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SLIT CHECK-DAMS FOR STONY TYPE DEBRIS FLOWS MITIGATION. EXPERIMENTAL STUDY TO EVALUATE SEDIMENT CONTROL EFFICIENCY

Miguel Silva[*], **Sérgio Costa**[*] **and António H. Cardoso**[†]

[*] AQUALOGUS, Engenharia e Ambiente, Lda.
Alameda dos Oceanos, Edifício Mar do Oriente, Lote 1.07.1 AN 2.4,
Parque das Nações, 1990-208 Lisboa, Portugal
e-mail: geral@aqualogus.pt, webpage: http://www.aqualogus.pt/

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Abstract. *There has been an increasing acknowledgement of debris flows as one of the most relevant geomorphic modifiers of many steepland valleys and fans. Despite of being a well-known phenomenon, debris flows are somehow unpredictable and complex to simulate. Due to several past harmful debris flows worldwide, there are already a significant number of mitigation structures with water and sediment control functions, which are essential features of short-term countermeasures against debris flows.*

This paper is based on laboratory experiments carried out to test slit dams (open-type retention dams), usually used as a structural countermeasure to mitigate debris flows in steep torrential channels. The experimental activity is part of the R&D project STOPDEBRIS, which was funded by QREN and developed by a multidisciplinary team from AQUALOGUS, Engenharia e Ambiente, with partnership of CEHIDRO-IST. Flume tests were conducted using a straight channel to assess the influence of different slit-dam solution types on the sediment retention efficiency against stony-type debris flows. Inspired by common slit dam solutions, two different piers shapes and two different piers widths were tested. The experiments were performed with two different discharges and three different slopes. The analysis of the sediments trapping efficiency suggests that $1.0d_{95}$ *to* $1.4d_{95}$ *free spacing shall be considered to design effective slit-dam solutions. It can also be concluded that the piers shape does not significantly influence the trap efficiency, while the water discharge and the initial bed slope have a remarkable influence, notably for high relative spacing. Preliminary experiments also suggest that, in some circumstances, the increase of slit density* ($\Sigma s/B$) *can lead into slightly enhanced efficiency of slit-dam solutions.*

1 INTRODUCTION

Debris flows are one of the most dangerous and destructive water-related phenomena, inducing massive disasters in mountainous areas all over the world, frequently including the loss of human lives. Therefore, these phenomena have attracted the attention not only by the society but also by the scientific community, resulting in the appearance of

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[†] CEHIDRO, Instituto Superior Técnico, Universidade de Lisboa, Portugal

detailed studies for several debris-flow related topics, such as its genesis, behaviour and mitigation measures.

Debris flow mitigation measures are usually classified as structural and non structural. Regarding to structural solutions, the most common is to construct check dams and perform channel works [1] and [2]. These solutions intend to control the transport and deposition processes of the sediments carried downstream by debris flows. Since check-dams are considered as one of the simplest and most effective engineering measures against debris flows by many authors (e.g. [3] and [4]), they were widely applied all over the world as a short-term mitigation measure. In fact, check-dams have a long history of implementation and progress. Back in the 14th century, check dams were built in the mountain range of the Alps. However they only became popular in the 19th century [3]. They have also been widely used in Taiwan, Japan and other mountainous areas of Europe [1] and [2], as well as in a few South America countries [6] and [7].

A check-dam can be defined as a dam constructed across a river channel to promote solid material deposition and stabilize the river bed by reducing erosion [8] and [9]. This structural measure aims at controlling the solid runoff to downstream areas as well as the velocity of a debris flow, ensured by a local reduction of the channel gradient. Mostly, check dams are composed of a weir, two wings and a robust foundation, although there are a variety of other check dam solutions. They can be closed or open-type and made of various materials including wood, boulders, and concrete blocks. According to [1], [2] and [9] the traditional check dams are closed-type, made of massive concrete and often constructed in cascade or series.

However, due to their reduced storage capacity and poor permeability, closed type check dams are usually backfilled with sediment deposits transported by modest discharges before destructive debris flows occur. In fact, according to several historical records (e.g. [2], [9], [10] and [11]), closed-type check dams tend to fail its function in a few years after their construction. In order to overcome this ineffective behaviour, open-type check-dam solutions have been developed since half of the 20th century [12] and they are widely used at present in countries such as Austria, Japan, and Taiwan [8].

In fact, whenever properly designed and employed, open-type check dams present a major function that the closed-type check dams lack: they allow finer (harmless) sediments to pass through, while trapping larger blocks with greater destructive capability. Consequently, they are preferable over closed-type check dams not only for their effectiveness during debris flow events but also for conserving as much as possible the natural environment and the landscape of mountain torrents, reducing the long-term downstream effects on morphological evolution according to [1], [2] and [12].

Open-type check dams can be materialized by many different solutions, mainly defined according to their functional openings' shape and building materials (*e.g.* slit dams, slot dams, grid dams). Regarding to slit dams, they can present single or multiple functional openings which are usually vertical (slit), going from the dam's base up to the top. For a dam with multiple slits, the piers are usually materialized by concrete or steel solutions.

The effectiveness of the slit dams in debris flows mitigation has been proven in several studies conducted mostly in Japan [2]. All those studies concluded that the spacing of the piers can be defined in order to decrease the debris flow peak discharge and to allow the non-harmful sediments to pass through freely, while catching the harmful sediments upstream of the dam [2].

However, despite of several experimental and numerical studies already performed (e.g. [1], [2], [8], [13], [14], [15], [16] and [17]), the uncertainty typically associated with the design of open-type structures for debris flow mitigation still persists. One of the most important factors in designing open-type check dams, namely slit-dams, is the spacing between the piers. Herein, it is important to note that slightly different characteristic particle sizes (d_{90}, d_{95} or d_{max}) are normally considered as a reference length, resulting into solutions with significant differences in debris flow control efficiencies. The adequate definition of sediments reference length is critical for any design criterion since a wrong value can lead into two different inappropriate situations: too small spacing will lead to trapping comparatively small particles transported in minor floods, which results in the reduction of storing capacity predicted to accommodate extreme debris-flow events; on the other hand, if the diameter of the largest size particles, that barely exist in the basin, is chosen as the width of the free spacing, it is highly likely that the dams do not clog, become ineffective since the concentration of such large particles in the forefront of debris flow will not be enough, *i.e.*, even large boulders existent in debris flows may pass through the check dam.

The objective of this paper is to present and discuss the preliminary results of an experimental study focused on the reduction of the uncertainty typically associated with the design of slit check-dams.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 Objectives of the experimental study

In accordance with the aim of the present study, an experimental facility was designed and built in order to perform tests to assess the influence of different slit-dam solutions on the sediment control efficiency to mitigate stony-type debris flows.

The design of the experimental setup was consistent with the type of the debris flows that occurred in Madeira Island, Portugal, in February 2010.

Thirty three flume tests were performed, focusing on the assessment of the following main issues:

- Trapping efficiency of different slit-dam solutions;
- Assessment of the grain size distribution of trapped and outflow sediments.

2.2 Experimental setup

The experiments were carried out at the Hydraulics Laboratory of Instituto Superior Técnico, Universidade de Lisboa, Portugal.

The experimental facility comprised a 3.5 m long and 0.5 x 0.5 m x m rectangular cross section flume, representing an approximation of a 1/30 scale model of the central cross-section reach of Ribeira de São João, Madeira Island. The flume slope, *i*, was adjustable between 3.5 % and 26.5 % and was endowed with a water recirculating system.

The flume was equipped with a sediments feeding system composed by a hopper, a conveyor belt and a tilted PVC plate which guaranteed the solid material input at the upstream cross-section of the flume.

The slit-dam was placed at ≈0.60 m upstream of the flume downstream end. Immediately downstream of the flume, a sieve was installed which sorted the water from the solid material passing through the slit-dam.

Figure 1 presents a scheme of the experimental facility, highlighting both water (Q_l) and solid material (Q_s) circuits.

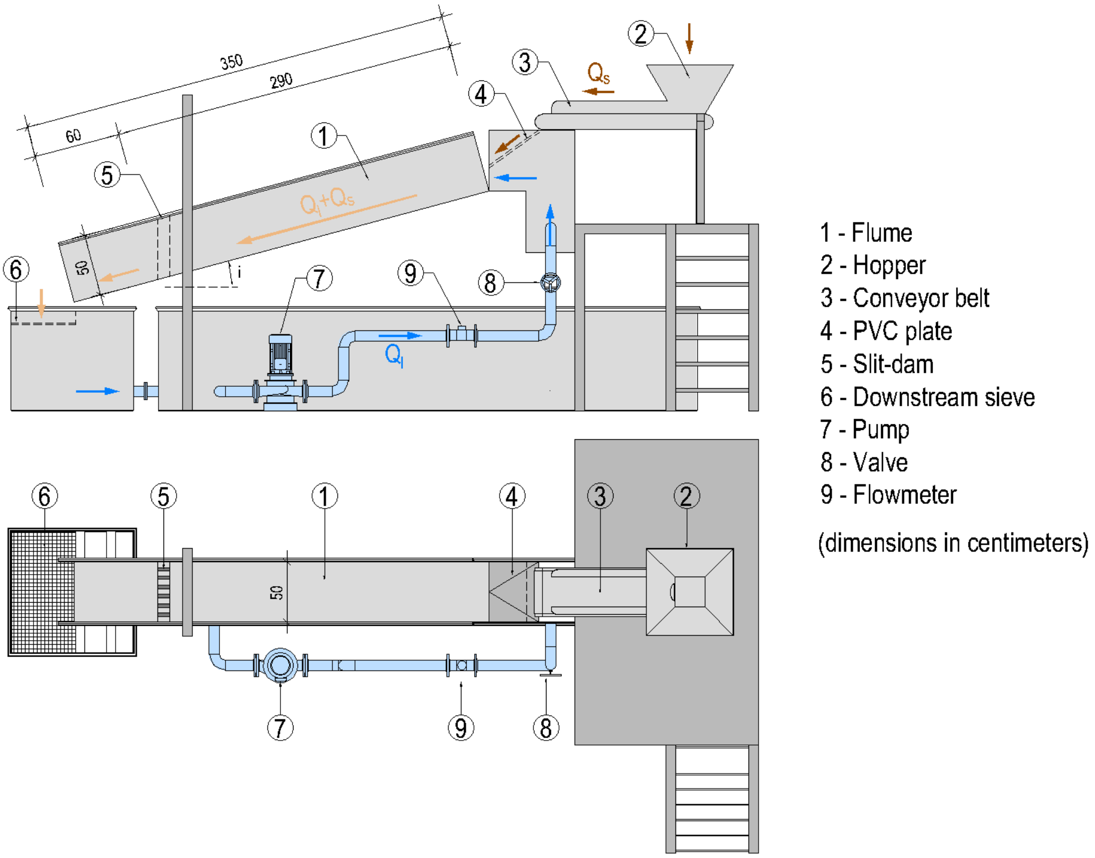


Figure 1: Scheme of the experimental setup

2.3 Experimental procedure

Prior to each run, a given slit-dam (defined by the piers shape and spacing) was installed and the bottom of the flume was roughened through an erodible 5 cm deep layer of the same gravel as the gravel used as feeding material.

The flume was continuously fed with water and gravel, resulting in a steady stony-type debris flow, which continued its movement downstream until the slit-dam or the sieve. The total volume of gravel involved in each run, V_e, including the 5 cm layer and the fed gravel, was approximately 0.525 m^3, ensuring that the flume storage capacity (upstream of the slit dam) was not exceeded. The material fed (excluding the 5 cm layer) in each run was discharged from the hopper into the conveyor belt, falling directly into a tilted PVC plate, which ensured a sediment gravity driven input into the flow at the upstream cross-section of the tilting flume.

The inputs of any experiment were the apparent volume (including voids) of sediments involved, V_e, the slope of the flume, i, and the water discharge, Q_l.

At the end of each test, the total volume of the discharged solid material (which passed through the slit dam) was measured in order to assess the slit dam trapping efficiency.

The grain size distributions were determined by using 4 different sieves with mesh openings of {11.2, 16.0, 22.4, 31.5} mm.

The debris flow deposition depths were measured with an adapted point gauge at five (5) different points (12.5 cm spaced) for twelve (12) cross-sections.

Additionally, debris flow deposition patterns and other qualitative aspects were assessed by a photo camera.

After each run, the main outputs were:

- Volume of sediments passing through the slit-dam (V_s);
- Grain size distribution of sediments which passed through the slit-dam;
- Sediment deposition depths upstream of the slit-dam.

2.4 Physical properties of the sediments

The solid material used in the experiments was composed by "naturally worn" gravel. It was defined by approximately scaling down, at a 1/30 scale, the sediments of Ribeira de São João, characterized through a field survey of a 4 meters deep deposits sample. The gravel grain size distribution is shown in Figure 2. It is worth noting that the minimum sediment dimension was limited to 5 mm in order to prevent sediment recirculation and, hence, avoid damage into the pumping system.

The main physical properties of the gravel are also presented in Table 1, where $s = \rho_s/\rho$ is the relative sediment density, d_{max} is the maximum diameter, d_{50} is the median diameter, d_n is the sieve diameter such that n% by weight is smaller and ϕ_s is the internal friction angle.

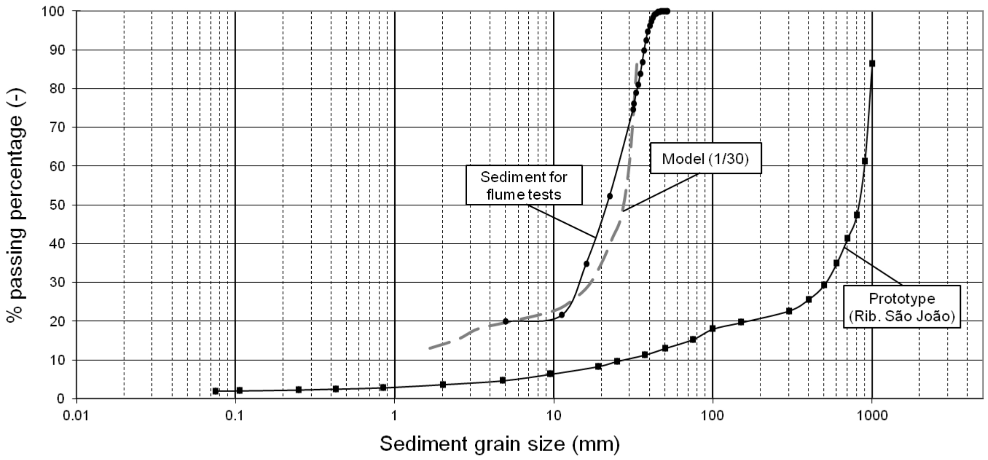


Figure 2: Grain size distribution of sediments

s	d_{max} (mm)	d_{95} (mm)	d_{84} (mm)	d_{50} (mm)	ϕ_s (deg.)
2.65 to 2.70	52	39	35	21	34

Table 1: Main physical parameters of the solid material used in the experiments

The mean Corey shape factor of the material used in the experiments, which characterizes the sphericity of the individual particles was $SF = 0.61$. SF is given by

$$\mathbf{SF} = \frac{\mathbf{d_3}}{\sqrt{(\mathbf{d_1 d_2})}} \tag{1}$$

where d_1, d_2 and d_3 are respectively the longest, the medium and the smallest diameter measured along three perpendicular axes.

It should be noted here that the value of SF for natural sand is ≈0.7, while it must be slightly smaller for large blocks since, in nature, they undergo much shorter rolling and abrasion processes than sand. In other words, the solid material used in the experiments is believed to reproduce the overall shape of natural debris flow blocks.

2.5 Characteristic variables of the experimental study

Before each experimental run, the following aspects were decided:

- Slit dam configuration, resulting from the definition of the piers shape (*P*) and free spacing (*s*);
- grain size distribution;
- clear water discharge (Q_l);
- flume slope (*i*).

The flume tests were carried out for three different slopes, *i*: 10%, 15% and 20% and two different water discharges, Q_l: 11 ls^{-1} and 18 ls^{-1}. Excluding one case, these discharge values cover the 1/30 Froude-scale range of unit peak discharges observed in the cross-sections of the Ribeira de São João, wherein check dams will be build.

Gravel feeding rates varied between ≈3 l/min, for $Q_l = 11\ ls^{-1}$ and $i = 10\%$, and ≈20 l/min, for $Q_l = 18\ ls^{-1}$ and $i = 20\%$.

Two piers shapes and two piers widths were tested, ensured by three different piers, *P*, as represented in the Figure 3 (dimensions in millimeters).

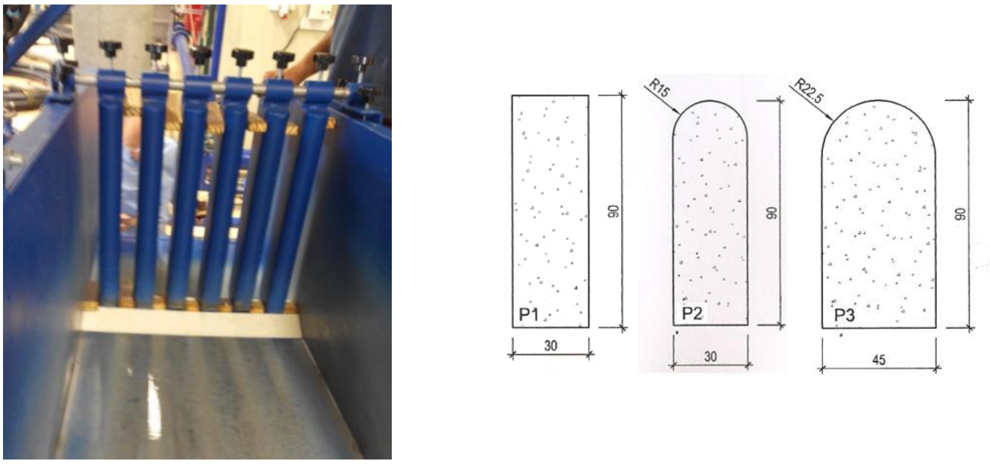


Figure 3: Slit-dam in flume and tested piers (*P*)

The free spacing, *s*, between the piers was defined according the grain size distribution of sediments used in the flume tests, considering d_{95} as the reference length. Four (4) different relative spacing, s/d_{95}, values between the piers were considered: 1.18, 1.36, 1.49 and 1.77, within the range reported in former experimental studies (e.g. [1], [2] and [13]) for open-type dams (namely slit and grid-dams). The thirty (30) experiments correspond to several combinations of variables mentioned above and summarized in Table 2.

i (%)	Q_l (ls^{-1})	s/d_{95}	Pier type
10; 15; 20	11; 18	1.18; 1.36; 1,49; 1.77	P1; P2; P3

Table 2: Characteristic experimental tests variables

3 EXPERIMENTAL RESULTS AND ANALYSIS – TRAPPING EFFICIENCY

3.1 Preliminary remarks

In this study, the sediment trapping rates were obtained for the performed flume tests in order to assess the efficiency of each solution.

The sediment runoff rate, S, is defined as the ratio of the sediment runoff volume passing through the slit-dam, V_s, to the supplied sediment volume, V_e.

$$\mathbf{S}=\frac{\mathbf{V_s}}{\mathbf{V_e}} \tag{2}$$

Sediment trapping rate or efficiency, E, is defined as the ratio of the sediment retained by the slit-dam ($V_e – V_s$) to the supplied sediment volume, V_e. It is given by:

$$\mathbf{E}=\mathbf{1}-\mathbf{S} \tag{3}$$

From historical records and previous studies, slit-dams of a single slit usually causes the rising of water level upstream from the dam due to backwater effect, promoting the solid material deposition [12] and [19]. This hydrodynamic effect was verified for single functional opening slit-dams [19] although it is expected that backwater effect can also occur whenever the obstruction is such that critical flow conditions occur in the slit-dam cross-section.

In the experiments, the cross-section obstruction due to the presence of slit-dams may be captured by the slit density, $\Sigma s/B$, defined as the ratio between the sum of all functional openings and slit-dam width. Thereby, the influence of slit density on the slit-dam trapping efficiency was also assessed.

3.2 Effect of relative spacing (s/d_{95})

Figure 4 shows the relationship between the sediment trapping efficiency, E, and the relative spacing s/d_{95} (ratio of spacing width to d_{95}) for each tested solution.

It is clear that the relative spacing has a remarkable influence on the slit-dam trapping efficiency, confirming the findings of previous studies (e.g. [1], [2], [5], [13], [15] and [17]). For the tested experimental conditions, slit-dams have shown to be effective to mitigate stony-type debris flows whenever the relative spacing of 1.18 and 1.36 were adopted. These thresholds were also assessed in previous experimental studies for slit [1], [2] and [5] and grid dams [13] and [18]. Regarding to former slit-dam experimental studies, efficient solutions should consider relative spacing of $0.5d_{max}$ to $1.0d_{max}$ [1] and $1.5d_{max}$ to $2.0d_{max}$ [2] and [5]. These threshold divergences suggest that several aspects can affect the sediment rate efficiency, leading to a difficult results comparison. In fact, comparing the present study with previous ones [1], [2] and [5], it becomes clear that many aspects/variables were different (e.g. debris flow type, grain size distribution, slit density tested ranges).

Although, as previously concluded in the referred studies (e.g. [1], [2] and [5]), it remains clear that slit-dam solutions appear to have a quite narrow functional/effective range regarding to relative spacing, once sediment runoff rate volume passing the slit dams tends to increase rapidly when the openings between the piers are greater than $1.36d_{95}$.

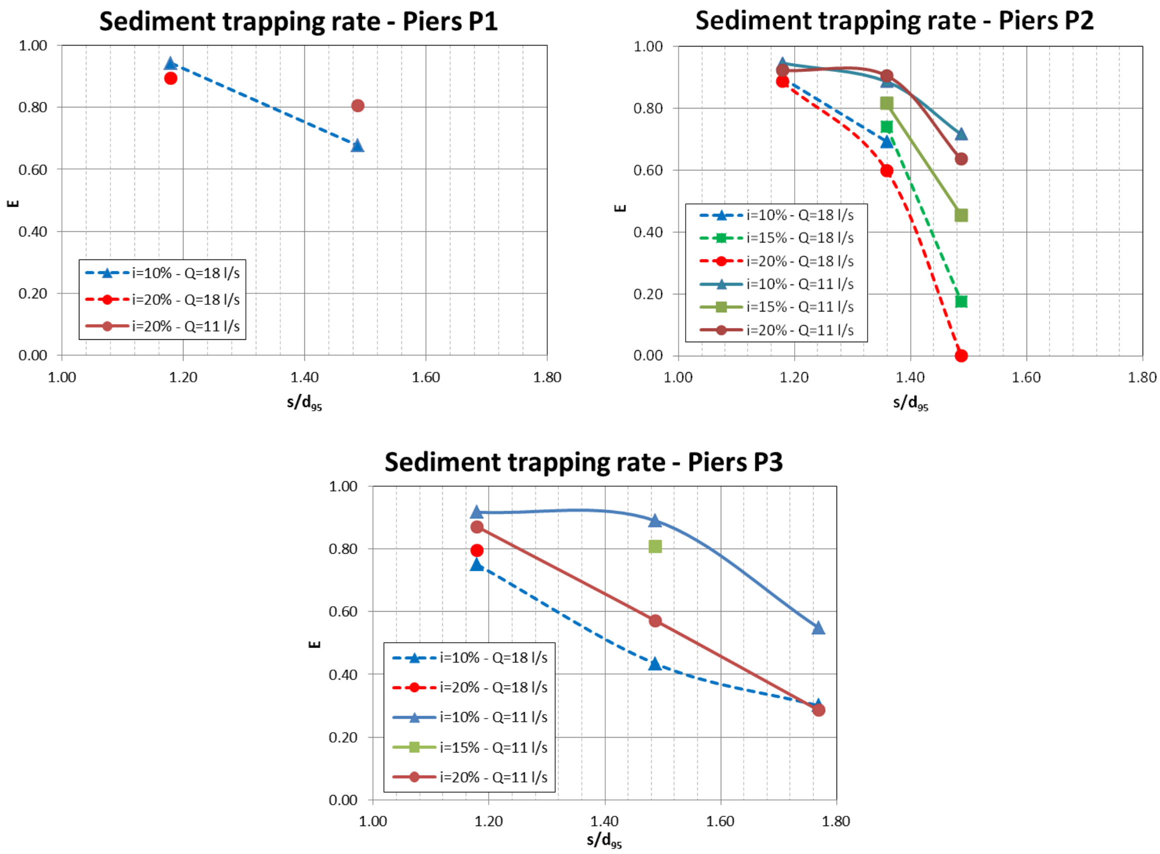


Figure 4: Sediment trapping efficiency results for all performed experimental tests.

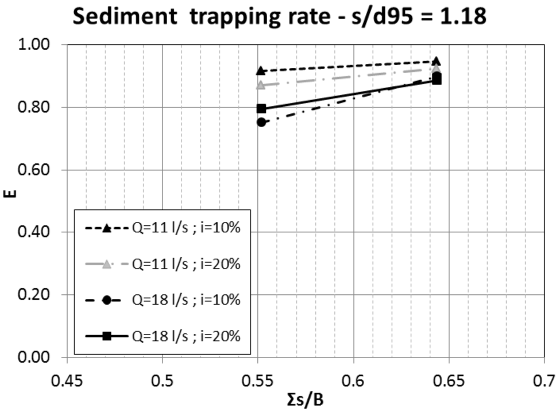
Moreover, the results suggest that the piers shape has no significant influence on the trapping efficiency of the slit-dam solution. On the contrary, the water discharge, Q_l, demonstrated to influence the trapping efficiency of the slit-dam solutions, remarkably for spacing higher than $1.36d_{95}$. In other words, less efficient solutions tend to be more influenced by the debris flow transport capacity, which, for a certain initial bed slope, i, is ensured by the liquid phase (Q_l). In these cases, which result in less- or non-efficient solutions (*i.e.* lower or nil sediment trapping rates), the transport capacity of the flow regime is larger than the sediment feeding from upstream and there is no significant bed slope decrease due to sediment deposition upstream of the dam.

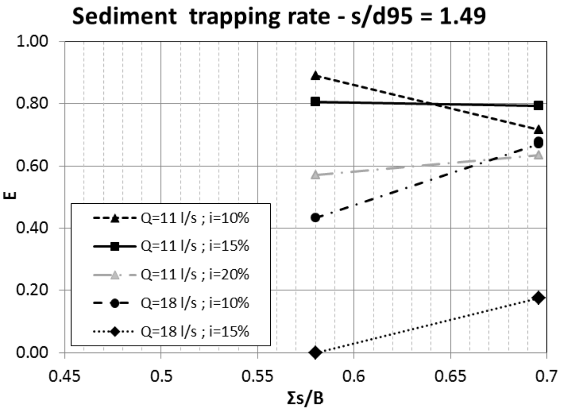
Regarding to the initial flume bed slope, i, two different behaviors were verified: for smaller relations of s/d_{95}, the bed slope has no significant influence on trapping efficiency as shown in previous studies [18]. This tendency is opposed for higher values of s/d_{95}.

3.3 Effect of slit density (Σs/B)

Herein, the slit density, Σs/B, is given by the ratio between the sum of all functional openings and slit-dam width (which in the present study is equal to the flume width). Therefore, this ratio is directly responsible for both water and solid discharge of the slit-dam and consequently for the possibility of occurrence of backwater effects.

Figure 5 show the relationship between the sediment trapping rate, E, and slit density, Σs/B, for two different tested relative spacing's' (s/d_{95}).





Except for one remarkable case (s/d_{95} = 1.49; Q_l = 11 ls^{-1}; i = 10 %), the results show that an increase in slit density (Σs/B) slightly increases the efficiency of the solutions, enhancing deposition upstream of the slit-dam. According to [1], this same behavior was observed whenever slit densities (Σs/B) between 0.2 and 0.4 were considered. For a given relative spacing, the increase of slit density implies a bigger number of narrower piers as well as the increase of the open cross-section area. For the same discharge, the average flow velocity decreases and the local stream power decreases too. The local reduction of sediment transport capacity – as compared with the sediment transport capacity for a smaller slit density – seems to impact in upstream increased deposition, at least, in circumstances that deserve to be investigated in future studies.

In the present study, the slit-dams were observed not to impose backwater effects. In fact, supercritical flow regime was achieved for all performed tests. Additionally, once sediments deposition upstream of the slit-dam progresses, percolating flow through the voids of the gravel deposits increases, contributing to exclude the possibility of occurrence of backwater effects. This aspect shall also be assessed in the future for lower slit density solutions.

4 CONCLUSIONS

The present experimental study demonstrates the efficiency of slit-dams to mitigate stony-type debris flows.

The experimental analysis of the sediments trapping efficiency of different slit-dam solutions suggest that 1.0d_{95} to 1.4d_{95} free spacing may be adopted for slopes between 10% and 20% and unit peak discharges up to about 6 m^3/s/m in order to mitigate stony-type debris flows effects. It was also shown that piers shape, P, does not significantly influence the trapping efficiency. The same applies to the initial bed slope, i, associated with small s/d_{95} ratios. On the contrary, the water discharge, Q_l, notably for spacing higher than 1.4d_{95}, and the initial bed slope, i, combined with high s/d_{95} ratios, do significantly influence the trapping efficiency.

The slit-density (Σs/B) seems to be quite important to design efficient slit-dam solutions. Preliminary experiments suggest that, in some circumstances, the increase in slit density (Σs/B) is compatible with slightly more efficient slit-dam solutions.

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