the presence of hazardous zones that are inaccessible to personnel frequently prevents the establishment of an optimal geometric configuration of ground control and check points. Therefore, this study analyzes the influence of both the quantity and spatial distribution of ground control and check points on the accuracy of survey results.

Before the introduction of digital surveying methods, the vertical cross-section method was commonly used for the determination of rock mass volumes, primarily in areas undergoing dynamic changes. Under appropriate computational conditions, this approach provided results that satisfied the required accuracy standards. Modern digital surveying technologies and software packages for data processing, however, enable the comparison of complete digital surface models generated at the beginning and the end of a reporting period. This approach is more efficient due to its convenience and superior visualization capabilities. At the same time, such methods impose increased demands on hardware resources, particularly with respect to computer memory capacity.

This paper presents the results of a comparative analysis of digital surface models generated for an open-pit mine. In some cases, a phenomenon referred to as model stratification was observed, even in areas that had remained unchanged during the analyzed time interval. For an open-pit mine, a vertical discrepancy between digital surface models of only 0.1-0.2 m may appear insignificant at first glance. However, even for a relatively small quarry with an area of 1.2 km², such a discrepancy may potentially result in volume calculation errors ranging from 120,000 m³ to 240,000 m³.

A comparative analysis of digital surface models corresponding to areas where no mining activities were carried out during the reporting period may also reveal a noise effect caused by random measurement errors, which generally tend to compensate for one another. Systematic errors, however, have a much greater impact on the calculation results, as they create the apparent uplift or subsidence of individual sections of the pit. This, in turn, leads to a significant increase in the errors associated with the determination of rock mass volumes.

It should be noted that errors arising from the comparison of digital surface models of relatively flat terrain are generally minimal. In such cases, vertical discrepancies between models often do not exceed 1-2 cm. Therefore, the problem addressed in this study is particularly relevant for areas characterized by complex topography and significant elevation differences, including mountainous terrain as well as surface mining facilities such as open pits, waste dumps, and subsidence zones.

An important component of surveying operations aimed at creating digital terrain models or digital representations of various objects is the software used for processing aerial survey data [26-28]. Experimental investigations have demonstrated that the accuracy of volume determination is influenced by the choice of mathematical algorithms employed within photogrammetric software packages for image processing and the generation of sparse and dense point clouds. The use of different algorithms for aerial image processing, noise filtering, interpolation, and data densification may lead to systematic discrepancies between digital surface models generated for different dates. These discrepancies directly affect the accuracy of rock mass volume estimation [29].

2. General characteristics of the unified digital model method

To investigate the accuracy of rock mass volume determination using the proposed approach, aerial survey data acquired over Open Pit No. 4 of PJSC Central Mining and Processing Plant were utilized. The surveys were carried out using an eBee unmanned aerial vehicle equipped with a senseFly Aeria X camera. The senseFly Aeria X digital camera features an APS-C sensor with a resolution of 6000 × 4000 pixels and a focal length of 18 mm, corresponding to a 28 mm full-frame equivalent. The camera is equipped with a global shutter and supports an ISO sensitivity range of 100-3200. The camera weight is 260 g.

For the present study, data from four aerial survey campaigns conducted over the open pit were used. The survey dates and the corresponding numbers of acquired photographs are presented in Table 1. The aerial survey dataset acquired in September 2025 (04.09.2025) contains a larger number of images because the flight mission additionally included the survey of a waste dump located south of the open pit.

Tab. 1. Number of Images Acquired
Tab. 1. Liczba uzyskanych obrazów

Survey date	Number of images
29 July 2025	540
27 August 2025	812
26 September 2025	671
22 October 2025	662

All four aerial survey campaigns were conducted using the same flight altitude and the same lateral and longitudinal image overlaps. However, the flight lines of each survey campaign had different azimuths, as their orientation was selected according to the wind direction on the day of the survey. At the Central Mining and Processing Plant PJSC, Pix4D is the primary software package used for the photogrammetric processing of the acquired data.

Several photogrammetric software packages were used to process the data acquired during the four aerial survey campaigns, namely Pix4D, which is the primary software package adopted by the enterprise; RealityScan; Agisoft Metashape; 3DF Zephyr; 3Dsurvey; and Dronet, a component of the Netcad software suite. Subsequent point cloud processing, including the generation of digital surface models and comparative analysis, was performed using Cyclone 3DR 2021.0. To ensure the impartiality of the results and eliminate the potential influence of commercial considerations, the names of the software products used in the study are not disclosed. Instead, they are designated as Software 1, Software 2, …, Software 6 and presented in an arbitrary order.

This study proposes a method for determining rock mass volumes based on the construction of a unified photogrammetric model incorporating two surveys conducted within the same calculation block. The exterior orientation parameters are transferred from the unified model to the individual survey models. Dense model generation is performed by sequentially excluding first the initial survey dataset and then the final survey dataset from the processing workflow.

The proposed method offers the following advantages:

ground control points are required for only one of the surveys;

the closest possible alignment of the digital models is achieved in areas where no changes have occurred, thereby improving the overall accuracy of the results;

the spatial geometry of the ground control point configuration is absolutely identical for both surveys;

the accuracy of image keypoint detection is improved through the extensive use of automated computer vision algorithms rather than manual operator input.

The disadvantages of the proposed method include the following:

low efficiency and, in some cases, the inability to apply the method during seasonal transition periods, such as summer to autumn and winter to spring, owing to substantial changes in the background appearance of the overall scene;

increased data processing time;

higher hardware requirements;

the occasional inability to generate a unified model on the first attempt, indicating solution instability;

the inability to construct a unified model for all surveys when numerous changes in terrain features occur during the time interval between surveys;

distortion of the output coordinate reference system of the generated digital model because the photogrammetric model is allowed the maximum possible number of degrees of freedom.

The above-mentioned limitations do not significantly affect the overall effectiveness of the method, which can substantially improve the accuracy of calculating the volumes of rock mass removed from and rehandled within the open-pit mine.

Figure 1 presents a colour-coded visualization of the changes within the open-pit mine obtained by setting the maximum threshold for the difference between the two models within the range of 5 to 10 m. The visualization provides reliable identification of the area of the open-pit mine in which mineral extraction was carried out.

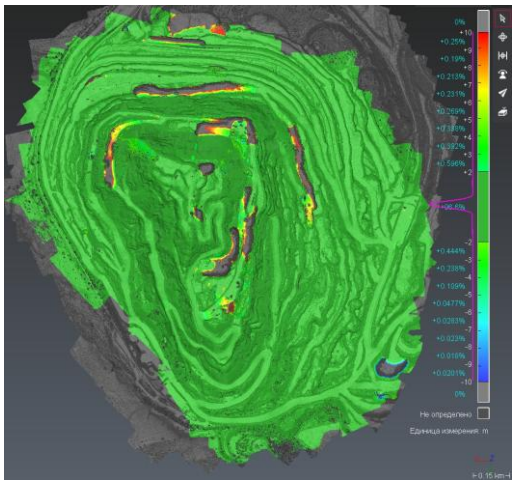
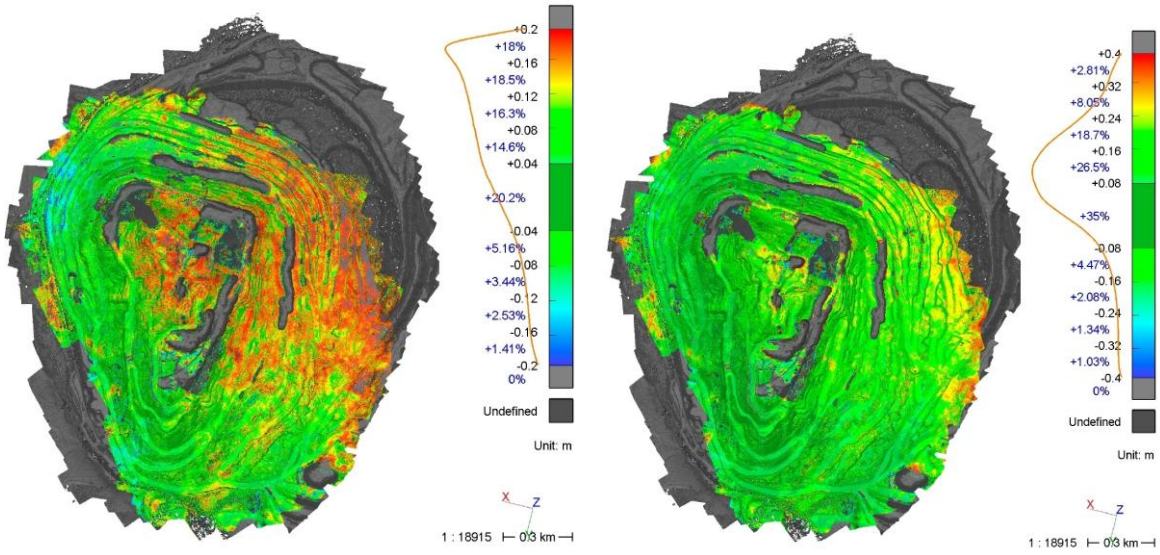


Fig. 1. Colour-coded representation of changes within the open-pit mine at a threshold value of the difference between the two models ranging from 5 to 10 m

Rys. 1. Kodowane kolorami przedstawienie zmian w kopalni odkrywkowej przy wartości progowej różnicy między dwoma modelami wynoszącej od 5 do 10 m

The colour scale and the histogram of deviations shown in Fig. 2 can be used to assess the overall alignment quality of the two surfaces when the maximum threshold value of the difference between the models is set to 0.2 and 0.4 m. As can be seen from Fig. 2, substantial systematic errors occur in this case, extending from the central part of the open-pit mine towards its eastern wall.



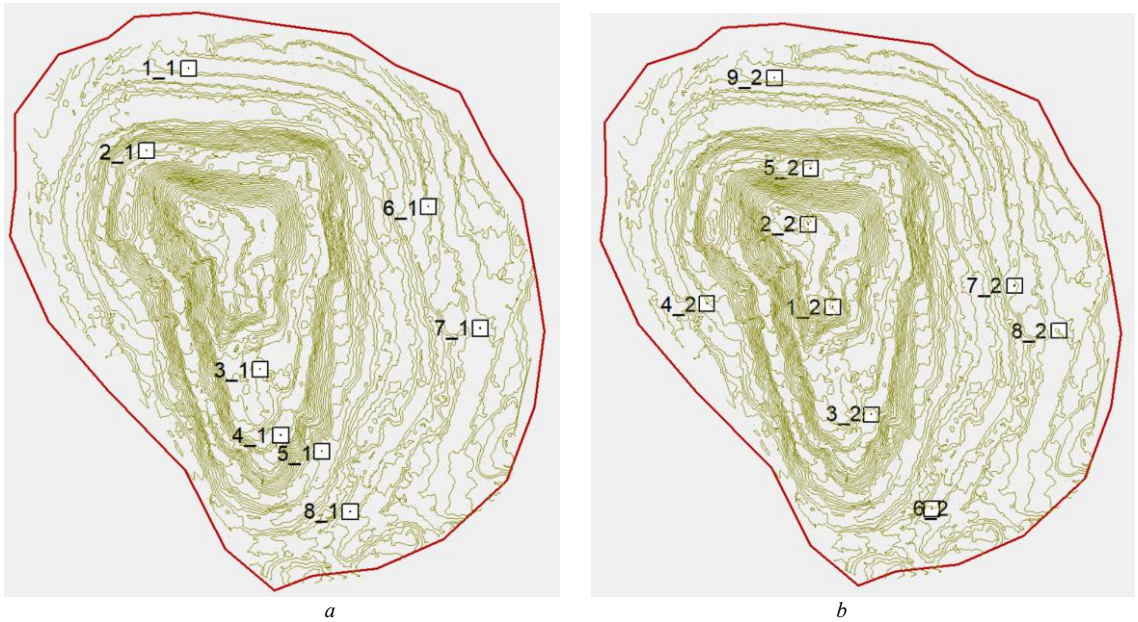
a *b*

Fig. 2. Differences between the two models at maximum threshold values of: (a) 0.2 m; (b) 0.4 m
Rys. 2. Różnice między dwoma modelami przy maksymalnych wartościach progowych: (a) 0,2 m; (b) 0,4 m

In the case described above, the error in determining the volume of excavated rock mass amounted to 161.2 thousand m³. The accuracy of the obtained value was low and did not meet the accuracy requirements for solving this task. It should be noted, however, that this result was the least accurate of all those obtained due to the inappropriate choice of software and the unfavourable geometric configuration of the ground control points.

At first glance, a possible solution would be to supplement the area characterised by large errors with additional ground control points, which would require an additional aerial survey. However, the previously established image-identifiable targets may have been destroyed, while the aerial survey conditions may have changed, for example, owing to a change in wind direction. This could undoubtedly lead to substantially different results and the occurrence of errors in another area of the open-pit mine (Fig. 3).

Analysis of the results obtained from the aerial survey of the open-pit mine operated by Central Mining and Processing Plant PJSC indicated that it is inappropriate to generate the model representing the beginning of the reporting period in one software environment and the model representing the end of the period in another. Nevertheless, such processing scenarios were examined to demonstrate the differences between the data-processing results produced by different software packages.



a *b*

Fig. 3. Locations of ground control points within the open-pit mine on the survey dates: (a) 29 July 2025; (b) 27 August 2025
Rys. 3. Lokalizacja punktów kontrolnych na powierzchni ziemi w kopalni odkrywkowej: (a) 29 lipca 2025 r.; (b) 27 sierpnia 2025 r.

Figure 4 presents the results of a study in which different software packages employing distinct processing algorithms were used to generate the models for the beginning and the end of the reporting period. As a result, close alignment of the digital models was achieved primarily in the vicinity of the ground control points, whereas noticeable discrepancies were observed in other areas.

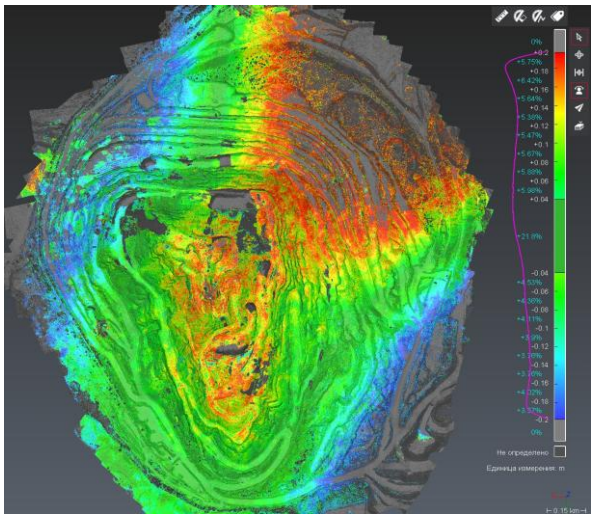


Fig. 4. Alignment results for models generated using different software packages
Rys. 4. Wyniki dopasowania modeli wygenerowanych przy użyciu różnych pakietów oprogramowania

The ground control and check points were surveyed using the GNSS RTK method with Topcon HiPer VR receivers. The base station was located no more than 2 km from the survey area; therefore, the horizontal and vertical coordinate errors of the ground control and check points did not exceed 20–30 mm.

For a preliminary assessment of the errors arising from discrepancies between multi-temporal digital models, the statistical indicators should be converted into metric units. The statistical data are presented as a histogram of deviations showing the deviation magnitudes and their percentage of the total dataset.

Depending on the selected comparison method, two substantially different types of histograms can be obtained. In the first case, the comparison is performed directly by calculating the differences between two point clouds. The advantage of this approach is the reduced processing time, since there is no need to generate surfaces from the point clouds. Figure 5(a) presents the results of the point-cloud comparison.

The time required for surface generation depends on the data volume and the performance of the computing hardware and may exceed 24 hours. The duration of this process is primarily affected by the performance of the graphics processing unit and central processing unit, as well as by the data transfer rate of the random-access memory. Given the large volume of read-and-write operations, storage-device performance is also an important factor in reducing processing time. Therefore, high-speed M.2 solid-state drives are recommended. Figure 5(b) presents the results of the surface comparison.

The disadvantage of this method is the increased noise level in the results. Furthermore, when only point clouds are compared, the resulting histogram shows only the absolute deviation magnitudes and the percentage of points within the corresponding intervals, without indicating the sign of the deviation, that is, whether it represents excavation or fill. Therefore, this approach is most appropriate for preliminary assessment. The greater the proportion of values falling within the intervals corresponding to the smallest deviations, the higher the accuracy of the calculated volume and the lower the influence of errors caused by the misalignment of surfaces representing unchanged terrain features.

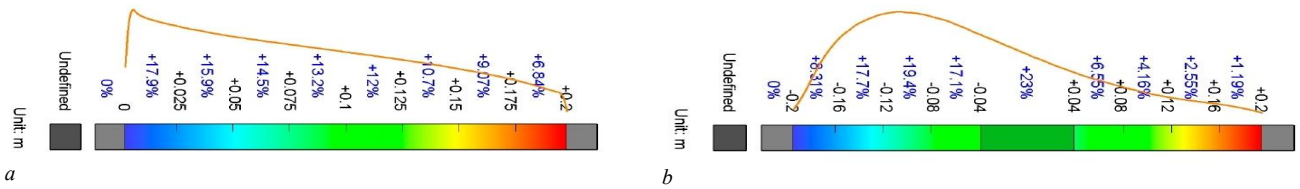


Fig. 5. Comparison results: (a) point clouds; (b) surfaces
Rys. 5. Wyniki porównania: (a) chmury punktów; (b) powierzchnie

In the second case, two surfaces are generated from the 3D point clouds. For preliminary analysis, only one surface may be generated and subsequently compared with the other point cloud. The generation of a detailed surface, particularly from a high-density point cloud, requires considerable computational resources and processing time. However, the resulting comparison histogram shows not only the absolute deviation magnitudes and the percentage of points within the corresponding intervals, but also the sign of the deviation, indicating excavation or fill. This makes it possible both to assess the quality of the computations and to estimate the approximate error in the calculated volumes. During surface generation, some values are averaged; therefore, the noise level in the results is substantially lower than that obtained using the first method. Consequently, the second method should be used to quantify the error caused by surface misalignment.

3. Accuracy of volume determination in various software tools

The processing of aerial survey data using different software packages produced models that differed substantially in terms of surface area (Table 2), point-cloud density, and overall accuracy. The most pronounced discrepancies were observed in the peripheral

areas of the surveyed site. This result was expected because the edges of the survey coverage were represented by fewer overlapping images than the central part, which inevitably reduced the accuracy. Consequently, some software packages generated point clouds for these areas, whereas others did not. This difference should not be regarded as a limitation of the method, since the objective is not to produce a visually appealing model, but rather to obtain mathematically substantiated and reliable results.

Tab. 2. Characteristics of the Generated Point Clouds
Tab. 2. Charakterystyka wygenerowanych chmur punktów

Software package and survey date	Number of points in the point cloud	Horizontal projected area, m²	Surface area, m²
Software 1, survey date: 29 July 2025	70867004	2293930	2580690
Software 1, survey date: 27 August 2025	107713312	3073519	3446532
Software 2, Normal Detail, survey date: 29 July 2025	198750927	2088128	2426501
Software 2, Normal Detail, survey date: 27 August 2025	162544449	2845854	3257973
Software 2, High Detail, survey date: 29 July 2025	688692433	3056917	3416210
Software 2, High Detail, survey date: 27 August 2025	621768390	3036685	3407409

Table 3 presents the results of the analysis of the generated model density for flat and mountainous terrain separately. The density of 3D points in the surface model was lower for mountainous terrain. The calculation results showed that model density had no significant effect on the accuracy of volume estimation, with the error ranging from 1% to 3% of the total volume.

Tab. 3. Density of the Generated Models
Tab. 3. Gęstość wygenerowanych modeli

Software package	Flat terrain		Mountainous terrain	
	Point-cloud density in the horizontal plane, points/cm²	3D point density, points/m²	Point-cloud density in the horizontal plane, points/cm²	3D point density, points/m²
Software 1 (29 July 2025)	0,032	30,9	0,036	27,5
Software 1 (27 August 2025)	0,029	35,0	0,032	31,3
Software 2, Normal Detail (29 July 2025)	0,011	95,2	0,012	81,9
Software 2, Normal Detail (27 August 2025)	0,018	57,1	0,020	49,9
Software 2, High Detail (29 July 2025)	0,004	225,3	0,005	201,6
Software 2, High Detail (27 August 2025)	0,005	204,8	0,005	182,5

In all the software packages used in this study, dense models were generated using the standard (medium-quality) settings. However, to assess the effect of model density, the maximum level-of-detail settings were also applied. Data processing at the maximum level of detail was performed using two software packages and for only two models, since the generation of high-density point clouds requires considerable processing time, storage capacity, and computational resources.

In particular, when the maximum settings were applied, the size of the resulting point clouds exceeded 46 GB and increased further after surface generation. Increasing the point-cloud density resulted in only a slight improvement in accuracy, averaging 1–2% for an area of stable terrain, that is, an area with no surface changes. Furthermore, the calculation results showed that model density did not have a critical effect on the accuracy of volume estimation; therefore, the standard medium-quality settings can be used.

One of the software packages used in the study was designated as Software 1 (Fig. 6).

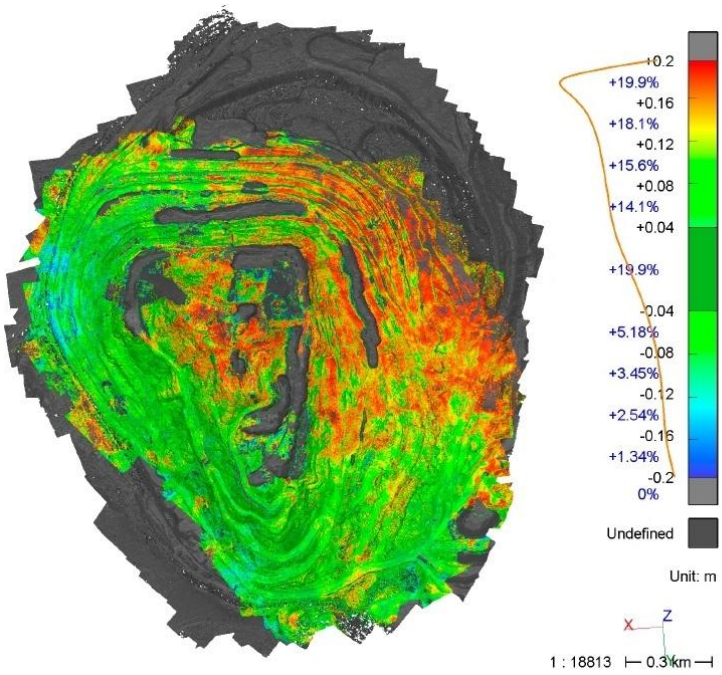


Fig. 6. Results of data processing using Software 1
Rys. 6. Wyniki przetwarzania danych przy użyciu oprogramowania 1

Based on the results of data processing using Software 1, a histogram and the corresponding graphical materials were generated. These clearly indicate the presence of a systematic error component, suggesting that either the number of ground control points in the areas highlighted in red should be increased or higher weights should be assigned to the ground control points located in these areas, provided that this option is supported by the software. The total error in the calculated volume was 161 thousand m³.

Based on the results of data processing in the Software 2 environment, an error histogram was generated (Fig. 7). The histogram exhibits pronounced distribution asymmetry, indicating the presence of systematic error components. The distribution of deviations includes both negative and positive values, indicating an asymmetric displacement pattern and suggesting that certain modelling factors or the survey geometry may have had a significant influence on the results.

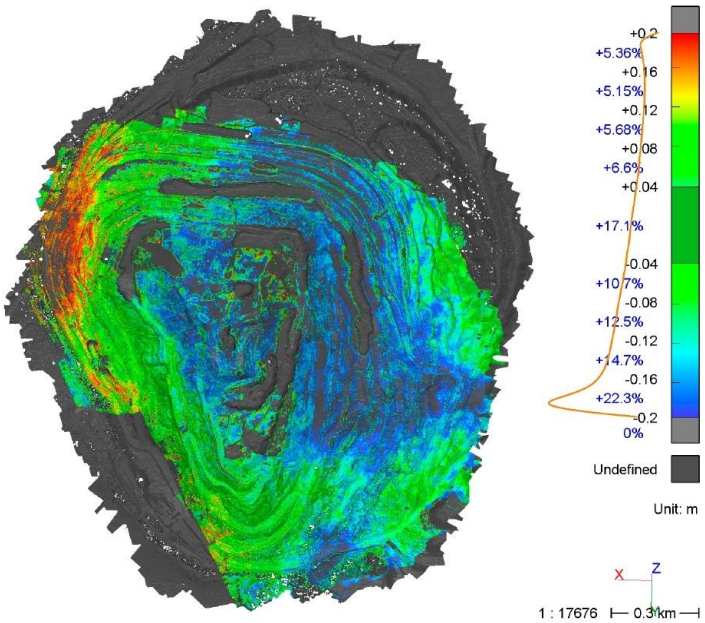


Fig. 7. Results of data processing using Software 2
Rys. 7. Wyniki przetwarzania danych przy użyciu oprogramowania 2

Based on the results of data processing using Software 3, an error histogram was generated (Fig. 8). The histogram exhibits pronounced distribution asymmetry, indicating the presence of systematic errors, predominantly negative. This distribution pattern suggests a possible displacement of the model relative to the reference values, which may be attributable to the specific characteristics of the reconstruction algorithms or the survey conditions.

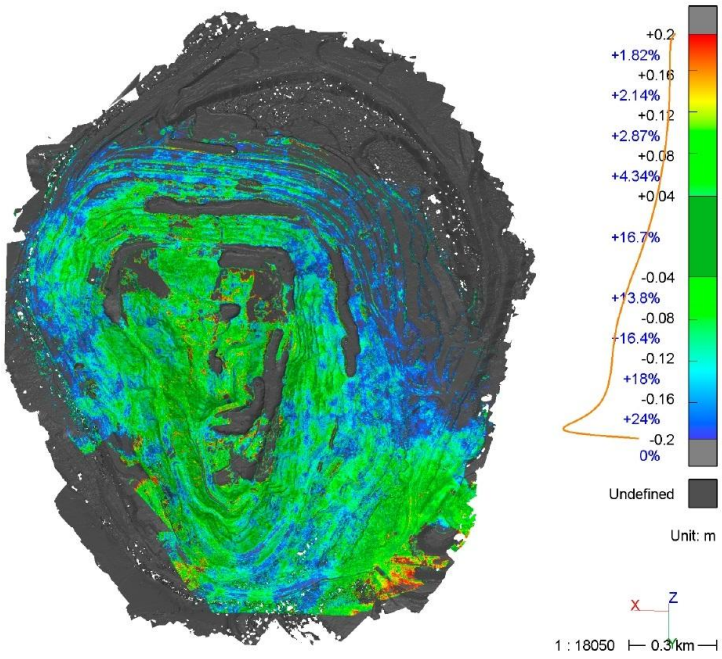


Fig. 8. Results of data processing using Software 3
Rys. 8. Wyniki przetwarzania danych przy użyciu oprogramowania 3

The results of the comparative assessment of different software packages for photogrammetric data processing showed that Software 4 achieved the highest accuracy (Fig. 9). Specifically, 66.7% of the unchanged areas of the two models were aligned within ±0.1 m, representing the best result among all the software packages tested.

Nevertheless, the resulting histogram exhibits pronounced distribution asymmetry, indicating the presence of systematic errors, predominantly negative. This distribution pattern may be attributed to the algorithmic characteristics of the software package or to the specific survey conditions.

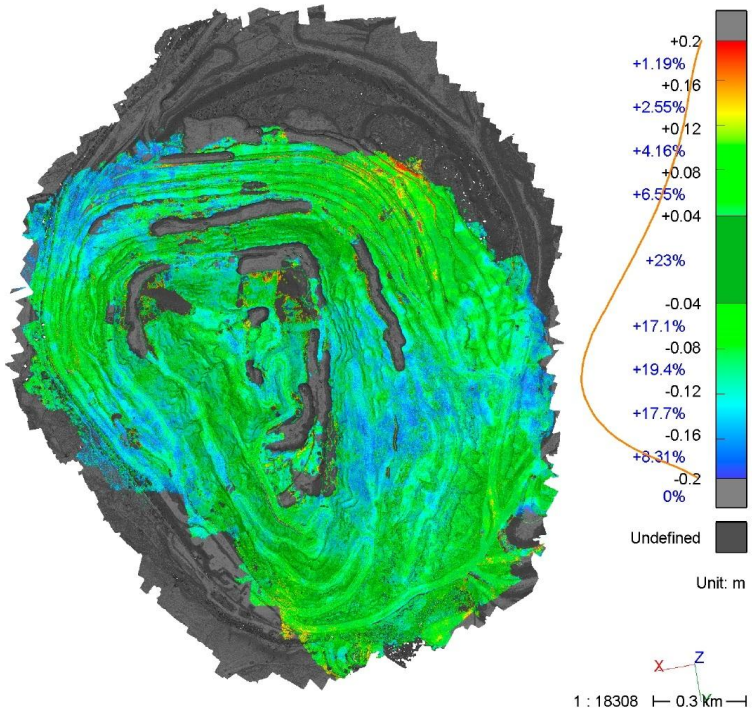


Fig. 9. Results of data processing using Software 4
Rys. 69 Wyniki przetwarzania danych przy użyciu oprogramowania 4

Based on the results of data processing using Software 5, an error histogram was generated (Fig. 10). The histogram exhibits pronounced distribution asymmetry, indicating the presence of systematic errors. However, it does not fully characterise the results obtained, as a large central area exhibits separation between the digital models, with absolute deviations exceeding 0.25 m. This area accounts for more than one-third of the open-pit mine.

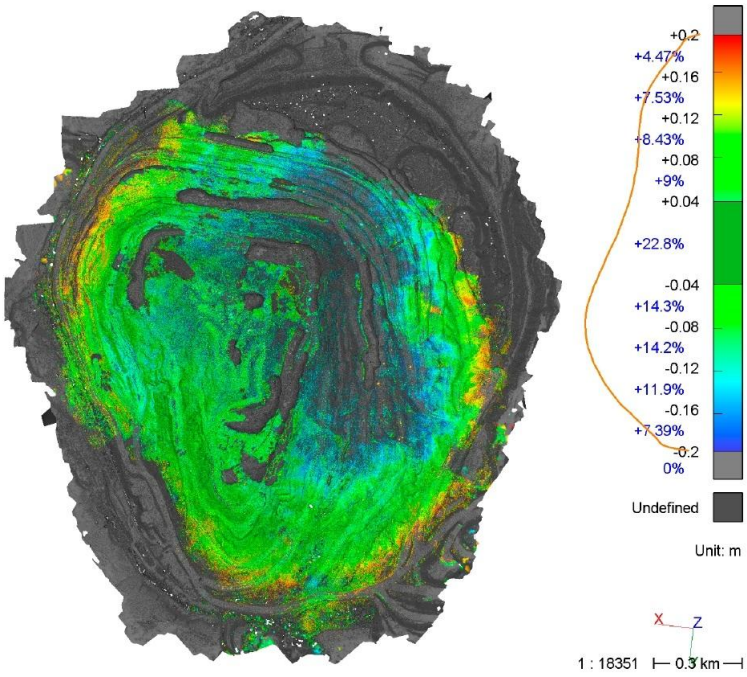


Fig. 10. Results of data processing using Software 5
Rys. 10. Wyniki przetwarzania danych przy użyciu oprogramowania 5

Software 6 yielded the lowest accuracy among the software packages tested, producing the least reliable results, with the largest error magnitudes and the greatest misalignment between the digital models (Fig. 11). Although this software generated the highest-density models, with a point spacing of 0.07–0.08 m at medium-quality settings, as well as a high-quality orthomosaic, its data-processing algorithms proved entirely unsuitable for rock-mass volume control and, more generally, for processing aerial survey data acquired in mountainous terrain. The histogram presented in Fig. 11 shows that most errors considerably exceed 0.2 m.

The surveyed site, Open-Pit Mine No. 4 operated by Central Mining and Processing Plant PJSC, is not among the deepest open-pit mines in the Kryvyi Rih iron-ore basin. Therefore, even larger errors can be expected for deeper open-pit mines characterised by complex terrain. This factor should be considered when selecting software and planning the aerial survey workflow for volume verification surveys.

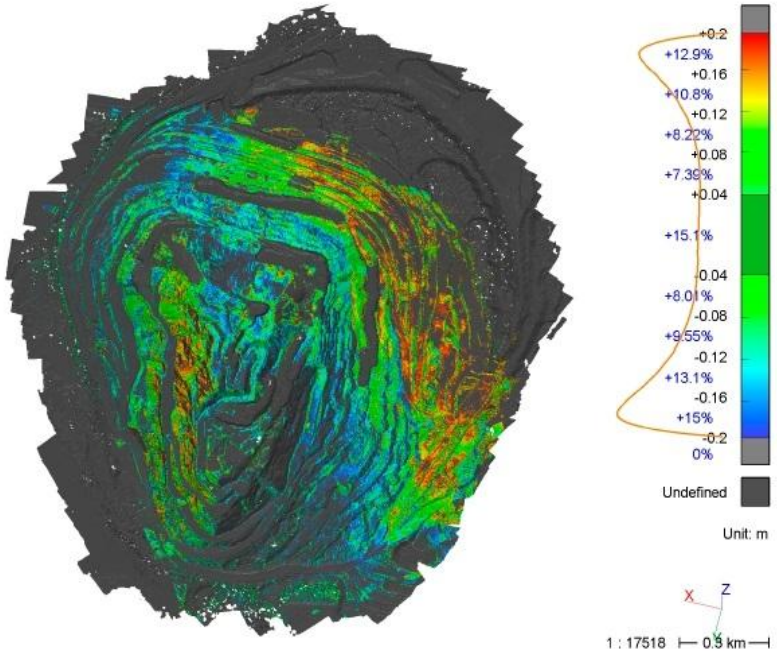


Fig. 11. Results of data processing using Software 6
Rys. 11. Wyniki przetwarzania danych przy użyciu oprogramowania 6

4. Results of using the single digital model method

Since none of the histograms exhibits a symmetric distribution, it can be concluded that the random errors in rock-mass volume estimation considerably exceed 0.2 m. The highest accuracy of volume estimation was achieved using the unified digital model method (Fig. 12).

The histogram of errors obtained from data processing using the unified digital model method exhibits an approximately normal distribution with no noticeable asymmetry. The analysis showed that 43.4% of the errors did not exceed 0.04 m, while 72.6% did not exceed 0.08 m (Fig. 12).

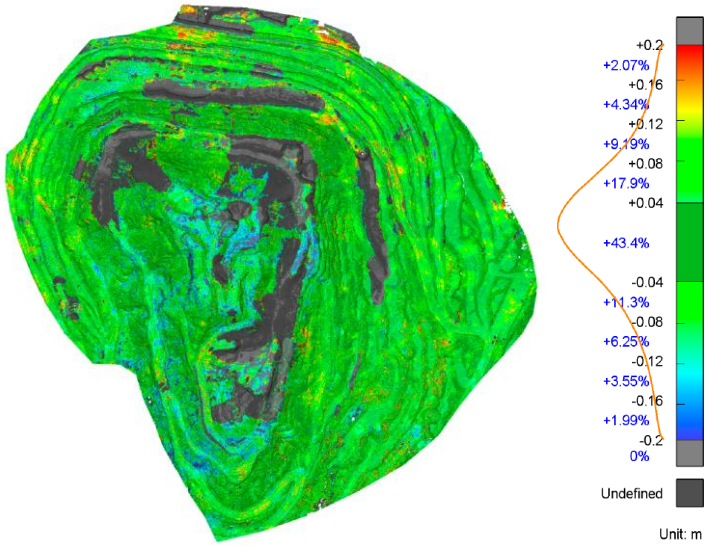


Fig. 12. Results of data processing using the unified digital model method
Rys. 12. Wyniki przetwarzania danych z wykorzystaniem metody ujednoliconego modelu cyfrowego

To verify the consistency of the accuracy and reliability of the results obtained, similar studies, with minor modifications, were conducted for the subsequent monitoring period between the aerial survey dates of 27 August 2025 and 26 September 2025. The results presented in Fig. 13 demonstrate an even higher accuracy than that reported above. Specifically, the proportion of errors not exceeding 0.04 m increased to 51.1%, while the proportion of errors not exceeding 0.08 m reached 79.5%. These findings confirm the consistently high accuracy and reliability of the unified digital model method (Fig. 13).

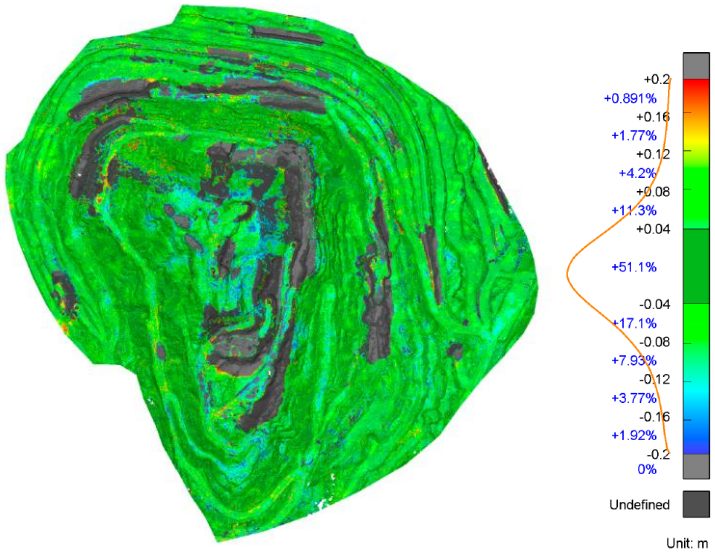


Fig. 13. Results of data processing using the unified digital model method for the period from 27 August to 26 September 2025
Rys. 13. Wyniki przetwarzania danych metodą zunifikowanego modelu cyfrowego za okres od 27 sierpnia do 26 września 2025 r.

Aerial surveying of open-pit mines has an important feature that should not be overlooked, namely, the substantial difference in image scale between the upper and lower levels of the mine, which also results in differences in pixel size. In practice, this leads to a noticeable variation in spatial image resolution. This effect can be clearly demonstrated using PhotoMesh software. Figure 14 shows that the image resolution at the upper and lower mine levels differs by almost a factor of two: it was 3.86 cm/pixel at the upper level and 7.57 cm/pixel at the lower level. For deep open-pit mines reaching depths of 700–800 m, such as Open-Pit Mine No. 1 operated by Central Mining and Processing Plant or the open-pit mine operated by Ingulets Mining and Processing Plant, this difference may be several times greater. However, the results of the present study indicate that this variation does not significantly affect the accuracy of 3D model generation or subsequent geospatial analysis.

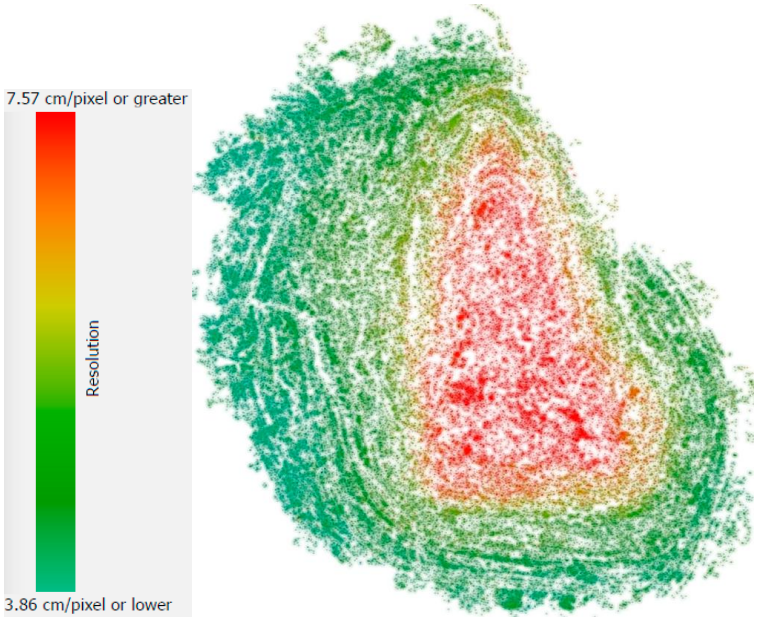


Fig. 14. Distribution of spatial resolution values across the open-pit mine image
Rys. 14. Rozkład wartości rozdzielczości przestrzennej na obrazie kopalni odkrywkowej

Figure 15 presents the results of processing the aerial survey data using different software packages. The errors obtained in volume estimation indicate that, among the methods investigated in this study, the proposed unified digital model method provides the highest accuracy. Software 5 exhibited the largest errors in estimating the cut and fill volumes. However, it achieved relatively high accuracy in determining the resulting net volume and ranked second in accuracy among the software packages considered. It should be noted that the high accuracy of the net volume calculated using this software package, as the algebraic sum of the cut and fill volumes, re-

sulted from the mutual compensation of errors. Therefore, this result cannot be considered reliable for volume verification surveys, since error compensation may conceal substantial deviations in the individual cut and fill estimates.

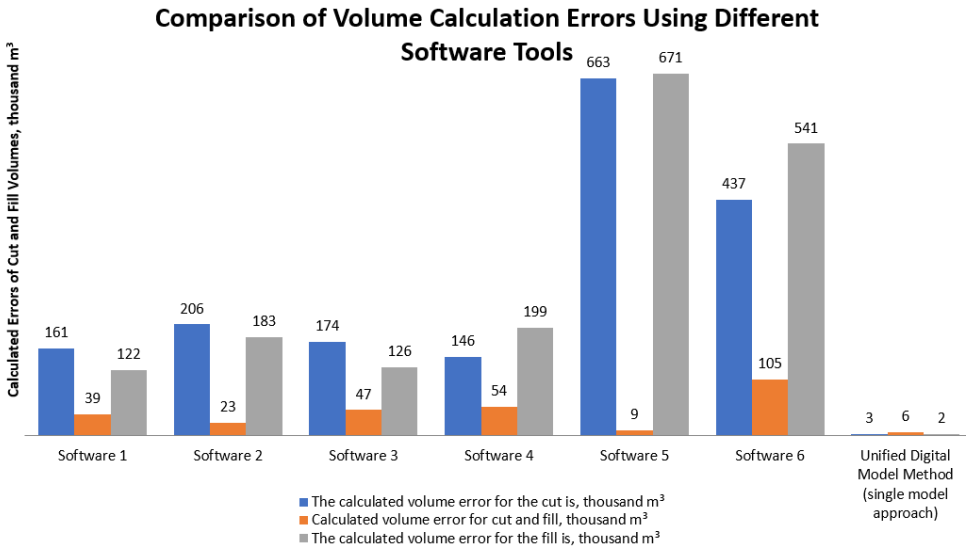


Fig. 14. Accuracy of volume estimation using different software packages
Rys. 14. Dokładność szacowania objętości przy użyciu różnych pakietów oprogramowania

To investigate the accuracy of the unified digital model method, two aerial survey data-processing schemes were applied, in which the entire study period was divided into two and three subperiods. One of these schemes is presented in Fig. 15. For each subperiod, aerial survey data acquired on its initial and final dates were used. First, the volumes were calculated independently for each of the two subperiods, from 29 July 2025 to 27 August 2025 and from 27 August 2025 to 26 September 2025, as well as for the entire period from 29 July 2025 to 26 September 2025. The sum of the volumes calculated separately for the two subperiods was then compared with the volume determined by processing the aerial survey data acquired on the initial and final dates of the entire study period. This comparison made it possible to assess the consistency of the results and verify the reliability of the proposed method for calculating volumes over a specified time interval. The difference between the sum of the volumes for the two subperiods and the volume calculated for the entire period was 151.9 m³.

Fig. 15. Results of the first aerial survey data processing
Rys. 15. Wyniki przetwarzania danych z pierwszego pomiaru lotniczego

For validation purposes, a second scheme was applied (Fig. 16), in which the entire period from 29 July 2025 to 22 October 2025 was divided into three subperiods: from 29 July 2025 to 27 August 2025, from 27 August 2025 to 26 September 2025, and from 26 September 2025 to 22 October 2025. As with the first scheme, the volumes were calculated from the aerial survey data for each subperiod and for the entire study period. The sum of the volumes calculated for the three subperiods was then compared with the volume calculated for the entire period. The resulting difference was 8,309 m³, corresponding to 0.22% of the total volume.

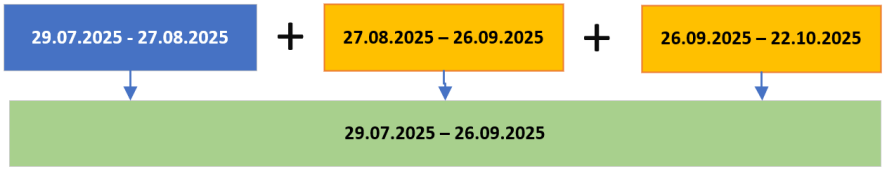


Fig. 16. Results of the second aerial survey data processing
Rys. 16. Wyniki przetwarzania danych z drugiego pomiaru lotniczego

5. Conclusion

The results of the study demonstrated that the proposed unified digital model method enables volume verification surveys of rock mass in open-pit mines to be performed within a short time frame and with the required accuracy. This contributes to improving the efficiency of mine surveying support for open-pit iron ore mining operations. Based on the data acquired during four aerial survey campaigns, the most effective software package was identified for use by the mine surveying department of a mining enterprise in addressing this task. When selecting software, priority should be given to minimising errors in the separate estimation of cut and fill volumes. It was also established that the same software package should be used to process all aerial survey campaigns and should not be changed when proceeding from one campaign to another. The study established the appropriate sequence of operations for processing images acquired during different aerial survey campaigns. Particular attention was paid to the sequence in which the corresponding digital models were excluded from the processing workflow.

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Author Contributions

Conceptualization and Methodology OD, RN; Validation OD, RN; Formal Analysis WS; Data Curation OD, RN; Writing – Original Draft Preparation OD, RN; Writing – Review & Editing WS; Visualization OD, RN; Supervision WS; Project Administration WS.

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Informed Consent Statement

Not applicable.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Loots, M., Grobbelaar, S., & Van der Lingen, E. (2022). A review of remote-sensing unmanned aerial vehicles in the mining industry. *Journal of the Southern African Institute of Mining and Metallurgy*, *122(7)*, 387–396. https://doi.org/10.17159/2411-9717/1602/2022
2. Karantanellis, E., Marinos, V., Vassilakis, E., & Hölbling, D. (2021). Evaluation of machine learning algorithms for object-based mapping of landslide zones using UAV data. *Geosciences*, *11*(8), 305. https://doi.org/10.3390/geosciences11080305
3. Dolgikh, O., Bolotnikov, A., & Sobczyk W. (2025). Monitoring of Mining Facilities Using Archival and Modern Aerial Photographs. *Inżynieria Mineralna*, *1*(1), 7-14. http://doi.org/10.29227/IM-2025-01-01
4. Török, Á., Bögöly, G., Somogyi, Á., & Lovas, T. (2020). Application of UAV in Topographic Modelling and Structural Geological Mapping of Quarries and Their Surroundings–Delineation of Fault-Bordered Raw Material Reserves. *Sensors, 20*(2), 489. https://doi.org/10.3390/s20020489
5. Do, T., Nguyen, L., Trinh, H., & Vambol, V. (2024). Comprehensive review of unmanned aerial vehicle application to safety mining management. *Ecological Questions, 35*(4), 1-41. DOI:10.12775/EQ.2024.049
6. Xiang, J., Chen, J., Sofia, G., Tian, Y., & Tarolli, P. (2018). Open-pit mine geomorphic changes analysis using multi-temporal UAV survey. *Environ. Earth Sci, 77*, 220. https://doi.org/10.1007/s12665-018-7383-9
7. Vacca, G. (2022). UAV photogrammetry for volume calculations. A case study of an open sand quarry, in: *Computational Science and Its Applications–ICCSA 2022 Workshops*, 505–518. https://doi.org/10.1007/978-3-031-10592-0_36
8. Du, W., Sheng, Q., Fu, X. *et al.* (2025). Application of Unmanned Aerial Vehicle Remote Sensing on Dangerous Rock Mass Identification and Deformation Analysis: Case Study of a High-Steep Slope in an Open Pit Mine. *J. Earth Sci, 36*(2), 750–763. https://doi.org/10.1007/s12583-023-1813-7
9. Türk, Y., & Balaban, B. (2025). Determination of Excavation Volume Using UAV-Based PPK Method in Open Mining Sites Tatlıdere Forests in Düzce. *Duzce University Journal of Science and Technology, 13*(1), 443-455. https://doi.org/10.29130/dubited.1515664
10. Kalinichenko, V., Dolgikh, O., Dolgikh, L., & Pysmennyi S. (2020). Choosing a camera for mine surveying of mining enterprise facilities using unmanned aerial vehicles. *Mining of Mineral Deposits. 14*(4), 31-39. https://doi.org/10.33271/mining14.04.031
11. Dolgikh, O., & Stupnik, M. (2026). Improving the accuracy of determining quarry wall deformations by optimizing the parameters of terrestrial stereophotogrammetric surveying. *Mining of Mineral Deposits, 20*(1), 71-79. https://doi.org/10.33271/mining20.01.071
12. Eker, R., Alkan, E., & Aydın, A. (2021). A Comparative Analysis of UAV-RTK and UAV-PPK Methods in Mapping Different Surface Types. *European Journal of Forest Engineering, 7*(1), 12-25. https://doi.org/10.33904/ejfe.938067
13. Si Son, T., LE, Q. T., TONG, T.-H.-A., NGUYEN, V. G., VU, P. L., & HA, L. T. T. (2020). Coupling Satellite Images and

Unmanned Aerial Vehicle Data to Monitor the Exploitation of Open-Pit Mine. *Inżynieria Mineralna, 1*(2)., 291-299. https://doi.org/10.29227/IM-2020-02-35

14. Nikolakopoulos, K., Kyriou, A., Kouzeli, E., Asadzadeh, S., Koellner, N., Koerting, F., Hildebrand, J.C., Micklethwaite, S., & Savinova, E. (2024). 3D representation of a bauxite mine in the frame of m4mining project. Proc. SPIE 13197, Earth Resources and Environmental Remote Sensing/GIS Applications XV, 131970M (13 Nov 2024). https://doi.org/10.1117/12.3031850
15. He, H., Xu, X., Chen, T., & Lu, P. (2020). Volume measurement of sand carrier using UAV-based mapping. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., V-3-2020, 19–24. https://doi.org/10.5194/isprs-annals-V-3-2020-19-2020
16. Jiang, Y., Huang, Y., Liu, J., Li, D., Li, S., Nie, W., & Chung, I-H. (2022). Automatic Volume Calculation and Mapping of Construction and Demolition Debris Using Drones, Deep Learning, and GIS. *Drones. 2022, 6*(10), 279. https://doi.org/10.3390/drones6100279
17. Ajayi, O.G., & Ajulo, J. (2021). Investigating the applicability of unmanned aerial vehicles (UAV) photogrammetry for the estimation of the volume of stockpiles. *Quaestiones Geographicae 40*(1), 25–38. https://doi.org/10.2478/quageo-2021-0002
18. Thiele, S. T., Bnoulkacem, Z., Lorenz, S., Bordenave, A., Menegoni, N., Madriz, Y., Dujoncquoy, E., Gloaguen, R., & Kenter, J. (2022). Mineralogical Mapping with Accurately Corrected Shortwave Infrared Hyperspectral Data Acquired Obliquely from UAVs. *Remote Sensing, 14*(1), 5. https://doi.org/10.3390/rs14010005
19. Pozzebon A., Benini M., Bocci C., Fort A., Parrino S., & Rapallo F. (2023). Grid-layout ultrasonic LoRaWAN-based sensor networks for the measurement of the volume of granular materials. *Measurement, 220*, 113404 https://doi.org/10.1016/j.measurement.2023.113404
20. Schmid, B.M., Williams, D.L., Chong, C.S., Kenney, M.D., Dickey, J.B., & Ashley, P. (2022). Use of digital photogrammetry and LiDAR techniques to quantify time-series dune volume estimates of the Keeler Dunes complex, Owens Valley, California. *Aeolian Res*., *54*, 100764. DOI: 10.1016/j.aeolia.2021.100764
21. Blistan, P., Jacko, S., Kovanič, Ľ., Kondela, J., Pukanská, K., & Bartoš, K. (2020). TLS and SfM Approach for Bulk Density Determination of Excavated Heterogeneous Raw Materials. *Minerals, 10*(2), 174. https://doi.org/10.3390/min10020174
22. Cho, J., Seungjin, J., & Lee, B. (2026). Optimal ground control point layout for UAV photogrammetry in high precision 3D mapping. *Measurement*, *257*, 118343. https://doi.org/10.1016/j.measurement.2025.118343
23. Park, J.W., & Yeom, D.J. (2021). Method for Establishing Ground Control Points to Realize UAV-Based Precision Digital Maps of Earthwork Sites. *J. Asian Archit. Build. Eng*., *21*(1), 110–119. https://doi.org/10.1080/13467581.2020.1869023
24. Gil, M., & Frąckiewicz P. (2019). Optimization of the location of observation network points in open-pit mining's. 26th Geographic Information Systems Conference and Exhibition "GIS ODYSSEY 2019" Conf. Proceedings, pp. 73-80. https://open.icm.edu.pl/handle/123456789/17684
25. Alkan, H.M. (2024). High-Precision UAV Photogrammetry with RTK GNSS: Eliminating Ground Control Points. *Hittite Journal of Science and Engineering. 11*(4). 139-147. https://doi.org/10.17350/HJSE19030000341
26. Michałek, A., Markiewicz, J., Wójcik-Leń, J., Kostrzewa, A., Kowalczyk, M., Łapiński, S., & Macek, A. (2026). Evaluation of open-source libraries and commercial software utilised for dense point cloud generation: a case study of cultural heritage objects. *Reports on Geodesy and Geoinformatics, 121*, 1–18. https://doi.org/10.2478/rgg-2026-0001
27. Verykokou, S., Soile, S., Bourexis, F., Tokmakidis, P., Tokmakidis, K., Ioannidis, C. (2021). A comparative analysis of different software packages for 3D modelling of complex geometries. Progress in Cultural Heritage: Documentation, Preservation, and Protection: 8th International Conference, EuroMed 2020, 228-240. https://doi.org/10.1007/978-3-030-73043-7_19
28. Elkhrachy, I. 3D Structure from 2D Dimensional Images Using Structure from Motion Algorithms. *Sustainability* **2022**, *14*, 5399. https://doi.org/10.3390/su14095399
29. Liu, Y., & Zheng, Y. (2021). Accurate Volume Calculation Driven by Delaunay Triangulation for Coal Measurement. *Scientific Programming*. 1-10. https://doi.org/10.1155/2021/6613264

Abstract

Wprowadzenie nowoczesnego sprzętu i oprogramowania przez wydziały geodezji górniczej przedsiębiorstw górniczych przyczynia się do doskonalenia metod geodezji górniczej, zwiększa efektywność całego cyklu wydobycia i przeróbki kopalin oraz obniża koszty wydobycia tony surowca.

Celem niniejszej pracy jest opracowanie metody przeprowadzania pomiarów weryfikacyjnych objętości wydobytego górotworu w okresie sprawozdawczym, w oparciu o aktualne praktyki w zakresie pomiarów lotniczych i przetwarzania danych. Metodyka opiera się na analizie wyników uzyskanych z fotogrametrycznego przetwarzania obrazów kopalni odkrywkowych, pozyskanych za pomocą bezzałogowego statku powietrznego w różnych terminach. Ocena dokładności uzyskanych szacunków objętości górotworu pozwoliła na określenie wymagań dotyczących liczby i konfiguracji geometrycznej punktów kontrolnych, a także zastosowanego oprogramowania i sprzętu. Określone zmiany powierzchni w określonych przedziałach czasowych wykazały wystarczająco wysoką dokładność i były zgodne z wymogami odpowiednich przepisów i instrukcji technicznych.

Nowością naukową pracy jest opracowanie i walidacja metody prowadzenia pomiarów weryfikacyjnych objętości górotworu, opartej na przetwarzaniu danych z pomiarów lotniczych, pozyskanych nad kopalnią odkrywkową. Szczególną uwagę zwrócono na dobór optymalnych warunków pomiarowych, określenie liczby i konfiguracji geometrycznej punktów kontrolnych i kontrolnych oraz dobór odpowiednich charakterystyk modeli cyfrowych generowanych dla kopalni odkrywkowej w różnych terminach. Uzyskane wyniki

potwierdziły skuteczność proponowanej metody pomiarów weryfikacyjnych, która umożliwia weryfikację i udoskonalenie danych eksploatacyjnych dostarczanych przez dział techniczny kopalni odkrywkowej w krótkim czasie i z wymaganą dokładnością. Praktyczne znaczenie pracy polega na opracowaniu skutecznej metody, która może być wdrożona przez działy miernictwa górniczego przedsiębiorstw górniczych.

Słowa kluczowe: kamieniołom, pomiar lotniczy, pomiar kontrolny, model cyfrowy