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The use of optical fibres for early prediction of slope failure

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Abstract – Landsliding is the macroscopic effect of the slope failure; however, it is only the final stage of an often long-lasting process of soil deformation. In many cases, slope movement remains extremely slow and undetected for a very long time; in other cases, failure is abrupt, preceded by only small deformations and followed by fast and destructive movements. The detection and interpretation of pre-failure deformations and the precise definition of the unstable area are of paramount importance for risk mitigation. To this aim, optical fibres can represent a new and efficient tool.

I. INTRODUCTION

Landsliding is only the final macroscopic effect of a process of slope deformation and failure. Often it is very slow and develops over very long times remaining undetected until failure. In other cases, it is preceded by extremely small deformations and consists in a sudden and abrupt slope collapse that is followed by fast and destructive movements: the detection of pre-failure deformation phenomena and the delimitation of the unstable area are then crucial to minimize damage and casualties.

Today the use of optical fibres for monitoring is quite usual in industrial engineering. For example, they are widely employed in aircrafts monitoring. However, their capability to monitor physical quantities with a resolution of tens of centimetres over lengths of hundreds of metres, and their adaptability to very different applications encourage an extensive use also in civil and environmental engineering. As a matter of fact, optical fibres have been adopted to record the deformations of different materials and structures, such as dams, bridges, tunnels, geosynthetics, pipelines or leakage from buried hydraulic infrastructure [1, 2, 3, 4]. Also, they have been used for the measurement of deep soil displacements based on the principle of the inclinometer tube [5, 6].

The Writers believe that optical fibres could be used also for the early detection of slope deformations in areas susceptible to rapid landslides in order to timely predict the slope collapse [7]. To this aim, a flume has been instrumented with optical fibres to test their performance in the physical modelling of the behaviour of small-scale slopes subjected to artificial rainfall [8]. Some results of experiments conducted on unsaturated granular pyroclastic soils are described in the following.

II. SCOPE OF THE RESEARCH

In Campania, the risk of landslide is very high. In fact, the diffuse landslide hazard is exacerbated by the density of population and of vulnerable infrastructure. Since the cost to build passive or active mitigation measures in all areas at risk is not sustainable, the development of reliable early warning systems is becoming an urgent issue, especially in areas occupied by very loose air-fall unsaturated pyroclastic soils that are susceptible to fast precipitation-induced flowslides.

The stability of slopes mantled by unsaturated soils is assured by the contribution of the matric suction to shear strength. However, rainwater infiltration consequent to long-lasting precipitations and the consequent drop in matric suction and associated apparent cohesion, can lead to slope failure. If this takes place in nearly saturated conditions, very loose non plastic soils can liquefy. This mechanism has been proven to be the basic cause of flowslide triggering in pyroclastic deposits widespread in Campania [9, 10]. In particular, both field surveys and flume experiments show that the pre-failure stage is characterised by some volumetric soil collapse and cracking. Some examples are reported in Figure 1 which shows the diffuse cracking recognized in the source areas of the recent destructive Cervinara [11] and the Bracigliano landslides [12].

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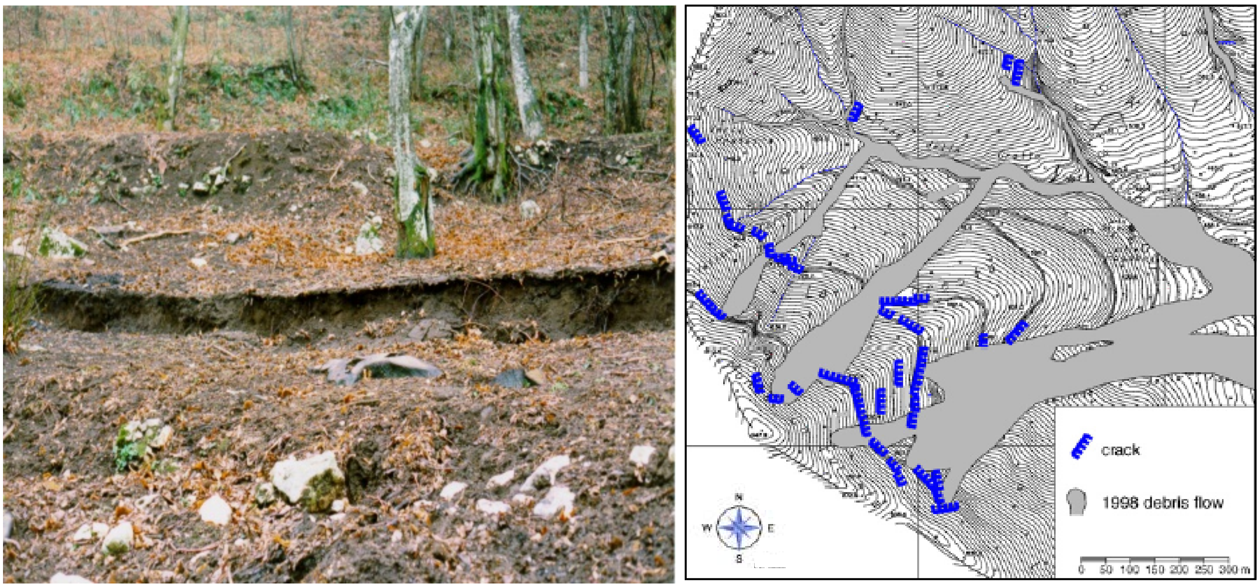

Figure 1. Soil cracking observed in the Cervinara (left) and Bracigliano slopes (right, [12]) a few days after the landslide events occurred respectively on December, 1999, and May, 1998.

These data suggest that an accurate monitoring of soil deformation during rainfall might be highly beneficial for the early warning of the landslide triggering. A key feature of such a system should be the capability to monitor the entire area susceptible to landslide in order to capture the first clues of the incoming failure, wherever they appear. On this line, the performance of optical fibres for the early detection of slope deformations is being investigated at Seconda Università di Napoli.

III. SHORT INFORMATION ON THE OPERATIONAL PRINCIPLES OF OPTICAL FIBRES

The strain monitoring procedure adopted in the experiments is based on stimulated Brillouin scattering, whose basic principles are shortly described below.

Two counter-propagating light waves in a fibre exchange energy in a measure that depends on their frequency offset. If the difference is comprised in an appropriate range, the radiation at higher frequency (pump wave) can transfer energy to the one at lower frequency (Stokes wave). The frequency difference at which maximum amplification of the Stokes wave occurs, known as the Brillouin frequency shift, varies as a function of the mechanical and thermal properties of the fibre. In particular, the Brillouin shift increases with both temperature and stress. The ability to measure deformation and temperature changes in a distributed way along the fibre (spatial resolution) can be achieved through a pulsed pump beam. In this way, the interaction takes place along successive sections of the fibre as the pump pulse propagates down the sensing cable. By recording the intensity of the Stokes radiation as a function of time, the Brillouin gain can be traced in every section. The measurement of this one as a function of time and wave frequency provides the profile of Brillouin shift along the fibre. This, in turn, can be transformed into a deformation or temperature profile through the use of appropriate calibration coefficients

These concepts represent the basis for distributed strain (or temperature) monitoring The spatial resolution depends on the light pulse duration: the shorter the duration, the better the resolution. In current applications, a pulse width of 10 ns leads to a spatial resolution of one meter; the measured strain in a section of the fibre is then the average value over a 1 m long distance, centered in that section. However, higher resolutions can be obtained. The basic idea for the applications considered in this paper is that a fibre buried in the soil can detect tensile strains caused by any change in the stress conditions along the monitored alignment. In particular, its capability to perform distributed strain readings allows to record soil deformations wherever in the slope, especially in the detachment zone where high tensile or shear strains take place due to stress relaxation associated with rupture, and in zones subjected to volumetric collapse which can lead to some subsidence of the ground surface and fibre elongation. A great advantage with respect to conventional monitoring devices which can record only local deformations possibly missing critical zones, is assured by the fact that a fibre can cover very long distances capturing any local effect of the changing stress field.

These considerations suggested an experimental program to test the reliability of optical fibres through experiments on small-scale model slopes.

IV. EXPERIMENTAL RESULTS

A. The instrumented flume

The length and width of the flume adopted in the investigation are respectively 190 and 50 cm (Fig. 2). The thickness of the model slope is less than 1/10 of its length, usually 10 cm. This allows to work on an "infinite slope". Its lowermost boundary is vertical and sustained by a geotextile sheet that assures free drainage; in contrast, the flume base is impervious. Rainfall is obtained by spray nozzles installed above the lateral sides. The monitoring system consists of tensiometers, pore pressure transducers, a TDR probe, displacement transducers, a pair of video-cameras and the optical fibre.

Some jet-fill type tensiometers are placed in the middle and in proximity of the base of the soil layer in order to record the advance of the humid front during infiltration, while miniature silicon diaphragm pore pressure transducers located at the base can measure the positive pore pressures which rise if some water ponding forms on the impervious bottom. A TDR probe installed through the layer, normally to the ground surface, allows to retrieve the entire volumetric water content profile by the inverse profiling method proposed by Greco et al. [14].

Slope deformations are monitored by the laser sensors located above the ground surface, the video-cameras and the optical fibre. In general, during formation of the fibre two parallel strands are buried into the soil, in the longitudinal direction of the flume; the spoil between the two buried strands is placed outside the flume thus it is not subjected to any strain. The spatial resolution of readings was 1 m; this means that the measured strains was more or less the average value over the entire slope length. A resolution of 20 cm was adopted only in the last experiment described below.

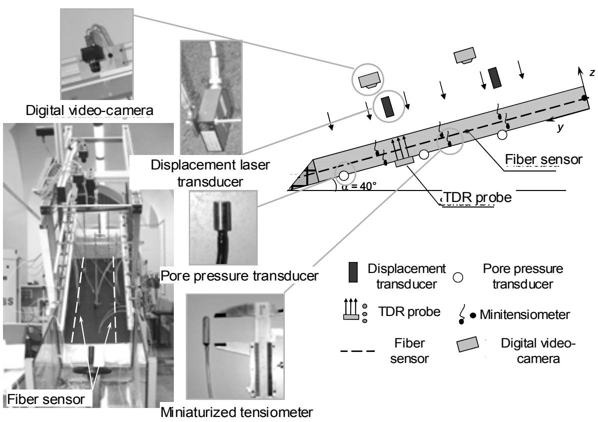

Figure 2. The instrumented flume [13].

The monitoring system includes a thermocouple placed at the base of the layer to measure changing temperature due to wetting. External air temperature and rainfall intensity are measured by a meteorological station.

B. The experimental programme

The soils used in the experiments were air-fall ashes taken from the sites of Cervinara [11] and Monteforte Irpino [15] both located a few tens of kilometres to North-East of Naples. The material is a silty sand with a non-plastic fine content comprised between 10 and 20%. Both soils present a field porosity around 70%. The saturated hydraulic conductivity measured in constant head tests is comprised between 10^{-6} and 10^{-7} m/s. The effective friction angle is 37°-38°. The soils are cohesionless, but in unsaturated conditions they present an apparent cohesion which can exceed 10 kPa depending on the matric suction [16]. Laboratory tests demonstrate their susceptibility to static liquefaction [17] evidenced also in the described experiments [9, 10].

In the flume, the soil is laid down on a rough base and is disposed in thin layers by the moist-tamping technique adopting a very low compaction energy in order to reproduce the high field porosity. The imposed water content ranged between 0.43 and 0.63 which corresponds to a degree of saturation much less than one. After suction equalization, the flume was tilted to an angle of 38° or 40°, then was subjected to continuous rainfall (i= 35-50 mm/h) until slope failure.

C. Fibre performance

Some results of the experiment D10 conducted on the Monteforte Irpino ash are reported in Figures 3 and 4.

Figure 3 shows the matric suction measured at two different depths (5 and 9 cm) and the cumulative settlement of the ground surface. The deepening of the wet front is revealed by the comparison between the suction trends in the middle and at the base of the layer. The consequent stress change causes a compressive strain in the soil that displays also some downslope movement (not shown in the figure) recorded by the video-cameras. As the wet front reaches the bottom of the layer, the soil strain increases significantly, attaining a value of about 3.2% which corresponds to an average settlement of 3 mm.

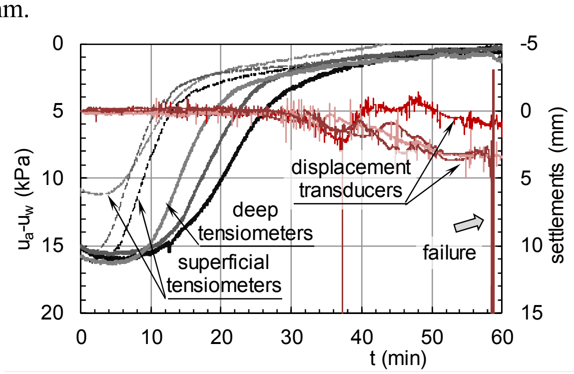

Figure 3. Soil suction and displacement normal to the ground surface during the experiment D10 [13].

In the final stage of the experiment, positive pore pressures develop at the base of the layer due to formation of some water ponding (Fig. 4), gradually leading to slope failure. This stage is characterised by almost uniform downslope movements with a rate which in a few seconds attains 1mm/s. Failure is sudden and is followed by further fast pore pressure increase, magnified in the plot in Figure 4, due to static liquefaction. This causes an abrupt drop in the soil strength and an acceleration which in a few seconds reaches a higher than 40 mm/s rate, while the movement turns into a flow.

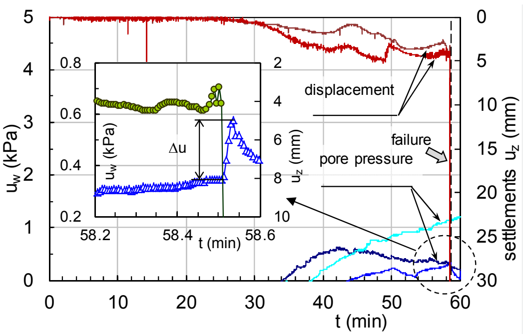

Figure 4. Pore pressure trends during experiment D10.

As shown by this and other similar experiments on very loose unsaturated granular soils, slope failure is accompanied by some volumetric soil collapse which represents the first clue of the failure process [10]. As this goes on, soil cracking may take place as a result of the same process and of both diffuse tensile stress and localised shear stress in the detachment zone. Such deformations can be captured by the optical fibre.

The strains recorded by the fibre in the experiment D10 are summarized in Figure 5, which shows the time sequences in terms of Brillouin Frequency Shift (BFS, Fig. 5a) and of associated fibre strain (Fig. 5b): the grey backgrounds in Figure 5a indicate the strands buried into the soil. The figure shows a progressive BFS increase along one of the two strands. Conversely, the decrease in the BFS along the free spoil exposed to rain water, in between the two buried strands, is caused by fibre cooling due to wetting: the corresponding decrease in temperature is about 8°C. The thermocouple placed in the soil indicated a local temperature decrease of only 1-2°C. This suggests that measured strains are essentially due to mechanical effects.

The small value of the measured strain, three orders of magnitude smaller than the volumetric soil compression, suggested an imperfect connection between the fibre and the soil, allowing relative displacements. In order to better capture local soil deformations, the system was upgraded by inserting along the fibre a number of small plastic geogrids at intervals of some twenty centimetres (Fig. 6).

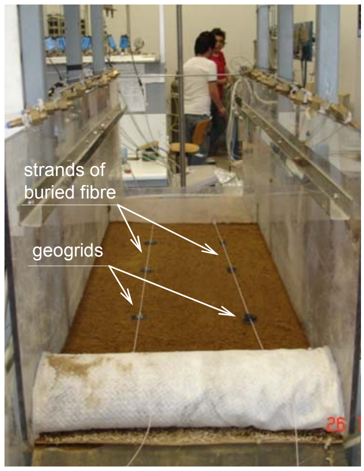

Figure 6. Adopted system to measure local soil strains [7]

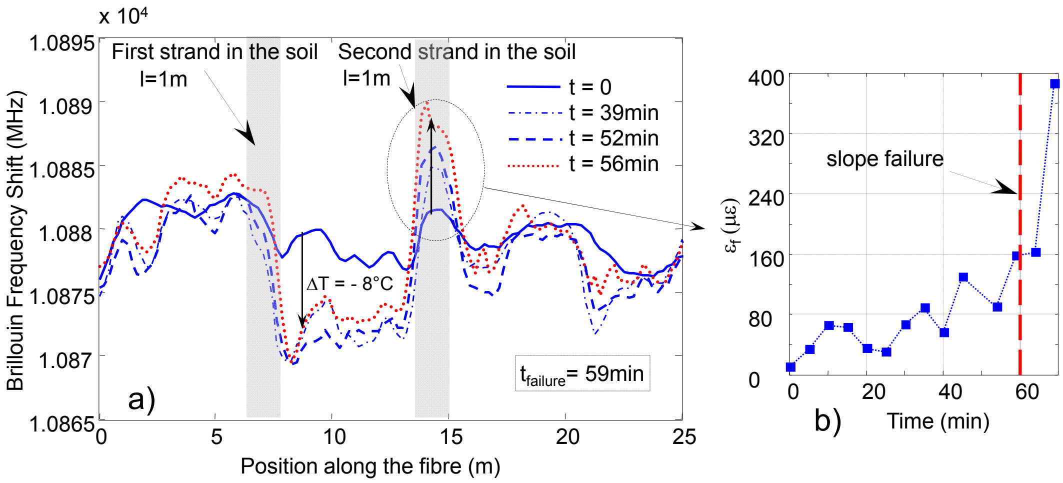

Figure 5. Experiment D10 [7]: a) changes in the BFS; b) strain measured in one of the two buried strands as a function of time.

The good performance of the upgraded system is shown by the results of further experiments. Figure 7 shows the pre-failure strains measured in the experiment D13 (Cervinara ash) before a temporary arrest of the rain. The fibre records deformations up to about 0.018% (i.e. one order of magnitude higher than the final value in the experiment D10). Moreover, the readings provided by both sensors are quite in a good agreement since they can contemporaneously capture the volumetric collapse of the soil about 25min from the beginning of the experiment while the deepest tensiometers were recording a drop in matric suction. Even though the strain measured by the fibre is two orders of magnitude lower than that the volumetric soil strain roughly calculated from settlement values ($\varepsilon_v \approx 2\%$), the figure demonstrates that the fibre can fully capture the process of deformation induced by wetting.

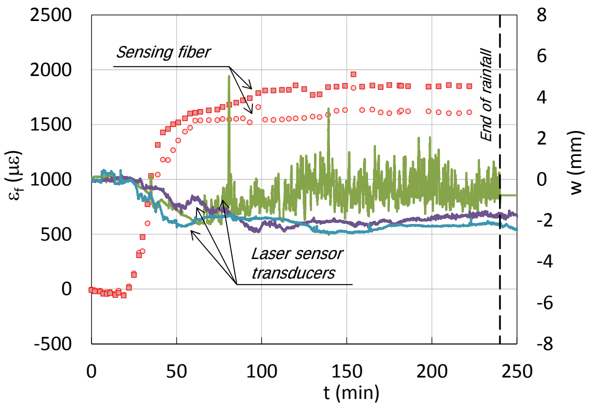

Figure 7. Experiment D13: temporal strain evolution in two fibre strands and ground settlement.

After the rain stop, the experiment D13 restarted and the slope failed 50 min later. The time sequences of the BFS during this phase are shown in Figure 8a. The first profile (t=0 in Fig. 8a) reveals the residual strain accumulated during the previous stage. The measurements during the ten minutes preceding failure show a progressive strain increase in both buried strands up to a peak value of about 0.05%. This is more than one order of magnitude higher than the value measured in the experiment D10, testifying the effectiveness of the anchoring system. Further readings carried out after the slope failure ($t>t_f$ in Fig. 8a) reveal an almost complete strain recovery. Figure 8b shows that a few minutes before failure the fibre undergoes a sharp increase in strain due to the formation of a crack in the upper part of the slope (Fig. 8c). This is a clear indication of the incoming slope failure. Measured strain corresponds to a fibre elongation of 5 mm, which is more or less the crack aperture a few minutes before the slope collapse. The progressive decrease in strain observed in the last few minutes is probably caused by a relative movement between soil and fibre due to plastic soil deformations around the geogrids.

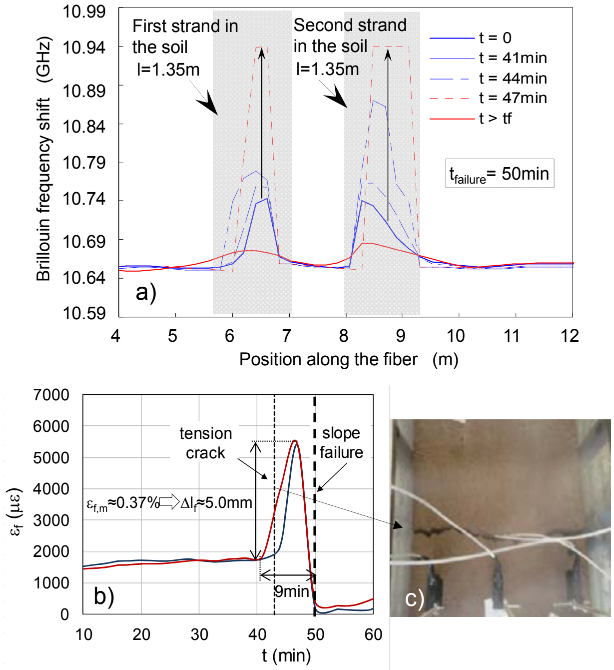

Figure 8. Experiment D13 [7]: a) BFS changes; b) cracks on the ground surface

In the last experiment conducted again on Cervinara ash, three strands of the fibre were buried on parallel cross sections of the slope (Fig. 9) and the monitoring system was upgraded in order to obtain a spatial resolution of 20 cm. Unfortunately one of the two longitudinal strands failed during the installation phase and was not substituted: readings were performed using a by-pass. The data reported below than refer to the records obtained from one longitudinal strand only.

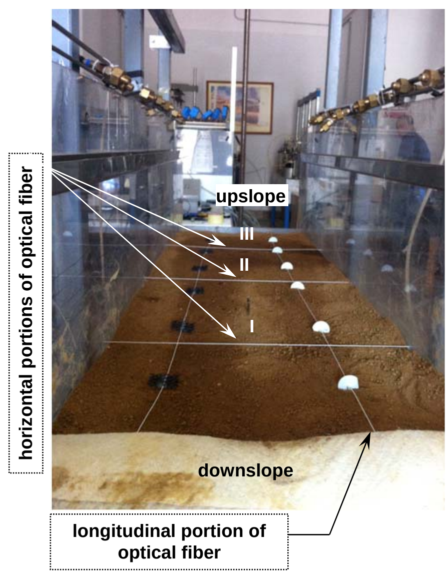

Figure 9. Installation of fibre strands

The records show that the sensor can discriminate between soil deformations measured in different sections of the longitudinal strand (Fig. 10). In particular, the highest strains occur in the uppermost part of the slope (sections D and C). The mechanism of slope deformation is consistent with the development of a crack at the top of the slope, about 20 minutes after the start of the experiment.

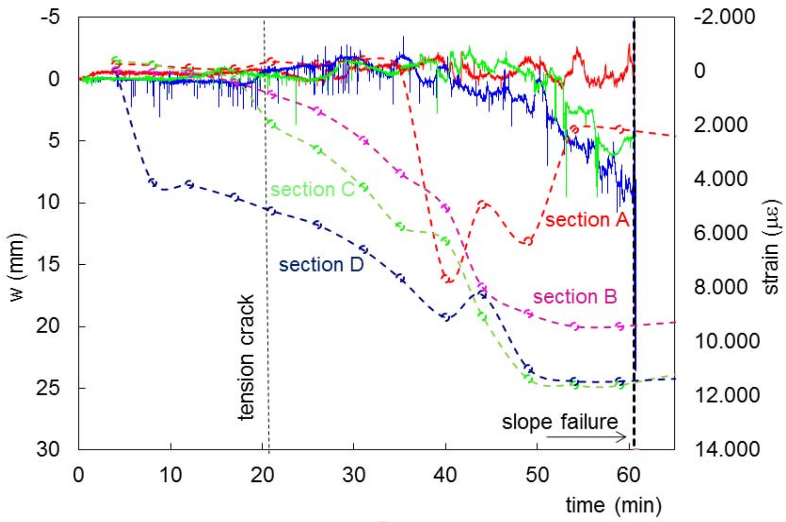

Figure 10. Strain measured in different sections of the fibre and displacement of the ground surface in the last experiment.

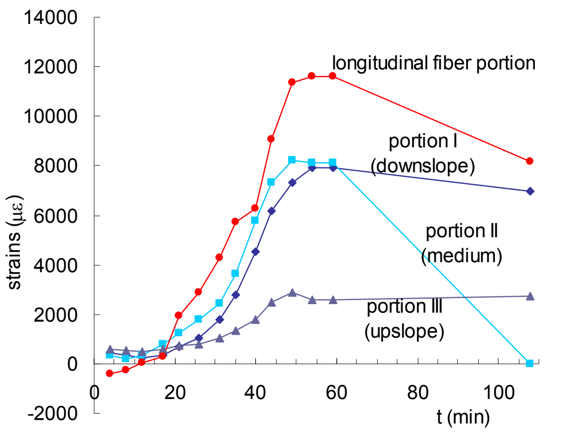

Figure 11. Temporal strain evolution of fibre strands in the last experiment

In Figure 11 the temporal deformations measured by the transverse strands are compared to the average value in the longitudinal one. After soil cracking the strains measured by the fibre greatly increase everywhere attaining a peak of about 0.12% in the longitudinal strand a few minutes before the slope failure. The uppermost transverse strand that is located upslope the crack records the lower soil deformation, while the lowermost ones are subjected to heavier stress conditions.

V. CONCLUSIONS

The use of distributed optical fibres for the early detection of pre-failure strains in slopes susceptibile to abrupt collapse and fast post-failure movements is being investigated at the Seconda Università di Napoli. The experiments are conducted on small scale model slopes consisting of loose unsaturated pyroclastic soils, instrumented with various devices including an optical fibre. The slope is subjected to continuous rain until failure.

The experiments demonstrate that the fibre is an efficient sensor which can properly record the process of volumetric collapse and soil cracking occurring prior to slope failure. A remarkable advantage of the fibre is its ability to record tensile soil strains wherever they take place, with a resolution of a few centimetres. In natural slopes a fibre could be installed in shallow trenches dug both in longitudinal and cross slope sections providing continuous information of the soil response in any point where soil strains may develop due to volumetric collapse or cracking of the soil induced by shear and/or tensile stress.

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