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Recent morphological evolution and slope instability in a hilly area of Piedmont (North Italy)

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ABSTRACT

In the hilly area of Langa, which is situated to the south of the city of Alba between the Belbo and Bormida Valleys, the heavy rainfall and subsequent floods of 3–6 November 1994 triggered numerous landslides. The slides caused serious damage to residential areas and various types of infrastructure.

Engineering geological, geomorphological, geotechnical, hydrogeological, and geophysical methods were applied to investigate the instabilities. Among hundreds of failures, most of them were planar slides and debris-mud flows. However, the numerous landslides directly connected to the event represent only a part of the large and varied types of phenomenon in this area. In fact, most of the recent landslides can be considered as reactivated older ones that were more-or-less quiescent. They intersect at the depth the marly basement and are directly connected to the recent geological and tectonic evolution of the area.

The paper describes the mass movements and their causative factors. It also focuses on the hazards and risks associated with the instabilities, and their mitigation measures.

INTRODUCTION

In the last five years, five great floods have hit the Piedmont (NW Italy). Among them, the flood of 3–6 November 1994 (which was the last of the series of events) was the exceptional one and was comparable to that of the spring of 1879. The flood occupied about 7,500 km^2 of the area and about 50% of it suffered from serious damages. The event triggered off numerous landslides in the hilly area of Langa (Fig. 1), which is situated to the south of the city of Alba between the Belbo and Bormida Valleys. Among hundreds of failures, most of them were planar slides and debris-mud flows (Barisone et al. 1995). A great deal of work has been carried out to find remedies against the damages or to understand the phenomena (Compagnoni et al. 1995; Forlati et al. 1995). The historical data and morphological evidences indicate that these phenomena have repeatedly damaged the slopes and modified the landform. On the other hand, the anthropogenic structures have also adversely affected this region. Because of the widespread instabilities, the residential areas and the means of communication are now confined to a narrow zone at the top of the hills.

Most of the failures were related to the heavy rainfall. For example, in the southern Piedmont, from 240 to 290 mm of rainfall (more-or-less a quarter of yearly amount) was recorded between 3 and 6 November 1994. It had peak intensities of 40–60 mm per hour.

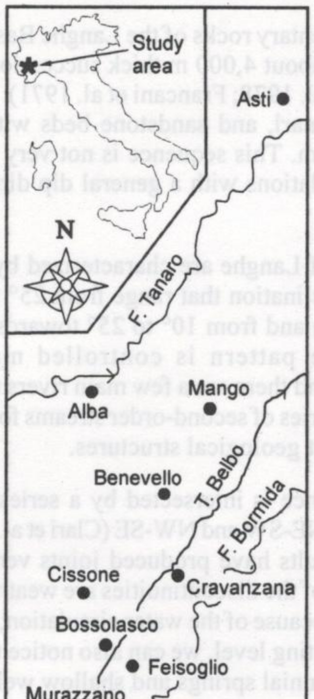

Fig. 1: Location of the study area in NW Italy

However, there were also significant human factors responsible for this disaster. The deterioration of channels and streams, planting of vegetation in the riverbeds, waterproofing of wide parts of the area, and the presence of various types of infrastructure (i.e. bridges, embankments, and buildings) obstructed the natural path of the flood.

Keeping in view the declining population in this area, it is needed to have a correct land planning and guidelines for the land development that are compatible with the physical and morphological aspects of the area. Therefore, it is necessary to identify the existing and potential unstable slopes and to evaluate the level of risk for existing structures. Consequently, it will be possible to identify the best possible use for various areas.

Assuming that it is impossible to move hundreds of residential areas that are subject to risks, we must develop, earlier in the process, new building plans, roads, and land use that take into account the stability of slopes.

In this paper we have outlined some of the most significant aspects of complex phenomena connected to the interaction between the heavy rainfall events and geological conditions. The land planning undertaken in the phases subsequent to the disaster are also discussed.

GEOLOGICAL AND GEOMORPHOLOGICAL ELEMENTS

The sedimentary rocks of the Langhe Basin are made up essentially of about 4,000 m thick succession of turbidities (Bortolami et al. 1978; Francani et al. 1971). The turbidities contain clay, marl, and sandstone beds with thickness of about 30–50 cm. This sequence is not very deformed, and has mild undulations with a general dip direction towards NW.

The hills of Langhe are characterized by asymmetrical slopes with inclination that range from 25° to 40° towards the scarp slope and from 10° to 25° towards the dip slope. The drainage pattern is controlled mainly by this morphology, and there are a few main rivers that are incised deeply and a series of second-order streams following mainly some important geological structures.

This sequence is intersected by a series of faults with main trends of NE-SW and NW-SE (Clari et al. 1994). In some areas, these faults have produced joints very pervasive in surface. Most of the discontinuities are weathered and filled up with clay, because of the water circulation; as an evidence of the high jointing level, we can also notice the presence of numerous perennial springs and shallow wells.

These geological structures are responsible for the tendency of the area to slide. There are a great number of instabilities that have evolved with time through a series of movements connected to the fluvial event like the flood of November 1994. Furthermore, the landslides themselves create a typical landform that plays an important role in their further development and reactivation.

MASS MOVEMENTS

Many authors have studied the fluvial events that triggered landslides. In particular, the studies of Boni (1941), Cortemiglia and Terranova (1969), Sorzana (1980), Govi (1988) and the Regione Piemonte (1994) revealed that many landslides were associated with the past events. In particular, in the last 150 years there were 25 events that produced large landslides in the Tanaro, Bormida, and Belbo Valleys. Among them, the landslides of 1887, 1951, 1957, 1960, 1968, 1972, 1974, and 1994 caused most sever damages.

The heavy precipitation that occurred between 4 and 6 November 1994, with values of about 300 mm recorded at the Treiso gauging station (376 m amsl), and about 200 mm at Mombarcaro (906 m amsl), have caused many failures. A systematic observation of more than 200 mass movements triggered by the heavy downpour enabled us to identify the following types.

Debris-mud flows

Debris-mud flows are widespread (both in number and extent) all over the region, and are encountered mainly on steep slopes. The flows usually involve only the colluvium or the superficial part of the weathered marly bedrock. They can be very long (up to 500 m) and often join with the second-order streams.

Falls

They are quite unusual and always of medium to small dimensions (< 10,000 m^3). They occur mainly on sandstone because of toe undercutting of the slope by water.

Planar slides

Planar slides are usually of large dimensions (>100,000 m^3) and involve the bedrock up to the depth of 25 m. The main moving part of the slide splits into a series of prisms that move along one or (rarely) more sliding surfaces, almost parallel to the dip of the layers. The sliding usually takes place on probable old sub-horizontal faults, which are filled up by weathered reddish-brown colored consolidated clay. These discontinuities always (even in periods particularly dry) contain water and, in case of heavy rains, the discharge can reach some litres per second along fronts of about 10 of metres in length. There are frequent cases where sliding has not yet begun but tension cracks are seen in the ground. These cracks are frequently more than 100 m long and sometimes open for more than 1 m.

The ground movement can be discerned by the development of cracks in the houses, by the movement of the transmission line with pylon, and by the hummocky ground morphology. But in most of the cases, it is a reactivation of an ancient slide. Among these landslides, we distinguished the following three types (Fig. 2) on the basis of their kinematics:

Rock block slides

The sliding takes place along surfaces with the inclinations similar to the dip of the slope (from 6° to 12°). The displacement of larger blocks is often more than 30 m and it causes intense deformation involving dilation in the top-middle part of the main body and compression in the lower part. The main scarp generally follows the pre-existing discontinuities constituted by traction joints or small faults, sometimes filled up with mud or debris.

Step slides

They are planar slides that took place along surfaces that were parallel to each other at different levels of the stratigraphic sequence. They usually develop on slopes steeper than the previous ones, involving the rock deeper than 20 m. On the basis of the geometry of these landslides, we think that the movement initiated in the lower part, starting soon afterwards translations in the upper parts. In all the cases we observed, the slides reach the bottom of the valley, creating sometimes landslide dams.

Rotational slides evolving into planar slides

They originate in slopes that are steeper than the dip of slip surfaces. The crown is characterised by rotational movement along new cracks, while the main body follows more-or-less translational movement. Morphologically, these

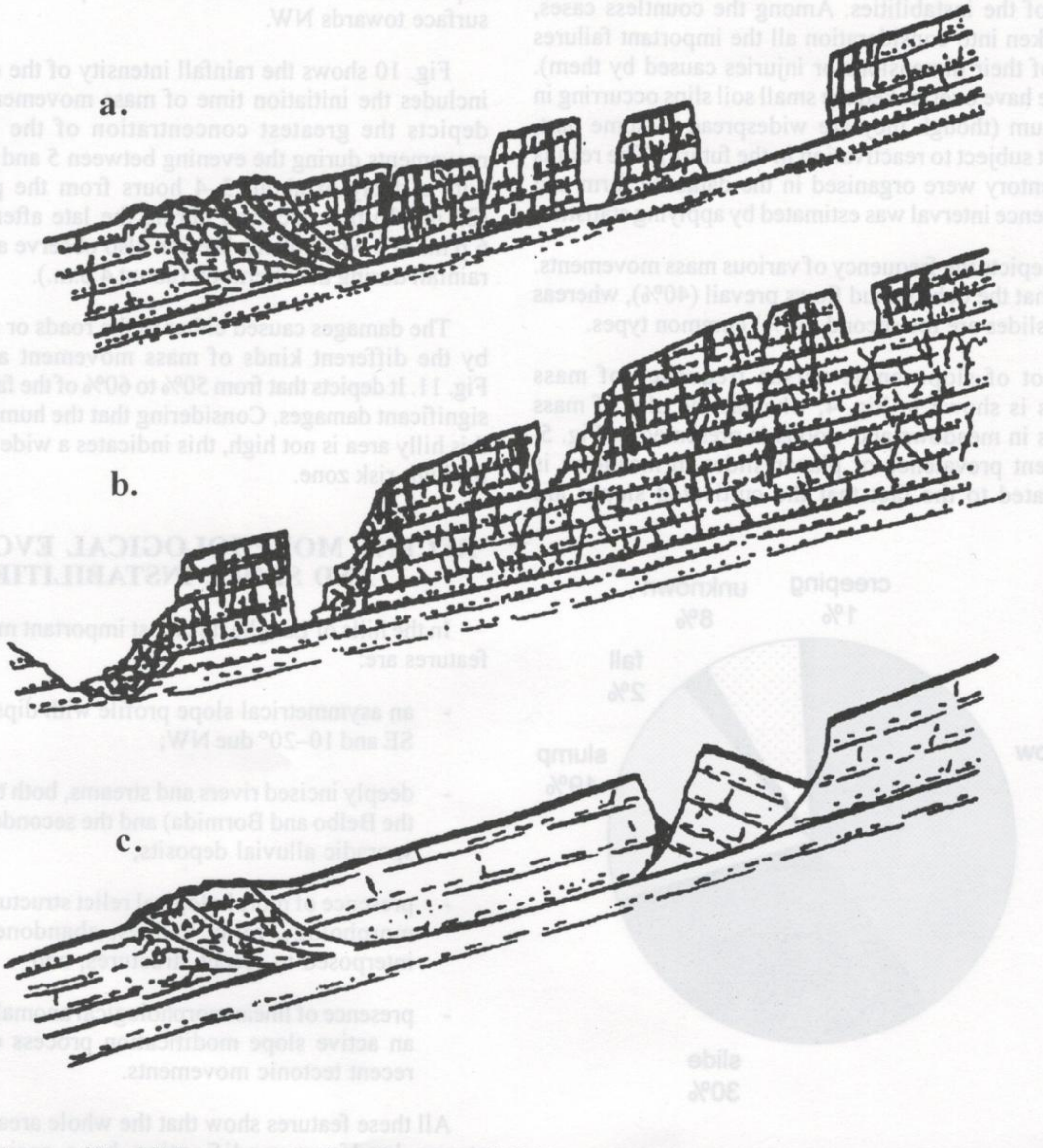

Fig. 2: Three types of landslide observed after the event of 1994: a. Rock block slide; b. Step slide; c. rotational slide evolving in planar slide

types can be identified by the presence of secondary scarps and depressions in the upper part, and translated blocks and areas deformed by compression in the lower part.

Rotational slides

These are slides not very common in the area. They usually take place on deposits more homogeneous, generally in clayey marls. The slides are usually small and occur on rather steep slopes resulting from river undercutting.

GEOMORPHOLOGICAL ASPECTS OF LANDSLIDES

In order to identify some of the basic parameters that cause these landslides strictly connected with the strong precipitation, we have carried out a general study and an inventory of the instabilities. Among the countless cases, we have taken into consideration all the important failures (in terms of their dimensions or injuries caused by them). Usually, we have overlooked the small soil slips occurring in the colluvium (though they are widespread in some part, they are not subject to reactivation in the future). The results of the inventory were organised in the database form and their recurrence interval was estimated by applying statistics.

Fig. 3 depicts the frequency of various mass movements. It reveals that the debris-mud flows prevail (40%), whereas the planar slides are the second (30%) common types.

The plot of slope angle versus frequency of mass movements is shown in Fig. 4, whereas the plot of mass movements in meadows and woods is presented in Fig. 5. The apparent prevalence of planar slides in meadows is mainly related to the fact that the cultivated slopes are generally gentle. In the same way, though the debris-mud flows show a clear concentration in woods, it just means that these areas are the ones with steeper slopes and hence difficult to cultivate. In other words, the study indicates that the main triggering factor was the exceptional precipitation. On the other hand, in case of lower intensities of precipitation, the tree coverage contributes to limit the debris-mud flows and soil erosion.

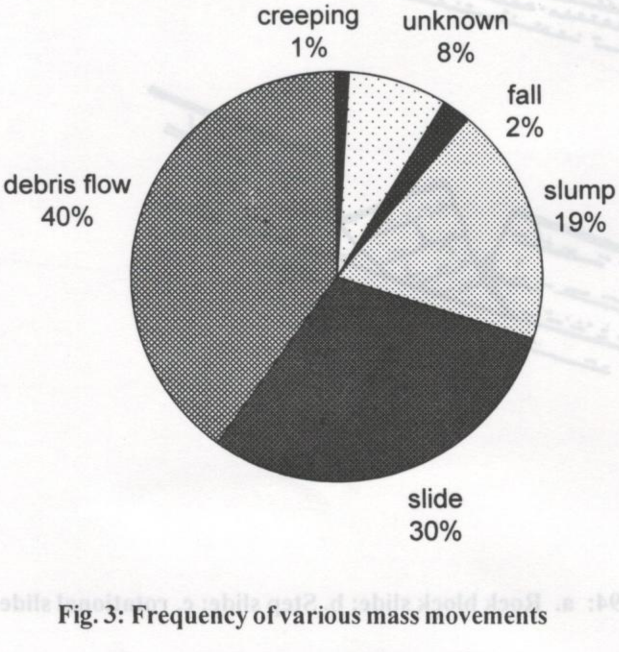

Fig. 3: Frequency of various mass movements

Fig. 6 and 7 depict respectively the area and volume occupied by various mass movement types. They reveal that debris flows are more frequent among the smaller (in area and volume) mass movements whereas slides prevail in larger ones. Fig. 8 and 9 show respectively the depth of failure and dip direction of the slip surface in the planar slides. They reveal that the most common planar slides have depth of failure of less than 5 m and dip direction of the slip surface towards NW.

Fig. 10 shows the rainfall intensity of the event. It also includes the initiation time of mass movements. The plot depicts the greatest concentration of the initial mass movements during the evening between 5 and 6 November with a delay of about 3–4 hours from the peak rainfall (25 mm/h) that occurred during the late afternoon (about 6 p.m. of 5 November). We can also observe an antecedent rainfall during the afternoon (about 4 p.m.).

The damages caused either to the roads or to the houses by the different kinds of mass movement are shown in Fig. 11. It depicts that from 50% to 60% of the failures caused significant damages. Considering that the human activity in this hilly area is not high, this indicates a wide area lying in the high-risk zone.

RECENT MORPHOLOGICAL EVOLUTION AND SLOPE INSTABILITIES

In the hills of Langhe, the most important morphological features are:

- an asymmetrical slope profile with dips 30–40° due SE and 10–20° due NW;
- deeply incised rivers and streams, both the main (i.e., the Belbo and Bormida) and the secondary ones with sporadic alluvial deposits;
- presence of morphological relict structures (step-like morphology, relict valleys, abandoned channels) interposed to recent structures; and
- presence of linear morphological anomalies that show an active slope modification process connected to recent tectonic movements.

All these features show that the whole area is subject to strong landform modification by a series of recent phenomena of deepening of basal level of the drainage

Fig. 4: Plots of slope angle versus frequency of mass movements

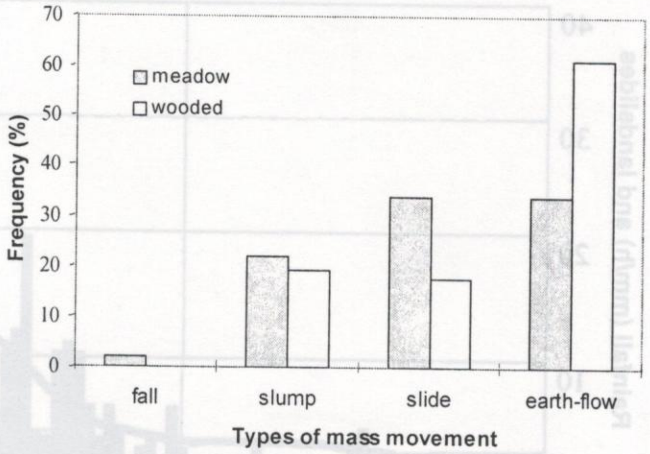

Fig. 5: Plot of mass movements in meadows and woods

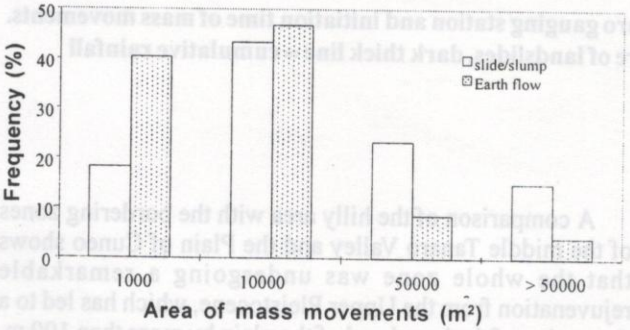

Fig. 6: Area occupied by various mass movement types

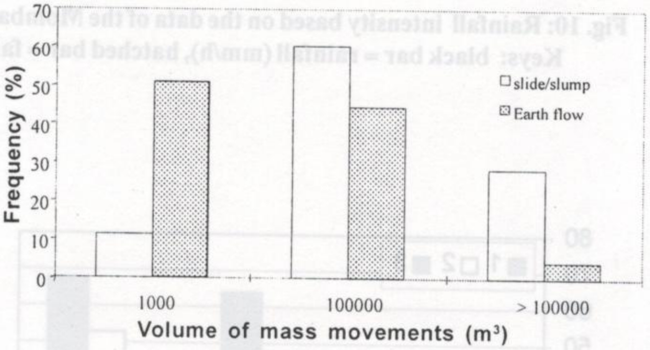

Fig. 7: Volume occupied by various mass movement types

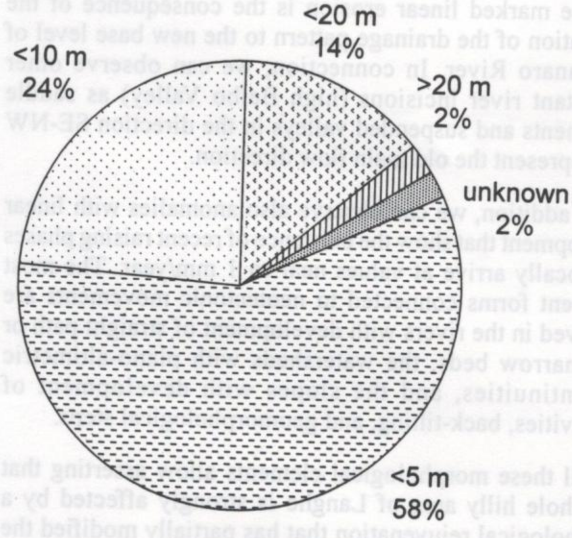

Fig. 8: Depth of failure of slip surface in the planar slides

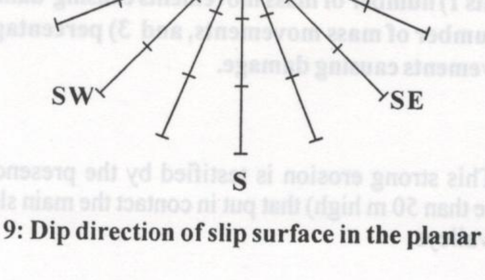

Fig. 9: Dip direction of slip surface in the planar slides

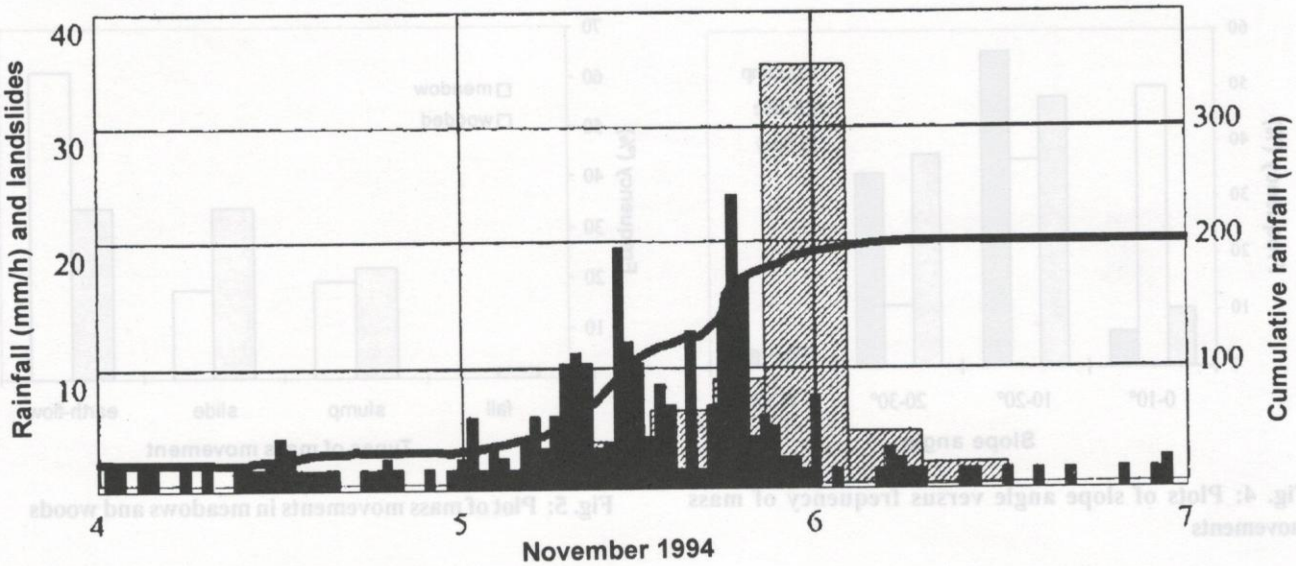

Fig. 10: Rainfall intensity based on the data of the Mombarcaro gauging station and initiation time of mass movements. Keys: black bar = rainfall (mm/h), hatched bar = failure of landslides, dark thick line = cumulative rainfall

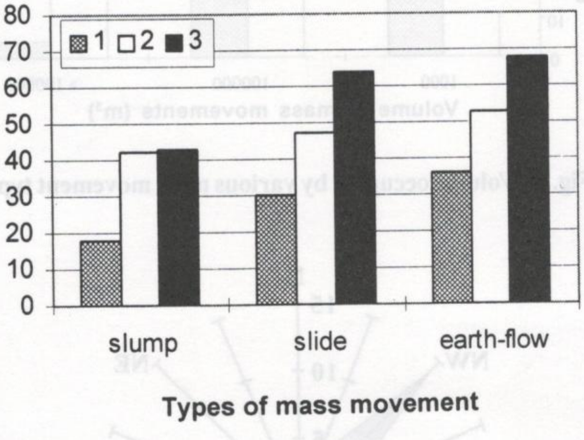

Fig. 11: Damage caused to roads and houses by various mass movements 1) number of mass movements causing damage, 2) total number of mass movements, and 3) percentage of mass movements causing damage.

pattern. This strong erosion is testified by the presence of cliff (more than 50 m high) that put in contact the main slopes with the valleys.

A comparison of the hilly area with the bordering zones of the middle Tanaro Valley and the Plain of Cuneo shows that the whole zone was undergoing a remarkable rejuvenation from the Upper Pleistocene, which has led to a deepening of the base level of the plain by more than 100 m. It was linked to the deflection and incision of the Tanaro River (Carraro et al. 1980).

The marked linear erosion is the consequence of the adaptation of the drainage pattern to the new base level of the Tanaro River. In connection, we can observe other important river incisions (high Belbo Valley) as saddle alignments and suspended valleys in the direction SE-NW that represent the old main flow direction.

In addition, we can observe also anomalies with linear development that show the existence of recent raising phases that locally arrive at values near to 1 mm/year. The most recurrent forms connected to neotectonic movements are observed in the rivers with development of straight path or with narrow beds, the watersheds with plano-altimetric discontinuities, and the slopes with development of concavities, back-tilting, and geomorphological steps.

All these morphological elements allow asserting that the whole hilly area of Langhe is strongly affected by a morphological rejuvenation that has partially modified the old landforms. At present, the rapid evolution is due both to the effects produced by the deepening of the base level of the valley as well as the raising of the hilly areas. All these geomorphological phenomena had a clear bearing on the distribution of failures of different types in that area. The following morphological elements contributed more or less directly to the development of the mass movements:

- presence of erosional scars that cut the slopes at the bottom (connected to the rapid and recent deepening of the drainage pattern);
- presence of structural discontinuities parallel to the bedding surfaces;
- presence of shear joints with a considerable length (more than 500 m) and opening;
- presence of deep deformations and old landslides in the area; and
- presence of secondary valleys in the upper reaches of streams characterized by incipient failures induced by the strong water erosion.

All these elements constituted an important cause that was responsible for the failure of numerous landslides in the slopes of Langhe. Fig. 12 is a morpho-structural sketch of an area close to the village of Cissone where we can see this connection among the recent landslides of 1994 and morphological anomalies linked to the recent evolution.

REDUCTION OF GEOMORPHOLOGICAL RISKS

Reduction of geomorphological risks needs actions based on mitigation of the hazards induced by the natural factors as well as the human presence. For this purpose, the following three measures were recommended:

- mitigation of natural hazards by stabilising the sliding slopes, improving surface drainage, and carrying out re-vegetation of slopes;
- resettlement in safe areas; and
- territorial management.

The first two points are generally very expensive because they involve the construction of complex structures, are not always completely effective, and sometimes need significant modifications of the ecosystem. But the third point is less expensive. Nevertheless, it is very difficult to do this type of effort in areas so complex, in which the problems arise after years of quiescence. In this case the probability and recurrence of the events should be valued in terms of "compatible risk". In this case, in addition to an evaluation based on the probability of the manifestation of the failures, we must deal also with an evaluation of the importance and singleness of some structures and also of the mitigation and monitoring systems that can be realistically used to reduce the risk to its lowest limits.

The basic aspects of this territorial management in which the risk evaluation can give an important contribution are: obligations and limitations of the land use, arrangement of monitoring and emergency systems programs for prevention and mitigation, also for the management of possible emergencies and calamities.

In addition, considering the widespread failures in the area, this method was not applied to the single landslide, but to the whole slopes even where they seemed to be apparently stable. We studied the representative slopes with typical morphological and geological characteristics. We also studied the areas hit by large landslides and the possible areas for resettlement. The representative slopes contained not only the areas apparently stable, but also the old instabilities (these old instabilities can be recognised from the historical data and aerial photographs), recent planar slides, and signs of incipient instability (such as fractures caused by traction and deformation of the slope). The study was confined to the following activities:

- analysis of the recent geomorphological evolution;
- study of lithology, stratigraphy, and structure;
- mineralogical analysis of the clayey and marly horizons;
- geotechnical studies;
- detailed study of landslides;
- geophysical analysis;
- analysis of the previous meteorological events;
- hydrogeological investigation of aquifers; and
- conceptual and numerical modeling.

The study revealed various complex phenomena. For example, with rather good geotechnical properties of soil (more than 30° of ϕ_{peak} and 20° of $\phi_{residual}$), the gentle (less than 10°) slopes suffered from many plane failures. Sometimes these slopes also showed the signs of old instabilities.

The geophysical profiles (Vertical Electrical Drilling) show also that the upper part (10–30 m) of the rock mass has very low resistivity values, pointing out to the presence of a very fractured zone (probably because of slow and prolonged gravity movement), considerably deeper than the depths of recent planar slides (Fig. 13).

The continuous monitoring of water level in the wells shows a direct relationship between the heavy rainfall and the impulsive behavior of the aquifer, with remarkable sudden rise in the piezometric level after a short delay. This particular hydraulic behavior is responsible for the initiation

Fig. 12: Geomorphological map of the Cissone area: 1) scarp, 2) 1994 planar slide, 3) 1941 planar slide, 4) isolated block, 5) area affected by gravitational process, 6) stream, 7) stream in erosion, 8) trenches, 9) hummocky topography, 10) lineation, 11) planar-altimetric discontinuities.

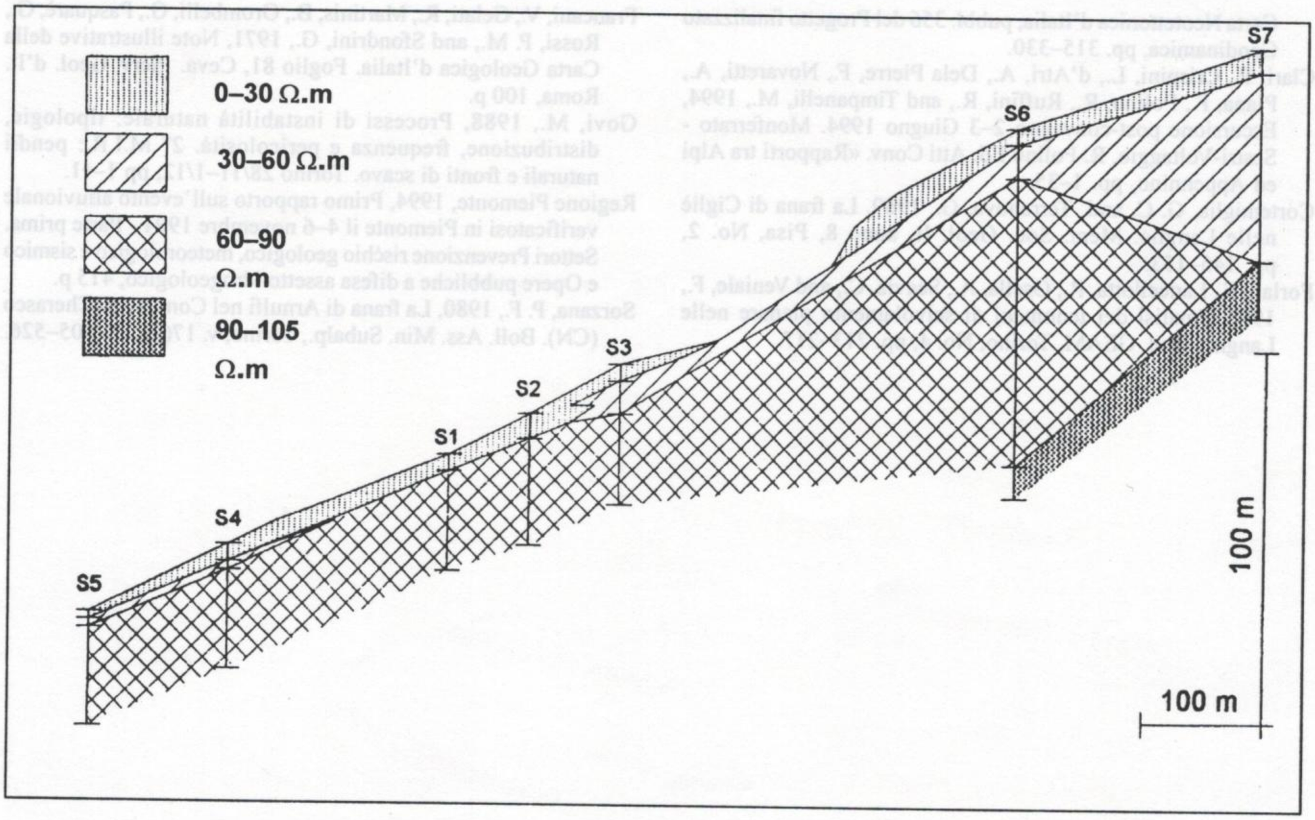

Fig. 13: Geo-electrical profile (resistivity) of Cissone Landslide-Loc. Pianezza

of landslides in this hilly area, as they have a good temporal correlation between the precipitation peaks and the activation of the landslides during the event of November 1994.

CONCLUSIONS

The heavy rainfall and floods of 1994 triggered several types of mass movement in the hilly area of Langhe. The geomorphological analysis of this area shows the presence of slopes highly susceptible to failures of various kinds. Furthermore, there are superficial landslides directly connected to the heavy rainfalls, and deep-seated failures linked to the recent morphological evolution of the drainage pattern and the tectonic activity in that area.

In this context, the proposed mitigation measures were not just the stabilisation of unstable areas but the efforts towards reducing the severity of triggering factors. Among these preventive works, reducing the riverbed erosion and river training works were the important ones. An overall rise in the base level of the drainage systems could effectively oppose the numerous instabilities linked to the toe undercutting of hills that undergo subsequent large-scale planar failures. It could also have a positive impact on the heads of the secondary valleys, having the opportunity to limit the shallow-seated slope failures. Therefore, the strategy of slope stability works should integrate the stabilisation of individual landslides with the overall stabilisation of the riverbeds.

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