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Studies of Flexible Barriers Under Debris Flow Impact: An Application to an Alpine Basin / Vagnon, Federico; Segalini, Andrea; Ferrero, Anna Maria. - In: PROCEDIA EARTH AND PLANETARY SCIENCE. - ISSN 1878-5220. - 15:(2015), pp. 165-172. [10.1016/j.proeps.2015.08.041]

Availability:
This version is available at: 11583/2960721 since: 2022-04-07T11:14:28Z

Publisher:
Elsevier

Published
DOI:10.1016/j.proeps.2015.08.041

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24 April 2024

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Procedia Earth and Planetary Science 15 (2015) 165 – 172

Procedia
Earth and Planetary Science

World Multidisciplinary Earth Sciences Symposium, WMESS 2015

Studies of Flexible Barriers under Debris Flow Impact: An Application to an Alpine Basin

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Abstract

The aim of this paper is to analyze the most relevant aspects that influence the interaction between debris flow phenomena and protection barriers. The volume of the debris and its lithological nature are conditioning the barrier size and strength. This system is often complicated by environmental and climate influences that need to be taken into consideration as well; therefore, a correct design of a protection barrier system in an alpine basin is a complex procedure that needs to be rationalized. This paper will concentrate on the barrier dimension design proposing a rational scheme of study of the global problem. The application to an Alpine basin is reported.

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Keywords: Debris flow; flexible barrier; impact forces.

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1. Introduction

Debris flows are one of the most frequent mass movement processes and play an important role in moving sediment from steep lands into river system. Many of the world's most devastating landslide disasters, in terms of life losses and/or economic damages, are attributed to debris flows (Jakob and Hungr, 2005). The latest events occurred in Northern Italy suggest the need of an accurate study on the debris flow processes (both triggering criteria and depositional process) to forecast possible consequences and to develop the best solutions to prevent these phenomena and to protect infrastructures and residential areas. Thus, the first approach to the problem requires

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doi:10.1016/j.proeps.2015.08.041

identifying fundamental parameters that could affect debris flow system, especially flow interaction with barriers. In order to obtain reliable results, engineers and geologists must have clearly in their mind which are the variables involved, the relationships between different parameters during the flow and the possible effects on the protection structures during the impact. At first, one needs to evaluate the influence that characteristic basin factors (unstable debris volume, grain distribution, morphometry, topography, hydrology) can have on the intensity, frequency and magnitude of debris flow events. In particular, definition of the potentially unstable debris volume and triggering causes (i.e. rainfall or snowmelt) are useful to define motion flow model, in terms of travelled distance, depositional height, and flow velocity. This paper, while identifying the most relevant parameters, suggests some experimental and theoretical tools to quantify the flow/barrier interaction. In-situ tests have been performed to characterize the glacial deposits that generate debris flow on the mountain slopes. In particular, a procedure for the estimation of the distribution of the grain size dimension of the glacial deposits that origin the flow has been used to evaluate the flow parameters. The debris flow motion process can be investigated using both analytical and numerical methods: flow velocity and depositional height can be estimated with empirical formulas or by applying a single-phase model based on depth-averaged Saint Venant equations, such as the RASH3D code (Pirulli, 2005), or double phase model such as TRENT2D (Armanini et al., 2009). This procedure allows the analysis of the phenomenon considering all of the aspects involved: from the rock mass conditions to the barrier characteristics, from the triggering causes to the consequences after flow affect (Ferrero et al., 2015). Finally, a simplified structural model (Brighenti et al., 2013) for the design of cable-like retention barriers is presented; the method allows parametrical analysis that can be proved useful for optimal barrier design. The use of the simplified model allows the evaluation of the influence of the parameters variability on the structure safety (Bedi and Harrison, 2013; Gambino et al., 2014).

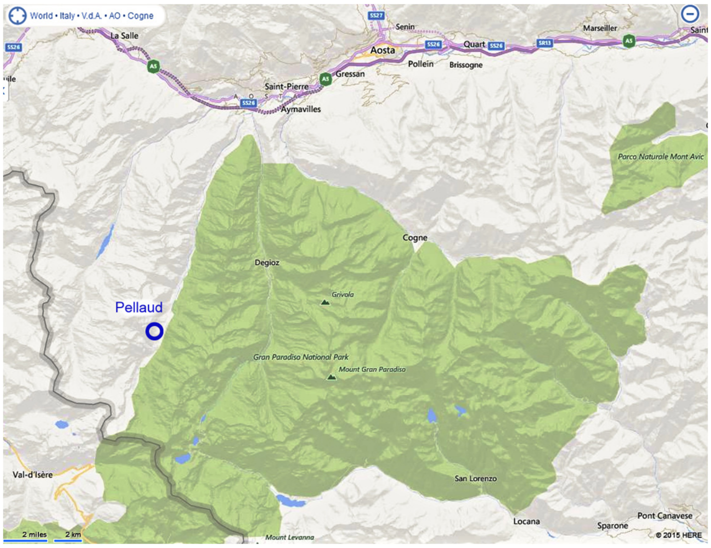

Fig. 1. Schematic map of zone with location of the Aosta Valley Region and the Pellaud basin, (bing.com/maps).

2. Application at the study site

The methodology has been applied to the study of the debris flow occurred in the basin of the Pellaud torrent, located on the orographical left side of the upper Rhêmes Valley, a secondary valley of Aosta Valley Region (Northwestern Italy) in the municipal district of Rhêmes Notre Dame (Figs. 1 and 2). The catchment basin has an amphitheatre like shape on which the Becca dei Fos (3459 m asl), Grand Rousse Sud (3555 m asl) and Grand Rousse Nord (3607 m asl) peaks overlook. In the upper part of the basin there is a glacier (Pellaud Glacier) and some small snowfields from which the torrent originates; actually the glacier has almost totally disappeared, leaving some loose material on the slopes (Curtaz et al., 2011). The amphitheatre walls are made of metamorphic rock (gneiss and mica schist) and are about 500 m high. Below, there are steep slopes (always more than 30°) with some cliffs that end at 2200 m asl in the alluvial fan where the Pellaud torrent runs up to the confluence (1810 m asl) with the main torrent of Rhêmes Valley, the Dora di Rhêmes river.

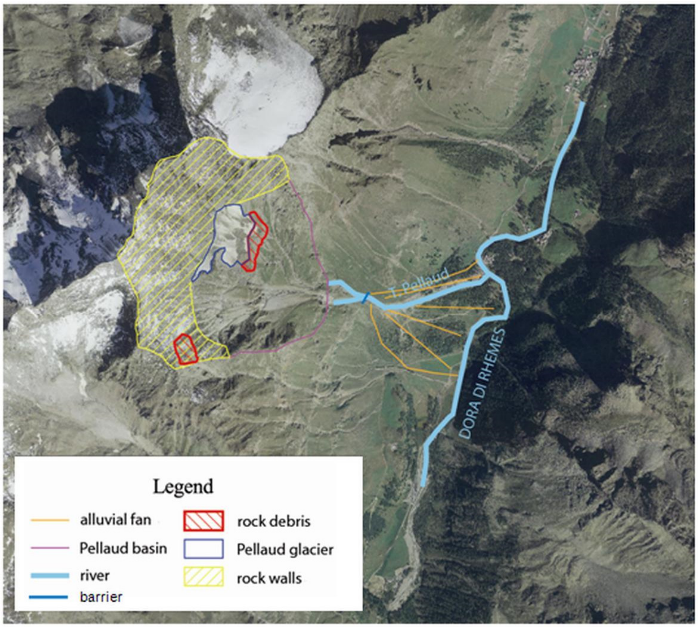

Fig. 2. Description of the study area. Area 1: rock debris on the orographical left side of the Pellaud Torrent; Area 2: rock debris on the orographical right side of the Pellaud Torrent.

The debris is periodically released from the above mentioned rock cliff and accumulates on the steep slope; after strong precipitations it is transported to the valley floor, causing flow-like movements. Considering that these phenomena take origin especially in late spring and previous surveys evidenced the presence of some ice in the fractured rock mass, it is possible to validate the hypothesis that permafrost degradation and instability phenomena could be correlated. The magnitude of the events varies in the range of 5000-15,000 m^3. Based on the interpretation of the orthophotos taken during the 2011 flight over the Aosta Valley glaciers, the presence of rock material deposited on the Pellaud upper slope was evidenced in two main areas:

- Area 1 (Fig. 2). On the orographical left side of the Pellaud Torrent, where glacial drift (i.e. the loose and unsorted rock debris distributed by glacial melt waters) is originated by the Pellaud glacier;
- Area 2 (Fig. 2). On the orographical right side of the Pellaud torrent, immediately below the rock walls of the basin, where rock material released from the cliff is deposited on steep slopes.

To protect the structures located in the Rhêmes Notre Dame municipality, the construction of a cable-like retention barrier is hypothesized; the location of this protection fence (Fig.2), is at 2000 m asl where the secondary streams flow into the principal basin.

2.1. Geo-morphological Aspects: Debris Characterization

In order to understand the consequences of the interaction between rock mass and debris conditions it is necessary to evaluate the main characteristics, in terms of grain size distribution, unstable volume and basin shape, influencing the global stability and the flow motion. Thus, the first step for the debris characterization is to define their nature in terms of grain distribution. Unfortunately, standard sieve tests are not applicable on this kind of materials since their size ranges from very fine clay particle up to blocks of metric dimension.

Consequently, an alternative approach considering the combination of standard and advanced procedure is hereafter proposed. The finest portion of the debris is tested at laboratory scale whilst the larger portion is analysed by image analysis on quoted photographs. In Fig.5 debris photo analysed by the code Split-Desktop is reported: the software automatically recognizes the block borders, measures their size and produces a grain size distribution curve as reported in Fig.6. Having estimated the fine portion in laboratory, these curves are then coupled with the one obtained by the images.

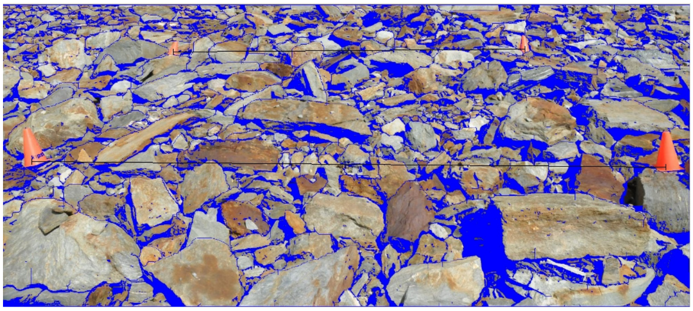

Fig. 3. Photo analysis of the glacial deposit produced by Split-Desktop software.

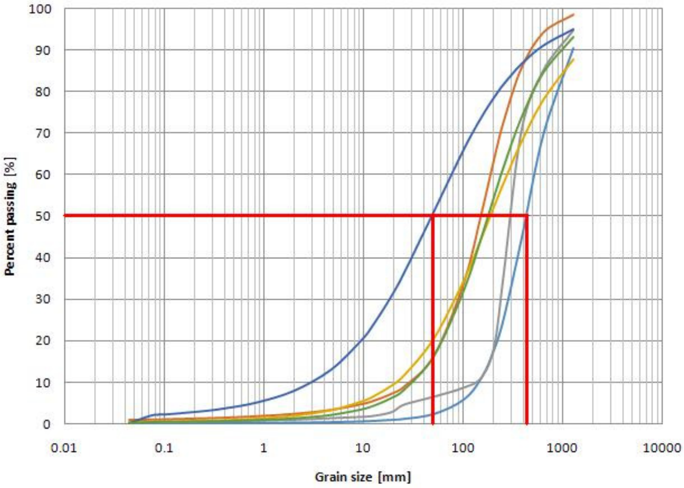

Fig. 4. Grain size distribution curve of the macroscopic portion deriving from the analysis of the debris flow deposit of the Pellaud site.

In this way, the grain size average diameter (D_{50}) and the coefficient of uniformity (C) can be obtained. Referring to Fig. 4, it's possible to define a range of variation of the value D_{50} between 50 and 400mm.

2.2. Triggering Phase

Stability analysis based on Limit Equilibrium Method (LEM), can be carried out to study the stability conditions of the rock-debris deposit (Area 1 in Fig. 2) under different climatic conditions. The analyses can be carried out along a vertical section obtained by knowing the basin and the bedrock position.

To evaluate how the alternation of frozen and thaw layers affects the deposit stability conditions with changing temperatures, the presence of frozen and thaw strata depending on the season can be considered. Each layer is characterised by a different strength parameter, depending on its level of compaction and its grain size distribution. The frozen material is characterised by a friction angle equal to the angle of the debris material and a cohesion due to the presence of ice in the intergranular spaces. The value of cohesion can be determined from the results of uniaxial compressive tests (UCS) carried out on cylindrical frozen specimens varying their temperature conditions from -1.5° to -28°C (Ferrero et al., 2014; Curtaz et al., 2012). In Fig. 5 a not-scaled sketch of the analysed sections with the geometrical parameters is reported. In this way, different unstable volumes for different seasons can be determined, depending on the strata mechanical characteristics, applied to the deposits. For instance, at the beginning of the summer, the deposit will start to thaw from the top and frozen strata of more consistent material will be located at the rock debris contact, while at the end of the summer, the strata will start to freeze from the top. During the winter, the deposit will all be frozen and more consistent, consequently releasing smaller volume that will develop into debris.

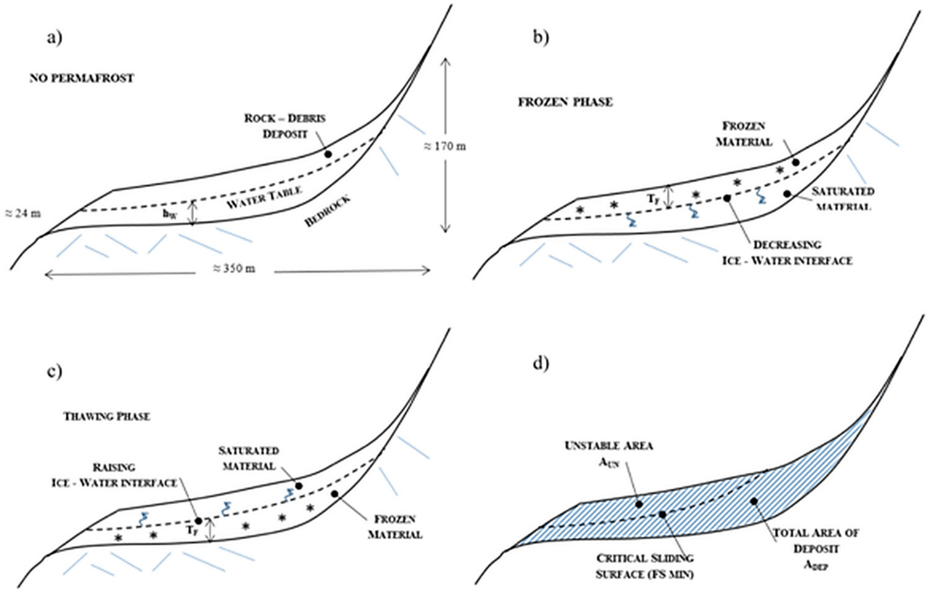

Fig. 5. Not scaled sketch of the analysed section reporting the geometrical setting: a) No-permafrost analyses; b) Freezing phase analyses; c) Thawing phase analyses; d) evaluation of the unstable slope volume (Ferrero et al., 2015).

For the aim of the barrier design, however, the most relevant aspect is the determination of the maximum debris volume during the year and consequently, parametrical analysis simulating the different frozen condition of the deposits are suggested.

2.3. Propagation Flow Models

The flow propagation plays an important role in the design of the protection structures against debris flow risk; in particular, it is very important to analyse both flow characteristics, in terms of velocity and depositional height, and flow path into the river basin. These characteristics can be determined with numerical or with analytical methods that are described below.

Numerical methods provide flow velocity, depositional height and run-out length solving motion equation. In this paper, the authors used the RASH3D code (Pirulli, 2010) to analyse the debris flow propagation in Pellaud basin. It is based on a continuum mechanics approach; in other words, the heterogeneous mass is considered as an equivalent fluid, whose rheological properties have to approximate the behaviour of the real mixture. The hypothesis is that the internal rheology is assumed to be frictional, while the basal rheology, which controls the basal shear stress, must be constrained by calibration using back analysis of past events Pirulli (2005). To carry out numerical analysis it is necessary to upload the digital terrain model (DTM) pre-event, the geometry of the unstable volume and to introduce a rheological law. The central point of the code and, generally, of these numerical methods, lies in the choice of the appropriate rheological law to describe the phenomenon: elementary rheology can imply rough mistakes; on the other hand, the calibration of a complex rheology, with many parameters, could be too hard. The code RASH3D implements two different rheologies: the frictional, in which the only parameter is the friction angle of the equivalent fluid (φ), and the Voellmy rheology, where, in addition to the frictional component (μ), the effect of a turbulent component (ξ) is considered. Modelling the potential events requires to estimate the unstable volume and to select the most appropriate rheological law. In consideration with the procedure previously described, the numerical analysis has been conducted using a released volume equal to 15,000 m^3. The numerical results have shown that the Voellmy rheology best approximates the behaviour of past debris flows events, both in terms of deposition height and propagation distance; further, it also allows to take into account the non-rectilinear stretches of the T. Pellaud basin. Thus, the rheological parameters, according to Ferrero et al., (2015), are: $\mu = 0.05$ and $\xi = 1000$ m / s^2 (Fig.8). In this first phase, we identified the range of variation of the flow parameters acting on the barrier: the flow velocity, v, ranged between 5 m/s and 13 m/s, and the flow height, h, that varies between 0.6 m and 1.7 m (Fig. 7). These two values are the expression of the debris flow characteristics and indirectly contain information about volume, potential energies and impact forces. These two variables are the input values of the barrier design model proposed by the authors (Brighenti et al., 2013).

Another methodology to evaluate the flow characteristics, in terms of flow velocity and depositional height, is the analytical method. There are some theoretical formulations, universally recognized, that take into account some debris parameters and morphological aspects.

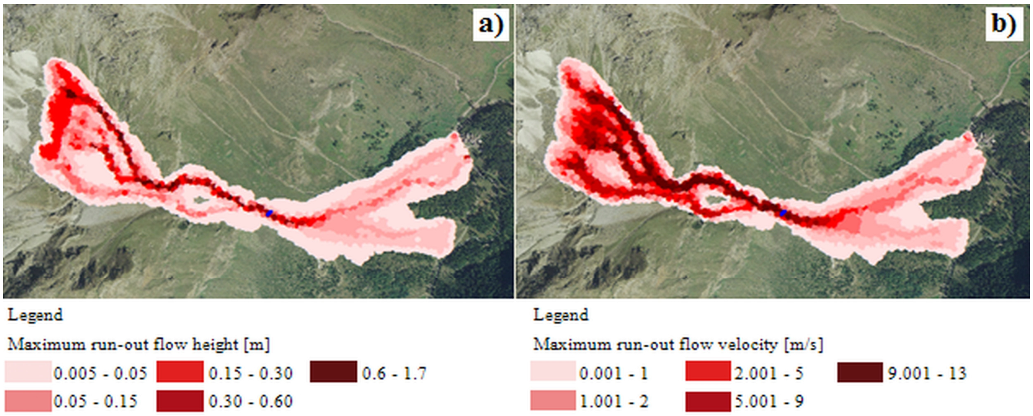

Fig. 6. Results from the numerical analysis using RASH3D code: maximum depositional heights (a) and maximum velocities (b) at the end of the phenomenon (after Ferrero et al. 2015).

According to Takahashi et al.(1992), the flow velocity v_0, needed for a debris flow to transport the load, without erosion or deposition, can be calculated as:

$$v_0 = \frac{2}{5D}\left(\frac{g\cdot\sin\theta_e\cdot\rho_d}{0.02\cdot\sigma}\right)^{1/2}\cdot\frac{1}{\lambda}\cdot h_0^{\;3/2} \tag{1}$$

where θ_e is the channel slope in which concentration c is in equilibrium and λ is the linear concentration of solids in the flow. The parameters required to calculate the flow velocity with Takahashi formulation are listed in Table 1.

Table 1. Debris parameters required for velocity v_0 calculation.

D	diameter of the 50% of passing grains
g	Gravitational acceleration
ρ_S	Mass density of solid portion
c*	Volume concentration of the solids in the static bed
c	Mean volume concentration of the solids throughout the entire flow depth
θ_ε	Internal friction angle of the bed
ρ_w	Mass density of the interstitial water
ρ_d	Medium mass density of the debris flow

The diameter of the 50% of passing grains D, can be determined with the above reported method whilst the volume concentration of the solids in the static bed and the mean volume concentration of the solids throughout the entire flow depth can be hypothesized using values suggested by Takahashi (1992). The depositional height can be determined through back analysis of past events or derived by literature data. The velocity value obtained should be compared with values proposed in literature to further validate the results.

Fig. 7 (left) shows the velocity variation with flow thickness for different grain dimensions (D), considering Takahashi's formulation, expressed by Eq. (1), and parameters listed in Table 1. The strong influence of the debris nature on the flow velocity determination is apparent, in terms of both grain distribution and flow thickness. Since this parameter, together with the flow height, is fundamental in the evaluation of the impact force on a protection structure, an accurate range evaluation needs to be carried out on this point. In this specific case, being D ranged between 50mm and 400 mm and the flow height between 0.6 m e 1.7 m, the maximum debris velocity at the barrier location is equal to 10.2 m/s.

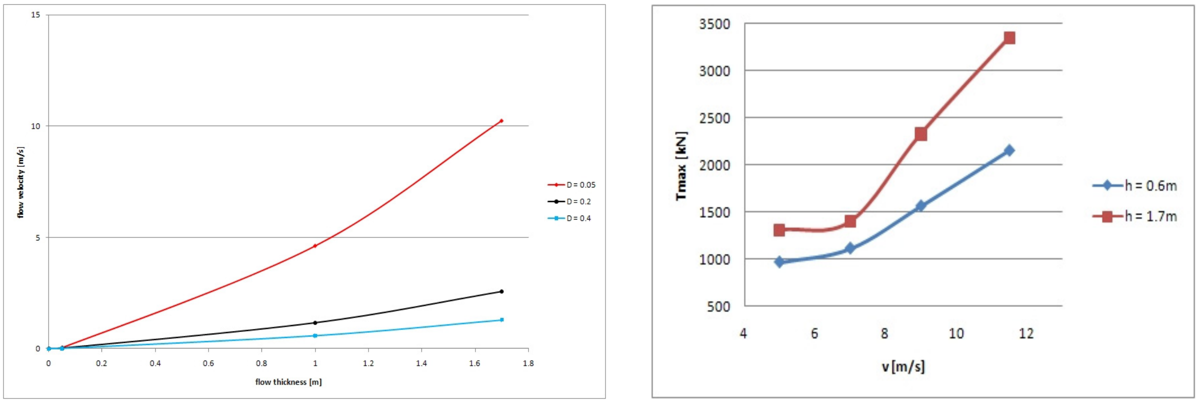

Fig. 7. (left) Variation of debris velocity with its thickness, according to different flow models (after Ferrero et al., 2015); the red lines specify the range of variation of the flow dept. (Right) Range of variation of maximum tensile force for cable 1 obtained using the simplified analytical model for different values of flow velocity and depositional height.

2.4. Flexible barrier design

The hypothesized barrier is 20 m long and 5 m tall; it is supported by 5 equally spaced steel cables with section of 0.024 m^2 each and elastic modulus, E, equal to 210 GPa. Each steel cable is equipped with a braking system that is activated by a tensile force greater than 100 kPa and can stretch up to 2 m. Using both, the values obtained by the analytical method and the numerical method, a series of analyses have been performed. In particular, the higher values in terms of velocity and flow height at the barrier location, obtained from the RASH3D analysis, have been considered to compute the state of stress in the horizontal cables. Figure 8 represents the upper and the lower limit that maximum tensile force can assume at different flow height and velocity chosen within the range of those obtained from the RASH3D analysis for an area located within 20 m distance from the barrier location. The wide range of possible tensile forces obtained suggests why an accurate evaluation of the input parameters and of the barrier location is required. As a result of the previous considerations, flow velocity and depositional flow height used for this analysis are respectively 11 m/s and 0.9 m. Fig. 8 (left) shows the trend of tensile forces vs. time for each cable, and, Fig. 8 (right) displays the horizontal displacement of the barrier calculated in the middle section during its progressive filling. In Fig. 8 (right) it can be seen that, at first, the larger deformation is induced in the lower cables ($z = 0$) and progressively moves towards the top of the barrier ($z = 5$). After 4 seconds, which is the total impact duration, no significant deformation of the barrier middle section occurs. This simple approach supplies the main input values required for the design of cable supported retention barriers: tensile force acting on the cables, total and progressive barrier displacement, energy dissipation and elongation of the brakes as well as the instantaneous load transferred from the flow to the barrier.

3. Conclusion and future developments

The paper is aimed to identify the parameters that play a relevant role on the flexible barrier design and to suggest a way to compute them. In particular, the depositional volume and nature of the debris, the channel geometry and the consequent flow speed and thickness are very important. At the centre of the proposed approach is a theoretical simplified model for the computation of the stress-strain state of the barrier. This model needs input parameters that cannot be determined entirely using standard geotechnical procedures. One among the other is the material grain size distribution that cannot be determined with standard laboratory tests but it needs the support of photogrammetry due to the extremely variable dimension of the material. This is an initial input that, by means of analytical and numerical approaches, can bring to the determination to the flow velocity and height at the barrier location. The analytical model can be used to perform parametrical analysis to quantify with interval analysis the influence of flow uncertainties on the barrier state of stress. The evaluation of the degree of safety of the barrier because of a barrier risk analysis within the uncertainties range of the most relevant parameters will be the further development of the work.

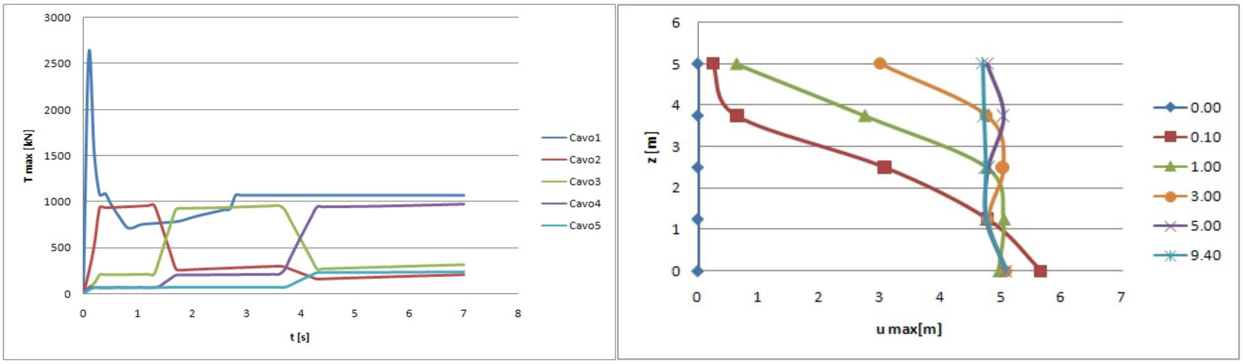

Fig. 8. Trend of the tensile force acting on each horizontal cable vs time during the impact (left). The total duration of the impact is around 4 seconds. On the right are the maximum displacement of the vertical middle section of the barrier at different times during the impact.

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