DOI: 10.4408/IJEGE.2013-06.B-30

USING SATELLITE RADAR IMAGES TO INVESTIGATE THE INFLUENCE OF TECTONIC SETTING ON LARGE SLOPE INSTABILITIES

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ABSTRACT

The paper focuses on identification of tectonic setting on large slope instabilities in the area of Giudicarie Valley, located in the south-western sector of the Trentino-Alto Adige region (northern Italy), with particular reference to those phenomena inducing a high level of risk. The study area, located in the Southern Alps, shows a complex structural setting, mainly influenced by the south Giudicarie Line and its associated steep to subvertical faults WNW-dipping. Tectonic setting strongly influences the evolution of slopes, it may be considered one of the main cause of the onset of current instability phenomena. Geological, geomorphological, structural and geomechanical field investigations were conducted on Prezzo landslide area (Giudicarie Valley) in order to investigate the relationship between the tectonic setting and the instability. Advanced DInSAR techniques, such as Permanent Scatterers (PS) and Small Baseline Subset (SBAS) algorithms, were applied to ERS 1-2 (1992-2010) and ENVISAT (2003-2010) satellite RADAR images, to detected displacement areas related to geological structural elements which could influence the Prezzo landslide development. Results show that PS and SBAS data interpretation is an helpful tools in investigating the influence of tectonic settings on landslide processes.

Key words: *DInSAR, tectonic setting, landslides*

INTRODUCTION

Nowadays, many paper were published regarding the relevance of InSAR methods in landslides characterisation (Hilley *et alii*, 2004; Colesanti & Wasowski, 2006; Wasowski *et alii*, 2008; Cascini *et alii*, 2012). Differential Interferometric SAR techniques (DInSAR), are a good approach to detect and characterise instability phenomena, because the use of a multi acquisition stack of images lets to reduce the limitations typical of SAR Interferometry (i.e. atmospheric distortions or temporal de-correlation). Using these multi temporal techniques allows not only the estimation of discrete deformation events, but also the evolution of displacements.

At regional scale DInSAR techniques allow detecting new landslides and improving the delimitation of landslide-prone areas. At local scale, DInSAR methods are an useful tool to rapidly recognise portions of unstable area with different displacement rates or to create a twenty years long displacement velocity dataset, where a complete field monitor is lacking.

The main aim of this paper is to verify if PS and SBAS data are able to detect unstable areas and to record displacement rates and directions, in order to define the influence of tectonic setting on landslide evolution.

PREZZO LANDSLIDE

The study area is located in the Giudicarie Valley (south-west sector of the Trentino-Alto Adige Region, NE Italy) were many instability phenomena are present. The paper is focus on Prezzo landslides, which

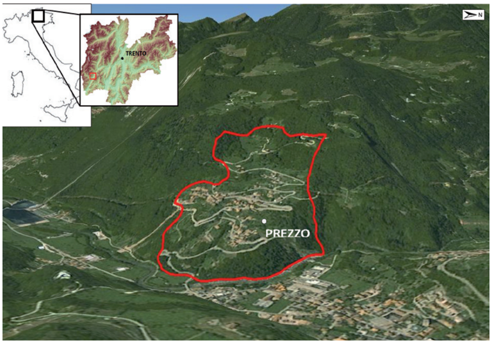

Fig. 1 - Location of study area

involves the medium-basal part of eastern flank of Mt. Melino. It is located between an altitude of 510 and 980 m and presents one main scarp on the top, with related morphologic structures (such as cracks and trenches) and two minor scarps on right and left boundary (Fig. 1). The phenomenon is an old landslide, reactivated, that involves silty deposits, with blocks of marly-calcareous and dolomitic rocks. The unstable area is 380 m wide and 1150 m long with average slope of 20°. The sliding surface depth is between 40 and 110 m, with a maximum thickness in the middle sector of the landslide. The total volume is 20 million m^3.

The houses of Prezzo Village and the county road show deformations and splits whereas water supply network presents losses and damages. The phenomenon is monitored by Trento Province Geologic Service through GPS, topographic stations, piezometers and inclinometers. Additional field investigations were carry out in order to better define the geologic and geomorphologic settings of the unstable area. DEM derived and LIDAR data were also used.

GEOLOGICAL AND STRUCTURAL SETTINGS

The geology of the Prezzo area is characterized by Triassic marine and coastal deposits (Fig. 2). The Angolo Limestone Formation is composed of flat-lying dark-grey fine limestone, marly limestone and siltstone. This Formation outcrop in the north flank of landslide. The Prezzo Limestone, is composed of black marly limestone with

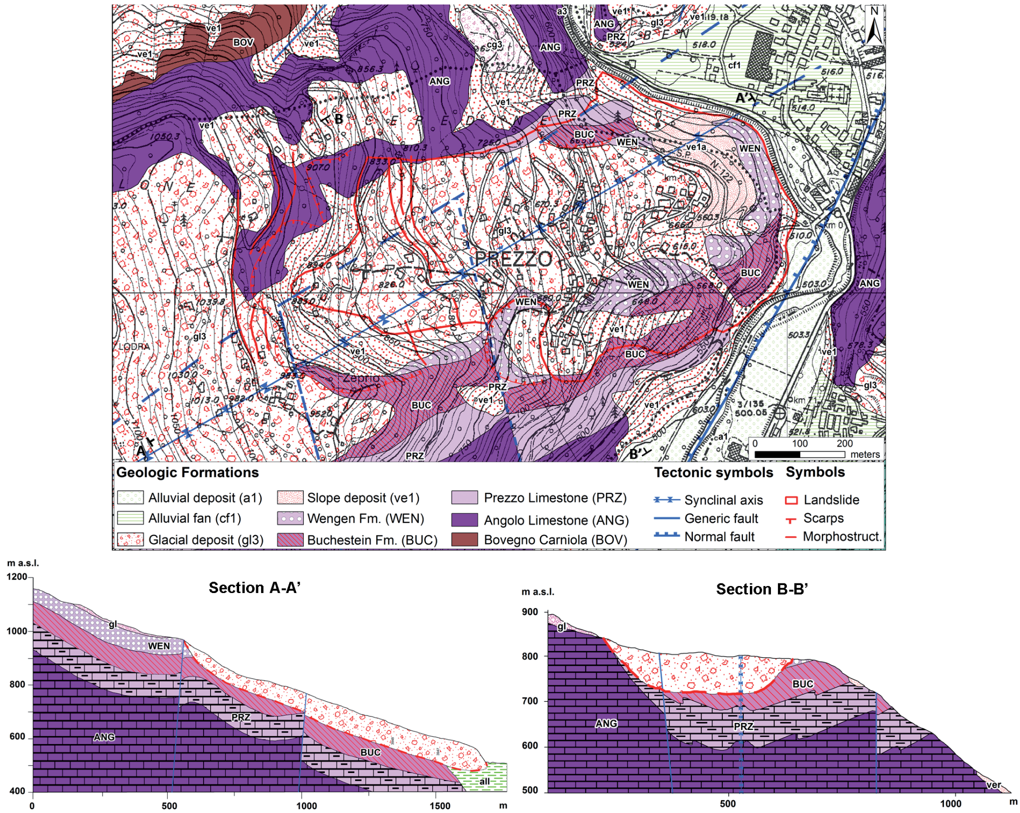

Fig. 2 - Geological map and sections of Prezzo area (modified from Bargossi et alii, 2012)

centimetric clayey marls intercalations. Buchenstein Formation and Wengen Formation are present in the lower part of landslide and dipping towards N-NE; the first one is composed of dolostone, limestone, marlstone interbedded with volcanoclastic deposits and chert nodules, the second one is a silicoclastic-carbonatic unit made of sandstone and marlstone interbedded with tuff layers.

The presence for long periods of Pleistocene broad glacial areas strongly influenced the characteristics of the Quaternary sediments. The slopes of Giudicarie Valley are mostly covered by glacial deposits and more rarely by moraine. The valley bottom is covered with large alluvial fans that rest on the flat alluvial plains.

The tectonic regional setting is characterized by the presence of the Giudicarie Fault which represents the tectonic boundary between the Southern Alps and the Austroalpine domain. Due to its location, oblique to the Southern Alps chain, the Giudicarie belt shows a very complex structural setting, mainly characterized by steep to subvertical WNW-dipping transpressive faults and moderate dipping N to NNE-trending reverse faults (Doglioni & Bosellini, 1987; Picotti *et alii*, 1995). This complex structural setting influences the evolution of slopes, causing the onset of large scale slope instability phenomena, sometimes evolving into catastrophic landslides (Perna, 1974; Bassetti, 1997).

The study area is tectonically bounded to the South by the South Giudicarie Line, whereas a NE-SW trending fault, probably associated to the South Giudicarie Line, limits the area to the North. The Triassic succession of the Prezzo area is folded forming a synclinal-type fold. The northern sector shows a moderate (30°-45°) SE dipping stratification, while in the southern one the beds dip towards N-NE with medium angle (35°-55°). The fold axis, which is located in the central part of the slope, gently dips towards E-NE (Fig. 3).

Geomechanical surveys were carried out to investigate the mechanical behaviour of the rock masses inside and outside the area affected by the slope instability . Besides the stratification, other three sets of mechanical discontinuities cut the rock masses. Sets K1 and K2 steeply (70°÷75°) dip respectively towards SW and W, while K3 is linked to the southern stratification, but showing a higher angle (65°÷70°) (Figg. 4a and 4b). The increase of fracturing is related to an expectable lowering of the rock masses quality of all the formations from the areas outside to those inside the landslide body. Geomechanical surveys have also provided two

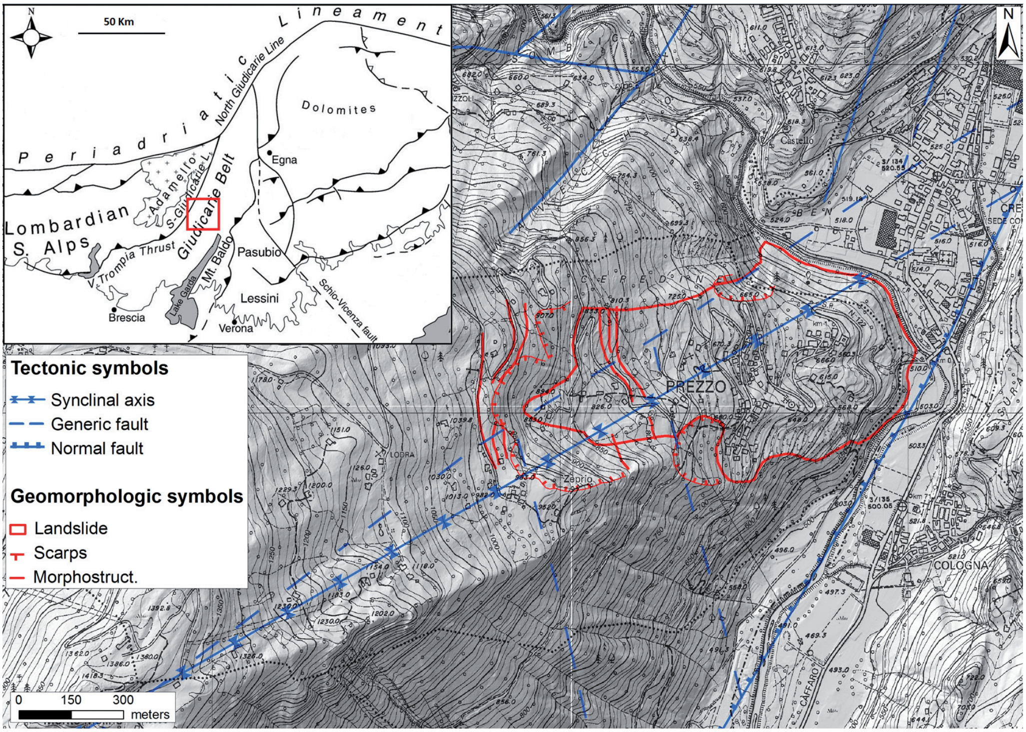

Fig. 3 - Tectonic and geomorphologic settings of Prezzo unstable area

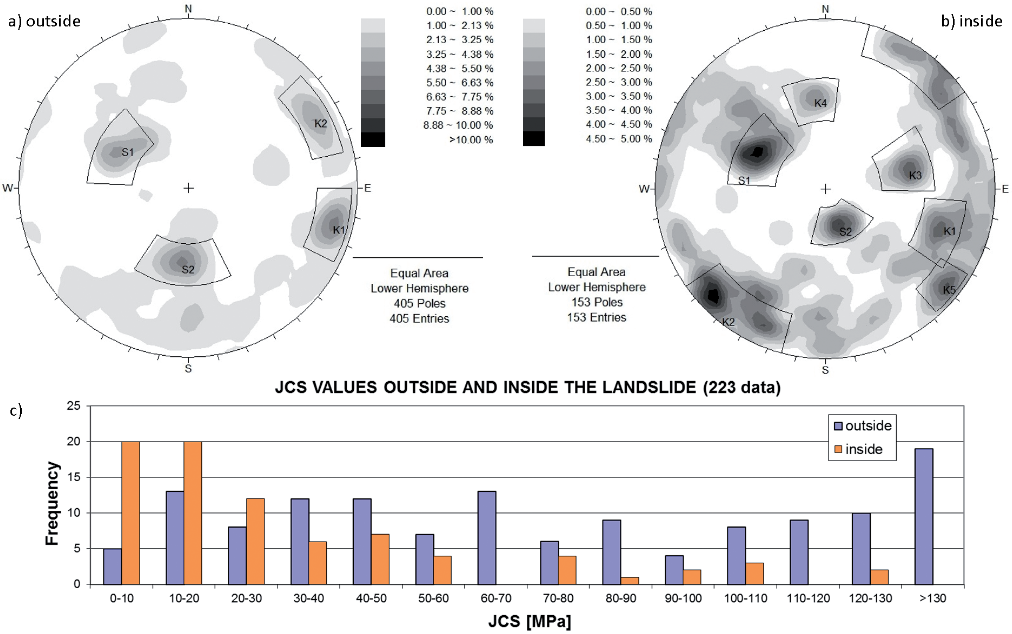

Fig. 4 - Stereoplots of geomechanical discontinuities outside (a) and inside (b) the landslide body (S(x) stratification K(x) secondary discontinuities). JCS data outside and inside landslide body (c)

important parameters to classify the mechanical behaviour of rock masses in terms of both Joint Compressive Strength (JCS) and Geological Strength Index (GSI) (Deere & Miller, 1966; Marinos & Hoek, 2000). The values of JCS, (Fig. 4c) show how the rock mass strength decreases starting from the stable areas of the slope, to the inside of the landslide body. GSI values highlight the weakness behaviour or rock masses inside the landslide body and in the areas approaching the fold axis (Fig. 5). The presence of a rock masses highly fractured is also confirmed by the boreholes executed by Geological Service (data not reported in this paper).

The Angolo Limestone shows, inside the landslide body , average values of JCS around 25÷35 MPa and GSI value of 35, whereas, far from it, the JCS increases up to 70÷130 MPa and the GSI is around 45-50, both in the northern and southern limb. More northerly, this trend is not observed and both JCS and GSI decrease, probably due to the proximity to the NE-SW trending fault. This trend could not be assessed for the other formations due to the lack of outcrops.

FIELD DATA

Several field instruments were installed on Prezzo landslide area and 13 boreholes were executed by local Geological Service, to improve the knowledge

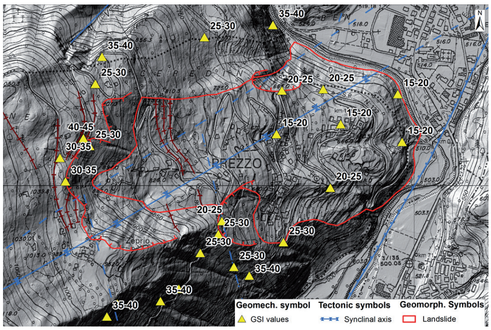

Fig. 5 - GSI Values outside and inside the landslide body

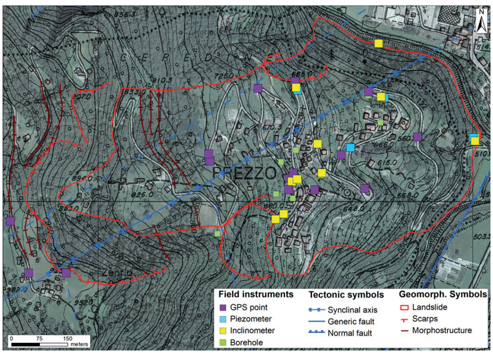

Fig. 6 - Location of field instruments install by Trento Geological Service

of geology of the unstable slope and monitoring the unstability (Fig. 6). There are 14 GPS point (some of them since 1995 and other since 2005), 10 inclinometers since 2002 and 4 piezometers since 2004. GPS network reveals a deformation velocity of 3 to 6 cm/y. The inclinometers show a sliding surface depth between a minimum of 27 m at the base of slope and a maximum of 110 m in the middle part of landslide.

Rainfall data from 2004 is available on the website of Trento Province weather forecast. But this dataset isn't complete because of some missing or not validate data in 2005, 2006, 2008 and 2009. However we compared the displacement velocity data from DInSAR processing with the rainfall data to find correlation between rainfalls regime and displacement of landslide.

DIFFERENTIAL INSAR METODOLOGY

Interferometric phase (phase difference between two SAR images) is the sum of many contributions: the topographic one is associated to the relationship between phase and topography, the displacement one is due to the land movements (subsidence, landslides, earthquake), the atmospheric one is due to the variation of atmosphere characteristics, and the noise one due to instrumental properties. Comparing two SAR images is possible exploit the phase contribution due to land movements, knowing the other phase components and subtracting them from the total phase difference.

The advanced DInSAR techniques include Small Baseline Subset (SBAS) (Berardino *et alii*, 2002) and Persistent Scatterers (PSInSAR) (Ferretti *et alii*, 2001) algorithms. These approaches involve the use of multiple acquisitions stacks (large SAR temporal series). The concept of combining InSAR information from a large number of SAR images (thanks to repeated satellite passes on the same area), allowing the solution of a deformation time series, has been introduced by Ferretti *et alii* (2000), Berardino *et alii* (2002), Lanari *et alii* (2004) and Lauknes (2004). Using a multi temporal technique allows to estimate both, discrete deformation events and evolution of displacements. SBAS method exploits the spatially distributed coherence, instead of estimating the coherence exclusively on local scatterers. In fact, PS methods is focus on the analysis of point targets, instead SBAS one is intended to the analysis of distributed targets.

The main limits of InSAR techniques are temporal decorrelation and geometrical distortions. Temporal decorrelation is due to changes of electro-magnetic response of objects with time, cause by atmospheric phenomena or anthropic changes or vegetation growth. Satellite look angle (θ) of 23.3° (for ERS and ENVISAT images) and right side-looking acquisitions mode are the responsible for geometric distortions effects. Layover effect is present where slopes inclination exceed the look angle, producing a strong image distortions, which prevent the correct signal interpretation. Shadow effect is present in areas that are not illuminated by the radar signal. These effects in relationship with aspect and inclination of slopes need to be taken in account before starting an investigation of mountainous area, because slope instability processes could be on area affected by layover or shadow effects.

Another important limit of DInSAR approach in the study of landslide is the measurements of displacements along the Line of Sight (LOS). Therefore, if the direction of displacements is not along LOS, the satellite will measure only a part of real velocity.

INTERFEROMETRIC ANALYSIS

To analyze the influence of structural setting on the evolution of slopes, the Earth Observation data (provided by European Space Agency, ESA) were used. Advanced DInSAR techniques, Permanent Scatterers (PS) and Small Baseline Subset (SBAS) algorithms, were applied to ERS 1-2 (1992-2010) and ENVISAT (2003-2010) satellite RADAR images to detected displaced areas.

The Prezzo area is affected by geometrical distortion (layover effect) in descending acquisition mode. Moreover, the ERS ascending dataset has many corrupted and unprocessable images. So the obtained displacement velocity dataset is provided by 43 ENVISAT images acquired in ascending mode, spanned from November 2004 to September 2010, with revisiting time of 35 days.

The PS density is high over the Prezzo village, where the houses represent a good Persistent Scatterers (122 PS were found on an area of 0.35 km^2), but outside the village, where trees and grass land prevailed, the PS density is very low (coherence threshold = 0.6). Also the Distributed Scatterers of the SBAS analysis are located on the Prezzo village. Both, PS and SBAS data distributions, show a clear identification of the unstable area on Prezzo village (Fig. 7).

In Figure 7, orange points show the maximum rate of movement detected by the two techniques (more than 10 mm/year with a maximum of 20 mm/year for the PS data) , whereas the green ones identify a stable area,

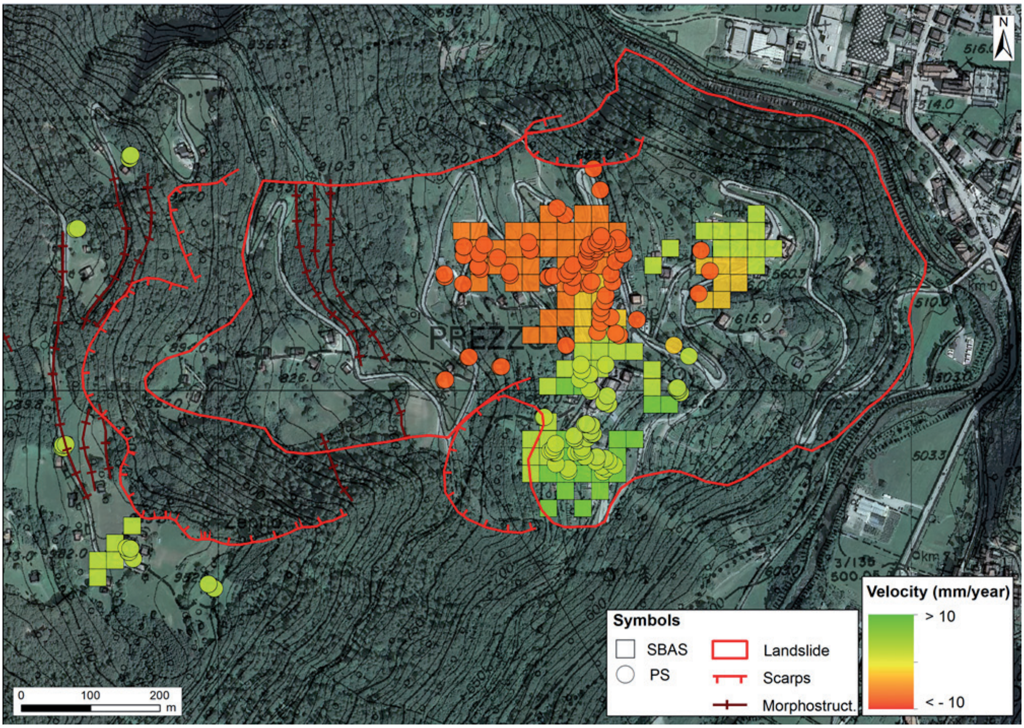

Fig. 7 - PS and SBAS data on Prezzo landslide area

with displacements rate close to zero mm/year (Line of Sight displacements). SBAS processing shows displacement velocity values similar to the PS one, although the SBAS values are lower than the PS ones. Furthermore, the direction of displacements is towards the direction of the fold axis and of maximum slope (E-NE), and its substantially parallel to LOS of ascending satellite track, so the real displacement velocity is substantially recorded.

Figure 8 shows the LOS displacements for two PS: PS 290 is located in the middle of unstable zone and shows a high annual velocity rate, while the PS 248 has a low annual velocity rate and it is located in the stable area on the southern part of landslide. Also the monthly rainfalls, from 2004 to 2010 are reported in figure 8 to describe the correlation between main rainy periods and main displacements of the landslide. In fact, a more in depth study of the rainfalls dataset evidences that the main displacement periods (indicate with pink arrows) follow the peaks in the rainfall trend (blue continuous line in Fig. 8).

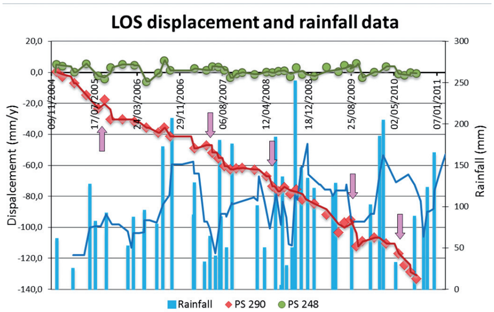

Fig. 8 - LOS displacement value for a red point (PS 290) and for a green one (PS 248)(see Fig.7). Rainfall data are plotted to investigate relationship between rainfalls regime and main displacement rates

DISCUSSION AND CONCLUSIONS

The Prezzo landslide is an example of how a complex structural setting influences the gravitational evolution of slopes (Fig. 2 and Fig. 3). The structural analysis shows the role played by the syncline fold as the main predisposing factor of the slope instability, thanks to its E-NE trending fold axis oriented favourably for wedge failure. In fact, the lower values of the JCS and GSI index inside the landslide body and near the syncline axis point out the great fracturing and weakness of the rock masses (Fig. 4 and Fig. 5).The advanced DInSAR approach allowed to improve the identification of the unstable area at Prezzo vil-

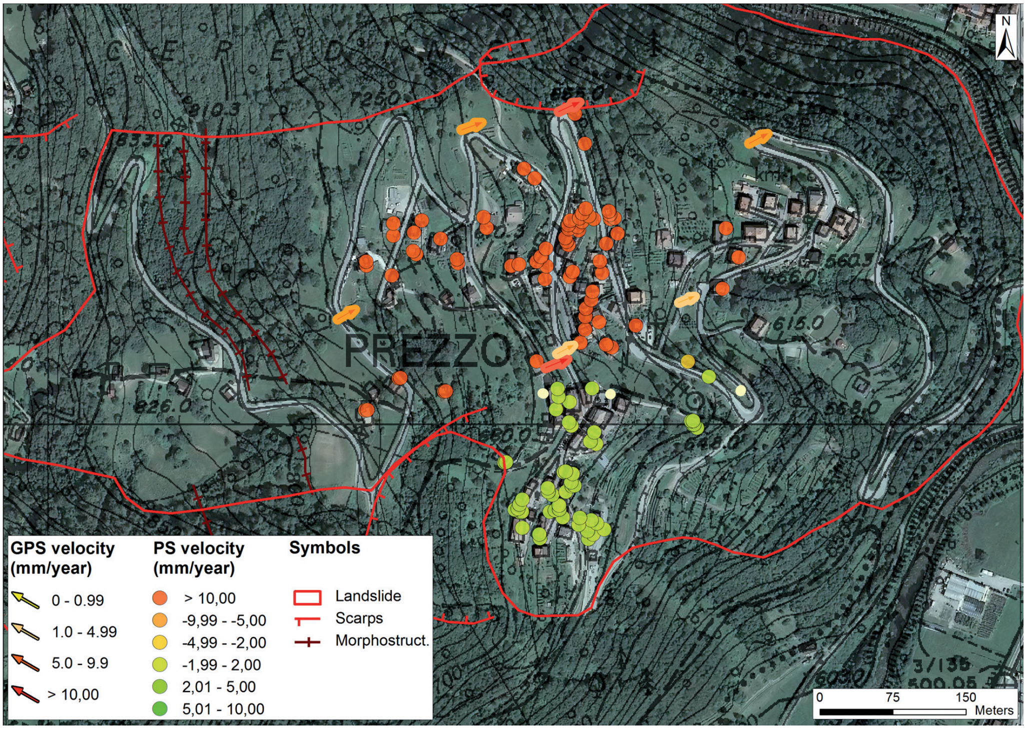

Fig. 9 - Correlation between GPS and PS data. The direction of the arrows corresponds to the landslide flow direction; the length is intensity of the displacement. The light yellow points represent the GPS which velocity is zero

lage with respect to the GPS measurement. The latter are distributed only along the northern and southern side of the landslide body allowing a first identification of the landslide area. The PS and SBAS data are distributed on the overall Prezzo village, permitting a better definition of the distribution of activity. As a consequences the integrations of PS, SBAS, GPS and geologic/geomorphologic data well define the sharp separation between the active and the stable zones, improving the identification of different displacement areas of the two landslide sectors (Fig. 7 and Fig. 9).

Furthermore, the displacement velocity dataset from 2004 to 2010 obtained with the PS and SBAS processing ENVISAT images, allowed to determine the annual displacements rate and to compare it with the GPS data (Fig. 9). In fact GPS maximum annual rate of movement (2004-2010 time interval) is 3 cm/y, for PS is 2,1 cm/y and for SBAS is 1 cm/y.

So, the conclusions regarding the data suggest that the field and interferometric analyses indicate an active central area, along the fold axis, whereas the southern sector of the landslide body is quite stable, suggesting again an influence of the structural setting on the slope instability. It is important to notice that comparison between field displacement and PS or SBAS data is not easy due to the different acquisition geometry (LOS vs. flow direction) and the different temporal coverage. But, thanks to E-NE directions of landslide displacements, essentially parallel to ascending LOS, the Prezzo landslide is a good test area to study the applicability of interferometric data on landslide study. It follows that PS, SBAS and GPS numeric data slightly differs from each other, but we notice that each methods clearly identify the active and stable zones. Moreover because the flow direction is determined by the syncline axis direction, we can use only the ascending LOS velocity data. Otherwise, both, ascending and descending images should be needed to exploit displacement vectors.

Regarding DInSAR techniques, PS and SBAS data interpretation jointly with geologic, geomorphologic and structural analyses, and with field investigations (e.g. GPS displacement data), are helpful tools in landslide identification and characterization. The twenty years of interferometric data allow the definition of a long displacements dataset permitting to retrace the history of land movements, also when a monitor system is lacking or incomplete.

Finally, we also compare main rainy periods with main displacements periods pointing out, in a qualitative way, that rainfall could be considered as the triggering factors of movements; whereas the high weakness of rock masses (low GSI and JCS near the fold axis), due to the complex tectonic setting, is the most likely the predisposing factor.

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