Geologic and Geomorphic Factors of the Landslides Triggered in the Cardoso T. basin (Tuscany, Italy) by the 19th June, 1996 Intense Rainstorm

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INTRODUCTION

On June 19, 1996 an exceptionally intense rainfall event fell in the southern Apuan Alps (Tuscany, Italy): ca. 474 mm rainfall was recorded within 12 hours (21% of the annual rainfall) and the maximum rainfall intensity recorded was 158 mm/hour. The rainstorm hit a territory ca. 150 km^2 wide in the area of the main watershed between the Versilia and the Serchio River basin. It caused hundreds of landslides, flooding of wide areas, 14 fatalities and very heavy damage (Caredio et al., 1998; D'Amato Avanzi, 1999).

Here, the results of the studies on the landslides occurred in the Cardoso Torrent basin are summarized. This basin (Fig. 1), 13 km^2 wide, was the most severely damaged area, where almost 400 landslides were triggered. Its morphology is typically mountainous, with deeply cut valleys and steep slopes, mostly underlain by mainly metamorphic, impervious rocks; among which the Pseudomacigno Fm. (metamorphic sandstone interbedded by phyllite) prevails. These slopes are largely covered by thin colluvial deposits, with a 30°-40° slope gradient and covered with woods. Permeable calcareous and dolomitic rocks form the highest peaks of the area, where the slope steepness is often greater then 60°-70°.

LANDSLIDE CHARACTERISTICS

The rainstorm triggered at least 382 mappable landslides (ca. 30 landslides/km^2): 357 were first time landslides, while the others partially mobilized dormant landslide bodies. According to some witness, many landslides were activated in a short time, when ca. 250 mm rainfall within 8 hours had been recorded (ca. 31 mm/hour). This rather high value may represent the landslide-triggering rainfall threshold in the study area.

Type of movement

According to Cruden and Varnes's (1996) classification, the types of movement of the landslides in the Cardoso T. basin were sub-divided into: a) fall, b) translational slide, c) flow, d) complex, translational slide-flow, e) complex, rotational slide-flow and f) complex, rotational-translational slide-flow. The percentage of each type of movement is represented in Fig. 2.

The typical landslide was a shallow landslide (0.5-2.5 m thick) with a high length to breadth ratio ($3<L/B<20$). This feature is probably due to loss of structure and fluidification of materials. In fact, because of the slope steepness, many debris slides attained high velocities (some m/sec) and turned in debris flows. The sliding and flowing masses often poured into the riverbeds, mixed with the runoff and overloaded streams with sediments and wood. Thus, the

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most common landslide movements were complex, very or extremely rapid, debris slides-debris flows (Cruden and Varnes, 1996); according to Campbell (1975), they may be named soil slips-debris flows. These phenomena represent typical effects of intense rainstorm: the rapid infiltration of rainfall, causing soil saturation and rise in pore-water pressure is probably the mechanism by which most shallow landslides were triggered (Wieczorek, 1987, 1996).

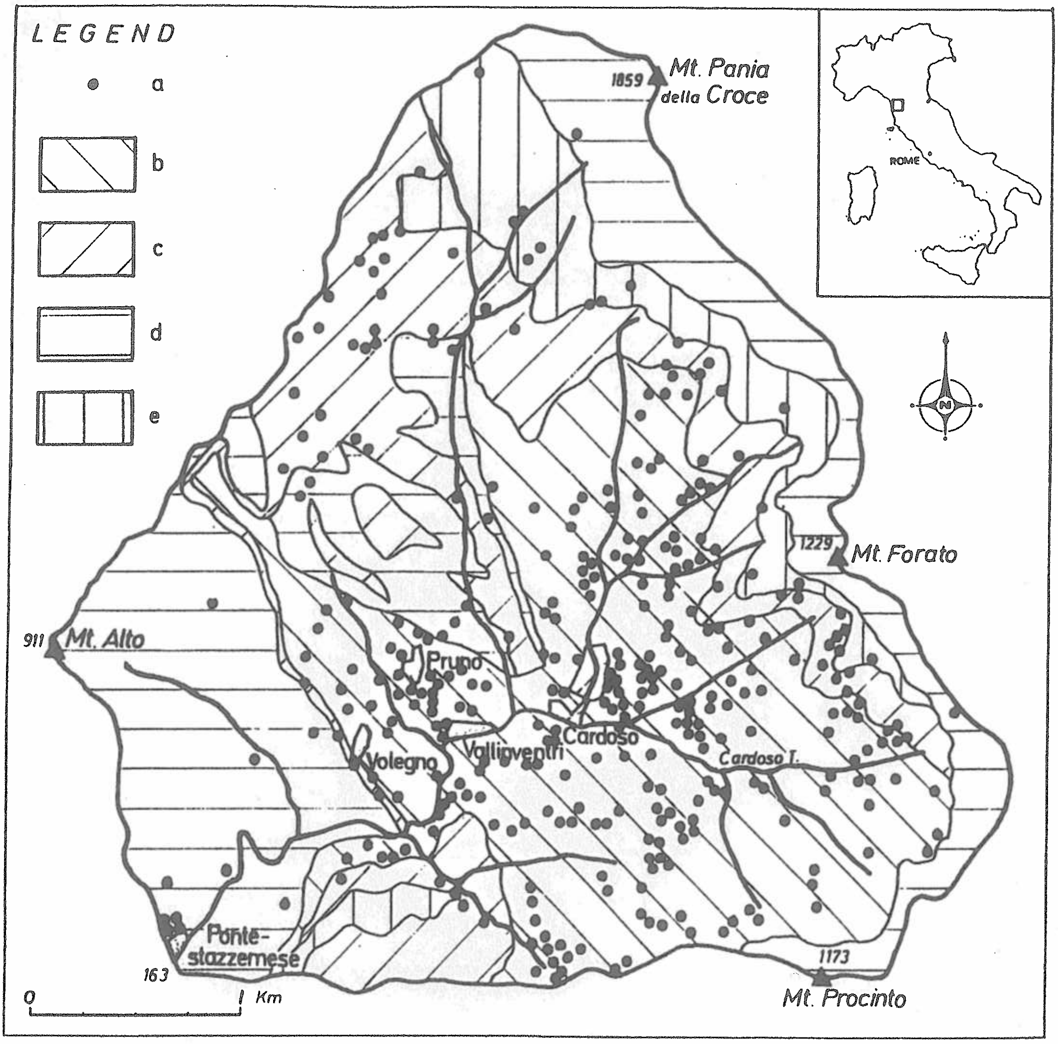

Fig. 1. Sketch map of the study area: a) landslide of June 19, 1996; b) metamorphic sandstone and siltstone (Pseudomacigno Fm.); c) phillyte and schist; d) limestone and dolomite; e) cavernous limestone.

Material involved

The landslides generally involved only the regolith cover of slopes (0.5-2.5 m thick). Among them, 96.1% involved colluvium (Fig. 3), consisting of a poorly sorted, matrix-supported, mixture of angular rock fragments and fine-grained materials; 3.3% involved talus deposits, mainly rock-supported, formed of calcareous and dolomitic angular rock fragments and forming screes and talus cones at the base of cliffs or rocky chutes. The failure surface usually

developed at the contact between the regolith cover and the bedrock, while sometimes the superficial portion of bedrock was also involved. Very few landslides occurred in man-made deposits (quarry dumps or filling materials). The scarcity of landslides in talus and man-made deposits was mainly due to their high permeability and also to their limited spread.
The most significant parameters of the landslides were analysed in order to identify the factors which most influenced their activation and effects. The studies in the landslide sites highlighted many geologically and geomorphically recurrent factors, explained below.

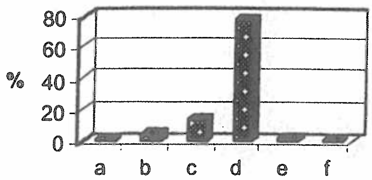

Fig. 2. Landslide distribution related to type of movement: a) fall; b) translational slide; c) flow; d) complex, translational slide-flow; e) complex, rotational slide-flow; f) complex, rotational-translational slide-flow.

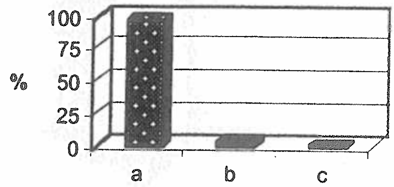

Fig. 3. Landslide distribution related to material involved: a) colluvium; b) talus; c) man-made deposits.

Bedrock characteristics

As shown above, the landslides of June 19, 1996 mainly involved the regolith cover of the slopes. Some characteristics of the bedrock (lithology, permeability, discontinuity) in landslide sites were investigated. The formations underlying the basin were grouped according to lithology: a) metamorphic sandstone and siltstone, b) phillyte and schist, c) limestone and dolomite, d) cavernous limestone. Percentage of basin area, landslide density (surface of landslides divided by total surface), percentage of total landslides and surface involved in sliding were calculated for each group. The main results are summarized by Fig. 4: in landslide sites, the bedrock was generally made up of impervious or scarcely pervious rocks; among them, the Pseudomacigno Formation (metamorphic sandstone with interbedded phillyte) was the most common one (8.4% of landslide density).

74.9% of landslides occurred on slopes underlain by metamorphic sandstone with interbedded phillyte (Pseudomacigno Fm.), while 17.8% occurred on slopes underlain by phillyte and schist; these types of rock respectively occupy 36.2% and 20.8% of the whole surface of the Cardoso T. basin. Then, we deduce 92.7% of landslides occurred in the covers of impervious or scarcely pervious rocks, occupying 57% of the area of the basin, while 7.3% only of landslides occurred in the covers of pervious rocks, occupying 43% of the basin. This is confirmed by the landslide density of the Pseudomacigno Fm. (8.4%), very higher than others.

The attitude of main discontinuities (bedding or schistosity) of the bedrock with respect to the slope immersion was also analized for 205 landslides, involving the cover of the Pseudomacigno Fm. in a sample area 3.25 km^2 wide (ca. 3/4 of its outcropping surface). This area was divided in three domains, according to the attitude of the discontinuity (downslope, upslope or oblique); area of domain, percentage of landslides and landslide density were calculated for each domain. Most of landslides (45.9%) occurred in the "downslope" domain

(Fig. 5), occupying only 33.5% of the sample area. This domain also favoured a large extent of landslides, which there reached 52.6% of the total landslide area.

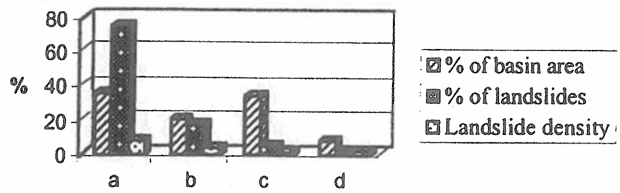

Fig. 4. Landslide distribution related to bedrock lithology: a) metamorphic sandstone and siltstone; b) phillyte and schist; c) limestone and dolomite; d) cavernous limestone.

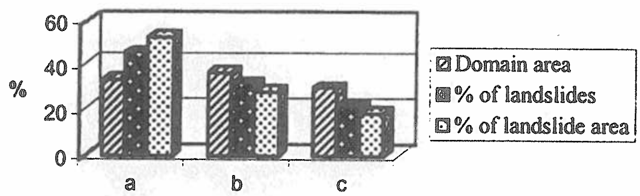

Fig. 5. Landslide distribution related to the attitude of main discontinuities: a) downslope; b) upslope; c) oblique.

Slope shape and gradient

Landslides were related to profile, surface (Panizza, 1992) and gradient of the slope in landslide sites.

Slope profile

According to Panizza (1992), the possible profiles for slopes are: rectilinear (the gradient is uniform from top to bottom), concave (the gradient decreases from top to bottom), convex (the gradient increases from top to bottom), concave-convex, convex-concave and complex. In the Cardoso landslide sites, the rectilinear profile was the most frequent one. Nevertheless, it should emphasized that this particular profile is very common in the studied basin and is probably not a significant parameter.

Slope surface

According to Panizza (1992), the possible shapes for slope surface are: planar (rectilinear counturs), truncated cone convex shape (counturs convex towards the slope toe), truncated cone concave shape (counturs concave towards the slope toe). In 55.8% of the examined landslide sites, the shape of the slope was truncated cone concave (Fig. 6), corrisponding to a small basin or hollow. In these situations the concave geometry of the regolith/bedrock interface favoured the convergence of groundwater flow and the build-up of pore pressure, leading to failure.

Slope gradient

Most of landslides occurred where the slope gradient was from 36° to 40° (Fig. 7); 89.5% of landslides occurred on rather steep slopes (31°-45°). On steeper slopes (less frequent), landslides were uncommon, probably because on these slopes the regolith cover is little developed or absent; moreover, these slopes are often underlien by pervious rocks.

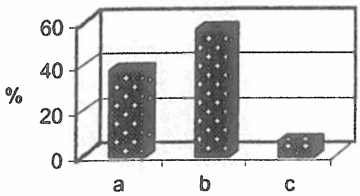

Fig. 6. Landslide distribution related to slope surface: a) planar; b) truncated cone concave shape; c) truncated cone convex shape.

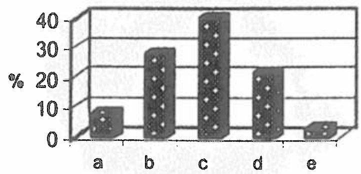

Fig. 7. Landslide distribution related to slope gradient: a) 25°-30°; b) 31°-35°; c) 36°-40°; d) 41°-45°; e) > 45°.

Land use and vegetation

By means of on-site investigation and using a vegetation map (Amorfini et al., 1997), the vegetation cover was examined and subdivided into four classes: chestnut wood, mixed wood (oak, hornbeam, beech, maple, ash), grassland (Brachypodium genuense) and cultivated or ex-cultivated, terraced areas. We can note that the chestnut wood was the area most involved in sliding (76.7% of landslides). On the other hand, chestnut woodland represents the most widespread coenosis throughout the basin and generally grows on impervious or scarcely pervious rocks (such as Pseudomacigno Fm., where most of the landslides occurred).

Surface involved and volume of mobilized material

The total surface involved in landslides of June 19, 1996 was estimated at ca. 0.55 Km^2, 4.2% of the whole basin surface. 81.4% of this surface was covered by chestnut trees: thus, more than 4,000 chestnut trees was uprooted by the landslides and fell into the riverbeds. It significantly contributed to the widespread destruction and blockage of bridge spans (with flooding), also downstream of the study area. We estimate the total volume of material mobilized by landslides at ca. 850,000 m^3: most of this volume (ca. 755,000 m^3) poured into the riverbeds, while the rest (ca. 95,000 m^3) remained on the slopes involved. The total volume of the material mobilized on June 19, 1996 by both slope and stream processes was estimated at ca. 1,400,000 m^3 in the whole Cardoso T. basin; thus, ca. 645,000 m^3 were mobilized by stream erosion in the riverbeds.

Conclusions

The results of the studies on almost 400 landslides triggered in the Cardoso T. basin by the June 19, 1996 rainstorm enable us to make some remarks. These studies identified some factors which most influenced location and characteristics of landslides.

The most common landslides were complex, very or extremely rapid debris slides-debris flows and involved the colluvium cover of the slopes. The characteristics of the bedrock (lithology, permeability and attitude of discontinuities) were of primary importance in determining landslide locations: most of landslides involved slope covers underlain by the Pseudomacigno Fm. (impervious, metamorphic sandstone with interbedded phillyte), which often had a significant discontinuity dipping downslope. This may explain the particularly high landslide density in some tributary basins, such as the Colombetta T. basin, where the landslide density reached 66.7 landslides/km^2. In fact, this particular basin is almost totally underlain by Pseudomacigno Fm. The distribution of landslides related to the slope morphology evidenced a rather typical slope configuration, characterized by rectilinear profile, truncated cone concave, hollow type shape, rather high gradient (31°-45°) and densely covered by chestnut wood.

On the other hand, some slopes showing these characteristics were not involved in sliding. This is probably due to the great heterogeneity of the rainstorm, so that a different rainfall intensity and/or amount poured on neighbouring slopes. Moreover, the present study considered only the most important parameters of landslides. The research is still in progress and involves particularly three areas of interest: determination of landslide-triggering rainfall thresholds, response of pore pressure to rainfall and geotechnical parameters of hillslope materials. These data would help us to evaluate better the conditions of slope stability and the critical landslide-triggering rainfall thresholds. However, the present results (through the knowledge of the recurrent factors in landslide activation) already enable us to perform risk scenarios and plan works of prevention, also in neighbouring territories, where risk conditions are similar.

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