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VAL GENASCA LANDSLIDE (NORTH ITALY): AN EXAMPLE OF THE METHODOLOG USED FOR THE IDENTIFICATION OF THE LANDSLIDE MAIN FEATURES AND ITS MONITORING

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EXTENDED ABSTRACT

Il Centro di Monitoraggio Geologico di ARPA si occupa del monitoraggio di 26 grandi frane individuate da Regione Lombardia come di interesse regionale. In questo articolo ci si prefigge di descrivere la metodologia utilizzata per incrementare le conoscenza circa i movimenti e poi giungere ad un controllo della frana denominata di Val Genasca. Il dissesto si trova nella parte inferiore della Valle Spluga e più precisamente all'interno del territorio comunale di San Giacomo Filippo in provincia di Sondrio.

Il metodo di lavoro è stato necessariamente modellato su step successivi che, a partire dalla realizzazione di un monitoraggio conoscitivo (misure distometriche, periodiche campagne di misura topografiche e GPS), permettesse poi, ove si fosse manifestata l'esigenza, di sviluppare la rete sino a farla divenire un monitoraggio ai fini di allertamento e per l'attivazione dei piani di protezione civile. Tale gradualità di intervento ha inoltre permesso che le conoscenze, via via acquisite sulla dinamica del dissesto, potessero meglio indirizzare gli approfondimenti successivi anche in relazione alle disponibilità finanziarie annuali. In relazione a ciò, dopo una prima individuazione areale del fenomeno (30.000 mq), si è provveduto ad uno studio finalizzato ad individuarne le principali caratteristiche cinematiche così da potervi successivamente installare una adatta sensoristica che permettesse di seguire in tempo reale l'evoluzione del dissesto. A tal proposito la frattura principale è stata monitorata mediante tre estensimetri a filo ed a monte dell'area di frana è stata installata una stazione meteorologica dotata di pluviometro termometro e nivometro. In questa fase anche il monitoraggio topografico è stato automatizzato con rilevamento dei movimenti di circa 20 mire ottiche poste sia all'interno che all'esterno dell'area in movimento. I dati così acquisiti sono quindi stati trasmessi, con cadenza semi oraria, al fine dell'immediata verifica dei movimenti.

Per quanto riguarda i dati del sottosuolo, dopo una prima indagine geofisica, è stato possibile programmare una campagna di perforazioni che, oltre a fornire i primi dati diretti sulla geologia del versante, ha permesso l'installazione di tubi inclinometrici e piezometrici. In dettaglio a monte della nicchia è stato installato un tubo inclinometrico, spinto sino a 130 metri dal piano campagna, per misure periodiche manuali ed un tubazione piezometrica strumentata con sensore per acquisizione in continuo del dato freatimetrico.

Un terzo sondaggio, ubicato nella parte medio alta dell'area in movimento (Fig. 6) , è stato spinto sino alla profondità di 103 metri da p.c. ed è successivamente stato strumentato con colonna multiparametrica, modello DMS, con caratteristiche tali da poter sopportare deformazioni elevate e rilevare oltre al movimento anche l'escursione di falda. Al fine di contenere al massimo i costi, ma sapendo di non poter escludere alcuna profondità dalle possibili "zone di movimento", la colonna è stata progettata con una alternanza di moduli DMS e moduli sterili. Ovviamente gli uni collegati agli altri mediante "snodi" in grado di conservare e trasmettere il movimento. La colonna è stata alimentata portando una linea in bassa tensione (12-24 V) fino al centro della frana.

Questa particolare configurazione (alternanza di modulo sensori con un modulo sterile), non ha permesso correlazioni dirette tra i movimenti di superficie e di profondità, ma ha comunque permesso l'identificazione precisa del fascia di taglio (con potenza di oltre 10 metri) e la quantificazione dei movimenti. Per poter attivare un monitoraggio, con finalità di protezione civile, è infine stata commissionata all'Università di Milano la modellazione del dissesto e lo studio delle prime soglie di allarme.

L'acquisizione e l'analisi dei primi 3 anni di dati della frana di Val Genasca ha permesso di individuare sette differenti periodi di accelerazione, che complessivamente hanno evidenziato movimenti di circa 9 metri (Fig. 13), intercalati da altrettanti periodi di stasi.

L'ultima accelerazione, durata circa 50 giorni fra la fine del 2013 e la prima metà del febbraio 2014, ha mostrato un movimento di circa 5 metri, sempre misurato lungo il vettore di massimo spostamento, in concomitanza di un significativo innalzamento della falda di versante. L'analisi dei dati di profondità (Fig. 16-17) ha permesso di individuare come questi movimenti metrici si siano localizzati nelle prime decine di metri da p.c., permettendo così di stimare in circa 500.000 metri cubi il volume di frana in movimento. I dati topografici (Fig. 22) hanno infine permesso di definire un cinematismo di un tipico slittamento rotazionale con i valori di abbassamento maggiore nelle aree altimetricamente più rilevate rispetto a quelli posizionati nella parte inferiore della frana.

ABSTRACT

The Geological Monitoring Centre supervises deformations in some major landslides in the Lombardy Region (Italy). This article aims to present the methodology used to increase the knowledge about the landslide of Genasca Valley, located in the municipality of San Giacomo Filippo (Sondrio), and to monitor its evolution. The approach to the problem has been developed through the implementation of various activities in different stages.

The monitoring activities started in summer 2010 with a cognitive monitoring based on distometric measurement, periodical topographic and GPS measurement. The slope areas (30.000 square meters) in movement were defined thanks to these activities and to the geological survey.

Second step was the set up of a real time monitoring with a meteorological station, three wire extensometers and one automatic topographic system. A geophysical investigation and three drilling boreholes were made to increase the knowledge of the subsurface.

Inclinometric casing and piezometric pipe for periodical check were placed in the two drilling boreholes out of landslide (above 10 meters upper the main scarp). A differential multiparametric system (DMS) for the depth monitoring inclinometric and piezometric was installed in the borehole at the landslide centre.

In order to minimize the costs of the DMS column we designed a particular configuration (alternation of sensors module with a sterile module), that didn't allow a direct correlations between the surface and depth movements but it has however allowed the precise identification of the shear band and the movements quantification.

In the meantime the University of Milan made a modeling of the collapse in order to verify spread models and propose preliminary warning thresholds.

This monitoring network has permitted to acquire and analyze data collected for more than three years. During this period Val Genasca landslide showed 7 different accelerations with static period intervals. Last acceleration, dated winter 2013/14, showed a 5 meters displacement, measured on the surface along the maximum displaced vector.

The data analysis showed that the shear band affected a thickness of about 15 meters and permitted to estimate in about 500.000 cubic meters the landslide volume in movement. The topographic data allowed to define a kinematic motion of a typical rotational slip with the values of lowering higher in areas near to the main scarp compared to those positioned in the lower part.

Fig. 1
Map of the area

Key words: landslide, geological monitoring, Lombardy, Genasca

INTRODUCTION

The "Val Genasca" landslide is located in the hydrographic right side of the valley in San Giacomo Filippo (Sondrio district). The territory of San Giacomo Filippo delimits the Southern borders of the well known Vallespluga, the north-western side of Sondrio district and, in general, the Lombardy entire area. (Fig. 1).

After some evidences of instability, in June 2010 the Local Authorities asked ARPA Lombardia to verify and monitor the situation on the slope. Below we will give account of the method used in the study of the collapse and its first results.

GEOLOGICAL SETTING

The Spluga valley, where Val Genasca landslide is located, is characterized by stacking of nappes belonging to the domain Pennidic Superior. More specifically, the slope of the landslide is characterized by rocks belonging to the Tambò formation stretching with trend southeast-northwest for about 25-30 km with a thickness of about 3.5 km (Mazzoleni, 2011). In the southern part of its base the Tambò formation is intruded by granitoid Truzzo metagranite, a Permian mass coeval to Roffna porphyry (Marquer *et alii*, 1998). The lithologies on site are micaschist unit (at higher altitudes) and the Unit of Truzzo Metagranite (in the lower part and on the valley bottom). The morphology of the slope is mainly due to the instability and deep gravitational movements (DGPV) of the area.

With particular reference to the collapse of Val Genasca, it was possible to acquire some information covering the period 2003-2010 prior to the installation of the monitoring. More specifically, after the rain event dated June 7th 2003, the Lombardy Region, Direzione Generale Territorio ed Urbanistica, carried out a survey (August 28th 2003) well summarized by Dr. Dario Fossati: "some landslides with a volume of some thousands of cubic meters moved in the lower part of the river Genasca, Val Scura and Tettavacca about 650 m above sea level". Subsequently, with the report dated September 1st 2006, the Lombardy Region updated the situation by informing that "an area between the isoline 850 and the confluence with the river Liro has been investigated. [...] In the range between 750 and 600 m above sea level, long fractures were detected with heights up to 5-6 meters which demonstrate the widening of a landslide (complex landslide with falls, slides and debris flows) in constant evolution. The material affected by the motion is on the whole estimated in 250,000-350,000 cubic meters [...]" (Ceriani, 2006). Further updates were recorded in May 2009, when a new line of fracture is inspected: "it is the reactivation of a landslip [...] it was possible to highlight the retrogression of the landslide with the formation of a new crown from altitude 824 m above sea level [...] The landslide is more marked on the left side, with heights that reach two meters and involve a total volume estimated in more than 200,000 cubic meters [...] Given the steepness of the slope and the geomorphological situation, it is very likely that the landslide may further evolve." (CERIANI *et alii,* 2009).

First report of ARPA (DEI CAS, 2010) highlighted since the beginning the presence of springs with variable flow, substantially in line with the isoline of 630/650 meters above sea level, located at the contact between bedrock and overlying deposit.

A summary of these events is attempted on the basis of aerial photographs by the University of Milan (Prof. T. APUANI), in relation to the agreement with ARPA Lombardia concerning activities of geotechnical modelling and identification of critical thresholds, which states that the first event of slippage has started between 1994 and 2000 (Fig. 2a-e). Subsequently, the instability has evolved involving portions of the slope upstream and along the sides, showing in the end a trend of evolution as retrogressive landslide and in enlargement.

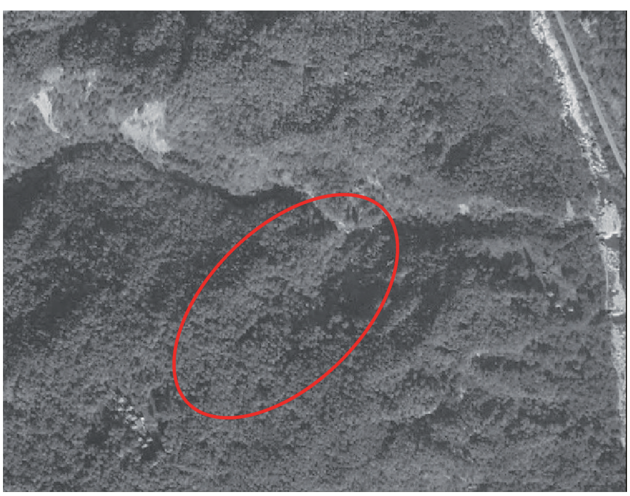

Fig. 2a - Aerial view 1994: orthophoto Environment Ministry

Fig. 2b - Aerial view 1999-2000: orthophoto IT 2000 (* photo Blom CGR Spa)*

Fig. 2c - Aerial view 2003: orthophoto IT 2000 (* photo Blom CGR Spa)*

Fig. 2d - Aerial view 2006: orthophoto IT 2000 (* photo Blom CGR Spa)*

Fig. 2e - Aerial view 2008: Aerial photo, DB Sondrio Municipality

METHOD

As mentioned in the introduction, from summer 2010 ARPA initiated a series of checks on the area aimed at deepening the knowledge and then to the installation of a real-time monitoring.

The method of work was necessarily modelled on steps, starting from the creation of a monitoring of knowledge (Dei Cas, 2011), and then allow (steps 1 and 2), where it was revealed the need to develop the network until to make it become a monitoring for the purpose of alerting and for the activation of civil protection plans (steps 3, 4, 5 and 6). This gradual approach has also allowed gradually acquired knowledge on the dynamics of the collapse could better address the following insights and allowed to develop intervention in line with the available budget (the total amount has been allocated over several years). In relation to that, after an initial identification of areal phenomenon, it was decided to identify the main kinematic characteristics so that can be possible to later install a suitable sensors that allow to follow in real time the evolution of the landslide. The knowledge of the subsurface, modeling and comparative analysis of the main movements were the last step of the project. In detail, the work can then be divided into six phases:

1. Geological survey and main findings of fractures
2. Installation of cognitive monitoring:
   a. Control of movements of the main fractures through distometric measures
   b. Control of global movements through topographic measures
   c. Control of back movements with GPS
3. Installation of real time monitoring:
   a. Installation of a meteorological station
   b. Installation of 3 extensometer
   c. Installation of automatic topographic system (Figg. 3 e 4)
4. Advancing geological knowledge of the subsurface:
   a. Geophysics
   b. Drilling and monitoring implementation design
   c. Drilling and coring
   d. Analysis of samples taken
5. Landslide Modeling and first threshold values[1]:
   a. Creation of detailed topography
   b. Modeling of landslide evolution
   c. First alert thresholds based on the instrumentation on the surface
6. Installation of deep monitoring:
   a. DMS, piezometer and inclinometers

A PTZ camera for visual inspection by remote area of the landslide was installed in addition to what has been done so far. The system was designed to activate and record when morphology changes are detected (change detection), considering the importance of having visual information as well.

[1] *It is evident that the process of modelling and definition of critical thresholds is by its nature a procedure always updating as the sets of ever-increasing movement data are acquired. In particular, an update of the modelling and thresholds will be compulsory as soon as it's possible to have a significant number of data acquired by the sensors.*

Fig. 3 - Automatic topographic station

Fig. 4 - Topographic target in landslide

SOLUTIONS IN PLANNING / IMPLEMENTATION OF THE MONITORING NETWORK

STEPS 1 and 2: after a careful survey of the slope movement it was possible to place 5 distometric chains to control the movements of the upper side, located in the middle part of the main scarp and on both sides, left and right parts of the landslide. These distometric chains, positioned along the line of maximum movement (substantially N-NE, orthogonally to the individual micro areas isoline), have taken into account the possibility of measuring in a different way both the movements of the main scarp (if present) and the back fractures. At this stage, with the support of Mountain Guides, a series (Fig. 4) of optical reflectors (both inside and outside the estimated maximum movement area) were placed to allow control from the opposite side. A concrete milestone has been built on the opposite side for the execution of topographical measurements, it has been specifically anchored to the rock, and made integral with the anchor plate for the positioning of the measurement equipment. Two master references were placed outside the landslide, with the aim to achieve the maximum measurement accuracy. Finally, some targets for recurrent manual measurements with GPS dual frequency detector (rover) were placed in the rock on the back of the main scarp, in order to quantitatively assess back movement of the landslide. The GPS reference was located on the opposite side, close to the topography measure building. The accuracy expected from these measures, albeit lower than that of topographic measurements, allows, once a topographic reflector is also equipped for GPS measurements, a mutual verification between the data acquired with different techniques (Fig. 5).

STEP 3: this network and 14 manual measurement campaigns in the period August 2010-January 2011 allowed the technicians of the CMG to precisely define the area affected by movements and to estimate their speed. In connection with these results, it was possible to identify the most significant points of the entire movement and to implement a extensometric monitoring in real time.

In step 3 only 3 of the 8 distometric bases previously positioned were automated (this was meant to limit costs without losing any significant information). The electrical signal of the extensometer, transmitted through cables to the data logger positioned at the back of the scarp, is transmitted via GPRS to the ARPA server. A sensor for the measurement of snow level on the ground, a thermometer and a rain gauge were also installed on the same station for a complete monitoring of meteorological variables.

The location of topographic measurement has been structured to perform continuous measurements for a more extensive control of the landslide surface. In this regard, after bringing the power line to the point of measurement, a shelter for the station with an anti-theft system (Fig. 3) was built. A series of measurement points on the area of the landslide have been implemented so as to be able to monitor, in addition to the whole landslide, even the areas nearby.

STEP 4: Fourth step, carried out in parallel with the third was the planning and execution of a geophysical survey required to identify the bedrock beneath the landslide body. The bibliography didn't permit to define any kind of geological data derived from direct surveys (drilling) or indirect (geophysics), which allow to produce a model of the slope.

In relation to this, and to the assumed considerable depth to investigate, a prospecting seismic refraction tomography data processing was chosen.

The analysis of the results obtained with the seismic survey has allowed to plan a deep geological survey and subsequent monitoring. This project was developed taking into account that it had to meet multiple needs summarized as follows:

a) To have at least two stratigraphies on which to calibrate the geoseismic survey;
b) To have three points of measurement to study the groundwater piezometric level;
c) To have three holes to check where the deep movements are (inclinometer measures). Lacking any information about the behaviour of the deposits identified by geoseismic, these verticals must reach the bedrock;
d) To have the ability to measure and transmit in real time the most depth data acquired;

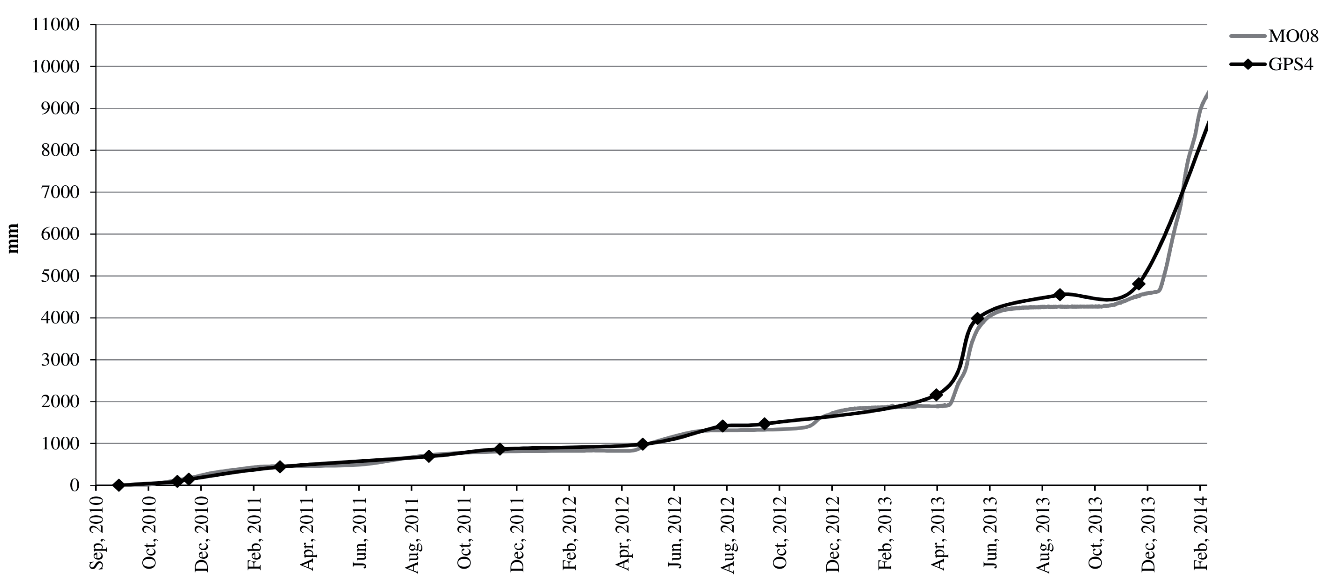

Fig. 5 - comparison between optical and GPS target

e) To have the best guarantee of long-term accessibility to the vertical drills taking into account that the landslide had decimetric movements in a short period (30 days);
f) To consider the nature of places and therefore the impossibility to reach the landslide with a street;
g) To consider the non-optimal slope sun exposure.

In relation to the above requirements, five drillings were planned (two with soil coring and three with soil destruction) located immediately upstream of the main scarp (the first two), in the middle of the landslide (the third) and in proximity of the lower scarp (the last two). In order to bring the equipment needed for the execution of the perforations to the landslide site, it is planned to repeat the process of disassembly / reassembly borehole drilling machine and subsequent transport on the survey points by helicopter. The two vertical drills upstream of the main and lower scarps are designed for the laying of the inclinometer tube and piezometer tubes for manual measurements.

The drilling placed at the center of the landslide body was instead designed with PVC pipe where to drop a multiparametric column (DMS Giuffredi, 2003) with features so as to withstand high strain. In order to limit the maximum costs, but knowing that the movement can be at any depth, the column has been designed with an alternation of DMS modules and empty modules. Obviously, each part is connected with the others in order to preserve and transmit the movement. The column was connected to a low voltage (12-24 V) electric line starting from upstream of the main scarp to the center of the landslide.

STEP 5: simultaneously to the stages of investigation, the University of Milan was asked to prepare a first model to identify the consequences of a possible landslide spread on the valley. The University has also been in charge of a detailed topographical slope construction needed to run landslide models. Prof. T Apuani, the University project manager, carried out a modeling after the creation of a digital terrain model based on the topographical construction of the slope, using the computer code Flow2D. The choice of the University was to model the movement of the masses potentially unstable as a debris flow with a high concentration of solid, characterized by high viscosity and a yield strength.

STEP 6: drillings showed an underestimation of geophysics in relation to the depth of the bedrock. In relation to this, the inclinometer tube upstream of the high scarp has been realized up to a depth of 130 meters and the DMS column to a depth of 102 meters from ground level. These economically burdensome design changes resulted in the abandonment of the holes placed at lower altitudes; a total of 3 drillings have been carried out with the possibility of having two distinct measurement points for both the water level and for the possible deep movements (respectively, one manually upstream of the main scarp and one automatically in the middle of the landslide).

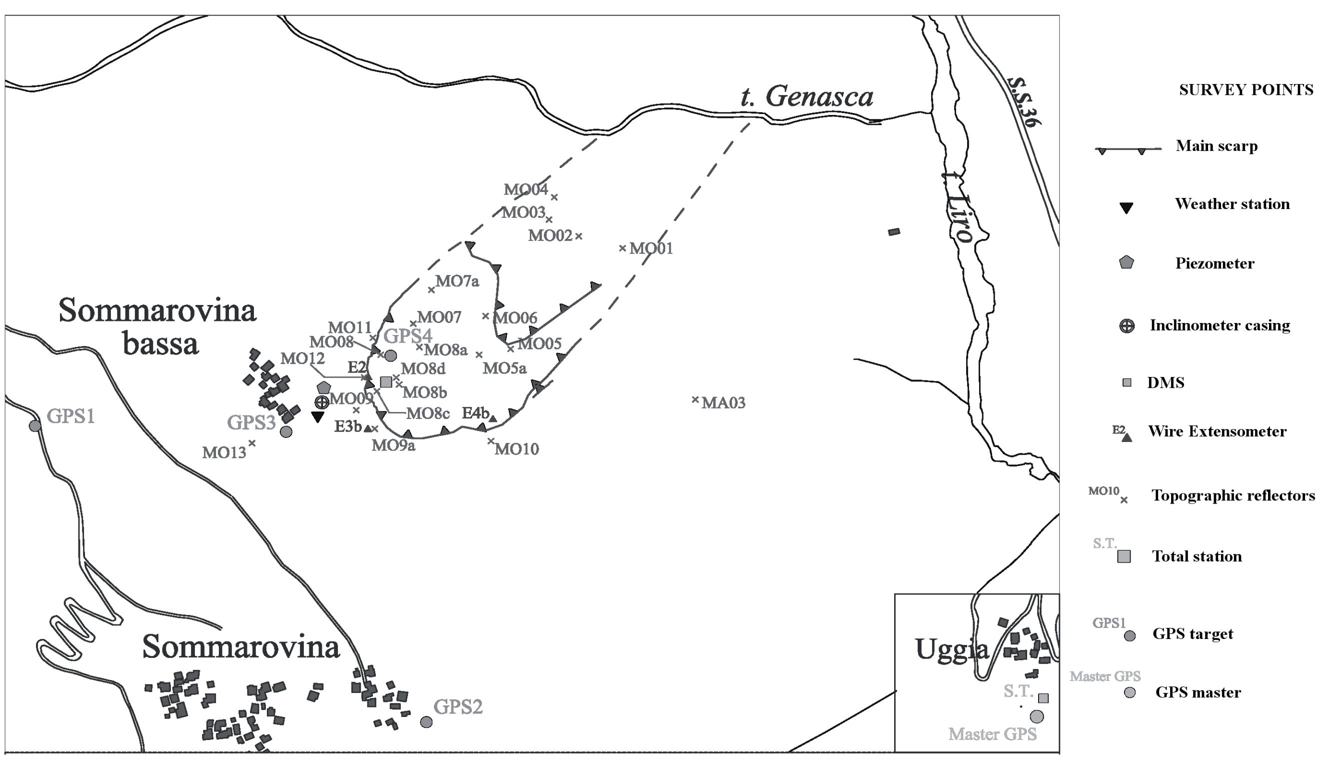

Fig. 6 - Map of installed monitoring network

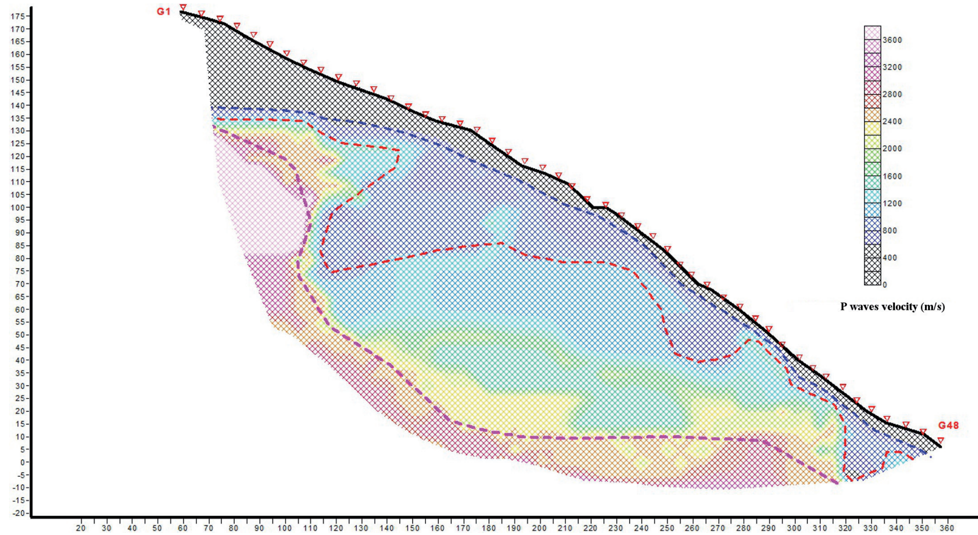

Fig. 7 - Seismic profile along the slope line of the landslide (CIS Geofisica s.r.l. 2011)

DATA

After about 44 months of investigation and acquisition of motion data, a great number of useful information for the interpretation of the phenomenon have been collected. The principal will be explained below:

GEOPHYSICS

Two measure lines located along the middle profile of the landslide and the around median high isoline were carried out in July 2011. The results of the two profiles (Fig. 7) allowed the identification of four geoseismic units with different features.

STRATIGRAPHY

ARPA has developed a drilling project that would allow to investigate and subsequently equip with inclinometer tubes, piezometric tubes and DMS column, some vertical drills upstream and within the landslide. The stratigraphy, obtained from continuous core drilling, relative to the survey site upstream of the main scarp of the landslide (survey up to 130 meters from the ground level) and within the landslide (survey up to 102 meters from ground level) showed a powerful non-consolidated coverage both upstream and downstream of the scarp where a layer underlies, interpreted as an ancient slide deposit, consisting primarily of crushed rock and broken blocks with interbedded sand and silt. In both holes, before reaching the weathered rock (consisting of mica schists and altered paragneiss) and the bedrock, there is a level, with a bigger thickness in the landslide, which consists mainly of silt (Fig. 8).

MOVEMENT DATA OUTSIDE MAIN SCARP

A series of GPS and optical targets for topographic measurements were placed upstream of the main scarp from August 2010 in order to establish the area with greater movement and to quantify any back movements of the landslide. GPS points 1, 2 and 3 and the

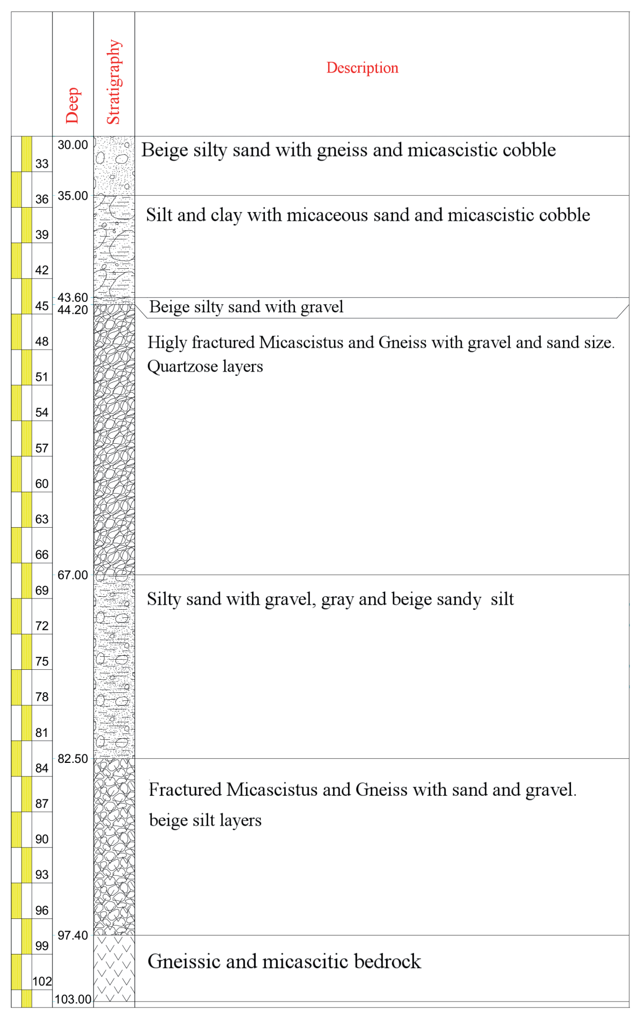

Fig. 9 - Stratigraphy of center landslide drilling (In.Co srl 2013)

Fig. 8 - Silty layer found in the center landslide drilling at depth between 67.00 and 82.50 m

optical targets MO9, MO9A and MO13 (these last two positioned in December 2012) were positioned upstream the upper scarp.

Downstream of the low scarp, between 610 m and 640 m above sea level, optical targets MO1, MO2, MO3 and MO4 have been positioned in order to monitor any movement of the outcropping bedrock (Truzzo Metagranite).

With reference to the upstream side of the landslide, after over 10 measurements GPS points have not shown displacements greater than the range of accuracy that can be expected from a periodic manual measurement system located in this area with static process.

The optical targets positioned a few meters upstream of the scarp show very low annual movements (Fig. 10).

Also points placed to control the outcropping bedrock below the area in greater movement do not show any appreciable movements (Fig. 11).

In December of 2012 some targets (MO10, MO12 and MO11) were also placed to control any widening of the area affected by the movement. Hereinafter the graph (Fig. 12).

MOVEMENT DATA INSIDE THE MAIN SCARP

Surface movements can be well explained by analysing the topographical displacement vector determined for each target positioned in the landslide (Fig. 13).

Additional data are supplied by the distometric measures on the opening of the main fracture delimiting, without interruption, the landslide area underlying the upper scarp (30,000 sq. m).

In the figure 14, measures derived from the 3 main lines (located in the altimetrically higher part of the main scarp and

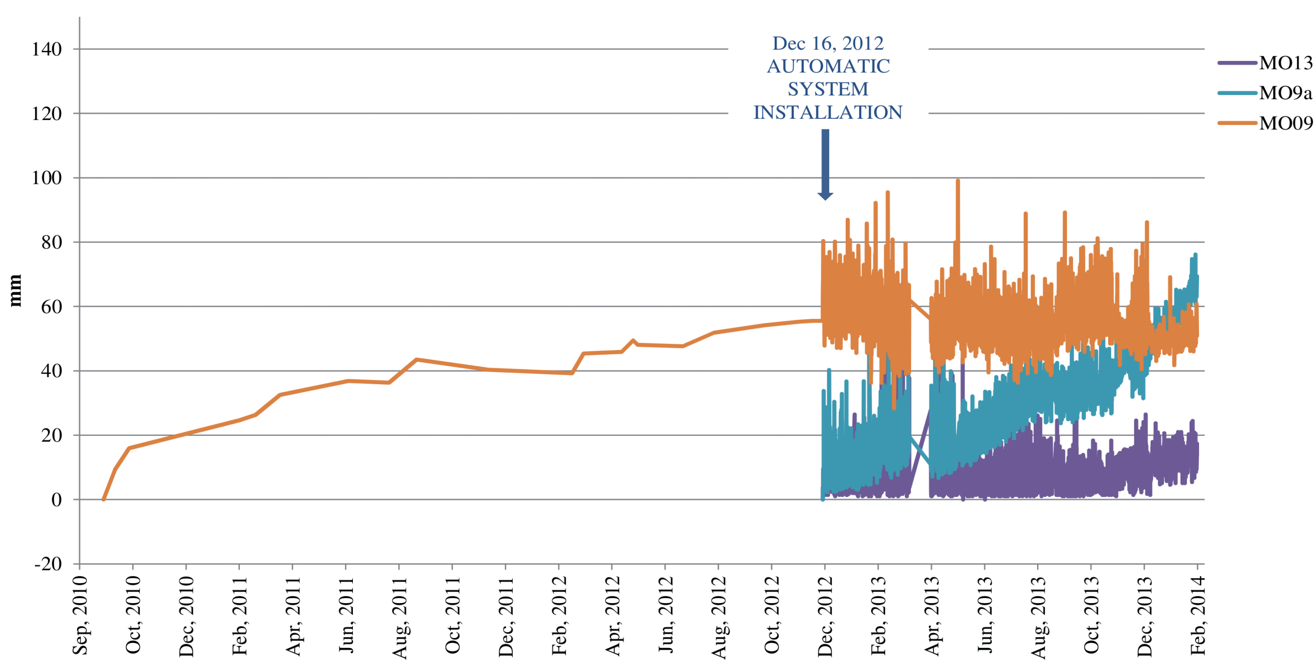

Fig. 10 - Movement of topographic target upstream the main scarp

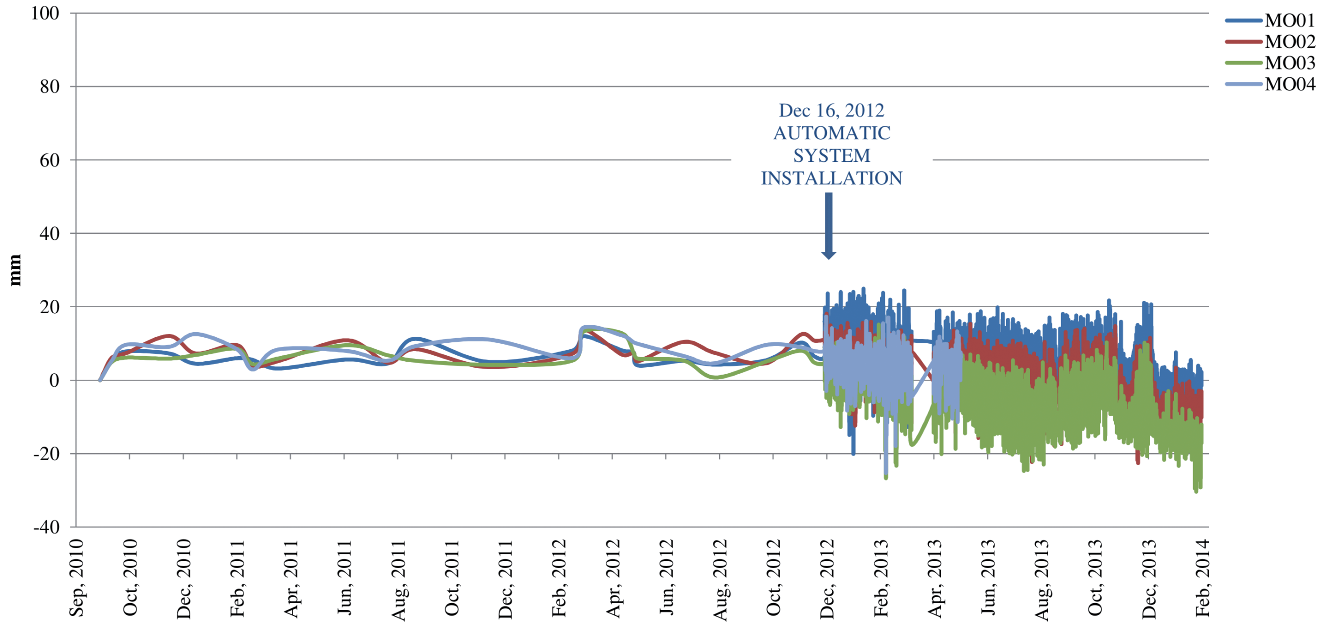

Fig. 11 - Movement of topographic target downstream the lower scarp

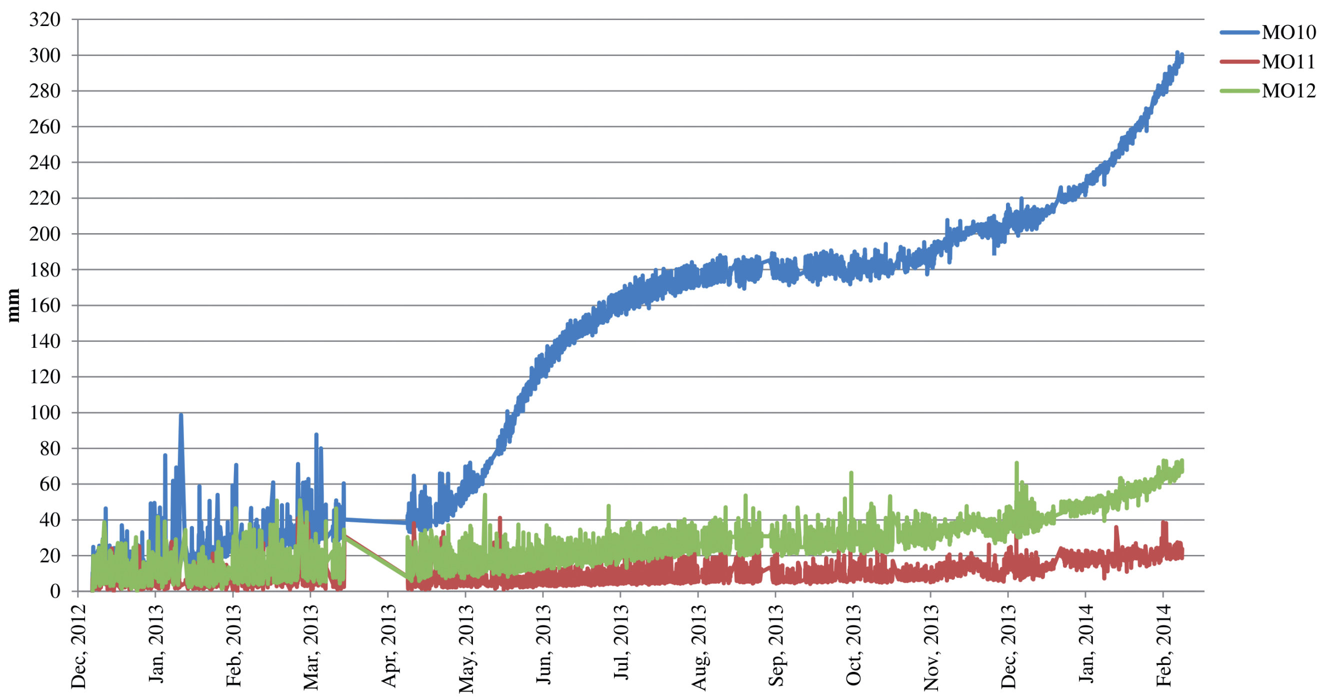

Fig. 12 - Movement of topographic target on the lower scarp sides

symmetrically in the middle part of the right and left sides of the fracture) are correlated with the cumulative rainfall as recorded by the rain gauge, which is located upstream of the landslide, and it is active since February 2011.

From the analysis of the chart above, would seem evident is some correlation between the value of cumulated precipitation within 30 days and the beginning of the events of acceleration.

The event of December 2013, as well as being the most par-

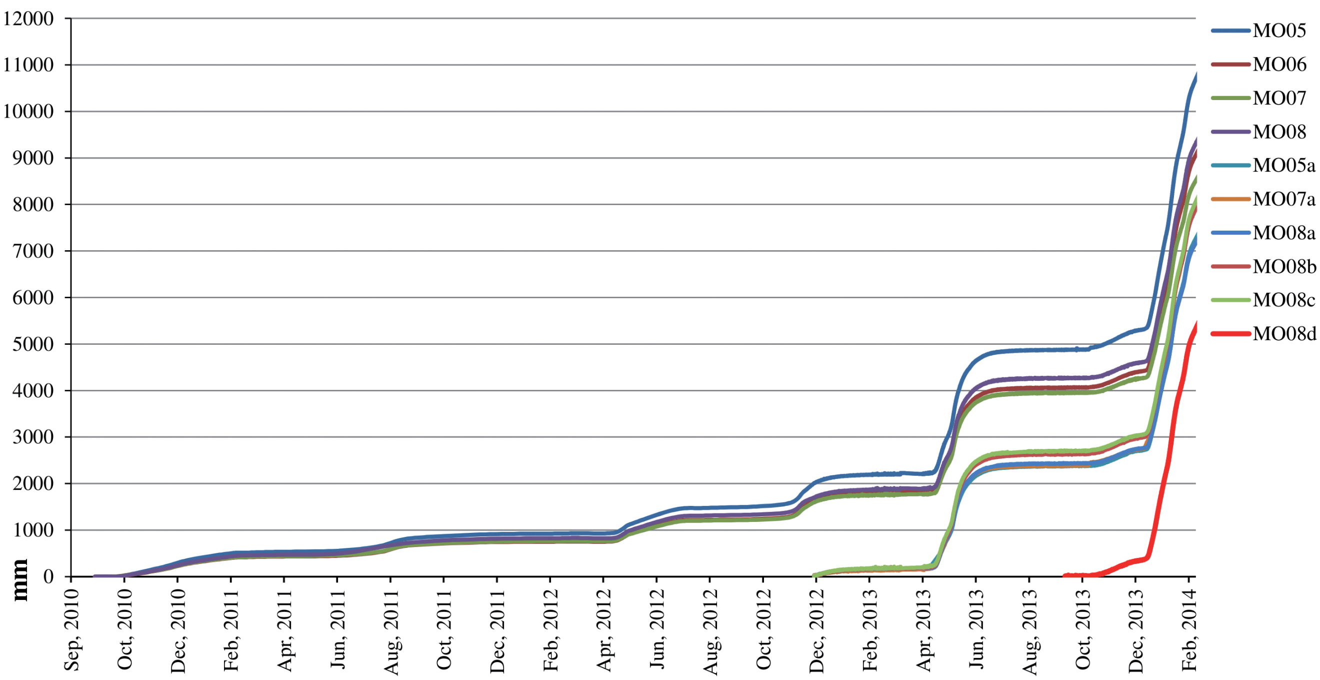

Fig. 13 - Movement of topographic target inside landslide

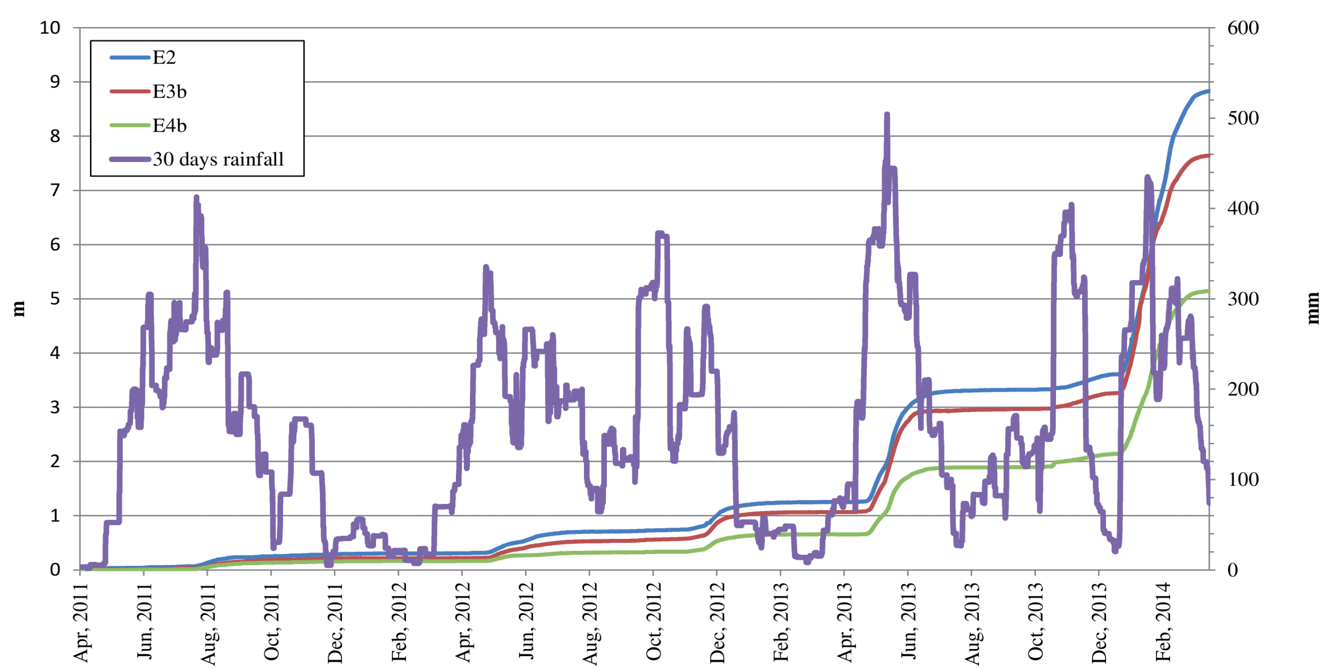

Fig. 14 - Extensometric data (left ordinate axis) and rainfall in 30 days (right ordinate axis) vs. time

oxysmal, is related to the passing of 200 mm of rain fallen in two days prior to the start of acceleration.

FIRST INCLINOMETER AND PIEZOMETRIC DATA

Since August 2013 it was possible to acquire the first data related to the depth movement and to the increase of the water level. Although the period is very limited, it is interesting to make

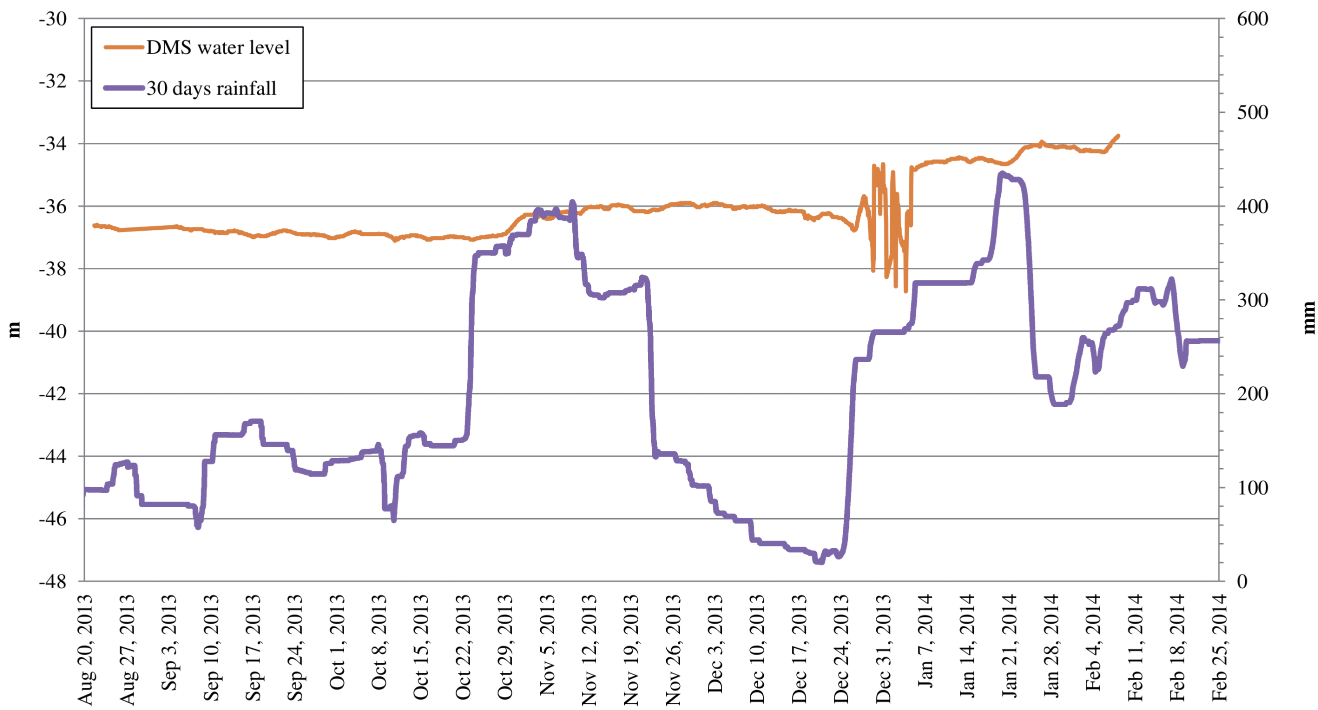

Fig. 15 - Water level measured (left ordinate axis) by DMS and rainfall in 30 days (right ordinate axis) vs. time

some remarks. First of all, we observe that in a rather dry period (in September and October), the water level is constant, close to the DMS, at a depth of about -37 m to ground level. The heavy rainfall in late October (205 mm in 7 days) had led to a rise (about 1 meter), which occurs the 6th day after the intense precipitation. For more than 1 month the water level remains at a depth of -36 m to ground level; when the water table lowers to share -37 m to ground level, there are very serious precipitation on the area, with around 210 mm of rain fallen between December 24th and 25th 2013: next rise is about 2 meters. In this last period, the delay between water level raising and rainfall appears almost non-existent, with the water level which begins to rise during the precipitation (unlike October when the elevation is with 6 days of delay). Also in this case the water remains at an high level well beyond the period of rain.

The rise of about 2 meters from October level is also confirmed by measurements made in the manual piezometric tube placed upstream of the landslide.

As for the deep movement, the graph shows an acceleration during the period October 2013 - February 2014 (Fig. 17); it is interesting to notice that during the period December 26th 2013 - February 8th 2014 after a first phase (December 26th to January 4th), characterized by movements only on the top, down to -30 m from the ground level, with a total displacement of about 35 cm, starting from January 5th the deformation affected, albeit with lower gradient, even the deepest part. In the first 8 days of Febru-

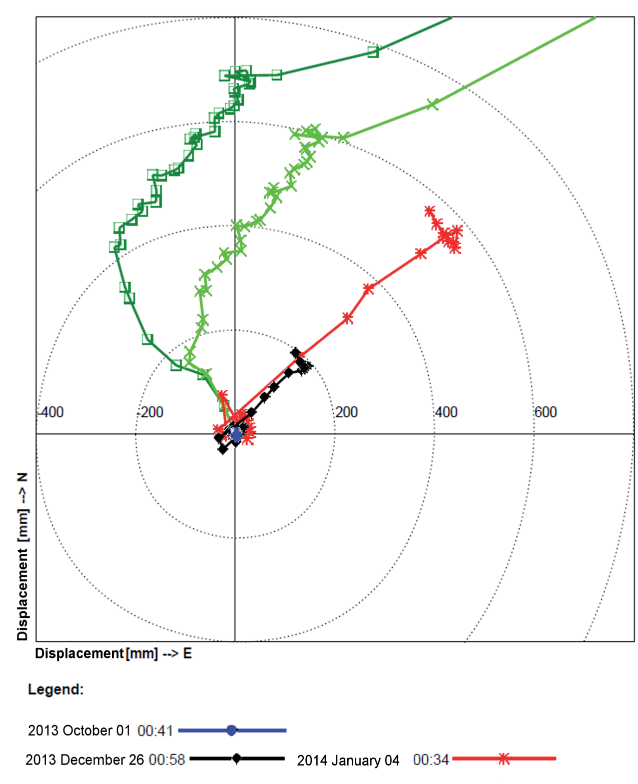

Fig. 16 - DMS polar diagram

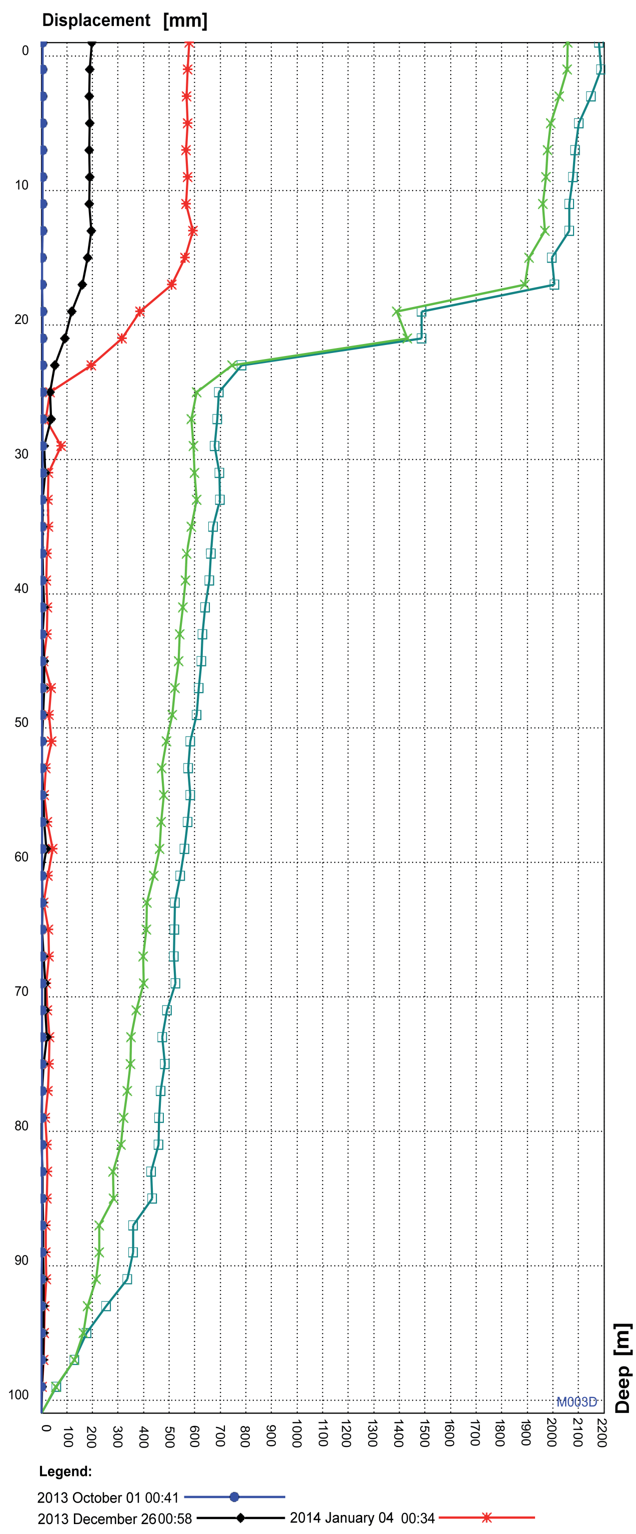

Fig. 17 - DMS Cumulative displacement DMS from October 2013 to February 2014

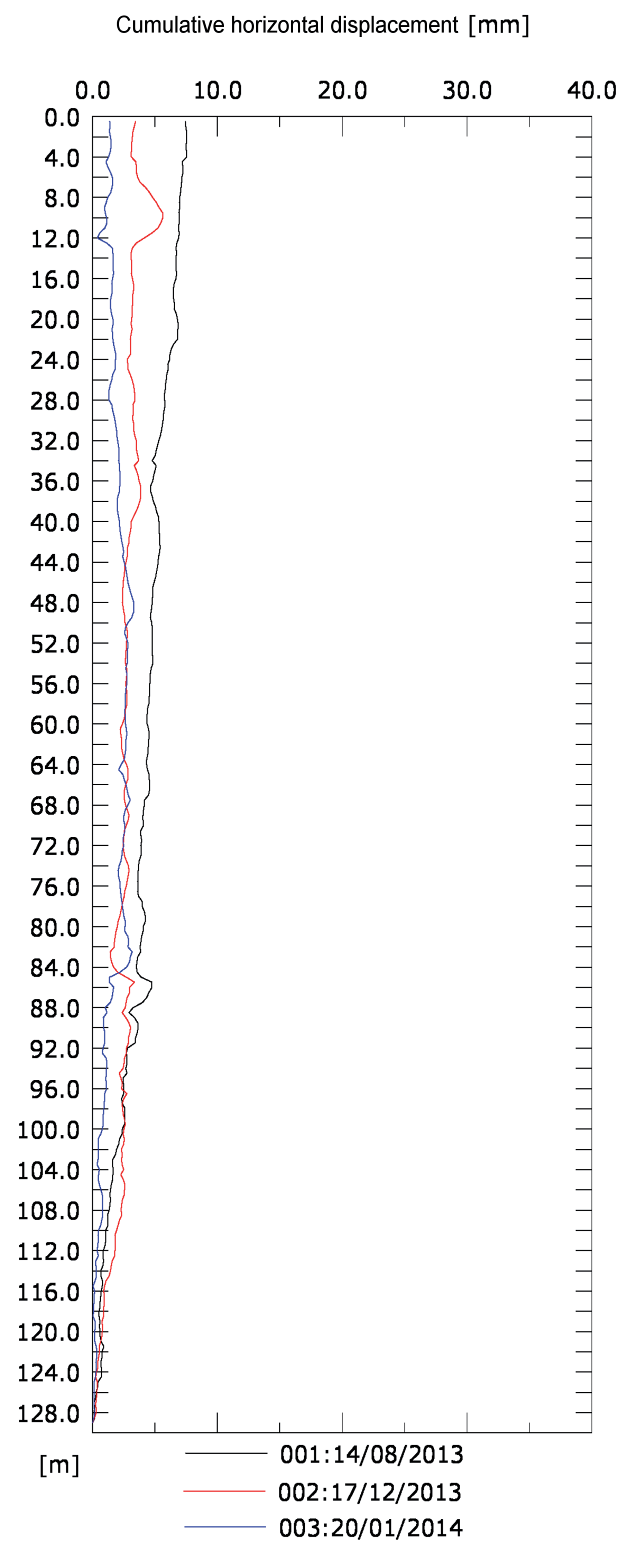

Fig. 18 - I3 inclinometric cumulative displacement

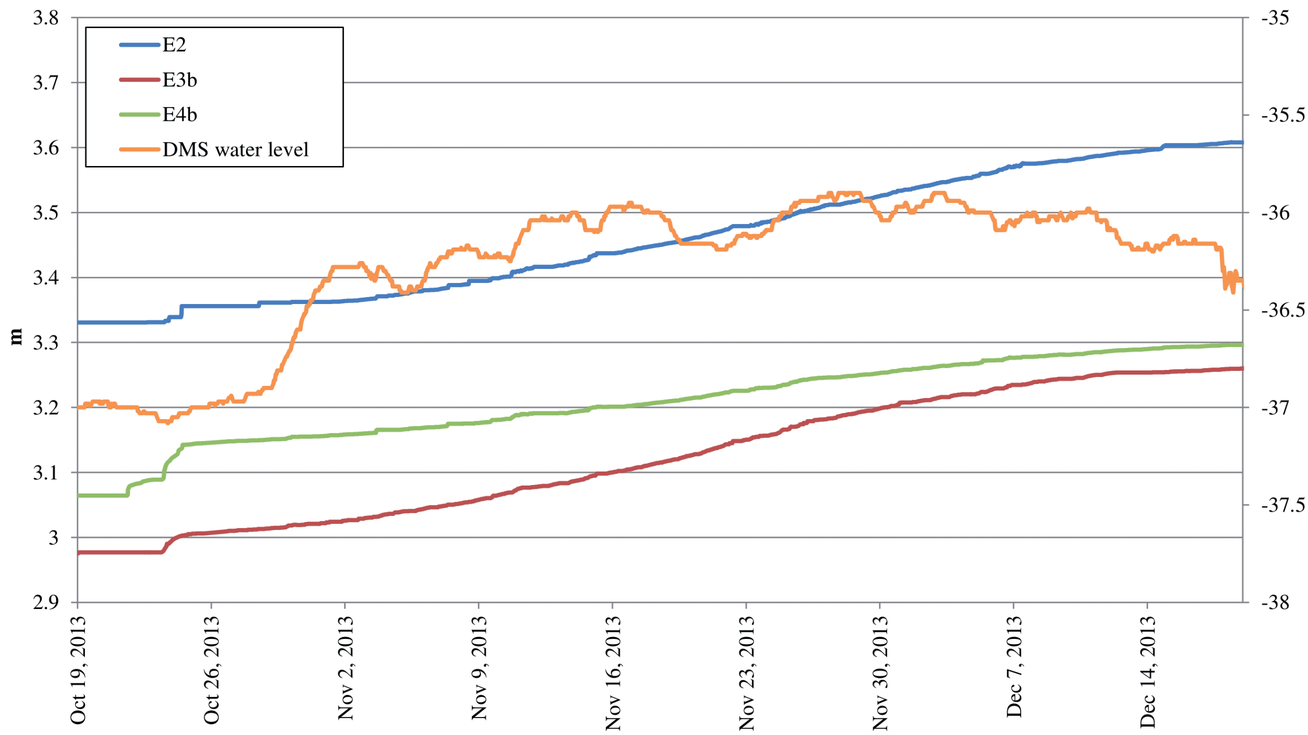

Fig. 19 - Water level (left ordinate axis) vs. extensometric data (right ordinate axis) from October 19 to December 18 2013

ary, while the remaining part of the column showed almost zero movements, a movement of about 13 cm has involved a band between 90 and 95 meters from ground level. The movement of this small section of the column has assumed a direction orthogonal to the movement (55° North) found by the whole column so far and, also in this period, from the top of the column (Fig. 16). It is possible that the deepest movement observed from February involve the lower part of the inclinometric column, installed in bedrock.

It is important to report the graphs produced on the basis of the first inclinometer measures carried out by technicians of ARPA CMG (Fig. 18) in the hole called I3, upstream of the upper scarp.

During the acceleration of November 2013 piezometric data were also available. It is observed that the movement (both in surface and in depth) occurs, after a sudden acceleration during the precipitation, with a delay of about 6/7 days from more intense precipitations (Fig. 14) and continues for a period of about 25 days compared to decrease of cumulative rainfall values. The piezometric data shows that the beginning of the movement coincides with the raising of the water level (Fig. 19).

Even the acceleration of December 2013-February 2014 is observed in conjunction to the raising of water level. The slowdown began in the second half of February (after the break of the piezometric module of DMS); the piezometer PZ3 upstream of the landslide shows the lowering of the water level at deceleration (Fig. 20).

INTERPRETATION AND DISCUSSION

As it can be deduced from the data reported in the previous paragraph, the moving area is estimated at 30,000 square meters with the crown at 830 m above sea level and foot at 640 m above sea level. In about 3 years of active monitoring, landslide showed 7 accelerations, which have affected simultaneously the entire area of 30,000 square meters, with periods of stasis or even static.

In this interval the overall displacements measured at the surface have been of about 9 meters along the surface vector of maximum displacement. Half of this movement has occurred within 50 days of the winter 2013/2014, while, if we consider a longer interval, we can say that 80% of the movement (7 meters) was observed between May 2013 and February 2014.

As shown in previous sections, all seven accelerations occurred as a result of large amounts of rain fallen on the area. The accelerations have had a velocity increasing over time: while the first 4 accelerations and the sixth had comparable velocity, the fifth and the seventh have been completely out of scale (Fig. 21).

From the analysis so far, the motion is detected, at the DMS, at a depth of 13 to 27 meters from ground level (Fig. 17).

It is not a conventional motion surface with a thickness of 2 or 3 meters, but in this case the shear band affects a thickness of about 15 meters (Fig. 23).

The topographic data allow to define a kinematic motion of a typical rotational slip (Cruden & Varnes, 1996): the values

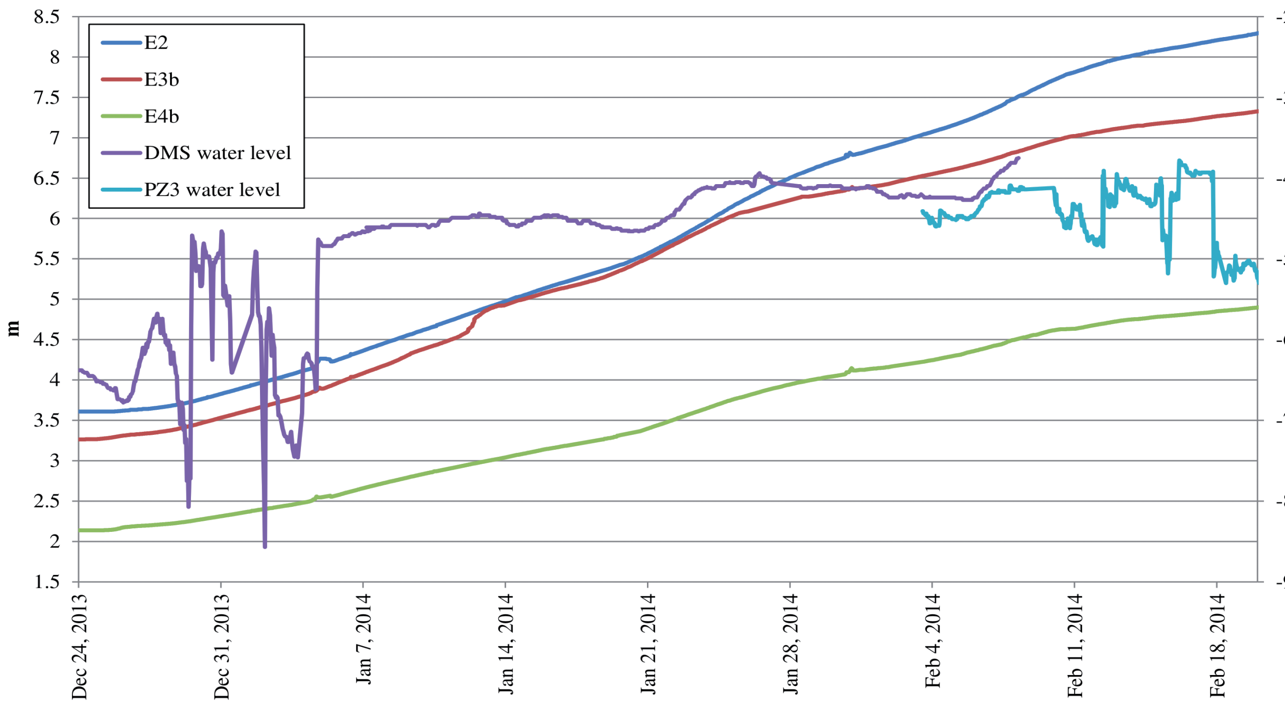

Fig. 20 - Water level (left ordinate axis) (measured by DMS, after his break by PZ3) vs. extensometric data (right ordinate axis) from December 24 2013 to February 20 2014

EVENT/PERIOD	DURATION (DAYS)	SENSOR	MM	MM/DAY
1 (aug/sep 10)	31	D2	35.15	1.1
	31	D3	47.32	1.5
	31	D4	15.2	0.5
2 (aug/sep 11)	37	E2	166	4.5
	37	E3	119.4	3.2
	37	E4	98.4	2.7
3 (may/jul 12)	73	E2	370	5.1
	73	E3	284.9	3.9
	73	E4	143.2	2.0
4 (nov/dec 12)	56	E2	438.9	7.8
	56	E3	437	7.8
	56	E4	282.4	5.0
5 (apr/jun 13)	59	E2	1974.7	33.5
	59	E3	1846.5	31.3
	59	E4	1203.1	20.4
6 (oct/dec 13)	56	E2	276.9	4.9
	56	E3	282.9	5.1
	58	E4	231.9	4.0
7 (dec/feb14)	58	E2	4727	81.5
	58	E3	4091.5	70.5
	58	E4	2785.4	48.0

Fig. 21 - E3 gradient in the 7 measured events

of lowering are higher in the areas closer to the crown (MO8a, MO8b, MO8c, MO8d) compared to those positioned in the lower part (MO5, MO5a, MO6, MO6a) (Fig. 22).

The specific configuration (alternation of a module DMS with a sterile module), used to minimize the costs of the DMS column, does not allow direct correlations between the surface movement, detected from the target optical MO8D, and the cumulative shift detected in depth (Fig. 24). The alternation of the modules has, however, allowed us to identify with precision the shear band and to quantify movements.

Despite this direct correlation is not possible, and it is evident an underestimation of the displacement given by the DMS column in relation to the target placed at the head of the hole (MO8d), however, it is currently possible to exclude movements involving the bedrock at a depth greater than that of the inclinometer column, as the data of the optical targets, on the sides and upstream of the main fracture, show no significant movement (only MO10 shows recall surface movements - Fig. 12).

DMS data show deep movements with displacements of few meters (the column was interrupted in conjunction with a shift in the measured area of approximately 4.5 meters).

The analysis of the collected data, in addition to the geophysical and stratigraphic available data, has allowed the construction of a geological model that can be well outlined by the section of Fig. 23. An area of 30,000 square meters, bounded upstream and on the sides by the main fracture and downstream by the emergence of some springs, moves with subsequent gradually higher accelerations. A sliding surface, easily recognizable in drilling

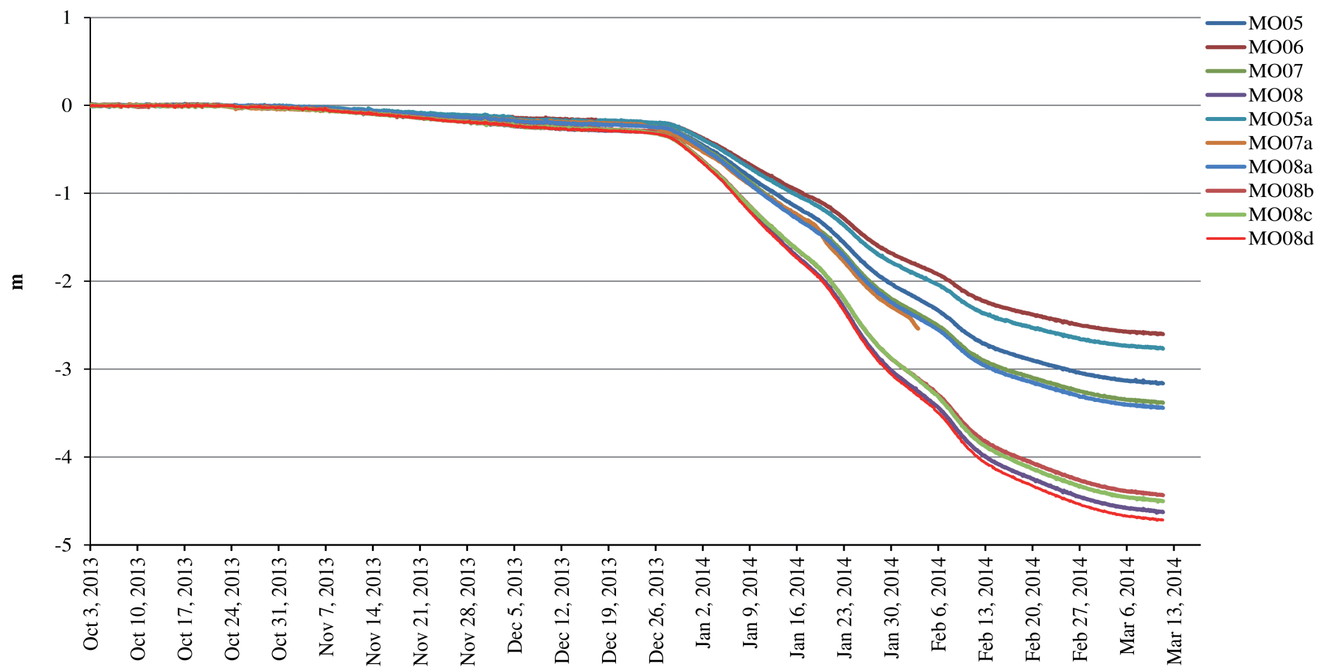

Fig. 22 - Topographic values of lowering

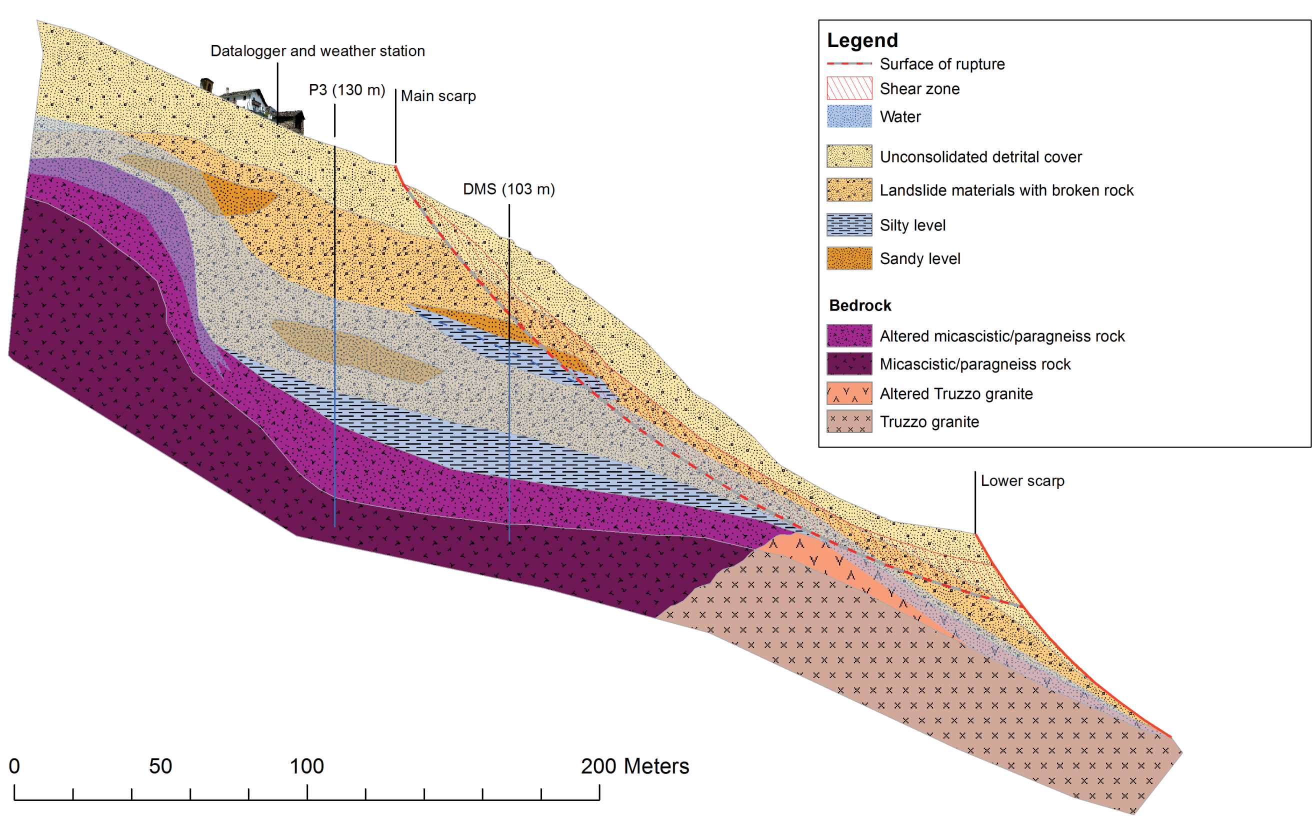

Fig. 23 - Interpretative geological section

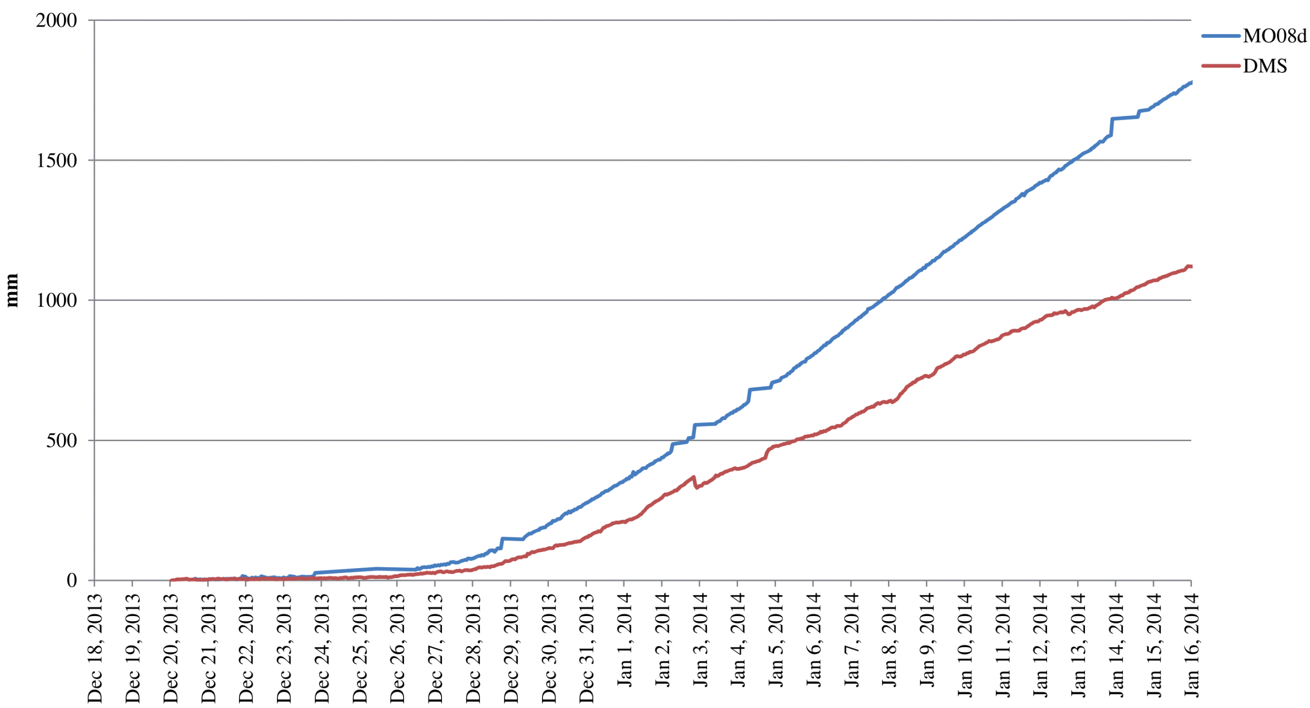

Fig. 24 - MO8d topographic target movement vs. DMS total shift (from 12.18.13 to 01.16.14)

Fig. 25 - Frontal view of landslide; snow highlights springs in the lower sector

stratigraphy, bounded downstream from contact with the bedrock close to the water springs (Fig. 25) is present on the bottom. On the basis of this model, the volume of paleo-landslide has been estimated at 500,000 cubic meters that, in conjunction with a rise in the water table of about 2 m, showed movement during the period December 2013- February 2014. At depths greater than 30 m and up to the bedrock, substantial movements were however observed (Fig. 17) albeit considerably lower than the upper part. Also in relation to the observation on the different direction shown by the deepest part of the column, it will be important to continue with deep monitoring activities.

The evolution of the instability can occur with subsequent acceleration cycles (concurrent with rainfall events that cause a rise in the water level), which, without leading to the sudden detachment of the entire mass, cause a progressive slide of the lower crown as happened in May 2013 and in the winter of 2013/2014. One paroxysmal scenario, but that cannot be excluded, is the simultaneous sliding of the entire mass (estimated, according to the most recent event, in about 500,000 cubic meters) with subsequent formation of a dam (the model proposed by the University shows thickness of accumulation of 30 meters) in the bed of Liro torrent. This scenario needs to be deeply examined for the interactions with civil protection planning.

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