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Laboratory tests of an innovative check dam

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Abstract

The flow of both solid and liquid particles, especially in mountain basins, is impulsive, not easily predictable and for this reason extremely dangerous. As to avoid the damages caused by this phenomenon, barriers are usually used. They are easy to install but are high maintenance and, in addition, they are aimed at blocking all the sediment, running the risk of under-designing the volume to be collected. Starting from this assumption, the need of a maintenance-friendly approach was investigated by Maccaferri Innovation Center with an innovative apparatus called Mini Skirt Check Dam (MSCD). This is a special dam which is made up of two parts: solid wings that have a vertical fissure in which a ring net is applied. The net is uplifted from the ground as to leave a part of the debris flowing and blocking only the top part of it. The research analyzed the design procedure of a standard weir and several laboratory tests were performed in cooperation with the University of Trento (Italy) that ended with the creation of a new approach against debris flow. The MSCD permits the cutting of the peak of the flow rate and, at the same time, blocking tree trunks and boulders. Laboratory tests conducted showed that the combination of weir and net slows down the debris and collects only the most dangerous part of the flow with a lower maintenance requirement and a good hydraulic performance.

Keywords: debris flow; on scale laboratory tests on weirs; hydraulic design procedure

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1. Introduction

According to Takahashi (1991), debris flow is a phenomenon of transport of both liquid and solid particles that occurs in mountain areas characterized by a severe slope where the motion of the solid phase is driven by gravity. The shape of the sieve curve of the solid phase is usually various, from a few centimeters to diameters of over one meter and it is transported by a water and mud matrix (Armanini et al, 2005). One of the more relevant factors of the phenomenon is that boulders and big stones usually float over the debris. The triggering factors of debris could be related to the presence of solid material and a fixed range of slope, between 15°9' and 23°5', as indicated by Takahashi (1978). One other possible cause is the rain, generally the event that causes the debris comes after a continuous light rain that is sufficiently able to saturate the soil.

This phenomenon is not constant in time and space and, in addition, is extremely violent and impulsive; this last characteristic makes forecasting and design extremely difficult because the rheology of the flow and its motion has not been fully explained yet.

1.1. Solutions in use for debris flow and their problems

The solution normally applied for debris flows are barriers. The principle application of this product is to block all the material that is flowing up to a certain prefixed retain volume and to leave all the other material overpassing the barrier. The threshold for the determination of the typology of barrier is a function of the recharge basin and its shape (so by the total amount of the material that could potentially be moved) and by the return period of design (in this case the amount of the material must be estimated for the design return period).

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As shown in Fig.1. there are two typical barrier applications: Fig. 1. (a) shows a typical barrier application on an open hill, this application is commonly used for both debris flow and landslides; Fig. 1. (b) shows the debris flow barrier application in a channel, in this case the barrier is a hydraulic structure that represents an obstacle for the material flow of the whole basin up to the install section.

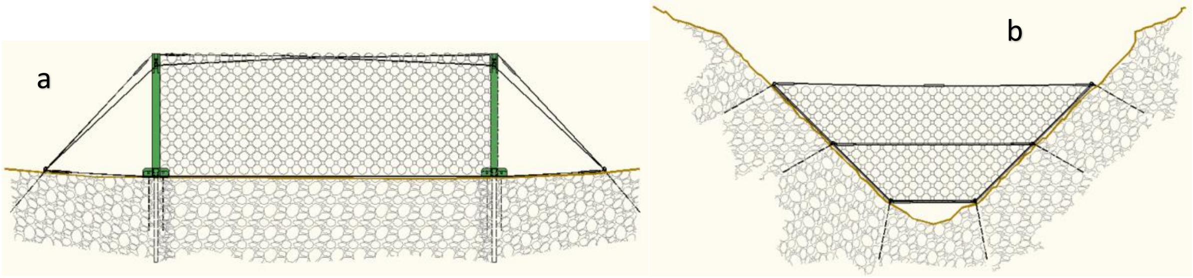

Fig. 1. (a) typical barrier for open hills; (b) typical barrier for channel (Courtesy of Maccaferri)

Based on existing knowledge of the phenomenon, the principle of blocking all the sediment that is flowing seemed to be the only solution against the violence and the destructive power of the flow. The cost of these types of nets is reduced because they are light and easy to install. However, the cost is extremely increased when taking the maintenance costs into account. As it is shown in Fig. 2. Barriers in general get clogged and the material in the upper section that has been successfully blocked, needs to be cleaned. In most cases, apart from the cost of the work and the related risk to this type of job the cleaning of the objects must also be considered as it is not possible in every site of installation due to the slope or the presence of unstable boulders.

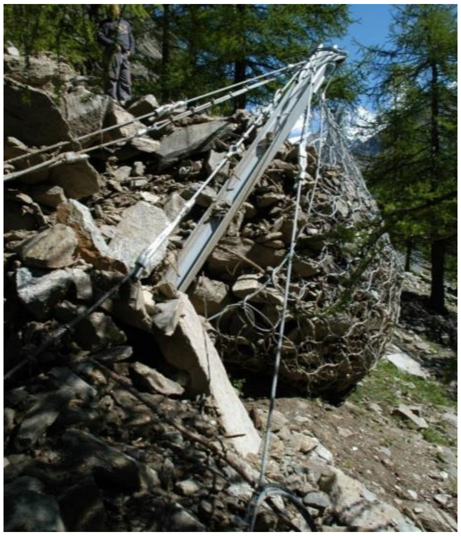

Fig. 2. Barrier clogged by rocks installed in the Alps (Courtesy of Maccaferri)

2. New approach

Starting from the hydraulic approach normally in use for weirs, a new apparatus called Mini Skirt Check Dam (MSCD), designed for debris flow, was studied. The main idea, as shown in Fig. 3 is not to block all the sediment as done in regular barriers but to dilute the debris, to cut the maximum amount of discharge and to release it in a second part of the event. This approach is environmentally-friendly because the discharge is reduced and could be designed according to the return period of the reference event and, in addition, effectively reduces the damage of the debris, ensuring a constant flow rate during the event that could be acceptable for the basin.

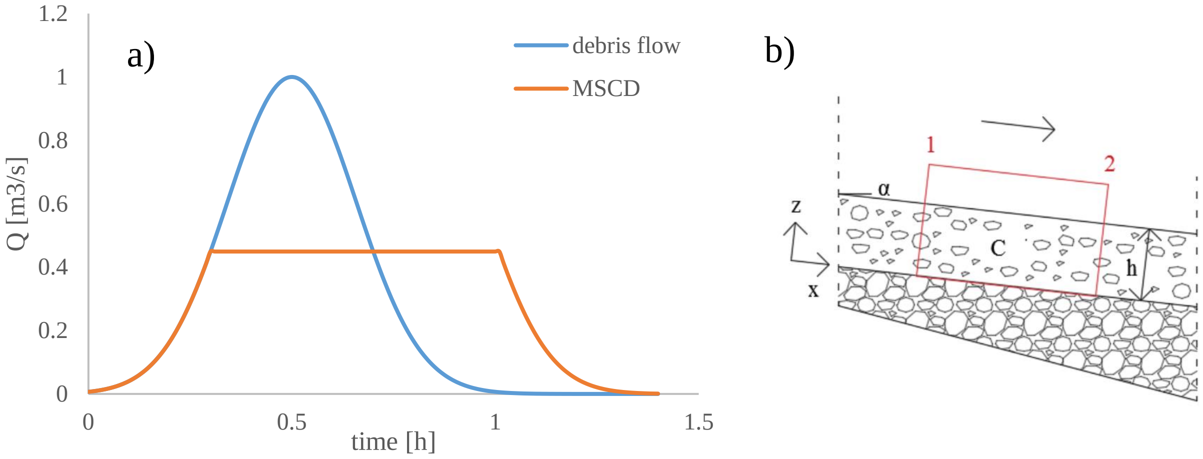

Fig. 3. (a) Performance of MSCD in comparison to the natural event in term of flow rate in the section after the apparatus; (b) the picture shows the control volume to which all the balance of energy and flow rate are referred to. The balance could be written between two generic sections 1 and 2, taking into account the direction of the flow rate. The picture on the right shows the different concentration in flow depth and the α angle.

The main goal of the research was to study and identify a new approach, based on the performance of the apparatus, that could be suitable for both weirs and MSCD, applicable for rivers and small basins (<10 km2) with intense sediment transport.

The general procedure studied for the design started from the application of the Navier-Stokes set equation in the direction of the flow, x, for both liquid and solid phase. The application of this approach on two general sections, 1 and 2, allows a system of three equations to be written: the conservation of the solid mass, the conservation of the liquid mass and the momentum, as done in Eq.1.

$$\begin{cases} (C\rho_s BUh)_1 = (C\rho_s BUh)_2 \\ ((1-C)\rho_w BUh)_1 = ((1-C)\rho_w BUh)_2 \\ \frac{\partial}{\partial x}\int_A (p + \rho_w gz + \rho_w u^2/2)\,(udA) = -i_E \rho_w g Q \end{cases} \tag{1}$$

Where C is the concentration of solid material in the control volume, ρ_s is the density of the solid phase, B is the width of the channel, U is the medium velocity, h is the flow depth, ρ_w is the density of the water, p is the pressure, g is gravity, u is the local velocity, A is area, i_E is the loss of energy, Q is the flow rate, x is the coordinate of the flow (supposed mono directional) and z is a vertical coordinate, defined in the opposite direction from the application of the vector g.

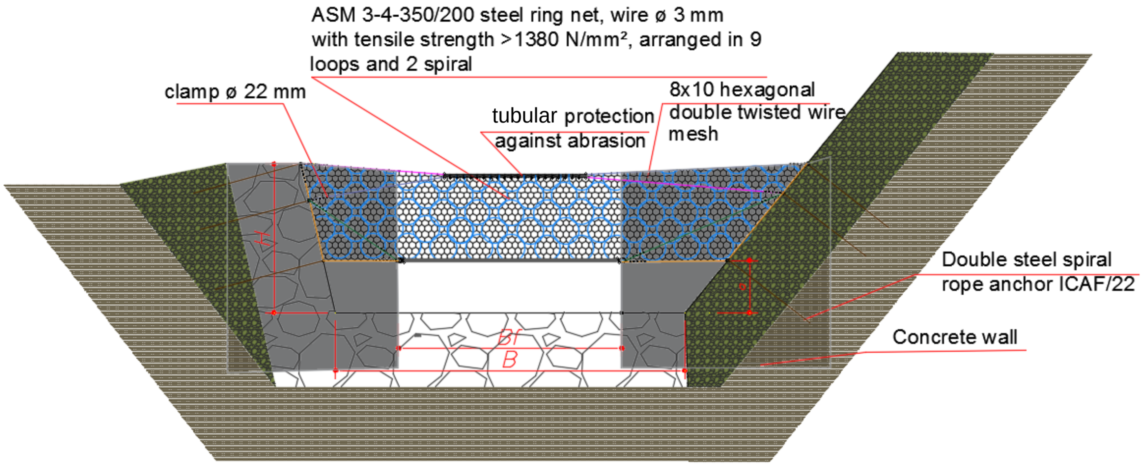

Fig. 4. General scheme of a MSCD: wings could be made by concrete or gabion, the nets, located downstream from the wall, is made by two layer of nets; the ring net for the structural function of transferring the force of the debris to the ropes and the anchoring, the double torsion net ensures a thin filter for the lower part of the sieve curve of the material.

The main goal of the project was to apply Eq. (1) on a new apparatus called Mini Skirt Check Dam. A general hydraulic scheme can be found in Fig. 4. The apparatus is composed of wings that are designed according to the hydraulic criteria used for weirs and a ring net (diameter 35 cm) with an optional double torsion net (Morstabilini et al., 2018). The advantage of the net is to block boulders and logs and at the same time to reduce the quantity of concrete needed for the wings. This reduction of material, if compared to a regular weir, allows for an easier installation procedure, so less time and cost. The presence of the concrete, that could be substituted by gabions, is necessary to force the accumulation of the material before the apparatus. The lower part of the net is void, this means that the net is uplifted from the ground, so that a certain amount of flow discharge is being left free to flow. The design of *a* parameter (with reference to Fig. 4) is a function of the regular flow rate of the channel, the maximum space available before the MSCD and the threshold of the return period in which the MSCD should be active.

3. Experiments on weirs

The simplification of this system was fully explained in Morstabilini et al. (2018) and resulted in a final design equation expressed in Eq. (2):

$$\Delta z + h_m \cos\alpha + \alpha_3 \frac{U_m^2}{2g} = h_f \cos\beta_f + \alpha_3 \frac{U_f^2}{2g} + \frac{(U_m - U_{o'})^2}{2g} \tag{2}$$

where: α_3 is a hydraulic coefficient that should be calibrated on the characteristics of the flow, U_i are velocities in each section and the other variables are expressed in Fig. 5. The coefficient is defined below and the quantity indicated with the capital letter is the average on the section volume and the lowercase letter is the punctual quantity:

$$\alpha_3 = \frac{\int_h cudy}{CUh} \tag{3}$$

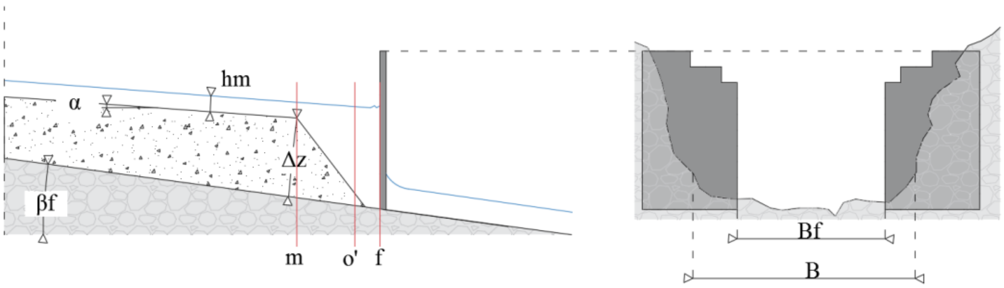

Fig. 5. Hydraulic scheme of a weir.

The application of Eq. (2) on weirs give the possibility of writing a design procedure focused on the $\boldsymbol{\Delta z}$ parameter (see Fig. 5), the weir considered for the application is reported in Fig. 5. The hypothesis of the method is that inside the weir the condition of Fr=1 is reached and that the weir is completely impermeable, so no filtration motion is allowed. This procedure could be extremely effective in defining the capacity of the weir to temporary block the flowing material, as a function of the Froude number and was fully explained in Morstabilini et al. (2018). In the case of a normal weir, Eq. (2) is applied between sections m and f and needs to define two different $\boldsymbol{\alpha_3}$ coefficients because the local velocity $\boldsymbol{U_i}$ is different in the two sections. The design parameter is represented by the R number, which is the ratio between B and Bf (see Fig. 5). In this case the design equation is:

$$\frac{\Delta z}{h_m} = R^{2/3} Fr_m^{1/3} \cos\beta_f + \frac{Fr_m^2}{2}\left[\left(\frac{R}{Fr_m^2}\right)^2 \alpha_{3f} - \alpha_{3m}\right] - \cos\alpha + \frac{Fr_m^2}{2}\left[1 - \frac{2}{3}(Fr_m R)^{-2/3}\right]^2 \qquad (4)$$

Eq. (4) was calibrated by a series of on scale experiments, conducted in the CUDAM laboratory of the Università degli Studi di Trento (Armanini et al., 2017). These experiments were conducted on a steady flow channel 0.3 m width for several categories of R parameters. Eq. (4) was simplified to be no-dimensional, as to have a reasonable comparison between the on-scale results and the real parameters on a full scale. In Fig. 6 and 7 the calibration for R=6.3 in two experiment settings is reported. In Fig. 6 the theoretical curve is compared to simulated debris flow with different d_{50} of the material. In Fig. 7 the theoretical curve is calibrated with different types of mixture by variating the concentration of the solid particles. Both the approaches of calibration show that there is a good correspondence between data and curve; moreover, it seems that the approach is independent to the sieve curve of the material.

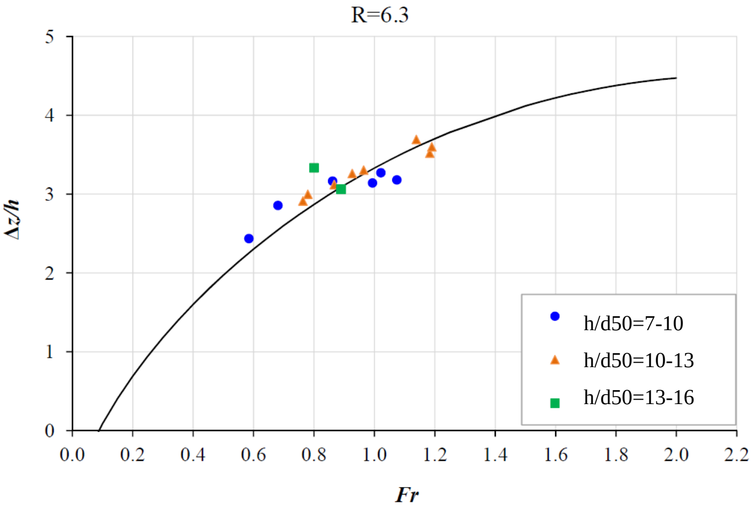

Fig. 6. Calibration of Eq. (4) for different sieve curve, as a function of d50 of the material and the flow depth.

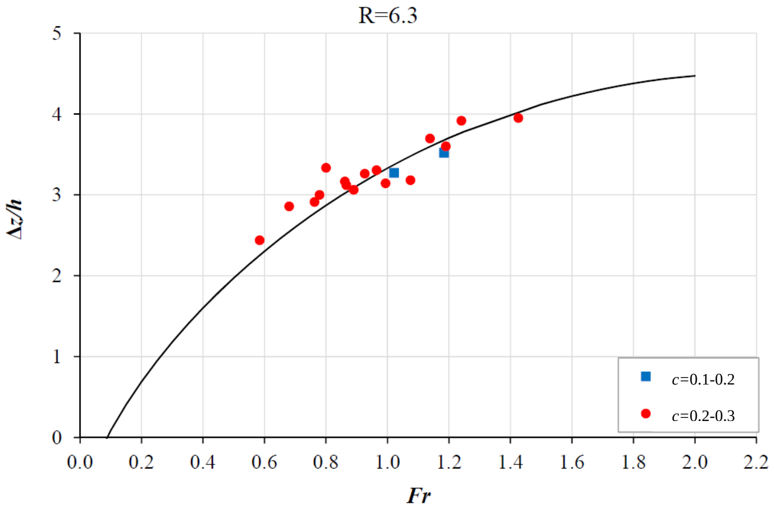

Fig. 7. Calibration of Eq. (4) for different concentrations of the mixture.

4. Experiments on MSCD

The application of Eq. (2) on MSCD required defining a new coefficient related to the occlusion of the mesh, Cf. This is a dimensionless coefficient that accounts for the degree of occlusion of the net, in case of total occlusion (safer hypothesis) Cf =1, otherwise Cf >1. In this case, the application of Eq. (2) could be expressed as:

$$\frac{\Delta z}{h_m} = \frac{a C_{cv} C_f}{h_m} \cos \beta_f - \cos \alpha + \frac{Fr_m^2}{2} \left[R^2 \left(\frac{h_m}{a C_{cv} C_{co} C_f} \right)^2 - \alpha_{3m} \right] + \frac{Fr_m^2}{2} \left(\frac{\Delta z / h_m}{1 + \Delta z / h_m} \right)^2 \qquad (5)$$

Where C_{ci} are coefficients related to the reduction of the horizontal and vertical flow depth, normally considered constant and equal to 0.61. Eq. (5) was calibrated with a series of on scale experiments conducted in the CUDAM laboratory of the Università degli Studi di Trento (Armanini et al., 2017). These experiments were conducted on a steady flow channel 0.3 m width for several categories of R and hm/a parameters.

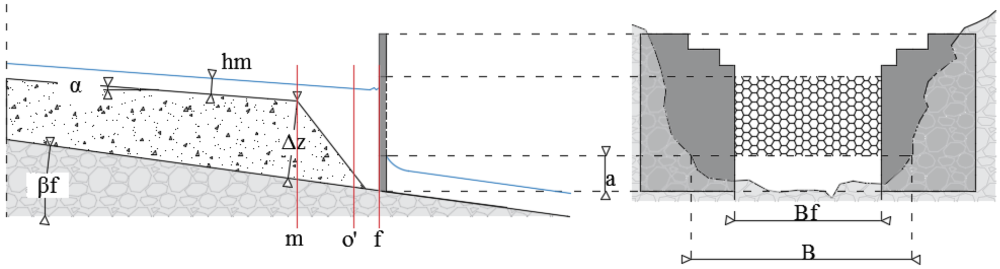

Fig. 8. Hydraulic scheme of a MSCD.

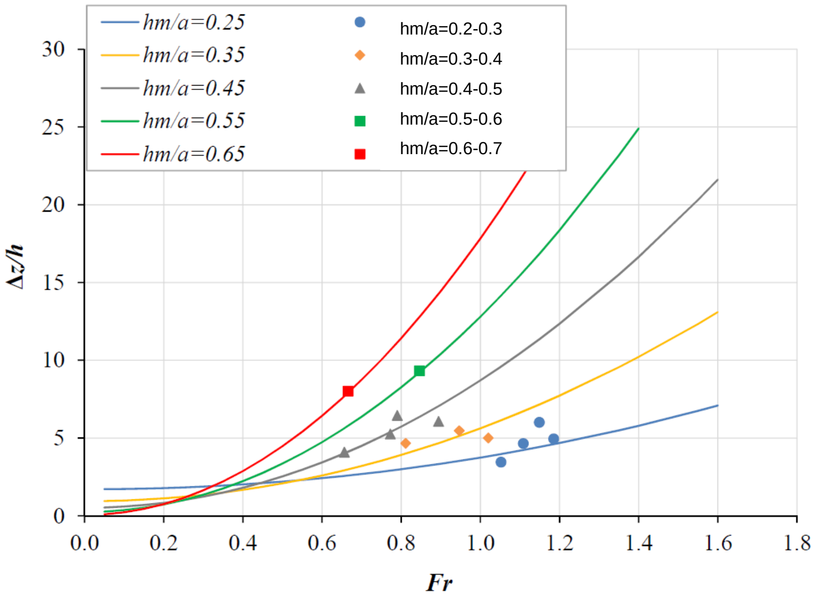

Fig. 9. Calibration of Eq. (5) for R=6.3, Cco = 1, Ccv = 0,61 and Cf = 1,1, different types of hm/a curves were investigated.

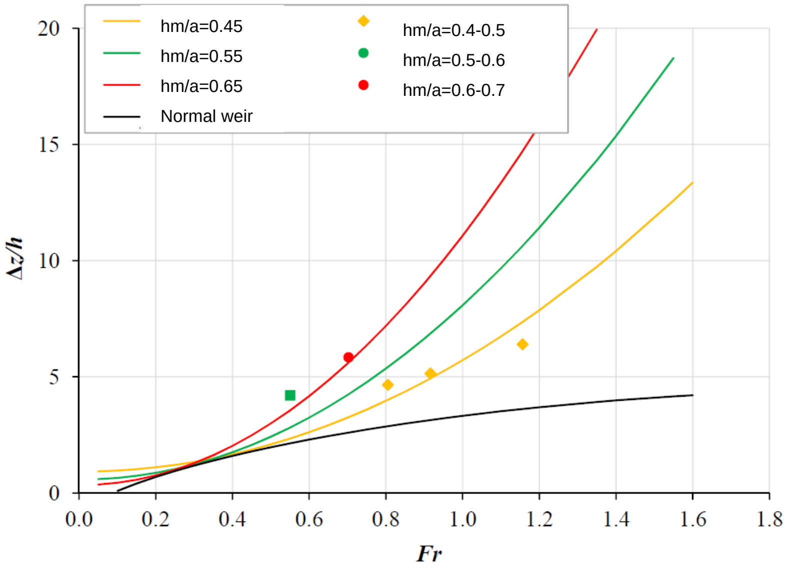

Fig. 10. Calibration of Eq. (5) for R=6.3, Cco = 1, Ccv = 0,61 and Cf = 1,4, different types of hm/a curves were investigated.

Fig. 9 shows the calibrating result for R=6.3 and for several values of h_m/a parameters. In Fig. 9 this calibration involved a complete occluded mesh, with C_f=1.1. On the other hand, Fig. 10 represent the calibration for a partially occluded mesh, with C_f=1.4. The data shows a good correspondence between Eq. (5) and the on-scale experiments.

It seems that this correspondence is better for C_f=1.1, which suggests that the design equation is more effective with a completely occluded mesh. This fact is related to the issue that, the partial occlusion of the mesh does not block all the material on the net but leaves some part of this material flowing through it. This suggests that another equation set should be studied in order to have a specific shape of the net for a filtering use and to lower the pressure of impact on anchoring.

The calibrating process was successfully done and showed that, if Eq. (5) is applied for the design, C_f should be considered equal to 1 for safety.

5. Conclusions and future development

A new approach for the characterization of the hydraulic apparatus has been defined by this research. This project investigated a new apparatus and its performances in diluting the discharge of a debris flow. Data used for the calibration of Eq. (3) suggests a no-correlation to the sieve curve of the material, which should be investigated by later experiments. Data used for the calibration of Eq. (5) suggests the need of investigating the filtering properties of the net to apply a more realistic coefficient that will express these properties and will be useful in reducing the pressure on the net.

The whole research investigated the innovative hydraulic design criteria for MSCD. The full-scale design of this apparatus requires further investigation of the impact pressure on a partially open obstacle. In addition, the filtering properties of the net should be correlated to the potential reduction of the pressure, as to have a more realistic design procedure for anchoring.

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