Thesis title: *Differential SAR Interferometry and numerical simulations used in slow-moving landslides investigation*

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Anthropogenic impact, through the geomorphological and hydrological changes it induces, is a triggering and preparatory factor for the triggering and/or reactivation of landslides. At the same time, as landslides evolve, they intervene in the control of human activities. This two-way action creates an interconnected loop of these two processes that depend on and influence each other.

Landslides are among the natural hazards that cause the greatest economic and human damage globally (Crozier and Glade, 2005). At the level of Romania, this hazard can become one of the important limiting factors, which interfere more and more with infrastructure development policies, the expansion of utility networks and which can limit the expansion of urbanized areas. At the same time, anthropic modernization actions lead to the triggering and reactivation of these geomorphological processes. In addition to urban development and anthropogenic impact as a result of urban development and expansion (Jaboyedoff et al., 2016), global climate change is another contributing factor and exponentially increases the possibility of triggering landslides (Gariano and Guzzetti, 2016).

As a result, the investigation and monitoring of landslides is a topic of great interest worldwide at the moment, their problem being identified since the last century (Brabb, 1991). For this reason, more and more studies are being carried out with the aim of understanding their production mode and dynamics. This is important in the attempt to prevent their production or to reduce the negative effects they cause, both on buildings (constructions), infrastructure, or heritage, and especially in order to prevent the loss of human life.

In critical situations, they destroy and cause damage to buildings, infrastructure and heritage (Fastellini et al., 2011) and can lead to very high economic losses, an aspect that began to be observed since the end of the previous century (Alexander, 1986, 1989; Schuster and Fleming, 1986; Schuster, 1996; Petley, 2008; Kjekstad and Highland, 2009; Haque et al., 2016; Froude and Petley, 2018).

Thus, being one of the natural hazards that can produce major damage at a global level, to combat the effects produced by them, or even prevent them, several methods, techniques and tools have been thought and developed to approach and better understand these processes. Among them are the advanced techniques of Differential SAR

Interferometry (A-DInSAR) (Bürgmann et al., 2000; Rosen et al., 2000) and numerical modeling (Duncan, 1996a; Lorig and Varona, 2017) which, lately , have become widely used methods for landslide detection, monitoring and investigation (Castaldo et al., 2015; De Novellis et al., 2016; Hu et al., 2020).

These approaches have seen a great progress in the last decades as a result of the technological advance that allows the use of high-performance computers for the rapid realization of advanced mathematical calculations. They are able to provide very good quality information regarding the size of the area affected by the landslide, data on the dynamics of the landslide (slip direction, speed of the slide), the identification of the mechanism and the surface of the slide, as well as the influence of the factors that condition the magnitude and process dynamics.

The information obtained by exploiting these methods is important from several points of view:

• geomorphologically, information is obtained about the sliding behavior that can further constitute a source of data for the investigation of these processes on a regional scale;

• geotechnical, information is obtained about the sliding surface and the sliding mechanism;

• economic and administrative, it provides the authorities with an important database for managing funds and implementing effective strategies to stabilize the phenomenon where necessary.

Currently, there are more and more studies that integrate MT-InSAR and numerical modeling techniques due to their high efficiency in monitoring and assessing the state of landslide dynamics, but they are used in areas that have a lot of in situ data (Calò et al., 2014; Cevasco et al., 2018; Hu et al., 2020; Notti et al., 2021). In contrast, their use in regions without adequate in situ measurements is still challenging and not yet fully exploited.

In this doctoral thesis, MT-InSAR techniques will be used primarily to identify critical areas in the city of Iași that present deformations related to landslides. Next, our interest is focused on the Țicău landslide, one of the active landslides affecting the residential district on the north-eastern slope of Copou Hill. The challenging part of the investigation is related to the lack of in situ data needed to model the behavior of the sliding material. To understand the mechanism and dynamics of the landslide, we used the Finite Difference (FDM) code on a section passing through the landslide and simulated several scenarios that can describe the observed deformations and pattern. Finally, we analyzed the simulations and MT-InSAR results, velocity maps, displacement time series, and displacement magnitudes

resulting from the simulations to highlight the active parts and most dangerous areas of the landslide body as well as to validate the landslide mechanism also proposed the geomorphological type of landslide.

Taking into account the above, it appears that the research topic chosen and treated in this doctoral thesis is a current topic, of global interest, which arouses international scientific curiosity and for which more resources should be granted, both at the level Romania, as well as locally, at the level of the municipality of Iași, in order to effectively combat and prevent the negative effects that these geomorphological processes can cause.

The objectives of this thesis have been established according to the current needs for knowledge and understanding of risks, both globally and locally, so as to contribute to improving the safety of people and increasing the resilience of the community in which they live. As it was also emphasized in the previous sub-chapter, landslides represent a current large-scale challenge that raises great problems and instigates debates in order to prevent and combat their effects.

In order to investigate landslides, it must be taken into account that these geomorphological processes are different from the point of view of the movement mechanism. For this reason, the approaches used in the investigation and analysis of landslide dynamics are not standard for all typologies, but on the contrary, it is often necessary to use methods specific to the investigated site.

In this thesis, we focus on landslides characterized by low movement speeds, which place them in the category of very slow landslides, with typical speeds of 16 mm/year, according to the classifications proposed by Cruden and Varnes (1996) and Hungr et al. (2014). These types of landslides require permanent strengthening and maintenance work to mitigate the damage they can cause. This situation is also found at the level of the municipality of Iași, a city that constantly faces problems caused by the presence of active landslides and the reactivation of old ones, especially on the north-eastern slope of Copou Hill where the Țicău residential district is located.

The aim of the PhD thesis is to assess the reliability of using two techniques from different but complementary fields to investigate and evaluate the dynamics of slow moving landslides affecting urbanized areas. These two approaches, namely, advanced multi-temporal Differential SAR Interferometry (MT-InSAR) and numerical modeling based on the Finite Difference Method (FDM), have been used so far in landslide investigation, but this only in cases where the respective slide had a lot of in-situ data: piezometers, inclinometers, appropriate geotechnical analyses, multi-temporal GPS (Global Positioning System)

measurements, etc. In the present case, the landslide does not have adequate data sources, which makes it much more difficult to correctly assess this process, in terms of magnitude, spatial area affected, displacement rate, typology and mechanism of the landslide.

For the investigation of areas with problems caused by landslides as well as the detailed analysis of the dynamics of the Țicau landslide, we propose to use the capabilities of these two modern and sophisticated techniques that have progressed enormously in the last 20 years, as a result of the technological advance at global level.

Based on these premises we can define two main objectives that we propose, namely:

OP.1 Identification of the areas in the city of Iași affected by active landslides using the multi-temporal techniques of Differential SAR Interferometry;

OP.2 Identification of the typology and mechanism of the Țicau landslide based on numerical modeling and MT-InSAR time series.

In order to achieve these major objectives, we aim to achieve the following specific objectives:

OS.1 Conceptual framework of advanced techniques of Differential SAR Interferometry and numerical modeling;

OS.2 Create maps of annual mean surface velocities for each set of satellite SAR images, both from the active Sentinel-1 mission and archived data from previous missions (ENVISAT and ERS);

OS.3 Analysis of travel time series in order to identify periods of acceleration and deceleration of travel;

OS.4 Analysis of displacement time series in relation to atmospheric precipitation;

OS.5 Calculation of vectors of vertical and horizontal components of InSAR measurements;

OS.6 Configuration of the geometric and geotechnical model of the Țicau landslide;

OS.7 Analysis of displacement magnitude fields and plasticity indicators of simulations to identify the sliding mechanism;

OS.8 Analysis of the dynamics of the sliding material based on historical points within the slide in order to understand the vertical displacements.

The PhD thesis follows the classic structure of a scientific paper in the field of Earth Sciences, of larger dimensions, divided into 6 representative chapters, to which are added the introductory aspects and the conclusions of the study. In these chapters, the motivation of the chosen research theme is presented, the current problems of the studied object/process,

namely landslides, are described, the techniques, methods and materials used are described, and finally the results obtained from the research on during the years of doctoral studies.

Thus, one can identify in the beginning of the paper, as is natural, the introductory elements of the thesis in which the importance of the study in question is presented, the motivation for choosing this research topic and the substantiation of the scientific objectives that we want to achieve during of this analysis and investigation. The first chapter is an up-to-date synthesis in which the working concepts and the current state of research are presented, both internationally and in Romania, in terms of landslide research directions. In the same vein, the current progress of the methods used in this thesis is presented, namely: the multi-temporal methods of Differential SAR Interferometry (MT-InSAR) and numerical modeling based on the finite difference method (FDM) and mathematical equations.

The second chapter briefly presents the study area, the city of Iași, with its main physical-geographical aspects and the relevant characteristics for the analysis of the geomorphological processes of the slope. Also in this chapter, the landslide that affects the Țicău neighborhood is presented in detail, as well as the landslides on the territory of Iași that have been documented.

In the third chapter, the materials and data used in our study are presented. These include satellite SAR images, existing geotechnical data in the literature, numerical terrain models, and daily rainfall data. The fourth chapter is closely related to the previous one, describing the methods used in the elaboration of the thesis. This is one of the most consistent chapters of the thesis because the techniques used in this study are not very well known and are very little used in Romania. This requires a detailed description of the techniques, a rather difficult task in this context where specialized literature in Romanian is almost completely lacking. In addition to remote sensing methods, which are increasingly used in physical geography studies, numerical modeling or simulations that require knowledge in geotechnical and engineering fields have also been used. Statistical analysis methods and post-processing of the results obtained in order to correlate them with climate data are described in a separate subsection due to their complexity.

The results are outlined in an individual chapter that presents what was obtained based on the two methodologies, which we can consider complementary. The results of advanced Differential SAR Interferometry techniques are identified in the form of maps of average annual deformation velocities on the one hand and time series of deformations, correlated with precipitation data, on the other hand. The results of numerical modeling include simulations of sliding for which the magnitudes of the displacements occurring inside

the sliding mass are calculated with information on the pattern of deformations and the sliding mechanism. Also based on the simulations, we analyzed the sliding behavior in supersaturation conditions, similar to the previous reactivation conditions.

Discussions based on the results are one of the most important chapters, if not the most important, in this thesis. In this chapter, the sixth, the obtained results are discussed, answers to the questions posed in the introduction are given, new problems are raised, the shortcomings and limitations of this analysis are mentioned, and some perspectives are drawn in order to improve and expand the study.

As expected, at the end of the thesis are formulated the conclusions we reached following the application of the methods considered for the investigation of sliding. In the conclusions, the focus is on the applicability and practical aspects of the study, the ideas on the basis of which the objectives were substantiated and the results of the thesis and the perspectives considered for improving the analysis are reviewed.