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DYNAMIC OF WOOD TRANSPORT IN TORRENTS

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ABSTRACT

The paper is addressed to the study of the hydrodynamic behaviour of floating logs in torrents, through a series of flume experiments at laboratory scale, by means of image analysis techniques. Two distinct flow conditions were considered: uniform flow and presence of a hydraulic jump. The experiments in uniform flow condition allow to evaluate the main features of log transport as a function of the bed roughness and the degree of congestion. Floating logs move at about the same velocity of the water surface and their orientation with respect to the flow direction is systematically lower for flows with increasing grain relative submergence. The floating logs tend to be oriented with an angle α that is greater in the centre of the channel than near the banks; this behaviour is related to the transversal water velocity gradients. The hydraulic jump strongly affects the wood transport: it tends to reduce the degree of congestion of floating woods volume and the effect is stronger for increasing logs concentration and Froude number of the incoming flow.

Key words: wood hydrodynamic, floating logs, wood transport angles

INTRODUCTION

The presence of floating logs in streams can assume great importance on the efficiency of check dams and on the stability of bridge piers during flood events. The problem gets a particular importance in torrents with strongly vegetated banks, where the wood supply can be very high and thus the risk of obstruction of these works is higher. The optimisation of works for preventing logs clogging is strongly related to the hydraulic behaviour of transported logs and, in particular, to the orientation assumed by the logs varying the wood congestion degree and the hydraulic characteristics of the flow.

Many laboratory and field studies underline that the logs mobility is conditioned by the imbrication forms assumed by the wood groups deposited along the river bed (Abbe & Montgomery, 1996). The study of the wood transport dynamics, even though simplified, needs to consider many parameters, related both to the stream channel hydraulics and to the logs characteristics. Analytical considerations (Ishikawa, 1990; Braudrick et al., 1997; Braudrick & Grant, 2001) lead to parameterise the transport type regime as a function of the wood relative submergence (h/D_{wood}), the grain relative submergence (h/D_{84}), the wood relative density (ρ_{wood}/ρ_{water}) and the orientation angle α that is defined as the angle between the log main axis and the flow direction.

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Braudrick et al. (1997) define three transport regimes for floating logs as a function of the ratio between the wood discharge (Q_{wood}) and the water discharge (Q): uncongested, semi-congested and congested. During uncongested transport, logs move without mutual interactions, so they respond to the obstacles and to the transversal velocity gradients by rotating or rolling independently from the other logs. In the congested transport, instead, the interactions between logs are so strong that they move together, like a single body. In this case, the wood tends to move in pulses. In case of semi-congested transport, logs still move in pulses but the degree of interconnection between the logs is less strong, so the wood clusters could be disaggregated more easily.

The orientation angle α is an important parameter that affects the transport type and regimes and the kind of deposition (Braudrick & Grant, 1997; Ishikawa, 1990). In literature distinction is made between the wood deposit angles and the wood transport angles (Ishikawa, 1990). Concerning wood transport angles, the literature data are scarce and generally only of qualitative type. In particular, Ishikawa (1990) considers as most important factors for logs orientation the stream slope S and the water depth h; moreover the author observes that the phenomenon of ordinary solid transport does not significantly affects the angles of movement and deposition of the logs. The flume experiments of Braudrick et al. (1997) and Braudrick & Grant (2001) underline the dependence of the α angle on the degree of congested transport regime for floating logs: in case of uncongested transport α assumes average values close to 20°-30°, with a symmetrical distribution of the values in a rose diagram; in congested transport conditions, instead, the trunks are often orthogonal to the flow direction and α is greater than 30° in the mean.

The experiments of Degetto (1999) and Dagostino et al. (2000) give some preliminary indications about the effect of hydraulic jump on the transport features of floating logs, in particular on the mitigation of the wood discharge degree due to the change of flow regime; this aspect however deserve further attention.

As previously mentioned, the hydraulic efficiency of open check dams or of other transversal hydraulic structures is strongly influenced by the presence of logs in the streams. These structures are often provided with devices, such as inclined grids, in order to prevent logs clogging. Actually the designing of such devices is often empirical and left to the practical experience; nevertheless, a deeper knowledge of the hydraulic behaviour of floating logs, concerning, for example, their transversal distribution and inclination with respect to the flow direction during their downstream motion, could be very useful for the optimisation of such devices and is not yet fully understood. The relevance of laboratory experiments for the investigation of this aspect is fundamental, especially if the paucity of available data is considered. In the following, some results on mean velocity and inclination distribution of logs in uniform flow conditions are presented, as a function of logs congestion and bed roughness. Moreover, the effect of localized phenomena, like a hydraulic jump, on logs flotation is analysed; this situation is quite common in mountain streams upstream an open check dam or a narrower cross section.

THE PHYSICAL MODEL

The experiments were carried out in a closed circuit flume 9 meters long, with rectangular cross section of 0.25 m width (B; see Fig.1). The flume is divided in three parts having different slopes (S): the upstream reach is 2.0 m long with slope S = 0.3% and it is used for the logs input, the central part is 4.0 m long and S = 15.0% and it tries to reproduce the relative high slopes, characteristic of mountain streams and creeks, the third reach is 2.8 m long and S = 3.5% and it simulates a strong change of inclination, that is frequent in proximity of check dams. The flume is provided with an upstream and a downstream tank; the discharge is controlled by a control gate located in the recirculating pipe, just downstream the pump and measured by an electromagnetic flow meter. The water level in the downstream reach is controlled by a sluice gate located at the end of the flume.

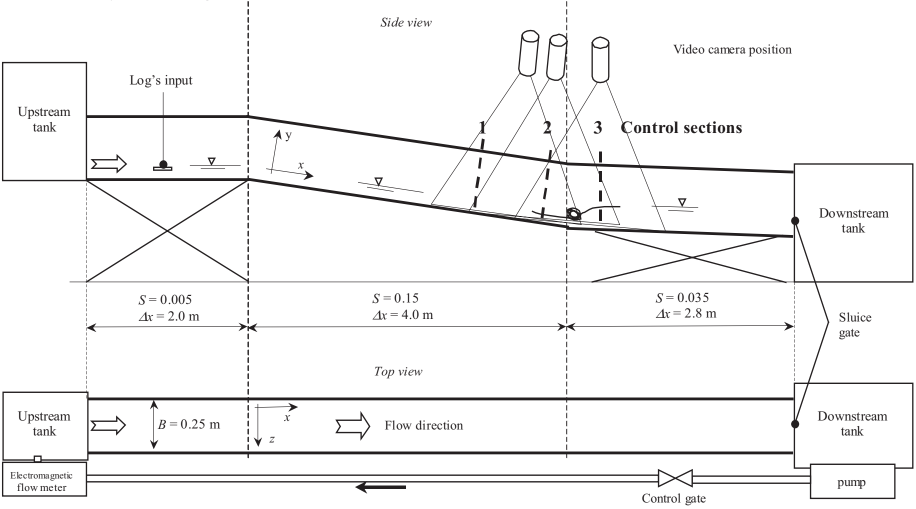

Fig.1: Schematic view of the experimental arrangement and photogrammetric acquisition system.

The logs were simulated using small wood grained cylinders 0.08 m long, having diameter $D_{wood} = 6\cdot10^{-3}$ m, specific weight $\gamma_{wood} = 8240$ N m^{-3}; the logs surface was made particularly rough, in order to overcome the surface tension effects that could affect the experiments.

The wood transport tests were performed in steady state flow conditions, both in smooth and rough bed: for each test, once the discharge conditions had been fixed, the free surface water level was measured all along the flume by means of a rank of hydrometers and piezometers located along the flume. In particular, concerning the second reach, for all the tests, the water uniform flow conditions were achieved at not more than 0.5 m downstream the beginning of the reach.

The rough bed conditions were reproduced using rounded gravel glued to the bed; the grain size distribution was as follows: D_{medium} = 0.017 m, D_{50} = 0.016 m, D_{84} = 0.019 m (D_{xx} = diameter for which *xx*% in weight of material is finer).

Photogrammetric acquisition system

The position, angle and velocity of floating logs were evaluated by means of image analysis techniques. Two synchronized analogic colour video camera were used in the second reach of the flume (see position 1 and 2 in Fig.1), with simultaneous top views on two distinct areas of the flow field. The recorded videos were independently analysed frame by frame, in order to evaluate the logs velocity, position and inclination with respect to the mean flow direction; the velocity evaluation was performed by means of a Particle Tracking Velocimetry (PTV) technique, based on the evaluation of the most probable trajectory of each log, validated on at least four consecutive frames (Serafini, 2003). The video cameras positions were preliminarily optimised in order to verify that the logs move really in uniform flow condition, that is verifying that the log's process of acceleration was exhausted; the use of the two video cameras with partially overlapped field of view allowed both to detect longer trajectories (thus enhancing the reliability of velocity and acceleration estimation) and to accelerate this operation. The experiments concerning the hydraulic jump used a third video camera (position 2 and 3 in Fig.1), located just downstream the hydraulic jump position, that allowed to evaluate the logs velocity, position and discharges also in this zone.

For each individual test the measurements were performed on the basis of the analysis of at least 200 logs, in order to guarantee the statistical significance of the measurements.

TESTS IN UNIFORM FLOW CONDITION

The experiments were performed both in smooth and rough bed conditions, with different water discharges Q, grain relative submergence and log relative submergence; the main characteristics of the different tests are reported in Tab.1, all the hydraulic data are referred to the uniform flow conditions achieved in the second reach, having slope S =15%. The tests in smooth bed conditions were performed for only one discharge value (Tests N. *1* in Tab.1); the tests in rough bed conditions were performed for three different discharge values (Tests N. *2*, *3*, *4* as reported in Tab.1). For each of these tests, 200 logs were released at central transversal position ($z = B/2$; Fig.1) and with an input angle α equal to zero degree.

For each of these runs the flow was fed with one log every second; this time interval was long enough to allow to consider that adjacent logs do not interfere with each other.

The logs inclination and velocity were evaluated with a video camera in position 2 of Fig.1; in this region both the fluid and the logs can be considered in uniform flow conditions and therefore it can be reasonably assumed that the logs motion could depend only on the manner of feeding and on the hydraulic characteristics of the uniform flow.

Tab.1: Hydraulic value on tests about the 2nd flume's part (S = 0.15) for log's motion analysis with smooth and rough flume (D_{84} = characteristic diameter of bed rough material; Q_{water} = water discharge; h = average hydraulic depth; D_{wood} = log's diameter; $U_{mean} = Q_{water}/(B \cdot h)$ water average velocity; Fr = Froude number; Re = Reynolds number; h/D_{wood} = wood relative submergence; h/D_{84} = grain relative submergence).

Test	D_{84} (m)	Q_{water} (m^3s^{-1})	h (m)	h/D_{84}	h/D_{wood}	U_{mean} (ms^{-1})	Fr	Re
1	Smooth	0.008	0.0165	-	2.75	1.94	4.82	$27 \cdot 10^3$
2	0.019	0.003	0.0210	1.11	3.50	0.57	1.26	$10 \cdot 10^3$
3	0.019	0.008	0.0330	1.74	5.50	0.97	1.70	$27 \cdot 10^3$
4	0.019	0.016	0.0480	2.53	8.00	1.33	1.94	$55 \cdot 10^3$

The hydrodynamic response of floating logs to the hydraulic jump phenomenon was investigated. The sluice gate was opportunely adjusted in order to locate the hydraulic jump zone just in proximity of the change of slope between the second and the third reach (section 2 in Fig.1); in this zone the incoming flow was at uniform conditions and the hydraulic jump was characterised by a sharp-cut roller. The tests were performed for five different discharge values, the main features of the tests are reported in Tab.2; for each of these tests, 200 logs were released at the centreline of the logs input section, always with angle α equal to zero, the feeding rate and consequently the feeding time varied for each test, as reported in Tab.3. Combining the discharge conditions (Tab.2) with the feeding characteristics (Tab.3), it can be deduced that twenty runs were performed and analysed.

The log analysis was performed both upstream and downstream the hydraulic jump (sections 2 and 3 in Fig.1); for each measuring section the logs velocity, discharge and the superficial and volumetric concentrations were evaluated. The volumetric concentration (C_v) is defined as the ratio between the volumetric logs discharge (Q_{wood}) and the water discharge (Q_{water}); a rough estimation of Q_{wood} can be done measuring the number of logs that flow through the measuring section per unit time, n_{wood} by means of the following equation:

$$C_v = \frac{Q_{wood}}{Q_{water}} = \frac{n_{wood} \cdot (\pi/4) \cdot D^2_{wood} \cdot L_{wood}}{U_{mean} \cdot B \cdot h} \qquad (1)$$

As reported in Table IV, the feeding characteristics allowed to analyse a relatively wide logs concentrations range; the time interval Δt spent in each experiment by the groups of logs to flow through the measuring sections 2 and 3 (Fig.1) and the corresponding mean concentration values, $\overline{C}_v$ are reported in Tab.4.

Tab.2: Hydraulic parameter for different liquid discharge before hydraulic jump (position 2 in Fig.1).

Test	Q_{water} (m^3s^{-1})	h_{IN} (m)	$U_{mean\ IN}$ (ms^{-1})	U^* (ms^{-1})	h/D_{84}	Fr_{IN}	Re_{IN}
5	0.003	0.021	0.57	0.163	1.11	1.26	$10 \cdot 10^3$
6	0.004	0.024	0.67	0.172	1.26	1.37	$14 \cdot 10^3$
7	0.008	0.033	0.97	0.196	1.74	1.70	$28 \cdot 10^3$
8	0.012	0.041	1.17	0.213	2.16	1.85	$42 \cdot 10^3$
9	0.016	0.048	1.33	0.226	2.53	1.94	$56 \cdot 10^3$

Tab.3: Manner of logs input for tests with hydraulic jump.

Test	Feeding rate *(logs/s)*	Feeding time *(s)*
e	20	10
f	50	4
g	100	2

For each run the wood volumetric concentration attenuation efficiency ε_v due to the hydraulic jump was also evaluated. It is worth of note that ε_v corresponds to the wood discharge attenuation efficiency and it can be defined as the ratio between the maximum wood volumetric concentrations at the sections just downstream and upstream the hydraulic jump, $C_{v\ max\ OUT}$ $C_{v\ max\ IN}$, respectively as follows:

$$\varepsilon_v = 1 - \left(\frac{C_{v\ OUT}}{C_{v\ IN}} \right)\Bigg|_{max} = 1 - \left(\frac{Q_{wood\ OUT}}{Q_{wood\ IN}} \right)\Bigg|_{max} \qquad (2)$$

where the subscripts $_{IN}$ and $_{OUT}$ indicate the values at the section just upstream and downstream the hydraulic jump respectively, that are the sections 2 and 3 in Fig. 1.

Tab.4: Experimental data.

Test	Δt_{IN} (s)	Δt_{OUT} (s)	$\overline{C}_{v\ IN}$ (eq. 1)
5e	11.44	15.80	0.0132
5f	4.88	11.55	0.0309
5g	2.68	10.80	0.0563
6e	8.80	14.20	0.0129
6f	4.44	11.50	0.0255
6g	2.32	10.70	0.0487
7e	6.16	12.50	0.0092
7f	3.36	11.05	0.0168
7g	1.60	10.40	0.0353
8e	4.68	11.42	0.0081
8f	2.68	10.70	0.0141
8g	1.32	10.25	0.0286
9e	3.76	10.59	0.0075
9f	2.28	10.40	0.0124
9g	1.20	10.16	0.0236

RESULTS

Floating logs velocity

The mean velocity of isolated floating logs was analysed in uniform flow conditions on smooth bed for a discharge of $8\cdot10^{-3}$ m^3s^{-1} (run *1,2,3,4*). During the test the logs moved on the free surface. Assuming that the fluid mean velocity profile can be roughly described by the classical velocity defect law (Hinze, 1975):

$$\frac{U_{(h)}-U_{(y)}}{U^*}=-\frac{1}{k}\cdot\ln\left(\frac{y}{h}\right)=-5.75\cdot\log\left(\frac{y}{h}\right) \qquad (3)$$

in which $U_{(h)}$ can be regarded as the free stream velocity, moreover, assuming that the mean velocity value at $y/h\cong0.42$ is equal to the mean velocity in the vertical U_{mean}, roughly evaluated as $U_{mean}\cong Q/(B\cdot h)$, than the free surface fluid velocity can be estimated as follows:

$$U_{\max}\cong U_{mean}+2.17\cdot U^* \qquad (4)$$

where U^* is the shear velocity, that can be estimated by momentum equation:

$$U^*=(g\cdot R_h\cdot S)^{1/2} \qquad (5)$$

The logs mean velocity was directly measured using the PTV method (Serafini, 2003); in Fig.2 the dimensionless logs mean velocity transversal profile is reported for runs *1* and *3*, it can be observed that, at least in the central part of the channel, the logs tend to assume the same velocity of the (estimated) free surface fluid, independently of the grain relative submergence (h/D_{84}).

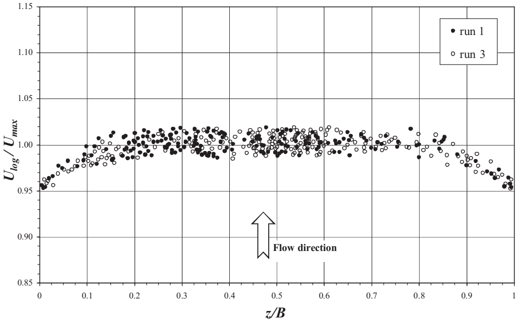

Fig.2: Cross section logs velocity distribution (logs velocity and maximum water surface velocity ratio) for run *1* and *3* (Tab.1).

Logs flotation angle

In the following the main results on the angles assumed by the logs are reported for different values of the relative grain submergence. The analysis refers to a central input of logs, initially parallel to the flow direction (runs *1,2,3,4* in Tab.1). In Fig.3 the transversal distribution of the measured angle of inclination α assumed by the logs as they flow at section 2 is reported. It can be observed that the values of α decrease as the relative

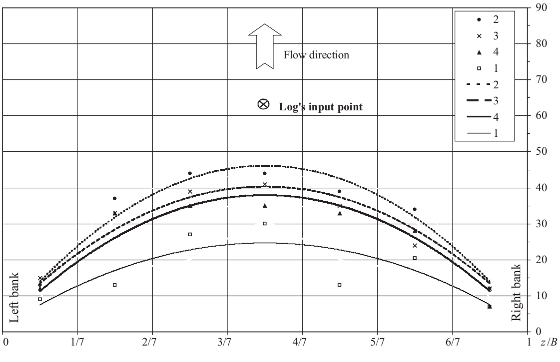

Fig.3: Measured orientation angle α as a function of the logs transversal position (flume width is divided in seven bands).

submergence increases, according to the fact that low submergence flows present high values of the turbulence intensity also close to the free surface, inducing higher irregularity in the orientation of the floating logs.

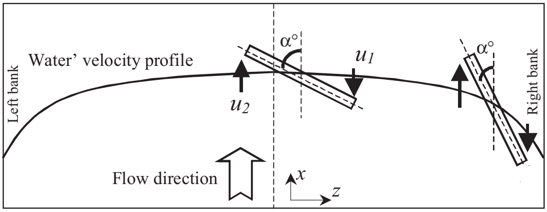

Fig.4: Qualitative figure about logs flotation angle and water velocity profile (transversal gradient).

Moreover, for each run, the mean inclination α assumed by the logs flowing in central position is systematically higher than that measured for the logs that flow in lateral position. This could be due to the transversal water velocity gradients ($dU_{(h)}/dz$) that take place close to the banks, that tend to realign the logs. In fact, referring to the sketch reported in Fig.4, when a floating log is considered, it moves with the same free surface fluid velocity. If the log is initially parallel to the flow and begins to rotate with the upstream end toward the centre of the channel, than the ends of the log experience two different relative velocities (u_1 and u_2 in Fig.4). As a consequence the torque due to the drag forces acting at the ends of the log, tends to realign it parallel to the main flow direction. This torque will be stronger for logs closer to the banks, where the transversal velocity gradient –and so the relative velocities experienced at the extremes– are stronger. On the other hand, when the log tends to rotate with the upstream end toward the bank, the resulting torque tends to enhance the log rotation; this can take place for the logs that flow in the central region and, on the other side, it can be effectively inhibited for the logs that flow in the lateral region by the bank presence.

What stands out from the analysis is that the grain relative submergence is a strongly affecting parameter: the mean value of the angle α orientation of floating logs increases when the values of this parameter decrease. These conclusions partially agree with the results and observations of Ishikawa (1990) and Braudrick & Grant (1997); nevertheless there are significant discordances with the results of Braudrick & Grant (2001), despite the fact that the grain relative submergence values are analogous to those used in the present experiments. In particular Braudrick & Grant (2001) observe that the logs tend to move almost aligned with the flow direction, especially in the central part of the flume.

This disagreement can be ascribed to the different values assumed by the log relative length L_{wood}/B: in the present data the relative length is about 0.2 but in the experiments of Ishikawa (1990) and Braudrick & Grant (2001) the relative length assumed values closer (and also higher) to unity. In this case it is reasonably expected that the logs movement is allowed only when they are aligned with the flow direction.

Hydraulic jump

The attenuation efficiency ε_v, evaluated for the runs reported in Tab.2 and Tab.3 is plotted in the Fig.5 as a function of the Froude number assumed by the flow just upstream the hydraulic jump. In Fig.6 the plot of the attenuation efficiency is reported as a function of the Froude number and of the mean volumetric logs concentration upstream the hydraulic jump. What can be deduced from the figures 5 is that, by almost constant mean concentrations of incoming logs, there is a marked dependence of the attenuation efficiency on the Froude number: if you increase the Froude number the attenuation efficiency increases. From Fig.6 it can be also recognized that the attenuation efficiency ε_v depends not only on the Froude number but also on the mean volumetric concentration. This behaviour can be explained if you consider the interaction between the roller that develops in the jump zone and the incoming logs. The way of interaction between the roller and the logs is in general quite complex and can be assumed as function of the features of the roller (that can be reasonably parameterised with the Froude number), the concentration of the logs and their physical characteristics (like e.g. the logs length, diameter, density,…); these characteristics were constant in present experiments. What emerged during the experiments was that the vortical motion of the roller entraps the logs and after a certain retention time it gives them back downstream. This circumstance gives reason of an increased transit time of the logs ensemble at the outlet and thus of the reduction of the logs discharge peak.

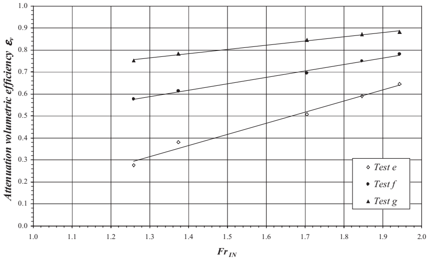

Fig.5: Relation between attenuation efficiency (eq.2) and Froude number upstream hydraulic jump for tests reported in Tab.3.

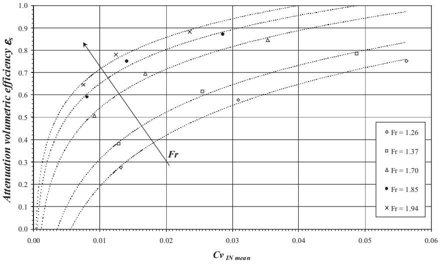

Fig.6: Relation between attenuation efficiency (eq.2) and mean volumetric concentration $\overline{C}_v$ upstream hydraulic jump.

Fig.7 shows the trend of the mean volumetric concentration as a function of the Froude number upstream the hydraulic jump. In Fig.8 is plotted the increment of the Froude number and of the mean volumetric concentration that are needed in order to obtain a certain increment in the attenuation efficiency: it can be noted that the Froude number has a stronger effect, with respect to the volumetric concentration, on the measured discharge reduction.

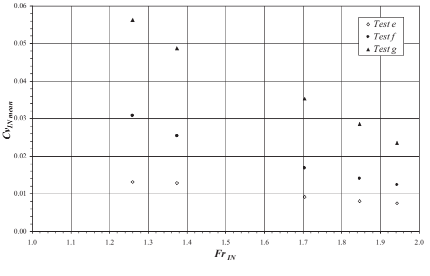

Fig.7: Relation between the mean volumetric concentration (eq.1) and Froude number upstream hydraulic jump for tests reported in Tab.3.

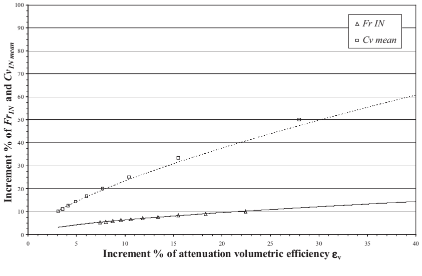

Fig.8: Relation between increment of Froude number and mean volumetric concentration upstream hydraulic jump and the measured increment of attenuation efficiency.

CONCLUSIONS

The experiments have been performed with the aim to have a deeper insight on the hydrodynamic behaviour of floating logs in streams, in particular on the orientation assumed by the logs in rough bed channels in uniform flow conditions and on their response to the hydraulic jump phenomenon.

The present data refer to hydraulic conditions that are typical of mountain streams, which are characterised by steep slopes, low grain relative submergence and confined channel. Therefore the obtained results differ from those of analogous studies, more focused on the logs movement in valley streams (Braudrick & Grant, 1997, 2001; Ishikawa, 1990).
As far as the logs orientation is concerned, the logs flowing in the central part of the stream tend to be less aligned with the flow direction than the logs located in the side of the stream; this non-alignment is more evident in low submergence conditions. The results we obtained suggest that in mountain streams the floating logs tend to move with angles that are in the mean significantly higher than zero; logs that float almost parallel to the flow direction are quite rare and this case can be practically neglected in creeks.
The presence of a hydraulic jump affects the logs motion: it mechanically disaggregates the clusters of logs, giving back a less congested log-flow with attenuated discharge peak. The Froude number is the parameter that mainly affects the attenuation efficiency: it you increase the Froude number the attenuation efficiency increases; on the other hand, the effect of the mean logs volumetric concentration upstream the hydraulic jump seems to be weak.

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