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ANALYSIS AND CLASSIFICATION OF ACTUAL GEODETIC METHODS FOR STUDYING THE QUANTITATIVE PARAMETERS OF EARTH SURFACE DEFORMATIONS

The aim of the work is to analyze and evaluate current methods for studying Earth's surface subsidence-dip deformation processes of technogenically impacted areas and to classify these methods. The analysis of existed methods for studying the spatio-temporal changes in the Earth's surface consists in their critical assessment based on studied literary sources and highlighting advantages and disadvantages of the geodetic methods for studying the deformation processes of hazardous territories (with landslides and failures). Applying the classification method, a scheme of geodetic methods used in the Earth's surface monitoring of technogenically loaded areas was developed. The analysis and evaluation of actual geodetic methods for studying the quantitative parameters of subsidence-dip deformation processes has been carried out. Literary sources written by Ukrainian and foreign scientists are processed. The advantages and disadvantages of the studied methods are presented. The classification of geodetic methods for studying and monitoring Earth's surface deformations has been developed. The obtained results can serve as a theoretical basis that allows for further improvement of the technology for studying subsidence-dip deformation processes of technogenically impacted territories in order to predict technogenic disasters, improve the environmental situation and ensure life safety. The presented classification structures the current geodetic methods of studying the quantitative parameters of the spatio-temporal changes of the Earth's surface.

Key words: Earth's surface; deformation processes; geodetic methods; geotechnical monitoring; extraction sites.

Introduction

Active mining in Ukraine has increased the influence of technogenic factors on the development of natural landscapes, and in some places has completely transformed them. The accelerating pace and scale of mining industry is associated with the improvement of mining machines, complexes and technologies, which made it possible to exploit more complex deposits and deepened the work levels [Palamar & Syzova, 2015]. That in turn leads to increase in the destabilization level of the natural environment and further negative consequences of the conservation of such enterprises, among which Earth's surface subsidence and landslide processes are especially hazardous.

It should be noted that the activation of vertical displacements of Earth's surface in the minefield areas is poorly predictable, however, it occurs mainly in the karst void areas of not deep-seated extraction sites, especially at the mines which are closed or mothballed [Zakharova et al., 2020; Hlotov et al., 2022b; Sahu & Lokhande, 2015]. According to the Law of Ukraine (The Code of Ukraine on Bowels), in the event of complete or partial liquidation of mining enterprises, mines and wells must be brought into a condition that guarantees the safety of people, property and natural environment. Violations of the norms, rules and requirements that guarantee the safety of mining operations lead to the emergence and intensification of the destabilization factors which impact on natural landscapes and lead to landslides, Earth's surface cracks and failures of a single or complex nature [Akgun et al., 2012; Sahu & Lokhande, 2015].

Significant negative effects of landslides and sinkholes in karst formation sites (mainly in closed or mothballed mines) have increased the attention of the researchers from different scientific branches [Palamar & Syzova, 2015; Akgun et al., 2012; Casagli et al., 2017; Jaboyedoff et al., 2012; Sahu & Lokhande, 2015]. This led to the availability of numerous methods for studying and monitoring Earth's surface deformations occurred due to the natural geodynamic processes, technogenic and exogenous factors. Monitoring of landscapes and technical systems is a part of interdisciplinary geotechnical (geodynamic, geomechanical, mine surveying) monitoring [Lavryk, 2018], carried out for comprehensive research of the Earth's surface changes and their dynamics, as well as the study of the factors impacting the displacements. The obtained data is used to protect the environment, ensure environmental safety and human life safety in the studied areas, rational use of natural resources, programs for regional development of territories [Zayats et al., 2017].

Purpose

The purpose of the paper is to perform a critical analysis of the means, methods and techniques which are used for studying subsidence-failure deformation processes of the Earth's surface at the territories with high technogenic impact, as well as to conduct the analyzed classification of the methods.

Methods

To achieve this goal, analysis is used in the work as a scientific method of research, on the basis of which a critical assessment of the geodetic methods for studying hazardous deformation processes of the Earth's surface destabilized due to anthropogenic activity was carried out. The classification of the analyzed methods is conducted.

Results

The study of spatio-temporal deformation changes in technogenically destabilized territories includes a number of geodetic, geological, geophysical, geotechnical methods or their combinations, which are presented in the works of Ukrainian [Mordvinov et al., 2018; Palamar & Syzova, 2015; Savchyn et al., 2019; Tretyak et al., 2015; Zakharova et al., 2020; Zayats et al., 2017] and foreign [Akgun et al., 2012; Beavan & Litchfield, 2012; Calcaterra et al., 2012; Casagli et al., 2017; Jaboyedoff et al., 2012; Sabuncu & Ozener, 2014] scientists. The choice of study method directly depends on the research goal and object, as well as available devices and instruments for conducting experiments to obtain input data.

In the next paragraphs, the geodetic methods for studying quantitative parameters of the Earth's surface deformations are considerate in details. Geodetic methods can be subdivided into terrestrial, terrestrial-remote and remote ones (Fig. 1), based on the spatio location of research instruments at the moment of the survey.

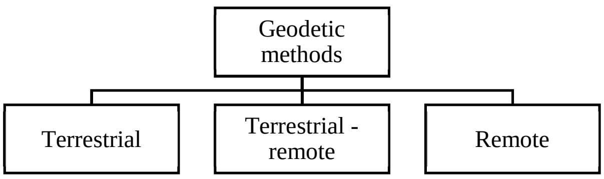

Fig. 1. Hierarchical model of geodetic methods used to study Earth's surface deformation

Terrestrial geodetic methods for studying the Earth's surface deformation include various types of leveling (differential, trigonometric); triangulation method and polygonometry method [Baran, 2012; Ostrovskyi et al., 2011]. These measurements are carried out pointwise at specially designated observation stations and include several profile lines with permanent and temporary benchmarks placed there. It should be noted that the permanent benchmarks are laid outside the deformation zone, and the temporary ones are located in the zone where vertical and subvertical surface movements are activated [Sabuncu & Ozener, 2014]. For determining spatial coordinates (horizontal plane) of the observation stations, benchmarks and their connection, the triangulation method or closed polygonometric passages are used, which are laid from the nearest available triangulation or polygonometric points [Baran, 2012; Ostrovskyi et al., 2011]. For height reference of benchmarks, first-order, class II leveling from triangulation points is used. These methods are usually used to monitor the deformations of buildings, engineering facilities (hydroelectric and nuclear power plants, dams, reservoirs, etc.), since they provide high accuracy of the obtained results (below a millimeter) [Sabuncu & Ozener, 2014].

Another terrestrial geodetic method for studying the quantitative parameters of the Earth's surface deformation is inclinometry. The inclinometry method is implemented by using high-precision instruments – digital inclinometers which can register changes in inclination angles [Mordvinov et al., 2018]. Inclinometers are widely used in mining, for monitoring bridge abutments condition, pipelines, buildings and engineering structures deformations. To conduct continuous monitoring of a certain area with inclinometers, a network of several instruments is required, being installed at special inclination stations, where electricity, access to the Internet and connection to a computer with specialized software should be provided [Zayats et al., 2017]. For monitoring purposes, inclinometric observations are combined with GNSS, which allows data correlation [Mordvinov et al., 2018; Calcaterra et al., 2012; Savchyn et al., 2019].

It is worth noting that terrestrial instrumental geodetic methods, along with sufficient knowledge and high accuracy of measurement results, are characterized by significant time-consuming processes of both surveying and laboratory processing and high cost of work. A number of factors influence the performance of field survey: weather conditions; the state of the atmosphere; limited operation of electronic devices batteries; vibration effects (at active mining sites, on sections of highways, railways, etc.); the presence of remote and dangerous sites to survey; the impossibility of ensuring visibility between survey points (presence of cliffs, landslides, dips). The listed factors affect the surveying periodicity and reduce the monitoring systematicity, or in certain areas do not allow it at all due to the insufficient number of observation points in the study area. Summing up, the methods of surveying profile lines in the study of karst failures are insufficient and financially inappropriate for the integrated monitoring of vertical and subvertical movements of the Earth's surface in high-risk areas.

Laser scanning and GNSS are terrestrial-remote geodetic methods for monitoring the quantitative parameters of the Earth's surface deformations. The laser scanner can be installed directly at the survey site (stationary), or be mobile on a vehicle (car, railcar, aircraft, sea vessel, satellite), the choice depending on the available technical means, the object and purpose of the study, as well as the required accuracy of the obtained data [Jaboyedoff et al., 2012]. During the terrestrial laser scanning, the distance from the scanner to the points of the survey object is measured with high accuracy and fixing the corresponding directions (vertical, horizontal angles). During the survey, laser rangefinders are used, which are based on pulse and phase methods for measuring distances and the angular intersection method. The result of terrestrial laser scanning is a point cloud that displays the scanned object in three dimensions. Among the advantages of terrestrial laser scanning are the high accuracy of the obtained data and their detailed specification; 3D visualization of the scanned object in real time; scanning speed. The disadvantages of terrestrial laser scanning include a large amount of data, usually containing redundant information which complicates data processing and undergoes further filtering; high cost of scanning works; the dependence on weather conditions; limited range scanning. In addition, it is necessary to install several scanning stations when surveying complex objects (buildings, dips, funnels, etc.), using spheres and marks for further data connection from different scanning stations, which is difficult to implement in high-risk areas [Jaboyedoff et al., 2012].

Mobile laser systems for aircraft play a special role in solving monitoring problems. They can be installed both on manned aircraft and unmanned aerial vehicles (UAVs) and allow scanning large areas in a short period of time, monitoring hard-to-reach or potentially dangerous areas [Hlotov et al., 2021a; 2021b]. Comparing to terrestrial laser scanning, the accuracy in aviation is lower, especially in areas where the number of points is insufficient (a sharp elevation change in places of landslides and cliffs, in which the scanning angle does not allow obtaining a detailed surface model) [Thiel & Schmullius, 2017].

The GNSS method, due to the high accuracy of determining the coordinates of not only ground-based objects, but also those placed in air and on water, and at a relatively low cost of equipment, has become widely used [Beavan & Litchfield, 2012]. Monitoring with the use of GNSS is based on the repeated determination of the spatial coordinates of the points of survey network using GNSS-receivers [Tretyak et al., 2015]. While determining the coordinates, the method of linear intersection method or trilateration is used, in which spacecraft (satellites) are reference points, the coordinates of which are determined at any time moment. For high-precision measurements of spatial coordinates, it is necessary to determine the position of the GNSS-receiver relative to at least four satellites. In order to improve accuracy, a network of permanent stations was built; in Ukraine it contains 140 stations, which also made it possible to connect the coordinate system of Ukraine to the International Reference System [Ukrainian network of GPS stations, 2022]. The use of the GNSS method ensures the efficiency of measurements and continuous monitoring, it does not require direct visibility between the points of the survey network, and is also characterized by a high level of measurement automation. In our opinion, a significant drawback of this method is that the method requires direct access to survey points to measure surface changes, that is, the method cannot be used for monitoring high-risk areas. The fact that in order to accurate determination of the coordinates the GNSS-receiver must be in the field of view of a sufficient number of satellites complicates the monitoring of failures or open pits, since surveying of lower levels cannot always meet this requirement. With using GNSS method the influence of the troposphere and ionosphere, time synchronization of satellites and the GNSS-receiver, changes in the phase center of the antenna installed at permanent stations during their replacement, and the stability of the stations should also be taken into account.

Since the 1970s, Earth remote sensing (ERS) data have been actively used to monitor and identify geomorphological changes [Cracknell, 2018]. ERS data depict the objective situation of processes and phenomena on the Earth's surface at a particular time, and regular repetition of images allows tracing their dynamics [Hlotov & Biala, 2022a]. Remote methods for studying deformation of Earth's surface changes are based on a non-contact method for obtaining information about the area under study, while using various ERS systems: digital, television, infrared, laser, radiothermal and radar. They differ in the range of the electromagnetic spectrum in which the data is obtained, and have various applications. The issues of deformation monitoring being solved, data obtained from digital, laser and radar systems are most often used [Burshtinska & Stankevich, 2010; Rakushev et al., 2020; Casagli et al., 2017].

Modern digital camera systems are equipped with a predominantly matrix-type charge-coupled device (CCD array). In ERS systems, CCD captures images by converting the reflected radiation of the Earth's surface (the visible and near-infrared range of the electromagnetic spectrum) [Burshtinska, Kh., & Stankevich, 2010]. The spatial resolution of the captured image refers to the dimension of the pixel representing certain area covered on the ground, so the data can be subdivided into low, medium, high and ultra-high resolution groups [Kokhan & Vostokov, 2009]. Data from multispectral imaging systems are widely used in classification methods, investigations with vegetation indices application, and in retrospective analysis of the spatial development of territories [Hlotov & Biala, 2022a; Casagli et al., 2017]. The ultra-high-resolution data make it possible to apply the structure from motion (SfM) method to detect vertical and sub-vertical displacements of the Earth's surface. The SfM method consist in building 3D models by using 2D images, under the condition that they are of the same scale and spatial resolution (minor deviations), thus forming a stereo effect [Scherer, 2019]. Ultra-high resolution satellite imagery is expensive, which limits its use by non-profit organizations [Rakushev et. al., 2020]. However, with the rapid development of aircraft remote sensing, namely the improvement of UAVs and the camera systems, GNSS receivers, inertial measuring units, and microsensors installed on them, it became possible to obtain images of hard-to-reach territories, high-risk areas with centimeter accuracy [Casagli et al., 2017]. Basing on the UAV survey data, it is possible to use the SfM method to monitor local deformation processes of the Earth's surface destabilized due to extraction activity [Scherer, 2019]. Despite a number of significant advantages of using UAVs, namely, high spatial resolution providing the identification of even minor changes, a non-complex data processing algorithm, the cost and efficiency of monitoring, the need to perform experimental work (physical and legal access to performing UAV survey) should be taken into account.

Radar systems, unlike digital ones, are intended to active data collection, that is, they use its own radiation source, then record and process the radiation reflected from objects and, as a result, form a radar image [Burshtinska, Kh., & Stankevich, 2010; Kokhan & Vostokov, 2009]. Space-based radar systems cover the microwave range of the electromagnetic spectrum. An interferometric synthetic aperture radar (InSAR) technique was developed with applying radar satellite data. It is used to determine the Earth's surface deformations, based on phase information of several cycles of coherent measurements with a change of the radar position in the space. This method allows accurate determination of vertical and subvertical displacement of the Earth's surface [Casagli et al., 2017]. Among the advantages of using radar imaging the non-weather dependence can be found (there is no significant effect of clouds, precipitation, high intensity of solar radiation on image quality); efficiency of data acquisition; possibility of retrospective monitoring. The paper [Scherer, 2019] compares the use of methods of InSAR (based on satellite data) and the SfM (based on UAV data) in the study of the Earth's surface deformations. Among the advantages of using InSAR, [Scherer, 2019] highlights the high accuracy of data in the vertical plane, global coverage, and a large image coverage area. However, the author also notes the low spatial resolution (mainly of freely available data), complex technical data processing and the high cost of commercial images. According to the author, the fields of research where the InSAR technique can be the most profitable are monitoring at global or regional levels, determining centimeter-scale vertical movements and time series analysis. Appropriate areas of research using the SfM method based on UAV surveys are the monitoring of local phenomena and recent events, the determination of vertical and subvertical changes in small areas/objects and studies with the integration of other digital elevation models (DEMs) [Scherer, 2019].

Taking into account the advantages of UAV surveys and their financial efficiency, scientists are actively working to improve the quality of surveys, increase the accuracy of data acquisition and reduce the impact of errors [Hlotov et al., 2018; 2021a; 2021b; Rossi et al., 2016].

Based on conducted analysis of literary sources, the classification of actual geodetic methods and techniques for studying the quantitative parameters of the Earth's surface subsidence-dip deformation processes of technogenically loaded objects is proposed (Fig. 2).

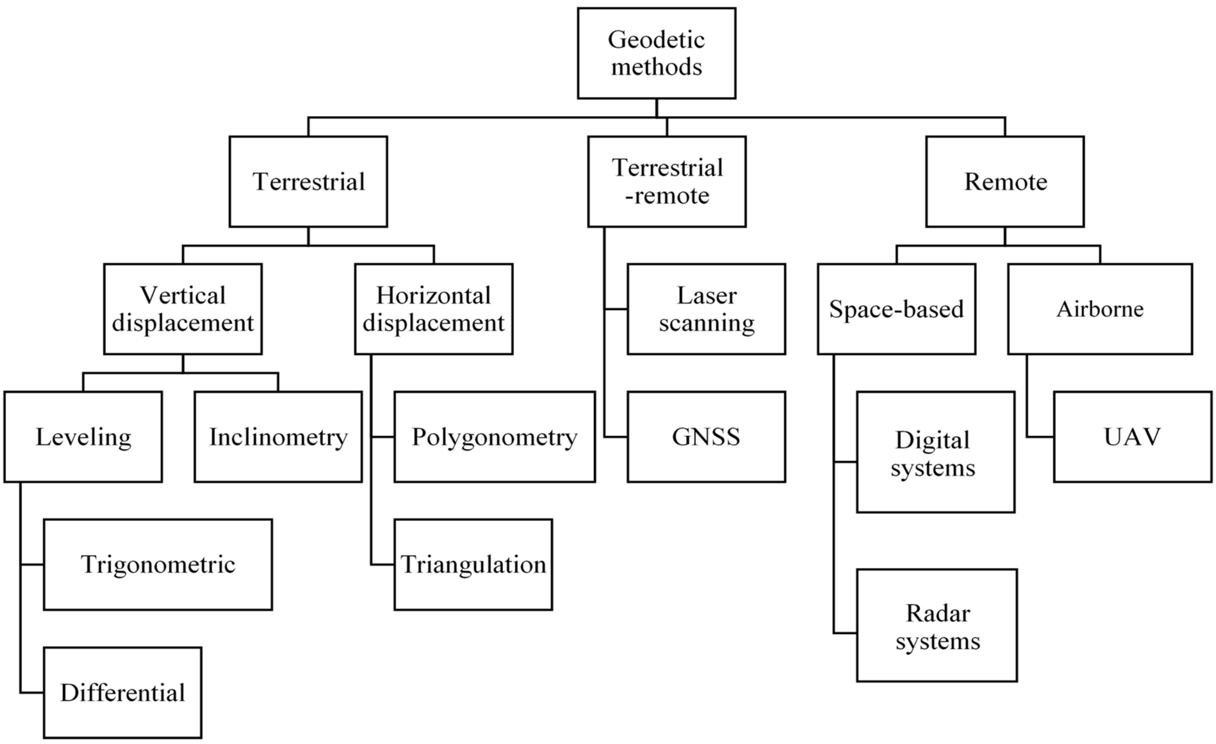

Fig. 2. Classification of actual geodetic methods for monitoring and studying deformation spatio-temporal changes of the Earth's surface in man-made destabilized territories

Practical significance

The presented results can be used as a theoretical basis for further improvements of techniques for studying and monitoring Earth's surface subsidence-deformation processes of technogenically loaded objects in order to improve the environmental situation and predict technogenic disasters. A classification of actual geodetic methods used to study quantitative parameters of the Earth's surface deformations has been developed, that structures these methods and approaches to the study of this phenomenon.

Conclusions

The performed analysis of literary sources demonstrates the existence of numerous geodetic methods for studying and monitoring the quantitative parameters of subsidence-dips deformation processes of the high technogenically impacted territories, the active use of methods confirms the relevance of these studies.

The critical evaluation of the methods under consideration made it possible to highlight their advantages and disadvantages, as well as to summarize that contact terrestrial geodetic methods are not effective enough while used in studies of the Earth's surface deformation of high-risks areas. The expediency of using remote methods for studying vertical and subvertical movements in places of landslides and sinkholes is substantiated. The effectiveness and prospects of using data from UAVs for the purpose of monitoring Earth's surface deformations of technogenically loaded objects are highlighted.

The presented study is practically significant and serves as the basis for further improvement of the complex technology for studying quantitative parameters and monitoring subsidence-dip processes of the Earth's surface in order to improve the environmental situation and ensure life safety in technogenically loaded areas.

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