The March 7th 2005 Cavallerizzo (Cerzeto) landslide in Calabria - Southern Italy

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Abstract: In the early morning of March 7th 2005, after a period of prolonged rainfall (645 mm in 90 days, about 72% of mean annual precipitation) and snowfall, the hamlet of Cavallerizzo was severely damaged by a vast complex debris slide-earth flow. In total, thirty buildings were severely damaged or destroyed by the landslide, and the main road connecting Cavallerizzo with the villages of Cerzeto and Mongrassano was disrupted. About 310 inhabitants had to be evacuated to nearby villages.

Several superimposed tectonic units, made of metamorphic rocks (Palaeozoic-Mesozoic) overlain by clastic terrains (Cenozoic-Neozoic), crop out in the vicinity of the study area. The main scarp of the slide developed at the eastern tectonic boundary of the Coastal Chain, marked by the "San Fili-Cerzeto-San Marco Argentano" recent N-S trending normal fault; its crown is mainly located within the cataclastic zone associated with such master fault. In the lower part of the landslide, two main earth-flows extended eastward along minor valleys, and merged down slope along the S. Nicola torrent.

The sector affected by the landslide belongs to a wider large-scale slope movement, which extends westwards up to about 800 m a.s.l. The 2005 event is only the last paroxysmal episode of a long history of deformation recorded in the area of Cavallerizzo since the XVIII century. The area has been kept under control by the CNR-IRPI, by means of desultory field measurements (essentially, deep and superficial displacements, and piezometric levels) since 1999. Velocities, recorded at superficial benchmarks along opening cracks, pointed out "anomalous" conditions in the weeks preceding the collapse: pre-rupture velocities ranged from 0.8 to 5-6 cm/day. Despite its emergency character, the monitoring carried out helped to support civil-protection activities, and helped in saving the inhabitants.

Résumé: Le 7 mars 2005, après qu'une période des précipitations extraordinaires (645 millimètres dans 90 jours, environ 72% de précipitation annuelle moyenne) combiné avec des chutes de neige, Cavallerizzo a été sévèrement endommagé par une vaste l'éboulement complexe de terrain. 30 édifices ont été sévèrement endommagés par l'éboulement et la route reliant le village de Cavallerizzo aux communes voisines a été interrompue. Environ 310 habitants ont dû être logé dans les villages voisins.

Plusieurs unités tectoniques superposées, faites de roches métamorphiques (Palaeozoic-Mésozoïques) et terrains clastiques de recouvrement (Cénozoïques-Neozoic) sont les lithologies qui affleurent dans la zone. L'escarpement principal du glissement s'est développé le long une ligne tectonique localisée a Ouest de la Chaîne Côtière, délimité par la récent faille normal "San Fili-Cerzeto-San Marco Argentano", orientée NS et vraisemblablement active. Le secteur de couronne est situé dans la zone cataclastique liée à la ligne tectonique mentionné ci-dessus. Dans la partie plus inférieure de l'éboulement, deux principaux corps de coulées se prolongent vers l'Est le long des drainages secondaires, réunissant ensemble le long du torrent S. Nicola.

Le secteur affecté appartient à un mouvement de terrain de grande ampleur, qui se prolonge à l'Ouest jusqu'à la ligne de partage des eaux. L'événement 2005 est le dernier d'une histoire de déformations qui se développe depuis le siècle XVIII. Le secteur a été occasionnellement contrôlé par le CNR-IRPI au moyen de mesures sur le terrain (déplacements profonde et superficielles et niveaux piézométriques) depuis 1999. Les vitesses de déplacement, enregistrées aux repères superficiels situés le long des fissures d'ouverture, ont précisé des conditions "anormales" pendant les semaines précédant l'éboulement: les vitesses de pré rupture se sont étendues de 0.8 à 5-6 cm/jour. En dépit de son caractère simplifié, la surveillance a aidé dans les activités de protection civile et a permis de sauver tous les habitants.

Keywords: case studies, geological hazards, landslides, monitoring, public awareness of science, slope stability.

INTRODUCTION

In the early morning of March 7th 2005, after a period of prolonged rainfall combined with snowfall, Cavallerizzo was severely damaged by a vast complex landslide. In total, thirty buildings were severely damaged or destroyed by the landslide, and the provincial road (locally called Emigranti Street) connecting the hamlet of Cavallerizzo to the main village of Cerzeto, and to Mongrassano was disrupted (Figure 1). About 310 inhabitants had to be evacuated to nearby villages.

The area affected by the event has suffered from continual landslide damage in historical times. Since 1982, the stability of the study area was investigated in two MSc research projects undertaken at the University of Calabria. In 1998, field investigations and a monitoring programme were funded by the municipality of Cerzeto. Subsequently, CNR-IRPI began carrying out measurements of inclinometers and piezometers and simple “low-cost” monitoring, aimed at evaluating the evolution of the area. The rudimentary character of monitoring was the result of the general chronic scarcity of funds for research in Italy, and of the peculiar prolonged history of generally-slow displacements. Thanks to these investigations, continuous, very slow displacements, with slight winter accelerations, were detected in a set of rupture surfaces in the upper part of the area that was to become active on March 7th 2005. By the end of February 2005 the long period of monitoring enabled anomalous behaviour to be recognised and a timely warning to be issued by the mayor of Cerzeto (acting as authority for Civil Protection measures), shortly before the landslide collapsed (Rizzo 2005). Despite its “basic” character, monitoring therefore helped to support civil-protection activities, and allowed all inhabitants to be saved.

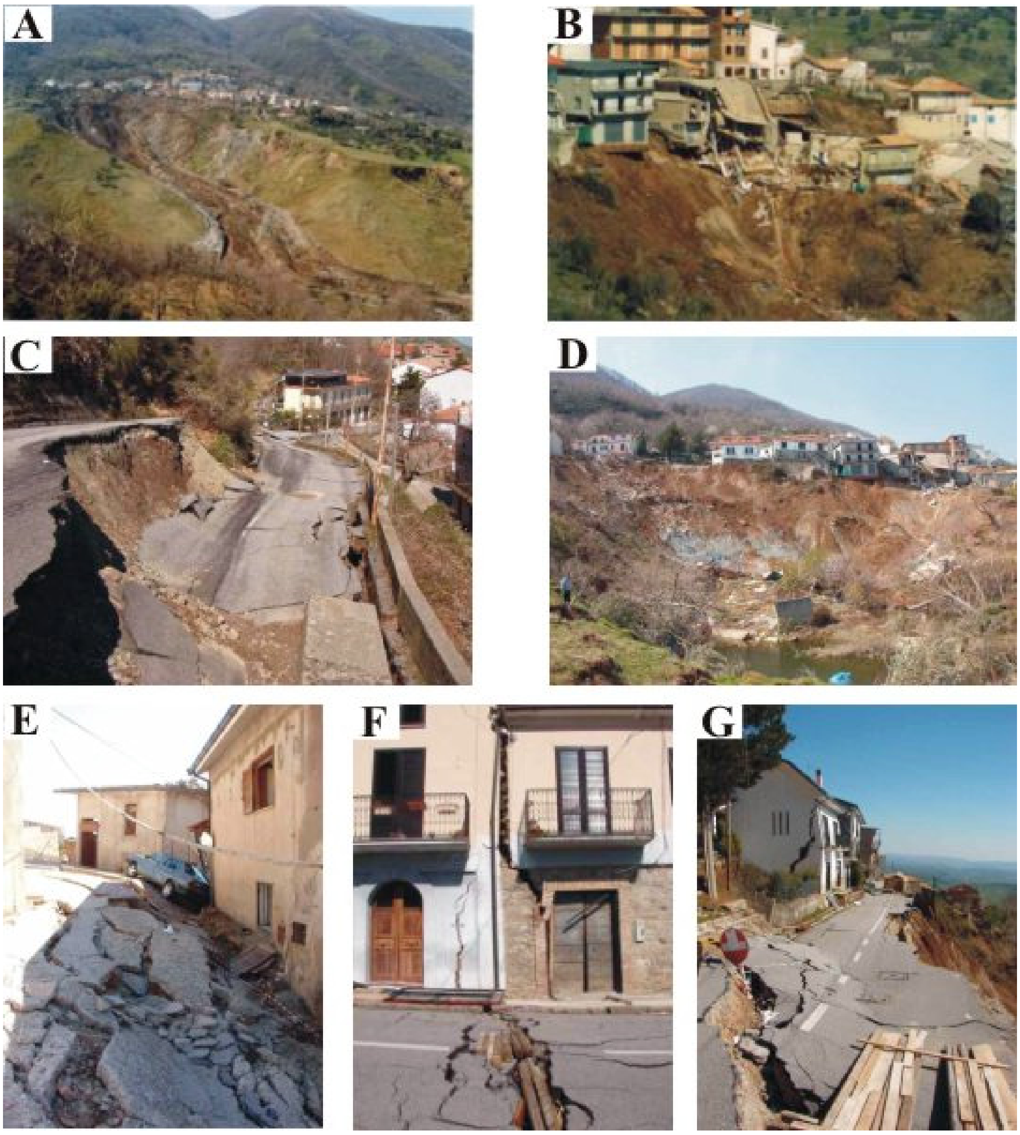

Figure 1. Some photographs of the March 7th 2005 landslide at Cavallerizzo. Key: a) a panoramic view of the village (in foreground, the main earth flow); b) view of buildings damaged along the crown; c) view of damage to the provincial road; d) view of the main scarp (in foreground, the landslide lake); e-g) view of damage to the urbanized area, along the main scarp.

GEOLOGICAL SETTING

The study area (Figure 2) is located along the western edge of the Crati graben (Lanzafame & Tortorici, 1981), a tectonic depression bounded by a N-S striking normal seismogenic fault system, active since the Late Pliocene. This system culminates with the 30 km long “S. Fili-S. Marco Argentano” master fault (Tortorici *et al.*, 1995), which crosses the study area just west of Cavallerizzo, and is responsible of the uplifting of metamorphic-crystalline rocks of the Calabrian Coastal Chain with respect to the deposits filling the Crati graben. In the study area the deposits in the Crati graben (Colella, De Boer & Nio, 1987; Lanzafame & Tortorici, 1981) comprise, in ascending order : 1) Late Miocene grey clay and silt, interbedded with white chalk and fossiliferous calcarenite layers; 2) marine Late Pliocene–Middle Pleistocene grey-light blue silty clay, passing to yellow sand and silt; 3) Late Pleistocene continental red fan-conglomerate, made of igneous and metamorphic elements in a sandy matrix; 4) Holocene deposits. The latter deposits consist of: a) tobacco colluvial deposits (characterizing the Cavallerizzo area, along the master fault); b) fan-conglomerate deposits, affected by mass movements.

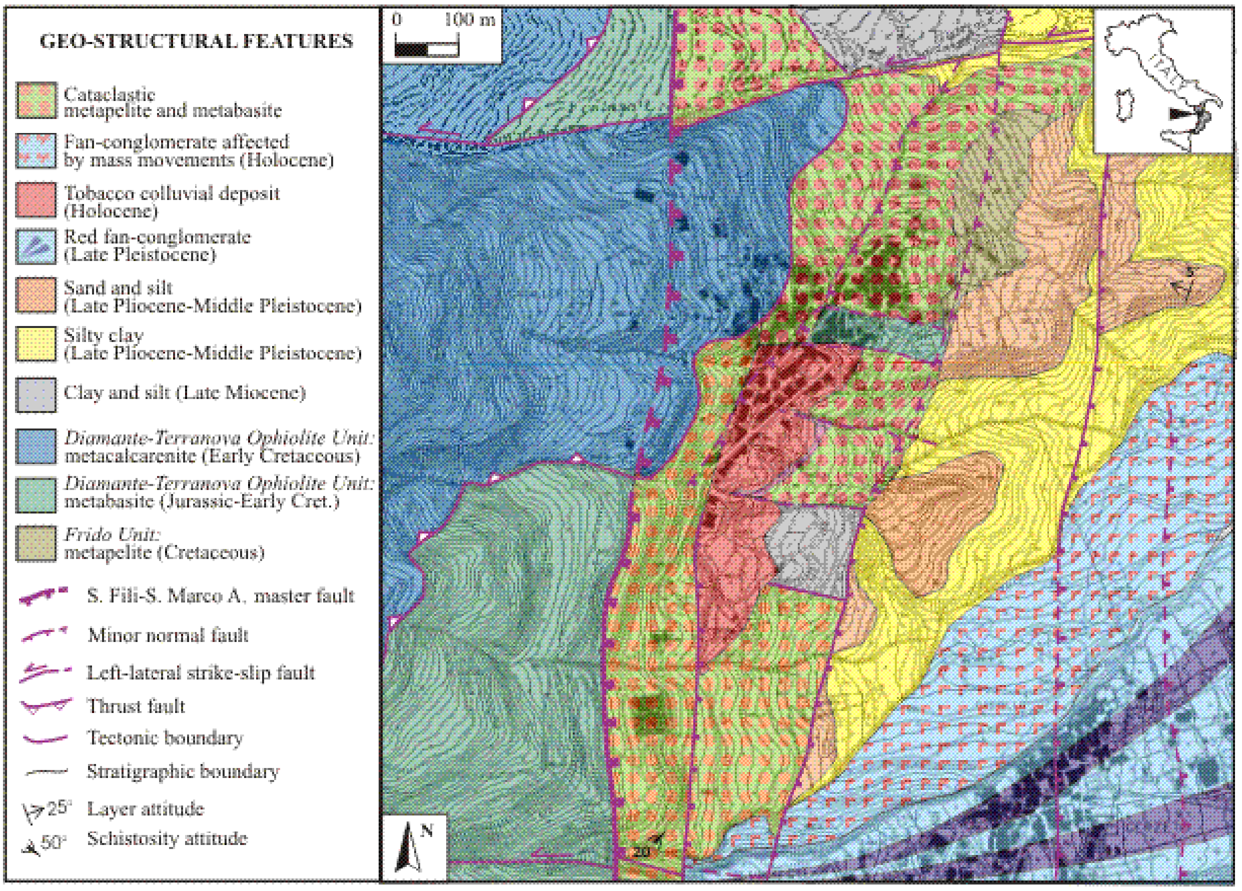

Figure 2. Geological map of the study area.

The metamorphic crystalline rocks belong to the Calabrian Arc, a Mediterranean orogenic belt derived from an accretionary wedge of crustal terrain, produced by the collision of Africa and Europe (Haccard, Lorenz & Grandjacquet, 1972; Alvarez, 1976). In the study area, the following tectonic units, emplaced during Oligocene-Early Miocene times, can be recognised (Amodio-Morelli *et al.*, 1976), in ascending order: Frido Unit (Cretaceous) - black metapelite, interbedded with metasilt, quartzite, and horizons of marble; Diamante-Terranova Ophiolite Unit (Jurassic-Early Cretaceous) - metabasite covered by metacalcarenite and by a polychrome schist sequence of Tithonian-Neocomian age. In proximity of the hanging wall of the master fault, rocks are intensely cataclasized.

In the study area, three systems of faults were distinguished, in the following described from older to younger.

- NE-SW to N-S oriented, east-vergence thrusts, dipping up to 45-50°. These structures are responsible for the emplacement of the different units of the Calabrian Arc, and determine the superposition of the metacalcarenite upon the metabasite (Diamante-Terranova Ophiolite Unit). Because of their age (Late Cretaceous-Early Miocene), evidence related to these thrusts is not very common. At a mesoscopic scale, thrust-planes are marked by mylonitic bands, characterized by evident schistosity and by transposition and boudin structures.
- E-W trending left-lateral strike-slip subvertical faults (Middle Miocene-Middle Pleistocene). These structures belong to a regional transcurrent fault system, affecting the whole northern sector of the Calabrian Arc (Van Dijk *et al.*, 2000), and dictate the main drainage lines crossing the area. At a mesoscopic scale, these faults are characterized by sub-horizontal to oblique slickensides.
- N-S to NNE-SSW trending normal faults, stepping eastward along planes dipping at 60-80° (Late Pliocene-Holocene). These structures are characterized by the strongest morphologic evidence. At the mesoscale, faults are characterized by sub-vertical to oblique slickensides, documenting a left-lateral component of motion.

Along mentioned faults, and especially where they intersect each other, strongly jointed bedrock and weathered material are to be found. In particular, the "S. Fili-S. Marco Argentano" master fault cuts the eastern slope of the Coastal Chain, just west of Cavallerizzo: the village is, therefore, located along its wide cataclastic zone.

When the geomorphologic setting which characterized the area before March 7th 2005 is considered (Figure 3), widespread slope movements are evident. In particular, several slides, and complex slide-flows, plus sectors affected by severe erosion and by superficial slope movements, can be recognized. Landslides generally showed "fresh" morphologies, indicative of recent activation.

Along the eastern border of the Coastal Chain, large-scale landslides and deep-seated gravitational slope deformations are also common. Among these, an ancient rock slide affects the area of Cavallerizzo, with the main scarp located at about 800 m a.s.l., and the toe presumably at 400 m a.s.l. (shown in blue in Figure 3). In this latter area, the gravitational-induced superimposition of metamorphic rocks over Pliocene clays can be appreciated in the field, along the landslide toe; similar evidence was also recently noticed in borehole records. The basal surface of rupture of the rock slide is presumably compound: steeper and irregular in its upper sector (developed in weathered metamorphic rocks), and gentler in the middle-lower sector where it passes first through the cataclastic zone, and then through Plio-Pleistocene sediments. The flanks of the landslide are defined by a couple of streams, corresponding to faults belonging to the E-W fault system. Note that, in its lower portion (along the provincial road), two sectors of the village were frequently damaged in historic time, as a consequence of continuous slow deformations, interrupted by brief local accelerations mainly induced by prolonged rainfall.

At the base of the slope, again along the provincial road and partly overlapping on the landslide described above, the crown of another large-scale rock slide is to be found (in brown, in Figure 3). This ancient gravitational deformation extends from Cavallerizzo to its cemetery, affecting the whole slope drained by the S. Nicola torrent. Within this area, secondary slope movements and severe erosion could long be recognized before the 2005 event. In particular, one of these landslides – located in the area of interference between the mentioned large-scale phenomena, and whose main scarp skimmed along Emigranti St. – roughly coincides with the area first affected by the recent paroxysmal activation (see the description below, and sector "A" in the chronologic sketch in the upper part of Figure 5).

From a hydrogeological point of view, the tectonic superimposition of terranes whose permeability strongly decreases with depth, combined with the lateral confinement caused by the mentioned N-S master fault and by E-W structures, certainly represent a strong predisposing factor with respect to slope instability in the area.

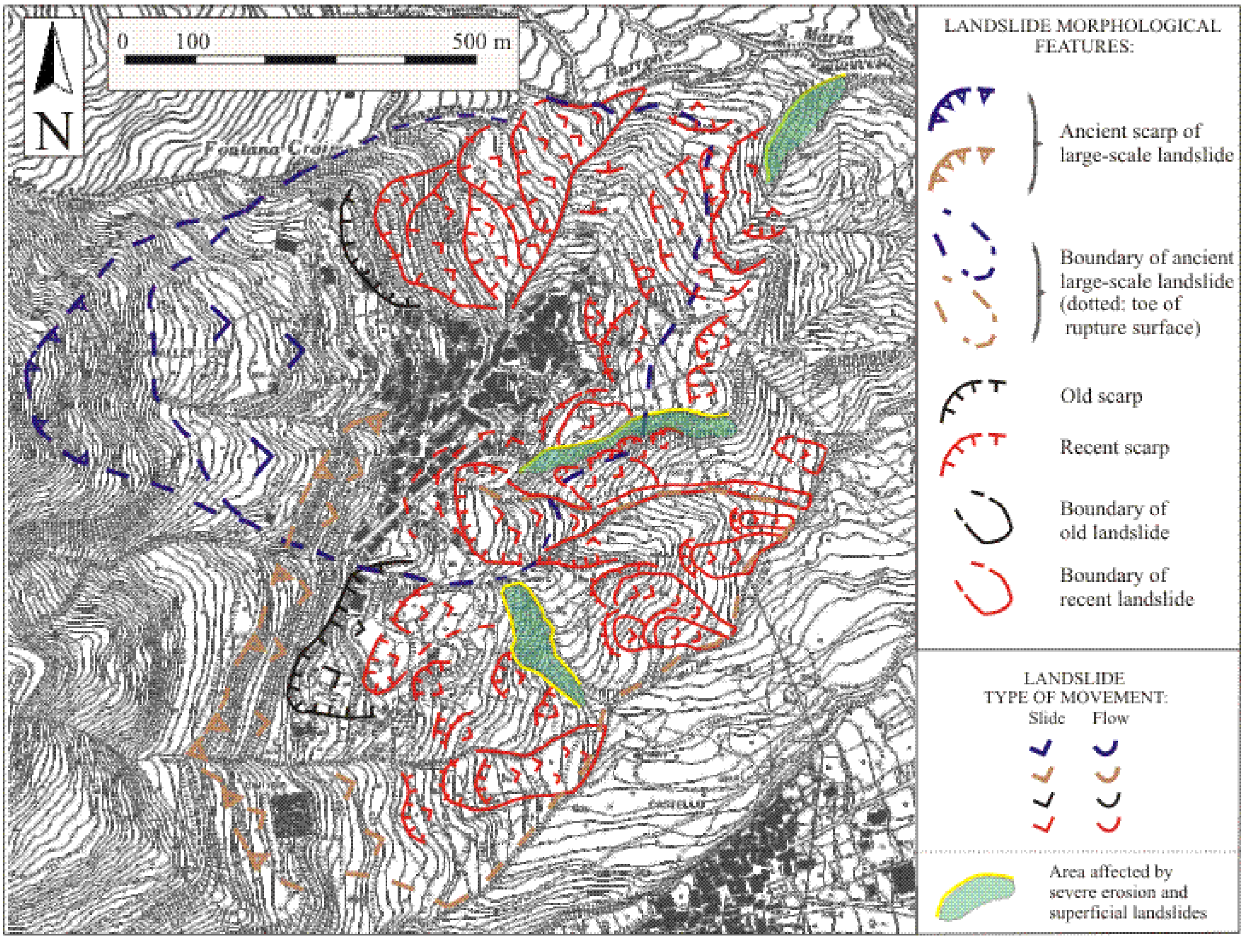

Figure 3. Geomorphologic map of the study area (setting before the March 7th 2005 activation).

HISTORICAL LANDSLIDE DAMAGE AT CAVALLERIZZO

The 2005 event is only the last episode of a long history of landslide-related damage that has occurred in the area of Cavallerizzo since the XVIII century. Historical research, recently carried out mainly in national, civil engineers and city archives, revealed more than 50 documents concerning both landslide damage and construction of remedial works. A summary of this data, spanning over about 400 years, is shown in Table 1. The greater number of events indicated in the XX century result from the greater interest in recording landslide information. Bearing this limitation in mind, the chronology of the main events of landslide-related damage was developed. In many cases, documents explicitly refer to landslides occurring after intense and prolonged rainy periods, sometimes even during snowy winters. Earthquakes seem not to have been a main cause of landsliding in the study area, there being only one case (No 4), where "recent earthquakes" are hinted as being responsible for "cracks opened in the ground". Moreover, although several ancient buildings suffered damage in the November 23rd 1980 earthquake, there were no reported landslides or landslide-induced damage in that event.

On some occasions (especially in the oldest documents), the area affected by landslide damage is not clearly indicated. Figure 4 shows the locations of unambiguous information of landslide damage: despite underestimating the local frequency of damage (non-georeferenced data having been ignored), the map serves to identify areas prone to landslide damage in historical time. These areas are located both north and south of Cavallerizzo, in the areas cut by the Cava and the Inserte ravines, respectively, and belong to an ancient large-scale gravitational phenomenon (cf. Figure 3). Historical reports of damage, whose levels range from low to high, refer to both these sectors, even during the last century.

On the other hand, no reports were found concerning damage to areas located east of Cavallerizzo: this gap could reasonably be explained by considering the nearly absence of elements of interest therein. Nevertheless, in some documents, slope instability processes – due to either erosion processes or superficial landslides triggered on the mountain slope west of the village – were reported along the upper reach of the Cava ravine: in fact, this latter drains the slope of the Coastal Chain right above the village and, after a marked left bend, crosses the urban area north of the Rosario church.

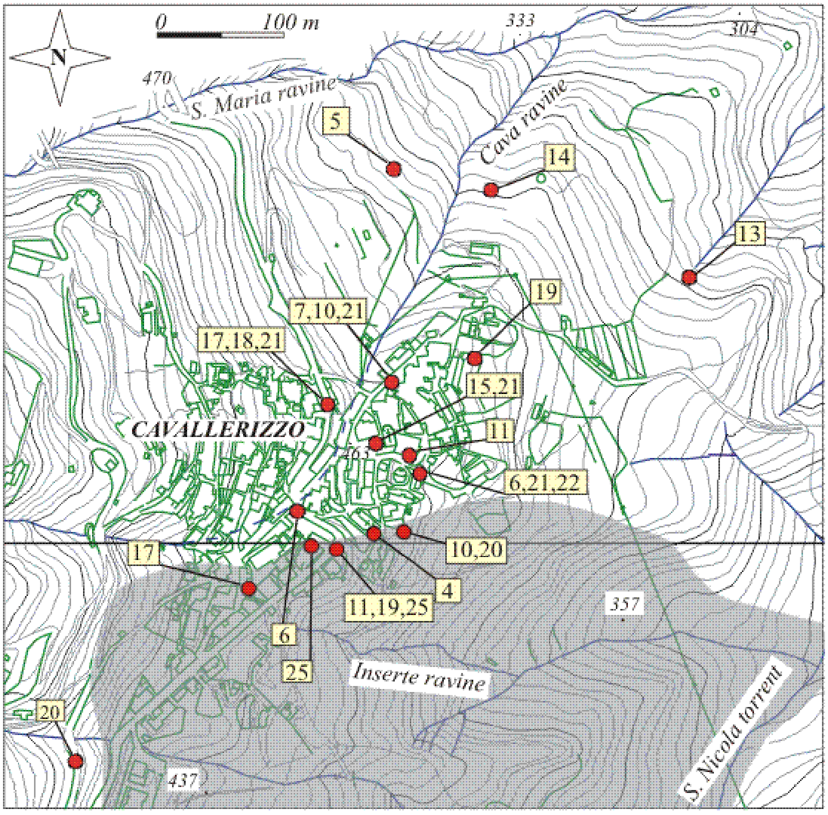

Figure 4. Geographical distribution of sites (red circles) damaged in historic time. Identification numbers refer to records listed in Table 1. In green, the urban setting of Cavallerizzo. In grey, part of the area affected by the March 7th 2005 landslide.

As a whole, buildings were the elements most affected by landslide damage (81% of cases); deaths or injuries were not recorded in any of the examined documents.

Several reports of damage refer to Emigranti St. and Inserte St., in the vicinity of the Rosario Ch. – i.e. in the sector where the main scarp of the March 7th 2005 landslide subsequently developed. It was, therefore, this sector that had been kept under control by the CNR-IRPI since 1999, by measuring deep and superficial displacements, and piezometric levels (for location of the instruments mentioned in the text, see Figure 5).

In particular, in the period May 1999-June 2000, inclinometer readings at S3 (i.e. head of the future 2005 landslide, sector "A") suggested the presence of a couple of rupture surfaces at depths of about 14 m and 34 m, respectively. At that time, observed velocities were very slow: only 2-3 mm/y, i.e. almost in the range of survey error. During a similar period from September 1999 to July 2000 cracks opened in the same sector, detected by means of a crack-opening device (*Eurogard*), at similar rates. Meanwhile, along Emigranti St., a couple of steps gradually developed in the road pavement . However, piezometric readings still indicated quite "usual" conditions, with oscillations of only 1-1.5m.

On May 2004, the water table at piezometer S2 (located within sector "A", not far from S3) rose about 2 m, but no exceptional displacements were being recorded at the same time.

Table 1. Historical data on landslide events at Cavallerizzo. Key: #=record number; Date=date of event (*YYYY*=year; *MM*=month; *DD*=day; ?=unknown); Description=a summary of the event (?=uncertain cause of damage; in Italics, locations plotted in Figure 4); Element=type of damaged elements (*B*=building, *R*=road, *O*=other - e.g. cultivated field, dike); Level=level of damage (L=low; M=medium; H=high); Source=archive. Reference numbers of the events are those shown in Figure 4.

#	Date			Description	Element			Level	Source
	YYYY	*MM*	*DD*		*B*	*R*	*O*		
1	1635	?	?	Landslides affected the village.	X			L	Parish archive
2	1720	?	?	Landslides affected the village.	X			L	Parish archive
3	1758	02	19	Many buildings disrupted by a landslide.	X			H	Parish archive
4	1827	02	28	Landslide activation near the *Rosario Ch*.	X			M	Parish archive
5	1903	10	30	Landslide activations at *Chicchi di Palma*.	X		X	L	Cosenza Nat. arch.
6	1917	02	21	Landslide activations at *Motticelle* and *Cancellata*.	X			L	Cosenza Nat. arch.
7	1929	11	?	Rain-induced damage to a building along *Catundi St*.	X			L	Cosenza Nat. arch.
8	1933	12	?	Rain-induced damage to several buildings.	X			L	Cosenza Nat. arch.
9	1935	03	09	Landslide activation near the village.	X			L	Civil Eng. arch.
10	1940	02	20	Rain-induced damage to 2 buildings along *Catundi St*. Landslide activation at *Lacchi*. Five dikes damaged by a landslide on the left flank of the Cava ravine.	X	X	X	M	Civil Eng. archive
11	1941	03	31	The *Posteraro* building damaged by a landslide (?). Two buildings along *Emigranti St.* damaged by a landslide (?).	X			M	Civil Eng. archive
12	1941	?	?	Four dikes damaged by a landslide re-activation on the left flank of the Cava ravine.			X	M	Civil Eng. archive
13	1944	?	?	Landslide activations at *Repantano*.	X			L	Civil Eng. archive
14	1946	?	?	Landslide activation at *Sciuraglie*.	X			L	Civil Eng. archive
15	1953	11	21	One building damaged by a landslide in *S. Giorgio Sq*.	X			L	Civil Eng. archive
16	1953	12	09	Some buildings damaged by a landslide.				L	Civil Eng. archive
17	1959	11	24	Rain-induced damage to two buildings along *Scescio St.* and *Inserte St.*, plus other buildings damaged at other locations in the village.	X			H	Civil Eng. archive
18	1963	02	20	Two buildings damaged along *Scescio St*. by a landslide (?), evacuated.	X			L	Civil Eng. archive
19	1970	01	?	Rain-induced damage to several buildings along *Emigranti St.* and *Centenaria St*.	X			M	Civil Eng. archive
20	1973	02	09	Landslide activation at *Lacchi*, plus erosion at *Ville*.			X	L	City archive
21	1973	04	24	Rain-induced damage to *Catundi St.*, *Scescio St.*, *S. Giorgio St.*, and *Motticelle St*.		X		M	City archive
22	1974	01	07	Rain-induced damage to a building along *Motticelle St.*, evacuated.	X			L	City archive
23	1980	02	?	Landslide damage to roads and buildings.	X	X		M	*La Gazzetta del Sud* (newspaper)
24	1987	01	11	Rain-induced damage to roads.		X		L	City archive
25	1999	03	?	Aggravation of landslide damage to roads and buildings along *Emigranti St*. and by the *ATERP* building, in the previous six months.	X	X		M	City archive

THE MARCH 7TH 2005 LANDSLIDE

In typological terms (following Cruden & Varnes, 1996), the event under consideration could be described as an enlarging, complex debris slide–earth flow. The main scarp developed within the cataclastic zone of the above mentioned N-S trending master fault. In the lower part of the landslide, two earth-flow bodies extended eastward along minor drainage lines. As a consequence of the initial slide activation, a 50 m wide earth flow developed along the Inserte ravine, and further propagated along the S. Nicola torrent for about 700 m (see sectors A-D in the inset to Figure 5). Following successive enlargement of the slide-affected area (sectors E-F), another smaller earth flow developed southward, and subsequently reached the torrent, and merged with the main flow body. According to eye witnesses, during paroxysmal sliding phases, very rapid velocities could be observed. For some days, springs along the main scarp discharged abundant water to the head of the landslide body; as a consequence, a landslide lake and some minor backwaters soon developed in poorly drained locations.

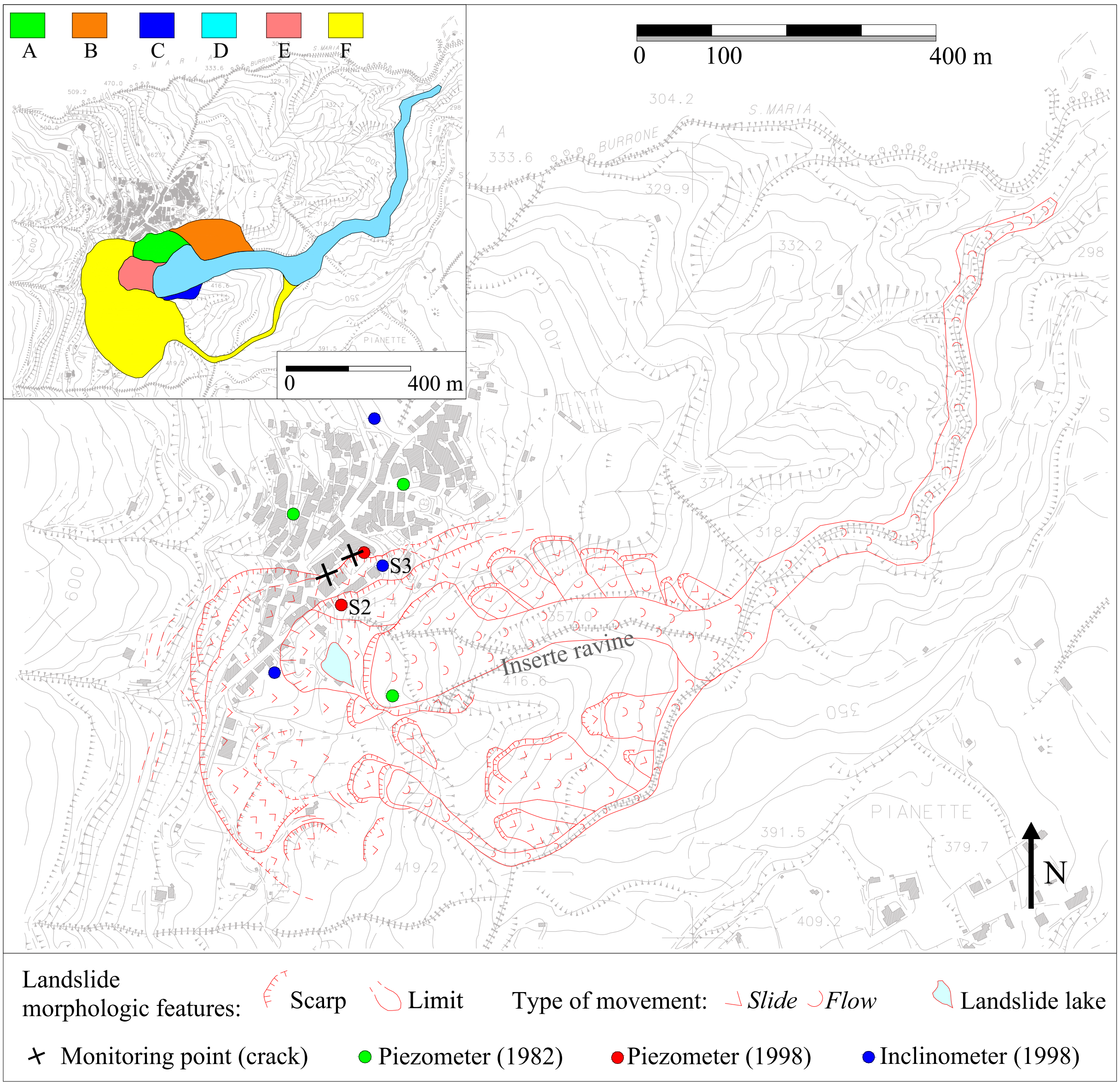

Figure 5. Geomorphologic sketch of the March 7th 2005 landslide at Cavallerizzo. Location of instruments mentioned in the text (in parenthesis, the year of installation), and of cracks monitored during final phases of deformation before collapse, are shown. The inset shows the sequence of development of the landslide sectors “A” to “F” (see text for more details).

The landslide sectors “A” to “F” (Figure 5,) developed in a sequence of three main phases, as follows:

- Activation of sector “A” (March 7th, 03:00 a.m.) – The debris slide started leaving a 10-20 m high scarp developed along Emigranti St., not far from the Rosario Ch. (note that this was the area kept under control). Almost contemporaneously, several smaller landslides (earth slides and complex earth slide-flows) activated on the flanks of the Inserte ravine (sectors “B”, and “C”). Meanwhile, an earth flow (“D”) mobilized along the same ravine, and rapidly reached the junction with the S. Nicola torrent.
- Activation of sector “E” (March 7th, morning) – The initial debris slide “A” widened on its right flank (toward SW), by involving other portions of the urbanized area along Emigranti St. through a couple of rapid mobilisation steps. By that time, the main scarp reached about 30 m in height, while the water abundantly issued from the scarp, thus generating a landslide lake (which was artificially drained).
- Activation of sector “F” (March 8th-12th, and later) – Slow and progressive displacements were observed also in the uppermost part of the slope, and to the right of the first mobilized slide blocks (“A” and “E”). Movement continued at reduced rates in this area during the next months, thereby inducing still more damage to the village. This evidence of the progressive widening and retrogression of the affected area all occurrred within the body of the ancient large-scale gravitational phenomena. On the west, the deformed area skirted the water system which serves most of the neighbouring villages, requiring a temporary by-pass to be installed. The measured velocity of crack opening (monitored just downslope of the by-pass) reached values of about 0.5 cm/day, and remained significant for several weeks though without collapse. In the same period, along a minor creek southward of the Inserte ravine, another small earth flow developed, and successively merged with the main flow along the S. Nicola torrent.

As a whole, it was estimated that the March 7^{th} 2005 landslide mobilised over 5 million of cubic metres of material. Along the S. Nicola torrent, the depth of earth flow deposit ranged from 1 to 10 metres. Due to the different pulses that occurred, flow deposits locally show "stratification" and reflect (even in terms of colour) the different materials involved.

EMERGENCY MONITORING OF DISPLACEMENTS AND RAISING THE ALARM

In the second half of February 2005, some alarming premonitory evidence had been noticed in the area of the future landslide: a) widespread landslide activations (either superficial and deeper-seated) on the slopes, and particularly on the flanks of the Inserte ravine, downslope of Emigranti St.; b) a notable increase of discharge at springs; c) a significant increase of piezometric levels (with a maximum of 5 m at S2); d) blockage of inclinometer S3 at a depth of about 28 m; e) widespread deterioration of damage to buildings and roads. Consequently, emergency monitoring was immediately started, and the progressive opening of cracks along Emigranti St. (Figure 5) was surveyed through daily measurements of displacement.

In Table 2, "classical" thresholds of maximum point velocities, and of mean velocities for sectors suffering from landslide activation are shown, according to Tran vo Nhiem, Guilloux & D'Apolito (1988). Note that such thresholds were generally proposed for displacements measured at the surface of rupture, coupled with measurements made at piezometers and visual observations; moreover, the proposed thresholds were associated with cases of monitoring in non-urbanized areas. In the case of the 2005 Cavallerizzo event however, a precautionary shift in seriousness of levels was adopted to reflect the threshold levels in an urbanized area. With respect to literature proposals, maximum punctual values suggested by Tran vo Nhiem *et al.* (1988) were generally maintained, except for level 0, whose lower limit was halved (Table 2).

Table 2. 'Classical' thresholds of maximum punctual velocities, and of average velocities, after Tran vo Nhiem *et al.* (1988), and "modified" thresholds of maximum punctual velocity for urbanized areas (present proposal). Note that, the modified proposal restricts *normal* status to v<0.75 cm/day.

Classical thresholds			
Level	Status	Average velocity (*cm/day*)	Maximum punctual velocity (*cm/day*)
0	normal	v < 0.5	v < 1.5
1	alert	0.5 ≤ v < 1.0	1.5 ≤ v < 3.0
2	pre-warning	1.0 ≤ v < 2.5	3.0 ≤ v < 5.0
3	warning	2.5 ≤ v	5.0 ≤ v

Modified thresholds	
Status	Maximum punctual velocity (*cm/day*)
normal	v < 0.75
alert	0.75 ≤ v < 1.5
pre-warning	1.5 ≤ v < 3.0
warning	3.0 ≤ v < 5.0
alarm	5.0 ≤ v

On March 1^{st}, observed punctual velocities reached about 0.8 cm/day (Figure 6) – an amount typical of "normal" conditions which equated with an "alert" status. The mayor was informed that the situation was becoming more dangerous. A team, composed of town technicians and volunteers was charged with monitoring the opening of cracks at pre-fixed time intervals. The intervals were decided on the basis of observed velocities, again considering literature proposals (Oboni, 1988): up to a velocity of 1.5 cm/day, daily measurements were considered to be sufficient; for higher velocities, at least six measurements per day were to be taken. Measurements of crack opening were converted into daily velocities, which in turn were compared with thresholds listed in Table 2.

In the period between March 1^{st} and 4^{th}, observed velocities slightly increased, though remaining in the range 0.8-1.0 cm/day. As a precaution, starting from March 5^{th}, intervals among measurements were reduced by employing an infrared distance-measuring equipment (AGA-12), which was in fact installed on a building (located well outside of the area in deformation) and trained on a mirror at the head of S3. An inhabitant of the same building was charged with making one measurement every 4 hours and to communicate the results to CNR-IRPI, unless observed values exceeded the next velocity threshold, in which case an immediate notice had to be made.

Measurements carried out at AGA-12 showed a wide range of variation, mainly due to adverse meteorological conditions (in Figure 6 only the most reliable values are shown). The initial velocities were even quite high (3.1 cm/day, at 20:00 of March 5^{th}); crack opening had in the meantime accelerated up to 1.2 cm/day and, in the crown zone, the opening of fissures was becoming more serious. Considering the results of monitoring and the near- "pre-warning" conditions, the mayor of Cerzeto, using his powers as a civil protection officer, ordered the partial evacuation of the village in the evening of March 5^{th}. Most of the people were in any case already moving away spontaneously.

On March 6^{th}, only a few people were still offering resistance to vacating the area of the prospective collapse. Highly-variable readings at AGA-12 (up to 5.2 cm/day at 18:00), coupled with a crack opening velocity of 4 cm/day, clearly indicated that "warning" conditions had been established. In the late evening, the remaining sceptical inhabitants were thus forced to move away.

At 3 a.m. of March 7^{th}, an inhabitant (D. Golemme) who was still in the area for monitoring purposes, having noticed a rapid increase of displacements (ca. 6 cm/day), gave the "alarm" by ringing the church bells, thus allowing any people still remaining in the vicinity of the affected area to escape. In fact, a little while later, through a series of rapid and progressive collapses, the southernmost part of the village was destroyed by the landslide activation. Activity continued in the next days, and gradually slackened during the following weeks.

In Figure 6, the history of displacement velocities (monitored both at fissures and by means of AGA-12) is shown, together with considered velocity threshold and main emergency measures adopted.

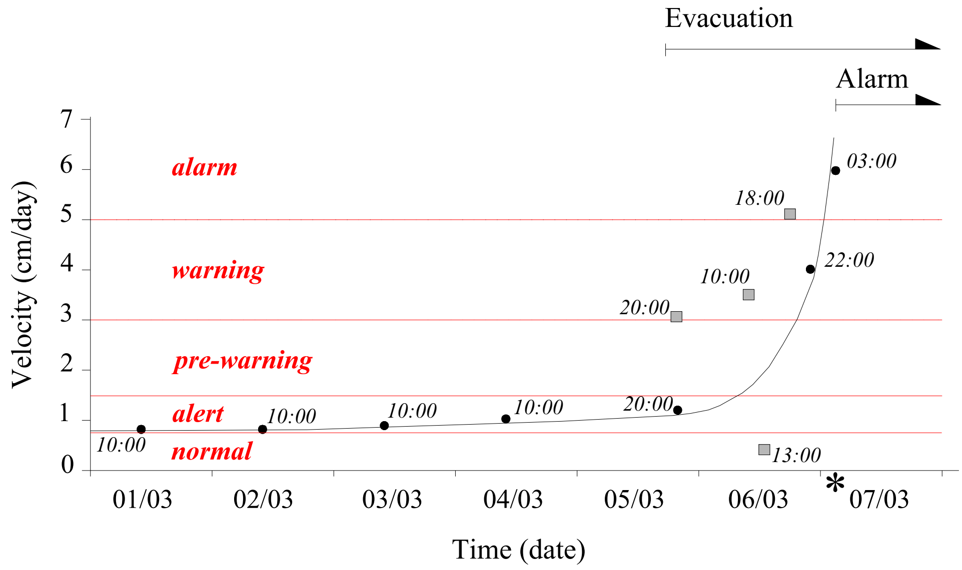

Figure 6. Observed punctual velocities (black dots) of crack opening versus time, during the week preceding the March 7th 2005 landslide activation. Assumed status thresholds are also shown with red horizontal lines (cf. also Table 2). Infrared distance measures, carried out starting from March 5th, are shown with grey squares. The times (*hh:mm*) of measurement are shown in italics. The times of the mayor's decision to evacuate the village and of the raising of the alarm are also shown. The asterisk indicates the time of collapse.

ANTECEDENT RAINFALL AND TRIGGERING CONDITIONS

Rainfall and temperature conditions before March 7th 2005 were analysed in order to estimate their severity in comparison with both their mean values for that period of the year, and also with those recorded before known landslide activations in the past.

At Cavallerizzo (470 m a.s.l.), rainfall is normally concentrated during winter months, with maximum values in December and January. Average temperatures vary between 10°C and 17°C in mountainous and in valley areas, respectively. The nearest available rain gauge is located NE of the village at Fitterizzi (185 m a.s.l.); unfortunately, its data set is quite short (spanning from 1990 to the present day) and discontinuous. By considering the difference in elevation between Fitterizzi and Cavallerizzo, a correlation altitude/rainfall had to be performed, by also employing data from seven surrounding rain gauges (namely: Roggiano Gravina, Sant'Agata C.C., Tarsia, Torano Scalo, Santa Sofia d'Epiro, Rose, and Acri). As a result, an increase of 4.1 mm of annual rain every 10 m of altitude is to be expected. In other words, rainfall recorded at Fitterizzi generally underestimates that at Cavallerizzo.

Considering daily rainfall before March 7th 2005, three rainy periods were recorded at Fitterizzi: the first started on January 19th and ended on 29th (maximum=56.2 mm on 26th); the second, from February 13th to 17th (maximum=51.8 mm on 14th); and the third from February 23rd to March 7th (maximum=40 mm on 7th). Such daily rainfall appears to be normal and less than the maximum historical value of 86.2 mm, recorded on 27.01.2004.

When considering cumulative antecedent rainfall of periods of 1, 3, 5, 7, 10, 30, 90, 180 days before March 7th, the exceptional character of winter 2005 can be better appreciated. In particular, during the 180 days preceding March 7th, rainfall totalled 928 mm, a value higher than the mean annual precipitation of 892 mm.

In order to better evaluate the severity of the rainfall described above, an additional rainfall series recorded at Torano Scalo (located SE of the village, at 97 m a.s.l.) was also considered as the records of this gauge extend from 1916 and include the gaps in the records of the Fitterizzi gauge. Using the Torano Scalo data, all antecendent rainfall accumulations preceding March 7th were higher than averages historically recorded in the same period of the year. In particular, the cumulative rainfall in 90 days (645 mm) is the highest never recorded in the same period of the year (Figure 7a), and represents about 72% of mean annual precipitation.

Cumulative rainfalls preceding historical landslide activations at Cavallerizzo (computed for the same aggregations) were also analysed, regardless of the season of occurrence of the events. Concerning events occurred in XX century (for which rainfall data are available), it could be ascertained that rainfall recorded in the 180 days preceding the 2005 activation is the highest never occurred before any other event of landslide damage in the same area (Figure 7b).

Finally, the role played by snow was also investigated. From January 23rd to 30th, Southern Italy was hit by heavy snowfalls; moreover, in the study area, two more snowy days occurred on February 20th and 27th. Unfortunately, no snow-gauges are available neither at Cavallerizzo nor in the immediate surroundings, and the only data available concern temperature. Periods characterized by increasing daily temperatures occurred on February 14th, and between February 20th and 27th, respectively. Finally, a last increase of maximum daily temperature (up to 16°C) was recorded between March 5th and 6th - that is, just before the landslide activation.

The rainfall analyses presented here therefore clearly point to the role of the antecedent, prolonged rainfalls as a triggering factor of the landslide. Moreover, periods of increase in temperature, and related snow-melt, could reasonably be assumed to have been a contributory factor to the event.

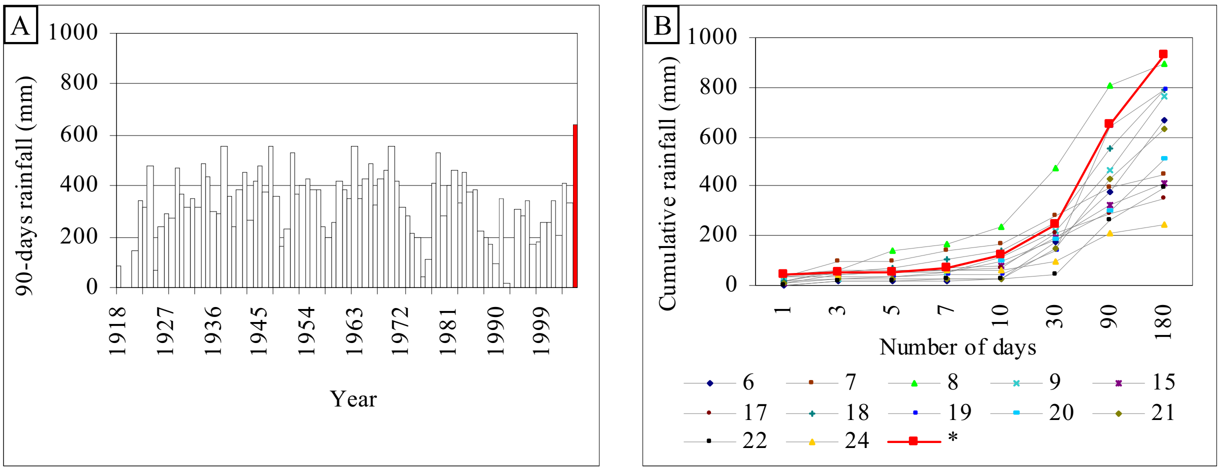

Figure 7. Antecedent rainfall data. Key: a) Cumulative rainfall in the 90 days preceding March 7th (computed for all available years). The value for 2005 is shown in red. b) Antecedent rainfall for periods of 1, 3, 5, 7, 10, 30, 90, 180 days before historical records of damage. The landslide damage events are numbered as in Table 1. Data for the March 7th 2005 event is shown in red (also marked by an asterisk).

DISCUSSION

With reference to information needed for the World Landslide Inventory data base (WP/WLI, 1990), the March 7th 2005 event at Cavallerizzo could be summarized as follows: the mobilized mass exceeded 5 millions of cubic metres; it did not cause any injury nor victims; some 310 inhabitants had to be evacuated for months, either in buildings or hotels of nearby villages; thirty buildings, mostly located in the area of the main scarp, were severely damaged or destroyed. As regards the causal factors that contributed to the landslide, the peculiar geomorphologic and structural settings of the area resulted in unfavourable ground conditions, thus acting as preparatory factors: almost all the factors listed in the Section 1 of Popescu's (1994) Table 1 characterize the area concerned (cf. items 1.4-1.9). Moreover, the effects of neotectonics (2.1) and of erosion (2.4 and 2.7) also certainly contributed with other geomorphologic processes to destabilisation. On the basis of available information, water leakage from services (4.6) and loading of the slope (4.2) could not be discounted. Finally, concerning the triggering factors, prolonged high precipitation (3.3), and perhaps even rapid snow melt (3.2), should be included in the physical processes responsible for the failure.

As mentioned above, when considering the displacements measured during the last week preceding landslide activation, velocities recorded at surface benchmarks along opening cracks, coupled with infrared distance-measuring, pointed out "true" anomalous conditions only about 30 hours before collapse (cf. Figure 6). Pre-rupture velocities reached 0.8 cm/day about 6 days before landslide activation, and gradually increased in the following 4 days to 1.2 cm/day. Then, in 30 hours, velocity accelerated by 5 times (6 cm/day), thus clearly indicating warning conditions. Fortunately, a rearrangement of the classical (cf. Oboni, 1988) classification of danger conditions related to velocity of displacement had been decided by CNR-IRPI for this specific case (Table 2), owing to the urban setting of the landslide and the rudimentary nature of the monitoring techniques. Accordingly, a status of alert had already been announced to the mayor on March 1st. Using the same danger status classification, the mayor decided on prompt evacuation of the inhabitants on the evening of March 5th when the velocity almost reached the upper bound of "modified" pre-warning conditions.

Following Saito (1965), velocity data of the Cavallerizzo landslide versus the number of days preceding collapse has been plotted on a bi-logarithmic diagram (Figure 8), together with similar data from other case studies. As already noticed by Azimi *et al.* (1988), with reference to other case studies, the data for the Cavallerizzo landslide shows an abrupt late change in slope of the interpolated line which could lead to an underestimation of the imminence of danger. Finally, it is worth mentioning that, even if either Saito's (1969) or Azimi *et al.* (1988) methods had been considered for assessing the time of failure, an erroneous underestimation of the imminence of collapse would have resulted up to "the last moment" (March 6th), when a better (but tardy, by then) estimation would had finally been possible.

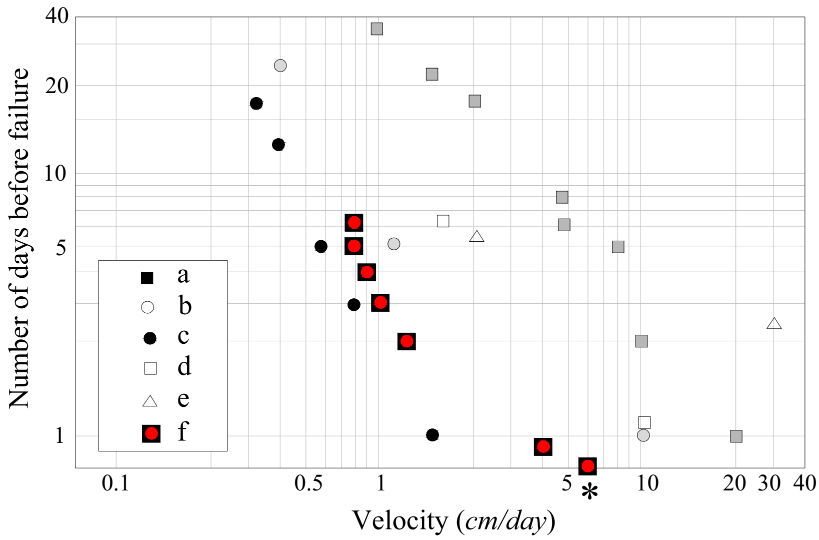

Figure 8. Velocity data of the Cavallerizzo landslide versus the number of days preceding collapse (after Saito, 1965; Azimi et al., 1988; mod.). Data related to other cases of study are also shown. Key: a) Vajont, b) Ooigawa railroad, c) CD926 Arvan, d) Dosan Line, e) Soya Line, and f) Cavallerizzo case studies. The asterisk indicates the time of collapse of the Cavallerizzo landslide.

CONCLUSION

According to available historical information, and geomorphologic analyses carried out through field survey and air-photo interpretation, the March 7th 2005 Cavallerizzo event should be considered as further stage in slope evolution in an already-unstable area, rather than in terms of mere re-activation. The landslide mobilised a series of adjacent unstable sectors, located within pre-existing large-scale gravitational phenomena through different mechanisms but, substantially, with a unitary movement. Moreover, several secondary slides were also activated, and diffuse cracks opened in the ground though these did not always evolve into fully-developed slope movements.

In detail, the landslide was initiated in the southern sector (“A” in. Figure 5) of the village, which had long suffered continual landslide damage in historic time, and rapidly extended over an area of about 305,000 square metres. Sector “A” is located within the zone of “interference” between a couple of ancient large-scale landslides (Figure 3), affecting the eastern slope of the Calabrian Coastal Chain. Moreover, the same area is cut by the Late Pliocene-Holocene “San Fili-Cerzeto-San Marco Argentano” N-S trending master fault, and by a couple of structures belonging to an E-W trending fault system. The upper portion of the landslide thus developed within cataclastic and deeply weathered material, already affected (and weakened) by ancient gravitational phenomena.

Analyses have indicated that the winter rainfall of 2005 was exceptional, when cumulative values for several periods before March 7th are considered. Accordingly, it can be concluded that antecedent prolonged rainfall, probably combined with the effects of a notable increase of temperature (responsible for the thawing of the snow cover), acted as triggering factor of the landslide.

The monitoring procedure employed in this case study demonstrated its effectiveness for supporting civil protection activities, despite its rudimentary character. Piezometric levels as well as displacements at inclinometers and at superficial cracks within crown and head sectors of the prospective landslide were only monitored on an occasional basis for the 6 years before the landslide. At the end of February 2005, when a significant worsening of the situation was detected, time intervals between readings and field surveys were made more frequent: about one day before failure, an additional instrument was installed and frequency of readings was revised. Thanks to the adoption of “modified” velocity thresholds for classifying the level of danger status appropriate for risk in an urban area and the collaboration of the inhabitants, the monitoring regime was successful in preventing injury. Finally, it is worth noting that, had classical methods for assessing the time of failure been adopted to issue the alarm, an underestimation of the imminence of collapse would have resulted with possible tragic results.

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