Код МРНТИ 36.29.27

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REMOTE SENSING OF INDUSTRIAL STOCKPILES UNDER SNOW COVER: METHODS AND SCIENTIFIC CHALLENGES

Abstract. Determining the volumes of stockpiled materials at industrial sites during the winter period is complicated by the presence of snow cover, which distorts surface geometry and reduces calculation accuracy. The aim of the study is to evaluate the effectiveness of remote sensing methods for mine surveying and geodetic support. The research is based on the analysis and comparison of laser scanning, satellite, radar, ground-penetrating radar, and photogrammetric methods. It is established that the integration of UAV-based photogrammetry and GNSS provides the highest efficiency. The scientific novelty lies in assessing the impact of snow cover on digital model accuracy and substantiating an integrated approach to their application.

Key words: *remote sensing, digital surface model, mine surveying and geodetic measurements, snow cover, industrial stockpiles, volume calculations.*

Қар жамылғысы жағдайында өнеркәсіптік қоймалар бетінің қашықтықтан зондталуы: әдістерге шолу және ғылыми мәселелер

Андатпа. Өнеркәсіптік қоймаларда сақталатын материалдардың көлемдерін анықтау қысқы кезеңде қар жамылғысының болуына байланысты күрделене түседі, себебі ол беттердің геометриясын бұрмалап, есептеулердің дәлдігін төмендетеді. Зерттеудің мақсаты -маркшейдерлік-геодезиялық қамтамасыз ету үшін қашықтықтан зондтау әдістерінің тиімділігін бағалау. Лазерлік сканерлеу, спутниктік, радиолокациялық, георадарлық және фотограмметриялық әдістер бойынша деректерді талдау және салыстыру қолданылды. Ең жоғары тиімділікті БПЛА-фотограмметриясы мен ГНСС интеграциясы қамтамасыз ететіні анықталды. Ғылыми жаңалығы қар жамылғысының цифрлық модельдердің дәлдігіне әсерін бағалауда және оларды қолданудың кешенді тәсілін негіздеуде жатыр. Қар қабаты өлшеу нәтижелерінің дәлдігіне әсер ететіні анықталды.

Түйінді сөздер: *қашықтықтан зондтау, беттік цифрлық модель, маркшейдерлік-геодезиялық өлшеулер, қар жамылғысы, техногендік объектілер, көлемдерді есептеу.*

Дистанционное зондирование поверхности промышленных складов в условиях снежного покрова: обзор методов и научных проблем

Аннотация. Определение объемов складируемых материалов на промышленных складах в зимний период осложняется наличием снежного покрова, искажающего геометрию поверхностей и снижающего точность расчетов. Цель исследования – оценка эффективности методов дистанционного зондирования для маркшейдерско-геодезического обеспечения. Применены анализ и сопоставление данных по лазерному сканированию, спутниковым, радиолокационным, георадарным и фотограмметрическим методам. Установлено, что наибольшую эффективность обеспечивает интеграция БПЛА-фотограмметрии и ГНСС. Научная новизна заключается в оценке влияния снежного покрова на точность цифровых моделей и обосновании комплексного подхода к их применению.

Ключевые слова: *дистанционное зондирование, цифровая модель поверхности, маркшейдерско-геодезические измерения, снежный покров, техногенные объекты, расчеты объемов.*

Introduction

Determining the volume of stockpiled materials is an important task in mine surveying and geodetic support for mining and industrial enterprises. The reliability of volume calculations affects inventory accounting, production planning, and economic assessment. In open storage areas, this task is complicated by the complex geometry of stockpiles, steep slopes, sharp elevation differences, and continuous changes in the shape of the stored material.

In winter, volume determination becomes less accurate because snow cover partially or completely conceals the actual material surface. As a result, the digital surface model obtained from survey data may represent the snow surface rather than the real geometry of the stockpiled material. This leads to the inclusion of snow mass in the calculated volume and causes systematic errors.

Traditional ground-based methods, including total station surveying, geometric leveling, and GNSS measurements, provide high accuracy for individual points. However, their use in winter is limited by labor intensity, safety requirements, and the difficulty of covering the entire surface. Therefore, remote sensing methods, including UAV photogrammetry, laser scanning, satellite imagery, and radar technologies, are increasingly used. Nevertheless, most of these methods record the upper visible or reflecting surface, which often corresponds to snow cover rather than the stockpiled material.

Most existing studies on snow cover remote sensing focus on natural landscapes, mountainous areas, snow depth, or snow water equivalent. Industrial stockpiles differ significantly due to their artificial and rapidly changing geometry, shaded zones, low textural informativeness of snow, and continuous material movement. Therefore, direct application of existing approaches to winter mine-surveying volume accounting remains limited.

The scientific problem of this study is the lack of an adapted approach for assessing the applicability of remote sensing and geodetic methods to reliable volume determination under snow-covered conditions. The purpose of this article is to analyze existing methods for surveying snow-covered surfaces, identify their limitations for industrial stockpiles, and substantiate directions for developing an adaptive methodology for determining stockpiled material volumes in winter.

Characteristics of snow cover and its influence on the accuracy of volume determination of stockpiled materials

Snow cover exhibits complex physical, structural, and optical properties that significantly complicate remote sensing and distort digital surface models of stockpiled materials. Its structure is formed under the combined influence of multiple factors, including atmospheric conditions, solar radiation, heat fluxes, wind loading, settling, and internal metamorphic processes [1, 2].

One of the key factors affecting the accuracy of mine surveying and geodetic measurements during the winter period is the optical properties of the snow cover. The absence of stable surface texture significantly limits the capabilities of photogrammetric modeling [3, 4]. Structure-from-Motion algorithms rely on detecting and matching image key points to establish correspondences between images. However, in snow-covered areas, the number of such features is often insufficient, especially when surveys are conducted under bright solar illumination. This results in sparse point clouds, increased matching errors, and local distortions in the digital surface model that do not correspond to the actual geometry of the stockpiled material [4].

Illumination conditions significantly impact modeling results. The reduced solar elevation during the winter period leads to the formation of elongated shadows, in which up to 60–70% of key points may be lost [4, 5]. At the same time, illuminated areas are often characterized by overexposure and a lack of contrast features. The sharp contrast between shadowed and overexposed zones generates false brightness gradients that processing algorithms interpret as terrain elements, resulting in additional distortions of the digital surface model and a decrease in the accuracy of volume determination [5, 6].

The heterogeneity of the snow cover is particularly pronounced at industrial stockpiles, where the interaction of wind flows with the artificial relief of stockpiles leads to the formation of scoured zones, local snow accumulations, cornices, and erosional depressions. These elements do not correspond to the actual geometry of the stockpiled materials and form false relief features [6, 7], resulting in local anomalies in the digital surface model and complicating the accuracy of volume calculations.

Additional complexity is introduced by metamorphic processes in snow cover, driven by changes in the structure of snow crystals under the influence of temperature fluctuations, pressure, and moisture. As shown by previous studies [7, 8], even the presence of a thin ice layer or crust significantly reduces image textural information, complicates photogrammetric processing, and adversely affects the accuracy of digital surface models. Moreover, surface models obtained at different times may differ substantially even with a short time interval between surveys, which increases uncertainty when comparing snow-on and snow-off data and complicates the assessment of actual changes in material volumes.

Thus, snow cover is one of the main factors distorting the surface geometry of industrial stockpiles and reducing the accuracy of volume determination for stockpiled materials. Its high variability, low textural expression, and sensitivity to external conditions necessitate the application of specialized methodological approaches to account for and compensate for the influence of snow cover when performing mine surveying and geodetic works during the winter period.

Remote sensing methods for snow-covered surfaces

Contemporary approaches to remote sensing of snow-covered terrain encompass diverse technologies designed to capture spatial information with different degrees of precision, resolution, and operational effectiveness. Their development is driven by the need to improve the accuracy and safety of mine surveying operations under conditions where ground-based methods are limited. During the winter period, this is associated with restricted site accessibility, hazards related to movement across snow-covered stockpile areas, and high surface variability, all of which significantly reduce the reliability of results in determining the volumes of stockpiled materials.

In the scientific literature, several key remote sensing approaches are distinguished for snow cover analysis, including laser scanning, satellite imagery, radar-based methods, ground-penetrating radar technologies, and photogrammetric approaches implemented using unmanned aerial vehicles. Each of these methods has specific advantages and limitations that must be considered when modeling the surface of technogenic objects under snow-covered conditions [1, 2].

Laser scanning (LiDAR) ranks among the leading remote sensing technologies due to its high accuracy, independence from illumination conditions, and ability to generate dense point clouds. Research results indicate that terrestrial laser scanning (TLS) enables detection of changes in snow cover height with an accuracy of up to several millimeters [3], making this method a reference standard for assessing the accuracy of other technologies. However, its application at industrial stockpiles is significantly limited: the considerable height of stockpiles, the presence of technological equipment, and continuous production activity hinder the placement of scanners in optimal positions and the acquisition of complete surface coverage. In addition, conducting surveys during the winter period increases risks to personnel and extends survey duration.

Airborne laser scanning (ALS) enables data acquisition over large areas; however, its application to industrial stockpiles is constrained by difficulties in capturing steep slopes and small-scale relief elements, variability in the geometry of stockpiled materials, and challenges in data interpretation under snow cover [4].

Satellite sensing methods provide regular observations and coverage of large areas, which makes them effective for analyzing snow cover dynamics at a regional scale. Modern satellite platforms enable the assessment of snow cover extent, melt boundaries, and snow water equivalent (SWE) parameters [5]. At the same time, the spatial resolution of even high-resolution satellite imagery typically ranges from several tens of centimeters to meters, which does not meet the requirements of mine surveying support, where an accuracy of 1–3 cm is required. For this reason, satellite imagery should be considered only an auxiliary source of information that complements data from ground-based and aerial survey methods. Additional limitations include cloud cover, insufficient illumination, and atmospheric distortions, which significantly reduce data availability during the winter period.

Radar-based methods, including SAR imaging, exhibit high sensitivity to the physical parameters of snow cover, particularly moisture content and density. The interpretation of radar data is complicated by the dependence of snow backscattering characteristics on crystal structure, degree of compaction, and the presence of ice inclusions. This makes the use of SAR data for accurate reconstruction of the surface geometry of technogenic stockpiles challenging [6]. As a result, radar methods are mainly applied in scientific studies focused on snow cover dynamics and metamorphism and are much less frequently used for applied mine surveying and geodetic tasks

Ground-penetrating radar (GPR) methods enable investigation of the internal structure of the snow cover and determination of its thickness and stratification, which are important for estimating snow water equivalent (SWE). However, in the presence of technogenic objects, the effectiveness of GPR is significantly reduced. Metallic structures, density-heterogeneous rock mass fragments, ice crusts, and technogenic materials cause multiple false signal reflections, leading to decreased accuracy of the results [7]. Under industrial stockpile conditions, GPR methods do not provide the reliability required for volume calculations. Studies show that, despite GPR's ability to measure snow thickness, sharp relief variations and medium heterogeneities result in significant measurement errors and false signals, thereby limiting the reliability of these methods for practical tasks of accurate volume determination.

GNSS measurements remain one of the most accurate methods for determining the coordinates of individual points and serve as the basis for geospatial referencing of digital models. The application of RTK and PPK technologies enables centimeter-level coordinate accuracy, making GNSS a key element in the formation of a geodetic control network. GNSS measurements are used both to determine the coordinates of control points for georeferencing and calibration of UAV-based aerial survey data, and to survey characteristic points on snow-covered stockpile surfaces. Determining the coordinates of such points enables refinement of the object's geometric parameters and improves the accuracy of digital surface model generation under snow-covered conditions [8, 9]. However, at industrial stockpiles, GNSS accuracy may decrease due to signal obstruction by high stockpiles, metallic structures, and equipment.

The most universal and practice-oriented remote sensing method for investigating stockpile surfaces under snow cover conditions is UAV-based aerial photogrammetry. This method provides an optimal balance among accuracy, detail, and data-acquisition efficiency. The flexibility of flight planning, including the selection of flight altitude, survey trajectory configuration, camera tilt angle, and image overlap, enables the acquisition of high-quality data even over surfaces with low textural contrast [9]. Research results show that the use of oblique imagery increases the number of identifiable key points and enhances the robustness of photogrammetric modeling, enabling the generation of digital surface models with high accuracy and point cloud density comparable to TLS results, but at significantly lower costs [10].

An important advantage of UAVs is their ability to conduct regular surveys in environments with high temporal variability in snow cover. The generation of multi-temporal digital surface models enables minimizing errors in volume calculations and enhances personnel safety by eliminating the need to work in potentially hazardous areas [11].

At the same time, photogrammetric methods have several limitations related to the optical properties of the snow cover. Low textural informativeness, overexposure, shadows, and surface heterogeneity complicate terrain reconstruction and reduce the accuracy of digital surface models. Studies confirm that quality depends directly on illumination conditions and survey parameters [10, 12]. To improve processing robustness, high-precision georeferencing based on RTK/PPK data is applied, followed by point cloud registration with reference *snow-off* surface models using ICP algorithms, which has demonstrated high efficiency in modeling technogenic objects [7].

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At the same time, it should be noted that the application of UAVs under snow-covered conditions is associated with several limitations. The main methodological drawback is that the photogrammetric model reflects the geometry of the snow cover surface rather than the actual shape of the stockpiled material. Under industrial stockpile conditions, this leads to the inclusion of snow volumes in volume calculations, whose magnitude and distribution exhibit high spatial heterogeneity [12]. This, in turn, introduces an additional error that cannot be eliminated solely by increasing survey resolution or point cloud density. Thus, the use of UAV-based photogrammetry during the winter period provides high accuracy in reconstructing the current surface but does not allow for the direct separation of the volumes of stockpiled material and snow cover.

An analysis of existing remote sensing methods shows that, for determining the volumes of stockpiled materials under snow-covered conditions, the highest efficiency is achieved by integrating GNSS measurements with UAV-based photogrammetric aerial surveys. This approach enables compensation for the limitations of individual methods, ensures continuous spatial coverage, achieves high modeling accuracy, improves the reliability of volume calculations, and enhances the safety of mine surveying operations.

Photogrammetry and surface modeling of stockpiles under snow-covered conditions using UAVs

During the winter period, the accuracy of surface modeling of stockpiled materials can be improved through the application of a combined approach that integrates UAV-based aerial photogrammetry and ground-based GNSS measurements [8, 9]. This approach makes it possible to account for the specific characteristics of snow cover formation and to reduce its impact on spatial modeling results and subsequent volume calculations.

Aerial photogrammetry is primarily used to obtain continuous coverage of the study area and to reconstruct the geometry of those parts of the stockpiles where the material surface is partially or fully exposed. These areas generally provide sufficient texture information for reliable photogrammetric reconstruction of stockpile shapes and operational platforms. Snow-covered areas, where the photogrammetric model mainly represents the snow surface, are supplemented and refined using ground-based GNSS measurements [8].

GNSS receivers operating in RTK and PPK modes are used to determine the coordinates of control points required for georeferencing and calibration of photogrammetric data, as well as to measure characteristic points such as edges, crests, and slopes. This makes it possible to refine the geometry of the object and improve the reliability of digital surface models under snow-covered conditions [8].

Aerial surveys are conducted according to a pre-designed flight scheme that is adapted to the characteristics of the object and survey conditions. Due to the low textural expression of snow surfaces, acquisition parameters are adjusted: longitudinal overlap is typically not less than 80–90%, transverse overlap is 70–80%, and flight altitude is selected to ensure higher spatial resolution and compensate for the loss of key points [9, 10].

To improve model quality, a combination of nadir and oblique imagery is applied. Nadir images are used to generate orthophotos and digital surface models, while oblique images with camera tilt angles of approximately 20–35° improve the accuracy of reconstructing steep slopes, edges, and low-texture areas [10]. Illumination conditions are also taken into account, as overexposure and shadows can significantly reduce processing quality [12].

The metric accuracy of photogrammetric models is largely determined by the accuracy of exterior orientation. The use of RTK/PPK technologies allows precise determination of camera positions and reduces georeferencing errors [8]. The integration of UAV-derived data with GNSS measurements of characteristic points ensures better agreement between the digital surface model and the actual geometry of the stockpiled material.

Thus, the combined method, based on the use of aerial photogrammetry for exposed areas and GNSS measurements for refining snow-covered zones, enables improved accuracy of spatial modeling and provides more reliable volume estimation of stockpiled materials under winter conditions [9, 11].

Scientific gaps and directions for further research

An analysis of published studies shows that existing remote sensing methods for snow cover are primarily focused on natural landscapes, mountainous areas, glacial environments, and tasks related to estimating snow depth or snow water equivalent [1–5, 9, 10]. However, determining the volumes of stockpiled materials at industrial storage sites during winter has a fundamentally different methodological nature, as it requires reconstruction not only of the snow surface but also of the actual geometry of the material partially or completely covered by snow.

One of the key scientific and methodological gaps is the lack of robust procedures for separating the snow surface from the surface of the stored material. UAV-based photogrammetry, laser scanning, and other remote sensing methods capture the upper visible or reflective surface of an object [6, 8, 11]. Under winter conditions, this surface is often snow, which forms drifts, cornices, local accumulations, and wind-eroded zones. As a result, digital models may include elements that do not belong to the actual geometry of the material, leading to systematic errors in volume estimation [6, 7].

A significant limitation is the insufficient adaptation of existing approaches to technogenic (man-made) terrain conditions. Most studies on UAV photogrammetry and laser scanning of snow cover have been conducted for natural slopes, mountainous regions, forested areas, or open terrain [3, 4, 7, 9]. In contrast, industrial storage sites are characterized by artificial geometry, steep slopes, sharp elevation changes, continuous material movement, and the impact of heavy machinery, which limits the direct transfer of existing methodologies.

Another issue is the insufficient reproducibility of digital models obtained from multi-temporal surveys. Even when maintaining similar acquisition parameters, differences between snow surface models can be significant due to variations in snow structure, illumination conditions, wind redistribution, and metamorphic processes [2, 6, 10, 12]. For industrial stockpiles, this problem is exacerbated by changes in the surface of the stored material itself due to loading, unloading, and material displacement, which limits direct comparison between *snow-on* and *snow-off* models [3, 7].

The optimization of aerial survey parameters for technogenic objects in winter conditions remains insufficiently studied. It is known that the accuracy of photogrammetric modeling of snow surfaces depends on flight altitude, image overlap, spatial resolution, lighting conditions, shadows, and the use of oblique imagery [4, 6, 9]. However, there are no universal recommendations for selecting camera tilt angles, flight altitude, flight planning schemes, and overlap parameters specifically for industrial storage sites.

An additional limitation is the ambiguity in applying radar and ground-penetrating radar (GPR) methods for volumetric assessment tasks. SAR data are sensitive to the physical properties of snow cover; however, their use for accurate reconstruction of stockpile geometry is complicated by the complexity of interpreting the reflected signal [1, 2]. GPR methods allow determination of snow thickness and internal structure, but their effectiveness at industrial sites is reduced due to the heterogeneity of stored materials, metallic structures, ice layers, and false reflections [2].

Thus, the research gap lies not in the absence of technologies for acquiring spatial data, but in the lack of an adapted methodology for their application to accurately determine the volumes of stockpiled materials under snow cover conditions. Future research should focus on the development of a combined approach integrating UAV photogrammetry, high-precision GNSS measurements, the use of multi-temporal digital surface models, and procedures for compensating the influence of snow cover [6, 7, 10, 12].

Conclusion

The conducted review has shown that the problem of determining the volumes of stockpiled materials in winter conditions cannot be solved solely by increasing the accuracy or level of detail of remote sensing data. The main methodological limitation lies in the fact that, in the presence of snow cover, the digital surface model reflects not the actual geometry of the stored material, but the upper surface of the snow. As a result, the calculated volume includes snow masses, the distribution of which is characterized by high spatial heterogeneity and temporal variability.

It has been established that most existing studies on UAV photogrammetry, LiDAR, SAR, and GPR are focused on natural snow-covered surfaces, tasks related to snow depth estimation, or the assessment of snow water equivalent. Their direct application to industrial storage sites is limited, since technogenic objects are characterized by complex artificial geometry, steep slopes, shadowed areas, low-texture zones, and a constantly changing surface of the stored material.

The most promising direction for solving this problem in practice is the integration of UAV photogrammetry with high-precision GNSS measurements and the use of multi-temporal surface models. Such an approach makes it possible to ensure continuous spatial coverage of the object, improve the reliability of georeferencing, and partially compensate for the influence of snow cover on volumetric calculations.

The scientific significance of this review lies in the systematization of sources of uncertainty arising in the modeling of industrial stockpiles under winter conditions, as well as in substantiating the need for the development of an adaptive methodology for accounting for snow cover. The practical significance consists in the possibility of applying the obtained results in planning winter mine surveying and geodetic operations, selecting UAV survey parameters, organizing GNSS control, and assessing the reliability of volume calculations for stockpiled materials.

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