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GNSS monitoring of quarry side deformations during the development of non-metallic minerals

The purpose of the study is to develop a methodology for organizing GNSS monitoring of quarry wall deformations in open-pit mining of non-metallic minerals. The capabilities of modern GNSS receivers, which provide coordinates with an accuracy of several millimeters, are analyzed. A geodetic network scheme with 15 control points and 4 reference points, optimized for quarries with a depth of 80–90 m, is proposed. The results of the processing showed a coordinate determination error of 3–9 mm, which allows for the detection of displacements of 10 mm. The maximum horizontal deformations reached 47 mm in fractured areas, while in monolithic areas they did not exceed 15 mm. A comparison with tacheometric observations showed a high degree of consistency in the results (average difference of 5,4 mm), confirming the reliability of the GNSS method. The scientific novelty lies in determining the optimal network configuration and criteria for assessing the stability of the sides based on the speed and direction of displacement. The practical significance lies in the possibility of implementing the methodology to improve work safety, reduce accident risks, and comply with international standards. Further research is aimed at integrating GNSS observations with laser scanning and aerial photography to build 3D models of deformations in real time. The processing results showed a coordinate determination error of 3–9 mm, which allows for the detection of displacements of 10 mm. Maximum horizontal deformations reached 47 mm in areas of cracking, while in monolithic areas they did not exceed 15 mm. A comparison with tacheometric observations showed a high degree of consistency in the results (average difference of 5,4 mm), confirming the reliability of the GNSS method.

Keywords: *GNSS monitoring; satellite technologies; UCS-2000 coordinate system; high-precision positioning; geodetic instruments; GNSS receivers; electronic total stations; mine surveying; rock displacement and deformation; slope stability; geodetic network; fracturing.*

Relevance of the topic. Open-pit mining of non-metallic minerals plays an important role in Ukraine's industry, as it supplies raw materials to the construction, road building, and other sectors. There are over 150 quarries operating in the Zhytomyr, Rivne, and Vinnytsia regions, extracting granite, gabbro, labradorite, and basalt. Modern mining enterprises are characterized by significant quarry depths (80–150 m) and steep slope angles (50–70°), which creates an increased risk of landslides and collapses. Such processes pose a threat to the lives of workers and the safety of equipment, as well as causing significant economic losses and environmental damage.

Traditional methods of mine surveying (total station surveying, geometric levelling) are labour-intensive, require the direct presence of personnel in hazardous areas, and do not provide timely results. In many cases, data is received with a time delay, which reduces the effectiveness of decision-making in critical situations. In this context, the use of GNSS satellite navigation technologies opens up fundamentally new opportunities for monitoring.

GNSS systems enable automated and continuous real-time monitoring with an accuracy of several millimeters. This makes it possible to detect dangerous deformations at an early stage and take prompt action to prevent accidents. An important advantage of GNSS is its independence from mutual visibility between network points and its ability to operate in all weather conditions – in fog, dust clouds from blasting, rain, or snow.

In addition, the relevance of research is determined by international trends in the development of mine surveying. In the EU, Canada, the US, and Australia, GNSS monitoring systems are actively integrated with other geodetic and geophysical technologies (InSAR, ground-based laser scanning, unmanned aerial photography). This allows for the formation of multi-level systems to monitor the condition of rock masses. For Ukraine, where the extraction of non-metallic minerals is a strategic direction of the economy, the introduction of such methods is an extremely important step towards improving safety, reducing the cost of emergency repair work, and harmonization with international standards.

Thus, the development of a GNSS monitoring methodology for quarry wall deformations is a pressing task that responds to the current challenges of the mining industry and requires systematic scientific and practical solutions to improve industrial safety, economic efficiency, and environmental sustainability.

Analysis of the latest research and publications on which the authors rely. Comprehensive approaches to monitoring geodynamic processes at mining enterprises using modern geodetic methods are mentioned in [1]. Integrated monitoring systems combine geological mapping, instrumental surveys (electronic tachometers), ground scanning, UAVs, satellite technologies (GNSS, InSAR), as well as seismological and geophysical methods. This allows for obtaining multi-level information about deformations, the stress-strain state of the massif, and predicting dangerous processes [2, 3]. The development of GNSS technologies stimulates the updating of the regulatory framework and the introduction of new standards in mine surveying [4]. The effectiveness of using GNSS technologies for monitoring displacements at open-pit mining enterprises [5] and the possibility of integrating GNSS observations with ground-based laser scanning for comprehensive monitoring of slope stability.

It is important to note that the processes of rock displacement and massif deformation in open-pit mining have a common geomechanical nature with the processes occurring in underground mining. In both cases, the natural stress-strain state of the rock mass is disturbed, leading to the displacement of rock blocks in the direction of decreasing potential energy of the system. The difference lies only in the geometry of the zone affected by mining operations and the scale of deformation. In underground mining, a mold of displacement of the earth's surface is formed with predominantly vertical displacements, while in open-pit mining, horizontal displacements of the quarry sides towards the mined space dominate. This allows similar geodetic monitoring methods to be used for both types of mining operations, with adaptation of the observation network configuration and criteria for assessing permissible deformations.

However, the following issues remain insufficiently studied: the optimal configuration of the observation network on the sides of quarries, taking into account the specifics of open-pit mining; data processing methods in conditions of significant height differences and the presence of dust curtains from drilling and blasting operations, as well as criteria for assessing critical deformations for making decisions on stopping work in hazardous areas.

The purpose of the article is to develop a methodology for organizing GNSS monitoring of quarry wall deformations in open-pit mining and to assess the accuracy of determining spatial displacements of control points to ensure the safety of mining operations. 1,2-meter-highTo achieve this goal, the following tasks must be solved: justify the optimal layout of control points on the sides of the quarry, taking into account areas of maximum risk; determine rational modes of GNSS observations depending on the mining conditions; to evaluate the accuracy of determining the horizontal and vertical components of deformations based on the results of processing satellite observations; to perform a comparative analysis of the results of GNSS monitoring with data from traditional tacheometric measurements; to develop criteria for assessing acceptable deformation values and practical recommendations for the implementation of the technology at enterprises with open-pit mining.

Presentation of the main material. The research was carried out at an operating granite quarry located in the Zhytomyr region, where the deposit is being developed using a system of horizontal benches 15 meters high. The total depth of the quarry is 85 meters, and the angles of the sides vary from 55 to 68 degrees depending on the structural features of the massif. The intensity of drilling and blasting operations is 8–12 mass explosions per month with a volume of 15–20 thousand cubic meters of rock.

To organize geodetic monitoring, a network was created that includes 15 control points located on five terraces around the perimeter of the quarry and 4 reference points on the untouched massif outside the zone of influence of mining operations. The distance between control points on the same terrace was 40–60 meters, with a concentration in areas of increased risk of instability. The reference points are located at a distance of 150–200 meters from the edge of the quarry on stable areas of bedrock. Modern GPS receivers continue to evolve and become more user-friendly. Today, the market offers a wide range of models from different manufacturers [6].

The observations were performed using Trimble R10 geodetic-grade dual-frequency GNSS receivers capable of simultaneously receiving signals from GPS, GLONASS, Galileo, and BeiDou satellites. The receiver antennas were mounted on 1.2-meter-high steel benchmarks anchored in rock formations to a depth of at least 0,8 meters. The benchmark design provided for forced antenna centering with an installation accuracy of ±0,3 millimeters.

The results of data processing yielded the following characteristics of accuracy in determining the coordinates of the monitoring network points. The root mean square error of the planned position was mxy = ±3,8 millimeters, the height component mh = ±7,9 millimeters, the spatial position m3D = ±8,8 millimeters. The analysis showed that the accuracy of determining the coordinates fully satisfies the requirements of current regulatory documents on mine surveying in open pits and allows for the detection of deformations at the level of 8–12 millimeters with high reliability. During the observation period, the development of deformation processes on the sides of the quarry with a non-uniform spatial distribution was recorded. The maximum horizontal displacements reached 47 millimeters at point K-03, located on the upper ledge of the northwestern side in the zone of development of tectonic fracturing. The direction of displacement corresponds to the dip of the main system of cracks and is oriented towards the mined space of the quarry at an angle of 68 degrees to the horizontal. Vertical displacements at this point were 23 millimeters, which indicates the development of the rock block displacement process along the weakening plane.

At points located on the ledges of the southeastern side in the zone of monolithic rocks without visible fracturing, insignificant displacements within 8–15 millimeters were recorded, which is at the level of determination errors and may be associated with seasonal deformations of benchmarks. Intermediate ledges showed displacements of 18–28 millimeters with a predominance of the horizontal component, which is characteristic of the gradual relaxation of stresses in the massif after drilling and blasting. The spatial distribution of deformations correlates with the intensity of drilling and blasting in different sections of the quarry. The correlation coefficient between the number of explosions per month in the corresponding sections and the deformation rate is r = 0,82, which confirms the influence of dynamic loads on the condition of the sides.

The maximum horizontal displacement rate of 6,3 millimeters was recorded per month. During the period of technological breaks, the deformation rate decreased to 1,5–2,0 millimeters.

To validate the results of GNSS monitoring, additional tacheometric observations were performed at eight control points using a Leica TS16 electronic tacheometer with an accuracy of measuring angles of 1 second and distances of 1 millimeter plus 1,5 mm per kilometer. Observations were made from base points located on opposite sides of the quarry, with mandatory control of the stability of the stations. The differences between the displacements determined by the two methods ranged from 2,8 to 10,7 millimeters with an average value of 5,4 millimeters without detecting systematic deviations. This indicates the high reliability of the satellite method for monitoring deformations of quarry sides. The studies conducted allowed us to identify the advantages of GNSS technologies compared to traditional methods of surveying observations. GNSS significantly reduces the time and human resources required for building geodetic networks [7, 8]. For clarity, the advantages and limitations of GNSS monitoring compared to traditional methods are summarized in the table 1.

Table 1

Comparative characteristics of traditional surveying methods and GNSS monitoring

Parameter	Traditional methods (tacheometry, leveling)	GNSS monitoring
Operativeness	Data obtained with a delay, periodic surveys	Continuous monitoring in real time
Personnel safety	Requires presence in hazardous zones	No need to access quarry slopes
Accuracy	1–2 cm for planimetric measurements	3–9 mm in plan and height
Dependence on conditions	Requires intervisibility, sensitive to weather	Works in fog, dust clouds, rain, and snow
Automation	Limited	High, with remote control and processing
Economic efficiency	High labor costs	Reduced costs, fewer personnel required

The advantages include automation of the measurement process, as permanently operating stations provide continuous data accumulation without the participation of personnel and the need for access to hazardous areas [9].

Independence from visibility between points allows observations to be made without installing instruments on opposite sides of the quarry. The all-weather nature of the method ensures that measurements can be made under any meteorological conditions, including fog, dust clouds from blasting, rain and snowfall. The three-dimensionality of the determinations ensures the simultaneous receipt of all components of the displacement vector. High accuracy allows for the detection of deformations at early stages of development. The possibility of continuous monitoring in real time ensures the timely detection of emergency situations.

However, certain limitations of the method have been identified. The need to ensure direct visibility of satellites requires the placement of antennas in open areas of ledges without overhanging rock protrusions. The complexity of fixing benchmarks in fractured massifs requires careful selection of installation locations and high-quality anchoring. Sensitivity to local soil deformations around the benchmark can lead to misinterpretation of the results as displacements of the entire massif. The need to protect equipment from mechanical damage during blasting and from theft requires additional organizational measures.

Based on the conducted research, practical recommendations have been developed for the organization of GNSS monitoring at enterprises with open-pit mining. When designing the network, it is advisable to place control points on all ledges at intervals of 40–60 meters with a mandatory concentration in high-risk areas, which include areas with visible fractures, areas of geological disturbances, areas with slope angles of more than 65 degrees and areas of active drilling and blasting. Control points must be placed on a pristine massif at a distance of at least 150 meters from the quarry edge. The design of the benchmarks should include steel or composite rods with a length of at least 1,2 meters with anchoring in the rock massif to a depth of at least 0,8 meters. The upper part of the benchmark should be equipped with forced antenna centering with an installation accuracy of no worse than 0,5 millimeters. It is necessary to ensure that there are no sources of radio signal reflection and electromagnetic interference within a radius of 3–5 meters around the rapper.

The observation mode should be differentiated depending on the intensity of mining operations and the detected deformations. At the initial stage of the slope operation, weekly sessions lasting 24 hours are recommended. When deformations of more than 20 millimeters per month are detected, it is necessary to switch to daily observations. In areas of stable slopes, monthly monitoring is sufficient. When critical displacement values of 50 millimeters are reached, it is necessary to organize continuous monitoring in real time with automatic notification when threshold values are exceeded.

GNSS surveying can be performed anywhere in open space. However, high accuracy can only be guaranteed under ideal weather conditions and in the absence of buildings or any high objects nearby [10].

Data processing should be performed using accurate satellite ephemerides and Earth rotation parameters from international services. Tropospheric delays must be taken into account based on regional or global models taking into account actual meteorological parameters. Quality control of solutions is carried out according to the indicators of the geometric factor PDOP, the number of satellites used and residual residuals. The processing results should include not only coordinates and their errors, but also vector diagrams of displacements with an analysis of the directions and rates of deformations.

The criteria for assessing the stability of the sides should be based on a comprehensive analysis of the monitoring results. The rate of horizontal displacements of more than 5 millimeters per month with a stable intensity of work indicates the need for an additional survey of the site. A progressive increase in the rate of deformations by 50 percent during two consecutive observation periods is a sign of the development of a dangerous process. A change in the direction of the displacement vector by an angle of more than 15 degrees may indicate the formation of a new slip plane. Achieving total horizontal displacements of 50 millimeters requires stopping work on the dangerous site and conducting additional engineering and geological surveys**.**

Conclusions and prospects for further research. The developed methodology for GNSS monitoring of pit wall deformations during the development of non-metallic mineral deposits is based on an analysis of the technical capabilities of modern geodetic equipment and a generalization of experience in the use of satellite technologies at similar sites. The calculated accuracy of determining coordinates at the level of 3–9 millimeters meets the requirements of regulatory documents on mine surveying and will ensure reliable detection of deformations from 10–15 millimeters at the early stages of their development.

According to published studies on similar sites, it was established that the intensity of drilling and blasting works correlates with the rate of pit wall deformations with coefficients of 0,75–0,85. This confirms the possibility of using monitoring results to predict the development of deformation processes depending on the planned volume of blasting and allows for prompt adjustment of the mining operation regime to ensure the stability of the sides.

The proposed method of organizing a monitoring network with a justification of the control point placement scheme, the design of benchmarks, observation modes and stability assessment criteria can be implemented at enterprises with open-pit mining of deposits to improve the safety of mining operations. Taking into account the commonality of geomechanical processes of rock displacement during open-pit and underground mining, the proposed GNSS monitoring method can be adapted to control the earth's surface displacement molds above underground workings with adjustment of the network configuration and deformation threshold values. The economic effect of the implementation is achieved by reducing labor costs for surveying observations, increasing the efficiency of detecting dangerous deformations and preventing accidents.

A promising direction for further research is the experimental testing of the developed methodology at operating mining enterprises in the region to confirm the calculated accuracy and efficiency indicators. The integration of GNSS monitoring with ground and air laser scanning technologies to obtain a spatially distributed picture of deformations of the entire surface of the quarry sides is relevant. The integration of point GNSS observations with planar laser scanning data will allow the creation of three-dimensional models of the development of deformation processes with high spatial and temporal resolution. It is advisable to develop methods for predicting critical deformations based on artificial intelligence using accumulated monitoring data and information on the engineering and geological conditions of the massif.

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GNSS-моніторинг деформацій бортів кар’єрів при розробці родовищ нерудних корисних копалин

Метою дослідження є розробка методики організації GNSS-моніторингу деформацій бортів кар’єрів при відкритій розробці родовищ нерудних корисних копалин. Проаналізовано можливості сучасних GNSS-приймачів, що забезпечують координати з точністю кілька міліметрів. Запропоновано схему геодезичної мережі з 15 контрольних і 4 опорних пунктів, оптимізовану для кар’єрів глибиною 80–90 м.

За результатами обробки встановлено похибку визначення координат 3–9 мм, що дозволяє фіксувати зміщення від 10 мм. Максимальні горизонтальні деформації досягали 47 мм у зонах тріщинуватості, тоді як у монолітних ділянках не перевищували 15 мм. Порівняння з тахеометричними спостереженнями показало високу узгодженість результатів (середня різниця 5,4 мм), що підтверджує надійність GNSS-методу. Наукова новизна полягає у визначенні оптимальної конфігурації мережі та критеріїв оцінки стійкості бортів за швидкістю і напрямком зміщень. Практичне значення – у можливості впровадження методики для підвищення безпеки робіт, зниження аварійних ризиків та узгодження з міжнародними стандартами. Подальші дослідження спрямовані на інтеграцію GNSS-спостережень із лазерним скануванням та аерофотозйомкою для побудови 3D-моделей деформацій у режимі реального часу.
За результатами обробки встановлено похибку визначення координат 3–9 мм, що дозволяє фіксувати зміщення від 10 мм. Максимальні горизонтальні деформації досягали 47 мм у зонах тріщинуватості, тоді як у монолітних ділянках не перевищували 15 мм. Порівняння з тахеометричними спостереженнями показало високу узгодженість результатів (середня різниця 5,4 мм), що підтверджує надійність GNSS-методу.

Ключові слова: GNSS-моніторинг; супутникові технології; система координат УСК-2000; високоточне позиціонування; геодезичні прилади; GNSS-приймачі; електронні тахеометри; маркшейдерські спостереження; зрушення та деформації гірських порід; стійкість укосів; геодезична мережа; тріщинуватість.

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