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Sensitivity of the initiation and runout of flowslides in loose granular deposits to the content of small particles: An insight from flume tests

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ABSTRACT

Landslides of the flow type are among the most destructive mass movements due to their potential high mobility, long runout distance and capacity of entraining further material during movement. Generation of positive pore pressure excess is considered to be a fundamental triggering mechanism which, in some cases, can produce stress state instability and fluidization of both fine-grained and granular deposits, resulting in extremely fast and catastrophic events. Several experimental works and theoretical studies have been carried out so far to investigate the initiation mechanism and runout of flowslides. However, efforts are still needed to improve the understanding, for instance, of the role of the soil grading on the initiation and evolution of the movement. To this aim, a series of flume tests has been carried out using granular mixtures of coarse and small particles. High temporal resolution data acquisition has been used to investigate the onset of failure in terms of pore pressures, surface and internal displacements and vibration signals. By means of shear-controlled triaxial tests and permeability tests, the hydraulic conductivity has been found to be a controlling factor in the landslide initiation, whereas the uniqueness of the instability line – the lower bound of potentially unstable stress states – regardless of the soil grading, suggests that pore pressure measurement in the field can serve as a reliable indicator in early-warning systems.

1. Introduction

Flow-like landslides can occur in a variety of soils and can be characterized by a wide range of movement patterns. However, their potential high mobility, long runout distance and capacity of mobilizing and entraining further material encountered along the slope make them one of the most destructive mass movement types (e.g. Sassa, 1998; Hungr et al., 2001; Schuster and Highland, 2007; Crosta and Frattini, 2008; Picarelli, 2010). Generation of positive excess pore pressures is considered to be a fundamental triggering mechanism and, in some cases, pore pressure build-up can result in liquefaction and fluidization of both fine-grained and granular soil deposits, producing extremely fast and catastrophic events which are referred to as *flowslides* (Hungr et al., 2014). Notable examples have been reported, for instance, in quick clays sediments, which can liquefy and fluidize upon remolding (Geertsema and Torrance, 2005), and in pyroclastic soils and loess deposits (Cascini et al., 2008; Picarelli et al., 2008; Zhang et al., 2009; Leng et al., 2017) after heavy rainfall or intense irrigation. The fluidized mass, exhibiting practically no shear strength due to the vanishing of the effective stress (Iverson, 1997), can keep running very fast also when it reaches the toe of the slope, covering a long further distance – up to hundreds of meters or kilometers – even if the ground surface is sub-horizontal or very gently inclined (Picarelli et al., 2008). Flowslides may evolve in *debris flows* (Hungr et al., 2001) when conveyed in steep drainage channels, resulting in even increased velocity and destructive power (Zhang et al., 2011; Peng et al., 2015; Wu et al., 2016).

In 2008, the 8.0 M_s Wenchuan earthquake in Sichuan Province, China, triggered a huge number of slope instabilities (Wang et al., 2009; Gorum et al., 2011), including shallow failures, debris flows and rock avalanches, which resulted in large deposits of loose granular materials along the slopes and at their bases. Since then, heavy rainfall events during the flood seasons have been triggering flowslides, some of which evolved in large-scale debris flows (Tang et al., 2009, 2012; Xu et al., 2012), such as those occurred after an extraordinary rainfall on August 13th 2010 in the Qingping area, about 80 km from the earthquake epicenter (Xu et al., 2012; Tang et al., 2012). Both runoff erosion and fluidization of the loose deposits – which have been shown to be susceptible of liquefaction – have been identified as a common mechanism of their initiation (Hu et al., 2016).

Several experimental investigations, theoretical and numerical

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analyses have been carried out to study the initiation mechanism and runout of flowslides. The entraining capacity, for instance, has been shown to influence the runout distance and the pore water pressure distribution in flow-like landslides remarkably. It can depend on several parameters, proper of both the flowing mass and the erodible bed, such as the solid to fluid mass ratio, the density and size of the solid particles, the saturation degree, stress state and slope angle of the bed (Cuomo et al., 2016). Bed entrainment and movement propagation have been recognized to be coupled processes, which should be analyzed within a common framework (Cascini et al., 2014).

Great attention has been given to the role of pore pressures in the initiation and runout of flowslides. Sassa (1984) showed that loose sand can collapse because of excess pore pressure development. In large-scale flume tests, Iverson et al. (1997) reported fluidization along the slip surface of loose sand deposits, resulting in slope collapse, and Gabet and Mudd (2006) showed a possible fluidization mechanism also in a dense granular material. Iverson and LaHusen (1989) observed dynamic fluctuations of pore pressures during rapid, steady shear deformation of saturated sand, which sometimes resulted in the complete vanishing of the effective stress. Both Iverson et al. (2000) and Wang and Sassa (2001, 2003) reported the initial soil porosity and dry density to be fundamental controls on the landslide displacement rate, and Take et al. (2015) showed a distinctive influence of antecedent rainfall events on the landslide travel distance.

On the other hand, Eckersley (1990), in instrumented flow slides induced by slowly increasing the water table, observed that failure can also initiate under essentially static, drained conditions, with a mobilized friction much lower than the steady state value, and that excess pore pressures can be generated during – rather than before – movement, and liquefaction can thus be a result of shear failure rather than the cause. By means of flume experiments, Okura et al. (2002) and Take et al. (2004) also highlighted different phases of slope collapse in loose sands, involving compaction and localized generation of excess pore pressure, and Ochiai et al. (2004) and Moriwaki et al. (2004) showed that – in real-scale problems – combinations of factors may produce different responses in different parts of the slope. Olivares and Damiano (2007), by studying flowslides in unsaturated pyroclastic soils, concluded that the dramatic acceleration can be the final step of a chain of mechanical processes, involving increase of saturation degree, mechanical degradation, volumetric collapse and static liquefaction, culminating in the complete fluidization of the soil mass.

The propagation of pore water pressure changes within the soil mass plays a key role during the propagation stage of a flow-like landslide. Pailha and Pouliquen (2009) and Pastor et al. (2009) suggested that the variation of pore pressures is influenced by both the changes of soil dilatancy and the stiffness of the basal surface over which the landslide propagates, which can be saturated and produce a water flow towards the landslide mass, resulting in a pore pressure increase (or vice versa, if the basal terrain is dilatant). The role of pore water pressures in the dynamics of flow-like landslides have been incorporated into landslide modelling relatively recently (Pastor et al., 2009). Cascini et al. (2016), for instance, applied the SPH-FDM model to simulate, in 2D and 3D conditions, the initiation and runout of well-documented flume tests, and showed the importance of accounting for the propagation of pore pressures for a correct simulation of debris flows dynamics. Cascini et al. (2010) analyzed the failure and post-failure stages of shallow flow-type landslides in weathered pyroclastic soils. The authors presented an approach for their geo-mechanical interpretation and proposed different modelling alternatives at different scales, pointing out that both site conditions and hydraulic boundary conditions are among the key factors to evaluate the susceptibility to such landslides. Rapid flow-type movement can also occur by transition from slow-moving landslides in fine-grained soils due to the build-up of positive excess pore pressures caused by the sliding displacement: Van Asch et al. (2006) and Van Asch and Malet (2009) focused on the influence of landslide geometry and kinematic deformation on the liquefaction process in such materials and proposed a simple analytical model which can be beneficial in hazard assessment.

Although numerous studies have been carried out so far, efforts are still needed to improve the understanding, in particular, of the role of the soil grading on the initiation and evolution of the movement. The experimental results reported by Wang and Sassa (2001, 2003) showed, for instance, that mixtures of sand with different percentages of fine, loessic particles exhibit different modes of flowslide motion, possibly in dependence of the different rate of pore-pressure dissipation in the shear zone. In order to get a deeper insight into the role of particle grading on the initiation of movement and fluidization process, a series of flume tests has been performed, the results of which are reported in the present work. Additionally, shear-controlled drained triaxial tests were carried out to clarify the role of the fraction of small particles and the related hydrological factors in the initiation of flowslides.

2. Materials

The granular soil used in the flume tests has been sampled from the coseismic rock avalanche deposits in the Wenjia gully, located in the Qingping area about 80 km apart from the 2008 M_s 8.0 Wenchuan earthquake epicenter, where on August 13th 2010 one of the largest post-seismic rainfall-induced debris flows occurred and further flowslides can be triggered in future.

The sampled material is constituted by fragmented limestone. It has a specific gravity $G_s = 2.62$ and grain size ranging from gravel to sand and silt. The soil was oven-dried and sieved and the dry particles were subsequently remixed to obtain the desired gradings for the flume tests. The grain size distributions of the small and coarse components are given in Fig. 1. In this work, small particles are considered such if their dimension, d, is lower than 0.5 mm, thus they correspond to a mixture of medium to fine sand and silt according to the ISO 14688-1:2002 classification (ISO, 2002). The choice of $d < 0.5$ mm is the result of preliminary tests on the sampled material to evaluate the grain size of the soil fraction subjected to internal erosion and transport by the groundwater flow in the test condition. The water outflowing at the base of the slope in the flume was in fact collected and filtered to reveal the eroded particles, the grading of which was then measured by a laser particle size analyzer (Mastersize 2000, Malvern Company). It is worth remarking that, in this work, the expression *small particles* is preferred to *fine particles* to stress their non-plastic nature, as they consist of particles with small dimension but with the same lithology as that of the coarse grains, rather than being a fine, plastic fraction of clayey nature.

3. Experimental setup and test procedure

3.1. Setup of the flume apparatus

The tests have been carried out using an equipped flume, 3.5 m in length and 1 m in width, with an inclination of the floor of 20° from the

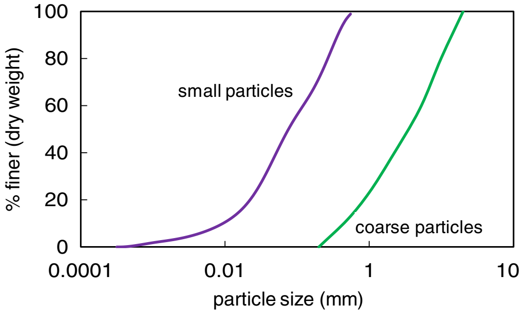

Fig. 1. Grain size distribution of the small particles and of the coarse particles used in the flume tests.