

Ground-Based Radar Interferometry (GBInSAR) for the monitoring of a deep-seated landslide (Aosta Valley, NW Italian Alps)

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Abstract

Ground-Based Interferometry (GBInSAR) has been used for monitoring a deep-seated landslide (Beauregard Landslide) in the Aosta Valley (NW Italian Alps), on the left slope of a reservoir with an original impounding capacity of 70 Mm³. The poor rock mass conditions of this slope were first reported in the fifties, during dam construction. Since 2002, additional geological, hydrogeological and geotechnical investigations have underlined the presence of a deep-seated (240-250 m) shear zone up to 20 m thick. Conventional monitoring of both the slope and the dam for more than 50 years has allowed to gain insights into the understanding of the behaviour of the basal portion of the landslide with limited and uncertain point-wise displacements in the upper slope sector. The available monitoring data indicate that the landslide toe is characterised at present by very low displacements (4-6 mm/year), from spring to early autumn, caused by the increase of the piezometric level in the slope (up to 15-20 m). During 2008 and 2009, two GBInSAR monitoring campaigns have allowed to obtain multi-temporal surface deformations of the upper portion of the landslide, unveiling the presence of a main sector in motion, previously unknown, characterized by a maximum downward displacement of 45 mm over 4 months. The results of the GBInSAR monitoring have been compared with topographic measurements carried out by a total station on 5 targets located along the slope. The up-to-date displacement data detected by GBInSAR have been used as a new tool for the global interpretation of the landslide mechanism.

Introduction

Since the beginning of the fifties, the investigations carried out during the Beauregard dam construction (Aosta Valley - NW Italian Alps), have shown the poor quality of the rock mass (micaschists and gneiss) along the left side of the Valgrisenche valley. A few years later and after further investigations a deep-seated landslide (in cases called deep seated gravitational slope deformation, DSGSD) has been recognised on the left slope of the valley. Movements were monitored since the first infilling of the reservoir and a maximum reservoir level of 1710 m a.s.l. was enforced by the Italian Dam Authorities in 1969, with a reservoir volume of 6.8 Mm³ (Barla et al. 2006).

Deep seated landslides have been widely described by many authors (e.g. Hutchinson, 1988; Agliardi et al., 2001; Ambrosi & Crosta, 2006). Although defined in different ways, in general terms these landslides occur on high relief slopes and with relatively small displacements (Agliardi et al., 2001). The surface displacements typically range from a few millimetres to several centimetres per year and are often close to the detection limit of conventional monitoring equipments (Bovis, 1990). Within the deformed mass, the development of sudden and rapid secondary landslides (rotational and planar slides, falls, topples and flow-like movements) is a common feature.

Displacement monitoring of deep seated landslides has generally been performed by conventional geotechnical in-situ instrumentation (inclinometers, extensometers, etc.) and topographic or GPS surveys. The information thus provided is limited to a given number of points within the landslide area. In large landslides, characterized by complex movement patterns and by a lack of displacement data at depth, single-point data are not sufficient to evaluate their kinematics and behaviour. Even if the instrumental and topographic measurements are carried out on extensive networks, there are difficulties in achieving spatial continuous information on the landslide displacement pattern (Tarchi et al., 2003).

The Ground-Based Interferometric Synthetic Aperture Radar (GBInSAR) technique can overcome most of these limitations: radar sensors can operate over wide areas in almost any weather conditions, continuously over a long time, providing near real time widespread information with millimetre accuracy, without the need of accessing the area.

In this paper, following a general updated overview of the geological, geomorphologic and tectonic settings of the site, both the conventional monitoring system installed on the

landslide and the GBInSAR system will be described, pointing out the results obtained so far. A distinctive feature of the work carried out is that the GBInSAR results have been compared with topographic measurements provided by an automated total station. Finally the implication of the up-to-date displacement data on the landslide mechanism will be discussed and a new geological-geomechanical model of the slope will be proposed.

Geological and geomorphologic settings

The investigated area lies in the NW Italian Alps, close to the Italian-French border, where tectonic units derived from the Briançonnais paleogeographic domain are present (Figure 1).

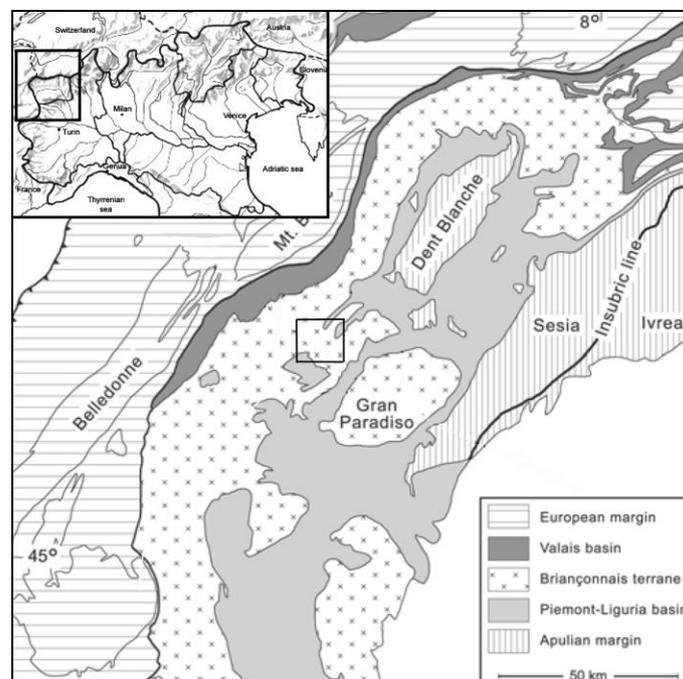


Figure 1 Paleogeographical domains of the NW Alps. The rectangle indicates the study area (Boucher et al., 2004)

Prior to the Tertiary collisional phase between the Apulian and the European plates, responsible for the formation of the Alps, the Briançonnais domain was part of a micro-continent (terrane) bounded by two oceanic zones, the Valaisan oceanic Domain and the more internal Piedmont-Ligurian oceanic Domain (Dal Piaz et al., 2003; Boucher et al., 2004; Schmid et al., 2004). The metamorphic rocks cropping out all along the Valgrisenche valley belong to the Pre-Permian (Guillot et al., 2002) crystalline basement of the Ruitor Unit, which consists of predominant garnet micaschists and albite bearing paragneisses with abundant intercalation of metabasites (prasinities and amphibolites). The rocks

belonging to the Piedmont-Ligurian oceanic nappe tectonically overlap the Ruitor Unit basement and consist of calcschists interlayered with marble lenses and metabasites. These rocks crop out in the Valgrisenche area along a tight syncline oriented NE-SW, called by some authors "Avisé Syncline" (Caby, 1996).

Figure 2 illustrates the geologic and morpho-structural map of the Valgrisenche left slope based on the studies carried out so far. Regarding the geomorphologic features, the deformation zone involves a significant portion of the slope and extends approximately 1500 m in height from the toe (1700 m a.s.l.) to the mountain ridge (3200 m a.s.l.). Steeply dipping into the slope are predominant sub-vertical (70° - 80°) discontinuities which strike parallel to the valley axis (NE-SW and NNE-SSW), associated to minor shear zones and discontinuities which are nearly orthogonal to them (ESE-WNW).

The main schistosity planes along the Beauregard slope dip on average 25° - 30° to S and SW. A main head scarp trending E-W with a maximum relief of about 250 m, associated with the double ridge of Becca De L'Aouille Mount is evident in the north sector of the landslide and it is interpreted as the day-lighted weathered portion of the main scarp delimiting the landslide surface of rupture.

By Scavarda Refuge the scarp turns to S forming a wide niche from which a rocky ridge (Scavarda ridge) has been lowered. The sector is highly weathered and fractured and it is affected by rock falls which result in discharge of rock in two main talus between 2100 and 2300 m a.s.l. In the upper part of the ridge, above the main landslide scarp, swarms of trenches up to 3 m wide trending parallel to the valley are present. These trenches are the continuation towards SW of an alignment of scarps, counterscarps and predominant joints cropping out between the Moriond Glacier and Becca de L'Aouille zone.

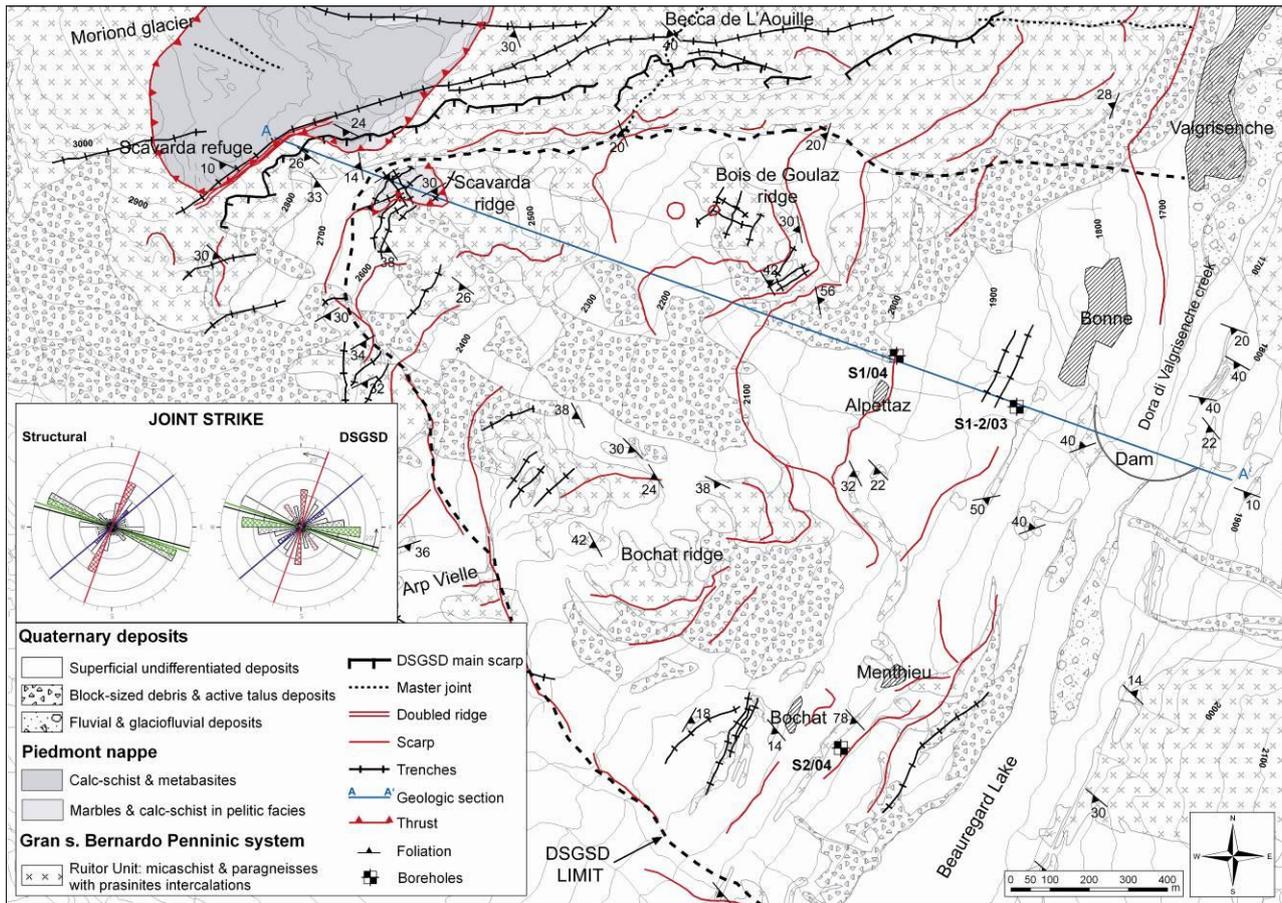


Figure 2 Geological and morpho-structural map of the Beaugard DSGSD. Rose diagrams show orientations of structural lineaments and the mean planes of the main discontinuity sets.

In the middle and lower portion of the landslide slope it is possible to recognize two distinct ridges to the N (Bois De Goulaz) and to the S (Bochat) characterized by bulging and convex profile. Swarms of trenches up to several meters wide and oriented NE-SW are developed behind both ridges.

In the Alpettaz area, between 2000 and 2200 m a.s.l., a major concave scarp is present which can be assumed to be the morphological expression of the basal sector of the landslide moving towards the reservoir. At lower elevations (1800-2000 m a.s.l.), close to the reservoir, numerous minor linear scarps and counterscarps trending parallel to the valley axis can be recognized.

Conventional monitoring system and recent in situ investigations

Since 1960, a monitoring system has been installed in order to record the displacement of the left slope and the dam movements. Topographic manual collimation and total station measurements on targets placed both on the dam and along the slope, including precision

leveling measurements of the dam crest, are continuously performed. Two plumb lines were installed in the central (P0) and in the 4S dam cantilever in order to monitor the uprightness of the structure. Moreover multipoint extensometers and extenso-inclinometers were used to monitor the displacements across visible cracks on the dam face (Italian CPD, 2009).

Since the end of the sixties, the most accurate slope movement monitoring consists of seasonal (spring and autumn) geodetic measurements of 22 topographic targets mostly located on the basal slope portion. Actually, 19 of these targets are continuously monitored by an automated total station. Measurements are performed daily, during the night. The values obtained for each target are used to calculate the x,y,z coordinates referred to a Cartesian coordinate system with origin in a fixed stable point.

In 1995, 16 GPS benchmarks were installed in the upper landslide portion. The target relative positions were determined with reference to a fixed point (FIX2) located on the right side of the valley using 4 dual receivers GPS at the same time. The more recent measurements were performed in 2000, 2004 and 2007, once or twice a year.

Displacement monitoring at depth inside the landslide mass has been performed by 5 plumb lines (PR1, PR2, PR3, PR4 and PR5). Each plumb line is a sequence of inverted and normal plumb lines which provide a relative displacement; the total displacement is obtained by summing up these relative values. The groundwater levels in the landslide mass are monitored by means of 14 standpipe piezometers, 10 of which are equipped with automatic sensors.

Detailed in situ investigations of the left slope carried out between 2003 and 2006 have allowed to identify a basal shear zone delimiting the more active portion of the landslide (Barla et al., 2006). As shown in Figure 3, essential for this interpretation were the results of both seismic refraction and seismic reflection surveys and the results of two boreholes (S1/03 and S1/04) drilled respectively from the left abutment tunnel at 1680 m a.s.l to a depth of 62.7 m and from the slope surface, near Alpettaz, down to a depth of 380.8 m.

Both boreholes encountered a thick shear zone (over 20 m thick in S1/04 and over 8 m in S1/03) characterized by the presence of highly fractured rock, locally reduced to a loose silty-clayey material. A third borehole (S2/04 - total depth 259.3 m) drilled near the Bochat area encountered a major shear zone at depth of 147 m, characterized by a lithology

similar to that encountered in S1/03 and S1/04 boreholes. The shear zone, 12 m thick, is interpreted as the continuation of the landslide basal shear surface towards the southwestern slope sector.

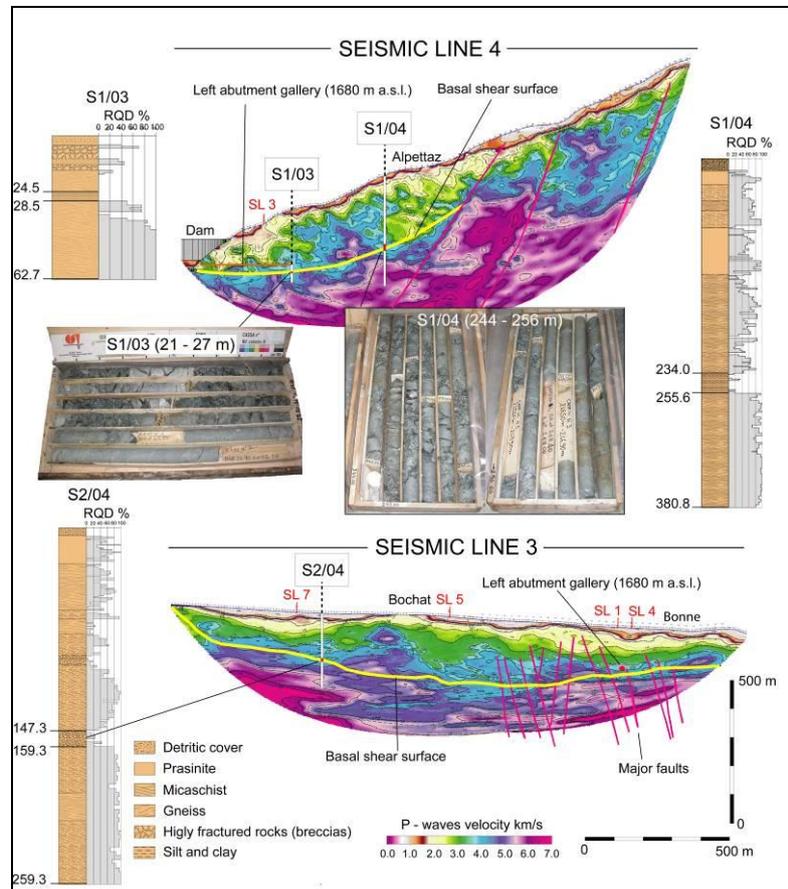


Figure 3 Site investigations results with indication of the main shear zones identified across boreholes S1/03, S1/04 and S2/04 and interpretation of seismic refraction tomographic lines 3 and 4.

GBInSAR monitoring

Over the last decade, radar interferometry has become a useful technique for landslide displacement monitoring and has demonstrated its capability in the assessment of ground surface displacements over wide areas (e.g. Massonet et al., 1993; Tarchi et al., 2003, Antonello et al., 2004; Luzi et al., 2006). The interferometric system adopted for the Beauregard landslide monitoring is composed of a coherent microwave trans-receiver unit working at Ku band which generates a set of sweep of electromagnetic waves of proper duration at different frequencies. The generated signal is then amplified and transmitted to the antennas. The synthetic aperture is realized by moving, via a linear positioner, a

motorized sled hosting the radar head along a straight rail 2 m long. The whole system is controlled by a toughbook PC equipped with specific software.

Monitoring of the landslide with the GBInSAR system was carried out in two distinct campaigns during 2008 and 2009. Each campaign lasted approximately 4 months. The rail anchoring points, fixed on a stable wall in the right valley slope at an elevation of 1770 m a.s.l., have been preserved and protected after the first GBInSAR removal in October 2008, allowing for the radar re-installation in the same position during 2009. This location has therefore ensured a frontal view of the landslide.

The duration, the total number of SAR images and the acquisition frequency adopted are reported in Table 1.

Table 1 Characteristics of the 2008 and 2009 GBInSAR campaigns.

Campaign	Duration	N° of SAR images	Acquisition frequency
2008	121 dd (18 June – 17 October)	8954	20 min
2009	124 dd (12 June – 14 October)	8006	20 min

The main radar parameters adopted during the 2008 and 2009 monitoring campaigns are summarized in Table 2. Under these operational conditions the spatial resolution in range was 0.5 m, while the azimuth resolution was 4.5 mrad (2.25 m at 500 m and 9 m at 2 km).

Table 2 Summary of the main operational parameters of the GBInSAR radar measurements campaigns.

Target distance	400-2800 m
Central frequency	17.2 GHz
Bandwidth	300 MHz
Polarisation	VV
Synthetic aperture	2m
Linear scansion point number	401
Range resolution (theoretical)	0.5m
Azimuth resolution (theoretical)	4.5 mrad
Antenna gain	20 dB

During the 2009 monitoring campaign, 6 artificial radar reflectors (corner reflector – CR) were installed along the slope in order to clearly materialize specific points in the SAR images. The images were subsequently processed using a specific software based on the Permanent Scatterers approach (Ferretti et al., 2001).

Results of GBInSAR monitoring

The results of GBInSAR monitoring are sequential displacements and velocity maps of the observed scene, which allow for a spatial and temporal analysis of the landslide behaviour.

During 2008 (Barla et al., 2010), a sequence of 6 displacement maps, covering a time span of 121 days was obtained as shown in Figure 4. The interferometric maps, which are referred to the same master image and to the same calibration set, were obtained through a masking procedure that discards low coherence zones. The color scale of the maps (saturated towards ± 4.5 mm) represents the ground movements along the LOS (Line Of Sight) of the instrument: negative values indicate a displacement towards the observer, i.e. a sensor to target distance reduction. All the deformation maps have been unwrapped and the atmospheric phase screen effect has been removed during processing. However, it has been observed that some local aliasing effect could remain in some maps, especially in areas where the radar data are not spatially continuous.

The cumulated displacement maps, previously geocoded, have been subsequently projected on a DEM of the area and completed with high resolution aerial photographs. As illustrated in Figures 4 and 5, an elongated sector in motion beneath the Scavarda ridge (between 2300 and 2500 m a.s.l.) can be observed. In this area the cumulated displacement reaches a maximum value of -45 mm. The geomorphologic analysis indicates that this sector belongs to the ridge that has been lowered along the landslide main scarp. The ridge consists of altered and fractured Ruitor crystalline rocks.

The displacement pattern in this area is due to various instability phenomena (rockfalls, block toppling, and sliding) which result in debris which accumulate in two main talus, developed between 2100 and 2300 m a.s.l. The interpretation of the high resolution aerial photographs and the field surveys allowed to map a well defined swarm of trenches above the area undergoing the most significant movements, between 2500 and 2700 m a.s.l.

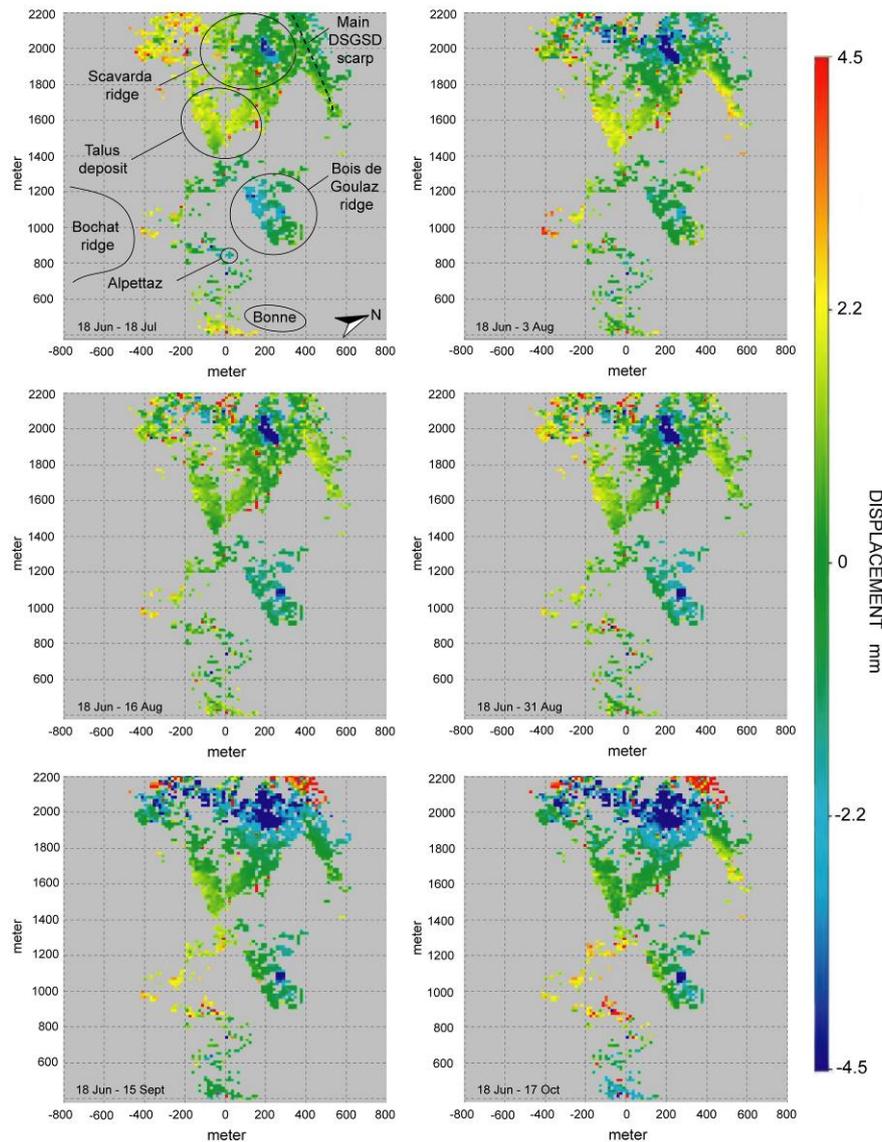


Figure 4 Results of the 2008 GBInSAR monitoring campaigns: sequence of cumulated displacement maps.

These linear and deeply cut morphologic structures are the expression of extensional openings of a vertical or a downward dipping surface. The fracture system shows a NE-SW trend parallel to the valley axis and can be related to the regional tectonic pattern of the Alpine chain. Significant movements characterize one further slope sector between the Alpettaz and Bois de Goulaz ridge, where the cumulated displacement reaches a maximum value of -15 mm. The area affected by movements is bounded uphill by a set of minor scarps as already noted for the sector beneath the Scavarda ridge, while a large talus is present in its frontal sector.

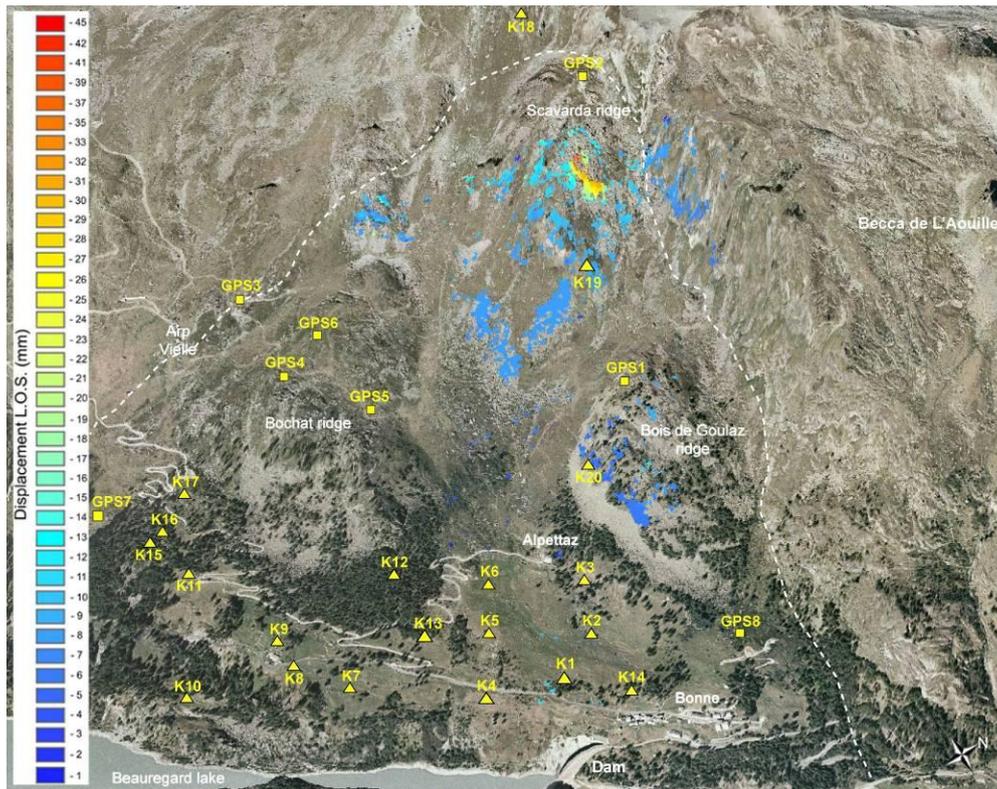


Figure 5 Cumulated displacement map referred to the monitoring period 8/06/2008 -17/10/2008 projected on DEM and high resolution ortho-photos with indication of the total station and GPS benchmarks. The dashed line indicates the DSGSD boundaries.

The middle landslide sector, between 2100 and 2300 m a.s.l., is characterized by the radar echoes originated from the talus at the base of the Scavarda ridge. The displacements detected are homogeneously distributed and reach a maximum value equal to -8 mm. In the lower part of the slope, between 1800 and 2100 m a.s.l., the lack of coherent radar reflectors limits the interpretation. It is only possible to distinguish the backscattering echoes due to few isolated rock blocks indicating displacements between -6 and -11 mm.

By comparing consecutive displacement maps step by step it has been possible to follow in detail the spatial and temporal landslide evolution. The temporal distribution of the movements showed a progressive spatial extension of the sector affected by the maximum displacements (Figure 4), with an increasing displacement rate since the end of August.

The results of the 2009 GBInSAR monitoring have substantially confirmed the magnitude and the displacement patterns detected during 2008 (Figure 6).

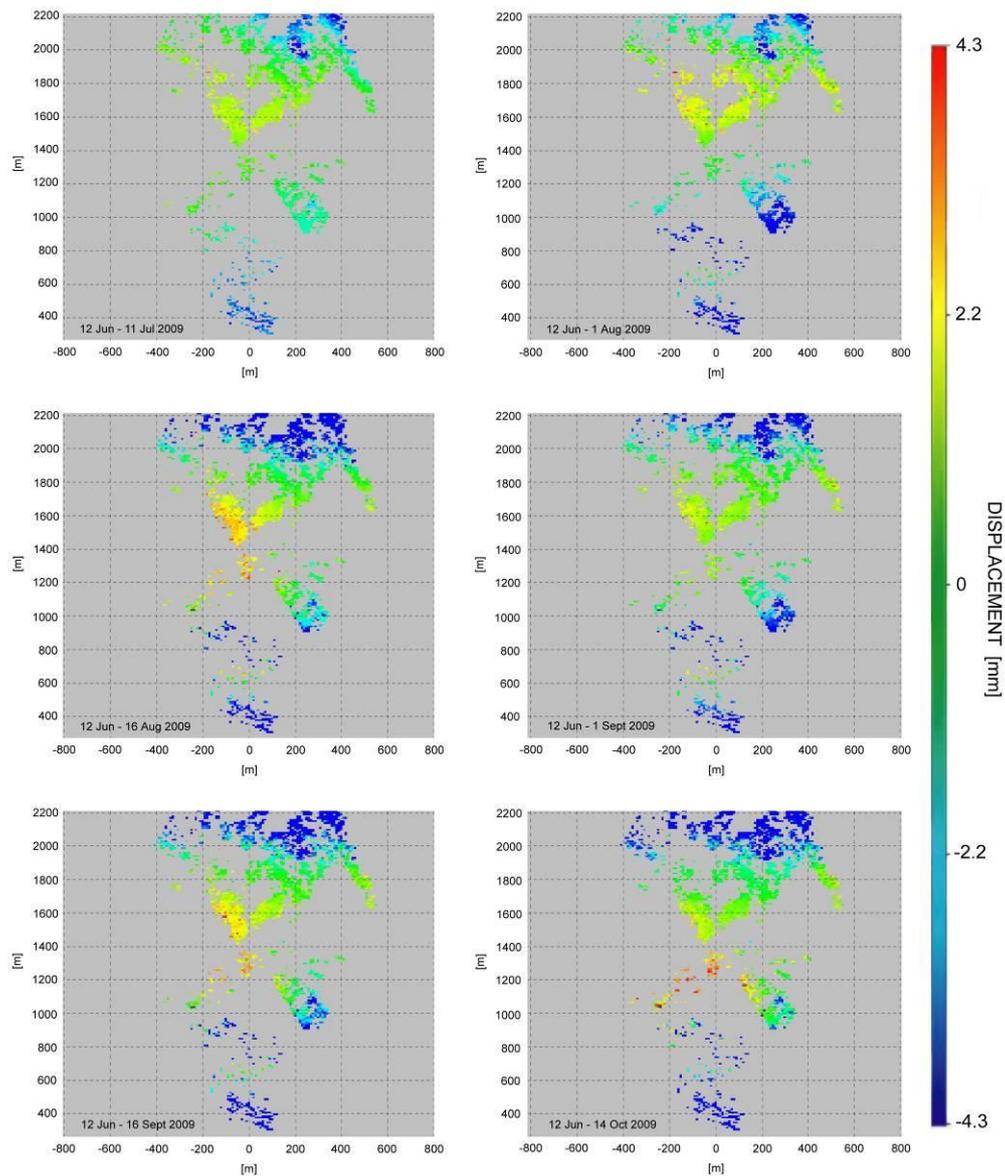


Figure 6 Results of the 2008 GBInSAR monitoring campaigns: sequence of cumulated displacement maps.

The elongated slope area beneath the Scavarda ridge (between 2300 and 2500 m a.s.l.) continued to be affected by the larger displacement (-35 mm). Unlike the 2008 GBInSAR campaign, the middle slope sector, characterized by the backscattering of the two large talus, is shown to be without the presence of appreciable deformation. As for the 2008 monitoring, the base of the Bois de Goulaz ridge (2100-2200 m a.s.l.) continued to exhibit a -4/-8 mm displacement, whereas in the basal landslide sector, the absence of coherent radar reflectors limits the reliability of the interferometric analysis. A few isolated pixels in the radar image indicate displacement between -6 and -11 mm.

The analysis of the 15 days-cumulative displacement maps obtained during the 2009 monitoring campaign highlights a significant increase in the displacement rate along the Scavarda ridge from the end of August (Figure 7a). In particular, if one pays attention to the pixels affected by the maximum displacement (-35 mm), the displacement rate increases from 0.24 mm/day (June-August) to 0.375 mm/day (September-October).

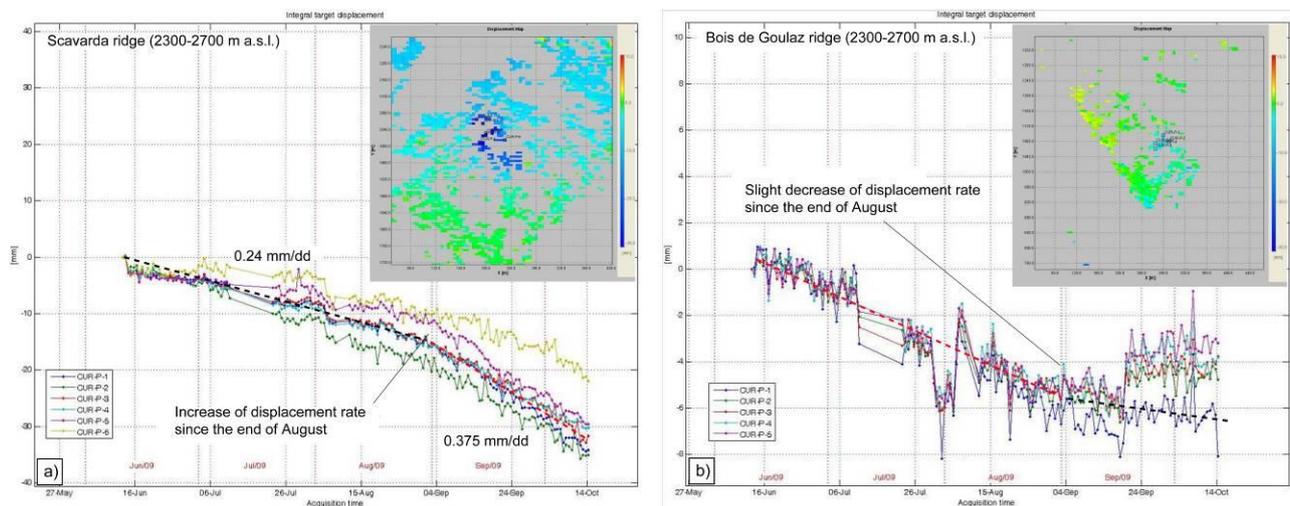


Figure 7 Results of 2009 GBInSAR monitoring campaign a) Time series of selected points on the Scavarda ridge (upper landslide sector) b) Time series of selected points on the Bois de Goulaz ridge (middle landslide sector)

The time series of pixels located on the Bois de Goulaz ridge shows a small decrease in the rate of displacement from the end of August to mid-September (Figure 7b). This seasonal behavior is well known from the conventional monitoring displacement data and it characterizes the whole middle slope portion. The basal slope sector shows instead a small decrease in the rate of displacement starting with the end of July, followed by an increase since early September.

The installation of 5 artificial radar reflectors (CR1, CR2, CR3, CR5 and CR6) along the slope has allowed for a direct comparison between the GBInSAR and total station results. Since the total station only measures the distance and the angle on particular targets, these points needed to be materialized in the radar image. The CRs were installed directly on the total station benchmark supports or as close as possible to them. Hence, the time series extraction of the corner reflectors data allowed a direct comparison with the total station displacements by applying a simple correction accounting for the different geometric features of the two systems.

The displacements measured by the two systems on the CRs and the total station benchmarks are shown in Figure 8. Comparing the CR1-K19, CR2-K20, and CR3-K3 time-series, a substantial agreement between the GBInSAR and the total station measurements is obtained. It is however worth noting that the total station data are characterized by high frequency oscillations. This behavior could be related both to the variations of the atmospheric parameters (temperature, humidity and pressure) which modify the air refraction index and to thermal effects on the benchmarks. This is particularly evident on benchmarks K19 and K20 located respectively 1.1 km and 1.7 km away from the total station, since atmospheric effects increase with the sensor-target distance.

The analysis of the CR6-K4 time series highlights a good agreement in the measured displacements from June to September, with some differences (4-5 mm in absolute value) arising by the end of the campaign (September-October). The comparison of the CR5-K1 time series shows that the displacements measured by the GBInSAR system differ significantly from the values given by the total station and towards the end of the monitoring campaign the difference between the two systems is near to 10 mm.

In the basal slope sector the lack of coherent radar reflectors limits the reliability of the interferometric analysis (i.e. the effectiveness of the phase unwrapping algorithm and the atmospheric phase screen correction). It is worth pointing out that the differences between the interferometric and the optical measurement data may be ascribed to the inaccurate spatial correspondence between the different targets used (corner reflectors versus benchmarks) and to the intrinsic differences of the two techniques. In fact, the total station displacements are recorded only on a single point (target) while the interferometric displacements are referred always to an area (up to 7 m² at a 3 km distance from the sensor).

Based on work done so far, for distances greater than 1.2 - 1.5 km in the Beauregard site, the results obtained with the total station are less reliable than the GBInSAR measurements.

Discussion and implications on the landslide mechanism

The occurrence of a non-homogeneous surface displacement pattern across the Beauregard deep landslide, with greater displacement rates in the upper slope (Scavarda

ridge) and small and steady displacements along the landslide toe, suggests two different trends of behavior for the two sectors.

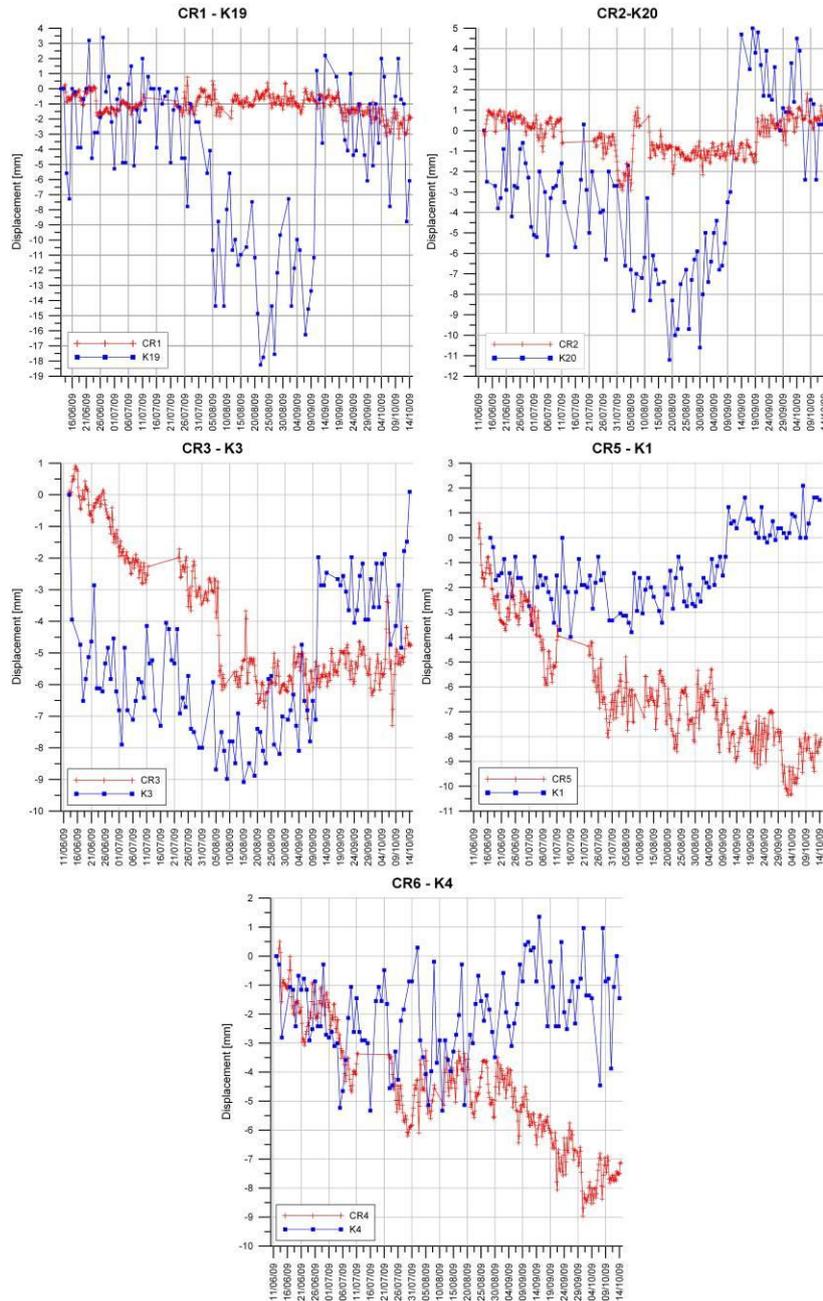


Figure 8 Comparison between the displacement measured from June 12th to October 14th 2009 by the GBInSAR system on corner reflectors CR1, CR2, CR3, CR5 and CR5 and total station on targets K1, K3, K4, K19 and K20

Morpho-structures such as faults, open cracks and trenches, widespread on the upper slope sectors, are clearly undergoing brittle deformations, while the basal portion of the landslide exhibits a creep behavior. Thus, based on the displacement field obtained with the GBInSAR monitoring, a novel interpretation of the upper and intermediate slope sectors is illustrated in Figure 9.

It is worth to say that the results of the 2008 and 2009 GBInSAR monitoring campaigns currently represent the only areal deformation data available for the upper portion of the landslide. The elongated sector characterized by the most significant displacements is bounded upward by a set of subvertical faults and joints oriented NNE-SSW (parallel to the valley). It has been observed that displacements decrease both towards the top of the Scavarda ridge, where a GPS target (GPS2) shows less than 5 mm annual displacement and towards the ridge's base, where the K19 total station target shows 13.5 mm annual displacement.

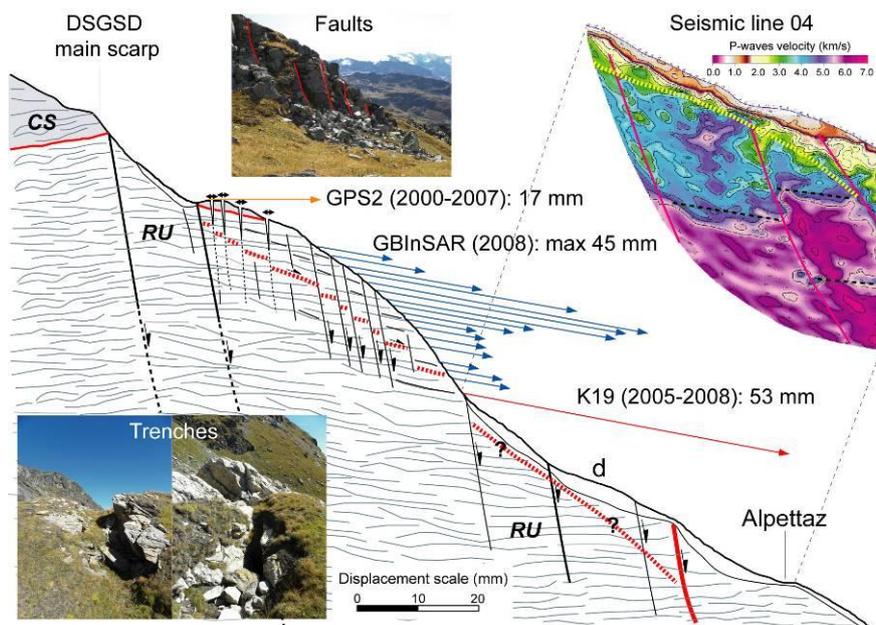


Figure 9 Geomorphological sketch and interpretative geologic section with indication of superficial deformations along the Scavarda ridge

Since direct and indirect information at depth is lacking, the displacements detected by the radar survey across the fault zone could be related both to surface differential movements of rock blocks and to displacements occurring along the active faults and fractures. The extension of movements at depth may be related to the widening of the persistent trenches in the upper Scavarda ridge. The previously described displacement pattern, characterized

by the opening of tension cracks and the formation of slope bulging, is thought to be the evidence of a progressive translational movement of the upper portion of the slope (Scavarda ridge) along an incipient basal rupture surface, according to the mode of failure described by Stead et al. (2006).

As shown in Figure 10, a stepped geometry of the incipient rupture surface controlled by the sub-vertical faults and by the schistosity planes dipping E - SE may be assumed. This surface is bounded upward by the main fault which has lowered the Scavarda ridge along the main landslide scarp. In particular, based on the analysis of the P-wave velocity profile along the slope sector above the Alpettaz (Figure 3), one may suggest that the well defined shear zone detected in the S1/03 and S1/04 boreholes could extend upwards connecting to the incipient rupture surface of the Scavarda ridge.

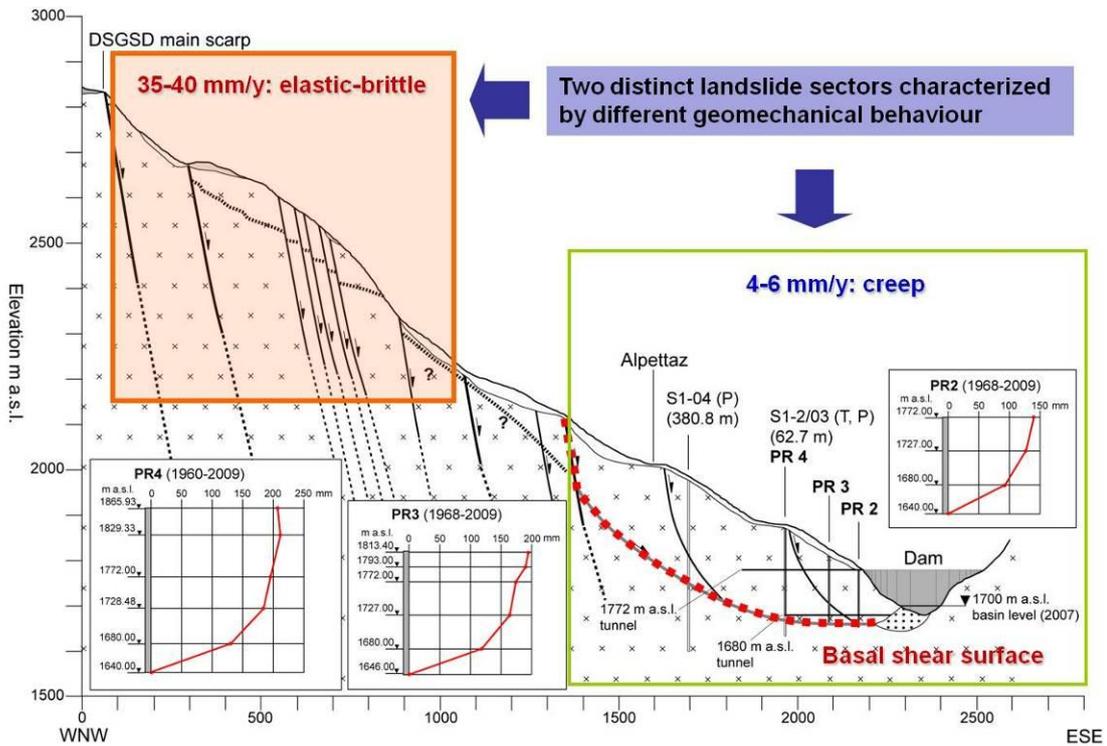


Figure 10 Interpreted geological section E-E'

The behavior of the slope at the toe, which impinges directly on the dam, is instead related to the geotechnical characteristics of the cataclastic rocks forming the basal shear surface of the landslide, at a depth up to 240 m, which are known to exhibit a time dependent behavior (Barla et al., 2009). The displacement patterns of this landslide sector show a small strain rate i.e. creep deformations which are likely to be related to the seasonal

fluctuations of the water table in the slope, resulting in changes of the effective stress along the basal shear surface (Barla et al., 2010).

Conclusions

Both conventional and advanced monitoring systems were used to monitor the displacements of the Beauregard landslide, located in the Aosta Valley (NW Italian Alps). Since dam construction, a conventional monitoring network of in-situ instruments (piezometers, plumb lines, extensometers and topographic targets) has been installed in the lower left slope and in the dam. At present, in the basal slope sector the monitored mean annual displacement rate is 4-6 mm/year.

In 2008 and 2009, the application of the GBInSAR technique has allowed to obtain the displacement field of the upper part of the landslide, which is characterized by a good radar reflectivity and coherence. The cumulated displacement maps have evidenced an elongated sector in motion between 2300 and 2500 m a.s.l. previously unknown, where a maximum downward displacement of -35 (2009) and -45 mm (2008) is reached.

The comparison of the ground based interferometry and the topographic measurements on 5 selected targets has shown that the precision of the two techniques is almost the same but beyond distances of 1.2-1.5 km the results obtained by the total station are markedly affected by atmospheric noise. Thus, GBInSAR has confirmed to be a powerful tool for monitoring superficial slope displacements over large landslide areas and within kilometer distances, even in slope sectors difficult or impossible to be reached.

Based on the up-to-date displacement data obtained with the GBInSAR monitoring, a novel interpretation of the upper landslide has been given. This displacement pattern is the expression of an elastic-brittle behavior of the rock mass and could be the evidence of a progressive translational movement of the upper portion of the slope along an incipient basal rupture surface. The behavior of the landslide at the toe, characterized by very small movement rates (4-6mm/y), is instead related to the geotechnical characteristics of the cataclastic rock forming the basal shear zone of the landslide, at a depth of up to 240 m, which is known to exhibit a time dependent behavior (creep).

The results so far obtained and the continuation of the monitoring activities will provide an overall view of the landslide deformations versus time and will contribute to improve the

understanding of the slope behavior for landslide hazard management based on advanced numerical modelling studies which are currently underway.

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