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# A new real-time debris flow and avalanches detection system based on optical fiber sensing

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**Abstract.** The real-time detection of potentially destructive water, earth and snow mixtures such as debris flow and avalanches is a topic of growing interest to mitigate the risk in anthropized areas such as the Alpine region. In view of this, a new cutting-edge debris flow and avalanche detection system, called OPTIALP, was developed. The proposed system exploits the polarization variations induced on the fiber by mechanical vibrations, for the automatic detection along their propagation path of potentially destructive snow and soil-water mixtures. One of the main values-add of the OPTIALP system is the "quasi distributed" and spatially continuous detection along the whole fiber which improves the current monitoring technologies relying on "discrete" monitoring points and sensors. The OPTIALP system was designed and thoroughly tested in the laboratory environment by means of a specific setup. Over 650 tests were carried out and a new signal processing algorithm developed in Matlab environment capable to interpret the data acquired was created. The results showed that the OPTIALP system is able to correctly identify the signals produced by lab-scale mass movements.

## 1 Introduction

In mountainous areas like the Alps debris-flow and snow avalanche processes, despite occurring in different seasons, often occupy common starting and runout zones. Despite the different rheology of material involved in the movement and the possible transformation occurring during their pathways, a common characteristic both of debris flow and snow avalanches is that such mass movements are generated by singular or multiple relatively shallow soil or snow/ice failure collapses which during the movement along a slope can combine with each other, channelize and entrain further material. Debris flows require the availability of cohesionless material and excess moisture to saturate and mobilize the debris [1] while snow avalanches are a direct consequence of the dynamic of the variable seasonal snow cover in steep mountainous terrain. The prerequisite for the occurrence of both snow avalanches and debris flows is a steep slope.

These phenomena represent highly dangerous types of mass movements, because of their high velocities, large impact forces and long runout distances. Their repeated occurrence results in characteristic landforms, such as cone-shaped debris accumulations at the mouth of gullies or torrent valleys where buildings and infrastructures are very often located.

The protection of infrastructures in mountain environments against debris flow and snow avalanches is of growing importance as an effect of global warming. The frequency, the areal distribution, and the intensity of precipitations have slowly but continuously changed while the occurrence of severe rainfalls has increased [2].

The consequent occurrence of debris flows and snow avalanches has increased as well [3] despite the presence of differentiated trends by basins not easily generalized on a larger scale [4]. This frequency in the Alpine area is sufficient to create high-risk conditions for people, settlements and infrastructures.

Consequently, there is a growing need for innovative tools to increase the adaption to these phenomena. In this sense, adaptation, i.e. the process of adjusting in response to current or expected climate change and effects, with the aim to reduce exposure and vulnerability to climate variability [5], is a fundamental strategy for reducing and managing the risks of climate change impacts on slopes and, more broadly, on all geostructures.

The aim of the proposed new optical fiber system, called OPTIALP, is therefore the detection and early warning of high velocities and large impact force mass movements like debris flows and snow avalanches. The novelty of the proposed solution is that the sensing system, capable to measure continuously and in real-time, can be used and extended over long distances (up to a few km) without any limitation so that the sensor becomes the whole optical fiber. Another important advantage is that optical fibers are completely buried in

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the soil. Therefore, the visual impact of the system is limited thus allowing the installation in contexts characterized by high environmental value (natural parks and natural reserves). A patent application was filed for the OPTIALP system last 7th December 2022 (n. 102022000025158).

In the present paper the characteristics of the OPTIALP system will be first described. An experimental setup, specially developed to test the technology at the laboratory scale, will then be illustrated along with the results obtained from the many tests performed. Finally, conclusions and possible further envisaged developments will be discussed.

## 2 Characteristics of the system and principle of operation

A general layout of the proposed system to detect debris flows and snow avalanches is shown in Figure 1.

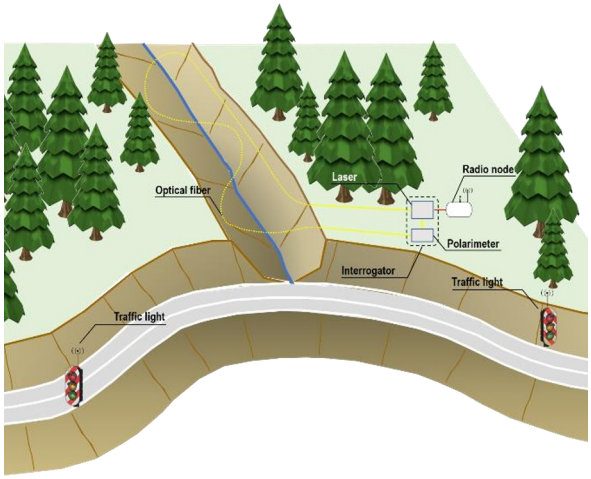


**Fig. 1.** Layout of the OPTIALP system along a road that crosses a gully subjected to debris flows/snow avalanches.

The system is composed of the following devices:
- Optical fibers;
- Laser i.e. optical source;
- Polarimeter;
- Laptop or embedded microprocessor system to process the acquired signals;
- Radio node to send the alarms to the informative devices;
- Traffic lights or alternative informative devices to convey specific messages to the elements at risk.

The laser source along with the polarimeter and the system used for signal processing, also called the interrogator, represents the core of the OPTIALP system.

The principle of operation of the system can be summarized as the measurement of the variation of the state of polarization of the signal emitted by the laser source along the optical fiber. The state of polarization (hereafter called SOP) can undergo changes over time due to a well-known property of the materials called birefringence. Birefringence in the optical fiber is caused by geometric asymmetries of its profile and is highly susceptible to mechanical stresses such as vibrations and distortions along the fiber path. The stronger the intensity of the mechanical stress occurring on the fiber, the more sudden the change of the SOP.

This allows real-time detection if something anomalous is occurring along the fiber. During their propagation, debris flows as well as snow avalanches generate mechanical and vibrational stresses along their paths that can be monitored by observing the variations of the SOP along the fibers in the domain of time.

Figure 1 also illustrates the installation scheme for the optical fibers consisting of different loops placed across the axis of the gully. As the optical fiber can be subjected to large mechanical stress and impact forces resulting in damages, it will be buried at a sufficient depth (0.3-0.5 m) in the soil for protection.

A key point for the mitigation of the risk of debris flows and rock avalanches occurrence is the prompt and correct detection of the masses propagating along a slope. Therefore, the adoption of a distributed sensing system buried in the ground along the whole propagation path represents an evident advantage with respect to the use of discrete sensors.

At the same time, another requirement of an early warning system for correct detection is to minimize the possible occurrence of false alarms. Given this, it is essential to adopt a robust algorithm for signal processing capable of correctly recognizing the vibrational characteristics of mass movements from any other random noise affecting the fibers. Therefore, a specific algorithm described in [6] and based on the selection of specific filtering and thresholding is adopted to process in real-time the SOP variation over time.

From a technical point of view the advantages of the OPTIALP system compared to other monitoring systems currently available on the market are:
- The spatially continuous detection of mass movements over the entire length of the optical fiber that makes it possible to use the system over long distances (up to 10 km) and for very large areas (several $km^2$).
- The instantaneous response of the system and the extremely high sensitivity to mechanical vibrations.
- The higher wear resistance than traditional electro-mechanical sensors due to the burial in the ground.
- The relative ease of installation and the possibility of direct installation within structures such as rockfall net barriers.

## 3 Experimental validation

### 3.1 Description of the experimental setup

To assess the effectiveness of the system, a physical scale model of a slope was built in the laboratory. The model consists of a phenolic plywood base and plexiglass sides with a size of approximately 3 m in length and 0.7 m in overall width (Figure 2).

For the experimentation carried out, a geometric configuration characterized by a uniform inclination equal to about 30° with respect to the horizontal was used. Above the wooden top, a layer of soil mixed with

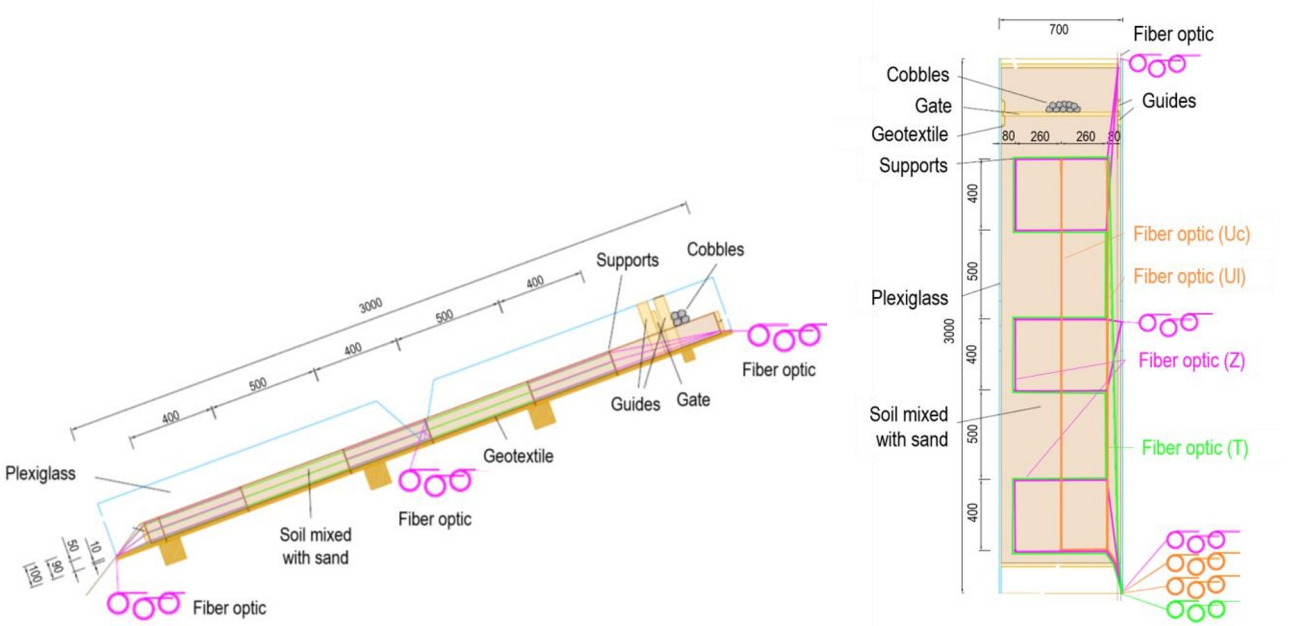


**Fig. 2.** Cross section and plan view of the lab-scale model with an indication of the different optical fibers installation schemes (T, U and Z).

sand of about 10-12 cm thickness was subsequently created, lying within a layer of geotextile (Figure 2).

The latter has the function of protecting the underlying wooden surface, facilitating the compaction of the mixture of soil and sand, and avoiding the removal of material during the simulation of falling materials, facilitating the execution of the tests. Inside the package of soil that was made by depositing the material by successive layers of a thickness of about 2-3 cm, different optical fibers of a length of about 10 m were buried and arranged in three different geometric configurations (U – longitudinal, T - transversal and Z – by zones) and three different depths (1, 5 and 9 cm from the surface) of the optical fibers were installed, for a total of 12 different configurations. Also shown in Figure 2 is a plan diagram of the physical model where the different optical fibers configuration schemes adopted are indicated. The green lines represent the T layout i.e. optical fibers installed in loops transversal to the slope of the model, orange lines represent the U layouts i.e. optical fibers installed parallel to the lateral boundaries both at the center of the physical model (Uc) and along one side (Ul), while magenta lines represent the Z fibers i.e. optical fibers installed in separate loops (by zones).

The fibers are connected to the optical source (i.e. laser) and at the fiber output, light is coupled into a polarimeter to measure the polarization state with a certain sampling frequency $f_s$. The samples are then passed to a PC where the signal processing is completed.

Three different types of experiments have been carried out over the slope to emulate the mass movements:

- Cylinder (C): the downfall of a test cylinder made of plastic material, 15 cm long and with a diameter of 5 cm.
- Single rock (SR): the downfall of a single rock with a mean diameter of 8 cm.
- Debris (D): the downfall of 25 rounded rocks with a mean diameter of about 5 cm.

The "background noise" on measurements has also been acquired when no event was generated, to analyze the rest conditions, and compare it to the effects of the events in the model.

More than 1500 different tests were carried out and a total of about 5 Gb of data were collected.

### 3.2 Results and discussion of the tests

The typical results of the tests carried out can be summarized as the variation of the state of polarization in the time domain (i.e. the duration of each test) as shown by the blue line in Figure 3. The raw signals are characterized by complex patterns in frequencies and intensities both for the background noise measures as well as for the C, SR and D simulations. Given this complexity, the need emerged to adopt a specific real-time data processing that would allow distinguishing in a semi-automated way the patterns generated by the mass movements from the background noise and any other event (for instance a tree falling or the transit of wild animals or people etc.) not related to the propagation of debris flows and/or snow avalanches.

Consequently, a new algorithm for the processing of the measured signals was created. The algorithm consists of a digital time-moving average filter ($T_{mov}$) that eliminates the noisy patterns from the measurements and a SOP threshold value ($\omega_{th}$). These two input parameters need to be defined in the processing scheme. Since they cannot be selected a priori, it was necessary to create specific matrices, called detection maps, able to synthesize the results in terms of Correct Detection (CD), Missed Detection (MD) and False Alarms (FA) for the different combination of the two parameters. These maps give a fundamental indicator for the appropriate choice of $T_{mov}$ and $\omega_{th}$ and they help the operators in minimizing the MDs and the FAs occurrence.

In Figure 3 a summary of the laboratory test results is shown for three different values of $T_{mov}$ and $\omega_{th}$ in the case of the T and the Uc fibers layout. It is shown that a satisfactory combination of the two parameters can be identified to correctly detect the mass movement.

Finally, a concept of a complete interrogator based on the previous algorithm was created and tested. The real-time interrogator performs the measurement of the state of polarization along the optical fibers using a specific sampling frequency and applies the algorithm to identify the mass movement phenomena along the slope based on the selected values of $T_{mov}$ and $\omega_{th}$. When the threshold value is exceeded, the interrogator generates, practically instantaneously (within less than 1 second), a specific warning sound and an emulated traffic light is turned red.

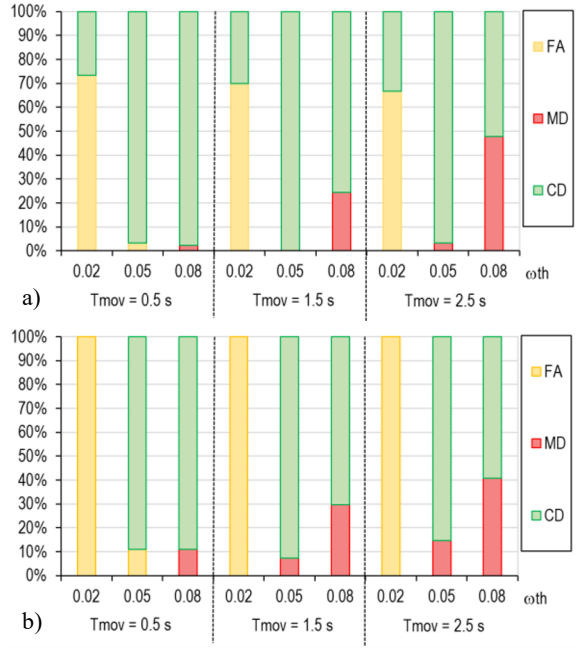


**Fig. 3.** Summary of the results of the laboratory tests in terms of CD, MD and FA for three different values of $T_{mov}$ and $\omega_{th}$ and two different layouts of the optical fibers: T (a) and Uc (b).

## 4 Conclusions

A new cutting-edge debris flow and avalanche detection system, called OPTIALP, was developed. The proposed system exploits the polarization variations induced on the fiber by mechanical vibrations, for the automatic detection along their propagation path of potentially destructive snow and soil-water mixtures.

The results of the experimental campaign at the laboratory scale obtained so far are highly encouraging and promising since the tests showed that the OPTIALP system is able to correctly identify the signals produced by lab-scale mass movements. Moreover, the correct identification of the mass movements seems to be independent of the depth and the scheme of the installation of the optical fiber. This implies that on the field it would be possible to adapt the path of the optical fiber to the morphology and characteristics of the specific site.

A preliminary economic assessment for the application of this technique to a real case study has indicated that, despite the initial additional costs for the excavation and burial of optical fibers in the ground, the overall costs are still comparable with those required for the deployment of monitoring systems based on traditional electromechanical sensors.

The advantage of the OPTIALP system with respect to current detection systems based on a large number of "discrete" traditional sensors is evident in terms of spatially distributed and continuous sensing, distances (up to 10 km) and areas (several km$^2$), instantaneous response and high sensitivity, higher wear resistance and relative ease of installation.

The results obtained in the laboratory will be confirmed in a relevant real-scale environment, i.e. along a gully subject to debris flows and snow avalanches. During the field activities, particular attention will be posed to study the potential scale effects between the signal generated by the mass movements and the natural noise levels of the site.

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