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GALLIVAGGIO LANDSLIDE: THE GEOLOGICAL MONITORING, OF A ROCK CLIFF, FOR EARLY WARNING SYSTEM

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EXTENDED ABSTRACT

La parete rocciosa di Gallivaggio, ubicata nel territorio comunale di San Giacomo Filippo (SO), è monitorata dal Centro di Monitoraggio Geologico di ARPA Lombardia (d'ora in poi CMG) dal 2011. In quell'anno Protezione Civile di Regione Lombardia (d'ora in poi P.C.) dopo aver contributo alla costruzione di un lungo vallo in terra (con rete paraschegge al vertice dello stesso) decise di chiedere ad ARPA l'installazione di un sistema di monitoraggio quale ulteriore presidio di sicurezza. Nel corso degli anni precedenti si era infatti manifestato il crollo di singoli blocchi rocciosi e ciò aveva suggerito un approfondimento delle conoscenze circa la situazione di staticità dell'intera parete, costituita da Metagranito del Truzzo appartenente alla Falda Tambò. Una tale attenzione è stata determinata dalla forte antropizzazione presente al piede della parete rocciosa di Gallivaggio. In tale area sono presenti numerose strutture antropiche e luoghi di culto che accrescono la presenza temporanea di persone; possiamo trovarvi lo storico Santuario della Madonna di Gallivaggio (costruito nel XVII secolo), un ristorante ed alcune abitazioni private oltreché il passaggio della Strada Statale 36 che collega il lago di Como alla Svizzera per il tramite del Passo dello Spluga.

Durante i primi anni di gestione del monitoraggio il CMG ha raccolto importanti dati che hanno permesso, sia di adeguare e meglio definire la rete, sia di avviare un lavoro di modellazione geologica geotecnica con individuazione delle soglie di allarme. L'attività di modellazione ha permesso di sintetizzare in due gli scenari di pericolo derivanti dalla parete: un primo scenario, frequente e non monitorabile con gli strumenti a disposizione, caratterizzato da crolli di blocchi rocciosi di volumetria non superiore a pochi metri cubi ed un secondo, individuato in relazione ad un'area in moderato movimento posta all'apice della parete e delimitata da una netta frattura, caratterizzato da un possibile crollo in massa di circa 5-6000 metri cubi. Rispetto al primo scenario le modellazioni di scoscendimento hanno evidenziato la possibilità che una percentuale sostanziale di crolli, dal 2 al 22%, potesse scavalcare le opere di difesa e raggiungere la strada o le costruzioni sottostanti. Relativamente allo scenario di crollo in massa sono state ipotizzate soglie di preallarme ed allarme e sono state definite le aree di probabile invasione del materiale.

Durante l'autunno 2017 e l'inverno 2018 i dati acquisiti con il monitoraggio hanno evidenziato un'accelerazione dei movimenti nella parte sommitale della parete, in dettaglio nell'area identificata con la modellazione come area di distacco per il secondo scenario, ed il CMG ha puntualmente segnalato tale situazione alla P.C. Successivamente, nella mattina del 13 aprile, alcuni blocchi del metagranito costituente la parete si sono staccati dall'area in movimento e sono crollati a valle andando ad impattare sia su campanile e Santuario che sulla Strada Statale 36. In relazione a questo crollo ed all'accelerazione dei movimenti riscontabili alla sommità della parete le aree sottostanti sono state evacuate e la strada è stata chiusa per alcune giornate. Un leggero rallentamento dei movimenti ha poi permesso di mantenere aperte alcune finestre di transito (per un toltale di 6 ore su 24) fino alla giornata del 24 maggio quando una ulteriore accelerazione, puntualmente segnalata alla P.C. dal CMG, ha consigliato la chiusura totale della viabilità statale. Da questo momento i movimenti sono proseguiti in maniera intesa ed alle 16 del 29 maggio il CMG ha inviato l'ultima comunicazione avvisando dell'imminenza del crollo che infatti è avvenuto 35 minuti più tardi. Il successivo confronto fra la nuvola di punti, acquisita da drone prima e dopo il crollo, ha permesso di stimare in circa 5.500 mc la massa rocciosa staccatasi dalla parte sommitale della parete. Dati strumentali ed immagini hanno permesso di ricostruire la dinamica del crollo con un movimento principale, che ha causato il crollo in massa in direzione ovest-sud/ovest, ed un successivo distacco di singoli blocchi, determinato da un movimento retrogressivo estesosi a monte solo a seguito del crollo della massa principale. In sostanza parte dei blocchi, presenti a nord ovest dell'ammasso principale, si sono mossi alcuni secondi dopo l'innesco del crollo in massa e sono precipitati con direzione Nord Ovest.

L'analisi delle velocità di spostamento orario dell'ammasso nelle ultime 12 ore ha evidenziato come il radar abbia restituito misure attendibili in tempo reale sino a pochi minuti prima del crollo (ore 16,15), mentre negli ultimi 20 minuti le misure (afflitte dal fenomeno del *wrapping* di fase) hanno necessitato di un post processing per avere un dato scientificamente corretto. Le velocità sono cresciute esponenzialmente nelle ultime ore con una velocità oraria media che nell'ultima ora è stata di poco meno di 10 cm/ora lungo la LOS del radar. I rilievi a terra sul materiale franato hanno sostanzialmente confermato la modellazione effettuata. In conclusione, è possibile affermare che quanto accaduto rappresenta un importante esempio di "monitorabilità" e di "*early warning*" rispetto ad una frana in roccia di dimensioni contenute.

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ABSTRACT

The Gallivaggio rock cliff, in the San Giacomo Filippo district (Sondrio province, Italy) has been monitored by ARPA, Lombardy's Geological Monitoring Centre (CMG) since 2011. The main mountain passage, route S.S.36, crosses this mountain area. The village of Gallivaggio was built at the beginning of 17th century and now has a restaurant, some houses and the important sanctuary heritage site.

ARPA CMG has carried out a variety of on-site observational approaches to manage the geological monitoring in Gallivaggio during the last few years.

The first few years of study and monitoring allowed us to categorize two main conditions. The first, a frequent but less hazardous one which is the single block fall. This is impossible to predict and has a 2-22% possibility of overriding the iron nets. The second one is the collapse of 5-6000 cubic meters of bedrock (Truzzo granite) from the top of the rock cliff which was marked by a large fracture.

During the winter of 2017/18 the data analysis values acquired, enabled CMG to notify the Lombardy Region Civil Protection of a dangerous acceleration of movement in the rock area regarding the second scenario.

Then, on 13th April, from the identified area single rock blocks began to come down and hit the road and sanctuary. During the following days the houses and restaurant were evacuated and the road was closed for 18 hours a day. Lastly, on May 29th, about 5500 cubic meters of rock collapsed and a part of it covered road and impacted the Sanctuary and the bell tower.

In conclusion, it is possible to verify that a suitable monitoring network plan and strategy realised by a reliable remote monitoring system, allowed CMG to alert the Civil Protection and the Municipality during a worsening of landslide movements and demonstrates the utility of an organized management of a monitoring geological network.

Keywords: geological monitoring network, rock cliff, early warning, civil protection

INTRODUCTION

The hazard activity of the rock cliff behind Sanctuary of Gallivaggio attracted the attention of the Lombardy Region due to the necessity of protecting the citizen (Macciotta *et alii*, 2016; Lato *et alii*, 2009) and location from this landslide (especially rock block falls) and to install a geological monitoring network (Carlà *et alii*, 2016; Atzeni *et alii*, 2015). In this article, we will explain the steps taken by the Geological Monitoring Center of ARPA Lombardia (called CMG) to realize a network which would enable us to forecast of a major rockfall (more than 5.000 mc) and to secure and protect human life (Mazzanti *et alii*, 2015).

SHORT NOTES ON THE GEOLOGICAL CHARACTERISTICS AND LOCATION OF THE AREA

The location of the landslide is shown in Fig. 1.

The monitored area is located in Valle Spluga, in the San Giacomo Filippo district (Sondrio province), and this specific rock cliff is directly behind the famous Sanctuary of Gallivaggio.

This area is inside the Tambò nappe which is constituted of Truzzo granite complex, and extends from here to Val Bregaglia (Switzerland) along a distance of 27 km (Ferrari *et alii*, 2014; Schmid *et alii*, 1990). The geomorphology of Spluga Valley reflects the erosive action of a Late Wurm glacier, which filled the main valley from Spluga Pass to Lake Como.

The rock cliffs, which represent the typical lateral border of the valley from Gallivaggio to Campodolcino, show morphological activity (Cita *et alii*, 1990). This situation is due to recent fracture systems, roughly oriented parallel to the valley and to the constitution of the Truzzo granite. At the surface the Truzzo granite is often locally disrupted and shattered facilitating the production of single rock blocks. The discontinuity sets, inside the rock sub vertical cliff, are strongly persistent; their orientation cause rock block instability.

THE HISTORY OF GEOLOGICAL NETWORK

In 2008, Lombardy Region's Civil Protection and the Mountain Community designed and built a long rockfall embankment (180 m) after some single rock block falls had

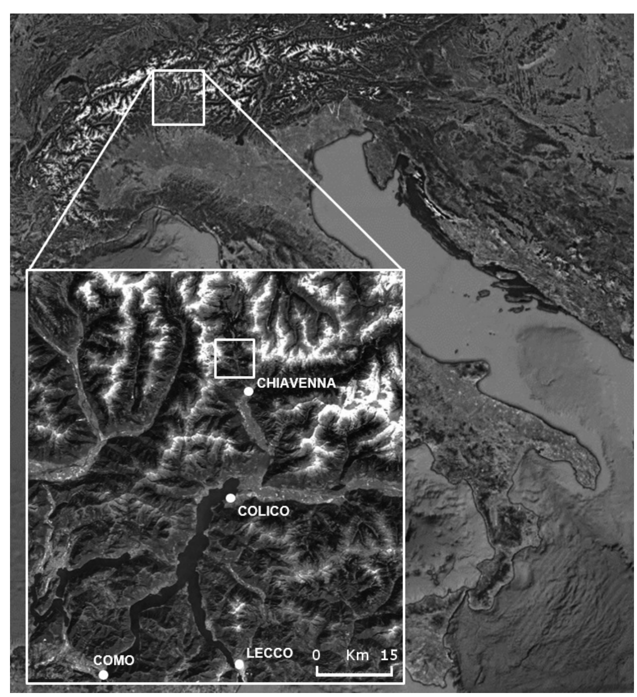

Fig. 1 - Location of the landslide

Fig. 2 - Pictures of the entire failing slope. The photo on the left shows rock cliff behind Sanctuary of Gallivaggio's bell tower and the red oval highlights the landslide detachment area. The photo on the right, taken from helicopter, shows rock cliff, Sanctuary of Gallivaggio and national route 36

occurred (FERRARI *et alii*, 2011). The aim of which was to protect the important heritage site of the Sanctuary of Gallivaggio, the houses, restaurant and road (national route 36) (Fig. 2)

Subsequently, in 2010 Civil Protection asked ARPA to design a monitoring network to acquire data values and to look into the situation more deeply (INTRIERI *et alii*, 2012).

The first monitoring network was realised by ARPA in 2011 and 2012. Some periodic measurements with ground based SAR radar were planned to investigate the condition of the rock and then, based on previous landslide experience ie. Rialba, a number of MEMS accelerometers and strain gauges were installed at the top of the rock cliff (ALIPPI *et alii*, 2015).

Strain gauges were installed with the purpose of monitoring movements across the main surface cracks of the rock. Strain gauges consist of a potentiometer displacement transducer housed in a stainless steel telescopic body with two anchoring points. The electrical signal output is 4-20 mA and the resolution is 0.01% of FS (full scale) in this case about 0.05 mm (DUNNICLIFF, 1988)

In the period up to 2014, CMG acquired measurements, from Mems and Strain Gauges, every 30 minutes and from the ground based SAR Lisalab radar, every 3 months.

During the summer of 2014, the data acquired during the first years was analysed. The examination of those measurements lead to the conclusion that a ground based SAR radar would be the most suitable system to monitor the complex rock mass movement of Gallivaggio.

The data values generated during the first years showed us that the ground based SAR radar was able to identify an area with slight displacement and was able to measure it (about 15 mm/year). On the other hand, the strain gauge measurements were not able to identify this area, probably because in that spot there were a lot of fractures and it was impossible to monitor each fracture with so few strain gauges.

The MEMS accelerometer demonstrated numerous critical signals, but we were unable to discriminate the significant signals from the false ones.

Therefore, CMG decided to increase the monitoring by ground based SAR radar system and to dismiss the ones with strain gauges and MEMS accelerometers (LEVA *et alii*, 2013; BARLA *et alii*, 2017).

In 2016, a permanent near real time monitoring system by ground based SAR radar was activated by Ellegi s.r.l. (SÄTTELE *et alii*, 2016; CROSTA *et alii*, 2017; CASAGLI *et alii*, 2010; CARLÀ *et alii*, 2017). The radar was installed at the top of the river embankment in front of the rock cliff, at a distance ranging between 150 m and 750 m. In order to fit operational needs, the entire system (i.e. sensor, related hardware and software tools and system recovery), has been specifically designed and implemented to ensure the requested level of reliability, availability and robustness.

In the present configuration, the ground based SAR radar system synthesizes an aperture of 3 m, covering a visible area of approximately 0.4 km^2. The permanent monitoring settings of

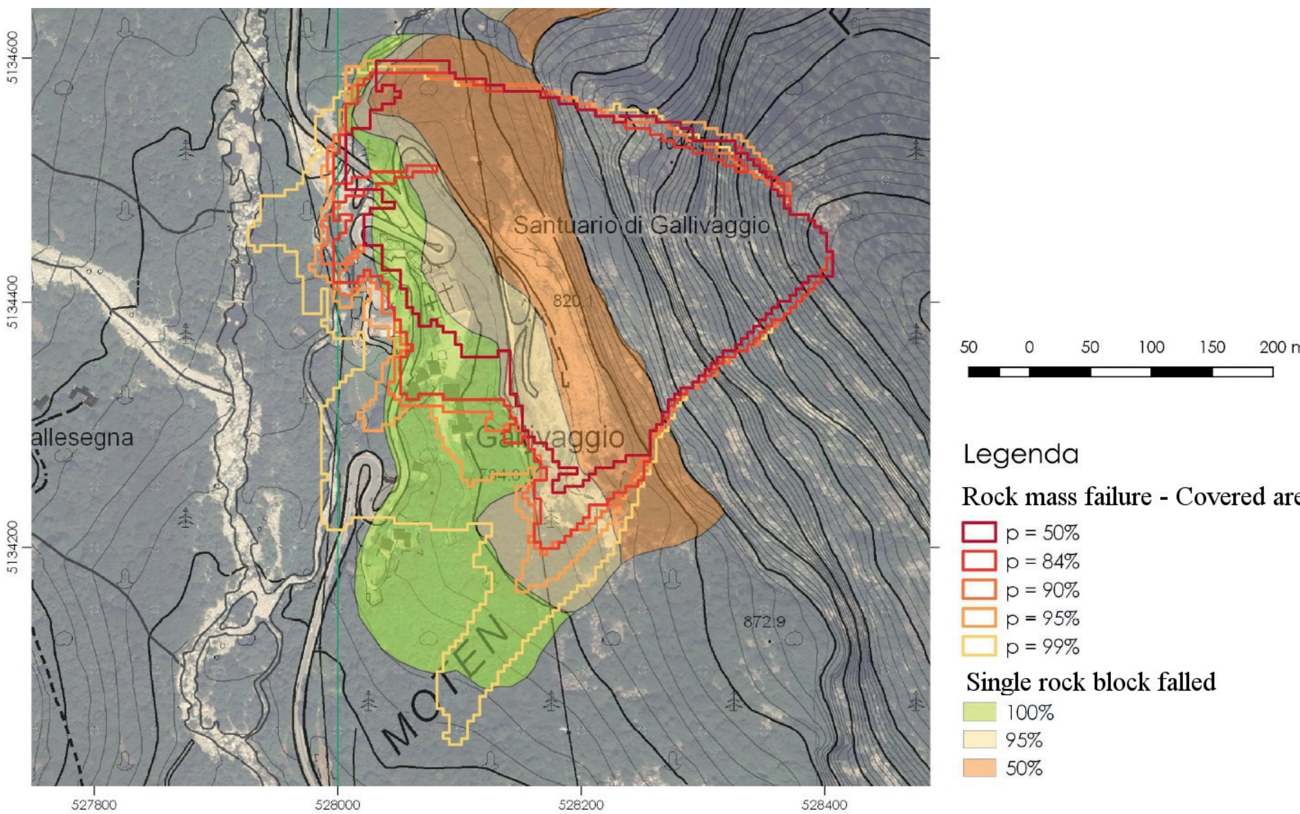

Fig. 3 - Cartography forecast for rock mass failure and single rock block failure (Cancelli et alii, 2017)

the system allow to acquire radar images and displacement maps with a range resolution of 0.5 m, an azimuthal resolution between 0.4 m and 2.2 m, providing approximately 30 displacement maps per hour. The system has been equipped with hi-speed data transmission mobile connections. With some minor adjustments, the instrumentation was connected to the public electric supply and a cover with radome was built to protect the radar.

CMG also decided to plan a specific modelling assessment using trigger identification by the establishing of suitable movement thresholds.

Cancelli engineering took the data values collected during the first years of monitoring and created a special landslide modelling study, which fixed the trigger thresholds and established different scenarios of rock mass failure.

The first scenarios consist of the falling of 5-6000 cubic meters of bedrock (Truzzo granite complex) present at the top of the rock wall and marked by a large fracture. The forecast of the areal distribution of the deposit was made by DAN3D software (Morgan, 2005). The most realistic analyses - which signifies, the most precautionary one - reveals areas overlaid with a probability (Corominas, 1996) of not exceeding 95% or 99% for mass collapses (Fig. 3).

As you can see in Fig. 3, the different coloured lines represent the landslide's changeable probability boundary. It is clearly evident why the infrastructure and cultural heritage Sanctuary are threatened by treacherous proximity the rock mass failure. The scenario triggers were fixed with three velocity thresholds (Tab. 1):

The first, at 1.5 mm/day, whose only purpose was to alert the CMG's technicians, the second one at 3.0 mm/day of moderate criticality and the last and greater one, at 4.00 mm/day, at high criticality.

In the same study the scenarios for single rock block falls were fixed. With a substantial amount of simulation of single rock block falls, (from the upper part of the rock wall) it is noticeable that from 2% to 7% of these falls would jump over the long embankment and flexible barriers.

Especially in section 2 the single rock blocks would reach (22%) the church, road or restaurant. This condition is more frequent but less hazardous than rock mass failure, but is impossible to predict with data values acquired from the geological monitoring network.

Threshold	***Attention***	***Moderate criticality***	***High criticality***
Velocity	*1.5 mm/d*	*3 mm/d*	*4 mm/d*

Tab. 1 - Trigger velocity thresholds

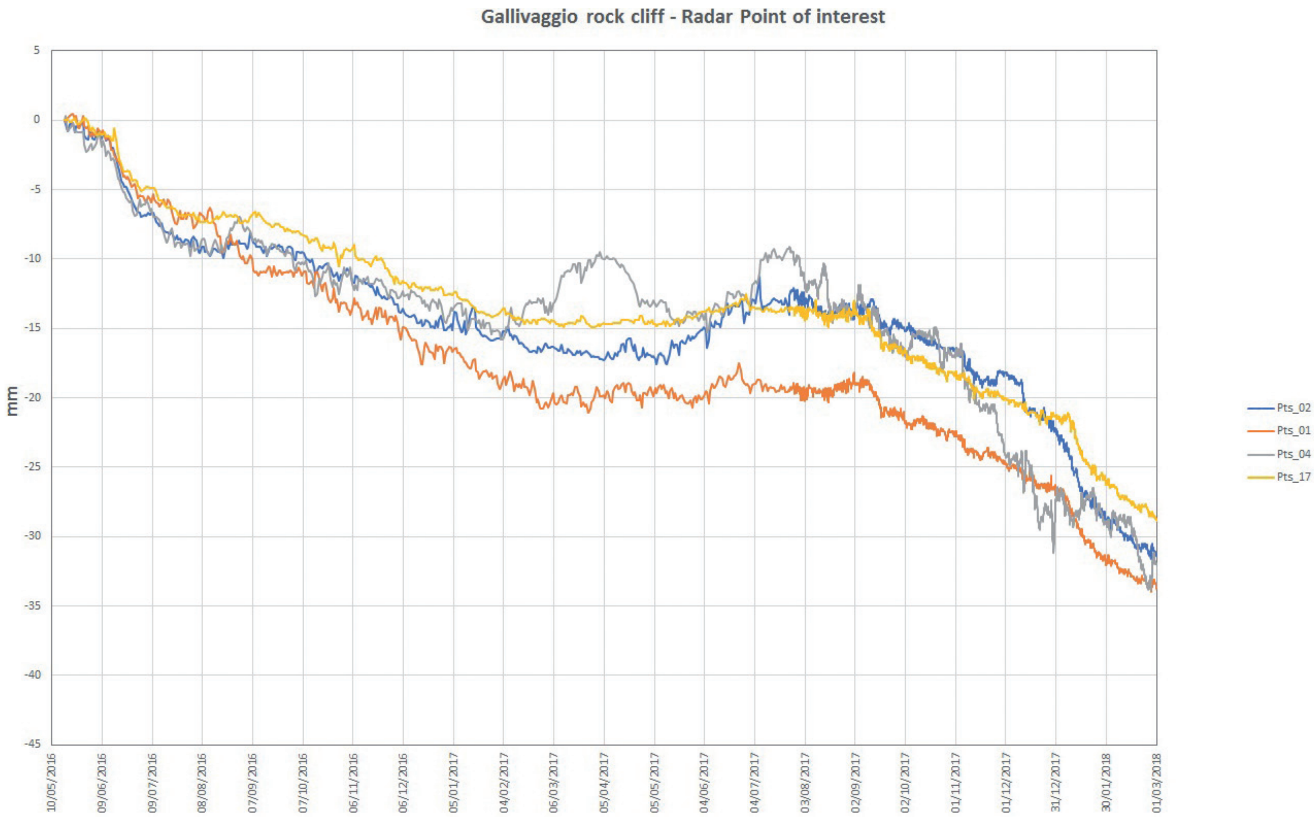

Fig. 4 - Correlation between noticed capacity and calculated capacity

When the modelling study was concluded in May of 2017, it was sent to the civil protection, municipality and the prefecture.

From then on, further monitoring was undertaken by the geological monitoring network for the civil protection.

In autumn 2017, CM Valchiavenna and Lombardy Region approved of a preliminary plan for the new embankment (Cancelli *et alii*, 2017).

FOCUS ON THE LANDSLIDE EVENT

During the autumn of 2017 the data analysis values acquired by the ground based SAR radar, enabled CMG to notify the Lombardy Region Civil Protection of a dangerous acceleration of movement of about 460 m^2 of rock area. Rock activity, is shown in selected points of interest during winter 2017/2018 in Fig. 4.

In February 2018, another notification was sent to the Civil Protection informing them of the acceleration, the values being taken at points in the monitored area, had doubled since the previous autumn.

After this second notification, the Valchiavenna Mountain Community begun the first intervention to support the unstable rock, but then, on 13th of April, a new single block crashed on the road.

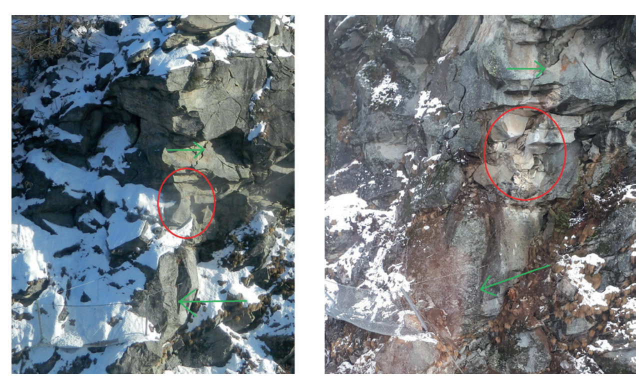

Fig. 5 - Area of rock block detached April 13th. The photo on the left, was taken on December 2017 by G. Merizzi and the photo on the right was taken on 13th April. The red oval highlights the area affected by the detachment, the green indicators are highlighting the same places

At 8 o'clock that morning, a single block of about 2 or 3 mc, detached from the upper part of the rock cliff (Fig. 5), rebounded and stuck the Sanctuary, the bell tower and the road below.

From 13th April the displacement of the active moving area located at the top of the Gallivaggio's sub vertical rock cliff, increased considerably and the mayor of San Giacomo decided to evacuated the areas and the fire fighters began to remove sacred paintings and other sacred objects from the Sanctuary.

On 24th of May the ARPA's Geological Monitoring Centre sent the Civil Protection, notice that the trigger thresholds had been exceeded (at first moderate and then high criticality) and the road was closed indefinitely. At 4 p.m. on the 29th of May, the CMG send the last notice in which they informed the Civil Protection that the rock mass was close to failure. 35 minutes later the landslide came down (Fig. 6).

After the failure, comparisons were made between the point clouds acquired by ARPA Lombardy using drone photos taken before (April 17th, 2018) and immediately after (May 30th, 2018) the collapse, calculating the volume of material that came down to be aprox. 5500 cubic meters.

Later, a landslide detachment analysis was carried out thanks to the numerous videos taken by witnesses, identifying the fundamental direction of the collapse W-SW, followed by a second detachment of several smaller rock blocks in a NW direction (Val D'Avero direction).

LANDSLIDE AREAL DISTRIBUTION OF THE DEPOSIT

The collapsed mass, mostly remained confined upstream of the embankment built in 2008, while a residual part bypassed it covering the road and square, and impacting the bell tower and Sanctuary.

Fig. 6 - On the left: the road after the event. On the right: the area outside the Sanctuary

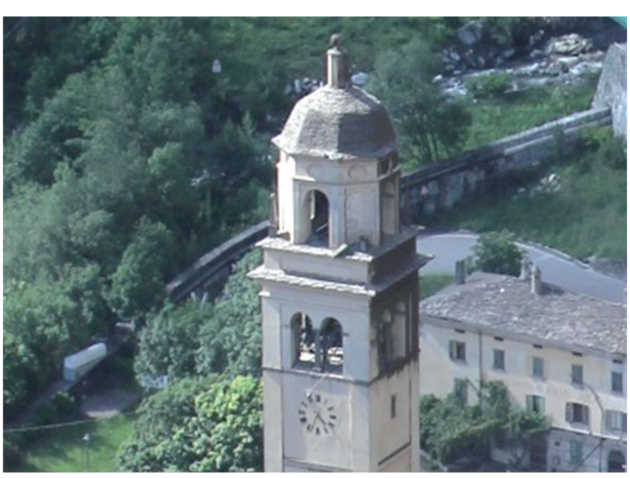

Fig. 7 - The bell tower at 6 p.m. of 29th May

It was interesting to observe (Fig. 7) how the forcible pressure of the dust cloud, made an evident mark high up on the bell tower. The dust cloud was also responsible for stopping the clock.

The data cross checking done on values acquired from both field and SAPR (Remote Pilot Aircraft System) analysis (model DJI PHANTOM 4 PRO with CMOS camera from 20 Megapixel)

Rock block over ½ **m³**	
Rock block between ½ and **1/20 m³**	
Rock block between **1/20 and 1/200 m³**	
Rock block over than **1/200 m³**	
Fine debris expanded with dust cloud	

Tab. 2 - Classification of rock blocks size

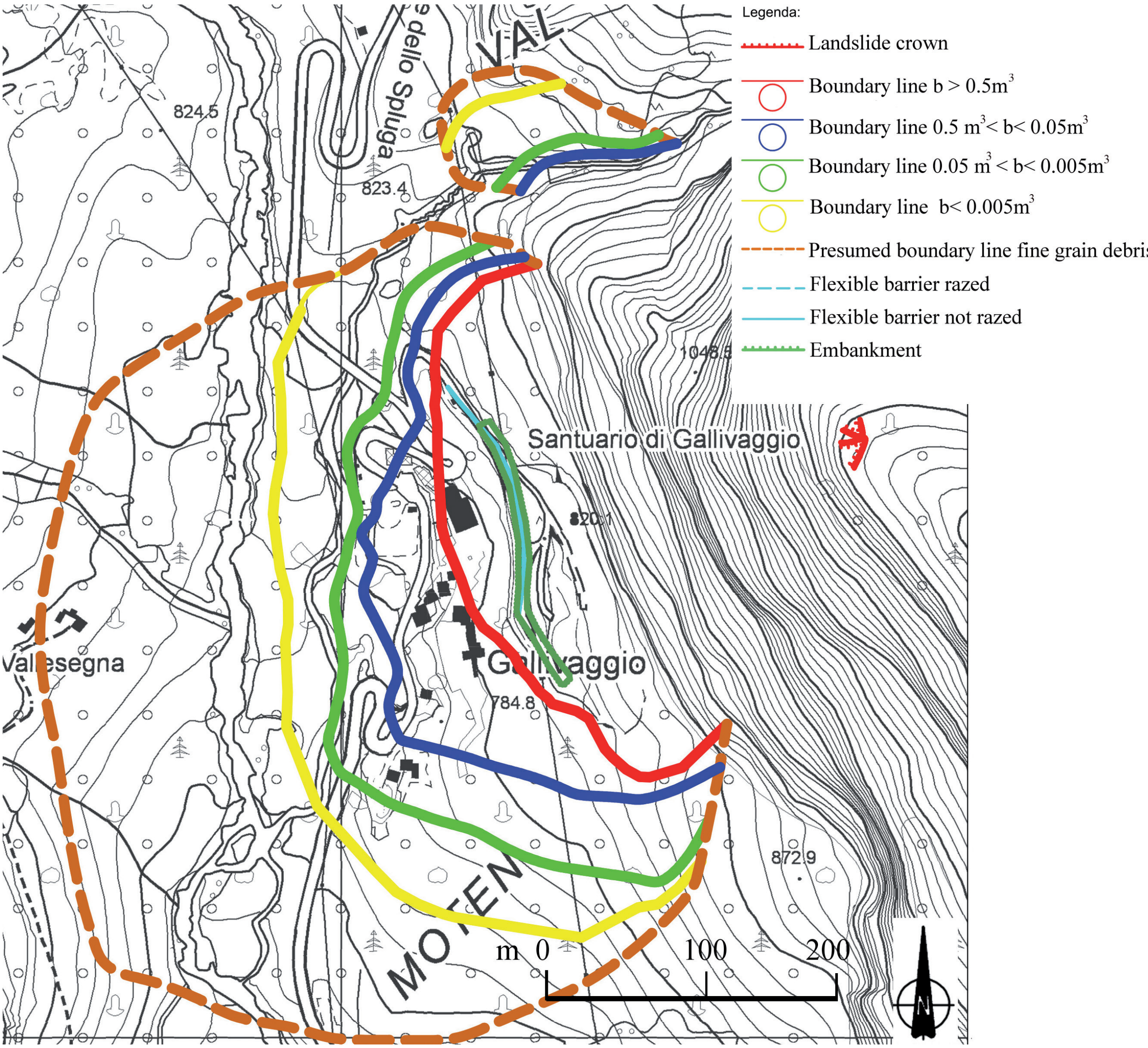

Fig. 8 - On the left: the road after the event. On the right: the area outside the Sanctuary

presented an accurate distribution description of the size of the blocks (Fig. 8).

CMG chose m³ submultiples to classify the deposit size, (1/2, 1/20 e 1/200) in order to comprehend the dimension, you must compare these submultiples with the photos in Tab. 2.

DISPLACEMENT DATA VALUES

Thanks to the expert operating of ground based SAR radar, it was possible to accurately measure movement of different orders of magnitude, during the activity of the rock cliff (measured along L.O.S.= Line Of Sight). The data values, shown in the next graph (Fig. 9), represent the displacement at some points located in the active area of the rock cliff. It represents only a few data values, acquired in each scan by the ground based SAR, out of thousands of values measured on the maps. When the displacements were small (under 16 mm/y) "extremely slow" (Cruden & Varnes, 1993) the interferometric analysis was set every 2 hours and 30-40 minutes even if the system revisiting time was 2.5 mins. This method of processing "radar scans" removed excessive environmental noise. With displacement rate from 0.03 mm/d to 0.1 mm/d (as from 2011 to winter of 2018) the data updated was set every 6 hours in

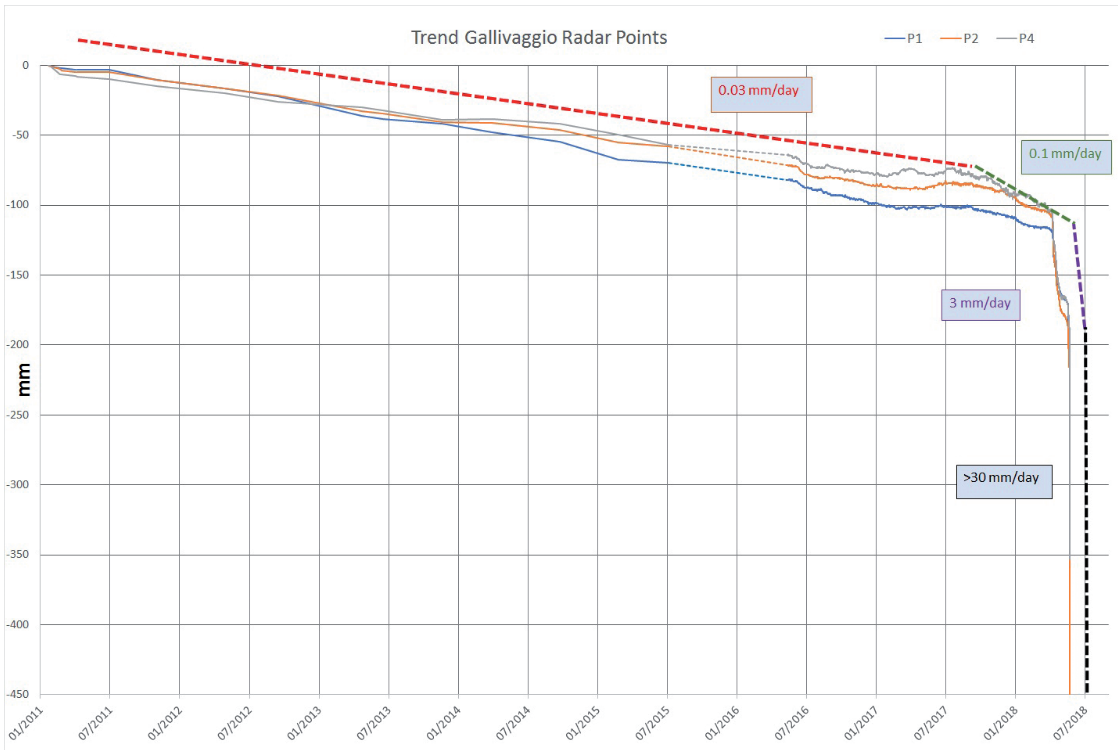

Fig. 9 - Graph pluriannual displacement at some single virtual points on the rock cliff. With red, green and black dashed line the average displacement

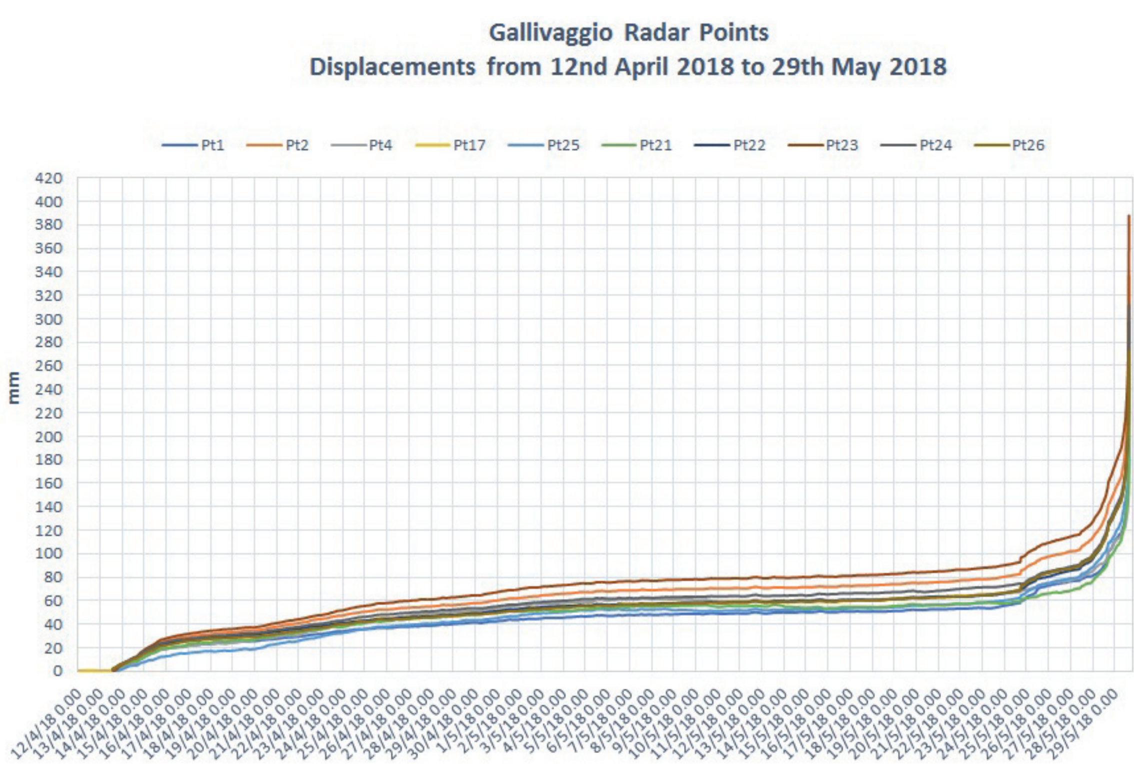

Fig. 10 - Displacement (measured on the radar Line of Sight) of some single virtual points on the rock cliff during the period April 12th to May 29th

order to have more accurate data. Accuracy is vital in order to correctly perceive the movements trends in situations where the displacement is of about 1/100th or 1/10th mm/day.

In the minutes prior to failure, see the end of the lines in Fig. 12, the SAR data measurements updated the frequency, increasing to a new value every 2 minutes and 30 seconds using every single radar scan. During the very last minutes (aprox. 20) when the failure was imminent, the displacement velocity was so high that even with a revisiting time, of only 2 minutes and 30 seconds, the values were affected by phase wrapping effect.

Radar data values are obtained measuring the microwave phase differences between one scan and the other. In particular, ground based SAR radar uses a wavelength of only 17, 44 mm; so every time the displacement is higher than that value, it is necessary to apply the phase unwrapping process.

After this process it was possible to see that in the last 46 days before the collapse, the total active area displacement was between 24.1 cm and 38.8 cm. (Fig. 10)

It is possible to see as daily movements increased from less than 1 mm to two orders of magnitude higher in the last days. In particular, in the last 24 hours the rock displacements were between 14.3 cm and 23.3 cm with an average displacement of 18 cm.

It is also possible to see how the different points of interest have the same movement trend. They don't have the same data values because the orientation between LOS and movement direction is different or because they belong to different parts of the moving area affected by differential movements. In Fig. 10 it's interesting to notice that the displacement shows the typical asymptote curve of the falling landslide.

If we observe rock mass velocity and acceleration, in the last days before the failure, we notice how they were appropriately measured thanks to the methodology used in monitoring. The Fig. 11 shows daily velocity in the last 10 days. From May 28th, we observed a daily velocity never seen before.

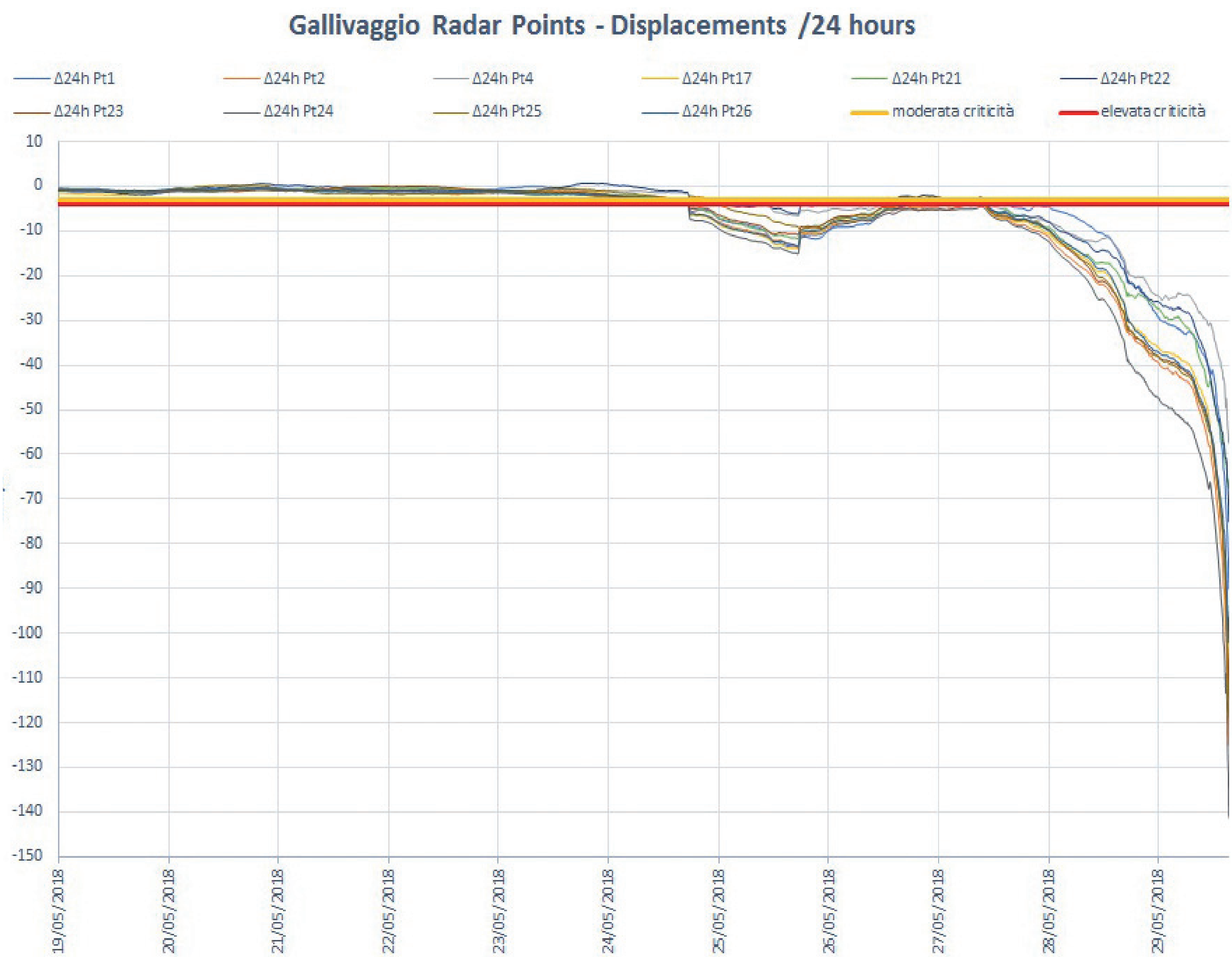

Fig. 11 - Displacement at some virtual points during last 10 days. Using red and yellow horizontal lines highlighting the velocity trigger thresholds

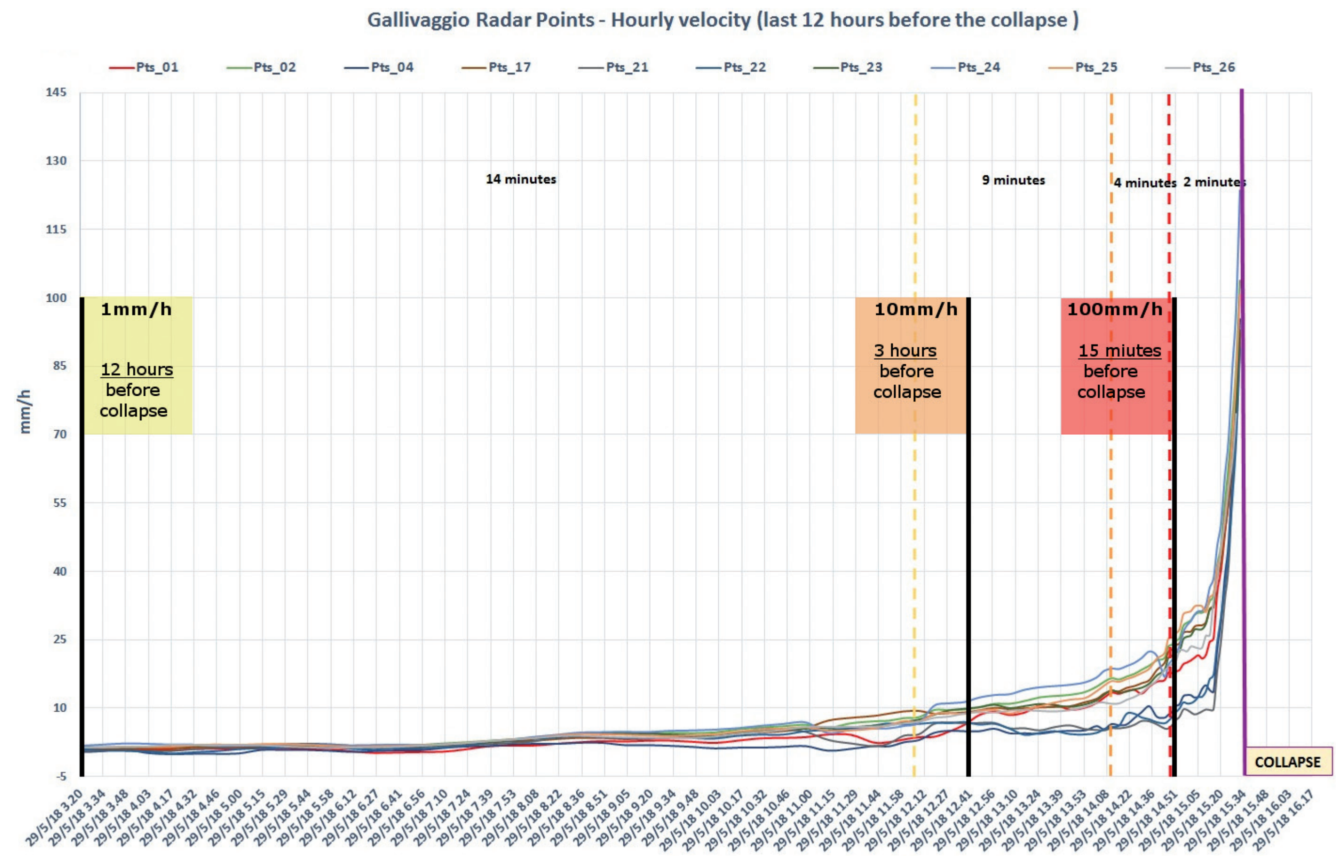

Fig. 12 - Hourly movement velocity, measured on the radar Line of Sight, at some single virtual points on the rock cliff. The highlighted dotted lines indicate periods of different interferometric frequency analysis

After the unwrapping process, the real hourly velocity graph can be drawn (Fig. 12). The graph line shows us the exponential increase (1 mm/h at 4.20 a.m., 10 mm/h at 1.25 p.m. and 100 mm/h few minutes before failure); in the last hour the displacement of different virtual points were between 7.5 cm and 12 cm with average hourly velocity of about 10 cm/h.

In addition to the data values acquired by ground based SAR radar, it is useful to notice data values acquire by 10 strain gauges. Most of them were installed in the days prior and complete strain gauges data values were available only after 8.37 p.m. on May 27th. It's important to say that the largest number of strain gauges (except EG2 and EA5) were installed behind the main fracture, which we thought was the crown failure. The areas, behind the main fracture, were not visible (out of radar view) from Ground based SAR Radar and so the strain gauges' data value was the only information we had.

When the rock mass fell, the strain gauges EH1, EH2, EF2, EF3, EA5, EG2 (highlighted with yellow in Fig. 13) fell with it.

Using the strain gauges data values (Fig. 14) and by observing the numerous failure video clips, the following considerations can be made:

- until the morning of May 29th, there was no displacement in the area behind the main fracture. The only movements acquired by strain gauges (EG2 and EA5) were across the main fracture;
- from the morning of May 29th, data values acquired by strain gauge (EF2) showed a displacement. At first it was slow and then it became faster and faster. Both strain gauge EF3 and EF2 share the same lower level anchorage on a rock block located immediately behind the main fracture. Between 4.21 p.m. and 4.28 p.m. strain gauges EF2 and EF3 reached the end of the stroke. At the same time the strain gauge EG2 broke. During the first few minutes of the afternoon data values, acquired by EG2 looked like the displacement had stopped. This situation confirmed that the displacement had begun to appear behind the main fracture as "retrogressive" displacement, but only in the areas nearest to the main fracture. On the other hand, data values acquired by EH2 and EH1 showed no displacement until after 4.23 when EH1 began to move (EH2 showed no displacement until the collapse);
- when the landslide collapsed, strain gauge EH2 has been

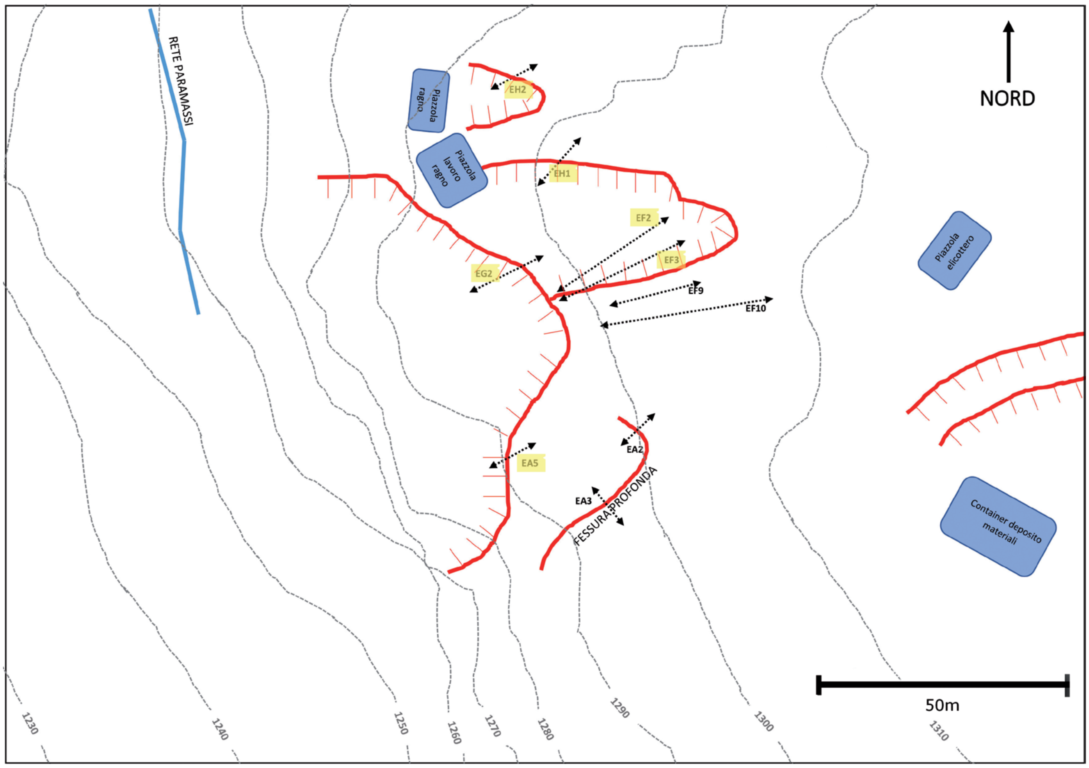

Fig. 13 - Schematic map that show the extensimeter positioning. (A. Pavan)

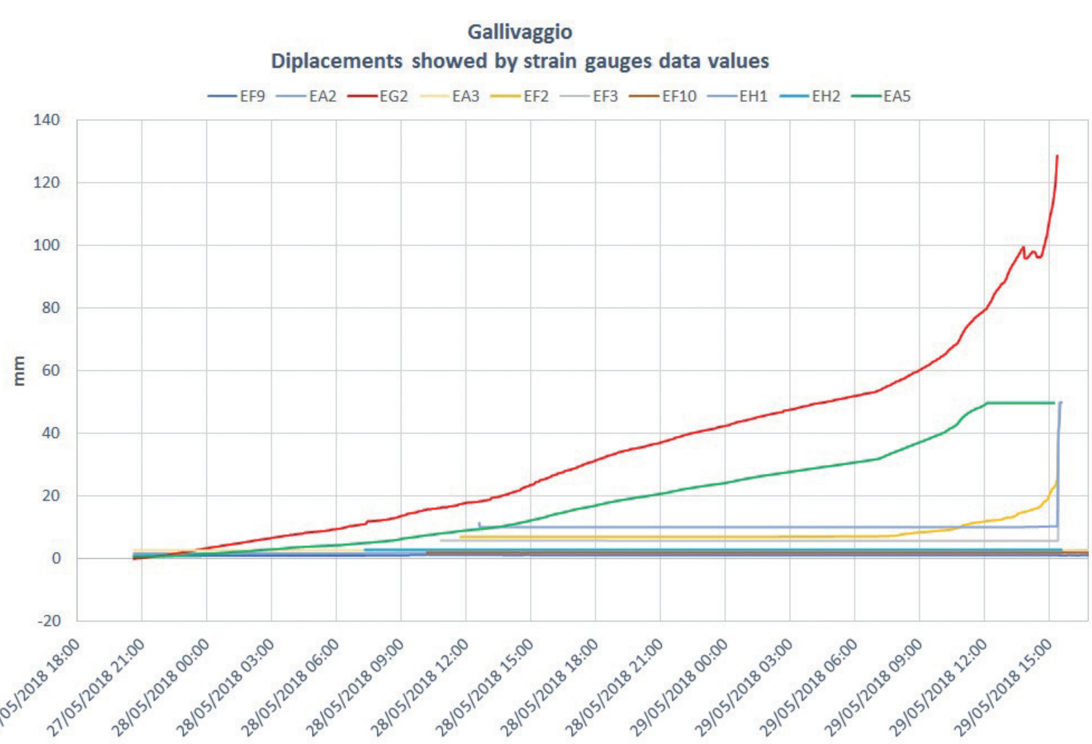

Fig. 14 - Displacement showed by data values acquired with strain gauges located behind and across the main fracture

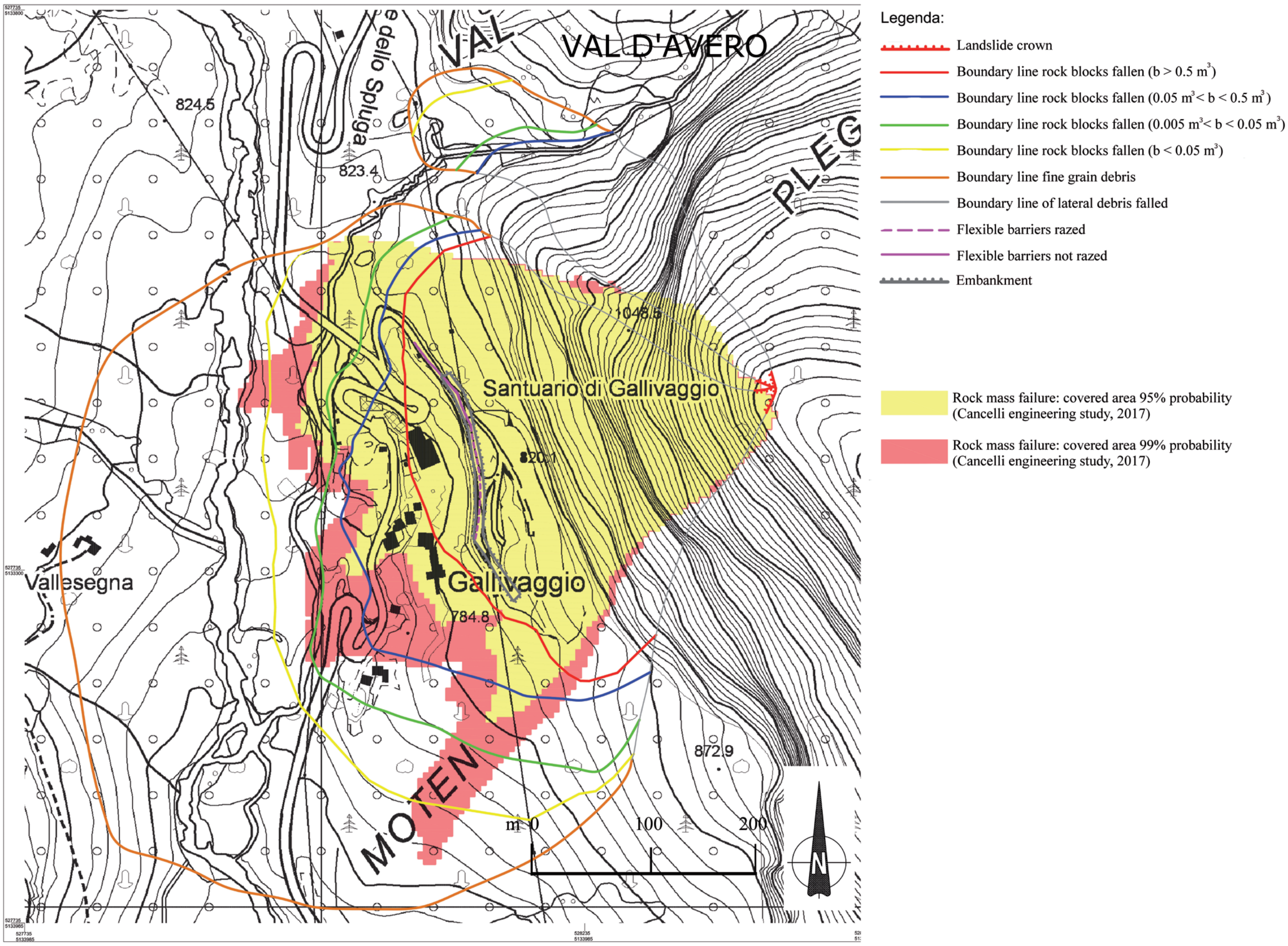

Fig. 15 - Overlapping between forecast of covered area, with 95% or 99% of not exceeded, and areal distribution of the deposit seen after the rock mass failure. (A. Priore – N. Petrella - A Pavan)

removed and fell down with the rock mass. This situation confirmed that in this area "retrogressive" displacement was related to the rock mass failure. Some rock blocks located on the NW side of the main rock mass failure detached within a few seconds after the main collapse. These rock blocks fell in the Val D'Avero direction (NW direction).

DISCUSSION

The first consideration to be made regards the comparison between the forecast model made in 2017 with what happened in reality on May 29th.

For a rock mass failure, the forecast for the areal distribution deposit, made with 99% probability of not exceeding, shows (Cancelli *et alii*, 2017) quite accurately what happened. This overlapping is especially clear in the area between Val D'Avero bridge and the hairpin bends south of the restaurant (Fig. 15).

On the other hand, the forecast shows two main differences. First in the southern most area and second in Val D'Avero.

This occurred in the southernmost area, probably due to software's' excessive sensitivity to ground morphology.

Regarding the minor and greater rock blocks detected in Val D'Avero (in the area above the Val D'Avero bridge) it's possible to observe in the numerous failure video clips, the particular order of detachment.

The collapse of the main rock mass caused the detachment of single rock blocks starting after a few seconds from the main failure. Before the main collapse these rock blocks were stationary as can be confirmed from looking at the data values acquired by strain gauges (Fig. 14).

Therefore, the modality of failure of the rock block which reached Val D'Avero was more similar to the single rock block fall than to rock mass failure. If this is true, it is important to notice how the forecast made in 2017, for the single rock block fall, shows that the Val D'Avero area is one of the areas affected

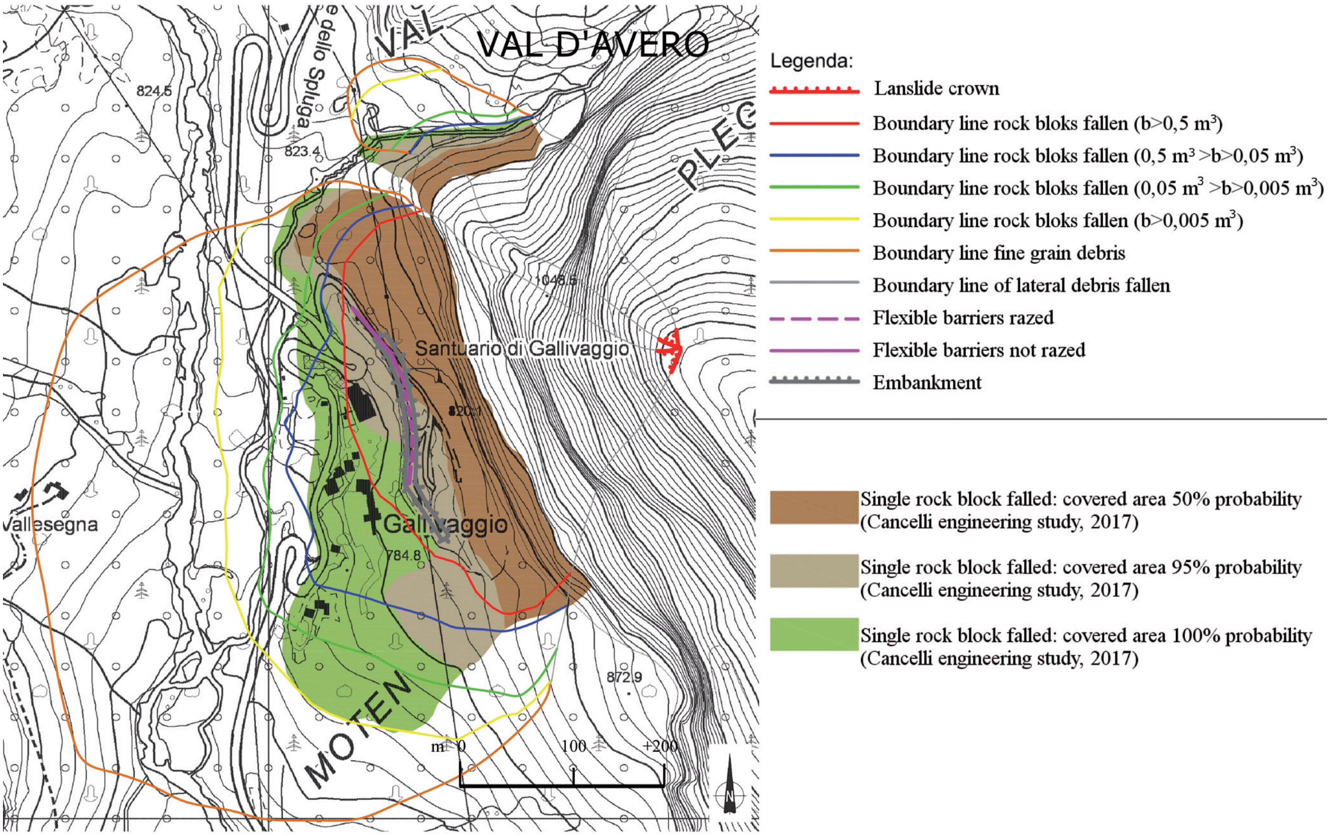

Fig. 16 - Overlapping between forecast for single rock block fall (covered area, with 50%, 95% or 100% of probability), and areal distribution of the deposit seen after the rock mass failure. (A. Priore – N. Petrella – A Pavan)

by block falls (Fig. 16).

Another consideration to be made is about the trigger velocity threshold (high criticality = 4 mm/d) as fixed in the forecast phase. The value of this threshold was exceeded only at three specific times;

- 74 hours between the April 13th and 16th.
- 45 hours between the April 22th and 24th.
- from the afternoon of the May 24th up to failure.

During the study of the landslide modelling for Gallivaggio, the thresholds have been compared to the trigger thresholds used for the Preonzo landslide. The comparison was made with Preonzo landslide because it was a rock mass landslide which was monitored until its collapse like Gallivaggio (Loew *et alii*, 2012).

In particular, the comparison was made with trigger thresholds for the official alarm of 3-5 mm/h (which allow the media and public to be informed) and by trigger threshold of 5 mm/h for evacuation (which causes evacuation of industry at slope toe and closure of cantonal and local roads). Compare these hourly thresholds with the Gallivaggio daily trigger thresholds which appeared too precautionary.

If we use the Preonzo trigger threshold (official alarm) with the data values acquired by Gallivaggio monitoring system, we can see (Fig. 12) that we should have informed population about landslide at 9 o'clock a.m. of the May 29th (about 7 hours and 30 minutes before the failure). With the Gallivaggio trigger threshold we informed population about the landslide 5 days and 8 hours before collapse.

Just the same for evacuation: with Preonzo evacuation threshold the road would have been closed 6 hours and 30 minutes before collapse rather than 5 days before.

Regarding daily trigger thresholds (4 mm/d), like the ones used in Gallivaggio monitoring system, it is possible to see that high criticality thresholds were exceeded on only three occasions (April 13th, April 22th and May 24th). If we had fixed a lower precautionary trigger threshold, i.e. at 1 cm/day or at 1.5 cm/day, the high criticality threshold would have been exceeded only two or one times.

But in the latter (with trigger threshold at 1,5 cm/d) the trigger would have been exceeded only 36 hours before the failure, which is, in our opinion, insufficient time for precautionary civil protection protocol.

CONCLUSION

In conclusion, some interesting observations came up during the Gallivaggio landslide regarding the monitoring network. Firstly, the landslide represents an important example of a suitable monitoring system with daily velocity trigger thresholds, which permitted the forecast of the rock failure of about approx. 5500 mc. The network is an example of early warning system for a rock mass failure of a few thousand cubic meters. The performance guaranteed by the ground radar monitoring system performance let us follow landslide movements from both when they were characterized by extremely slow movement (0,03 mm/d) and when they accelerated up to the movements immediately prior to the failure. It is important to remember that this monitoring network is not effective for single rock block falls.

Having the ability of following extremely slowly movement which gradually becomes faster, it is possible to observe movement at every stage from the start of acceleration to the exact moment of the failure (0.1 mm/h 6 day from failure, 1 mm/h 40 hours from failure, 10 mm/h 3 hours from failure, 100 mm/h 15 minutes before failure). By varying the time interval and number of radar images used to obtain the interferometric analysis, it was possible to observe a rock movement of over 10 cm/h. This movement velocity is four orders of magnitude over the velocity measured in the first few years.

Another consideration to be made is about the necessity to have a realistic geotechnical modelling to permit an efficacy of early warning forecast. In the Gallivaggio case history the scenarios of rock mass failure and single rock block failure had a realistic overlapping with the landslide phenomenon which occurred on May 29th.

Regarding the type (daily or hourly velocity) and the values of the trigger thresholds, we think daily trigger thresholds are more recommended than hourly thresholds for a rock mass failure early warning system, as in Gallivaggio. Because of the need to keep the hourly rock mass displacement under surveillance for an early warning system, thresholds would need to be of only a few millimetres. If in Gallivaggio we had used the Preonzo thresholds we would have started the evacuation only 6 hours before the failure, which is insufficient precautionary time for civil protection protocol.

But by monitoring hourly displacements of only a few millimetres (ie. 1 or 2 mm/h) by radar scans analysis on hourly basis, it is easy to run into errors being so close to the real limit of precision and accuracy of onsite instrument (with environmental noise), which could result in the release of false alarms.

The final consideration concerns the monitoring system management. The first reports, about an increase of rock displacement, were carried out in December 2017 and February 2018, and then the last notice was sent on May 24th 2018 (high criticality exceeded trigger threshold notice) and ultimately the warning notice was given prior to failure (at 4 p.m May 29th). Evidently, at the time of the landslide, the monitoring system was the only defence in place to safeguard citizens and cultural heritage.

During the period of April/May 2018, numerous initiatives and public safety programs were set up to protect citizens and heritage. The restaurant and homes in the area at risk, were evacuated and access to the sanctuary was prohibited. A large part of the sacred works of art present were removed and put into safety by the Fire fighters. In that period, traffic conditions were only resumed when the rock movement speed was below 4 mm / day and only then, for a few hours a day in order to minimize the risk for the public.

All these accomplishments, were only made possible thanks to the monitoring system which entailed a reasonable cost. At the same time, the setting up and implementation of the geological monitoring network carried out at Gallivaggio from 2011 to May of 2018 cost substantially less, (approx. 200 k€) than the financial outlay which would have been required for the protective structures mechanisms (about 3.4 M€) according to the price quotation for November 2017 project C.M. Valchiavenna.

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