Landslide Risk Analysis by means of Remote Sensing Techniques: Results from the ESA/SLAM Project

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***Abstract*— In the framework of the SLAM project (Service for Landslides Monitoring) funded by the European Space Agency, the Permanent Scatterers processing and the analysis of high resolution images (e.g. SPOT5 and aerial-photos) have been performed at a basin scale, on the whole territory of the Arno River basin (Central Italy). About 350 SAR images have been interferometrically processed by means of the PS technique, detecting about 650,000 PS. The processing of SPOT5 images and aerial-photos, still in progress, have been performed for the extraction of features related to the landslide presence, useful for the geomorphological analysis and, as a consequence in order to give a spatial meaning to the punctual information provided by the PS. This procedure has been coupled with a intense geological interpretation phase characterized by the analysis of traditional in situ monitoring data, ancillary data and the performing of field surveys. The final results will impact on the current instruments used by the Arno Basin Authority for the landslide risk management (e.g. Hydrogeological Management Plan - Piano per l'Assetto Idrogeologico – PAI).**

Keywords: landslides hazard, Permanent Scatterers, SAR interferometry

I. INTRODUCTION

Landslides represent one of the natural hazard with major social and economic impact in the world, even if often damages caused by mass movements are addressed to other natural phenomena, such a s floods or earthquakes, which are their main triggering factors [1]. Italy, characterized by about 75% of the territory composed of mountainous and hilly terrains, and by climatic conditions and a geological setting favorable to the occurrence of slope instabilities, is strongly affected by landslides, which deeply influence the socio-economic conditions of the country, threatening urban areas, anthropogenic activities and environmental heritage [2].

The need of live together with landslides in a sustainable way requires a strong effort in terms of landslide risk analysis. Traditional methods used for mapping and monitoring mass movements can benefit from the application of remote sensing techniques coupled with GIS analysis. In fact, the use of new remote sensing technologies (such as SAR interferometry and very high resolution optical images) allows a rapid acquisition of quantitative data over wide areas, reducing the field work and, as a consequence, the costs.

This approach has been adopted within the framework of the SLAM project (Service for Landslides Monitoring). The project, which is actually still in progress, aims to develop and qualify an end-to-end service chain for the provision of slope instability products, derived mainly from Earth Observation satellite imagery, that can facilitate the operational activities of Italian and Swiss institutions in charge of the hydro-geological risk management. For the Italian territory two test sites have been selected, one in the Northern Apennines, the Arno River Basin and one in the South of Italy, a mountainous area within the Campania Region. This note focus on the results obtained up to now on the first site.

II. STUDIED AREA

The drainage basin of the Arno River is almost entirely situated within Tuscany. The river is 241 km long, while the catchment has an area of about 8830 km^2 and a mean elevation of 353 m a.s.l. (Fig.1). The catchment area is located within the mountain belt of the Northern Apennines and from a geological point of view it can be considered a quite homogeneous area. In fact, this mountain chain is characterized by the presence of arenaceous and calcareous turbidite sequences and chaotic argillaceous terrains of sedimentary and tectonic origin. The test basin has been chosen for the presence of a high number of mass movements (up today more than 30,000 individual landslides and about 300 areas at high landslide risk have been mapped from the institutional authorities) and for the high number of elements exposed to landslide risk. About 16.000 civil buildings, 460 industrial areas and 350 km of roads are

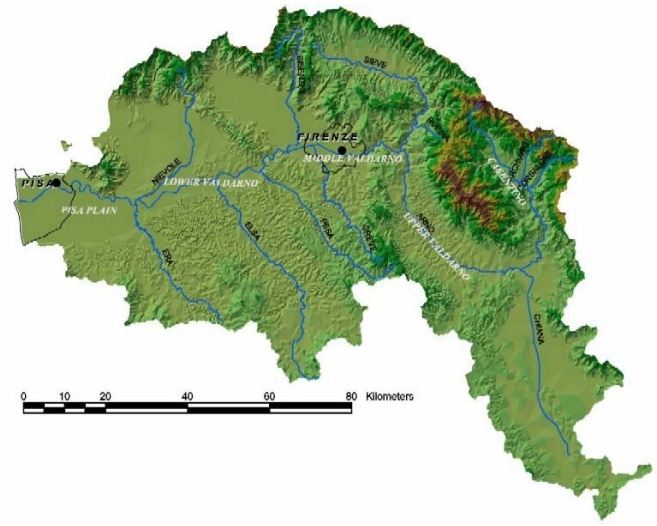

Figure 1. Shaded relief of the Arno River drainage basin.

directly involved in gravitational movements. In addition, the Arno Basin has been selected for its significance with respect to the Italian Apennine territory, in terms of landslides type and environmental conditions. The type and frequency of mass movements are primarily controlled by lithological and structural factors, secondarily by the high relief and the rather severe meteorological conditions. With reference to the scheme proposed by Cruden and Varnes [3], recorded velocities range between extremely slow to moderate. As mapped by the Arno Basin Authority, which is the institutional entity remitted by the Italian law to landslide and flood risk management within the Arno River territory, 74% of mass movements within the basin are represented by rotational and planar slides, 20% by shallow landslides and creep, while 5% by flows. Most of the them are reactivations by pre-existing ones, which have occurred in periods of climatic conditions different from those of the present. These dormant landslides, characterized by residual values of strength parameters, can be re-activated by natural causes, such as rainfall or snowmelt, as well as anthropogenic factors.

III. RESULTS

By considering the technical requirements imposed by the Italian legislation for the documents related to landslide risk management, three products obtained through the integration of EO-data within traditional methodologies have been defined. In particular the work has been carried out at two different levels. In order to provide to the selected end user, the Arno Basin Authority, a tool for landslides risk management at regional scale, landslide inventory mapping and landslide hazard zonation services have been produced. Whilst by working on a local scale the monitoring of several restricted areas affected by slope instability problems has been performed.

A. Landslides inventory mapping

Landslides inventories consist of surface mapping of existing slides which include at least an evaluation of their location and size and an assessment of their recent activity. These documents, representing the description of state of nature, are the first step for every landslides hazard analysis [4]. Methods of landslide mapping over the past years have changed little. Landslides are routinely detected by means of multi-temporal analyses of aerial-photos, both in stereoscopic and monoscopic configurations supported by field surveys [5,6].

An inventory of active and dormant landslides, at a reference mapping scale of 1:10.000, has been carried out during the 2003 by the Arno Basin Authority, for the whole Arno River area, through traditional geomorphological tools. The aim of the SLAM activity was to integrate such an inventory with the information coming from the Permanent Scatterers interferometric analysis [7]. This technique allows to identify individual radar benchmarks (called Permanent Scatterers) where very precise displacement measurements along the satellite line of sight can be carried out. The PS technique, although overcomes many drawbacks of conventional interferometric approach, such as de-correlation problems, provides point-like information, which are quite dense only in urban areas. In order to give a spatial meaning to the PS information it is necessary to combine it with the analysis of satellite optical images or aerial-photos.

About 350 SAR images, acquired by ERS1/2 from 1992 up to 2002 on the Arno River basin, have been interferometrically processed by means of the so-called Standard PS Analysis. Such an analysis has permitted to detect more than 650.000 PS, estimating their average velocity by an automatic and cost-effective procedure useful to process large amounts of data relative to large areas, in a limited period of time. Linear motion model is searched and information about linear velocity are extracted. The resulting PS have been imported in a GIS environment and compared with the previous inventory map. Discrepancies between the two dataset has been intensively analyzed by means of the visual interpretation of SPOT 5 images rendered on a DTM and aerial-photos at different spatial scales (varying from 1:30.000 to 1:10.000). This step has been devoted to identify diagnostic morphologies and terrain features, such as scarps, disrupted vegetation covers and deviations in the drainage systems, possible indicators of landslides occurrence.

The work, up to now completed and validated for about 2.000 km^2, has provided information about the spatial distribution and the state of activity of already mapped landslides, allowing also to detect new unstable areas (Fig.2).

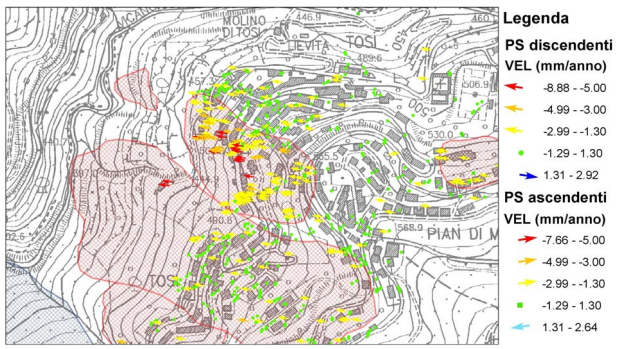

Figure 2. Map overlay of the PS classified with reference to the velocity and the updated landslides inventory map.

On an area of 1750 km^2, characterized by about the 60% of forested terrains, 35% of agricultural areas and 5% of urban fabric, the found PS density was 154 PS/km^2. On a total number of landslides mapped by the Arno Basin Authority on the zone of 3550, 352 landslides, which correspond to the 10.1%, are characterized by the presence of at least one PS. In addition, other 154 new unstable areas, corresponding to the 6,5% of the total number of landslides, have been mapped. These preliminary results seem to confirm the potentiality of the methodology as a support for landslides mapping.

B. Landslide displacements monitoring

The analysis of the superficial deformation field of a landslide which causes high risk scenarios, due to the presence of element at risk of high value, often represents the only one solution for the prediction of the phenomenon future evolution. The information coming from SAR interferometry can be employed as a monitoring tool for slow landslides (up to few centimeters per year) complementary to other in-situ instruments which can provide data about the underground movements.

In the framework of the SLAM project, several landslides located within the Arno River Basin have been selected as test sites in order to be monitored by means of an integrated approach which combines traditional in-situ measurements with Permanent Scatterers. The final product of such an analysis consists of a monographic report for each of the monitored site, which includes a geological modeling of the phenomenon obtained by the integration of monitoring data (in-situ and EO-derived) with the geological-geomorphologic characteristics of the site. The interferometric processing employed for this type of product is the so-called Advance PS Analysis. This procedure, suitable for those small areas where a full exploitation of the information content of the SAR data is required, allows to investigate also non-linear movements and to obtain the time series of displacement for each detected PS. The provided data are useful for evaluating the past temporal evolution of deformations, highlighting trends of acceleration or deceleration. The activity foresee a preliminary collection and review of bibliographic information after which the map overlaying of the PS data on an existing geomorphologic map is performed. This permits to distinguish precisely areas stable from areas in movements and to map zones affected by different deformation rates. The comparison and the integration between in-situ and PS time series allow to better understand the geological model of the movement, such as the kinematics and the possible evolution.

Up today the analyzed landslides are Carbonile, an ancient earth-slide re-activated in the 1985, located along the Arno River, close to the city of Firenze (Fig.3), Casalino, an urban areas in the Poggibonsi municipality affected by instability problems due to the work for the highway construction, and the northern part of the Chianciano Terme town, which is interested by a large earth-slide. The results obtained, as shown in Fig.4,5, are very satisfactory both for the density of radar benchmarks and for the quality of the information. In fact, they have been employed by the geologists of the Arno River Basin Authority in order to check the effectiveness of the mitigation works performed in the last years and,as a consequence, to modify the boundaries of the areas at risk in the official document requested by the Italian law, the P.A.I. (Hydro-geologic Management Plan).

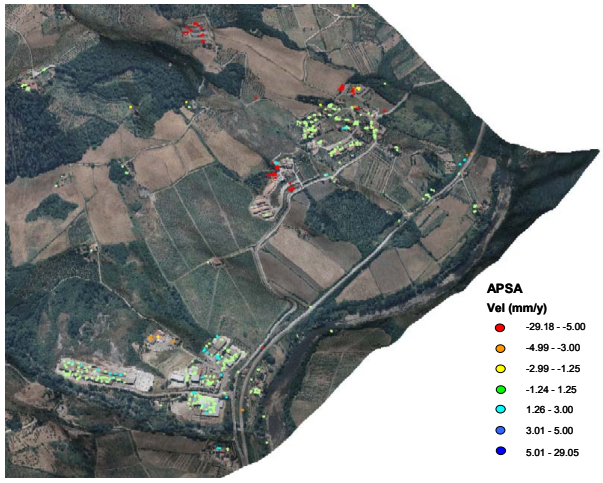

Figure 3. PS of the Carbonile landslide overlaid on an aerial-photo rendered on a 10m cell-size DTM.

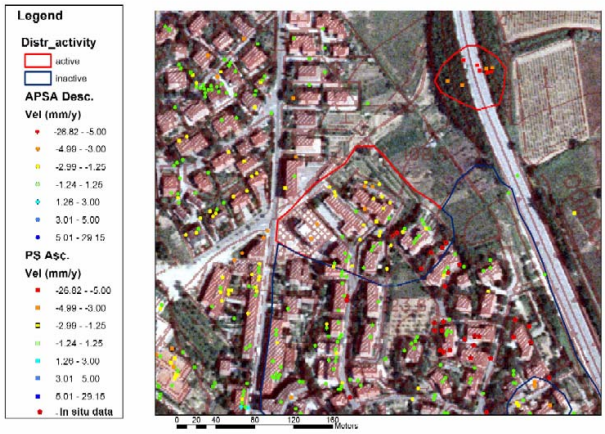

Figure 4. PS and in-situ instruments locations in the Casalino village.

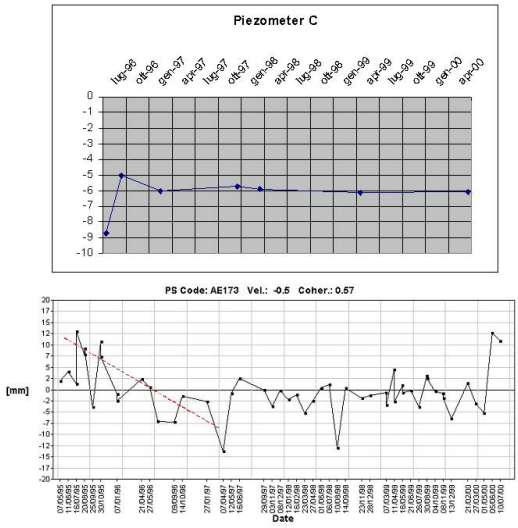

Figure 5. Piezometric and PS readings in the Casalino area.

C. *Landslide Hazard mapping*

Hazard, one of the fundamental components which contribute to the definition of landslide risk, represents the probability that a mass movement may occur in a defined area in a given period of time [8].

The spatial prediction of landslide hazard normally is computed based on the assumption that future landslides are most likely to occur in conditions similar to those that have caused past failures. For this reason by correlating the frequency distribution of the so-called "instability factors", such as lithology, slope, land use, etc., with the spatial distribution of past landslides, the prediction of landslides occurrence also in areas not currently affected by mass movements is possible. Clearly, in order to obtain acceptable results the presence of a high quality landslides inventory is mandatory. Within the SLAM project, the inventory map integrated with the interferometric information will be used for the statistical analysis of the instability factors, in order to assess the hazard spatial distribution on the whole basin.

On the other hand, the temporal prediction of landslides occurrence, due to the difficulties in its assessment, is normally evaluated by using the landslides state of activity, which is assumed as a sort of proxy variable of the landslide frequency. Such a characteristic traditionally is obtained by means of conventional geomorphologic tools, based on recognition of the "sharpness" of signs of landslide activation. For the Arno River basin, in order to simplify the state of activity interpretation in a so wide and complex area, landslides were characterized on the inventory map provided by the users on the basis of only three increasing levels of activity, modifying the original classification proposed by Cruden & Varnes (1996):

- active – landslides that show signs of a recent activation (e.g. less than 2 years old)
- dormant – not moving landslides typically showing signs of movement occurred more than 2-10 years ago.
- inactive - not moving landslides that prob-bly activated in periods characterized by different climate conditions respect to the pre-sent ones.

The contribution of the interferometric information is this step of the hazard assessment is strong. In fact, in order to discriminate between the three levels of activity two different temporal dataset of SAR images have been processed. In particular, the average velocity along the satellite line of sight of the PS has been computed for the period 1992-2002 and also for the period 1999-2002. The two dataset allowed to distinguish between active, dormant and inactive landslides.

By combining the zonation obtained for the spatial prediction of landslides occurrence and the one obtained for the temporal prediction a landslide hazard map, classified in 4 hazard levels, will be produced as the last step of the SLAM activity.

IV. CONCLUSIONS

This note has focused on the description of the activity related to the SLAM project. The work aims to assess on wide areas and under different climatic and geologic conditions the capabilities of SAR interferometry to become an operational tool for the different steps of the landslide risk procedures. The results obtained up to now on the Arno River basin seem to be promising both for the analysis at regional scale, such as the landslide inventory map for the whole basin and for the work at local scale, such as the monitoring of single phenomenon which causes high risk scenarios. In addition, the possibility to access to a long period database (SAR images have been acquired continuously by the ERS satellites since 1992) allows to retrieve the "temporal factor" for landslide hazard assessment. The expected results at the end of the SLAM project (January 2005) rely the possible integration of the products and methodologies coming from the project activity within the current practices used every day by the geologists of the Arno Basin Authority for their work.

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