Distributed acoustic sensing of debris flows in a physical model

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Abstract: We used a distributed acoustic sensing (DAS) system to monitor the evolution of debris flows in an inclined flume that was instrumented with approx. 800 m of fiber, wound in 20 coils acting as an array of coherent acoustic sensors. The analysis of the acquired signals confirmed the viability of DAS as a tool for debris flows monitoring.

1. Introduction

Debris flows are natural geomorphological phenomena consisting in a rapid, gravity-induced flow of a mixture of fragmented rocks, mud, water, and air [1] that rushes down mountainsides, often causing casualties and damages to infrastructure. According to the literature, the flow is accompanied by intense ground vibrations [2]. Therefore, ground vibrations and seismic signals generated by the flows, have been used since many years in the monitoring practice of such phenomena [3]. The most common sensors used in this application are geophones or seismometers. Nonetheless, the difficulty of access to the debris flows prone areas and the wide spatial coverage of the phenomena, make the implementation of a standard sensors network very cumbersome, due to the lack of power supply and to the signal attenuation over long distance. To overcome these limitations, fiber optic sensors (FOS) have been also proposed. Up to now, their use in this field is however at an early stage, and the very few solutions proposed so far are basically mimicking traditional sensors (such as geophones), without fully exploiting the advantages of FOSs. In particular, all the proposed sensors are single-point and cannot be concatenated [4–6]; furthermore, performances are not up to those of traditional ones.

In this perspective, Distributed Acoustic Sensing (DAS), as a novel tool for detecting vibration and seismic signal using a standard optical fiber as the sensor [7], may solve some of these issues. In this work, we have investigated the viability of using DAS for debris flows seismic monitoring by performing some experiments in a physical model. In the following, the experimental setup is described, and the analysis in the time- and frequency-domain of the seismic signals generated by the flow of debris, made of particles of different size, is presented and discussed.

2. Experimental setup

The DAS system used in the experiments to detect the acoustic response is based on a phase-sensitive optical time-domain reflectometer (Φ-OTDR) using chirped pulses [8], which allows for a better identification of acoustic events, thus reducing the number of false alarms. The scheme of this DAS implementation is shown in Fig. 1. For a detailed description of this setup and its features please refer to [9]. Here, some details of the system has been specifically tuned for the kind of signals expected from debris flows. According to characterization tests, the system can detect and identify the position of the vibration produced by any acoustic event, anywhere close to the fiber, which can be as long as 35 km (70 km using the integrated Raman amplification). The spatial resolution can be set between 2 and 10 m with a spatial sampling step down to 2 m. For the experiments, the spatial resolution and spatial sampling have been set to 4 m and 2 m, respectively.

The typical acoustic sampling rate is about 1 kHz (but can be increased depending on the actual configuration of the fiber link), thus allowing measurements of acoustic events up to 500 Hz. The sensitivity to strain variations depends on the acoustic bandwidth of the measured stimulus, with an estimated noise-level of 20-30 $\mathrm{p}\varepsilon/\sqrt{\mathrm{Hz}}$ (measured at 10 m spatial resolution). At a sampling frequency of 1 kHz (that is the one used in the experiments), this determines a total RMS noise of ± 1 nε.

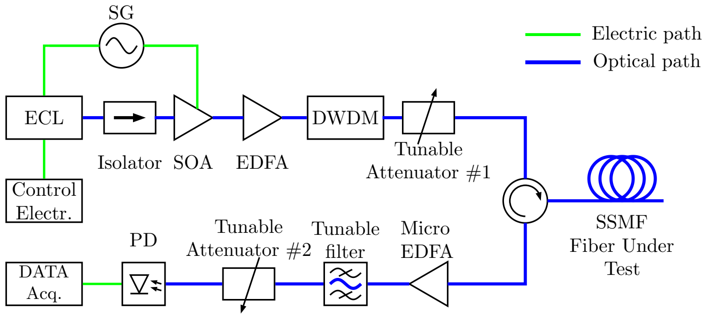


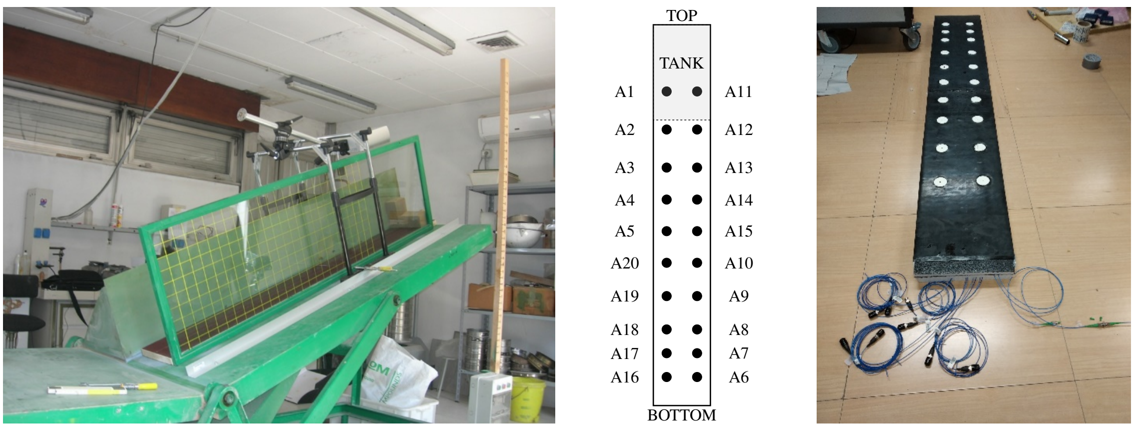
Fig. 1. Setup of the chirped-pulse Φ-OTDR employed in the experiments (ECL: external cavity laser; SG: signal generator; SOA: semiconductor optical amplifier; EDFA: erbium-doped fiber amplifier; DWDM: dense-wavelength division multiplexing; PD: photodiode). Modified from [9].

The physical model for the experiments consists of a flume (2.0 m×1.5 m), shown in Fig. 2(a), with a variable inclination from 0° to 38°, on which it is possible to install a channel 30 cm-wide. The channel is delimited by a 36 cm-high metal wall and a 54 cm-high transparent wall. A fixed horizontal surface, which constitutes the test material area, measuring 1.5×1.5 m, is joined to the lower end part of the channel. A storage tank, with a removable front wall, is placed in the upper part so to occupy the first 40 cm of the flume. It stores the debris for the experiments, which are release by removing its front wall.

Despite the relatively high spatial resolution of the DAS system (4 m), the short length of the apparatus (2 m) did not allow to simply deploy the fiber linearly, down to the flume. To cope with this scale problem, we embedded the sensors (the optical fiber and some additional electrical sensors) into an engineered mat, consisting of a foam mattress, 7 cm-thick, which hosts an array of 20 optical fiber coils (hereinafter referred to as the acoustic sensors) and the additional electrical sensors.

Figure 2(b) and 2(c) show a scheme of the position of the sensors in the mattress and the implemented mattress, respectively. Twenty acoustic sensors (A1…A20) have been integrated in the mattress (the white circles visible in fig. 2(c)), each with approx. 40 m of G.657 fiber, for an overall length of almost 800 m. This means that, with the specific DAS performance, we can collect signals from approx. 400 sensing points, 20 per each acoustic sensors of the mattress. The acoustic sensors were realized by coiling the fiber around 5 cm-diameter PVC mandrels (height 2 cm) by means of an automatic winding machine, opportunely designed for the purpose. In addition, some additional electrical sensors were embedded in the mattress and a camera was mounted laterally, at the transparent wall side, used to perform particle image velocimetry (PIV) analysis.

The fiber is coiled in the mandrels from A1 to A20, according to the scheme of fig. 2(b): please note that the fiber path does not follow the flume direction and, therefore, the 20 acoustic sensors are expected to be impacted by the debris flows not according to their numbering. This setup has been chosen to spread in time the expected



(a) (b) (c)

Fig. 2. (a): The flume used for the debris flows experiments. (b) Positions of the optical acoustic sensors in the mattress. (c) the implemented mattress (upside-down); at the bottom, 2 optical patch cords and 8 electrical coaxial cables are used to interrogate 20 optical acoustic sensors and 8 additional electrical sensors.

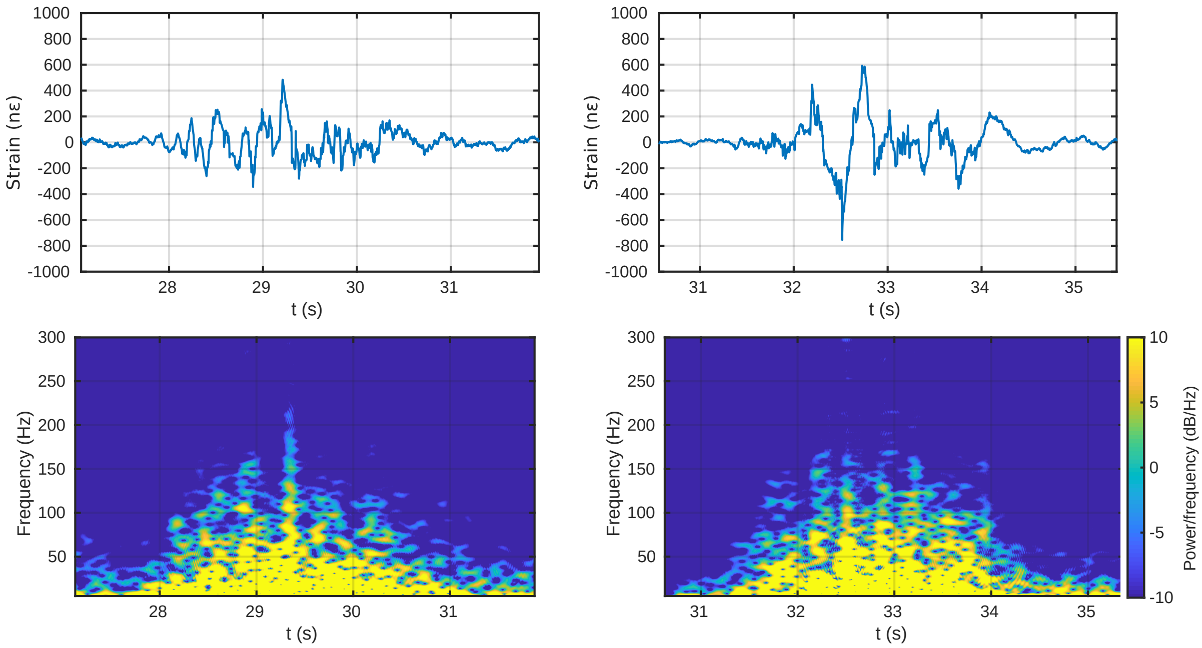


Fig. 3. Upper plots: signals collected at the optical acoustic sensor A20, for debris size of 1-4 mm (left plot) and 11.2-16 mm (right plot). Lower plots: corresponding spectrograms.

acoustic response of the debris flows to portions of the fiber, well separated along the path.

3. Results

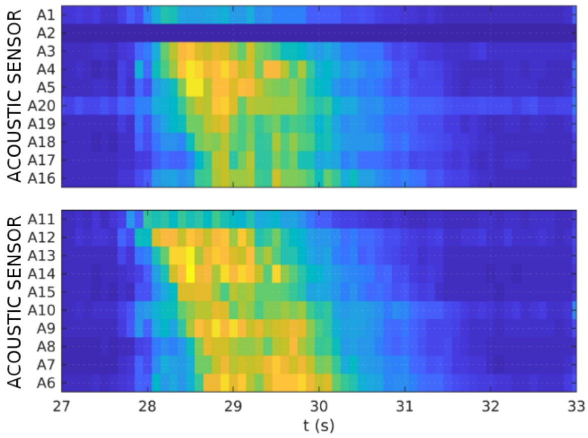
The experiments consisted of a series of flows carried out for different configurations obtained by varying the diameter and roughness of the gravel particles. The overall weight of debris was approx. 40 kg. Here, due to the limited space, only a selection of the results regarding the optical acoustic sensors will be presented. Some signals collected at a single point and the aggregation of signals collected along the flume will be presented and discussed in the conference. This is done to disclose the potentialities of DAS, not only as a replacement of standard single-point seismic sensors, usually adopted in debris flows monitoring, but also as a novel distributed sensing tool, to coherently monitor debris flows with unprecedented spatial resolution.

As an example, left and right plots of fig. 3 show the signal collected at one of the sensing point of the coil A20, placed in the middle of the flume, for two different sizes of the debris (1-4 and 11.2-16 mm, respectively). The signals represented here have been post-processed via 5-points median-filtering technique to mitigate the presence of outliers occurring for large dynamic strains [10]. As one can note, despite the relative small diameter of the particles the peak-to-peak signals reach up to a thousand of nanostrain. It is also evident that the size of the particles directly affect the strain intensity. The corresponding spectrograms are represented in the lower plots: both signals have similar frequency patterns where low-frequency-content precedes the high-frequency ones, which is limited to 200 Hz. A more flat spectrum also characterizes the large-particles-size experiment. At the same time, the small-particles-size spectrogram shows some isolated high-frequency peaks.

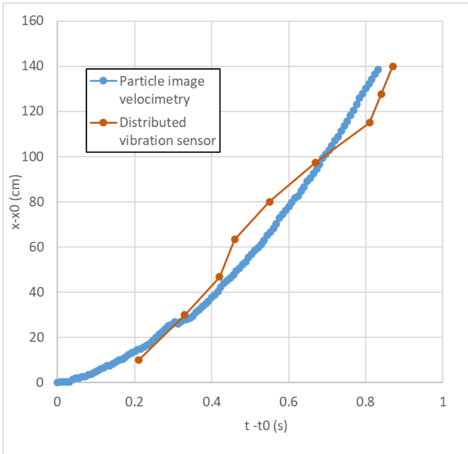
The analysis of the aggregated signals collected along the flume reveals some important features of the debris flow, such as the flow velocity. Figure 4(a) shows the spectrograms of the mean acoustic energy vs time and distance (encoded in term of acoustic sensors sequence of the arrays at the two sides of the flume) for one of the debris flow experiment with 1-4 mm size gravel. The progressive detection of energy down the flume is clearly detected, in particular for the lower plot, corresponding to the sensor array at the right-side of the flume. For a given threshold, it is possible to determine the time-of-detection along the flume (and the corresponding velocity) and, therefore, determine the curve distance vs time of the acoustic-energy propagation along the flume, which is represented with red dots joined by a red line in the figure 4(b) for the array of acoustic sensors at the right-side of the flume. In the same plot, the same curve, as obtained by PIV, is represented with blue dots joined by a blue line. The agreement is very good.

4. Conclusion

In this work, we have investigated and proved the viability of distributed acoustic sensing for debris flows monitoring. To this aim, we have performed a series of experiments in a physical model constituted by an inclined



(a)



(b)

Fig. 4. On the left: Mean acoustic energy. The upper and lower plots refer to the arrays of acoustic sensors at the left- and right-side of the flume, respectively. The dark band at the mandrel A2 is because this was damaged during one of the first tests. On the right: in red color, the distance vs time curve of the acoustic-energy propagation along the flume of the debris flow for the right-side array of acoustic sensors; in blue color, the same curve as obtained by PIV.

flume instrumented at its bottom with an engineered mattress containing approximately 800 m of fiber wound in 20 plastic coils, acting as acoustic sensors. These sensors were interrogated by a chirped-pulsed DAS while the debris were released at the top of the flume. The results show the capability of the system to provide seismic signals at a specific location as standard seismic single sensors commonly used in debris flows monitoring. In addition, thanks to the high acoustic bandwidth and the availability of a large number of coherent sensing points typical of DAS, other important features of debris flows can be disclosed, such as the harmonic content and the flow velocity.

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