

# LANDSLIDES FORECASTING ANALYSIS BY DISPLACEMENT TIME SERIES DERIVED FROM SATELLITE INSAR DATA: PRELIMINARY RESULTS

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## ABSTRACT

In this paper preliminary results of the Cat-1 project “Landslides forecasting analysis by displacement time series derived from Satellite and Terrestrial InSAR data” are presented. The project focuses on landslide forecasting analysis, based on the application of slope creep models. Displacements data through time, related to landslides strain evolution, are usually derived by classical monitoring methods. Here we propose the use of spaceborne synthetic aperture radar (SAR) differential interferometry (DInSAR) to achieve past displacements information of already collapsed landslides. Persistent Scatterers (PS) InSAR and Small Baseline Subset (SBAS) InSAR are considered and discussed in the perspective of proposed application. Furthermore, a rating method to evaluate the suitability of landslide prediction and investigation by Satellite InSAR technique is presented and tested over two case studies.

## 1. INTRODUCTION

Slope instabilities are caused by several complex processes taking place at different levels: geological and hydrogeological, climatic (e.g. rainfall distribution or freeze-thaw cycles), earthquakes, volcanism, human activities etc. The combination of these factors and processes can lead to an instability condition that is manifested by mass movements of slopes occurring under the action of gravity. Landslides rarely behave as a rigid body that responds instantly to stresses. More frequently, especially in cases of large landslides (> 500.000 m<sup>3</sup>), they are characterized by a strain pattern (i.e. displacements), increasing over time. This particular behavior is known as “creep” [35, 36]. Starting from the basic theory of creep, several efforts have been done over the last decades in order to develop

forecasting solutions for landslides. The most used approach to address the problem is the semi-empirical one, since it is the most reliable in forecasting analysis. Several semi-empirical models to predict the time of failure of slopes, as a function of velocity variation over time, have been proposed over the last decades [31, 30, 13, 38, 8, 3, 25].

Instrumental continuous collection of displacements data through time is a basic requirement for the application of the above-mentioned approaches. Among displacement monitoring techniques, remote sensing ones are increasing in over the last years. However, terrestrial and aerial remote sensing techniques can collect displacement data only after that suitable equipments have been installed.

Differently, satellite SAR data are continuously collected by suitable satellites since 1992 and are continuously increasing over time in terms of quantity (sampling rate and number of SAR satellites) and quality (ground resolution etc). Hence, a large amount of displacement data can be obtained for several areas of the world. Furthermore, by multi-stack analysis like Persistent Scatterers Interferometry (PSI) [12], or Small Baseline Subset technique (SBAS) [1] time series of displacements with millimeter accuracy can be obtained.

These data can be a very useful tool for the temporal prediction of landslides failure by applying semi-empirical models.

In the frame of the ESA CAT-1 project – ID: 9099 - “Landslides forecasting analysis by displacement time series derived from satellite and terrestrial InSAR data” long term SAR data stacks provided by ERS and ENVISAT ASAR satellites will be processed and analyzed in order to investigate large scale landslides (>1,000,000 m<sup>3</sup>) recently occurred in Italy, with the aim to better define their slope dynamics. Specifically, two slopes affected by large landslides, already collapsed, are being back-

analyzed, in order to understand their predictability by semi empirical methods.

Time series of displacement derived from InSAR multi-stack data processing are analyzed in order to obtain graphs of inverse of the velocity vs. time. Hence, efficacy of satellite InSAR data for temporal prediction of landslides is analyzed and discussed, and the main limitations of InSAR data for the application of landslide time of failure forecasting models is assessed and investigated in detail.

The expected results of this project are the following: a) identification of limits and potentiality of PSI and SBAS methods for landslide forecasting; b) identification of type of landslides that can be investigated by InSAR techniques (for forecasting purposes); c) development of new landslide forecasting models (or adaptation of existing ones) specifically based on Satellite InSAR data; iv) comparison of predictive landslide capabilities of Satellite and Terrestrial InSAR data

## 2. LANDSLIDES FORECASTING

Forecasting the collapse of a landslide is a complex matter because of the high complexity of landslide phenomena. As a matter of fact, “landslide” is a generic term that assembles gravity-controlled slope instabilities characterized by different features in terms of geometry, size, material etc [2].

Existing classifications for landslides are usually based on parameters such as: type of process, morphology, geometry, type and rate of movement, type of material and state of activity [36, 20, 9, 19]. The size is rarely used as a classification parameter, since the contribution to knowledge, provided by it is considered too small if compared with above-mentioned ones. A classification based on the volume was proposed (tab.1) by [11] while a size classification for debris flows have been proposed by [21] in order to address specific practical issues.

Size class	Size description	Volume (m <sup>3</sup> )
1	Extremely small	<500
2	Very small	500–5000
3	Small	5000–50,000
4	Medium	50,000–250,000
5	Medium–large	250,000–1,000,000
6	Very large	1,000,000–5,000,000
7	Extremely large	>5,000,000

Table 1. Size classification for landslides (after Fell, 1994) (from Jacob, 2005)

In the authors opinion the interest on the landslides size as a physical parameter, is not only related to classification purposes. As a matter of fact, different processes can be recognized if small-scale or large-scale landslides are accounted for, especially if we look at the pre-failure stage.

Materials involved represent another important factor in terms of different responses to stress and different mechanical and kinematic behaviour [36].

### 2.1. Slope-creep approach

Landslides rarely behave as a rigid body that responds instantly to stresses. More frequently, especially in cases of large landslides (> 500.000 m<sup>3</sup>), they are characterized by a strain pattern (then displacement), increasing over time [34]. Therefore, time-dependent failure relationships must be considered in order to correctly describe the long-term deformation pattern, known as “slope creep” [35, 15], that represents the slow deformation of slopes involving soil and rock, taking place under gravity and external loadings [10].

In the creep model, materials show a particular evolution of the strain pattern characterized by three phases: a primary creep, a secondary one and finally, a tertiary creep in which a continuous strain acceleration leads the material to failure (see fig.1).

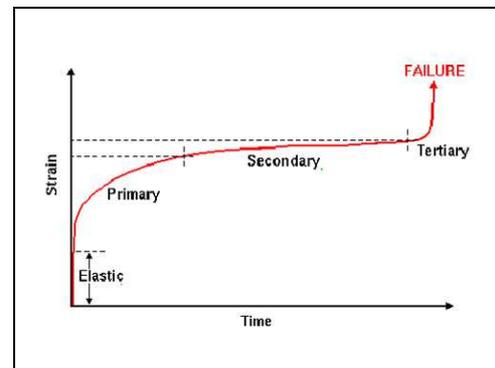


Figure 1. Example of typical creep behaviour of a natural material

Three main approaches can be considered in studying a landslide on the basis of the creep behaviour:

- “micromechanical” approach, which relates the stress-strain mechanism to molecular scale process [26], therefore not particularly useful to describe a creep deformation at the slope scale;
- rheological-mechanical approach, that is based on ideal models (e.g. viscoelastic, viscoplastic, mod. Burger, mod. Maxwell etc.) able to mathematically explain the process and that can be solved numerically by suitable codes also at the slope scale;
- empirical approach in which the time series of displacement are used to describe the behaviour and evolution in terms of material’s failure on the basis of empirical and semi-empirical relations.

The latter is the most commonly used since it is the most constrained, being closely related to observational methods (it is based on real observed displacement data for predicting the future

behaviour). The models of landslide prediction by displacement time series [31, 30, 13, 38, 8, 3, 25] are based on the assumption that the slopes collapse are preceded by a creep behavior characterized by an acceleration of movement in time.

By large scale experiments results, observing surficial displacements, [13], demonstrated that a proportionality between logarithm of velocity and logarithm of acceleration exists. Starting from this evidence, several authors [38, 8, 3, 25] have tried to afford the issue of landslide forecasting based on the slope creep models in which the time of failure is defined using the inverse velocity of displacements vs time. In a graph in which there is the reciprocal of the velocity vs time, you can define the instant of collapse of the landslide observing the intersection of the function versus time.

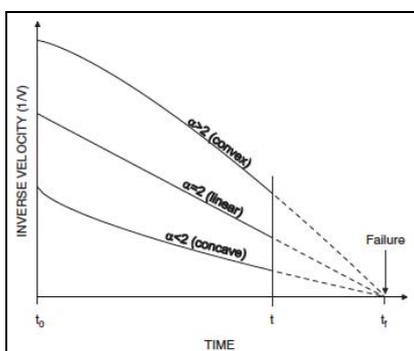


Figure 2. Inverse-velocity versus time relationship preceding slope failure – (after Fukuzono, 1985) (from Rose and Hungr, 2007).

Besides the methods of time series, also the "threshold methods"[32] are mentioned for completeness. They use geotechnical data to determine the collapse of first and second generation landslides. In analogy with the methods used in structural, this approach uses the threshold values of displacement, velocity and acceleration as a boundary between the stable and unstable condition of the slope.

Furthermore, advances in modern techniques of numerical modeling methods make it an attractive alternative of analysis that can be exploited in the future for landslide forecasting purposes.

### 3. LANDSLIDE DISPLACEMENTS MONITORING

Continuous collection of displacements data is a key requirement for the application of semi-empirical models and as a calibration for numerical models based on simplified rheological models. Therefore, displacements monitoring systems play a relevant role in landslide forecasting. In what follows a short review of monitoring techniques is presented

starting from conventional ones to more advanced ones (like Satellite InSAR).

#### 3.1. "Future oriented" monitoring techniques

The displacements monitoring of structures and ground surface in slopes affected by landslides can be performed by mean of various techniques.

It's first of all necessary to distinguish the monitoring techniques able to investigate the processes in depth (such as inclinometer, assestimeter and extenso-inclinometer methods) and which observe surface displacements. Among the latter ones, different methods, able to measure displacements with great accuracy through time exist and can be subdivided into three main categories: geotechnical, geodetic, and remote sensing. Geotechnical measurement techniques (e.g. by strain gauges, tilt meters, accelerometers) are characterized by the peculiarity of providing local results, typically with punctual distribution.

The geodetic methods (by leveling, total stations, and satellite-based methods to detect movements by means Global Positioning System - GPS), instead, provide geo-referenced information on displacements in one, two or three dimensions.

Also methods based on Remote Sensing are able to provide geo-referenced data displacements, but without being in contact with the objects observed. They exploit electromagnetic waves emitted or reflected by them and take advantage of cameras, lidar and radar. These methods often operates from aircraft or spacecraft platforms, but also as ground based instruments, such as terrestrial laser scanner. One of more interesting innovations in this direction, is represented by Terrestrial InSAR (TInSAR). Thanks to this technique, measurements of displacements with temporal scale of minutes are executed by means a terrestrial radar interferometer [27, 25].

All above-mentioned techniques, however, allow to investigate the movements only after the installation of the instruments while they do not give any kind of information about past displacements.

#### 3.2. "Past oriented" monitoring techniques

Photogrammetric techniques, have been for long time a fundamental tool for monitoring actively moving landslides and for analyzing the velocities fields. These techniques allow the detection of ground displacements over long periods of time, by comparing the corresponding sets of aerial photographs. Nevertheless, they are discontinuous through time and especially not able to provide accurate quantitative data.

Techniques based on satellite remote sensing, such as InSAR, represent a kind of tool able to address this kind of need. In this project, in fact, we're trying

to establish a link between the empirical approach to study the creep phenomena and satellite InSAR. The main aim of our work, is to rebuild deformations pattern of large landslides occurred recently, in order to determine if these phenomena were predictable before the collapses.

The only technique that can allow compute past displacements is Satellite InSAR.

#### **4. INSAR TECHNIQUES IN LANDSLIDE MONITORING PERSPECTIVE**

The first applications of Satellite InSAR technique (that dates back to the beginning of 1990'), carried out for the determination of the displacements caused by earthquakes and volcanic deformation, were based on the analysis of single or a couple of interferograms. However, this standard DInSAR (Differential SAR Interferometry) methodology is strongly influenced by the presence of atmospheric disturbance and the presence of residual heights of the DEM used. In single pair-configuration, the atmospheric ambiguity can introduce effects in phase, which can be confused with displacements of centimeters [16, 29]. A new approach aiming to solve these limitations was suggested by [12], i.e. the "Permanent Scatterers" technique, that is based on stack analysis of several multi-temporal SAR images. By such a technique, accurate measurements of displacements of high reflective and temporally stable objects on the scene can be carried out.

Another completely different approach, still based on multi-temporal analysis of SAR data stacks, is well known as SBAS [1]. In this method, multiple classical interferograms are generated after an accurate selection of best pairs, then, information on displacements are calculated in a subsequent processing step.

##### **4.1. PS InSAR: advantages and limitations**

The PS technique allowed for the first time the execution of full-resolution data analysis by providing the time-series of movements [4].

Because of PS InSAR exploits signals from localized objects, which are much more reflective than the surrounding, multi-temporal SAR data pairs characterized also by baselines larger than critical values can be used. PSInSAR approach is spatially discontinuous, and low-effective in areas characterized by limited "high and permanent reflectivity targets" like densely vegetated areas [6, 7].

Several attempts to solve this limitation have been done by using corner reflectors installed in problematic areas to create a highly reflective target visible in the SAR image. However, it is worth to note that in this way InSAR technique is losing its "past oriented" prerogative.

In case of landslides characterized by a good number of Permanent Scatterers, the advantages PS InSAR for landslide monitoring are evident: i) displacement data available since 1992 (if at least 25 or 30 images before a landslide event have been collected); ii) high accuracy on deformational trends and single measurement; iii) ability of exploit SAR data affected by large normal baselines.

Nevertheless, by looking at landslide analysis for prediction purposes a further feature of PSInSAR technique must be accounted for: the "phase unwrapping" [14]. As a matter of fact, PS InSAR technique assumes a linear model of phase variations to detect the displacements, thus strongly influencing its efficacy in detecting non-linear temporal movements. Addressing the issue of predicting landslide by slope creep based models (i.e. semi-empirical models) the linear model in linear unwrapping assumed by PSInSAR is a major criticism.

A new approach, based on the temporal under-sampling of PS time series [5], was attempted in order to overcome the linear trend imposed to detect displacements. However, in that particular case, the post-processing, was also based on a priori information about processes and temporal evolution of phenomenon.

A different approach based on a nonlinear models in the processing of PS InSAR has been recently proposed by [23]. In this case, the good knowledge of the observed phenomenon (subsidence of soil for consolidation process), has inducted the authors to adopt an hyperbolic model instead a linear one.

##### **4.2. A different approach: SBAS**

As well known, normal baseline is a parameter which directly influences the sensitivity of InSAR technique to detect topography effects (then large baselines are preferred to produce DEM from SAR data). In opposition, baselines tend to zero, are the best to detect displacements occurred between two acquisitions. Also considering this matter of fact, the Small BAseline Subset data approach (SBAS) makes use of multi-temporal stacks of SAR data characterized by small normal baselines (in order to minimize decorrelation effects) to determine the temporal evolution of surface deformation. The large number of interferograms, computed between appropriate pairs of SAR images forming the stack, are then subjected to a process of inversion, allowing the connection of information between data separated by large baselines.

It is worth to note, that this processing allows the removal of the atmospheric contribution, in addition to the topography [1]. It is also possible to adopt different models for estimating the linear velocity

and it is possible to determine displacements and accelerations over time.

Because of SBAS results are not as isolated points, it could be possible to gather information on the processes analyzed, which might reveal itself as more spread than hypothesized. Preliminary analyses by SBAS processing technique, have been carried out by an SBAS processing tool available in the GENESI-DEC web platform running in the ESA GRID infrastructure (for information in details please refer to <http://portal.genesi-dec.eu>).

#### 4.3. Combined techniques

A good compromise among the above mentioned approaches: PSInSAR & SBAS has been suggested by several authors [18, 39, 24]. In this way the capability of PS technique to detect local displacements with extremely high accuracy and capability of SBAS to give a more homogeneous distribution of the information can be obtained.

### 5. RATING OF LANDSLIDE MONITORING BY SATELLITE INSAR

As stated above, Satellite InSAR is a quite promising technique for landslide prediction even if several limitations must be accounted for. In order to quantitatively evaluate if a specific landslide can be investigated (and eventually predicted) by satellite InSAR technique a preliminary approach has been developed and discussed below.

predisposition of the phenomenon to be observed by InSAR methods). Several factors have been considered as follows.

For the “technique rating”:

- presence of strong and temporally stable backscatterers, which influences the results achievable in relation to the InSAR technique adopted (e.g. PS, SBAS);
- moving direction of landslide: is well known the impossibility to detect displacements along N-S direction;
- topographical conditions of the studied area, because too steep slopes can introduce layover and shadowing effects able to make unusable quantitative information;
- availability of data in order to appropriately rebuild time-series of displacements to use in the slope-creep models.

For the “landslide rating”:

- extension of the landslide, large enough, that it can be investigated by old not very high resolution SAR data (ERS, Envisat), since the stage of interest is the historical evolution of the processes;
- amount of movement: because of we focus on pre-failure lapse of time, not too big displacements are expected to occur;
- presence of detectable surface deformations;
- presence of ancient landslides or previous documented phenomena on the slope, which

Table 2. “Technique rating”: parameters and related values

Parameters	Rate	1	2	3	4	5
1. Area affected by radar distortions (layover-shadowing) (%)		>15	15 - 10	10 - 5	5 - 0	0
2. Area interested by strong backscatterers (%)		<5	5 - 10	10 - 20	20 - 30	>30
3. Direction of movements (degrees to N-S)		0-15	15 - 30	30 - 50	50 - 70	70 - 90
4. Available data (average of SAR images per year)		≤5	6	7	8	≥9
5. N° of PS (PS/kmq)		<50	51 - 100	101 - 150	151 - 200	>201

Table 3. “Landslide rating”: parameters and related values

Parameters	Rate	1	2	3	4	5
1. Area (m <sup>2</sup> )		<2x10 <sup>3</sup>	2x10 <sup>3</sup> - 2x10 <sup>4</sup>	2x10 <sup>4</sup> - 1x10 <sup>5</sup>	1x10 <sup>5</sup> - 1x10 <sup>6</sup>	>1x10 <sup>6</sup>
2. Expected velocities (v) (mm/y)		v>100 or v≤2	80<v≤100 or 2<v≤3	60<v≤80 or 3<v≤6	40<v≤60 or 6<v≤10	10<v≤40
3. On site detected deformations		None	Isolated	Local	Diffuse	Very diffuse
4. Slope activity		None	Inactive	Dormant	Recorded in Historical time	Recorded in last 10 years

Such an approach accounts for both landslide features and technical efficacy of InSAR monitoring. Specifically, this approach is based on a combined rating, ranging from 1 (non suitable) to 5 (completely suitable) referred to the technique (considered as the capability to detect a specific process), and the landslide (to evaluate the

may facilitate the occurrence of low strain evolution through time in the study areas.

In tab. 2 and 3, some parameters calibrated on ERS and Envisat data will be shown for the rating approach. They will be used to evaluate the feasibility analysis for two case studies described below.

## 6. CASE STUDIES

In order to evaluate the efficacy of the here presented rating approach, we identified two large landslide recently occurred in Italy: the Maierato landslide (VV) and the San Fratello landslide (ME) both collapsed in February 2010. These two case histories are characterized by collapse events which have affected some villages.

Table 4. Ratings performed for the two case studies

	MAIERATO		SAN FRATELLO	
	value	rate	value	rate
<b>Techniques parameter</b>				
1. Area affected by radar distortions (layover-shadowing) (%)	0%	<b>5</b>	0%	<b>5</b>
2. Area interested by strong backscatterers (%)	4%	<b>1</b>	17%	<b>3</b>
3. Planimetric direction of movements (degrees to North-South)	54	<b>4</b>	88	<b>5</b>
4. Availability of data (average of SAR images per year)	8	<b>4</b>	9	<b>5</b>
5. N° of PS presents in area, from literature (PS/kmq)	18	<b>1</b>	101	<b>3</b>
<b>Landslide parameters</b>				
1. Areal extension (m <sup>2</sup> )	2.65x10 <sup>5</sup>	<b>4</b>	5.96x10 <sup>5</sup>	<b>4</b>
2. Expected average velocities range (mm/y)	2	<b>1</b>	1	<b>1</b>
3. Detected deformations on buildings, road or natural elements	Local	<b>3</b>	Very diffused	<b>5</b>
4. Events already occurred	Recorded in historical time	<b>4</b>	Recorded in historical time	<b>4</b>
<b>TOTAL</b>		<b>27</b>		<b>35</b>

### 6.1. The Maierato Landslide

The huge Maierato landslide involved a slope, which in its basal part is characterized by evaporitic calcarenites with interbedded silt, and silty clay (representing the predominant part of landslide body) topped by clay and silty clay with locally interbedded sands. The kinematics of the landslide occurred in a basin, already affected by major gravitational instability (such as the landslide of 1932, which affected the opposite slope of the valley), could be considered as complex rototranslational. Moreover, the same landslide under study, spreads over an area already accorded as a dormant landslide in IFFI archive. After the main event, a retrogression of the crown area was observed. The landslide, presents a width of 500 m and the estimated volume is about 1.7 millions m<sup>3</sup> [22].



Figure 3. Aerial view of the Maierato landslide

### 6.2. The San Fratello Landslide

The San Fratello landslide is referred, instead, to a large instable area, characterized by the presence of several buildings and life lines. The mobilization of the landslide, with a scar of almost 1 km, has led to the evacuation of more than 1.500 people. From a purely geological point of view, soil affected by the process has mainly silt-clay composition, while kinematically is intended as a complex landslide

with multiple niches of detachment.

Again, the landslide is setting on a slope instability due to a precedent phenomenon dated 1922 [33].



Figure 4. Aerial view of the San Fratello landslide

## 7. DISCUSSION AND CONCLUSIONS

Achieving time series of past displacements is an excellent opportunity in predicting landslides and reducing their impact on the society. Multi-stack InSAR analyses allow this type of information to be obtained; however, several limitations must be considered and accounted in landslide monitoring perspective. In order to evaluate the effectiveness of InSAR data to be used for landslide prediction purposes a dedicated CAT-1 project (Id: 9099) is carrying out. As a first step a critic analysis of available multi-stack analyses has been performed thus allowing to identify the most effective one.

InSAR processing methods based on linear models have been envisaged as unsuitable for landslide prediction purposes since landslide creep are characterized by a strongly non linear behaviour. Furthermore, the presence of few PS in landslide areas (often not intensely urbanized areas) suggests that dispersive and partially coherent approaches must be considered with respect to purely persistent scatterers ones.

Furthermore, a preliminary quantitative rating approach allowing to evaluate the efficacy of satellite InSAR in landslide monitoring perspective, have been proposed. This rating approach has been tested by back analyzing two large landslides recently occurred in Italy (Maierato and San Fratello landslides) by considering ERS and Envisat ASAR data. Results show that both landslides could be considered eligible to be investigated and monitored by InSAR technique for prediction purposes. However, short revisiting time of ERS and ENVISAT data do not guarantee that prediction models could be applied. Hence, future activities will consist in evaluation of the impact of new generation SAR satellites (Cosmo Sky-Med, Terra SAR-X) in landslide prediction perspective. Furthermore, improvements of the herein proposed rating approach mainly looking at coefficient values for the considered parameters.

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