ISSN 2071-1859 (Print), ISSN 2521-6635 (Online)
UDC 622.1:528.7 https://doi.org/10.33271/crpnmu/84.097

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MEASUREMENT OF THE VOLUMES OF CRUSHED STONE WAREHOUSES BASED ON PHOTOGRAMMETRIC METHODS

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ВИМІРЮВАННЯ ОБ'ЄМІВ СКЛАДІВ ЩЕБЕНЕВОЇ ПРОДУКЦІЇ НА ОСНОВІ ФОТОГРАММЕТРИЧНИХ МЕТОДІВ

Purpose. To substantiate the effectiveness of digital photogrammetric surveying for determining the areas and volumes of finished product stockpiles and constructing three-dimensional models of mining objects.

Methodology. The study is based on the use of UAV aerial photography, digital image processing, and the generation of a dense point cloud with subsequent construction of a digital surface model and determination of volumetric and spatial parameters.

Results. It was found that the photogrammetric approach ensures the required measurement accuracy within a short time depending on the camera resolution and the number of acquired images. The optimal survey parameters were determined: flight height 30–50 m, number of images 25–50, resolution 12–18 MP. The obtained results showed a deviation of 0.09–0.25 % from reference tacheometric measurements, which confirms the effectiveness of the method. Additionally, variations in image processing parameters affect the accuracy of digital model construction and volume calculation.

Scientific novelty. It was established that the accuracy of determining the volumes of crushed stone stockpiles depends on the parameters of aerial photogrammetric surveying, in particular UAV flight height, camera resolution, and the number of images. The optimal survey parameters (flight height 30–50 m, number of images 25–50, resolution 12–18 MP) were substantiated, ensuring minimal deviation of the results (0.09–0.25 %) from reference tacheometric measurements. The influence of photogrammetric data processing parameters on the accuracy of three-dimensional model construction and volume calculation was determined.

Practical significance. The practical significance lies in the possibility of integrating photogrammetric technologies into the mine surveying support system of mining enterprises for operational monitoring of finished product stockpiles and digital modeling of mining objects. The proposed approach makes it possible to reduce the duration of field and office work, minimize the influence of the human factor, and increase the efficiency of stockpile volume determination.

Keywords: *aerial photogrammetric survey, UAV, digital surface modeling, dense point cloud generation, stockpile volume determination, mine surveying support.*

Introduction. Today, the development of mining enterprises is accompanied by an increase in productivity and the volume of extracted and processed mineral resources. These processes require modernization of surveying equipment and improvement of spatial data acquisition methods to ensure reliable production control and accurate volume accounting. Digital photogrammetric surveying combined with modern image processing software enables the creation of three-dimensional models of mining objects and finished product stockpiles. Compared with classical ground-based surveying techniques, photogrammetry provides rapid data acquisition, sufficient measurement accuracy depending on camera resolution and image quantity, reduced human influence, and significant automation of both field and office operations.

Photogrammetry as a scientific and applied discipline has always been aimed at reducing the volume of field geodetic and topographical works, moving the central weights from the field to more favorable and cheaper chamber conditions for constructing topographic or thematic maps [1].

Despite the limitations of the part of the spectrum (visible and near-infrared regions) used for imaging, photogrammetry is the most universal and effective in terms of the amount of information obtained, the prevalence of its use in agriculture and scientific research related to the study and use of natural resources. The transition of modern photogrammetry to high-performance analytical processing methods made it possible to improve and automate a large number of photogrammetric processes. Analytical photogrammetry, which combines the advantages of analytical methods and the possibilities of more informative one, and possessing exceptionally high imaging properties of analog photo images, is the most accurate.

At the same time, the digital representation of pictures has become widespread, which, unlike analog photographs, allows for their transformation to be carried out more thoroughly. Digital images allow you to apply transformations to them that are not possible for analog and analytical photogrammetry, for example, projective and non-linear. In addition, digital methods allow multiple copies of images without loss of quality to improve imaging properties, apply detailed analysis to them, color conversion and much more.

Digital photogrammetry does not require expensive equipment, which makes it available for many branches of the national economy. A new stage in the development of photogrammetry as a science is facilitated by the emergence and spread of digital technologies. On the one hand, the shooting process itself is simplified, and on the other hand, processing can be carried out at digital photogrammetric stations based on personal computers. Photographic data are transferred directly from the digital camera to the computer, bypassing the stage of photochemical processing. The widespread implementation of digital methods in geodetic production is hindered by the lack of the preparation technology, execution and processing of digital surveying. Existing classical technology cannot be directly transferred to digital methods due to significant technical difficulties.

Advances in computer graphics and digital image recording methods have led to the creation of a new type of photogrammetric technique - a digital photogrammetric

system, which has replaced optical-mechanical and analytical instruments. Today it looks like a standard personal computer or laptop with the installed appropriate software for processing images.

Analysis of recent research. Recent studies confirm the rapid development of digital geomatics technologies in the mining industry. Y. Choi, J. Baek and S. Park (2020) emphasize the significant role of geographic information systems in planning, operational control and environmental management of mining enterprises [1]. H. Fan et al. (2021) demonstrate the effectiveness of three-dimensional deformation monitoring using remote sensing techniques in mining areas [2]. P. Y. Fedorenko et al. (2021) highlight the importance of mining geometric monitoring and subsurface modeling for improving safety and measurement reliability [3]. M. Hosseinpour, M. Osanloo and Y. Azimi (2022) analyze the impact of advanced spatial modeling technologies on mining productivity and decision-making processes. M. Kunytska and V. Kotenko (2023) substantiate the feasibility of determining mining mass volumes based on multicopter surveying. Furthermore, M. Kunytska et al. (2023) confirm the effectiveness of digital simulation in organizing open-pit mining systems. [4, 6]. A. Krawczyk (2023) identifies mining geomatics as a key direction in the integration of unmanned aerial systems and digital spatial analysis [5].

Formulation of the problem and research aim. Despite the considerable number of studies devoted to digital modeling and remote monitoring, the issue of optimizing aerial photogrammetric survey parameters for accurate stockpile volume estimation under specific mining enterprise conditions remains insufficiently investigated.

Scientific novelty of the study consists in establishing quantitative relationships between aerial photogrammetric survey parameters, software processing settings and the accuracy of crushed stone stockpile volume determination under real mining enterprise conditions [7].

The aim of this study is to determine rational aerial survey and digital data processing parameters that ensure regulatory measurement accuracy and practical applicability of photogrammetric methods for stockpile volume estimation in mining enterprises. To achieve this aim, the technical characteristics of unmanned aerial systems were analyzed, the aerial photogrammetric workflow was optimized and implemented in practice, digital images were processed using specialized software to generate a three-dimensional model, and the obtained results were compared with classical surveying measurements to evaluate accuracy.

Results. Advances in computer graphics and digital image recording methods have led to the creation of a new type of photogrammetric technique - a digital photogrammetric system, which has replaced optical-mechanical and analytical instruments . Today it looks like a standard personal computer or laptop with the installed appropriate software for processing images.

Advantages of photogrammetric scanning:

- low cost of equipment and processing;
- equipment for field facilities is light and convenient to transport;
- reduction of field work time;

- the ability to work on an unstable basis for the tool;
- the possibility of scanning moving or unstable objects and dangerous zones;
- the ability to scan very small objects if they have a texture;
- obtaining high-quality textured 3D models [8].

When it comes to stock volume measurements, stocks don't fit perfectly. Photogrammetric imaging shows the actual distance at which each pixel is depicted, which allows for a more detailed description of the finished products warehouses. Horizontally, high-resolution photogrammetric results produce more accurate stacking patterns and therefore better volume measurement accuracy than interpolated from specific measurement points.

The increase in interest in unmanned aerial vehicles is caused by their successful use in solving problems in various areas of human activity. UAVs are used in various fields. The main advantage of UAVs is the complete or partial exclusion of the human factor, which allows you to minimize the risk of loss of human resources when performing the task and exclude the possibility of a threat to human life [9].Other advantages of using an unmanned aerial vehicle include: a reduction in the cost of performing work and a smaller number of routine operations, compared to manned equipment, there is no need for highly qualified technical assistance during maintenance, it is much easier to ensure safety at the work site, and in the case of using a drone it is necessary to note the long service life of the UAV [10]. Overlap can be calculated using flight and camera parameters such as altitude, speed and spacing, line density (spacing), and more. In our research work with warehouses of finished goods, we have chosen a standardized common starting point. We took the drone and held it at a height of 30–80 meters and kept it level, focused on completing transitions on the site.

The quadcopter operator selects working maps for the selected area, checks the necessary pre-flight calculations and studies the area for the presence of obstacles on the given route, determines places for conducting aerial photography. Studying the territory, the interior for aerial photography, definitely makes it easier to lay aerial routes. When constructing the route for the UAV, we used the method of laying from the edges to the center, which ensured the best overlap of images and the completeness of the image. Before the flight, the completeness of the UAV and its settings are checked.

The cleanliness of the lens and aerial camera must be ensured from the outside and inside, and the operation of the shutter; power, turning on the aero camera, and 2–3 cycles are done.

The priority requirements for photogrammetric surveying of warehouses of finished products by UAV are:

- Quadcopter flight speed – 70–110 km/h (20–30 m/c);
- The flight height of the quadcopter is 30–1500 m;
- Camera matrix – 10–20 MP;
- The focal length of the cameras is 20–50 mm;
- Longitudinal overlap of images – 80%;
- Transverse overlap of images – 40%

The dependence of the influence of the megapixels of the camera matrix on the volume of the model can be displayed on the graph (fig. 1).

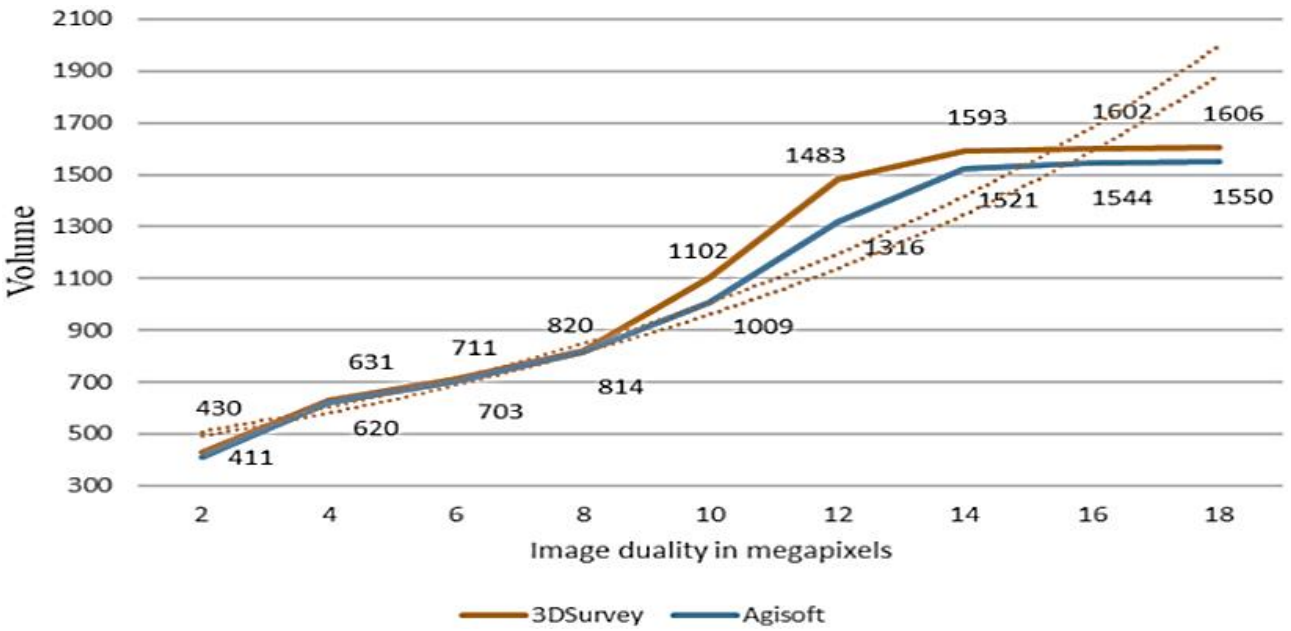

Fig. 1. The dependence of the volume results from the camera megapixels

Also, an important factor that directly proportionally affects the future volume of the model is the flight height. Shooting was done at different shooting heights, after which the photo was processed in the software and the optimal flight height was obtained to simplify processing in the software, namely a height from 30 to 50 meters (fig. 2.).

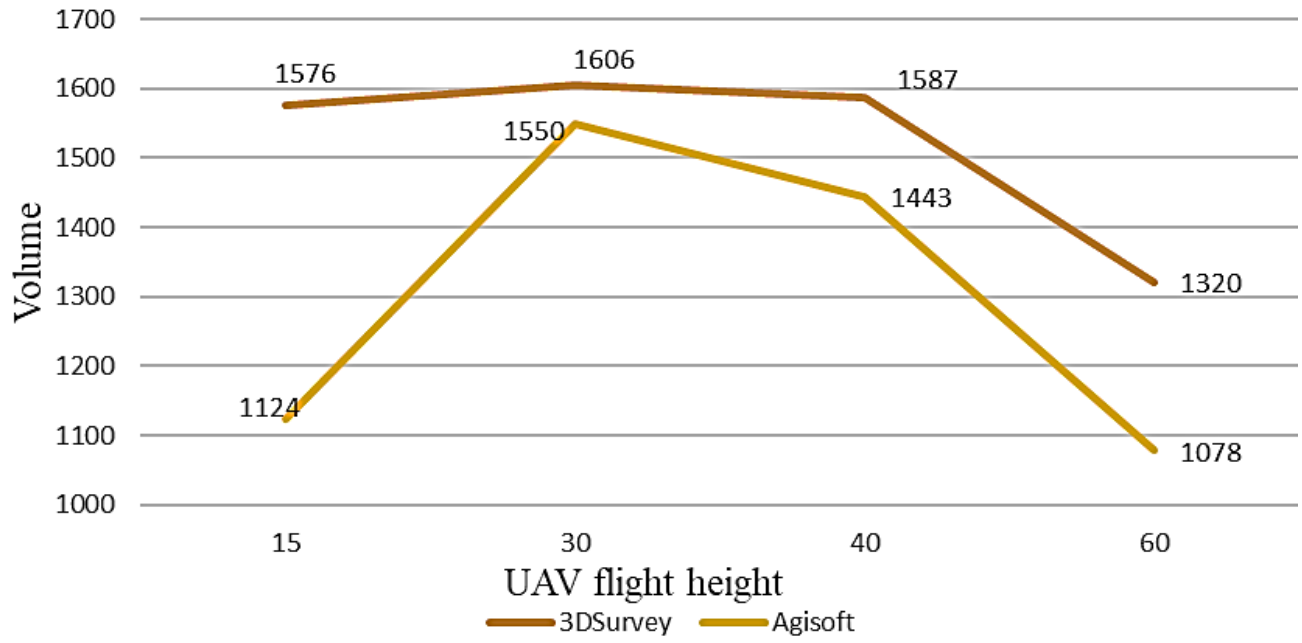

Fig. 2. The dependence of the flight height of the UAV shooting relative to the obtained volume results

During the completion of the diploma project, the optimal characteristics for the UAV and the characteristics of the environment for obtaining high-quality images were determined.

The study showed that with different parameters of the shooting camera, namely, they established a dependence on the megapixels of the camera matrix relative to the volume of the future model, that the quality with which the pictures were taken directly proportionally affects the calculation of the volumes by the software.

And the optimal shooting height from the quadcopter was also determined which is from 30 to 50 meters. Aerial photography using coded marks has been researched and tested in practice. An algorithm and optimal parameters of the software for building high-quality 3D models of warehouses of finished crushed stone products in the 3D Survey and AgiSoft programs have been developed. The parameters of shooting and photo processing are compared based on the results of 3D model construction. An unmanned quadrocopter called DJI Phantom 4 Pro was used for the photogrammetric shooting.

Coded stamps were used during aerial photography. Coded stamps are printed stamps that can be placed within the scene before photography and subsequently used in image processing in photogrammetric software as reference points to specify the coordinate system and scale the model or as true correspondences between two images to facilitate the photo alignment procedure.Add printed coded stamps within the scene or around the subject so that they are clearly visible in at least two photos. Note that the coded marks should not be too large or too small compared to the object or scene.

The main stages for building warehouse models of finished crushed stone products in 3DSurvey and AgiSoft programs are:

- Alignment of photo cameras
- Orientation of pictures in space using coordinates or markers
- Building a dense point cloud by calculating the depth of the cameras
- Construction of a digital model of the warehouse
- Scaling and obtaining a quantitative characteristic

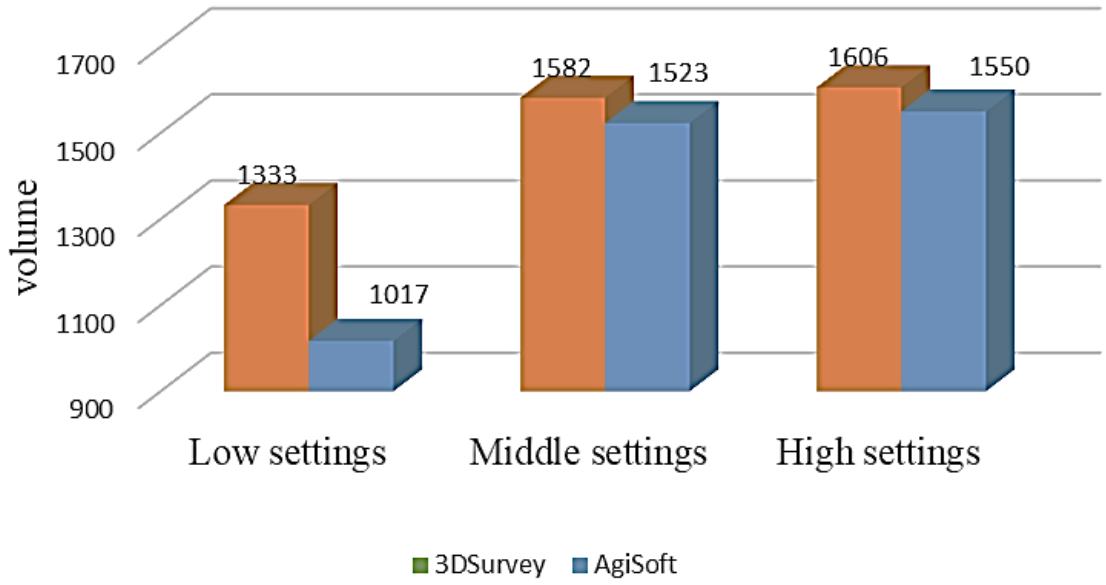

Fig. 3. The dependence of the accuracy of volume determination on photo processing parameters

In parallel with the works of photogrammetric value, work was carried out on the determination of volumes by the surveying service of the quarry. The company's staff used classic methods of calculating finished product warehouses using a modern Sokkia 650RX total station. This type of tacheometer helps to obtain high-quality measurement results with minimal error in tacheometric surveying. The results of measurements by the surveying service in this diploma project are accepted as standards. The measurements obtained during field work were processed using the graphic editor AutoCADCivil 3D, in which the quantitative characteristics of the object were determined, namely the volume of 1607.75 m ^{3} The minimum number of photos that must be used during processing varies from 25 to 50 for 3DSurvey and 60 and more for Agisoft to obtain a relatively optimal result depending on the software used, the dependence can be shown on the graph (fig. 4).

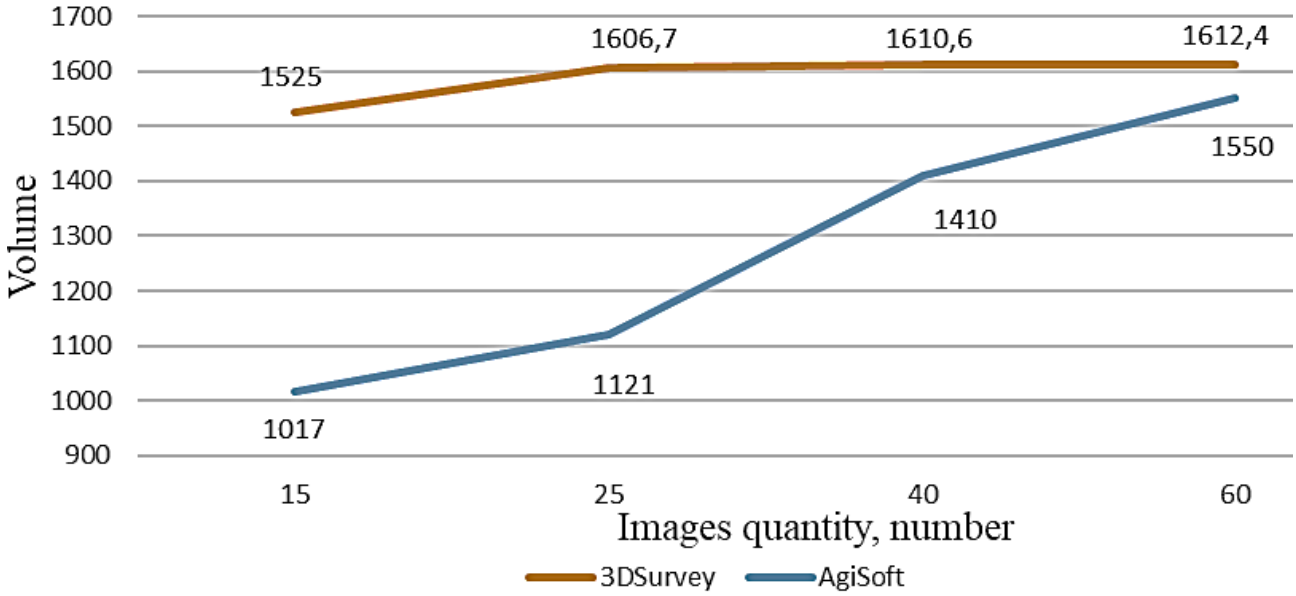

Fig. 4. The comparative graph of the obtained results
to the number of photos used during processing

The time spent by the software when processing the photo material and obtaining quantitative characteristics of the object during processing in the 3DSurvey program is greater than the duration of processing photographs in Agisoft, but the results are also excellent at different durations for these programs (fig. 5). It’s worth mentioning that the time the program spends on photo processing depends on the power of your personal computer.

During the research, we also investigated the number of coded marks that should be placed around the shooting scene in order to obtain correct measurement results. Photo material using three, five and seven marks was processed in the program. The results of the study showed that the optimal choice is 7 marks and more (fig. 5.).

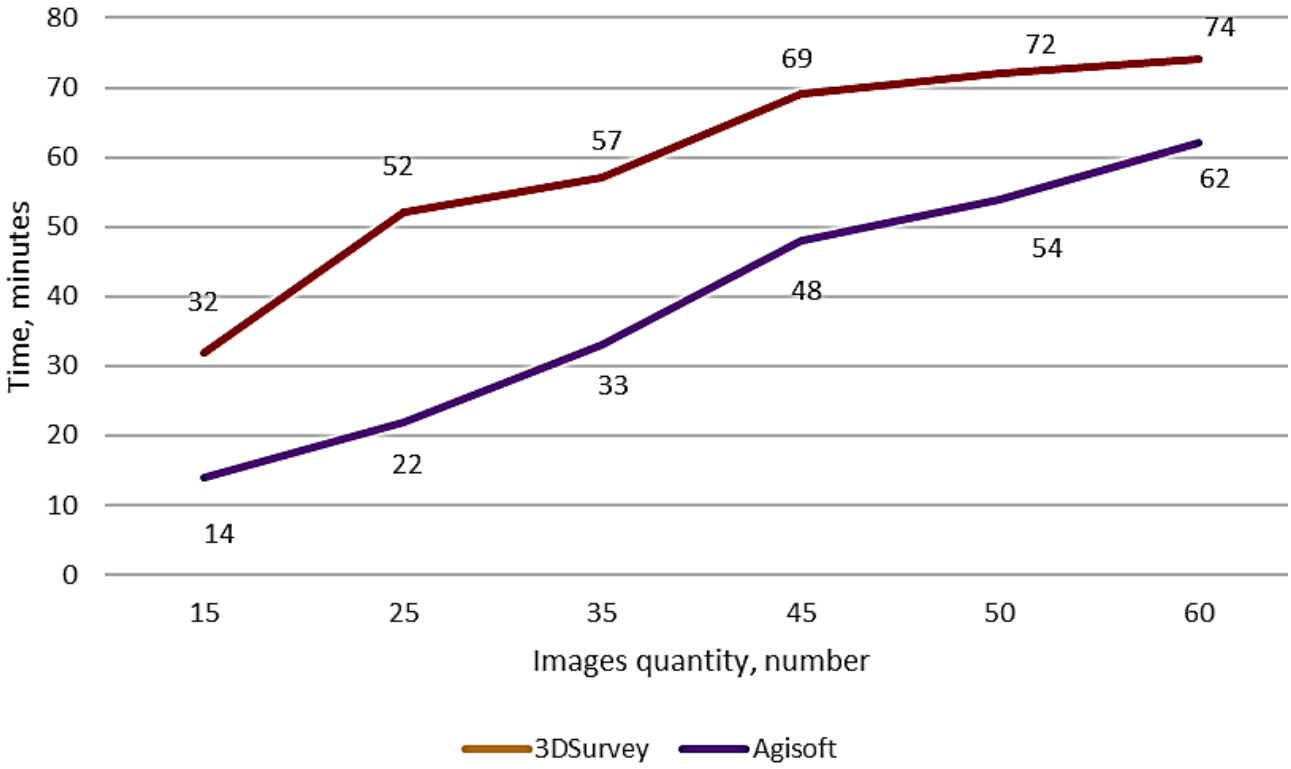

Fig. 5. The dependence of the time spent on the number of processed photos

The number of marks for the program gives an understanding of the dimension of the object. On the example of AgiSoft, which uses marks to scale and orient a photo in space, 3DSurvey can scale the model or understand the outline of the model that needs to be measured during the construction of the model. At the stage of building a digital model consisting of triangles of specified sizes, the relationship between the number of triangular polygons and the measurement result, namely the volume, was established. This dependence of the influence of the number of polygons on the volume can be traced on the graph (fig. 6.).

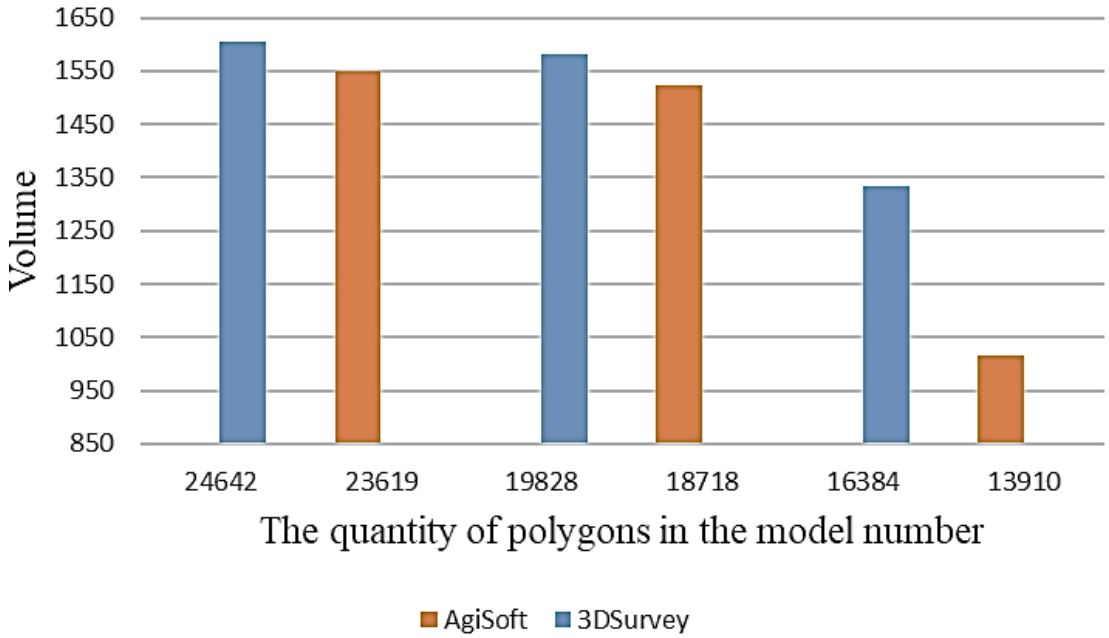

Fig. 6. The dependence of the volume on the number of triangular polygons in the digital model

We can see that with an increase in the number of polygons parameter, which depends on the settings you selected at the processing stage, the volume of the model depends.

After the conducted research, it is possible to perform comparative characteristics when doing the work on measuring the volumes of warehouses, namely to compare the results of measurements, time during field and camera work, the cost of equipment, the number of used photos, marks, etc. Such characteristics are indicated in the table below.

Table

Comparison of methods for measuring crushed stone stockpile volumes

Indexes	Tacheometry	3D Survey	Agisoft Photoscan
Field work	30 min	30 min	30 min
Office work	1 h	52 min	62 min
Total time	1 h 30 min	1 h 22 min	1 h 32 min
Number of images	—	25	60
Flight height	—	30 m	30 m
Camera resolution	—	18 MP	18 MP
Number of marks	8	7	7
Volume result	1607.8 m³	1606.4 m³	1550.4 m³
Deviation from reference	—	0.09 %	3.57 %

The obtained results confirm the applicability of aerial photogrammetry for stockpile volume determination under mining conditions. The deviation of 0.09–0.25 percent from the reference tachymetric measurements demonstrates that the method satisfies operational surveying accuracy requirements.

The optimal flight altitude of 30–50 meters ensures a balance between spatial resolution and processing efficiency. Lower flight heights increase the number of images and computational load without significant improvement in volumetric accuracy, while higher altitudes reduce model detail and measurement precision. The analysis also indicates that the use of 25–50 images is sufficient for stable three-dimensional reconstruction without excessive data redundancy.

The slight differences between the results obtained in Agisoft and 3DSurvey are explained by variations in dense point cloud generation algorithms and triangulated surface construction. Despite these differences, both software packages provide acceptable accuracy for practical application.

Compared to classical total station measurements, the photogrammetric method significantly reduces fieldwork time and minimizes human-induced errors. Therefore, aerial photogrammetry can be considered a reliable and efficient alternative for operational monitoring of crushed stone stockpiles at mining enterprises.

Conclusions. After all the manipulations with the photo material in the AgiSoftPhotoscan and 3DSurvey programs, the optimal parameter algorithms were found to obtain results that fully satisfy us and the prospects for this project. In its turn, it proved that remote and short-term measurements can meet mining standards and accuracy limits.

The optimal shooting parameters with the help of DJI Phantom 4 Pro were studied, namely, the shooting height from 30–50 meters, the minimum number of shots from 25 to 50 pieces for a typical object. The parameters of the camera matrix expansion range from 12 to 18 megapixels, which satisfy the parameters of the quality of images when processed to obtain quality results with minimal deviation. All these parameters are basic when taking pictures with a UAV and affect the result.

As a result of carrying out the experimental part of the research, namely, photographing the composition of crushed stone products with the help of a Phantom 4 Pro quadrocopter, initial digital data was obtained in the form of 60 high-resolution photographs, which were processed in two modern programs 3DSurvey and AgiSoft Photoscan. As a result, Photogrammetric methods with the use of software for measuring warehouses of crushed stone products under the same initial conditions of digital image processing showed the following results: Agisoft Photoscan – 1550.4 m^3; 3DSurvey – 1612.6 m^3.

The time spent and influencing factors on the terms of processing photographs in the software were studied. Based on these studies, the time costs depend on the number of images uploaded to the program, the choice of settings and the power of the personal computer.

A comparative analysis was carried out between modern methods of digital. photogrammetry and classical methods of obtaining the volume of the warehouse of finished products and it was found that the deviation from the reference value of the volume of the warehouse, obtained with the help of tacheometric survey, is 0.09–0.25% in the case of using 3DSurvey, what is acceptable. Therefore, the method of photogrammetric measurement in combination with modern software can be considered as an alternative to the classical methods of measuring and calculating the composition of finished crushed stone products for mining enterprises.

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АНОТАЦІЯ

Мета. Обґрунтування ефективності застосування цифрової фотограмметричної зйомки для визначення площ і об’ємів складів готової продукції та побудови тривимірних моделей гірничих об’єктів.

Методика. Дослідження ґрунтується на використанні аерофотозйомки з БпЛА, цифрової обробки зображень та формування щільної хмари точок із подальшою побудовою цифрової моделі поверхні та визначенням об’ємних і просторових параметрів.

Результати. Встановлено, що фотограмметричний підхід забезпечує необхідну точність вимірювань у короткий термін залежно від роздільної здатності камери та кількості отриманих зображень. Визначено оптимальні параметри зйомки: висота польоту 30–50 м, кількість знімків 25–50, роздільна здатність 12–18 Мп. Отримані результати показали відхилення 0,09–0,25 % від еталонних тахеометричних вимірювань, що підтверджує ефективність методу. Додатково встановлено, що зміна параметрів обробки зображень і щільності хмари точок впливає на точність побудови цифрової моделі та результати обчислення об’ємів.

Наукова новизна. Встановлено залежності точності визначення об’ємів складів щебеневої продукції від параметрів аерофотограмметричної зйомки, зокрема висоти польоту БпЛА, роздільної здатності камери та кількості знімків. Обґрунтовано оптимальні параметри зйомки (висота 30–50 м, кількість знімків 25–50, роздільна здатність 12–18 Мп), які забезпечують мінімальне відхилення результатів (0,09–0,25 %) від еталонних тахеометричних вимірювань. Визначено вплив параметрів обробки фотограмметричних даних на точність побудови тривимірної моделі та розрахунку об’ємів.

Практична значимість. Практична цінність роботи полягає у можливості інтеграції фотограмметричних технологій у систему маркшейдерського забезпечення гірничих підприємств для оперативного моніторингу складів готової продукції та цифрового моделювання гірничих об’єктів. Запропонований підхід дозволяє скоротити тривалість польових і камеральних робіт, зменшити вплив людського фактору та підвищити ефективність визначення об’ємів складів.

Ключові слова: *аерофотограмметрична зйомка, БпЛА, цифрове моделювання поверхні, щільна хмара точок, визначення об’ємів складів, маркшейдерське забезпечення.*

date of first submission of the article to the publication	01/10/2026
date of acceptance of the article for publication after review	02/13/2026
date of publication	03/31/2026