Influence of man-made cuts on the stability of pyroclastic covers (Campania, southern Italy): a numerical modelling approach

F.M. Guadagno · S. Martino · G. Scarascia Mugnozza

Abstract Intense rainfall in May 1998 and December 1999 caused disastrous landslides in the Sarno-Quindici and Cervinara areas (Campania, southern Italy). The landslides began with slips of the local pyroclastic covers mantling the carbonate relief and then evolved into debris flows/avalanches. The study discussed in this paper used a numerical modelling approach to assess the influence of man-made cuts on the stability conditions of pyroclastic covers. The model that was developed took into account initial failure conditions in order to better simulate the impact of man-made cuts along the slopes, with or without water seepage into the permeable pumiceous layers of the pyroclastic multilayer. Numerical analysis of stress-strain field clearly showed that tracks or geomorphological discontinuities had a negative impact on the multilayer stability conditions. Consequently, preservation of this vulnerable environment requires correct forest management practices.

Keywords Campanian Apennine · Volcanoclastic soils · Catastrophic landslides · Numerical modelling · Forest management · Southern Italy

Introduction

The pyroclastic deposits that mantle the Mesozoic limestone massifs surrounding the volcanic centers of Somma-Vesuvius and the Phlegrean Fields (Campania region, southern Italy) were recently involved in disastrous landslides (Fig. 1). In May 1998, following an intense rainstorm in the Sarno-Quindici area, over 100 initial slope failures turned into debris flows and avalanches, which struck the downslope human settlements causing a high number of casualties and the destruction of several houses and infrastructures (Del Prete and others 1998; Celico and Guadagno 1998; Guadagno 2000; Pareschi and others 2001). In December 1999, prolonged and heavy rainfall triggered similar landslide events, which hit the Valle Caudina area, namely the town of Cervinara, killed six people and entailed serious damage (Fiorillo and others 2001). Such events are the most recent ones which occurred in the Campania area, after numerous catastrophic landslides, which struck many areas around the Campania Plain, as reported by many authors (Penta and others 1954; Civita and others 1975; Celico and others 1986; Guadagno 1991).

Celico and Guadagno (1998), Del Prete and others (1998) and Fiorillo and others (2001) focused on the phenomena which took place in the areas of Sarno and Cervinara (Fig. 2), describing the conditions of initial failure and the mechanisms of the movements. They also identified the following critical factors: previous rainfall events, possible perched-water conditions, physical and mechanical properties of recent pyroclastic covers and buried soils, and morphological conditions along the slopes (natural scarps and man-made cuts and fills).

Among the above-mentioned factors, some authors (De Riso and others 1999; Guadagno 2000; Guadagno and Perriello Zampelli 2000; Fiorillo and others 2001) paid particular attention to the morphological conditions of the source areas, highlighting that landslides are generally linked to the presence of specific morphological features, such as natural scarps and cuts for the construction of tracks and dirty roads. Consequently, different scenarios were proposed in terms of initial failure mechanisms, motion and run-out processes (Del Prete and others 1998; Del Prete and Del Prete 1999; Revellino and others 2002).

This paper contributes to a better understanding of the failure mechanisms leading to landslides. In particular, the study analysed the influence of the general and local morphological setting on the stability of pyroclastic covers, suggesting the need for more correct forest management practices. Celico and Guadagno (1998)

Received: 9 April 2002 / Accepted: 2 July 2002

F.M. Guadagno (✉)
Department of Geological and Environmental Studies,
University of Sannio, 82100 Benevento, Italy
E-mail: guadagno@unisannio.it

S. Martino · G. Scarascia Mugnozza (✉)
Department of Earth Sciences,
University of Rome "La Sapienza", 00185 Rome, Italy
E-mail: gabriele.scarasciamugnozza@uniroma1.it

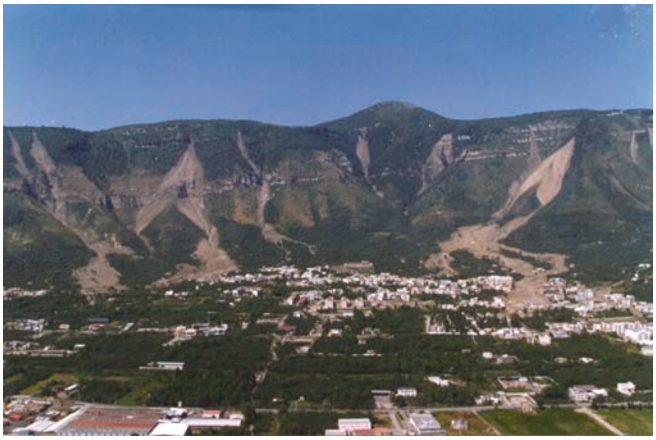


Fig. 1
Panoramic view of the landslides in the Pizzo d'Alvano and Sarno area

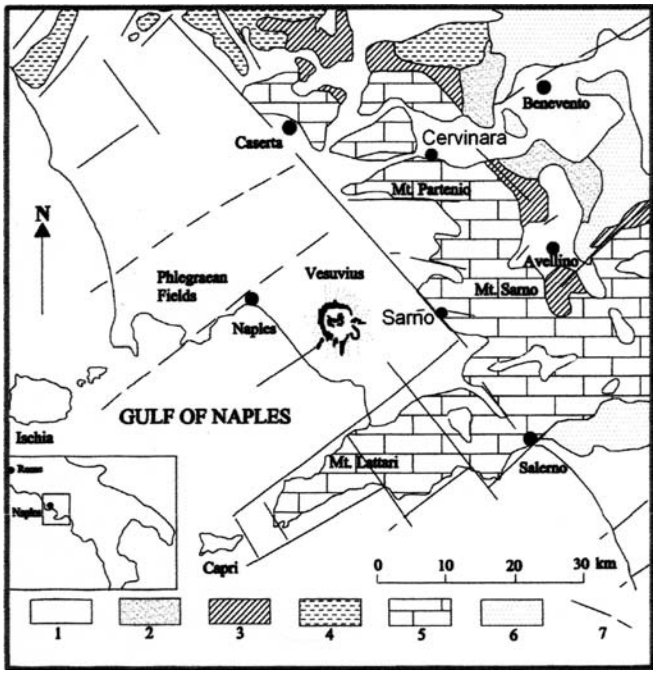


Fig. 2
Geological sketch map of western Campania. *1* Plio-Pleistocene deposits, *2* sand and clay Altavilla unit (Tortonian–Middle Pliocene), *3* flysch of the Irpinia unit (Langhian–Tortonian), *4* carbonate Matese unit (Trias–Paleocene), *5* carbonate unit of the Alburno-Cervati (Trias–Paleocene), *6* sicilide varicoloured clay (Cretaceous–Eocene), *7* faults (modified after Ippolito and others 1975)

and Guadagno (2000) emphasised the major changes that have been made to the roads of access to the local chestnut and hazelnut forests in the last decades (Amato and others 2000). Use was thus made of numerical modelling techniques to evaluate the impact of local morphological setting, seepage into the pyroclastic covers and technical properties of the volcanoclastic deposits on ground failure initiation mechanisms.

Geological, geomorphological and geotechnical background data

The reliefs east of the Somma-Vesuvius and Phlegrean Fields volcanic centres are characterised by NE-dipping monoclinal ridges, mainly composed of limestone sequences belonging to Mesozoic carbonate platforms (Ippolito and others 1975) and with a decimetre- to metre-scale bedding thickness. These ridges are separated by NE-SW- and NW-SE-trending faults (Fig. 2), forming blocks that are surrounded by fault slopes and dip slopes. The slopes have sharp differences in the slope angle, as they range from 20° (foot zone) to 50–90° (top zone) and from 35° to 45°, respectively (Brancaccio and others 1978). Since 30,000–40,000 B.P., as a result of intermittent volcanic activity, the limestone reliefs have been mantled by air fall and pyroclastic flow deposits, which were layered at an angle similar to the one of the bedrock surface. Figure 3 is a sketch indicating the varying thickness of pyroclastic deposits over the stepped limestone reliefs. Deposition and erosion processes, as well as pedological evolution, gave rise to a typical mantling sequence, where ashy and pumiceous layers alternate with buried horizons (Fig. 4).

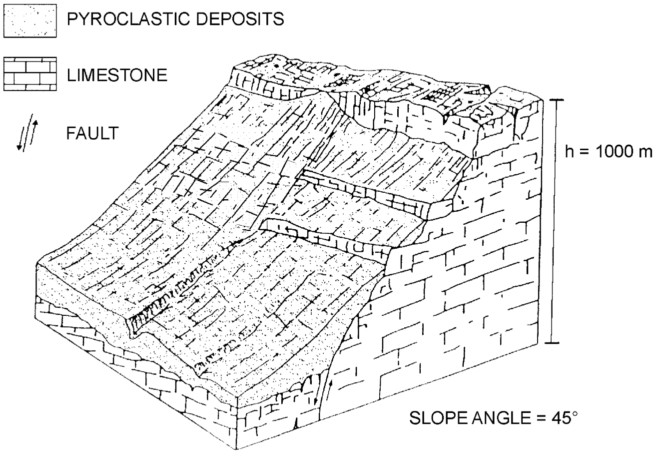


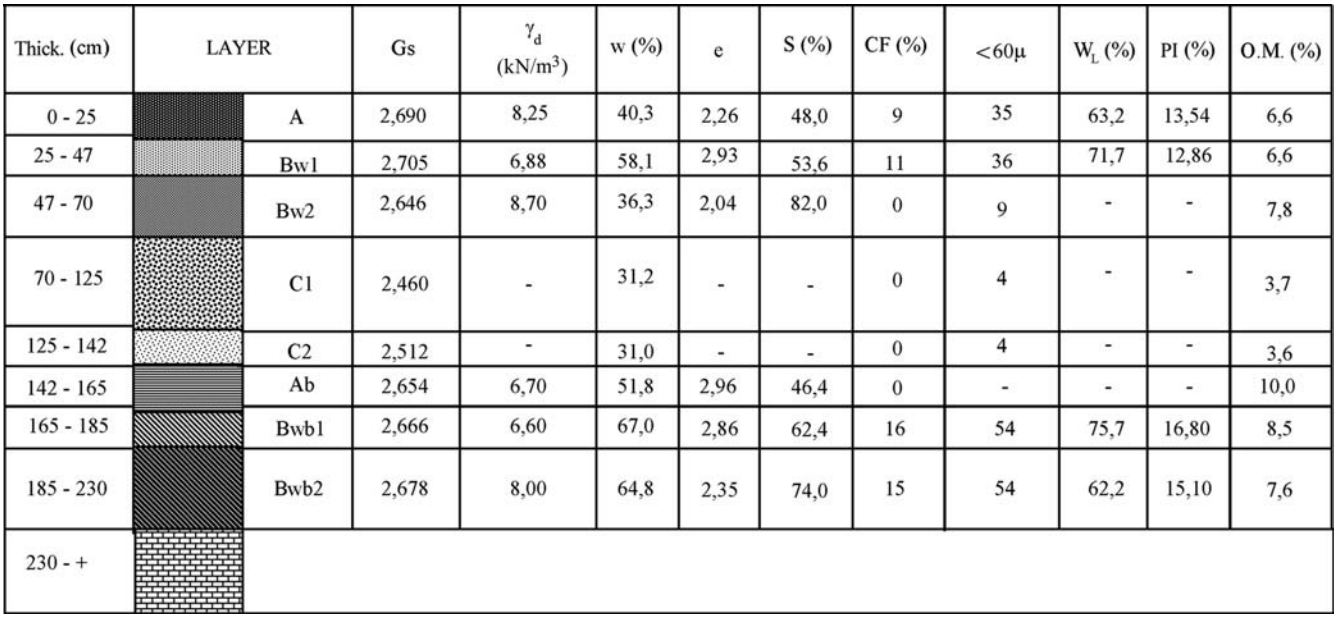
Fig. 3
Geological sketch showing the varying thickness of pyroclastic covers over the stepped limestone relief

Fig. 4
Typical sequence of pyroclastic deposits and buried horizons

As layering is evident in the undisturbed pyroclastic sequence on open slopes, the lack of clear layering in some deposits along the lower slope and in the gullies suggests that the material was re-deposited through gravitational and colluvial processes. Variable thickness is due to eruption-type processes and to the morphology of the sites of deposition, although progressive thinning from the foot to the top of the slopes is observed. In particular, the investigated areas display pumiceous levels that were ascribed to various volcanic events. The base of the sequence displays a typical, yellowish, silty-clayey layer of decimetre scale, which directly overlies the bedrock units, filling gullies and penetrating into discontinuities. This layer is related to a pyroclastic flow and probably to the Campanian Ignimbrite (30,000 years B.P.; Barberi and others 1978). Guadagno (2000) previously reported that the above conditions compare with those of snow-covered mountain areas. Similarly, pyroclastic covers are generally characterised by different densities and mechanical properties that impart a typical multilayer appearance to their mass. Figure 5 exhibits a broadly representative soil profile of the multilayered covers of the Sarno and Cervinara areas, together with their geotechnical properties, inferred from laboratory investigations on representative samples (Guadagno 1991; Esposito and Guadagno 1998; Guadagno and Magaldi 2000). While the pumiceous layers are well-graded granular materials, the soil horizons are cohesive materials with notable differences in shear strength and hydraulic conductivity. The geotechnical properties of pyroclastic deposits were studied by many authors (e.g. Whitham and Sparks 1986). More specifically, Esposito and Guadagno (1998) stressed the unique physical characteristics of pumices which contain interconnected voids whose size is such as to cause suction and strongly influence water diffusion. In addition, the significant influence of allophane on the behaviour of pyroclastic horizons was investigated by Wesley (1977), Maeda and others (1977) and Rao (1995) and, more recently, by Guadagno and Magaldi (2000) for the volcanic soils of the Campania area. In this study, the presence of allophane clay particles together with organic matter was demonstrated by Terribile and others (1999). Specific testing methods were thus adopted to accurately characterise the main parameters of the investigated materials. Although these materials appeared to be overconsolidated (OCR>5), probably as a consequence of suction, the tests that were conducted did not reveal significant cohesion (Guadagno and Magaldi 2000). Moreover, their residual shear strength had high values (ϕ>25°), close to peak strength ones, as indicated by previous studies (Rao 1995). This typical behaviour may, in part, explain the stability of pyroclastic covers, even along the steep slopes of the study areas. In conclusion, the investigated pyroclastic layers, which mantle calcareous slopes, may be regarded as complex systems whose evolution depends on their specific geometry, as well as on their mechanical and hydraulic behaviour. As these parameters have a dramatic impact on slope failure mechanisms, they were carefully considered to develop a reliable numerical model.

Types and kinematics of landslides

Figures 6 and 7 illustrate the catastrophic events that devastated the Sarno-Quindici and Cervinara areas. Based on morphology, kinematics and type of material involved, these events were generally defined as debris flows (Varnes 1978; Johnson and Rodine 1984; Pearson and Costa 1987; Hutchinson 1988). Under the classification proposed by Cruden and Varnes (1996) and Hungr and others (2001), they may be considered as complex landslides, resulting from the evolution of shallow translational slides into



Thick. (cm)	LAYER		Gs	γ_d (kN/m^3)	w (%)	e	S (%)	CF (%)	<60μ	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	▧	Bwb1	2,666	6,60	67,0	2,86	62,4	16	54	75,7	16,80	8,5
185 - 230	▧	Bwb2	2,678	8,00	64,8	2,35	74,0	15	54	62,2	15,10	7,6
230 - +	▦											

Fig. 5
Schematic profile of pyroclastic covers and geotechnical properties (after Guadagno 2000)

Fig. 6
Typical view of the source areas of landslides in the Quindici area

Fig. 7
Typical view of the source area of landslides in the Cervinara area

debris avalanches and debris flows, with velocities ranging from very rapid to extremely rapid. Some of these flows turned into hyper-concentrated stream-flows reaching distal depositional areas.

Field surveys revealed erosion processes in the local alluvial-colluvial deposits, which increased the mass of the flows by incorporating soil and rock blocks as well as vegetation into them. Splash phenomena were also recognised downslope of the vertical limestone scarps (Fig. 8). This finding suggests the critical role of

Fig. 8
Example of splash phenomenon downslope of a vertical limestone scarp in the Sarno area

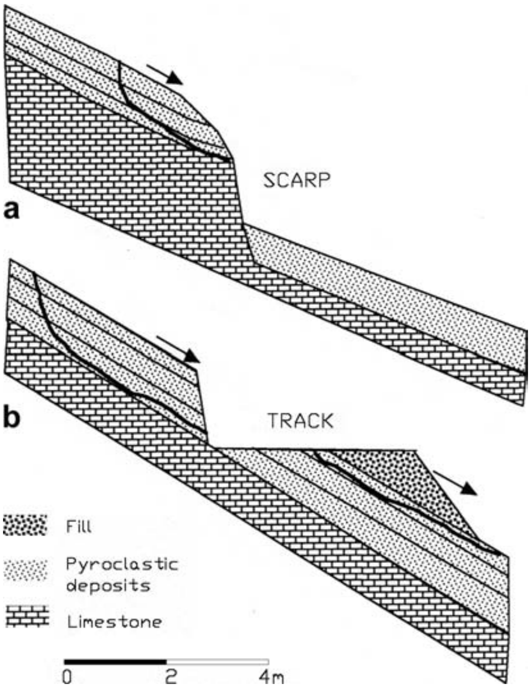
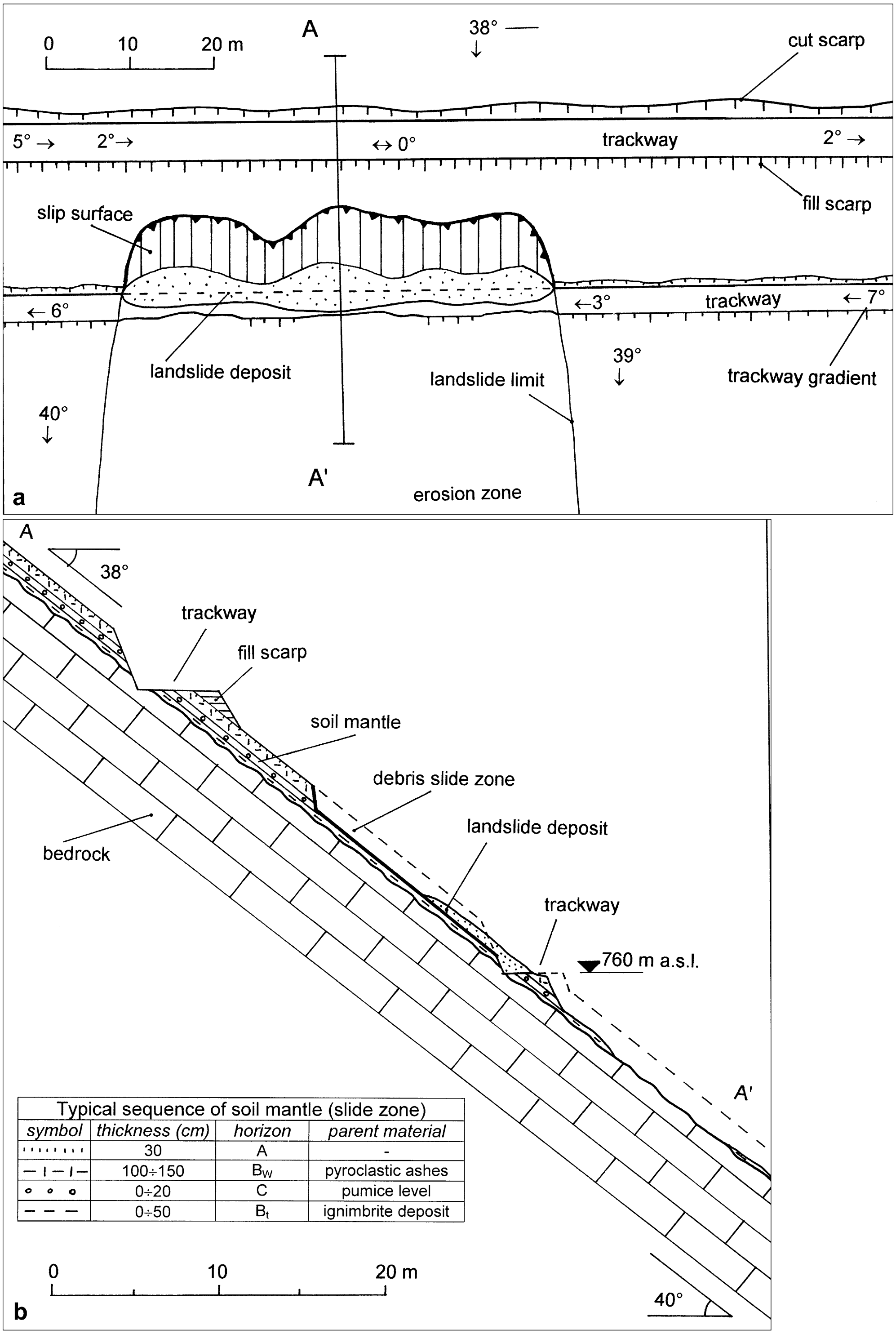


Fig. 9
Schematic cross section along a slope, showing natural scarp (**a**) and man-made cut (**b**); instability area is also shown (modified after Guadagno 2000)



Typical sequence of soil mantle (slide zone)			
symbol	*thickness (cm)*	*horizon*	*parent material*
' ' ' ' ' ' ' '	30	A	-
— I — I —	100÷150	B_w	pyroclastic ashes
o o o	0÷20	C	pumice level
— — —	0÷50	B_t	ignimbrite deposit

Fig. 10
Main geometrical and morphological features in the source area of the landslide (**a**) and geological cross section *A–A'* (**b**) (after Fiorillo and others 2001)

mechanisms of undrained loading (Hutchinson 1986; Sassa and others 1985), which is caused by the failing masses on the pyroclastic covers, similarly to soil avalanches reported in Canada (Hungr 1997).

Guadagno (2000) and Fiorillo and others (2001) highlighted some conditions in the Sarno and Cervinara areas that may be regarded as critical to the understanding of the catastrophic events involving the pyroclastic mantles. Initial instability was often observed immediately above an outcropping, thickly bedded, limestone band, where a stepped topography was evident, or just upslope of tracks that had been extensively cut across the slopes. In both cases, the pyroclastic cover had been exposed to kinematic freedom conditions. The initial slides studied in the Sarno-Quindici area and in the Cervinara area were associated with the morphological conditions outlined in Fig. 9. The number of initial slides that were apparently caused by cut and/or fill failures was very significant. Guadagno and

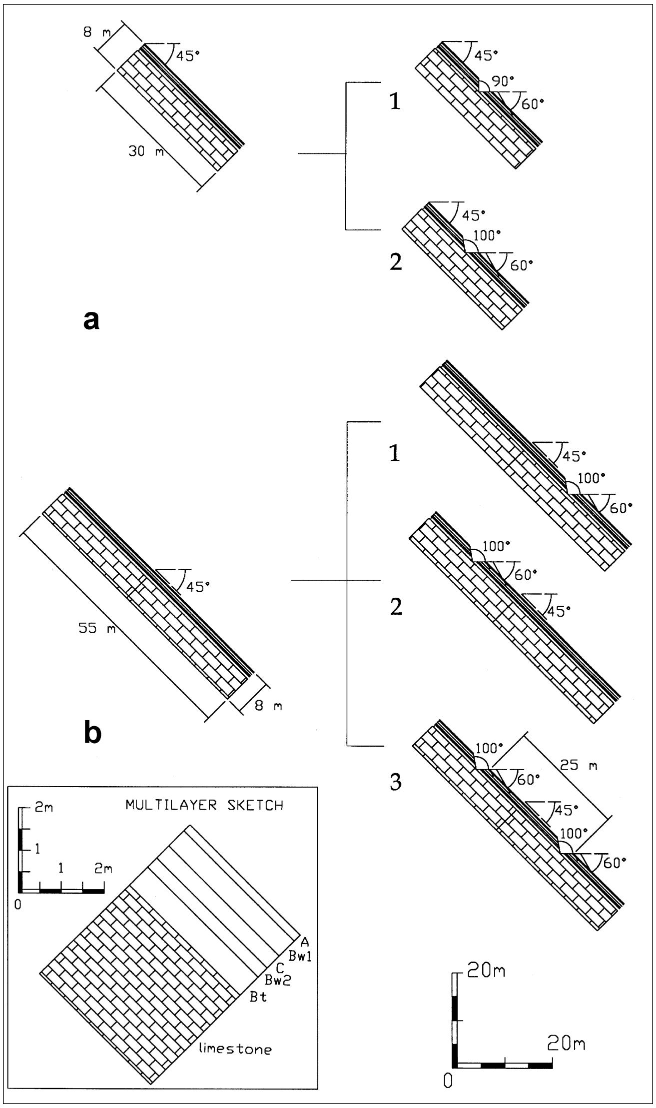


Fig. 11
Sketch showing the complete slope model project

Perriello Zampelli (2000) emphasised that the widespread presence of cuts or escarpments along the slopes breaks the continuity of steep "infinite slopes", mostly covered by loose and cohesionless soil, thereby altering their borderline equilibrium conditions. In addition, the fills were made downslope of the tracks without any compaction and drainage work or removal of vegetation and soil cover. The cuts in the pyroclastic covers also induced major changes in both surface water and groundwater circulation. These roads, with a mean gradient of about 3–4%, concentrated the runoff along the sides of the slopes (as evidenced by deep gullies) and channelled it towards specific points, such as bend zones or sections, with a slope gradient close to zero (Figs. 10a, b). Groundwater circulation was also affected by the exposure of permeable pumiceous layers along the cuts, which facilitated and increased the infiltration of water into a geologically complex system.

The initial slip surfaces are generally located in the pyroclastic multilayer, close to the contact between the buried soil and the cineritic (air fall, pumice) level (Bt and C in Fig. 5, respectively). The slide material generally involved and mobilised the entire pyroclastic and colluvial cover downslope. Along open slopes, this process took place with a typically triangular downward-fanning pattern similar to snow avalanches (Guadagno 2000, Hungr and others 2001). Based on the above-mentioned observations, referring to the Sarno and Cervinara areas, a numerical model was developed.

Numerical modelling: model project

Numerical modelling techniques are powerful tools to analyse the influence of anthropogenic changes to slope stability conditions (Stead and Benko 1998; Griffiths and Lane 1999; Lane and Griffiths 2000). In this study, use was made of the finite difference code, FLAC 4.0 (ITASCA 2000), with a view to determine the stress-strain conditions induced by cut-and-fill works along the slopes, identifying failure surface development and investigating the influence of pore water pressure. Taking into account the goals of this numerical modelling exercise, the authors implemented a geological model capable of accommodating a wide range of conditions as shown in Fig. 11. This figure displays two different geometries: both of them are 8 m deep and 45° inclined, but their length is 30 and 55 m (models A and B, respectively), so as to make boundary effects negligible and to replicate an infinite slope model under all the investigated conditions. The meshes contain finite difference square zones whose dimensions (10×10 cm) are consistent with the minimum thickness of each pyroclastic level (cf. Fig. 5). The adopted representative multilayer consists of five pyroclastic levels resting upon the limestone bedrock. Their total thickness is equal to 2 m, in line with observations in the study areas. The soil mass was assumed to be elasto-plastic according to the Mohr-Coulomb constitutive criterion. Table 1 summarises

Table 1
Parameters of mechanical and hydraulic behaviour which were assumed for the numerical model (hydraulic conductivity values k_1 and k_2 refer to the simulated conditions depicted in Fig. 15)

	Den (kg/m^3)	E (Pa)	K (Pa)	G (Pa)	ν	c (Pa)	ϕ (°)	k_1 (m/s)	k_2 (m/s)
Limestone	2500	1.00E+10	3.92E+09	4.35E+09	0.15	4.00E+07	0	1.00E–06	1.00E–06
Bt	1400	1.00E+08	4.44E+07	4.00E+07	0.25	2.00E+04	21	1.00E–11	1.00E–11
Bw2	1300	7.00E+07	3.11E+07	2.80E+07	0.25	8.00E+03	27	1.00E–11	1.00E–05
C	900	8.40E+07	4.31E+07	3.11E+07	0.35	0.00E+00	48	1.00E–04	1.00E–04
Bw1	1200	6.00E+07	3.33E+07	2.14E+07	0.40	5.00E+03	25	1.00E–11	1.00E–05
A	1100	2.50E+07	1.39E+07	8.93E+06	0.40	5.00E+03	20	1.00E–11	1.00E–11

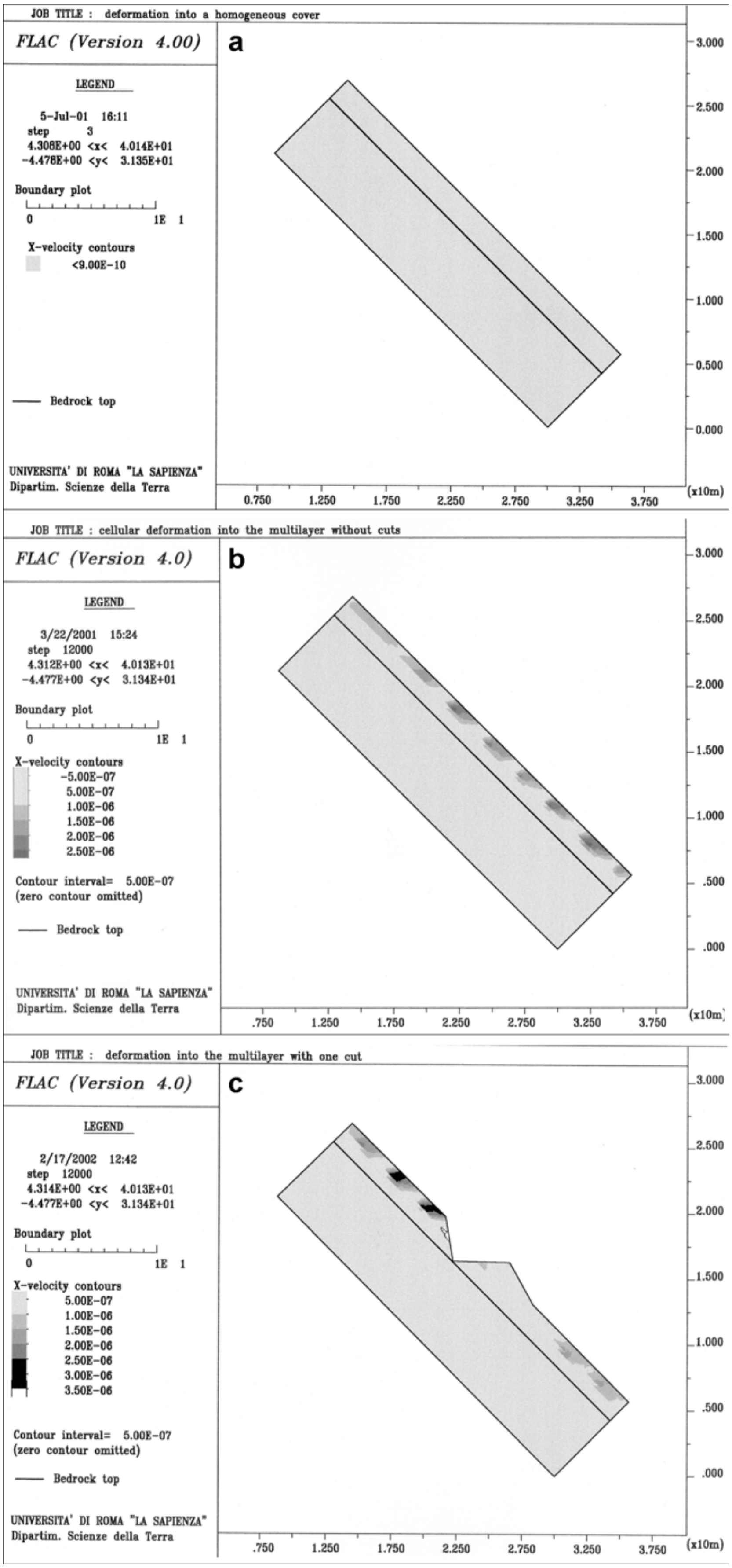


Fig. 12
Distribution of the velocity field in a homogeneous pyroclastic mantle (**a**), in a pyroclastic multilayer without cuts (**b**) and in a pyroclastic multilayer with one cut (**c**)

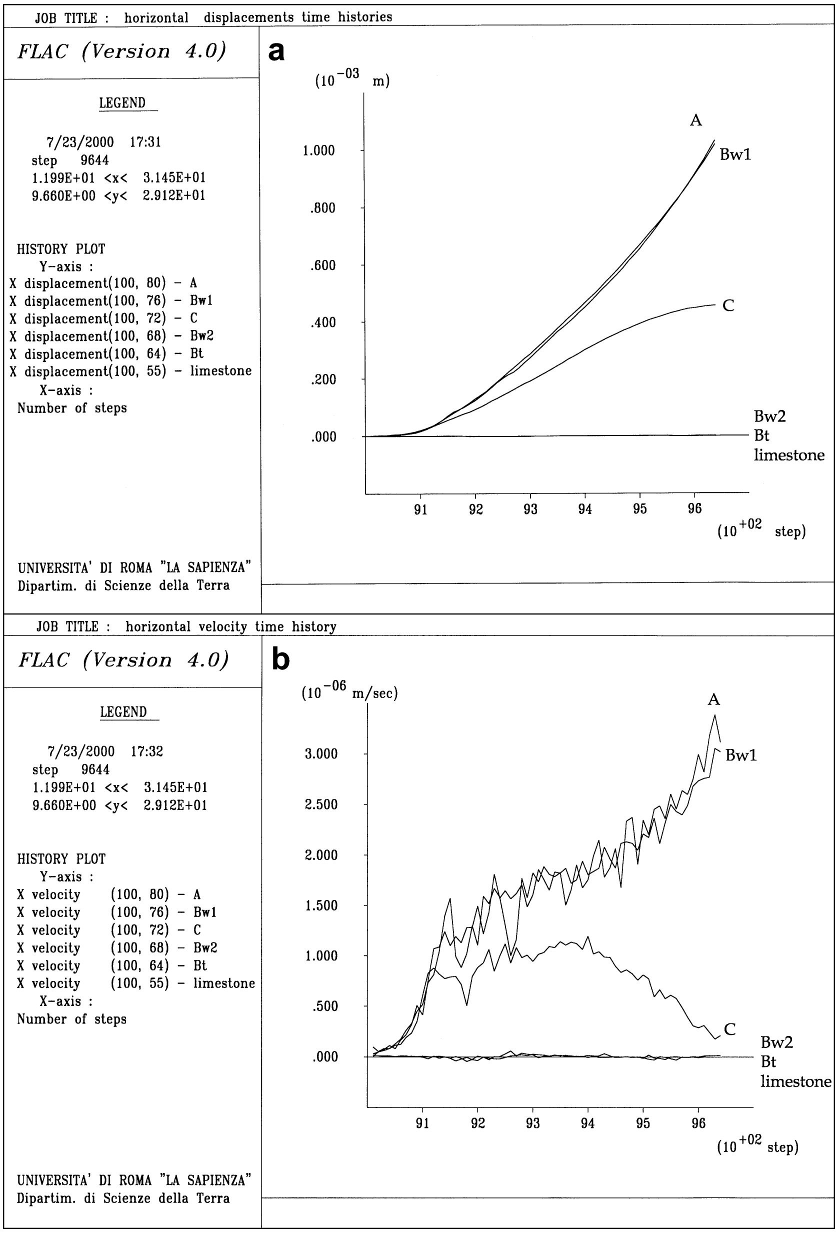


Fig. 13
Multilayer displacement time histories (**a**) and velocity time histories (**b**) recorded by the numerical model

the multilayered soil mass properties according to the above-mentioned authors. In both models, the changes in slope geometry caused by cuts and fills were analysed after attaining initial stress-strain conditions.

The geometry of model A was modified in two ways (Fig. 11a): (1) by considering a vertical cut along the slope (A1) and (2) by assuming an 80° dipping cut (A2). Both cuts involve the whole depth of the pyroclastic multilayer and, in both cases, the excavated material volume is replaced downslope with a 60° dipping fill.

The geometry of model B was modified in three ways (Fig. 11b): (1) by assuming a single cut, dipping 80°, in the lower slope section (B1); (2) by assuming a single cut, with the same inclination, in the upper slope section (B2); (3) by considering two cuts, both dipping 80° and spaced 25 m from each other, in the upper and lower slope sections (B3), respectively. In this case, too, all the cuts involve the entire depth of the pyroclastic multilayer and in each case the excavated material volume is replaced downslope with a 60° dipping fill.

Seepage was considered only in model B. This further step was targeted to evaluate rainwater infiltration, due to the complex hydraulic behaviour of the multilayer system (Celico and others 2000) and to its impact on stress-strain conditions.

Results and discussion

Model A

In this model, the attainment of initial equilibrium conditions involves the identification of stress loci within the pyroclastic multilayer, as also shown by the velocity field (Fig. 12b). The observed distribution of deformations is ascribed to the heterogeneity of the pyroclastic multilayer, because a single homogeneous layer would not cause the

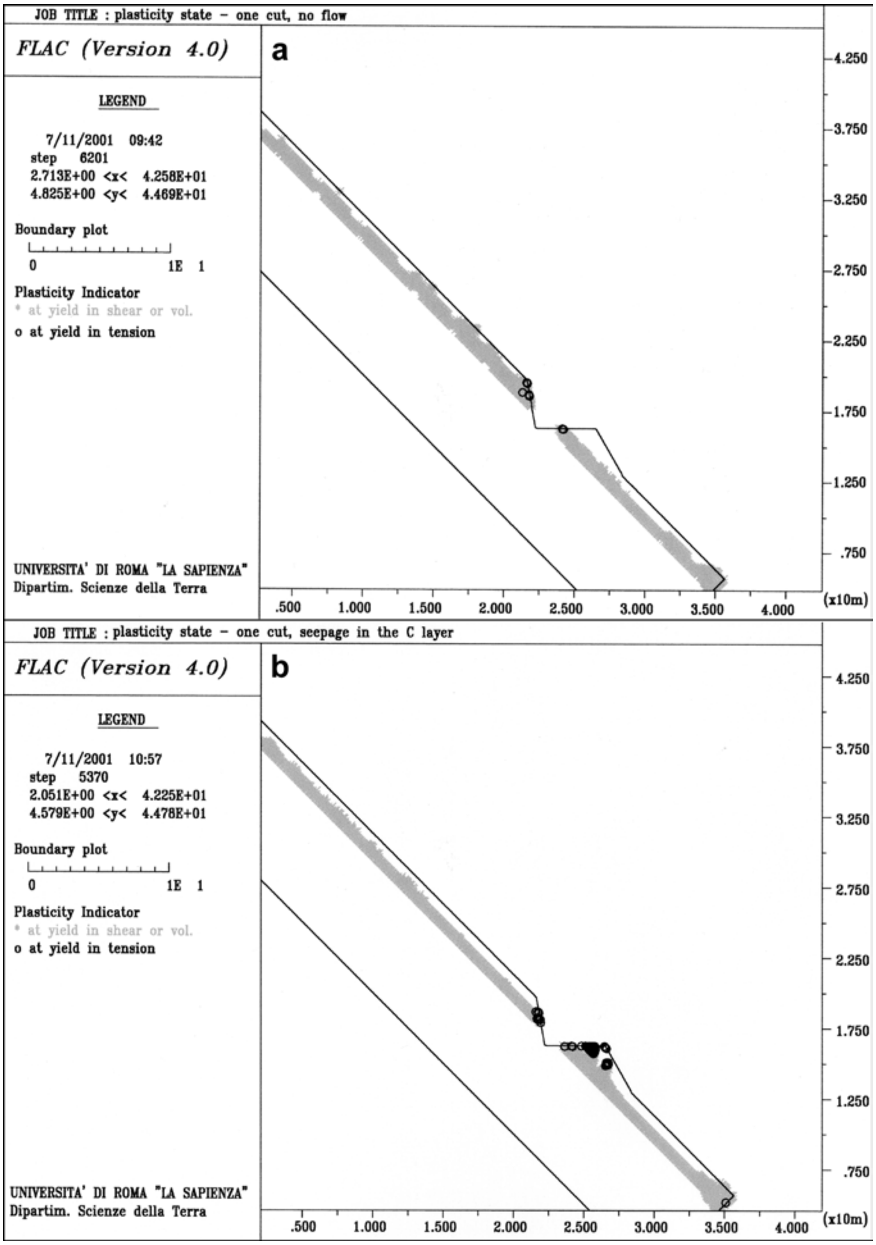


Fig. 14
Cuts in the lower slope section without seepage (**a**) and with seepage only in level C (**b**): plasticity state

same distribution (Fig. 12a). The boundaries of equal displacement zones and the continuous plasticity band in level C of the multilayer infer that this level might act as a sliding surface within the pyroclastic covers.

The presence of cuts significantly changes the stress-strain conditions of the surrounding area. Local effects (e.g. plasticity bands upslope of the cuts which tend to propagate to the fills), complicate the initial stress-strain conditions along the entire slope. Moreover, the cuts break the continuity of the pyroclastic multilayer, generating a more intense velocity field in the stress loci upslope of the cuts (Fig. 12c). In this context, the cineritic level C plays a key role, as it forms a sliding surface in the pyroclastic covers. This role is confirmed by the displacement and velocity time histories monitored by the model along the same vertical and upslope of the cuts. Levels A and Bw1 show significant mobilisation, whereas level C displays partial mobilisation, and levels Bw2 and Bt, as well as the limestone bedrock, fail to show significant displacements (Fig. 13a, b).

Model B

1. Dry slope
   Model B was mainly used to analyse the effects that one or two cuts might induce in the displacement field along the slope. With respect to model A, this model has the same high resolution, but is more extensive and thus less analytically accurate upon the application of the finite difference code. The introduction of a cut in the lower section (case B1) increases the horizontal components of downslope displacements, resulting in "toe erosion" of a slab. Also in this case, analysis of the consequent displacements gives evidence of the role of

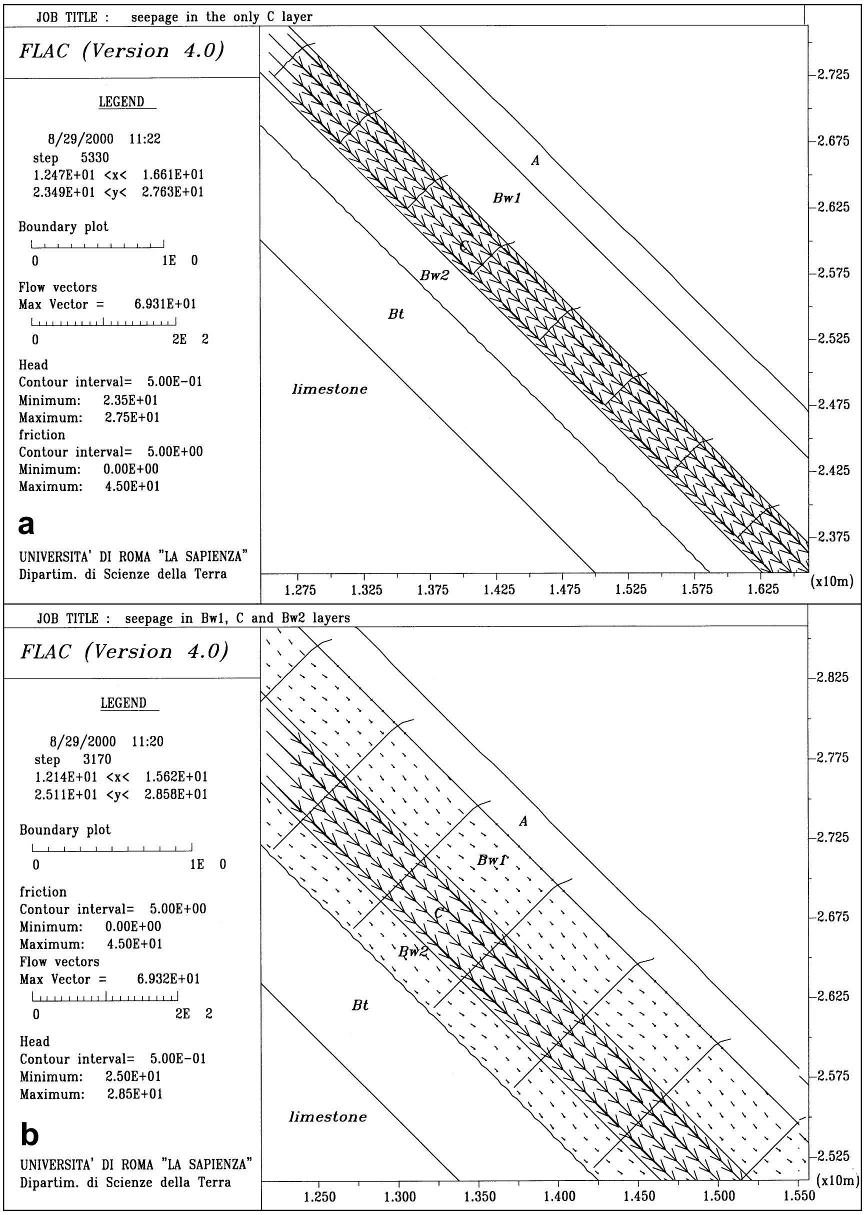


Fig. 15
Seepage simulation in level C (**a**) and in levels Bw1, C and Bw2 (**b**)

level C, accommodating yield points at its top and bottom and acting as a sliding surface (Fig. 14a). The introduction of a single cut in the upper section (case B2) induces displacements that are smaller than in the previous case (B1) whose displacements assume values close to 10 cm. In the latter case (B2), the displacements are evenly distributed along the downslope section of the pyroclastic multilayer. Once again, the presence of both cuts (case B3) produces displacements that are evenly distributed among the cuts in the pyroclastic cover. The time histories of displacements and velocities show significant values for levels A and Bw1, increasing deformations in level C and the lack of displacements in levels Bw2, Bt and in the limestone bedrock. The break which the simultaneous presence of two cuts induces in the pyroclastic multilayer, brings about a re-distribution of stresses which decreases the magnitude of displacements along the slope. A more concentrated distribution of plasticity indicators is observed in the areas of the pyroclastic multilayer that lie close to the cut faces, suggesting potential slip surfaces (Fig. 16a; cf. Fig. 9).

2. Slope with seepage
   In model B, steady-state flow conditions in the multilayer were evaluated on two different assumptions. In the first one (case 1), filtration occurs in level C (Fig. 15a), while in the second one (case 2) filtration takes place in levels Bw1, C and Bw2 (Fig. 15b). These assumptions refer to partial saturation conditions in the pyroclastic covers due to intense or prolonged rainfall. Stress-strain conditions along the slope, in the B1 and B3 cases with seepage in level C, are depicted in Figs. 14b and 16b, respectively. Note the widening of yield areas due to water seepage with respect to no flow conditions.

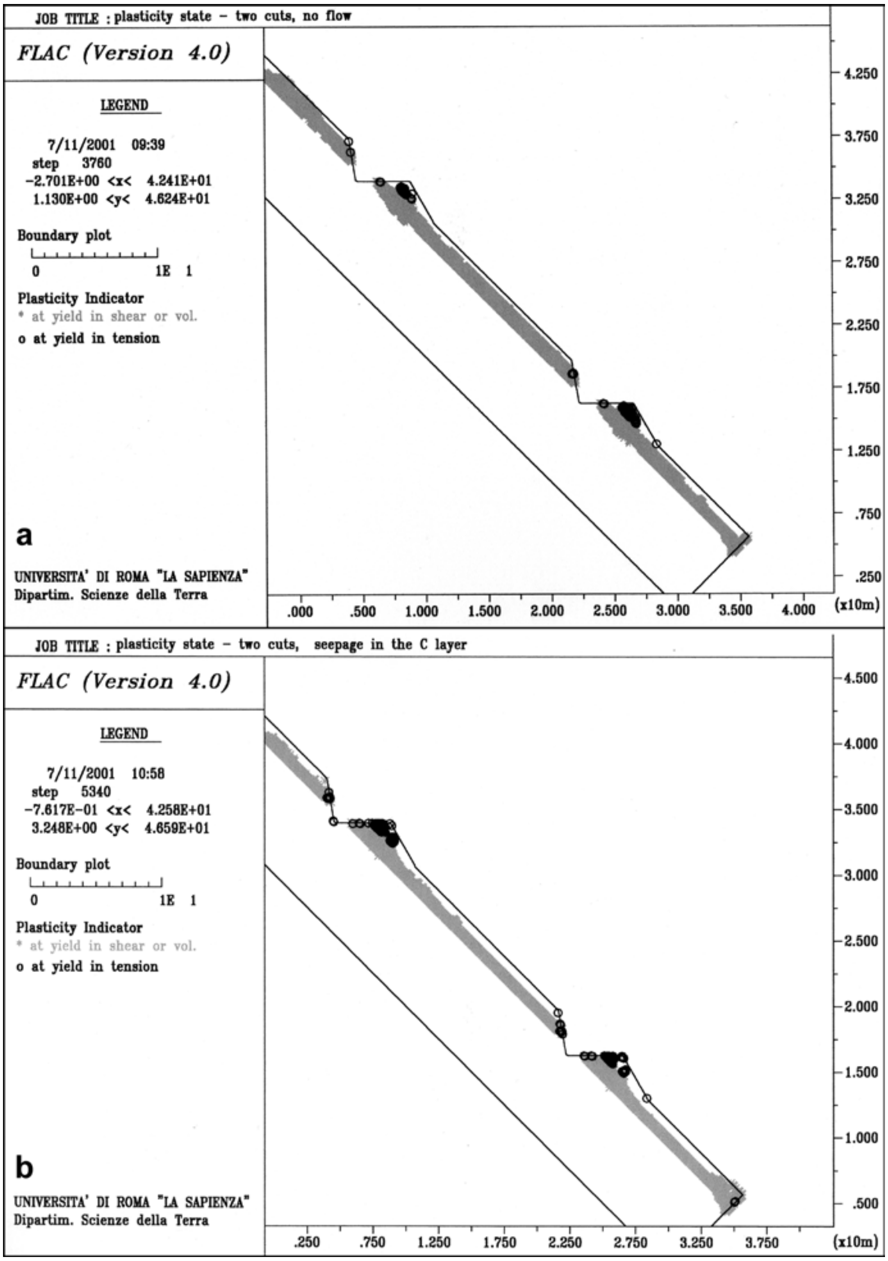


Fig. 16
Cuts both in the lower and in the upper slope section without seepage (**a**) and with seepage only in level C (**b**): plasticity state

Discussion

The plot of Fig. 17 shows the maximum displacements measured in the model under all the assumed conditions. The presence of two cuts induces the highest displacement values. In particular, the introduction of cuts together with seepage in levels Bw1, C and Bw2 (case 2) is clearly responsible for failure conditions. These conditions are reached via roto-translational mechanisms upslope of the cuts (Fig. 18), which trigger sliding events. Actually, such events were the initial step of the observed debris avalanches, which largely involved the pyroclastic covers downslope, also via undrained loading mechanisms (Sassa and others 1998, Hutchinson 1986). Field measurements of tension fracture openings upslope of the cuts indicated values as high as 10 cm (Fig. 19). The computed values, consistent with the measured ones, enabled us to assume a displacement threshold in the range of 10 cm.

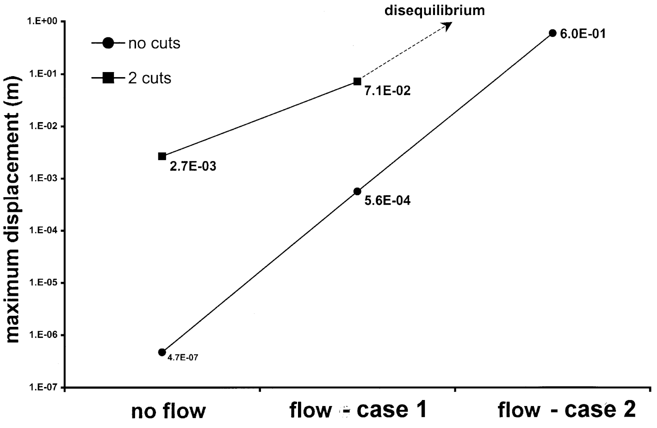


Fig. 17
Maximum displacements recorded by the numerical model under the different simulation conditions

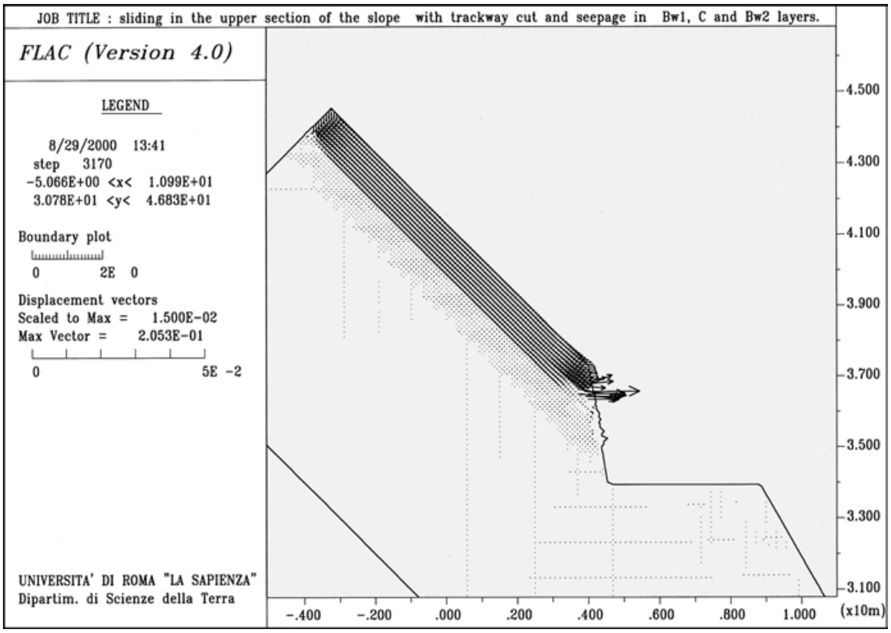


Fig. 18
Sliding phenomena upslope of man-made cuts

Conclusions

Field investigations in the source areas of debris flows and avalanches, causing extensive damage and numerous casualties in Campania in May 1998 and December 1999, allowed the authors to determine the significant impact that geological, geomorphological and geotechnical conditions have on initial failure mechanisms. The main determinants of the initiation of landslides (soil slips turning into debris flows/avalanches) were:

- the specific nature of the cover deposits, composed of fall-type volcanoclastic materials instead of soils resulting from weathering of the outcropping bedrock;
- the particular setting of the pyroclastic covers, originating from depositional mechanisms and subsequently modified by erosional, weathering and fluidization processes, resulting in extremely variable cover deposits in terms of thickness, geotechnical and hydraulic properties;
- the presence of natural scarps and man-made cuts within the limestone bedrock and the pyroclastic covers that imposed kinematic freedom conditions for the masses along the boundaries which controlled the water seepage network.

Fig. 19
Approximately 10-cm-wide tension fracture in the pyroclastic covers

A numerical model was then developed to prove the greater insight about the initial failure mechanisms, which represented a crucial stage in the reported events. The initial phase may be regarded as fundamental in triggering the flow/avalanche phenomena that subsequently affect the downslope pyroclastic deposits. The results of the numerical modelling simulation showed equilibrium conditions consistent with the continuous and uninterrupted multilayered pyroclastic covers along the slope. On the contrary, geomorphological and man-induced breaks along the slopes caused significant modification of the equilibrium conditions, leading to the development of local yield zones. The latter were typically distributed over the pyroclastic multilayer, depending on geometrical changes of the slope profile. In fact, the number of cuts and their dip had a significant impact on the shape of the slip surfaces. The presence of man-made cuts also allowed

Fig. 20
Winter panoramic view of the Pizzo d'Alvano northern slope, evidencing the cuts made for construction of tracks in the forest

water to seep into the extensive, more permeable pumiceous levels. As the phenomena under review may be regarded as dependent on rainfall, this factor has utmost importance among failure initiation mechanisms. Also the saturation of soil masses is 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.

The results of this numerical modelling simulation are compatible with previous statistical analyses (Guadagno and Perriello Zampelli 2000) on the relationship between debris flow source areas and cuts made for the construction of tracks along the slopes.

In a vulnerable scenario such as the one of the pyroclastic-blanketed Campanian hill slopes, it is imperative to adopt rational and correct land use practices (sustainable development and management of chestnut and hazelnut tree forests without making inappropriate changes to the local topography and geomorphology). In the last decades, mechanised forest management practices have favoured the formation of a dense track network, which significantly altered the already sensitive original setting (Fig. 20).

Acknowledgements Authors wish to thank the Firemen Department of Campania (Corpo Nazionale dei Vigili del Fuoco – Centro di Documentazione di Napoli) for aerial photos. The research was supported by CNR-GNDCI grants (U.O. 2.34, resp. F.M. Guadagno, and U.O. 2.21, resp. G. Valentini) and by Campania Region grants. This paper is GNDCI publication no. 2325.

References

Amato M, Di Martino P, Di Pasquale G, Mazzoleni S, Migliozzi A, Strumia S (2000) Il ruolo della vegetazione nelle frane di Quindici. Quad Geol Appl 7(1):97–108

Barberi F, Innocenti F, Lirer L, Munno R, Pescatore T, Santacroce R (1978) The Campanian Ignimbrite: a major prehistoric eruption in the Neapolitan area (Italy). Bull Volcanol 41(1):1–22

Brancaccio L, Cinque A, Sgrosso I (1978) L'analisi morfologica dei versanti come strumento per la ricostruzione degli eventi neotettonici. Mem Soc Geol It 19:621–626

Celico P, Guadagno FM (1998) L'instabilità delle coltri piroclastiche delle dorsali carbonatiche in Campania: attuali conoscenze. Quad Geol Appl 5(1):129–188

Celico P, Guadagno FM, Vallario A (1986) Proposta di un modello interpretativo per lo studio delle frane nei terreni piroclastici. Geol Appl Idrogeol 22:73–193

Celico P, Aquino S, Esposito L, Piscopo V (2000) Problematiche idrogeologiche connesse con i fenomeni di instabilità delle coltri piroclastiche della dorsale di Pizzo d'Alvano (Campania). Quad Geol Appl 7(2):167–187

Civita M, de Riso R, Lucini P, Nota d'Elogio (1975) Studio delle condizioni di stabilità dei terreni della Penisola Sorrentina (Campania). Geol Appl Idrogeol 10:129–188

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides investigation and mitigation. Transport Research Board, Spec Rep 247, National Research Council, National Academy Press, Washington, DC, pp 36–75

Del Prete M, Guadagno FM, Hawkins AB (1998) Preliminary report on the landslides of 5 May 1998, Campania, southern Italy. Bull Eng Geol Environ 57:41–50

Del Prete M, Del Prete R (1999) Il caso di Quindici (AV) del 5 maggio 1998 nel quadro dei movimenti di massa distruttivi delle coltri piroclastiche della Campania occidentale. Quad Geol Appl 6:79–102

De Riso R, Budetta P, Calcaterra D, Santo A (1999) Le colate rapide in terreni piroclastici del territorio campano. Convegno "Previsione e prevenzione di movimenti franosi rapidi" Trento, Giugno 1999, Associazione Georisorse e Ambiente, Torino, pp 133–150

Esposito L, Guadagno FM (1998) Some special geotechnical properties of pumice deposits. Bull Eng Geol Environ 57:41–50

Fiorillo F, Guadagno FM, Aquino S, De Blasio A (2001) The December 1999 Cervinara landslides: further debris flows in the pyroclastic deposits of Campania (southern Italy). Bull Eng Geol Environ 60:171–184

Griffiths DV, Lane PA (1999) Slope stability analysis by finite elements. Geotechnique 49:387–403

Guadagno FM (1991) Debris flow in the Campanian volcanoclastic soil. Proc Int Conf on Slope Stability. Thomas Telford, London, pp 125–130

Guadagno FM (2000) The landslides of 5 May 1998 in Campania, southern Italy – are they natural disaster or also man-induced phenomena? J Nepal Geolog Soc 22:463–470

Guadagno FM, Magaldi S (2000) Considerazioni sulle proprietà geotecniche dei suoli allofanici di copertura delle dorsali carbonatiche campane. Quad Geol Appl 7(2):143–155

Guadagno FM, Perriello Zampelli S (2000) Triggering mechanisms of the landslides that inundated Sarno, Quindici, Siano and Bracigliano (S. Italy) on May 5–6, 1998. Proc 8th Int Symp Landslides, Cardiff, Thomas Telford, London, 2:671–676

Hungr O (1997) Analysis of the motion of a debris avalanche event. In: Fukuoka H (ed) Special issue focused on debris flow hazard. Chikyu (Earth) Magazine, Japan, pp 661–665

Hungr O, Evans SG, Bovis MJ, Hutchinson JN (2001) A review of the classification of landslides of the flow type. Environ Eng Geosci 7(3):1–18

Hutchinson JN (1986) A sliding-consolidation model for flow slides. Can Geotech J 23:115–126

Hutchinson JN (1988) General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. Proc 5th Int Symp on Landslides, Lausanne. Balkema, Rotterdam, pp 3–36

Ippolito F, D'Argenio B, Pescatore T, Scandone P (1975) Structural-stratigraphic units and tectonic framework of southern

Apennines. In: Squyres C (ed) Geology of Italy. Earth Sciences Society of the Libyan Arab Republic, Tripoli, pp 317–328

ITASCA (2000) FLAC 4.0: user manual – Itasca Consulting Group

Johnson AM, Rodine JR (1984) Debris flow. In: Brunsden D, Prior DB (eds) Slope instability. Wiley, New York, pp 257–361

Lane PA, Griffiths DV (2000) Assessments of stability of slopes under drawdown conditions. J Geotech Geoenviron Eng 126 (5):443–450

Maeda T, Takenake H, Warkentin BP (1977) Properties of allophane soils. Adv Agron 29:229–264

Pareschi MT, Santacroce R, Sulpizio R, Zanchetta G (2001) Volcanoclastic debris flows in the Clanio Valley (Campania, Italy): insights for the assessment of hazard potential. Geomorphology, 43:219–231

Pearson TC, Costa JE (1987) A rheologic classification of subaerial sediment-water flows. Geol Soc Am Rev Eng Geol 7:1–12

Penta F, Lupino OR, Capozza F, Esu F (1954) Effetti dell'alluvione del 26 ottobre 1954 nel salernitano. Geotecnica I, Milan

Rao SM (1995) Mechanistic approach to the shear strength behaviour of allophanic soils. Eng Geol 40:215–221

Revellino P, Hungr O, Guadagno FM, Evans SG (2002) Dynamic analysis of recent destructive debris flow and debris avalanches in pyroclastic deposits, Campania region, Italy. In: McInnes RG, Jakeways J (eds) Instability – planning and management. Thomas Telford, London, pp 363–371

Sassa K, Kaibori M, Kitera N. (1985). Liquefaction and undrained shear of torrent deposits as the cause of debris flows. Proc Int Symp Erosion, Debris Flows and Disaster Prevention, Tsukuba, pp 231–236

Sassa K, Fukuoka H, Wang F, Evans S (1998) Sliding surface liquefaction and undrained loading mechanism in rapid landslides in Japan and Canada. Proc 8th Cong IAEG, Vancouver, vol 3, 1923–1930. Balkema, Rotterdam

Stead D, Benko B (1998) The Frank slide: a reexamination of the failure mechanism. Can Geotech J 35:299–311

Terribile F, Basile A, di Gennaro A, Aronne A, Buonanno M, De Mascellis R, Vingiani S, Mulacelli F (1999) The soil of the landslide of Sarno and Quindici. In: Proc Symp Degradation Processes in Volcanic Soils. University of Napoli, pp 48–64

Varnes DJ (1978) Slope movements types and processes. In: Schuster RL, Krizek (eds) Landslides analysis and control. Special Report 176, Transp Res Board, Natl Academy of Sciences, USA, 234 pp

Wesley LD (1977) Shear strength of halloysite and allophane clays in Java, Indonesia. Geotechnique 27 (2):125–136

Whitam AG, Sparks RS (1986) Pumice. Bull Volcanol 48:209–223