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Influence of density of large stems on the blocking probability at spillways

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Abstract: *Dam safety is strongly linked to the probability of occurrence of large floods. Floods can transport large wood (LW) into reservoirs and towards water release structures as spillways. Due to blocking and clogging, LW may significantly influence the discharge capacity of spillways and thus result in dangerous rise of the water level in the reservoir. For a better assessment of the related risk, the behaviour of LW in contact with hydraulic structures has to be known. Thus the understanding of LW blockage processes at the spillway and the resulting water level rise in the reservoir is important for the safety evaluation of a dam. The aim of the present study is to describe how LW characteristics can influence blocking probabilities at a spillway inlet equipped with piers. By investigating the parameters linked to LW blockage like slenderness and density, or different hydraulic conditions and transport scenarios, it becomes possible to quantify the behaviour and consequences of LW interactions with spillways. Through systematic laboratory experiments, the influence of LW density on blocking probabilities of individual stems is analysed. Experiments were conducted for reservoir approach flow type, implying small magnitudes of reservoir flow velocity. The results were considered statistically as Bernoulli experiments and the methodology applied was a logistic regression. For the combinations explored, a relation between blocking probability and density, among other parameters, is studied.*

Keywords: *Large wood, blocking probability, spillway inlet, logistic regression, density.*

1. Introduction

Trees entrained into a stream, typically longer than 1 m and larger than 0.10 m in diameter, were classified as Large Wood (LW) (Braudrick, Grant, Ishikawa, & Ikeda, 1997; Ruiz-Villanueva, Piégay, Gurnell, Marston, & Stoffel, 2016; Wohl et al., 2016). Large floods can initiate the transport of such floating material when passing through forested areas. Landslides or erosion of shorelines are also common events that can trigger the movement of LW into a stream. If LW deposits, creating jams on bridge piers, weirs or spillways, it can inhibit the proper evacuation of a flood (Figure 1).

Figure 1: Asakura city, Japan (www.aljazeera.com, 03/11/17) (left). Yazagyo dam, Myanmar (www.thutatuam.net, 06/10/16) (right)

The characteristics of LW are strongly linked to the event that transported it. The interactions of LW with other objects such as rocks or structures, for example, can be evaluated through the presence or absence of branches, leaves, root wards or bark. LW density can be associated to the type of tree, its age, or to the time in contact with water. Depending on the recruitment and transport process, water content of LW can vary significantly (Gurnell, Piégay, Swanson, &

Gregory, 2002). For entrainment processes, density of stems is one of the key parameters to define the threshold of movement and transportation, having also a great influence in the drag coefficient and floatability (Braudrick & Grant, 2000; Buxton, 2010; Crosato, Rajbhandari, Comiti, Cherradi, & Uijttewaal, 2013; Gschnitzer, Gems, Aufleger, Mazzorana, & Comiti, 2015; Lollino et al., 2015; Merten et al., 2010; Ruiz-Villanueva, Piégay, Gaertner, Perret, & Stoffel, 2016; Ruiz-Villanueva, Stoffel, Piégay, Gaertner, & Perret, 2014). For debris racks, it has been studied how different densities interact with backwater rise due to LW blockage or how the shape of LW jams against some hydraulic structures can change in function of the LW density (Hartlieb & Obernach, 2014; Piton & Recking, 2016; Schmocker & Hager, 2011, 2013). Nevertheless, for blocking probabilities of hydraulic structures such as ogee crested spillways with piers, density of LW remains an essential but unquantified parameter.

This study aims to characterize the influence of stem density on blocking probabilities at an ogee crested spillway with piers. With a systematic approach, a simplified representation of LW was done in a physical model. Different LW characteristics were analyzed in combination to diverse hydraulic conditions to understand the complex process of LW blockage. It is fundamental to understand the influence of the involved main parameters so it can be later translated into practice for more complex situations.

2. Model set-up

Experiments were conducted at LCH of Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. The model was placed in a 10 m glass-sided flume with a rectangular cross-section of 1.50 m per 0.70 m. Water was supplied through a tank upstream of the channel. An ogee crested spillway with five symmetrical bays (b=0.26 m) was fabricated of PVC (Figure 2). The piers were round-nosed piers, following WES design criteria and considering a design head $H_d = 0.15$ m. The ogee was chosen due to its broad application and study. The pier nose protruded 0.04 m upstream of the vertical spillway face. With vertical gates, the number of functioning bays was changed by either one (the central bay) or five.

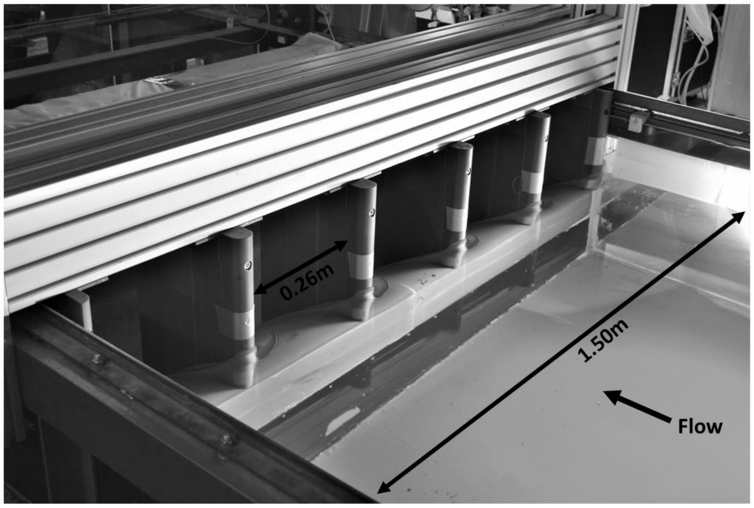

Figure 2: Picture of the spillway inlet with 5 opened bays.

The water surface *h* [m] was measured 2.60 m upstream the ogee crest using a point gauge (±0.5 mm). The discharge *Q* [m^3/s] was measured with a magnetic inductive flow meter (±0.5% at full span). The head *H* [m] was calculated based on the level measurements and the kinematic head. The head will be normalized with the diameter of the stem (*H/d*) and will be further referred as a relative head. A reservoir approach flow type was analyzed, implying very small magnitudes of flow velocities upstream of the spillway.

2.1. Stems

LW was represented with simplified plastic cylindrical stems. Different stem densities were fabricated, being related to different types of wood or stages of decay. Four categories of stem densities (ρ_s) were defined and normalized with the water density ρ, ρ_{s1} = [0.40 - 0.47]; ρ_{s2} = [0.47 - 0.67]; ρ_{s3} = [0.67 - 0.88]; ρ_{s4} = [0.88 - 0.99]. Stems were separated in three different classes according to their size (Table 1). The length of stems was related to the width of the bay and will be further referred as relative length *L/b*.

Table 1 Characteristic of stems.

Class	**Stem length** ***L* [m]**	**Stem length / Bay width** ***L/b* [-]**	**Stem diameter** ***d* [m]**	**Stem density** **ρ_s [-]**
A	0.21	0.80	0.010	ρ_{s2}; ρ_{s3}; ρ_{s4}
C	0.30	1.20	0.016	ρ_{s1}; ρ_{s2}; ρ_{s4}
E	0.52	2.00	0.025	ρ_{s1}; ρ_{s2}; ρ_{s3}; ρ_{s4}

2.2. Test procedure and parameters

The water level *h* and discharge *Q* were measured without stems as initial condition. A single stem was supplied in the center of the flume, parallel to the flow direction. It was noted if the stem passed or blocked at the ogee crest. Blocked stems were removed before the successive stem arrived, avoiding interactions. One experiment was composed of 30 repetitions of the same procedure for statistical accuracy (Furlan, Pfister, Matos, & Schleiss, 2017). The parameters studied can be seen in Table 2.

Experiments 1 to 9 were designed to isolate the influence of density in blocking probability estimations. By fixing *L/b*, *H/d* and number of open bays in one experiment and systematically changing density it could be observed its effect on the probability of blockage for a single stem. The aim of experiments 10 to 12 was to evaluate the blockage of Class A with constant ρ_s for different combinations of *H/d* and number of open bays.

Table 2: Table of experiments.

N°	**Class**	***L/b* [-]**	**Stem density ρ_s [-]**	***H/d* [-]**	**Open bays [-]**
1	A	0.80	0.59,0.79,0.99	1.40	1
2				1.00	5
3				1.20	5
4	C	1.20	0.43,0.56,0.97	0.94	1
5				0.94	5
6				1.06	5
7	E	2.00	0.40,0.54,0.76,0.99	0.96	1
8				0.76	5
9				1.00	5
10	A	0.80	0.59	1.20	1,5
11				1.50	1,5
12				0.90,1.00	5
13			0.79	1.20	1

3. Effect of density

An experiment was considered as a Bernoulli trial were only two outcomes were possible for the single stem: passed or blocked. The blocking probability $\widehat{\Pi}$ was estimated as a ratio between the number of blocked stems and the total number of supplied stems after 30 independent repetitions. To estimate the accuracy of the results, the Clopper-Pearson method was used to calculate the confidence interval (Clopper & Pearson, 1934). A 90% confidence level was defined for the calculation of the intervals.

With the systematic approach taken for the experiments, it was possible to discriminate the influence of each tested parameter for blocking probabilities of individual stems at an ogee crested spillway with piers. Figure 3 illustrates the estimated blocking probability after 30 repetitions for Class A (*L/b* = 0.80) in function of stem density. Different relative heads and number of open bays were compared. For experiment 1 it can be seen that the blocking probability increased from ρ_{s2} ($\widehat{\Pi}$ = 0.10) to ρ_{s3} ($\widehat{\Pi}$ = 0.20) and decreased again for ρ_{s4} ($\widehat{\Pi}$= 0.03). For experiment 2, the opposite happened as the probability of blockage decreased from ρ_{s2} ($\widehat{\Pi} = 0.60$) to ρ_{s3} $(\widehat{\Pi} = 0.53)$ and increased again for ρ_{s4} ($\widehat{\Pi}$=0.63). Experiment 3, showed that while increasing stem density, the blockage probability was decreased as it passed from $\widehat{\Pi}$ = 0.27, 0.20 to 0.17 respectively for ρ_{s2}, ρ_{s3} and ρ_{s4}. For the tested conditions, the stem density did not change the blocking probabilities in magnitudes larger than 0.10 except for experiment 1, ρ_{s4}. Based on the confidence intervals of experiment 1, for $\widehat{\Pi}$ of ρ_{s2}, ρ_{s3} and ρ_{s4} and how they range in between similar values, the variation of $\widehat{\Pi}$ in function of stem density could be considered negligible. When increasing the relative head from Experiment 2 to 3, the blocking probability decreased.

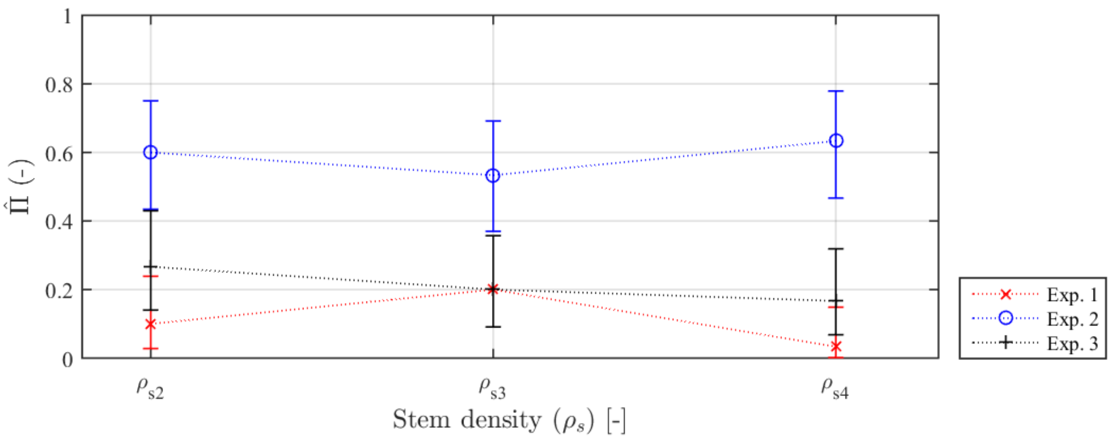

Figure 3 Estimated blocking probability of class A in function of stem density.

A logistic regression was performed to quantify the influence of each tested parameter for the blocking probability of a single stem. A logistic regression was chosen as it ranges between 0 and 1, being consistent with blocking probability estimations. This methodology allows to analyse if one parameter (or a combination of them) can increase the odds of a blockage probability by a specific factor. The logistic regression function can be expressed as:

$$\widehat{\Pi} = \frac{e^z}{1+e^z} \tag{1}$$

$$z = \beta_0 + \sum_{i=1}^{n} \beta_n x_n \tag{2}$$

where $\widehat{\Pi}$ is the estimated blocking probability; x_n are the *n* independent variables tested as *L/b*, *H/d*, ρ_s and number of open bays; β_0 is the intercept coefficient of the regression and $\beta_n$are the corresponding coefficients computed per variable analyzed. The coefficients are determined based on the observed outcomes of the experiments using maximum-likelihood estimation. The experiments performed with class A and the scenario of five open bays were taken into account for the regression. Different logistic regressions were evaluated, changing the number of parameters. Herein the coefficients of a simple preliminary model are presented to illustrate the influence of the parameters (Table 3).

Table 3 Logistic regression coefficients.

	Model coefficients		Wald's test	
Explanatory variable	Estimate	Standard error	Z	Significance level
Constant	6.35	1.26	5.017	**<0.001**
ρ_s	1.02	0.82	1.244	0.214
H/d	-7.10	1.13	-6.25	**<0.001**

Based on the significance level of the Wald's test, it can be seen that the relative head has a noteworthy effect on the blockage probability. Nonetheless, under the tested conditions, stem density seems to be unimportant in the analysis of blocking probability, in concordance with Figure 3. Figure 4 shows the comparison between the function obtained with the logistic regression against the results obtained from the physical model. The figure was separated for the 3 densities tested of class A. The agreement of the regression with the results from the physical model can be noticed. As observed in the experiments, when increasing the relative head, blockage probabilities tend to decrease.

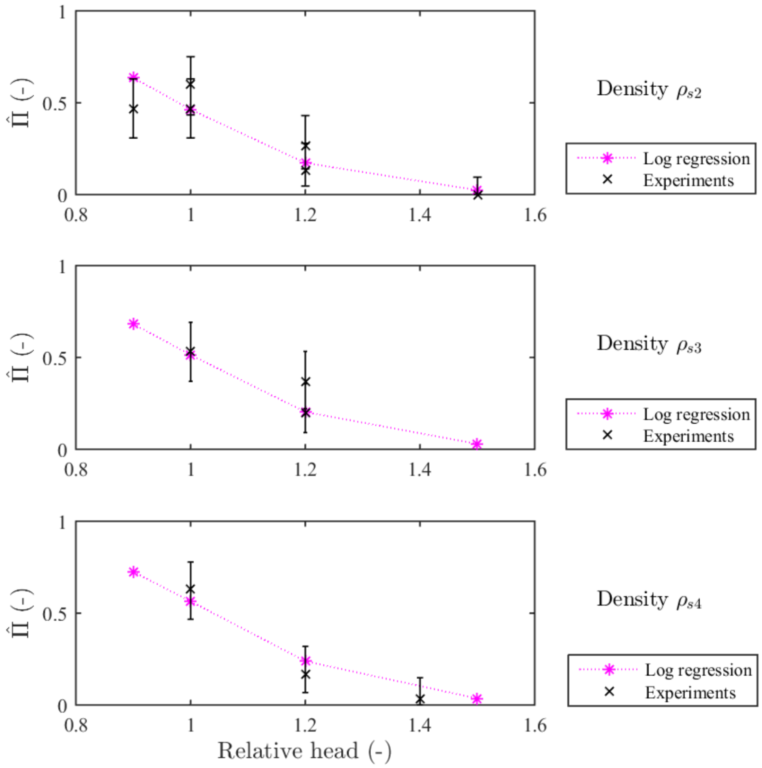

Figure 4 Logistic regression model for class A in function of relative head.

When changing *L/b*, it was observed that the tested parameters (Table 2) started to interact differently. Figure 5 shows the results obtained with the physical model for class C and E with five open bays. The results show that stems with a high density (ρ_{s4}) have blocking probabilities close to 0.80 or higher. In addition, when increasing the stem density, the blocking probability was also increased. The analysis performed for class A is being conducted for both classes combined as their blocking probabilities showed to be rather sensitive to changes in stem density.

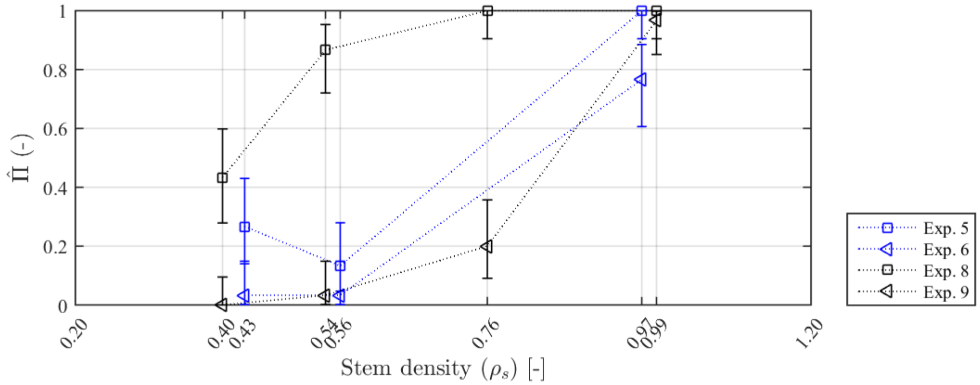

Figure 5 Estimated blocking probability of class C and E in function of stem density.

The logistic regression function for class C and E, will provide a better understanding on the effect of L/b, H/d and ρ_s for the blocking processes of single stems at ogee crested spillways with piers.

4. Conclusions

By systematically testing the effect of certain LW characteristics or different parameters on the LW blockage process at hydraulic structures, their individual effect can be quantified. Simplified and systematic tests are crucial before adding the complexity inherent of natural processes. For the different sizes of stems studied, it was evaluated how blocking probabilities of single stems can change in function of stem density. It could be shown that stem density can influence the blocking probabilities as a function of L/b. It was also noted that stem densities close to water density, have high blocking probabilities when the length of the stems is larger than the opening of the spillway bay. Therefore, under the tested conditions, heavier stems tend to block more frequently than lighter stems. The assessment of blocking probability models is part of the ongoing work of this research for ogee crested spillways with piers.

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