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LANDSLIDE HAZARD IN HIGH MOUNTAIN AREAS: SOME CASE HISTORIES (ITALY)

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ABSTRACT

This paper mostly outlines the geological and structural aspects of the Italian Dolomites (very famous mountains which make part of the Eastern Alps) and their influence on the areal distribution and types of mass movements. It describes also the most frequent types of movement and their effects on human activities.

Finally some experiences of landslide investigations and monitoring, carried out in the past few years for both research and civil protection purposes, are described.

Key words: landslide, hazard, monitoring

INTRODUCTION

From the tectonic point of view Italy is a young region, with 75% of the territory which is mountainous.

The physical setting of the Apennines and the Alps are significantly different, with very different problems as regards the slope stability.

You can have areas mostly constituted of rock materials (crystalline, metamorphic and carbonatic-dolomitic rocks in the Alps) and areas mostly constituted of clay materials (in the Apennines).

In the Alpine chain (North Italy) 58 peaks exceed 4,000 metres of altitude (up to the 4,800 metres of the Mt. Bianco), whereas the valleys show themselves deeply cut, with differences in elevation up to some thousand of metres.

The above conditions seem to be predisposing for the development of different landslide typologies, as deep seated gravitational phenomena, slides, mudslides and debris flows. Such phenomena show a remarkable spreading and a significant recurrence in the territory, and time by time they have caused numerous victims and important damages, with entire villages destroyed.

In the following you can read through two tables which indicate the number of the villages which were affected in the past by landslides and/or floods and the number of the victims.

Table 1. Villages damaged by landslides and/or floods (since XVIII century)

Region	Typologies	n° of villages	n° of victims
Piemonte and	landslides	40	1,335
Valle d' Aosta	floods	77	360
Lombardia	landslides	55	1,511
	floods	61	68
Triveneto	landslides	51	2,640
	floods	69	452
Total		353	6,366

Table 2. Catastrophic landslides occurred in the Veneto Region in the last three century

Village	Date	Typology	n° of victims
La Valle	April 1701	Flow	49
S. Vito di Cadore	2nd May 1730	Debris Avalanche	52
Borca di Cadore	7th July 1736	Complex	7
Alleghe	11th January 1771	Slide	48
Borca di Cadore	21st April 1814	Debris Avalanche	314
Selva di Cadore	November 1851	Complex	17
Borca di Cadore	28th July 1866	Complex	11
Taibon Agordino	3rd December 1908	Fall	28
Selva di Cadore	27th May 1917	Complex	27
Vittorio Veneto	14th May 1937	Complex	8
Longarone (Vaiont)	9th October 1963	Slide	2,000
Falcade	4th November 1966	Flow	11

Table 1 is referred to the whole area of the Northern Italy whereas Table 2 is referred to the Veneto region.

The paper describes cases of landslides in the Dolomites area and one huge landslide occurred in the Central Alpine area. Some of these cases were monitored also for purposes of civil protection.

PHYSICAL SETTING OF THE DOLOMITES AREA

The Dolomite area is well known all over the world for the beauty of their natural landscape and for the presence of well-organized Winter/Summer resorts, located at different elevations along the slopes and at the bottom of the valleys. The territory includes some very high mountains (such as Mt. Antelao, 3,264 m ASL; Mt. Pelmo, 3,168 m ASL; Tofane Mountains, 3,244 m ASL, etc.) alternated to densely populated areas (i.e. Cortina d'Ampezzo).

From a geological point of view the area is characterized by the presence of formations dating from Permian to Cretaceous periods. The predominant structural setting is represented by a sequence of rigid and plastic formations (Fig. 1).

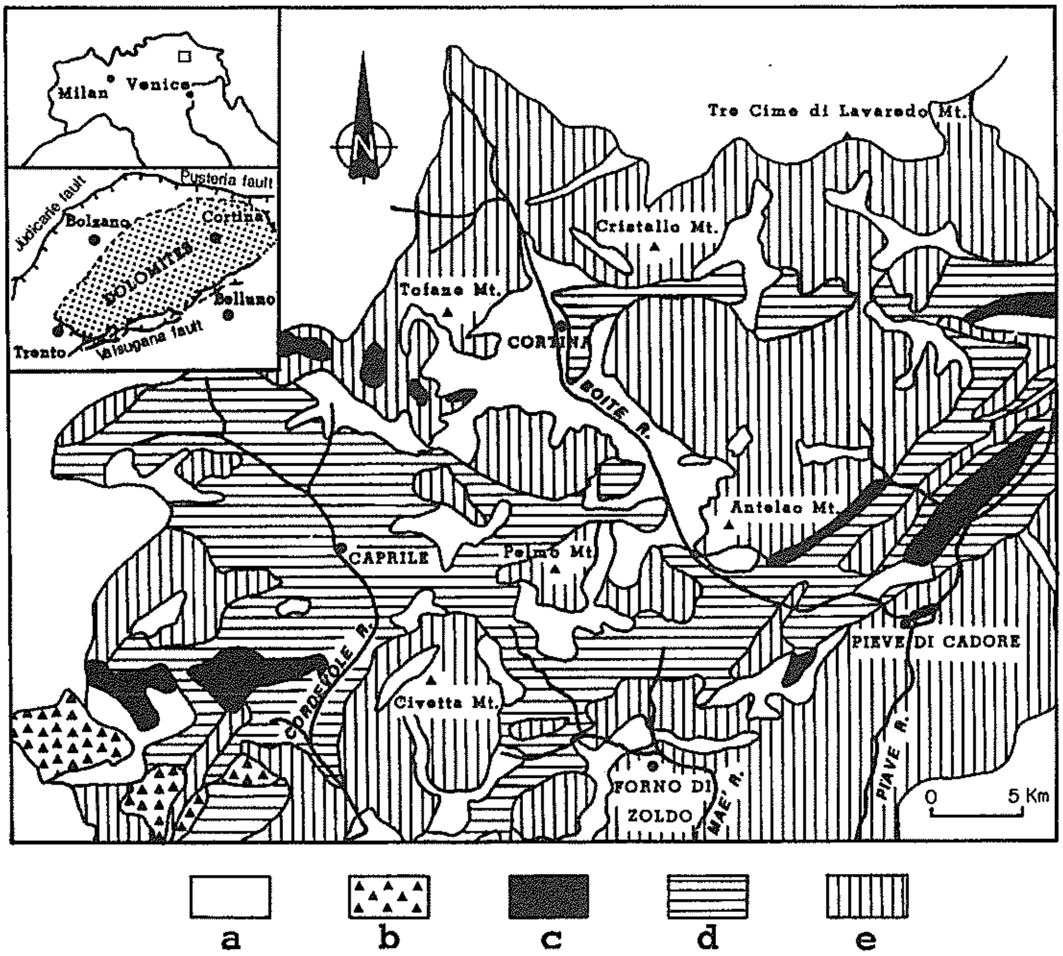

Figure 1. Geological sketch of the Eastern Dolomites areas: a) Quaternary Deposits; b) Eruptive Complex; c) Gypsum-Calcareous Complex; d) Sandstone- Clayey-Tufaceous Complex; e) Limestones and Dolomite Complex.

The plastic lithotypes generally outcrop in the lower parts of the mountain slopes. They give rise to a flat morphology and a widespread hummocky topography.

The rigid lithotypes overlying the above ones are formed of dolomites and limestones. The alternance of stiff and plastic lithotype sequences makes the area particularly prone to development of ruinous landslides.

During the last glaciation the morphology of the whole area was strongly modified by glacial erosion processes which have deepened and enlarged the valleys. The postglacial period, in which the glaciers underwent a reduction in size following intense climatic changes, was characterized by huge mass movements which affected the structure of the hydrographic network. Somewhere the streams, depending on the susceptibility to erosion of the lithotypes which constitute the watershed, give rise to ruinous debris flows.

Most of the villages are located on alluvial fans or at the bottom of the valleys or at the toe of ancient landslide accumulations. This geographical situation implies that the villages are prone to serious damage whenever critical climatic conditions occur and floods, landslide reactivations and debris flows take place.

The climatic conditions of the area are those typical of a high mountain setting, characterized by two distinct seasons during which the temperature remains below 0°C or above 0°C respectively (Fig. 2). Two peaks of rainfall can be observed in late Spring or in Autumn.

Especially during the Summer season the intensity of some rainfall events can reach even 150 mm per hour and rapid mass transport phenomena may occur. The mean yearly rainfall reaches 1,200 mm, whereas the total precipitations can even exceed 1,600 mm. The maximum snowfall mainly occurs in January and February and the daily mean value of temperature remains below 0°C from December to March.

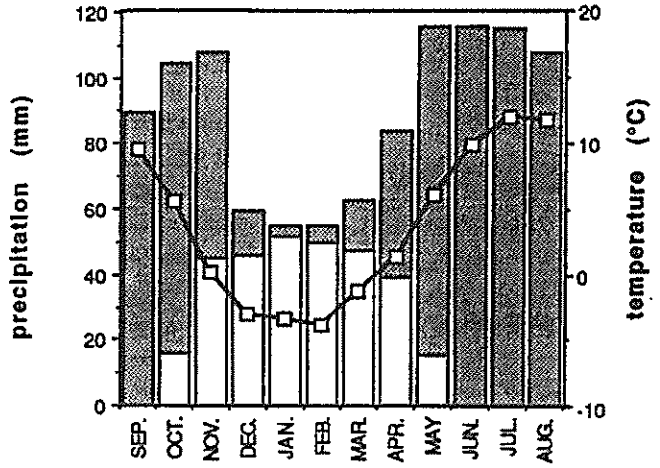

Figure 2. Climatic characteristics of the Dolomites area. White bars show snowfall precipitation, gray bars show rainfall precipitation.

CASE HISTORIES

Ru delle Roe Landslide

This slide took place in the right bank of Ru delle Roe stream (about 1,300 m ASL) in the lower part of its basin (Zoldo Alto, Belluno), an area particularly known for its landslide susceptibility. The landslide events occurred in the past caused substantial damage to built-up areas and roads, thereby being subject to many control measures by the Local Government. The most important landslide events occurred on occasion of the 1882, 1890 and 1966 floods especially along the right bank of the stream. Furthermore, in 1971 (April), 1977 (April), 1982 (November) and 1991, phenomena of minor intensity occurred.

A matter of particular concern was the hazardous position of the village of Molin, just 500 m downhill from the last slide event of the 1991. The slide took place in the winter period, with extremely low temperatures and under a thick snow cover.

From a geological point of view the most common lithotypes in this area belong to the Dolomia Principale of the Norian period, as well as to the Raibl Formation and to the formations of La Valle and S. Cassiano (Fig. 3). The Dolomia Principale, which is the upper formation of the series, due to intense fracturing tend to form aquifers of remarkable volume in the lower detrital-morainic deposits. The Raibl Formation is made up mainly of shales, marls, marly limestones and sandstones, normally in this area covered by detrital and morainic deposits. The formations of La Valle and S. Cassiano are made up of marls, tufaceous marls and well-bedded and tectonized tuffs. Precisely these last formations are involved in the landslide phenomena in progress.

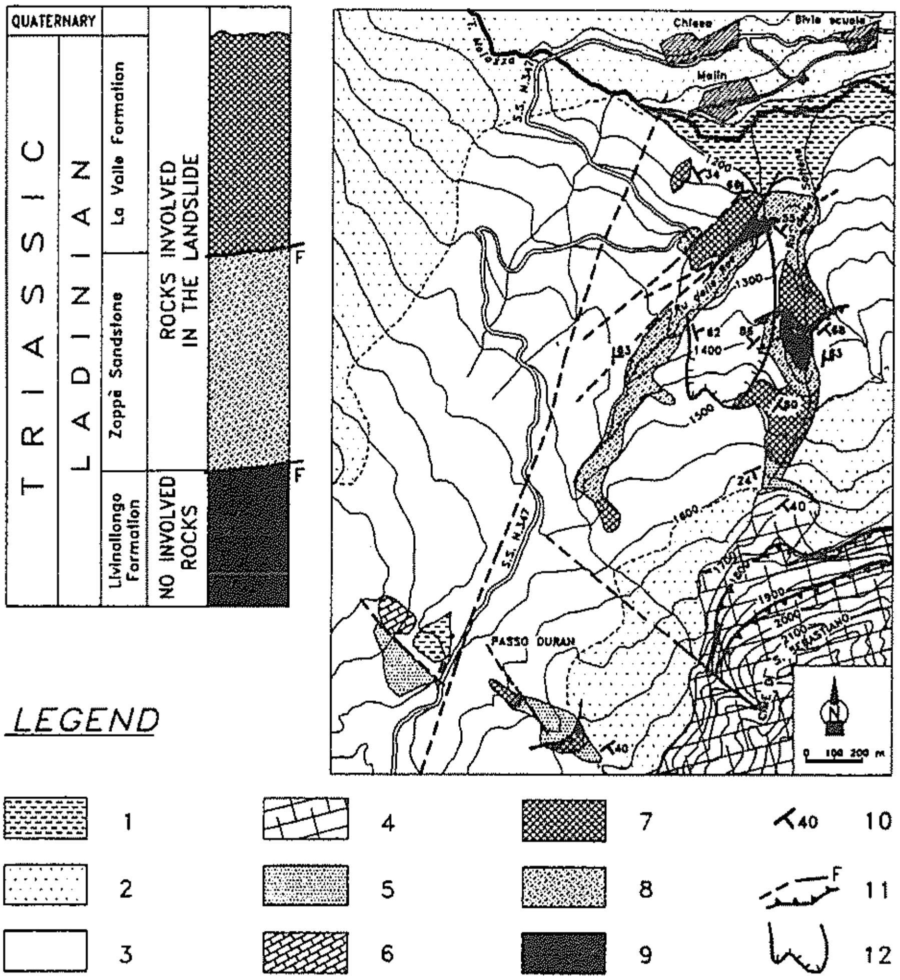

Figure 3. Schematic geological map and lithostratigraphic succession: 1- alluvial deposits; 2- active scree slope; 3- old scree slope and colluvial deposits; 4- Dolomia Principale (Norian-Upper Carnian); 5- Raibl Formation (Upper Carnian) and "Infraraibl Group" (Upper-Lower Carnian); 6- Cassian Dolomite (Lower Carnian); 7- La Valle Formation (Lower Carnian-Upper Ladinian); 8- Fernazza Formation, Acquatona Formation and Zoppè Sandstone (Upper Ladinian); 9- Livinallongo Formation (Upper Ladinian p.p.-Lower Ladinian); 10- Strata orientation; 11- Fault (F) and Thrust (certain and uncertain); 12 - Landslide boundary.

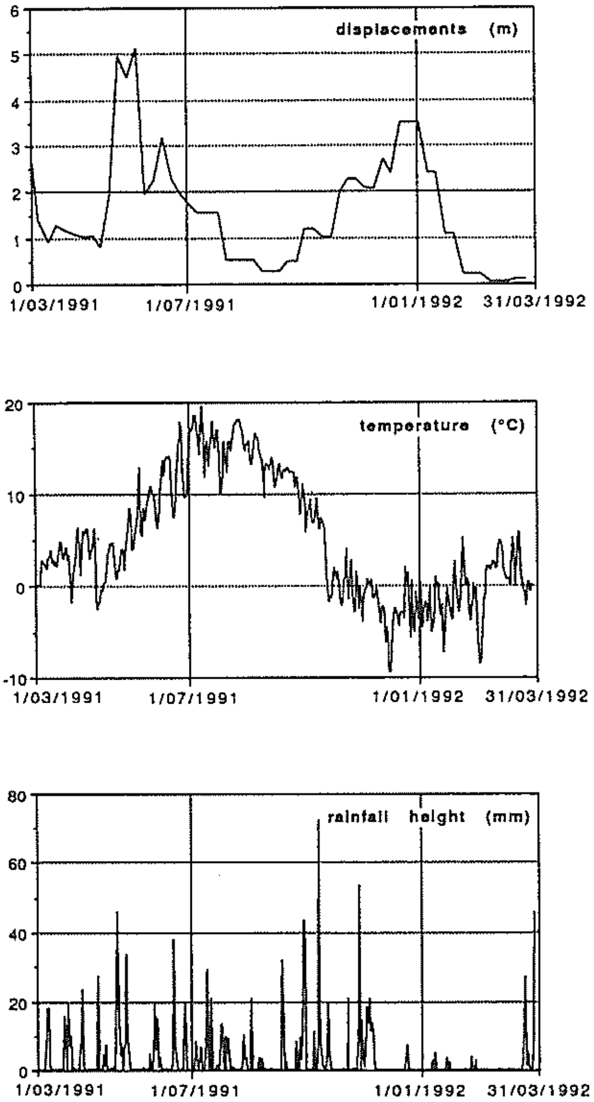

Figure 4. Correlation between displacements, temperature and rainfall amount of during the period March 1, 1991-March 31, 1992.

From a morphological point of view, the area is distinguished by the deep valley of the Ru delle Roe stream in which a very steep river bed is cut into the weak layers of the S. Cassiano Formation.

The landslide took place on 31st January 1991 in coincidence with the extremely severe climatic conditions, when the minimum temperatures ranged approximately between -15°C and -20°C. A similar event occurred the following winter, in January 1992, during another particularly cold period (Fig. 4).

The landslide involved about 1,500,000 m^3 of material belonging to the S. Cassiano and La Valle Formations as well as to the overlying detrital accumulation. The landslide affected an area of about 100,000 m^2. The thickness of the landslide body reaches about 80 m (Fig. 5).

Before the landslide event of 1991 the area was covered by a mantle of snow 150 cm

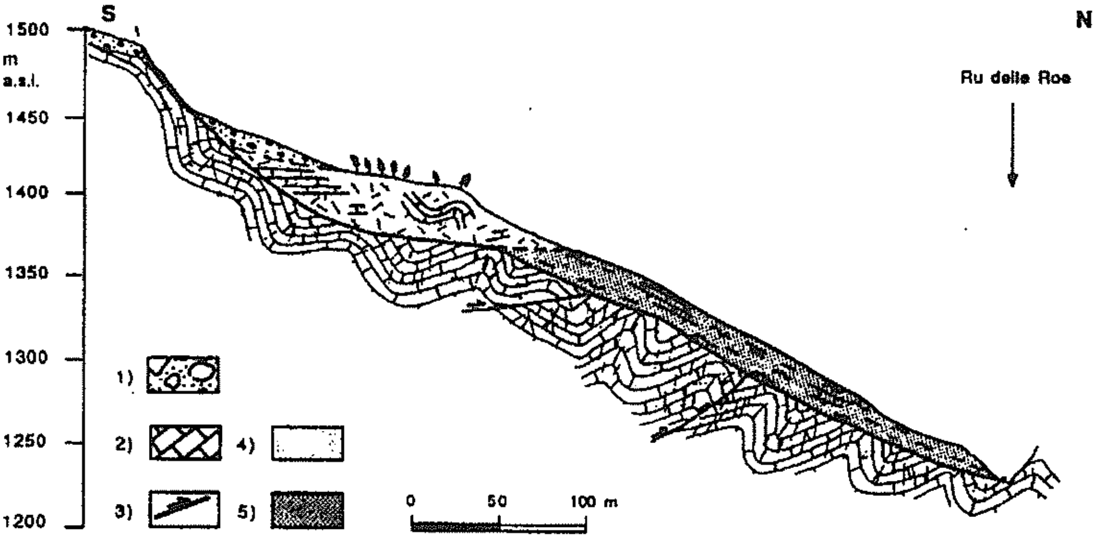

Figure 5 - Schematic geological longitudinal profile: 1) Scree slope (Quaternary); 2) La Valle Formation and Zoppè Sandstones (Upper Ladinian); 3) Thrust; 4) Landslide of 1991; 5) Landslide of 1982.

thick; in the middle of February, the thickness of the mantle reached over 2 m. In addition, these abundant snowfalls were preceded by heavy rainfalls.

A comparative analysis of the aerial photographs, allowed to define the edge of a small escarpment on the wooded slope since 1954. This escarpment was some ten meters high and was recognized as a part of the main scarp of the 1991 landslide. The sequential sets of photographs of the area allows the delineation of an old landslide that was reactived in 1982. This last reactivation represents the right-hand sector of the 1991 slide.

Figure 6 shows a graphical representation of the directions of the displacement vector and the paths of the points on the vertical plane. These measurements confirm the presence of two distinct landslides: the main, which corresponds to the January 1991 events, and the right-hand mass corresponding to the 1982 landslide.

As the landslide movement started during a period of very low temperatures, the hypothesis frost had obstructed the springs present inside the body of the slide was made.

The obstruction of the springs would have caused an abrupt rising of the groundwater table inside the slope and the consequent landslide mobilization.

The high rate of movement recorded during the first days strengthened the hypothesis that the movement could evolve into a sudden collapse of the whole mass, with a consequent obstruction of the stream and the possible formation of a debris flow.

This was a considerable risk factor for the little village of Molin, located a few hundred metres downstream. The inhabitants of the village were moved out as soon as possible.

In order to check the rate of the movements in progress a topographic network was soon built up. Alarm systems were installed both in the landslide area and along the river bed, for the purpose of detecting the possible occurrence of debris flows in real time.

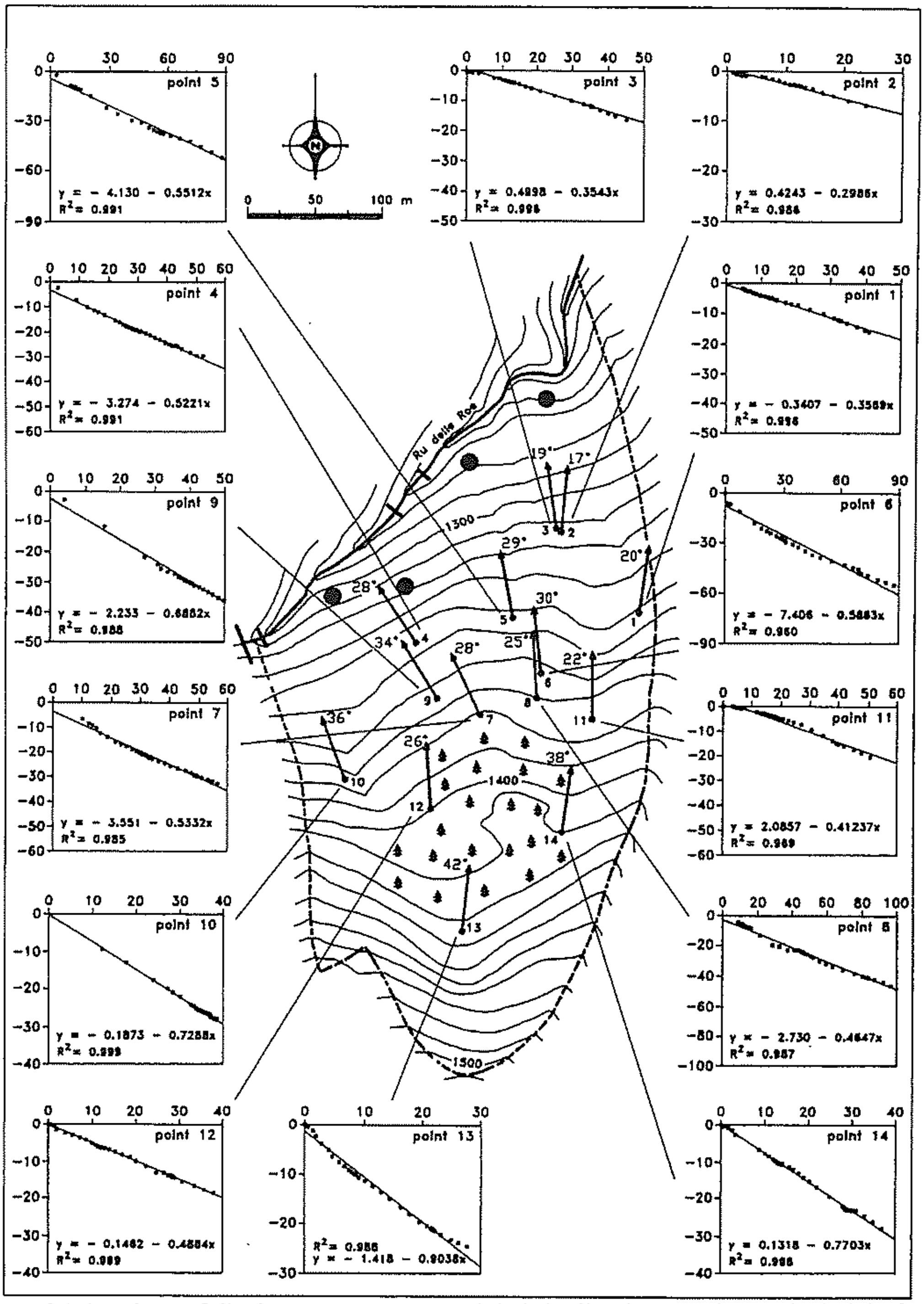

Figure 6. Directions of displacement vectors and their inclinations on the vertical plain for 14 bench marks (x and y values are expressed in meters). The black spots indicate the locations of froozen springs.

In collaboration with various different authorities the following instruments were installed on site:

- three geophones connected to a recording system in order to evaluate the intensity and frequency of rock noise related to the landslide movement;
- a climatological station for measurement of snow, rainfall and temperature;
- two water level gauges, situated along the Ru delle Roe (upstream and downstream with respect to the landslide), in order to determine differences in flow rates related to possible slide damming;
- two hanging bars working as inclinometers, situated downstream of the landslide on the Ru delle Roe channel for an active alarm in case of a debris flow;
- a photo-theodolite survey was carried out at fixed intervals, at first daily and subsequently weekly.

The particular features of this landslide movement made necessary to protect the village of Molin with control works, since it would have been endangered in the event of a sudden collapse of the mass together with other towns located downstream along the Moiazza stream:

- a deviation of the final reach of the Ru delle Roe to move the confluence with the Moiazza stream approximately 300 m downstream; the construction of a bank about 10 m high and 300 m long, designed to resist the impact of a possible debris flow;
- the installation of a by-pass culvert, about 600 m long on the Moiazza stream; the culvert is 3 m in diameter and is designed to allow of up to 90 m^3 of a water per second, in the event of a blockage of the main Moiazza channel by a debris flow coming from the Ru delle Roe.

More precisely these works had the following objectives:

- to prevent the landslide debris from running over the Ru delle Roe fan and the village of Molin;
- to provide an area of expansion, in the Ru delle Roe river fan where some hundred thousand cubic metres of material can be deposited;
- to reduce the confluence angle between the Ru delle Roe and the Moiazza streams, so that Moiazza stream can more easily remove the sediment load contributed by the tributary;
- to prevent the possibility of an impoundment due to the blockage of the Moiazza stream.

The above control measures have guaranteed the total safety of the villages up to today.

Giau Landslide

Hydrogeological and geotechnical investigations have been carried out since 1982 on a landslide located at 1,670 m ASL, in the middle-lower part of the Codalonga River basin, near Passo Giau (2,236 m ASL) which represents the top part of the basin.

The landslide affects a steep slope formed by morainic deposits overlaying a bedrock of marls belonging to the Werfen Formation.

Laboratory tests were carried out on samples collected either from the morainic materials or directly along some parts of the slip surface, there coinciding with the clayey-marly bedrock. The matrix of the morainic material was classified as a clay of low plasticity (PI=3.7-11.8%). The matrix relative to the clayey-marly material collected from the bedrock was classified as clay of intermediate plasticity (PI=15.3-17.4%).

The distinction revealed by the results of the classification tests was confirmed also by the results of the residual shear strength tests. They in fact yielded two values of ϕ'_r equal to 35° and

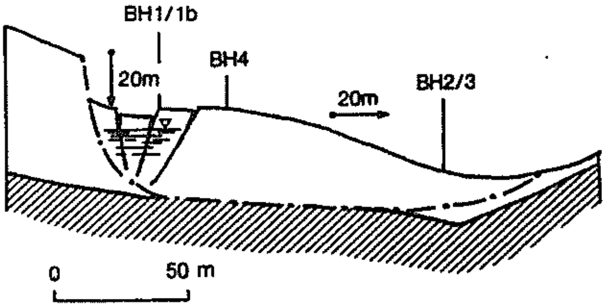

Figure 7. Schematic cross-section of the Giau landslide after collapse; borehole drillings and vector displacements are indicated.

39° in one case and two values equal to 15° and 17° in the other case.

The results of in situ permeability tests gave values of k of about 10^{-7} m/s, as it concerns the permanently saturated portion of the slope.

From reports provided by the inhabitants of the villages surrounding the area, it seemed that the landslide was triggered by the erosive action of the Codalonga stream during the ruinous flood occurred on 4th November 1966.

At the first investigation on the spot, made in early 1981, the landslide appeared as a case of "compound slide" (Skempton and Hutchinson, 1969), characterized by a large graben area in the upper part of the slope and by a translation of the main mass on an almost sub-horizontal slip surface. The maximum thickness of the landslide body was about 50 m, whereas its maximum length was about 150-200 m. The slip surface was identified as being located at the contact surface between the morainic deposits and the Werfen marls bedrock, at least as regards its rectilinear extent. Its curvilinear extent is completely contained inside the morainic deposits. In late 1981, the main scarp was already formed to a great extent: 6 metres in height and 250-300 metres in width. Further enlargements of the main scarp occurred during the following years, up to the complete slope failure (Fig. 7).

The slope was gradually equipped with standard and automatic instrumentation: 3 Casagrande piezometric cells, 2 electric pressure transducers, 2 deep-seated steel wire extensometers, 4 inclinometric tubes, a rainfall gauge, a snow gauge, an air thermometer.

A summary of some standard hydrological and kinematic data collected for 7 years on the slope examined are shown in (Fig. 8). The correlations among precipitation depth, piezometric elevations and inclinometric displacements appears quite evident.

The automatic instrumentation installed in the landslide body in late 1986 allowed a detailed recording of two critical events concerning stability (Angeli *et al.*, 1990; Angeli *et al.*, 1991; Angeli, 1992). During the first event (April 1987), displacements of a few centimetres were recorded, whereas in the second occurrence (April 1988), the complete collapse of the landslide mass was detected with displacements of up to 20 m (Fig. 9).

It must be noticed that the two events occurred under very similar climatic conditions, as to the temperature and the snow depth.

But a comparative analysis of the temperature variations during the Winter months preceding the two events showed significant differences in climatic conditions.

In particular, over the period December 1986 - January 1987 the hourly temperature recorded at the landslide site (1,670 m ASL) generally remained below 0°C, whereas over the period December 1987 - January 1988 it generally remained above 0°C. This trend was then checked even at a higher elevation (2,183 m ASL), at a meteorological station situated near the top of the hydrographic basin.

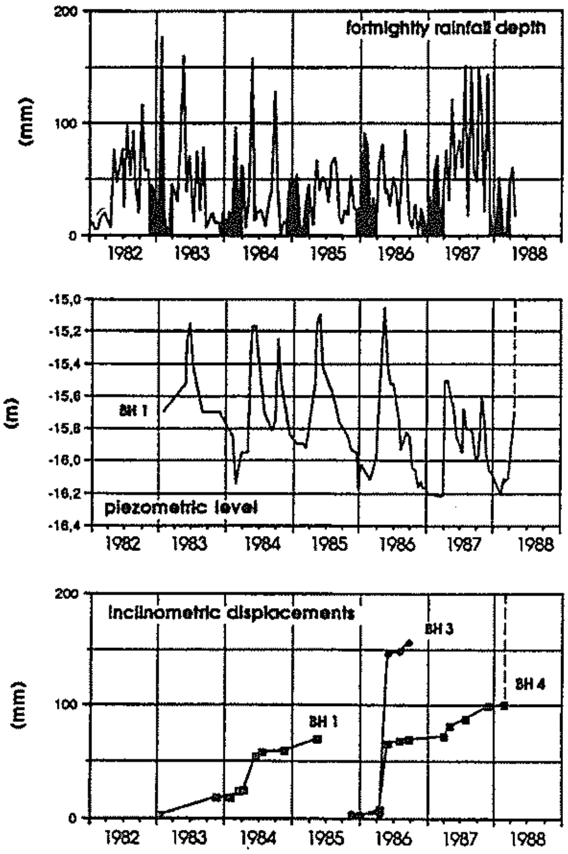

Figure 8. Giau landslide: correlation between rainfall, groundwater level and inclinometric displacements over 7 years of recording; the black areas indicate snowfall precipitation.

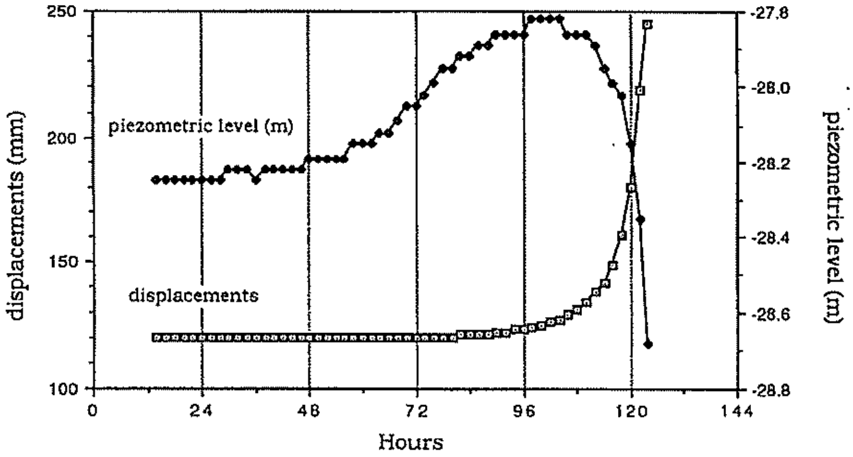

Figure 9. Giau landslide: hydraulic and kinematic characteristics of the collapse (20th-24th April 1988).

Under these conditions the infiltration processes which occurred in the upper part of the hydrographic basin would have magnified the effect of the Spring snowmelting process on the rising of the groundwater level within the landslide body.

This could have provided an additional groundwater supply, delayed in time due to the long distance that the water particles had to run, flowing from the top of the basin to the investigated site and caused the landslide collapse.

Alverà Landslide

The Alverà landslide is located at about 1,380 m ASL on the left-hand slope of the Boite River valley, close to Cortina d'Ampezzo.

Historical sources report significant landslide movements in the past, leading the residential area of Staulin to complete destruction and reducing the number of inhabitants as a consequence of the landslide. For this reason a Governmental law has established the village to be transferred elsewhere from its present location.

This area, situated in the eastern Dolomites, is surrounded by high mountainous massifs more then 3,000 m high.

The geological structure of the area, characterised by an alternance of dolomitic bodies with a rigid behaviour and of a succession of prevalent pelitic component with consequent plastic behaviour, has conditioned in a decisive way the morphological evolution of the slope after the retreat of the Würmian glaciers (in this period the thickness of the ice would have reached 1,000 m). The resulting morphology is in fact gently sloping where more plastic terrains, both outcropping and sub-outcropping, are present.

A research carried out in the reconstruction of geomorphological evolution of the valley allowed to identify and date by means of radiometric measurements numerous landslides (Tab. 3).

From these data it seems clear that the majority of the important landslide took place during two periods: at the beginning of the Holocene, between 10,000 and 9,000 B.P. and between 5,000 and 4,000 B.P. at the end of Sub-Boreal (Panizza *et al.*, 1996).

The subsequent evolution principally consisted of the reactivation of these phenomena which generally involved relatively small thicknesses of material (about 15-30 m).

Alverà landslide is one of these last phenomena. It is still active and considering the implications of geological risk, it is subject to continuos monitoring.

From a lithological point of view the most prevalent lithotypes of the Alverà landslide belong to a particular clayey facies of the S. Cassiano Formation (middle-upper Carnian, distinguished by an alternance between of clays and silts of vulcanic origin, calcareous banks and marly levels) up to 80 m thick.

From seismic and electric soundings and from inclinometric measurements, a main slip surface located at about 23 m in depth and a secondary one located at 5 m have been identified.

The analysis of the cores from the boreholes allowed to recognize two separate layers. The upper one (about 25 m thick) within the landslides occurred, consist of irregular poorly sorted blocks of the original rock dispersed in an argillaceous matrix and widely affected by cracks. The lower layer consists of more consolidated homogeneous clays.

A system of fissures filled with calcite deposits up to some centimeters thick seems to indicate the occurrence of abundant water circulation coming from the upper calcareous massif.

A first monitoring system was installed in 1989. It consists of inclinometric tubes and

Table 3. Mass movements recognised in the area of Cortina d'Ampezzo (Dolomites)

name	type	date of first known failure (yr B.P.)
Chiave landslide	complex	4,520±60
Brite de Val landslide	fall	
Crepe de Cianderou landslide	complex	
Comate landslide	complex	
Sponates landslide	slide	
Sote Crepe landslide	fall	
Cadin landslide	slide	12,150±435
Cadin di sotto landslide	flow	
Cadin di sopra landslide	flow	
Cadelverzo di sopra landslide	flow	
Col Drusciè landslide	slide	9,000±150
Colfiere landslide	fall	
Ronco landslide	flow	
Pierosà landslide	slide	10,850±80
Cortina d'Ampezzo landslide	flow	4,350±60
Alverà landslide	flow	
Staulin landslide	flow	
Chiamulera landslide	complex	4,700±60
Malga Larieto landslide	slide	
Col da Varda landslide	slide	
Pecol landslide	flow	155
Albergo Cristallo landslide	slide	
Rio delle Vergini landslide	flow	
Pomedes landslide	complex	
Lacedel landslide	complex	10,035±110
Rio Roncatto landslide	flow	
Rutorgo landslide	flow	
Son dei Prade landslide	flow	
Col landslide	flow	
Pocol landslide	complex	
Grotte di Volpera landslide	fall	
Rio Costeana landslide	slide	
La Riva landslide	complex	4,220±60
Zuel landslide	slide	9,440±105
Pezziè landslide	flow	
Acquabona landslide	flow	

piezometric standpipes, these last equipped with electric transducers for the measurement of the hydraulic head in the slope. The inclinometric tubes are provided with a steel wire extensometer for the continuos measurement of the landslide displacements. Moreover a network of benchmarks for the topographic survey has allowed surficial movements to be detected. A meteorological station was also set up in order to record the precipitation values (both rainfall and snow water equivalent), the air temperature and the snow cover thickness. The data obtained from this system are shown in Figure 10.

The aim of the research in Alverà landslide (included in an E.U. project) regards the definition of a visco plastic model capable of simulating the velocity trend in landslides using piezometric data as input.

To this purpose, during the 1994 other 10 boreholes were drilled in the Alverà landslide and equipped with inclinometric tubes, open standpipe piezometers and steel wire extensometers.

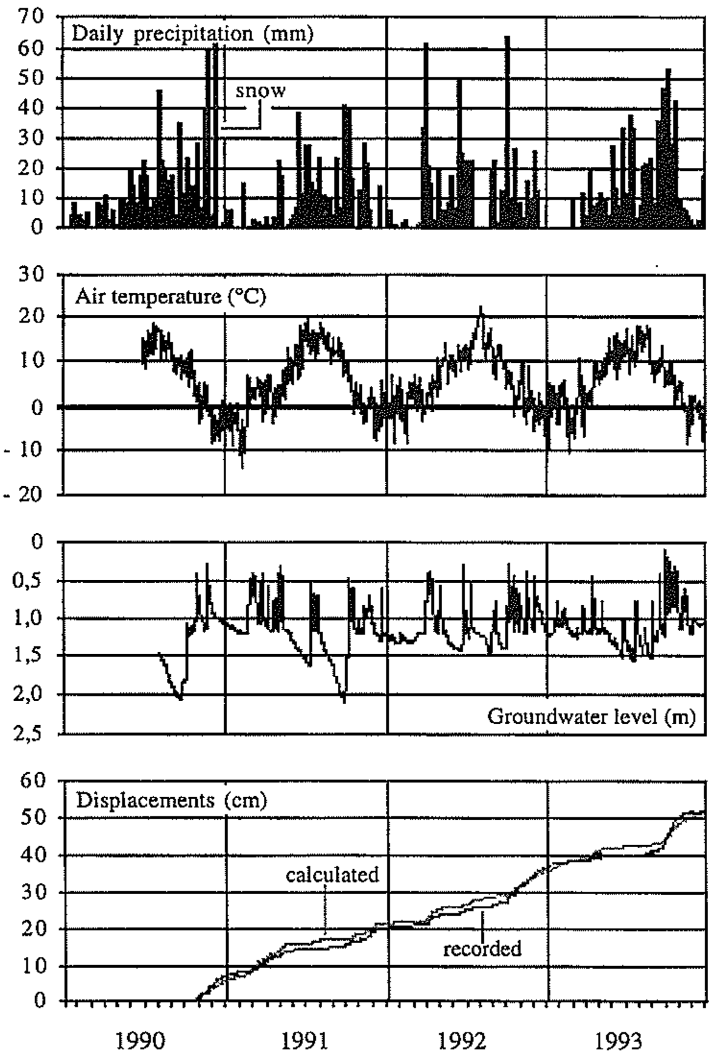

Figure 10. Alverà landslide: correlation between precipitation depth, air temperature, groundwater level and recorded and calculated (by means of a visco-plastic rheological model) displacements.

All the boreholes were then equipped with electrical pressure transducers. An automatic system records the data every ten minutes.

Tessina Landslide

On 17 April 1992, after a snow-melt period and heavy rainfall, a landslide known as the "Tessina landslide" reactivated causing alarm and creating a dangerous situation for some villages in the north-eastern Italy.

The landslide, which was first triggered about 30 years ago, is a complex phenomenon with a source area affected by rototranslational slide movement in the upper section; the slide was transformed downhill through a steep channel into a mud flow.

The landslide developed in the Tessina valley between elevations of 1,220 and 625 m, with a total longitudinal extension of nearly 3 km and a maximun width of about 500 m. The source zone is more or less elliptical, with the longest axis oriented N-S for about 600 m, while the shortest axis is about 500 m long.

The mud flow laps the village of Funes and continues down to an elevation of 625 m, where it stops near the town of Lamosano (Fig. 11).

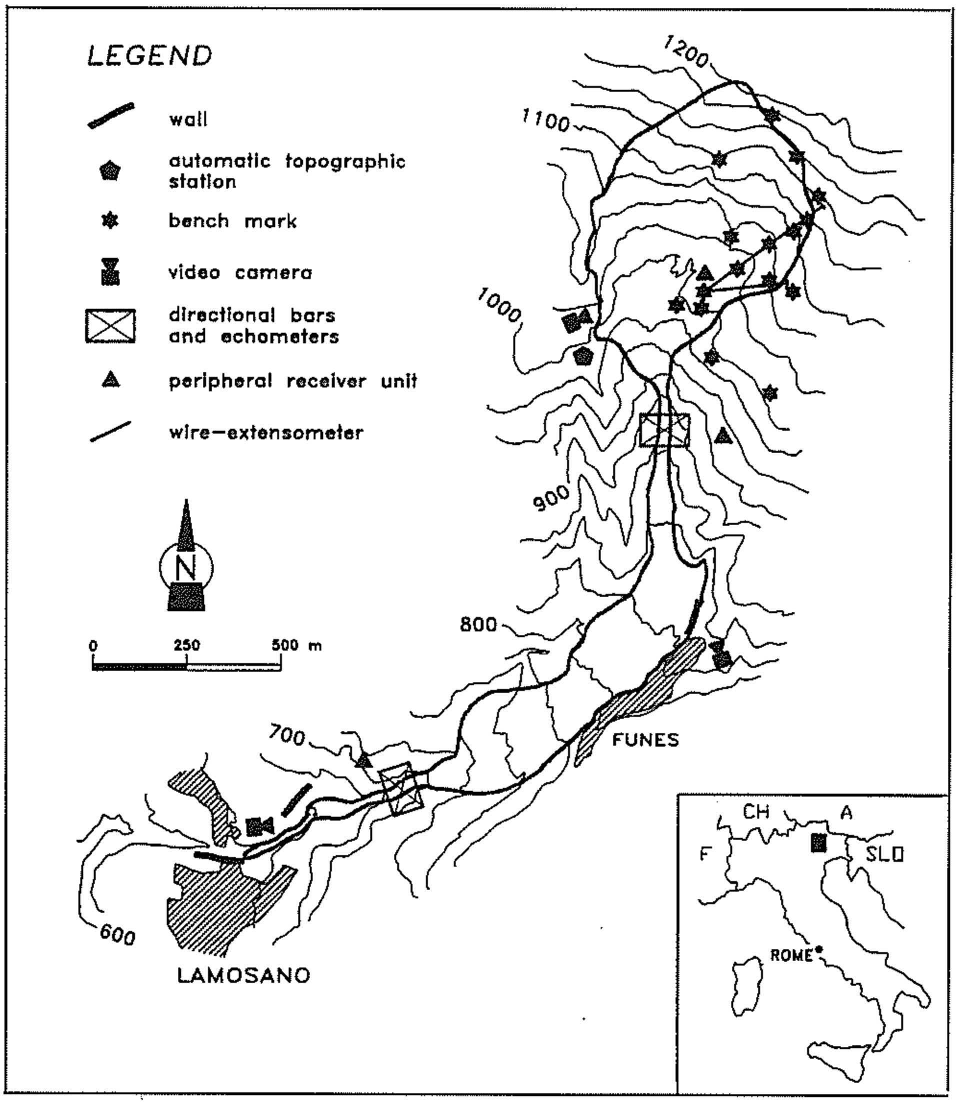

Figure 11. Index map and location of the instruments within the Tessina Landslide.

The lithology of the area varies considerably. We can identify three main formations: 1) Monte Cavallo Limestone (Cretaceous), which consists of layers of varying thickness from about a centimetre up to approximately a metre with a downslope dip of about 70°. This makes up the main structure of Mt. Teverone. 2) Scaglia Rossa (Upper Cretaceous), which consists of marly limestone with a maximum thickness of about 50 m, outcropping on the southern slope of Mt. Teverone. 3) Flysch (Middle Eocene), which consists of a rhythm marly-argillaceous and calcarenite layers with a thickness of about 1,000 to 1,200 m. This formation makes up the impermeable substratum of the entire sliding area and outcrops at the foot of Mt. Teverone.

The Quaternary deposits consist of a vast scree slope at the foot of Mt. Teverone and in morainic Würmian deposits from the glacier of the Piave River valley and from other small local glaciers.

The landslide first moved on 30 October 1960, after a particularly heavy rainfall period in which 398 mm of rainfall were recorded in 30 days. This movement involved a total volume of approximately 1 million m^3 of material. The highly fluid material turned into a channelled mud flow moving down the Tessina Valley. It was possible to distinguish an area of feeding in constant expansion, a flat upper accumulation area, a lower accumulation area consisting of the main flow, and a steep narrow discharge channel connecting the two latter areas.

Further landslide events occurred at the site in 1962, 1963, 1973, 1987, 1988, and 1989 after long-term rainfall.

These events caused the filling of the Tessina valley with thicknesses of material ranging from 30 to 50 m, seriously endangering the village of Funès, which is situated on a steep ridge originally quite high above the river bed, but now nearly on a level with the mud flow.

In April 1992, a period of quite heavy rainfall (160 mm in 15 days), followed the annual snow-melt period. Under these circumstances, on 17 April 1992 an area of about 40,000 m^2, collapsed on the left-hand slope of the Tessina Stream, involving a volume of approximately 1 million m^3 of material. During the months before, signs of intense fracturing (which became worse just a few days before the main event) appeared in this sector.

The main event, a roto-translational slide, with an estimated depth of slip surface ranging from 20 to 30 m, involved even the flysch substratum. It produced a main escarpment approximately 15 m high and moved about 100 m downhill. This caused breakage of the entire unstable mass and disruption of a drainage works built in previous years.

The highly fractured and loosened material from this area ran down into the river bed and, due to constant remoulding and the continuous increase of water content, became more and more fluid, transforming it into a series of earth flows that contributed to increased mud flow.

This flow in just 5 days had reached the village of Funes. This mass, which was about 5 m wide and 1 m thick, moved at an approximate velocity of 10 m/hr, whereas the main slide was moving at a speed of about 15 m/day.

Flow movement continued with varying intensity until July 1992, when it had almost reached the outskirts of Lamosano after having overrun the earlier flows.

After these events, the inhabitants of Funes and Lamosano were evacuated; in the meantime the Ministry for Civil Defense began assigning funds for works to be carried out on a short- and medium-term basis, in order to safeguard residential areas, as well as for installation of a monitoring and warning system.

Civil engineers of Belluno Province built three artificial embankments in order to protect the villages. Close to Lamosano, an experimental structure was constructed, including a concrete bed and several nozzles capable of spraying water at high pressure for the purpose of fluidizing the material of the mud flow and therefore of preventing its accumulation and backwater flooding.

The particular features and evolution pattern of the slide, together with the extension of the area involved, made it necessary to plan a series of innovative solutions for the installation of an automatic monitoring and warning system that would guarantee the safety of the population.

The instruments that were considered the most suitable for monitoring several different types of phenomena (such as the roto-translational slide of the upper section and the mud flow close to the villages) were identified and connected to three peripheral units.

The peripheral units are powered by photovoltaic panels and equipped with backup batteries. These units receive and perform preliminary processing of data coming from the instruments (i.e. echometer, tietmeter bars, extensometer) and check that these instruments work properly.

Two multiple-base wire-extensometer units, measuring 280 m and 390 m, were installed in the upper section of the slide in order to obtain a constant check of the movements occurring on the landslide surface. These units consist of a series of 12 measuring pulleys fitted with an appropriate scaler system capable of detecting movements as small as a millimetre.

On the upper section of the slide, a topographic system with an automatic benchmark detector for measuring surface movements was installed. It consists of a high-precision theodolite provided with a servomotor run by means of a personal computer, which controls the system activity and insures data reading and recording of 13 points every 30 minutes. Each group of recorded data (angles and distances) is immediately compared with the previous readings to obtain displacement trends.

On the mud flow, two control units, one consisting of three tiltmeter bars and an ultrasonic echometer, the other of two tiltmeter bars and an echometer, were installed some 100 m uphill from the villages.

Three videocameras were also installed to record and watch over the slide movements in the most critical areas.

A central monitoring station, located inside the building of the local government of Lamosano, receives data coming from the peripheral stations to which the sensors are connected. It also defines possible situations of danger and sends data and signals, via modem, to a warning station situated at the Fire Brigade Station of Belluno. Basically the central monitoring station consists of an MS DOS computer running dedicated software which handles and processes data with the aim of highlighting situations of possible danger.

In the event of a critical development of the situation, various warning levels can be determined, with an indication of the peripheral units and sensors directly involved.

It is at any rate possible to access data in real-time mode by connecting to each peripheral device and checking on the instrumentation, as well as providing access to recorded data coming from each sensor.

In conclusion we feel that the monitoring system installed in the Tessina landslide is providing the necessary data for carrying out a Civil Defense programme, including the evacuation of the population from the residential areas in the event of a catastrophic reactivation of landslide activity.

Val Pola Landslide

The Valpola landslide devasted on 28th July 1987 the bottom of the Valtellina valley (Central Alps) for over 4 Km and killed 27 people, detaching from the flank of Mt. Zandila (Fig. 12).

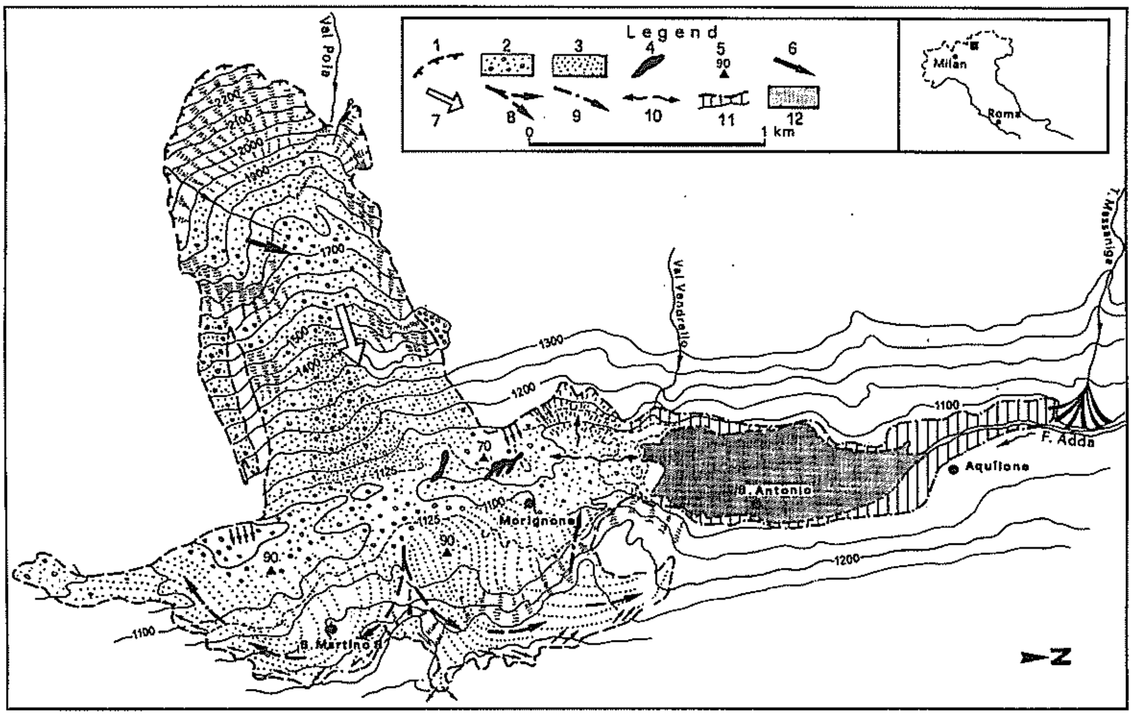

Figure 12. Morphological sketch map of the Valpola Landslide. Legend: 1) landslide scarp; 2) landslide debris with prevailing coarse grains; 3) landslide debris with prevailing fine grains; 4) lacustrine deposits mixed with landslide debris; 5) maximal thickness of accumulation; 6) slide direction; 7) rock avalanche direction; 8) movement direction on the opposite slope; 9) backward movement directions; 10) mud wave direction; 11) mud wave tracks at the foot of the slopes; 12) dammed lake (After Govi and Turitto, 1992).

The landslide was then recognized by means of aerial photographs taken before the event as a prehistorical slide with a crown scarp about 100 m high and 700 m long.

The Mt. Zandila is mainly composed of igneous and metamorphic rocks.

The sliding was preceded by some days with heavy rainfall which caused severe floodings and debris flows throughout the whole area of upper Valtellina; in particular between 17th and 18th July 129 mm of rainfall had been recorded (the average value of July is 114 mm).

On 18th July a debris flow dammed the Adda River, forming a lake extended about 260,000 m^2; starting from the 24th July frequently rock fall (almost 100 in the 24 hours before the slide) took place from Mt. Zandila, and craks were detected.

At 7:25 a. m. of 28th July the detachment of a large rock volume of about 34 million cubic meter, including the prehistorical slide, occurred; the collapse took place at a great velocity and the Morignone village previously evacuated, was destroyed.

A portion of the collapsed material rised the opposite slope of the Valtellina valley up to 300 m from the valley bottom and fell into the previously formed barrier-lake caused by the debris flow. A large mud wave moved very rapid, destroying the village of Aquilone and killing 27 people. At beginning the wave was ten meters height; in San Antonio Morignone, located 1,300 m north of the source, the wave was 15 meters height and moved with a velocity of 2 km per minute.

The volume of the accumulation, which filled the valley for about 2.5 Km, was estimated as 40 million cubic meters, with a maximum thickness of 90 m. On the surface of the landslide deposit the finer fraction was composed of millimetric to decimetric fragments, whilst the coarser material was concentrated along the flanks of the mass movement route.

The accumulation caused a new lake whith a maximun extension of about 760,000 m^2. In order to reduce the risk of a potential dam failure, it was decided to lower the level of the lake. Soon a spillway channel was constructed and three pumping stations were installed. Soon after two bypass tunnels with a total discharge of 400 m^3/sec were built.

The direct witnesses and the morphological evidences recorded after the event of the collapse allow to reconstruct the main phases of the development of the landslide:

- the first displacements, consisting of a progressive widening of the ancient landslide crown, occurred just one hour later heavy rainfalls;
- after a few seconds the entire rock mass started to slide along two main shear planes: the first was known to have a 45° dip to the east, the second was a neo-formation plane dipping 35° to the north;
- the translation movements to the north, along the latter plane (that is, toward the deep valleyfloor of Valpola), took place initially with a series of short successive impulses and with a progressively increasing acceleration until it reaches a complete stop, after the impact with a rock bluff which bordered the unstable slope; the thickness of the rock body that came into collision was estimated to be in excess of 70 m;
- following the impact, the displaced rock, which up to that moment had remained fairly compact, was subdivided into several fragments of various dimensions, falling to the valley-floor in an easterly direction from altitudes ranging from 600 to 850 m. Therefore during this phase the gravitational event which had started as a slide, rapidly turned into a rock avalanche, involving in its movement also the wood cover and the debris depositis distributed along the underlying slope. The fragmented collapse rocks, after having obstructed a large area of the valley-floor, went up the opposite slope to a height of about 300 m, preceded by a cloud of dust which rose to an altitude of 2,000 m (Govi and Turitto, 1992).

CONCLUSIONS

Most of the case histories examined in the paper show some of the main landslide typologies which occur in the Eastern Alps. Only one case is referred to the Central Alpin area.

The analysis of the climatic records (more than 50 years of recordings) has allowed to detect some critical events during the year: abundant snowfalls associated with mean daily temperatures getting significantly below 0°C during the entire Winter season; snow melting during the Spring season often associated with long, heavy rainfalls; heavier stormy rainfalls, of short duration, during the Summer season; long, heavy rainfalls, during the Autumn season.

It is quite evident that the climate in the Alps is on average very severe during all the seasons. As a consequence, it would be obvious to infer a relation which univocally links the landslide remobilizations with the above critical climatic periods.

But, the analysis of the above case histories (although referred to a limited number of landslides) has clearly shown that a remobilization does not necessarily coincide with the same critical climatic period and that it may occur during any one of these periods.

The reason of this behaviour can be ascribed firstly on the yearly climatic changes. In fact, the climatic conditions may be very different from year to year. As an example, the total rainfall may range from a minimum of 500 mm to a maximum of about 2,000 mm. This fact obviously strongly influences the landslide development.

Also the location of the landslides inside their own catchment areas and the different size of these catchment areas play a fundamental role in the landslide occurrence and/or reactivation. In fact, all the cases examined have occurred in the middle-lower part of the basins, where a larger amount of water is available the whole year round and especially during the above critical climatic periods.

Under these conditions, the groundwater recharge of the landslide bodies is partly given by the direct run-off (which may fill the opened tension cracks along the landslide surface) and partly by the subsurface flow coming from the upper part of the basins.

Furthermore, the larger amount of water which flows in this middle-lower part of the streams makes the floods particularly dangerous for the stability of the banks. In fact, the erosive action of the flooded streams may trigger off landslides and their successive reactivations, as occurred in some of the case histories here discussed.

Therefore, as the upper part of the basins strongly contribute in supplying additional amounts of water to the lower part, in which most of the phenomena has taken place, it could be of interest to enlarge the monitoring area. These enlargements should take into account not only the immediate surroundings of the landslides (as usually occurs!) but also part of the basins well uphill.

This instrumentation should give climatic and hydrological data in real time, for the purpose of detecting the additional rate of water flow coming from the upper part of the basins and therefore predicting the occurrence of landslide events.

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高山地區的山崩災害：以義大利部份地區爲例

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摘要

本文主要在描述東義大利阿爾卑斯山白雲岩地區之地質構造與其對塊體滑動間在分布上及形式上的影響，以及此種滑動最平常的形式及其破壞對於人類活動的影響。本文並提供過去幾年來，本研究區曾進行各種坡體滑動之調查及監測工作，及一些工程上的防治措施上的經驗。

關鍵字：地層滑動、災害、監測