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The CAMILab and CIRIAM contribution

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INDICE

Le catastrofi prodotte dalle frane interessano quasi tutti i Paesi ed ogni anno mietono vittime e producono danni incalcolabili. Per tale motivo la comunità scientifica internazionale, con sempre maggiore frequenza, si interroga sulle cause di questi fenomeni e sulle strategie da porre in atto per la mitigazione del rischio, mettendo a confronto le esperienze maturate nei diversi contesti.

Nel dicembre del 2007 si è tenuto ad Hong Kong un Forum internazionale sulla gestione dei disastri idrogeologici (Landslide Disaster Management), che ha riunito un ristretto numero di studiosi invitati da diversi Paesi per discutere alcuni temi di grande rilievo, quali: la gestione del rischio di frana, le indagini e le nuove tecnologie adottate per lo studio di alcuni fenomeni che hanno avuto particolare impatto, i modelli capaci di simulare i movimenti di versante.

Il Forum ha avuto grande rilevanza sia per il livello scientifico che lo ha caratterizzato e l'importanza degli argomenti trattati sia per il carattere intersettoriale e interdisciplinare che lo ha contraddistinto e che va in qualche misura controcorrente rispetto agli innumerevoli convegni disciplinari e settoriali che si svolgono in varie parti del mondo.

Anche per la sede in cui ha avuto luogo, il Forum appare di grande significato, perché Hong Kong è all'avanguardia nella lotta per la mitigazione del rischio di frana, con il quale si confronta quotidianamente, subendo rilevanti condizionamenti nello sviluppo e conquistando ogni metro quadro di territorio grazie ad un impegno organizzativo e finanziario che costituiscono un modello ancora insuperato.

Il contributo italiano al Forum è stato importante, con la presentazione di diverse relazioni e una partecipazione attiva alle numerose discussioni che hanno caratterizzato il meeting.

In particolare il CIRIAM e il CAMIlab, forti della loro pluriennale esperienza nel settore del rischio idrogeologico e mettendo a frutto la loro consolidata collaborazione, hanno presentato tre relazioni, riportate in questo volume, che affrontano, sotto diverse angolature e con diverse scale spaziali di riferimento, alcuni aspetti essenziali per la mitigazione del rischio di frana.

La prima delle tre relazioni riguarda la gestione del rischio di frana in Italia (*Disaster Landslide Management in Italy*) e si configura come un Country Report che descrive per grandi linee i problemi causati dalle frane in Italia e le soluzioni che nel tempo sono state adottate. Dopo aver ricordato alcune delle più gravi catastrofi che hanno interessato nel tempo varie parti del Paese, la relazione si sofferma sulle principali caratteristiche meccaniche dei movimenti di versante nei differenti contesti geologici, con particolare riferimento alle colate di fango che costituiscono oggi la sfida principale che la comunità scientifica è chiamata ad affrontare. Sono poi descritte le norme principali che governano la identificazione delle aree a rischio e le strategie di intervento strutturale e non strutturale per la mitigazione. Sono infine descritti alcuni dei casi più significativi di gestione dell'emergenza e della successiva ricostruzione e messa in sicurezza che sono stati affrontati nel nostro Paese.

La seconda relazione (*Prediction of Rainfall-Induced Landslides in Unsaturated Granular Soils for Setting Up of Early Warning Systems*) affronta il problema del preannuncio dei movimenti franosi che, all'interno di un piano di emergenza adeguato ed efficiente, consente di ridurre in modo rilevante la perdita di vite umane. La relazione pone l'accento sulla necessità di conoscere bene il comportamento dei materiali che potrebbero essere interessati da eventi di tipo catastrofico, in modo da cogliere i segnali precursori e gli indicatori che consentono di prevedere l'evento con un anticipo sufficiente per l'attivazione delle misure di salvaguardia. Sono, pertanto, descritti i principali risultati conseguiti dal CIRIAM nel corso di lunghi anni di studio, teorico e sperimentale, sul comportamento dei terreni granulari non saturi. Viene poi descritta l'applicazione del modello FLaIR, messo a punto presso il CAMIlab, che consente di correlare, sia pure in modo empirico, le precipitazioni meteoriche e i movimenti di versante da esse innescati. La relazione, infine, descrive le componenti essenziali che devono caratterizzare un sistema articolato e complesso di *early warning*.

La terza relazione (*Landslide Investigation and Risk Mitigation. The Sarno Case*), infine, descrive l'evento catastrofico che nel Maggio del 1998 causò tante vittime e distruzioni nella città di Sarno ed in altri Comuni della Campania. Dopo una breve descrizione dell'evento e degli effetti devastanti prodotti sul territorio, la relazione mette a fuoco le principali caratteristiche geologiche, geomorfologiche e geotecniche delle coltri piroclastiche che ricoprono i versanti di Sarno e degli altri Comuni e che collassarono nell'evento del 1998. Sono poi descritte con il necessario dettaglio le strategie adottate dal Commissario di Governo per ridurre il rischio di frana nei territori colpiti e le tipologie degli interventi strutturali realizzati, con la descrizione puntuale di alcune delle opere più importanti.

I temi affrontati nelle tre relazioni riportate in questo volume e, più in generale, i risultati del Forum di Hong Kong sono di evidente rilievo e meritano di essere adeguatamente divulgati e discussi per favorire i necessari approfondimenti in un settore scientifico e tecnico che sta acquistando nel tempo una rilevanza sempre maggiore.

Novembre 2008

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LANDSLIDE DISASTER MANAGEMENT IN ITALY

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Abstract: *Italy is one of the most developed countries in the world with the highest risk of landslide. This depends on both the high hazard which features extensive hilly and mountainous areas and the density of population, structures, infrastructures and industries. Historic catastrophic landslides are testified by old chronicles, but even in the last tens of years a number of people have lost their lives because of slope movements.*
Due to the permanent risk posed by landslides and by other natural events such as floods, earthquakes, snow avalanches etc., in the last years some national and regional laws have been approved giving a strong impetus to the organization and development of the Civil Protection National Service as well as of other public institutions whose goal is the prediction and the prevention of natural risks. The paper offers a framework of the present situation in Italy concerning the state of the research on the prediction and prevention of landslides and the policy for disaster management.

FOREWORD

Italy is one of the most developed countries in the world with the highest risk of landslide. Historic catastrophic events are reported in old chronicles and echoes of huge landslides can even be found in literary and poetic masterpieces; unfortunately even today recurrent catastrophes continuously remember politicians and researchers the actuality of the problem and the need to make safer our towns, infrastructures and environment. Moreover, new and greater problems are posed by both climatic changes, which are causing an increase in the frequency of some types of landslides, and the unstoppable increase of exposed goods caused by the growth of both the population and the national income. Such problems are increased by the growing unease of modern society in accepting to be subject to these risks, and also by media campaigns sometimes dictated by unmentionable political reasons. Since also other natural phenomena, as floods, earthquakes, snow avalanches, volcanic eruptions and summer forest fires provoke continuous damages and even casualties, the establishment of organisms devoted to risk prevention and disaster management became necessary. As a matter of fact, after the Florence overflow, in 1966, and the catastrophic earthquakes of Friuli, in 1976, and Irpinia, in 1980, a Ministry for Civil Protection was established in 1982. The first designed Minister was Giuseppe Zamberletti who had managed the emergency phase following both earthquakes. Later on, first, a National Department (1992), then, regional agencies for Civil

Protection have been set up: their goal is the prediction and prevention of natural events as well as the management of emergency. In recent years, the engagement of the Civil Protection rapidly has grown because of the occurrence of other disastrous events, as the Val Pola rock avalanche (1986), the Piedmont flood (1994), the Sarno debris flows (1998), the Versilia flood and landslides (1998), the Stromboli eruption and tsunami (2002) as well as seasonal summer forest fires etc. However, other institutions are engaged in landslide prevention, management and protection of the territory. Concerning the hydro-geological risks, the most important ones are the so called River Basin Authorities, established through a national law promulgated in 1989.

The Italian scientific community is deeply involved in such activities. Referring to landslides, it has been engaged, in the 1980's and 1990's, in some nationwide programmes funded by public organisms as the Ministry for Research and University and the National Research Council. In addition, researchers and scientists provide a significant support to the Department for Civil Protection and the River Basin Authorities.

A general overview of the present situation about landslide disaster management in Italy. is shortly reviewed in the following.

A SHORT OVERVIEW OF RECENT CATASTROPHIC LANDSLIDES IN ITALY

Landslides represent a permanent hazard in large parts of the Italian territory. Italy is the first country in Europe in the number of victims and missing people and the second one in the context of the most industrialised countries of the world. Guzzetti (2000) provides a comprehensive overview of the situation: only in the last century, almost 8,000 people were killed by landslides (Fig. 1) and the homeless or evacuated people were about 100,000; in particular, in the last decade of the 20^{th} century, the average number of casualties has been 26 per year (263 victims). Finally, the cost of repairing damages caused by landslides has been evaluated between 1 and $2•10^9$€ per year, i.e. 1.5% of the national gross product; adding indirect costs (loss of productivity, property devaluation etc.), it could reach $4•10^9$€ per year (Canuti et al., 2002).

The main causes of this severe situation are:

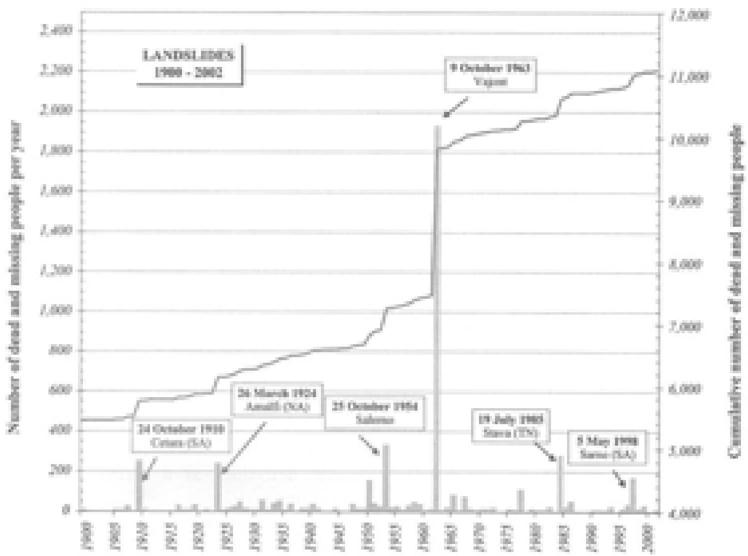


Figure 1. Number of victims and missing people due to landslides in the period 1900-2002; the initial value of the cumulated curve refers to the total of victims since 1300 (Barla, 2005)

- the morphology and recent geological history of the peninsula;
- the extent of sedimentary formations constituted by fine-grained soils and sedimentary and igneous-metamorphic highly fractured or weak rocks;
- the high seismicity of most of the country;
- the climatic conditions, which are characterised by relatively long-lasting and/or intense rainfalls, acting as an important triggering factor in the context of the "weak" geomorphological setting of the territory .

The type of landslides is extremely wide because of the variety of geomorphological conditions: rock falls, rock slides and rock avalanches are the main landslides in fractured rocks, while slides, debris flows, flowslides and mudslides are typical movements in granular and in fine-grained soils; also lateral spreads are quite diffuse.
The variety of geomorphological situations implies a variety of mechanisms and a wide spectrum of sizes and velocities of the mobilised soil masses. These factors, in turn, affect the measures to be taken for land management and risk mitigation.
Large landslides, which can attain tens of millions of cubic metres, are mostly represented by slides, mudslides and lateral spreads in clay, but also debris flows may reach large sizes. The fastest landslides are debris flows, flowslides, rock avalanches, rock slides and rock falls which attain tens of metres per second; slides and mudslides in their initial stage may be quite rapid, reaching tens of metres per minute. On the other side, active slides, mudslides and lateral spreads can be as slow as a few millimetres per year or even per decade. Typically, fast mudslides progressively turn into slow long-lasting movements, but the reverse, i.e. a sudden acceleration, can also occur (Picarelli, 2001). The duration and run-out of landslides depends on their velocity: rapid landslides are also very short, running hundreds of metres up to kilometres, while slow landslides can last tens of even hundreds of years, covering only a few tens of metres. As a consequence, the risk is highly variable and the measures to face it must be carefully chosen just as a function of landslide behaviour or expected behaviour.
Catastrophic landslides are those movements which cause destruction and casualties because of their kinetic energy, which governs the run-out and impact on obstacles. Faster than the speed of a running man, not only do they not leave time to escape, but also, to set up any measure to stop the movement.

Examples of recent catastrophic landslides

The geological framework of the peninsula is related to the Alpine-Himalayan orogenesis, during which, since Cretaceous age until Pliocene, the African plate collided with the Eurasian plate. During such a time-span, following complex subduction processes and huge overthrusts, Alps and Apennines were formed. As a result of the convergent plate boundary, seismicity and extensive active volcanism are still widespread.
The history of Italy is constellated by catastrophes caused by landslides. A description of some of the most recent catastrophic phenomena occurred in the main geological settings of Alps, Apennines and Calabrian Arc is shortly reported in the following.

Landslides in the Alpine chain

The Alpine chain can be conventionally subdivided into Western Alps and Eastern Alps. The western part of the chain is mainly made up of plutonic and metamorphic rocks reaching more than 4000 m in elevation. In the Eastern part, dolostones, volcanic and metamorphic rocks prevail, with peaks that seldom exceed 3000 m.
The remarkable relief energy, along with intense erosional phases partly related to the last glacial periods, favoured the formation of deep valleys bordered by steep flanks which are subjected to frequent mass movements. Debris flows and rock avalanches, but also huge

reactivated relict landslides, pose major problems.
The Vajont slide (1963) and the Val Pola rock avalanche (1987) are among the most destructive events in the recent history. Another catastrophic event, not described here, is the Val di Stava flowslide (Colombo and Colleselli, 2004) which involved a tailings dam built on a slope located in the North-Eastern part of the chain to collect the slurry produced by a fluorite mine. The landslide body covered about 500 m in about 60 seconds reaching an estimated velocity of about 30 m/s; it impacted against 3 hotels, 52 buildings, 6 industrial buildings and some bridges killing 269 people.

The Vajont rockslide

On October, 9, 1963, at 6.30 pm, a catastrophic landslide occurred in the Vajont valley (Fig. 2a), located in the south-eastern part of the Dolomite area of Eastern Alps, about 100 km north of Venice (Mueller, 1964). The mouth of the valley hosts a reservoir with a doubly curved arch dam, which at that time was the world's highest thin arch dam, reaching about 265 m above the valley floor. During the drawdown of the reservoir, a block of approximately 270 million m^3 detached from the right flank of the valley and slid into the lake, attaining an estimated velocity of 30 m/s. As a result of the impact with water, a high wave rose high on the opposite slope hitting the villages of Casso and Erto; at the same time, it overtopped the dam crest at heights of 150 to 210 metres, reaching the valley below, where almost 2000 people were killed, mostly in the town of Longarone located about 500 m below, while the dam remained unbroken.
The valley presents a syncline structure made up of Mesozoic sedimentary formations (mainly carbonate, with clay beds). The sliding surface has been located in a thin clay layer interbed. The cause and mechanisms of that event have been debated among the researchers but a definitive conclusion has not been reached: in particular, some authors argue that it was the reactivation of an old landslide (Hendron and Patton, 1985), while others suppose that it was a first-time movement (Skempton, 1966; Petley, 1996).

The Val Pola rock avalanche

In Val Pola, central Alps, a catastrophic rock avalanche occurred on July, 28, 1987, in an extremely warm period characterised by intense rainfall Fig. 2b). About 40 million of cubic metres were mobilized along the eastern slope of Mount Zandila, as a consequence of the reactivation of a large prehistoric landslide: its maximum estimated velocity ranges between 70 and 110 m/s (Crosta et al., 1994). The soil mass rapidly moved downslope into the Adda River valley, forming a landslide dam lake, but part of the debris ran up 300 m rising up on the opposite flank of the valley; in addition, after reaching the bottom-valley, it moved both upstream and downstream, extending up-valley by 1.0 km and down-valley by 1.5 km. As a consequence, a wave up to 95 m high went upstream for about 2.7 km: 40 people were killed in the villages of Sant'Antonio Morignone and Aquilone located along the Adda river.
Local bedrock consists of isoclinal folds of highly fractured and jointed gneiss intruded by gabbro and diorite and overlain by thin glacial and colluvial deposits (Crosta, 1991). Regarding the triggering factors, Dramis et al. (1995) suggest that permafrost-related processes, such as ground ice melting due to climatic warming and related changes in the groundwater regime, could have played a prominent role. It must be noted that the landslide occurred 8 days after the most intense rainfall period, as typical for very large-scale mass movements: in that month (July) the cumulated rainfall reached a value three times higher than the monthly mean value; in particular, the return time of the cumulated rainfall between 15 and 19 July has been estimated to be between 200 and 500 years (Crosta et al., 2004).
A description of the activity carried out to prevent a failure of the formed landslide dam is reported further on.


a)


b)

Figure 2. a) The Vajont landslide; b) the Val Pola rock avalanche

Apennines chain

The Apennines chain is the backbone of the Italian peninsula, extending, almost continuously, for more than 1000 km from Liguria Region to Sicily. Quite different geomaterials outcrop along the chain. In the northern Apennines, metamorphic rocks and terrigenous formations prevail. In contrast, the central-southern Apennine and the western Sicily are essentially made up of carbonate rocks, which are locally mantled by loose pyroclastic deposits. In the easternmost areas of the chain, turbiditic sequences are present.

All the main settings of the Apennines are affected by a variety of landslides: moderate to slow slides and mudslides in structurally complex formations and very rapid debris flows in pyroclastic soils, are the phenomena which most severely affect urban settlements and infrastructures. Examples of such phenomena are the mudslides provoked by the Irpinia earthquake (southern Italy, November, 1980), the Ancona slide (central Italy, December, 1982), the 800 landslides triggered during the Piedmont flood (northern Italy, November, 1994), the Covatta mudslide (southern Italy, April, 1996), the numerous landslides occurred in Tuscany during the Versilia flood (central Italy, June, 1998) and the recurrent rainfall-induced debris flows in pyroclastic soils.

The Ancona slide

Following an intense rainfall period, in the night of December, 12, 1982, a huge landslide having a surface of about 220 hectares developed in the west of Ancona the capital of Marche Region (Cotecchia et al., 1996). The landslide caused only one victim, but about 2300 people were evacuated from their homes, about 280 buildings were damaged, 80% of which could not be repaired. In addition, the highway and the railway connecting Bologna to Bari, were either interrupted or badly damaged. The movement has been supposed to be the reactivation of a pre-existing landslide: historical information concerning movements in the same area since the 18th century are reported by Crescenti (1986).

The geological setting of the area is characterized by an anticline structure, where clay and sand crop out alternated with marine clay, Plio-Pleistocene in age (Ciancetti et al. 1986). A number of studies based on site investigations have shown the presence of multiple slip surfaces in the Plio-Pleistocene clayey bedrock, the deepest of which exceeds 100 m, well below the sea level. A careful analysis of the landslide has been carried out by Sciotti (1997).

The Covatta mudslide

The Covatta mudslide occurred on April, 12, 1996, in Molise, a Region characterised by 58 unstable centres over a total of 136 towns, as shown by an official list published in 1904. The landslide is located in the Biferno River catchment, where an inventory carried out in the 1970's recognizes more than 4000 slope movements. The slope had been partially mobilized during 1995 and at the beginning of 1996, when the Biferno river had been partially dammed. The April, 12, event involved a soil mass bounded by a 500 m long crown, having a length of about 1400 m, an accumulation zone 200 m wide, a thickness of 12 m in the main track and of 17 m in the accumulation zone, and probably, a volume larger than 1 million of cubic metres (Fig. 3a). The main consequences of the landslide, whose peak velocity was at least some tens of metres per hour (Picarelli and Napoli, 2003), were the destruction of a viaduct along the State Road n. 647 located along the river, and the formation of a landslide dam which created a lake having a volume of about two millions of cubic metres (Fig. 3b): a vast area was inundated, damaging some private houses.
The landslide involves structurally complex clayey and clayey-marly-arenaceous soils. A comparison among air-photos covering the 1987-1996 time span reveals a complex landslide system made up of active and dormant sub-systems, which probably were reactivated by a roto-translational movement of the bedrock and channelled within the main body. The landslide, and especially its accumulation zone, underwent a further remobilization on May 1997, when the remedial measures built during the emergency phase and a temporary road by-pass were damaged.
A short description of the works carried out to avoid further reactivations is reported later on.

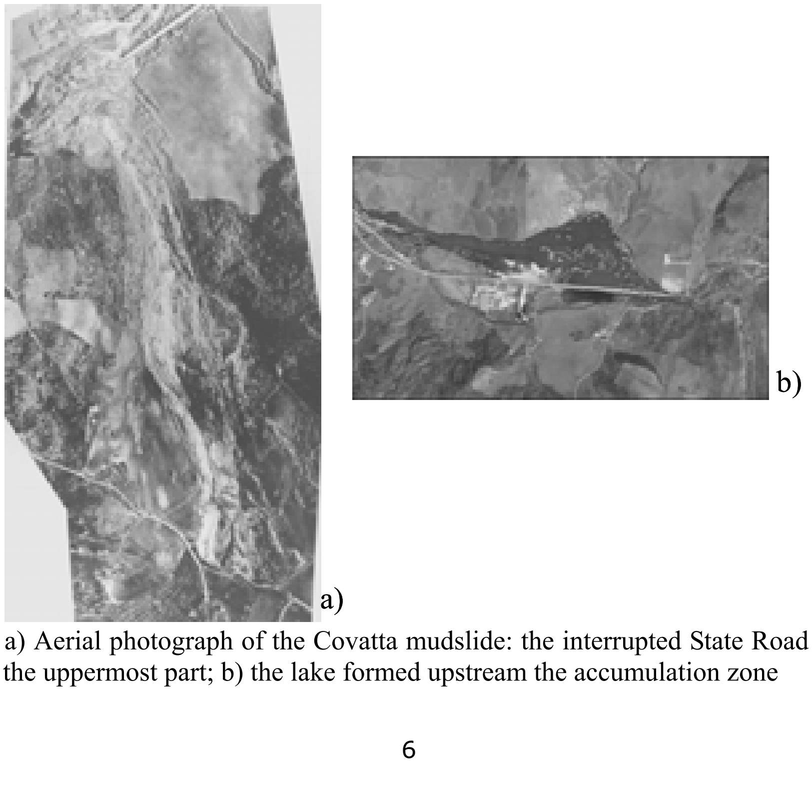


Figure 3. a) Aerial photograph of the Covatta mudslide: the interrupted State Road no 647 is shown in the uppermost part; b) the lake formed upstream the accumulation zone

Landslides reactivated by the Irpinia earthquake

On November, 23, 1980, a 6.9 M earthquake involved a wide part of Campania and Basilicata Regions, Southern Italy, causing about 3000 casualties, 9000 injuries and widespread severe damage. Among the most relevant consequences of the earthquake, a number of slides and mudslides were reactivated mostly in highly fissured tectonized clay shales: the largest ones were the Calitri, Buoninventre, Serra dell'Acquara, Torella dei Lombardi, Andretta and San Fele mudslides and the Bisaccia lateral spread (D'Elia et al., 1985).

A large complex slide-earthflow involved the town of Calitri, located on a hill constituted by a Pliocene sequence including grey stiff clays, weak sandstones, sands and conglomerates. Highly fissured tectonized clay shales also outcrop in the urban area. The landslide (approximately 850 m long and up to 100 m deep) caused the death of 7 people and destroyed or badly damaged over 100 houses. Four main elements were recognized within the landslide body (Del Prete and Hutchinson, 1985): a) a major, deep-seated slide, having a volume in the order of 20 million of cubic metres and a depth estimated up to about 100 m; b) associated secondary retrogressive slides around the rear scarp of the main slide; c) shallow slides in the toe area of the main slide; d) shallow translational mudslides which formed part of the colluvial apron extending down to the Ofanto river.

Two large movements were triggered in the Sele valley (Carrara et al., 1986): the Buoninventre (Fig. 4a) and the Serra dell'Acquara mudslide (Fig. 4b). The Buoninventre mudslide is a complex movement, with a length of about 3 km and an estimated volume of about 25 million of cubic metres made by multiple rotational and translational slides, evolving into a mudslide. The landslide involved old landslide debris along with alternating calcarenites, sandstones, marly limestones and clays. The Serra dell'Acquara mudslide occurred in an area whose bedrock is made up of Mesozoic carbonate rocks, in tectonic contact with flysch deposits. Following the main shock of the earthquake, a pre-existing mudslide was gradually remobilized over a couple of weeks; finally, a 2500 m long and up to 500 m wide mudslide was mobilized, involving a soil mass of about 28 million of cubic metres. The slip surface was hosted entirely in the flysch sequence, reaching a maximum depth of 33 m.


a)

b)

Figure 4. a) The crown and the depletion zone of the Buoninventre mudslide; b) the Serra dell'Acquara mudslide

Another important earthquake-induced movement was the lateral spread which involved the town of Bisaccia, located at the top of a hill consisting of a Quaternary in age formation, made up of polygenic conglomerate in a sandy-clayey matrix, in turn overlying highly fissured tectonized clay shales (Di Nocera et al., 1985). The lateral spread, already active because of continuing erosion but extremely slow, experienced a moderate acceleration which provoked cracks in the pavements and fissuring in the houses. Further information about the landslide is given below.

Debris flows in the pyroclastic soils of Campania

In Campania Region, whose capital is Naples, catastrophic flowslides and debris flows in pyroclastic soils are usual. An incomplete list of some recent events is reported in Table I, which includes also information about the size of the landslide and the number of casualties. The basic features of such events are known since long time. In fact, pioneer studies have described similar phenomena occurred in the Sorrento Peninsula, on the Lattari Mts. (Montella, 1841; Ranieri, 1841) and along the Amalfi coast (Bordiga, 1924; Lazzari, 1954; Penta et al., 1954), highlighting the close link existing between rainfall and landslides.
The first series of landslides in the terrible 1997-2006 decade occurred on January, 10, 1997, when intense rainfall caused about 400 landslides, some victims and severe damage. Data about those landslides have been published by Calcaterra et al. (1997) and Calcaterra and Santo (2005) which stressed some peculiar aspects of the triggering and evolution phases.
On May, 5, 1998, and December, 16, 1999, a huge number of debris flows were triggered on the slopes of Pizzo d'Alvano (Fig. 5a) and Partenio Mts (Fig. 5b), causing 165 victims and immense damage to urban centres. Those phenomena have been the topic of several papers which describe the most significant geomorphological, hydrological and geotechnical aspects of slope failure and post-failure evolution (Cascini et al., 2000; Olivares et al., 2004).
The last killer events occurred on April, 30, 2006, in Nocera Inferiore, and on March, 5, 2005, in the Ischia island, causing further victims.
As a result of continuing disasters, debris flows became of great scientific interest and several models for the triggering and channelization of flow-like landslides have been developed through geomorphological, hydrogeological and geotechnical approaches. Some data are reported in this paper; further information can be found in papers by Calcaterra et al. (2004), Cascini (2005) and Olivares and Picarelli (2006).

Table 1. Features of some recent flowslides and debris flows (Picarelli et al., 2008)

Sector (Fig. 15)	Site	Date	Victims	Length (m)	Volume (m^3)
Ba	Ischia	2006	4	450	$3*10^4$
Fb	Cervinara	1999	5	$2*10^3$	$4*10^4$
Fb	Avella	1998	-	$15*10^2$	$2*10^4$
	S. Felice a C.	1998	1	$8*10^2$	$3*10^4$
Fc	Sarno	1998	137	$2\text{-}4*10^3$	$5*10^5$
Fc	Bracigliano	1998	5	$1\text{-}2*10^3$	$15*10^4$
Fc	Siano	1998	6	$14*10^2$	$4*10^4$
Fc	Quindici	1998	11	$1\text{-}4*10^3$	$5*10^5$
Fd	Gragnano	1764-1997	153	$2\text{-}10*10^2$	$1\text{-}6*10^4$
Fe	Maiori	1954	>300	10^3	$5*10^4$
Ff	Massalubrense	1973	10	$3*10^2$	$7*10^3$
Fg	Avellino	2005	1	$4*10^2$	$2*10^4$
Fh	Montoro Inf.	1997	-	$2*10^3$	$3*10^4$
Fi	Salza	1970	-	$4*10^2$	$20*10^3$

Calabrian Arc

Most of the Calabrian Arc is a portion of the Alpine Chain which, following the opening of the Tyrrhenian sea, moved away from the Sardinia-Corse block overthrusting the Apennine chain. The main massifs of the Calabrian Arc are made up of plutonic and highly fractured and deeply weathered metamorphic rocks. This part of the Italian peninsula is one of the most severely affected by earthquakes and landslides.
A crucial role on landslide occurrence is played by weathering (Le Pera et al. 2001), which affects rock masses outcropping in the main mountain ridges. Saprolite and residual soils are subjected to debris flows, while joint-controlled movements are typical of less weathered

horizons, where planar or wedge failures may occur. Finally, reactivations of pre-existing, sometimes deep-seated movements, are not uncommon (Calcaterra and Parise, 2005). Some case studies concerning the Sila massif have been investigated in recent times (Cascini et al. 1994), following pioneer works which had already focused on the critical situation which involves several towns and related lifelines (Almagià 1910).

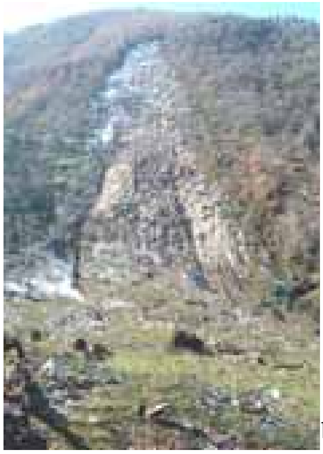

a)

b)

Figure 5. a) Southern side of the Pizzo d'Alvano Mt.: the May, 5th, 1998, debris flows and the town of Sarno; b) the Cervinara flowslide (December, 16, 1999)

The Cavallerizzo Landslide

On March, 7th, 2005, after a period of prolonged rainfall (645 mm in 90 days, about 72% of the mean annual precipitation), the hamlet of Cavallerizzo, in the Cerzeto town, was severely damaged by a vast complex slide-earthflow shown in Figure 6 (Iovine et al. 2006). Thirty buildings were damaged or destroyed and an important road was disrupted. About 310 inhabitants had to be evacuated to nearby villages.

Several tectonic units, made up of Palaeozoic-Mesozoic metamorphic rocks overlain by clastic terrains (Cenozoic-Neozoic) crop out in the study area. The zone affected by the landslide belongs to a wider large-scale slope movement. The 2005 event has been interpreted as an episode of a long deformation history recorded in the area since the 18th century. Data collected from 1999 and the integrate use of PS and very high resolution optical images (Casagli, 2007) revealed movements occurring in the weeks preceding the collapse, with a pre-rupture velocity from 0.8 to 5-6 cm/day.

FACTORS GOVERNING THE VELOCITY OF LANDSLIDES

Landslide velocity is a fundamental factor to consider when dealing with risk assessment and mitigation (Hungr, 1981). In fact, its meaning is deemed equivalent to earthquake magnitude. The displacement rate is one of the factors which affect the strategy to adopt for risk mitigation: in fact, while in case of slow movements a timely stabilization of the slope, through earthworks, retaining structures, drainage etc., is often possible, in case of rapid slope movements it is impossible, and passive works or early warning procedures are compulsory.

The mechanisms and velocity of landslides depend on several factors related to the morphology of the slope, to the structure of the subsoil and constitutive laws of the single layers, and to the initial and induced state of stress. Rapid movements are provoked by soil instability caused by the development of a unbalanced force equal to net value between the driving and the resisting force: this is responsible for the acceleration of the landslide body

(Leroueil et al., 1996). In the case of long and steep slopes, the velocity attained by the soil mass may be very high, up to tens of metres per second.


Figure 6. The Cavallerizzo mudslide

Development of an unbalanced force may be the result of either increase of the driving force or decrease of the resisting force. For natural slopes, the first mechanism is not usual, unless slope failure is caused by an earthquake which may provoke a transient and cyclic variation of the mean shear stress: a global increase of this can happen mostly in case of small and stiff landslides which can be driven by more or less synchronous acceleration in the points of the soil mass. The second mechanism (decrease of the resisting force) is by far the main cause of instability, which may be provoked by either a drop of the strength parameters in the post-peak phase or a pore pressure increase (short-term conditions). The first cause, i.e. post-peak reduction of strength parameters, is usual, because natural slopes are typically constituted by brittle OC soils or fractured rocks. The case of quasi NC soils, as sensitive clays or young pyroclastic soils, will be discussed below.

The drop of the parameters of shear strength is characterized, firstly, by vanishing of the cohesion then, by decrease of the friction angle. Vanishing of the cohesion is a consequence of the rupture of interparticle bonds due to cementation (destructuration) or to capillary forces (unsaturated soils); it is sudden because of the stiffness of bonds. Decrease of the friction angle may be due to different causes: in the case of OC clay, it is mainly provoked by rearrangement of soil fabric (dilation) until formation of a slip surface and particle alignment, i.e. transition from a "continuous" to a "discontinuous" medium; in fractured rocks it is provoked by smoothing of the joint profile during movement. In clay, it is quite gradual, because of the magnitude of the shear strain which is required to modify the soil texture, while along joints it is quite rapid because of the stiffness of the asperities.

Excess pore pressures may build up either in granular or fine-grained soils because of shear or of compression. This phenomenon occurs if the deformation which leads to rupture or which develops after rupture, is rapid enough, thus it is usual in clay, less usual in sand unless rupture is sudden and acceleration very high: this is not unlikely on steep slopes. Liquefaction is a typical process in metastable loose sands and silts as well as in quick clays (Castro, 1969). It is revealed by continuous pore pressure increase even after mobilisation of the available strength: this implies a further decrease of the shear strength along the failure envelope up to an even negligible value. If the shear strength vanishes, liquefaction turns into fluidization (Iverson, 1997). Excess pore pressure provoked by compressive stress seems to be a typical mechanism in mudslides (Hutchinson and Bandhari 1971; Picarelli, 2001). In fact, even though clay does not liquefy, in some cases a pore pressure very close to the total stress has been measured (Pellegrino et al., 2004). The main causes for excess pore pressure building up are: undrained loading because of accumulation of debris, due to erosion or slumping, on softened landslide bodies; internal changes of the state of stress provoked by changes of boundary conditions (Picarelli et al., 2005); earthquakes etc. Excess pore pressures caused by compression have been supposed to build up also in flowslides (Olivares and Picarelli, 2006).

Figure 7 reports the simple case of infinite slope subjected to shear failure: depending on soil brittleness (either drained or undrained), the change of the potential energy during movement can be totally transformed into friction at the base of the landslide body (case a, ductile soil) or into both friction and kinetic energy (case b, brittle soil). However, some role can be played by internal plastic strains and by friction mobilized along internal discontinuities, which lead to dissipation of a part of the potential energy. According to some experience on small-scale physical models (Reik and Hesselmann, 1977), the part or energy which is consumed by friction along internal discontinuities is minor. The same could be supposed for internal plastic strains, but for mudslides moving on a thick shear zone, the dissipation of energy through plastic shear strains could be relatively larger (Picarelli et al., 2007a). In case of undrained failure and generation of positive excess pore pressure, the dissipation of this during movement leads to an increase of friction along the slip surface and consequent deceleration of the landslide. Naturally, the magnitude of this phenomenon depends on the rate of consolidation, which is quite slow in case of mudslides. Some considerations regarding flowslides in essentially granular soils are reported by Hutchinson (1986), while simplified analyses have been presented by Comegna et al. (2007) in the case of rapid mudslides turning into slow slides. In "drained" phenomena, a similar role as friction increase due to excess pore pressure dissipation is played by viscosity, which is a function of the displacement rate and is able to contrast any increase in velocity (Corominas et al., 2005): in principle, for slides and mudslides, the most of the energy should be dissipated along the slip surface, i.e. the residual shear strength should depend of the displacement rate. Unfortunately, this has not been definitely clarified (Kenney, 1967; Tika et al., 1996).

The model of infinite slope discussed above helps very much in the understanding of the mechanics of movement, since it allows to identify the main factors which affect the velocity of landslides. For different morphological conditions, further factors come into play. For instance, if the shear surface is curved (rotational slides), a component of the weight of the soil mass progressively passes among the resisting forces favouring a rapid arrest of the movement (D'Elia et al., 1998).

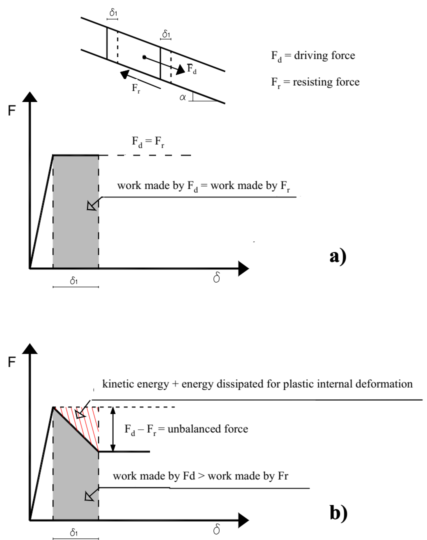


Figure 7. Components of energy possessed by a translational slide (Picarelli et al., 2007a)

It is worth noting that, according to different observations, either fast landslides or slow landslides can equally be triggered even in apparently similar materials and in similar geomorphological contexts, because of little differences in one of the factors discussed above (Picarelli et al., 2007a). This has been shown by Flechter et al. (2002) who describe two very different landslides mobilized in the same fluvio-lacustrine deposits. Similar considerations concern the Allori and the Bomba landslide (D'Elia et al., 1998) triggered respectively in highly fissured tectonized OC clay and in slightly fissured stiff clay outcropping in the same open pit mine, in Central Italy (Fig. 8). The strong difference in their post-failure behaviour can be explained by the different Brittleness Index of the two materials (Bishop, 1967), the second one being more brittle than the first one.

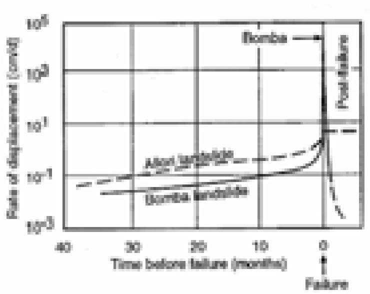


Figure 8. Course of the displacement rate of two slides in fine-grained formations, triggered during excavation in the same open pit mine (D'Elia et al., 1998)

Previous mechanisms of movement, schematically summarized in Figure 7, mostly apply to the case of slides, mudslides and flowslides. Different mechanisms affecting the landslide velocity can be invoked for other types of landslides, as falls and dry debris flows or debris avalanches. For instance, in the case of debris avalanches, a major topic is the fracturation and comminution of blocks during movement (Davies and MacSavenay, 2003). Finally, a special issue, which is not discussed here, is the mechanics of some movements, which are caused by hyperconcentrated mountain flows and can be correctly investigated only using the principles of the fluid mechanics.

The life of rapid landslides is generally very short, in the range of tens of seconds to minutes, because of their high velocity which rapidly carries the mobilised soil mass to gentle ground, favouring the development of a negative acceleration due to increase of the resisting force and decrease of the driving force. However, the landslide can still cover quite a large distance because of its inertia or continuous excess pore pressure generation. A special case is the one of flowslides and liquefied debris flows in unsaturated pyroclastic soils of Campania. This point will be discussed in more detail in next sessions.

PREDICTION OF SLOPE FAILURE AND OF ACCELERATION OF ACTIVE MOVEMENTS

Prediction of slope failure and of the velocity of the consequent landslide is a good training, although a most difficult one. However, for a rational approach, the cases of active and of first-time landslides should be considered separately.

The movement of active landslides is generally slow, because of the ductile behaviour of soil along the slip surface, and is essentially governed by pore pressure fluctuations. The behaviour of first-time landslides is strongly affected by the post-peak soil behaviour. In most cases this is brittle thus the landslide body is subject to acceleration: the velocity that can be attained is just related to soil brittleness and to slope height and angle (or profile).

Slow movements are diffuse in the alpine arc and, mainly, all along the Apennines chain.

Most of them involve fine-grained deposits. In some cases the landslide is so slow that living with it is a normal condition.
Musso and Provenzano (2004) propose the use of neural networks as a reliable and simple way to predict the velocity evolution of slow slope movements. This method has been applied successfully to the case of a landslide which affects a slope within a reservoir area in Sicily, accounting for the oscillation of the water impounding. An even simpler approach has been proposed by Mandolini and Urciuoli (1997), based on a statistical analysis and interpretation of the recorded values of rainfall height, pore pressure and displacement, and on the extrapolation to the near future of the relationships between these factors.
With these approaches, the behaviour of slow slope movements, such as slides, might be predicted with some confidence unless a sudden change of boundary conditions occurs (Picarelli et al., 2004). In fact, there are slow movements which can suddenly accelerate. This is the case of landslide bodies consisting of softened clay, which can experience a sudden increase in pore pressures due to an earthquake or to a significant change in the internal state of stress provoked by a fast loading (Picarelli et al., 2005): as a result, slides can suddenly turn into catastrophic mudslides. The mudslides provoked by the Irpinia earthquake and the Covatta and Cavallerizzo mudslides are good examples of that.
In the case of first-time landslides the problem is much more complex because the slope failure is likely to cause significant and quite rapid movement, which can provoke damages to structures and infrastructures located on the slope or even downslope, depending on the type of landslide.
In the case of impending landslides which might present a moderate to rapid velocity (Cruden and Varnes, 1996), as for slopes constituted by fine-grained soils, monitoring by piezometers, inclinometers and other "usual" instruments is widespread in our country, even though no rational procedures for alerting exist. Therefore, the decision is highly subjective being generally entrusted to the expertise of the operators. However, some criteria for analysis of historic data have been adopted by single researchers. For example, Pellegrino and Urciuoli (1996) find a relationship between the current acceleration of the soil mass in the pre-failure stage and the time to failure. They propose thresholds based on the time span to slope failure which is necessary to guarantee the take off of all the procedures required to assure the safety of people (Fig. 9). The use of this or of other similar methods can be supported by automatic readings which is rapidly spreading.

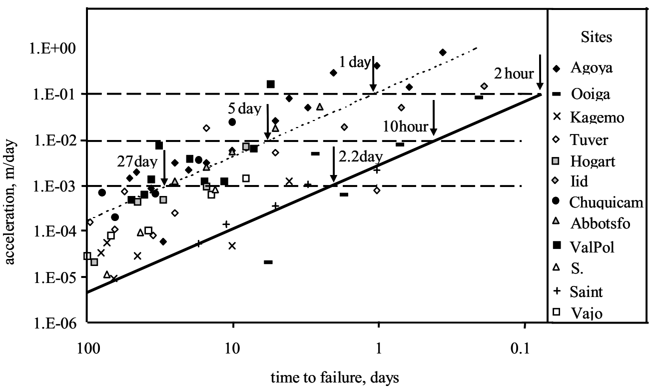


Figure 9. Relationship between the current landslide acceleration in the pre-failure stage and the time to failure (Pellegrino and Urciuoli, 1996).

If failure is supposed to cause a sudden and strong acceleration of the involved soil mass (as in the case of flowslides and debris flows), usual monitoring for alerting is not reliable thus more advanced methods are required. The analysis of microseismic waves propagating from fractures in rock masses subjected to pre-failure movements represent an innovative procedure which is being tested in France (Senfaute et al., 2003). This method has been adopted also in the case of fine-grained soils: some examples are reported by Amitrano et al. (2007). The analysis of the signals captured through optical fibers laid down in the ground is being investigated at the Seconda Università di Napoli. Preliminary data concerning prediction of debris flows in loose pyroclastic soils are encouraging (Picarelli et al., 2007b; Damiano et al., 2008). Alternative procedures to predict rainfall-induced debris flows are based on hydrological methods, i.e. on relationships between cumulated rainfall and landslide occurrence: such methods are well known and have proven reliable in well defined geomorphological contexts (Versace et al., 1998).

SOME MECHANICAL ASPECTS OF RAPID RAINFALL-INDUCED LANDSLIDES IN UNSATURATED PYROCLASTIC GRANULAR SOILS

Rainfall-induced flowslides and debris flows in pyroclastic soils represent for Italy a major landslide problem. These phenomena are mostly concentrated in Campania, which is largely mantled by very loose cohesionless volcanic products (Fig. 10). As a matter of fact, old chronicles report huge disasters occurred in the past. Because of the extension of the areas covered by pyroclastic soils, of the growth of population and development of structures and vital infrastructures occurred after the Second World War, the situation has become explosive. Today more than 200 towns and tens of thousands of people are judged at risk. As a result, in the last tens of years hundreds of people have lost their lives.

Pyroclastic soils are the result of the activity of some volcanic centers, the most famous of which are the Phlegraean Fields and the Somma-Vesuvius, in the last tens of thousands years. The thickness of these covers depends on the number and magnitude of the events, on the distance from the vent and on the slope angle: on relatively steep slopes, generally it does not exceed a few meters. The stratigraphy, grain size and texture of covers depend on the mechanisms of deposition (flow, surge or fall). Air-fall deposits are layered and consist of alternating layers of volcanic ash and pumice (primary deposits); they are more uniform and seem characterized by a higher porosity than other types of deposits (Picarelli et al., 2006). Interbedded with these layers, paleo-soils and altered slightly cemented or plastic ashes can be found. Secondary deposits, typically located at the foot of the slopes where they can reach a thickness of tens of meters, consist of reworked material constituted by ash with inclusions of pumices and, sometimes, of lapideous fragments.

Typically, these materials cover steep slopes. Because of their high saturated permeability and of slope steepness, they present a relatively low degree of saturation, and conversely, a relatively high suction. Therefore, due to the strong influence on slope stability of the apparent cohesion of soil due to suction, thin granular covers can be stable on slopes having an angle even much higher than the friction angle. Moreover, since deterioration is a negligible phenomenon, the main cause of rupture is by rainwater infiltration, consequent increase of the water content and decrease of suction: on relatively gentle slopes, full saturation is attained prior to failure.

Soil failure can bring to a rapid landslide, if the resisting force cannot balance the driving force: this is generally caused by a drop of the resisting force. In non-cemented unsaturated granular soils as most volcanic ashes in Campania, a post-peak decrease of the shear strength can be provoked by a drop of the cohesion because of rupture of interparticle bonds due to capillary forces, while in saturated soils, which are cohesionless, it can depend on a decrease of the friction. If the soil is very loose, its drained behaviour is ductile, but its undrained response can be brittle because of continuing pore pressure increase (static liquefaction).

Such a behaviour, which is well known in the case of uniform silty sands (Sladen et al., 1985), has been recognized also in air-fall volcanic ash (Olivares and Picarelli, 2001; Damiano, 2004; Lampitiello, 2004). As a consequence, the peak velocity of landslides occurring on steep and long slopes may attain a high velocity. As a matter of fact, through the analysis of damages provoked by the impact on structures, Faella and Nigro (2004) argue that the debris flows triggered during the events of 1998, reached peak velocities up to 20 m/s.

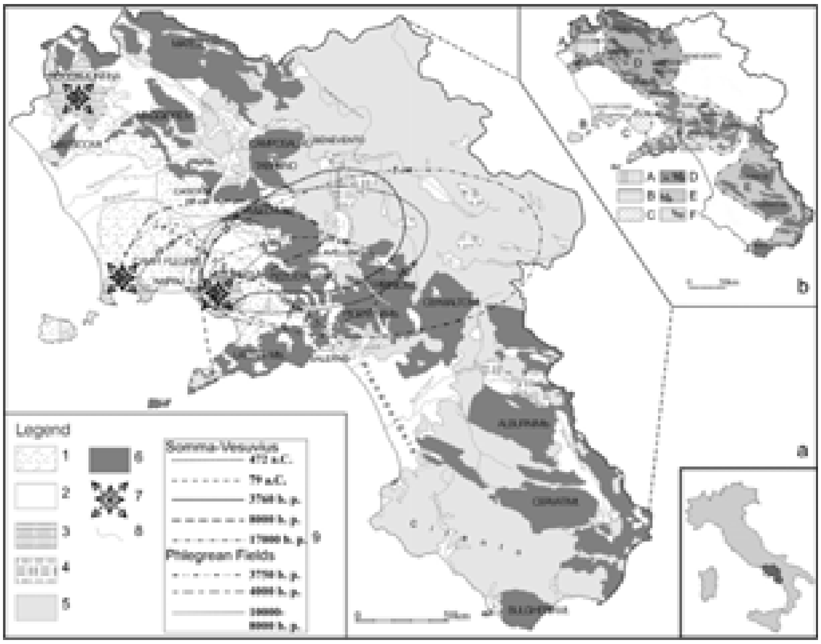


Figure 10. a) Geological map of Campania; b) Pyroclastic macro-areas. 1. Pyroclastic air-fall deposits; 2). alluvial deposits; 3. lavas, pyroclastic flows and tuffs, 4. arenaceous conglomerates; 5. marly arenaceous terrigenous deposits with clay interbeds; 6. carbonate rocks; 7. volcanic centres; 8. rivers; 9. pyroclastic air-fall deposits of Phlegraean Fields and Somma-Vesuvius (Picarelli et al., 2008)

Landslides provoked by liquefaction are called flowslides (Hungr et al., 2001; Hutchinson, 2004); the expression debris flow is used when the mobilized soil mass enters a gully located on the slope and propagates within this until to the toe of the slope where it spreads forming a fan shaped accumulation zone. If the pore pressure is high enough, the soil can propagate far from the toe, reaching even very large distances. Bearing on theoretical considerations and on the results of some flume tests on volcanic ash, Musso and Olivares (2004) suggest that rapid movements can lead to a complete soil fluidization, i.e. to a complete loss of the strength and transition from a frictional regime to a collisional regime. Referring to the 1998 events, this seems to be confirmed by eyewitness and by some movies.

It is worth to remark that liquefaction can occur only if the soil is saturated and presents a void ratio higher than a critical value (Castro, 1969). Hence, since pyroclastic sloping grounds are unsaturated, liquefaction is not a phenomenon to be taken for granted (Olivares and Picarelli, 2006). In fact, it can develop only if the amount of infiltrated water is such to completely fill the voids. If this does not occur, i.e. on very steep slopes whose failure occurs before saturation has been accomplished, different types of landslide can be triggered: in fact, small falls typically involve rather tall cliffs and debris avalanches occur on very steep slopes (Picarelli et al., 2008). In contrast, gentle slopes, i.e. slopes having an angle less than the friction angle, fail only after saturation: if the soil is susceptible to liquefaction, thus it has a void ratio higher than a critical value, and the process of rupture is fast enough to trigger a positive excess pore pressure, a flowslide can develop; if the soil is not liquefiable, typically a slide takes place.

A couple of examples of landslides involving volcanic ashes are reported in Figure 12. Figure 12a shows a debris avalanche which stopped at the toe of the slope: in fact, the houses shown in the lowermost part of the photograph were not touched by the soil mass. In contrast, Figure 12b shows one of the 1998 debris flows which killed eleven people in the town of Quindici: the soil mass, probably completely fluidized, ran within a deep gully and propagated in the piedmont, rapidly reaching the town.

Figure 11. a) The Monte Spina debris avalanche, occurred in Naples (2001). b) The San Francesco debris flow, occurred in the town of Quindici (1998).

LOCATION OF THE AREAS SUBJECT TO MAJOR RISK IN CAMPANIA

According to previous considerations, the areas in Campania with the highest hazard are those which are susceptible to flowslide, especially when this can turn into a debris flow. A relatively smaller hazard is posed by debris avalanches, which occur on very steep slopes but present a shorter run-out.

Since the friction angle of both volcanic ash and pumice typically ranges between 33 and 40°, in the assumption of infinite slope and vertical flow, the maximum slope angle compatible with the hypothesis c'=0 (i.e. nil suction or full saturation) is the friction angle of soil. It is worth noting that the adopted assumptions are consistent with typical geomorphological conditions in the parts of the Region which are covered by volcanic soils, which are characterised by long slopes and thin covers overlying fractured rock (generally, limestone).

For slopes higher than the friction angle, rupture occurs in unsaturated conditions. However, accounting for the shape of the water retention curve of these soils, for slope angles only slightly higher than the friction angle, the degree of saturation at failure should be very close to 100%. For this reason, Picarelli et al. (2007c) assume that debris avalanches involve only slopes higher than 45°.

For slope angles less than 45°, rupture should essentially occur for full saturation conditions thus the type of expected landslide is a function of the susceptibility of soil to liquefaction. According to the present knowledge, this essentially depends on grain size, plasticity and initial density. The highest liquefaction potential is possessed by loose uniform silty sand with non plastic fines. Hunter and Fell (2003) report the grain size curves of soils which proved to be liquefiable, which are quite in a good agreement with those of air-fall deposits in Campania, regardless of the site of deposition (Picarelli et al., 2006). In addition, these

materials are non plastic, with the exception of old weathered deposits, thus the conditions concerning the index properties for liquefaction to occur are fully satisfied. Concerning density, it is well known that liquefaction takes place only in those soils which have a void ratio at rupture well above the Steady-State Line of soil (Castro, 1969). For thin covers of air-fall ash, Picarelli et al. (2007c) suggest a void ratio comprised between 1.5 and 1.8 as the one which separates liquefiable soils (e>1.5-1.8) from non liquefiable soils (e<1.5-1.8). Available data throughout the region show that air-fall ashes can present values of the void ratio up to 3-4. In contrast, a quite lower void ratio, and a lower susceptibility to liquefaction, seem to feature materials deposited by flow and by surge, weathered and altered deposits as well as secondary deposits.
In conclusion, the features of volcanic products susceptible to liquefaction should be the following (Picarelli et al., 2008):

1) a grain size falling in the range of silty sands, which mostly characterises primary air-fall deposits;
2) absence of plasticity, which features all unweathered ash deposits;
3) absence of true cohesion, as in all non altered ash deposits;
4) a low density, which is typical of primary air-fall deposits.

The minimum slope angle for which a slope failure can occur (critical slope angle) strongly depends on the permeability of the bedrock. For infinite slope and vertical seepage, which can take place only for highly pervious bedrock, the critical slope angle is equal to the friction angle of soil. For impervious bedrock, the minimum value of the critical slope angle may obtained assuming the groundwater level at the ground surface and seepage parallel to slope: for γ_{sat}=15 kN/m^3, the slope is definitely stable only for angles less than 13°-15°. Therefore, if soil is susceptible to liquefaction, a flowslide is theoretically possible for β roughly comprised between 15° and 45° depending on the nature of the bedrock.
All these considerations match experience. Figure 12 reports the slope angle of the sources of flowslides and liquefied debris flows occurred in Campania in the last years. A major factor is the nature of bedrock, which can be constituted by either fractured limestone (pervious bedrock) or flysch (impervious bedrock). For pervious bedrock, about 80% of the liquefied landslides occurred for angles in the range 30°-45° and 90% in the range 30°-50°, while for impervious bedrock, about 80% of the landslides occurred for angles in the range15°-35° and 95% in the range10°-35°.

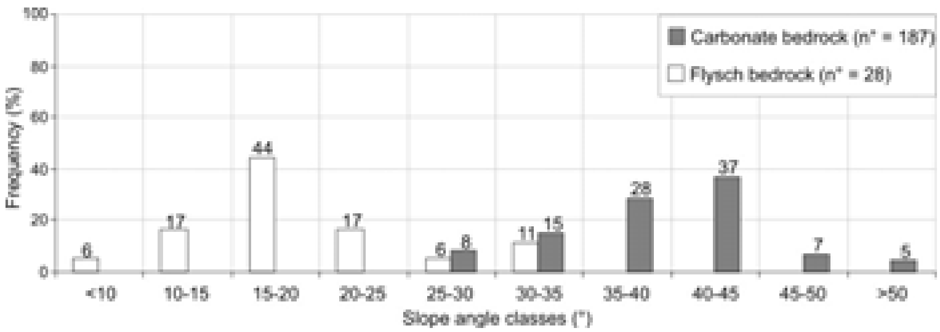


Figure 12. Slope angle in source areas of flowslides in pyroclastic soils (Picarelli et al, 2008)

Using the available data, a qualitative macro-zoning of the areas which are exposed to major hazard (i.e to catastrophic flowslides or liquefied debris flows) can be carried out (Fig. 13).
The same approach can be employed for detailed zoning of hazard areas, through the results

of investigations providing a detailed stratigraphy and site and laboratory tests aimed at quantifying the liquefaction potential of soil (Picarelli et al., 2007c). An example is reported in Figure 14a, which concerns an area close to Sarno, where some debris flows were triggered in May 1998. The location of the landslides and of a number of cracks recognized on the ground surface after the event are reported in Figure 14b. It is shown that the potential sources of liquefaction correspond to those areas where debris flows were really triggered or cracks appeared on the ground surface.

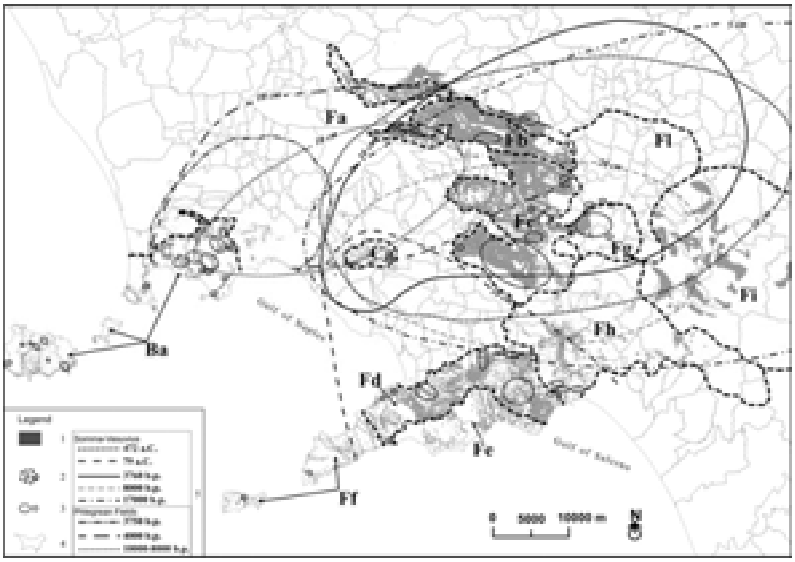


Figure 13. Areas exposed to the highest risk of catastrophic rainfall-induced landslides (Picarelli et al., 2008). 1. Potential sources of flowslides in pyroclastic materials. 2. Sector; 3. Flowslide or group of flowslides. 4. Boundary of municipality. 5. Pyroclastic air-fall deposits of Somma-Vesuvius and of Phlegraean Fields

POLICY, LAWS AND REGULATIONS

Because of the continuous occurrence of catastrophic events, over the last years considerable changes have been made in the policy of protection against natural hazard. Up to the 1980’s the only existing general regulations were those promulgated at the beginning of the century. The first important law, in 1908, concerned land protection in hilly and mountainous areas. In particular, it included a list of the towns to be abandoned or subjected to stabilization works because of landslides. Such a list has been progressively integrated with further towns. Another law promulgated in 1923 imposed hydro-geological planning control on land use.

However, the societal awareness of natural risks has gradually changed. Initially, the population was quite fatalist, considering natural risk as something unavoidable to be accepted. This, naturally, was a consequence of the relatively high return period of catastrophic events in the same area, which leads to forget what happened in the past, especially when nothing occurred passing from a generation to another. Recently, this attitude has been changing because of a number of reasons such as: the growing number of catastrophic events caused by the increase in vulnerability of exposed areas; the role played by the mass-media which offer ample account of catastrophes occurring in other parts of the world which had never been covered before; the increasing sensibility to safety, which is related to the growth in individual and social wealth. As a result, in the last years the production of laws and regulations is greatly increased. As usual, the main adjustments always follow natural disasters

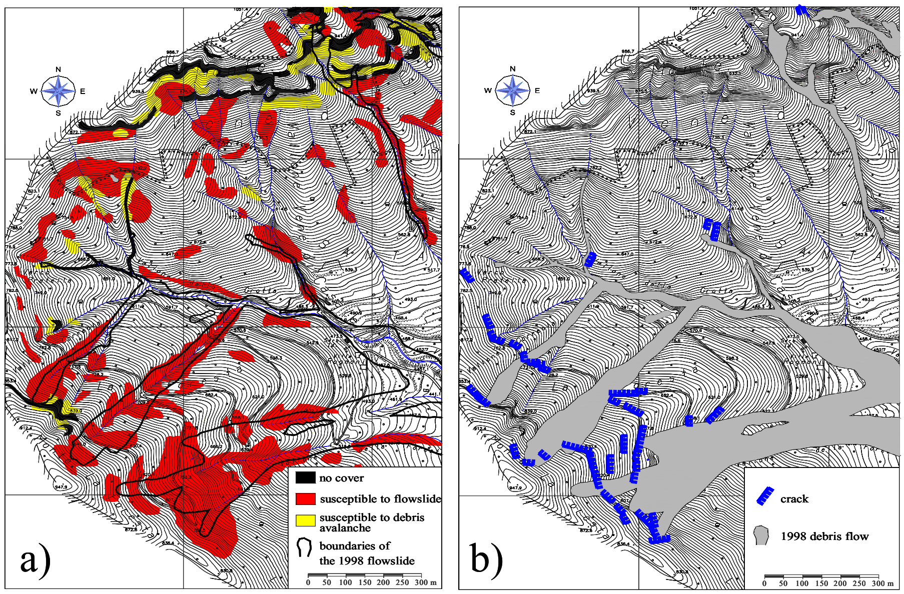


Figure 14. a) Slopes judged to be susceptible to flowslide in an area close to Sarno. b) Location of cracks and rainfall-induced debris flows on May, 1998

In 1952, a law was promulgated concerning the measures to adopt in dealing with the consequences of a disastrous overflow of the Po river (1951).
In 1966, as a consequence of the flooding of Florence, a special scientific Commission coordinated by Prof. Giulio De Marchi was appointed. The Commission collected an extraordinary number of data, giving a precise account of the hydro-geological state of the country. In addition, it prepared a “General plan and guidelines for the hydraulic regulation and control of rivers, including the measures required”. The main propositions of such a plan was the establishment of “Basin Authorities”, each one located in a specific hydrographic system, with the task of predisposing the Basin Master Plans. These plans had to include in-depth analysis of hydro-geological risks and proposals for mitigation, based on identification of risk prone areas, risk assessment, adjustment of mitigation strategies and mitigation procedures. The plan had also to cover measures to deal with water resources and protection. Such a noticeable work convinced the public opinion and the Parliament to provide, after an extremely long and complex debate, a “National Law for Soil Protection” which was promulgated about twenty years after (National Law no 183, 1989). The main reason of such delay was the political situation of the Country which at the time was abandoning its State organization in favour of a local politics of ample regional autonomy. Such a law can be considered a very innovative one; in fact, it put the Country in the van to the point that only in 2000 the European Parliament emanated a directive imposing all its Members to adopt a norm analogous to the one contained in Law no 183.
The main goal of the Law no 183 was to safeguard from floods and landslides human lives, properties and the environment, according the Basin Authorities the role of coordinating centres of the State and of the Regional Institutions for the hydro-geological risks. That law

was followed by regulations and guidelines promulgated at different times, especially on the occasion of catastrophic events, as for the Laws of 1998, after the Sarno event, and of 2000, after the Soverato overflow. In particular, the first one imposed that the Basin Authorities map the areas at risk and adopt measures for risk mitigation; in addition it stimulated urgent programs for the mitigation of hydro-geological risk.
The Civil Protection began effectively carrying out its functions only after the 1976 and 1980 earthquakes. However, only after a long time, the Law no 225, 1992, promoting the establishment of the Civil Protection National Service, was approved.
The basic elements of such law were:

- The setting up in Rome of the National Department for Civil Protection.
- The attribution to Civil Protection of the forecast, prevention and rescue deeds.
- The classification of catastrophic of events in three groups according to their magnitude and the establishment of three corresponding levels of intervention: 1) at a local level; 2) through coordinating institutions; 3) with extraordinary powers and means.
- The delegation to the Council of Ministers of the power to command the state of emergency that allows to operate notwithstanding the existing provisions of the law: it provides for the coordination of the National Service and the promotion of civil protection services through the Civil Protection Department.
- The division of the roles to be carried out by all involved institutional subjects.
- The establishment of a National Group for Protection against Hydro-geological Disasters (G.N.D.C.I.) and a "Great Risks National Commission". The G.N.D.C.I., which was already operative since 1986, has been an important link between the civil protection system and the scientific community.

A number of consecutive norms has divided the national system of Civil Protection into separate levels: national (through the Civil Protection National Service), regional, municipal and inter-municipal. In case of disastrous events, the Civil Protection National Service has to assess in a very short time the magnitude of the event and its possible consequences and the capability, or not, of the local structures (at the municipal level) to face it. In case of National emergencies, is the Civil Protection Department which takes on all the responsibilities. This strategy became more and more efficient, giving rise to a system which at present appears to be working satisfactorily.
In principle, the activities to be carried out for risk mitigation are the following.
The forecast which consists in identifying risk areas: it is carried through by the Basin Authorities which predispose maps of the areas subject to landslide risk.
The prevention which is mostly aimed at offering real-time forecasting of the events through a system of national warnings and immediate realization of safeguarding measures for the population and evacuation of risk areas. The national warning system is coordinated by the Civil Protection Department. Functional Centres operate basically in each region managing automatic rain gauges and hydrometer networks and, very soon, a system of meteorological radars. Functional Centres launch warnings according to forecasting or measurement of occurring rainfall with regards the areas subject to occurring or foreseen events. The Centres make use of very simple mathematical models, as FLaIR (Versace et al., 1998), which rely on pluviometric thresholds, or of more complex numerical models. Warnings are sent off to the involved Municipalities which activate plans of emergency as shown below.
The rescue starts after the event; it either involves local structures or other territorial institutions according to the event. In the case of severe events and high numbers of casualties, the Council of Ministers proclaims the state of emergency. A Delegate Commissary is appointed, who is usually the Governor of the hit region or the Mayor, as in

the case of large Municipalities. The Commissary must guarantee aids to the population and indemnities for suffered damages. He also oversees and manages the overcoming phase of the emergency. In fact, he must predispose in a short time plans of intervention for recovery and rehabilitation of the damaged areas and, once received the necessary funding, carry them through.
The normative frame in Italy is, however, much more complex than what has been briefly drawn here, considering that the normative sources are at least three. There is the European level where Italy figures along with 26 more countries: the European Parliament emanates directives to which all the member Countries have to accommodate their national legislations. There is the national level with the laws emanated by the National Parliament and the directives emanated by the Government. There are also the Regions which have to add the laws and national directives to their regulations and promulgate autonomous laws concerning their areas of competence which includes the soil protection. The Civil Protection system includes also the whole of the Municipalities which must uniform themselves to national and regional norms.
A complex and contradictory frame which has nonetheless allowed, in the past twenty years, for significant improvement in the Civil Protection and soil protection.

STRATEGIES FOR RISK MITIGATION

The strategy adopted in Italy to face tackle heavy hydro-geological events is quite complex and articulated. Its fundamental elements are research, organization and planning.
From the 1970's onward, research has been increasingly enhanced through strategic projects funded by the National Research Council. Such an impulse increased even more after 1986 thanks to the establishment of the G.N.D.C.I. which promoted a research line on "Prediction and Prevention of Highly Risk Landslides", which involved about thousand researchers providing beneficial effects even at the operative level. This activity was stimulated even more by the establishment of the Basin Authorities and of the National Department for Civil Protection. In addition, the no 183 Law produced a significant change in the activities concerning land planning.
Today risk analysis is carried out through quite a uniform approach all over the territory, regardless of the Basin Authority involved. The risk is defined through the classical expression proposed by Varnes (1984): R= E V H. Since the assessment of the single factors present in such an expression (elements at risk, E, vulnerability, V, and hazard, H) is quite complex, approximate methods are used based on a qualitative evaluation of some of the factors concerned (as hazard) and the consequent establishment of risk classes. Starting from the simplified procedure originally proposed by Versace et al. (1995), risk assessment is essentially carried out as in the following:

1) hazard assessment and classification in a range comprised between H_0 (no hazard) and H_3 (very high hazard);
2) assessment of the magnitude of the expected landslide based on its presumed velocity; the magnitude is classified between I_0 (negligible) and I_3 (for velocity higher than 10^{-4} m/s);
3) assessment of the exposition to risk; the factor E ranges between E_0 (desert or unproductive areas) and E_3 (urban areas, industrial and commercial settlements and so on);
4) assessment of the potential damage which ranges between D_0 (negligible) and D_3 (risk for human lives, potential damage to buildings and infrastructures, potential interruption of economic activities); the potential damage is obtained from the hazard, H, and the magnitude I, through the following matrix:

	I_0	I_1	I_2	I_3
E_0	D_0	D_0	D_0	D_0
E_1	D_0	D_1	D_1	D_2
E_2	D_0	D_1	D_2	D_3
E_3	D_0	D_2	D_3	D_3

5) risk assessment; the risk is classified in a range comprised between R_0 (negligible) and R_3 (unacceptable); it is obtained from the potential damage, D, and hazard, H, using the following matrix:

	D_0	D_1	D_2	D_3
H_0	R_0	R_0	R_0	R_0
H_1	R_0	R_1	R_1	R_2
H_2	R_0	R_1	R_2	R_3
H_3	R_0	R_2	R_3	R_3

Such a methodology with further simplifications has been adopted by the Law and is used by the Basin Authorities. The Law identifies four risk classes, between R_1 and R_4, R_4 being the maximum risk level. The entire territory has been consequently classified, and land planning must now take into account of the risk concerned.

Risk mitigation is carried out by so called “non structural” and “structural” measures.

Non structural measures are those which do not require any type of work for risk mitigation, but impose restrictions in land use and emergency plans. The restrictions in land use concern the areas which are classified in the categories R_3 and R_4, where new constructions or even the enlargement of existing buildings is forbidden. The emergency plans are discussed in next section.

Structural measures are all those works which are purposely built for slope stabilisation or for protection of exposed goods. Earthworks, drainage, retaining works, anchors and nailing are currently used for slope stabilisation; often, a combination of different measures is employed. Passive works, such as barriers, check dams, sedimentation basins etc. are adopted in those areas where active measures are too expensive or cannot be used because of complex morphological conditions or of other restrictions.

Some examples of structural and non structural measures adopted to tackle catastrophic landslides are reported in the following. The measures adopted in the Sarno area after the events of May,. 1998, are described by Versace et al. (2007).

The financing for the measures for risk mitigation is sometimes irregular. In fact different and often uncoordinated financing sources exist. Some funds are directly disbursed by the Ministry for the Environment; some by Basin Authorities; others are the result of agreements between the Government and the Regions. It has to be remarked that an important percentage of public financing concerns post emergency measures which take place in the follow up of catastrophic events. In such cases a special structure is set up at the hands of a Delegate Commissary who manages the reconstruction and safeguarding of the hit zone and nearby areas with major investments, especially if compared to ordinary ones.

A complex and long debate has been taking place in Italy about the role and the actual impact of such emergency measures. A major point concerns the fact that an efficient coordination between ordinary and emergency activities has not yet been attained. Undoubtedly however, an articulated and complex system of efficient measures as those adopted after the Sarno event could have never taken place without the extraordinary management of all available resources as in that emergency phase (Versace et al., 2007). Surely, that event has constituted a turning point for Civil Protection in Italy.

EMERGENCY PLANS

The Emergency Plan describes the actions to undertake before and after catastrophic events. In Italy these plans may concern the national, regional and municipal level. The key points of the plans which are adopted at a municipal level are shortly described in the following.
Generally, three phases are accounted for before the occurrence of the event: the “advice”, the “watch” and the “warning” phase; an emergency phase is activated after the event. The Plan adopts a series of actions to be carried out in each phase (Fig. 15). The main components of the plan are:

- A *monitoring network* to capture in real time relevant hydrological and, when available, geotechnical parameters , to be sent to the Regional Functional Centre. In the majority of cases the monitoring network includes only automatic rain gauges.
- A *data-bank* containing mathematical models able to compare the monitored values of the selected factors to the threshold values. In the easiest case, the “advice”, “watch” or “warning” level are associated to pluviometric thresholds corresponding to an established rainfall duration (Versace et al., 1998). In more complex situations numerical models can be adopted, able to simulate the phenomena which occur at the slope scale up to collapse. According to the collected data and elaborations carried out through such models, the Functional Centre sends off a warning to all involved municipalities.
- *Risk scenarios* which define the areas which can be subjected to landslides and the typology of the expected event, especially concerning the velocity of the movement.
- A *network of observers* empowered to immediately reach the areas exposed to risk and assess, based on experience, the seriousness of the expected event. The observers contribute to a much more precise definition of risk scenarios based on documentation filed by Basin Authorities. As an example, a so called Field Survey Team has been established in the Sarno area where a number of geologists and engineers with ample expertise and knowledge of the territory can reach through safe paths a few designated points of observation to transmit information in real time. This is extremely important in case of warning. Such positive experience has progressively spread all over the country.

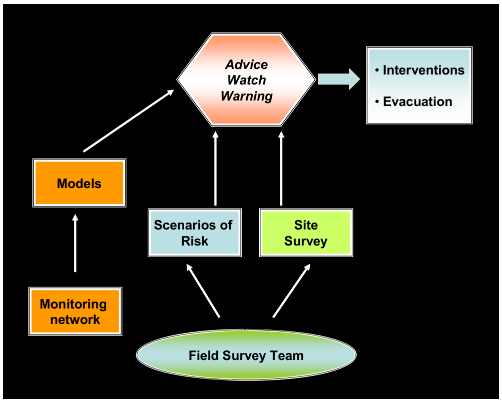


Figure 15. Main components of the Emergency Plans

Prominent information to decide the activation of the Plan can be obtained according to the observations carried by the Field Survey Team and the warning launched by the Functional Centre. Decisions are to be made by the Major. As a general rule, the advice and watch phases are automatically activated. The warning phase is more delicate and requires careful assessment through information provided by the Field Survey Team.
The Plan concerns the activities to undertake in the different phases of the event and the assignment to people of concerned tasks. During the advice phase it is necessary to activate a municipal operative office and guarantee a continuous presence of people, and an efficient connection by phone or fax to all civil protection structures. It is also demanded that the people assigned to the management of the subsequent phases be put on alert. The watch phase activates direct observations of the phenomenon, carried by the Field Survey Team or by other subjects appointed to the task. It also requires an increase of personnel which would be responsible for different tasks concerning road conditions, communication, health, volunteering etc. Subjects responsible for successive operation phases are also to be alerted. During the warning phase the number of competent subjects is enlarged while decisions are taken concerning possible direct actions in the critical areas, carrying out, if necessary, immediate operations for risk mitigation or realizing safeguarding operations such as closure of risk areas, partial or total evacuation of vulnerable areas etc. Such activities are the duty of Fire Brigade and police corps with the aid of volunteers. The emergency phase takes over after the event and is aimed at securing the population, taking care of the wounded and collecting the victims in the case of such a tragic occurrence. To realize timely and effective rescue, it is demanded that the Plan be extremely detailed with regards the management and operation teams and means (excavators, scrapers, trucks and so on) as well as the population of the exposed areas, with special attention to those who, due to age or health condition, are not autonomous and cannot take refuge on their own.
At a more general level, the Plan must appoint a number of subjects to each task (direct observation and field survey, participation in the promoted activities etc.), it must also identify in advance a number of safe areas for collecting evacuated people and ensuring their shelter in tent camps, as well as the rescuers accommodation and resources storage. It is worth noting that the Plan can assume very specific aspects according to the size of the town, the number of people living in the exposed areas, the presence of other types of risk (floods, sea-storms etc.), but it must always be consistent to the reference frame drawn above.
The municipal Plan of emergency is aimed at managing emergencies which the Municipality can face with the aid of nearby municipalities and the Province to which it belongs. When the event is spread and severe, direct intervention of the National Civil Protection is demanded.

SHORT EXAMPLES OF DISASTER MANAGEMENT

As shown, the type of measures to adopt for risk mitigation and disaster prevention strongly depends on the features of the existing or expected landslide. In particular, it is of prominent importance to distinguish between slow, often active, landslides and rapid landslides.
In the case of slow landslides, active measures as earthworks, drainage and retaining woks are often adopted. Some of these measures can be adopted also for stabilization of landslides attaining velocities up to metres per day (from moderate to rapid landslides). In the case of extremely slow movements (slides, mudslides, lateral spreads), living with landslide is sometimes a natural style of life for several communities.
Picarelli and Simonelli (1991) report a slide consisting of calcareous debris which moves over a clay deposit with a practically constant displacement rate of 1 cm/y, recorded over the

period 1988-1989 (Fig. 16). The landslide body is extremely pervious and can rapidly drain downslope the infiltrating rainfall water; hence, ponding water cannot form and the pore pressure measured at the base of the landslide is very small, being subjected to only minor changes. As a consequence, the movement is primarily driven by creep along the slip surface and will presumably continue in the future with the same velocity. As a matter of fact, structures built on the slope ten years before the installation of the instruments present only very small fissures. Only a monastery built about some hundreds of years before, at the time of monitoring appeared badly damaged because of large cracks. In fact, it was subsequently demolished.

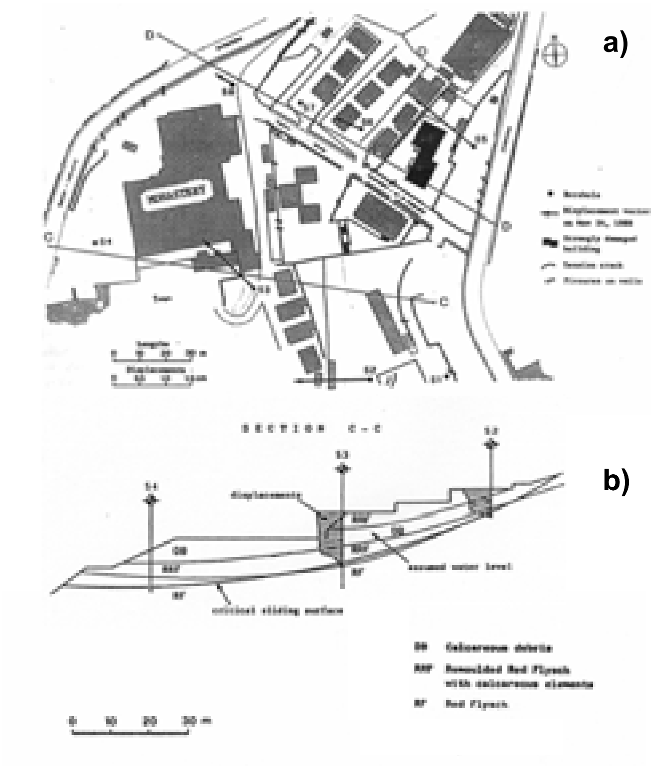


Figure 16. Plan and cross section of a slow landslide consisting of calcareous debris over stiff clay (Picarelli and Simonelli, 1991)

Another very different situation regarding the interaction between a very slow landslide and a urban settlement is the one of the Bisaccia hill, already described above. The movement of the hill is governed by continuing erosion in the basal clayey formation, responsible for a deficient pore pressure regime due to the relatively "fast" decrease of the total stresses with respect to the dissipation rate of induced excess pore pressures. The interpretation of data suggests that the present velocity (a few millimetres per decade) will not significantly change in the near future, unless erosion will strongly accelerate, but even in this last case the deformation process should be delayed by building up of higher negative excess pore pressures. The most likely change of boundary conditions is by seismic activity which in the Bisaccia area is intense. As a matter of fact, investigations carried out after the Irpinia earthquake (1980) show that the interaction of the hill with underlying stiff clays provoked a temporary increase of pore pressures in the clay deposit located below the hill, which gave rise to a post-seismic subsidence monitored during 8 years after the quake (Fenelli et al., 1992). The peak settlement rate due to subsidence was something more than one centimetre per year, thus slow enough to not convince the population to evacuate. It is to mention that according to the 1908 Law, in 1930 Bisaccia was included among the towns to be abandoned, but a part of people refused the evacuation and remained home.

These cases demonstrate that leaving with landslides is sometimes possible, especially when hydro-geological and mechanical conditions are favourable and the size of the landslide body is such that structural measures are too expensive. Moreover, the cost to definitely arrest extremely slow landslides can be very high; in addition, a complete stop is not always sure because of the role of both residual internal strains and creep along the slip surface, which can display an only slightly smaller rate than the velocity monitored before stabilization (Russo et al., 2004).

The Bisaccia case is representative of a typical problem in Italy, concerning the stability conditions of old urban centres built on slopes, which has been the topic of several national conferences and workshops (Firenze, 1980; Bologna, 1986; Spoleto, 1993) and of special investigations and researches. The cases of Agrigento, Pienza, Orvieto, San Leo and of other famous old towns are well know, but there are numerous other towns which present similar problems: some of them have been abandoned. In the case of the magnificent Orvieto, central Italy, which rises on a tuff slab resting on overconsolidated clay, important stabilization works have been carried out on both the slab and the basal clay deposit. In several other cases the town has been abandoned because of large landslides which have involved a great part or the entire urban centre, as for the town of Craco, abandoned in 1963, and of the wonderful Civita di Bagnoregio. Some aspects concerning the mechanics of slow landslides and the interaction of these with settlements and man made works have been discussed by Picarelli et al. (2004).

A special situation is the intermediate one between rapid and slow landslides, because the velocity of the landslide (tens of metres per hour) is not such to provoke victims, but the movement can provoke strong damages.

The case of Covatta mudslide, mentioned above, is quite interesting in this respect because, for the size of the landslide and the cost for a complete stabilization, the adopted measures were not addressed to a full stabilization of the slope, but to a mitigation of its peak velocity, in order to avoid a further complete damming of the Biferno river and favour a progressive decrease of the average velocity. This goal has been progressively achieved through two separated design phases: in the first one (Picarelli and Napoli, 2003), a row of structural wells was built in the accumulation zone with the aim to avoid the river damming, while the run-off converging in the landslide basin was intercepted by ditches and drainage trenches located upslope the main crown; finally, the continuous alimentation of the right side of the landslide body caused by a smaller mudslide was definitely stopped by some retaining works. In the second phase, the crown of the landslide, which represents the major alimentation zone, has been reshaped, a large part of the softened clay which constitutes the depletion zone has been substituted with a better material while deep drainage works have been carried out in order to maintain the pore pressures at low values; finally, a retaining structure located at the mouth of the depletion zone has been built in order to cut the flow of clay downslope, avoiding any increase of the state of stress and consequent excess pore pressure generation in the material which fills the track (Fig. 17). Today, the landslide is moving very slowly.

In the case of very rapid to extremely rapid landslides (velocity from metres per minute to metres per second) active works cannot be carried out during the event. Since for many reasons a definite evacuation of people at risk is not easy, when possible, passive works are carried out in order to protect the life of people, structures and infrastructures. However, today, the idea to set up early warning systems is being seriously accounted for, mostly where the construction of passive works is impossible for technical or economic reasons (Picarelli et al., 2007b).

Figure 17. The depletion zone of the Covatta mudslide during the second phase of stabilization works

A good example of risk management concerning a huge very rapid landslide is that of the Val Pola event briefly illustrated above. It was one of the first cases in which Civil Protection had the opportunity to deal with a catastrophic landslide testing the efficiency of the system.
The meteorological event which triggered the landslide was anticipated on July 16th, 1987, by weather forecasting which predicted exceptional perturbations in the following 72 hours. Such an information gave way, for the first time in Italy, to an important and complex informative chain among different technical and operating bodies of the Civil Protection. As a consequence, the Mayors of small villages located in the threatened area were induced to evacuate several settlements and to check the structures at risk (roads, bridges, banks of rivers, etc.). On July, 18th, rainfall was so intense that the Adda river overflowed, provoking floods and damage in numerous towns. In addition, the road network was practically out of work, and the employment of helicopters was necessary for rescue. Furthermore, about 500 volunteers were employed in the removal of mud from houses and in the management of shelter centres. During the following days, experts of different organisms (Lombardia Region, Fire Brigade, Italian Army etc.) started an accurate slope survey. On July, 25th, a very large crack was recognized on the Zandila Mt about 2 Km meters over the Adda river, suggesting the probability that a huge landslide could be triggered. As a consequence, the Minister responsible for the Coordination of Civil Protection established in Val Pola the "Great Risks National Commission" which declared the status of high landslide risk. Therefore, on July, 27th, the Minister decided the immediate evacuation of 1.280 people. Those fears came true on Tuesday, July, 28th, at 7.23, when 40.000.000 m^3 of rock and mud slipped towards Adda valley covering 2.5 Km in 23 seconds (Fig. 2b). The kinetic energy of the landslide was such that the landslide body raised about 300 m as a gigantic wave on the opposite slope of the valley, causing great damage. Thanks to the evacuation, only 27 people were killed, but 341 houses were completely destroyed and 1545 were injured.
The debris dammed the course of the Adda river, creating a dam and a lake, which grew at a constant speed of bout 20 cm/h up to a maximum height of 100 m. The risk of a dam break

and of the consequent uncontrolled overflow of the lake induced the Ministry to entrust the Commission for the assessment of the risk and of the works to adopt for risk mitigation. Through different mathematically and physically based risk scenarios, the Commission decided to empty the lake through a pumping system. However, since, the Adda discharge was higher than the predicted, on August, 23rd, the lake level was already at the crest of the dam. Insofar, an anticipated artificially controlled overflow of the lake was rapidly conceived by digging a 10 m wide an 1 m deep channel on the crest of the landslide accumulation and pumping water from the lake. The operations started on August, 29th, and were completed on August, 31st (Fig. 18), restoring the continuity of the Adda river about one month after the collapse.
Further interventions included:

- strengthening of the landslide dam;
- construction of two by pass tunnels;
- monitoring of the slope through the installation instruments capable to survey hydrometeorological, topographic and microseismic parameters.

According to a special Law (no 102, 1990), the area involved in the event was classified as an "active landslide zone" and the prohibition of building was imposed.

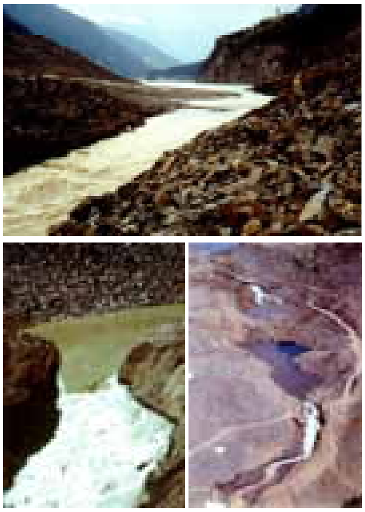


Figure 18. Artificially controlled overflow of the Val Pola lake

In the years after, the National Department of Civil Protection has been involved in other events including the Sarno event, in 1998. This caused 159 casualties in four villages (Sarno, Bracigliano, Siano and Quindici) located at the foot of the Pizzo d'Alvano mountain as a consequence of 40 different debris flows which were triggered in a time span of about 16 hours. In some towns (Quindici, Siano) risk areas were immediately evacuated. In fact, the phenomenon was immediately deemed critical, because a similar event, although of lesser intensity, had taken place in 1997 in Quindici: although there were some victims (16), a major tragedy was avoided. In contrast, in Sarno the seriousness of the situation was underestimated so that there was no evacuation and buildings and more casualties were caused by debris flows. The Civil Protection intervened without delay but only in the aftermath of the event. More than 2 million cubic meters of mud were excavated, victims were recuperated and a young man was found alive under the mud three days after the event. Regular emergency plans were arranged: sheltering of the population, management of the aids coming from all over the country, organization of volunteering teams taking part in the excavation operatios, safeguarding of the abandoned buildings in order to prevent robberies. Additional interventions took place such as:

- involvement, through the GNDCI, of the national scientific community which was involved in landslide analysis and in mapping of the areas still exposed to risk; the cartography was indeed produced in a very short time (Cascini, 2005);
- appointment of a committee wit the task to plan urgent measures for risk mitigation;
- appointment of a Field Survey Team with the task to survey and document the state of the sites involved in movements.

A key point was the question concerning the reconstruction of the most damaged and unsafe districts elsewhere, or plan their reconstruction on the same location, arranging adequate protection measures. The debate was animated even at the governmental level. Eventually, the hope to reconstruct the buildings on the same site prevailed, mainly because of the pressure of the population. In a few weeks, after the first reassessment operations had taken place, people slowly began to go back to the abandoned households. A very effective emergency plan was then arranged involving rainfall monitoring, establishment of pluviometric threshold values, institution of operative centres at each municipality, development of the activities of the Field Survey Team concerning direct site survey and recognizing of anomalous phenomena. The success of the early warning model adopted in Sarno (Picarelli at al., 2007) has been taken as an example for the whole country. The reassessment plan has been effectual, including the realization of a number of works that have brought the risk to an acceptable level (Versace et al., 2007). In particular, cautionary measures have been adopted in the reconstruction phase, as the interdiction in the residential use of ground floors up to 6 meters, partitions in the ground floor unconnected from the structural frame, strengthening of this last to resist the pressure exerted by debris or even the blows caused by bodies dragged by the mud.
Even though the events of May, 1998, uncovered the limits of the national system of civil protection, through the legislative measures which were then promulgated they constitute a turning point for a further development in the defence against catastrophic landslides.

CONCLUSIONS

Italy is one of the parts of the world characterised by the highest risk of landslides. This, not only because of the high hazard posed by the geomorphological and geotechnical features of the territory, but mostly because of the density of population and of infrastructures all over the territory. Because of the number of disasters occurred recently this situation became unbearable. As a consequence, some laws devoted to protection of the territory have been approved and different organisms have been set up for land management and planning and civil protection. This approach is supported by researchers and scientists which are giving a strong contribution not only in terms of knowledge improvement and spreading, but also in the operative approach.
Despite the present state of the art is complex and still unsatisfying, the increase in the knowledge of the mechanics of landslides and of the efficiency of the National Department for Civil Protection and of other institutions have determined a strong increase in the capability of the State, of the Regions and of the Municipalities to manage with some success such situations.

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PREDICTION OF RAINFALL-INDUCED LANDSLIDES IN UNSATURATED GRANULAR SOILS FOR SETTING UP OF EARLY WARNING SYSTEMS

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Abstract: *Early warning is being used more and more for protection against natural risks. In some cases, as for extreme meteorological events, it has proven efficient for risk mitigation; in other cases, as for rapid landslides, the use of early warning is conditioned by the very short lead time which is available between the event and its impact on exposed goods. In particular, in the case of rainfall-induced landslides, early warning should rely on monitoring of rainfalls and on empirical relationships between these and landslide occurrence, forcing to launch the warning signal before the event when the probability of occurrence is considered to be high enough. Because of the complexity of the problem and of the risk of false or missing alarms, landslide prediction should bear on a clear knowledge of the mechanics of slope failure, with the support of advanced technologies for monitoring and data transmission and of reliable procedures for a timely analysis of collected data.*
The paper examines some of these problems, with particular reference to prediction of landslides, reporting experience on events involving pyroclastic soils.

INTRODUCTION

The risk of landslide is extremely variable. In fact, slope movements present a wide range of velocity, size and run-out, thus their magnitude and impact on exposed goods can be either very low or very high, depending on site conditions, geomaterial involved and other factors. Landslide velocity is presently considered to be a key factor for risk assessment. It can range between some tens of metres per second (as for rock falls and avalanches, for debris flows and flowslides) and some millimetres per year (as for active slides in clay and for some lateral spreads): landslide velocity not only affects its destructiveness, but also the procedures to adopt for risk mitigation. For instance, active measures usually adopted for stabilization of slow to moderate landslides in clay, cannot be applied to rapid landslides due to the very short time which is available for any type of intervention. Therefore, in some cases, the safety of individuals depends only on luck, unless preventive passive works have been built in advance, or procedures for a timely people evacuation have been adopted.

THE CONCEPT OF EARLY WARNING

Early warning can be defined as the whole of the actions to be taken during the lead time of a catastrophic event. The lead time is the time interval elapsed between the moment when the occurrence of the event in a given place seems reasonably certain and the moment of its actual occurrence. In more general terms, early warning is the provision of timely and effective information allowing individuals exposed to a hazard to take action in order to avoid or reduce the risk (Gasparini et al., 2007). In order to do it, rapid disaster information systems are of crucial importance.

In the last years, early warning systems have been employed for protection against some natural risks. In some cases, as for heavy meteorological events (tornadoes, typhoons etc.), for volcanic eruptions and for tsunami, they prove quite efficient. In fact, in such cases, the length of time comprised between the impact on exposed goods and the initiation of the event (as in heavy meteorological phenomena or tsunami), or the detection of first reliable precursors of this (as in volcanic eruptions or floods involving large basins), is long enough to take action, as evacuation or protection of some crucial structures and infrastructures: tens of minutes to days, depending on the event. In other cases (as for earthquakes, floods involving small basins, rapid landslides), the time between the event and its impact is extremely short thus adoption of early warning procedures may require special solutions. As a matter of fact, in some cases, early warning is adopted only for limited goals; in others, the signal is launched well before the event, when its probability is high enough but the event isn't really certain. This last approach implies a high subjectivity in the decision and can determine false or even missing alarms, posing additional problems concerning the social, economic and legal consequences of mistakes.

For earthquakes, the occurrence of the event is unequivocal, as the lead time must be evaluated from the time when the first seismic waves released by the source are detected. Since strong ground shaking is provoked by shear and surface waves whose travel speed is about half the speed of primary waves, and these are much slower than electromagnetic signals transmitted from the epicentre by cable or wireless, transmission of information regarding the faster primary waves and a first real-time analysis of the effects of these, may provide warnings concerning the approaching ground shaking (Gasparini et al, 2007). As a matter of fact, the real-time analysis of signals can be exploited to locate the epicentre, to assess the magnitude of the quake and to estimate the distribution of ground motion. This analysis requires some little time, thus the remaining length of time to take action depends on the distance of the area to be protected from the epicentre. If such a length of time is at least a few seconds to tens of seconds, automated actions can be taken, as turning off of electrical power, shutdown of pipelines and gas lines, arrest of trains, activation of special protection systems of critical structures, as nuclear power plants, etc. This is the case of the town of Naples, which is situated some tens of kilometres from the most likely epicentral areas located in the Apennines chain.

Early warning systems could also be used to mitigate the risk posed by rapid landslides. Since the time elapsing between the onset of slope failure and its impact on exposed goods is typically in the order of tens of seconds, the problem is similar to the one posed by earthquakes, but even more complicated because the lead time is equally short but the landslide can occur everywhere, in areas lacking any type of instrument able to recognize the event. Research in this field is active, even though just beginning.

This paper examines the methods which can be used in the case of rainfall-induced landslides in granular soils, with particular reference to debris flows occurring in pyroclastic materials outcropping in Campania Region, and discusses the lines along which new and more refined procedures can be developed for timely prediction of slope failure.

INDICATORS OF IMPENDING RAINFALL-INDUCED SLOPE FAILURE IN UNSATURATED GRANULAR SOILS

Data from experience and experiments

In general, it is thought that slope failure in granular soils is preceded by too small and fast displacements to be considered as indicators of impending failure. However, this point deserves some insight, because of the relevance of the topic. Experiments on full-scale or even small-scale physical models can be extremely useful in this respect. This is one of the goals of an experimental program which is being carried out at the Geotechnical Laboratory of C.I.R.I.AM. with particular reference to rainfall-induced landslides (Fig. 1).

Figure 1. The flume available at the Geotechnical Laboratory of C.I.R.I.AM.

Figure 2 reports the main results of two tests performed on a 10 cm thick, 1.2 m long 40° model slope made up with very loose (e=2.70, on the left side) or relatively dense (e=1.85, right side) unsaturated volcanic ash, resting on a rough impervious base. The soil is a cohesionless silty sand (the Cervinara ash) with a friction angle of 38°. In the experiment, the average initial suction, u_a-u_w, was respectively 60 and 50 kPa, corresponding to an apparent cohesion around 9 kPa (Olivares, 2001). Failure was provoked by uniform artificial rainfall. The course of suction recorded with superficial and deep tensiometers (uppermost diagrams) suggests the evolution of the wet front from the ground surface to the base of the layer, which is reached when the deep tensiometers indicate vanishing of suction because of full saturation (Fig. 2a). Since then, in the last few minutes before failure, the probes installed at the base of the layers start to measure a positive pore pressure (Fig. 2c). The effects of suction decrease are shown in the intermediate diagrams, which display a settlement of the ground surface, measured with laser transducers. The average volumetric strain of loose soil attains a value as high as about 7%; in contrast, the dense soil shows a negligible strain, or some dilation just prior to failure. This is confirmed by personal experience: in fact, even when general slope failure is not attained, man made works located on sloping grounds may reveal deformation and fissuring provoked by infiltration, while the ground surface is subjected to cracking (Picarelli et al., 2007a). The lowermost diagrams in Figure 2 show that failure in loose soil is followed by a sudden pore pressure increase which can attain a peak value very close to the total stress, suggesting the occurrence of liquefaction. The same does not occur in dense soil.

Significant volumetric deformation of soil prior to failure has been recognized also by Take et al. (2004) through small-scale centrifuge tests. Similar data about the behaviour of loose soil have been obtained by Ochiai et al. (2004) and by Moriwaki et al. (2005) through full-scale tests.

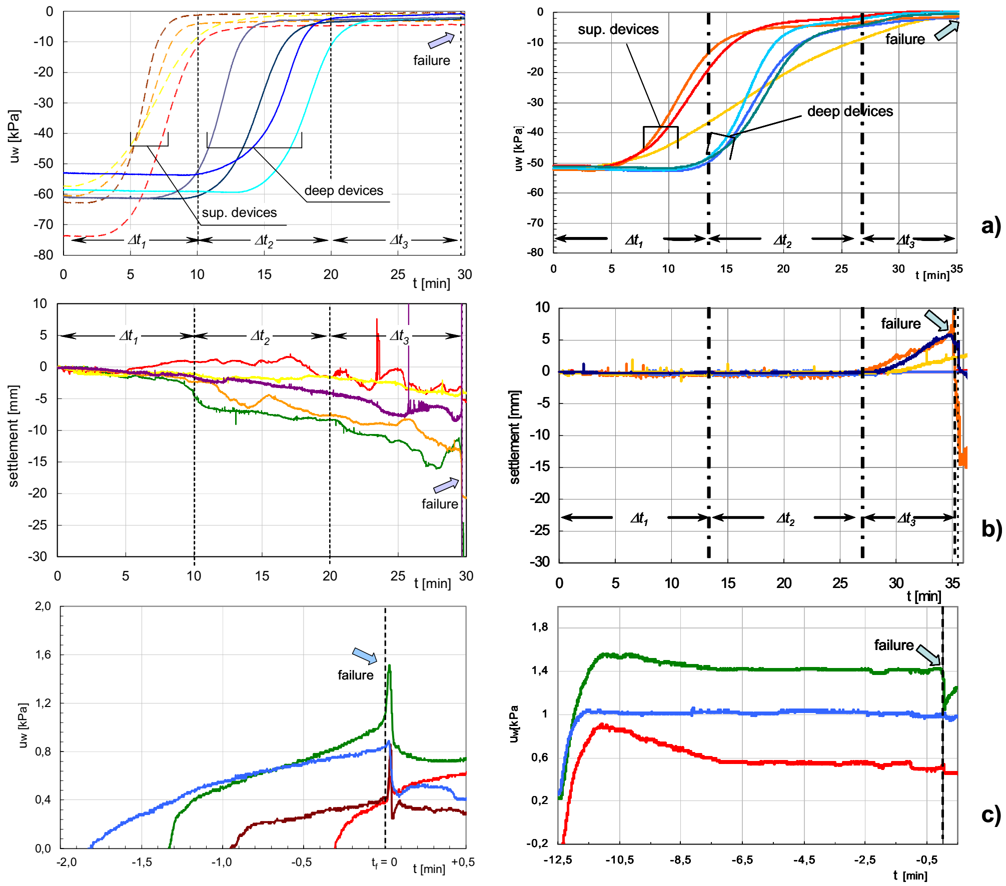

Figure 2. Results of a flume test carried out on the Cervinara volcanic ash (loose soil on the left side; dense soil on the right side): a) suction measured at two different depths; b) settlement of the ground surface; c) pore pressure recorded at the base of the layer (modified from Damiano, 2004)

Such data demonstrate that either suction decrease (or the correlated value of water content) or soil deformation, can be used as indicators of impending failure: however, while suction must be correlated to the other factors (such as the slope angle or the friction angle) to provide information about slope stability, soil deformation must be evaluated as such.

The role of suction on slope stability in unsaturated granular soils has been clearly demonstrated by several Authors (see for instance Lim et al., 1996). Figure 4 shows some data regarding suction measured in the years 2002-2003 and 2006-2007 in a 2.5 m thick 40° sloping deposit covering fractured limestones (Fig. 3). The cover consists of alternating layers of pumice and volcanic ash, the same which has been used for flume tests discussed above: the average void ratio of the volcanic ash is around 2.0. Suction continuously fluctuates as a consequence of changes of humidity and of rainfall: it reaches values as high as 80 kPa, corresponding to an apparent cohesion of about 10 kPa, but can rapidly drop to a few kPa. This strongly affects the stability conditions of the slope. As a matter of fact, on December, 16th, 1999, the slope just aside the instrumented zone failed, as a consequence of rainfall which lasted two consecutive days, amounting to 329 mm (Olivares and Picarelli, 2003). The mechanism of failure was very similar to the one shown in Figure 2 for loose soil (flowslide).

The discussed remarks about phenomena which precede slope failure in unsaturated loose pyroclastic soils, either in model slopes or in natural slopes, stimulated a research aimed at developing methods to capture in advance any indicator of impending slope failure, to exploit in the design of early warning systems: a team composed of experts in geotechnical and in hydraulic engineering, as well as in optoelectronics, is closely working at C.I.R.I.AM. on such a project (Olivares et al., 2007; Damiano et al., 2008). Following this idea, flume tests are being carried out on small-scale slopes instrumented with either “usual” laboratory sensors, such as micro-tensiometers, probes for pore pressure measurement, laser transducers for displacement readings as well as with video-cameras, either instruments conceived to be used in site for warning purposes, as TDR probes and optical fibers.

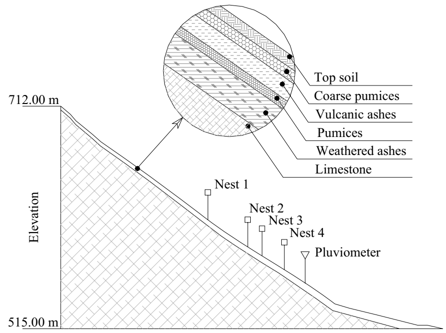

Figure 3. The instrumented Cervinara slope

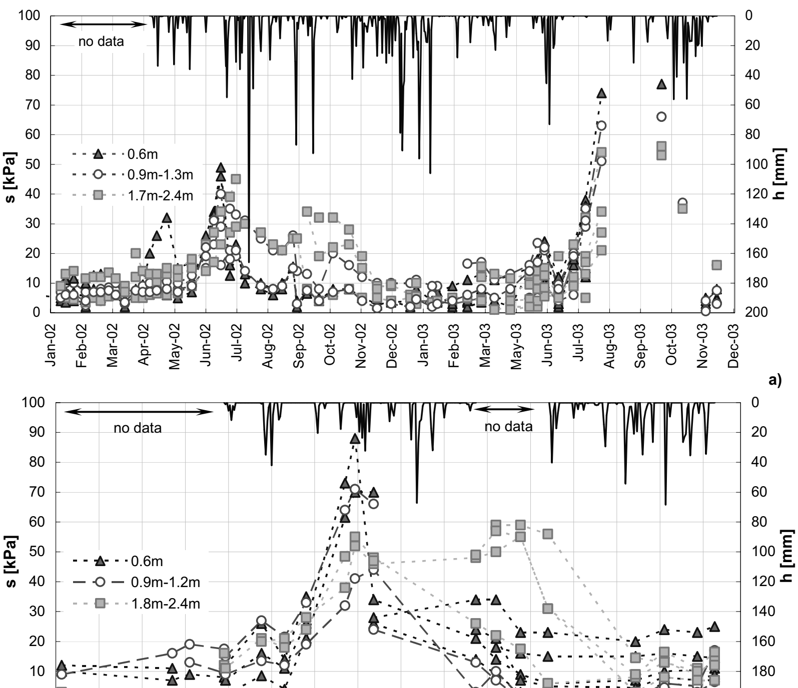

Figure 4. Suction measured at different depths in the slope of Figure 3: a) 2002-2003; b) 2006-2007.

Capturing of failure indicators

In principle, prediction of landslides might be based on the assessment of indicators to be monitored in selected critical points. This approach is somewhere used to predict rock fall through readings of the aperture of joints. In rock masses, a new approach is being investigated by French researchers through the analysis of microseismic waves propagating from fractures which are subjected to pre-failure movements (Senfaute et al., 2003). Further experiences bearing on monitoring of precursors and indicators of different types of landslides in different materials are being carried out in some parts of the world (see for instance Baum et al., 2005; Flentje et al., 2005).

As discussed above, at C.I.R.I.AM., flume tests are being carried out to calibrate different sensors to capture indicators of impending failure in pyroclastic soils. At present, TDR probes and optical fibers are being tested.

The TDR technique has been used from decades to measure the volumetric water content of shallow soil layers through a metallic probe which is gently buried in the soil with very small disturbance. The volumetric water content, θ, can be obtained from the strong correlation existing between this and the bulk dielectric permittivity ε_r of soil (Campbell, 1990). Usually, soil permittivity is estimated by measuring the mean speed of an electromagnetic pulse travelling along the probe, which is correlated to the mean water content in a cylindrical volume of soil around the probe. Several expressions of $\varepsilon_r(\theta)$ relationship, obtained from either empirical correlations (Topp et al., 1980) or semi-analytical approaches (Roth et al., 1990; Whalley, 1993; Gong et al., 2003), are available in the literature. However, the retrieval of the entire profile of the volumetric water content along a vertical section can be much more useful in prediction of landslide triggering, than the average value obtained from usual correlations. An inverse procedure from TDR measurements has been recently developed by Greco (2006). Such a technique appears very consistent to landslides in pyroclastic soils, which generally present a thickness comprised between some decimetres and a couple of metres; as a consequence, the complete water content profile might be investigated through few long probes driven vertically from the soil surface. The water content profile can lead to the suction profile through the retention curve of soil. Since TDR probes are very cheap and do not require significant maintenance, site measurement can be carried out with a very low cost. In the flume, a probe is placed vertically from the ground surface, allowing the assessment of the complete profile of the volumetric water content because of the relatively small thickness of the layer (10 cm).

Monitoring of soil deformation through optical fibers is performed by stimulated Brillouin scattering (SBS). This allows measurement of temperature and strain along a single-mode optical fiber. The basic measurement scheme involves the interaction between a pulsed pump beam and a counter-propagating cw (continuous wave) probe beam at a different wavelength. At any section of the sensing fiber, a power transfer between the light pulse and the probe beam occurs, this interaction being maximum for a precise value of their frequency offset (the so-called Brillouin frequency shift), which in turns depends on the material condition (temperature and strain): in particular, Brillouin frequency shift increases linearly with temperature and tensile strain. Positional information is obtained through a time-domain analysis; shorter pulses increase the spatial resolution. The key idea is that optical fibers can be laid down in very shallow trenches dug along the slope, in order to capture every soil deformation in the pre-failure stage everywhere it is occurring. In fact, differently from much more expensive instruments, as extensometers or inclinometers, measurement with optical fibers is not local but distributed. The experiments performed in the flume are carried out by a single-mode standard optical fiber having a total length of about 35 m. Two 1 m long strands are buried in the soil, in the longitudinal section of the

flume. The two strands are separated by a fiber spoil of about 15 meters, placed outside the soil and no subjected to strain.
Some tests have been carried out in the flume using either TDR probes either optical fibers. An example is reported in Figure 5 which reports internal values of suction and vertical displacements of the ground surface (Fig. 5a) as well as vertical profiles of the volumetric water content (Fig. 5b) in a test performed on a 40° slope made up with the same material used in previous experiments (Fig. 2). In this case the void ratio of soil was 2.35. Once again slope failure is preceded by suction decrease and volumetric compression of soil as a consequence of water infiltration. Regarding the volumetric water content, Figure 5b shows that, at any depth, it continuously increases with time. In particular, in the first stage of the test, the curve (Θ, z) shows a strong curvature since infiltration involves the uppermost layer only. In the successive phases, the water content tends to a uniform value: a practically vertical profile is attained when suction practically vanishes (Fig. 5a) and the degree of saturation becomes close to one. This indicates either soil uniformity either saturation of the entire soil layer before failure.

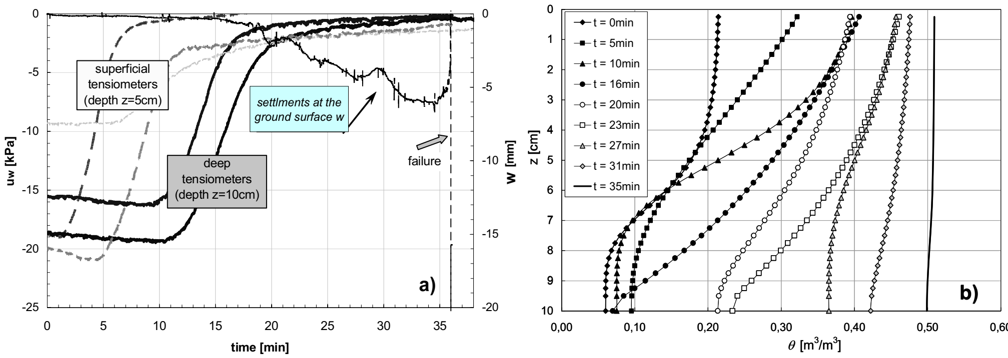

Figure 5. Records of suction and settlement of the ground surface (a) and assessment of the volumetric water content (b) in a flume test (Damiano et al., 2008)

Figure 6 shows the response of the fiber during the test: the two grey zones indicate the position of the two strands of fiber embedded into the soil. The profile recorded 18 minutes after the beginning of the test shows that the only significant change is localized in the fiber spoil comprised between the two embedded regions. As this part of the fiber is not subjected to strain, such variation is to be attributed to the cooling due to water wetting. A successive profile recorded 15 min later shows that the central fiber spoil is still at a lower temperature with respect to the reference profile. Also, a net Brillouin frequency increase is recorded around the position z=28 m of the sensing fiber, i.e. in one of the two strands embedded into the soil; a smaller Brillouin frequency shift increase can also be recognized in correspondence of the other embedded strand, but it is barely visible due to noise. Since no changes in temperature have been measured in the soil layer through thermocouple measurements, the increase in Brillouin frequency can be interpreted as a result of tensile strain induced by soil movement. The final record taken after failure shows that the Brillouin frequency in the embedded regions is going back to the value measured before failure.
In conclusion, the test clearly shows that incoming failure is announced by all instruments. Before collapse, suction progressively falls to zero while the soil is subjected to continuing vertical settlement, then a positive pore pressure (as in Fig. 2, but not reported here) is measured at the base of the layer as a consequence of formation of water ponding. In this stage, the water content becomes uniform all over the layer, as shown from elaboration of

data provided by the TDR probe. This reveals the usefulness and reliability of this instrument for continuous temporal and spatial information about water content changes. Approaching failure is revealed also by records taken by the SBS-based set-up: in fact, slope collapse occurs 5 minutes later the appearance of strain shown in Figure 6. This confirms the reliability of optical fibers to capture deformation occurring prior to failure.

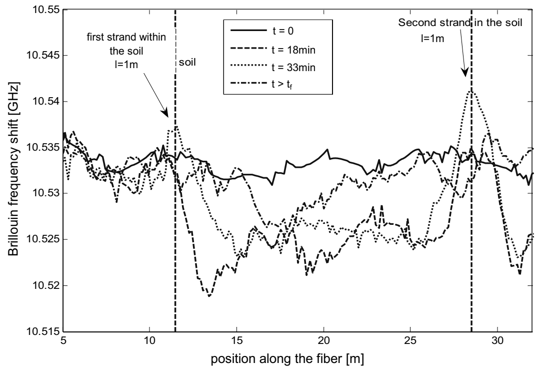

Figure 6. Records taken by the SBS-based set up (Damiano et al., 2008)

PREDICTION OF RAINFALL-INDUCED LANDSLIDES IN UNSATURATED GRANULAR SOILS

Foreword

Large parts of the world are subjected to catastrophic rainfall-induced landslides. This is particularly true for tropical regions covered by granular geomaterials, as residual soils, which are subjected to intense seasonal precipitations. Based on collection of data on landslides and related triggering rainfall, thresholds often based on a combination of rainfall intensity and duration, have been obtained for several regions, as Hong Kong (Finlay et al., 1997), California (Campbell, 1975; Wilson and Wieczorek, 1995), New Zealand (Glade et al., 2000) etc. Bearing on empirical data, these approaches can be employed only on a local scale.

In some of these countries, early warning systems have been conceived to prevent disasters. In fact, these thresholds, in combination with rainfall forecasts and real-time rainfall monitoring, can lead to operational landslide warning systems. As an example, in 1977, the Hong Kong Geotechnical Engineering Office established a warning system, which has been continuously updated and improved in the years (Chan et al., 2003). Similar systems have been elaborated to prevent the consequences of rainfall-induced debris-flows in the S. Francisco Bay (Keefer et al., 1987) and in Nagasaki (Yano and Senoo, 1985). d'Orsi et al. (1997) report the Rio-Watch, an alert system based on a network of 30 telemetered rainfall gauges and weather radars which cover the city of Rio de Janeiro issuing 42 warnings between 1998 band 2003. Similar systems have been set up in the State of Oregon (Mills, 2002), in UK (Cole and Davis, 2002) and in the area between Seattle and Everett, Washington (Baum et al., 2005). Even though a true early warning system is not active, in the landslide prone area around Wollongong, Australia, monitoring is active, and continuous information about slope stability conditions is provided on the WEB (Flentje et al., 2005).

Most of these and other systems are simply based on real-time rainfall monitoring and data transmission. However, there are more sophisticated systems which rely on different indicators through measurement of soil wetness, pore pressures, ground displacements etc.

Analysis of all data is used to establish different levels of warning with successively shorter lead times. For instance, to make safe the rail traffic between Seattle and Everett, three warning levels have been established (Baum et al., 2005): the first one, "advisory", is based on water contents measured in monitored sites; the second one, "watch", is activated when an empirical rainfall intensity-duration threshold is being exceeded; the third higher level, "warning", is based also on monitored values of pore pressures.

Landslide hazard in Campania Region

Old chronicles demonstrate that the pyroclastic cohesionless soils which mantle mountains and hills in Campania are periodically subjected to catastrophic landslides (Cascini and Ferlisi, 2003). As a consequence of the rapid and extensive development of urban areas and infrastructures occurred after the second World War, in the last half of century the loss of lives and the damages provoked by rainfall-induced debris flows and flowslides (Picarelli et al., 2007b) has been exceptional. In particular, in the last ten years debris flows provoked almost 180 victims in ten different sites of Campania, but much higher is the number of slopes which were subjected to landslides bearing no severe consequences. A major catastrophe occurred on May, 5, 1998, when 160 people lost their lives in five different towns: in the only town of Sarno 137 people died (Cascini et al., 2000). The last killer landslide in this decade occurred in 2006, in the well known touristic island of Ischia.

This situation is frankly unbearable for an advanced country which should employ a significant part of its gross national product to guarantee the wealth and safety of people. As a matter of fact, in the last years hundreds of millions of euros have been spent to protect with passive works the urban areas subjected to the 1998 debris flows (Versace et al., 2007). In addition, an early warning system is being used to prevent further loss of lives in non protected zones of the same area. However, since the total number of towns at risk has been evaluated to be higher than 200, a global approach urges, based on sophisticated and possibly cheap systems for risk mitigation. Even with limitations due to the complexity of the procedures and to some uncertainties in the interpretation of data, the use of methods for precocious prediction of incoming failure remains an effective and economic way for risk mitigation.

Following sections shortly describe the method presently used in the area subjected to the 1998 catastrophic debris flows, and discuss further ideas for timely prediction of slope failure.

The FLaIR hydrological model used in Sarno and in surrounding areas

Previous short considerations show that today prediction of rainfall-induced landslides is mostly carried out through the so-called hydrological models, which are based on historical data regarding landslides and related triggering rainfall (Fukuoka, 1980; Mitchue, 1985). In Italy, Sirangelo and Versace (1992) proposed the general hydrological model FLaIR (Forecasting of Landslides Induced by Rainfall), which has been recently extended to landslides in pyroclastic soils (Versace et al., 1998, 2003).

FlaIR consists of two modules: RL (Rainfall-Landslide) and RF (Rainfall Forecasting). Through a calibration of available data, the first module, correlates precipitations and landslide occurrence, in order to determine a mobility function *Y(t)*. This module enables model calibration and permits the reproduction of historical movements. The second module provides a probabilistic prediction of rainfall events through a stochastic rainfall or meteorological rainfall nowcasting, which is used to identify hazard conditions for landslide occurrence suitably in advance. Using both modules, the model enables a probabilistic evaluation of future landslide occurrence.

In the RL module the mobility function *Y(t)* which, at any time, depends on the amount of infiltrated water, is associated with the probability $P[E_t]$ of landslide occurrence at the time t, by the relation:

$$P[E_t] = g[Y(t)], \qquad (1)$$

where $0 \le g(.) \le 1$.

Among various relationships between the mobility function and the probability of landslide occurrence, a very simple threshold scheme can be assumed:

$$P[E_t] = \begin{cases} 0 & if \quad Y(t) \le Y_{cr} \\ 1 & if \quad Y(t) > Y_{cr} \end{cases}, \qquad (2)$$

being Y_{cr} the threshold value of $Y(t)$.

According to the (2), which establishes a deterministic relationship between the value assumed by the mobility function and landslide occurrence, the event is certain only if the mobility function $Y(t)$ exceeds the threshold value Y_{cr}.

The mobility function $Y(t)$ is defined as:

$$Y(t) = f[I(u)] \qquad 0 < u \le t, \qquad (3)$$

where $I(u)$ is the infiltration rate.

In particular, the mobility function can be linked to the infiltration through the expression:

$$Y(t) = k_0 \int_0^t \psi(t-u)\, I(u)\; du, \qquad (4)$$

where $\psi(.)$ is a filter function and k_0 is a constant depending on the features of the subsoil. It is worth noting that a critical role is played by the choice of the filter function which can model a wide range of situations (Sirangelo and Versace, 1996).

The infiltration rate $I(u)$ is considered to be proportional to the rainfall intensity, $P(.)$, according to the following relationship:

$$I(u) = rP_*(u) \qquad P_*(u) = \begin{cases} P(u) & when \quad P(u) \le P_0 \\ P_0 & when \quad P(u) > P_0 \end{cases}, \qquad (5)$$

where P_0 depends on soil features, and r is a factor of proportionality. Because the mobility function is defined up to an arbitrary multiplicative factor, it is possible to choose $rk_0=1$ so that:

$$Y(t) = \int_0^t \psi(t-u)\, P_*(u) du. \qquad (6)$$

As shown, the use of FLaIR for real time forecasting of landslide occurrence consists in evaluating the probability that at time t the mobility function $Y(t)$ reaches or exceeds the critical value Y_{cr}, established through historical information on previous slope failures.

The value $Y_\tau(t)$ that the mobility function will assume at time t, calculated at the time τ (τ<t), may be written splitting the convolution integral (4) in two parts:

$$Y_\tau(t) = \int_0^\tau \psi(t-u) P(u) du + \int_\tau^t \psi(t-u) P(u) du. \qquad (7)$$

The first one, on the right-hand side, is calculated on the basis of observed rainfall. It can be considered as the deterministic component, $Y_\tau^{(det)}(t)$ which depends only on the rain fallen in the past and is known at the current time, after model identification and parameter evaluation. The second one is the stochastic component $Y_\tau^{(sto)}(t)$ which depends on the rain which should fall in the interval $]\tau, t]$, and can be estimated through rainfall forecasting. Therefore, the equation (7) may be expressed in the following form:

$$Y_\tau(t) = Y_\tau^{(\det)}(t) + Y_\tau^{(sto)}(t). \qquad (8)$$

The division of the mobility function into a deterministic and a stochastic component plays a fundamental role in the procedure of real-time forecasting. In fact, it allows the calculation of the deterministic part of the mobility function through a real-time monitoring of rainfall, so the data uncertainty in the evaluation of $Y_\tau(t)$ is limited to the stochastic component. As a consequence, the model may be usefully employed to forecast the hazard of rainfall-induced landslide, allowing the activation of the necessary procedures for civil protection. Through the probabilistic forecast of future rainfall, it could be used for the definition of operative rainfall thresholds.

The strategy of civil protection agency with respect to landslide or inundation events is usually based on three warning levels: “attention” (or “advisory”), with instrumental real-time monitoring and real time simulation model running; “alert” (or “watch”), involving civil protection agencies and field direct control; “alarm” (or “warning”), involving population to be evacuated. Using FLaIR, a characteristic mobility ratio $\chi=Y/Y_{cr}$ can be associated with each warning level.

Let Y_a be the mobility function value related to “attention”, (“alert” or “alarm”) threshold, and let $Y^{(0)}(t)$ be the deterministic component, by the condition $Y_\tau(t) \leq Y_a$, the expression (7) becomes:

$$\int_\tau^t \psi(t-u)P(u)du \leq Y_a - Y_\tau^{(0)}(t) \qquad with \qquad Y_a \geq Y_\tau^{(0)}(t). \qquad (9)$$

Therefore, it is straightforward to obtain the rainfall heigth $H_{\tau,t}$ cumulated over the time interval $]\tau, t]$ such that the mobility function does not exceed a given threshold value Y_a.

FLaIR can be used for warning using only the RL module, so each warning threshold is activated simply when a fixed value of the mobility ratio χ is exceeded (Sirangelo and Braca, 2002), or using also the RF module, thus each warning threshold is activated when the probability of the mobility ratio $\chi=Y/Y_{cr}$ exceeds a fixed value in a fixed forecasting time.

The choice of the values of index χ for each warning level must fit considering the necessity to have an adequate safety margin, that needs a low mobility ratio, and to avoid false alarms, that needs a high mobility ratio. Values of the mobility ratio used in different applications are the following: $\chi=0.40$, for the “attention” threshold, $\chi=0.65$ for the “alert” threshold and $\chi=0.85$ for the “alarm” threshold.

Application of FLaIR

On May, 5th, 1998, after heavy and persistent rainfalls, more than one hundred landslides were triggered in a time span of a few hours along the slopes of the Pizzo d’Alvano mountain, triggering more than one million of cubic meters of material (Cascini et al., 2000). According to several site observations, failure took place in the steepest parts of the slopes, in many cases at the head of gullies, where the top of the bedrock, consisting of fractured limestone, presents a slope ranging 40-45°. The landslides gave rise to twenty main debris flows, which ran 2-3 km into the surrounding lowlands, reaching the towns of Sarno, Siano, Bracigliano and Quindici, all located at the foot of the mountain: 159 people died and severe destruction was provoked. During the same event another people was killed in the town of San Felice a Cancello, which is located relatively far from Pizzo d’Alvano mountain.

In the following years, the area has been protected with passive works; in addition, an early warning system based on FLaIR has been adopted to prevent further victims in non protected zones. The model has been calibrated using the rainfall data recorded by the Santa Maria La Foce rain gauge, the only instrument present in the area of Sarno (Fig. 9), located at an elevation of 36 m above s.l. and active for 66 years.

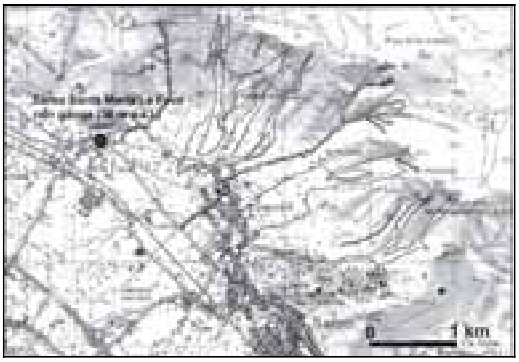

Figure 9. Location of the Santa Maria La Foce rain gauge and main debris flows triggered by the 1998 event in the town of Sarno

The model calibration led to the following filter function:

$$\psi(t) = \omega\beta_1 \exp(-\beta_1 t) + (1-\omega)\beta_2 \exp(-\beta_2 t) \qquad \beta_1 \geq \beta_2 \qquad (10)$$

Such an expression is the result of two negative exponential functions: the first one reproduces the effect of recent rainfall (short term component); the second one, those of the antecedent rainfalls (long term component). The parameter ω is representative of the relative weight of the two mechanisms in the behaviour of the hillslope.
In particular, for the area around Sarno, it has been assumed:
$\omega = 0.1$;
$1/\beta_1 = 0.75$ days = 18 h;
$1/\beta_2 = 150$ days = 3600 h.
$P_0 = 7.5$ mm/h.
Accounting for the rainfall which led to the event of May, 1998, the threshold value of the mobility function (2) is Y_{cr}=9.11 (Fig. 10).

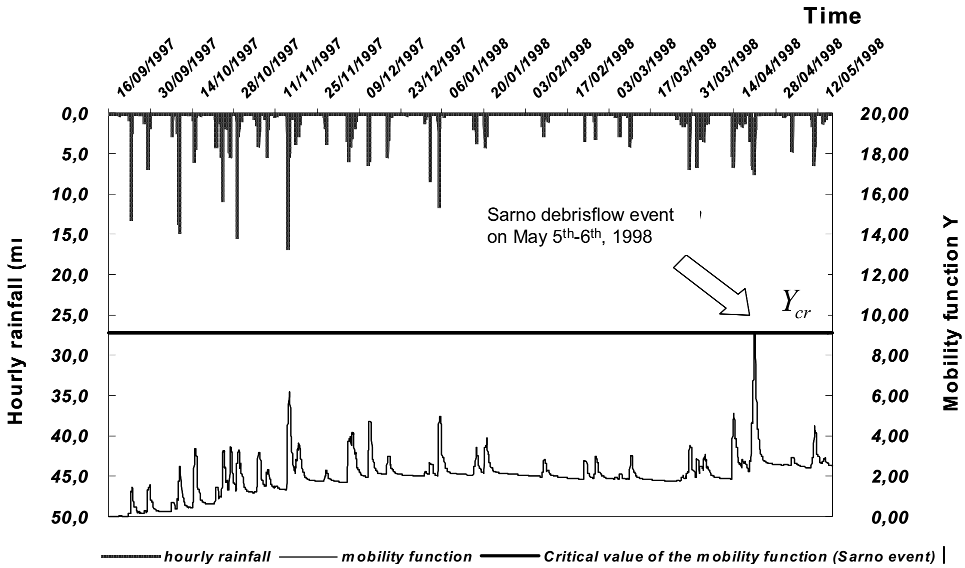

Figure 10. Threshold value of the mobility function matched during the event of May, 5^{th},1998.

Referring to the rainfalls records at the Santa Maria La Foce rain gauge in the last 33 years, the mean and minimum time span between the attainment of the “alert” and of the “alarm” thresholds has been respectively 5 and 4 hours which have been considered long enough for all the operations to be carried out in the following phase of “alarm”.
To check the performance of the forewarning system, in Figure 11 are summarised the data concerning the wet seasons 2000–2001. It is shown that in the period October, 2000 - June 2001, the attention level has been attained several times, the alert level has been reached three times, while the signal of warning has been launched just one time.
It is worth to mention that an early warning system based on a hydrological model has been adopted also by the Società Autostrade Meridionali (SAM), which manages the highway between the towns of Napoli and Salerno (Fenelli, 1998). The highway, built about fifty years ago, is located alongside the bays of Naples and Salerno, not far from the coast, running at the foot of some calcareous relieves covered by pyroclastic soils. In the last fifty years the highway has been subjected to three landslide events: the first one occurred on December, 8, 1960, when two flowslides were triggered at a time interval of a few hours each other; another flowslide occurred on March, 6, 1972; the third event happened on January, 10, 1997, and caused the death of a driver. As a consequence of this last event, the SAM decided to set up an early warning system whose aim is to stop the traffic when rainfall attains a given threshold. The threshold has been established assuming as a reference the three mentioned landslide events, accounting for the cumulated rainfall over the last 58 days and in the last 24 hours. The relationship between rainfall and landslide triggering has been established on the basis of rainfall data concerning the period comprised between January, 1951, and September, 1997. The system exploits the data provided by three automatic rainfall gauges located near by of the highway. The warning signal has been activated twice: by the event of Sarno (May, 5, 1998), which is not far from the highway, provoking no landslides in the vicinity of this, and by another event occurred on March, 5, 2005, causing some victims in the proximity of the highway.

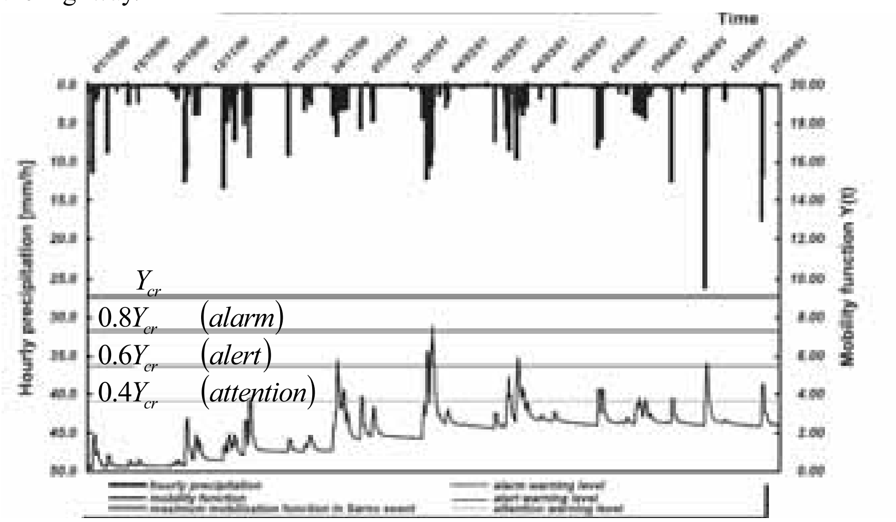

Figure 11. The mobility function during wet season 2000–2001 in the Sarno area.

Some considerations about criteria for precocious alerting in instrumented areas
Hydrological models can be very useful to predict rainfall-induced landslides in well known geomorphological contexts for which documented data are available. Because of the great uniformity of the geomorphological features of the areas subjected to flowslides and debris

flows (Picarelli et al., 2006, 2008), this approach applies very well in Campania. The same reason encourages the use of advanced methods based on the analysis of infiltration and of its consequences on the stability of slopes. As a matter of fact, the use of simplified numerical codes supported by GIS is becoming usual: for instance, the SHALSTAB (Montgomery and Dietrich, 1994) and the TRIGRS codes, (Baum et al., 2002), which integrate data on rainfall with analysis of consequent infiltration and slope stability, are well known. In spite of their still strong limitations, as the use of 1D analysis for both infiltration and stability and the assumption of full soil saturation, these methods represent a major strategy to employ for prediction of rainfall-induced landslides in vast areas for which, only today, weather forecasting can be carried out with some degree of reliability.

C.I.R.A. (the Italian Centre for Aero-Spatial Research) and A.M.R.A. s.c.a.r.l. (Analysis and Monitoring of Environmental Risks) are jointly developing a research program which follows precisely this strategy (Schiano et al., 2007). The goal of such a project is to develop advanced integrated models for weather forecasting at a relatively detailed scale, and analysis of the consequent slope response. In order to check the reliability of such models, an experimental program will be carried out on small and medium scale physical models (flume tests) reproducing simple representative geomorphological situations in the context of Italian Apennines, and back analyses will be performed of the behaviour of sample slopes subjected to previous landslides.

However, a major problem is the still poor quality of weather forecasting at the scale of single slopes. This does not allow a confident use of early warning procedures based on the analysis of slope behaviour, due to the high probability of false or missing alarms As a consequence, the analysis should bear on real-time monitoring of local rainfall and of other fundamental indicators, as pore pressure. Since accurate analysis is a very hard problem because of the difficulty in fixing reliable initial conditions, especially for unsaturated soil (suction), the main advantage of such an approach is that monitoring can provide local values of suction or of water content profiles (which can be related to suction profiles) through TDR probes. Therefore, any numerical simulation can start from a correct initialisation of the governing factors. In addition, the continuous check of these factors can lead to a real-time calibration and adjustment of the model. Finally, as with FLaIR, prediction can be carried out starting from the present (well known) situation, using a stochastic forecasting of incoming rainfall as an input.

Just to summarise such considerations, an advanced early warning procedure concerning instrumented slopes covered by unsaturated pyroclastic soils should require the following steps:

1. weather forecasting;
2. start of analysis, if it is the case;
3. calibration and adjustment of the analysis;
4. iteration of analysis and prediction;
5. decision making.

Weather forecasting

Naturally, the basic situation corresponds to "normal" weather conditions, which are characterised by absence of rainfall or by "normal" rainfall. In this situation, periodical surveys on site and consequent updating of the geological and geotechnical data should be carried out. In addition, routine checking of all instruments and of the systems to be used for data transmission should be demanded: technical signals regarding malfunctioning of instruments activate maintenance and repairing operations.

An "advisory" signal should be launched when weather forecasting anticipates the approaching of an abnormal rainstorm. Such a signal activates a technical office in charge of all activities concerning analysis and interpretation of data from monitoring.

Start of analysis
As the advisory signal has been received, local administration is warned about what is happening and can prepare all actions to be activated in case of further warning signals. In particular, purposely appointed people should carry out surveys in the critical sites to collect any additional information to evaluate what is happening and could still happen. A prominent action to be carried out is strengthening of the monitoring in the instrumented sites and analysis of the likely effects of approaching rainfall (which can be roughly estimated through weather forecasting) accounting for monitored values of suction.

Calibration and adjustment of analysis
Data coming from monitoring allow a continuous and timely check of the analysis by comparison of calculated and monitored values of suction during rainfall. In particular, the data provided by site monitoring of rainfall and suction, can be used to update the initial and boundary conditions as well as other parameters which govern the slope behaviour: hence, the variation of the safety factor of the slope can be continuously updated. As a consequence, a framework about what can happen in next hours, i.e. of the presumed scenario of event, can be drawn.

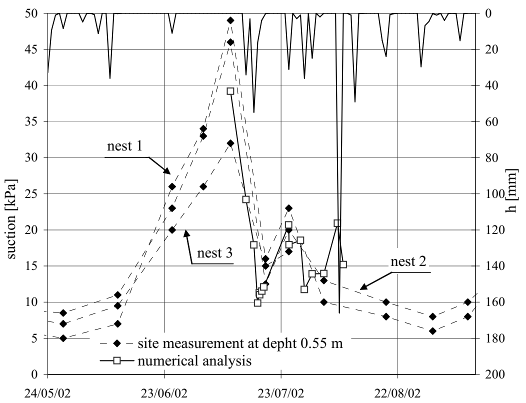

Figure 12. Comparison between measured and calculated values of suction at a depth of 55 cm for the slope in Figure 5 (Olivares et al., 2003)

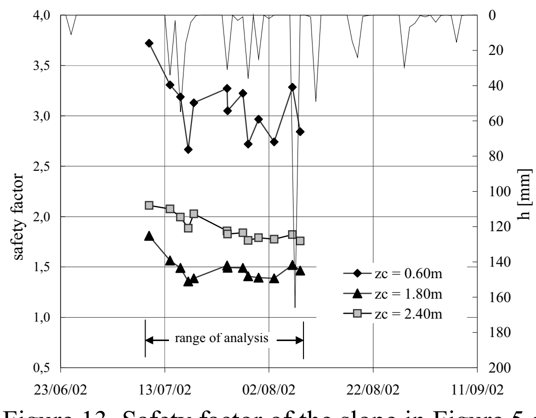

Figure 13. Safety factor of the slope in Figure 5 as a function of precipitations (from Olivares et al., 2003).

As an example, Figure 12 shows the analysis of suction changes performed with the ABAQUS code and using a well known equation to predict the evaporative flux (Wilson, 1990) for the case reported in Figure 3. Accounting for the friction angle of soil (38°) and for slope morphology (which is very close to the one of infinite slope), failure should occur when suction approaches zero. Accordingly, the figure suggests that the slope has been several times not far from collapse: the changes in the safety factor caused by alternating wet and dry phases are reported in Figure 13.

Iteration of analysis and prediction

Adjustment of the analysis allows to improve the quality of the results and more and more rely on prediction. In this phase, prediction of what can happen in the next x minutes can be carried out through numerical modelling of infiltration and slope stability analysis in the assumption that rainfall will continue with the same intensity or through stochastic forecasting of continuing rainfall. The process must be iterated until possible attainment of one of the established levels of warning or cessation of the state of danger.

Decision making

The decision depends on the values of the thresholds which have been established. The first step after the advisory signal is the "watch" signal. This should be launched when the time span before "warning" is long enough to perform all the operations required to assure safety; in particular, it should activate a series of actions, such as:

- transmission of data to the municipal office charged for spreading of information and activation of safety measures;
- information to population, which is invited to stay in touch with the authorities to receive further updates about the degree of risk;
- activation of self-protection measures as closure of basement areas, preservation of goods located in area susceptible to invasion of mud, securing of vehicles;
- interruption of activities with which the event could interfere, and securing of machineries;
- possible evacuation of pre-established buildings located in critical areas.

In this phase, indicators of failure as inclinometers, optical fibers or other instruments, and mostly, site survey, might be highly beneficial, supporting next decision.
When the "warning" signal is spread, pre-established actions must be activated, as:

- self-protection measures as switch off the electric power and secure the gas valve and immediate abandoning buildings located in areas exposed to mud invasion;
- prevention and rescue manoeuvres, mobilization of task force and voluntary organizations;
- security procedures established by the emergency plan (activation of waiting and shelter areas, meeting points…….).

As discussed above, in any phase of the process of landslide prediction the evolution of rainfall intensity and of suction (or pore pressure) must be closely monitored in order to check if prediction matches reality. In particular, any change of rainfall features or any disagreement between prediction and reality must be accounted for. For instance, if in the mean time rainfall intensity declines and suction evolves differently than predicted, a "normal" condition can be established once again. Therefore, the watch level is crucial because it can lead to warning or to return to an advisory stage depending on the evolution of the meteorological event.

CONCLUSIONS

Early warning is becoming a fundamental tool for mitigation of natural risks. However, it cannot be considered a panacea for any type of risk. In fact, it can be very well applied to situations characterized by a lead time which is long enough to activate procedures for risk mitigation. This is possible for intense meteorological events, tsunami and floods involving very large basins. The problem is much heavier for events having a very short lead time, as earthquakes or rapid landslides, which require special procedures to be adopted. In case of earthquakes, the only way which can been chosen, is to be satisfied to activate, before ground shaking, only some actions as the turning-off of electric power or of shutdown of gas lines or of aqueducts.

In case of landslides, early warning systems are still based on empirical methods relating rainfall intensity with landslide occurrence. Such an approach, which is presently adopted in Sarno and in other areas of the world, can be applied with some confidence only where uniform deposits outcrop and well documented data exist about historic events. In addition, it is subjected to false or even missing alarms. Today, the focus is on more refined procedures based on real-time analysis of slope behaviour, bearing on meteorological forecasting and real-time monitoring of rainfall. A major problem is, generally, the absence of reliable data about stratigraphy, soil properties and initial conditions on the vast areas which can experience slope failure. Today, this approach could be more effectively applied to selected instrumented slopes for which data on stratigrapy and soil properties are available. In these areas, monitoring can provide prominent data on initial conditions to be used and continuously updated within a real-time analysis of slope behaviour. Indicators of impending landslide occurrence to collect through cheap and extensive monitoring, as well as continuous site surveying, can be highly beneficial in the crucial phase of decision making.

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LANDSLIDE INVESTIGATIONS AND RISK MITIGATION. THE SARNO CASE

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Abstract: *In recent years, a number of catastrophic debris flows revealed the high risk in an extensive area of the Campania Region, Southern Italy. Following intense rainfall, on May 5th 1998, over 100 flow slides occurred on Pizzo d'Alvano mountain and hit the urban areas of Sarno and neighboring. The hills and mountains of this area are covered by air-fall pyroclastic soils deposited during volcanic eruptions occurred in the last tens of thousands years. In order to reduce the risk a lot of studies and investigations have been carried out and, then, big and meaningful structural measures have been achieved.*
Besides describing geo-morphological context and relevant aspects on dynamic of the events, this paper reports main geo-mechanical and hydraulic characteristics of the pyroclastic cover and the most meaningful protective structures realized in Sarno area.

INTRODUCTION.

On May 5th 1998 more than 100 slides were triggered on Pizzo d'Alvano mountain, due to heavy and prolonged rainfall. Many slides developed into debris flows hitting the urban areas of four small towns at the toe of the mountain: Sarno, Siano, Quindici and Bracigliano. 159 people died, the majority of them in the Episcopio, district of Sarno. Over 300 houses were destroyed or highly damaged, leaving more than 1000 people homeless.
It was one of the most serious events among those happened in Italy and it has deeply modified the way of planning risk mitigation measures and civil protection activities. Some laws, unapplied for many years, have received a new and meaningful impulse with extraordinary funding. Master plains for landslide and flood risk mitigation have been developed all over the Country, in order to identify the risk prone areas and the consequent measures for risk mitigation.
After the event the Governor of the Campania region was designated Commissioner to plan and manage structural and non structural measures in the area affected by debris flows. A technical office has been set up to carry out studies, in situ surveys and investigations, and then to design measures for achieving population safety.
In collaboration with many Italian Universities, different mathematical models were performed to support field observations and, also, to improve the knowledge of phenomena. A lot of protection works have been realized with a cost of over 285 million of euro (Versace et al. 2007), some of whom are still in progress due to their complexity or to difficulties in their financing.
This paper describes some outstanding aspects. Discussion will be specifically on: morphological and geological context, event dynamics, main geotechnical and hydraulic characteristics of the pyroclastic cover. Finally, the paper illustrates some of the most meaningful works realized in Sarno and its surroundings. Information about the non structural measures, adopted in this area, can be found in Picarelli et al (2007).

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The area in which the landslides took place has an extension of around 60 Km^2 and includes the Pizzo d'Alvano massif, a NW-SE oriented morphological structure, consisting of a sequence of limestone, dolomitic limestone and, subordinately, marly limestone dating from the Lower to Upper Cretaceous age and reaching a thickness of several hundred meters (figure 1). The geo-structural assessment of the massifs is determined by the primarily compressive poly-phase tectonic during Miocene and Pliocene, followed during the Pliopleistocene age by trans-tensive tectonics that induced normal faulting, creating horst and graben-like structures (Del Prete et al. 1998). Starting from upper Pliocene a marine to fluvio-lacustrine sedimentation took place in the whole area occupied, at present day, by the Gulf of Naples and by the Sarno plain. Due to intense Pleistocenic volcanic activities from Phlegraean Fields and Mount Somma, the alluvial deposits became intermingled with huge pyroclastic and volcanoclastic deposits, providing to fill the graben.

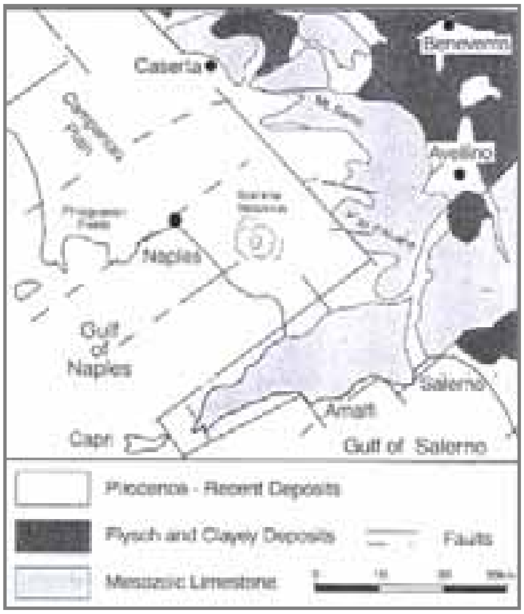

Figure 1. Geological map with the locations of some major faults (from Del Prete et al. 1998)

The Pizzo d'Alvano relief is a broadly quadrangular and NW-SE oriented morphological structure, characterized by gently sloping summit plains, endoreic basins and relatively smooth summit ridges. Strata gently dip (25°-30°) toward N-NW, outlining a monocline. Along the relatively steep outer perimeter slopes the drainage pattern is formed by deep gullies which also shape the alluvial fans in the downhill part (figure 2). Two joint systems, trending NE-SW and NW-SE, are the major regional structures. Elevation ranges from 30 m a.s.l. to 1133 m a.s.l. The average slope angle is 34° whereas subvertical limestone cliffs, called "pestelle" in the local dialect, interrupt their morphological continuity (figure 3). In particular, the slopes are generally higher than 30°, with maximum values around 50°, not including the "pestelle" zone. The slope of the piedmont areas is, generally, less than 20°. The bedrock is affected by karstic processes which influence both the geomorphologic settings and the deep groundwater flow (Celico and Guadagno 1998). The Pizzo d'Alvano slopes are mantled by very loose pyroclastic soils, produced from the explosive phases of the Somma-Vesuvius volcanic activity, both as primary air-fall deposits and re-worked deposits (volcanoclastic deposits). Air-fail deposits were dispersed from N-NE to S-SE, according to prevailing wind direction and covered a wide area reaching distances up to 50 km. Pumiceous and ashy deposits belonging to at least 5 different eruptions were recognized. From the oldest to the youngest, they are: *Ottaviano Pumice* (8000 years b.p.), *Avellino Pumice* (3800 years b.p.), *79 A.D. Pumice*, *472 A.D. Pumice*, *1631 A.D. Pumice*.

Figure 2. Overview of Pizzo d'Alvano massif.

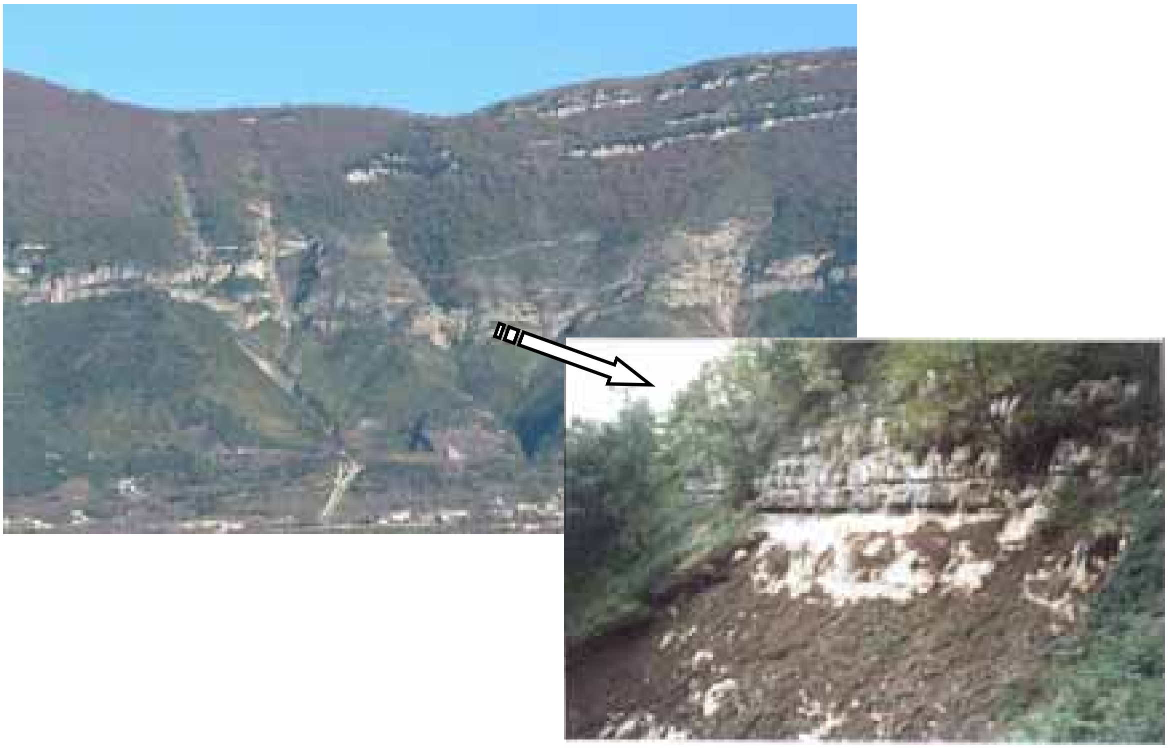

Figure 3. The presence of rocky cliffs interrupting the morphological continuity of the slopes.

The deposits are affected by pedogenetic processes determining paleosoil horizons during rest phases of the volcanic activity, then the primary deposits consist of alternating layers of ash and pumice, with interbedded paleosoils (figure 4).
Secondary deposits, re-worked by sheet wash waters and by mass-wasting processes, are mainly found as debris and colluvium at the toe of the valleys in the lower part of the belt, and also in the morphological concavities on the slopes and in the karstic depressions at the top of the limestone ridge, so forming the so-called "Zero Order Basins" (ZOB) (Guida 2003). The term "Zero Order Basins" was introduced by Tsukamoto (1973) to indicate unchannelled convergent slope located above ephemeral, intermittent or perennial first-order streams. Despite of their variability in size, shapes and morphostratigraphical characters, a few of ZOB-type landforms can be identified. (figure 5).

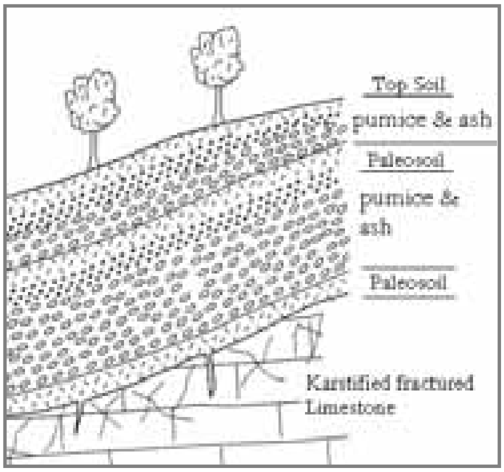

Figure 4. Schematic profile of the pyroclastic deposits in the Pizzo d'Alvano area. (modified from Del Prete et al. 1998)

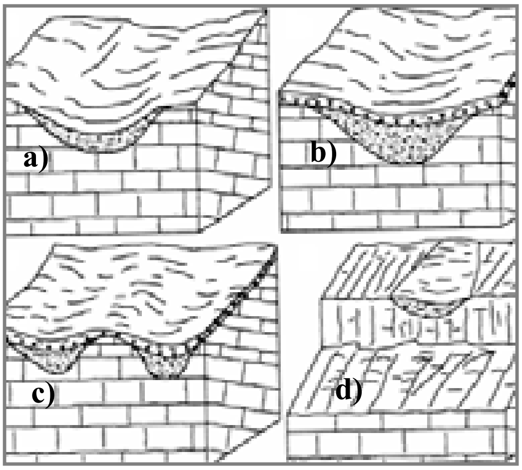

Figure 5. ZOB-type landforms in Pizzo d'Alvano: a) Simple zob; b) Buried simple zob; c) Buried multiple zob; d) Hanging zob. (from Guida 2003)

The total thickness of the pyroclastic covers in these areas ranges between few decimetres to 10 metres, near to the uppermost flat areas. The general structure of the soil progressively adapts itself to the morphology of the calcareous substratum showing, therefore, complex and variable geometries.
Field surveys and in situ investigations showed that the total thickness of the pyroclastic cover increases to the foot of slopes (several meters), in agreement with observations in similar geomorphologic settings. Wide coalescing alluvial fans form the transition from alluvial plains to calcareous slopes. The considerable area and volumetric extent of the alluvial fans, as well as the sedimentologic evidence suggests that, besides a consistent primary volcanic sedimentation, a great sediment supply from upslope took place, both as post-eruption remobilization of unstable air-fall volcanoclastic deposits and as debris flow activity.
Karstic springs are located at the foot of the slopes. Water supplies to the deep karstic aquifer is modulated by the overlying pyroclastic aquifer. At higher elevation, the bedrock is shaped by the joint superficial system, which allows the ground water circulation and the forming of local weak springs. Deep gullies, along the Pizzo d'Alvano slopes, are scoured by ephemeral creeks that are active during intense rainfall and rill erosion is evident along the slopes. The upper flat areas and the toe of the slopes have been terraced for prevalent hazelnut cultivation. In relation to this activity an extended road network has been realized. From analysis of aerial

photos a great increase in road density can be recognised in the last 30 years. A detailed analysis of geomorphological elements led to the definition of a geomorphological model referred to the Sarno slopes. With reference to the southern side of the Pizzo d'Alvano relief, the geomorphological system has (figure 6):

- ✓ summit tablelands;
- ✓ basin areas, divided by the morphological frame (pestelle) into one upper zone, where the paleo-drainage network of the limestone slopes are mainly filled with air-fall deposits or with debris colluvial material coming from upstream slopes (ZOB) and one lower zone, or lower catchment drain, where owing to the steeper slope angle, erosional and transportational processes take place on barren slopes, and shaped them by gullies;
- ✓ area with the ancient and recent alluvial fans.

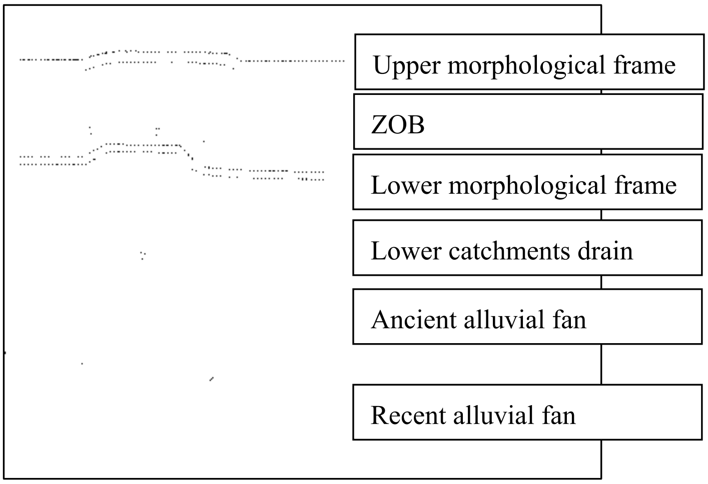

Figure 6. Geomorphological model of "Sarno-type" slope.

SOME CONSIDERATIONS ABOUT THE MAY 1998 DEBRIS FLOWS

Landslides that occurred in the 1998 event are classified as very rapid to extremely rapid soil slip/debris flows. The debris flows attained volumes up to 180,000 m^3, due to the contribution of landslides occurring in the same gully, more or less contemporaneously. The mechanism of these phenomena might be led to the same scheme whose essential characters are described below.

The debris flows occurred in most of the basins of the mountain, with the triggering zones located primarily in the uppermost parts of the slopes, in the ZOB areas, or near to the morphological frame, and also above and below trackways (Del Prete et al. 1998).

The size of landslides increased along their path down slope, digging and moving the debris which fill the gullies. The debris flows reached the broadly urbanized piedmont areas, releasing their huge destructive power, with high velocity (more than 10 m/sec). Figure 7 reports a scheme of most of the debris flows, based on eyewitness and accurate site surveying.

Every debris flow, in the general outlined behaviour, had a typical evolution. Along the gentle slopes, with limited coverage of sediments, the shallow phenomena develop, and become wide, sliding toward the valley (figures 8, 9).

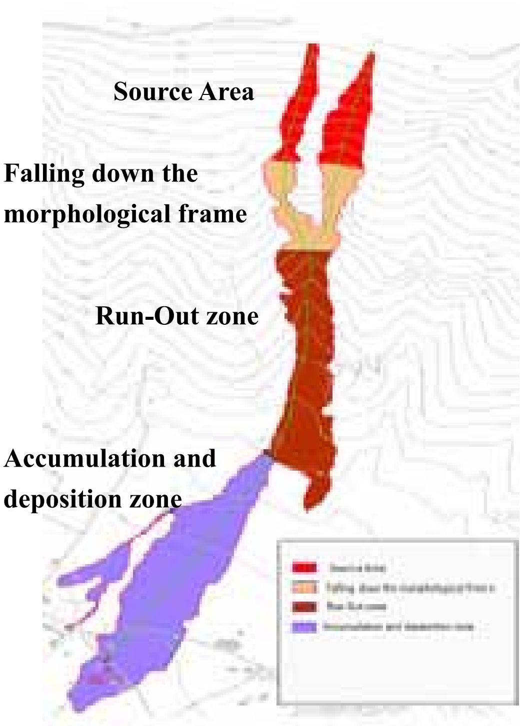

Figure 7. Sketch indicating the prevalent phenomena in the different morphological zones

On the contrary, in strongly shaped slopes, with remarkable thickness of sediments, the debris flows tend to make deeper and canalize. This has been the largely prevailing typology on Pizzo d'Alvano massif (figure 10). Some phenomena, especially the largest ones, had a complex evolution because they spread in different and successive stages, in some cases owing to the formation and the subsequent collapse of ephemeral obstructions.

Concerning the dynamics of the ruptures, an univocal and shared opinion does not exit. The role of the rains, either fallen immediately prior to the event, or accumulated during previous wet season, is beyond dispute (Versace et al., 2003; Capparelli, 2005) What appears more debatable is the identification of the phenomena that, activated by the rains, led to the development of the debris flows.

Slope failure was a result of shear rupture, provoked by decreaing shear strength of soil, as a consequence of variations in water pressure distribution. This variation could have been caused by two different mechanisms:

- ✓ water content increase, as a consequence of infiltration, and following suction decrease;
- ✓ upward water flow from the underlying fractured limestone and saturation of the lowermost layer. For many days after the May, 1998, event, a continuous flow of water was observed, in some cases, from the uncovered limestone. Nevertheless, the occurrence of this last mechanism requires a unlikely water supply directly from the ground surface, through the complex network of joints within the rock mass.

The post-failure mechanism of the mobilized soil mass is liquefaction, which is a fundamental process responsible for the flow mechanism. Such a mechanism has been suggested for landslides involving wasted saturated coarse grained materials (Bishop 1973; Dawson et al. 1998; Blight et al. 2000), and natural slopes (Sassa 2000). It will be discussed in the next paragraph in the context of the properties of pyroclastic soils.

Hutchinson (1986) has proposed a new model, the so-called consolidation model, to analyse the post-failure kinematics and the run-out of debris flows. According to this model, the post-failure soil behaviour is governed by dissipation of excess pore pressure and following friction increase.

Figure 8. Bracigliano - May, 5th, 1998

Figure 9. Nocera - December 26th, 2000 **Figure 10. Sarno – May 5th, 1998**

The occurrence of liquefaction in loose saturated volcanic ash has been demonstrated by Olivares and Picarelli (2001, 2006). This phenomenon develops when induced deformation is so rapid to provoke a sudden increase of the pore pressures. Deformations like these spread a chain from the upper sector, starting from the failure zones, toward the areas below, because of the pressure induced downstream by the mobilized volumes. Deformations also increase owing to the dynamic effect of material that, falling from the morphological frames, or quickly crossing steep paths, stress underlying gullies. As will be focused in the next paragraph, it is possible to observe this phenomenon only in saturated soils, relatively thin, permeable, loose and cohesionless. Moreover, the velocity of evolution of the phenomenon must be so fast as to preserve the undrained conditions, avoiding the dissipation of the induced pore pressure. When these conditions are not present, the failure does not evolve into debris flow. This incomplete evolution characterized a lot of movements in May 1998.

PROPERTIES OF AIR-FALL PYROCLASTIC ASHES OUTCROPPING TO THE NORTH OF NAPLES

Recent catastrophic debris flows in pyroclastic soils have stimulated a number of investigations focused on the interpretation of these phenomena. Some of these investigations concern the hydraulic and mechanical properties of the soils which extensively outcrop in the Campania Region. According to experience and to both geomorphological and geotechnical data, the major risk of debris flow is concentrated in a wide zone located to the North and to the East of Naples, which is mantled by air-fall products of the Somma-Vesuvius volcanic centre. As already mentioned, the pyroclastic products cropping out in the area subjected to major debris flows consist of unsaturated alternating layers of ash and pumice. Because of the complete absence of interparticle bonding, they are completely cohesionless. Figure 11 reports grain size curves of some deposits involved in debris flows. Despite the extension of the concerned area, these materials are highly uniform: volcanic ash displays a high sandy component and a significant amount of non-plastic silt, as well as some gravel due to the presence of isolate pumiceous grains. The figure includes, also, data concerning two different outcrops (Episcopio and Lavorate) in the area of Sarno, which presents a content of non-plastic fines equal to about 20%, while the percentage of pumices ranges between 10 and 20%. A higher percentage in fines can be argued from data reported by Cascini et al. (2003) concerning the same site. A high porosity, typically ranging between about 65% and 75%, is another peculiar property of these deposits. In particular, in the two sites of Episcopio and Lavorate, in Sarno, it assumes an average value of 69% (ranging between 65 and 72%).

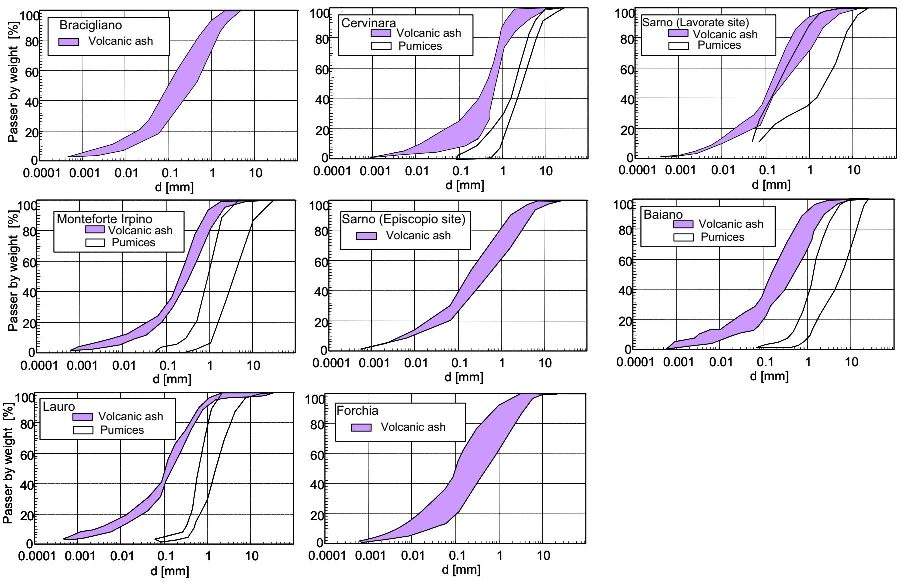

Figure 11. Grain size distribution of samples taken from different sites

Such a high porosity, which depends on the mode of formation, reveals the presence of macropores. In addition, through photographs with SEM, (Lampitiello 2004) recognized sandy particles bridged to each other through chains of silt, what is considered an indicator of metastable behaviour, i.e. of proneness to volumetric collapse under shear. This characteristic, the grain size and the absence of plasticity can explain the susceptibility of soil to liquefaction. These materials typically cover steep slopes. Because of the steepness of the slopes and of a relatively high hydraulic conductivity, generally they are not saturated. This can justify the slope angle being much higher than the friction angle.
As a matter of fact, systematic field measurements carried out by fixed or portable tensiometers show that suction generally fluctuates between values close to zero, in the wet season, and several tens of *KPa* in the dry one. Figure 12 reports the values of suction measured on slopes around Sarno, in particularly close to the Tuostolo basin (figure 13). Daily average of suction measurements were plotted against time, for the period May-June 2006 and November-December 2006, together with the daily rainfall recorded in the same period, at 0.35 m deep from the ground surface.

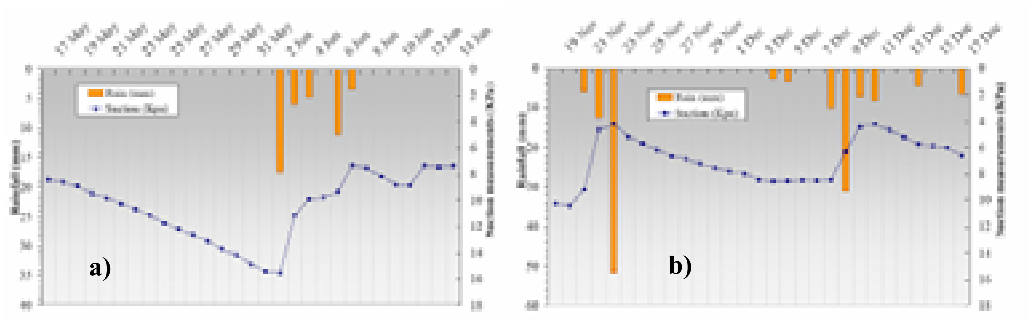

Figure 12. Daily rainfall and daily average of suction measurements at 0.35 m depth, during dry season, May/June 2006 (a) and wet season, November/ December 2006 (b)

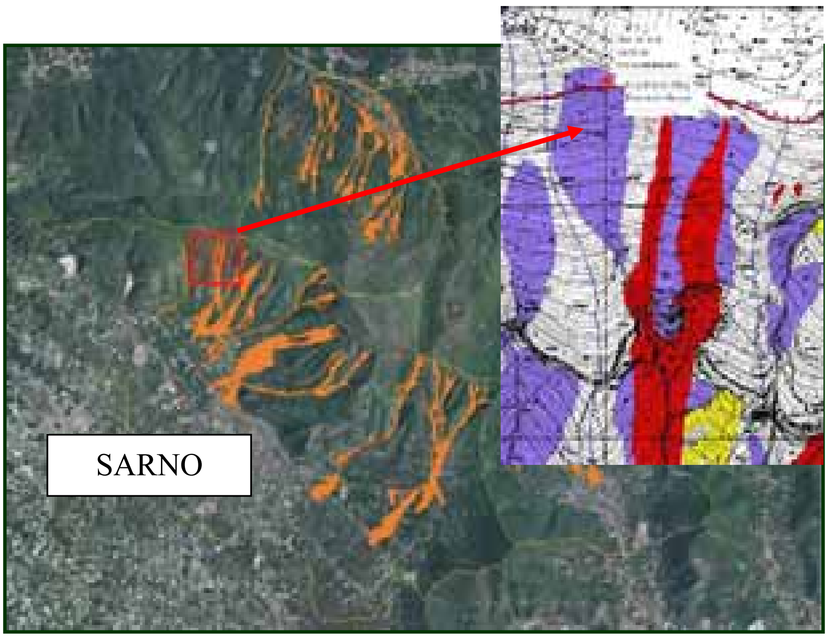

Figure 13. Site of soil suction and water content measurements

Because of the absence of true cohesion, sampling is never easy. However, it can be successfully performed, at least on ash, just thanks to suction, especially if it is carried out in pits by hand or by the help of a hydraulic jack. In contrast, the difficulty of sampling cannot be overcome for pumices for which reliable data about hydraulic and mechanical properties are not available. The hydraulic and mechanical properties of samples taken from several sites in the area mentioned above or in other sites covered by volcanic ash have been investigated by different researchers (Evangelista et al. 2002; Olivares and Picarelli 2003; Lampitiello 2004). A comprehensive review is reported by Picarelli et al. (2006).

Because of the low degree of saturation, testing must be carried out through non-conventional suction controlled procedures. In particular, the coefficient of permeability of unsaturated specimens can be obtained by the interpretation of the transient phase of suction equalisation relative to oedometer or triaxial tests on unsaturated specimens. It rapidly decreases as the saturation degree decreases reaching values as low as 1.0E-10 m/sec for values of suction around 100 kPa.

The saturated permeability can be obtained by constant head tests in the oedometer or in the triaxial apparatus; it falls within the range of values comprised between 1.0E-06 and 1.0E-07 m/sec.

These are the values of the coefficient of permeability which also characterise the Sarno ash.

As discussed above, pyroclastic soils can present an apparent cohesion depending on suction. Measurement of this cohesion must be obtained by suction controlled triaxial tests.

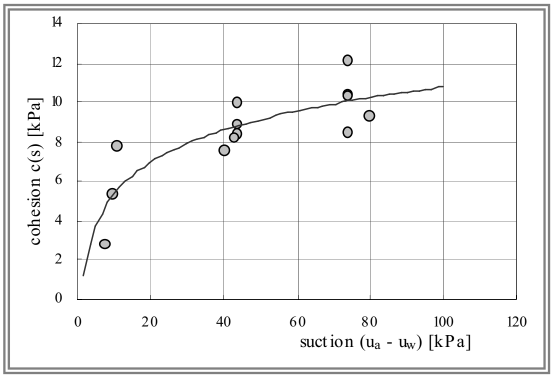

Figure 14. Cohesive intercept of natural Cervinara ash as a function of suction (Olivares 2001)

An accurate procedure to do that has been described by Picarelli et al. (2006) who report data obtained on the Cervinara ash. The most relevant aspect of this experience is the strong non-linearity of the relationship between suction and cohesion (Figure 14). The latter is a few kPa for values of the suction up to $10kPa$ and reaches values as high as $12kPa$ for suction around $70kPa$. These numbers can explain the stability of thin covers of ash mantling steep slopes.

Data regarding the shear strength of saturated specimens are also important to investigate on soil behaviour after prolonged rainfall. It is worth mentioning that saturation of such loose soils provokes a volumetric collapse and consequent change in the void ratio. This occurs also in the laboratory during saturation of natural soil specimens in the triaxial cell and leads to error in the interpretation of the tests. In order to minimize these effects, Olivares and Picarelli (2001) proposed an original technique based on the use of carbon dioxide in the saturation phase. Typically, the soil exhibits a ductile and contractive behaviour under shear in drained conditions, while its behaviour is brittle when subjected to undrained shear, reflecting a continuous increase in pore pressure (Olivares and Picarelli 2001): in other terms, loose volcanic ash is liquefiable and this can explain the generation of flow-like movement as a consequence of slope failure (Sladen et al. 1985) or transition from slide to debris flow.

It is well-known that this behaviour depends on a number of factors such as grain size, plasticity, density, initial and induced state of stress. Lampitiello (2004) investigated the role

of these factors through an extensive laboratory programme carried out on the Cervinara ash. Figure 15 reports the results of a number of undrained triaxial tests after isotropic consolidation (CIUC tests) performed on reconstituted specimens prepared at different void ratios and subjected to a confining stress comprised between $25 kPa$ and $159 kPa$.
As discussed above, the soil behaviour strongly depends on initial conditions, being contractive or dilative as a function of the initial void ratio and confining stress.

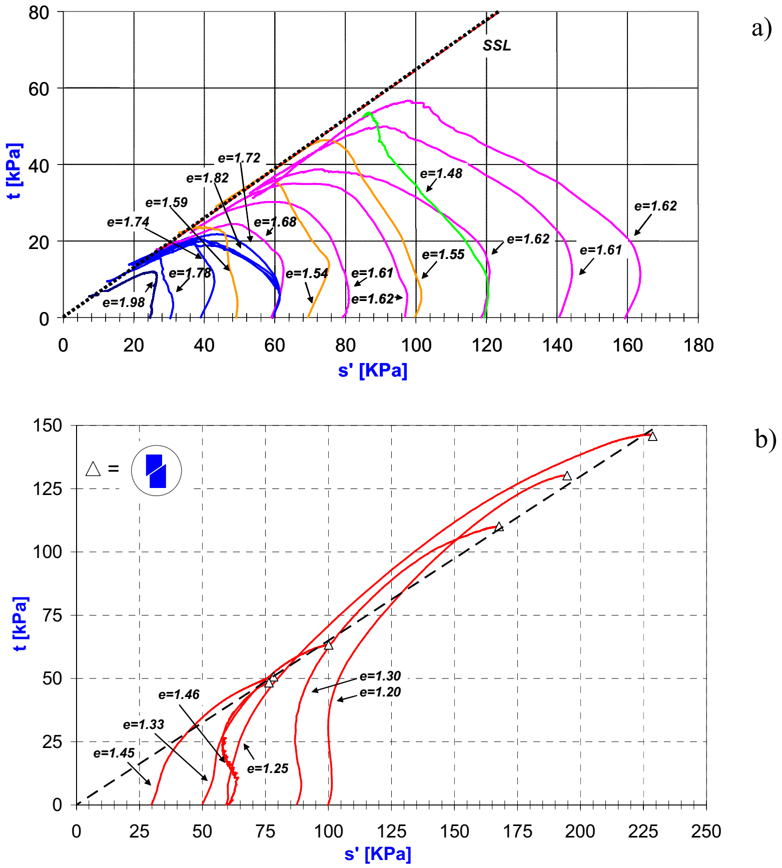

Figure 15. Results of undrained compression triaxial tests on reconstituted specimens of the Cervinara ash (from Lampitiello 2004): a) loose specimens; b) dense specimens

However, the Steady State Line is unique, regardless of the initial state and type of test, while the mobilised strength strongly depends on the pore pressure which develops in the shear stage. This is clearly shown in the compression plane of Figure 16. This diagram allows distinction between specimens which are susceptible to liquefaction (with an initial void ratio above the Steady-State Line, SSL), and specimens which are not susceptible to liquefaction (below the SSL). Naturally, these data are very useful to select deposits which can give rise to debris flows as a consequence of slope failure (Olivares & Picarelli 2001). Figure 15 also suggests that the peak strength can be enveloped within a line, the Instability Line (Lade and Pradel 1990), which can be located below the Steady State Line. Figure 17 reports the stress paths of specimens subjected to both CIUC and CAUC tests (undrained triaxial tests after anisotropic consolidation), whose void ratio at the end of the consolidation phase was comprised between 1.6 and 1.7 .

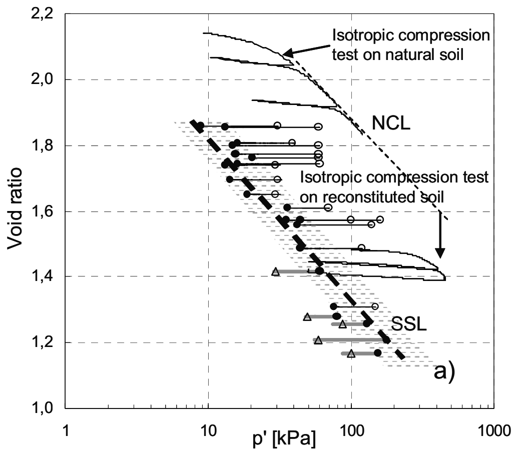

Figure 16. Results of undrained triaxial compression tests on reconstituted specimens of Cervinara ash, reported in the compression plane (from Olivares et al. 2003)

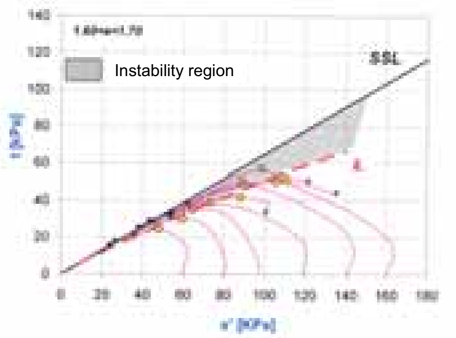

Figure 17. Stress paths of undrained triaxial tests on reconstituted specimens of the Cervinara ash (from Lampitiello 2004)

The test results are quite consistent and allow the identification of an Instability Line which envelopes peaks located below the SSL. This suggests that a failure process which is entirely undrained can mobilise a shear strength less than the one available if rupture were entirely drained. In addition, a rupture process starting from a high initial deviator stress (CAUC tests), as typically occurs in the case of steep slopes, can favour a sudden and unexpected collapse even under a very small increase of the shear stress. However, the experimental programme showed that the Instability Line is not unique depending on the void ratio of soil at the end of the consolidation stage: the instability domain is wider the higher the void ratio. Testing on natural samples of Cervinara ash which present a void ratio well above the SSL, fully confirm these results. Similar results were obtained on Sarno ash. Figure 18 reports the results of drained and undrained triaxial tests on natural samples taken from the Episcopio and Lavorate outcrops. The Steady-State friction angle varies between 33° and 39°, a typical range of values for air-fall volcanic ash. In spite of the ductile behaviour under drained conditions, the undrained behaviour is highly brittle, suggesting that liquefaction can really be the fundamental mechanism of debris flow generation.

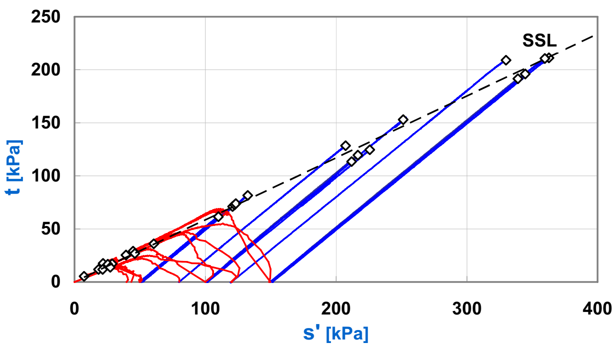

Figure 18. Results of drained and undrained CID and CIUC tests on natural samples of Sarno volcanic ash

PROTECTION WORKS FOR RISK MITIGATION IN THE SARNO AREA.

Structural measures for risk mitigation in the Sarno area follow a complex and articulated strategy, which intends:

- to reduce proneness to failure in source areas;
- to restrain bed and slope erosion along gullies and then to control the increase of debris flow volume along its path;
- to control rainfall water runoff toward the major rivers, i.e. the Sarno River or Regi Lagni channel, whose beds are not adequate to contain floods even with a low return period;
- to create storage area for debris flows;
- to canalize debris flows to this area.

To attain these objectives the following works have been carried out:

- slope erosion reduction works based on bioengineering techniques;
- check dams in the upper part of the gullies, for bed erosion control and slope stabilization;
- channel for collecting rainfall water;
- retarding reservoir for flood routing;
- control structures, like sediment basins, diversion structures, transverse walls, that bound the debris flow prone area and protect the inhabited ones.

Different kinds of work have been combined in order to obtain an articulated risk mitigation systems. In the Sarno area debris flow control has been obtained with slope stabilization, check dams, and three large deposition basins (Episcopio, Curti, Mare), located in the piedmont area above the town. In each basin more than one gully flows. The rainfall water drainage has been allowed by the channel network which cross the deposition basin and reach retarding reservoirs, located below the town, which reduce the peak flow toward the Sarno River. The Episcopio system will be described later on in this paper.

To identify the most correct strategy, some basic criteria have been adopted. The first one concerns the option, perhaps only theoretical, between active works, like bioengineering slope medications, and passive works, like check dams, channels, basins, etc. It is not a real question, because it is impossible to entrust people's safety only to bioengineering techniques, in cases like Sarno. Flowslides and debris flows can be triggered in all the areas characterized by slope angle higher than 30° and significant pyroclastic cover. This phenomenon is mainly possible in areas where ZOBs or buried channels or undrained trackways which concentrate water in impluvium, are present. Identification of all the areas with similar characteristics, often located on not easily accessible hill slopes, is difficult. Moreover, collapse may occur also in areas where these risk factors are not so evident or are even apparently lacking. Other aspects have also to be considered: the very high cost of such works extended over all the hill slope; technical difficulties in reaching the impervious area, where the marking out of new paths could generate further landslides and change the small-scale drainage network of rainfall water; very high vulnerability of wooden works in fire risk prone areas.

On the other hand, bioengineering works are beautiful (figure 19), they can be pleasantly inserted into the natural environment, and can be very effective if they are properly designed and located. Therefore the right choice is the integration of both types of works. The active ones reduce the probability of failure in the upper part of the hill slope, where the risk of collapse seems higher. The passive ones mitigate and drastically reduce damage induced by debris flow that could be activated despite the presence of active works.

The location of the debris flow mitigation structures is another important issue. The chaotic development of many urban areas, in Sarno and in other towns, has produced the loss of natural courses which debris flows followed in the past.

Figure 19. Example of bioengineering works along Pizzo d'Alvano side

The random growth of the town toward the mountain and the upsetting of both the natural drainage network and existing hydraulic works, produce a tangle of natural and manmade systems. Sedimentation basins built in the past above the town are now included in it and are used for different purposes: such as a football ground. Many channels disappear in long culvert with unknown pattern and unable to guarantee hydraulic linkage. In such cases the main target is to separate natural and manmade functions, to free water and debris flow courses and to minimize meddling with built-up areas. This goal may be achieved also by existing houses delocalization, natural drainage network restoration, and a green belt boundary. In practice this latter is unlikely, as it requires a long time, large investment, and social conflict. When risk is pending, mitigation works are needed immediately. The better choice is to disconnect and separate the upstream natural system and the downstream artificial system, i.e. the built-up areas. So risk mitigation is quickly achieved and future land restoration is still possible and even easier.
Different works have been carried out, in Sarno, to disconnect the downstream and upstream areas. In many cases large basins with deposition areas have been adopted, which allow the debris flow to spread and to slow down owing to sudden gradient decrease, breakers, discharge control orifices at basin outlet. The basin volume is equal to the predicted one, as the routing effect is disregarded because outlet orifices occlusion is always possible during debris flow. This hypothesis, otherwise, leads to an increase of the safety factor.
However, the routing effect is considered for downstream channel design, when runoff is only produced by rainfall and no debris flow is expected to occur.
More than one gully often ends into one single basin, which can collect debris flow from all of them but also from the inter-gullies areas, so greatly increasing the safety of the downstream area. This *single basin system* allows the total volume for debris flow storage to be reduced by a proper reduction factor, as a simultaneous flow from all the confluent gullies has a very low probability of occurrence. A single basin system of Episcopio, in Sarno, is described in figure 20. The system includes slope stabilization in mountain zone along main tracks; a large basin with capacity of more than 170,000 cubic meters; two deep channels, with walls or levees on

the outer side, which bound the debris flow prone areas. The basin was realized by digging, so its visual impact is very low. Lateral channels present a top protection to prevent avulsion in the bend.
Episcopio is the most stricken district of Sarno with 90 victims and more than 120 houses destroyed or damaged. Downstream of the basin system many houses have been reconstructed with some extra precautions, that is with special technical rules. The ground floor cannot be used for residence. The structural frame is adequately reinforced. Each family was free to choose between rebuilding its own house in the same place or buying a new one in another part of Sarno or also in another town. In both cases the Italian Government bore the cost.

Figure 20. Single basin system, in Episcopio

In some cases slope morphology does not allow a single basin system, so one sediment basin for each gully is needed, and more basins are present at slope bottom (*multiple basin system*). If both systems are possible the single one seems better, as it can contain inter-gullies debris flow and is safer in the case of debris flow produced only from a single gully. Figures 21 and 22 show a multiple system in Quindici and details of one of the basins (Connola basin). These have to be filled only when debris flow occurs, i.e. once in many years. During normal periods, the clear water must be diverted and cannot reach the basin, because sediments could reduce the available capacity. So clear water must follow a different course to reach the downstream drainage system. The debris, on the contrary, has to come into the basin and only a very small part of it can flow downstream. Then an appropriate diversion structure has to be designed, taking into account the fast flow regime. Usually this kind of basin is blind, i.e. there is no outlet, then its capacity needs to be large enough to contain all the design volume. Of course when the basin is filled by mud, it has to be cleaned rapidly. Figure 22 shows the diversion system of the Connola basin. An orthogonal channel receives clear water up to a discharge of about 30 m^3/s. For larger values, i.e. when the debris flow occurs, the flow passes over the channel and reaches the basin. The discharge in the orthogonal channel changes a little. This device may exhibit some problems owing to both high flow velocity and conspicuous sediment transport. So it seems better to allow diversion inside the basin than to do it upstream. This choice drastically reduces the risk of exceeding the designed downstream discharge. Moreover the diversion occurs in the basin with slow flow or in any case with low Froude numbers, so the risk of outflow is highly reduced. A low flow channel is built along the basin with proper outlet for clear water runoff.

Figure 21. Multiple basin system in Quindici

If the basin length or slope change between the upstream reach and the basin bed are not large enough, breakers have to be inserted into the basin, otherwise only riprap protection in the inlet area is achieved.
Separation between upstream area, where debris sources are located and downstream urbanized area, which must be protected, can be also performed by diversion structure, which deviate water and debris flow into a not vulnerable area (figure 23). The structure is formed by

(i) a large and deep channel, with high slope, not less than 6-7%, so no debris deposition may occur inside, and (ii) a wall in the downstream side so avulsion may be avoided.

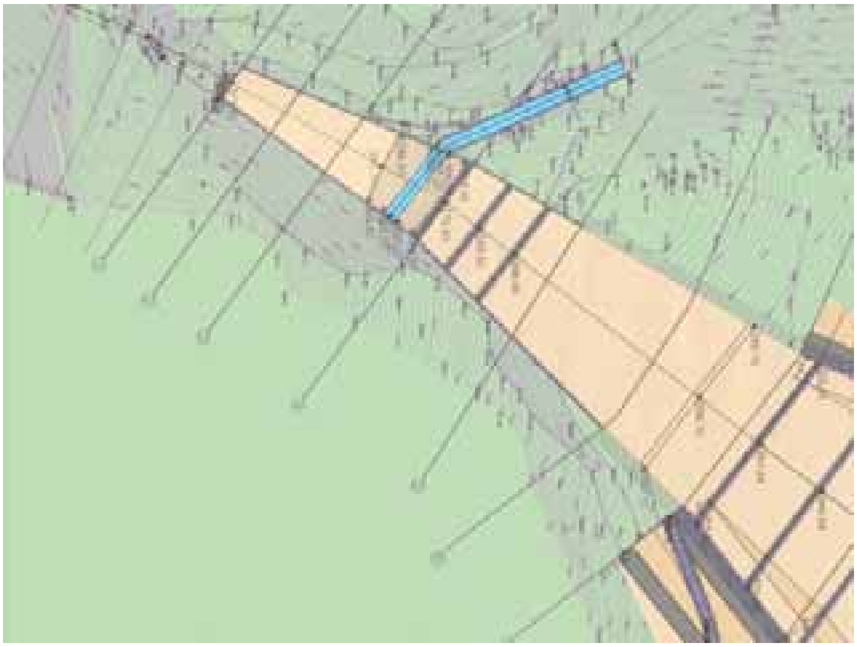

Figure 22. Detail of the Connola basin

In some cases an embankment effect is obtained by increasing the downstream channel edge, which is built higher and stronger, and can be integrated within the channel or not.

Figure 23. Diversion structure in Siano area

In the Episcopio system there are both basin and diversion structure. In this case the latter deviates the flows into the basin area.
One of the most important works is the first upstream check dam, which is the one that withstands the highest stress. It closes the whole system upward, breaks and slows down debris flows, stabilizes both the bed and banks, traps and stores sediment transport. Moreover, it directs flows towards the canalized reach. Open check dams, like that in figure 24 can also select transported sediment, trapping the largest one. When the opening is very high, these dams can work for a long time, as occlusion gradually increases upwards. Periodic cleaning of course is needed.
The breaking and slowing down effect are only transient owing to the very steep gradient which allows velocity and sediment loading capacity to increase over a short distance. Then other check dams downstream of the first one are needed. Figure 25 shows a series of check dams in the Cantariello gully in Sarno.

Figure 24. Upstream open check dam in the Cantariello gully in Sarno

Figure 25. Check dams in the Cantariello gully in Sarno

CONCLUSIONS

The tragedy that happened in Sarno caught our defence systems unprepared, incapable of assuring acceptable safety conditions. The event shook people's consciences and gave new impulse to the management of soil defence and civil protection systems. A lot of resources were allocated to these sectors and the situation has certainly improved, but there is still much work to do. Since Sarno and its neighbourhood was hit hard by the debris flows, to better support the operative management of the emergency, numerous investigations and studies were set up that allowed, also, to deepen the knowledge of these phenomena and perform useful simulation models. Huge funding has been devoted to building of the structural systems that have been, mostly, successfully completed, even if with some mistakes.
Nevertheless, an acceptable defence strategy from the debris flows has been focused, which provides the correct integration of active and passive works.
As regards the containment structures, the *single basin system*, which can receive debris from more than one gully, greatly increases downstream area safety, as it can intercept material also from the inter-gully areas. When the slope morphology requires a multiple basin system, that is, one basin for each gully, the better choice is to allow diversion from the clear water and debris flow into the basin instead of building this diversion upstream.
However, even if it has not been discussed in this memory, the events of Sarno have also allowed a turning point in the management of civil protection. In fact, a control scheme has been carried out that assembles real time monitoring systems, forecasting models, and above all, the Territorial Survey composed of technical staff, engineers and geologists, who look after the territory during the emergency phases, when the models suggest the threshold values have been exceeded (Picarelli et al., 2007).
However, even though with some contradictions, Sarno delineates a meaningful model of protective measures in Italy and indicates useful guidelines for risk mitigation control works.

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