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Observations on 1998 Campanian debris avalanches and debris flows

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ABSTRACT. The debris avalanches and debris flows of the western Campanian relief are among the most hazardous landslides in the Italian Apennines. On 5/6 May 1998 over twenty flows hit the piedmont towns of Sarno, Quindici, Siano, Bracigliano, 30 Km to the east of Naples. Triggered by intense rainfalls, high velocity flows destroyed a large number of houses killing 161 people. The typical geological environment of such debris flows is characterized by the presence of limestone bedrock mantled by pyroclastic deposits originating from the eruptions of Campi Flegrei and Somma-Vesuvius volcanoes. The surveys performed pointed out that the landslides initiated in the upper part of the slope and of the main and secondary gullies; the largest number of cases indicate that the natural or artificial scarps have an important role in triggering mechanisms. The presence of filling material in the gullies is also crucial in developing the high-velocity flows.

Key terms Debris avalanches, Debris flow, Pyroclastics, Campania.

Introduction

In May 1998 prolonged rainfall triggered catastrophic debris avalanches and debris flows along the slopes of the Pizzo d'Alvano calcareous ridge in the Campania Region (FIG. 1). The towns of Sarno, Quindici, Siano and Bracigliano at the foot of the hillslopes suffered severe destruction and 161 people lost their lives. The landslide events mainly involved the airfall products of Somma-Vesuvius and Phlegraean Field eruptions. Geologically, these landslides should be considered as secondary and delayed effects of volcanic activity. An inspection of FIG. 1 shows that, in the Campania Region an area of about 2,000 km^2 can be considered subject to hazard. As shown by DEL PRETE ET AL, (1998), historical analyses of landslide phenomena indicate that flow-type instabilities have affected, many times in the past, a widespread sector of the Campanian slopes.

In this paper, based on field surveys, we report some observations on geological setting, landslide characteristics and triggering features as well as failure mechanisms and runout areas.

Geological environment

The Campanian Apennines are characterised by a geological setting with a special convergence of geomorphological and lithological factors. The calcareous monocline ridges, sited on the western sector of the chain, are characterised by fault and dip slopes (GUADAGNO ET AL., 2005). The former, controlled by normal faults, are characterised by slope angles ranging from 20° (basal zone) to 50-90° (top) and by irregular surfaces where one or more breaks of slope are present, coinciding with the outcropping of the head-scarps of more competent and thick strata. The dip slopes have angles ranging from 30° to 45° and a more uniform morphology. Karst phenomena, including a number of dolines, is present as well as a tectonic-karstic water circulation (REVELLINO ET AL., 2004).

Pyroclastic airfall and flow deposits, resulting from the intermittent volcanic activity of the Campi Flegrei and Somma-Vesuvius Volcanoes, have mantled the ridges of this sector of the Campania Apennines. The pyroclastic sequences directly cover the bedrock where native regolith is generally absent. Moreover, it is formed by ashy and pumiceous layers alternating with buried soil horizons, resulting from the pedogenic evolution. Layering of the mantle dips at angles similar to those of the bedrock surface. The thickness of the pyroclastic sequences increases from the top of the slope (0.5-2 m) to the foot of the hill (over 10 m) as a consequence of the eruption type and prevailing wind directions, the morphology of the slopes and their exposure, as well as the effects of erosion and colluvial processes.

Figure 2 schematizes the typical geomorphological setting of the slopes. It can be compared to snow mantles in mountain areas. The snow is deposited in successive layers, as the winter progresses, characterized by variable density and mechanical properties. Similarly, the cyclic deposition of volcanic airfall material, separated by periods of weathering, formed a complex sequence of soils. Similar to snow avalanche environments, the described layered structure is fundamental in developing landsliding processes. Each layer presents different lithological characteristics, grain size and thickness as well as hydrogeological and mechanical properties. Layering is not well defined at the scarp edges and at the flanks of gullies, because of erosion and creep phenomena.

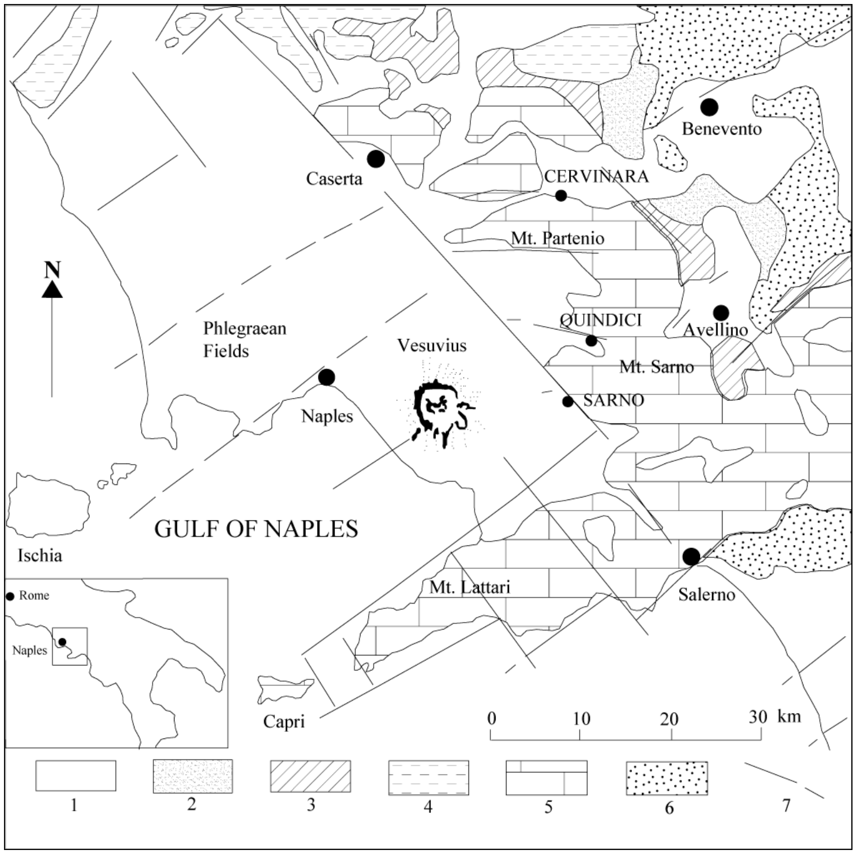

FIG. 1 - Generalised geology and location map. Legend: 1) Plio-Pleistocene deposits; 2) Altavilla units (Tortonian Middle Pleistocene); 3) Irpinia units (Langhian-Tortonian); 4) Carbonate Matese unit (Trias-Paleocene); 5) Carbonate unit of the Alburno-Cervate unit (Trias-Paleocene); 6) Sicilide units (Cretaceous-Eocene); and 7) Principal faults. Locations of Sarno/Quindici area is also shown (after GUADAGNO, 1991).

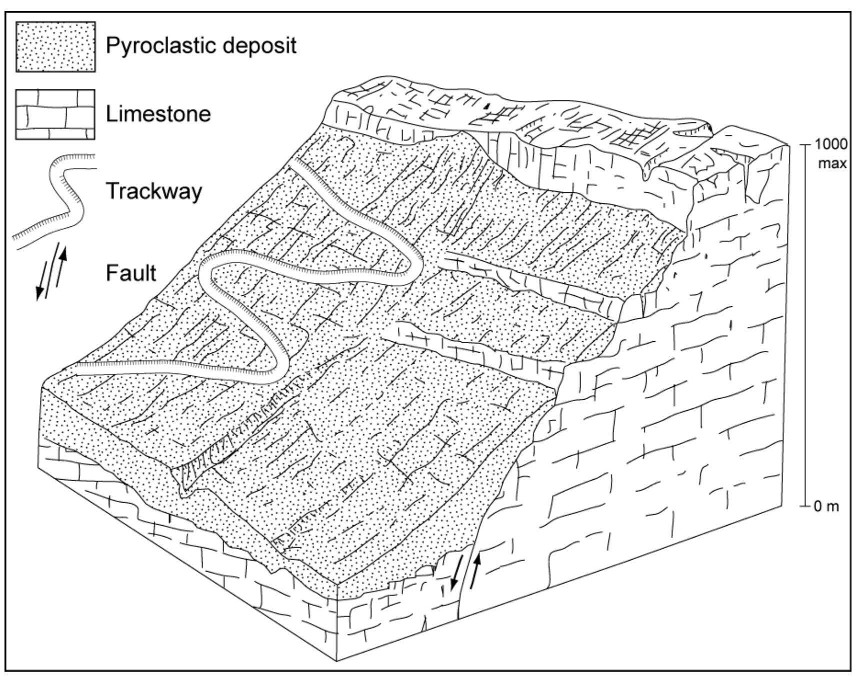

FIG. 2 - A block diagram showing the peculiar geomorphological setting in the Campanian Appenines (after GUADAGNO ET AL., 2005).

Finally, it should be noted that the landscape of the Campanian Apennines is strongly influenced by the land use. Since Roman times the population has developed chestnut and hazelnut plantations on slopes since the thin pyroclastic mantle is very fertile. In previous times, access to the plantations was on foot and hence only limited pathways were created.

Despite the fragile equilibrium of the slopes, trackways have been developed during the last twenty-five years for vehicular access. The roadways have been cut into the pyroclastic mantle rising in a zigzag manner up the slope being almost parallel to the contours (FIG. 2). Being for service only, trackway construction has generally been carried out without any drainage or compaction works.

Geotechnical Properties and Behavior of Pyroclastic Soils

As already described, the sequences of pyroclastic layers and soil horizons consist of discontinuous layers with varying geotechnical properties. GUADAGNO AND MAGALDI (2001) described some characteristics through analyzing representative samples. TABLE 1 shows some typical parameters from different sites in the area.

The contrast in basic properties between pumiceus layers and horizons of buried soils is quite evident. Pumices should be considered as a typical granular material, even if they are characterized by special behavior (ESPOSITO AND GUADAGNO, 1998), while soil horizons should be considered as cohesive materials. In particular, in the pumice layers, interconnected capillary-size voids within the grains influence water flow circulation, causing suction phenomena and complex water diffusion (WHITAM AND SPARKS, 1986). The presence of allophane minerals (MAEDA ET AL., 1977) in the horizons determines specific geotechnical behaviors of the materials. Generally, these soils exhibit high values of liquid limit at relatively low clay contents. As already described by MITCHELL (1976), the residual friction angle is generally high (close to 30°), and comparable to the peak angle defined for some volcanic soils of Campania (GUADAGNO AND MAGALDI, 2000).

As in situ tests show, layers and horizons of soil exhibit different permeability values (TABLE 1). The pumice layers can be considered as drain layers, while the clayey horizons are quasi-impervious. In such a hydrogeological setting, cuts for roadways can cause important changes in the groundwater flow pattern, and in particular in water infiltration.

TABLE 1. Typical schematic soil profile and geotechnical parameters of the pyroclastic mantle in the Sarno/Quindici (after GUADAGNO AND MAGALDI, 2001, modified)

Depth (cm)	Horizons		Gs	γ_d (kN/m^3)	W_n (%)	e	S (%)	CF (%)	<60 µm	W_L (%)	PI (%)	O.M. (%)
0 - 25		A	2.690	8.25	40.3	2.26	48.0	9	35	63.2	13.54	6.6
25 – 47		Bw1	2.705	6.88	58.1	2.93	53.6	11	36	71.7	12.86	6.6
47 – 70		Bw2	2.646	8.70	36.3	2.04	82.0	0	9	-	-	7.8
70 – 125		C1	2.460	-	31.2	-	-	0	4	-	-	3.7
125 – 142		C2	2.512	-	31.0	-	-	0	4	-	-	3.6
142 – 165		Ab	2.654	6.70	51.8	2.96	46.4	0	-	-	-	10.0
165 – 185		Bwb 1	2.666	6.60	67.0	2.86	62.4	16	54	75.7	16.80	8.5
185 – 230		Bwb 2	2.678	8.00	64.8	2.35	74.0	14	54	62.2	15.10	7.6
		Bedrock										

From a granulometric point of view, it should be noted that, debris flow deposits range from *silty sand with gravel* and *sand with silt and gravel*. A large amount of limestone clasts is also present. The landslide material is formed by typical melanges. Calcareous boulders (up to 2 m in diameter) as well as trees or anthropogenic elements were observed in the depositional area. A large contribution comes from the materials present along the gullies where the flows are confined.

The Instabilities and the Triggering Conditions

Triggered by intense rainfall, the landslides of 5/6 May 1998 originated from the upper part of the relief of Pizzo d'Alvano (900 m a.s.l.) and reached the piedmont towns located at elevations between 100 and 50 m a.s.l. In the area included in the quadrilateral of Quindici, Sarno, Siano, and Bracigliano, the rain began around 2 a.m. of 4th of May and continued with some interruption up to May 6.

The piedmont area pluviometric stations recorded a total precipitation of between 80 and 100 mm with maximum intensity of 12-13 mm/h. Moreover the zone most struck by the rains was the upper part of the relief of Pizzo d'Alvano lacking in pluviometric stations. In this area a total rainfall of around 200 mm was estimated by the National Hydrographic Service (1999), with maximum intensity of the order of 20 mm/h.

The mass movements began in the morning of 5th May and the most catastrophic events reached Quindici at 6 p.m. of 5th May and on Sarno at 0.30 a.m. of 6th May. The surveys performed immediately after the disaster pointed out the following geological and morphological evidence:

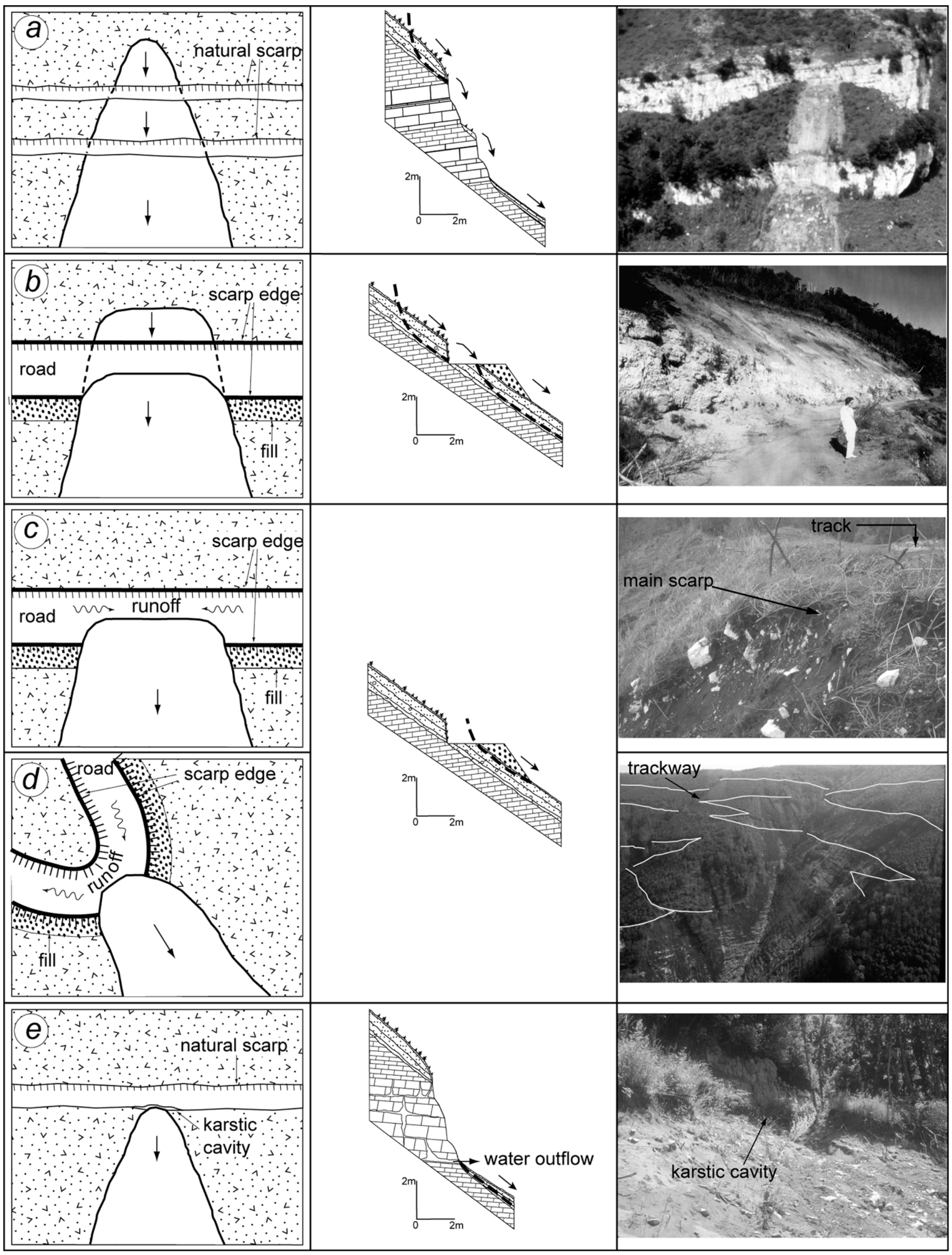

FIG. 3 - The geomorphological setting of the four main source area types for the 1998 landslides (after GUADAGNO ET AL., 2005).

- the landslides developed from the upper part of the slopes and of the main and secondary gullies;
- the largest number of cases indicated the natural or artificial scarps as starting points of the landsliding (GUADAGNO ET AL., 2005; GUADAGNO ET REVELLINO, 2005);
- other forms of activation were also observed in the upper steeper part of the gullies, which are zones of convergence of superficial and deep waters (DEL PRETE M. & DEL PRETE R., 1999).

The subsequent motion and liquefaction of the gully material can be explained by sudden loading and structural collapse of the saturated porous filling material.

Analyses of the morphological characteristics of the initial slides have been performed by GUADAGNO AND PERRIELLO (2000), GUADAGNO (2000) and GUADAGNO ET AL. (2005). They have shown that morphological discontinuities, associated with natural scarps and with road tracks, appear to be the controlling factors. Figure 3 shows typical examples of initial slide in different morphological settings. In all cases, pyroclastic masses possess the kinematic freedom necessary for failure.

TABLE 2: Recurrence of the morphological settings recognised in the failure areas

Morphological conditions of initial failures	**Location**				
	Sarno (57)*	**Quindici** (88)*	**Siano** (11)*	**Bracigliano** (20)*	**Total** (176)*
Failures above natural scarps	21 (37%)	17 (20%)	8 (73%)	5 (25%)	51 (29%)
Failures below natural scarps	2 (3%)	0 (0%)	1 (9%)	0 (0%)	3 (2%)
Failures above man-made cut	18 (31%)	57 (65%)	0 (0%)	11 (55%)	86 (49%)
Failures involving fills	8 (14%)	11 (12%)	2 (18%)	0 (0%)	21 (12%)
Failures without morphological control	8 (14%)	3 (3%)	0 (0%)	4 (20%)	15 (8%)

* Number of initial failures

Statistical analyses of initial instabilities of Pizzo d'Alvano slopes (TABLE 2) show that a large percentage (61% of the initial instabilities) of the debris avalanches is connected with artificial road tracks.

GUADAGNO ET AL. (2005) considered the development of the avalanches as failure phenomena of the pyroclastic slab. Since they were characterized by recurrent triangular shape, analyses of significant morphometric parameters can be performed. In particular, the width of the apex angle of the triangular-shaped avalanche scars, one of the most significant parameters, appears systematically controlled by the slope angle and the height of the natural or man-made scarps (FIG. 3).

As already mentioned, flows occur during a period of prolonged rainfall. Since landslides are shallow, surficial water and water seepage play a fundamental role in triggering the initial failures. Detailed analyses show that instabilities generally occur where specific hydrogeological conditions can be recognized on the slopes (DEL PRETE M. E DEL PRETE R., 2002; GUADAGNO ET AL, 2003b). In particular, natural and human-induced morphological settings can create concentrated runoff to specific points that generally correspond to the source points of the debris avalanches. Hydraulic condition can be induced in such a zone, in terms of full saturation, pore pressure and infiltration, necessary for triggering the instabilities. Moreover, the saturation of soil masses should be considered a key factor in the development of undrained loading mechanisms within the pyroclastic multilayer as well as in the transformation of sliding mechanisms into more or less viscous flows.

Cuts for trackways interrupt the normal downslope flow of surficial water. Water, flowing downslope through the more permeable deposits can be temporarily confined by the relatively impermeable ones. In this condition, hydrostatic pressures could be created, inducing failures. These conditions have been ascertained also for other phenomena in different areas. (FIORILLO ET AL., 2001)

Slope stability analyses have also been performed by means of numerical models, such as the finite difference codes, and in different geomorphological and hydrogeological situations, to verify the described initial failure mechanisms (CROSTA AND DAL NEGRO, 2003, GUADAGNO ET AL., 2003a). The results show that the continuous and uninterrupted multilayered pyroclastic covers can be considered at equilibrium. On the contrary, man-induced cuts along the slopes cause significant modification of the natural equilibrium conditions, leading to the development of local yield zones typically localized in the pyroclastic sequence. The analysis shows that the geometry of the cuts can have a significant impact on the shape of the slip surfaces.

TABLE 3: Rain and recharge data

	04 May 1998	05 May 1998	TOTAL
TOTAL RAIN	31.6	158.4	190.0

DAY	TIME TABLE	HOURS	RAIN (mm)	TOTAL RAIN (mm)	INTENSITY OF RAINFALLS (mm/h)	DURATION (h)	RECHARGE (mm/h)
04 May 1998	2	0	0.00	0.00	0.00	0	0.00
04 May 1998	4	2	7.93	7.93	3.57	2	1.25
04 May 1998	5	3	5.00	12.93	10.29	1	3.60
04 May 1998	6	4	9.77	22.70	9.26	1	3.24
04 May 1998	7	5	3.60	26.30	0.00	1	0.00
04 May 1998	8	6	0.00	26.30	0.00	1	0.00
04 May 1998	17	15	0.00	26.30	0.00	9	0.00
04 May 1998	19	17	0.65	26.96	0.65	2	0.23
04 May 1998	21	19	2.05	29.01	1.24	2	0.44
04 May 1998	23	21	2.60	31.61	2.16	2	0.76
05 May 1998	0	22	3.26	34.87	2.83	1	0.99
05 May 1998	2	24	8.10	42.97	4.65	2	1.63
05 May 1998	7	29	32.32	75.29	8.28	5	2.90
05 May 1998	11	33	49.39	124.68	15.43	4	5.40
05 May 1998	14	36	41.19	165.87	15.43	3	5.40
05 May 1998	16	38	15.38	181.25	5.11	1	1.79
05 May 1998	17	39	5.32	186.57	2.55	1	0.89
05 May 1998	20	42	3.43	190.00	0.00	3	0.00

TABLE 4: Rate of discharge of the gullies

			Gully San Romano	Gully Cortadonica	Gully Tuostolo
		Gullies width (m)	650	565	500
DAY	TIME TABLE	HOURS	DISCHARGE (m/sec*m)	DISCHARGE (m/sec*m)	DISCHARGE (m/sec*m)
04 May 1998	2	0	0.00E+00	0.00E+00	0.00E+00
04 May 1998	4	2	2.26E-04	1.96E-04	1.74E-04
04 May 1998	5	3	6.50E-04	5.65E-04	5.00E-04
04 May 1998	6	4	5.85E-04	5.09E-04	4.50E-04
04 May 1998	7	5	0.00E+00	0.00E+00	0.00E+00
04 May 1998	8	6	0.00E+00	0.00E+00	0.00E+00
04 May 1998	17	15	0.00E+00	0.00E+00	0.00E+00
04 May 1998	19	17	4.11E-05	3.58E-05	3.17E-05
04 May 1998	21	19	7.87E-05	6.84E-05	6.05E-05
04 May 1998	23	21	1.37E-04	1.19E-04	1.05E-04
05 May 1998	0	22	1.79E-04	1.55E-04	1.38E-04
05 May 1998	2	24	2.94E-04	2.55E-04	2.26E-04
05 May 1998	7	29	5.23E-04	4.55E-04	4.03E-04
05 May 1998	11	33	9.75E-04	8.48E-04	7.50E-04
05 May 1998	14	36	9.75E-04	8.48E-04	7.50E-04
05 May 1998	16	38	3.23E-04	2.81E-04	2.49E-04
05 May 1998	17	39	1.61E-04	1.40E-04	1.24E-04
05 May 1998	20	42	0.00E+00	0.00E+00	0.00E+00

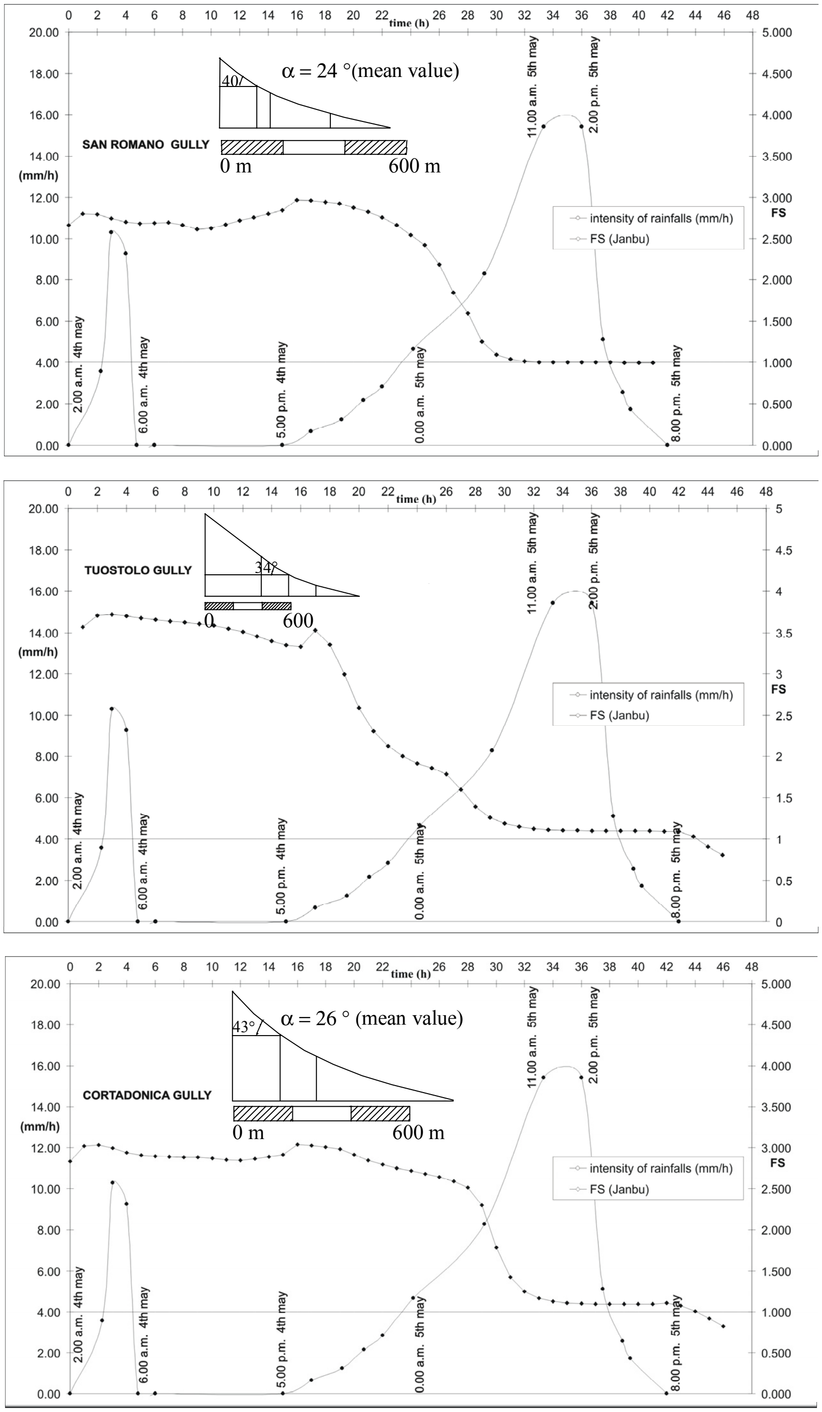

FIGURE 4. Variation of factor of safety with rainfalls and slope angles of gullies.

Another fundamental effect can be associated with the channeling of rainfalls along the trackways. The roads, with a mean gradient of about 3-4%, induce channeling towards specific points, in particular to the curving segments of the zigzag pathways. As a result, such localized concentrations of water can induce pore pressures triggering the failure of the downslope side of the trackway. Here uncompacted materials form fills whose angle is generally higher than that assumed by the pyroclastic deposits in a natural condition.

The fundamental importance of the local setting seems to be demonstrated by the temporal-spatial distribution of the landslide. Debris avalanches and debris flows occurred in a discontinuous manner along the slopes of Pizzo d'Alvano over a period of about 12 hours. To explore the hypothesis of initial slides of gully material, along more pendent profiles, the Tuostolo, Cortadonica, and San Romano gullies were considered.

Despite a number of uncertainties, some stability analyses were calculated assuming the hypothesis of slip surfaces between the limestone bedrock and fill materials in the gullies.

A geological model consisting in three main aspects was considered:

- the filling material of gullies with thickness of 6 m;
- a strongly fractured limestone top bedrock of 10-m thickness;
- a less fractured underlying limestone bedrock.

Using a software with finite elements, the water circulation was simulated.

In TABLES 3 and 4, the discharges of gullies are shown on the basis of reconstructed rain intensity. Figure 4 gives the results of stability analyses, from which it can be observed that the safety factor drops around the second peak of rain, coinciding more or less with news reports.

By measuring the superelevation of the flowing masses in channel bends, flow velocities were estimated for several phenomena. Maximum velocities of about 13 m/sec were calculated near the toe of the slopes. These values are confirmed by video clips taken during the landslide events and by eyewitnesses.

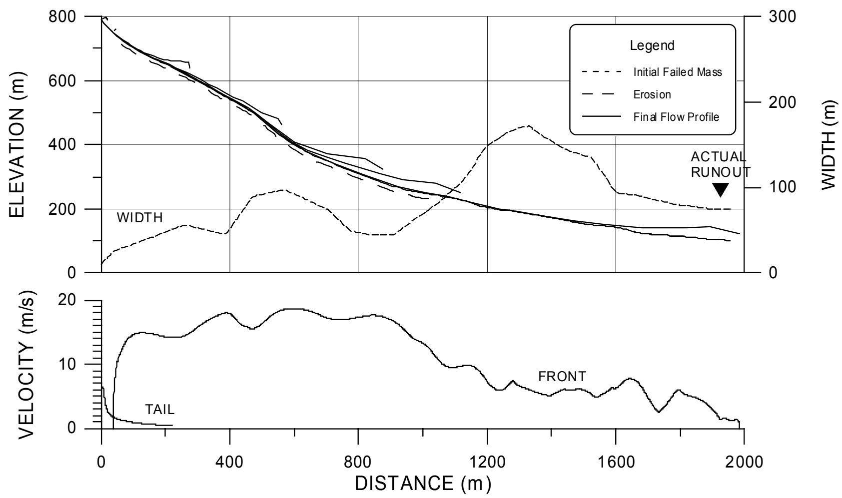

FIG. 5 - Example of DAN back-analyses using the Voellmy model. The flow profiles are plotted at 20 second intervals. All normal depths (flow depths and erosion depths) are exaggerated 10 times (after REVELLINO ET AL., 2004, modified).

TABLE 5. Summary of the analysis of measured cross-sections, velocity, runout, and deposit thickness and their comparison with DAN model analysis (after REVELLINO ET AL., 2003, modified).

Slide	*Velocity*			*Runout*		*Deposit Thickness*		
	Cross-section	*Superelevation (m/s)*	*Model (m/s)*	*Actual (m)*	*Model (m)*	*Site*	*Actual (m) (min./max)*	*Model (m)*
1	b g	5.5 12.8	6.1 10.2	3,397	3,280	a	1.5/3.0	2.8
2				2,560	2,591	b	0.7/1.4	1.5
3				1,895	1,995			
4				1,860	1,890	c d	0.8/1.0 0.4/0.5	0,6 0,2
5				2,051	2,074	e f	0.4/0.7 0.6/0.8	0,4 0,5
6	a	10.3	9.4	1,535	1,589	g	0.4/1.0	2.3
7				1,955	2,069	h	0.2/0.4	0.2
8				2,028	2,077			
9				1,122	1,145			
10				1,052	1,170			
11				1,965	2,058			
12	c d	5.9 6.1	6.2 5.9	3,210	2,990			
13	e	10.9	13.9	1,234	1,250	i	0.4/0.8	0.4
14	f	10.3	14.2	736	760	l	0.6/1.0	1.5

The use of the *DAN* program (HUNGR, 1995), based on an explicit Lagrangian solution to the equations of unsteady non-uniform flow in a shallow open channel, has permitted the debris avalanches and flows to be modeled. The methodological basis of the application of the model to the Campania flows can be found in REVELLINO ET AL. (2004). The analyses assumed that the source volumes consisted of a slab of constant depth (1.5 m) and that, downslope of the source area, the debris avalanches were eroding the same constant thickness of material.

Through a systematic program of back-analysis of real cases and by using a trial-and-error procedure, runout distances, velocity at points of the path, where velocity was estimated by measuring superelevation in path bends, and the thickness and distribution of the debris deposits were obtained.

An example of the analyses is shown in FIG. 5, while Table 5 presents data of comparisons between some real measurements of the flows and those derived from DAN analyses.

Conclusions

The landslides phenomena that hit the towns of Sarno, Quindici, Siano and Bracigliano, should be considered as typical in a geological context where pyroclastic soil sequences mantle limestone ridges. The characteristics of the initial instability, debris slides at the edges of natural scarps or along the road-track cuts, and the rapid evolution along open slopes, allow us to classify some of them as debris avalanches. The successive channeling of the landslide material transformed the phenomena into debris flows that rapidly increased the volume through involving the gully deposits.

Therefore, the peculiar nature and setting of the cover deposits composed of pyroclastic materials, instead of native regoliths, and the presence of natural scarps and man-made cuts within the limestone bedrock and the pyroclastic covers produced kinematic freedom for the masses along the edges and at the same time controlled the surface and groundwater flows.

The mobilization of the slope materials after the initial slides should be consequent to processes of undrained loading, responsible also for probable structural collapse and liquefaction phenomena.

The characterization of the gullies, on the basis of their geometry, inclination and tortuosity, is very important for an evaluation of the volume and the velocity of flows, while a knowledge of mass movement magnitude allows us to prepare better maps of risk. Moreover, identification of the initial mechanism of flow processes is decisive in order to define:

- the priority areas of stabilization which should coincide with the upper network of the basins;
- the types of stabilization works for a control of the unstable scarps and the effects of deep and superficial water.

In addition, in the last few decades, mechanized forest management practices have favored the formation of a dense trackway network, which has significantly altered the already sensitive original setting.

Correct land use practices and, in particular, management of woods without making inappropriate changes to the local topography seem to be very important, to avoid the increase of hazard that, as shown in the case of Sarno-Quindici, has increased dramatically.

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