Bedload trapping in open check dam basins - measurements of flow velocities and depositions patterns

Guillaume Piton, Eng.[1]; Ségolène Mejean, Eng.[2]; Costanza Carbonari, Msc.[3]; Jules le Guern, Msc.[2]; Hervé Bellot, Msc.[2]; Alain Rrcking, PhD[2]

ABSTRACT

In steep slope streams, torrential-hazards mainly result from abrupt and massive sediment deposits. Open check dams are regularly used in natural hazard mitigation to trap sediment and driftwood. A good comprehension of the phenomena that occur in these structures is needed to optimize their design. In this paper, we present new results from small scale experiments addressing (i) a validation of water stage - discharge formula proposed in the literature for slit and slot dams; (ii) recommendations in the use of formula dedicated to deposition-thickness-estimation; (iii) geomorphic and hydraulics descriptions that seek to help field practitioners and numerical modelers to better understand what can be observed in labs and in the field and what kind of phenomena should be modeled. A special attention has been paid to highlight the implication of our results in the use of formula and in structure design and maintenance.

KEYWORDS

slot and slit dams; sediment trap; photogrammetry; Large Scale PIV; small scale model

INTRODUCTION

In steep slope streams and especially on their fan part, torrential–hazards mainly result from abrupt and massive sediment deposits. To curtail such phenomenon, soil conservation measures as well as torrent control works have been undertaken for decades. Since the 1950s, open check dams complement other structural and non-structural measures in watershed-scale mitigation plans [Armanini et al., 1991; VanDine, 1996]. Hundreds of these structures have thus been built for about 60 years. Their design evolved with the improving comprehension of torrential hydraulics and sediment transport processes; however numerous open check dams have a general tendency to trap most of the sediments supplied by the headwaters and to weakly self-clean. Secondary effects such as channel incision downstream of the structures often occur after their creations. Sediment starvation trends tend to propagate to the main valley rivers and to disrupt past geomorphic and ecologic equilibriums.
To minimize useless dredging operations and to promote sediment continuity, while maintaining the mitigation effect of open check dams, a better selectivity of sediment trapping must be sought in open check dams [Armanini et al., 1991; SedAlp, 2015]. To approach

1 IRSTEA Saint-Martin-d'Hères, FRANCE, guillaume.piton@irstea.fr
2 Irstea, centre de Grenoble, UR ETGR, St Martin d'Hères, France and Univ. Grenoble Alpes, F-38041 Grenoble, France
3 Univ. Firenzi, Italy and Irstea, centre de Grenoble, UR ETGR, St Martin d'Hères, France and Univ. Grenoble Alpes, F-38041 Grenoble, France

optimal structures that would trap sediments during dangerous floods and flush them partially during small floods, we must improve the scientific knowledge on hydraulic and deposition processes that occur in sediment traps during floods.
Four trapping processes (TP) eventually act in sediment trap basins (Fig. 1 a): a decrease in transport capacity due to a milder energy slope in the basin (TP1); a decrease in transport efficiency due to flow spreading in a basin wider than the upstream channel (TP2); a drop in the shear stresses in the calm water area upstream of the dam (hydraulic control - TP3); and mechanical blockages against the dam openings (mechanical control - TP4).

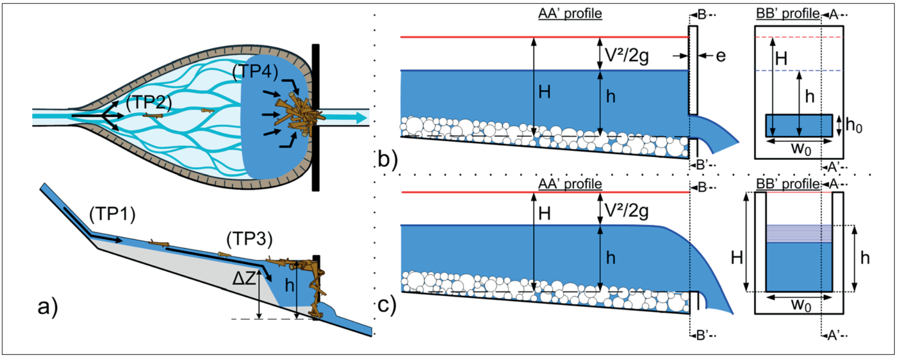

Figure 1: a) Trapping Processes (TP) resulting in sediment deposition in sediment trap basins: (TP1) slope decrease; (TP2) width increase; (TP3) delta-type hydraulic control; and (TP4) direct mechanical blockage and; Longitudinal and transverse view of flows through: b) a slot dam and c) a slit dam.

The mechanical blockage process [Fig. 1 (TP4)] is relatively well understood [Piton and Recking, 2015a, 2015b]. On the contrary, case studies testing the existing criteria on (TPs 1-3) remain scarce. This paper addresses three scientific issues, two deal with (TP3): (i) How accurate are the current hydraulic approaches describing the water stage–discharge Eqs.? and, (ii) Do the approaches proposed for deposit thickness estimation give satisfying results? The last issue concerns (TPs 1-2): (iii) what are the flow conditions and the resulting geomorphic patterns that occur during sediment trap basin filling in a relatively wide and mild basin? We gather new elements on these questions, based on an experimental approach using a Froude scale model. The first runs were performed in pure water hydraulics to validate water stage-discharge Eqs.. Sediment was added in the subsequent runs to look at deposition processes.

MATERIAL AND METHODS

The small-scale sediment trap was built in a 6-m-long, 1.2-m-wide, 0.4-m-deep, 10%-steep tilting flume. The water was recirculated and measured by a flowmeter with a maximum discharge of 4 l/s. The sediment feeder was composed of a hopper, associated with a conveyor belt, with a maximum solid discharge capacity of 200 to 300 g/s depending on the grain size distribution of the sediment mixture. Two sediments mixtures were used, hereafter refer to as

GSD1 & GSD2, consisting in natural poorly sorted sediments with diameter from 0.2 to 20 mm. The median grain size D_{50} of GSD1 and GSD2 are 3.8 and 2.4 mm, respectively; and the mean arithmetic diameters are of 6.4 and 4.9 mm, respectively.

High quality pictures of the flume were taken with two CANON 100D cameras fixed on a trolley to the ceiling of the laboratory. Digital elevation model (DEM) of the deposits were reconstituted, with a 1-mm accuracy [Le Guern, 2014], using the Agisfost Photoscan software. Before each DEM measurement, a high speed camera Phototron FASTCAM took videos of the flow at 125 frames/s. The Fudaa software was used to obtain surface flow velocity fields by large scale Particle Image Velocimetry (PIV) [Carbonari, 2015]. A point gauge fixed on three graduated perpendicular rails allowed to measure flow surface and bed altitudes with a 2-mm-accuracy.

RESULTS

Open check dam pure water hydraulics

The hydraulic control of the deposit [Fig. 1 (TP3)] is a characteristic delta dynamic, i.e. is controlled by the water level of the tranquil water area formed by the open check dam backwater effect. A large number of open check dam are designed as slit or slot types (Fig. 1 b & c). Table 1 gathers the existing water stage–discharge Eqs. describing the flow conditions that may occur in these dams: free surface or pressure flow (Fig. 1 b & c).

Table 1: Water stage – discharge formula for slot ant slit dams

Flow type	Source	Equation	Eqs. number
Free surface	Zollinger [1983]	$Q = {}^{2}/_{3}\,\mu w_0 \sqrt{2g\,H^3}$	(1)
Free surface	Armanini and Larcher [2001]	$Q = w_0\sqrt{g\left({}^{2H}/_{3}\right)^3}$	(2)*
Free surface	D'Agostino [2013]	$Q = w_0\sqrt{g\left({}^{2H}/_{3*1.2}\right)^3}$	(3)*
Pressure flow	Torricelli [1644]	$Q = \mu w_0 h_0\sqrt{2g(H - h_0/2)}$	(4)
Pressure flow	Zollinger [1983]	$Q = {}^{2}/_{3}\,\mu w_0\left[\sqrt{2gH^3} - \sqrt{2g(H-h_0)^3}\right]$	(5)

Note: see Fig. 1 for parameter definition, with Q the discharge [m³/s], w_0 the width of the opening [m], h_0 the height of the opening [m], μ the contraction coefficients [-], g the gravitational acceleration [m/s²] and H, the hydraulic head [m] with $H = h + V^2/2g$ with h the water depth [m] and V the flow velocity in the upstream section [m/s] approximated by Q/Wh, with W the basin width [m].

** Eqs. 2 and 3 are equivalent to Eq. 1 with values of μ = 0.577 and μ = 0.439, respectively.*

Eq. 2 and 3 are based on theoretical considerations. Zollinger [1983] proposed using a value of 0.65 for μ but did not provide the calibration data. We propose to use our measurements to discriminate which equation and which μ-value are the most relevant in typical torrential flows.

Height dam-configurations were tested, without sediment transport, to answer this question: 3 slits w_0 = [6;10;14cm] and 5 slots $w_0 x h_0$ = 10x6cm, 10x4cm, 10x2cm, 14x6cm, 14x4cm, 14x2cm. The dam was made of a 7.5mm-thick PVC plate. The basin immediately upstream of the dam was 20cm-wide and its floor was covered with pebbles 14-18mm in diameter. 64 measurements with Q ϵ [0.5;3.8 l/s] and h ϵ [16;140 mm] were taken at different stable states. The results are synthetized in Fig. 2 and more details on the experimental set-up, the data and an error analysis can be found in Mejean [2015].

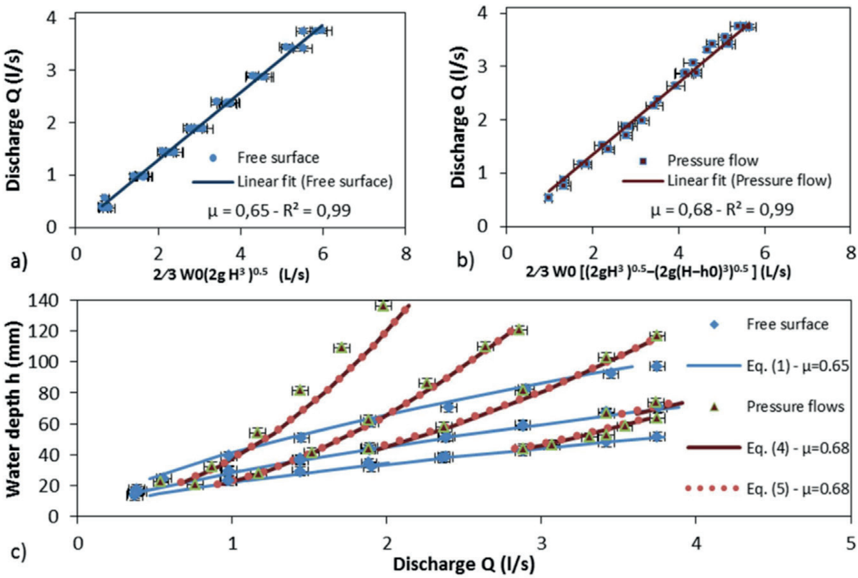

Figure 2: Water stage–discharge relationship analyses: calibration of µ, contraction coefficient for a) free surface flows in slits and slots using Eq. 1 and b) pressure flows in slot using Eq. 5 and; c) comparison between experimental data and computed water-stage discharge. Note: Eqs. 1, 4 and 5 were used taking into account the inertia term $V^2/2g$ in H the hydraulic head term of the formula

The linear best fit (Fig. 2 a) confirms the µ-value of 0.65 in free surface flow. Eq. 1 is thus recommended, rather than Eqs. 2 and 3, for equivalent thin-dam-configurations, i.e. for h/e ϵ [0.05;0.47], with e the dam thickness in the flow direction (Fig. 1 b). The results still need to be confirmed for thicker dam configurations were the Eq. 2 may be more adapted. **For pressure flows in slots (Fig. 2 b), the linear best fit shows a µ-value of 0.68,** close to the 0.65 value also retained by Zollinger [1983]. Eqs. 4 and 5 are almost indistinguishable in our results (Fig.2 c) if the hydraulic head, in the Torricelli [1644] formula, is corrected by half the slot height as written in Eq. 4.

For high H/h_0 ratio, Eqs. 4 and 5 underestimate slightly h, and conversely they overestimate h for low H/h_0 ratio (Fig. 2 c). It results from the use of a constant value of µ whereas the contraction effects increase with H/h_0. Complementary experiments should be performed to calibrate a variation of μ with the contraction, i.e. varying with H/h_0 and W/w_0, this in torrential context, i.e. with steep slope, rough beds and sediment transport. In addition our results demonstrate that **taking into account the inertia term $V^2/2g$ in H the hydraulic head is important**: Using the sole h term in the Eqs. would result in an underestimation of the structure discharge capacity and consequently in overestimation of the deposition and trapping performance (see later), which is not conservative in hazard mitigation.

Delta thickness estimation

During a trap filling, when sediments reach the open check dam backwater area, where flow velocities are low, they deposit as a delta. ΔZ, the delta thickness at the front (Fig. 1 a), directly controls the trapped sediment volume, e.g., a lower ΔZ means a lower trapped volume. ΔZ estimation is thus a key step in the trap design. Armanini and Larcher [2001] and Jordan et al. [2003] proposed formulas to estimate ΔZ that can be rearranged as follow [Mejean, 2015]:

[Armanini and Larcher, 2001]

$$\Delta Z(T) = h(T)\left(\frac{W-w_0}{w_0}\right) / \left[1+\left(\frac{W-w_0}{w_0}\right)\right]$$

Equation 6

[Jordan et al., 2003]

$$\Delta Z(T) = \frac{1}{T}\int_0^T h(t)\mathrm{d}t$$

Equation 7

With *W*, the basin-width upstream of the open check dam; w_0, the slit-width, *T* the duration since the beginning of the flood and *h(T)* the flow-depth upstream of the structure at time *T* (Fig. 1 b & c), varying in time during the flood and computed using Eq. 1 and μ=0.65.

It is worth stressing that Eq. 6 has been calibrated in laterally confined flows, i.e. the flow covered all the deposit due to the flume relatively narrow width (0.4 m). On the contrary, Eq. 7 has been calibrated in laterally unconfined flows, i.e. the deposit showed a more classical delta pattern with few mobile active channels narrower than the total basin width. In addition, the authors of Eq. 6 assumed that the delta thickness is always equilibrated with the flow constraints and thus only depends on the instantaneous water depth *h(T)*. On the contrary, Eq. 7 takes into account all the water depth evolution during the flood through the integral.

To test these Eqs., five flood experiments were performed in the aforementioned flume, under constant solid concentration, $C = \frac{Qs}{Qs+Q}$, varying from 1 to 5%, with Qs, the solid discharge. Triangular hydrographs were used with water discharge reaching 2.75 l/s at the peak for all runs. The cumulated sediment supply was the same in the all runs (500 kg). The hydrograph duration was thus inversely proportional to the concentration (see Mejean [2015] for more details).

In our experimental conditions, the flows were laterally unconfined, i.e. sediment entering the open check dam-backwater-area was transported in an active channel narrower than the basin width and flowing between deposit terraces. Several photogrammetric measurements were taken on each experiment at different times on the hydrographs, thus for various instantaneous discharges and water depths. Taking it into account and, as could be expected from Eqs. 6 and 7, ΔZ evolved between measurements. Width-averaged-deposit-longitudinal profiles were extracted from the DEMs [Mejean, 2015]. The delta-thickness was identified at the break in the slope and measured from the bottom of the open check dam (Fig. 1 a). Fig. 3 shows the comparison between measured and calculated values of ΔZ, using Eq. 6 and 7.

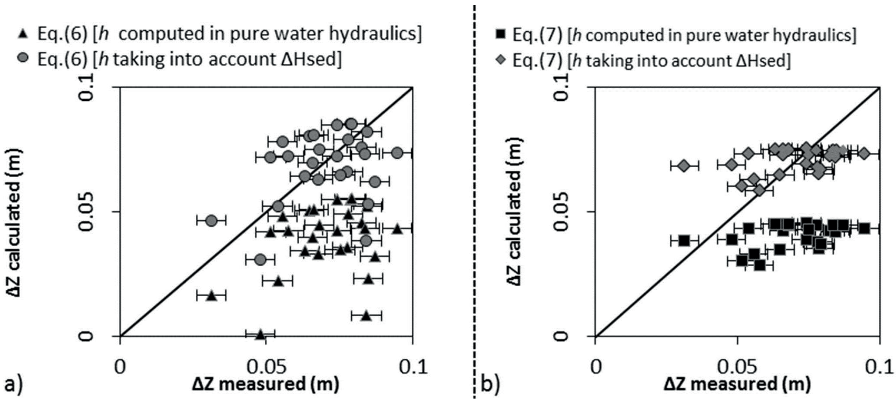

Figure 3: Comparisons between measured values of delta thickness, ΔZ, and predicted values by a) Eq. 6 and b) Eq. 7, in pure water hydraulics and with ΔHsed. Taking into account ΔHsed in the h estimation is necessary to achieve a satisfying estimation of ΔZ.

One can notice in Fig. 3 that, all other parameters being geometrically fixed, **Eqs. 6 and 7 underestimate ΔZ when using the pure water hydraulics described by the unique Eq. 1 to estimate *h(t)***. To estimate the total water depth of sediment-laden flows in slits and slots, Piton and Recking [2015a] recommend to take into account an additional head loss related to the sediment transport, $\Delta H_{sed} = 1.5 D_{MAX}$, with D_{MAX} the maximum transported sediment diameter [m]. Using this adaptation to the clear water hydraulics, the water depth is computed using:

$$h(t) = h_{pure\ water}(t) + 1.5\mathrm{D}_{\mathrm{MAX}}$$

Equation 8

Taking into account this additional head loss, Eqs. 6 and 7 give a rather good approximation of ΔZ, though some scattering remains (Fig. 3 a & b, grey dots). This scattering is probably due to ΔZ-measurement uncertainties (the transversal profiles at the delta fronts were not flat, thus their representative height, here taken as the median altitude on the profile, are subject to interpretation) combined to a natural variability of the phenomenon, e.g., high deposition or incision preceding the measurement. In addition, the hypothesis that the delta-front-shape is always equilibrated with the flow constrains rapidly fall in defect during the hydrograph recession, as supposed initially by Armanini and Larcher [2001], explaining the low ΔZs computed in Fig. 3 a. Eq. 6 is thus not adapted to compute ΔZ in wide basins during the hydrograph recession. **Eqs. 7 give thus a good approximation of ΔZ if the water depth is correctly computed, i.e. taking into account all additional head losses related to torrential hydraulics (strong sediment transport, driftwood accumulation).**

GEOMORPHIC DESCRIPTION OF A SEDIMENT TRAP FILLING

When entering the basin, flows and sediment pass from a steep-laterally-confined to a milder-laterally-unconfined situation. In this situation, Zollinger [1983] observed both mono-channelized and braided fan-shape deposits. The transition from confined to unconfined flows raises complex issues in field observations and in numerical modeling [Piton and Recking, 2015a]; e.g. does channelized and braided patterns come from different flood-types? or how to compute the deposition slope of an unconfined massive bed-load supply?

13-experiments, 5 with a slit-dam (analyzed before) and 8 with a basin without open-check-dam (same concentration and hydrographs feedings, two sediment mixtures [Mejean, 2015]), were performed to observed deposition-processes and hydraulics' conditions of bed-load trapping. Cycles of channelized and braided-like-patterns were systematically observed (e.g. Fig. 4). These patterns are simply different phases of a basin-filling, which is not a deposits-continuous-progression but rather jerky-sediment-propagations occurring after reconstitution of sufficient sediment stocks in the inlet-vicinity. Grain size sorting and deposit armoring play key roles in these cycles: braided patterns were observed to be steep and paved while channelized pattern to be milder, with a bed smoothed by the finer subsurface materials released during the channelization.

There is thus not a unique value of deposit-slope but rather a range of slope in which a dynamic-equilibrium fluctuates. A method to estimate the slope range should be developed in further analysis. In addition, laterally-confined complementary experiments demonstrated that **the deposition-slope increases in unconfined configurations** (see Mejean [2015]). As a method to estimate deposition slope is still lacking, it is generally recommended in new sediment trap design to measure deposition slopes in the field, for example upstream of existing check dams, to estimate the deposition slope in the future trap. Our results demonstrate that deposition slopes measured above check dams, i.e. in quite confined configurations, must be considered as minimum values of the possible bedload deposit slopes in sediment trap basins. One must note that it is not the case for mud flows which may deposit with very gentle slopes [Piton and Recking, 2015a].

Partial self-cleaning was also observed systematically: (i) during the hydrograph recession in slit-dam experiments and conversely (ii) during the peak-flows in dam-less experiments. Slit dams prevent peak-flow-releases due to the delta-like dynamics [Fig. 1 (TP3)], which is maximum at the peak flows. The volumes that were stored in the delta-front were subsequently re-eroded and partially flushed during the flow-recession, leaving terraces'-like patterns. The observation of a clear-incised-channel in the downstream part of the deposits is thus an evidence of partial self-cleaning. Adding a slit-grill or driftwood would have created a jam on the slit and prevented this self-cleaning phenomenon [Piton and Recking, 2015a, 2015b].

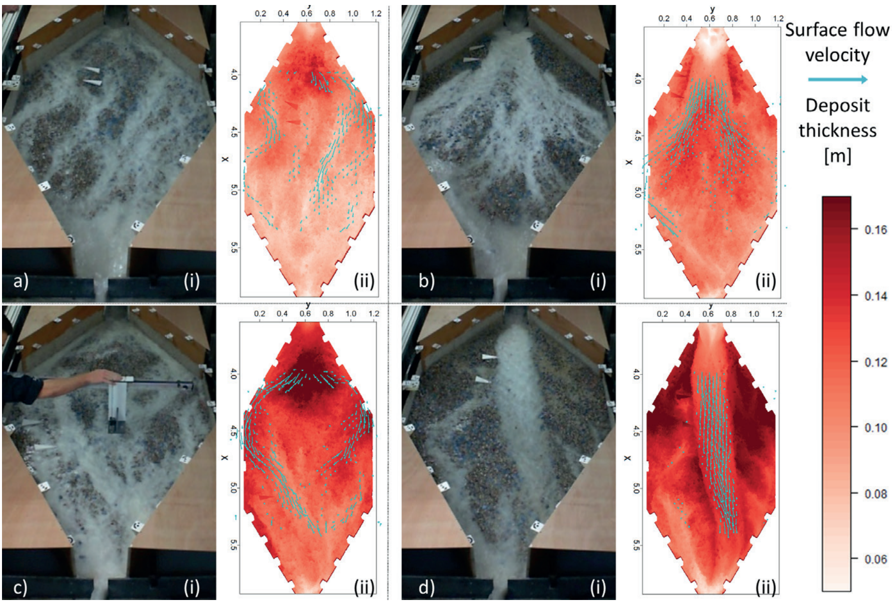

Figure 4: Photos of flows, DEM representation of deposit thickness and surface velocity fields of a) braided like-patterns during the initial filling of the inlet-vicinity; b) armor breaking leading to a channelization transferring sediment to the basin central part; c) new braided like patterns followed by d) another channelization, whose channel connect the inlet to the outlet, leading to a partial self-cleaning. Flow from the top to the bottom of the pictures.

HYDRAULICS ON MASSIVE DEPOSITS

PIV and DEM measurements were analyzed to deduce the slope, Froude and Shields numbers on massive-bed-load deposits (Fig. 5). Before each DEM and LSPIV measurements, the water depth, h_{gauge}, has been measured using the point gauge. At the same coordinates, the topographical profile, transverse to the flow direction, was also measured. The surface velocity was interpolated on a 1-mm-transversal step on the profiles (N values/profile). The mean value of the interpolated surface velocities, $\|\vec{V_s}\| = \frac{1}{N}\sum_{i=1}^{N}\|\vec{V}_{s,i}\|$, gives a rough estimation of , the $\overline{V} = \frac{Q}{A}$ profile mean velocity. The deposition slope S has been measured on the DEM along a longitudinal profile passing by the transversal profile. Rough estimation of, $\boldsymbol{Fr}$ and τ^*_{84}, with the Froude and the Shield stress for the $\boldsymbol{D_{84}}$,respectively, were computed using: $Fr \approx \frac{\|\vec{V_s}\|}{\sqrt{g h_{gauge}}}$ and $\tau^*_{84} \approx \frac{h_{gauge} S}{\Delta D_{84}}$, with Δ the submerged sediment density taken as 1.65. All dimensionless number analyzed hereafter are representative of local values of flow features in active channels. They are not averaged on the basin width.

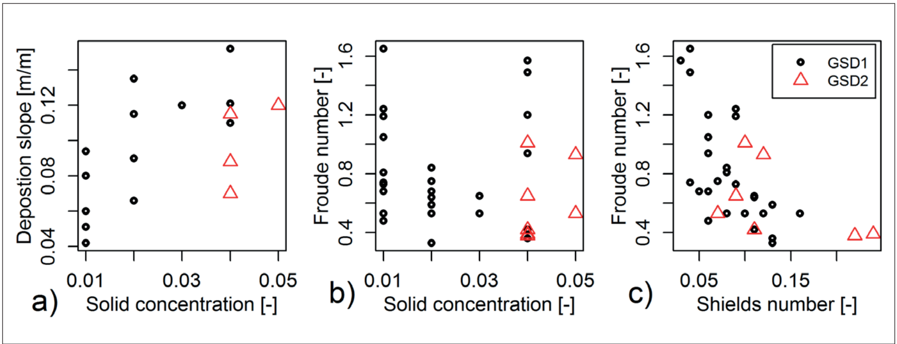

Figure 5: Rough estimation of main flow dimensionless numbers: a) deposition slope vs inlet solid concentration; b) Froude number vs inlet solid concentration and; c) Froude number vs Shield number

The absolute values illustrated in Fig. 5 are rough estimations because of the high uncertainties on h_{gauge} , however some general trends of interactions between geomorphology and hydraulics can be observed: (i) the deposition slope strongly fluctuates for a given solid concentration (Fig. 5 a) highlighting the geomorphic cycles' magnitude and that armoring process lead to various equilibrium slope despite a constant solid concentration at the inlet. (ii) The Froude number also strongly fluctuates (Fig. 5 b) which is likely to be mainly related to the varying velocities related to varying bed roughness within the geomorphic and armoring cycles. (iii) Interestingly an unintuitive inverse correlation seems to appear between the Froude number and the Shields number (Fig. 5 c): Low Shields numbers were computed on the milder slopes observed during chenalisations but where the smooth bed allowed high velocities and Froude numbers. Conversely, steep paved braided fan-patterns showed high slopes (and thus Shield numbers) and low velocities (and thus Froude numbers) due to their rough and paved beds. Local measurements of sediment diameter should be done to compute more accurate value of Shields numbers and to confirm this inverse correlation. These preliminary results need to be more deeply analyzed to specify the autogenic fluctuating hydraulics of massive bed-load deposits related to grain size sorting and to define which friction law and transport formula are the most relevant to compute such phenomena.

CONCLUSIONS

The new elements listed in this paper will help designers to more accurately design and numerically model the structures, specifically slot and slit dams, so to better adapt them to each site and their natural-hazard-specificities and mitigation-objectives. They also highlight the varying nature of sediment transport of poorly sorted mixtures and the necessity to push further the research on this subject, which, so far, is not enough understood to provide accurate design methods to practitioners.

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