The role played by mountain tracks on rainfall-induced shallow landslides: a case study

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Abstract: Mountain tracks often play a key role for landslide occurrence inside shallow soil deposits affecting both superficial and sub-superficial groundwater circulation. This is essentially related to local changes of topography and soil hydraulic conductivity. Significant examples of tracks-related landslides were observed during the event that affected the Campania region (Southern Italy) in May 1998. These phenomena occurred inside source areas characterised by complex landforms, stratigraphy and groundwater regime. Referring to this event, the paper addresses the role played by the stratigraphy on the first-failure stage by using limit equilibrium and stress-strain analyses. The numerical results outline some important aspects that must be carefully considered in analyses aimed at an advanced characterisation of landslide source areas.

Keywords: Rainfall, Shallow landslides, Flow-type, Mountain tracks, Cuts.

1. INTRODUCTION

Rainfall is the most frequent triggering factor for shallow landslides in a variety of unsaturated soils [Alonso et al., 1995]. For these landslides, the infiltration process and consequent failure stage are primarily controlled by rainfall patterns (i.e. intensity and duration) [Rahardjo et al., 2001], soil initial conditions [Tsaparas et al., 2002], and local natural factors such as slope angle breaks, thinning of deposits and close-ended layers. Slope instability phenomena can also be induced by anthropogenic factors such as mountain tracks and cut slopes, especially when acting on singular points of the hillslope. Mountain tracks are generally associated with changes in topography, discontinuities of stratigraphy and lower soil hydraulic conductivity values compared to those of the neighbouring zones [Gasmo et al., 2000; Luce and Black, 2001]. As a consequence, along the tracks, rainwater can generate surface runoff, ponding conditions and erosion processes that often produce significant rills and gullies, as reported for well documented cases of Thailand [Ziegler et al., 2004], Australia [Croke and Mockler, 2001], US Virgin Islands [McDonald et al., 2001] and Malaysia [Sidle et al., 2004]. Cut slopes, commonly associated to mountain tracks, can also cause increased erosion processes and volumes of water runoff. Finally, lateral redistribution of water runoff can occur at the bends of tracks affecting the adjacent zones [Ziegler et al., 2004]. The effects of anthropogenic factors on superficial and sub-superficial groundwater circulation are particularly relevant in some areas of the Campania region (Southern Italy) where pyroclastic deposits overlie carbonate massifs. A paradigm example is provided by the May 1998 Sarno-Quindici event when some destructive landslides systematically occurred inside source areas characterised by complex landforms, stratigraphy and groundwater regime. A comprehensive analysis of the occurred phenomena requires a careful investigation of the previously mentioned factors. Among these, the paper focuses on the soil stratigraphy taking into account the typical in-situ conditions and local boundary conditions related to mountain tracks.
2. CASE STUDY

2.1 The landslides occurred in May 1998

In May 1998, heavy rainfall [Cascini et al., 2000; Fiorillo and Wilson, 2004] triggered several destructive landslides of flow-type in unsaturated pyroclastic deposits overlying the Pizzo d’Alvano limestone massif (Sarno-Quindici event) [Cascini, 2004; Cuomo, 2006] caused by different and complex triggering mechanisms. Cascini et al. [2008] recognised that the 16% of the 133 analysed landslide source areas were related to the presence of mountain tracks (Fig. 1a, b), along the hillslopes facing the town of Quindici (Fig. 1c). These slope failures mostly occurred along the flanks of gullies that were extensively affected by anthropogenic modifications especially in the last decades [Calcaterra et al., 2003]. Particularly, the failures occurred at the bends of tracks (scheme M3a of fig. 1b), later propagating downwards and upwards along the hillslopes. Adjacent zones were also systematically affected by landslides (scheme M3b of fig. 1b) due to lateral enlargement of the original unstable areas. In some cases, source areas with compound landforms were observed also due to the combination of the above anthropogenic factors and natural discontinuities of the pyroclastic deposits (i.e. bedrock scarps up to tens of meters tall) (Fig. 2).

The correspondence of some landslide source areas with mountain tracks is widely emphasised in the current literature. Di Crescenzo and Santo [2005] outline that 44% of these areas were connected to man-made cuts and tracks, located at distances lower than 10 m in most cases. Guadagno et al. [2005] recognise that 49% of the analysed failures occurred above man-made cuts and 12% involved fills downslope the tracks. These authors interpreted the failures as debris avalanches phenomena (i.e. characterised by triangular shaped source

Figure 1. Shallow landslides of flow-type connected to mountain tracks during the May 1998 event.

Figure 2. In-situ evidences for some landslides occurred along the hillslopes facing the town of Quindici.
areas) and performed statistical analyses to correlate the height of cuts to other morphometrical parameters (i.e. apex angle of source areas and slope angle). However, poor correlations were obtained essentially due to the assumed triggering mechanism and because some key triggering factors were not included in the analysis (i.e. pore water pressures, local boundary conditions).

By modelling the first-failure stage of landslides induced by mountain tracks, Guadagno et al. (2003), referring to steady-state saturated flow conditions, outline that natural or anthropogenic discontinuities of pyroclastic deposits strongly increase the simulated displacements for upslope portions of the slope up to failure. The role of the above discontinuities for landslide occurrence is also emphasised by Crosta and Dal Negro (2003), on the basis of analyses that model the transient groundwater regime during the critical rainfall event of 4-5 May 1998.

These contributions, while providing useful insights on the topic, do not exhaustively analyse the relationships between tracks and landslides occurrence, neglecting some relevant aspects such as, for instance, the superficial water circulation and the role played by local stratigraphy. These aspects are addressed in the following sections that provide a preliminary modelling of the first-failure stage inside the landslide source areas.

2.2 Proposed approach, in-situ conditions and soil properties

Rigorous modelling of superficial and sub-superficial water circulation should take into account several factors, i.e. rainfall intensity, soil unsaturated conditions, soil hydraulic conductivity, topography, stratigraphy as well as anthropogenic factors that, in singular points and/or zones of the hillslope, can produce runoff phenomena and concentrated superficial water fluxes. To this aim, the physically-based model proposed by Savage et al. [2003] can be used. However, the lack of an accurate DTM can notably reduce the potentialities of these models. In such a case, a preliminary insight in the superficial water circulation can be obtained referring only to topography and computing the contributing areas along the hillslope (Pack et al., 1998; Tucker and Bras, 1998). The latter ones represent, at each point, the upslope catchment areas and the highest values can be reasonably assumed as corresponding to the zones where superficial rainwater concentrates. Once the hydraulic boundary conditions are outlined for different zones of the hillslope, pore water pressures can be computed with an infiltration model also considering soil unsaturated conditions through the numerical integration of the Richards’ equation [Richards, 1931]. The failure stage can be thus simulated through either limit equilibrium or stress-strain analyses, adopting a Mohr-Coulomb criterion extended to unsaturated conditions [Fredlund et al., 1978].

This simplified approach is applied to the May 1998 event, using the available data set that outlines the presence of three main soil classes differently arranged along the Pizzo d’Alvano massif (Fig. 1c). Considering the aim of the study, parametric analyses are performed, referring to simplified schemes (Fig. 3) that reproduce typical stratigraphical settings observed all over the massif. The schemes include finer deep ashy soil (Class A) and/or coarser superficial ashy soil (Class B) also
eventually including continuous pumice soil layers. The mechanical properties of these soils in saturated and unsaturated conditions are provided by the scientific literature (Sorbino and Foresta, 2002; Bilotta et al., 2005; Cascini et al., 2005, among others) and summarised in table 1.

<table>
<thead>
<tr>
<th>Class</th>
<th>Dry unit weight ($\gamma_d$) (kN/m$^3$)</th>
<th>Saturated unit weight ($\gamma_{sat}$) (kN/m$^3$)</th>
<th>Porosity ($n$)</th>
<th>Saturated conductivity ($k_{sat}$) (m/s)</th>
<th>Effective cohesion ($c'$) (kPa)</th>
<th>Friction angle ($\phi'$) (°)</th>
<th>Suction rate ($\phi_b$) (°)</th>
<th>Poisson's ratio ($\nu$)</th>
<th>Young's modulus ($E$) (MPa)</th>
<th>Dilatation angle ($\psi$) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class B ashy soil</td>
<td>7.30</td>
<td>13.1</td>
<td>0.58</td>
<td>$10^{-4}$</td>
<td>0</td>
<td>$36 \div 41$</td>
<td>20</td>
<td>0.26</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Pumice soil</td>
<td>6.20</td>
<td>13.1</td>
<td>0.69</td>
<td>$10^{-4}$</td>
<td>0</td>
<td>37</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Class A ashy soil</td>
<td>9.10</td>
<td>15.7</td>
<td>0.66</td>
<td>$10^{-6}$</td>
<td>5</td>
<td>$32 \div 35$</td>
<td>20</td>
<td>0.30</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

$\gamma_d$, $\gamma_{sat}$: dry (saturated) unit weight of soil, $n$: porosity, $k_{sat}$: saturated soil conductivity, $c'$: effective cohesion, $\phi'$: friction angle, $\phi_b$: rate of increase in shear strength due to suction, $\nu$: Poisson's ratio, $E$: Young’s modulus, $\psi$: dilatation angle.

3. GEOMECHANICAL MODELLING

3.1 Groundwater modelling

The modifications of superficial water circulation induced by mountain tracks were firstly evaluated, referring to a schematic steep (30°) hillslope, crossed by a steep track (14°) with one or more bends (Fig. 4a, 4b). The contributing areas were computed at each point of the hillslope through a detailed 0.5m×0.5m digital elevation model. The highest contributing areas concentrate at the bends of tracks (scheme M3a in Fig. 1 and 4) and complex scenarios are simulated for the scheme including more than two bends. Particularly, the zones adjacent to the bends are strongly affected by lateral redistribution of runoff (scheme M3b in Fig. 1 and 4). Concisely, both zones near and adjacent to the bends are outlined as prone to runoff phenomena and similar analyses can be extended to real cases if detailed topography (> scale 1:1000) and field data on the anthropogenic factors are available.

Based on these findings, the groundwater regime was modelled for different zones of the hillslope, i.e. near and adjacent to the bends, considering typical in-situ conditions and the stratigraphical schemes in figure 3. Pore water pressures induced by the 4-5 May 1998 rainfall storm were computed through the Seep/W Finite Element code (Geoslope, 2004) using the computational schemes of figure 5 that...
reproduce the schemes M3a and M3b of figures 1 and 4. Concerning scheme M3a, the rainfall values provided by Cascini et al. [2003] were assumed as boundary condition at the ground surface while a local ponding was considered downslope of the bend. For scheme M3b (Fig. 5b), the same ponding condition was assumed taking into account the possible lateral redistribution of surface runoff highlighted in figure 4b. For scheme M3a, the obtained results highlight that the ponding condition assumed at the bend of the track and downslope produce different effects depending on the local stratigraphy (Fig. 6). Particularly, if only ashy B soils are present (scheme 1 of Fig. 6) a local and slight increase of pore water pressures can be simulated; strong variations are conversely computed due to presence of both ashy A and B soils (scheme 2 of Fig. 6). Finally, for slopes with continuous pumice soil layers (scheme 3 of Fig. 6), pore water pressures increase involving larger portions of the slopes than in the previous cases. Similar results are obtained for scheme M3b (i.e. corresponding to zones adjacent to the bends), thus highlighting that the groundwater regime is primarily controlled by both the assumed boundary conditions at the ground surface and the stratigraphy rather than by local geometrical discontinuities.

3.2 Slope stability analyses

For the scheme M3a, limit equilibrium analyses (Fig. 7) were performed through the Slope/W code (Geoslope, 2004) assuming as input the computed pore water pressures. The obtained results show that for scheme 1 of figure 6 (only ashy B soils) a local ponding condition does not cause any failure, as the slope safety factor (FS) is greater than one (Fig. 7a). Conversely, for the scheme 2 of figure 6 (ashy A and B soils) failure is simulated along slip surfaces involving zones both downslope and upslope the cut slope (Fig. 7b). Similar results are obtained for the scheme 3 of figure 6 with a slip surface involving both the upslope and downslope zones of the track.

Similar limit equilibrium analyses were performed for scheme M3b. Figure 8 provides the results obtained, at the same time instant of figure 7, for different stratigraphical settings assuming an equal local ponding condition. Particularly, for scheme 1 (only ashy B soils) failure conditions are not simulated (Fig. 8a); conversely these conditions involve different zones of the slope in the case of scheme 2 (only ashy A
The obtained results clearly outline the role played by the stratigraphy on the failure onset. Moreover, comparing scheme 2 of figure 7 with scheme 2 of figure 8 it derives that the slope safety factors are about the same (respectively FS=0.89 and FS=0.88) independent of the presence of a geometrical discontinuity inside the pyroclastic deposit.

To validate the previous results, pore water pressures were used as input for uncoupled and coupled stress-strain analyses. For scheme M3b, Figure 9 shows the displacements computed for an homogeneous soil deposit (scheme 1 of Fig. 6). It is worth noting that in the case of rainfall only as boundary condition, the failure onset is not simulated. On the contrary, including a ponding condition, the simulated displacements are characterised by quite high gradients leading to failure conditions after about 24 hours (Fig. 9).

4. CONCLUSION

Anthropogenic factors often influence the superficial groundwater circulation during rainfall. Particularly, mountain tracks and cut slopes cause erosion processes and runoff that can locally trigger slope instability phenomena. Sometimes, multiple failures develop inside large areas according to complex mechanisms not easy to recognise and/or to model.

Examples of significant landslide source areas related to anthropogenic factors were recorded in the Campania region (Southern Italy) in May 1998, when several and multiple landslides affected shallow unsaturated pyroclastic deposits covering a carbonate massif. Considering the complexity of the occurred phenomena, few contributions in the scientific literature address the topic. In order to obtain a preliminary insight in the role played by different factors on the triggering mechanisms, groundwater and slope instability analyses were performed, in a parametric form, referring to simplified and bi-dimensional schemes of the landslide source areas.

Groundwater modelling highlights that ponding conditions strongly affect the transient
pore water pressures, mostly depending on the local stratigraphical setting. Limit equilibrium and stress-strain analyses outline that geometrical discontinuities act as an important aggravating factor for slope stability conditions. However, stratigraphy is confirmed as the key factors for the triggering of large instability phenomena for all the landslide source areas. Consequently, more advanced numerical models than those used in the present paper should take stratigraphy into account together with more elaborate methodologies such as, for instance, the three-dimensional analysis of slope stability conditions.

REFERENCES


