Abstract

In the last decades, landslide activity and the associated economic consequences have increased substantially. This trend has been observed for many other natural disasters and is possibly related to the climate changes observed in recent years. The natural outcome is that environmental perturbations play an increasingly important role in risk assessment procedures.

From this point of view, fast landslides induced by rainfall represent a major concern. These catastrophic phenomena are characterised by a very rapid and rather unexpected activation and have the potential to mobilise huge volumes of material over large areas. In these cases, the material flows over very large distances, attaining extremely high velocities. The dramatic social impact of fast landslides and the need to face the associated risks require the development of reliable and consistent approaches.

This thesis focuses on the study of fast landslides dominantly triggered by intense rainfall events and aims to investigate and model their activation using geomechanical principles. For this reason, one of the main goals of the dissertation is to establish a conceptual link between recent advances in geomechanics and landslide susceptibility evaluation. In particular the work focuses on the study of landslide phenomena in which the soil suffers a phase transition from solid to fluid. These types of slope instabilities are commonly referred to as *flow slides*, and are believed to be a result of a particular type of unstable process called *static liquefaction*.

This phenomenon of has been widely studied in the literature, and it is commonly believed to be one of the main triggering factors of subaqueous flow slides in poorly compacted sandy slopes. As far as subaerial landslides are considered, however, there is a lack of understanding of the processes underlying the onset of rainfall-induced flow slides. Even though there is large in situ evidence of flow-like mass movements induced by rainfalls and these phenomena have been reproduced in laboratory conditions, a well established theoretical framework is not yet available to explain past case histories and develop a consistent mechanical interpretation of the triggering stage.

The main motivation for this work stems from these premises, and the thesis represents an attempt to explain landslide activation processes driven by rain infiltration. For these reasons, the attention of the thesis is focused on the study of mechanical instability at material point level and on its engineering implications in terms of slope stability analysis.

The work has been aimed at answering three major questions: (i) Is it possible to activate liquefaction phenomena by means of purely hydraulic perturbations? (ii) Can these instabilities take place during the saturation process, i.e., when the soil is still characterised by an unsaturated state? (iii) If this is possible, in which way, and under which circumstances can these hydro-mechanical instabilities take place?

In order to provide an answer to these questions, a new methodology for slope stability analyses has been developed by using the theory of material stability and an adequate constitutive framework for unsaturated soils. Well-established theories for saturated soils have been reconsidered and extended to the more general case of unsaturated porous media. The developed theory has finally been applied to the stability analysis of unsaturated slopes, investigating the effects of both hydraulic and mechanical perturbations.

The main scientific contributions of the thesis can be summarized as follows:

- The application of a coupled hydro-mechanical constitutive model showed that unsaturated soils can suffer a broad range of instabilities induced either by shearing or wetting. Some of the predicted unstable modes (here classified as 'soaking collapses') share a number of features with the well known process of static liquefaction. However, the striking difference is that these phenomena are predicted to occur when the material is not yet saturated. Another remarkable feature of the predicted collapses is that they can take place in the form of *latent instabilities*, i.e. as unstable mechanisms whose activation is contingent to particular boundary conditions.
- In order to cope with these phenomena, an extended theory of material stability for unsaturated soils has been developed. Two classical tools have been reconsidered: the concept of second-order work and the theory of controllability. An extended definition of the second-order work valid for unsaturated soils allowed to establish an appropriate set of hydro-mechanical incremental stress-strain measures. A surprising aspect is that these variables do not coincide with the rate of the work-conjugate stress measures commonly adopted at the first-order.
- The concept of controllability has been extended to

unsaturated soils. Such an extension demonstrated the importance of hydraulic control conditions when coupled instabilities are to be predicted. In particular, the simulations showed that a minor tendency to instability is predicted when suction changes are directly imposed (i.e., when capillary contributions are removed in a controlled manner). On the contrary, when the variation in water volume is imposed (e.g., by means of water inundation) the predicted response is prone to produce unstable mechanisms, and volumetric collapses can anticipate the occurrence of shear failure. These results provide a possible explanation to *wetting-collapse* phenomena, suggesting that the way in which saturation is imposed is a key issue to assess stability conditions.

- Finally, the stability of unsaturated slopes has been investigated by means of material point analyses. A simplified methodology based on the scheme of infinite slope has been used, studying the effect of both mechanical and hydraulic perturbations. The study enabled to quantify the magnitude of the disturbances able to trigger a slope failure and showed that two types of triggering modes can occur: a localised shear failure and a flow failure. In addition, the range of slope inclinations susceptible to these instability modes were identified, cautioning that, depending on the material properties, the predicted response may change dramatically. In particular, in the case of soils rather insensitive to wetting paths, a localised failure is predicted. In contrast, wetting-collapse is the first unstable mode that can be activated upon suction removal in highly collapsible deposits. What is somewhat surprising is that in the latter case fully saturated conditions are not necessary for initiating a flow failure. The saturation of the pores is in fact a consequence of a volumetric instability rather than its cause and the collapse takes place when the material is not yet saturated. According to this interpretation, a rainfall-induced flow slide can originate from a rather complex chain process which consists of a volumetric collapse, a subsequent saturation of the pores and, eventually, a catastrophic failure of the slope due to a stress state beyond the stability limits for static liquefaction.