

Improving the accuracy of determining quarry wall deformations by optimizing the parameters of terrestrial stereophotogrammetric surveying

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Abstract

Purpose. The research aims to develop and experimentally validate a methodology for terrestrial digital stereophotogrammetric surveying to monitor deformations of deep quarry walls with determination of optimal parameters for the survey basis and initial observation cycle, providing the necessary accuracy in determining deformation values.

Methods. The research involved designing and conducting a quarry survey on the initial and subsequent dates of deformation observations using a professional digital camera. The obtained digital images were processed using an improved version of the traditional photogrammetric method – the displacement method. In order to improve the efficiency of deformation monitoring using photogrammetric method, requirements for conducting an initial cycle of observations with the determination of optimal parameters for data capture and processing have been substantiated.

Findings. Based on the results of using terrestrial digital surveying and an improved photogrammetric displacement method, the deformation values at the experimental sites of the quarry walls have been determined with a sufficiently high accuracy during image processing. Requirements for performing the initial cycle of observations of deformation processes have been substantiated, and the influence of its parameters on the effectiveness of further monitoring has been identified. The practical effectiveness of the developed methodology was confirmed during the study of deformations caused by mining operations at the quarries of Private Joint Stock Company “Central Iron Ore Enrichment Works” (PJSC “Central GOK”).

Originality. Optimal parameters for the initial cycle of observations of quarry wall deformations using the terrestrial digital surveying method have been determined. Patterns have been identified between the accuracy of determining the coordinates of points using a created digital terrain model and the spatial position of the survey basis. Requirements for computing equipment characteristics that ensure efficient processing of large volumes of digital images and increased productivity of office work have been substantiated.

Practical implications. The photogrammetric displacement method for determining deformations from images taken at different times has been improved. The developed method for monitoring shear processes and other types of deformations based on this method provides for the determination of the values of spatial changes in the position of examined object points with the necessary accuracy and prompt obtaining of information about its current state and prospects for further safe operation.

Keywords: digital images; terrestrial stereophotogrammetric surveying; survey basis; point coordinates; multi-temporal images

1. Introduction

The actual task of the surveying service of a mining enterprise is to improve the methodology for monitoring deformation processes at its facilities and adjacent territories, as deformation processes cause damage not only to the efficient mining of minerals, but also to the environment. It is known that the traditional method of monitoring deformations is to use observation stations consisting of profile lines resting on stable benchmarks located outside the area influenced by mining operations.

The traditional method is based on performing linear measurements between profile benchmarks and determining their height position, which makes it possible to obtain values for horizontal and vertical deformations. The defor-

mation values make it possible to conclude whether the obtained values correspond to the stable position of the benchmarks or, on the contrary, to the occurrence of critical changes. The results of research into deformations in the territories influenced by mining operations are used to make a prediction about the further condition of these territories.

The devices for performing linear measurements and leveling have changed radically, and there are no longer any operations involving visual estimation of sites. With the improvement of the instrumental base, research methodology changes and its effectiveness increases: the time required to perform work is reduced; the accuracy and reliability of the results increases; the digital form of materials allows them to be effectively analyzed, processed, and stored.

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Another advantage of modern digital methods for capturing and processing data is that measurement error can be detected even after a certain time, after several observation cycles, using the results of data analysis in software tools.

Undoubtedly, when studying deformations of territories that are dangerous for observers to be in, it is advisable to use remote methods with modern measuring devices that operate without a reflector, or using photogrammetric methods. It should be noted that photogrammetric methods have advantages when observing deformations over large areas, since deformation values are determined for a large number of points per one physical moment.

Today, most studies devoted to the use of photogrammetric methods for solving various engineering problems in mining and other industries are focused on the use of aerial photography for this purpose [1], [2]. In their research papers, the authors prove that improvements in sensors installed on aircraft have made it possible to expand the range of remote sensing methods. In this context, the effectiveness of the photogrammetric method is emphasized. Analysis of academic journal papers on the use of this method at all stages of deposit development: exploration, mining, exploitation, and reclamation, has led to the conclusion that it is most often used in topographic surveys of enterprise facilities, in monitoring completed reclamation, and in managing the slopes of quarries and dumps.

At the same time, unmanned aerial vehicles (UAVs) have become the most popular means of aerial photography, significantly increasing the productivity and economic efficiency of monitoring quarries, dumps, tailings dams and industrial sites in the mining industry [3]. The increased use of UAVs in mining significantly improves the productivity of surveying work and the effectiveness of remote sensing in the mining industry at all stages of mineral deposit development, from exploration to exploitation and reclamation of depleted land.

Many scientific studies examine the use of various platforms for surveying, but preference is given to different types of UAVs, such as Sensefly eBee, Skywalker X5, Drone AscTec Falcon 8, DJ Phantom 4, Atmos-7, and others. Various cameras can be installed on UAVs. The type of camera is selected depending on the tasks to be solved: when observing shears, it is advisable to use digital cameras and interferometric radars; when investigating fires in coal mines, thermal imaging infrared cameras are effective; when examining vegetation, a multispectral camera gives the best results, etc. The selected camera type allows obtaining digital images, point clouds, multispectral images, etc., which are further used to compile the necessary documentation, determine various characteristics of objects, calculate the volumes of mining operations, study deformations, etc. [4]-[7].

Contemporary scientific research covers important topics in surveying and mining in general: methods of remote sensing of the Earth's surface and objects located on it, using terrestrial or aerial survey for this purpose; methods for processing and managing large datasets generated by photogrammetric and satellite survey methods, using innovative software tools for this purpose [8]-[11]. One of the main tasks of modern scientific research is to improve the efficiency of mapping shear, monitoring terrestrial phenomena, assessing shear risks, and evaluating the relationship between shear and other hazards caused, for example, by proximity to tectonic faults, etc. [12].

It is known that at the present stage, modern digital surveying methods are used to solve many tasks of the surveying service of a mining enterprise. Digital surveying methods allow solving a wide range of tasks – from drawing up a mine survey plan to determining the volume of excavated rock mass, planning works, etc. [13]-[15].

From the time when photographic imaging methods were used in photogrammetry to the modern period of digital technology use, an effective remote method for determining deformations of quarry and dump slopes is the photogrammetric method using images and models taken at different times. Modern digital technologies, which are used at all stages of performing research into shears and various types of deformation, have greatly simplified the processes of obtaining and processing raw data [16]-[18]. The processes of surveying and referencing are carried out using modern technologies without the labor-intensive work as before, which is much more efficient. Processing of the images obtained is also performed in a short period of time without exhausting long-hour orientations using special photogrammetric devices.

Modern digital photogrammetry is focused on obtaining a point cloud and its subsequent processing using appropriate software tools [19], [20]. Auxiliary photogrammetric equipment, such as stereoscopes, is rarely used, or is used for a very limited range of tasks.

When performing stereo observations and measuring parallaxes in areas with signs of deformation, which then allows the actual deformation values to be determined, a binocular stereoscope system can be used.

Modern software tools for processing images obtained by digital photogrammetric methods, such as Agisoft, 3DF Zephyr, Meshroom, RealityCapture, have tools for exporting orientation elements for one or a group of images, but their practical use is imperfect due to a number of objective and subjective factors.

Each software tool is designed for a “full data processing cycle”, that is, from data input to obtaining the result in the form of a digital plan, model, or array of deformation values. However, exporting data from software of one manufacturer to software of another, for example, in Delta/Digitals, for further processing, such as determining deformation values using a stereoscope, causes certain problems. Therefore, when creating an effective method for surveying shears/deformations using photogrammetric method, it was necessary to solve the problem of selecting software and the necessary characteristics of computing equipment.

In addition, an important task was to determine the optimal parameters for terrestrial photogrammetric surveying and the accuracy with which the coordinates of benchmarks should be determined during the initial observation cycle.

Therefore, one of the tasks addressed in this research was to determine the dependence of the accuracy of determining the coordinates of points according to the digital model created from images on the basis length and its location (Fig. 1).

Figure 1 schematically shows that the stations are densely located. This allows obtaining a sufficiently complete digital model, which can be used to determine the deformation values with the required accuracy. Thus, despite the widespread use of photogrammetric methods in mining, the issue of substantiating the optimal parameters of terrestrial digital stereophotogrammetric surveying to improve the accuracy of determining the deformations of deep quarry walls remains insufficiently researched.

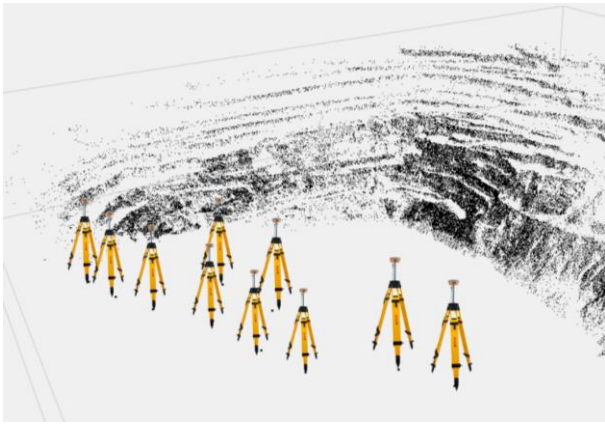


Figure 1. View of the arrangement of stations on the quarry wall

The purpose of this research is to develop and experimentally validate a methodology for terrestrial digital photogrammetric surveying for monitoring quarry wall deformations, while determining the optimal characteristics of the survey basis and the parameters of the initial observation cycle. To achieve the purpose set, it is necessary:

- analyze the influence of the length and orientation of the basis on the accuracy of determining the coordinates;
- substantiate the requirements for conducting the initial cycle of observations;
- assess the accuracy of determining deformations using the photogrammetric displacement method.

2. Material and methods

To study the daylight surface of the quarry and other objects influenced by mining operations, a digital method for determining the deformations of quarry and dump walls was developed and implemented at mining enterprises in the Kryvyi Rih Iron-ore Basin, based on the use of images taken at different times. The methodology combines modern digital technologies for obtaining and processing images with a high-precision photogrammetric method for determining deformations based on images taken at different times.

To study the proposed method of observing shear processes in the quarry, its accuracy and capabilities, digital survey of the examined objects was performed using an EOS 5D Mark III camera, which has a frame size of 36×24 mm and a resolution of 22.3 MP. The camera has a Digic 5+ processor and an ISO 100-25600 sensitivity range.

Based on the results of each survey, the position of 47 points was examined. For this purpose, a digital model was constructed based on images from each observation stage. A total of 998 images were processed. The processing was performed on a Dell 7910 dual-processor graphics station with two 22-core processors. To solve this problem, the amount of RAM should be at least 240 GB.

It is known that photogrammetric methods differ in the methodology of processing survey results. According to one of the methods, deformations are determined by the difference in coordinates of points from two models taken at different times, while according to the other method, deformations are determined by the results of measuring displacement values of points over the period between surveys. The latter method, known as the displacement method, was used in the research.

The method for determining deformations proposed in this paper made it possible to improve the accuracy of predicting the occurrence of deformations at the facilities of mining enterprises. This was facilitated by the introduction of a terrestrial digital photogrammetric surveying method. The method has a number of characteristics that have made it possible to bring terrestrial digital stereotopographic surveying closer to modern laser scanning in terms of accuracy.

This method was used to determine deformations in the studied areas of the quarries. At the same time, in all observation sessions, except for the initial one, no reference points were used, which in other methods should be used throughout all observation sessions for deformations and checked each time for the constancy of their position. When processing images, the mutual orientation process was performed using high-precision machine contour matching, which eliminated human errors.

A distinctive feature of this method is that the obtained deformation values do not depend on errors in the initial traverse for subsequent observation stages, which made it possible to achieve a sufficiently high accuracy of determinations. This is facilitated by the high accuracy of the initial traverse at the initial stage.

When using the proposed method, the essence of the work is the possibility of simultaneous processing of images obtained with a digital camera and archival images obtained with a photographic camera. In doing so, the property of continuity of new surveys in relation to previous or archived ones was used, which does not impair the accuracy of the results obtained. Particular attention was paid to the selection of computing parameters, as a large number of images were processed simultaneously, which requires significant amounts of memory and high performance.

Another advantage of using the proposed relative method for studying the deformation process is that the accuracy of the result does not depend on the chosen coordinate system or on the transition from one coordinate system to another. The work can be performed in any coordinate system.

It should also be noted that when using a relative method for determining deformation values, taking into account all its advantages, one of the important conditions is to conduct a high-quality initial cycle of observations. The accuracy of data obtained from the initial series of observations affects the accuracy of subsequent determinations, since later images from subsequent series of observations are processed together with images from the initial series.

It is precisely at zero cycle of observation that it is important to solve problems involving the selection of locations of survey bases and the determination of traverse point coordinates. It was difficult to solve these problems using traditional methods due to a number of factors, such as:

- significant distances to research objects (up to 1000-1500 m);
- large monitoring areas, that is, areas where deformation values are studied (up to 5-10 km²);
- dangerous conditions or the inability for other reasons to have direct performers on the walls and slopes of quarries and dumps.

That is, when choosing a survey type, it is important to consider the parameters and characteristics of the research objects.

In addition, it was taken into account that for deep quarries, when performing surveying operations and coordinating traverse stations, there are restrictions on the use of GNSS-technologies and tacheometric surveying with a non-reflector measurement mode. It is clear that these restrictions also apply to operations in deep iron ore quarries, such as those in Kryvyi Rih, which have specific geological characteristics of the surfaces and distances from one wall to another ranging from 1000 to 3000 m.

The maximum range of electronic tacheometers when operating in quarries and dumps in the Kryvyi Rih Iron-ore Basin decreases when pointing at dark rocks, as in such cases the laser beam is absorbed. Therefore, the maximum range of the device is less than the passport value of 1500 m and ranges from 750 to 1070 m. This means that the maximum operating range of an electronic tacheometer in non-reflective mode does not exceed 1070 m, which is insufficient for conditions in which deformation studies are performed in the Kryvyi Rih quarries.

The disadvantage of using modern satellite equipment at mining facilities to determine point coordinates is that performing work in both static and RTK modes is complicated by the inability to locate a person on the slope of a quarry or dump, where the traverse points are located.

Given the above, the research used a photogrammetric method in the design and implementation of the initial observation cycle, which is important for performing further series of deformation observations.

During the initial observation cycle, the following work was performed:

- the locations of control points were determined, which ensure their stable position over a long period of time;
- a project for the location of traverse points was compiled and transferred to the terrain, taking into account the best ratio of the basis length to the distance to the survey object, which provides the necessary accuracy in determining the coordinates and constructing a digital model;
- the coordinates of control points and traverse points were determined, most of which are physically inaccessible without special equipment;
- the required number of survey stations with their corresponding locations was designed and transferred to the site, ensuring the survey of the maximum area with a minimum number of areas not covered by the survey, due to various obstacles.

It was also taken into account that the area of the quarry or dump where rock shear monitoring work is carried out may be currently being mined and undergoing significant changes.

Work on the implementation of digital photogrammetric surveying for the study of shears/deformations caused by mining operations was carried out at various facilities of mining enterprises in the Kryvyi Rih Basin [21]-[23]. One of the research facilities was quarry No. 4 of PJSC “Central GOK”. This mining facility is relatively small compared to other quarries in the Kryvyi Rih Iron-ore Basin, measuring 1100 × 200 m. Working conditions were complicated by intensive quarrying and the fact that the research was conducted on the western and southern walls of the quarry, where mining operations take place in difficult hydrogeological conditions.

Control measurements of deformation values were performed using a SOKKIA SET630R electronic tacheometer, the main characteristics of which are:

- angle measurement accuracy – 6";
- magnification – 26";
- operates at a distance of 250 m (without reflector) to 5000 m (with reflector);
- the accuracy of measuring line lengths using a prism (reflector) is $\pm (2 \text{ mm} + 2 \text{ ppm})$ and $\pm (3 \text{ mm} + 2 \text{ ppm})$ without a prism;
- memory capacity – 10000 points.

In addition, a Topcon Hiper Plus GNSS receiver with 128 MB of memory capacity was used for coordinate determination; horizontal accuracy – 3 mm + 0.5 mm/km (L1 + L2); vertical accuracy – 5 mm + 0.5 mm/km (L1 + L2).

Mining facilities of open-pit mining enterprises – quarries and waste rock dumps, unlike engineering buildings and structures, usually have a complex and irregular geometric shape. Therefore, when planning terrestrial digital photogrammetric surveying, it was important not only to create a traverse [23], but also to develop a scheme for the location of bases that would contribute to the most effective solution of the problem of determining deformation values.

The selection of basis locations, given the complex shape of the quarry and the presence of areas dangerous for people to be in, is a particularly important task when conducting research on the process of quarry wall shearing using the photogrammetric method. Due to the complex shape of the quarry, terrestrial digital stereophotogrammetric surveying of a single wall or the whole quarry is practically impossible to perform under the ideal conditions provided for in classical photogrammetry. However, it is known that the accuracy of the results obtained depends on how well the requirements for selecting surveying conditions are taken into account.

To create the initial digital model, a complex survey basis was planned with 10 stations in quarry No. 4 of PJSC “Central GOK” (Fig. 2).

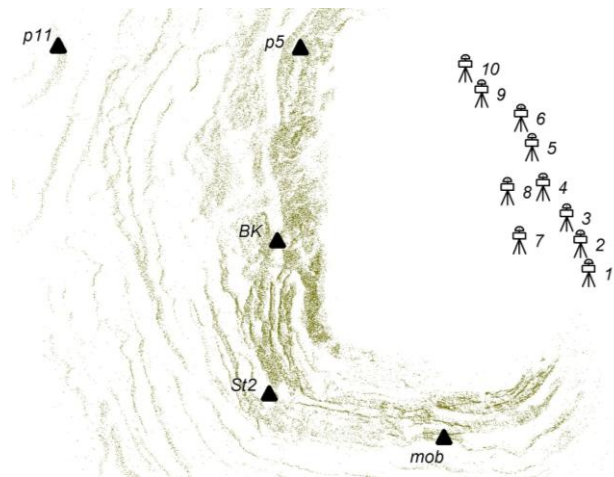


Figure 2. Layout of stations and reference points

This complex basis has a total length of 570 m with elevation differences between survey stations ranging from 98.31 to 125.32 m. This basis was used to study the proposed methodology using the example of performing observations on the state of quarry walls. Figure 2 shows the layout of stations 1, 2, ..., 10 and reference points *p5*, *p11*, *St2*, *BK* and *mob*.

At the initial stage of observing the state of the quarry walls, reference and control points were first fixed in the locations specified by the project, in accordance with the requirements of the relevant instructions and guidelines.

After fixing these points, work was performed to determine their initial coordinates. Subsequently, observations are made based on the state of these points in order to determine changes in their coordinates over time in a given system.

It is known that recently one of the most effective methods for observing shears/deformations is a method that combines satellite-based determination of the coordinates of starting points, leveling of benchmarks, and measuring the distances between them using an electronic tacheometer. This method ensures high accuracy of observing various types of shears/deformations at quarries and other facilities of mining enterprises. However, despite the high accuracy and efficiency of this method, it is inferior to the photogrammetric method, which has the advantages of significantly reducing field work and the ability to record a large number of points for one physical moment, which allows determining their mutual deformation. In addition, remote methods, one of which is photogrammetric, allow for the investigation of areas that are inconvenient or dangerous for workers to access [24]-[26].

Figure 3 and 4 show that the reference points are located on the slope of the permanent quarry wall, and therefore their coordinates can only be determined by remote methods, using the photogrammetric method.



Figure 3. Location of two points on the steep slope of the eastern wall of quarry No. 4



Figure 4. Location of reference points on the slope of the eastern wall of quarry No. 4

Since this method of monitoring rock shear/deformations at mining enterprise facilities – as well as at other facilities – uses data on the initial state of the surface or facility, such work was performed during the initial observation cycle. During the initial observations cycle, the planned-high-altitude position of the reference and control points was determined using photogrammetric mark. The coordinates of the points were verified using GPS and an electronic tacheometer.

3. Results and discussion

The developed methodology for monitoring shear/deformation processes, using terrestrial digital stereophotogrammetric surveying, was applied at quarries No. 1, 3 and 4 of PJSC “Central GOK”. The accuracy of point coordinate determination based on survey results from bases of different lengths and projection is graphically shown in Figure 5a-e.

In the graphs showing the accuracy of determining benchmark coordinates (Fig. 5), the results obtained from the normal basis are shown in blue, while those obtained from the elongated basis – with its stations located on different horizons – are shown in red. The results indicate a higher accuracy of obtaining coordinates from the basis, the stations of which are located on different horizons.

Terrestrial digital photogrammetric survey was conducted using bases of varying lengths and orientations. Both normal bases, which in terms of their characteristics are typical for photogrammetric surveys, and elongated bases were used, with stations located on different horizons of the quarry. In order to obtain deformation values with the highest accuracy, a study was conducted on the issue of selecting the necessary characteristics of the survey basis: its length; its position relative to the object; the ratio of the distance between the basis and the object to the basis length.

The use of 570 m basis, formed by the distance between survey stations 1 and 10 to survey the wall section between benchmarks *St2* and *BK*, made it possible to obtain deformation values with the highest possible accuracy. However, based on the results of the survey from the basis formed by the distance between survey stations 2 and 7, the horizontal projection of which is 140 m, the wall section located near the *mob* benchmark, a significantly lower accuracy was obtained, since the accuracy was influenced by the significant difference in the scale of images (Fig. 2).

Using photogrammetric and geodetic methods, the coordinates of five benchmarks were determined; these benchmarks are located at varying distances from the survey basis and are oriented differently relative to it. After obtaining these initial coordinate values with the required accuracy, they were taken as “ground control” and used for further orienting of photogrammetric models with a given accuracy.

Table 1 shows the accuracy of determining coordinates for different lengths of the photogrammetric survey basis. The results presented in Table 1, prove that for distances between the basis and the object from 600 to 800 m, the accuracy of coordinate determination varies, as it depends on which basis is used, whether it is a normal or multilevel basis, that is, one that is higher in length and with stations located on different horizons. The results indicate a higher accuracy in determining coordinates when using an elongated multilevel basis.

Since the accuracy of constructing a photogrammetric model is influenced by the basis length and its location, this issue was more thoroughly investigated. An assessment of the influence of the basis length on the accuracy of determining the coordinates of benchmarks and other survey points is presented in the graph comparing the accuracy of determining the coordinates of points *BK* and *St2* (Fig. 6). These two benchmarks are almost perpendicular to the basis. As a rule, two types of surveying were performed from each basis – normal and oblique. When surveying obliquely, the camera’s optical axis is deviated from the normal, which reduces the projection of the basis onto a plane parallel to the survey plane.

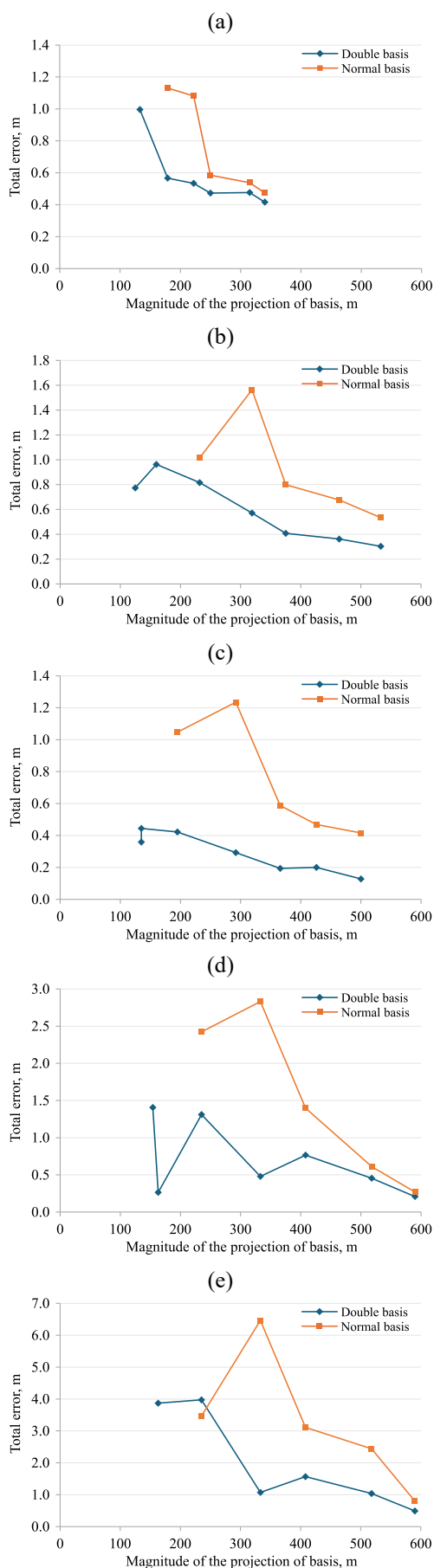


Figure 5. Accuracy of determining benchmark coordinates depending on the basis characteristics: (a) on BK benchmark; (b) on St2 benchmark; (c) on 5 benchmark; (d) on mob benchmark; (e) on 11 benchmark

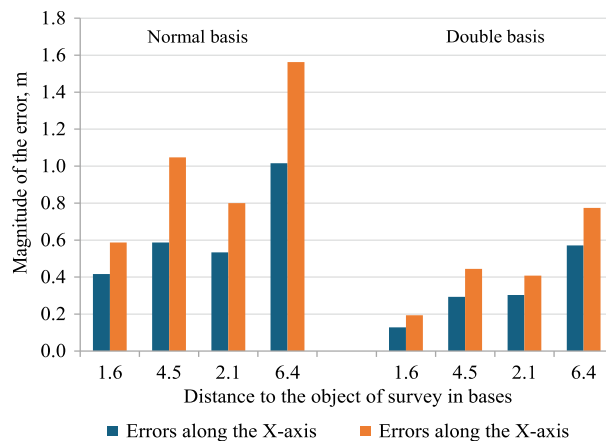


Figure 6. Comparison of the accuracy of determining the coordinates of benchmarks when using normal and double bases

When determining the coordinates of points *BK* and *St2*, it was taken into account that the ratio of the basis projection to its actual length is from 0.82 to 0.9. At a distance of 600 m from the *BK* benchmark, the ratio of the actual basis length to its projection is 1.7-1.2.

With a basis projection length from 360 to 500 m, the most accurate and stable results with permissible deviations were obtained for *BK* benchmark. When the basis length is less than 300 m, the results of determining point coordinates are less accurate compared to the case of using an elongated multilevel basis. Good results – that is, higher accuracy in determining coordinates – were obtained by using three stations on the same basis, with the stations located on the main and adjacent horizons. Using this basis made it possible to improve the accuracy of coordinate determination by 3 times compared to the accuracy achieved when using a normal basis. For example, when using an elongated multilevel basis, the accuracy of determining point coordinates was 0.128-0.194 m, and when using a normal basis, the accuracy was 0.416-0.587 m.

The research results led to the conclusion that it is expedient to use elongated multilevel bases, the effectiveness of which is proved by obtaining the coordinates of points with the required accuracy; these coordinates were subsequently used to determine the deformations of the daylight surface and the examined objects.

With stations located on different horizons, the accuracy of determining the coordinates of control and reference points increases by 50-75%. With a basis length of 500 m, the coordinates of the points were obtained with a mean square error of 0.16 m, and with a basis length of 130 m – with a mean square error of 0.42 m (Table 1).

The results presented in the graphs and in Table 1 show a significant difference in the accuracy of coordinate determination depending on the characteristics of the bases. The basis, with its stations located on the main and adjacent horizons, provides significantly higher accuracy in determining the coordinates of the initial traverse points and greater stability in obtaining results. The graph in Figure 7 shows, as percentages, the error components in determining the coordinates of points along the *X*, *Y* and *Z* axes, respectively.

The smallest component in the total error value is the height *Z*, and the largest – along the *X*-axis. With this level of accuracy in determining the coordinates of traverse, subsidence in the studied area is measured with an accuracy of up to 10 mm, which meets the accuracy requirements for determining deformations in quarries, dumps, and tailings dams.

Table 1. Errors in coordinates on reference benchmarks

Control benchmark	Distance to the benchmark, m	Basis length, m	Distance in basis fractions	Accuracy of determining coordinates X, Y, Z, m
BK (multilevel basis)	607	500-366	1.2-1.6	0.128-0.194
BK (normal basis)	607	500-366	1.2-1.6	0.416-0.587
BK (multilevel basis)	607	292-135	2.1-4.5	0.293-0.444
BK (normal basis)	607	292-135	2.1-4.5	0.587-1.047
St2 (multilevel basis)	802	533-375	1.5-2.1	0.303-0.408
St2 (normal basis)	802	533-375	1.5-2.1	0.534-0.800
St2 (normal basis)	802	319-125	2.5-6.4	1.016-1.563
St2 (multilevel basis)	802	319-125	2.5-6.4	0.571-0.774

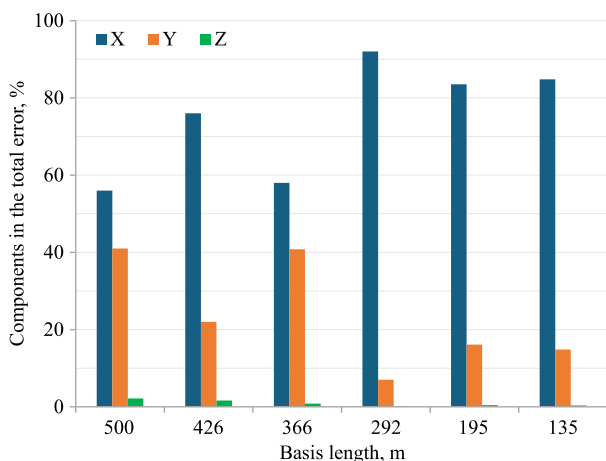


Figure 7. Values of the error components X, Y, and Z (in percent) for different basis lengths

The error components in determining coordinates along the X, Y, and Z axes vary, as they depend not only on the basis length, but also on the distance to the object and the accuracy of determining the position and orientation of the basis. That is, given all the surveying parameters, when using a basis with the proposed characteristics, the errors in determining coordinates of points and deformations are smaller and meet the requirements of the instructions and guidelines for their lengths.

The results of this research, which focused on monitoring various types of shears/deformations using terrestrial digital stereo imaging have proven the effectiveness of the method and its ability to compete with other methods based on modern technologies, such as: laser scanning [27], surveying from UAV [3], surveying using modern electronic devices and GNSS, etc.

Since remote sensing methods are preferred for monitoring deformations at mining facilities, the results obtained in this research should be compared with those obtained using photogrammetry and scanning methods. Many studies by domestic and foreign authors refer to the mean square errors, ranging from 0.05 to 0.2 m, in determining the position of points using equipment mounted on UAVs. However, technology continues to improve every year, and research methods are becoming simpler; for example, the accuracy and capabilities of digital photogrammetry in 2024-2026 differ significantly from those of previous years [12].

This paper proposes a new approach to the simultaneous processing of archival and new images of mining facilities, which makes it possible to identify deformations over a significant period of time and to control previously obtained research results regarding shears/deformations over large areas.

Recent scientific works in this area of research have focused on selecting: imaging equipment, the type of platform for installing on it the imaging equipment, and the most effective software for processing large datasets. An equally urgent task is to develop a method for monitoring deformations that would allow for obtaining results of the required accuracy at minimal cost.

4. Conclusions

The results of the conducted research have revealed that when observing deformations of quarry walls using the traditional photogrammetric method and standard survey parameters, the accuracy of determining the positions of reference points used to create the initial digital model is insufficient. The low initial model accuracy leads to a decrease in the reliability of determining the deformation values in subsequent observation cycles, since the current and initial models are compared each time.

It has been substantiated that the key stage is conducting the initial observation cycle. The use of a complex multilevel basis with stations located on adjacent horizons is proposed, which has made it possible to triple the accuracy of determining the coordinates of reference points and ensure compliance of the obtained values with the requirements for the traverse accuracy.

It has been proven that the use of a normal basis results in lower accuracy compared to an elongated multilevel basis. The use of an improved photogrammetric relative method (displacement method), in which images taken at different times are processed simultaneously, made it possible to obtain deformation values with an accuracy that meets regulatory requirements. In particular, for points located at a distance of 600 m from the basis, the accuracy of determining deformations was ± 50 mm, and at a distance of 800 m – ± 80 mm. Accuracy was verified using an electronic tacheometer and GNSS-measurements.

The high efficiency of the photogrammetric displacement method in monitoring deformation processes in quarries has been confirmed. At the same time, directions for further research have been identified, including: determining the optimal grid spacing for the model, developing a rational scheme for the location of reference and control points, as well as clarifying the criteria for selecting survey basis parameters.

The proposed methodology is operational and ensures the necessary accuracy in determining deformation values and their components, provided that the requirements for conducting the initial observation cycle are met. The main drawback of this method is the need for significant computing resources to simultaneously process a large array of digital images.

Author contributions

Conceptualization: OD; Formal analysis: OD, MS; Investigation: OD, MS; Methodology: OD; Project administration: OD; Supervision: OD; Visualization: OD, MS; Writing – original draft: OD; Writing – review & editing: OD, MS. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Підвищення точності визначення деформацій бортів кар'єрів шляхом оптимізації параметрів наземного стереофотограмметричного знімання

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Мета. Розробка та експериментальне обґрунтування методики наземного цифрового стереофотограмметричного знімання для спостереження за деформаціями бортів глибоких кар'єрів із визначенням оптимальних параметрів базису зйомки та початкового циклу спостережень, що забезпечують необхідну точність визначення величин деформацій.

Методика. Дослідження передбачали проєктування та виконання зйомки кар'єру на початкову й наступні дати спостережень за деформаціями з використанням професійної цифрової камери. Опрацювання отриманих цифрових зображень здійснювалося за удосконаленим варіантом класичного фотограмметричного методу – способу зміщень. З метою підвищення ефективності моніторингу деформацій фотограмметричним способом обґрунтовано вимоги до проведення початкового циклу спостережень із визначенням оптимальних параметрів знімання та обробки даних.

Результати. За результатами застосування наземної цифрової зйомки та удосконаленого фотограмметричного способу зміщень при опрацюванні знімків із достатньо високою точністю визначено величини деформацій на дослідних ділянках бортів кар'єрів. Обґрунтовано вимоги до виконання початкового циклу спостережень за деформаційними процесами та встановлено вплив його параметрів на ефективність подальшого моніторингу. Практичну результативність розробленої методики підтверджено під час дослідження деформацій, спричинених гірничих робіт на кар'єрах ПрАТ “Центральний гірничо-збагачувальний комбінат”.

Наукова новизна. Визначені оптимальні параметри початкового циклу спостережень за деформаціями бортів кар'єрів при застосуванні способу наземного цифрового знімання. Встановлено закономірності між точністю визначення координат точок за створеною цифровою моделлю місцевості та просторовим положенням базису зйомки. Обґрунтовано вимоги до характеристик обчислювальної техніки, що забезпечують ефективне опрацювання значних обсягів цифрових зображень і підвищення продуктивності камеральних робіт.

Практична значимість. Удосконалено фотограмметричний спосіб зміщень для визначення деформацій за різночасовими зніманнями. Розроблений метод спостереження за зсувними процесами та іншими видами деформацій на основі цього способу забезпечує визначення величин просторових змін положення точок досліджуваного об'єкта з необхідною точністю та оперативне отримання інформації про його поточний стан і перспективи подальшої безпечної експлуатації.

Ключові слова: *цифрові зображення; наземна фотограмметрична зйомка; базис зйомки; координати точок; різночасові знімки*

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