Entrainement de bois flottant dans un déversoir a crête standard avec piliers: Influence des caractéristiques de bois flottant en probabilités de blocage.

Les déversoirs sont des structures de sécurité des barrages pour permettre le passage des crues. Ils déversent de l'eau pour éviter le débordement et ses éventuels dommages structuraux au niveau du barrage et de l'environnement en aval. Néanmoins, il peut être dangereux de supposer qu'une inondation ne porte que de l'eau claire. Les grands bois flottants (LWD en anglais) sont souvent transportés par les rivières vers des réservoirs pendant des événements de fortes précipitations. Le comportement du bois flottant dans les déversoirs est encore un sujet inconnu. L'accumulation et le blocage du bois flottant dans les déversoirs est un problème important car il peut changer la charge sur structure et aussi le fonctionnement du déversoir en réduisant sa capacité de décharge et en augmentant le niveau de l'eau dans le réservoir. Une fois ce point atteint, des nouvelles conditions sont développées en amont du réservoir comme l'augmentation de la charge ou l'élargissement des zones inondées. La littérature fournit principalement des connaissances sur l'effet du bois flottant pour les ponts sur des rivières avec des vitesses d'écoulement relativement élevées. Cependant, les effets et les conséquences dans les conditions d'écoulement des réservoirs sont pratiquement inconnus. La connaissance des processus de blocage du bois flottant dans un déversoir peut être vitale en ce qui concerne l'évaluation de la sécurité d'un barrage. Le présent document résume une série d'expériences de laboratoire où des différentes caractéristiques du bois flottant ont été liées à des probabilités de blocage dans un déversoir de crête standard équipé avec piliers.

Mots-clefs: Bois flottant; probabilité de blocage; crête standard; déversoir; crue.

Entrapment of driftwood at ogee crested spillways with piers: Influence of woody debris characteristics on blocking probabilities

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Spillways are safety elements of dams that allow to release floods. They spill water to avoid overtopping with its potential structural damages at the dam and the downstream environment. Nevertheless it may be unsafe to assume that a flood only carries clear water. Large woody debris (LWD) are often transported by rivers into reservoirs during heavy rainfall events. There is still a lack of knowledge regarding the behaviour of LWD at spillway inlets. The accumulation and blockage of LWD at spillway inlets is a significant problem as it can change the load on the structure and also the functioning of the spillway by reducing the discharge capacity and increasing the reservoir water level. Once this point is reached, new conditions upstream are developed for the reservoir as head increase or enlargement of inundated areas.

Literature provides mainly knowledge on the effect of LWD at bridges in rivers with relatively high flow velocities. However, information of the effects and consequences for reservoir approach flow conditions is generally unknown. Knowledge of the LWD blockage processes at a reservoir spillway may be vital regarding the safety evaluation of a dam. The present paper summarizes a series of laboratory experiments, where different LWD characteristics were related to blocking probabilities at an ogee crest spillway equipped with piers.

Key words: Large woody debris; blocking probability; ogee crest; spillways; floods.

I INTRODUCTION

Woody debris frequently arrive to hydraulic constructions due to heavy rainfall events that carry such material into streams. Braudrick, Grant, Ishikawa, & Ikeda (1997) defined trees entrained into the stream as large woody debris (LWD) corresponding typically to stems longer than 1 m and larger than 0.10 m in diameter. The recruitment and entrapment process of LWD can vary according to the mechanism that triggered the debris movement and conveyed it into the water. Once the LWD is inside a riverine stream it can be transported or deposited in different areas. Deposition patterns are related to the channel characteristics, which differ for narrow, sinuous and wide-thread channels.

LWD deposits at the banks of a river and creates new habitats, diversifying riverine ecosystems, and also playing a role for sediment transport. Generally, wood has important environmental attributes. However, it can also be considered a threat for hydraulic constructions. If woody debris arrives to hydraulic structures located within the stream, it may clog and accumulate while reducing the flood capacity. By reducing the flow capacity, sedimentation processes are exacerbated, increasing the upstream water level. Thus, the potential for upstream flooding may be substantially increased and lead to overtopping (Lyn, Cooper, & Condon, 2007). Along history different events have proved how LWD blockage affects the functioning of a hydraulic construction, as for example Palagnedra Dam (Switzerland) (Vischer & Trucco, 1985) and Shihmen Reservoir (Taiwan) (Chen & Chao, 2010) where damages in the structures took place, increasing the uncertainties connected to the arriving flood (Figure 1). Yazagyo dam (Myanmar) (Steijn et al., 2016) and Three Gorges dam (Hartford et al., 2016) are contemporary reminders that floating woody debris must be consider as a possible source of incidents.

Figure 1 Picture of Palagnedra dam (left) (Bruschin, Bauer, Delley, & Trucco, 1982) and Shihmen Reservoir (right) (Chen & Chao, 2010).

Little is known about the behaviour of LWD in contact with hydraulic structures. Physical models are used to understand interactions between LWD and the structures but those physical models neglect some considerations regarding the random process that LWD involves. To infer statistically sound conclusions, experimental campaigns should have a significant number of tests repetitions (Welber, Bertoldi, & Tubino, 2013). Repeated occurrence of similar events must also be expected in nature (Bezzola & Hegg, 2007) and it can be linked to the repetitions of experiments. Consequently, the reliability and accuracy of results obtained from experiments, are linked to the number of repetitions performed.

Table 1 Repetitions of experiments for LWD physical modeling.

	Author	**Subject of study**	**Number of repetitions**
1	Bocchiola et al. (2008)	LWD accumulation patterns in dams and bridges	4
2	Schmocker & Hager (2011)	LWD blocking probabilities for bridges	8
3	Hartlieb (2012)	LWD jams at spillways	20
4	Pfister et al. (2013)	LWD blocking probabilities at piano key weirs	25 to 50
5	De Cicco et al. (2016)	LWD accumulation at bridges piers	10
6	Gschnitzer et al.(2016)	LWD blocking process for bridges	8

Table 1 shows the differences in defining the number of repetitions undertaken for experiments. It is clear that conclusions cannot be drawn from only one repetition of an experiment, but it is unknown how this can influence the reliability of results.

Another gap in knowledge concerns the influence of LWD density on blocking probabilities at spillway inlets. How LWD enters a stream will be linked to its water content and its related buoyancy. When trees roll into a river after decay, they can spend several months or years in contact with water until a flood removes them and transports them through the stream. In the case of a landslide, a tree will not be in contact with water before. Depending on the recruitment and transport process, water content of LWD can vary greatly (Gurnell, Piégay, Swanson, & Gregory, 2002). Density of LWD remains as an essential, yet un-gauged, parameter in terms of transport, forces induced to structures and blocking probabilities. It is of primary importance to know if the LWD density affects its blocking probabilities as this can be reflected in the actions to be taken to maintain safe structures and in hazard mitigations.

Existing literature focused partially on the LWD behaviour by simplifying the random process into plausible physical modelling although leaving aside some statistical considerations. So far for spillway inlets, explicit the minimum numbers of repetitions for having reliable experimental results, are absent. Neither, detailed systematic tests of the influence of density for blocking probabilities at ogee crested spillway with piers. It was aimed with this study to underline the importance of systematic physical modelling of LWD blocking probabilities for accurate estimations of reality and to gasp the influence of density for blocking probabilities at ogee crested spillways.

II EXPERIMENTAL MODELLING, MATERIALS AND METHODS

II.1 Experimental facility

Physical model tests were conducted at the Laboratory of Hydraulic Constructions (LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. The flume was glass-sided of 1.50 m wide, 0.70 m high and 10 m long (Figure 2).

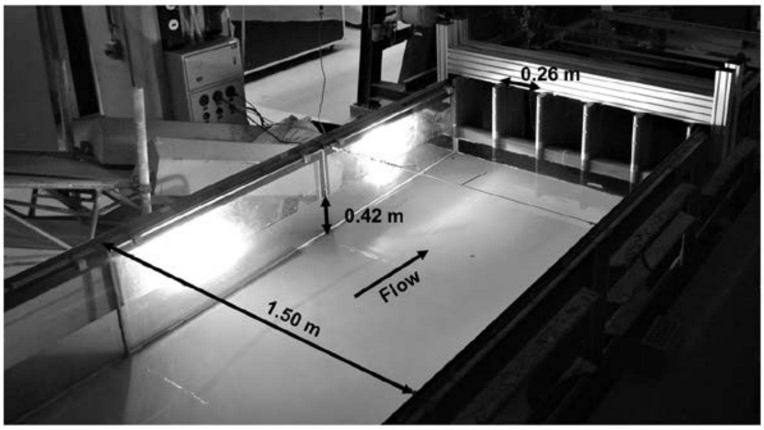

Figure 2 Picture of the flume and the physical model.

The model consisted of an ogee crested spillway of PVC with a design head H_d = 0.15 m and weir height P = 0.42 m. Round nose piers created 5 equal bays of width b = 0.26 m. Three different lengths of piers were defined. For the first pier configuration, the nose was located in the same vertical plane as the spillway face (Configuration N_1), the following configurations were overhanging one and two pier widths (equal to the diameter of the nose) upstream of the spillway face respectively (Configuration N_2 and N_3).

Among different spillways, the ogee crested spillway was chosen because of its broad use. Using vertical gates the quantity of open bays could be changed from 5 to 1 by fully closing 4 gates and leaving the central bay open (Figure 3Figure 3). To assure homogenous velocity fields, a tranquillizer wall was installed downstream of the channel inlet.

Figure 3 Picture of the front face of the spillway with 5 opened bays (left) and 1 opened bay (right).

The level of water in the channel h [m] was measured with a point gauge (±0.5 mm) in a zone with stagnant water, some 2.60 m upstream of the ogee. 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. A reservoir approach flow type was analysed, implying small magnitudes of reservoir flow velocity. Different flow conditions were established by varying the inflow discharge. Based on preliminary experiments, ratios of head to stem diameter (H/d) range from 0.72 to 1.40.

II.2 Artificial stems

In order to model the LWD artificial plastic stems with cylindrical shapes were used to exclude geometrical irregularities. Consequently, the blocking probabilities are those of stems. Five different sizes of stems were used. The characterisation of their length was made in function of the bay width (Table 2).

Different stem densities (ρ_s; where the subscript s stands for stem) were possible by varying the plastic used to construct the stems while keeping the same volume. The chosen densities were related to the average density of dry wood in Europe (ρ_w = 0.520 t/m^3) and its standard deviation (σ_w = 0.119 t/m^3) (Chave et al., 2009). Four ranges of densities were defined for the artificial stems, ρ_{s1} = [0.40 - 0.47]; ρ_{s2} = [0.47 - 0.67]; ρ_{s3} = [0.67 - 0.88]; ρ_{s4} = [0.88 - 0.99].

Table 2 Classification and characteristics of the stems

Class	**Stem length *L* [m]**	**Stem diameter *d* [m]**	**Stem length / Bay width *L/b* [-]**	**Stem density [-]**
A	0.21	0.01	0.80	ρ_{s2}; ρ_{s3}; ρ_{s4}
B	0.26	0.012	1.00	ρ_{s2}
C	0.30	0.016	1.20	ρ_{s1}; ρ_{s2}; ρ_{s4}
D	0.40	0.02	1.50	ρ_{s2}
E	0.52	0.025	2.00	ρ_{s1}; ρ_{s2}; ρ_{s3}; ρ_{s4}

II.3 Test procedure

Systematic experiments were performed. Water surface level and discharge were measured without stems in the flume to have the initial conditions of each experiment. With a mechanical equipment, an individual stem was supplied into the stream in the centre line of the channel oriented parallel to the flow. The mechanical equipment allowed to repeat tests, reducing human interaction. Once the stem arrived to the spillway, it was noted if the stem blocked or passed. If the stem was blocked, it was removed before a next stem was supplied to the flume. Several repetitions were performed per experiment always with the same initial conditions.

For the number of repetitions analysis, fourteen random combinations of parameters were defined to evaluate its influence in the estimation of blocking probabilities for stems (Table 3).

Table 3 Table of parameters variation in the “repetition experiments”

Class	Open bays	Nose configuration	Stem density	*H/d*	N° repetitions
A	5	N_3	ρ_{s3}	0.8	60
B	1; 5	N_1; N_2; N_3	ρ_{s2}	0.83; 1.25	60; 70
C	5	N_1; N_3	ρ_{s1}; ρ_{s2}	0.81	60; 70
D	5	N_1	ρ_{s2}	0.9	70
E	1; 5	N_1; N_2; N_3	ρ_{s1}; ρ_{s2}; ρ_{s3}	0.72; 0.76; 0.82; 0.88; 1.06	20; 40; 60; 70

For the density effect, thirty-three combinations were defined to evaluate the influence of density regarding the stems blocking probability (Table 4). For this type of experiments, Class, *H/d* and open bays were kept constant while changing systematically the density.

Table 4 Table of parameters variation in the “density experiments”

Class	Open bays	Nose configuration	Normalized stem density	*H/d*	N° repetitions
A	1; 5	N_2	ρ_{s2}; ρ_{s3}; ρ_{s4}	1.00; 1.20; 1.40	30
C	1; 5	N_2	ρ_{s1}; ρ_{s2}; ρ_{s4}	0.94; 1.00; 1.06	30
E	1; 5	N_2	ρ_{s1}; ρ_{s2}; ρ_{s3}; ρ_{s4}	0.76; 0.96; 1.00	30

III NUMBER OF REPETITIONS EFFECT

To analyse the influence of required repetitions to estimate blocking probabilities, one experiment was composed of several repetitions. Each result was considered a Bernoulli experiment in which two outcomes were possible for a stem: block or pass. The resulting blocking probability of one experiment *($\hat{\Pi}$)* is the ratio between the number of stems that blocked at the spillway inlet (*X*) and the total number of stems that were supplied (*n*) (Equation 2).

$$\hat{\Pi} = \frac{X}{n} \tag{2}$$

When computing the blocking probabilities, it was noted that the number of repetitions does not have the same influence in all the experiments. To see this effect, a normalized blocking probability was calculated by dividing the result of every repetition by the last repetition of that experiment. Figure 4 shows 8 experiments taken as example on how the blocking probability variates. The legend of the figure includes: Class - stem density - *H/d* relation - Number of open bays - Nose configuration.

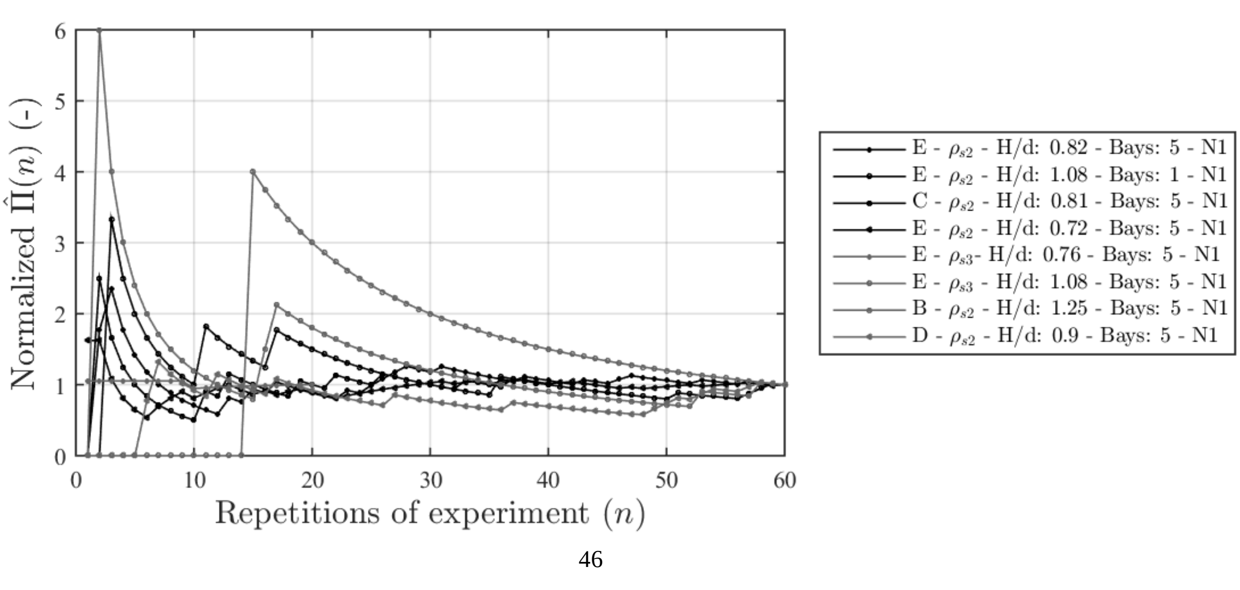

Figure 4 Normalized blocking probability in function of repetitions, for eight experiments performed.

Large scattering of data can be seen in the figure for small numbers of repetitions. This scattering is reduced for roughly n > 30 but not in all experiments. So the question remains, how much data is enough to represent reliably the stems blocking probabilities at a spillway inlet or in other words, what is the minimum number of repetitions needed to have statistical sound conclusions.

The aim of the physical model is to estimate the “real” blocking probability π, but π is an unknown value. The result of the experiments are point estimators of the real blocking probability hence it is needed to compute the “margin of error” or the confidence interval for that interval to englobe the true value of π.

Figure 5 shows how the blocking probability changes if the number of repetitions is incremented. The experiment includes Class B, H/d = 0.83, 5 open bays with pier nose configuration number 3. For 1 to 10 repetitions, the confidence interval is broad and it starts to decrease with the increment of repetitions. For 35 to 59 repetitions, it can be seen than $\widehat{\Pi}$ starts to be practically constant with a variation of ± 0.05 compared to the blocking probability computed after 60 repetitions (plotted with dashed red lines).

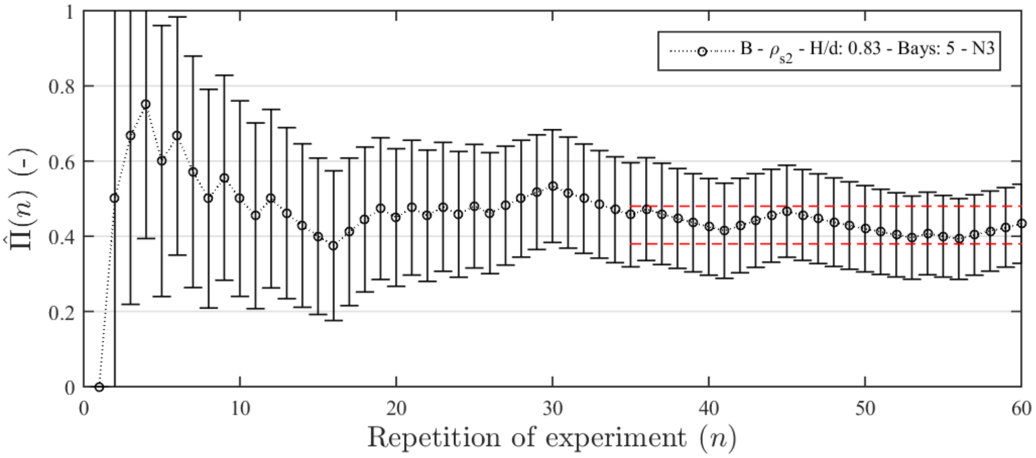

Figure 5 Estimated blocking probability for Class B with confidence interval (α = 0.1), ρ_{s2}, 60 repetitions.

One commonly used method to calculate confidence intervals is the "Normal” or “Wald" method (confidence interval in Figure 5). This method assumes that the blocking probability behaves with a Normal distribution. Equation 3 defines the standard deviation, where π is the stems blocking probability and n is the number of stems supplied.

$$s = \sqrt{\frac{\pi(1-\pi)}{n}} \tag{3}$$

$$(e^-, e^+) = \left(\pi - (z_{\alpha/2} \cdot s), \pi + (z_{\alpha/2} \cdot s)\right) \tag{4}$$

The lower and upper boundary of confidence intervals (Equation 4) can be calculated using the standard deviation, where $Z_{\alpha/2}$ is the upper α/2 percentage point of the standard normal distribution (Wallis, 2013). When the confidence interval is large, the estimation performed with the experiments will be more uncertain. As π is unknown, $\widehat{\Pi}$ is used to calculate the interval with an associated confidence level. This method is simple and practical. It states that a bigger number of repetitions will provide a thinner confidence interval, hence more accurate estimations.

Nevertheless, the “Wald” method has limitations when π tends to 0 or 1 and when the sample size n is not large. For example when computing the interval for 2, 3 or 4 repetitions (Figure 5), it gives a confidence interval that exceeds the range [0-1] and this does not have a physical significance for blocking probabilities.

The influence that repetitions have on the accuracy of blocking estimations is important. In this article only the Wald method was discussed but different methods can be used to quantify confidence intervals, therefore to define the accuracy or "error" of a statistical estimation.

IV DENSITY EFFECT

These experiments allow to see the influence of density for blocking probabilities of stems at an ogee crested spillway with piers. Figure 6 illustrates the influence of the density on the blocking probabilities. The blocking probability has been estimated after 30 repetitions, and the confidence interval has been calculated for 90% confidence. By taking one *H/d* relation and one number of open bays (one dotted line) it can be seen that the blocking probability increases with the normalized density. For the tested conditions, it appears that the blocking probabilities for stems densities near water densities are independent of the hydraulic conditions (for this class) as they have a blocking probability near 1.

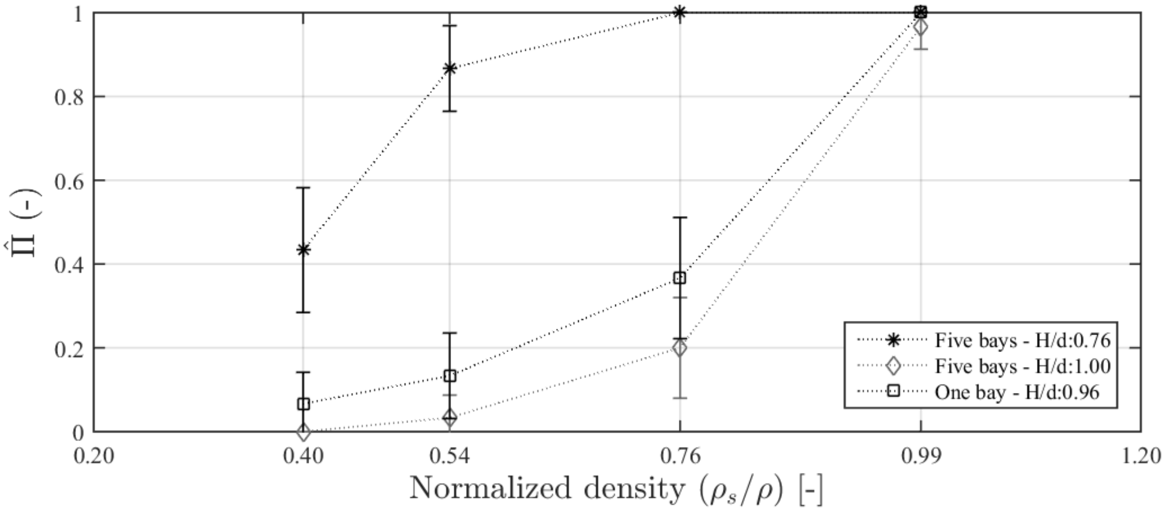

Figure 6 Stems blocking probability in function of density, class E.

The results for Class A and C are still being analysed as the relation of density and blocking probability might also be linked to the size of stems used.

V CONCLUSIONS

Few studies have considered individually the effects of different parameters for LWD blocking probabilities at spillway inlets. From the limited information available, major improvements are currently being made to decrease the uncertainties of LWD behaviour and to guide or support the decisions that must be taken for spillways safety.

Repetitions of experiments has been barely considered related to the accuracy of experimental campaigns and the confidence interval of stems blocking estimations was so far ignored. As a first approximation, the "Normal" or "Wald" method is effective to understand the difference between an estimation respects to a real blocking probability. As a general recommendation *n* should always be equal or larger than some 30 repetitions to have flexibility for applying different statistical methods and to have reliable results. The minimum number of repetitions of an experiment will determine the accuracy of the estimations performed.

Density appears to have an influence in the stems blocking probabilities as an increment of density implied an increment of blockage under the tested conditions. Heavier stems appear to block independently of the hydraulic conditions for the experiments analysed.

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