



THEORETICAL AND METHODOLOGICAL
FOUNDATIONS OF MONITORING HAZARDOUS
GEOLOGICAL PROCESSES

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ABSTRACT

This article discusses the theoretical and methodological foundations of monitoring hazardous geological processes. Natural and anthropogenic factors influencing the formation and development of landslides, subsidence, displacement, deformation and other geological processes are analyzed. Modern approaches to monitoring hazardous geological processes are considered, including geodetic observations, remote sensing technologies, synthetic aperture radar interferometry, multispectral optical imagery and geographic information systems. The integration of data from different sources provides opportunities to identify hazardous areas, assess the spatial and temporal development of geological processes and improve the reliability of monitoring results.

Introduction. Today, hazardous geological processes driven by natural and anthropogenic factors can impact the environment, residential areas, transport infrastructure, industrial facilities, and other critical structures. Processes such as landslides, land subsidence, ground displacement, deformation, and rock mass movement manifest and evolve differently across various regions. Failure to detect these processes in a timely manner can limit the ability to assess their progression and mitigate associated risks. The monitoring and assessment of hazardous geological processes constitute a key area of



modern geological, geodetic, and geoinformation research. The monitoring process focuses on the systematic observation of geological conditions in a specific area, the processing of acquired data, the comparison of this data with previous results, and the identification of trends in process development. The primary objective is not merely to determine the current state but to understand how geological processes evolve over time. Traditional monitoring methods employ field observations, geodetic measurements, leveling, GPS or GNSS technologies, and other measuring instruments. These methods make it possible to determine changes in the coordinates and elevations of specific points. However, relying solely on ground-based measurements may prove insufficient when regular monitoring of large areas is required. Consequently, the use of remote sensing and geoinformation technologies is becoming increasingly important in modern monitoring systems. In recent years, advancements in satellite data have significantly expanded the capabilities for monitoring hazardous geological processes. Satellite imagery enables the regular observation of vast areas, the comparison of data acquired at different times, and the detection of changes within a region. In particular, the combined use of radar and optical data offers significant potential for the comprehensive assessment of geological processes.

Main section. The formation and development of hazardous geological processes can be linked to the region's geological structure, topography, the physical-mechanical properties of rock formations, groundwater, precipitation levels, seismic activity, and other natural factors. The composition of geological layers and their spatial arrangement influence the stability of the land surface. In areas situated on slopes, deformation processes may develop as a result of the saturation of rock masses, changes in their physical properties, or the intensification of water flows.

Landslides are a widespread type of hazardous geological process characterized by the movement of rock or soil masses down a slope. Factors such as the slope's geological structure, moisture levels, precipitation, groundwater, and human activity can influence landslide development. In certain areas, activities such as road construction, slope excavation, building works, or the improper use of land resources can alter existing natural conditions. Land subsidence is another significant geological process requiring monitoring. This process can result from the compaction of subsurface layers, long-term groundwater extraction, mining operations, or other natural and anthropogenic factors. When subsidence develops gradually, it can be difficult to detect through simple visual observation; therefore, the use of high-precision geodetic and satellite monitoring is essential.

When studying hazardous geological processes, determining their spatial and temporal evolution is of particular importance. A single observation reflects the state of a specific area only at a particular point in time. Regular monitoring makes it possible to determine the rate at which the process is developing, identify areas where changes have intensified, and detect locations showing signs of deformation. Consequently, repeated observations play a crucial role in the monitoring system. The theoretical framework of the monitoring process involves



establishing the area's initial state, collecting data regularly, processing that data, and comparing the results. Initially, the geological, geomorphological, hydrological, and other characteristics of the area are studied. In subsequent stages, new data is acquired and compared with previous observations. This enables conclusions to be drawn regarding the direction and developmental characteristics of changes within the area. Geodetic monitoring methods allow for the assessment of deformations by determining the coordinates and elevations of points on the Earth's surface. GNSS technologies make it possible to detect changes in the spatial position of observation points. While these methods provide high-precision measurements, they require the pre-selection of monitoring points and regular observation. Therefore, geodetic monitoring often yields the most effective results when used in conjunction with other observation methods. Remote sensing technologies make it possible to expand the area subject to monitoring. Satellite data allows for the observation of changes occurring over vast areas. Radar and optical imagery offer distinct capabilities in this regard: while optical images are useful for identifying land cover, vegetation health, water bodies, and other surface features, radar data is crucial for detecting ground surface deformations.

Interferometric Synthetic Aperture Radar (InSAR) technology is a modern method that enables the detection of ground surface deformations using radar imagery. By interferometrically processing radar images acquired at different times, it is possible to obtain information about displacements occurring on the earth's surface. Thanks to its ability to monitor large areas, this technology serves as a vital tool for tracking hazardous geological processes.

One of the key aspects of InSAR technology is the ability to monitor surface changes based on repeat radar imagery. By comparing images acquired at different times, it is possible to assess the temporal evolution of deformation processes; this is particularly important for studying slow-moving subsidence and other deformation phenomena. Advances in InSAR technology have also led to the widespread use of time-series-based monitoring methods. Approaches such as PSInSAR and SBAS utilize multiple radar images to evaluate how surface deformations change over time. These methods enable a more detailed analysis of regional deformation by leveraging points with stable radar backscatter or sequences of small-baseline interferograms. Proper data processing and result validation are crucial when working with radar data. Factors such as atmospheric conditions, surface characteristics, and radar signal propagation can influence interferometric results; therefore, comparing InSAR findings with geodetic observations or other independent data enhances the reliability of the monitoring process. Multispectral optical data serve as an additional source of information for assessing hazardous geological processes. For instance, Sentinel-2 satellite imagery allows for the analysis of land cover, vegetation health, moisture characteristics, and other parameters. The data obtained provide further insight into the



natural conditions of areas experiencing landslides or deformation. Another key capability of optical data is the ability to detect changes in land cover by comparing images captured at different times. Indicators such as shifts in vegetation cover, fluctuations in moisture levels, or the expansion of bare soil areas can offer valuable information for assessing the conditions under which geological processes develop. However, given that optical imagery depends on cloud cover and lighting conditions, it is advisable to use it in conjunction with radar data.

Combining radar and optical data enhances the scope of monitoring results. For example, an area where surface deformation has been detected via InSAR can be further analyzed using multispectral imagery. In this context, data regarding land cover, vegetation, water bodies, and terrain helps in understanding the potential causes of deformation processes. Geographic Information Systems (GIS) also serve as a vital tool for monitoring hazardous geological processes. Within a GIS environment, data from diverse sources can be integrated into a unified spatial system, mapped, and compared. The joint analysis of geological maps, terrain data, satellite imagery, deformation maps, hydrological data, and other information enhances the ability to assess the spatial status of hazardous areas.

GIS technologies also enable the visualization of monitoring results in map form. By displaying deformation values, hazardous zones, geological layers, water bodies, and infrastructure within a single spatial environment, it becomes easier to observe the interrelationships between them. This not only facilitates the scientific analysis of monitoring results but also presents them in a format convenient for practical application.

Data accuracy and correct interpretation are also crucial when analyzing monitoring results. Radar data can be influenced by atmospheric effects, variations in image quality, and surface characteristics. In the case of optical imagery, however, cloud cover and lighting conditions affect data quality. Therefore, cross-verification and comprehensive analysis of data from various sources serve to enhance the reliability of monitoring results.

Another methodologically significant aspect of the monitoring system is ensuring temporal data consistency. When data collected at different times are processed using identical or mutually compatible methodologies, comparing changes within the area becomes easier. Furthermore, conducting regular observations helps distinguish between the short-term and long-term characteristics of deformation processes. Terrain is also a key factor in monitoring hazardous geological processes; slope steepness, elevation differences, and slope orientation can be used to assess the conditions under which landslides and other processes develop. Integrating digital elevation models with other data within a GIS environment enables a more detailed analysis of the spatial characteristics of hazardous areas. Opportunities for utilizing artificial intelligence and machine learning methods in modern monitoring systems are also expanding; such technologies can be employed for the automated analysis of large volumes of remote sensing data, change detection, and the identification of hazardous areas. However, the



effectiveness of such approaches depends on the quality of the data used, the appropriate selection of algorithms, and the verification of results by experts.

AI-based approaches can reduce the time required to process monitoring data and enhance the ability to extract essential information from large datasets. In this process, changes in an area can be analyzed based on historical monitoring data and compared with new data. At the same time, expert verification of automated analysis results remains crucial, as the natural conditions governing geological processes vary across different regions. The effectiveness of monitoring hazardous geological processes depends not only on technology but also on the proper organization of the monitoring system itself. Key components of monitoring include selecting the observation area, determining the frequency of data collection, identifying interrelationships between various data sources, and conducting regular analysis of the results. Consequently, monitoring should be viewed not merely as a process of taking individual measurements or images, but as a system for continuous data collection and analysis.

The time factor holds particular methodological significance in geological monitoring. This is because the nature of a given amount of deformation can vary depending on the timeframe in which it occurs. For instance, a specific displacement might develop gradually over several years, whereas in another instance, an identical displacement could occur within a very short period. The latter scenario may indicate a high level of dynamic activity in the process. Therefore, when evaluating monitoring results, it is essential to consider not only the absolute change but also its rate over time. In general terms, the average rate of change of the process can be expressed as follows:

$$V = \Delta S / \Delta t$$

Here, V is the rate of change, ΔS is the change between two observation periods, and Δt is the time interval.

However, this relationship cannot be accepted as a complete monitoring model; it represents only one of the dynamic indicators. In practical assessment, the variation of the rate over time is also important.

If, in successive observations:

$$V_1 < V_2 < V_3$$

If such a trend is observed, it may indicate that the process is intensifying. Conversely, a decrease in the rate could suggest that the process is relatively stabilizing. However, such a conclusion should be drawn only based on a sufficiently long observation period and the quality of the data.

The uncertainty of monitoring data is also a distinct methodological issue. Any measurement involves a certain margin of error. Therefore, a detected minor change should not automatically be interpreted as actual geological deformation.

In general, the observed value can be represented as follows:



$$X_o = X_r + \varepsilon$$

Here, X_o represents the observed value, X_r the true value, and ε the uncertainty arising from measurement and other sources. Consequently, to assess the significance of a change detected during monitoring, its magnitude must be compared against the observational uncertainty. If the change is smaller than or close to the level of measurement uncertainty, interpreting it as a definitive geological change requires caution. This issue is particularly important when integrating data from various sources, as each source possesses its own specific accuracy, spatial coverage, and temporal characteristics. Modern monitoring studies indicate that accuracy, temporal resolution, spatial coverage, and the method's suitability for the speed of the process must be evaluated in conjunction. Thus, it is advisable for the modern methodology of monitoring hazardous geological processes to be based on the integration of diverse data sources rather than relying on a single observation method. While geodetic measurements can provide high-precision local data, radar imagery enables the detection of deformations over large areas, and multispectral optical data allows for the assessment of the area's natural features and land cover characteristics. GIS technologies enable the integration of this data into a unified environment and facilitate spatial analysis. Such a comprehensive approach allows not only for the assessment of the current state of hazardous geological processes but also for the monitoring of their developmental dynamics. By comparing data acquired at different time intervals, it is possible to determine whether deformation processes are intensifying or stabilizing. Consequently, the monitoring system serves to regularly assess the geological condition of an area and generate the information necessary for making informed scientific and practical decisions.

Conclusion. Monitoring hazardous geological processes is crucial for ensuring the geological and environmental safety of territories. Regular observation of phenomena such as landslides, subsidence, slumping, and surface deformations makes it possible to identify their developmental characteristics and delineate hazardous zones.

The formation of hazardous geological processes can be linked to human activity alongside natural geological conditions. Therefore, it is important to consider geological, geomorphological, hydrological, and anthropogenic factors collectively during the monitoring process. By establishing the initial state of an area and comparing it with subsequent observations, it is possible to evaluate the dynamics of geological process development. Research findings indicate that the integrated use of geodetic measurements, remote sensing, InSAR, multispectral optical imagery, and GIS technologies represents a methodologically significant approach to monitoring hazardous geological processes. In particular, combining radar and optical data enables the analysis of land surface deformations alongside the area's natural conditions and land cover characteristics.

In the future, integrating artificial intelligence and machine learning technologies into monitoring systems could further expand capabilities for the automated detection of hazardous



geological processes and the assessment of their evolutionary dynamics. Comprehensive monitoring systems developed on this basis could serve as a scientific and methodological foundation for the timely detection and assessment of hazardous geological processes, as well as for planning appropriate mitigation measures.

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