Cohesive sediment removal from a fixed bed

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ABSTRACT: A few experiments were carried out, in a 1:1 scale laboratory flume, to evaluate, by the acquisition and processing of photographic images, the capability of currents flowing in a stream to remove cohesive sediments deposited on the bed of a river. The results of the experiments, expressed in terms of area and volume eroded, and changes in the concentration of suspended sediments carried by water, were consistent with the physical phenomenon, and congruous with others results already reported in the literature. Considering the goodness of the results obtained by the experiments carried out, it was possible to assert that the procedure adopted for the evaluation of sediment removal is suitable for studying the erosion and transport phenomena involving most kinds of granular or cohesive sediments.

1 INTRODUCTION

Starting from the XIX century, the study of sediment transport in both rivers and channels is a very important topic in hydraulic engineering and a challenging task in the research. Most of the analyses carried out were focused on deposit/erosion phenomena involving granular sediments, whereas there is poor experience on the behaviour of cohesive sediments. Indeed, cohesive sediments exhibit different capability to resist to the flow actions, strongly depending on the composition of sediment itself and, then, on the strength of electrical attraction forces among particles. Besides, it is practically impossible to reproduce these forces in a smaller scale: as a consequence, when a problem arises involving the evaluation of erosion/deposit behaviour of cohesive sediments subject to a flow, it is usually impossible to bring useful information from the literature.

Starting from these considerations, some experiments were carried out at the laboratory of the Department of Hydraulic and Environmental Engineering *Girolamo Ippolito* of the University of Naples *Federico II*, aiming to reproduce, in a 1:1 scale flume, the capability of currents flowing in a natural river (the Bagnoncino Creek, Tuscany, Italy) to remove cohesive sediments deposited on the river bed.

In particular, the cohesive sediments specifically considered in this study were *aluminum hydroxide flocs*, diffusely found on the river bed, with layers up to 0.40 m thick. These flocs were discharged into the river, for a very long time (about 1 year), because of malfunctioning of a few water treatment plants, whose goal was to remove, by adding aluminum salts, the sediments present in the water coming from some tunnel digs and containing high level of suspended solids.

The flocs covered the river bed, at first destroying the fluvial vegetation, and then provoking the disappearance of fish, riparian fauna and vegetation.

As a consequence, in order to evaluate the possibility that the sediments were *naturally* removed, and transported until prefixed “sediment traps” to locate along the creek, it was important to individuate the hydraulic conditions needed to have sediment removal by the currents flowing in the stream.

For this reason, some laboratory activities were carried out to evaluate: i) the capability of flow to remove cohesive sediment from a fixed bed; ii) the mechanic of transport of this kind of sediment; iii) the time required for complete sediment removal.

The experiments have regarded five different aspects: i) the evaluation of the optimal conditions to artificially produce aluminum hydroxide flocs; ii) the massive production of aluminum hydroxide flocs and their subsequent transfer into the laboratory flume; iii) the acquisition of the flow velocity profiles by an Acoustic Doppler Velocimeter Profiler (*ADVP*); iv) the acquisition and processing of photographic images taken during the sediment removal; v) the evaluation of the capability of flows to remove the sediments.

It could be important to observe that the work presented here could be considered of some importance not only because it aims to solve a few specific problems, such as the determination of critical flow conditions for starting erosion of a given cohesive sediment or the evolution in time of erosive phenomena, but also because it proposes a new kind of laboratory approach, that could be useful even for studying the behaviour of other kinds of cohesive or granular sediments.

2 LABORATORY SET-UP

The experimental work aimed to reproduce natural phenomena that could be observed, both during low discharge periods and in consequence of floods events, in the *Bagnoncino Creek* (Tuscany, Italy), that was interested, a few years ago, by large deposit phenomena of cohesive sediments. Because of the impossibility to know and scale the inter-particles attraction forces originating the flocs, and the strength of links among the flocs themselves, it was decided to try to reproduce, in a 1:1 scale channel, the actual conditions that could be usually observed in a central region of the creek cross-sections. As a consequence, a Perspex channel 18.0 m long, 0.76 m wide and 0.60 m deep, having a fixed slope $i = 0.001$ m/m, was used for the experiments (Fig. 1). To adequately reproduce the field conditions, the bed of the experimental flume was covered with a single layer of stones. The grain size distribution of sediments used in the experiments fitted quite well that of sediments observed at the bottom of the Bagnoncino Creek (Fig. 2). In particular, the d_{50} diameter of the stones used in the experiments was equal to 30 mm.

Figure 1. View of the experimental channel

In the middle of the channel, a removable wood tablet, 0.45 m long and 0.76 m wide, with fixed stones was arranged (Fig. 3). The tablet was covered with aluminum hydroxide flocs produced inside a 1 m^3 tank and then positioned in the channel.

It was decided to produce cohesive sediment into the tank to avoid water contamination in the general laboratory circuit.

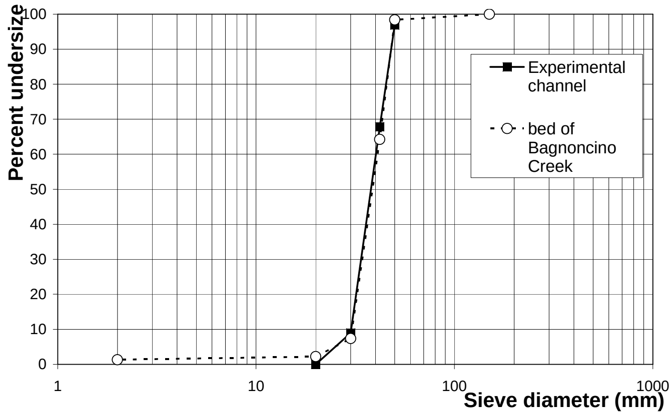

Figure 2. Grain size distribution of the sediments at bed of the Bagnoncino Creek and of the sediment used in the experiments

Figure 3 – Plain view of the removable tablet

2.1 *Procedure used to obtain the optimal chemical dosage for pollutant production*

The first phase of the experiments was focused to establish the optimal conditions to produce aluminum hydroxide flocs. To achieve this purpose, a great number of *Jar-Tests* were carried out, adding in the water samples variable dosages of lime, polyelectrolyte and aluminium chloride and changing the environmental conditions. The procedure used in the tests is made of the following steps: 1) addition of lime in the water (to correct the *pH* value) and its rapid mixing for 10 minutes; 2) addition of the polyelectrolyte solution, and its rapid mixing for at least 10 minutes; 3) addition of powdered aluminium chloride, and its slow mixing until the flocs are done. The optimal conditions resulting from *Jar-Test* were the following: $pH = 9$; lime dose = 0.15-0.25

g/l; polyelectrolyte dose = 0.125 ml/l; aluminium chloride dose = 0.01 g/l.

2.2 *Pollutant production*

As above mentioned, the massive flocs production have taken place in the 1 m^3 tank, using the optimal conditions resulting from *Jar-Tests*. The procedure was carried on until the removable tablet was totally covered with flocs (Fig. 4). In addition, blue of methylene was added to colour the flocs, in order to be able to optically scan the variation of their concentration at bed.

Figure 4. A top view of the contaminant on the table

2.3 *The photographic image acquisition*

At the end of the flocs production step, the wood tablet was removed from the tank and positioned at bed of the experimental flume. A digital camera was positioned at the top of the channel and snap shots were taken at regular time steps. Then, the pictures taken during each experiment were processed, by using a specific software, to identify the blue pixels associated with the pollutant presence. Given the dimensions of the pictures, it was possible to calculate both the pollutant quantity on the tablet and its variation in time due to the erosion processes originated from the shear stresses transmitted by the flow. Picture definition and luminosity were essential to be able to correctly process them by using the software. Some problems were encountered due to the presence of light reflections, the non uniformity of the water surface and the non homogeneous luminosity in the room. Thus, a correct alignment of the camera was necessary to avoid errors due to perspective. Furthermore, a black screen was positioned over the entire area to eliminate reflected light.

2.4 *The software*

The software determined the variations in blue from one shot to the following one, by comparing the corresponding pixels on the pictures. The colour information for each pixel is a 24 bit datum, ranging from black (value=0) to very light blue (value=255). The area with non zero values was calculated and monitored in time. A software filter was utilized to compare the single pixel datum with the adjacent ones in order to remove isolated black pixels due to light reflections or water waves at the surface, thus obtaining homogeneous areas of contaminant.

Afterwards, the value of each pixel was compared against a threshold value in order to obtain an output with only two colours. All pixels with values below the threshold value became black, and the rest were white. The threshold value falls in the range 25-28, and could be considered low enough to include also dark blue.

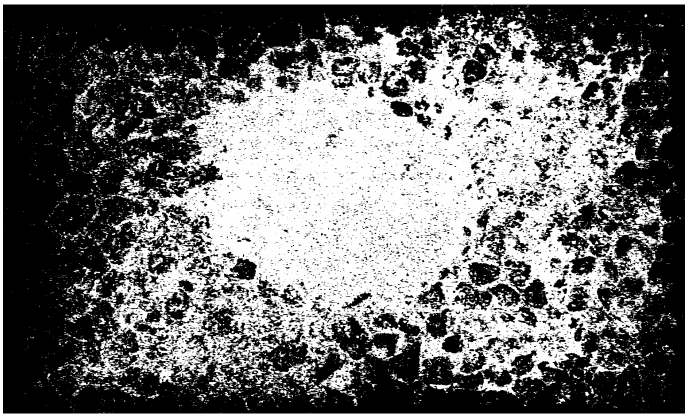

Figure 5. The output of the software

It is possible to show that the white area obtained by the procedure proposed perfectly corresponds to the area of the contaminant (Fig. 5).

2.5 *Hydraulic flow characteristics*

An *ADVP* was used to acquire the vertical distribution of mean local velocities along the channel axis. The number of longitudinal sections considered for measurements was 8, 20 cm spaced (Fig. 6). The range of the discharges used in the experiments was 20-85 l/s. Flow depths were also measured by using a point gauge with a *vernier scale*.

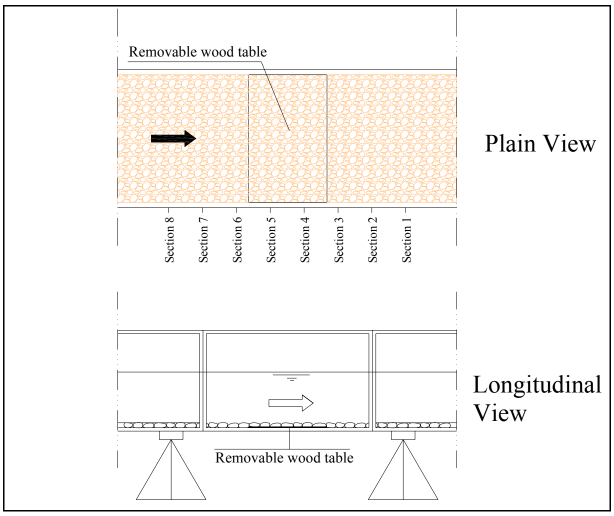

Figure 6. Schematic representation of experimental flume carrying the position of measurement cross-sections

For *large-scale roughness* conditions, like those observed during the experiments, the shape of the flow velocity profile is affected by local phenomena developing near the bed. According to the experimental data of Bathurst (1988) and Marchand et al. (1984), velocity profiles could be considered *S-Shaped* when the velocities measured near the free water surface are noticeable greater than the ones measured near the bed.

The particular shape of the velocity profile is due to the existence of two different regions (Bathurst 1988): a *lower zone*, immediately over the boulders, in which the flow is delayed by drag effects due to the coarser elements; an *upper zone*, located above the boulders up to the free water surface, in which a quasi-smooth flow occurs (Morris 1959; Marone 1970).

According to Bathurst (1988), the development of a *S-Shaped profile* can be observed if: i) the value of the depth/sediment ratio is $1 \le h/d_{84} \le 4$; and ii) the size distribution of the bed materials is non uniform, in order to allow the development of the lower zone flow (Baiamonte et al.1995).

In the cases examined, d_{84} = 45 mm and h/d_{84} = 1.9÷3.2.

As a matter of fact, the local velocity profiles were characterized mainly by the presence of a progressive transition to the *S-Shaped* form that is peculiar to gravel bed streams (Baiamonte et al. 1995; Nikora & Smart 1997).

With reference to the experimental data, the velocity profiles show a progressive transition to the *S-Shaped form*. This behaviour is confirmed by the observations.

As an example of experimental results, in Figure 7 is represented the vertical profile of local mean velocity at the cross-section n.1, corresponding to a flow rate *Q*=80 l/s and a ratio *B/h*=5.46. For comparison, the experimental results obtained in these conditions are plotted, in dimensionless form, together with those reported, by Baiamonte et al. (1995), for *B/h*=5.29 and *B/h*=7.64, respectively.

It seems evident that the vertical profile of local mean velocity is actually *S-Shaped*.

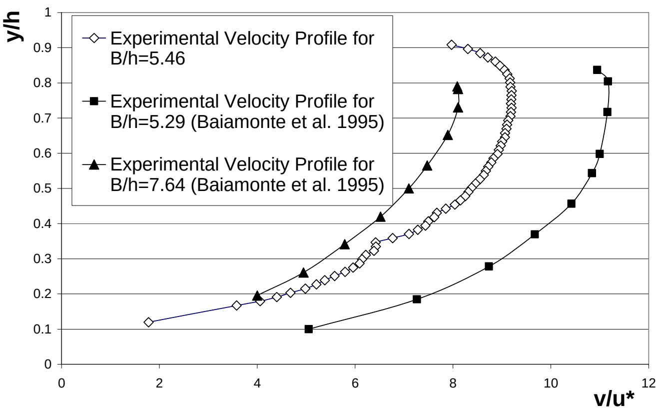

Figure 7. Experimental Velocity Profile in Section 1

For large-scale roughness, the velocity distribution in the lower zone can be described by the following logarithmic profile:

$$\frac{u(y)}{u_*} = \frac{1}{k} \ln \frac{h}{K_s} + a \quad (1)$$

where *y* is the distance from the top of the bed, *h* is the flow depth, u_* is the shear velocity, *u(y)* is the local mean flow velocity, K_s is the roughness height, *a*=8.48 is the value frequently used for rough bed, and *k* is the Von Karman's constant, that can be assumed equal to 0.4 for low concentration field. Note that the values of u_* and K_s in the Eq. (1) are unknown, that have to be determined by experimental data.

Substituting the values of the constants *a* and *k* in the Eq. (1), it is possible to write:

$$\frac{u(y)}{u_*} = 5{,}75 \log \frac{h}{K_s} + 8{,}48 \quad (2)$$

Referring to the present data, the velocity distribution (2) could be considered valid for $y u_*/\nu \ge 30$ and $y/h < 0.2$.

The best fit of the lower part of the velocity profiles along the channel axis and along each vertical was obtained by using the least square method.

The u_* and K_s values found by using this approach are listed in the Table 1. The K_s values are congruous with the ones reported in literature, included in the range 2-3 d_{50} (Becchi 1978).

Table 1. Values of $q=Q/B$, Ks, u_*, τ_o, h

Q (l/s)	q (m^2/s)	K_s (m)	u_* (m/s)	τ_o (N/m^2)	h (m)
20*	0.0263	-----	-----	-----	0.084
30	0.0395	0.055	0.0289	0.8328	0.097
40	0.0526	0.084	0.0495	2.4547	0.107
55	0.0658	0.098	0.0640	4.0956	0.116
60	0.0789	0.068	0.0796	6.3362	0.125
70	0.0921	0.081	0.0881	7.7605	0.134
80	0.1053	0.096	0.0944	8.9087	0.139
85*	0.1118	-----	-----	-----	0.143

* For *Q*=20 l/s and 85 l/s the velocity profiles are not available.

The shear stress values τ_o were obtained considering the average of the u_* values, through the expression:

$$\tau_0 = \rho\, u_*^{\,2} \quad (3)$$

where ρ = density of the water at 20 °C.

In Figure 8 are reported the τ_o and $q=Q/B$ values, where *B*=width of experimental channel.

The experimental relationship obtained between τ_o and *q* was:

$$\tau_o = 2404.4 q^{2.3955} \cong 2400\ q^{2.4} \quad (4)$$

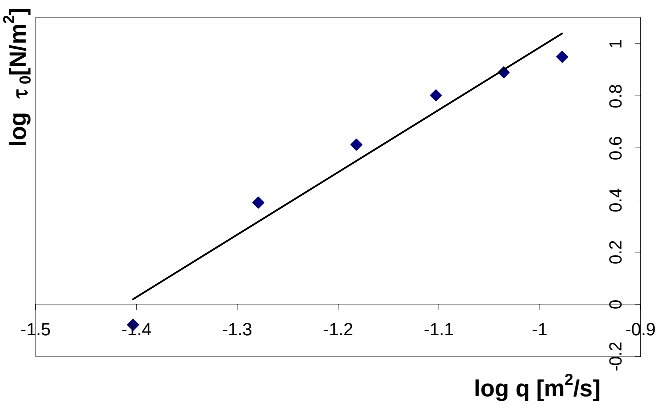

Figure 8. Relationship between τ_o and q.

The τ_o values for Q = 20 l/s and Q = 85 l/s were obtained from the equation (4).

3 EVALUATION OF THE EROSION RATE

By using the technique described before, the erosion process of cohesive sediment vs time was evaluated for discharges Q=20, 40, 55, 70 and 85 l/s (Fig. 9).

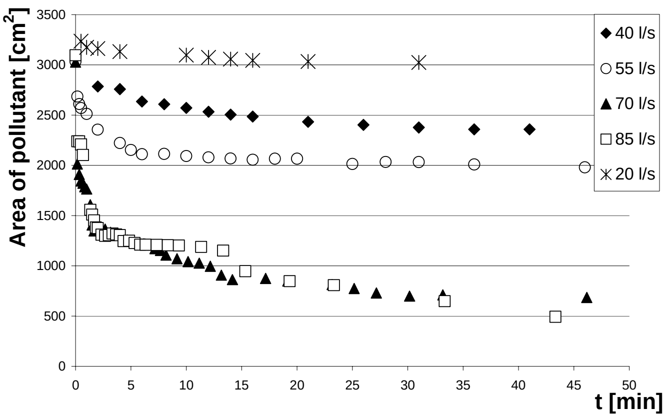

Figure 9. Area of cohesive sediments remaining on the tablet vs time.

It appeared that the resistance to the erosion increases with decreasing bulk density of the pollutant. In fact, the initial erosion rate of sediment at the bed is high and it concerns the first layer, where the bulk density of the contaminant is low. Then, after a time t_c that could be considered to be constant for all the experiments, the erosion rate decreases. This behaviour could be explained considering that the lower layers, after compaction and loss of water, oppose higher resistance to the action of flow.

Vice versa, in the layers near the bed the strength of the flocs might be more and, thus, the erosion could be more difficult.

In the first phase, the erosion could be considered as exponentially decreasing with time, while in the second phase it seems to be linear.

Between the two phases, there is a kind of plateau, that might be explain as a stabilization phase where the flocs, notwithstanding the stresses induced by flow, are not removed. After a few time, the steady action of the flow weakens the links between the flocs (Partheniades 1965), and erosion can start again, though with lower rate.

It appears that the area of contaminant decreases with increasing of the value of discharge and at 85 l/s almost all the contaminant is eroded.

At the discharge Q=20 l/s, the contaminant eroded was very little and, therefore, this condition was taken as the value of the critical discharge, or condition for the *first breakaway*. The corresponding shear stress value is $\tau_{o,cr}$ = 0.39 N/m^2.

To obtain the variation in concentration over time, it was necessary to calculate the volume eroded in time:

$$V(t) = A(t) \cdot Z(t) \tag{5}$$

where $V(t)$ = volume of pollutant eroded in time; $A(t)$ = area of pollutant eroded in time; $Z(t)$ = pollutant thickness.

The following law was chosen to represent the area variation in time:

$$A(t) = \frac{A_0}{(1 + t/t_\alpha)^\beta} \tag{6}$$

where A_o= area of pollutant at the time zero, t_α and β are unknown parameters.

The parameters t_α and β were calculated using the experimental values of $A(t)$ evaluated in the time interval [t = 0, t = t_c = 50 minutes], when the erosion rate is greatest.

According to the experimental results of Winterwerp & Kranenburg (1997), which used suspensions of kaolin, the behaviour of $Z(t)$ was considered to be a decreasing exponential function. The trend considered for following evaluations is represented in Figure 10, where the dimensionless ratio $Z(t)/Z_{initial}$ vs. time is plotted, together with a few experimental values.

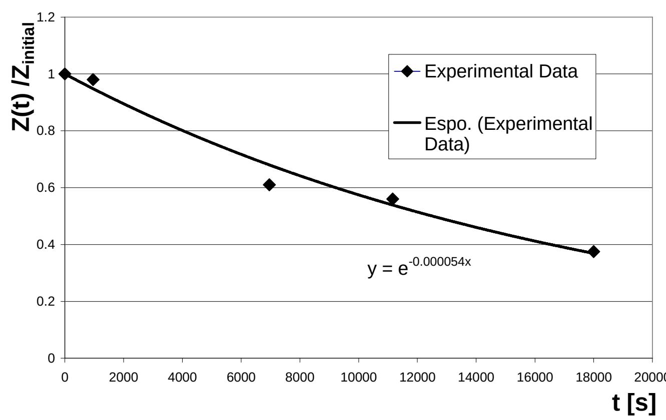

Figure 10.Variation of $Z(t)$ vs time.

By comparing these results with those of Winterwerp & Kranenburg (1997), it is possible do observe that the aluminum hydroxide flocs show an erosion rate significantly lower than the kaolin, due to the differences existing in interacting forces be-differences existing in interacting forces between the particles.

In Figure 11, the variation of the calculated volume V vs time is represented for the present data:

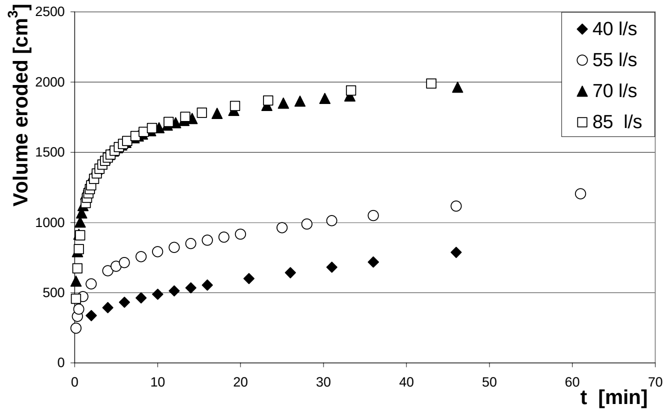

Figure 11.Variation of volume eroded vs. time.

The trend is similar to that given by Kuti & Yen (1976) for kaolin.

In order to compare to the results obtained from the experiments with those by Patheniades & Metha (1965) and of Metha & Parchure (1985), it was also evaluated the concentration of eroded material with time (Fig. 12).

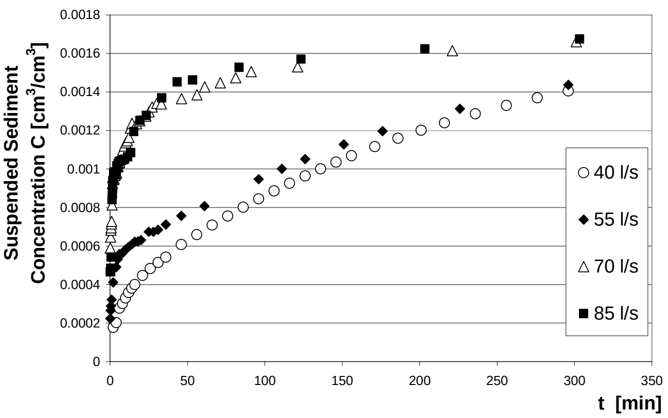

Figure 12. Suspended Sediment Concentration C vs time.

It is possible to observe that the suspended sediment concentration increases with time. The rate of increasing is greater in the first phase; then, the curve tends to a constant value, because the shear stress of the flow doesn't overcome the shear stress of the cohesive soil. In particular, for Q=70-85 l/s, at the end of the test, all the contaminant initially present at bed of the flume was eroded.

4 CONCLUSIONS

The main objective of this work was the evaluation of the hydraulic conditions needed to have removal, by currents flowing in a stream, of a specific cohesive sediment (*aluminum hydroxide flocs*), for which seem not available literature data.

The first difficulty was the lack of solidity of the *flocs* considered in the experiments. For this reason, it was not possible to utilize the traditional procedures of measurement. So, a new procedure was used, based on the acquisition and processing of photographic images during sediment removal. The results of area eroded, volume eroded and suspended sediment variation of concentration were consistent with the physical phenomenon and congruous with the results of literature.

However, in order to evaluate in a more rigorous way the cohesive sediment erosion, it is necessary to reproduce a greater number of experiments. Moreover, it can be interesting to repeat the tests with other types of flocs at different time of consolidation to evaluate the relationship between the time of consolidation and the capability of erosion of the flow.

By comparison with the results obtained by other researchers, it is possible to assert that the new procedure proposed, based on the acquisition and subsequent processing of photographic images taken during sediment removal processes, gives solutions consistent with the results reported in literature, and then seems suitable for studying the removal of both cohesive and granular sediments at bed of rivers and channels.

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