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Using the typification of mining-engineering facilities to substantiate deformation monitoring of opencast mining

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Abstract

To date, in the field of monitoring deformations of the earth's surface in the area of opencast mining, there is almost no current regulatory and methodological documentation that regulates the conduct of observations and at the same time takes into account the features of existing mining facilities of opencast mining and the possibilities of modern survey technologies. The paper gives an approach to determining a set of methods for deformation monitoring within the territory of mining enterprises engaged in open-pit mining, based on the results of the typification of mining facilities. The developed typification makes it possible to estimate the degree of complexity of mining-engineering facilities, taking into account their size, features of engineering-geological, hydrogeological and orographic conditions, geodynamic processes. To increase the information content of mine surveying, as well as the quality and accuracy of deformation monitoring as a whole, it is proposed to include technologies for Earth remote sensing from space, namely, satellite-based synthetic aperture radar (SAR) interferometry, used within the proposed concept for areal monitoring of deformations and detection potentially hazardous areas at complex and particularly complex opencast mining facilities. The proposed approach to the organization of deformation monitoring was tested within the territory of the Khibiny apatite-nepheline deposit of the Rasvumchorr Plateau: the complexity of conditions for the development of the Tsentralny open pit was evaluated and recommendations were formulated for conducting mine surveying of deformations of the earth's surface in its territory using satellite-based SAR interferometry. This method was used to analyze deformations of the earth's surface for the periods from 2007 to 2011 and from 2015 to 2016 according to data from the ALOS PALSAR, TerraSAR-X and Sentinel-1 satellites.

Keywords**:** deformation monitoring, open-pit mining, typification of mining-engineering facilities, multicriteria analysis, Earth remote sensing from space, satellite-based SAR interferometry.

Introduction

The intensification of open-pit mining in the Russian Federation is accompanied by a constant increase in the volume of strip mining, an increase in the size of mine workings and dumps. Thus, the Korkinsky open-pit mine, which ceased exploitation in 2017, is characterized by a length of ~ 5.5 km, a width of ~ 3.5 km and a depth of 500 m. The Bachatsky open-pit mine operating in Kuzbass currently extracts about 70 million m^3 of rock mass from the subsurface; it is ~11 km long, ~2 km wide, and 320 m deep. At the same time, dump structures occupy areas up to 1000 hectares and are characterized by heights of more than 100 m. The depth of the Tsentralny open-pit (Murmansk region) exceeds 500 m with a length of more than 3 km. Operation of mining facilities – sides and dumps – with those parameters is accompanied by the development of hazardous mining and geological processes and phenomena, the scale of which is proportional to the increasing parameters. In particular, the landslide that occurred in 2015 at the outer dump of the Zarechny open-pit mine in Kuzbass was accompanied by the involvement of 27 million m^3 of technogenic rocks into the deformation process. The elimination of the consequences of this landslide required significant material costs – several billion rubles. These circumstances require special studies of the stability of the slopes of the formed mining and technical structures carried out within the framework of monitoring observation of the surface deformations of the mining and land allotment, as well as the structures and various infrastructure facilities. The variety of mining and geological conditions of opencast mining of mineral resources and methods of mine surveying and geodetic measurements that have appeared in recent years predetermines the use of an integrated approach to monitoring the safety of mining facilities in general and deformation monitoring in particular.

Analysis of the study of the issue

The practice of organizing and performing monitoring observations in Russia is currently characterized by the absence of regulatory and methodological documents based on

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Table 1. Criteria for typification of mining-engineering facilities.
Таблица 1. Критерии типизации горнотехнических объектов.

Factors	Mining-engineering facilities and classification features
Engineering and geological	Open-casts and open pits: – type of deposits by rocks; – deformation processes and behavior of massifs Dumps, hydraulic waste disposals and tailings dumps: – type of technogenic rocks; – basement strength; – basement soil type (for mining-engineering facilities)
Mining-engineering	Open-casts and open pits: engineering specifics – depth Dumps, hydraulic waste disposals and tailings dumps: – engineering specifics – height; –basement tilt (for dumps)
Hydrogeological	Open-casts and open pits: water content degree Dumps, hydraulic waste disposals and tailing dumps: presence of aquifers
Physical-geographical	Territory of a mining enterprise: – maximum intensity of seismic vibration; – terrain structure; – climatic factors

modern methods of measuring and processing deformations of the earth's surface. "Instructions for observing deformations of sides, bench slopes and dumps in open pits and the development of measures to ensure their stability" is still among the current documents at coal enterprises for about 50 years (approved by Gosgortehnadzor of the USSR 21.07.1970) [1]. This document was developed by All-Russian Research Institute of Mining Geomechanics and Survey based on the results of observations of deformations of mining facilities using tape measures and optical instruments of various accuracy. Over the five decades since the publication of this manual, the instrumental base, the method of making measurements and interpreting the data obtained have changed significantly, in particular:

– new measurement methods have appeared: laser scanning, radar sensing, aerial photography from unmanned aerial vehicles (UAVs), etc.;

– new possibilities for automating measurements have appeared: using ground-based radars, robotic total stations, laser scanners, GNSS receivers, etc.;

– Earth's remote sensing (ERS) from space has been particularly actively developed: new survey technologies have been developed (in particular, the method of satellite-based synthetic aperture radar (SAR) interferometry), the accuracy of measurements (both optical and radar), the number of satellites (including satellites with data in the public domain) and, accordingly, the amount of available data have increased;

– today, computer technologies and software systems (including open source software) are used to process measurement data, which also makes it possible to automate the processes of obtaining monitoring results;

– ways to bring measurement results to the end users on the basis of geoinformation technologies (in particular, web cartography technologies) are being continuously improved [2, 3].

The availability of new technologies, measuring instruments and data processing methods requires the development of a new regulatory and methodological document. However, despite the urgency of this problem for the mining and coal industries, it still remains without a solution at the national level. At the same time, a positive aspect is the presence in the technical literature of a fairly large number of sources devoted to monitoring the stability of sides and dumps using modern methods, as well as measurements of the earth's surface and structures within the territories involved in various subsoil use industries – coal, oil, gas, etc. [2–7]. It is emphasized the need to implement and justify the use of advanced survey technologies, in particular, satellite-based SAR interferometry, which provides data for the entire territory of a mineral deposit, which can also be used in calculating the stability of objects and modelling deformation processes based on various techniques [8, 9]. However, the existing studies are more devoted to the issues of using the method at specific objects/enterprises, and the generally accepted methods and recommendations for the use of space radar surveys as part of integrated deformation monitoring have not yet been developed.

Typification of objects within the territory of a mining enterprise

It is well known that the composition, methodology and instrumental base of monitoring are determined by the mining and geological conditions of the object, the parameters and technology of its formation and functioning. Therefore, in order to determine the most effective monitoring program, it is first necessary to develop a typification of open-pit mining facilities according to their degree of complexity, and then, for each of the identified types, substantiate a set of different

Table 2. Composition of the deformation monitoring complex.
Таблица 2. Состав комплекса деформационного мониторинга.

Methods of deformation monitoring	The degree of complexity of the objects			
	Simple	Medium	Complex	Highly complex
Visual	+	+		
Ground-based tools		+	+	
GNSS monitoring		+	+	+
Laser scanning				+
Ground-based radar survey				+
Aerial photography			+	+
satellite-based SAR interferometry			+	+
Optical remote sensing from space			+	+

observation methods used. At present, there are no general typifications of natural-technological systems (NTS). The existing typifications [10, 11], unfortunately, do not take into account all the key characteristics of opencast mining facilities and cannot be applied to substantiate integrated monitoring scenarios.

The proposed typification has been developed in relation to the main mining facilities of open cut mining – open pits and open cast mines, dumps and hydraulic waste disposals. For each of the listed objects, key indicators have been selected that correspond to engineering-geological, hydrogeological, physical-geographical and mining-engineering factors affecting their stability (Table 1) [12].

To estimate the **engineering-geological conditions** of open-casts and open pits, the type of rocks, deformation processes, basement strength (for dumps and mining-engineering facilities), and the type of basement soil (for mining-engineering facilities) are determined.

To estimate rocks and technogenic rocks, the existing engineering-geological typification of solid mineral deposits [13] was supplemented taking into account the special state of rocks, their fracturing (for open-casts and open pits) and the technology of formation of dump massifs and mining-engineering facilities:

1. There are 6 groups of rocks corresponding to open-casts: hard (rocky monolithic and fractured), relatively hard (semi-rocky); unconsolidated and noncohesive, soft and coherent, special state (frozen and quick);

2. For dumps, 7 groups of bulk technogenic rocks have been determined: bulk from rocky, semi-rocky, unconsolidated and noncohesive, soft and coherent, and special state (frozen) rocks;

3. Hydraulic structures are subdivided into two groups of alluvial technogenic rocks: alluvial from unconsolidated and noncohesive, and soft cohesive rocks.

The main types of deformations were identified on the basis of “Methodological guidelines for observing deformations of the sides of open-pits and dumps, interpreting their results and predicting stability” [14]: landslides, filtration deformations and collapses correspond to open pits (taking into account the surface to which the deformation is associated), dumps – subsidences associated with compaction of rocks, landslides above, below and on the dump bottom, filtration deformations, and for hydraulic structures – subsidences associated with the dispersion of excess pore pressure in alluvial rocks, landslides, filtration deformations. The analysis also takes into account the possible impact of underground mining, namely, subsidences from the movement of rocks in subsided areas.

The base of the dumps and mining-engineering facilities can be characterized as “strong” (the strength of the base is higher than the strength of the dump), “weak” (the strength of the dump is higher than the strength of the base) or “very weak” (represented by water-saturated rocks of a fluid consistency).

In accordance with the adopted classification for mining-engineering facilities [15], the characteristic called “type of basement soil” is also given, which includes three groups: rocky; sandy, coarse clastic and argilliferous in the solid and semi-solid state; argilliferous water-logged in a plastic state.

Mining-engineering conditions are evaluated based on the analysis of engineering specifics: the depth of open-pits and heights of dumps and hydraulic structures. The scale of open-casts depths includes 5 gradations: small (up to 40 m); relatively small (from 40 to 100 m); medium (from 100 to 200 m); large (from 200 to 400 m); very large (over 400 m). To estimate dumps, the classification adopted more than 30 years ago [16] was updated taking into account the current scale of dump operations. Thus, 4 groups of dumps were identified by their height: low (less than 30 m); medium (30-100 m); high (100–200 m); very high (over 200 m). Taking into account the existing classification [15], mining-engineering facilities are also subdivided into 4 classes: low (less than 10 m); medium (10–20 m); high (20–50 m); very high (over 50 m). When analyzing dumps, the slope of their basement is also taken into account, which can be flat, inclined, steeply inclined – these gradations are highlighted on the basis of current documents [17].

Hydrogeological conditions are evaluated as follows:

– water content degree in open-casts is analyzed: weakly water-flooded and water-free, moderately water-flooded, water-flooded or very water-flooded open-casts.

– in accordance with [18], the complexity of dumps and mining-engineering facilities is analyzed depending on the characteristics of aquifers: simple (with a phreatimetric

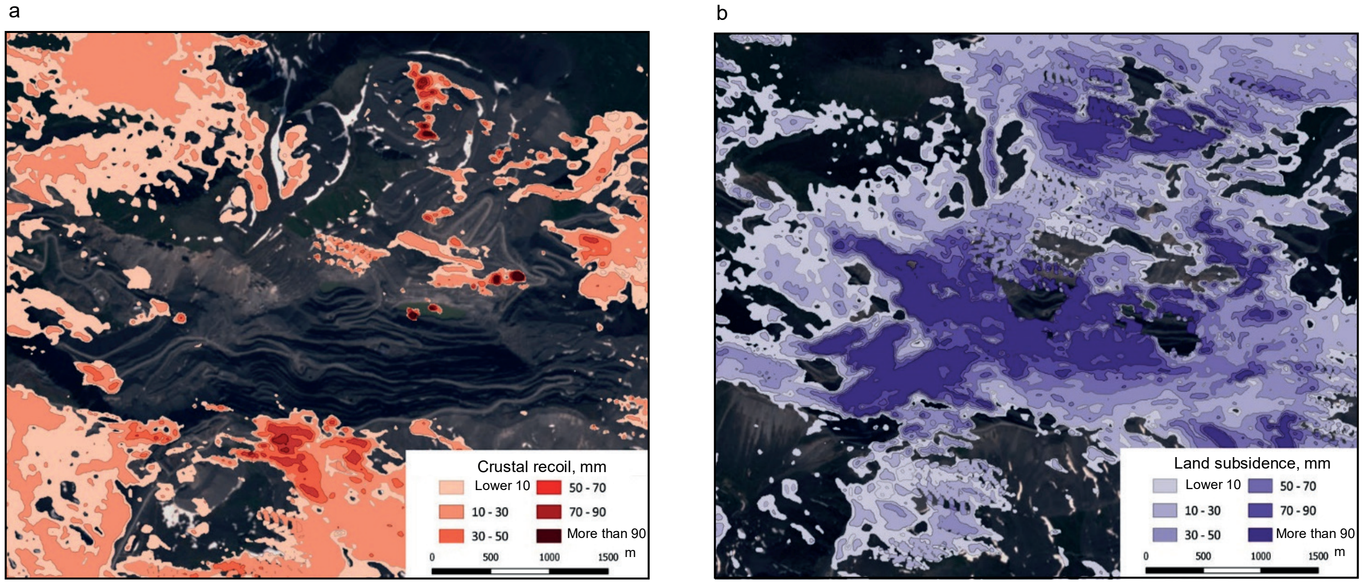

Figure 1. Uplift (a) and subsidence (b) of the earth's surface within the territory of the Tsentralny open-pit mine for the period 08.07.2015–09.09.2016 according to TerraSAR-X data.

Рисунок 1. Поднятия (а) и оседания (б) земной поверхности на территории карьера «Центральный» за период 08.07.2015–09.09.2016 гг. по данным TerraSAR-X.

aquifer), complex (with a pressure aquifer in the waste dump/mining-engineering facilities or at its basement), especially complex (with several confined aquifers in dump/mining-engineering facilities or at its basement).

The stability of mining facilities is also affected not only by hydrogeological factors, but tectonic stresses and seismicity as well [19, 20]. In this regard, the typification includes an analysis of **physical and geographical conditions** of development, namely the following factors: general seismicity of the area; terrain structure; the presence of climatic factors contributing to deformations of the earth's surface and structures.

On the basis of expert analysis, each selected indicator was assigned a value on a scale from 1 to 10. To obtain a quantitative expression of the complexity of objects, multicriteria analysis is used. On the basis of the obtained range of values, 4 classes of objects were identified in terms of complexity: simple, medium complexity, complex and highly complex objects [12].

Integrated use of deformation monitoring methods

In accordance with the proposed approach, the choice of methods for complex deformation monitoring is based, on the one hand, on the features of the observed object, characterizing the degree of its complexity, and on the other hand, on the features and technical characteristics of the monitoring methods themselves [12].

It is proposed to justify the choice of a set of methods for implementing deformation monitoring taking into account the required observation accuracy and the analysis of characteristics of survey methods, such as spatial coverage, degree of automation, and observation technology. The listed characteristics make it possible to divide the existing observation methods into areal and point ones; non-automated, automated and automatic; contact and remote.

Ground instrumental mine measurements, surveying with the use of GNSS technologies, ground laser scanning, aerial photography, ground-based radar, satellite-based SAR interferometry are considered as the basic deformation monitoring methods. Additional methods include visual observations and optical Earth remote sensing from space.

The main principle for determining the scope of work is that as the complexity of objects increases, the requirements for the degree of automation of monitoring methods, accuracy and spatial coverage of the survey increase (Table 2):

– observation of complex and highly complex objects is carried out using the most complete set of automatic areal methods; monitoring of objects of medium complexity allows the use of non-automated observation instrumentation;

– control of simple objects can be carried out using visual observations.

Due to the fact that when monitoring complex and highly complex objects, it is necessary to ensure the receipt of areal data on deformations within the territory of mineral deposit, a high degree of measurement automation and a minimal human presence in hazardous areas; special attention is paid to the use of methods for remote sensing of the Earth from space – optical and radar imagery. Thus, satellite-based SAR interferometry is used as a supplement to the system of high-precision areal and point ground observations, namely, as a basic method of regular monitoring for promptly identifying areas where high-precision instrumental observations are required. At the same time, evaluation of qualitative parameters of deformations on complex and highly complex objects is carried out using satellite imagery in the optical range (high and ultra-high spatial resolution data).

Testing of the proposed method

Practical approval of the proposed technique was carried out for the objects of open pit mining of apatite-nepheline ores of the Rasvumchorr Plateau (Khibiny massif, Murmansk region). The analysis of the mining-geological, hydrogeological, engineering-geological and physical-geographical conditions of the Tsentralny open-pit made it possible to identify 2 types of objects according to the degree of complexity: the open-pit itself is classified as complex object, and dump No. 11 as object of medium complexity. In accordance with the typification performed, recommendations were developed for the implementation of deformation monitoring within the territory of this mining enterprise [12]:

– determination of quantitative indicators of deformation processes (their magnitude, speed and direction) within the territory of the open-pit is carried out using areal automated remote sensing methods, in the territory of the dump–using ground instrumental mine surveying;

– determination of the qualitative characteristics of deformations in the territory of the open-pit should be carried out on the basis of the complex application of visual and remote sensing methods, in the territory of the dump – according to the results of visual observations.

Characteristic features of the climatic conditions of the studied mineral deposit (negative average annual air temperatures, prolonged frosts, long-term occurrence of snow cover, significant wind load), as well as orographic factors (strong dissection of the relief, natural and technogenic seismicity of the territory) not only negatively affect the stability of mining facilities but significantly limit the period of instrumental observations and the range of survey methods used.

In this regard, satellite-based SAR interferometry was used as the basic method for the areal monitoring of the mineral deposit. Determination of deformations of the earth's surface for the periods from 2007 to 2011 and from 2015 to 2016 was carried out according to data from the ALOS PALSAR, TerraSAR-X and Sentinel-1 satellites. Analysis of the data made it possible to identify subsidence associated with underground mining at the Rasvumchorr mine, surface mining operations in the open-pit itself, as well as deformations at the site of the old dump. The spatial coverage of the radar images made it possible to analyze the deformations not only in the open pit but in the territory of the dump as well, where uplifts caused by the storage of rock mass were revealed (Fig. 1) [4, 12].

Conclusions

The analysis has shown that as a basic approach to the organization of integrated deformation monitoring, it is advisable to use the typification of open-pit mining objects according to the degree of complexity, in accordance with which a set of monitoring methods is selected. The results of testing indicate the prospects of its application for open-pit mining facilities. In particular, the use of typification to substantiate the application of the method of satellite-based SAR interferometry makes it possible to increase the reliability of surveying measurements, the timeliness of detecting deformations and the information content of the data obtained.

At the moment, studies are being carried out to adapt the proposed methodology in relation to underground mining facilities, namely, to subsided areas of the earth's surface within the territory of closed and abandoned mines.

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Использование типизации горнотехнических объектов для обоснования деформационного мониторинга открытых горных разработок

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Аннотация

На сегодняшний день в области мониторинга деформаций земной поверхности в зоне ведения открытых горных работ практически отсутствует актуальная нормативно-методическая документация, регламентирующая проведение наблюдений и при этом учитывающая особенности существующих горнотехнических объектов открытых разработок и возможности современных технологий съёмки. В статье предложен подход к определению комплекса методов деформационного мониторинга на территории горных предприятий, осуществляющих открытую разработку месторождений, по результатам типизации горнотехнических объектов. Разработанная типизация позволяет оценить степень сложности горнотехнических объектов с учётом их размеров, особенностей инженерно-геологических, гидрогеологических и орографических условий, развивающихся геодинамических процессов. Для повышения информативности маркшейдерских измерений, а также качества и точности деформационного мониторинга в целом, в состав комплекса применяемых методов наблюдений предлагается включить технологии дистанционного зондирования Земли из космоса, а именно - метод космической радарной интерферометрии, применяемый в рамках предложенной концепции для площадного контроля деформаций и выявления потенциально опасных участков на сложных и особо сложных объектах открытой разработки. Предложенный подход к организации деформационного мониторинга апробирован на территории Хибинского апатит-нефелинового месторождения Плато Расвумчорр: выполнена оценка сложности условий разработки Центрального карьера и сформулированы рекомендации по проведению маркшейдерского контроля деформаций земной поверхности на его территории с применением космической радарной интерферометрии. С использованием этого метода выполнен анализ деформаций земной поверхности за периоды с 2007 по 2011 г. и с 2015 по 2016 г. по данным со спутников ALOS PALSAR, TerraSAR-X и Sentinel-1.

Ключевые слова: деформационный мониторинг, открытая разработка месторождений, типизация горнотехнических объектов, многокритериальный анализ, дистанционное зондирование Земли из космоса, метод космической радарной интерферометрии

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