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THE 1998 SARNO LANDSLIDES: CONFLICTING INTERPRETATIONS OF A NATURAL EVENT

Francesco Maria GUADAGNO(*), Paola REVELLINO(*) & Gerardo GRELLE(*)

(*) University of Sannio - Department of Geological and Environmental Studies - via dei Mulini, 59/A – 82100 Benevento, Italy. Tel: +39 0824 323634

ABSTRACT

Landslides affecting on 5-6 May 1998 the towns of Sarno, Quindici, Siano and Bracigliano in Southern Italy represent a case history of great significance both from a scientific and technical point of view. The casualties, the huge economic damage and the severe destruction attracted great attention on the part of the scientific community. Following the landslides, both the national and international scientific community and technicians have given rise to numerous studies in order to provide suitable elements for designing remedial works. From the scientific side, till 2010 hundreds of articles and reports were produced concerning researches carried out on the Sarno-type landslides. In order to make comparisons not only on different methodologies adopted but even on contrasting interpretations and results concerning landslide triggering and propagation mechanisms in a global and comprehensive picture of the knowledge, more than 200 scientific papers on this type of instabilities, published on national and international journals and conference proceedings, were collected. Analyses on specific aspects of the landsliding frequently show huge disagreements among different authors and research groups. The discussion particularly focuses on landslide classification aspects, criteria adopted and their real application. Wide-ranging ambiguities cause uncertainties in applying landslide classification criteria.

Key words: *Sarno-type landslides, classification criteria, Southern Italy*

INTRODUCTION

The landslides affecting on 5-6 May 1998 the towns of Sarno, Quindici, Siano and Bracigliano (Southern Italy; Fig. 1) represent a case history of great significance both from scientific and technicalmanagerial point of view. The casualties (161), the huge economic damage and the severe destruction attracted great attention on the part of the scientific community.

This interest also arises from the awareness that the area of the Campania Region that can be considered subject to hazard is very large. About 2,000 km^2 of the region, a part of which is devoted to tourist activity, may be considered at risk owing to the widespread presence of human activities

As a consequence, problems connected with the assessment of the areas at risk are key aspects in land-

Fig. 1 - May 1998 landslides at Sarno

planning activities and in defining mitigation strategies.

Following the 1998 landslides, both the national and international scientific community and technicians have give rise to numerous studies and investigations in order to provide suitable elements for designing remedial works.

From the scientific side, till 2010 more than 200 articles were published on national and international journals and conference proceedings from different research groups, individual scholars or experts concerning the investigations carried out on the Sarno-type landslides in different areas of the Campania Region, where similar geological settings produced analogous instabilities. The instabilities were the topic of a large number of technical reports as well.

A so rich set of scientific papers and documents offers the opportunity to make comparisons not only on different methodologies adopted in the studies but even on contrasting results concerning landslide triggering and propagation mechanisms. In particular, the latter is crucial for landslide classification. It is also important for the definition of the residual risk in the areas of the Campania Region that have already experienced landslides, and it provides essential information for the prediction of future occurrences into areas which have not previously failed.

Therefore, this is an opportunity to develop a comparison between different interpretations developed by different research groups on a complex natural phenomenon, where the influences of different controls and triggering factors are overlapped

The paper aims to compare some aspects of the landsliding described by the authors in several papers (e.g. Del Prete *et alii*, 1998; Fiorillo *et alii*, 2001; Guadagno & Revellino, 2005) with those of other authors in order to find agreements and disagreementsin a global and comprehensive picture of the knowledge.

The discussion particularly focuses on landslide classification aspects, criteria adopted and their real application. Wide-ranging ambiguities cause uncertainties in applying landslide classification criteria

SOME ASPECTS OF LANDSLIDE CLASSIFICATION

The classification of a natural phenomenon is always full of difficulties when precisely quantifiable elements do not subsist. Problems connected to a hierarchical taxonomy are particularly extensive for landslides because of the large variety of discriminating factors (Hansen, 1984). Over the years, this fact led to favour type-kind classifications better suitable, in the case of landslides, for giving categorizations which are not only descriptive but also behavioural..

Therefore, few comments are here reported on sub-aerial landslide classification aspects and, in particular, on landslides of the flow type involving soils, where the mass and "the general appearance is more obviously that of a body that has behaved like a fluid" (Varnes, 1978). These instabilities should be considered as transition phenomena of the morphological evolution between the field of the mass movements and that of the mass transports (Pierson & Costa, 1987).

At the present time, the most widely accepted classification systems in the international academic world are those of Varnes (1978), subsequently modified by Cruden & Varnes (1996), and of Hutchinson (1988). The first two suggest the movement mechanism and the material type as basic discriminating factors, whereas landslides are included in categories with similar kinematic patterns in the last one (Hungr *et alii*, 2001).

In all cases, the morphology of landslide bodies and, therefore, of detachment areas is one of the main criteria in order to succeed in classifying slope instabilities and defining mechanisms of movement. Material types and properties are significant as well in identifying movement kinematic. Other features, such as e.g. the velocity of the landsliding mass, help in giving a better description of the assigned classification.

It stands to reason that the complexity of the predisposing triggering factors can induce uncertainties in defining the kinematic model of the landslide and, consequently, incorrect evaluations in the classification of phenomena.

As pointed out by Hungr *et alii* (2001), particularly clear difficulties are associated to the classification of landslides of the flow type, due to the significant effect of factors influencing the mass behaviour during motion. As an example, the water content affects the movement characteristics of more or less fluid masses; in some channelled flows, it may induce those transition conditions as described by Pierson & Costa (1987).

Within the above-mentioned articles, the authors mostly refer to the landslide classification of Varnes (1978). Leaving out creep and solifluction, which cannot be classed as landslides (Coates, 1977; Huchinson, 1988), sub-aerial flow-like slope movements of engineering soils in the VARNES (1978) classification are scheduled as follow, where landslide phenomena are discriminated for mechanism, involved material and velocity: i) Debris flow; ii) Debris avalanche; iii) Mud flow; iv) Earth flow; v) Rapid Earth flow (usually in sensitive materials); vi) Block streams; vii) Dry sand flow/dry silt flow; viii) Wet and silt flows; ix) Loess flow.

It is important to note that, VARNES (1978) highlight that "there is complete gradation from debris slides to debris flows" and "from debris slides to debris avalanches". This remark considerably follows the initiation model of debris flows proposed by JOHNSON & RAO (1970) and afterwards reutilized by Johnson and RODINE (1984). They define triggering mechanisms connected to the instability of soil blocks that can "rotate, jostle, dilate and incorporate water as they slide". In an overview, this definition has a lot of similarity whit the PIERSON & COSTA's rheological classification (1987) concerning the transition among the different types of flows. In VARNES's classification (1978), flow slides are reported as sub-aqueous flows of non-cohesive sand or silt characterised by retrogressive mechanism.

HUTCHINSON (1988) classifies flow landslides in loose material as "debris movements of flow-like form" distinguishing five main types: i) Mudslides (Earth Flows of VARNES, 1978); ii) Periglacial mudslides; iii) Flow slides (distinguished for material types); iv) Debris flows (distinguished for material types and environment of occurrence); v) Strurzstroms.

HUTCHINSON (1988) restores the term flow slide used by BISHOP *et alii* (1969) & BISHOP (1973) extending this to describe different phenomena. In the original definition, a flow slide is typically triggered by a temporary increase in pore pressure, with consequent decrease in strength. The initial failure is directly connected to the pore pressure increase in loose, coarse material. A sudden disturbance causes the failure that provokes the skeleton destruction, the decrease of porosity and the liquefaction of the material. Usually, the involved slopes are not so deep and debris consists of waste materials. As regards debris flows, Hutchison point out that an important mechanism in their generation is the development of porewater pressure by repeated undrained loading associated with their movements. Moreover, debris flows involving loose or weathered material and associated to high-intensity rainfall can develop from slides and eroded deposit if water and debris supply is sufficient and slope is steep enough to accelerate the whole mass.

CRUDEN & VARNES (1996) propose a series of limited modification of the 1978 Varnes's classification. The abbreviated classification of flows can be resumed as: i) Earth flows; ii) Debris flows; iii) Rock flows

HUNGR *et alii* (2001) investigate on the ambiguous aspects existing among the above-mentioned classification systems. After re-analysing the main features of the instabilities, they attain to the description of the kinematic mechanism of different flow classes. Landslide types, which are linked to specific pattern of deformation, are defined as: i) Dry (or non liquefied) Sand (Silt, Gravel, Debris) Flow; ii) Sand (Silt, Debris, Weak rock) Flow Slide; iii) Clay Flow Slide; iv) Peat Flow; v) Earth Flow; vi) Debris Flow; vii) Mud Flow; viii) Debris Flood; ix) Debris Avalanches; x) Rock Avalanches

It should be noted that debris flows, debris avalanches, earth flows and dry sand flows tend to slide during the initial failure, subsequently transforming in a flow-like movement. Differently, some other flows, such as flow slides, are triggered by initial internal collapse of the material structure responsible of full or partial liquefaction of the mass..

It results in different triggering mechanisms linked to welldefined causes. Sliding failures of a mass of material imply specific geometric and pore-pressure conditions of the material; kinematic freedom condition may be realized as well.

In addition to the ambiguities pointed out in the current international landslide classifications, further troubles are added, in Italy as well as in other countries, as a consequence of the local translation from the original terms and of the frequent employment of obsolete terminologies.

In Italy, the 1978 Varnes's classification was translated by CARRARA *et alii* (1978). In our opinion, at that time, the translation was not developed by using strictly physically-based criteria by which the Varnes's classification was inspired. The Flow class was translated as Colamento, for the general class, that literally means "streaming or straining", and as "Colata", which is only partly synonym of Flow, for landslides occurring in soil. The no use of the term Flow has added further substantial ambiguities to landslide descriptions. The term colata (or colamento) inspires the wrong idea of moisture or saturation of the system.

THE CLASSIFICATION OD THE SARNO-TYPE LANDLIDES

As said before, the catastrophic event of the 5-6 of May 1998 inspired a great number of scientific contributions to the understanding of this type of landslides.

Further disastrous occurrences followed those of 1998 in Campania (e.g. Cervinara in 1999, Nocera Inf. in 2005, Ischia island 2006). The similarity of both mass movement features and geomorphological environments in which they occur allows the landslides to be considered under a common denominator and the term Sarno-type landslides to be used.

A significant number of scientific papers (about 206) have been, thus, collected in order to compare both the different classification criteria used to describe the events and the triggering mechanisms proposed. Figure 2 shows the article type rate used for comparison and inserted in the database. Among them, articles published on international peer review journals and international conference proceedings account for more than 62%. Conversely, about the 36% are in Italian, published on national journal or proceeding; many of them report an English abstract useful to reconstruct the classification criteria used. Finally, a very little slice (about 1%) concerns books and book chapters. It should be noted that in the analysis were not reported the numerous technical reports supported by research institutions or public bodies, and the monographs.

As regard the landslide classification and taking into account the articles published on international journals and international proceeding only, Table 1 lists the main terms used to categorize the Sarno-type landslides, grouped according to the affinity of the material type, of the movement type and of the order of the cinematic mechanism. Figure 3, on the other hand, shows the percentage of the terminology used in the groups

As shown, the most used macro-classes fall into the following main landslide types: debris flows, debris avalanches, mud flows, earth flows and flowslides. The wide classification range highlights the difference in the choice of the classification criteria and, therefore, in the assignment of a certain landslide type among the authors and research groups (Tab. 2).

It should be noted that most authors refer to the well-know classification systems shown above. Consequently, the phenomenon is interpreted in significantly different ways.

Before the Sarno events, only a few articles had been published on international journal, but a wealth of literature in Italian exists. The analysis of this bibliography leads to a generalized classification (as colata), even though landslide initiation is well described as consisting in initial sliding followed by fluidification.

Group	Landslide Classification
1	Debris flows - Volcanoclastic debris flows
2	Mudflows - Quick mudflows - Mud flow - Muddy debris flow
3	Soil slip/debris flows - Soil slide/debris flows - Translational slide/debris flows - Debris slide/debris flows - Soil slides/debris- mud flows
4	Debris avalanche/debris flows - Debris slide/debris avalanche/debris flows - Debris avalanche/extremely rapid debris flows
5	Slide/extremely rapid debris earth-flows - Soil slide/debris-earth flows - Rapid earth flow - Unchannelled and channelled debris slide-rapid earth flows
6	Flowslides - Flowslide/Debris flows - Flowslides and mudslides

Tab. 1 - Groups of terms used in the landslide classification from international journals and proceedings

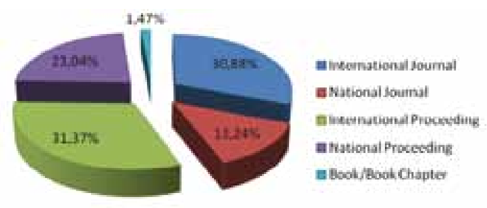

Fig. 2 - Type of bibliography collected on the Sarno-type landslides

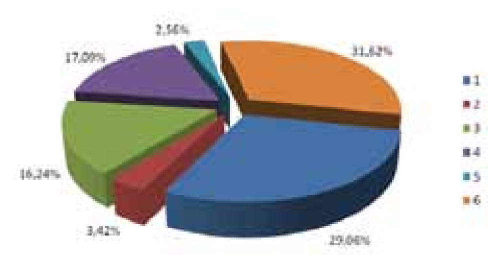

Fig. 3 - Classification rate of the Sarno Type-landslide. The legend correspond to the groups of terms in Table 1

COMPARISONS OF LANDLIDE FEATURES

INITIATION

Generally, landslide initiation is one of the main aspects in the differentiation of flow-like movements. Different flow types usually show dissimilar triggering mechanism.

As regards the Sarno-type landslides, the diverse classifications imply disagreement on the conceptual model of the instabilities and on the landslide processes among the different authors. By way of example, some descriptions of the landslide events are reported below extracted from articles on international journals (cf. Tab. 2).

Landslide Classification	International Journal Article
Debris flows Volcanoclastic debris flows	Del Prete et al., 1998; Pareschi et al., 2000; De Vita and Piscopo, 2002; Mazzarella and Diodato, 2002; Chiessi et al., 2003; D'Ambrosio et al., 2003a, 2003b; Iovine et al., 2003; Zanchetta et al., 2004; Iovine et al., 2005; Barbarella and Gordini, C., 2006; D'Ambrosio et al., 2006; De Vita et al., 2006; Bisson et al., 2007; D'Ambrosio et al., 2007; Oramas Dorta et al., 2007; Scotto di Santolo and Evangelista, 2009; Sorbino et al., 2010
Mudflows	Sirangelo and Braca, 2004
Soil slip/debris flows Soil slide/debris flows Translational slide/debris flows Debris slide/debris flows	Esposito and Guadagno, 1998; Guadagno et al., 1999; Budetta , 2002; D'Ambrosio et al., 2002; Pareschi et al., 2002; Calcaterra at al., 2003; Crosta and Dal Negro, 2003; Frattini et al., 2004; De Vita et al., 2006; De Vita et al., 2007; Toyos et al., 2008
Debris avalanche/debris flows Debris slide/debris avalanche/debris flows Debris avalanche/extremely rapid debris flows	Guadagno, 2000; Fiorillo et al., 2001; Guadagno et al., 2003; Budetta and de Riso, 2004; Calcaterra and Santo, 2004; Fiorillo and Wilson, 2004; Revellino et al., 2004; Guadagno et al., 2005; Iovino and Perriello Zampelli, 2007; Vingiani and Terribile, 2007; Revellino et al., 2008; Perriello Zampelli, 2009; Budetta 2010 Sorbino et al., 2010
Slide/extremely rapid debris earth-flows Unchannelled and channelled debris slide-rapid earth flows	Calcaterra and Santo, 2004; Di Crescenzo and Santo, 2005
Flowslides Flowslide/Debris flows Flowslides and mudslides	Olivares and Picarelli, 2003; Cascini, 2004; Bilotta et al., 2005; Cascini et al., 2005; Di Maio et al., 2007; Olivares, and Damiano, 2007; Di Crescenzo et al., 2008; Picarelli et al., 2008a, 2008b; Pastor et al., 2009; Damiano and Olivares, 2010; Greco et al., 2010; Sorbino et al., 2010

Tab. 2 - Landslide classification from international journal articles

Pareschi *et alii. (2000) report that: "....many landslides began at the head of the drainage channels where source areas commonly show a denuded carbonate substratum; the detachment surface is located at the boundary between bedrock and surficial deposits. The slide scarps often displays a saw-tooth shape, indicating collapse of the overburden toward the channel….After failure the material rapidly evolved into debris flow….*"

Crosta & Dal Negro (2003) describe that: ".... *soil slips were triggered and most of them transformed into debris flows……They scoured the pyroclastic cover and vegetation along their path, and incorporated bedrock fragments…More than half of initial slides are located upslope of morphological discontinuities such as limestone cliffs and roads .... in all the observed cases failure surface is located within the pyroclastic cover..*"

Olivares & Picarelli (2003) illustrate that: "... *static liquefaction is the fundamental mechanism that is responsible for flowslide initiation, mostly in loose granular soils ... infiltration during rainfall can saturate the cover, leading to soil failure ... flowslide can ensue if the soil is very loose and susceptible to static liquefaction....*"

Calcaterra & Santo (2004) say that: "…. *an initial small landslide detached from the edge of a pathway ... This first landslide body has then undergone a sudden acceleration, with a jump-andfall effect, due to the presence of a sub- vertical calcareous cliff ... showing features of a translational slide …. the slope instability occurred in the upper part of the slope can be referred to as debris avalanche….. In the middle portion of the event, the landslide channelized into a preexisting gully... transformed into an extremely rapid debris flow …*".

Zanchetta *et alii*. (2004) report that: "... *Soil slips were suddenly transformed into flows ... and moved downslope. The progressive failure and liquefaction produced, on rectilinear slopes, a downslope enlargement ... The progressive enlargement of the failure area may be explained by undrained loading ...*".

The descriptions above show both convergent and divergent points. Most of authors describe initial masses which are subject to transformation processes of fluidification and/or liquefaction. Some others highlight that the channelling into gullies makes a progressive dilution of the moving masses which tend to change into hyperconcentrate flows (*sensu* Pierson & Costa, 1987).

The recognition of the mechanism of initial failure supports the importance of this first stage of the instabilities as main genetic element in the later evolution of the phenomenon. In order to better define this mechanism, some important elements are reported hereafter.

MAIN GEOLOGICAL ASPECTS

(1) The slope morphology is strongly influenced by rock structure. The calcareous slopes can be generally considered as fault and dip slopes whose angles range from 20-30° (basal zone) to 50-90° (top). The fault slopes are characterised by irregular surfaces where one or more natural scarps can be present. The lower-angled slopes have a more uniform morphology, even though faultcontrolled gullies interrupt their continuity, with many localised dips.

(2) The slopes have been mantled by airfall and pyroclastic flow deposits of volcanic activity of the Phlegrean Fields and Somma- Vesuvius Volcanoes. The pyroclastic sequence is formed by ashy and pumiceous layers alternating with buried horizons of soil. They dip at angles similar to those of the bedrock surface. The thickness increases from the top of the slope (0.5-2 m) to the foot of the hill (over 10 m).

(3) Therefore, the sequences of pyroclastic layers and soil horizons consist of discontinuous layers with varying geotechnical properties. Pumice should be considered as a graded granular material while soil horizons as cohesive materials. In the pumice layers, the presence of interconnected capillary-size voids within the grains influences water flow circulation, causing suction phenomena and complex water diffusion. Owing to the retention capacity of the pumice, a greater volume of water is needed to obtain fully saturated conditions than that necessary for soils made of non-porous clasts (Esposito & Guadagno, 1998).

(4) The presence of allophane minerals with some organic matter in the horizons determines specific geotechnical characteristics in the materials. There are problems connected with soil testing, where a special methodology must be used (Guadagno & Magaldi, 2000). Generally, these soils exhibit high values of liquid limit at relatively low clay contents. The residual friction angle is generally high (close to 30°), and comparable to the peak angle.

(5) As expected, layers and horizons of soil exhibit extremely variable permeability. The pumice layers can act as drain layers, while the clayey horizons are quasi-impervious. In such a hydrogeological setting, any geometrical modifications can provoke important changes in the ground water flow pattern.

(6) The granulometric characteristics of the matrix of debris flow deposits range from silty sand with gravel and sand with silt and gravel. A large amount of limestone clasts is also present. Calcareous boulders (up to 2 m in diameter) as well as trees or anthropogenic elements were observed in the depositional area

(7) Finally, slope micro-morphology, considered as local geomorphological setting, plays a decisive role in locating the source of the instabilities and in controlling the development of the phenomena..

SOME EVIDENCES

In our opinion, there are some unequivocal evidences describing the event in its first stage. They can be listed as follows.

(1) Mass detachments occur in specific slope points involving sometimes very limited volumes (few cubic metres). As reported by many authors, these points correspond to edges of natural scarps (Fig. 4). In some cases, the first movement can be related to rock fall down the scarp. The presence of more scarps prevents retrogressive movements. More extensive instabilities take place in correspondence of man-made cuts (Fig. 5).

(2) The source areas exhibit the typical morphological characters of translational slides. In the source

Fig. 4 - Debris avalanches and debris flows of Ischia Island on 30th April 2006. Source areas are located in correspondence of a natural scarp

area, the slope should be considered as open slope and the trigger is independent from the presence of well-defined drainage lines.

(3) The location of the sliding surface, within the pyroclastic sequence or at the contact with the bedrock, is an area of disagreement. Actually, field observations demonstrate that a large part of the initial failure surfaces are generally located in the pyroclastic multilayer cover and often highlight the presence of clayey deposits at the base.

(4) In the upper part of the slopes, before becoming channelled, landslides displayed a triangular shape in plan, this being a typical characteristic of many debris avalanches and related to the progressive entrainment of material downslope. Field survey also show that gullies are lacking of material.

(5) An important aspect is related to the very high velocities of the flows. The cleaned gullies, tilting along channel bends, lateral deposit, high impact energies, and other numerous evidences highlight top-down mechanism.

DISCUSSION AND CONCLUDING REMARKS

If the same landslide phenomenon is classified in different ways, it is plain that the discriminating criteria for its classification are not clear or they show areas of uncertainty. Therefore, there is the need to have at disposal a classification system that leaves no doubts and describing the landslide mechanism in terms of susceptibility and hazard assessments too. Landslides described in the various classification systems propose different trigger mechanisms, but it should be particularly important ascertain what are the predisposing factors and those triggering the landslide from a propositional viewpoint rather than descriptive only.

Fig. 5 - Debris avalanche at Nocera Inferiore on 4th March 2005. Road cuts at the source area location are also shown

As far as we said, it is possible to define a theoretical model of the initial instabilities and of the subsequent evolution.

the initial instabilities and of the subsequent evolution. There are no doubt that the initial movement consists in the failure of relatively coherent slabs of pyroclastics in the highest parts of the slope. The slabs slide on failure surfaces, usually located within the pyroclastic sequence. The plastic behaviour of the initial sliding mass is proven by tensional cracks present on some sites where the landsliding process was aborted and by the fact that many initial slides occur in the back-slope of trackways and natural scarps. Increase of pore pressure within the pyroclastic cover should be considered as the more likely mechanism in triggering the failures.

The mobilised mass of the initial failure generally impacts on downslope deposits where liquefaction phenomena, by means of rapid undrained loading (Johnson, 1984), could be triggered. In nearly all cases the initial slides transformed into extremely rapid flows, growing substantially in volume by incorporating materials and surface water.

According to the Varnes's classification (1978) these landslides can be classified as debris avalanches and debris flows; by applying the criteria of Cruden & Varnes (1996) as complex landslide, debris slide/debris flow, from very rapid to extremely rapid and high water content; hillslope debris flows and debris flows if we use the classification of Hutchinson (1988). Moreover, these landslide mechanisms can be compared to those described by Hungr *et alii* (2001), as debris avalanches, phenomena that involve open slopes and therefore are typically not confined in gullies, at least in their initial stages.

In the case of the Campania landslides, many debris avalanches can became confined in gullies in middle or lower portions of the slope, transforming into debris flows, still eroding the pyroclastic and colluvial cover from the slope. At the base of the slopes, the flows spread out in thin depositional fans. Deposition generally occurs in the basal plain where the velocities decrease. If large amounts of water are present in the area or in the gullies, the landslide material can be reworked by hyper-concentrated flows.

Finally, the analysis carried out on the wide bibliography after the 1998 landslide events has pointed out the need to redefine the correct nomenclature of flow-like landslides, taking into account the practical effect for mitigation strategies, and preventing distortion of the general terms due to national and local effects.

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