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COMPREHENSIVE DIAGNOSTICS OF SLOPE AND SLOPE DEFORMATIONS USING DRONES, GROUND-PENETRATING RADAR AND SATELLITE INTERFEROMETRIC MONITORING

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Abstract

The article discusses the complex process of diagnosing slope and slope deformation through the combined use of unmanned aerial vehicles (UAV), ground-penetrating radar (GPR), and satellite interferometric monitoring. The article emphasizes that deformation processes can often occur covertly and be accelerated by factors such as humidification, seasonal freezing and thawing cycles, intense precipitation, and human activities. Traditional observation methods often lack the ability to provide sufficient information on the underlying causes and mechanics of these displacements.

The article describes a method that utilizes UAVs to precisely record surface changes, GPR to detect subsurface inhomogeneities, and InSAR to generate spatially distributed displacement time series over large areas. This approach allows for a more comprehensive understanding of the deformation process and its various contributing factors. A simple algorithm for data integration is presented, including the unification of spatial and temporal reference systems, quality-filtering, allocation of activity areas, their detailed analysis, and final risk categorization. The procedure for practical implementation at a selected site is also described.

Keywords: *slope deformations, slopes, landslides, monitoring, unmanned photography, photogrammetry, georadar, GPR, satellite interferometry, InSAR, time series of displacements, diagnostics, risk zoning*

Relevance of the study

The relevance of this study stems from the fact that the stability of slopes directly affects the safety of transportation and engineering infrastructure, as well as mining and construction facilities and buildings in areas prone to landslides. Deformation processes can develop covertly and accelerate with changes in soil water content, seasonal cycles of freezing and thawing, heavy precipitation, and human activities such as slope pruning, vibration, and drainage changes. In these conditions, early detection of signs of instability is crucial for preventing emergencies and minimizing the cost of repair and emergency measures.

A variety of factors, including the availability of hazardous sites, the labor intensity required, the time discreteness of observations, and a lack of information about the underlying structure and causes of deformations often limit traditional observation methods. Diagnostics based on a single type of data can only provide a partial picture, as they may capture surface manifestations without fully understanding the internal inhomogeneities of an array, or vice versa, the presence of anomalies without a reliable assessment of actual displacement kinematics.

Combining three complementary technologies – unmanned imaging (for detailed geometry and surface features), georadar (for assessing subsurface inhomogeneities and potential attenuation zones), and satellite interferometry (for objective assessment of time shifts over large areas) – allows us to move from scattered observations to systematic diagnostics. This approach enhances the reliability of identifying hazardous areas, improves the accuracy of engineering solutions (such as drainage, reinforcement, profile recycling, and operating regulations), and creates the basis for risk-based monitoring. In this approach, the frequency and volume of observations are determined by the actual dynamics of deformations and the criticality of the facility, ensuring that resources are allocated efficiently.

The purpose of the study

The aim of this research is to develop and describe a comprehensive approach for diagnosing slope deformations using a combination of unmanned surveying, georadar, and satellite interferometry. We will also create an algorithm to integrate the results and produce a consistent diagnostic model, which will then be used to categorize sites according to their degree of deformation activity.

Materials and research methods

The research materials are based on the analysis of open sources on the engineering and geological classification of slope movements and diagnostic signs of deformations, as well as data obtained through three instrumental methods: unmanned aerial vehicle (UAV) photogrammetry, ground-penetrating radar (GPR), and satellite interferometry (InSAR).

The methodology involves classifying slope movements based on their mechanism and material; comparing diagnostic signs of deformation with their expected spatial distribution; and constructing a comprehensive monitoring system that uses InSAR to identify areas with stable movement trends, UAVs for detailed surface observations and boundary refinement, and GPR for assessing subsurface inhomogeneities related to deformation.

The results of the study

In engineering geology and geotechnics, the term "landslide/slope displacement" is used to refer to the process of moving masses of soil, clastic material, or rocks downhill due to gravity. However, modern terminology recognizes that this phenomenon is not limited to land and is not solely related to sliding in the traditional sense. Instead, it includes various mechanisms such as falling, tipping, spreading, and other types of movement.

Table 1. *Classification of slope displacements by movement mechanism and material type*

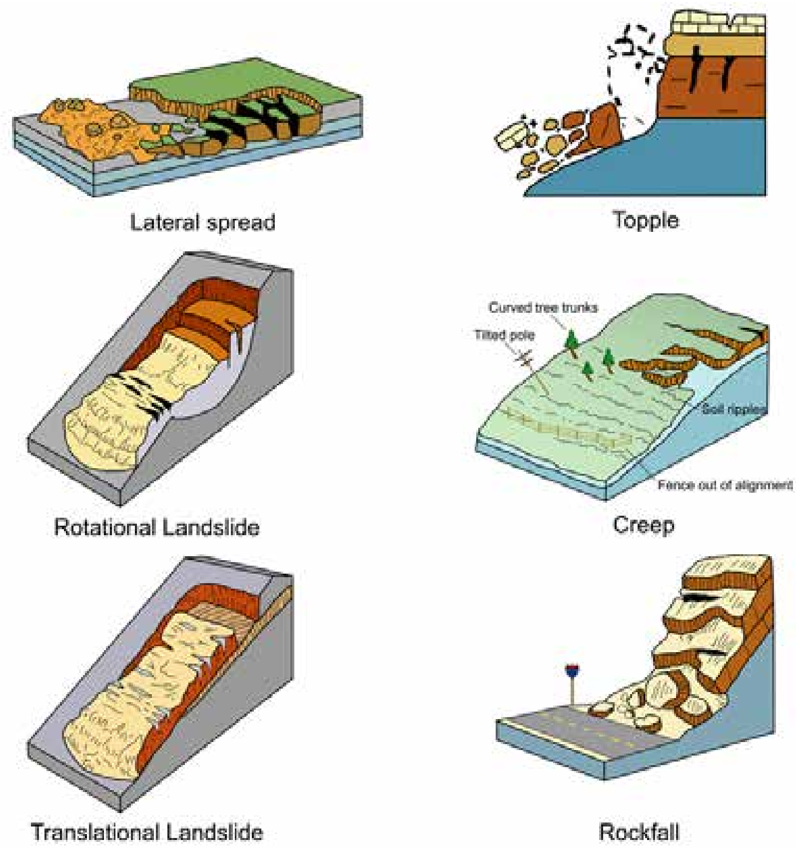
Movement mechanism	Rock material	Mainly coarse-grained material	Predominantly fine-grained material
Fall	Rock Fall	Debris collapse	Landslide
Tipping over	Rocky Rollover	Clastic overturning	Ground tipping
Sliding	Rock Slide	Clastic slip	Ground slip
Spreading (stretching of the array)	Rock sprawl	Detrital sprawl	Ground sprawl
Current (flow)	Rocky current	Detrital flow	Ground flow

Source: author's development

To accurately describe the deformation of slopes and natural terrains, a unified classification system is essential. This system categorizes slopes based on two key factors: the type of material involved and the mode of movement (as shown in Table 1). In applied work, this scheme is important not just as a "formal" tool, but also as a tool that directly determines the expected geometry of the displaced surface, the type of deformations at the edges and sole, as well as a set of diagnostic signs that help to recognize deformations in field and remote data (Landslides: investigation and mitigation).

Below is Figure 1, which clearly illustrates the main mechanisms of slope displacement used in engineering and geological classification.

Figure 1. *The main types of slope deformations (spreading, overturning, rotational and translational landslide, creep, rockfall) (Landslides | Idaho Geological Survey)*



Practical diagnostics of slope stability and deformation is based on understanding that the same event often involves phases and a possible change in kinematics (e.g., an initial displacement along a fracture surface followed by mass movement into a stream). It also involves distinguishing between "activity style" and "stage", which refers to how the deformation propagates and how the body shifts and develops over time.

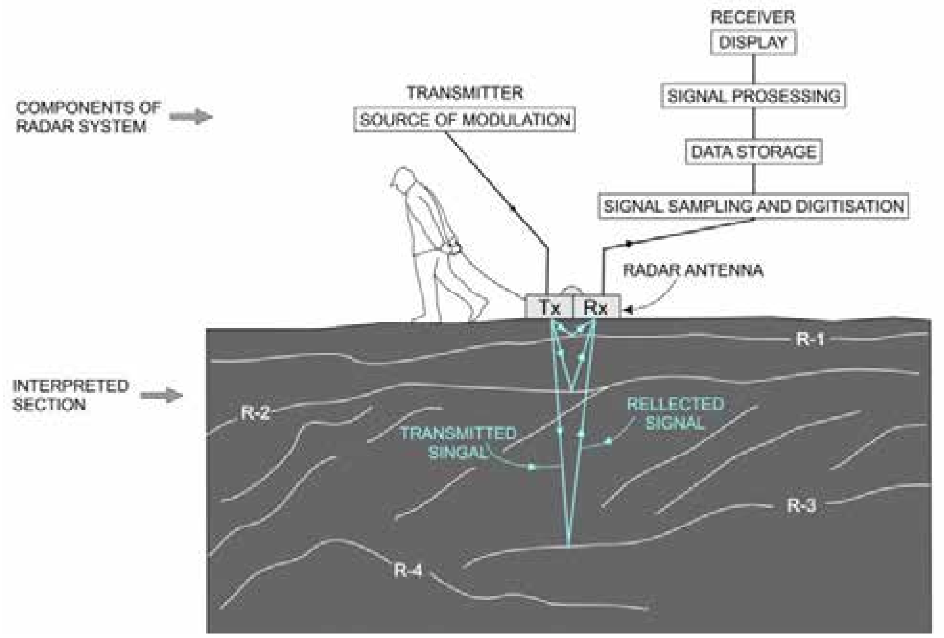
A separate place in the theoretical foundations is occupied by the rate of deformation, which is a parameter that relates the observed shape to the level of danger and monitoring regulations. In engineering practice, a speed scale is widely used to distinguish classes of movement, from extremely slow to extremely fast. For each class, approximate thresholds in mm/s and typical speeds in familiar units (m/year, m/month, etc.) are given, making it possible to compare the results of repeated surveys, geodesy, or satellite measurements with accepted engineering activity categories and correctly interpret whether the observed change is a sign of creep or indicates acceleration that requires immediate action.

Diagnostic signs of slope and slope deformations are verified by a combination of morphological changes in the terrain and "object" indicators on infrastructure. The most reliable early warning signs include the appearance of new cracks and bulges on the ground surface, deformations of roadways and arches, the presence of areas of moisture/water outlet on the slope, or conversely, the emergence of local "puddles/damming" where previously this had not been observed, as well as signs of displacement of artificial elements: tilt of poles, fences, trees, changes in tension of communications, distortion and cracks in buildings and foundation parts.. It is noted that a single feature may have an alternative explanation. Therefore, practical diagnostics focus on the appearance of a group of features and their spatial relationship to the expected deformation zones (upper part stretching and cracking, lower part bulging and deformation at the sole) (What are the signs of landslide development?).

Drones are used to take detailed surface photos: an orthophoto map and a digital model of the surface are created from overlapping images. In the case of repeated flights, the models are compared over time to identify changes in relief and deformations.

Georadar is used when it is necessary to understand what is going on in the upper layers of the ground: it provides sections of reflections that allow you to distinguish differences in properties (layer boundaries, disturbances, areas with high humidity/decompression) within a certain depth, which decreases sharply in conductive and water-saturated soils. A general scheme of how the reflected signal is sensed and recorded is shown in Figure 2.

Figure 2. *Schematic diagram of GPR sensing: pulse transmission and reception, signal processing and interpreted GPR section (Ground penetrating radar – Mine Closure)*



Satellite interferometry (InSAR) is essential for regular regional monitoring. It provides data on offsets along the radar line of sight and over time, which is particularly useful for detecting slow deformations and "background" activity over large areas. The results must always be interpreted with caution, as the direction of the measurement does not always directly coincide with the true displacement vector, and depends on the geometry of the survey.

Table 2. *Characteristics of slope and slope deformation monitoring methods (drone, georadar, In SAR)*

Method	What measures / what shows	Main output materials	A key limitation for interpretation
Drone (UAV, photogrammetry)	Surface geometry and visual manifestations (cracks, ledges, subsidence, blurring)	Orthophotoplane, 3D model/DEM (DS), maps of changes during re-shooting	It requires stable geolocation and accuracy control between shots.

Method	What measures / what shows	Main output materials	A key limitation for interpretation
Ground-penetrating radar (GPR)	Contrasts of properties in the upper stratum, anomalies, boundaries, violations	Radar images (profiles), anomaly maps / interpreted horizons	Attenuation in wet/conductive soils, ambiguity without calibration
In SAR	Time shifts along the line of sight (LOS), velocities/ trends	Velocity maps, time series by points	Decorrelation (vegetation/ snow/ surface changes), LOS geometry

Source: author's development

Table 2 outlines the role of each method in comprehensive monitoring of slopes and slope deformations. It details what is being measured, the data obtained, and the limitations to consider when interpreting results.

The integration algorithm in integrated monitoring starts with bringing data to a common spatiotemporal basis and consistent quality metrics, as the products themselves are inherently different. InSAR provides line-of-sight (LOS) displacements and coherence/ stability indicators for the lens, UAV photogrammetry offers detailed surfaces and textures, and GPR generates profiles and reflection maps that are interpreted based on the physical properties of the medium.

Open manuals and reviews on multi-temporal InSAR emphasize the importance of time series in strain interpretation, as they are sensitive to atmospheric effects, decorrelation, and survey geometry. Time series analysis and quality measurements at each point are crucial for accurate strain interpretation. In order to improve the understandability of LOS offsets and approximately the "engineering" components of motion, data from ascending and descending passes are used in practice. This makes it possible to separate measurements into vertical and east-west components (based on standard assumptions and with the presence of both geometries). This approach is described in open materials on the use of multi-temporal InSAR techniques and the separation of LOS velocities (Multi-temporal In SAR analysis for monitoring ground deformation in Amorgos Island, Greece).

Table 3 presents the minimum data integration algorithm (a sequence of steps and the expected outcome at each stage) that allows you to combine UAV imagery, ground-penetrating radar, and InSAR data into a single model for deformation analysis.

Table 3. *The minimum data integration algorithm*

Stage	Action	Result
1.	Bringing to a single coordinate basis and agreeing on dates	All data is comparable in place and time.
2.	Quality filtering (UAV/InSAR/GPR)	Elimination of «false» changes and noises
3.	Allocation of activity zones by InSAR	Prioritization of sites for detailed survey
4.	UAV details (geometry, features, changes between dates)	Boundaries and manifestations of deformation on the surface
5.	Checking GPR conditions within the identified zones	Subsurface features that support interpretation
6.	Assembling a single model and risk zoning	Map and passport of the site for monitoring decisions and regulations

Source: author's development

The methodology is tested on a specific slope, for which the boundaries of the site, the type of object (slope of excavation/embankment, quarry side, natural slope near the road, etc.), signs of trouble (cracks, ledges, subsidence, erosion, distortion of structures), and initial conditions (engineering, geological, and hydrogeological data, drainage features, man-made impacts) are determined. At the beginning of the chapter, the object is briefly described and the exact purpose of the methods is formulated: to determine where movement occurs, how it manifests itself on the surface, and what subsurface conditions may be associated with deformation.

Next, the program of work is presented in a single time interval. Using InSAR, a velocity map and a time series of displacements are created, and zones with a stable trend are identified. A drone is used to take detailed surface photographs to obtain an orthophoto and a digital surface model; when re-photographing, changes in the terrain are recorded and the boundaries of deformation phenomena are clarified. Georadar is carried out along profiles within selected zones in order to obtain subsurface sections and interpret any inhomogeneities or boundaries that may explain the observed phenomena.

The main outcome of the testing process is data reconciliation. In SAR identifies areas with dynamic displacement, UAV confirms or clarifies surface features and changes in geometry, and GPR provides additional information about the upper layer thickness. The results are presented as a zoning of the site into stable, under supervision, or active categories, and practical recommendations for improved control or engineering measures such as drainage, strengthening, and limiting impacts. These recommendations indicate which areas require priority attention.

Conclusions

Thus, comprehensive diagnostics of slopes and slope deformations, based on a combination of unmanned surveys, ground-penetrating radar, and satellite interferometry, allows us to move from isolated observations to a more systematic interpretation that considers displacement kinematics, surface manifestations, and subsurface conditions together. This approach reduces the risk of an incomplete or one-sided assessment of the slope condition and increases the reliability of identifying hazardous areas. It also improves the validity of engineering solutions, including drainage and reinforcement measures, forming the basis for risk-based monitoring. Monitoring should be based on the frequency and volume of observations, taking into account the actual dynamics of deformations and the criticality of the object.

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