Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

BLOCKING PROBABILITY OF DRIFTWOOD AT OGEE CREST SPILLWAYS WITH PIERS: INFLUENCE OF WOODY DEBRIS CHARACTERISTICS

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ABSTRACT

Spillways are designed to evacuate floods in a safe way. They should safely release water in order to avoid dam overtopping with its related damages. Nevertheless, it may be dangerous to assume that a flood is only carrying "clear" water. Large woody debris (LWD) and sediments 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 equipped with piers and gates. The accumulation and blockage of LWD at spillway inlets are a significant problem as they can reduce the discharge capacity of the spillway and consequently, an uncontrolled increase of the water level in the reservoir may occur. Literature provides mainly knowledge on the effect of LWD at bridges in rivers with relatively high flow velocities. However, the latter is hardly applicable for reservoir approach flow conditions. Knowledge of the LWD blockage processes at spillways is important regarding the safety assessment of a dam. The present paper summarizes a series of preliminary laboratory experiments, where the influences of different LWD characteristics are linked to blocking probabilities at an ogee crest spillway equipped with piers. The results highlight the influence of repeatability of events and density of LWD on blocking probabilities under different hydraulic conditions.

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

1 INTRODUCTION

Large floods initiate the transport of sediments and floating material when passing through forested areas. Trees entrained into the stream are called large woody debris (LWD) corresponding typically to stems longer than 1 m and with more than 0.10 m in diameter (Braudrick, Grant, Ishikawa, & Ikeda, 1997). LWD is an important subject for risk evaluation due to its potential to block on bridge pillars, weirs or spillways and avoid them to evacuate properly a flood. When it reduces the discharge capacity, flow velocity also decreases promoting sediment deposition. Thus, an uncontrolled increase of the upstream water level can occur, flooding the upstream area of the structure or overtopping it. In different floods, it has been seen how LWD blocked and affected the functioning of a hydraulic construction such as in Palagnedradam (Switzerland) (Vischer & Trucco, 1985), Sa Teula (Italy) (Galeati, 2009) or Yazagyo dam (Myanmar) (Steijn et al., 2016) causing damages in the structures or increasing the risk connected to those events.

Physical models were used to study interactions between LWD and hydraulic structures. It seems erratic in which position stems reach a construction and so experimental campaigns should have a significant number of test repetitions to infer statistically sound conclusions (Welber, Bertoldi, & Tubino, 2013). Therefore, is of primary importance to conduct enough repetitions of experiments, namely to consider the repeatability as an influential parameter for the consistency of results given the random LWD blocking processes (Schmocker & Hager, 2010). In Braudrick & Grant, (2000, 2001) and Braudrick et al., (1997), it was shown that it is necessary to repeat experiments a certain number of times to have statistical reliable results but no further analysis was presented.

Few articles were found where the effect of the repeatability was considered in the experiments (Table 1). Literature shows a lack of criteria to define reliable numbers of repetitions and it is not considered yet, as a significant variable. Partially, even contradictions were found among the articles.

In the analysis made for LWD in contact with bridges, Bocchiola, Rulli, & Rosso (2008) and De Cicco, Paris, & Solari (2016) mentioned the number of repetitions without further examination of its influence on the results. Schmocker & Hager (2011) presents the analysis and recommendations for reproducibility of experiments in the case of bridge piers, that has been followed by Gschnitzer, Gems, Mazzorana, & Aufleger (2016) in their experimental campaign.

In the case of spillways and check dams, it can be noted in Hartlieb, (2012); Pfister, Capobianco, Tullis, & Schleiss (2013); Shrestha, Nakagawa, Kawaike, Baba, & Zhang (2011) that there is still a lack of unifying criteria. It was foreseen to have statistical reliable results, improving the accuracy of their experiments but without a clear guideline of how to achieve it.

Table 1. Repeatability of LWD experiments in physical models, literature review.

	Author	Subject of study	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	Shrestha et al.(2011)	LWD blocking probability for slit-check dam	3
4	Hartlieb(2012)	LWD jams at spillways	20
5	Schmocker & Hager (2013)	LWD accumulation at debris rack	3
6	Pfister et al. (2013)	LWD blocking probabilities at PKW	25 to 50
7	De Cicco et al. (2016)	LWD accumulation at bridges piers	10
8	Gschnitzer et al.(2016)	LWD blocking process for bridges	8

LWD can be entrained into a stream for a long period due to decay or a short period due to a flood. Depending on the recruitment and transport process, water content of stems can vary greatly (Gurnell, Piégay, Swanson, & Gregory, 2002). Density of LWD remains as an essential parameter in terms of transport, forces induced to structures and blocking probabilities. 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; Merten et al., 2010; Crosato, Rajbhandari, Comiti, Cherradi, & Uijttewaal, 2013; Ruiz-Villanueva, Stoffel, Piégay, Gaertner, & Perret, 2014; Lollino et al., 2015; Ruiz-Villanueva, Piégay, Gaertner, Perret, & Stoffel, 2016).

To analyse potential risk due to LWD in hydraulic structures, it is essential to know if the water content (i.e., density) of the stems affects their blocking probabilities or increases its effects as backwater rise and shape of jams against different structures (Schmocker & Hager, 2011; Schmocker et al., 2013; Hartlieb & Obernach, 2014; Piton & Recking, 2016).

Literature gives no explicit numbers of repetitions necessary to have independent results for the case of spillways inlets. The aim of the herein presented study is to consider repeatability as a new parameter and systematically test it to find a compromise between justifiable test effort and accurate probability interpretation.

Further, there is a gap of knowledge in literature regarding density and its effect on blocking probabilities at spillways. It is aimed with this study to quantify the influence of density in blocking probabilities at an ogee crested spillway with piers. This is fundamental to understand how different densities of LWD can represent a different degree of blockage and thus, different blocking probabilities when arriving to an ogee crested spillway.

Both objectives follow a systematic experimental approach with a simplified set-up to understand the influence of replications and density for such tests. It is foreseen to evaluate other parameters related to LWD blockage to have fundamental knowledge of the process before analyzing real cases.

2 PHYSICAL MODEL

2.1 Model set-up

Experiments were conducted at LCH of Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. The flume was 1.50 m wide, 0.70 m high per 10 m long and had a glass side wall to allow visual observation. Water was supplied through a tank upstream of the channel. A tranquillizer wall was placed 2.40 m downstream of the channel inlet to assure a homogenous velocity field (Figure 1).

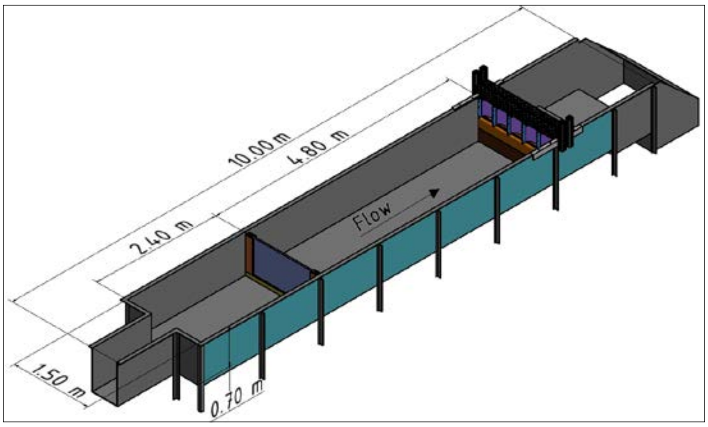

Figure 1. 3D Schematic view of the channel.

The model represented an ogee crested spillway with five bays of width b=0.26 m, created by round-nosed piers, all made with PVC to be considered hydraulically smooth. WES design criteria was followed, considering a design head H_d=0.15 m and a weir height P=0.42 m (Figure 2). The ogee was chosen due to its frequent application and effective discharge capacity. A metallic beam was attached outside the flume to hold the piers above the spillway. The pier nose extruded one time the width of the pier (equal to the diameter of the nose) upstream of the vertical spillway face. In addition, the number of open bays was varied, and partially closed with vertical gates.

The water surface in the channel h [m] was measured using a point gauge (±0.5 mm) in a zone with stagnant water some 2.60 m upstream 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. Photographs were taken systematically with a PeauPro82 3.97mm GoPro H4 Black in order to record each experiment. Visual evaluation of blockage was performed; notes were taken with the results (Block or Pass).

A reservoir approach flow type was analyzed, implying small magnitudes of reservoir flow velocity. Different flow conditions were established by varying the inflow discharge. Ratios of head H[m] to stem diameter d[m] (H/d) ranged from 0.41 to 3.10. These limits were defined based on preliminary experiments.

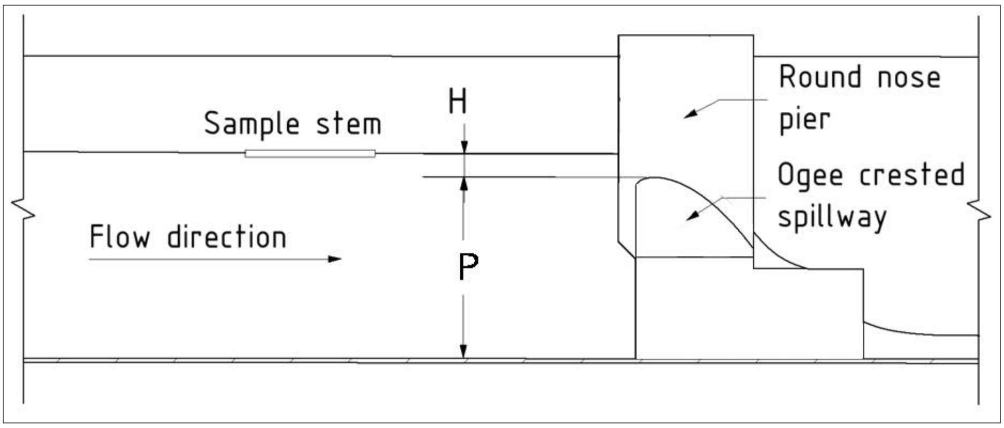

Figure 2. Longitudinal section along the experimental channel with weir.

2.2 Stems

Artificial (PVC) cylindrical stems were chosen to exclude geometrical irregularities of the LWD (Figure 3). Stems were built of plastic pipes with homogeneous weight and volume. Stems were attributed to classes according to their length L [m] and diameter d [m] (Table 2).

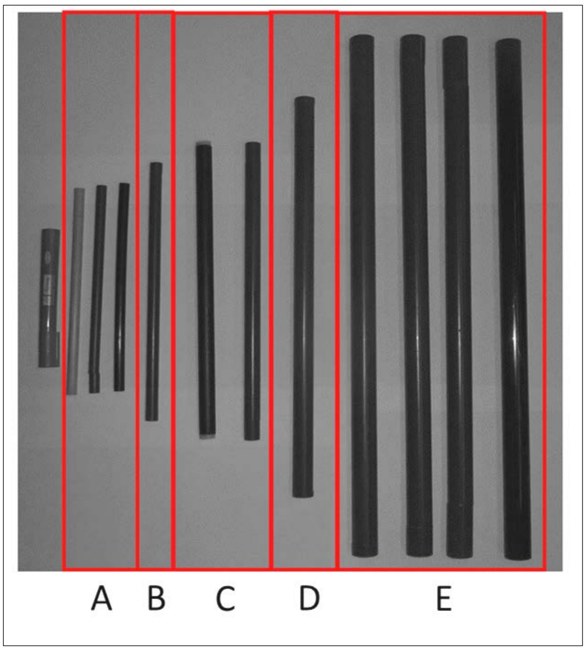

Figure 3. Picture of stems and their classification.

The stem lengths were chosen in relation to the bay width, to cover certain ratios of L/b by keeping $L/d≈20$, as seen in literature. For these particular experiments, classes A, C and E were used.

For each class, different densities were established in relation to databases of average dry wood density along Europe and its standard deviation (Chave et al., 2009). Four typical stem densities ρ_S were tested, being generally $\rho_{S1}≈0.4$ t/m^3; $\rho_{S2}≈0.52$ t/m^3; $\rho_{S3}≈0.63$ t/m^3; $\rho_{S4}≈0.99$ t/m^3. The individual densities relative to water density (ρ) per log type are given in Table 2.

Table 2. Characteristic of stems.

Class	**Length *L* [m]**	**Diameter *d* [m]**	**Length / Bay width *L/b*[-]**	**Relative density ρ_S/ρ**
A	0.21	0.01	0.80	0.59
				0.79
				0.99
B	0.26	0.012	1.00	0.56
C	0.30	0.016	1.20	0.43
				0.56
				0.97
D	0.40	0.02	1.50	0.63
E	0.52	0.025	2.00	0.40
				0.54
				0.76
				0.99

2.3 Test procedure and parameters

For an experiment, flow depth h and discharge Q were measured without stems as initial condition. A stem was supplied in the centre of the flume parallel to the flow direction, and it was noted if the stem passed or blocked at the spillway inlet. In the latter situation, it was removed and the procedure was repeated. In order to reduce the random component induced by human interaction, stems were supplied with a mechanical device into the stream guaranteeing identical conditions per test. The device was placed at approximately 4.0 m upstream of the ogee to have at least five stem's length between the insertion point and the ogee.

Twenty-eight test combinations were defined. The varied parameters were: Stem class (Table 2); H/d ratio; relative density ρ_S/ρ and amount of open bays (Table 3).

Table 3. Parameters variation.

Class	**Ratio *H/d***	**Relative density ρ_S/ρ**	**Open bays**
A	1.00; 1.20; 1.40	0.59; 0.79; 0.99	1; 5
C	0.94; 1.00; 1.06	0.43; 0.56; 0.97	1; 5
E	0.76; 0.96; 1.00	0.40; 0.54; 0.76; 0.99	1; 5

3 EFFECT OF REPEATABILITY

Blocking probabilities $\pi(i)$ were calculated as the number of stems blocked at the inlet of the spillway divided by the number of stems supplied in total. The blocking probability is defined in **Eq. [1]**, where $\pi(i)$= blocking probability, $R(i)$= result obtained for each individual stem (pass$R$=0;block$R$=1), i= individual stem and n is the total number of stems supplied.

$$\Pi(\mathrm{i}) = \frac{\sum_{\mathrm{i}=1}^{n} \mathrm{R}(\mathrm{i})}{i} \qquad [1]$$

A plot of the results obtained in a particular experiment with class E, density ρ_{s1} and five bays open is shown in Figure 4. It can be noted that the first stem blocked (R_1=1 so that $\pi(1)$=1), the second did not (R_2=0 so that $\pi(2)$=0.5) and the third one blocked (R_3=1 so that $\pi(3)$=0.67). The repetition i=5 considers the amount of stems blocked until 5 repetitions (3 stems), divided by the number of stems provided (5 stems) giving $\pi(5)$=0.60. This plot emphasizes the variability of π according to the number of repetitions i. For example, repeating 5 times ($\pi(5)$=0.60) and repeating 30 times ($\pi(30)$=0.43) implies a $\Delta\pi$ of almost 0.20 for this particular case.

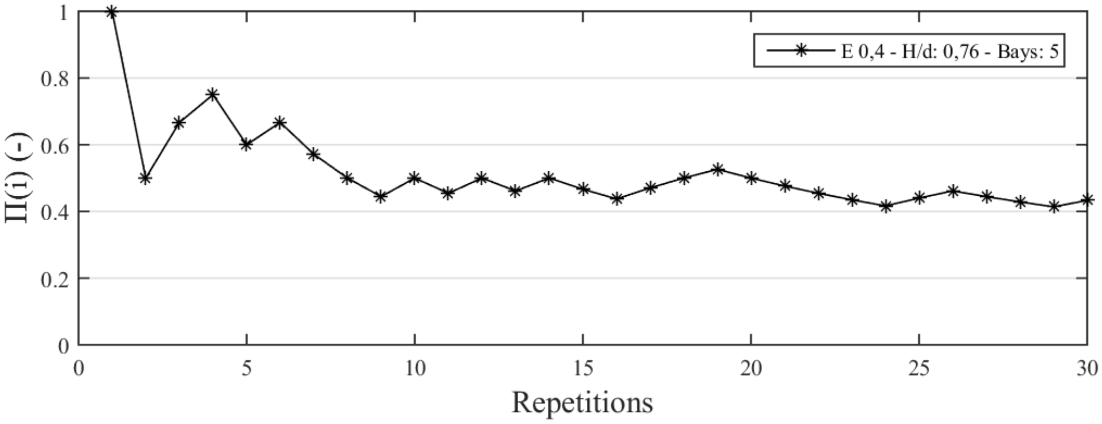

Figure 4. Example of blocking probabilities a function of repetitions. Class *E*, ρ_1, *H*/*d* = 0.76 and five bays.

Figure 5 displays results obtained in an experiment with class *E*, density ρ_{s1} and one bay open. In this case, the first stem passed, the second did not and the third one either. Repetition i=5 considers 2 stems blocked divided by 5 stems provided, giving $\pi(5)=0.40$ blocking probability. In this situation, repeating 5 times ($\pi(5)=0.40$) and repeating 30 times ($\pi(30)=0.06$) implies a $\Delta\pi$ of more than 0.30.

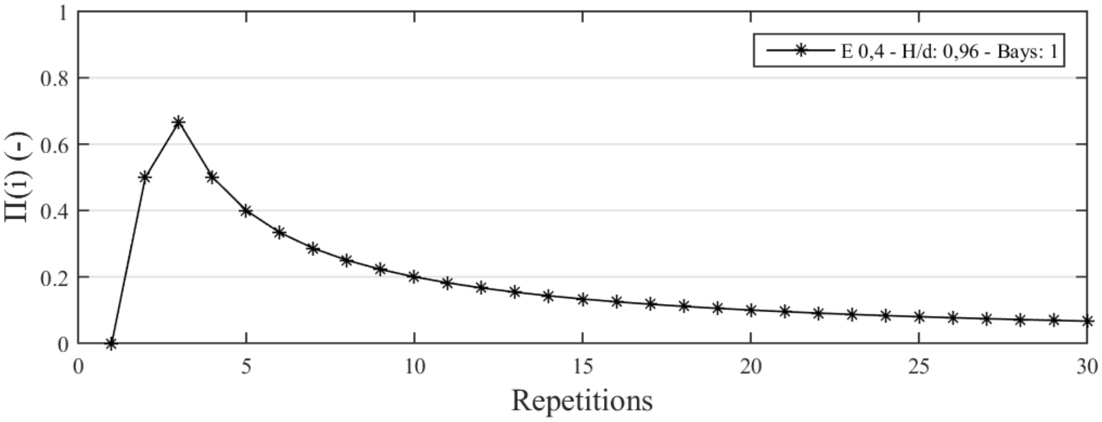

Figure 5. Example of blocking probabilities a function of repetitions. Class *E, ρ_1, H/d* = 0.96 and one bay.

Analyzing how π developed along the increment of repetitions *i*, it could be inferred that the repeatability has a strong influence in the variability (or error) of its estimation.

To compare the effect of repeatability on the blocking probabilities along experiments, a relative blocking probability was expressed as indicated in Eq.[2] where $\pi(i)$ is the blocking probability for the current repetition and $\pi(n)$ the blocking probability taking into account the last stem supplied.

$$\frac{\left|\Pi(i) - \Pi(n)\right|}{\Pi(n)} \qquad [2]$$

Plotting the normalized results obtained for the 28 tested parameter combinations (Table 3), it can be seen how much the blocking probability varies for less than i=10 repetitions, regardless of the experiment performed (Figure 6). The standard deviation was calculated per repetition for all the experiments, shown as a black dotted line in the plot. It can be seen how it tends to zero with an increasing number of repetitions.

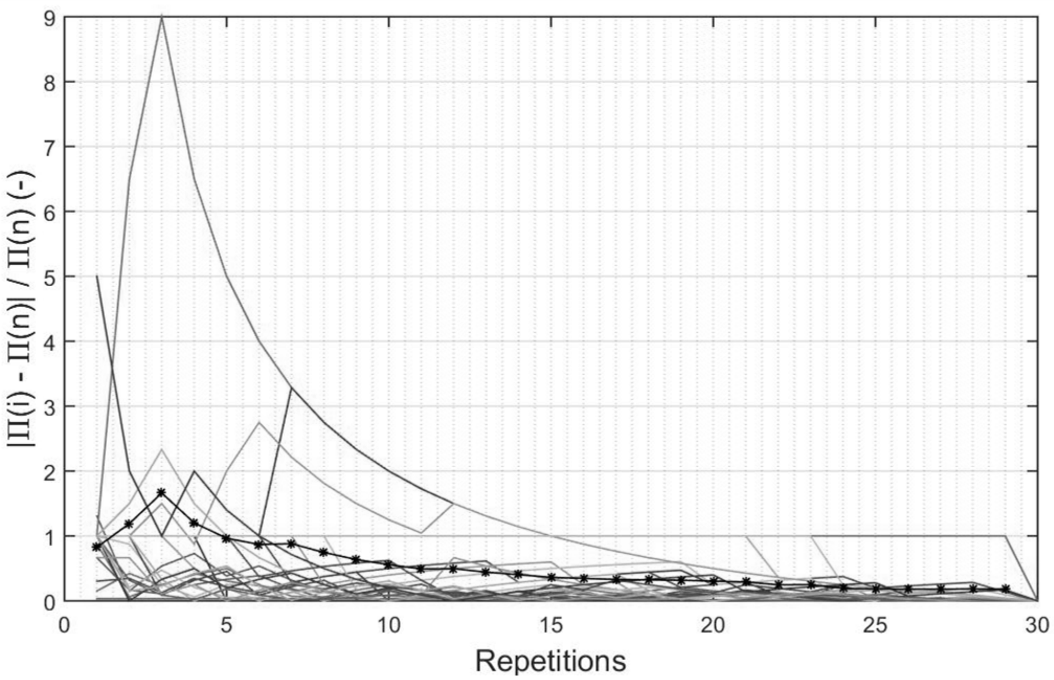

Figure 6. Normalized blocking probabilities as a function of repetitions of all experiments. The black dotted line corresponds to the standard deviation.

4 EFFECT OF DENSITY

Based on the experiments performed, it was also possible to analyze the influence of density on the blocking probabilities of LWD at the ogee crested spillways with piers. Here, the class *E* is considered as an example. Three different hydraulic combinations were evaluated for that class using four densities (Table 3).

Figure 7 shows the results obtained for class *E* with a relation of *H*/*d*=0.76 and all bays open. Densities were represented with different scales of grey in the plot. It can be seen that higher densities (e.g., ρ_4 in black), for the same hydraulic conditions, imply increments in the final value of π (after 30 repetitions). Between ρ_1 (light) and ρ_4(heavy), the relative difference in blocking probabilities is $\Delta\pi$=0.57.

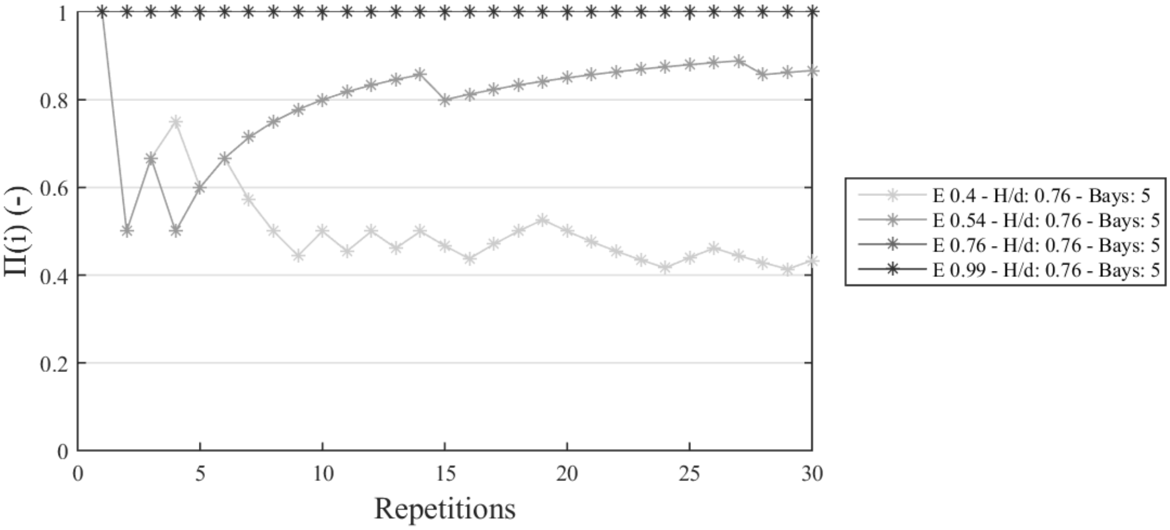

Figure 7. Example of blocking probabilities as a function of repetitions. Class *E, H/d*=0.76 and five bays open, for changing densities.

If increasing the head ratio to *H/d*=1.00 (Figure 8), density has the same effect on π as for the lower ratio. The heavier stems with ρ_{s4} blocked (π(30)=0.96), regardless of the hydraulic condition. A difference was noted for less dense stems where π(30) decreased from 0.43 to 0 (for ρ_{s1}) in comparison to Figure 7. In the case of ρ_2 and ρ_3, π(30) changed from 0.86 to 0.03 and from 1.0 to 0.20, respectively, showing a strong influence of *H/d* on π.

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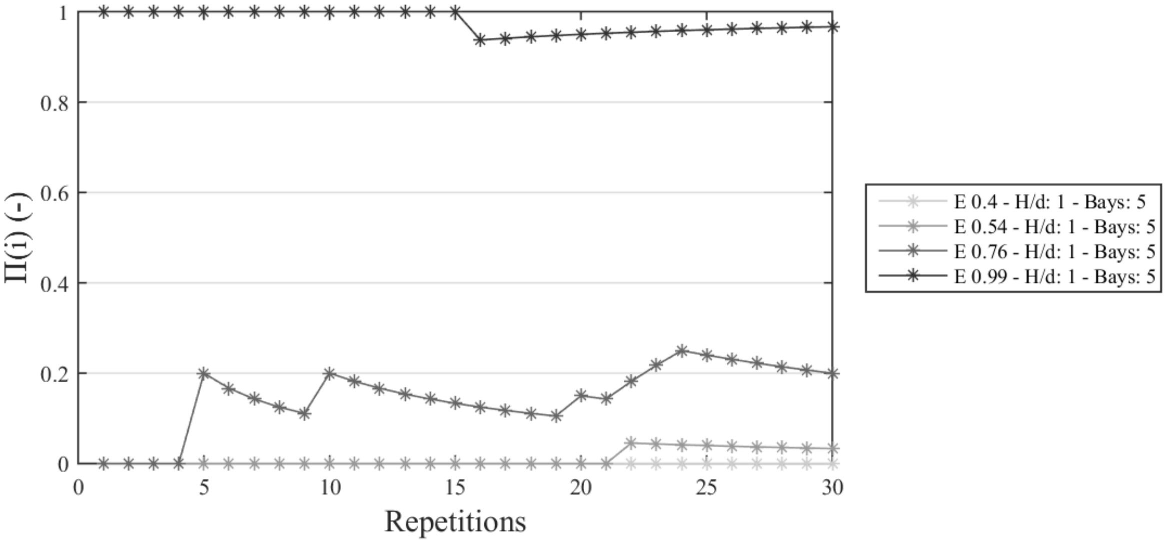

Figure 8. Example of blocking probabilities as a function of repetitions. Class *E, H/d*=1.00 and five bays open, for changing densities.

Finally, the number of open bays was changed for *H/d*=0.96 (Figure 9). It can be seen that $\pi(30)$ for ρ_{s4} was not influenced by the hydraulic conditions or the change of gate configuration, giving always $\pi(30)$ near 1. The number of bays open was tested to analyze if different configurations of open gates would also cause an effect on π. For this class, only density and *H*/*d* gave clear indications of having an influence on $\pi(30)$.

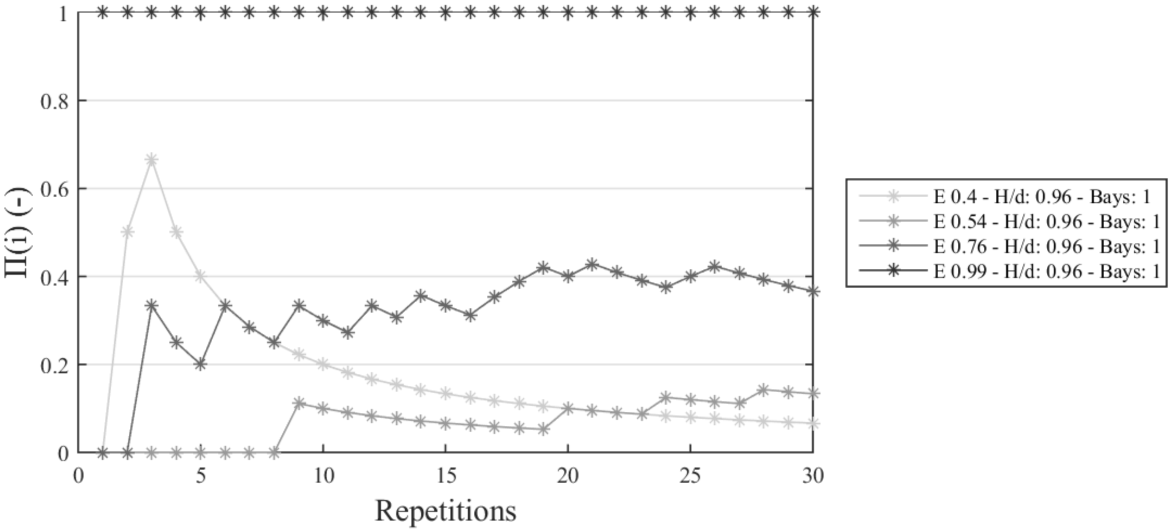

Figure 9. Example of blocking probabilities as a function of repetitions. Class *E, H/d* = 0.96 and one bay open, for changing densities.

5 CONCLUSIONS

The effect of repeatability and density as important parameters to estimate the blocking probabilities of LWD at ogee crested spillways with round nose piers is physically tested. Experiments have shown that the number of repetitions has a strong influence in the final estimation of the blocking probability π. According to the results obtained, some 15 to 25 repetitions should be considered as minimum number for such experiments as it will provide enough data to apply different statistical analysis and will decrease the standard deviation of results. This number of repetitions (for example 24) represents a standard deviation of the relative blocking probability smaller than 0.01 and this is considered acceptable taking into consideration the random nature of LWD processes. Accordingly, the precision aimed with each research will determine the level of incertitude accepted of the results and implicitly the number of repetitions.

For the class evaluated, it is demonstrated that the stem (or trunk) density is an important parameter related to the estimation of the blocking probability π. The blocking probability of individual stems travelling to an ogee crested spillway with round nose piers depends on the density of the stems. Heavier stems tend to block more frequently than lighter stems.

ACKNOWLEDGEMENTS

This project is supported by "Fundaçãopara a Ciência e a Tecnologia" (FCT) from Portugal (PD/BD/52664/2014) under IST-EPFL joint PhD initiative H2Doc. Further support is provided by the Laboratory of Hydraulic Constructions (LCH, EPFL), Switzerland, and by Électricité de France (EDF), France.

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