Engineering Geology 165 (2013) 105–132

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Unsaturated soil mechanics in rainfall-induced flow landslides

Giuseppe Sorbino [a,*], Marco Valerio Nicotera [b]

[a] Dipartimento di Ingegneria Civile, Università di Salerno, via Ponte don Melillo 1, 84084 Fisciano (SA), Italy
[b] DIGA—Dipartimento di Ingegneria Idraulica, Geotecnica ed Ambientale, Università di Napoli Federico II, via Claudio 21, 80125 Napoli, Italy

ARTICLE INFO

Article history:
Accepted 7 October 2012
Available online 7 November 2012

Keywords:
Flow-slides
Pyroclastic soils
Unsaturated soils
Mechanical properties
Monitoring
Modelling

ABSTRACT

Rainfall-induced flow landslides in coarse-grained soils pose significant threats to populations and structures due to their high velocities, long travel distance and the absence of definite warning signs during the pre-failure stage. The triggering phase of these phenomena is frequently related to rainfall events which significantly reduce matric suction in the shallower soil layers. In this paper the processes leading to the onset of such phenomena are illustrated and some observations on their modelling are briefly recalled. The failure stage at different scales is then modelled with reference to a case study from southern Italy which draws on high-quality experimental data sets from extensive in situ and laboratory investigation.

1. Introduction

The behaviour of natural slopes is generally the result of different and often complex hydro-mechanical processes, which depend on the slope geometry, the nature, structure and hydro-mechanical properties of the soils, the boundary conditions and the initial state of the slope. Every action causing a change in either the boundary conditions, or the loading conditions can trigger strains and displacement; climatic processes can be considered among the main triggering causes of such displacements that may generate landsliding (Fell et al., 2000).

In general, the main climatic factors are precipitation (both rainfall and snow), temperature, humidity, solar radiation and wind. Any modification of the above factors (typically, intensity and duration of precipitations, as well as temperature and humidity) influences the water content and the pore water pressure regime in the slope, hence the stress state, and the available strengths, possibly generating slope failure (Blight, 1997; Gens, 2010).

The most widespread types of weather-induced landslides are slides and flows (Cruden and Varnes, 1996) in both coarse- and fine-grained soils. Landslides in fine-grained soils are most commonly slow slides, either compound slides or mudslides, frequently involving pre-existing shear surfaces. Their displacements are essentially controlled by positive pore water pressures and by their seasonal fluctuations. In particular, the highest rate of displacement is attained during the wet season, with a progressive reduction as the dry season approaches. Most of the slow landslides described in the literature cover lapses of time of many years, and some movements are known to be active for centuries (Cotecchia et al., 2008).

Weather-induced landslides in coarse-grained soils exhibit completely different kinematics. They mainly develop as first-time failure and their velocities are generally much higher than those attained in fine-grained deposits, with displacements not preceded by any significant slow stage and extreme stages developing rapidly. The high velocities are frequently related to constitutive instability of the soil skeleton, which can induce the transition of the mechanical soil response from a frictional type to a viscous fluid type and hence produce flow-type landslides. These landslides typically travel long distances and often pose significant threats to populations and structures. The triggering phase is frequently related to short, intense rainfall events which are able to produce significant increments in pore water pressure. These increments can be directly linked to rainwater infiltration through the slope surface and/or indirectly to the subsurface water flux from the bedrock that may also increase due to the rainfall event. Due to the characteristics of the water retention and hydraulic conductivity properties of coarse-grained soils (i.e. low air entry values and medium to high saturated hydraulic conductivity), the triggering processes may develop in unsaturated conditions.

To date, weather-induced landslides in coarse-grained soils have posed a major challenge for modelling boundary value problems in unsaturated soils. Among such landslides, this paper addresses those that turn into the flow type. After a brief illustration of the triggering processes leading to the onset of such phenomena, a case study from Campania region (southern Italy) is presented. The results of extensive in situ and laboratory investigations are discussed and used to model the triggering mechanisms of the huge event which

* Corresponding author. Tel.: +39 089 964329.
E-mail addresses: g.sorbino@unisa.it (G. Sorbino), nicotera@unina.it (M.V. Nicotera).

0013-7952/$ – see front matter
http://dx.doi.org/10.1016/j.enggeo.2012.10.008

occurred on 4–5 May 1998, when dozens of flow-type landslides were triggered by rainfall along the Pizzo d'Alvano slopes.

2. Main features of rainfall-induced flow landslides

Rainfall-induced flow-type landslides can be triggered in many geo-environmental contexts and generally involve shallow soil deposits of varying grading and origin. In areas of uniform slope covers and uniform rainfall features, such landslides can occur at the same time on several slopes (as recorded in areas up to tens of km^2). Significant examples are those involving pyroclastic deposits in Central America (Capra et al., 2003), New Zealand (Ekanayake and Phillips, 2002) and Italy (Cascini, 2004), in situ weathered soils in Hong Kong (Take et al., 2004) and Japan (Wang et al., 2002), and colluvial weathered deposits in Brazil (Lacerda, 2004) and Hong Kong (Fuchu et al., 1999).

Flow-type landslides can be considered complex slope instability phenomena since they exhibit different kinematic characteristics during failure, post-failure and propagation stages (Fell et al., 2000; Hungr et al., 2001; Pastor et al., 2002; Leroueil, 2004). Failure and post-failure stages occur inside the so-called landslide source areas. Failure is strictly related to the increase in pore water pressures and the consequent reduction of the mean effective stresses (Anderson and Sitar, 1995; Alonso et al., 1996; Iverson et al., 1997). According to Leroueil (2001), the failure stage of rainfall-induced flow landslides in natural slopes formed by coarse soils is generally a drained process. The post-failure stage is represented by the rapid generation of large plastic strains and the consequent sudden acceleration of the failed soil mass (Hungr, 2004). The propagation stage includes movements of the failed soil mass from the landslide source areas to the deposition areas. With reference to the failure stage, rainfall-induced shallow landslides can be considered as translational slides according to the classifications proposed by Hutchinson (1988) and Cruden and Varnes (1996). Conversely, in the post-failure stage they should be classified as flow landslides (Hungr et al., 2001) (i.e., slides turning into flows) or as flowslides (Hungr et al., 2001), when liquefaction phenomena occur.

The transition from slide to flow during the post-failure stage is attributed to different causes by different researchers. Most of the contributions on this topic identify as the main cause the development of totally or partially undrained conditions which can produce excess pore water pressures during shearing. Static liquefaction of loose saturated soils has been discussed by several authors (e.g. Wang et al., 2002; Olivares and Picarelli, 2003; Van Asch et al., 2006; Casini et al., 2010; Carrera et al., 2011) and observed in undrained triaxial tests (e.g. Yamamuro and Lade, 1998; Chu et al., 2003), in constant-shear-drained (CSD) stress-path triaxial tests on saturated samples during which the effective confining pressure was gradually reduced while the shear stress was held constant (e.g. Anderson and Riemer, 1995; Dai et al., 1999; Chu et al., 2003) and in undrained ring shear tests under controlled strain rates (Wang et al., 2002). On the other hand, some authors have discussed the role played by instability phenomena occurring during wetting of unsaturated loose soils. In particular, the behaviour of unsaturated pyroclastic loose soils during wetting upon shearing was investigated in suction-controlled triaxial tests (Olivares and Damiano, 2007), suction-controlled direct shear tests (Nicotera, 2000; Cecconi et al., 2005; Yasufuku et al., 2005), and in suction-controlled simple shear tests (Sorbino et al., 2010a). A theoretical framework, which embodies all these phenomena affecting the stability of unsaturated soils was recently proposed (Buscarnera and Nova, 2011; Buscarnera and di Prisco, 2012) and applied to the analysis of a infinite slope (Buscarnera and di Prisco, 2011). Using the framework in question it may be ascertained which combination of factors, including constitutive instability, can lead to the onset of flow-sliding.

Other contributions point out that the transition from slide to flow may be caused by local failures producing the onset of local variations in the slope geometry (Iverson et al., 1997; Take et al., 2004). This mechanism is the effect of transient localised excess pore-water pressures that are not associated to undrained conditions, but are generated by local variation of the hydraulic boundary conditions at the bottom of the shallow soil deposits. Typical examples are represented by phenomena triggered by the water fluxes from springs at the contact between the bedrock and the soil cover (Johnson and Sitar, 1990; Anderson and Sitar, 1995; Cascini et al., 2000, 2008; Lacerda, 2004; Onda et al., 2004; Matsushi et al., 2006), or by rising of the water table from the bedrock upwards (Montgomery et al., 1997; Leroueil, 2004). Experimental evidence on the effects of varying hydraulic boundary conditions is provided by centrifuge tests on small-scale slope models (Take et al., 2004) and small-scale flume tests (Lourenco et al., 2006), showing that the transition from slide to flow can occur for both loose and dense soils and can be associated to an increase in pore-water pressures during the post-failure stage.

Cascini et al. (2010) proposed a qualitative reference scheme (Figure 1) to describe the conditions leading to the occurrence of slides, flowslides and slides turning into flows in an unsaturated slope formed by either loose or dense soil. The rainwater infiltrating directly into the slope surface, and the water flowing from a spring in the bedrock are both considered in the proposed scheme.

Fig. 1 provides: the schematic picture of the sliding mechanism consisting of one or two slip surfaces (i.e. S1 and S2); the effective stress paths followed by the stress state in the deviatoric stress q versus mean effective stress p' plane, for two different points of the slope (i.e. point A on the slip surface S1 nearby the spring; point B on the slip surface S2 away from the spring); the variation with time of the displacement δ of the soil mass enveloped by the slip surface; the variation with time of the driving force F_d (i.e. the resultant of the shear stresses acting along the critical slip surface) and the available resisting force F_r (i.e. the resultant of the limit values of the shear stresses along the critical slip surface).

For slides (Figure 1b), the mechanical behaviour of the soil is controlled, in drained conditions, by the hydrologic response of the slope up to failure onset. The resisting force (F_r) decreases to the current value of the driving force (F_d) (Figure 1b, $t = t_1$) along the slip surface S1, which includes the zone where the bedrock spring is located (point A in Figure 1a). If drained conditions persist after failure, small accelerations develop during post-failure (Figure 1b, $t > t_1$). In loose saturated soils, the above process is associated with a volume reduction of the soil. However, in the case of loose soils, if the pore-water pressure cannot dissipate freely, partially or totally undrained conditions develop and during the post-failure stage the slide turns into a flowslide (Figure 1c, $t > t_1$). In particular, in the spring zone (point A in Figure 1a), pore water pressures build up further due to volumetric coupling, and the stress state, after following the stress path 0–1, converges towards the origin leading to catastrophic failure (Figure 1c, $t > t_1$). Alternatively, the slide can turn into flows (Figure 1d) as a consequence of complex mechanisms characterised by a decrease in the shear strength due to local hydraulic boundary conditions that can lead to failure of a portion of the slope near the spring zone (Figure 1b $t = t_1$). Above this zone (point B in Figure 1a), the mobilised shear stresses increase due to the unbalanced driving forces along an upslope potential slip surface (Figure 1d, $t > t_1$) and a further slide can occur (Figure 1d, $t = t_2$). As the latter has a high initial acceleration, it can become a flow (Figure 1d, $t > t_2$).

From Fig. 1, Cascini et al. (2010) concluded that the greatest differences among slides, slides turning into flows and flowslides arise from the differences in generation of excess pore water pressures at failure. Besides, in the cases sketched in Fig. 1b and d, drained failure takes place at the critical state line, and can be of a localised type (Pastor et al., 2002, 2004). By contrast, either fully or partially undrained failure of loose soils (Figure 1b and c) of diffuse type