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Experimental study on entrainment of large wood in lowland rivers

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ABSTRACT. Wood transport in rivers, typically occurring during flood events, represents a relevant hazard for its potential to create obstruction at bridges and narrow cross-sections. Therefore, the understanding and prediction of entrainment and transport dynamics of woody material of different shapes, density and dimensions is of great interest for river managers. The paper presents results from laboratory experiments carried out to assess the entrainment conditions of large wood in lowland rivers, *i.e.* with negligible longitudinal slopes, relatively smooth bed and low flow Froude numbers. The tests were performed in a straight flume with fixed bed and smooth side walls for several flow conditions. Entrainment was studied for circular and square logs having different initial orientation. Integrating the results with other data available in the literature allowed to derive a semi-empirical entrainment threshold based on a force balance. This threshold is based on simple parameters, such as normal flow characteristics, log size and density as well as median diameter of bed sediments.

KEYWORDS: *large wood entrainment, floating debris, lowland rivers.*

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1. Introduction

Floating wood is increasingly recognized as one of the major hazards during flood events along river networks, mostly because of its potential to clog bridges and hydraulic structures. On the other hand, large wood increases the hydromorphological diversity of river channels (Montgomery *et al.*, 2003), with beneficial influences on aquatic biodiversity and abundance (Benke & Wallace, 2003). Therefore, the ability to predict wood stability/entrainment and log transport route, distance and velocity is essential for a correct design of hazard mitigation measures, such as wood trapping structures (Rimböck, 2004; Mao & Comiti, 2010) as well as restoration interventions. Furthermore, the modelling of wood transport dynamics is fundamental when carrying out a wood budgeting analysis at larger spatial scales and longer time scales (Benda *et al.*, 2003).

To date, only few investigations have analyzed wood entrainment and transport in the field, and most of them have dealt with small mountain streams were travel distances are typically short (Nakamura & Swanson, 1993; Berg *et al.*, 1998; Gurnell, 2003; Haga *et al.*, 2002; Wohl & Goode, 2008; Cadol & Wohl, 2010).

Flume experiments dedicated to log entrainment on immobile gravel bed were presented by Braudrick and Grant (2001), after having developed a theoretical model for motion thresholds (Braudrick & Grant, 2000). They observed that log entrainment is primarily a function of log orientation relative to the flow direction, of log diameter and density. In addition, the presence of roots was found to greatly affect the threshold for motion. Similar experiments were later carried out also by Bocchiola *et al.* (2006). These tests were performed on fixed sand and gravel bed using wooden cylindrical logs having density ranging from 320 to 740 kg m^3. They noted how the entrainment mechanism (rolling vs. sliding) depends on log orientation, whereas Braudrick and Grant (2001) considered sliding only. In particular, Bocchiola *et al.* (2006) proposed a threshold condition for the entrainment of cylindrical logs.

The present work develops further the work initiated by Braudrick and Grant (2001) and Bocchiola *et al.* (2006) in the context of lowland rivers. The overall goal is to establish incipient motion thresholds for logs having different initial orientation with respect to flow direction and different cross-sectional shapes. Wooden log entrainment was reproduced experimentally at several sub-critical flow conditions in a straight flume with horizontal wooden and gravel bed and smooth side walls.

2. Experiments

2.1. Experimental set-up

The flume experiments to study initiation of motion of logs of different shapes were conducted in the Fluid Mechanics Laboratory of Delft University of Technology. The flume was 14 m long and 40 cm wide, with a horizontal fixed bed and glass side walls. Two different types of tests were performed:

1. to establish the friction coefficient between wooden logs and channel bed (friction coefficient experiments).
2. to assess the water flow conditions at incipient motion of logs having different density, cross-sectional shape and orientation with respect to water flow (log entrainment experiments).

All logs were made in Betonplex wood and their density was measured before and after each test, they were initially either dry or wet.

2.2. Friction coefficient

The friction coefficient between an immobile channel bed and the logs was derived for two types of horizontal bed surfaces: in wood or covered by 5-6 mm gravel. The bed was either dry (static friction) or wet (lubricated friction, with water as lubricant), *i.e.* covered by a1 mm thick film of water.

To move an object on a rough surface, the static friction force must be overcome by an applied force, F. The friction force, F_F, is given by the product of the coefficient of static friction, μ, and the normal force, F_N, counterbalancing the log weight, W in subaerial conditions or the submerged weight (weight, W, minus buoyant force, B) if the log is placed in still water. Therefore, the friction force between the two surfaces (of log and channel bed) can be measured by measuring F at the instant the object starts moving. In the experimental tests, a log not immerged in water was pulled using a LSH Load cell. The force required to move the log was recorded by the instrument. The process was repeated five times. The friction coefficient was determined using the averaged value of the maximum applied force F. The tests were carried out using 25 cm long square logs having cross-section of 13.24´13.24 cm^2. Surprisingly, no significant differences were found between wet and dry bed conditions. In both cases, for the wooden bed surface the friction coefficient resulted 0.47 and for the gravel bed 0.64. Apparently, the 1 mm thick water film did not act as lubricant. An explanation might be that the water film was too thin and possibly not continuous on the top of gravel elements. The value of 0.47 found for the wooden bed is identical to the value derived by Ishikawa (1990) for wood on a fine-sand bed, supporting the validity of our tests.

2.3. Log entrainment

The flow characteristics at incipient motion on a horizontal channel bed were assessed for two types of bed surfaces: wooden or covered with 5-6 mm gravel glued to the bottom (Figure 1). The tests were carried out using 25 cm long circular and square logs having the same cross-sectional surface (Table 1).

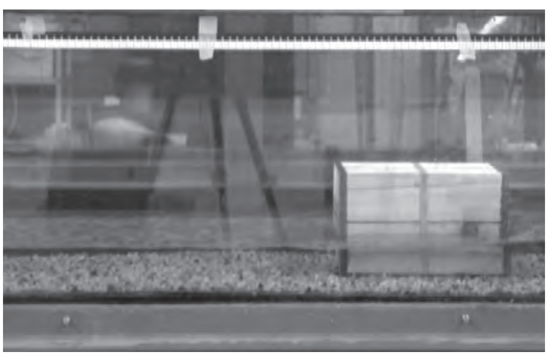

Figure 1. Entrainment experiment (square log) with gravel bed.

Table 1. Design log sizes for the friction coefficient and log entrainment experiments.

Log shape Set A	Circular	Square
Width (cm)		13.24
Height (cm)		13.24
Diameter (cm)	15	
Length (cm)	25	25
Cross-sect. area (cm^2)	175	175
Volume (cm^3)	4379	4379

The logs were initially placed on the channel bed either parallel or perpendicular to the flow direction**.** The log length was 0.625 times the channel width; the log diameter 0.375 and the square log size 0.331 times the channel width. This means that the logs were relatively large with respect to the flume width so that their presence considerably affected the water flow, creating strong flow acceleration along their sides. The undisturbed flow conditions, discharge, reach-averaged water depth and flow velocity at critical condition for incipient motion as well as the log properties are listed in Table 2. The buoyant water depth is the water depth at which a log starts to float in still water (to be compared with the undisturbed water depth at initiation of motion).

Logs perpendicular to water flow started to move at smaller discharges than logs that were parallel to the water flow (Table 2). This is due to the tendency of perpendicular logs to rotate, which was observed also by Bocchiola *et al.* (2006).

3. Results

The derivation of an entrainment parameter to characterize the condition of a log at initiation of motion is based on the balance between friction and drag force, assuming the flow as unaffected by the presence of the object. It is here assumed that the surface A_n is proportional to the water depth, h_w. In this case, for a unit length of log in transverse direction, the drag force F_D is proportional to the product of water density, depth and velocity to the square:

Table 2. Undisturbed flow conditions and log properties at incipient motion.

Log	Initial orientation (degrees)	Discharge (l/s)	undisturbed water depth (cm)	flow velocity [1] (m/s)	Submerged volume [2] (cm^3)	Average weight (g)	Log density (kg/m^3)	Buoyant water depth (cm)
Gravel bed								
Circular -dry	0	9.9	7.84	0.32	2324.79	1591.3	364.55	5.85
Circular -dry	90	2.9	4.62	0.16	1151.33	1591.3	364.55	5.85
Circular -wet	0	10.3	7.86	0.33	2332.23	1639.3	375.53	5.96
Circular -wet	90	3.2	4.44	0.18	1089.65	1639.3	375.53	5.96
Square -dry	0	9.8	8.32	0.29	2724.8	2014.2	462.39	6.05
Square -dry	90	6.4	6.62	0.24	2168.05	2014.2	462. 39	6.05
Square -wet	0	10.6	8.27	0.32	2708.425	1973.3	453.00	5.93
Square -wet	90	6.1	5.62	0.27	1840.55	1973.3	453.00	5.93
Wooden bed								
Circular -dry	0	7.2	6.15	0.29	1697.80	1604.8	367.64	5.92
Circular -dry	90	1.4	3.35	0.10	733.37	1604.8	367.64	5.92
Circula r-wet	0	12.1	8.35	0.36	2514.01	1796.9	411.65	6.48
Circular -wet	90	1.5	3.45	0.11	764.63	1823.2	417.67	6.52
Square -dry	0	9.4	6.47	0.36	2118.925	2016.2	462.84	6.06
Square -dry	90	3.5	4.67	0.19	1529.425	2016.2	462.84	6.06
Square -wet	0	10.1	6.63	0.38	2171.32 5	2068.2	474.78	6.22
Square -wet	90	3.9	4.21	0.23	1378.775	2068.2	474.78	6.22

$$F_D \propto \rho_w u_w^2 h_w \qquad (1)$$

The friction force, F_F, can be written as:

$$F_F = -\mu(\rho_{\log} V_{\log} - \rho_w V_w) \qquad (2)$$

Where μ is the friction coefficient; V_w is the submerged log volume and $V_{\log}$ is the total log volume. For one metre of log (unit length in direction perpendicular to the flow) V_w is proportional to $D_{\log} h_w$, with $D_{\log}$ being the log diameter (or the log height for rectangular and square logs); $V_{\log}$ is proportional to $(D_{\log})^2$. As a result, the friction force is proportional to:

$$F_F \propto \mu g(\rho_w D_{\log} h_w - \rho_{\log} D_{\log}^2) \qquad (3)$$

Assuming that at incipient motion the water depth h_w and $D_{\log}$ have the same order of magnitude, we can assume $h_w \sim D_{\log}$ and thus simplify Equation 3 in:

$$F_F \propto \mu D_{\log}^2 g(\rho_w - \rho_{\log}) \qquad (4)$$

We define an entrainment parameter, E^*, based on the balance between the two forces F_D and F_F.

$$E^* = \frac{F_D}{F_F} \propto \frac{\rho_w u_w^2 h_w}{\mu D_{\log}^2 g(\rho_w - \rho_{\log})} \qquad (5)$$

Assuming that the friction coefficient is proportional to k/h_w, where k is the Nikuradse bed roughness (Nikuradse, 1933), which can be approximated by the D_{50} of the sediment on the bed surface, Equation 5 transforms in:

$$E^* = C_o \frac{u_w^2}{D_{50} g \left(\frac{\rho_w - \rho_{\log}}{\rho_w}\right)} \left(\frac{h_w}{D_{\log}}\right)^2 \qquad (6)$$

In which C_o is an empirical coefficient to take into account log orientation. Based on experimental results, we suggest using the following values (preliminary results): C_o = 0.5 for logs parallel to the flow direction; C_o = 1 for logs perpendicular to water flow direction. In Figure 2, the entrainment parameter E^* is plotted versus the Reynolds number of the flow:

$$\mathrm{Re} = \frac{h_w u_w}{\mu} \qquad (7)$$

(μ = 1.004E^{-6} Ns m^2, dynamic water viscosity). The results of our experiments (in black) are plotted together with the results of the experiments by Bocchiola *et al.* (2006) (in grey).

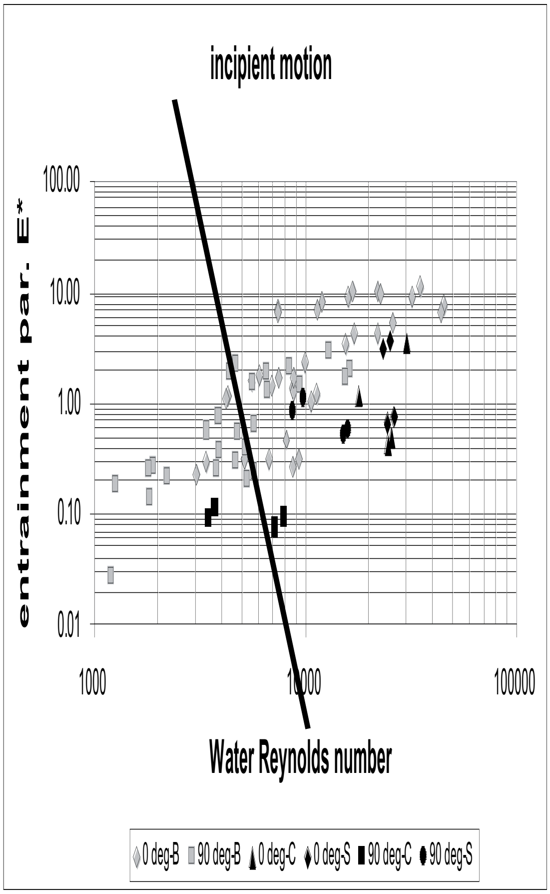

Figure 2. Entrainment parameter plotted *vs.* Reynolds number of water flow. Black: data collected in the framework of this study. Gray: data collected by Bocchiola *et al.* (2006). S = square; C = circular; B = from Bocchiola *et al.* (only cylindrical logs). The thick black line represents the threshold between entrainment and non-entrainment.

4. Conclusions

We carried out laboratory experiments to study the entrainment by flowing water of circular and square floating logs having different initial orientation. We derived a semi-empirical entrainment threshold line based on a force balance. The results are based on laboratory experiments carried out on logs having cylindrical or square shapes, *i.e.* without irregularities such as branches and roots. Therefore, the method should be tested on real river cases, which will most probably result in adaptation of the threshold line and possibly also to the inclusion of some extra parameters counting for log irregularities and river bed material.

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