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DinSAR monitoring of the landslide activity affecting a stretch of motorway in the Campania region of Southern Italy

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Abstract

The paper deals with the landslide activity affecting a wide and steep slope crossed by a stretch of about 2.5 km of the provincial road *Tirrena inferiore* in the Campania region of Southern Italy. Some years ago, the road has been affected by the partial reactivation of dormant landslides, which caused both severe damages to the piers of a viaduct and considerable road surface deformations. By means of geognostic surveys, laboratory tests, geophysical prospecting as well as rainfall data, the modeling of landslides was performed in detail, and residual slope movements were monitored by means of inclinometers and satellite-based measurements (Cosmo-SkyMed interferometric data). A good correlation there is between the results provided by the two used techniques. With reference to the viaduct failure, DinSAR data allowed to ascertain the date on which the sudden acceleration of the landslide body pointed out the beginning of the landslide reactivation, in its paroxysmal phase. Ground deformations happened starting from January 2014 following an intense rainfall period that has been spreading between December 25 2013 and January 26 2014.

Keywords: Landslide monitoring; transportation corridors; interferometric data

1. Introduction

According to the IFFI (*Inventario dei Fenomeni Franosi in Italia*) catalogue (APAT, 2007) about 4.52% of landslides inventoried in Italy until to 2008 affected the national road network. With reference to the Campania Region

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of Southern Italy, this percentage attains about 9.35%, and the main encountered slope instabilities involving the roads include rotational and translational slides, flows and, to a lesser extent, rockfalls. These landslides cause severe damages, road closures, economic consequences and injuries. Sometimes, the road corridors are also involved in the reactivation of dormant landslides caused by intense rainfall or earthquakes.

The entire road network managed by the Province of Salerno, consisting in motorways, primary, and local roads, develops for about 2,600 km involving, for the most part, intense morphological relief characterized by outcrops of flysch and rock masses.

One symbolic case study concerning the monitoring of the residual slope movements, which affect a wide and steep slope crossed by a stretch of about 2.5 km of the provincial road *Tirrena inferiore* connecting Agropoli to Sapri is here showed. On January 2014, following a period of intense and prolonged rainfall, the reactivation of two dormant slides caused both the failure of piers of a viaduct and considerable deformations of another road stretch located downstream from a waste disposal site. Consequently, it was needed the demolition and reconstruction of the viaduct and to make strengthening interventions on the remaining hazardous road stretch by means of a cut-off wall, gabions and drainage wells.

Due to significant shear surface displacement, which caused the failure of installed inclinometers, for only nine months the residual slope movements were monitored. In order to extend the observation period in the previous time span 2011-2014, and so perform a more carefully check of the activity state of landslides, the available Cosmo-SkyMed interferometric data were used.

2. Geological setting and geotechnical characterization

The studied area (Fig.1) is located in the Cilento area of the Campania region characterized by lithological sequences, which can be attributed to the ‘Cilento group’ divided in three main Miocene formations: the *Crete Nere*, *Pollica* and *San Mauro* (Bonardi et al. 2009). In the area, only the younger *San Mauro* formation outcrops, which is characterised by alternations of sandstones and tightly layered argillaceous marls (Budetta and Nappi 2011; Budetta and De Luca 2015). This is a flysch formation with high strata heterogeneity due to: (i) the presence of a fine grained (pelitic) argillaceous matrix, which is both interbedded and contains rock layers/fragments; (ii) the presence of strong and weak bands; (iii) the presence of clay mineral horizons and sheared discontinuities. A characteristic stratigraphic marker (“*Fogliarina*”), made up of layers (up to about 5 metres thick) of Langhian-Upper Burdigalian grey-to-bluish-grey calcareous marly strata interbedded into sandstones and argillaceous marls, at various heights in the flysch sequence is often found (Bonardi et al. 2009).

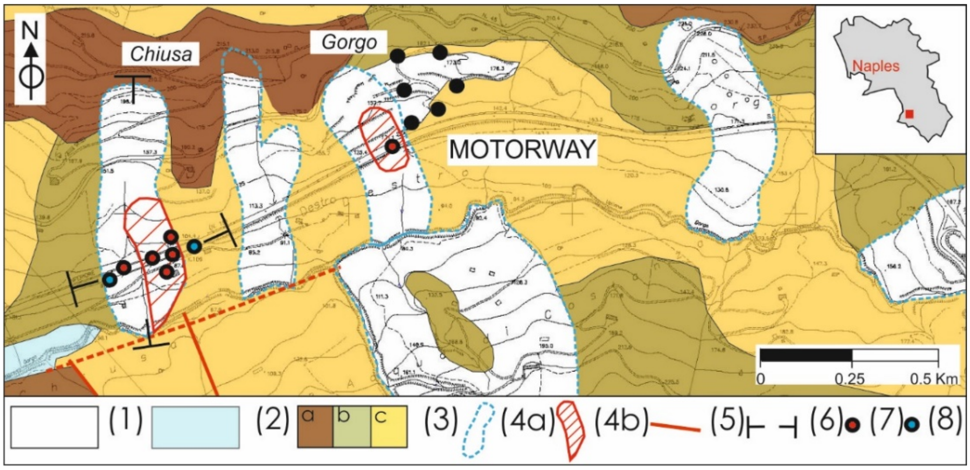

Fig. 1. Engineering geological map of the studied area. Key: Landslide debris and waste dump materials (1); Alluvial deposits (2); San Mauro flysch formation (3): “*Fogliarina*” stratigraphic marker (3a); Sandstones alternating with argillaceous marls showing S/P ratios ranging between 2 and 1 (3b); Sandstones alternating with argillaceous marls showing S/P<1 (3c); Dormant landslide (4a); Reactivated landslide (4b); Fault (5); Geological section trace (6); Borehole equipped with inclinometer (7); Borehole equipped with piezometer (8).

For recording in the flysch, the amount of hard rock (Sandstone) relative to weak or plastic soil (Pelite), the S/P ratio has been established (Budetta and Nappi 2011). This is a simple but important factor for assessing the relative weight of the hard rock fraction in relation to that concerning the argillaceous matrix. The S/P ratio is in close relationship with landslides because where pelitic fraction is predominant more slides or complex landslides can occur. In the study area (Fig. 1), the S/P ratio is very variable ranging between 2 and less then 1. In the central sector of the area, straddling the main river, predominant argillaceous marls layers with S/P<1mainly outcrop. Instead, in the northern sector S/P ratios ranging between 2 and 1 along with *Fogliarina* strata interbedded into sandstones are predominant.

The physical and mechanical characterization of soils was performed with laboratory tests on samples coming from the boreholes drilled in the landslide areas. Both the landslide debris and underlying in situ soils belonging to the flysch with S/P<1 were tested. The main properties of the tested materials are reported in Table 1 where the variability of results was evaluated on the basis of the standard deviation (*SD*) and coefficient of variation (*Cv*) (Table 1). With reference to the landslide debris, the grain size consists of 'sandy silt with clay', which is characteristic of 'inorganic silts of medium plasticity'. Several direct shear tests were carried out on these soils in order to determine the peak and residual shear strength values. These data show that peak friction angles (ϕ'_p) are high, while for both the tested terrains, there is not much difference between residual friction angle values.

Table 1. Results of the main geotechnical properties of the analyzed soils. Key: γ = unit weight; w = water content; n = porosity; e = void ratio; Sr = degree of saturation; W_L = liquidity index; I_P = plasticity index; c' = effective cohesion; ϕ'_p = peak friction angle; ϕ'_r = residual friction angle. M = mean value; SD = standard deviation; Va = coefficient of variation.

Soil		Samples N.	γ (KN/m^3)	w (%)	n (%)	e (-)	S_r (%)	W_L (%)	I_P (%)	c' (KPa)	ϕ'_p (°)	ϕ'_r (°)
Landslide debris	**M**	7	**19.55**	**19.41**	**38.93**	**0.64**	**82.84**	**44.08**	**19.59**	**13.79**	**27.9**	**14.8**
	SD		1.04	1.84	2.94	0.08	13.33	5.94	4.29	8.92	3.0	
	Va (%)		5.33	9.48	7.55	12.90	16.09	13.47	21.91	64.65	10.9	
S/P<1	**M**	12	**20.21**	**19.49**	**36.86**	**0.58**	**89.85**	**41.60**	**18.21**	**24.01**	**29.0**	**15.4**
	SD		0.67	2.62	2.38	0.06	10.97	3.95	2.27	11.27	3.0	
	Va (%)		3.34	13.45	6.47	10.20	12.21	9.49	12.45	46.94	10.4	

The main deformability parameters (Elastic modulus and Shear modulus) of the outcropping terrains (Table 2) were inferred from the multi-channel analysis of surface waves (MASW) technique (Park et al. 1999). Indeed, the relationships between deformation moduli, surface wave velocities, and shear wave velocities suggest that mapping the spatial variability in subsurface shear wave velocities of heterogeneous materials with MASW might be expected to provide an efficient method for in-situ soil and rock characterization (Duffy et al. 2014).

Table 2. Main geomechanical properties obtained by means of the seismic prospecting (MASW). Key: V_p = longitudinal wave velocity; V_s = shear wave velocity; E = elastic modulus; G = shear modulus.

Soil	V_p (m/s)	V_s (m/s)	E (MPa)	G (MPa)
Landslide debris	610.5	536.5	67.02	27.92
S/P<1	1,263.7	774.0	268.47	111.86

3. Activity of the landslides

By means of boreholes, piezometers, geophysical prospecting as well inclinometers, an in-depth analysis of spatiotemporal modeling of the main landslides affecting the road corridor was performed. In close proximity of the kilometer 109+100, the road crosses the Chiusa stream by means of an 800 metres-long viaduct founded on piers. On January 26th 2014, the partial reactivation of a dormant translational slide, in form of an earth flow, caused the failure of two piers and the consequent settlement of the bridge deck (Fig. 2). This entailed the demolition and reconstruction of the viaduct.

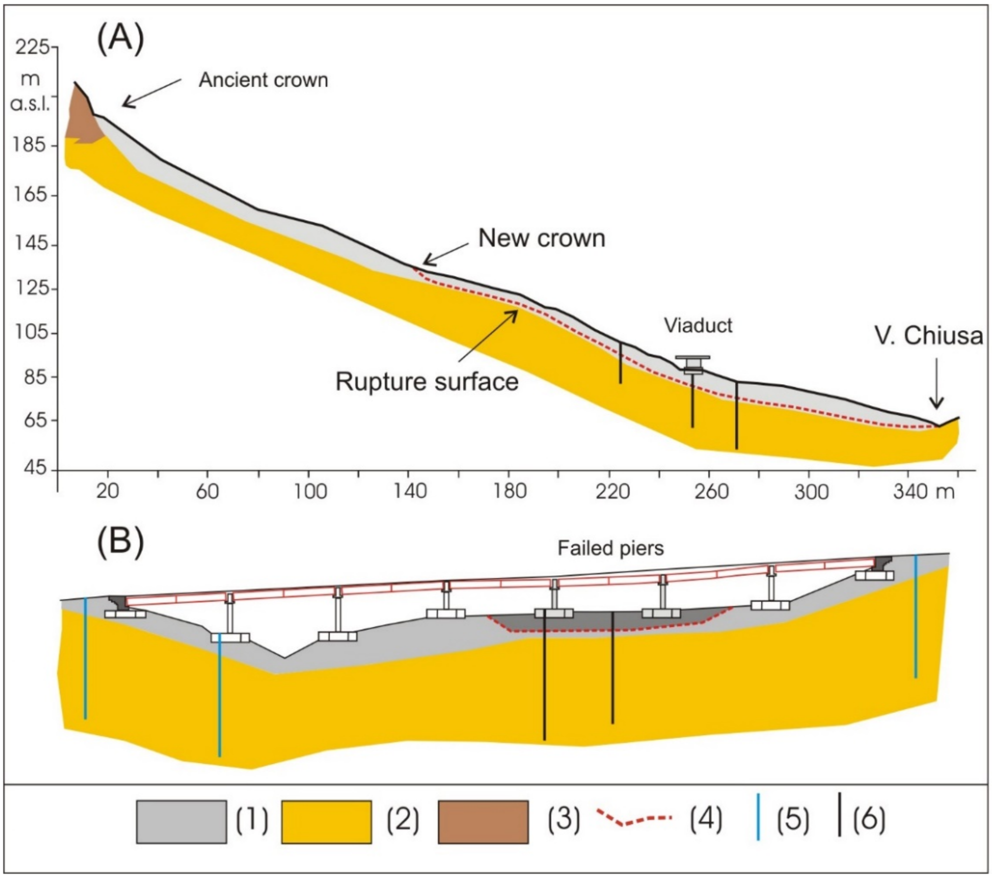

Fig. 2. Geological sections of the Vallone Chiusa landslide. Longitudinal section (A); Transversal section (B). Key: Landslide debris (1); Sandstones alternating with argillaceous marls showing the ratio S/P<1 (2); "*Fogliarina*" stratigraphic marker (3); Rupture surface of the reactivated landslide (4); Borehole equipped with piezometer (5); Borehole equipped with inclinometer (6).

The slope failure was triggered by intense rainfall happened in the months before. Daily accumulated rainfall from December 25th 2013 until to January 26th 2014 totalized about 400 mm. With reference to the time spans September 2013 - March 2014 and the similar months of the period 1921-1950 (considered as the reference), and for the rainfall gauge closer the study area (Gioi Cilento at 385 m a.s.l.), the average monthly rainfalls were 212 and 141 mm, respectively. Over time, major differences in average monthly rainfall amounts are found whereas extreme weather events (intense rainstorms) have become more frequent.

The inclinometer measurements performed in boreholes located near the viaduct, allowed to ascertain that the rupture surface of the debris flow is at depth of about 6 - 9 metres. The inclinometers ceased to be usable in October 2014 after 9 months of monitoring due to significant shear surface displacement inducing localised bends within the casing sufficient to no longer allow the torpedo probe to pass (Fig. 3).

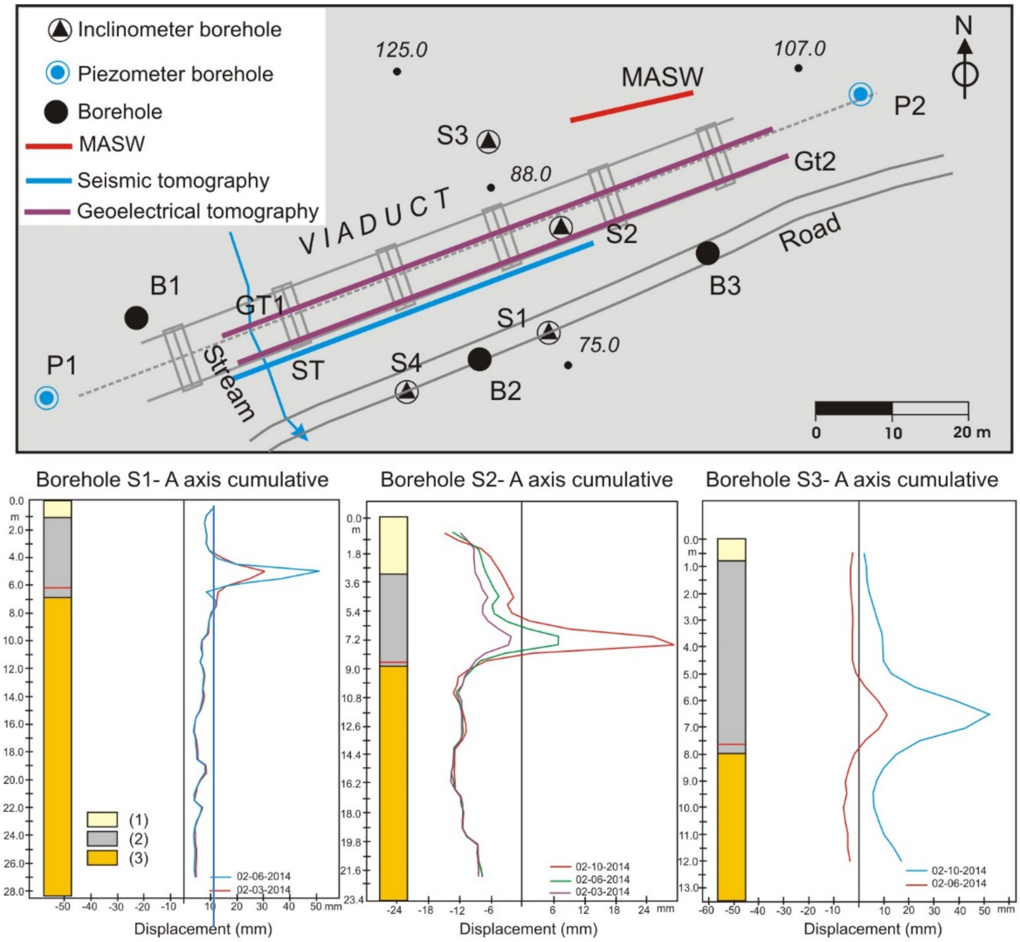

Fig. 3. Inclinometer cumulative displacement profiles along the main axis of the landslide as measured in the S1, S2 and S3 boreholes. The landslide slip surface has been also highlighted (red lines) Key: Organic soil (1); Landslide debris (2); Sandstones alternating with argillaceous marls showing the ratio S/P<1 (3).

Another landslide that affected the road happened in close proximity of the kilometer 109+800. Here, by means of an embankment, the road crosses the Gorgo stream (Fig. 1) and due to movements caused by the slope failure, the road was affected by longitudinal and transversal deformations. Again, the partial reactivation of a dormant slide in form of a complex movement (translational slide evolved in form of earth flow) was triggered by copious groundwater mixed with the leachate coming from a waste dump located upstream of the road. From the crown of the earth flow, until to the toe of the movement the landslide debris extend itself for about 25 metres and the slope failure surface, encountered by boreholes, is at depth of about 3 meters.

The last dormant landslide involving the road has been mapped between the kilometers 110+300 and 110+600. Fortunately, here minor movements seem to involve the road surface (Fig. 1).

4. Interferometric data analysis

By means of the DinSAR (Differential Interferometric Synthetic Aperture Radar) technique (Berardino et al. 2003; Colesanti and Wasowski 2006), vertical displacements (positive and negative) of about 70 Permanent Scatterers (PSs) located on the road stretches intersecting the landslides were monitored. As is well known, DinSAR allows obtaining detailed topographical surveys (millimeter accurate) by different SAR (Synthetic Aperture Radar) image-pairs coming from slightly different positions (space baseline) and over time (temporal baseline), conveniently combining the radar signals (amplitude and phase) received by PSs at intervals along the direction of flight of the satellite. This technique allows a high resolution also in the azimuth direction. If in the time interval between two different images, the ground surface has changed, with high precision these displacements can be surveyed (Colesanti and Wasowski 2006).

Due to the high radar reflectivity of the road asphalt, along the studied road most of PSs have a high density (Fig. 4), whereas the lack of buildings or rocky outcrops in the landslide areas do not allows the detection of PSs. However, the high PSs density affecting the road allowed millimeter accuracy of the landslide displacements to be monitored, except for the Gorgo landslide (C in Fig. 4) where only four points are available. The Cosmo-SkyMed satellite data (only the ascending dataset) referring to the time span 2011-2014, provided by the Italian Environment Ministry (2019), was used and analysed. As the descending dataset is not available, it was impossible to extract the horizontal (in West-East direction) component of the movement and, consequently, the real vector of displacement of the landslides.

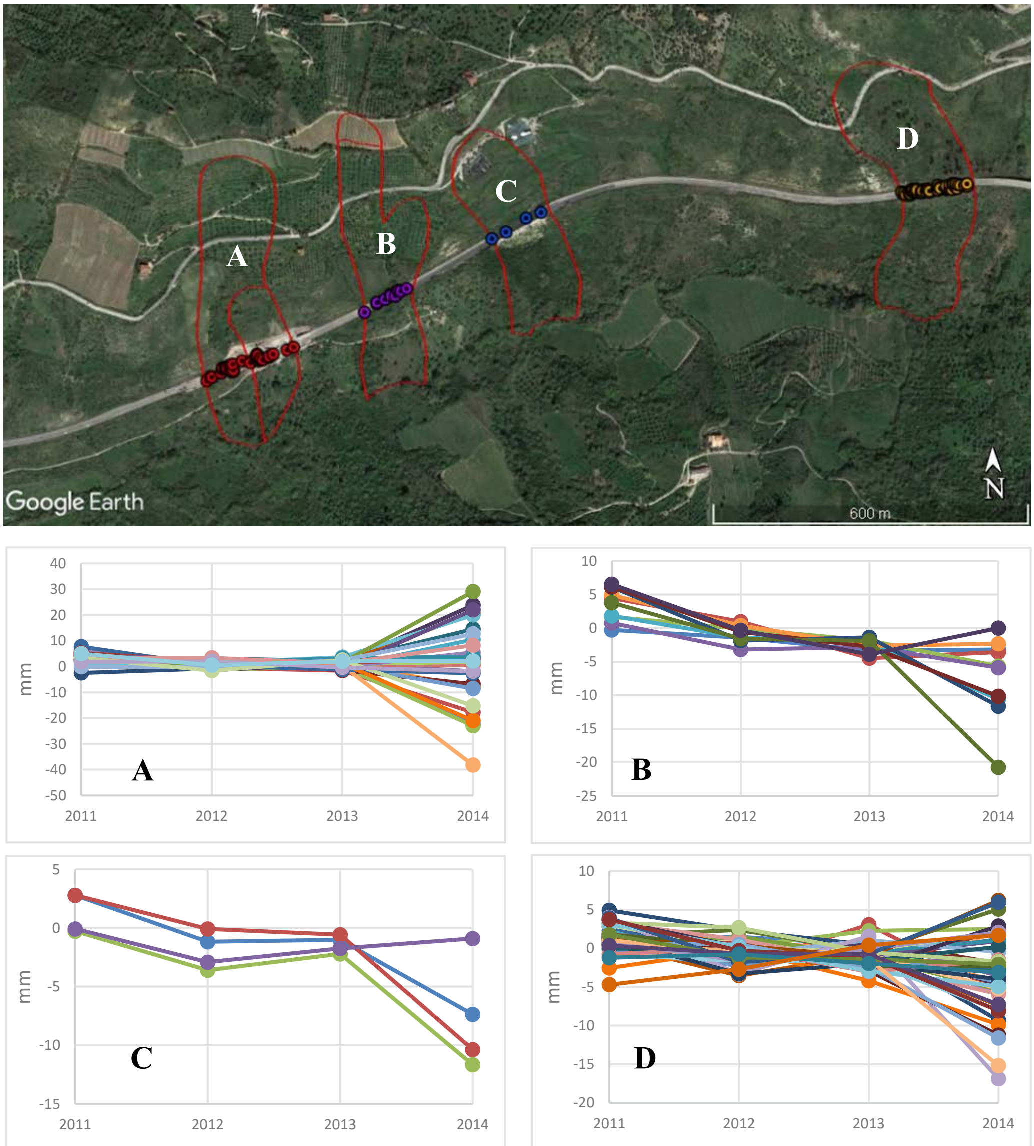

Fig. 4. The COSMO Sky-Med Permanent Scatterers, which refer to the road stretches crossing the inventoried landslides. The graphs show the cumulated annual displacements of each PSs in the time span 2011 – 2014.

As can be seen on graphs of Figure 4, during the time interval 2013-2014 and for all the landslides great vertical displacements have been registered. For the road stretch crossing the landslide A, the maximum height differences range between +30/-40 mm. Minor values were detected for the other monitored landslides. Vertical deformations in the central sector of the landslide bodies is thought to reflect also lowering movements, which can be linked with displacements evolving downhill into earth flows. In order to highlight vertical deformations occurring in the above-mentioned period in detail, graphs of vertical displacements versus dates, for the time span 2013/01/15 – 2014/03/19, were drawn (Fig. 5).

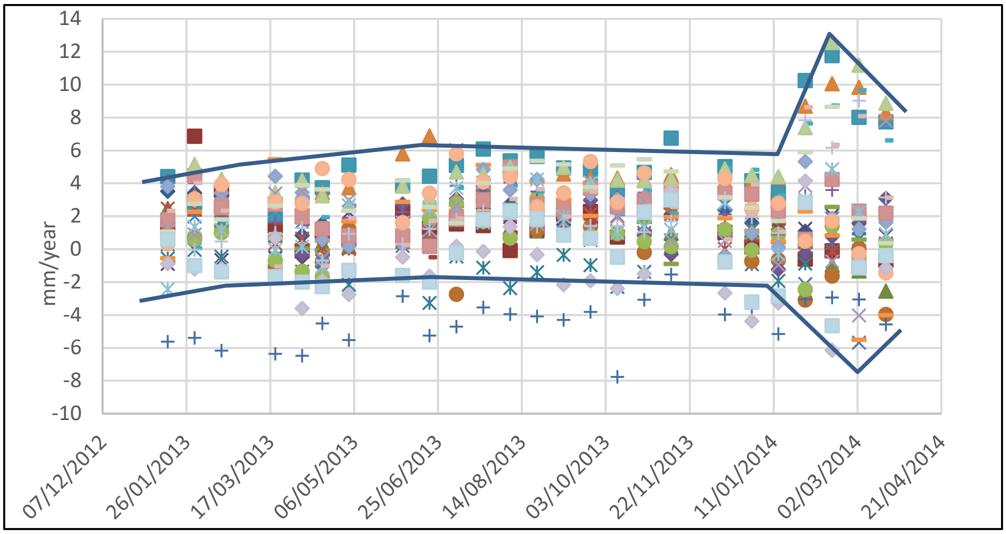

Fig. 5. The graph shows the recorded vertical displacements of PSs located along the road stretch crossing the Vallone Chiusa landslide, for the time span 2013/01/15 – 2014/03/19.

With reference to the Figure 5, it is clear that a sudden acceleration of ground movements happened starting from January 2014 following the intense rainfall of the period December 25th 2013 - January 26th 2014. During that time, the reactivation of the dormant landslide became evident.

5. Discussion and conclusions

The study allowed ascertaining that several dormant landslides, which can be periodically reactivated following intense rainfall, affect the Provincial road. Ground movements cause deformations of the road and, sometimes, the failure of the man-made structures essential for the viability. On January 2014, the collapse of the viaduct crossing the Chiusa landslide was triggered by daily-accumulated rainfall, which, from December 25th 2013 until to January 26th 2014, totalized about 400 mm. Inclinometer measurements allowed to ascertain that the landslide body moved very quickly, at least until October 2014. Unfortunately, in that time due to the failure of the inclinometers they ceased to be usable.

The Cosmo-SkyMed data concerning about 70 PSs, mainly located along the road, were used for the monitoring of ground vertical movements starting from 2011, during a time span not covered by the inclinometers. For the time span for which both satellite and in situ measurements were available, DinSAR showed that a good correlation there is between the two used techniques. With reference to the Chiusa landslide (A in Fig. 4) and for the time span March – August 2014, the DinSAR dataset along the ascending Line Of Sight (LOS) was compared with displacements of heads of the inclinometers. In order to perform a good quantitative comparison, DinSAR data along the direction of the inclinometer measurements were projected. The entire set of available data shows a trend of the ground displacement, from December 2013, with increasing values ranging between 3.5 and 12.6 mm (Fig. 6). This confirms the ground surface settlement below the viaduct as well its acceleration due to movements of the landslide body along the slip surface.

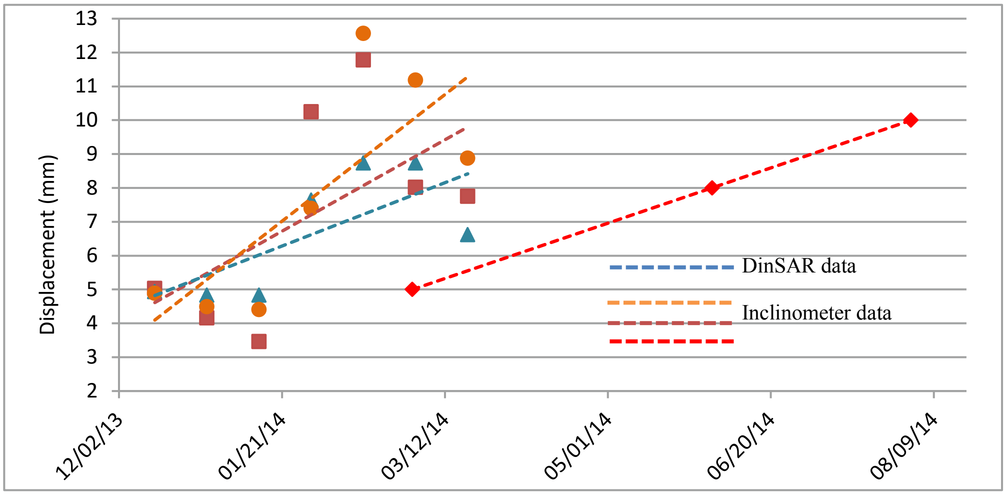

Fig. 6. Comparison of displacements of PSs and inclinometric data for the Vallone Chiusa landslide.

Unfortunately, the lack of the descending dataset not allowed the detection of the real vector of displacement of the landslide. However, it was possible to detect the exact date on which the sudden acceleration of the landslide body pointed out the beginning of the landslide reactivation in its paroxysmal phase.

Nevertheless, it will be necessary in the future to continue to monitor closely the stability of this road stretch acquiring the Cosmo-SkyMed descending dataset. In such a way, it will be possible to detect the real velocities of the landslides. This represent a key topic of current researches aimed to detect the landslide hazard conditions to the improvement of risk management and possible rehabilitations.

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