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NEW TECHNOLOGIES FOR THE STUDY AND MONITORING OF LANDSLIDES AFFECTING CRITICAL TRANSPORT INFRASTRUCTURE

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Rezumat. *Monitorizarea alunecărilor de teren devine din ce în ce mai importantă pentru atenuarea şi eliminarea riscurilor pentru infrastructura critică (drumuri şi autostrăzi, cale ferată, canale navigabile, rețele de transport energie, etc.). Această lucrare îşi propune să prezinte tehnica de tomografie de rezistivitate electrică (ERT) pentru analiza şi monitorizarea alunecărilor de teren coroborat cu datele sateliților radar, InSAR (Interferometry for Synthetic Aperture Radar). Metodele ERT şi InSAR sunt completate de metodele de monitorizare continuă automată pe durata execuției şi în exploatare a structurilor şi infrastructurilor critice prin introducerea componentei de avertizare în timp real a evenimentelor în curs de producere. Prin aplicarea acestor tehnici moderne se poate reduce riscul geotehnic în faza de proiectare, se pot reduce costurile de construire şi exploatare, dar şi evitarea unor pierderi datorate producerii unor alunecări de teren ce poate scurtcircuita infrastructuri critice de transport.*

Abstract. *Landslide monitoring is becoming increasingly important for mitigating and eliminating risks to critical infrastructure (roads and highways, railways, waterways, energy transmission networks, etc.).This work aims to present the technique of electrical resistivity tomography (ERT) for the analysis and monitoring of landslides in conjunction with radar satellite data, InSAR (Interferometry for Synthetic Aperture Radar).The ERT and InSAR methods are complemented by the methods of automatic continuous monitoring during the execution and in the exploration of critical structures and infrastructures by introducing the real-time warning component of the events in progress. By applying these modern techniques, it is possible to reduce the geotechnical risk in the design phase, it is possible to reduce the construction and operation costs, but also to avoid losses due to landslides that can short-circuit critical transport infrastructures.*

Keywords: landslide, electrical resistivity tomography, InSAR, monitoring

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1. Introduction

Landslides, as defined in the literature, are movements of rock masses on sloping surfaces (slopes), generally in the direction of the line of the highest slope, due to natural or anthropogenic factors [1]. As indicated by the definition of this phenomenon, its onset and evolution are related to the degree of relief of the relief, the characteristics of the geological substrate, but also the use of land, all expressed in a climatic context.

The article aims to provide key recommendations on the use of innovative technical solutions in infrastructure and to examine the potential contribution of innovative technical solutions and technologies to better, more cost-effective and sustainable infrastructure projects.

Swelling, cracking or displacement of the ground as a result of landslides in the vicinity of the road is the most common incidence to be taken into account during the current monitoring of the behavior of the construction in operation.

The integration of different recommended techniques (ERT geophysical investigations, geodetic measurements, and continuous monitoring) involves the adoption of specific investigation methods for geology, geomorphology and geographic information systems combining both classical and modern methods. All these applications and measurements offer the possibility to answer the questions instigated from a study area, to analyze the triggering factors, but also the future travel trends.

Surface geophysical methods have been used for slope stability investigations for over 35 years [2]. Today, the use of geophysical methods is increasingly addressed since that the data obtained from such studies provide useful and diverse information in a fast and low-cost way. Geophysical methods used to investigate landslides are considered to be the most effective methods of observing these long-term processes [3], [4].

Geodetic, inclinometric and piezometric measurements are usually used to monitor the behavior over time of areas with high potential for landslides. Inclinometric measurements corroborated with piezometric ones are used to assess the state of stress and deformations in structures such as abutment, retaining walls, permanent support works, etc.

2. Geophysical method

ERT (Electrical Resistivity Tomography) is a modern investigation technique aimed at rapidly achieving knowledge upon the electrical resistivity distribution in the subsoil. Several factors contribute to the volumetric resistivity of soil and rocks, the most important ones being mineralogical composition, porosity and permeability, porous space liquid content and chemical composition of that liquid. Therefore, for most sedimentary rocks, the electrical resistivity can be directly linked to some hydrological and geotechnical parameters of interest. Even more specifically, the electrical parameter is directly related to the soil and rocks water content, which is known to play an important role is mass movements' mechanisms [5].

The resistivity is measured in the field with a quadripolar AMNB device consisting of an AB emission line through which a current of intensity I is introduced into the ground by 2 emission electrodes A, B and M, N reception line by which the difference in the ΔV potential created between the M, N electrodes is measured at the current passing through the resistance represented by the basement. The 4 electrodes are stainless steel rods that are placed in the soil, and the connection between them and the measuring apparatus is made by electrical cables on the ground, so the method is non-invasive and can be applied on any type of field.

Inversion of resistivity data is a combination of forwarding simulation and inverse simulation resulting in the final production of the structural model of the basement (the image of the basement obtained based on the resistivity data measured on the land surface).

First, a direct simulation or modeling is performed (virtual projection, a model-to-data application, from cause to effect), on a model built on known primary information (distribution of apparent resistivity in the basement, electrode configuration) or presumed (average resistivity of a sector, user hypothesis or basement structure), obtaining a set of synthetic data. Direct modeling (direct solution) is achieved by solving the partial derivative equation in the field of the Fourier transform:

$$\frac{\alpha}{\alpha x}\left(\sigma\frac{\alpha V}{\alpha x}\right)+\frac{\alpha}{\alpha z}\left(\sigma\frac{\alpha V}{\alpha z}\right)-k^{2}\sigma V=-I\delta(x)\delta(z), \qquad (1)$$

where, V - the scalar electrical potential in the field of Fourier transform,

I - is the intensity of the electrical current of the source,

σ - is the electrical conductivity, a size functioning (x,y), the inverse of resistivity.

Then, the synthetic dataset (measured apparent resistivity section) is subjected to an inverse simulation (the process of determining model parameters, a data-to-model, from effect to cause) to rebuild the distribution of resistivity in the basement based on the V and I data measured on the surface. A model of the basement (calculated apparent resistivity section) is thus obtained which is compared with the initial synthetic model and modified by successive iterations until the difference between them falls below a set threshold. The mean square error (RMS Error, Rooth Mean Squared Error) characterizes the consistency between the data measured in the field and the calculated model data:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}\left(\frac{d_i^{Pred} - d_i^{Meas}}{d_i^{Meas}}\right)^2}{N}}\,100\% \qquad (2)$$

were, N - total number of measurement, d^{pred} - predictable data, d^{meas}- measured data.

The electrode switching is done by the instrument via passive multielectrode cables, which have at equal distances a take-out for connecting the stainless steel electrodes, and cables with passive electrodes (FlexLite Passive Electrode Cable).

The final result is the Inverted Resistance Section (Fig. 1), which represents the distribution of resistivity in the basement reconstructed by the process of inversion of synthetic data. It is the final result of the electrical investigation, an image directly related to the geological structure of the basement in terms of the electrical properties of its various components. Based on this image and taking into account all geological and other data from the researched perimeter, the user engages in the final process of geological interpretation of geophysical results.

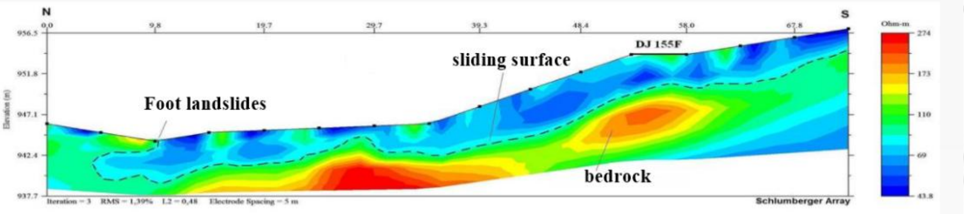

Fig.1.Highlighting the constituent elements of landslides.

Benefits: Following the geophysical resistivity investigations, the bedrock, the sliding surface, the sliding extension, foot landslides, and the aquifer level can be identified. It is also possible to identify the depth at which the monitoring tubes will be installed (inclinometers, piezometers).

3. Monitoring landslides

3.1. Interferometric Synthetic Aperture Radar (InSAR)

The interferometric synthetic diaphragm (InSAR) is a non-invasive geodesic technique that can identify the movements of the Earth's surface. When combined with ground geodesic monitoring, such as global satellite navigation systems, InSAR can potentially measure changes to millimeter-scale deformation over periods of days to years with high spatial resolution. It has applications for geophysical monitoring of natural hazards, e.g. earthquakes, volcanoes and landslides, and in structural engineering, in particular the monitoring of structural subsidence and stability, but also for identifying problem areas along the route of existing or design critical transport networks.

“The PSI approach is based on the use of a long series (the larger the number of images, the more precise and robust the results) of co-registered, multi-temporal SAR imagery. Rapid advances in both remote sensing sensors and data processing algorithms allowed achieving significant results in recent years, underscored by numerous applications. In particular, the application of multi-interferograms SAR Interferometry (PSI) techniques to the study of slow-moving landslides” (*velocity < 13 mm/month, according to Cruden et al. 1996* [6]) is a relatively new and challenging topic [7].

“InSAR-based displacements are 1D measurements. SAR sensors are side-looking radar and operate with a LOS direction tilted concerning the vertical direction. Because of the rather small incidence angle (usually between 23° and 45°), the sensor is much more sensitive to vertical deformation than to horizontal deformation” [8]. Hence, the resulting datasets can estimate only a small component of the 3D real motion of the landslide, i.e., the projection along with the satellite LOS. “Under the assumption of the absence of N-S deformation components, combining ascending and descending information permits one to extract the vertical and horizontal (in the east-west direction) components of the movement and, consequently, the real vector of displacement” [9].

The LOS deformation of a real vector motion is differently measured from the ascending and descending orbits ($LOSA \neq LOSD$) and is directly correlated with the angles of incidence. Field conditions are also a key factor in understanding the measurements obtained from both orbits. Figure 2 represents two different case scenarios in which measurements are taken from both orbits.

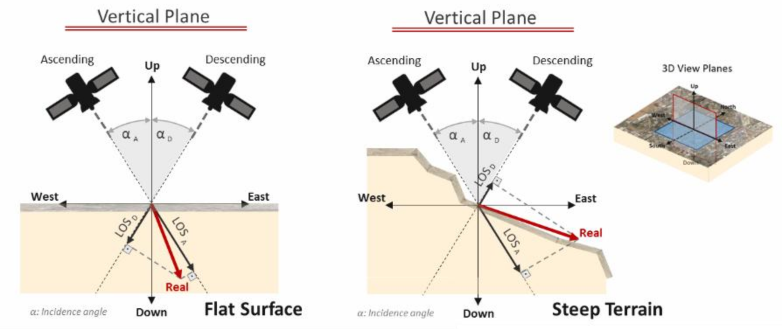

Fig. 2. Măsurători în LOS în orbite ascendentă şi descendentă.
a. Scenariu de caz al unei mişcări de subsidență pe o suprafață plană. **b**. Scenariul de caz al unei mişcări de alunecare pe un teren abrupt.

The results are presented in maps in which the georeferenced measures are represented by points. As an observation, the velocity values show the average value of the deformation during the study period. The measured deformation of a PS at each date is given in the cumulative deformation at the chosen date. To study the behavior of a PS throughout the study period, an analysis of the time series must be made (Fig. 3).

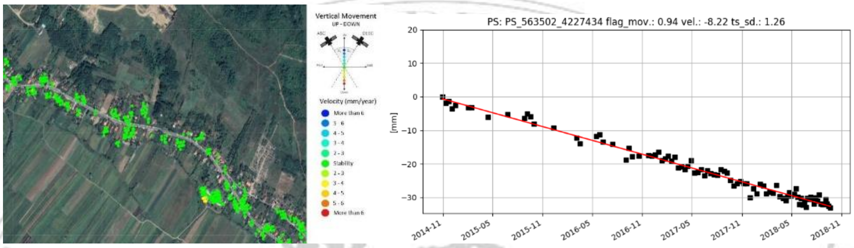

Fig. 3. Deformation of PS.
a.Vertical motion deformation rate (UP - DOWN) with Sentinel-1;**b.**Graph of a PS time series showing a compaction/subsidence trend;

3.2. Inclinometers

"The inclinometer is one of the most commonly used monitoring devices for measuring tilt which is used in several calculations (computations) to quantify displacement and deflections of slopes, embankments and structures" [10]. An empty plastic tube (do not use aluminium tubing) is installed in a drilled hole, which can then be measured periodically to determine the variation of the original inclination of the tube. Also, are used to monitor the movement of structures: retaining walls, abutment, pipes subjected to certain loads, etc. Ideally, the underground location of a landslide rupture can be detected with the inclinometer and the information to what depth should be installed is provided by resistivity geoelectric tomography (ERT) studies. Furthermore, the method determines in detail the depth of the surface of the slide, the magnitude, speed and direction of the movement of the landslide [11], [12].

"The slope inclinometer commonly used today is derived from a prototype built in 1952 by Stanley D. Wilson. The inclinometer first became commercially available in the late 1950s from the Slope Indicator Company" which Stan Wilson founded [13].

"A slope inclinometer is a device for monitoring the onset and continuation of deformation normal to the axis of the borehole casing by passing a probe along with the casing"[14].

The inclinometers are manual and automatic. The automatic ones work based on the same principles as the manual ones, only the whole process is automated and can be controlled remotely.

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Automatic inclinometers have, especially in the long run, several advantages, among which [15]:

- Use of just one probe to measure all the length of the borehole;
- High accuracy and repeatability of measurement;
- Complete and continuous measurement of the inclinometer deformation along the tube (measuring step 0.5 m or 1m);
- Measurement of velocity and acceleration of deformations and of the phenomenon;
- Possibility to change the starting point and step of the measurements;
- Reuse of the equipment even after large deformations of the inclinometer tube.

These advantages, combined with complete automation and remote control, pointed out an integration/alternative to "in-place inclinometer" in all fields of Engineering Geology where precise data on deep movements were needed (landslide phenomena, fronts digging, retaining walls, etc.).

“The probe measures the tilt of the casing which can be converted to a horizontal movement. The angle θ is the angle of tilt measured by the inclinometer probe, and L is the measurement interval” (Fig. 4)[16].

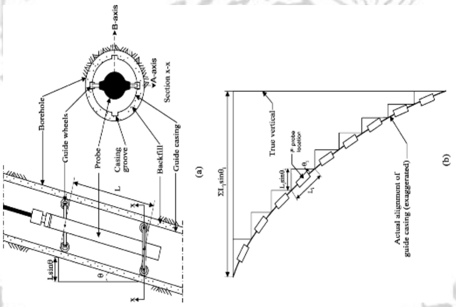

Fig. 4. Principles of inclinometer configuration of inclinometer equipment. illustration of inclinometer operation (modified from [14], [16], [19].

The deviation from vertical, i.e., horizontal displacement, is determined by the sine function and expressed as follows: Deviation from vertical: L x sin θ

"The zero readings are important because all subsequent inclinometer readings are referenced to the changes from the zero measurements. The zero or initial measurement of the original profile should be established by at least two sets of readings. If any set of readings deviate from the other, these reading should be rechecked" [17], [18].

3.3. Piezometers

Piezometers are used to measure pore water pressure and groundwater level. An interesting observation is that this device has no underground capsules and creates a vertical connection between the layers. Applications of the use of piezometers fall into two general categories. The first, for monitoring the water flow model and the second, to provide an index corresponding to the resistance of the earth or rock mass.

- To study the effect of water in pores of soil or rock is to reduce the load-bearing capacity of soil or rock. The effect is more pronounced with higher pore water pressure leading eventually in some cases to total failure of the load-bearing capacity of the soil;
- To determine the level and flow pattern of groundwater;
- To determine the flow pattern of water in earth/rockfill, concrete dams, and their foundations;
- To delineate the phreatic line.

There are several types of piezometers, including: Open Standpipe piezometers, electric piezometers, hydraulic piezometers, pneumatic piezometers, vibrating wire piezometers.

As with inclinometers, some piezometers can perform automatic readings and can be controlled remotely.

Figure 5 shows the general scheme of remote monitoring of parameters using automatic measuring instruments.

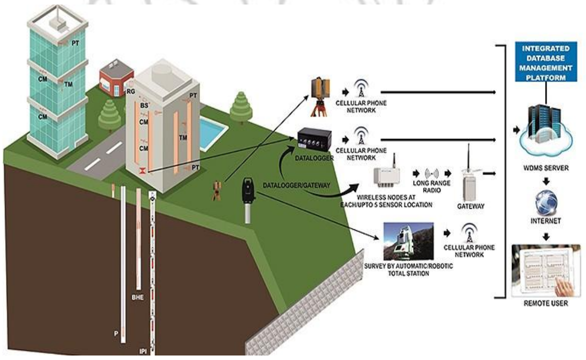

Fig. 5. Typical Instrumentation Scheme-Pile Testing Foundation, [20].

Conclusions

The proposed technologies for monitoring the areas of instability that can affect the critical transport infrastructure are mandatory to be used in the design phase, but also in the construction phase, especially in the operation phase.

Thus, the historical study of the deformations produced on the route of a future route can be provided using InSAR technology, which thus reduces the area that requires increased attention strictly to the areas identified as having movements in the past. After identifying these areas, geoelectric resistivity tomography (ERT) investigations are performed, which provide us with data related to the bedrock, the sliding surface, the sliding extension, the sliding foot, the aquifer level, the depth at which the monitoring tubes will be installed (inclinometers, piezometers, etc.) and together with the data from the geotechnical drillings lead to the calculation of the slope stability. Then the real-time monitoring system is installed for the analysis of in situ movements but also for the real-time warning component of the movements produced that can provide information according to the set alert thresholds and can intervene in time to reduce damage and apply solutions for stabilization techniques.

We often find in practice a reluctance to use the methods listed above due to their price not taking into account the long-term benefits they have.

Thus, the InSAR method can generate thousands of measurement points annually on the route of transport infrastructure and has the advantage that you can access data from the past (since 2014) for the same sector by preparing a historical study. The same number of points if measured by traditional topography methods using the total station and/or GPS would require a long time and much higher costs.

Resistive geoelectric tomography profiles provide information on the distribution of lithology between geotechnical drillings performed canceling the risk of identifying local phenomena (local faults, caverns, caves, unidentified utility networks, rock blocks, former loan pits, landfills, sites archeological, etc.) in the execution or exploitation phase. If we compare the prices practiced in the market for manual vertical electrical surveys (EVS) - technology used successfully in the 70s - with those practiced in geoelectric resistivity tomography (ERT) we find that for the same number of electrodes used (56SEV *vs* 56ERT), tomography they are clearly cheaper but also much faster (ERT day *vs* EVS weeks) and with a much better data resolution (tens of EVS data compared to thousands of ERT data).

Automatic in-situ monitoring systems (piezometers, inclinometers, etc.) are more expensive in the acquisition phase but, after 6 years, are depreciated and become profitable compared to manual systems. Instead, the advantages of the real-time database are especially evident through the real-time warning component of imminent danger. Much more than that it gives us a real-time picture of the state of stability/health of the slope, construction, infrastructure, etc. helping to reduce design, construction, and operating costs.

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