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An investigation on progressive failure in granular slopes leading to flow-like landslides

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Abstract

Rainfall-induced flowslides in loose granular slopes involve many and different geomorphological contexts causing heavy economic and human losses. Usually the triggering mechanism is associated with suction reduction or increase of the groundwater level. During rainwater infiltration sloping soils may experience a non-uniform stress field possibly leading to progressive failure. In special cases, this can trigger mechanisms of undrained instability leading to rapid flow-like slope movements. In spite of the severity of the consequences of such phenomena, little attention has been paid until now to this problem. This paper is aimed at providing a contribution on this topic by some results of experiments conducted on small-scale slopes consisting of loose sandy soils subjected to artificial rainfall.

1 INTRODUCTION

Rainfall-induced landslides are one of the trickiest challenges for engineers as they can involve different geomorphologic contexts and materials in wide areas of the world. The events, which involve loose granular soils may be catastrophic as a consequence of soil liquefaction (Wang and Sassa, 2001; Take and Beddoe, 2014; Gens, 2019). In fact, in these cases triggered landslides are very rapid and can cover long distances.

A wide area around Naples, Southern Italy, is threatened by these phenomena, which involve shallow pyroclastic covers (Fig. 1). The stability conditions of these sandy covers are usually guaranteed by the apparent cohesion due to partial saturation. However, the increase of the saturation degree induced by long-lasting precipitations may lead to slope failure, which generally occurs abruptly, preceded by small deformations and often followed by rapid, destructive flow-like movements.

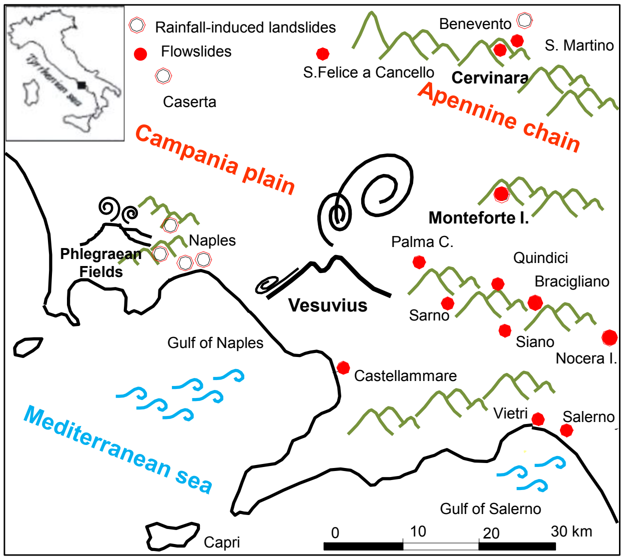

Figure 1. Catastrophic landslides events occurred in Campania in the last 25 years

Several studies have been conducted in the last decades to investigate the triggering mechanisms of these events. They consisted in:

- site investigations and monitoring of instrumented slopes (Damiano et al., 2012; Sorbino and Nicotera 2013; Pirone et al., 2012; Comegna et al., 2016, Greco et al., 2013; Di Maio et al., 2020)
- laboratory tests on undisturbed and reconstituted volcanic ashes aimed at evaluating the susceptibility to liquefaction of the soils (Picarelli et al., 2007; 2020a; Olivares et al., 2019);
- physical modelling (Olivares and Damiano, 2007; Olivares et al., 2009; Picarelli et al., 2008; Darban et al., 2019; Pagano et al., 2019).

In particular, through physical modeling on small-scale instrumented slopes consisting of volcanic ashes, Olivares and Damiano (2007) observed that, in the simplified assumption of infinite slope characterized by inclination equal to the friction angle of the soil, a mechanical chain process characterized by water content increase, mechanical degradation due to suction decrease and volumetric collapse culminate in soil liquefaction and consequent generation of a flow-like slope movement. However, the failure of slopes characterized by a more complex morphology, is generally the result of inhomogeneous stress and strain fields, leading to progressive failure.

To investigate on this topic, a new series of experiments have been performed. In particular, this paper reports the results of two experiments aimed at favoring the triggering of progressive failure under the combined influence of slope morphology and of artificial rainfall.

2 MATERIALS AND METHODS

2.1 Soil properties

The soil adopted in the experiments is a volcanic ash taken from the slope of Cervinara, about 40 km northeastern of Naples (Italy), in an area affected several times by large debris avalanches (REF…) (Fig.1). The slope covers consist of air-fall deposits of pyroclastic origin mainly constituted by pumices and ashes. The air fall deposition gave rise to a very loose soil (Picarelli et al., 2007). As a matter of fact, the soil porosity is as high as 75%.

This ash may be classified as silty sand with 10–20% of non-plastic fine content (Figure 2). It falls within the bounds of deposits which are susceptible to static liquefaction (Hunter and Fell, 2003). The susceptibility to liquefaction is enhanced by the presence of non-plastic silty grains and by the high soil porosity (Picarelli et al., 2007).

The main index and state properties are reported in Table 1 in terms of specific unit weight G_s, dry unit weight γ, porosity n, saturated conductivity k_{sat}, effective cohesion c' and friction angle ϕ'.

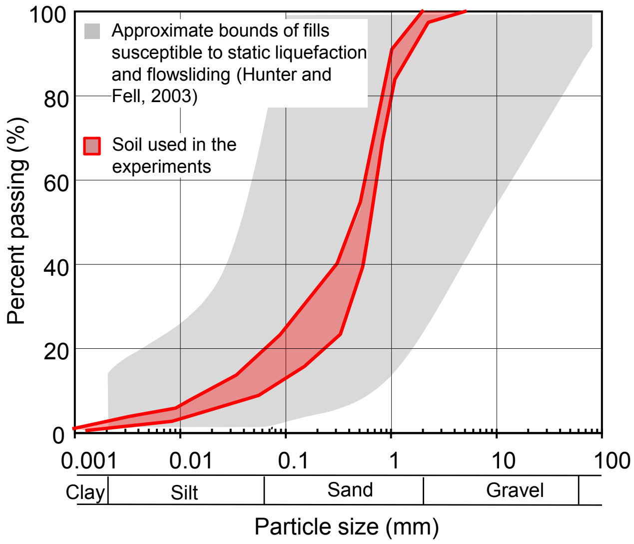

Figure 2. Grain size distribution of the soil used in the experiments

Table 1. Main properties of the investigated soil

Grain size distribution	Gs	γ_d (kN/m^3)	N	k_{sat} (m/s)	c' (kPa)	ϕ' (°)
Silty sand	2.65	14	0.75	$1 \cdot 10^{-6}$	0	38

The material is characterized by a friction angle of 38° and by a nil cohesion intercept. Such values depend on the subangular shape with sharp edges of the soil particles, typical of fall deposits, and on the negligible influence of the non-plastic fine grained component. However, while the drained soil behavior is ductile, under undrained shearing it displays a brittle response.

Figure 3 reports the stress-paths of specimens reconstituted at void ratios between 1.8 and 2.0, close to the natural values, in isotropically and anisotropically consolidated compression triaxial tests (CIU and CAU tests). As shown, after peak the deviator stress progressively decreases until the reaching of the steady state condition (line SSL in Fig. 3). An Instability Line and an Instability Region can be clearly recognized in the figure.

These data suggest that sloping natural soil deposits, which after full saturation, are subjected to a state of stress falling in this zone, might rapidly lose their shear strength as a result of any even small disturbance (Picarelli et al., 2020b).

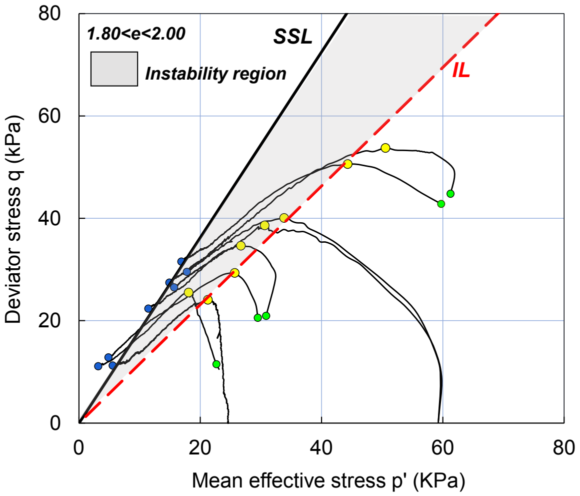

Figure 3. Stress paths of triaxial compression tests on isotropically and anisotropically consolidated specimens with void ratios of 1.8–2.0 (Picarelli et al., 2020a)

2.2 The experimental setup

In order to investigate the potential occurrence of progressive failure and the subsequent generation of a flow type movement, two experiments on small-scale model slopes have been performed. The development of progressive failure has been favored by the geometry of the models, which present a local change in the basal angle, similar to the one of slopes in Campania subject to liquefied debris-flows and avalanches (Picarelli et al., 2020b).

The first model slope is characterized by a thickness of 10cm and an inclination of 38°, equal to the friction angle of the soil, which rises to 42° in the uppermost part of the slope (Fig. 4). The second model is characterized by an uniform basal inclination of 35°. In this case, the inclination of the ground surface only has been set at 40° in the upper part of the slope (Fig. 4). Figure 4 reports a schematic cross-sections of the two model slopes with location of the sensors used in the experiments.

In particular, both slopes have been instrumented with: miniaturized tensiometers, to monitor suction at two depths during rainwater infiltration; displacement sensors, to monitor settlements at the ground surface; pore pressure transducers at the bottom of the soil layer to record pore pressures; video-cameras to retrieve displacements of the ground surface.

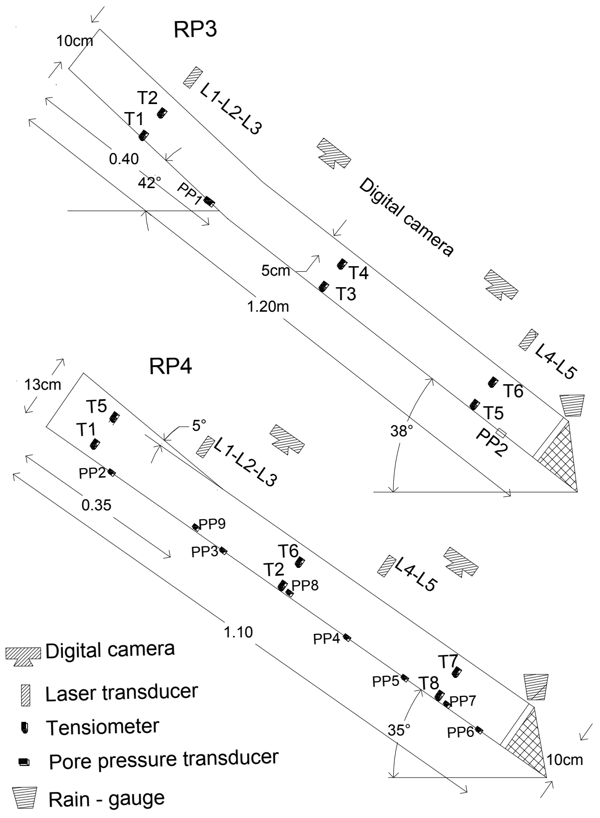

Figure 4. Schematic cross-sections of the instrumented slopes.

3 TEST RESULTS AND DISCUSSION

Table 2 reports slope angles, initial water content and soil porosity, and finally, rainfall intensity and duration, adopted in the two experiments.

Table 2. Basic geometrical and physical parameters adopted in experimental program

Test	Slope angle* (°)	Water content (%)	Porosity (%)	Rainfall intensity (mm/h)	Duration of rainfall (min)
RP3	38°-42°	40	70	30-36-40	126
RP4	35°-40°	44	76	100	29

*In the experiment RP3 the adopted slope angles (38° and 42°) characterize both basal and ground surface. In the experiment RP4, 35° is the angle of the entire basal surface, while 35° and 40° are the angles adopted for the ground surface

3.1 RP3 experiment

The main results of the first experiment are reported in the Figures 5, 6 and 7. During the experiment RP3 the rainfall intensity has been changed two times: during the first 78 minutes it has been of 30mm/h; in the following steps it has been increased, first, to 36mm/h, then, to 40mm/h.

The effects of water infiltration have been investigated by suction measurements (Figure 5), which display an abrupt decrease at the passage of the wetting front. As shown by the settlements of the ground surface (laser sensors in Figure 5), soil saturation is accompanied by volumetric soil strains, which attains values up to about 4%.

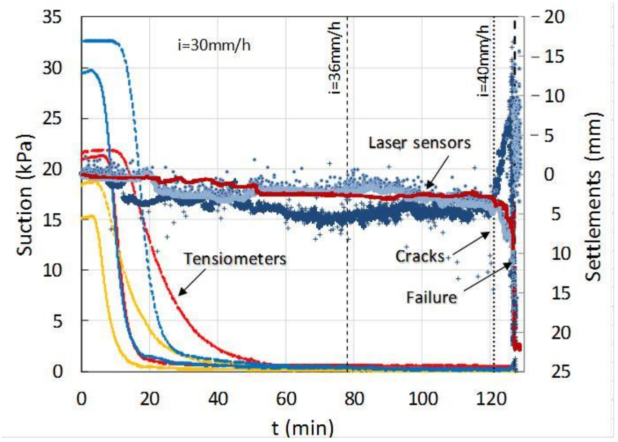

Figure 5. Suction and settlements measured in the RP3 experiment.

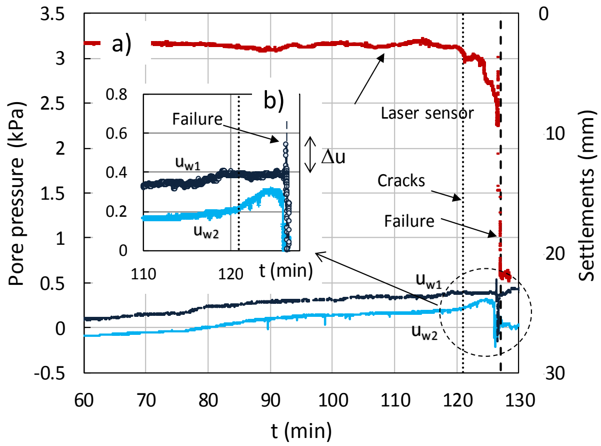

Figure 6. Pore pressures and settlements during test RP3 (a); magnification of the pore pressure records close to failure.

About 80 minutes since the beginning of the test, the process seems to have reached a steady-state condition as no more suction variations and slope deformations occur (Fig. 5 and 7). For this reason, the rainfall intensity was increased. As a consequence, a positive pore pressure is first measured at the base of the steepest section of the slope (uw_1 in Fig. 6), then, 20 min later, a similar result is recorded also by the downslope transducer (uw_2 in Fig. 6). Moreover, a few seconds after slope failure, which occurs when the pore pressure measured by the upslope transducer is 0.4 kPa, a further rapid and transient pore pressure increase of about 0.2 kPa takes place (Figure 6b). This suggests a mechanism of undrained failure.

Figure 7 reports the downslope displacement rate (Vy), obtained from the PIV technique, at different points of the ground surface along the section A-A’. The figure shows that, during a first stage of about 25 minutes, it gradually increases reaching a peak value of about 0.08 mm/s. In this stage, the displacement rate presents a progressive downslope reduction, with the highest values measured in the uppermost section (point 5). However, in the following stage, the slope reaches a stable configuration, as denoted by the displacement rate which decreases everywhere up to a negligible value.

As mentioned above, in order to induce slope failure, rainfall intensity was increased two times. As a result, the slope displays a block-type movement. Failure takes place 126 min after the beginning of test. Visual surveys revealed a flow-type movement with soil particles no more distinguishable within a muddy practically fluidized mass.

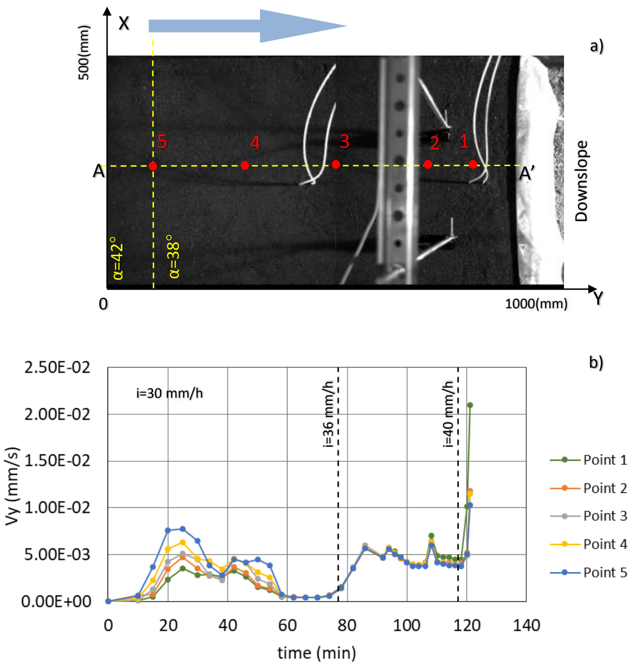

Figure 7. (a) Monitored points; (b) displacement rate from PIV records.

3.2 RP4 test

In this experiment the imposed rainfall intensity was very high (100mm/h) and the entire process up to slope failure lasted about 29min. Despite the very different rain intensity, the rate of the infiltration process (which depends on hydraulic conductivity and gradient) is similar to the one observed in the first stage of previous test. In fact, just as in experiment RP3, a saturation degree close to 100% is reached 20 to 30 minutes after the beginning of rainfall. Suction measurements at mid depth show that, despite the high rainfall intensity, the passage of the wetting front was not able to fully saturate the soil as small values of suction were recorded till the end of test.

Indeed, as soon as rainwater reaches the bottom of the slope, the laser sensors start to record continuous settlements of the ground surface up to a mean value of 8mm, which is measured before slope failure, corresponding to a volumetric strain of 8%.

Monitoring data also indicate that the arrival of the wetting front at the base of the slope causes soil saturation, first at the toe of the slope (blue lines in Fig. 8), then, at section marking the change of the slope angle. Based on tensiometer records the middle part of the slope does not seem to attain a complete saturation.

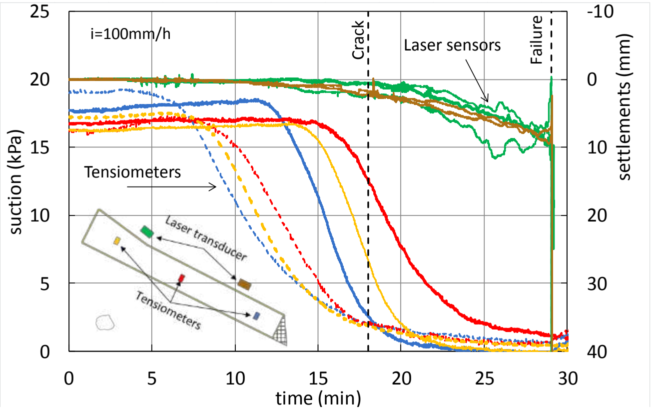

Figure 8. Suction and settlements measured in the RP4 experiment at mid height (dashed lines) and at the base of the layer (solid lines).

Again, such data are consistent with those obtained in the experiment RP3. Positive pore pressures are recorded at the toe of the slope 24 minutes after the beginning of the rain (blue lines in Fig. 9) and, two minutes later, at the section corresponding to the change of the slope angle (yellow lines in Fig. 9). Here the rate of pore pressure increase is higher than in the other parts of the slope, probably as a result of a partially undrained process induced by progressive slope deformation.

This is revealed by the displacement rates along ~~s~~the section A-A’ (Figure 10). As in the previous test, the uppermost part of the slope (point 5), where the slope inclination is higher, starts to move earlier with a higher velocity than in the lowermost part of the slope. Differently from previous experiment, the deformation process, characterized by higher speed in the upper part of the slope, is displayed during the entire experiment. Moreover, the displacement rate is one order of magnitude higher.

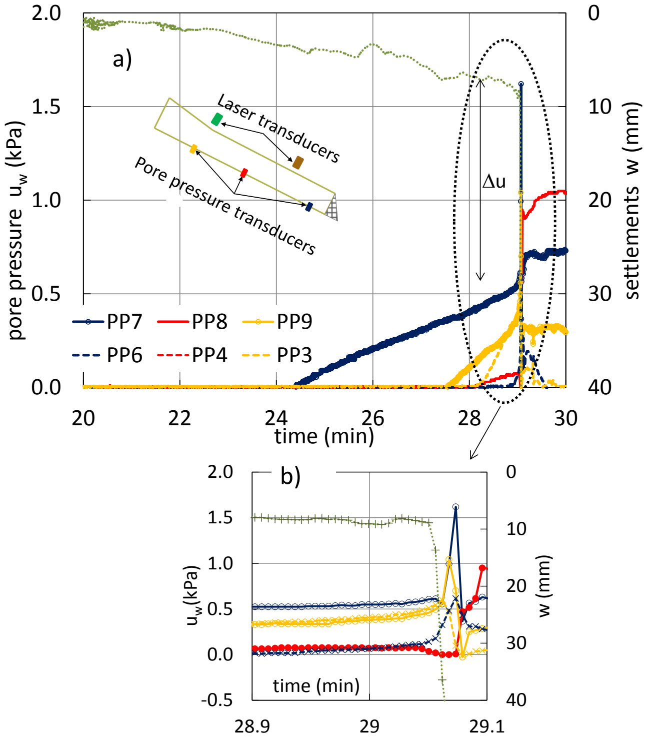

Figure 9. Pore pressures and settlements in test RP4 (a); magnification of pore pressure records closely around the onset of failure (b).

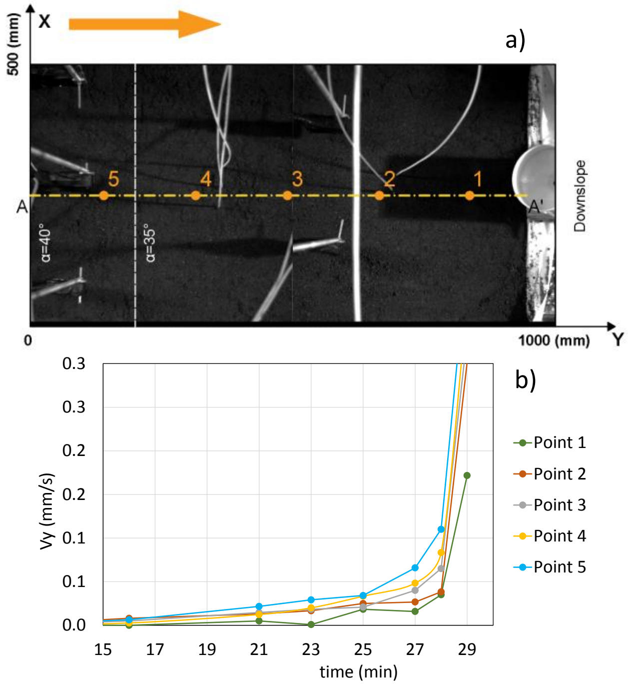

Figure 10. RP4 experiment: (a) monitored points and (b) displacement rates trend.

Slope failure takes place 29 minutes after the beginning of test and, again, a sudden pore pressure increase is measured. This increase, which takes place in a few seconds, is an evident effect of undrained failure, which leads recorded pore pressures from values of 0-0.6 kPa to values of 1.1-1.6 kPa. In particular, the highest value (1.6 kPa) corresponds to a piezometer head some centimeters above the ground surface. Assuming a nil pore pressure at the ground surface, this leads to an average hydraulic gradient around 0.6, which is close to critical gradient corresponding to vanishing of the effective stress (Picarelli et al., 2020b).

4 CONCLUSIONS

Liquefied debris flows and avalanches are typical landslides events in a wide area of Campania, where they periodically cause destruction and sometimes casualties. Some key mechanical aspects of such events have been identified and understood through in depth investigations and analysis. However, some aspects still deserve to be definitely clarified. One of them is the mechanical process induced by rainwater infiltration, which prepares and leads to sudden and brittle failure. The experiments, which are presently being carried out at the Università della Campania, intend to check the hypothesis that the debris flows and avalanches, which take place in volcanic ashes, are the result of a mechanism of downslope undrained progressive failure leading to soil liquefaction. The first results of this investigation are providing good data about the validity of this hypothesis.

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