Blocking probability of large wood and resulting head increase at ogee crest spillways

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"But can you really forbid a man from harbouring a desire
to know and embrace everything that surrounds him?"

Alexander Von Humboldt.

A los afectuosos, y siempre presentes, suaves vientos.

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Abstract

Large wood increases the hydraulic complexity of rivers, yet it may block and modify the flood discharge capacity of hydraulic structures such as bridges and spillways. When spillway blockage occurs, dangerous and hazardous situations have been observed at several dams. To assess the related risk, blocking probabilities and head increase quantifications for free surface spillways are needed.

For this reason, the blocking probability of large wood and the resulting head increase is estimated, with an original systematic approach, for ogee crest spillways equipped with piers. The study is based on an experimental campaign using artificial stems. The evaluated variables related to large wood are: stem length, diameter and density, plus stem group size. The variables related to the structure and hydraulic conditions studied are: head, number of open bays and, bay width. A reservoir approach flow type is considered, implying small flow velocity.

A statistical analysis relating the number of experimental repetitions and accuracy in blocking probability estimations of large wood is presented. The evaluation analyses individual stems and groups. It is suggested to conduct at least 30 experimental repetitions for blocking probability estimations of individual stems to have standard errors smaller than 0.10 (with 90% confidence). For groups of stems, between 10 and 30 repetitions are suggested, according to the number of stems inside the group and the desired accuracy.

For the first time, the influence of stem density on blocking estimations was evaluated for a reservoir approach. Results show that an increasing stem density increases the blocking probability of individual stems, when the stem length is greater than the bay width. Stems with a density close to water density, have higher blocking probability and may trigger wood jams when blocked. Regarding the head at the weir crest, the influence on blockage is not linear but usually an increasing head decreases the blocking probability.

The influence of the number of open bays on the blocking probability was studied. Generally, for constant large wood characteristics and head, five open bays result in lower blocking probability than one open bay. Regarding the stem length related to the bay width, if the stem length is greater than the bay width, this parameter has limited influence on the blocking. Nonetheless, it was not possible to isolate the stem length influence as it was connected to the effect of stem diameter and head.

Abstract

The group size effect on the blocking probability of stems could be observed. For stems larger than the bay width and blocking probability lower than 0.80, an increasing group size increases the blocking of stems, compared to individual stems. The blocking probability of 4 stems can be the double of that of an individual stem for a constant head. However, increasing the group size from 4 to 16 stems has a mild influence on the blocking probability.

Finally, varied groups of blocked stems allowed to measure the head increase in the reservoir. The head increase is influenced by the volume of blocked stems, jam shape, position and composition. A simple theoretical formulation to estimate the head increase as a function of an equivalent bay width is obtained. The formulation represents adequately the trend of head increase measured for blocked stems experimentally.

Key words: Large wood, blocking probability, spillway with piers, wood jams, head increase, experimental modeling.

Résumé

Les bois flottants augmentent la complexité hydraulique des rivières mais peuvent bloquer et modifier la capacité de transit de crue des ouvrages hydrauliques. Le blocage des déversoirs a mis plusieurs barrages dans des conditions dangereuses. Pour évaluer le risque associé, des probabilités de blocage ainsi que la quantification de l'augmentation de charge des déversoirs à surface libre sont nécessaires.

Pour cette raison, la probabilité de blocage des bois flottants et l'augmentation de la charge sont estimées à l'aide d'une approche systématique pour les déversoirs à crête de type standard et équipés de piliers. L'étude est basée sur un modèle expérimental avec des tiges artificielles. Les variables évaluées relatives aux bois flottants sont : la longueur, le diamètre et la densité de la tige, ainsi que la taille du groupe de tiges. Les variables liées à la structure hydraulique sont : la hauteur, le nombre de passes ouvertes et la largeur des passes. Un flux d'approche de réservoir est considéré, impliquant une petite vitesse d'écoulement.

Une analyse statistique reliant le nombre de répétitions expérimentales et la précision de l'estimation de la probabilité de blocage est présentée. Il est suggéré d'effectuer au moins 30 répétitions expérimentales pour l'estimation du blocage de tiges individuelles afin d'avoir des erreurs inférieures à 0,10 (confiance de 90%). Pour les groupes de tiges, entre 10 et 30 répétitions sont suggérées, en fonction du nombre de tiges à l'intérieur du groupe et de la précision souhaitée.

Pour la première fois, l'influence de la densité de la tige sur les estimations de blocage a été évaluée. Une augmentation de la densité des tiges augmente la probabilité de blocage de tiges individuelles lorsque la longueur de la tige est supérieure à la largeur de la passe. Les tiges avec une densité proche de la densité de l'eau ont une probabilité de blocage plus élevée et peuvent déclencher une accumulation du bois. En ce qui concerne la charge à la crête du déversoir, l'influence sur le blocage n'est pas linéaire, toutefois une augmentation de la tête diminue la probabilité de blocage en générale.

L'influence du nombre de passes ouvertes sur la probabilité de blocage a été étudiée. En règle générale, pour géométries de tiges et charges constantes, cinq passes ouvertes ont une probabilité de blocage inférieure à celle d'une. Concernant la relation entre la longueur de la tige et la largeur de la passe, si la longueur de la tige est supérieure à la largeur de la passe, ce paramètre a une influence limitée sur le blocage. Néanmoins, l'influence de la longueur de la tige n'a pas pu être isolée étant directement liée à l'effet du diamètre de la tige et de la charge.

Résumé

L'effet de la taille du groupe sur la probabilité de blocage des tiges a été évalué. Pour les longueurs de tiges supérieures à la largeur de la passe et pour des probabilités de blocage inférieures à 0,80, une taille de groupe croissante augmente le blocage des tiges en comparaison avec les tiges individuelles. La probabilité de blocage de 4 tiges peut être le double de celle d'une tige individuelle pour une charge constante. Toutefois, l'augmentation de la taille du groupe de 4 à 16 membres a une légère influence sur la probabilité de blocage.

Divers groupes de tiges bloquées ont permis de mesurer l'augmentation de charge dans le réservoir. L'augmentation de la charge est influencée par le volume bloqué des tiges, la forme et la composition du groupe de tiges accumulées. Une relation théorique simple permettant d'estimer l'augmentation de charge lie à une largeur de passe équivalente a été obtenue. La relation trouvée représente adéquatement la tendance de l'augmentation de la charge mesurée expérimentalement avec des tiges bloquées.

Mots-clés : Bois flottants, probabilité de blocage, déversoir avec piliers, accumulation de bois, augmentation de charge, modélisation expérimentale.

Resumo

A existência de material lenhoso flutuante aumenta a complexidade do escoamento em cursos de água, podendo obstruir e modificar a capacidade de vazão de estruturas hidráulicas, como pontes e descarregadores de cheias. Em diversas barragens registaram-se acidentes e situações catastróficas decorrentes da obstrução dos descarregadores de cheias. Por forma a avaliar o risco relacionado com este tipo de fenómeno, torna-se necessário quantificar a probabilidade de obstrução da soleira descarregadora e o aumento da carga hidráulica a montante.

Devido a esta razão, foi levado a cabo um estudo sistemático da probabilidade de obstrução e do consequente aumento da carga hidráulica a montante de soleiras descarregadoras do tipo WES equipadas com pilares. O estudo é baseado numa investigação experimental onde se utilizaram hastes artificiais. As variáveis relacionadas com material lenhoso flutuante avaliado foram as seguintes: comprimento, diâmetro, densidade da haste, assim como o número de elementos do grupo de hastes. As variáveis relacionadas com a estrutura descarregadora e com as condições hidráulicas estudadas foram as seguintes: carga hidráulica, número de vãos abertos e largura do vão. A velocidade de aproximação do escoamento foi muito reduzida, representativa do escoamento numa albufeira.

Apresenta-se uma análise estatística com o objetivo de relacionar o número de repetições experimentais com a precisão da estimativa da probabilidade de obstrução por material lenhoso flutuante. A metodologia abrange hastes individuais e grupos de hastes. Um conjunto de 30 repetições experimentais afigura-se adequado (com nível de confiança de 90%), para hastes individuais com erro padrão inferior a 0,10. Para grupos de hastes, o número de repetições pode variar entre 10 e 30, dependendo do número de hastes por grupo e a precisão desejada.

Pela primeira vez, analisou-se a influência da densidade do material lenhoso na estimativa da obstrução, para condições de aproximação do escoamento representativas de uma albufeira. Os resultados evidenciaram que o aumento da densidade do material lenhoso flutuante conduz ao aumento da probabilidade de obstrução por hastes individuais, quando o comprimento da haste é maior do que a largura do vão. Hastes com uma densidade próxima da densidade da água têm maior probabilidade de obstrução, podendo provocar uma aglomeração do material lenhoso, quando ocorre a obstrução. Relativamente à carga hidráulica a montante da soleira descarregadora, a influência na obstrução não é linear, embora o aumento da carga hidráulica conduza usualmente à diminuição da probabilidade de obstrução.

A influência do número de vãos abertos na estimativa da probabilidade de obstrução foi também objeto de estudo. Geralmente, para material lenhoso flutuante com características contantes e carga hidráulica constante, cinco vãos livres conduziram a uma menor probabilidade de obstrução comparativamente a um vão livre. Em relação ao comprimento do haste adimensionalizada pela largura do vão, se o comprimento da haste é maior do que a largura do vão, este parâmetro tem uma influência limitada na obstrução. Contudo, não foi possível assegurar o efeito do comprimento da haste de forma inteiramente independentemente do diâmetro da haste e da carga hidráulica.

A influência do número de hastes de cada grupo na probabilidade obstrução foi objeto de estudo. Para hastes com comprimento maior do que a largura do vão e probabilidade de obstrução menor do que 0,80, um aumento do número de hastes do grupo conduz ao aumento da probabilidade de obstrução, comparativamente a ensaios com hastes individuais. A probabilidade de obstrução de quatro hastes pode atingir o dobro da probabilidade de obstrução de uma haste, para a mesma carga hidráulica. No entanto, o aumento do número de hastes de 4 para 16 exerceu apenas uma pequena influência na probabilidade de obstrução.

Por fim, avaliou-se aumento da carga hidráulica a montante da soleira descarregadora para grupos de hastes bloqueadas. O aumento da carga hidráulica é influenciado pelo volume de hastes bloqueado, pela forma da aglomeração de hastes e pela sua composição. A posição das hastes no interior da aglomeração pode determinar a forma da aglomeração e a sua influência no aumento da carga hidráulica. Uma formulação teórica simplificada para estimar o aumento da carga hidráulica em função da largura equivalente do descarregador após obstrução foi obtida. Esta formulação representa adequadamente a tendência de aumento da carga hidráulica medida experimentalmente para hastes bloqueadas.

Palavras-chave: Material lenhoso flutuante, probabilidade de obstrução, soleira descarregadora com pilares, congestionamento de material lenhoso, aumento da carga hidráulica, modelação experimental.

Contents

List of symbols

These symbols are used throughout the report:

Roman letters

A	Catchment area	[km^2]
A_f	Forested catchment area	[km^2]
b	Bay width	[m]
C_Q	Discharge coefficient	[-]
d	Stem diameter	[m]
d_{PN}	Pier nose diameter	[m]
g	Gravity acceleration	[m/s^2]
G_i	Stem group size	[-]
h	Free surface water elevation	[m]
H	Hydraulic head	[m]
H_d	Hydraulic design head	[m]
H_0	Hydraulic head initial condition (without stems)	[m]
L	Stem length	[m]
$L_L; U_L$	Lower and upper limit of confidence interval	[-]
L_{PN}	Pier nose protrusion from the weir into the reservoir	[m]
L_Q	Weir length	[m]
n	Number of repetitions	[-]
N	Nose configuration	[-]
O_R	Occupation ratio	[-]
Q	Discharge	[m^3/s^1]
$S.E$	Standard Error	[-]
v	Mean inflow velocity	[m/s]
V	Wood volume	[m^3]
W	Weir height	[m]
X	Number of blocked stems	[-]

Greek letters

α	Error level	[-]
α_s	Ratio of bay width with blocked stems	[-]
β	Wood to sediment volume ratio	[-]
β_0	Intercept of a logistic regression	[-]
$\beta_{1,..,p}$	Regression coefficients for explanatory variables	[-]
θ	Angle of large wood stems relative to flow direction	[$\circ$]
κ	Large wood rugosity	[m]
λ	Coefficient to modify the bootstrap technique	[-]
μ	Water viscosity	[kg/ms]
π	Blocking probability	[-]
$\hat{\Pi}$	Estimated blocking probability	[-]
$\hat{\Pi}(n)$	Estimated blocking probability for n number of experimental repetitions	[-]
$\hat{\Pi}_G$	Estimated blocking probability for group of stems	[-]
ρ	Water density	[t/m^3]
ρ_s	Stem density	[-]
ρ_w	Wood density	[t/m^3]
σ	Water surface tension	[kg/s^2]
σ_w	Standard deviation wood density	[t/m^3]
ϕ	Pier nose diameter	[m]

Abbreviations

AIC	Akaike Information Criterion
CI_W	Confidence interval width
CP	Clopper-Pearson method for calculating confidence interval
EPFL	Ecole Polytechnique Fédérale de Lausanne
IST	Instituto Superior Técnico
LCH	Laboratoire de Constructions Hydrauliques of EPFL
LW	Large wood
PKW	Piano key weir
W	Wald method for calculating confidence interval

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1 Introduction

1.1 Background and motivation

The increasing demand for fresh-water will likely require the construction of new dams and flow diversion projects worldwide (Buxton, 2010). With escalating environmental challenges to preserve natural processes, it is key to advance with the research and solve existing problems. In-stream wood has positive effects on the morphological and hydraulic complexity of rivers but floods can transport great amounts of woody material towards reservoirs in forested basins. For dams in areas prone to produce and transport woody material it can be an exacerbating hazard factor (Mazzorana et al., 2017).

Accumulations of floating debris into reservoirs can have significant negative impacts on the operation and functioning of a dam. During August of 1978, the Palagnedra Dam in the southern canton of Ticino (Switzerland) was overtopped. After a heavy rain event along the area, woody material was flushed towards the spillway inlet and accumulated there due to blockage at the piers of the ogee crest weir. The hydropower plant was obstructed with twisted tree trunks in the spiral casing of the turbines (Bruschin et al., 1982, Maggia, 1979). The United States National Research Council reported that about 30% of spillway malfunctions in the United States were caused by cases of spillway blockage due to floating debris. Still in 2015, the National Performance of Dams Program reported 23 accidents at United States dams involving debris blockage of spillways (Hartford et al., 2016).

Among the different types and sizes of woody material, the term large wood (LW) comprehends stems longer than 1 m, having a diameter above 0.10 m. If LW reaches a weir located within the stream, it may block and accumulate while narrowing the bay opening, causing backwater flooding (Braudrick and Grant, 2001). Hence, an adequate spillway design in view of driftwood is of paramount importance to overcome potential impacts on dam safety. If LW continues to accumulate, effects of floods, scouring or sediment deposition can be intensified.

LW has been included in some hazard and risk assessment guidelines (Mazzorana et al., 2011b, Wohl et al., 2016). Research on LW transportation and movement inside rivers is currently

ongoing (Comiti et al., 2016). Knowledge on diverse LW processes has increased significantly in the last decade, but the risk it represents when blocked has been barely studied for hydraulic structures.

Quantification and understanding on the blockage process at dams is vital, however to date it remains unaccomplished. Analysis of large wood blocking probabilities and head increase are a timely advance towards better risk assessment tools.

1.2 Research objectives

In order to properly assess and mitigate the inherent risk of large wood blockage at a hydraulic structure, a comprehensive understanding of the process is needed. The amount of literature regarding LW inside rivers is currently growing, however, the blocking probability of this material on structures like spillways with a reservoir approach is not yet available.

Some main parameters that influence the blocking probability of LW were recognised for other types of structures. In this research, the goal is to go further and to determine systematically how these, and new parameters, influence the blocking probability for the case of an ogee crest spillway equipped with piers. Nonetheless, due to the randomness of the LW behaviour, a statistical approach to evaluate accurately the blocking probability is fundamental.

Furthermore, when LW blocks at different types of structures it can lead to head increase and extended inundated areas. Only fragmented information can be obtained from previous cases of LW blockage and field observations are difficult. A contribution to the current knowledge of head increase estimations due to LW blockage is aimed in this research.

More specifically, the objectives to be achieved can be summarized as follows:

1. To define the required number of experimental repetitions, justified statistically and in accordance to experimental efforts, that assures accurate estimations of blocking probabilities.
2. To identify and quantify the influence of stem length, diameter and density on blocking probabilities of stems, related to hydraulic characteristics of an ogee crested spillway inlet with piers, such as head, bay width and number of open bays.
3. To quantify the influence of the size of stem groups (number of stems) on the blocking probability compared to individual stem experiments.
4. To investigate the effect of a blockage by stems, at the spillway inlet, on the head increase in the reservoir.

These objectives were selected taking into account the gap in knowledge that emerged from a literature review presented in Chapter 2 and summarized in Section 2.10.

1.3 Structure of the report

This report is divided into 9 chapters. The first chapter presents a broad overview of the topic, outlining the motivation behind the research project. In Chapter 2, a comprehensive literature review of current knowledge on LW behaviour for rivers and reservoirs, is presented. The experimental set-up, instrumentation and methodology are detailed in Chapter 3. Chapter 4 focuses on the statistical analysis to determine a number of experimental repetitions, to assure accuracy in the blocking probability estimation for individual stem experiments. The blocking probability of individual stems is presented and discussed in Chapter 5. In Chapter 6, the number of experimental repetitions needed for statistical accuracy is evaluated for the blocking probability of stem group experiments. The influence of stem groups for blocking probability is fully addressed in Chapter 7. Chapter 8 addresses the evaluation of head increase due to blocked stems. Finally, Chapter 9 summarizes the key findings and presents an outline for future work. Chapters 4, 5 and 6 were conceived and prepared as journal articles. Further publications are to be submitted from Chapter 7 and 8.

2 State of the art

2.1 Driftwood and large wood: definitions

Driftwood is wood that has been conveyed into a water surface and can be mobilized by the flow, transported or retained at obstacles. It may consist of trees, shrubs and anthropogenic wood such as construction timber. Trees that are entrained during a flood normally include branches, leaves and rootstocks which can be detached during the entrainment and transportation process. Consequently, driftwood material exhibits various sizes and characteristics.

Large wood (LW) has been defined as stems longer than 1 m, having a diameter above 0.10 m (Braudrick et al., 1997, Ruiz-Villanueva et al., 2016b, Wohl et al., 2016). When different floods transport driftwood towards hydraulic structures like weirs, bridges and spillways, mixes of LW with anthropogenic materials can been found (Figure 2.1). Such mixtures are more often called floating debris.

(a) Wigan bridge, New Zealand (www.maoritelevision.com, 05/06/18)

(b) Thurnber reservoir, Austria (Photo of Heinz-Peter Bader, www.hpb.at, 4/10/16).

Figure 2.1 – Examples of large wood blocked at hydraulic structures.

LW will have different physical characteristics according to the geographic location, tree specie or age, among other variables. Nonetheless, these characteristics are not constant in time and do not

necessarily represent the characteristics of instream LW as it usually breaks during transportation, absorbs water or loses branches.

LW jams are defined as three or more elements of large wood in contact (Wohl et al., 2011), where one piece has been previously mobile and has been "trapped" by another piece or structure (Dixon, 2016). Jams are complex and porous accumulations of heterogeneous material (Manners et al., 2007). Estimation of the arriving jam volume with its characteristics, although complex, should be considered in the design of the hydraulic structure since it influences its performance.

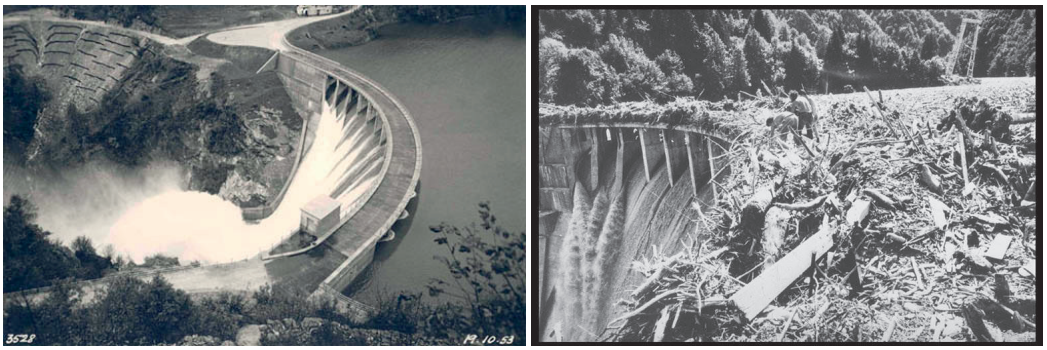
2.2 What can happen if large wood moves into reservoirs?

As stated by Rundqvist (2005), "spillways are designed with the implicit assumption that extreme floods will essentially function with clean water floods, which is wishful thinking". In several cases, blockage of hydraulic structures has lead to damages and unforeseen loads to the structure.

2.2.1 Spillway blockage in Palagnedra dam, Switzerland

Palagnedra dam is located in Ticino, Switzerland. It creates a reservoir for the last step of the Maggia hydroelectric scheme (Maggia, 1979). The storage capacity is almost $5 \cdot 10^6$ m^3 being fed from a catchment area of 140 km^2, over 50% of which is forested.

The structure consists of an arched gravity dam 120 m long and 72 m high, blocking the main valley. The spillway comprises an ogee crest with a steep chute followed by a ski-jump. The non-gated spillway had 13 openings, 5 m wide and 3 m high, separated by piers supporting a road bridge (Bruschin et al., 1982). Figure 2.2 shows the spillway operating in 1953 and after the flood of 1978.



(a) Archive of OFIMA, Locarno (b) Bruschin et al. (1982)

Figure 2.2 – Palagnedra dam operating in 1953 and after the flood of August, 1978.

During the first years after completing the dam, large quantities of sediment were transported during every major flood. To preserve the storage capacity of the reservoir and to protect the

bottom outlet and the power intake, some of the fine alluvial deposits were pumped over the dam crest between 1968 and 1973. An intermediate submerged dam and a sediment by-pass tunnel were built in the upper part of the reservoir to deal with reservoir sedimentation (Bruschin et al., 1982).

Before the flood of August 1978, the spillway operated during several large floods without causing any damage. But on August, the Palagnedra reservoir and other installations of the hydroelectric scheme, were severely affected by the flood raising the following events:

- Overtopping of the dam crest along its full length.
- Erosion breach 30 m deep and 25 m wide in the loose rock valley-side.
- Blockage of 25000 m^3 of wooden debris of all dimensions at the spillway.
- Deposition of 1.8 millions m^3 of sand and gravel.
- Blockage of the inlet of the diversion tunnel by a layer of sand and wood.
- Destruction inside the power intakes.

The large discharge combined with an unknown degree of obstruction of the spillway lead to the dam overtopping which created a very dangerous situation. After the event, scarce woody material was removed from the reservoir, the majority had to be burnt on spot as it was impregnated with sand and became useless (Bruschin et al., 1982). Operations to unblock the pressure tunnel took place for more than 6 months, removing about 70000 m^3 of material.

The spillway of Palagnedra dam was completely redesigned, based on a supplementary sample of 37 annual floods recorded in the Melezza river. A new bridge was built 25 m downstream of the dam. Consequently, by removing the bridge and the piers, the original spillway with 13 openings was transformed to a constant length of 80 m (Figure 2.3). The ski jump was also modified to accommodate a discharge five times larger than the original design flood (Bruschin et al., 1982).

(a) Picture by Philipp B (mapio.net, 19/01/16)

(b) Picture by Helga Ammann (www.fotocomunity.de, 19/01/16)

Figure 2.3 – New design of Palagnedra dam spillway crest.

2.2.2 Bridge blockage in Ichinomiya, Japan

On July 2, 1990 a typhoon occurred in Aso, Japan. An intensive torrential downpour caused several slopes to fail in the Ichinomiya district with a total failed mass volume of one million cubic meters (Yatabe et al., 1992). The slope failures caused enormous debris flows, involving large amounts of wood and rocks. Trees were blocked at Matsubara bridge, over a national highway, and the flood was diverted towards the town. The flooded area was 2 km^2 in which 72 houses were completely or partially destroyed and 8 persons were killed (Figure 2.4).

(a) Debris flow in the forest of Japanese cedar (Yatabe et al., 1992)

(b) Damages near Matsubara bridge (Yatabe et al., 1992)

Figure 2.4 – Ichinomiya flood of July, 1990.

2.2.3 Spillway blockage in Sa Teula dam, Italy

In December 2004, a flood event with an estimated peak of 340 m^3/s (of 500-years return period) occurred in Sardinia, Italy. A considerable transport of floating debris, including tree trunks of wide dimension, took place. The dam of Sa Teula had an automatic gated spillway. The dimension of the spillway bay width was 12 m and the height 3 m. The floating material blocked and reduced the water inflow to the galleries containing the floats of the gates, preventing the spillway gate from opening.

The restricted width of the overflow spillway together with the reduced distance to the gallery intake made the release of the floating material impossible. As a consequence, an almost full blockage of the openings lead to the overtopping of the dam (Galeati, 2009). The considerable loads that affected the gate, in addition to some tree trunks trapped between the edge of the gate and the service footbridge, resulted in the complete detachment of the gate (Figure 2.5).

(a) LW accumulation upstream of the spillway inlet (Galeati, 2009)

(b) Gate torn downstream of the dam (Galeati, 2009)

Figure 2.5 – Sa Teula dam after two days of the flood of December 2004.

2.2.4 Spillway blockage in Yazagyo dam, Myanmar

Yazagyo dam was designed to provide irrigation from the Nayizaya river in Myanmar. On August 2015, after several days of heavy rain, enormous volumes of LW entered and congested the reservoir, partially blocking the spillway (Figure 2.6).

LW was removed with heavy machinery at the dam site, conveying it through the spillway (Brakenridge et al., 2017). All extra water stored during the preceding days was released quickly when the blockage was removed. The large amount of LW was composed by cut trees during the construction (Steijn et al., 2016). In this example, there were no major damages and it was possible to unclog the LW in time.

(a) Blockage of the spillway seen from upstream, (www.thutatuam.net, 07/10/16)

(b) Blockage of the spillway seen from downstream, by Martin Wieland

Figure 2.6 – Flood event in Yazagyo dam, 2015.

2.3 Origin and behaviour of large wood inside streams

Most LW comes from trees growing close to a riverine area (Diehl, 1997). Such trees fall into the stream due to bank erosion, wind, ice or snow avalanches, disease or age. Animal activity has not been found as a main source of LW in streams (Kramer et al., 2017). The main events that trigger LW movement are heavy rains, landslides on steep slopes, high flows causing shoreline erosion and strong winds associated with storms (Wallerstein et al., 1996, Mazzorana et al., 2009). Land use changes, related with human activities (e.g., forest cutting, farmland development or abandonment), can also play a role in LW production. If LW is recruited by debris flows or landslides, higher breakdown of LW pieces can be expected. Driftwood can also be associated to local mobilizations of stable wood jams, including branches, leaves, stems and rootstock.

Several studies have been performed to determine entrainment and transportation of driftwood in accordance with its geometrical and physical characteristics, stream flow depth, water velocity, and channel morphology (Braudrick et al., 1997, Braudrick and Grant, 2000, Gurnell et al., 2002, Bragg and Kershner, 2004, Bocchiola et al., 2006b, Curran, 2010, Merten et al., 2010). Some studied characteristics of driftwood for entrainment processes in rivers include stem length and diameter, stem shape, wood density, orientation of stems relative to the flow direction, and presence/absence of rootstock or branches. Transportation and deposition patterns are also related to the channel characteristics.

Once inside the stream, stems tend to align their longitudinal axe parallel to the stream lines, regardless of the initial orientation (Braudrick and Grant, 2001, Bocchiola et al., 2006a, Welber et al., 2013). Figure 2.7 shows in time step 1 that the velocity is higher at the downstream end of the LW piece than the upstream end of it. Because of this difference in velocity, the LW piece rotates towards a more flow-parallel orientation as shown in time step 2. The piece continues to rotate aligned to the flow direction achieving a stable orientation shown in time step C (Braudrick and Grant, 2001). Additionally, Diehl (1997) observed that stems on the water surface are not consistently aligned with the flow or across it, but rotating under the influence of large moving eddies.

Due to the transportation process, branches and roots of trees in contact with fixed objects tend to break, turning trees into bare trunks. As branches can break, also the length of stems can vary along the way if the water velocity is high.

Braudrick et al. (1997) suggested a relative stem diameter (defined as the stem diameter divided by the average flow depth in the channel) as a key driver of wood mobility. Wood will float until this relative stem diameter drops below a critical value for flotation. Lange and Bezzola (2006) and Bocchiola et al. (2008) noted that the accumulation/deposition probability of driftwood increases with its length (relative to the width of the stream) but decreases with the Froude number, defined as

$$Fr = \frac{v}{\sqrt{gh}} \tag{2.1}$$

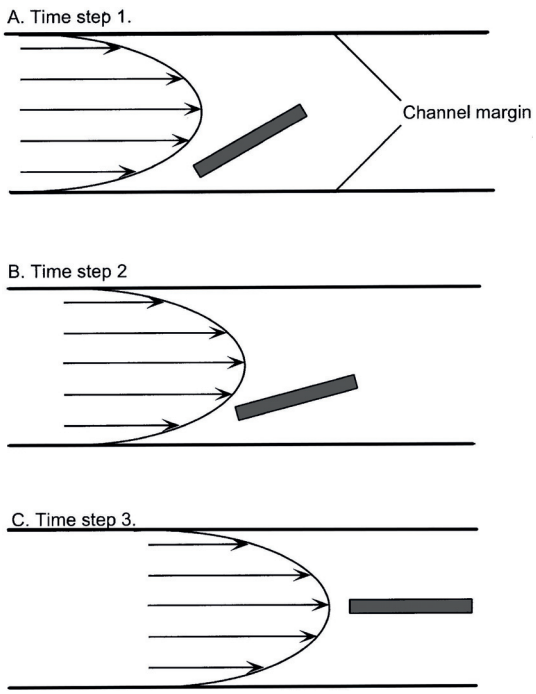


Figure 2.7 – Schematic diagram showing velocity field across a hypothetical channel, and its effect on LW piece orientation (Braudrick and Grant, 2001).

where v is the mean inflow velocity [m/s], g is the gravity acceleration [m/s^2] and h is the flow depth [m] in the river. For transportation in rivers, it was shown that flow depths of at least 75% of the stem diameter are required for the transportation process to begin if $Fr \sim 0.75$. When $Fr \geq 1.25$, the flow depth should be 125% of the stem diameter (Lange and Bezzola, 2006). These minimum flow depths required for transportation are also influenced by wood density, which depends on a number of factors including tree species, climatic conditions and water absorption (Welber et al., 2013).

2.4 Influence of large wood density

The density of entrained woody material varies according to the tree species, age, state of decay and water content but also as a function of the event that triggered the movement. When external forces drag living trees into a stream, they will have a high density due to the content of sap and water. In contrast, when dead trees are dry and a flood recruits them, their densities tend to be lower. Nevertheless, because of decay, water saturates faster the wood thus the density can rapidly increase (Braudrick et al., 1997). If a dead tree is in contact with water for a long period, degradation processes, absorption of water and fossilisation will make its density to differ considerably, implying densities higher than water density called Waterlogged Large Wood (WLW) (Buxton, 2010).

Different measurements of wood density can be found in literature. Densities of trees in northern

Europe can range between 800 to 1050 kg/m^3 (Hartford et al., 2016). When considering oven-dry mass of wood divided by green volume, European trees densities range between 406 to 644 kg/m^3 (Chave et al., 2009). Although, it should be noted that most studies of wood density are linked to the analysis of wood inside forests. The latter may differ compared to the density of instream wood as it is exposed to wetting and drying cycles (Ruiz-Villanueva et al., 2016a).

In Ruiz-Villanueva et al. (2016c,a), a sensitivity analysis of wood density and its influence on wood transport was performed. Wood density showed to have a high influence on the likelihood of driftwood movement, as it affects the buoyancy and mobility of the piece. Hence, both the geometry and density of prototype trees should be taken into consideration in a physical model study (Yang and Stenstrom, 2011).

In addition, the residence time of wood in a channel is reflected in the state of decomposition of the wood and thus its density. In riparian areas a single tree specie rarely dominates (Curran, 2010) and a mix of wood with distinct densities may be entrained (Gurnell et al., 2002). Therefore, homogeneous characteristics for instream volumes of wood, constant in time, are barely representative of reality.

2.5 Estimation of large wood volume

An important parameter to evaluate LW transport is the transported wood volume for a given flood event (Ruiz-Villanueva et al., 2014b). These estimations generally account all sizes of trees and woody material, therefore are estimations of wood and not only large wood. The estimation of transported volumes may be based on observed events, detailed analysis of the catchment area, hazard maps, transport diagrams or empirical formulae.

Empirical methods to determine the transported wood volume have been developed for mountainous rivers. Some formulas were proposed by Uchiogi et al. (1996), based on major disaster precedents. The woody volume V [m^3] can be related to the sediment yield amount (Equation 2.2).

$$V = \beta \cdot V_y \tag{2.2}$$

where V_y is the total transported sediment volume during the flood event [m^3] and β is the wood to sediment volume ratio (for the studied areas it was taken 2% but it can be different for small forested watersheds).

Evaluations of floods in Switzerland, Japan, and the United States lead to a formula that estimates the effective wood volume as a function of the catchment area and the flood event (Rickenmann, 1997) (Equation 2.3),

$$V = 45 \cdot A^{2/3} \tag{2.3}$$

where V [m^3] and A is the catchment area size [km^2]. With a validity between 0.054 to 6273 km^2.

Assuming that only the forested area adds LW during a flood, the potentially transported wood

volume can be estimated with Equations 2.4 or 2.5 (Rickenmann, 1997),

$$V = 90 \cdot A_f \tag{2.4}$$

$$V = 40 \cdot L_f^2 \tag{2.5}$$

where V [m^3], A_f is the forested area [km^2] and L_f forested length of the upstream reach [km], applicable when $L_f^2 < 20$ km. Reviews of different methods can be found in Comiti et al. (2016), STK (2017) for further information on this topic.

However, wood budgeting is a task deeply linked to temporal variations of LW in rivers (Tonon et al., 2018) and to case-by-case studies. Wood volumes potentially mobilized in tributaries are not always going to be delivered into the main channel. Indeed, dams, wood-trapping structures or low bridges may effectively disconnect tributaries and thus reduce the total volume reaching the main channel (Comiti et al., 2012). When structures prone to LW blockage are present, they should be included in a driftwood transport diagram (Schmocker et al., 2014). Therefore, estimations of blockage probabilities are a fundamental information for the correct assessment of LW volume .

2.6 Blockage of large wood at hydraulic structures

In some areas, woody material used to be removed to prevent it entering to riverine streams (Wohl, 2014, Comiti et al., 2016) regardless its positive influence for the diversification of aquatic ecosystems. Few studies focused on the fact that buoyant objects like LW, may clog water-intake or water-release structures. The transport of driftwood can induce dangerous obstructions at hydraulic structures during floods (Schmocker and Hager, 2011, Pfister et al., 2013b,c, Allen et al., 2014, Iroumé et al., 2015, De Cicco et al., 2015, Piton and Recking, 2016, Hartford et al., 2016, Schalko, 2017, Gschnitzer et al., 2017). Excessive LW accumulations can block flow sections at bridges, weirs or spillways and limit their functionality during extreme flood events, when discharge capacity is mostly needed (Godtland and Tesaker, 1994, Ettema et al., 2000, Marche, 2009). Blockages can exacerbate a flood magnitude and its impact, developing hazardous situations due to a quick augmentation of backwater with flow diversions or local scouring processes (Mazzorana et al., 2011a).

The obstruction risk and the consequent changes, must be considered at different stages of a project. Floating debris can create jams due to insufficient clearance under/above obstacles or too narrow openings. The design of hydraulic constructions should take into account the sensitivity of the watershed to produce floating debris (Bruschin et al., 1982); the physical and geometrical characteristics of the place; the structure sensitivity for blockage, mainly width of openings, overhead clearance and presence of sharp edges (CFBR, 2013, STK, 2017).

Godtland and Tesaker (1994) presented design guidelines to avoid LW blockage above 10-20%

for an **ogee crested spillway with a bridge**. For single trees, the minimum spacing between piers should be 80% of the tree length. When considering the root diameter, different vertical clearances between the spillway crest and the bridge bottom were tested (Figure 2.8). The vertical free space should be larger than 85% of the root diameter. Under the tested conditions, this was equivalent to 15% of the tree length.

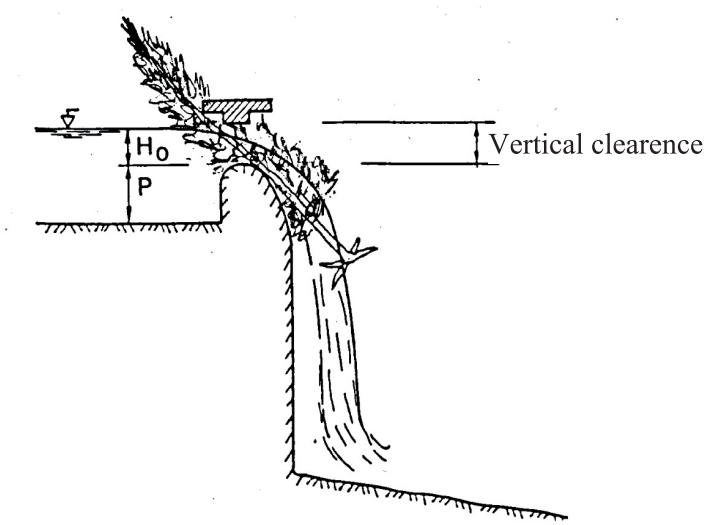


Figure 2.8 – Schematic representation of vertical clearance, adapted from Godtland and Tesaker (1994).

The number of open bays and the geometrical configuration of a dam can affect the likeliness of woody debris passing a spillway opening. When all the spillway bays are functioning, the movement of stems tends to be more erratic in comparison to a single open bay (Johansson and Cederström, 1995, Hartford et al., 2016). With only one bay functioning, LW tends to align to the stream lines and passes more frequently to the downstream side of the dam.

For **ogee crested spillways with gates** a quantification of blocking probabilities was presented by Hartlieb (2012). For relations of stem length to bay width (L/b) ranging from 1 to 2, blockage can be estimated with Equation 2.6,

$$\hat{\Pi} = (L/b - 0.96) \cdot 0.73 \tag{2.6}$$

where $\hat{\Pi}$ represents the estimate of the blockage probability, L the stem length [m], and b the bay width [m]. Under the tested conditions, the approach flow and the Froude number had no significant influence on $\hat{\Pi}$ (Hartlieb, 2015). This formulation was obtained for Froude numbers ranging from 0.072 to 0.350 and H from 0.175 to 0.45 m.

For **piano key weirs** (PKW), Pfister et al. (2013b) presented a quantification of blockage for relations of stem diameter to hydraulic head (d/H) from 0.33 to 1 (Equation 2.7),

$$\hat{\Pi} = 1.5 \cdot (d/H) - 0.5 \tag{2.7}$$

where d represents the stem diameter [m], and H is the total upstream head relative to the crest elevation [m]. Under the tested conditions, stems with a relatively short length under relatively high upstream heads (relative to the crest elevation) passed the PKW independently of location and initial orientation.

For **bridge decks**, the blocking of individual stems was analysed in Schmocker and Hager (2011). The tested Froude numbers ranged between 0.3 and 0.8, as with lower values stems would not have contact with the structure (with the resulting freeboard there was no contact of single stems with the bridge deck) and higher values would unblock them. Blockage can be estimated with Equation 2.8,

$$\hat{\Pi} = L/b \cdot (h + d/2)/h_o \tag{2.8}$$

where b is the channel width [m], h the approach flow depth [m], and h_o the bridge clearance [m].

For **bridges with and without piers**, blocking probabilities of stems were analysed in Gschnitzer et al. (2015). Blockage was defined as a stem spending more than 30 seconds at the bridge. It was demonstrated that cylindrical stem geometries have lower blockage probability than natural geometries. Their blockage estimation of stems at the bridge relate geometrical, hydraulic and LW characteristics. Blockage increased with increasing initial water level (bringing stems closer to the bridge structure) and increasing channel slope, stem length, number of branches, and quantity of stems travelling simultaneously.

For **slit-check dams**, Shrestha et al. (2011) studied the interaction between debris flows and LW with a numerical and a physical model. A relation was obtained for blocking probability at a slit-check dam as a function of the number of stems reaching the structure simultaneously.

$$\hat{\Pi} = 0.23 \cdot (L/(b-d))^{1.02} \cdot n^{0.28} \tag{2.9}$$

where b is the slit width [m] and, n the number of stems arriving simultaneously. For the tested conditions, n takes the values of 1,2,3 and 4 stems.

For small velocities, as typical in the vicinity of **reservoir spillways**, LW accumulations tend to form a "carpet" with a loose volume mainly floating on the water surface (Hartlieb, 2012). When velocities are increased, water flows underneath of the jam and will change its shape first into a prismatic body and gradually into parallelepipeds depending on the flow velocity and duration of sojourn (Bruschin et al., 1982). This shape change could be influenced by the density of the floating material besides the hydraulic conditions (Hartlieb, 2012).

Due to accumulations of LW, the reduced free flow cross section results in a backwater rise upstream of the structure (Lyn et al., 2003, Johansson and Cederström, 1995). Rusyda et al. (2014), for the tested single pier bridge, estimated a relation between LW volume blocked to a loss coefficient and determined the head losses near critical flows or higher. The influence of LW blocked on the backwater rise, for a vertical debris rack, was found to be dependant on the

approach flow Froude number, compactness of the LW accumulation, and percentage of organic fine material (Schmocker and Hager, 2013, Schalko et al., 2018).

2.7 Hydraulic modeling of large wood: physical models

Hydraulic modeling remains one of the principal engineering tools to design and optimize complex hydraulic processes (Pfister et al., 2013a). Physical models are useful tools when designing structures exposed to appreciable amounts of LW as they can reproduce the behaviour of drifting wood. However, physical modelling of LW processes is challenging due to its intrinsic uncertainties, scaling and diversity of governing parameters.

To analyse driftwood interactions with structures, physical models have been used as they allow to systematically investigate different aspects of the process (Wilcox and Wohl, 2006). Given that driftwood is naturally in contact with water, a physical model should quantify realistically the variability of LW characteristics (Mazzorana et al., 2017). In Schmocker and Hager (2013), wood density was only considered for the experimental design and not for the head increase upstream of the rack. The aim was to represent floods of some hours, therefore it was decided to soak the woody material less than 8 hours and keep a relatively constant wood density during the experiments. For the tested conditions, stem density was only influential in the head increase upstream of the structure when stems were fully submerged.

From the revised literature, the main parameters studied for blocking estimations have been the Froude number, the hydraulic weir head (or flow depth) relative to the stem diameter and the opening of the structure relative to the length of the woody material (Lyn et al., 2003, Schmocker and Hager, 2011, Shrestha et al., 2011, Hartlieb, 2012, Pfister et al., 2013b, Piton and Recking, 2016, Gschnitzer et al., 2017, Schalko, 2017). The geometry of stems has also been considered as an important parameter for transport and when interacting with hydraulic structures. Considering the exposure of driftwood to external forces and the time in contact with water, it could be expected that drifting wood arrives at hydraulic structures, such as spillways, more or less free of longer branches (Hartford et al., 2016) (as seen in the figures of section 2.2).

2.8 Hydraulic modeling of large wood: numerical modeling

Up to now, few authors have modelled the behaviour of LW floating on water surface. Numerical simulations with non linear behaviour can be conducted but simplifications and assumptions must be taken as there is still no available information for stochastic approaches. LW blockage cannot be accurately simulated by numerical models as no physical–mathematical formulation that encompasses all parameters has been proposed so far. Some of the numerical models reviewed had to assume movement restrictions to avoid stem colliding or rotating in the vertical plane (only translation of the cylindrical bodies was represented) (Shrestha et al., 2009). The process of LW accumulation or interactions among multiple pieces is challenging given

the randomness involved (Braudrick and Grant, 2001) and so, assumptions of the probability distribution for blockage interfere with the basic understanding of the phenomena. A 2D model was developed coupling LW behaviour and the hydrodynamics of a stream in Ruiz-Villanueva et al. (2014a). Additionally, the transport of a cylinder in a two-dimensional stream based on a dynamic approach has been recently accomplished in Persi et al. (2018). Previously, models would first perform the hydraulic simulations and after, results would be bridged with analytical or experimental approaches for the LW behaviour as in Mazzorana et al. (2011a), for example. Nonetheless, a 2D model for blockage studies is not enough as the third dimension becomes important when stems are trapped at hydraulic structures.

Simplifications in the geometry of stems is a common technique for experimental and numerical work. Complex shapes of trees and their interaction with water for 3D numerical models is still not accurately represented and there is plenty of work ahead (Xu and Liu, 2016).

2.9 Influence of experimental number of repetitions in large wood studies

LW experiments provide only restricted approximations of reality (Piton and Recking, 2016), where uncertainty and data scattering are present (Schmocker and Hager, 2013). The scattering of results can be correlated to the accuracy of such estimation and thus, it should be treated with caution.

In the experimental campaigns to analyse LW movement and transport parameters inside streams, Braudrick et al. (1997) and Braudrick and Grant (2000) performed five trials per experiment. Braudrick and Grant (2001) sought to obtain accurate and reliable results and minimize statistical error by repeating each experiment a maximum of 10 times. Bocchiola et al. (2006a,b) used 3 repetitions per experiment to improve accuracy and minimize human errors when estimating entrainment of LW in rivers. Welber et al. (2013) repeated experiments 10 times to study bed morphology and LW dispersal.

Statistical accuracy in experimental campaigns was examined in Schmocker and Hager (2011) where an evaluation of the number of repetitions was performed. Recent research of Schalko (2017) proposed a maximum standard deviation limit of 0.10 to define the necessary number of experimental repetitions. In spite of their relevance to the topic, these works do not provide general methods or guidelines to be used by others.

Table 2.1 shows the repetitions for studies of LW interacting with hydraulic structures. Godtland and Tesaker (1994) used physical experiments to define construction recommendations for an overflow weir. These guidelines were later used in Johansson and Cederström (1995), Wallerstein et al. (1996), Wallerstein and Thorne (1995), Galeati (2009), Hartlieb (2015), among others. However, their methodology of experiments and the respective analysis was not documented.

Table 2.1 – LW experiments with hydraulic structures and number of repetitions.

Author	Subject of study	Repetitions
Godtland and Tesaker (1994)	LW blocking at gated ogee weirs	?
Johansson and Cederström (1995)	LW blocking at gated ogee weirs	?
Lyn et al. (2003)	LW accumulation at bridge piers	16 to 50
Bocchiola et al. (2008)	LW accumulation patterns	4
Schmocker and Hager (2011)	LW blocking for bridges	8
Hartlieb (2012)	LW jam at gated ogee crested weirs	20
Schmocker and Hager (2013)	LW accumulation at debris rack	3
Pfister et al. (2013b)	LW blocking at piano key weirs	25 to 50
De Cicco et al. (2016)	LW accumulation at bridge piers	10
Gschnitzer et al. (2017)	LW blocking at bridge piers	8
Schalko (2017)	LW accumulation at bridge piers	40
Schalko et al. (2018)	LW accumulation at debris rack	3

Blocking probabilities were evaluated in Johansson and Cederström (1995) for an overflow weir. The main parameters tested were the ratio of stem length to the bay opening and the vertical clearance between a bridge and the weir. Fifty stems were tested, individually or in pairs. It is not clear if each stem was considered as one experiment or if a stem would represent one repetition of an experiment for the case of individual blockage. The same question arises in the case of pairs, that is, did an experiment consist of providing two stems simultaneously and was it repeated 25 times? For the case of PKW, Pfister et al. (2013b) repeated between 25 to 50 times experiments of individual stems for LW blocking probabilities.

Bocchiola et al. (2008) used 4 repetitions to predict wood accumulation patterns that can be used for evaluation of hazard at hydraulic structures, giving a simplified overview of the multifaceted process of LW jams with a statistical approach. To describe LW characteristics and their effect on the jam shape and on the discharge capacity at blocked overflow spillway inlets, Hartlieb (2012) repeated experiments 20 times. In Hartlieb (2015) the LW jamming process and its effects were applied to the design of a debris rack.

When estimating blocking probabilities at bridge decks, Schmocker and Hager (2011) performed preliminary experiments seeking a compromise between test effort and accurate probability interpretation. It was noted that from 8 to 30 repetitions, no improvement in the statistical accuracy was achieved although the statistical analysis was not documented. A risk assessment tool was defined by using their blocking probability equation to estimate, before a flood, if blockage of single stems or rootstock would occur at a bridge. Gschnitzer et al. (2017) used 8 repetitions for a statistical assessment on bridge clogging process with LW, associated to flood risk management.

De Cicco et al. (2016) defined 10 repetitions per experiment to investigate LW accumulation

at historical bridge piers. For great number of supplied LW and five different pier shapes, the capacity of LW blocking for each pier shape was tested and compared. Lyn et al. (2003) aimed to have higher accuracy with the experiments using a maximum of 50 repetitions. However, it was concluded that 50 repetitions were not enough for having a so called "stable result", in order to understand the physical processes involved in single-pier debris accumulation at bridge crossings. Schalko (2017) performed 300 repetitions of a single experiment to determine a statistical reliable number of repetitions. Under the tested conditions, it was observed that after 40 repetitions the standard deviation calculated was less than 0.10 (maximum limit defined by the authors). Other combinations of parameters tested required 60 repetitions to reach the desired standard deviation.

A sensitivity analysis of repetitions for head increase experiments due to LW blockage at a debris rack was made in Schmocker and Hager (2013) and Schalko et al. (2018). For head increase measurements, repeating 3 times each experiment resulted in standard errors of estimations lower than 10%.

2.10 Research needs

The previous sections highlighted the research done for LW processes such as entrainment, transportation and LW interactions with hydraulic structures mainly inside rivers. To date, investigation of large wood dynamics has focused principally on riverine environments. But what happens when large wood moves into reservoirs? The blockage of a spillway can be dangerous and hazardous. The randomness of LW behaviour has been acknowledged as a crucial aspect and gaps in knowledge were found present, demanding the need of further research.

Although previous studies provide important contributions, the interaction of main recognised parameters for the estimation of blocking probabilities of large wood is not completely understood. In order to properly assess and mitigate the inherent risk of large wood blockage at a spillway inlet, a statistical approach is needed.

Moreover, the events presented in this literature review underlined the damages and uncertainties connected to a spillway blockage. Head increase estimations are crucial for better assessments of risk and to improve the hydraulic design of structures when dealing with large wood.

Overall, the following issues have been recognised:

- An experimental protocol based on a significant number of test repetitions is of primary importance. Statistically sound conclusions on LW blocking processes can be obtained. Reliable procedures of experimentation to estimate accurate blocking probability are to be elaborated, linking statistical tools with engineering practice.
- The difficulty to investigate LW blocking probability relies in two points: first, study cases only allow analysis of singular events; and second, many experimental programs lack

sufficient repetitions. Without accurate results, a probabilistic approach to understand and estimate LW blocking is not possible. A qualitative and quantitative study of LW parameters (i.e. stem length, diameter and density) and hydraulic/structural conditions (i.e. head, bay width, number of open bays) influencing LW blockage is needed. Additionally, LW density has been considered an important factor in transport processes but no previous knowledge is available for its influence on the blocking probability.

- Previous studies dedicated little or none attention to the influence of the supplied number of stems on the LW blockage process. Studies range from individual stem experiments to great volumes of LW, thus a gradual transition is absent. By understanding how the blocking probability is affected by the number of supplied stems, respect to individual stems, the different scenarios can be compared.

- LW blockage in a structure leads to unforeseen efforts and impacts affecting its performance and causing head increase. For some retention structures, studies of head increase are being performed, but other types of structures were not considered. The relation of LW blocked at a spillway inlet with the head increase should be assessed.

3 Materials and methods

3.1 Overview

The present research project focuses on two main aspects. First, to quantify the influence of dominant parameters for the blockage probability estimation of stems at an ogee crested spillway with piers. Second, to measure the effect of blocked stems on the head increase upstream of the structure.

The investigation is based on an experimental approach. A physical facility was defined based on the literature review. The facility and the methodology used for the experimental campaign is presented in this chapter.

3.2 Dimensional analysis

The variables that influence the LW blockage process may be identified through a dimensional analysis considering existing literature. The main parameters identified amidst literature for LW processes are shown in Table 3.1, with the dimensions in a 3-dimensional system (mass, length, time).

The natural roughness of wood, although important for studies concerning the beginning of transportation processes (Pagliara and Carnacina, 2010), it was not considered herein. Based on literature, θ was discarded as LW tends to align itself with the flow direction upstream of the structure (Braudrick and Grant, 2001, Pfister et al., 2013b, Schmocker and Hager, 2013, Welber et al., 2013, Davidson et al., 2015) often rotating significantly as it travels (Lyn et al., 2003). After these simplifications, the remaining parameters have been selected to investigate.

According to the Buckingham theorem, 14 - 3 = 11 dimensionless parameters should be considered to describe the blocking probability process. These are shown in Equation 3.1.

$$\hat{\Pi} = f\left[\frac{h}{b}, \frac{h}{d}, \frac{h}{L}, \frac{\rho_w}{\rho}, \frac{h}{L_{PN}}, \frac{h}{d_{PN}}, Fr, Re, We, G_i, N_{OP}\right] \tag{3.1}$$

Table 3.1 – Dimensions of parameters

		Mass	Length	Time
1	v (mean inflow velocity)	0	1	-1
2	ρ (water density)	1	-3	0
3	h (flow depth)	0	1	0
4	d (LW diameter)	0	1	0
5	L (LW length)	0	1	0
6	ρ_w (LW density)	1	-3	0
7	κ (LW rugosity)	0	1	0
8	b (opening of the structure - bay width)	0	1	0
9	L_{PN} (protrusion of the pier-nose into the reservoir)	0	1	0
10	d_{PN} (diameter of the pier-nose)	0	1	0
11	g (gravity acceleration)	0	1	-2
12	μ (water viscosity)	1	-1	-1
13	σ (surface tension)	1	0	-2
14	θ (angle of the LW relative to the flow direction)	0	0	0
15	T (LW jam height)	0	1	0
16	L_j (LW jam length)	0	1	0
17	G_i (number of LW pieces)	0	0	0
18	N_{OP} (number of open bays)	0	0	0

From this analysis, the Froude, Reynolds and Weber numbers are involved. Only the Froude similarity is considered herein due to free surface flow (section 3.3.3). Combining the dimensionless parameters of Equation 3.1 and removing the Reynolds and Weber number, some well known dimensionless parameters are shown in Equation 3.2.

$$\hat{\Pi} = f\left[\frac{L}{b}, \frac{h}{d}, \frac{\rho_w}{\rho}, \frac{h}{L_{PN}}, \frac{h}{d_{PN}}, Fr, G_i, N_{OP}\right] \tag{3.2}$$

For the evaluation of blocking probability of large wood, the pier nose geometry has been set constant due to the great number of parameters evaluated. The nose protrusion L_{PN} was only varied in the experiments of Chapter 4 for the analysis of the required number of experimental repetitions.

Since we are dealing with a reservoir flow type, the inflow velocity has a small magnitude and Fr numbers are typically below 0.01. Nevertheless, the hydraulic head H was calculated taking into account the kinetic energy and the flow depth. In the following chapters, the analysis will be presented for H instead of h. Therefore, the nondimensional relations to be evaluated in the following chapters for blocking probability estimation are summarized in Equation 3.3.

$$\hat{\Pi} = f\left[\frac{L}{b}, \frac{H}{d}, \frac{\rho_w}{\rho}, G_i, N_{OP}\right] \tag{3.3}$$

3.3 Experimental facility

3.3.1 Experimental set-up

To design the physical model, the most frequently used overflow spillways and piers were reviewed. The ogee crested weir with round nose piers was chosen due to its effective discharge capacity and frequent application in practice. Its ability to pass flows efficiently and safely, when properly designed, has enabled engineers to use it in a wide variety of situations (Savage and Johnson, 2001). A vertical upstream face with a smooth chute was defined. The Equation 3.4 was used (Chow, 1959, Vischer and Hager, 1998),

$$Q = C_Q L_Q H^{3/2} \tag{3.4}$$

where Q is the discharge over an uncontrolled ogee crest $[m^3/s]$, C_Q is a discharge coefficient, L_Q the effective crest length [m], and H is the total upstream head relative to the crest elevation [m].

Experiments were carried out in a 10 m long and 1.50 m wide straight channel assembled at the Laboratory of Hydraulic Constructions (LCH) of the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. An ogee crested weir (USACE, 1987) was located at the end of the channel (Figure 3.1).

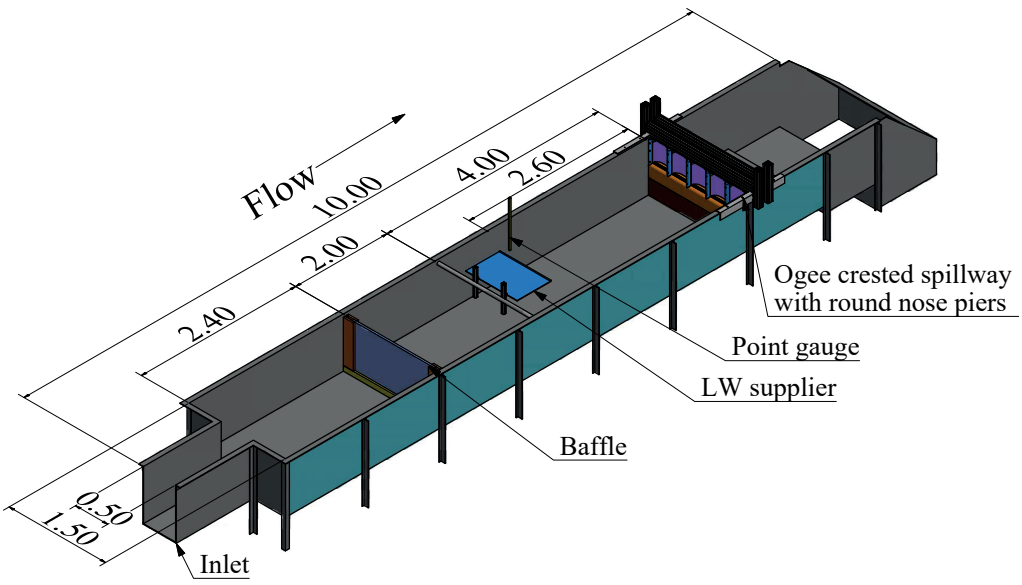


Figure 3.1 – 3D representation of the channel with the model built (dimensions in m).

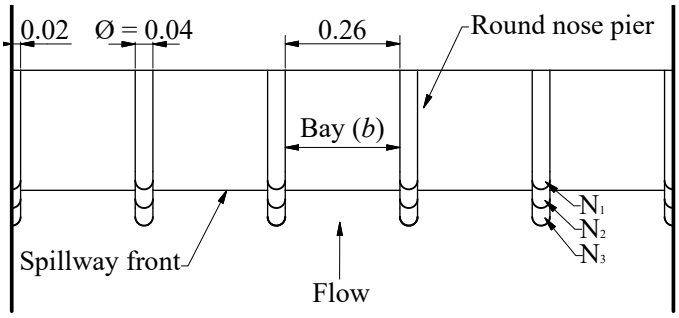
Three different configurations of round nose piers were done, focusing on the nose intrusion in the upstream face of the weir, namely (Figure 3.2a):

N_1 : Aligned with the front of the weir

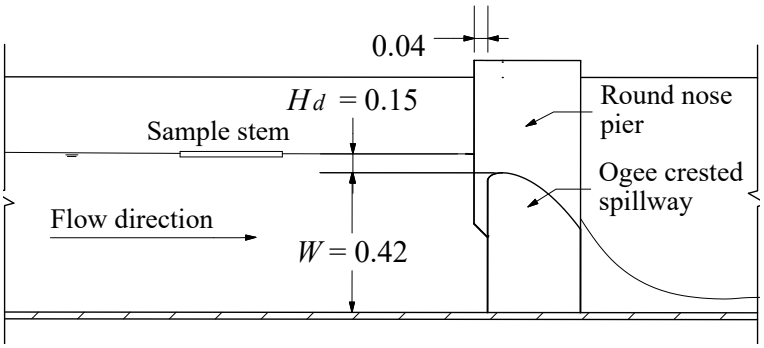
N_2 : Protruded 0.04 m from the weir into the reservoir

N_3 : Protruded 0.08 m from the weir into the reservoir

Round nose piers created 5 symmetrical bays of width $b = 0.26$ m for a design head $H_d = 0.15$ m and weir height of $W = 0.42$ m (Figure 3.2b). The piers had a transversal thickness of 0.04 m. The weir and piers were fabricated from PVC thus were considered hydraulically smooth.



(a) Top view of the physical model



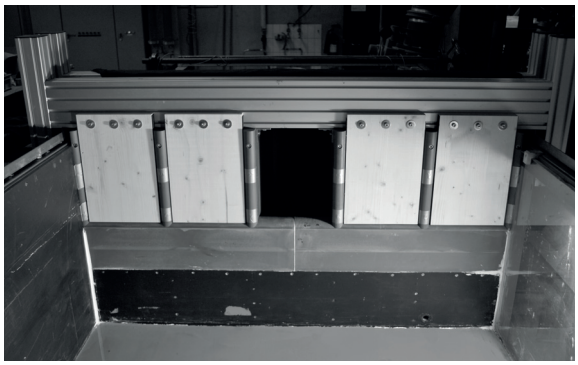
(b) Longitudinal view of the channel with pier nose N_2

Figure 3.2 – Schematic representations of the model built (dimensions in m).

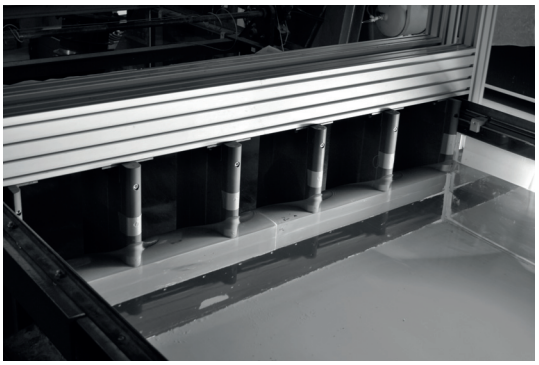
The number of open bays could be changed thanks to removable vertical gates that could be attached to a support metallic beam (Figure 3.3a and b). A baffle was placed 2.40 m downstream of the channel inlet to assure homogeneous flow (Figure 3.3e); further explanation can be found in Section 3.3.4.

The design of the physical model permits flexibility in combinations. A metallic beam was used to support the piers above the spillway and was attached outside of the flume. The beam could be moved vertically along the columns and the piers can be moved horizontally (Figure 3.3c).

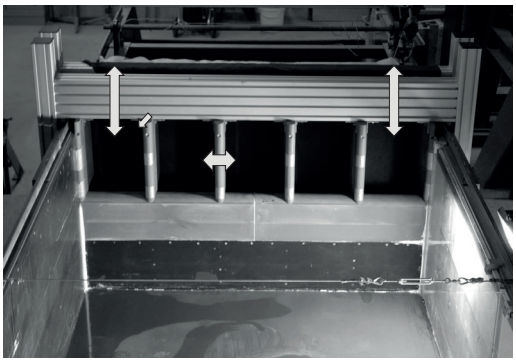
A mechanical equipment was designed to supply the LW (Figure 3.3f). It was chosen to work with a PVC plate controlled manually. The columns of the device allowed to vary its vertical position.



(a) One open bay



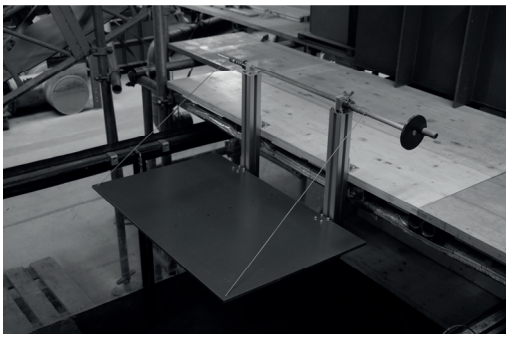
(b) Five open bays



(c) Movement possibilities

(d) Connection between piers and metallic beam

(e) Baffle inside the channel (downstream view).



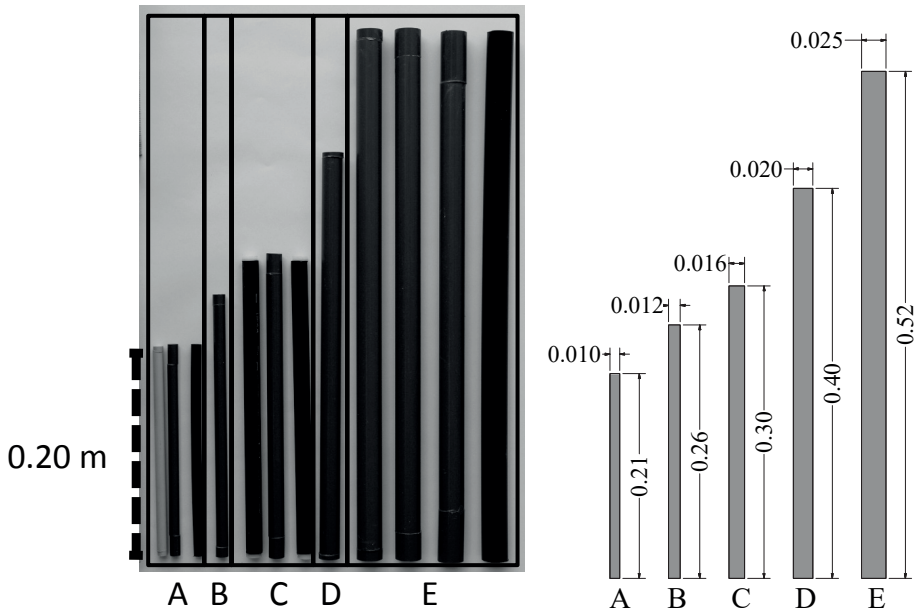
(f) Equipment used to supply the stems

Figure 3.3 – Physical model built at LCH.

3.3.2 Artificial stems

Artificial plastic stems with constant cylindrical geometry were chosen to represent LW in the experiments. Geometrical irregularities were excluded due to the large number of parameters

evaluated (Figure 3.4). Priority was given to cylindrical geometries so the shape would remain constant while easily changing the weight of stems or their size.



(a) Artificial stems used

(b) Schematic representation of artificial stems (m)

Figure 3.4 – Classes of artificial stems used in the experiments.

Stems were separated in classes according to their relation of length L and bay width b (equal to 0.26 m, Section 3.3.1), defined as relative stem length L/b. Four categories of stem density (further referred to with subscript s and the category number) were defined and normalized with respect to water density ρ ($\rho_s = \rho_w/\rho$): ρ_{s1} = [0.40 - 0.47[; ρ_{s2} = [0.47 - 0.67[; ρ_{s3} = [0.67 - 0.88[; ρ_{s4} = [0.88 - 0.99[. In these categories, ρ_{s1} represents densities of light wood (Chave et al., 2009), ρ_{s2} represents average dry wood in Europe (Chave et al., 2009) or instream wood, ρ_{s3} green wood (Ruiz-Villanueva et al., 2016a) and ρ_{s4} can be considered as waterlogged large wood (Buxton, 2010). The dimensions of each class with the respective stem density is shown in Table 3.2. Stems were fabricated using PVC and PE pipes with covers attached in the extremes to have stagnant bodies.

The range of the stem length was chosen to cover different relative stem lengths L/b compared to bay opening, but keeping constant $L/d \simeq 20$ as seen in field observations after the 2005 flood in Switzerland (Bezzola and Hegg, 2007). Class **A** has a relative length of 80% and is of particular interest since it was recommended by Godtland and Tesaker (1994) as a minimum bay width for spillways in contact with LW to have blocking probabilities lower than 20%. Class **E** has a relative length of 200% respect to the bay width.

Table 3.2 – Artificial stems used (Model dimensions)

Class	Length L [m]	Diameter d [m]	L/b [%]	Stem density ρ_s [-]
A	0.210	0.010	80	0.59
				0.79
				0.99
B	0.260	0.012	100	0.56
C	0.300	0.016	120	0.43
				0.56
				0.97
D	0.400	0.020	150	0.63
E	0.520	0.025	200	0.40
				0.54
				0.76
				0.99

3.3.3 Scale effects

Working with physical models in a laboratory involves an attempt to represent prototype conditions with a smaller scale. In free-surface flows (e.g. rivers and wave motion), gravity effects are predominant. Model-prototype similarity is performed usually with a Froude similitude. Scale models based upon the Froude similitude may overestimate effects related to the fluid surface tension σ and the viscosity μ as the use of another fluid than water is not possible (Chanson, 2004, Peltier et al., 2015). This leads to retarded overflow under small weir heads, affecting the rating curve. The surface tension effect on the rating curve is negligible if the flow depth exceeds some 0.015 to 0.02 m particularly for standard ogee weirs (Breitschneider (1978), seen in Pfister et al. (2013a)). Pfister et al. (2013a) state that a head of 0.015 m generates an error of 5% only in terms of discharge coefficient at a piano key weir. Herein, heads ranging from 0.008 to 0.027 m were tested for the blocking probability estimations and from 0.028 to 0.03 m for the head increase measurements (see Section 3.4). The rating curve of some tests was accordingly potentially influenced by surface tension for the estimation of stems blockage probability. The experiments with artificially blocked stems may be influenced by surface tension effects. For the experiments of head increase with batches, the values of head used (H = 0.028 m and 0.030 m) are above the aforementioned limits.

The physical model designed is not related to a prototype or case study, therefore no scale factor was defined. It was intended to reflect different conditions, for an ogee crested weir with piers, to interpret the influence of LW parameters in the blockage process.

3.3.4 Model effects

As noticed in literature, driftwood models have scaling issues regarding mechanical properties of wood. In prototype, driftwood when lodged inside a spillway can break due to interactions with other pieces. In the model, stems could never produce the necessary force to break other pieces. Hence, only the movement of stems was simulated and not the breakage nor the bending of driftwood (Hartung and Knauss, 1976, Schmocker and Hager, 2011, Pfister et al., 2013b, Simonett et al., 2012). In addition, the rugosity of wood was not scaled.

In LW experiments, if side-walls effects are present the movement of the stems can be modified due to contacts with the flume walls (Savage and Johnson, 2001, Braudrick and Grant, 2001, Bocchiola et al., 2008). To avoid such effect, stems were always supplied in the flume centre axis. For the individual stem experiments, if stems would stop their motion due to interactions with the lateral walls, the experiment was ceased and restarted. For the case of groups, if stems were stopped in the lateral walls they were consider as passed.

A baffle was designed to overcome the jet effect linked to the expansion of the flume section, assuring a uniform velocity field. A metallic grid was installed 2.40 m downstream of the expansion (Figure 3.1 and Figure 3.3e). To evaluate its efficiency, flow velocity was measured in a cross-section 2 m downstream of the baffle using a flow probe with a propeller (in total 36 points were measured, Figure 3.5). Measurements were performed for 3 different discharges (Q_1 = 67 l/s, Q_2 = 131 l/s, Q_3 = 183 l/s).

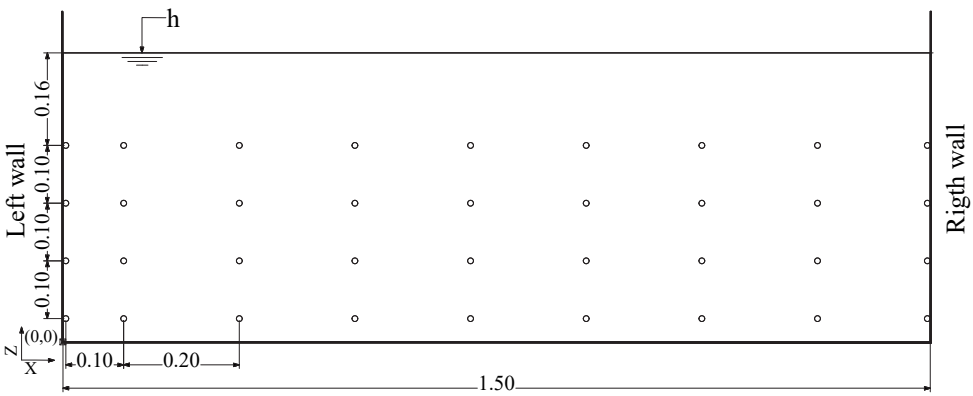
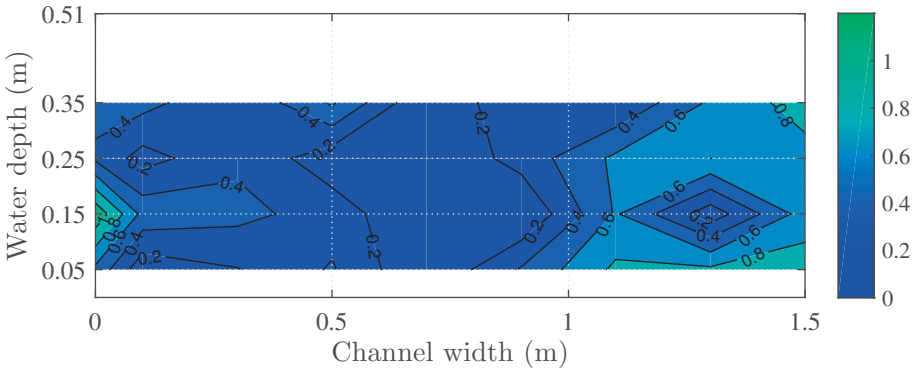
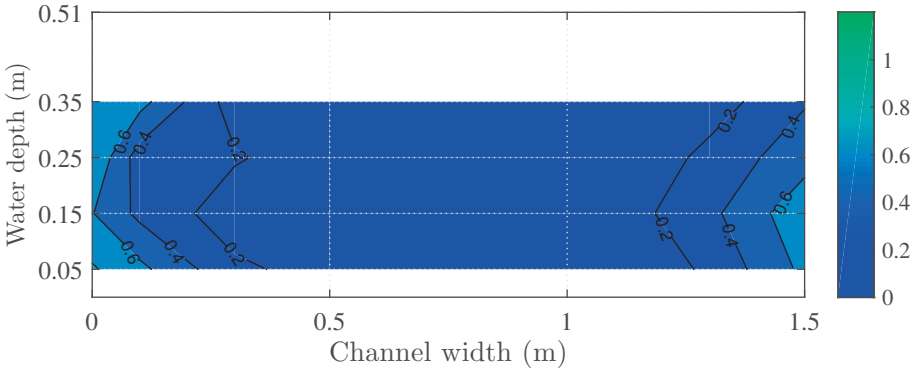


Figure 3.5 – Scheme of the cross-section of measurement points (dimensions in m).

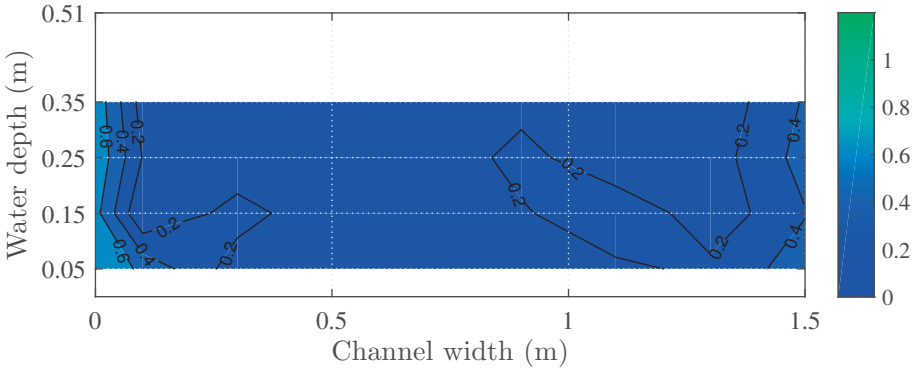
An oscillating jet-flow was detected in the initial condition. A metallic grid was therefore implemented, improving the uniformity of the velocity field in the central area of the channel. Additionally, geotextile layers were added in the central section of the metallic grid to decrease the permeability. The velocity contour plots represent the relative value of flow velocity measured respect to the velocity in the central line (0.70 m from left wall and 0.80 m from the right wall, considering the flow direction) (Figures 3.6 to 3.8). The initial velocity field and the subsequent changes are shown for the three discharges evaluated.



(a) Initial condition

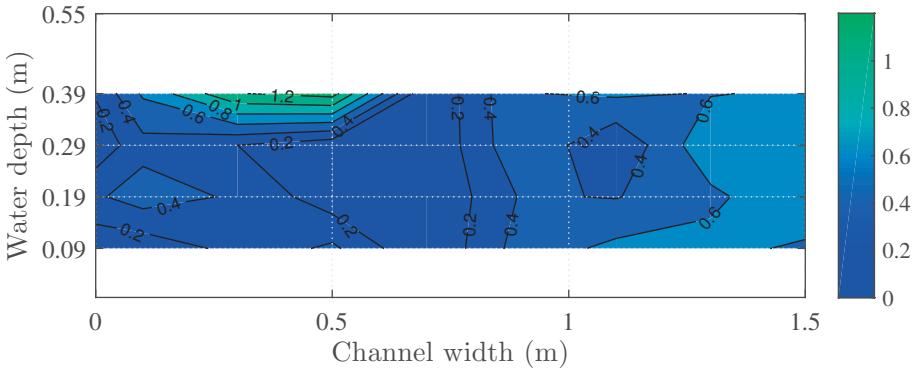


(b) Metallic grid

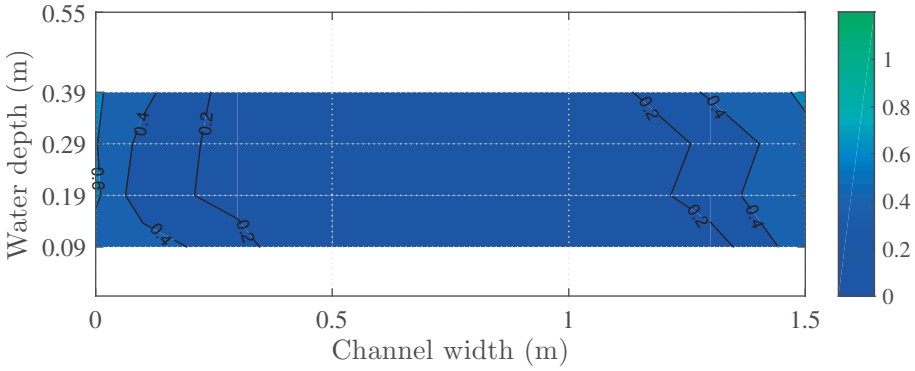


(c) Metallic grid and geotextile

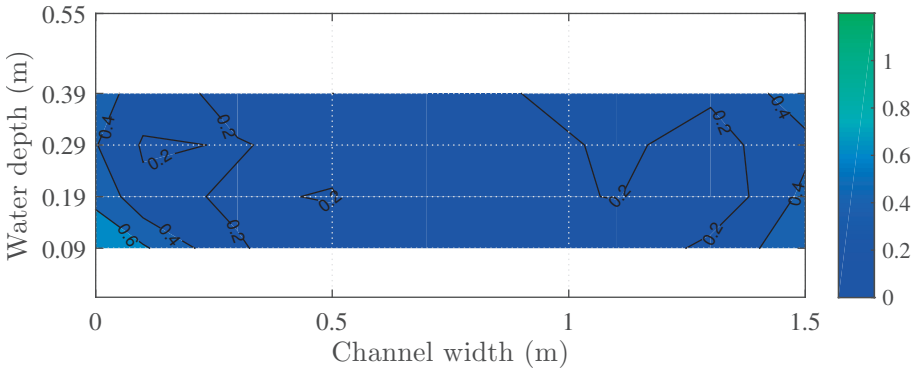
Figure 3.6 – Contour plots of the approach flow in the reservoir for relative velocities with a discharge of 67 l/s.



(a) Initial condition

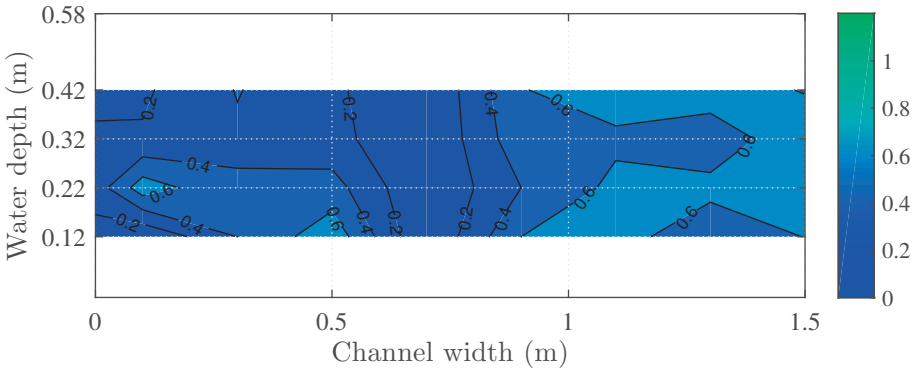


(b) Metallic grid

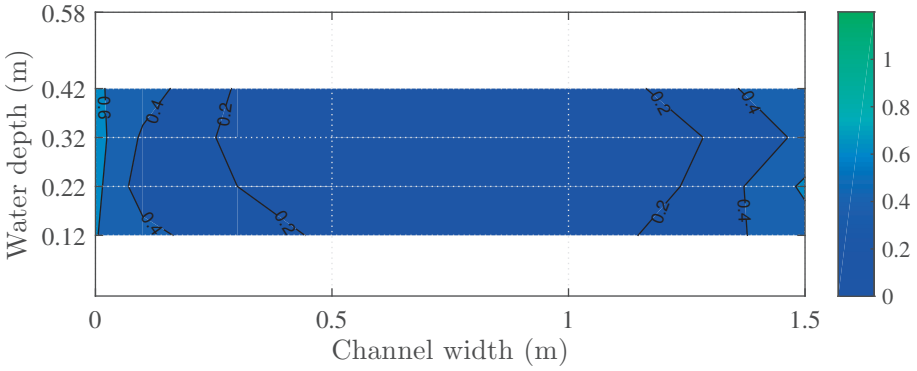


(c) Metallic grid and geotextile

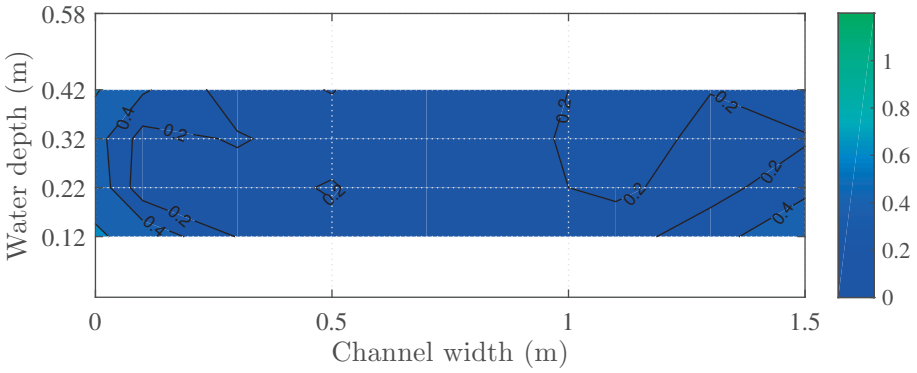
Figure 3.7 – Contour plots of the approach flow in the reservoir for relative velocities with a discharge of 131 l/s.



(a) Initial condition



(b) Metallic grid



(c) Metallic grid and geotextile

Figure 3.8 – Contour plots of the approach flow in the reservoir for relative velocities with a discharge of 183 l/s.

With the addition of the metallic grid, the central 0.90 m of the cross-section had practically uniform velocity fields. With the geotextile addition, for low discharges, a wider cross-section of the flume had uniform velocity field. Also, a polystyrene foam sheet was placed downstream of the baffle to avoid waves in the water surface.

3.3.5 Instrumentation

The water level in the channel was measured 2.60 m upstream of the weir (Figure 3.1) using a point gauge (±0.5 mm) and an ultrasonic distance sensor (±0.3 mm). The discharge Q was measured with a magnetic inductive flow meter (±0.5% at full span). Photographs were taken systematically in order to record each experiment.

3.4 Methodology of experimentation

The experiments were divided into two parts: the first one deals with the LW characteristics and hydraulic conditions to systematically quantify their influence on the estimated blocking probability. The second part, deals with the effect of a blockage at the spillway inlet and the resulting the head increase.

For all experiments, water was conveyed from a tank through a baffle into the channel, ensuring homogeneous flow distribution. At the beginning of the experiment, the flow depth was measured 2.60 m upstream of the structure without stems. A reservoir flow type was analysed, implying small flow velocity.

In this work, only two different open bay scenarios were evaluated namely, only one (central) open bay or five open bays. The central bay was chosen in order to be aligned with the location of the supply point of the stems. Asymmetrical bay scenarios were not evaluated as they would probably influence the trajectory of stems having a more erratic movement, adding more randomness to the blockage probability.

Stems were supplied with a mechanical equipment positioned 4.00 m upstream of the weir, in the flume centre axis. A mechanical device was used to reduce human interaction, guaranteeing equal conditions per repetition. Stems were placed in the plate horizontally (generally parallel to flow direction for blocking evaluations). The plate was manually tilted and stems would smoothly slide into the water and float towards the weir.

For the estimation of blocking probability, the number of stems that blocked at the weir was noted for each experiment. Blockage herein means that stems stopped their motion at the weir or the piers and did not pass further downstream of the weir. After, stems were removed and the procedure was repeated with the same initial conditions. The frequency of an outcome (blockage) after a certain number of repetitions was obtained. The probability of stem blockage was denoted as π, being $1-\pi$ the probability of stem passage. These frequencies were used as estimates of the unknown probabilities found in prototype and will be further referred to as blocking probability. For each experiment, n independent repetitions (trials) were performed.

The maximum likelihood estimator, $\hat{\Pi}$, of the blocking probability π is given by (Eq. 3.5):

$$\hat{\Pi} = \frac{X}{n \cdot G_i} \tag{3.5}$$

where X is the number of blocked stems, G_i the amount of supplied stems per trial (group size), and n is the total number of repetitions. This means that the blocking probability π is estimated as the ratio of the number of stems that blocked with the number of stems that were supplied, averaged in the repetitions. Without loss of generality, both the estimator and the estimate will be denoted by the same symbol $\hat{\Pi}$.

It should be recalled that if $x_1, x_2, ..., x_n$ is a sample of n observations, the sample variance is:

$$s^2 = \frac{\sum(x_i - \bar{x})^2}{n-1} \tag{3.6}$$

The sample variance measures dispersion or variability and the sample standard deviation, s, is the positive square root of the sample variance.

When a mean value is estimated $\hat{\Pi}$, the interest is not in the mean itself but in the mean of the population from which the sample comes π. Data is collected to generalise from the means and make estimates for the whole population. The standard error ($S.E.$) is a measure of the precision of an estimation. The sample mean will vary from sample to sample. It can be estimated how much, different sample means, will vary from the standard deviation of a sampling distribution. As π and its variance are unknown, the values from the samples are used as estimators to obtain:

$$S.E = \frac{s}{\sqrt{n}} \tag{3.7}$$

When the estimator follows a normal distribution, the true value of the parameter can be found within two standard errors of the estimate (Montgomery and Runger, 2011).

For head increase measurement, a batch was supplied in the longitudinal axis of the flume and it was noted the number of stems that blocked. Once stems were blocked, it was waited 5 minutes and a new flow depth measurement was taken with the ultrasonic distance sensor. The stems that passed the weir were collected, quantified and classified. After 10 minutes, another flow depth measurement was taken. If more stems had passed, they were noted. Finally, all stems were removed and the procedure repeated with the same initial conditions.

3.4.1 Varied parameters

The experimental design gave priority to one parameter per time in order to understand its effect for blockage estimations and head increase, systematically.

A list of the parameters and the range of variation is presented herein,

- Stem length relative to bay width $0.80 \leq L/b \leq 2$
- Head relative to stem diameter $0.64 \leq H/d \leq 1.56$
- Stem density $0.40 \leq \rho_s \leq 0.99$

- Group size $1 \leq G_i \leq 200$
- Number of open bays 1 ; 5

The experiments are presented in Table 3.3 for the blocking probability estimation and Table 3.4 for the head increase evaluation. As previously mentioned, supply angle of the stems and pier nose protrusion were only varied in the experiments of Chapter 4. The influence of the supply angle was discarded for the analysis. It was seen that the supply angle was not influential in the stems movement as stems self-pivoted and aligned themselves with the flow direction upstream of the weir. The influence of the nose protrusion, although interesting, had to be discarded due to the challenges the other variables presented and the limited amount of time.

The experimental program will be displayed again at the beginning of each chapter.

Table 3.3 – Experimental program for evaluating influence of LW characteristics and hydraulic conditions on the blocking probability of individual stems and groups (Chapter number indicated in the first column).

Exp. N°	**Class**	**Density ρ_s**	***H/d***	**Open bays**	**Nose type**	**G_i**	**Repetitions**
4 - 1	E	0.54	0.82	5	N1	1	60 (90°)
4 - 2	E	0.54	1.08	1	N1	1	40 (90°)
4 - 3	C	0.56	0.81	5	N1	1	60 (90°)
4 - 4	E	0.54	0.72	5	N1	1	60 (90°)
4 - 5	E	0.76	0.76	5	N1	1	20 (90°)
4 - 6	E	0.76	1.08	5	N1	1	70 (0°)
4 - 7	B	0.56	1.25	5	N1	1	60 (45°)
4 - 8	D	0.63	0.90	5	N1	1	70 (0°)
4 - 9	E	0.54	0.88	1	N2	1	58 (0°)
4 - 10	B	0.56	1.25	1	N2	1	70 (90°)
4 - 11	B	0.56	0.83	5	N3	1	60 (45°)
4 - 12	E	0.40	0.72	5	N3	1	60 (135°)
4 - 13	C	0.43	0.81	5	N3	1	70 (90°)
4 - 14	A	0.79	0.80	5	N3	1	60 (135°)
5 - 1	A	0.59, 0.79, 0.99	1.40	1	N2	1	30
5 - 2	A	0.59, 0.79, 0.99	1.00	5	N2	1	30
5 - 3	A	0.59, 0.79, 0.99	1.20	5	N2	1	30
5 - 4	C	0.43, 0.56, 0.97	0.94	1	N2	1	30
5 - 5	C	0.43, 0.56, 0.97	0.94	5	N2	1	30
5 - 6	C	0.43, 0.56, 0.97	1.06	5	N2	1	30
5 - 7	E	0.40, 0.54, 0.76, 0.99	0.96	1	N2	1	30

Table 3.3. Continuation.

Exp. N°	Class	Density ρ_s	*H/d*	Open bays	Nose type	G_i	Repetitions
5 - 8	E	0.40, 0.54, 0.76, 0.99	0.76	5	N2	1	30
5 - 9	E	0.40, 0.54, 0.76, 0.99	1.00	5	N2	1	30
5 - 10	A	0.59	0.90,1.00, 1.20,1.50	5	N2	1	30
5 - 11	C	0.56	0.56,0.75,0.94, 1.00,1.25,1.56	5	N2	1	30
5 - 12	E	0.54	0.64,0.80, 0.84,0.96,1.00	5	N2	1	30
5 - 13	B	0.56	0.75,1.00,1.25	5	N2	1	30
5 - 14	D	0.63	0.80,1.00,1.25	5	N2	1	30
5 - 15	A	0.59	1.50,1.20	1	N2	1	30
5 - 16	B	0.56	1.00,1.25	1	N2	1	30
5 - 17	C	0.56	0.75,0.94	1	N2	1	30
6 - 1	B	0.56	1.00	5	N2	2	60
6 - 2	C	0.97	1.06	5	N2	4	60
6 - 3	A	0.79	0.90	5	N2	8	60
6 - 4	C	0.43	0.94	5	N2	16	60
6 - 5	B	0.56	1.00	5	N2	32	60
7 - 1	A	0.59	1.00	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
7 - 2	A	0.59	1.20	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
7 - 3	C	0.56	0.94	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
7 - 4	C	0.56	1.00	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
7 - 5	C	0.56	1.06	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
7 - 6	E	0.54	0.76	5	N2	1,2, -,8,16,32	30,15, -,4,3,3
7 - 7	E	0.54	0.84	5	N2	1, -,4,8,16,32	30, - ,8,4,3,3
7 - 8	E	0.54	0.96	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
7 - 9	A	0.59	1.20	1	N2	1,16	30,3
7 - 10	C	0.56	0.94	1	N2	1,16	30,3
7 - 11	E	0.54	0.76	1	N2	1,16	30,3

Table 3.4 – Experimental program for evaluating head increase (Chapter 8).

Exp N°	Class	Density ρ_s	H_0 [m]	Open bays	Nose type	G_i	Repetitions
8 - 1	All	mix	0.028	5	N2	200	30
8 - 2	All	mix	0.030	5	N2	200	30
8 - 1 *	A	0.59	0.010	5	N2	1,2,4,8,16,32	3
8 - 2 *	A	0.59	0.012	5	N2	1,2,4,8,16,32	3
8 - 3 *	C	0.56	0.015	5	N2	1,2,4,8,16,32	3
8 - 4 *	C	0.56	0.016	5	N2	1,2,4,8,16,32	3
8 - 5 *	C	0.56	0.017	5	N2	1,2,4,8,16,32	3
8 - 6 *	E	0.54	0.019	5	N2	1,2, -,8,16,32	3
8 - 7 *	E	0.54	0.021	5	N2	1, -,4,8,16,32	3
8 - 8 *	E	0.54	0.024	5	N2	1,2,4,8,16,32	3

*Experiments were executed by Selene Hewes during a semester project at LCH-EPFL, supervised by Prof. Anton J Schleiss and Paloma Furlan.

4 Influence of experimental repetitions on the accuracy of blocking probability for individual stems[1]

4.1 Overview

The intrinsic variability of LW requires enough repetitions to identify causal relationships, as any other estimation of a random parameter. As described in Chapter 2, the experimental campaigns seen in literature show a lack of agreement for a statistically justified number of experimental repetitions. When dealing with probability estimates, in this case LW blocking, reliable procedures of experimentation are fundamental, linking statistical tools with engineering practice.

In LW-related literature, methods to quantify the accuracy of experimental results were not found. The novelty herein presented is the link of statistical tools with LW research. The accuracy of the estimated blocking probability is evaluated by means of confidence interval calculations. Two well known statistical methods, the Wald and Clopper-Pearson methods, are applied to blocking probability estimations. The results and comparison of different evaluated numbers of experimental repetitions is presented.

4.2 Methodology

Fourteen experiments were defined testing all parameters in random combinations, as detailed in Table 4.1. Experiments were performed for individual stems, supplying one single stem and noting if it blocked or passed the weir.

The supply angle was changed testing four different possibilities, taking 0° as parallel to the flow. The different pier nose types can be seen in Chapter 3. The main parameter that changes from one nose type to the next one is the nose intrusion in the upstream face of the weir, namely: N_1

[1] This Chapter is based on the published article "Experimental repetitions and blockage of large stems at ogee crested spillways with piers" by Furlan P, Pfister M, Matos J, Amado C, and Schleiss A.J (2018) in *Journal of Hydraulic Research*. The experimental work and the analyses presented hereafter are original and were performed by the author.

is aligned with the front of the weir; N_2 protrudes 0.04 m from the weir into the reservoir; N_3 protrudes 0.08 m from the weir into the reservoir.

Table 4.1 – Experimental program for evaluating the influence of the number of experimental repetitions in the accuracy of blocking probability for individual stems

Exp.N°	Class	Density ρ_s	*H/d*	Open bays	Nose type	Repetitions n	Supply angle
1	E	0.54	0.82	5	N1	60	90
2	E	0.54	1.08	1	N1	40	90
3	C	0.56	0.81	5	N1	60	90
4	E	0.54	0.72	5	N1	60	90
5	E	0.76	0.76	5	N1	20	90
6	E	0.76	1.08	5	N1	70	0
7	B	0.56	1.25	5	N1	60	45
8	D	0.63	0.90	5	N1	70	0
9	E	0.54	0.88	1	N2	58	0
10	B	0.56	1.25	1	N2	70	90
11	B	0.56	0.83	5	N3	60	45
12	E	0.40	0.72	5	N3	60	135
13	C	0.43	0.81	5	N3	70	90
14	A	0.79	0.80	5	N3	60	135

Different stem densities ρ_s were defined based on wood density values ρ_w normalized with respect to water density ρ ($\rho_s = \rho_w/\rho$). This has been described in Chapter 3.

For the estimations of blocking probability, the result noted was the number of stems that blocked at the weir. After, stems were removed and the procedure was repeated with same initial conditions. The frequency of an outcome (blockage) after a certain number of repetitions was obtained. The probability of stem blockage was denoted as π, being $1-\pi$ the probability of stem passage. These frequencies were used as estimates of the unknown probabilities found in prototype and will be further referred to as blocking probability. For each experiment, n independent repetitions (trials) were performed.

The maximum likelihood estimator, $\hat{\Pi}$, of the blocking probability π is given by,

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

where X is the number of blocked stems, and n is the total number of repetitions. This means that the blocking probability π is estimated as the ratio of the number of stems that blocked with the number of stems that were supplied, averaged in the repetitions. Without loss of generality, both the estimator and the estimate will be denoted by the same symbol $\hat{\Pi}$.

4.2.1 Statistical analysis

An experiment was defined as one combination of parameters (Table 4.1) and it was composed of several repetitions or trials (n) under constant initial conditions. The 14 experiments performed represent 818 independent results. To analyse the influence of the number of repetitions on the blocking probability estimation, each experiment was considered as a Bernoulli trial where only two outcomes were possible (blocked or passed).

For each experiment, results were normalized with $\hat{\Pi}$ of the last repetition. This normalization helps to examine the variation of π as a function of the number of repetitions. Figure 4.1 shows how normalized blocking probabilities obtained for the 14 experiments varies with the repetitions. For example, the value of the normalized estimated blocking probability for experiment 1, 2, 3, 7 and 12 with less than 6 repetitions is more than twice than the normalized value after 60 repetitions. The overall behaviour observed in the figure is that after some 30 repetitions, the dispersion magnitude of the normalized estimated blocking probability starts to range in ±0.10.

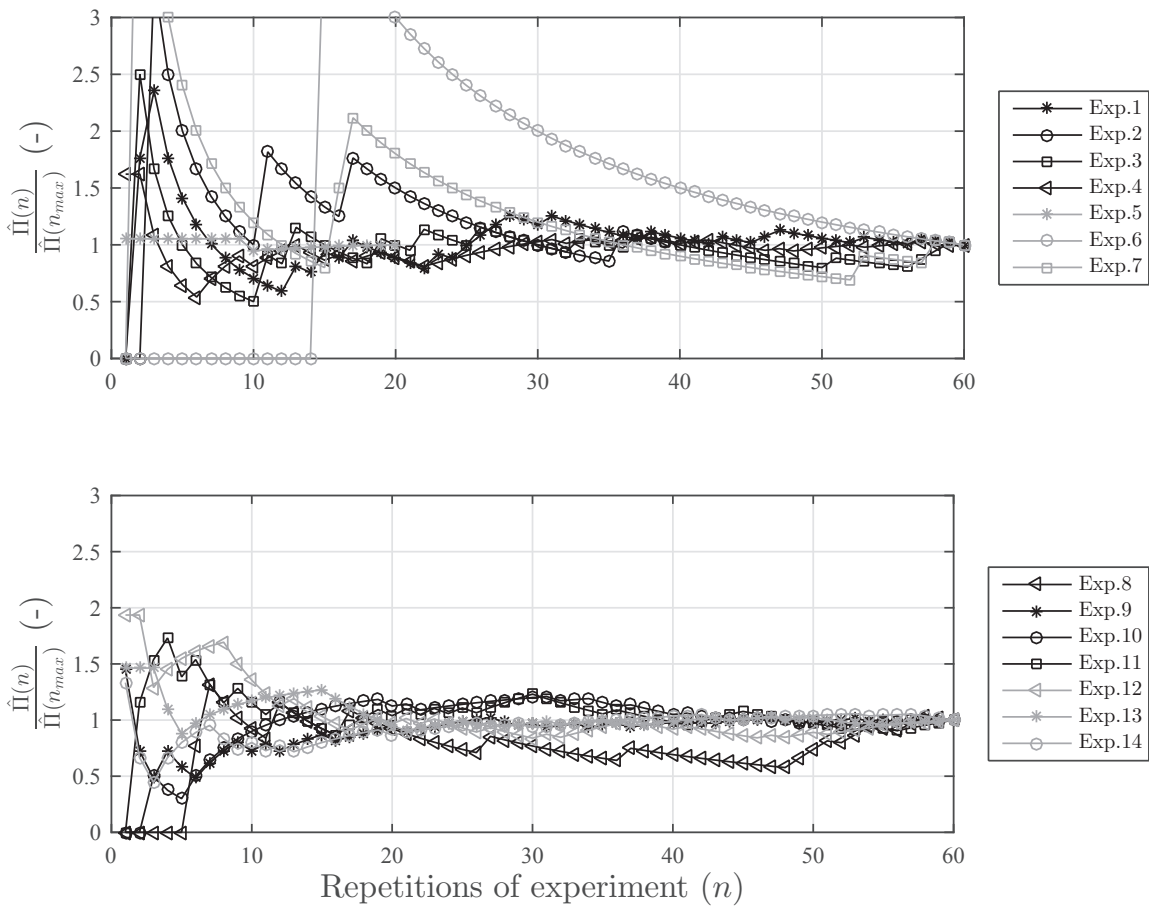


Figure 4.1 – Normalized estimated blocking probability ($\hat{\Pi}(n)/\hat{\Pi}(n_{max})$) in function of repetitions n.

To infer from the experiments, with some confidence, what the real value of π might be, confidence intervals were computed. Confidence intervals allow to understand the variability related to the number of repetitions (sample size) and thus the error of the estimation.

A confidence interval states that, with a given level of "certainty", the true value will likely be in the identified range (Wallis, 2013). The width of the interval will be smaller when higher accuracy in the estimation is achieved. A lower and upper limit defines the interval estimator of π with a pre-defined confidence or coverage, and will be denoted by $[L_L; U_L]$. $[L_L; U_L]$ will have a nominal confidence level of $100(1-\alpha)\%$ (being α the error level) assuring that the interval constructed based on the sampling distribution of $\hat{\Pi}$ will contain the true value of π, that percentage of times (Pires and Amado, 2008). The random variables L_L and U_L depend on X, n and on the method of calculation.

Two common methods were applied to calculate the confidence intervals for π, the "Wald" method and the "Clopper-Pearson" method.

Wald method

The Wald method is the most common approach for calculating symmetric binomial confidence intervals. It is based on the approximation of the binomial by the Normal distribution. If X is binomially distributed with parameters n and π, then X has the same distribution as the sum of n independent Bernoulli random variables (Ross, 2009, Montgomery and Runger, 2011). Then, by the central limit theorem, the binomial distribution can be approximated using a standard Normal distribution as n approaches $+\infty$. A rule of thumb to well-approximate a binomial by a normal distribution can be given by the relation: $n\pi(1-\pi) \geq 10$ (Ross, 2009). The $[L_L; U_L]$ Wald interval estimator of π was calculated according to Equation 4.1.

$$\hat{\Pi} - z_{\alpha/2}\sqrt{\frac{\hat{\Pi}(1-\hat{\Pi})}{n}} \leq \pi \leq \hat{\Pi} + z_{\alpha/2}\sqrt{\frac{\hat{\Pi}(1-\hat{\Pi})}{n}} \tag{4.1}$$

where $z_{\alpha/2}$ denotes the $1-\alpha/2$ quantile of the standard Normal distribution (Vollset, 1993, Agresti and Coull, 1998). The term $\sqrt{\hat{\Pi}(1-\hat{\Pi})/n}$ in this context is the standard error (SE) of the point estimator $\hat{\Pi}$.

Apart from being asymptotic, the Wald method may have two limitations. First, when π tends to the extremes $\{0\}$ or $\{1\}$, the product $\pi(1-\pi)$ tends to 0, leading to an underestimation of the error. Second, the interval can exceed $[0;1]$ limits (Agresti and Coull, 1998, Wallis, 2013).

Clopper-Pearson method

To overcome the normal theory approximations of Wald intervals, the Clopper-Pearson method is suggested to calculate confidence intervals for π. The Clopper-Pearson confidence interval for π with a coverage probability of at least $1-\alpha$ can be obtained by solving Equation 4.2 for L_L and

U_L (Clopper and Pearson, 1934).

$$\sum_{k=x}^{n} \binom{n}{k} L_L^k (1-L_L)^{n-k} = \alpha' \tag{4.2a}$$

$$\sum_{k=0}^{x} \binom{n}{k} U_L^k (1-U_L)^{n-k} = \alpha'' \tag{4.2b}$$

where $\alpha' + \alpha'' = 1$. For $\alpha' = \alpha'' = \alpha/2$ these correspond to the inversion of the two sided exact binomial test and lead to the central exact interval. For $x = 0$ the solution of Eq.4.2 is explicit and given by $L_L = 0$ and $U_L = 1 - (\alpha/2)^{1/n}$. For $x = n$ the solution is also explicit and given by $L_L = (\alpha/2)^{1/n}$ and $U_L = 1$. When $x = 1, 2, ..., n-1$, the lower endpoint is the $\alpha/2$ quantile of a beta distribution with parameters x and $n - x + 1$, and the upper endpoint is the $1 - \alpha/2$ quantile of a beta distribution with parameters $x + 1$ and $n - x$ (Agresti and Coull, 1998). The relation between the beta distribution and the Snedecor's F distribution leads to the following result (Equation 4.3) for the Clopper-Pearson confidence interval for π:

$$\left[1 + \frac{n-x+1}{xF_{2x,2(n-x+1),1-\alpha/2}}\right]^{-1} < \pi < \left[1 + \frac{n-x}{(x+1)F_{2(x+1),2(n-x),\alpha/2}}\right]^{-1} \tag{4.3}$$

for $x = 1, 2, ..., n-1$, and $F_{a,b,c}$ denotes the $1 - c$ quantile from the F distribution with degrees of freedom a and b.

The Clopper-Pearson method provides more reliable confidence intervals with smaller samples than the Wald method (Clopper and Pearson, 1934, Sauro and Lewis, 2005). Clopper-Pearson produces conservative confidence intervals, and are therefore wider (Agresti and Coull, 1998).

4.3 Results and discussion

Figure 4.2 shows the results obtained from an experiment with class E, density ρ_{s1} and pier nose configuration N_3 for $H/d = 0.72$ and five bays open (experiment 12 of Table 4.1). It can be seen that the first and second stem were blocked but the third one passed. For example, the repetition $n = 30$ considers 13 individually provided stems that blocked, divided by 30 provided stems and results in a (estimated) blocking probability of $\hat{\Pi} = 0.43$. The last repetition performed $n = 60$, shows that 31 of 60 stems blocked at the weir, resulting in a blocking probability of $\hat{\Pi} = 0.52$. Between repetition $n = 30$ [$\hat{\Pi}(30) = 0.43$] and $n = 60$ [$\hat{\Pi}(60) = 0.52$], there is a difference between blocking probabilities of $\Delta\hat{\Pi} = 0.09$. If only 4 (like in Bocchiola et al. (2008)) or 20 (like in Hartlieb (2012)) repetitions of an experiment were considered, the estimation of the blocking probability would be 0.75 and 0.50 respectively. This analysis highlights the importance of knowing the variance of the estimated $\hat{\Pi}$ and how it changes with the number of repetitions.

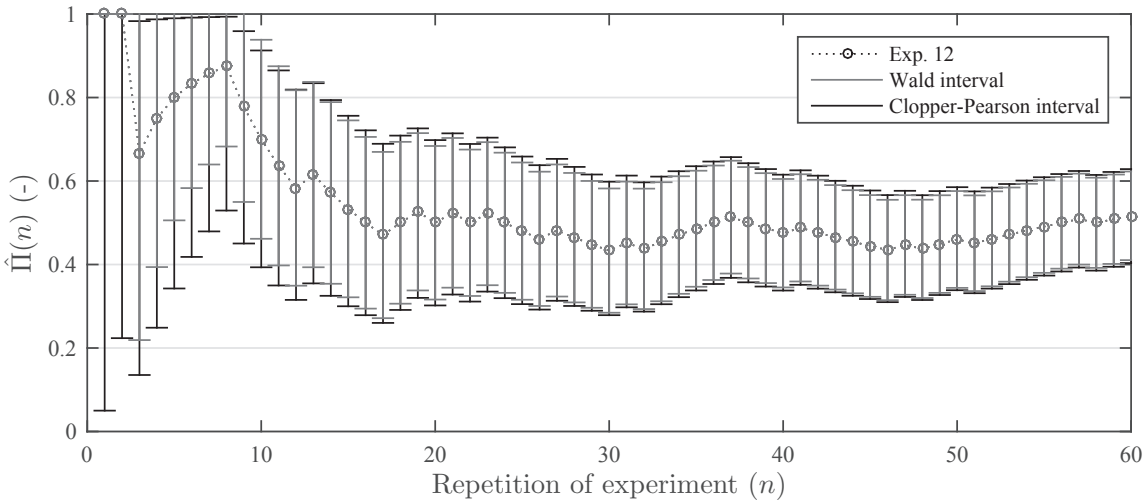


Figure 4.2 – Estimated blocking probability ($\hat{\Pi}(n)$) for experiment 12 (Table 4.1).

Figure 4.3 shows the results of experiment 4 (Table 4.1). In this case, the blocking probability after 30 repetitions is $\hat{\Pi}(30) = 0.63$, meaning that 19 out of 30 stems supplied blocked at the weir. For the repetition $n = 60$, $\hat{\Pi}(60) = 0.62$. Between repetition $n = 30$ [$\hat{\Pi}(30) = 0.63$] and $n = 60$ [$\hat{\Pi}(60) = 0.62$], there is a difference between blocking probabilities of $\Delta\hat{\Pi} = 0.01$ for individual stems.

For each repetition, 90% confidence intervals are presented in Figures 4.2 and 4.3 with the respective error bars. As expected, the confidence interval width reduces when n increases, meaning that the error in the estimation of π decreases, therefore the accuracy of the estimation increases. A confidence level of 95% was also evaluated but the results showed that an excessive number of repetitions ($n \geq 90$) would be needed to achieve errors smaller than 0.10 in the estimation of blocking probabilities.

With the results obtained from the experiments, it was shown that the blocking probability depends on the variables of Table 4.1 as the estimated probability of blockage changed from one experiment to another. Nevertheless, the main focus relies on the influence of repetitions for the accuracy of probability estimations and not on the parameters involved in the process of blockage. The different magnitude of $\Delta\hat{\Pi}(n)$ of Figure 4.2 and 4.3 is influenced by the variables combined for those experiments, but the width of the confidence interval (considering any method) has a similar magnitude. Therefore the accuracy of those results can be considered similar.

The results shown in Figures 4.2 and 4.3 were obtained in the experimental facility using augmented design (Federer and Raghavarao, 1975). The augmented design is a class of experimental design where, because of different constrains, experiments cannot be replicated. Meaning that the experiments herein presented are a sample with n experimental repetitions but they are only

one sample. In order to achieve a consolidated analysis, different sample sizes by subsampling bootstrap (Politis et al., 1999) have been computed for the estimated blockage probability.

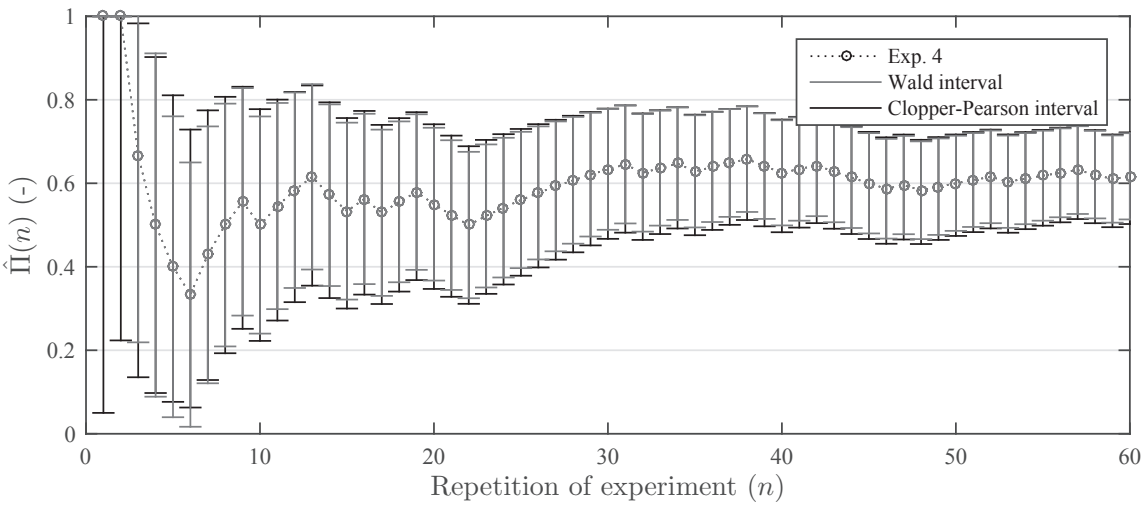


Figure 4.3 – Estimated blocking probability ($\hat{\Pi}(n)$) for experiment 4 (Table 4.1).

Figure 4.4 shows experiment 12 (Table 4.1) as an example of the error bars obtained after 1000 re-samples with different sample sizes. It can be seen that the variability in the width of the confidence interval is similar to that seen in Figure 4.2 based on augmented design; as the sample size and the repetitions increased, the confidence in the estimated blocking probability increased accordingly. Nonetheless, due to the time and cost incurred per experiment in physical models, this type of analysis is only feasible numerically. Hence, the augmented design was kept as the remaining methodology.

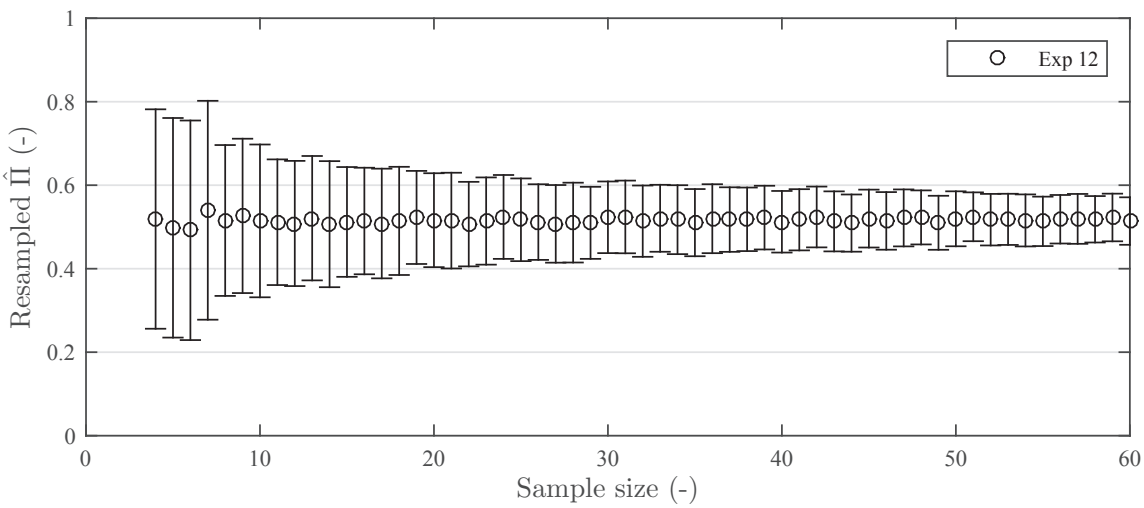


Figure 4.4 – Variability of blockage estimation for different sample sizes.

The limitation of the Wald method when dealing with extreme blocking probabilities (i.e. 0 or 1) becomes visible (Figures 4.2 and 4.3) as the confidence interval for the first two repetitions could not be calculated. In the case of the Clopper-Pearson method, it can be seen that for $n < 10$ the width of the interval tends to be larger, hence more conservative, than the Wald interval.

The standard errors can be seen in Figure 4.5, for all the replications and experiments performed. For a given n, the maximum standard error (SE) was obtained for $\hat{\Pi} = 0.50$. If $n = 60$, the maximum error in the estimation of π is about 0.06. For the case of $n = 30$, the maximum error is about 0.09. If n continues to decrease, it can take values up to 0.50 as it can be seen in Figure 4.5 with the continuous line for the maximum standard error.

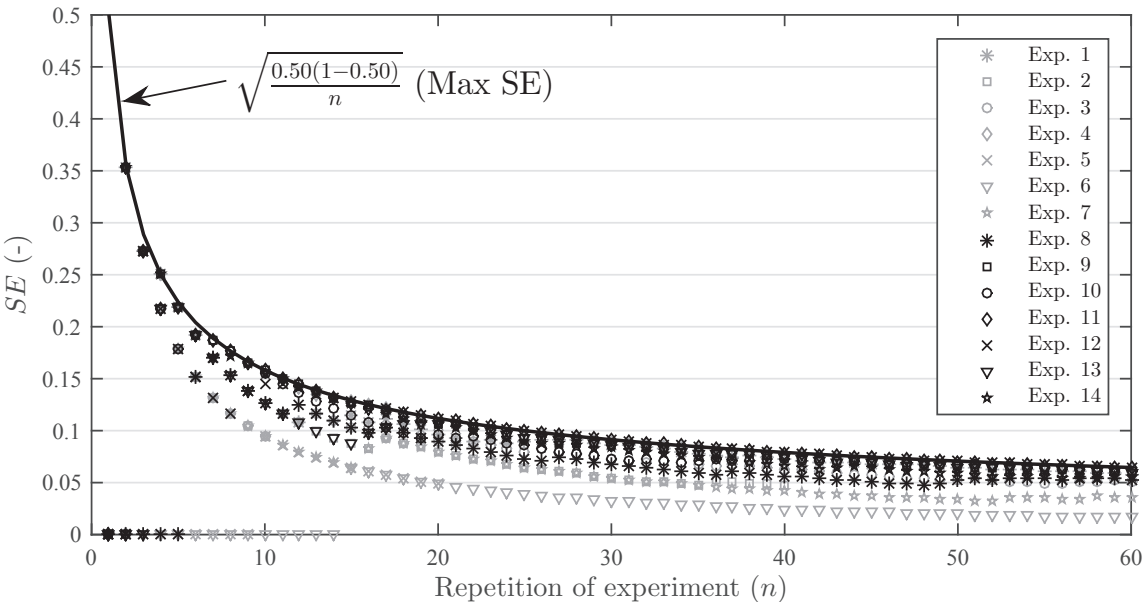


Figure 4.5 – Standard error (SE) of the point estimator as a function of the number of repetitions (n).

The width of the intervals according to both methods, for $n = 4; 10; 30; 60$ with 90% confidence is shown in Table 4.2. For the Wald method, when $[L_L; U_L]$ exceeded $[0; 1]$ it was taken either 0 or 1. Experiments 5 and 6 are good examples of the limitations of the Wald method. For experiment 5, as the number of repetitions was smaller than 30 and the estimated blockage probability was close to 1, the confidence interval calculated exceeded the $[0; 1]$ interval therefore the external limits had to be taken. Experiments 6 and 7 had 70 and 60 repetitions respectively but $\hat{\Pi}$ was close to 0, leading to forced calculations of confidence intervals. The use and interpretation of the Wald method should be done thoughtfully as the calculation is always feasible but can be misleading if the data cannot be approximated by a Normal distribution.

The maximum standard error after one repetition can be of 0.50 (Figure 4.5), being the worst case scenario with a blocking probability of 0.50. For a small number of repetitions $n \leq 4$, the estimation has a wide confidence interval or a significant possible difference with the real

Table 4.2 – Width of confidence intervals (W: Wald method. CP: Clopper-Pearson method.).

	$n = 4$			$n = 10$			$n = 30$			$n = 60$		
Exp.N°	$\hat{\Pi}(n)$	**W**	**CP**	$\hat{\Pi}(n)$	**W**	**CP**	$\hat{\Pi}(n)$	**W**	**CP**	$\hat{\Pi}(n)$	**W**	**CP**
1	0.50	0.82	0.80	0.20	0.42	0.47	0.33	0.28	0.31	0.28	0.19	0.20
2	0.25	0.71	0.74	0.10	0.31	0.39	0.10	0.18	0.21	-	-	-
3	0.25	0.71	0.74	0.10	0.31	0.39	0.20	0.24	0.27	0.20	0.17	0.18
4	0.50	0.82	0.80	0.50	0.52	0.56	0.63	0.29	0.31	0.62	0.21	0.22
5	1.00	0.00	0.53	0.90	0.31	0.39	-	-	-	-	-	-
6	0.00	0.00	0.53	0.00	0.00	0.26	0.03	0.11	0.15	0.02	0.05	0.08
7	0.25	0.71	0.74	0.10	0.31	0.39	0.10	0.18	0.21	0.08	0.12	0.13
8	0.00	0.00	0.53	0.20	0.42	0.47	0.17	0.22	0.25	0.22	0.17	0.19
9	0.50	0.82	0.80	0.50	0.52	0.56	0.67	0.28	0.31	0.68[a]	0.19[a]	0.21[a]
10	0.25	0.71	0.74	0.60	0.51	0.55	0.80	0.24	0.27	0.67	0.20	0.21
11	0.75	0.71	0.74	0.50	0.52	0.56	0.53	0.30	0.32	0.43	0.21	0.22
12	0.75	0.71	0.74	0.70	0.48	0.52	0.43	0.30	0.32	0.52	0.21	0.23
13	0.75	0.71	0.74	0.80	0.42	0.47	0.67	0.28	0.31	0.68	0.20	0.21
14	0.50	0.82	0.80	0.60	0.51	0.55	0.70	0.28	0.30	0.75	0.18	0.20

[a] only 58 repetitions considered

blockage probability. For example experiment 3 has a width of 0.71 (Wald method, Table 4.2) with a confidence level of 90%. Thus if that experiment is performed twice again and the outcomes, after 4 repetitions, are $\hat{\Pi}_1(4) = 0.25$ and $\hat{\Pi}_2(4) = 0.75$, both estimations could be inside the first confidence interval although they represent different blockage scenarios. With this perspective, for instance the results obtained in Bocchiola et al. (2008) after 4 repetitions can have a maximum error of 0.25 in the probability of stems being entrapped into a jam in function of their length.

Increasing the number of repetitions to $8 \leq n \leq 10$ as in Schmocker and Hager (2011), De Cicco et al. (2016) and Gschnitzer et al. (2017) reduces the width of the confidence interval to almost half of the width given for $n \leq 4$ and the maximum standard error is 0.16. With $n \leq 30$ and $n \leq 60$ the width is notably reduced meaning that the difference of the estimation from experiments with the real value is small. Also, the maximum standard error is 0.09 and 0.06 respectively. Although, to repeat an experiment 60 times means a significant use of resources for achieving slightly better accuracy.

The Wald method needs to have at least $n \geq 30$ and blocking probabilities different than 0 or 1 to be correctly applied. It can provide a false sense of accuracy because of slender intervals (Agresti and Coull, 1998). The Clopper-Pearson method performs better when having small amounts of repetitions and avoids the assumption of a Normal distribution. It allows to calculate confidence intervals even if the probabilities are close to the extremes (for example, experiment 8 Table 4.2 for $n = 4$), although it gives wider intervals to be more conservative. Wald and Clopper-Pearson methods provide a good overview of the variability of blocking probabilities related to repetitions and can be easily applied with high levels of confidence. Both are adequate for binomial results, having a simple calculation process and being present in most of statistical software. The chosen method will depend on the type of data available and if the assumption of a Normal distribution

is possible. If more complex approximations are to be used, they can be found among statistical literature (Vollset, 1993, Newcombe, 1998, Correa M and Sierra L, 2001, Sauro and Lewis, 2005, Pires and Amado, 2008).

Thus, the achieved accuracy per experiment depends of the number of experimental repetitions. It is recommended that $n \geq 30$ is used, as it will give an estimated blocking probability with standard errors less than 0.09 for 90% confidence levels. This number of repetitions will give a statistically reliable estimation of the unknown value of the blockage probability. Furthermore, it is recommended to express the blockage probability of LW with its confidence interval and its level of confidence, as it remains a point estimator of an unknown quantity. As mentioned in Wohl et al. (2010), some common metrics are needed in complex topics such as LW behaviour.

4.4 Conclusions

Experiments have been conducted to evaluate the influence of repetitions on the accuracy of LW blockage probability estimations at an ogee crested weir with piers. This research has pointed out that stem experiments require a systematic approach and common metrics. Physical models are used to study LW processes, hence a statistically justified minimum number of repetitions is valuable. Nevertheless, previous works often ignored the importance of defining this number based on statistical accuracy. As a result, the importance of accuracy in probabilistic estimations has been a minor topic. To provide a blocking probability estimation $\hat{\Pi}$ with any information of how close it is of π is inconclusive. When this point estimate is reported, it is necessary to give an order of the accuracy of that estimation.

A wide range of typical stem dimensions and hydraulic conditions were tested, simultaneously with changing parameters regarding the stems characteristics or the hydraulic structure. Experiments indicate that the variability of the estimated blocking probability has a strong relation with the number of repetitions per experiment. Herein, the application of mathematical tools related to the problem of LW behaviour by determining an interval estimate for a binomial proportion is analysed. Knowing the error in an estimation is the first step in inferential statistics and it allows to calculate how reliable an observation is, without the need of further sampling (Wallis, 2013). Based on the results and the statistical methods presented, it is recommended for experimental campaigns to make $n \geq 30$ repetitions per experiment so that estimations of blockage probabilities with errors smaller than 0.10 occur (with 90% confidence). In accordance with Schalko (2017), the maximum acceptable error of the experimental estimations should be 0.10 to have rigorous assessments of LW blockage risk. Such number of repetitions can be decreased if less accuracy of results is tolerable. Blocking experiments with less than 10 repetitions are not recommended as they have large scattering of results and large width of confidence intervals. Confidence intervals are valuable methods for estimating accuracy of observations and they should be included when referring to an estimated probability, with their implicit confidence level. As a common metric for calculating confidence intervals, the Wald or Clopper-Pearson method are proposed with confidence levels of 90%.

5 Estimation of blocking probability for individual stems[1]

5.1 Overview

This work intends to relate driftwood characteristics to hydraulic parameters for blocking probabilities estimation at an ogee crest weir inlet with round nose piers. Throughout a statistical approach, using generalised linear models (GLM), stem length, diameter and density have been related to head and bay width. LW density has been previously considered as a key parameter for movement estimations, quantification of wood budget and transport equations. The influence of stem density has also been studied regarding the shape of jams against hydraulic structures. Nevertheless, it has not been considered yet as an influential parameter for blockage estimations. A controlled method to test stem density influence on blocking probability was analysed and is presented herein, adding new information to the current state of the art.

5.2 Methodology

Based on the dimensional analysis presented in section 3.2, experiments were conducted to test the key variables identified. Twelve experiments were defined, testing the effect of stem length, stem diameter, stem density relative to the hydraulic head, bay width and the number of open bays, on the blocking probability as detailed in Tables 5.1 and 5.2. Ratios of head H to stem diameter d (H/d, relative head) ranged from $0.56 \leq H/d \leq 1.56$. For the first 9 experiments, stem density was systematically varied to analyse its influence on blockage, leaving the other variables constant. For experiments 10 to 12, the relative head was systematically varied to quantify its influence on blocking probability. In Table 5.2 experiments 10 to 12 from Table 5.1 are presented again as for experiments 10 to 17, the focus was to keep a constant head H while changing systematically the stem length (two scenarios of one and five open bays were evaluated). A pier nose that protrudes 0.04 m from the weir into the reservoir was used (N_2).

[1] Parts of this Chapter are based on the submitted article "Blockage probability modeling of large stems at ogee crested spillways with piers" by Furlan P, Pfister M, Matos J, Amado C, and Schleiss A.J submitted in *Water Resources Research*. The experimental work and the analyses presented hereafter are original and were performed by the author.

Table 5.1 – Experimental program for evaluating influence of stem density and relative head on the estimation of blocking probability for individual stems, with two bay scenarios.

Exp.N°	Class	Density ρ_s [-]	*H/d* [-]	Open bays
1	A	- ,0.59, 0.79, 0.99	1.40	1
2	A	- ,0.59, 0.79, 0.99	1.00	5
3	A	- , 0.59, 0.79, 0.99	1.20	5
4	C	0.43, 0.56, - , 0.97	0.94	1
5	C	0.43, 0.56, - , 0.97	0.94	5
6	C	0.43, 0.56, - , 0.97	1.06	5
7	E	0.40, 0.54, 0.76, 0.99	0.96	1
8	E	0.40, 0.54, 0.76, 0.99	0.76	5
9	E	0.40, 0.54, 0.76, 0.99	1.00	5
10	A	0.59	0.90,1.00, 1.20,1.50	5
11	C	0.56	0.56,0.75,0.94,1.00,1.25,1.56	5
12	E	0.54	0.64,0.80,0.84,0.96,1.00	5

Table 5.2 – Experimental program for evaluating influence of the relative stem length on the estimation of blocking probability for individual stems, with two bay scenarios.

Exp.N°	Class	Density ρ_s [-]	*H/d* [-]	*H*(m)	Open bays
10	A	0.59	0.90,1.20,1.50	0.009,0.012,0.015	5
11	C	0.56	0.56,0.75,0.94, 1.00,1.25,1.56	0.009,0.012,0.015, 0.016, 0.020, 0.025	5
12	E	0.54	0.64,0.80,1.00	0.016,0.020,0.025	5
13*	B	0.56	0.75,1.00,1.25	0.009,0.012,0.015	5
14*	D	0.63	0.80,1.00,1.25	0.0160.020,0.025	5
15*	A	0.59	1.50,1.20	0.015,0.012	1
16*	B	0.56	1.00,1.25	0.012,0.015	1
17*	C	0.56	0.75,0.94	0.012,0.015	1

*Experiments 13 to 17 were executed by master students at EPFL in the framework of a semester project supervised by Prof Anton J Schleiss and Paloma Furlan.

For the estimations of blocking probability, the result noted was the number of stems that blocked at the weir. After, stems were removed and the procedure was repeated with the same initial conditions. The frequency of an outcome (blockage) after a certain number of repetitions was obtained. These frequencies were used as estimates of the unknown probabilities found in prototype and will be further referred to as blocking probability. For each experiment, $n = 30$ independent repetitions (trials) were performed in agreement with Chapter 4.

The maximum likelihood estimator, $\hat{\Pi}$, of the blocking probability π is given by,

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

where X is the number of blocked stems, and n is the total number of repetitions. This means that the blocking probability π is estimated as the ratio of the number of stems that blocked with the number of stems that were supplied, averaged in the repetitions. During the experiments,

one stem was supplied individually with the mechanical equipment and it was waited for it to block or pass the weir, after it was removed and another stem was supplied.

Some combinations were duplicated, such as, class A with ρ_{s2} was tested twice using $H/d = 1.00$ and $H/d = 1.20$; class C with ρ_{s2} was tested twice using $H/d = 0.94$ and $H/d = 1.00$; class E with ρ_{s2} was tested twice using $H/d = 1.00$. Hence, for those combinations two different but statistically acceptable results are presented in Section 5.3.

5.2.1 Statistical analysis

Using the statistical tool R (R Core Team, 2017), logistic regressions were performed to model the relation of the variables studied. A logistic regression is a generalized linear model (GLM) that allows to estimate or predict the probability of an outcome, based on a set of observed explanatory variables (Hosmer and Lemeshow, 2000). The response variable is the occurrence of a stem getting blocked at an ogee weir, being a value of 1 for blockage or 0 for passage.

The logistic regression is based on the modelling of a logit-transformed probability, the log odds, by a linear combination of p independent explanatory variables (Equation 5.1).

$$logit(\Pi) = log\frac{\Pi(x)}{1-\Pi(x)} = \beta_0 + \beta_1 x_1 + ... + \beta_p x_p \tag{5.1}$$

Here β_0 is a constant parameter (intercept), $\beta_{1,...,p}$ are the regression coefficients for the explanatory variables, determined with the maximum-likelihood estimation method, and $x_{1,...,p}$ are the explanatory variables. The coefficients of the linear combination can be used to estimate the odds ratio for each explanatory variable (Casanoves et al., 2012). The odds ratio is defined as the ratio of the odds of the occurrence of an event (blockage) to the odds that it does not occur (passage) and is computed as e^{β} for each explanatory variable (Chen and Wang, 2007). A positive coefficient β indicates that the explanatory variable increases the log odds ratio, assuming that the other variables are held constant.

The Wald test is obtained by comparing the maximum likelihood estimate of the coefficient, β, to an estimate of its standard error. The resulting ratio, under the hypothesis that $\beta_0 = 0$, will follow a standard normal distribution (Hosmer and Lemeshow, 2000). To determine the significance of each β, the fix significance level test is performed. A null hypothesis of $\beta_0 = 0$ is done and compared to the hypothesis that $\beta_0 \neq 0$. It is tested if that value should or should not be rejected at a specified p-value or level of significance α. The p-value is the smallest level of significance that would lead to rejection of a null hypothesis with the given data. The limit normally taken is 0.05 as level of significance. Therefore, the p-value could be considered as the "observed" significance level (Montgomery and Runger, 2011).

The Akaike information criterion (AIC) was used to compare models herein (Parzen et al., 1998, Simonoff and Tsai, 1999). The AIC measures the goodness of fit, penalizing a model based on the

number of parameters it contains (Davidson et al., 2015). The regression model with the lowest AIC value was considered as the best model for the measured data.

5.3 Results and discussion

The systematic approach chosen for the experiments aims to discriminate the influence of each explanatory variable in the blockage process of individual stems at an ogee weir with piers. A bar chart of the blocked stems is derived for all explanatory variables. The bars allow for one to observe the distribution of results and perceive if one variable has a stronger influence on blockage than the others (Figure 5.1). Each bar represents, per category, the percentage of blocked stems to supplied stems with five open bays. For visualization purposes, four categories of the relative head were defined: H/d_1 = [0.56-0.82[; H/d_2= [0.82-1.08[; H/d_3 = [1.08-1.34[; and H/d_4 = [1.34-1.60[.

Comparing the effect of relative stem length, class E has higher blockage probability (>20%) than the other classes (Figure 5.1). For the different stem densities and the relative heads, no category has an outstanding effect (difference higher than 20%) on the blockage of stems.

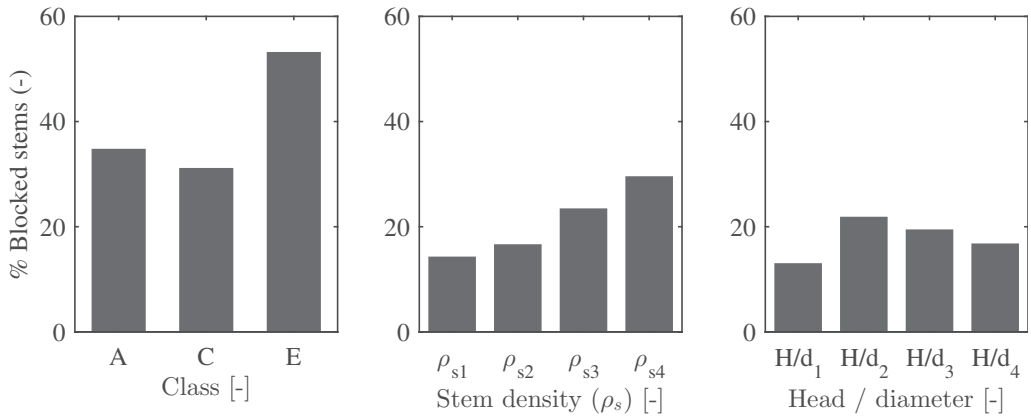


Figure 5.1 – Bar chart of blocked stems (in percentage) as a function of the relative stem length Class (left), the stem density ρ_s (centre) and the relative head H/d (right) for five open bays.

During the experiments, the variables interact differently from one experiment to the following. For instance, the effect of relative head or stem density is not constant for blockage probability if the relative stem length is varied. Hence, experiments were separated based on the relative stem length for a case-by-case analysis.

5.3.1 Estimation of blocking probability for individual stems, class A

The blocking probabilities obtained for class A (relative stem length L/b = 0.80) in the physical model, after 30 independent repetitions, are listed in Table 5.3.

Table 5.3 – Blocking probability estimated for individual stems of class A with varied stem density, relative head and number of open bays, from physical experiments.

		$\hat{\Pi}$		
Open bays	***H/d***	ρ_{s2}	ρ_{s3}	ρ_{s4}
1	1.40	0.10	0.20	0.03
5	0.90	0.47		
	1.00	0.47 / 0.60	0.53	0.63
	1.20	0.13 / 0.27	0.20	0.17
	1.50	0.00		

A 90% confidence interval was calculated for the blocking probabilities obtained experimentally using the Clopper-Pearson method (Clopper and Pearson, 1934). The inherent stochastic behaviour of LW processes leads to, for example, two different blocking probabilities for identical conditions in the experiments with ρ_{s2} for $H/d = 1.00$ and 1.20 (Table 5.3). By means of the confidence intervals and their overlap, it can be stated that both estimates are statistically acceptable with 90% confidence.

Stem blockage as a function of stem density, for class A, is shown in Figure 5.2. For these experiments, the probability of blockage varies less than 10% ($\Delta\hat{\Pi} \leq 0.10$) when the stem density is increased, except for experiment 1 (one open bay), where $\Delta\hat{\Pi} = 0.17$ from ρ_{s3} to ρ_{s4}. Based on the results obtained in Godtland and Tesaker (1994), blocking probabilities lower than 20% were expected as the stem length is only 80% of the bay opening. Nevertheless, 5 of 12 experiments with class A have higher $\hat{\Pi}$ (Table 5.3).

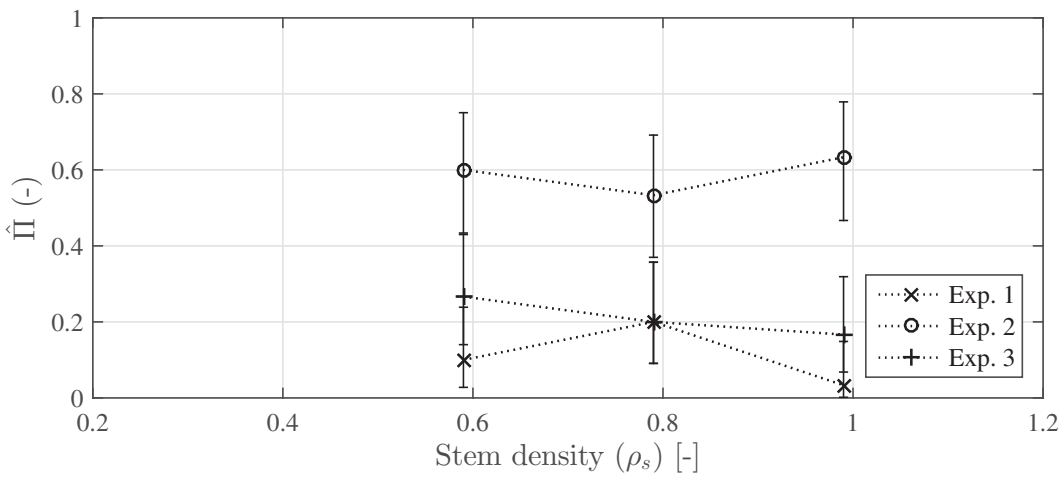


Figure 5.2 – Blocking probability ($\hat{\Pi}$) for class A as a function of stem density, obtained from the physical experiments (Table 5.1).

The small variation of $\hat{\Pi}$, as a function of stem density for class A, seems negligible and within the confidence interval. Here, it can be considered that density is not influencing the blockage of the individual stems. If attention is drawn to the relative head, from experiments 2 to 3 an increment in the head causes the blockage probability to decrease. The relative head is analysed separately

in experiment 10 (Table 5.1). With a relative head increase from $H/d = 0.90$ to $H/d = 1.50$, the blocking probability decreases from $\hat{\Pi} = 0.47$ to $\hat{\Pi} = 0.00$.

Logistic regression model for class A

A logistic regression model was performed for class A considering five open bays (GLM A, Table 5.4). The model considers 10 experiments, hence 300 independent results. The variables taken for the logistic regression are continuous explanatory variables. The relative head *H/d* ranges between 0.90 to 1.50, and stem density ρ_s between 0.59 to 0.99. Other models have been evaluated, one without stem density and another considering ρ_s and *H/d* as categorical variables, but no major improvements in terms of AIC were found, and thus, they are not discussed.

Table 5.4 – Coefficients for stem density and relative head from the logistic regression for class A, with 5 open bays (GLM A).

Explanatory variable	**Model coefficients**		**Wald's test**	
	β	Std error	z	Significance level
Intercept	6.357	1.26	5.01	**<0.001**
ρ_s	1.021	0.82	1.24	0.214
H/d	-7.100	1.13	-6.25	**<0.001**
AIC	49			

Table 5.4 shows that the relative head *H/d* has a noteworthy effect on the blocking probability (the significance level is lower than 0.05), being the most influential variable for blockage. Under the tested conditions, stem density ρ_s does not significantly add to the predictive power of the logistic regression as the p-value exceeds 0.05. A model without stem density was evaluated but showed no better AIC. The negative sign of the coefficient for *H/d* indicates that an increase in the relative head decreases the blockage probability, as observed in the experiments (Table 5.3). A comparison of the experimental blockage probability with the logistic regression model can be seen in Figure 5.3. The probability $\hat{\Pi}$ ranges from 0 to 0.63 as obtained in the physical model (Table 5.3). The predictions of blockage from the logistic regression model remains inside the confidence intervals of the experimental results.

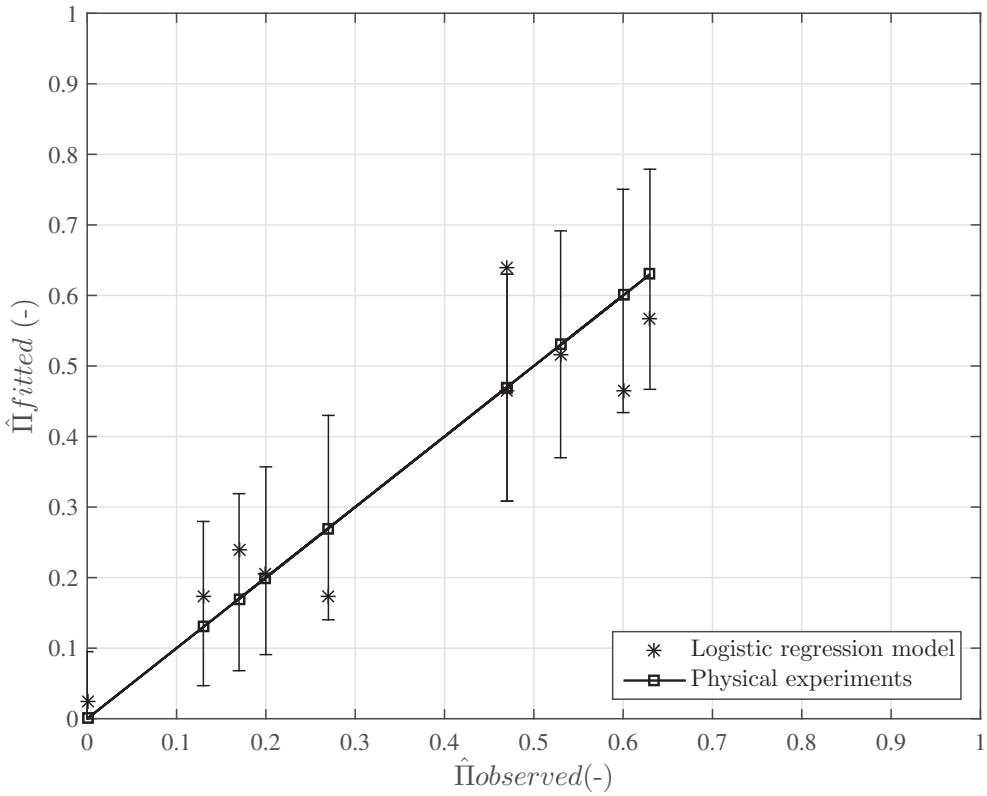


Figure 5.3 – Estimated blocking probability for class A from experiments versus logistic regression model (GLM A), for individual stems.

Increases in the relative head decrease the blockage probability for the three stem densities evaluated in class A (except for ρ_{s2} with $H/d = 1$) (Figure 5.4). Each dashed line of Figure 5.4 represents the logistic regression model, for the three stem densities.

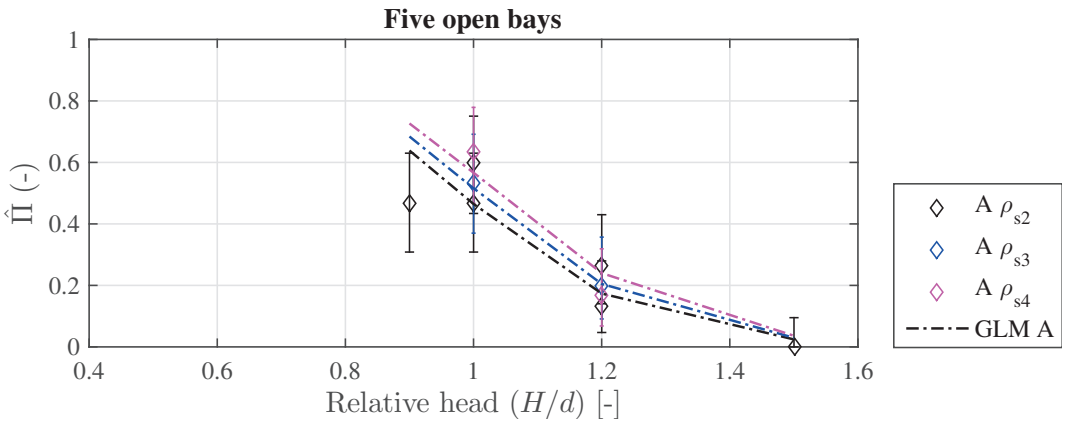


Figure 5.4 – Estimated blocking probability ($\hat{\Pi}$) for class A as a function of the relative head *H/d*. Experimental results and logistic regression model (GLM A) for three stem densities, considering five open bays.

For this relative stem length (L/b = 80%) the possibles types of blockage were due to stems touching the weir crest and stopping the movement when leaning against a pier, parallel or oblique to the flow direction. No blockage of a stem bridging between two piers was possible as the stem length was shorter than the bay width. However, for $H/d > 1$ blockage was generally lower than 0.20 as stems would not touch the weir crest and would pass. With lower head values, the chances of stems getting blocked would increase slightly as there was more contact between stems and the weir crest.

5.3.2 Estimation of blocking probability for individual stems, class C

For class C, experiments 4 and 5 have the same relative head but different number of open bays (Table 5.1). For these experiments, one open bay has higher blockage probability than five open bays for ρ_{s1} and ρ_{s2}, but it is inverted for ρ_{s4} (Figure 5.5). In experiment 5, the blocking probability decreases from ρ_{s1} to ρ_{s2} and increases abruptly for ρ_{s4} ($\Delta\hat{\Pi}$ = 0.87). The same behaviour is observed in experiment 6 between ρ_{s2} and ρ_{s4} ($\Delta\hat{\Pi}$ = 0.73). Stems with density comparable to light wood and average dry European wood (ρ_{s1} and ρ_{s2}) for class C (L/b = 120%), have similar blocking probabilities (Table 5.5).

Table 5.5 – Blocking probability estimated for individual stems of class C with varied stem density, relative head and number of open bays, from physical experiments.

		$\hat{\Pi}$		
Open bays	***H/d***	ρ_{s1}	ρ_{s2}	ρ_{s4}
1	0.94	0.50	0.50	0.73
5	0.56		0.97	
	0.75		0.63	
	0.94	0.27	0.03 / 0.13	1.00
	1.00		0.00 / 0.17	
	1.06	0.03	0.03	0.77
	1.25		0.00	
	1.56		0.00	

Between experiments 5 and 6, the increase in the relative head decreases the blocking probability for all stem densities (Table 5.5). When comparing blockage within H/d = 0.94 and 1.06 for ρ_{s1} and ρ_{s4} with five open bays, the variation is similar (decrease of $\Delta\hat{\Pi} \approx 0.20$), but for ρ_{s2}, the variation is smaller (decrease of $\Delta\hat{\Pi} \approx 0.10$). Hence, the relative head influences the process of blockage to a different magnitude, presumably as a function of stem density and relative length.

For class C, heavier stems result in higher blocking probabilities for five open bays compared to only one open bay, in contrast to the observations made for lighter stems (Figure 5.5). Thus, WLW is more probable to block if all the bays are open compared to only one bay, under the same relative head.

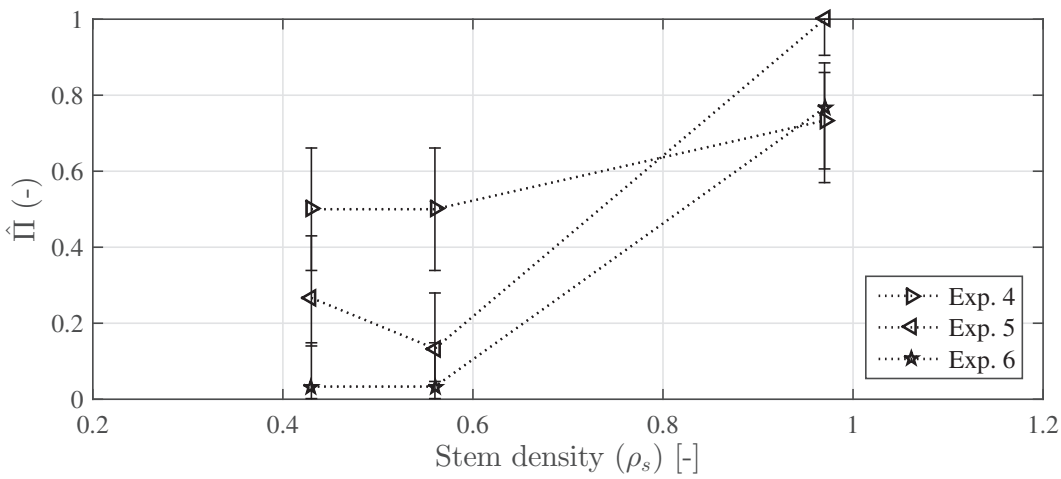


Figure 5.5 – Blocking probability ($\hat{\Pi}$) for class C as a function of stem density, obtained from the physical experiments (Table 5.1).

5.3.3 Estimation of blocking probability for individual stems, class E

Class E presents a particular relation between blocking probabilities and stem density. Systematically, increases in stem density lead to higher probability of blockage (Table 5.6 and Figure 5.6).

Table 5.6 – Blocking probability estimated for individual stems of class E with varied stem density, relative head and number of open bays, from physical experiments.

		$\hat{\Pi}$			
Open bays	***H/d***	ρ_{s1}	ρ_{s2}	ρ_{s3}	ρ_{s4}
1	0.96	0.07	0.13	0.37	1.00
5	0.64		0.97		
	0.76	0.43	0.87	1.00	1.00
	0.80		0.80		
	0.84		0.40		
	0.96		0.13		
	1.00	0.00	0.03/0.10	0.20	0.97

For the same *H/d* relation with ρ_{s2}, the blocking probability remains equal for one and five open bays (Table 5.6). For similar relative heads in experiments 7 and 9, one open bay results in greater blocking probability than five open bays, for all stem densities (Figure 5.6). The influence of the relative head on blockage is observed in experiments 8 and 9 as stems block less when *H/b* increases. For class E with ρ_{s2}, a marked decrease in blockage exists for increments of relative head in scenarios with five open bays. The other stem densities also show smaller blockage probabilities when the relative head is increased. Compared to class C, with increasing relative length (class E, $L/b = 200\%$), ρ_{s2} blocks more frequently than ρ_{s1} (Table 5.6).

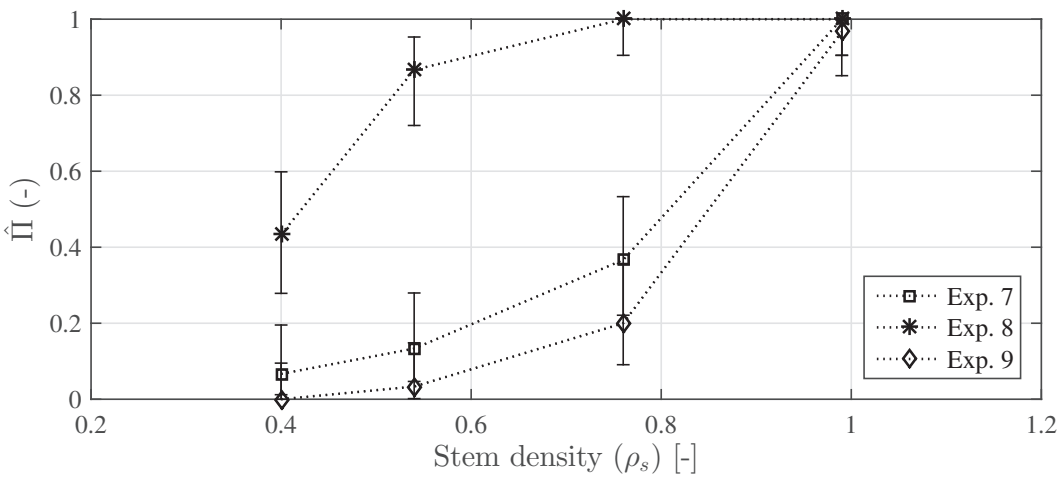


Figure 5.6 – Blocking probability ($\hat{\Pi}$) for class E as a function of stem density, obtained from the physical experiments (Table 5.1).

Logistic regression model for class C and E

Classes C (L/b = 120%) and E (L/b = 200%) behave differently than class A regarding the stem density influence on the blocking probability for individual stems. Hence, a model was done for both stem classes together.

To quantify the influence of the tested explanatory variables on the blockage probability of individual stems, different logistic regression models have been evaluated for classes C and E together (780 independent results for five open bays). Both classes are included in one model due to the pronounced effect of stem density on the blocking probability. The relative length is a variable with two categories (class C and E, C being the reference value). Density (ρ_s) and relative head (H/d) are considered continuous variables. The GLM C/E is the best logistic regression model obtained from the combinations studied in terms of AIC (Table 5.7).

Table 5.7 – Coefficients for class, stem density and relative head from the logistic regression for class C and E, with 5 open bays (GLM C/E).

Explanatory variable	**Model coefficients**		**Wald's test**	
	β	Std error	z	Significance level
Intercept	7.252	1.02	7.07	**<0.001**
Class	0.166	0.25	0.65	0.51
ρ_s	10.604	0.83	12.64	**<0.001**
H/d	-15.695	1.27	-12.32	**<0.001**
AIC	129			

The blockage probability estimates of GLM C/E compared to the results obtained in the physical experiments can be seen in Figure 5.7. Four values estimated with the logistic model are outside the confidence interval of the results from the physical experiments. For these cases GLM C/E overestimates blockage in comparison to the physical experiments and can be considered as a

conservative estimation. The experiment with class C, ρ_{s1} and $H/d = 0.94$ (Experiment 5 from Table 5.1) gave higher blocking probability than the logistic model.

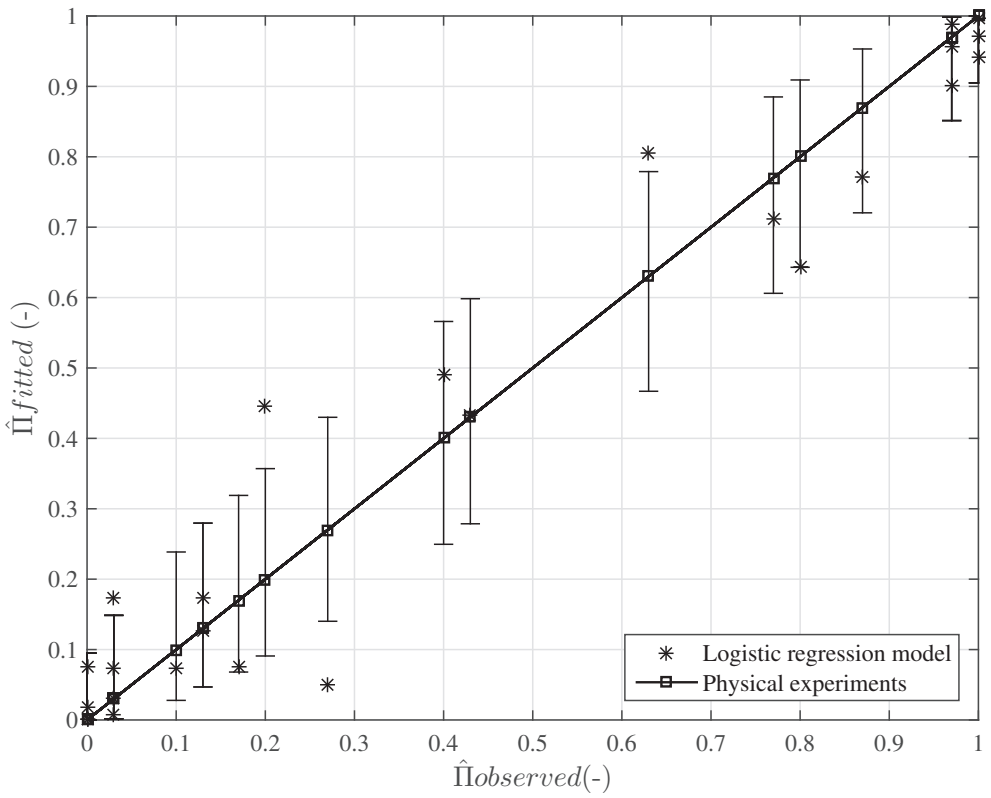


Figure 5.7 – Estimated blocking probability for classes C and E from experiments versus logistic regression model (GLM C/E), for individual stems.

The variable class (or relative stem length, L/b) is kept as an explanatory variable in the model regardless the fact that its significance level is larger than 0.05. The reason is the important influence of the relative length for blockage seen in the literature. The relative stem length evenly influences the blockage probability for spillways and bridges with piers since longer stems block more often than shorter ones for equal hydraulic conditions (Gschnitzer et al., 2017). The lack of variation (only two categories) might influence the significance of the variable included in the model. Further investigation would be needed with additional relative stem lengths to accurately quantify the influence of this variable. Models with interactions between the variables were tested, but they were not statistically possible due to this design of experiments.

The blocking probability of individual stems, larger than the bay width, is influenced by stem density and relative head. A negative coefficient associated with the relative head states that an increment of head will decrease the blockage probability, whereas a positive coefficient of density proves that stems with higher density block more often (Figure 5.8).

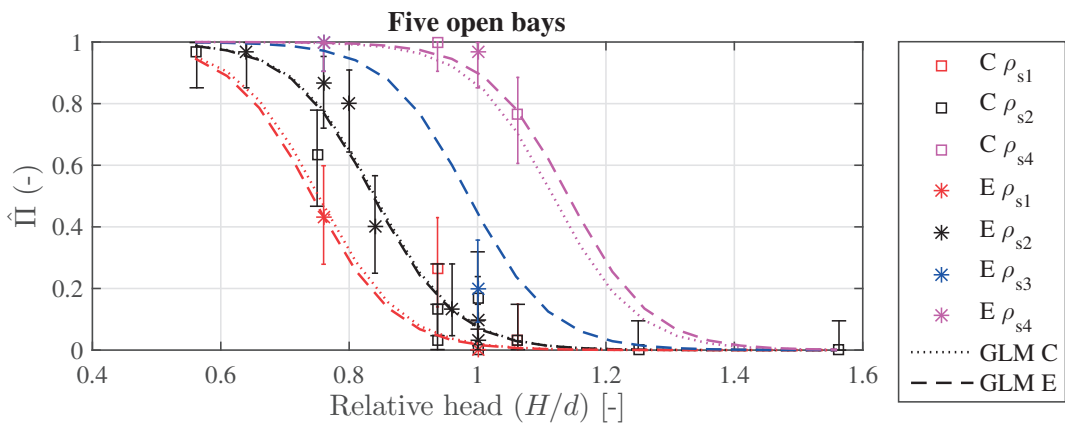


Figure 5.8 – Estimated blocking probability ($\hat{\Pi}$) for classes C and E as a function of the relative head *H/d*. Experimental results and logistic regression model (GLM C/E) for four stem densities, considering five open bays.

For the tested conditions, "blockage curves" for individual stems at ogee crested weirs with piers were obtained with the logistic regression model (Figure 5.8). Each curve corresponds to a different stem density and relative stem length. The results obtained herein for ogee crested weirs are in agreement with the observations made for PKW in (Pfister et al., 2013b). By decreasing the relative head, the blocking probability can increase. Herein, as with class A, the main types of blockage observed were of stems leaning against the pier in an oblique or parallel direction to the flow direction. Few cases of stems bridging between two piers were observed for class E.

The effect density has on the movement of stems can be related to the buoyancy of stems. As seen in Braudrick et al. (1997), a theoretical submerged height of stems (h_s) can be calculated by knowing the stem density and diameter (Figure 5.9). Blockage was mainly due to stems touching the weir crest and pivoting between the piers, finally stopping the movement when leaning against a pier parallel to the flow direction. A higher stem density represents a higher submerged height thus the chances of stems interacting with the weir crest can increase and consequently the blocking probability can increase also.

The flow depth at the weir crest (h_0) can be estimated and compared to the theoretical submerged height of the stems as seen in Figure 5.10. For the geometry of an ogee weir equipped with piers, the flow depth at the crest was considered approximately as $0.80 \cdot H$ (Chow, 1959, USACE, 1987), where H is the total upstream head relative to the crest elevation. For ratios of flow depth at the weir crest and submerged height lower than 1.30, the blocking probability of individual stems is generally higher than 0.20. It is important to remember that these estimations have a respective confidence interval and it has not been presented for a better understanding of the figure.

A logistic regression model is foreseen for this new normalized ratio. Only with one parameter, the physical characteristics of stem density and diameter of LW would be represented and connected to the flow depth at the weir crest.

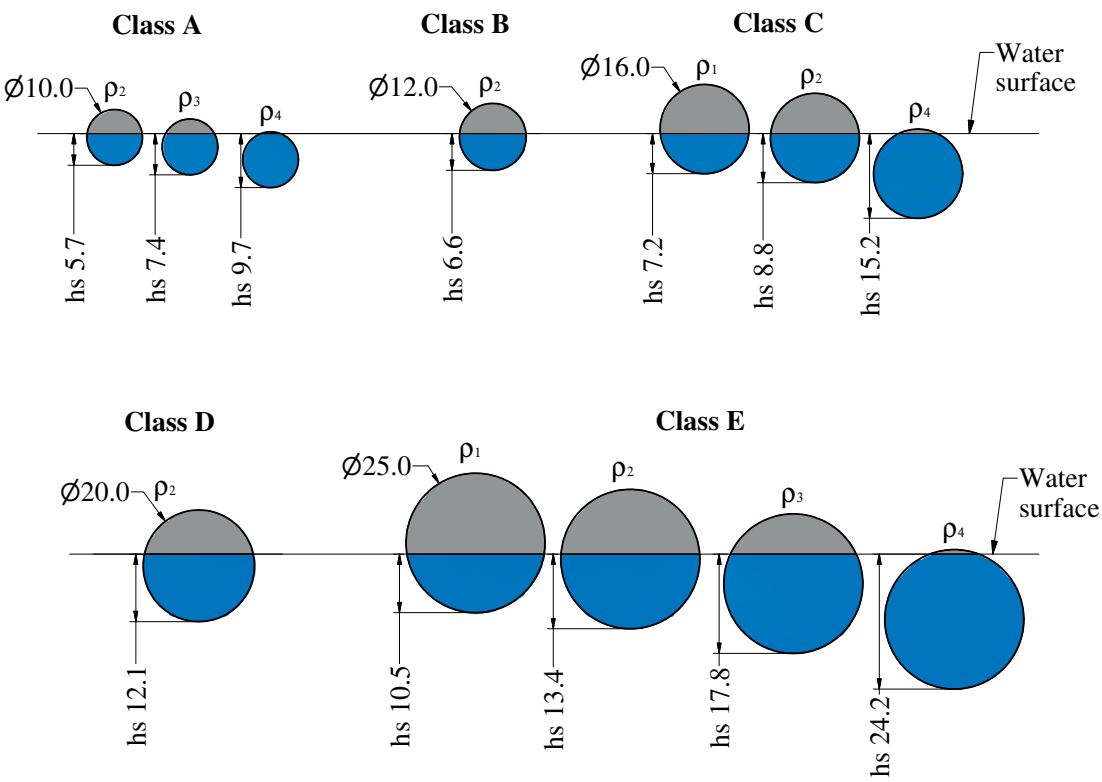


Figure 5.9 – Schematic representation of submerged height of stems (h_s), separated by class and stem density (ρ_s) (dimensions in mm).

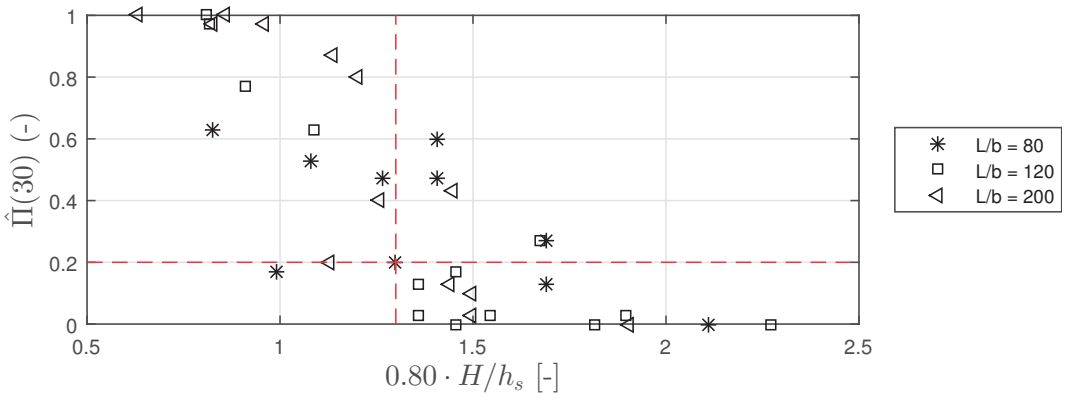


Figure 5.10 – Estimated blocking probability ($\hat{\Pi}$) for classes A, C and E as a function of the estimated flow depth at the crest ($0.80 \cdot H$) and submerged height of stem (h_s), obtained from the physical experiments.

5.3.4 Influence of the relative stem length on blocking probability of individual stems

The blocking probability obtained for class A (L/b=80%), B (L/b=100%), C (L/b=120%), D (L/b=150%) and E (L/b=200%) after 30 experimental repetitions is shown in Table 5.8. The stem density tested

corresponds to ρ_{s2}, being representative of average dry wood density in Europe.

Table 5.8 – Estimated blocking probability of stems of classes A, B, C, D and E with stem density ρ_{s2} for individual stems for varied number of open bays and head, from physical experiments.

		$\hat{\Pi}$				
		A	**B**	**C**	**D**	**E**
Open bays	***H*** (m)	*L/b*=80%	*L/b*=100%	*L/b*=120%	*L/b*=150%	*L/b*=200%
1	0.015	0.00	0.07	0.60	-	-
	0.012	0.37	0.73	0.60	-	-
5	0.009	0.47	0.73	0.97	-	-
	0.012	0.13	0.33	0.63	-	-
	0.015	0.00	0.00	0.03	-	-
	0.016	-	-	0.00	0.70	0.97
	0.020	-	-	0.00	0.27	0.80
	0.025	-	-	0.00	0.00	0.10

The blocking probability has been estimated as the number of blocked stems divided by the total number of stems supplied. Confidence intervals were calculated using the Clopper-Pearson method with 90% confidence.

Results show that an increasing head H decreases the estimated blocking probability. It is also observed that increasing the stem relative length L/b, increases in general the blocking probability for a constant H. Figure 5.11 shows the blocking probability estimated of all stem classes, with stem density ρ_{s2}, as a function of head, for individual stems considering 5 open bay. The change in the blocking probability as a function of the head seems to be linear. Nonetheless, this is not equal with one open bay (Figure 5.12).

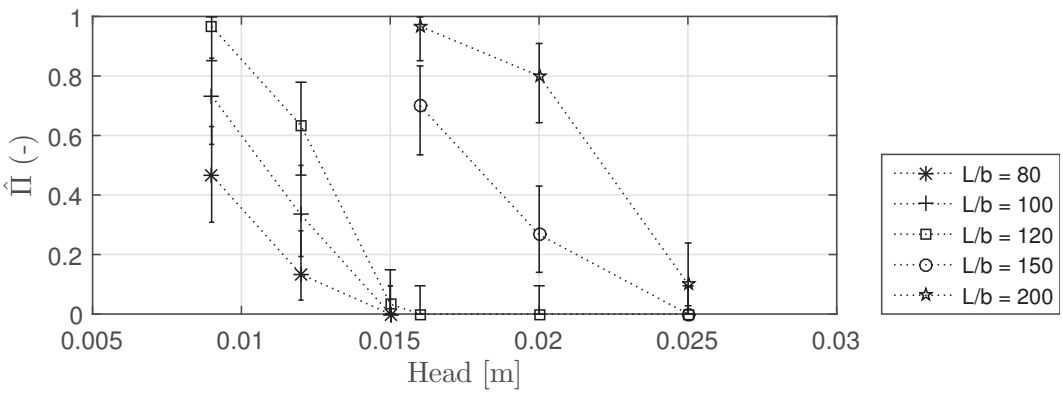


Figure 5.11 – Estimated blocking probability ($\hat{\Pi}$) of all stem classes, with stem density ρ_{s2}, as a function of head, for individual stems considering 5 open bays.

With 1 open bay, for $L/b = 120$ the blocking probability is not influenced by the increase of H. For shorter stems ($L/b = 80$ and 100) an increasing head, decreases the blocking probability. The change of $\hat{\Pi}$ for class B ($L/b = 100$) is greater than for class A ($L/b = 80$).

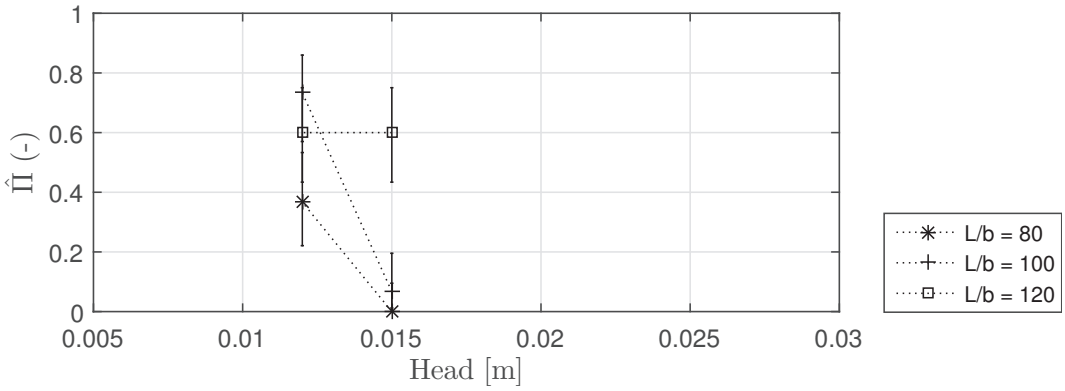


Figure 5.12 – Estimated blocking probability ($\hat{\Pi}$) of all stem classes, with stem density ρ_{s2}, as a function of head, for individual stems considering 1 open bay.

This analysis shows a brief comparison of the influence of the relative stem length on the blocking probability of individual stems, for two different bay scenarios. Increasing relative stem length tends to increase the blocking probability for a constant head. Nonetheless, the head H when related to the stem diameter d has a significant effect on the blocking probability. Because of the different stem diameters of the artificial stems used, the isolated analysis of the relative stem length influence was not feasible. Further analysis with constants stem diameters for changing stem length should be performed.

5.4 Conclusions

The behaviour and interactions between LW and structures like weirs involves random processes, and thus, different outcomes can be expected for equal scenarios. Such behaviour requires the use of statistical tools in order to understand the effects and probabilities of LW blockages. In this study, relations between key explanatory variables and blockage probabilities at ogee crested weirs with piers were established. The results provide new insight into the process but also reveal the limited predictive capacity of statistical models due to the strong stochastic behaviour of LW. Logistic regression models are suitable tools for quantifying the influence of the variables involved for blockage of LW. Herein, generalized linear models were used to rank the importance of explanatory variables in simplified physical experiments.

Statistical models based on averaged parameters reinforce the need of systematic approaches to study LW behaviour. The present research quantified the relation of relative stem length and relative head with blockage probabilities adding stem density as a new variable. Yet, the natural stem geometry, surface roughness, stiffness and stem interactions were not accounted for. With complex stem geometry, the blockage probability could increase.

According to the experiments, the explanatory variables have different effects on the individual stem blocking probability at ogee crested weirs. Stem density influences the blocking probability

for relative stem lengths equal or larger than the bay width $L/b \geq 1$. Increasing stem density will increase the blocking probability for that stem relative length. Therefore, stem density should be included in studies of large wood behaviour. It is recommended to quantify or avoid the change of stem density in experimental campaigns as it can influence the studied process. Waterlogged large wood (ρ_{s4}) has high blocking probability. It is recommended to considered WLW as a possible key element in large wood jams.

From the results obtained, the relative head influences the blocking probability of individual stems. Increasing H/d will decrease the blocking probability in the case of individual stems. Nonetheless, the relation is not linear, varying for each LW characteristic. Generally, H/d greater than 1.20 will lead to a blocking probability equal or lower than 0.20. From the different number of open bays tested it can be said that increasing the number of open bays from 1 to 5 bays, for the same H/d ratio, will decrease the blocking probability for a stem density lower than ρ_{s4}. For a stem density close to the water density, one open bay has lower blocking probability than five bays with the same H/d.

Finally, the influence of stem length relative to bay width (L/b) on the estimation of blocking probabilities of individual stems remains unquantified. The evaluations for constant H and stem density, have shown that increasing L/b leads to increasing blocking probabilities. However, when the longitudinal dimension of stems (L) was changed, also the transversal dimension changed (d). Because of this, the relative head H/d was different for each stem class and thus two parameters where changed at the same time.

6 Influence of experimental repetitions on the accuracy of blocking probability for groups of stems[1]

6.1 Overview

As mentioned in Chapter 2, an experimental protocol based on a significant number of test repetitions is of primary importance. A number of experimental repetitions for individual stems has been defined in Chapter 4. The difference between individual stems and groups are the interactions among multiple pieces that can affect the blocking probability for identical geometrical and flow conditions. The process of individual stems was considered as a Bernoulli-type experiment, where only two outcomes were possible (pass or block). In the case of groups, results are a percentage of blocked stems from a group hence the statistical approach needs to be modified. The definition of a statistically justified number of experimental repetitions for accurate LW blockage estimation of stem groups, is herein presented.

6.2 Methodology

Five experiments were defined throughout random combinations of the parameters, as previously performed for the individual stem experiments of Chapter 4 and are shown in Table 6.1. Experiments were performed for groups of stems, supplying always the same quantity of stems and noting the number that blocked or passed. The number of stems that compose a group was defined as $G_i = 2^m$, where $m = 0;1;2;3;4;5$. A pier nose that protrudes 0.04 m from the weir into the reservoir was used (N_2).

The maximum likelihood estimator, $\hat{\Pi}$, of the blocking probability π is given by,

$$\hat{\Pi} = \frac{X}{n \cdot G_i}$$

[1] Parts of this Chapter are based on the submitted article "Statistical accuracy for estimations of large wood blockage in a reservoir environment" by Furlan P, Pfister M, Matos J, Amado C, and Schleiss A.J submitted in *Environmental Fluid Mechanics*. The experimental work and the analyses presented hereafter are original and were performed by the author.

Table 6.1 – Experimental program for evaluating the influence of the number of experimental repetitions in the accuracy of blocking probability for groups of stems.

Exp.N°	Class	Density ρ_s	*H/d*	Open bays	Nose type	Group size	Repetitions
1	B	0.56	1.00	5	N2	2	60
2	C	0.97	1.06	5	N2	4	60
3	A	0.79	0.90	5	N2	8	60
4	C	0.43	0.94	5	N2	16	60
5	B	0.56	1.00	5	N2	32	60

where X is the number of blocked stems, G_i is the group size and n is the total number of repetitions. Experiments with stem groups are no longer Bernoulli-type experiments. The probability of blockage still ranges between [0;1] but intermediate values exist. Fractions of a group can block and result in X/G_i. This means that the blocking probability π is estimated as the ratio of the number of stems that blocked with the number of stems that were supplied, averaged in the repetitions. Without loss of generality, both the estimator and the estimate will be denoted by the same symbol $\hat{\Pi}$.

6.2.1 Statistical analysis: subsampling bootstrap technique

The bootstrap is a technique for estimating the distribution of an estimator by resampling data without imposing assumptions about the data-generating mechanism (Politis et al., 1999). A new dataset from the existing one is created by sampling with replacement.

The standard bootstrap procedure is:

1. Let $\{X: i = 1,..., n\}$ be a sample from a population with a distribution F unknown.
2. Let γ be a parameter to be estimated by $\hat{\gamma} = \hat{\gamma}(X_1, ..., X_n)$ from $\hat{F}_n$; for this particular case the interest is in estimating the mean therefore, $\hat{\gamma} = \bar{X}$.
3. Generate a bootstrap sample of size n, $\{X_i^*: i = 1,..., n\}$, by sampling the distribution corresponding to $\hat{F}_n$, randomly. If F_n is the empirical distribution function of the estimation data set, then the bootstrap sample can be obtained by sampling the estimation data randomly with replacement.
4. Compute $\hat{\gamma}^* \equiv \hat{\gamma}(X_1^*, ..., X_n^*)$.
5. Use the results of many repetitions of steps 3 and 4 to compute the parameter of interest from the empirical probability of the event (Horowitz, 2001).

This method is herein applied to quantify the accuracy of blockage estimations as a function of the experimental number of repetitions. To quantify the accuracy, the number of repetitions had

to be varied. Thus the bootstrap technique had to be adapted in step 3. The subsample size n was modified with a coefficient λ (Babu, 1992) and $\lambda \cdot n$ samples were taken without replacement.

$$\lambda = \frac{1 - (1/\sqrt{5})}{2} \tag{6.1}$$

The bootstrap technique might have some problems in terms of convergence, if the size of the re-sample is less than the sample size, and $\lambda \cdot p$ allows to correct this issue.

The subsampling bootstrap technique was applied 1000 times. Confidence intervals for the resampled results were calculated simply as the mean value plus or minus the standard deviation of the resampled results.

6.3 Results and discussion

An estimated blocking probability is calculated from the experiments of Table 6.1. An experiment is defined as one combination of parameters and it is composed by 60 repetitions or trials (n) under constant conditions. The 5 experiments represent 300 independent results.

Figures 6.1 and 6.2 show the blocking probability obtained in the experiments for the different group sizes evaluated. At the right in these figures, the frequency of outcomes is shown with histograms. For visualization purposes, frequencies were divided in 5 bins. Two bins containing the extreme values 0 / 1 and, 3 intermediate bins of 1/3 width for a better representation. For example, in experiment 1, two stems blocked more frequently than zero or one from a group of two stems. In experiment 4, the second bin had the highest frequency, meaning that 24 repetitions resulted in 1 to 5 stems blocked from a group of 16.

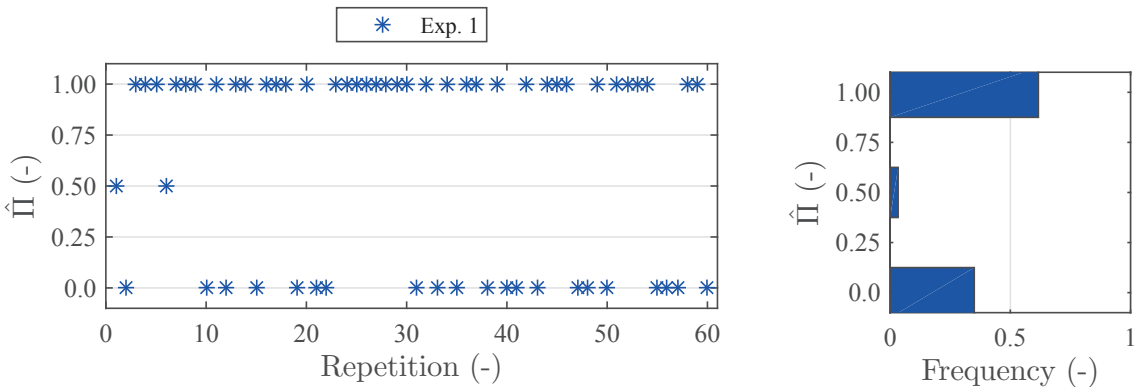


Figure 6.1 – Scatter plot of the results and histograms for the estimation of blockage ($\hat{\Pi}$) for groups of stems (experiment 1).

At the left in Figures 6.1 and 6.2, the scatter plots represent the blocking probability for each single repetition, not the averaged value as in Chapter 4. As seen in the individual experiments,

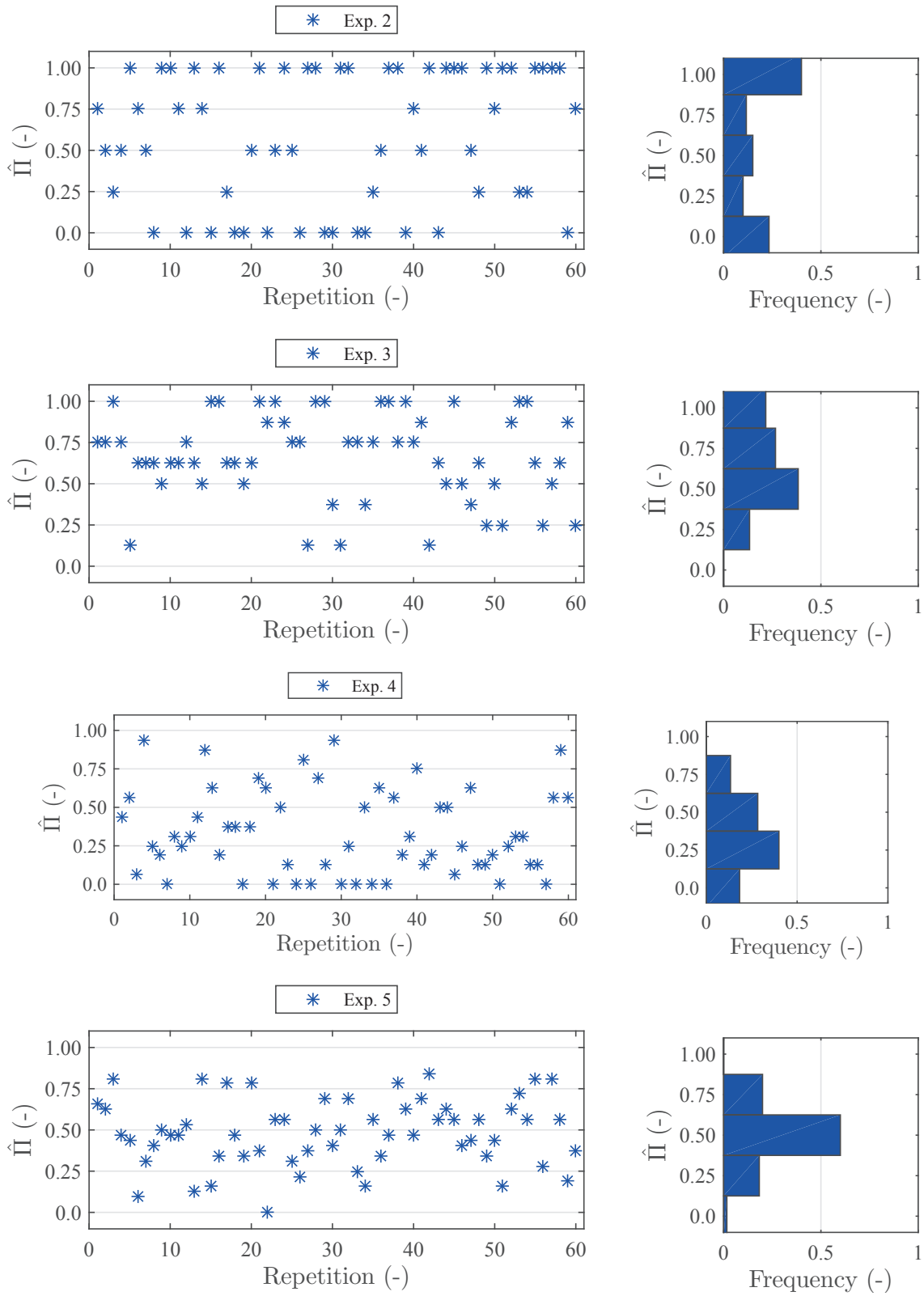


Figure 6.2 – Scatter plot of the results and histograms for the estimation of blockage ($\hat{\Pi}$) for groups of stems (experiments 2, 3, 4 and 5).

results might differ when repeated under constant conditions.

To quantify the scattering of the results, the standard deviation was calculated for experiments 1 to 5 after 60 repetitions (Table 6.2). For the tested conditions, with equal number of repetitions, the standard deviation of the data tends to decrease with increasing stem group size. Nevertheless, it should be noticed that the process of blockage, and thus $\hat{\Pi}$, is a function of the parameters tested (stem relative length, stem density, relative head, group size). The variability of results might be modified in relation to the parameters affecting the blockage process.

Table 6.2 – Blocking probability estimation ($\hat{\Pi}$) for different stem group sizes and its standard deviation (Std) from the physical experiments.

N° Exp.	Group size	$\hat{\Pi}$	Std
1	2	0.63	0.48
2	4	0.59	0.41
3	8	0.66	0.26
4	16	0.33	0.27
5	32	0.48	0.20

The different standard deviation of the results shows that each combination of parameters (stem relative length, relative head, stem density, stem group size) influences differently the blocking probability. The deviation of results is higher for smaller groups sizes. If the number of stems supplied is increased, more interactions between stems occur which may affect the blocking probability. This will be further developed in Chapter 7 when the influence of the group size is analysed.

When evaluating the number of occurrences or not of stem blockage, results can be considered binomials. In the case of experiments with stem groups, outcomes different than 0 or 1 were allowed. The estimations of blocking probabilities shown in Table 6.3 were calculated using the statistical tool InfoStat (Di Rienzo et al., 2017). Confidence intervals with 90% confidence were defined using the Clopper-Pearson method. The number of repetitions n displayed is in accordance with Chapter 4.

Table 6.3 – Blocking probability estimation ($\hat{\Pi}$) of stem groups from experimental results with confidence interval width (CI_W) for different number of repetitions.

		$n = 4$		$n = 10$		$n = 30$		$n = 60$	
N° Exp.	Group size	$\hat{\Pi}$	CI_W	$\hat{\Pi}$	CI_W	$\hat{\Pi}$	CI_W	$\hat{\Pi}$	CI_W
1	2	0.63	1.00	0.70	0.60	0.73	0.32	0.63	0.25
2	4	0.50	0.64	0.63	0.49	0.52	0.31	0.59	0.21
3	8	0.81	0.40	0.64	0.32	0.70	0.18	0.66	0.13
4	16	0.50	1.00	0.33	0.38	0.37	0.22	0.33	0.15
5	32	0.64	0.44	0.48	0.28	0.45	0.16	0.48	0.11

The statistical distribution of the LW blockage process at an ogee crest weir equipped with piers is currently unknown. To study the influence of experimental repetitions on the accuracy of blocking estimations without assumptions on the probability distribution is challenging. In

order to remove this major constraint and to achieve a consolidated analysis, different sample sizes by subsampling bootstrap technique (Babu, 1992, Politis et al., 1999) have been computed for the estimated blocking probability. Figures 6.3 and 6.4 show the error bars obtained after 1000 re-samples with varied sample sizes for the different group sizes. For the application of the subsampling bootstrap technique, repetitions were considered independent.

The confidence interval width, from the generated data by the subsample bootstrap, decreases with the increment of the number of samples taken (Table 6.4). When the sample size and the repetitions increase, the accuracy of the estimated blocking probability increases accordingly. It is expected that larger stem group sizes (experiment 4 and 5) have a similar level of accuracy than smaller stem groups with less repetitions, based on the narrower confidence intervals for the tested conditions.

For $n = 4$ (Table 6.4), for groups of 2 and 4 stems $CI_W = 0.81$ and 0.77 respectively. For the case of groups with 8, 16 and 32 stems, with $n = 4$, the confidence interval is reduced to $CI_W = 0.49$; 0.53 and 0.40 respectively. When increasing n for the resampled results, the width of the intervals is decreased for all group sizes.

Table 6.4 – Blocking probability estimation ($\hat{\Pi}$) for different group sizes with confidence interval width (CI_W) after subsampling bootstrap technique for different sample sizes.

		$n = 4$		$n = 10$		$n = 30$		$n = 60$	
N° Exp.	**Group size**	$\hat{\Pi}^*$	$\mathbf{CI}_W$	$\hat{\Pi}^*$	$\mathbf{CI}_W$	$\hat{\Pi}^*$	$\mathbf{CI}_W$	$\hat{\Pi}^*$	$\mathbf{CI}_W$
1	2	0.63	0.81	0.64	0.41	0.64	0.11	0.64	0.05
2	4	0.57	0.77	0.59	0.34	0.59	0.09	0.59	0.04
3	8	0.65	0.49	0.66	0.22	0.66	0.06	0.67	0.03
4	16	0.34	0.53	0.33	0.24	0.33	0.07	0.34	0.03
5	32	0.49	0.40	0.48	0.17	0.48	0.05	0.48	0.02

Figure 6.5 shows the comparison of the standard errors for different sample sizes, as a function of the group size. Increasing the sample size, in an experiment with 2 stems, decreases the standard error significantly. When the sample size is increased in experiments with 32 stems, the error decreases in a smaller magnitude.

The improvement in accuracy, based on the magnitude of the standard error, when comparing 30 and 60 subsamples is lower than 0.03. The magnitude of change in the standard error, indicates that the improvement done increasing a sample size from 30 to 60 repetitions is not beneficial in terms of time consumed per experiment.

Clearly, having 60 samples of one physical experiment, 1000 times would incur into extensive experimental campaigns. Nevertheless, it is important to justify statistically the size of n adopted by computing the accuracy of experimental results.

Figure 6.5 shows that, similarly than for individual stem experiments, the obtained accuracy per

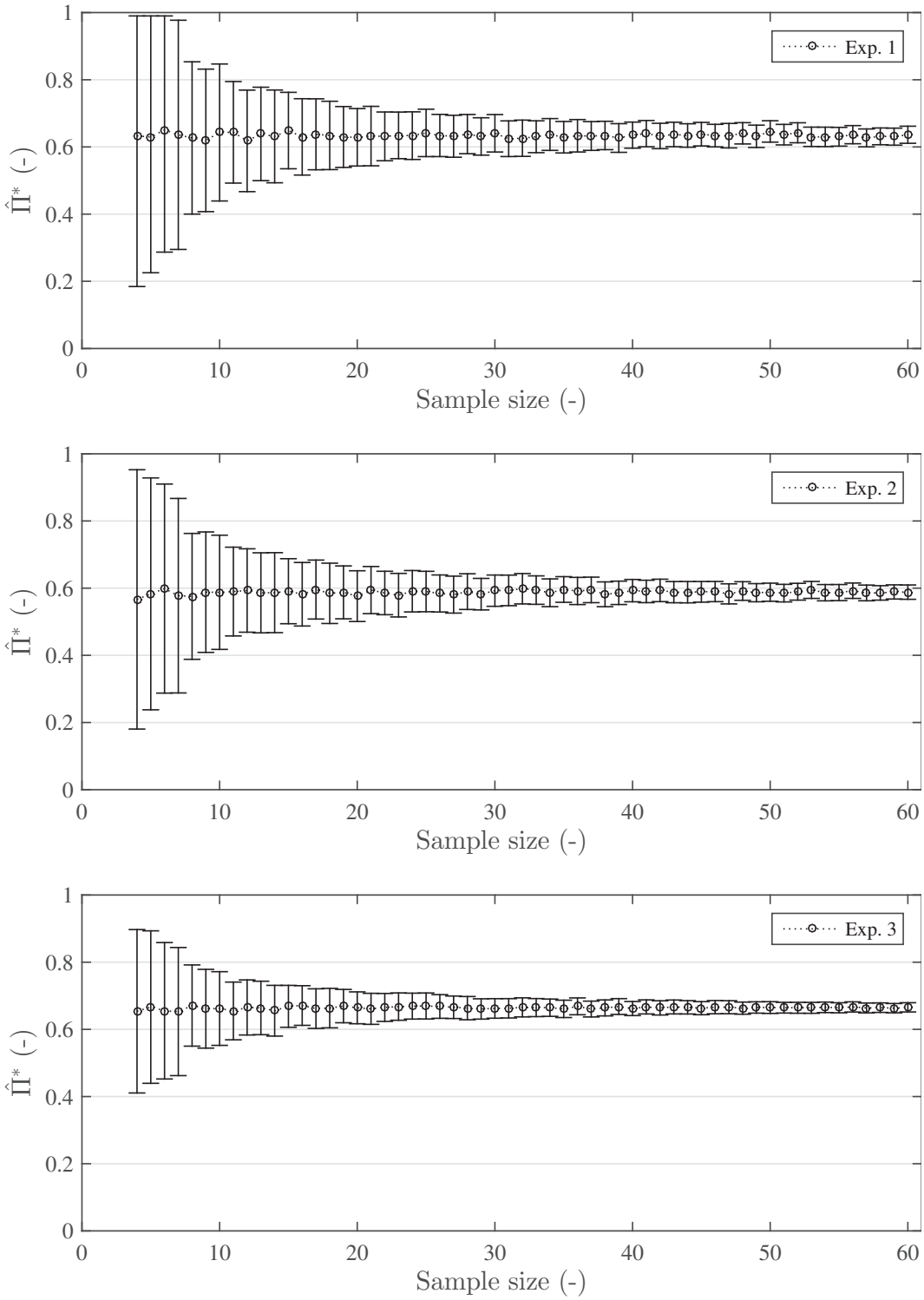


Figure 6.3 – Variability of the estimated blocking probability ($\hat{\Pi}^*$) for groups of stems as a function of the sample size, after the subsampling bootstrap technique (experiments 1, 2 and 3).

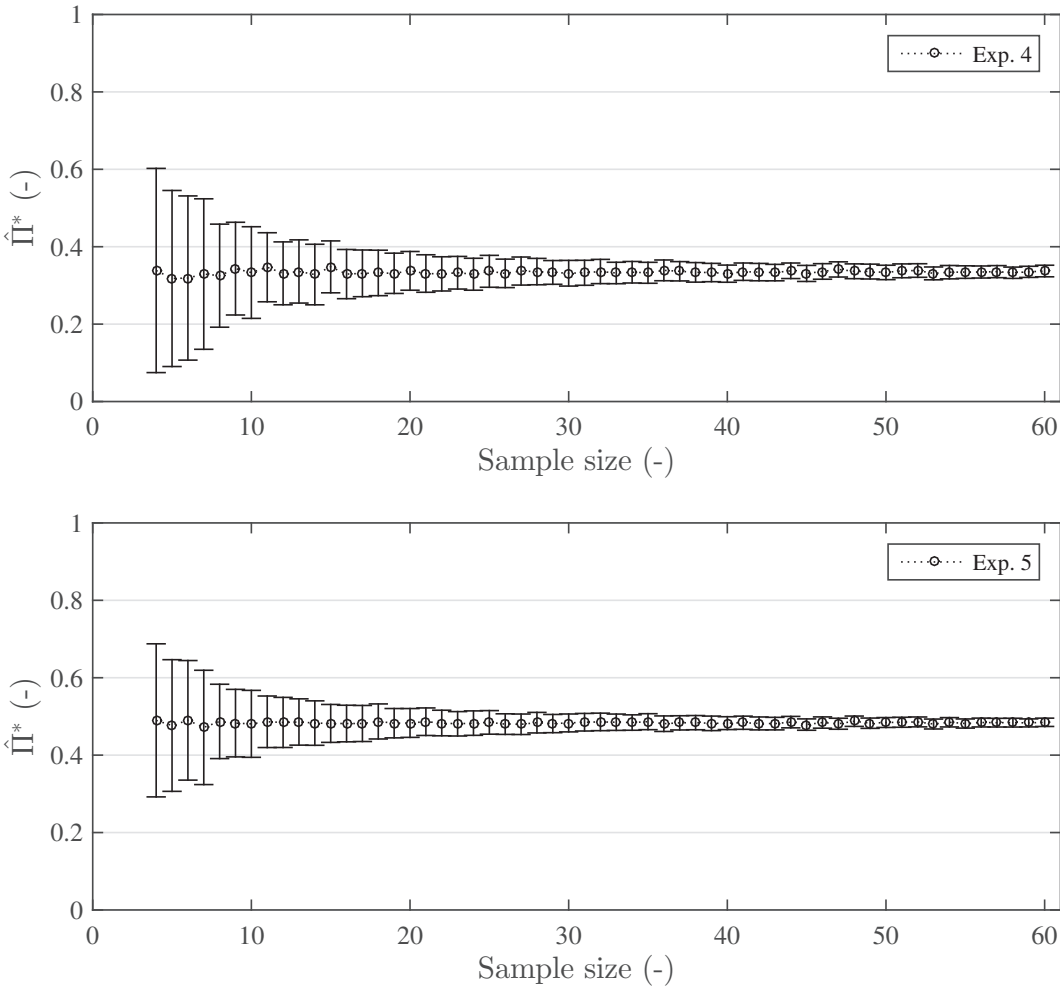


Figure 6.4 – Variability of the estimated blocking probability ($\hat{\Pi}^*$) for groups of stems as a function of the sample size, after the subsampling bootstrap technique (experiments 4 and 5).

experiment will depend of the number of repetitions. It is recommended that $n \geq 30$ is used as it gives statistically reliable estimations of the blockage probability with standard errors lower than 0.10 (Figure 6.5). The decreased variability of the blockage process as a function of the stem group size allows, in some cases, to decrease the number of repetitions. From Figure 6.5, for groups of 2 and 4 stems the number of repetitions could range (approximately) between $10 \leq n \leq 30$; for groups of 8, 16 and 32 stems the number of repetitions could be $n = 10$. Nevertheless, a statistical analysis is recommended if n is decreased, as the other involved parameters also play a role in the blockage process and the standard error should be calculated to verify the adopted value of n.

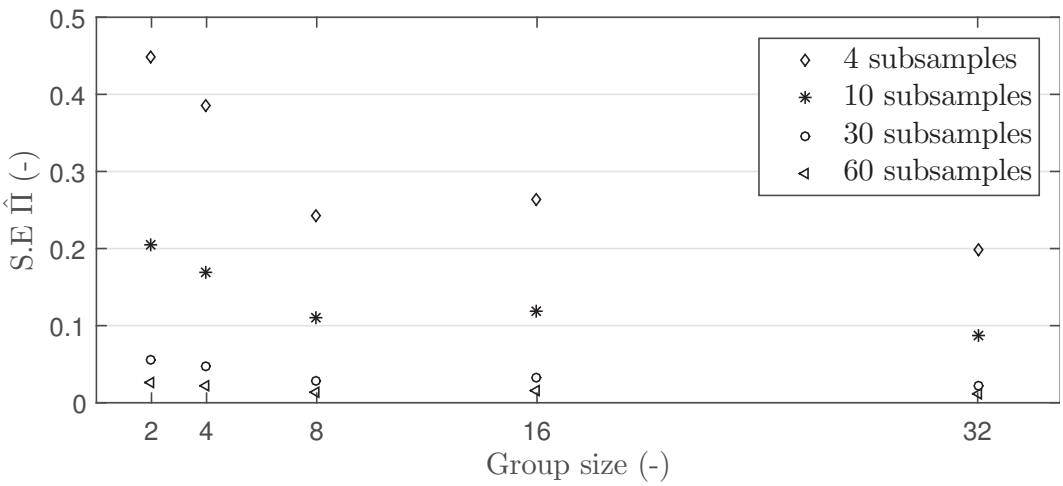


Figure 6.5 – Standard error (SE) of the estimated blocking probability for groups of stems, calculated with the subsample bootstrap technique for different sample sizes.

6.4 Conclusions

Experiments were conducted to evaluate the influence of experimental repetitions on the accuracy of LW blocking probability estimations for groups of stems, at an ogee crest weir with piers. Knowledge on the variability the estimations of blocking probabilities have, provides researchers with a better understanding of the phenomenon. Measurements of the accuracy an estimated value has respect to the parameter it represents, should be always given (Kelley and Maxwell, 2003). The experiments revealed that the number of experimental repetitions and the mathematically simulated repetitions, influence the accuracy of statistical estimations. It is important to report an estimated value like $\hat{\Pi}$ with confidence intervals to give an overview of its accuracy.

A wide range of stem dimensions and hydraulic conditions were tested. The experiments showed that the accuracy of the estimated blocking probability depends on the number of repetitions per experiment. These observations are aligned with the results obtained in the individual stem experiments (Chapter 4). The main mathematical difference of groups of stems and individual stem experiments is that groups are no longer considered as a Bernoulli experiment. It is recommended for experimental campaigns to adopt $n \geq 30$ repetitions per experiment in order to estimate blocking probabilities with errors smaller than 0.10. From a physical point of view, experiments with increasing groups of stems have more interactions between stems and this leads to smaller standard deviations of the blocking estimation. This is an advantageous finding that allows to decrease the number of repetitions n for increasing stem group sizes, while keeping a similar accuracy. For groups of 2 and 4 stems the number of repetitions could range between (approximately) $10 \leq n \leq 30$ with maximum errors up to 0.20; for groups of 8, 16 and 32 stems the number of repetitions could be n equal to 10 with errors approximately of 0.10. However, as the blocking process depends of LW characteristics and hydraulic conditions, the analysis to

decrease n should be based on the evaluation of the parameters tested and not only on G_i. Such reduction in n will represent different levels of accuracy and they should be stated always with the blocking probability estimation. Confidence intervals or some measurement of statistical accuracy should be included when referring to an estimated probability.

7 Estimation of blocking probability for groups of stems

7.1 Overview

The study of LW characteristics influencing the blocking probability has been presented in Chapter 5 for individual stem experiments under different hydraulic conditions. A statistically justified number of experimental repetitions has been analysed in Chapter 6 for the case of stem groups. Stem-to-stem collisions can drag previously blocked pieces and therefore decrease the blocking probability. Immobile stems at the ogee crest can obstruct the ones moving and increase the blocking probability, while triggering formation of jams. The probability of a jam formation is supposedly linked to the number of arriving stems to the structure (Yang and Johansson, 2009). Therefore, the estimated blocking probability of an individually supplied stem was compared to the blocking probability of groups of simultaneously supplied stems. In this chapter, a systematic evaluation of the influence of stem group size on the blocking probability for different hydraulic conditions and classes of stems is presented.

7.2 Methodology

In addition to the study of relative stem length and relative head influence on the blocking probability, a varying stem group size is included in this chapter (Table 7.1). The number of stems that compose a group has been defined as $G_i = 2^m$, where $m = 0;1;2;3;4;5$. The number of experimental repetitions is shown in Table 7.1. Due to time constraints the number of repetitions for the larger groups of stems has been decreased compared to Chapter 6. The significant reduction of the sample size has influenced the accuracy of the estimations therefore, the error of the estimations is presented for each result. The 11 experiments represent 580 independent results. The characteristics of each stem class are shown in Chapter 3, Table 3.2. A pier nose that protrudes 0.04 m from the weir into the reservoir was used (N_2).

The blockage probability for a group of stems is estimated as the number of stems blocked divided by the number of stems supplied, averaged in the experimental repetitions. Therefore,

Table 7.1 – Experimental program for evaluating the effect of group size on the blocking probability.

Exp. N°	Class	Density ρ_s	*H/d*	Open bays	Nose type	Group size	Repetitions
1	A	0.59	1.00	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
2	A	0.59	1.20	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
3	C	0.56	0.94	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
4	C	0.56	1.00	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
5	C	0.56	1.06	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
6	E	0.54	0.76	5	N2	1,2, -,8,16,32	30,15, -,4,3,3
7	E	0.54	0.84	5	N2	1, -,4,8,16,32	30, - ,8,4,3,3
8	E	0.54	0.96	5	N2	1,2,4,8,16,32	30,15,8,4,3,3
9	A	0.59	1.20	1	N2	1,16	30,3
10	C	0.56	0.94	1	N2	1,16	30,3
11	E	0.54	0.76	1	N2	1,16	30,3

the blockage probability estimation for a group represents the frequency of having stems blocked when supplying a group and not the probability of having a complete group blocked. The temporal order in which stems block has not been measured thus a final general value of blockage is considered. The maximum likelihood estimator, $\hat{\Pi}$, of the blocking probability π is given by,

$$\hat{\Pi}_G = \frac{X}{n \cdot G_i}$$

where X is the number of blocked stems, G_i is the group size and n is the total number of repetitions.

The blocking probability of groups of stems is compared to the blocking probability of individual stems throughout a normalized value expressed as $\Delta\hat{\Pi}/\hat{\Pi}_1$ where $\Delta\hat{\Pi} = \hat{\Pi}_{G_i} - \hat{\Pi}_1$.

Ratios of head H to stem diameter d (H/d, relative head) ranged between 0.76 to 1.20. The stem group size was systematically varied in order to analyse its influence on blockage. One stem density was used per stem class, restricting the number of evaluated parameters that affect the blockage process. For experiments 1 to 8, scenarios with five open bays were used. Situations with one bay open were investigated using two group sizes in experiments 9, 10 and 11.

Confidence intervals with 90% confidence were calculated with the Clopper-Pearson method using the statistical tool InfoStat (Di Rienzo et al., 2017). Results are considered binomials by establishing a specified criterion: presence or absence of blockage. To calculate the confidence intervals, X takes continuous values (proportion of stems that blocked from the group) instead of only 0 or 1. Due to the small quantity of experimental repetitions for groups of 8, 16 and 32 stems, the standard error of estimation ($S.E$) is also computed.

It is important to note that the mean value $\hat{\Pi}$ depends on the parameters being tested in the experimental facility and the accuracy of the estimation depends on the experimental repetitions. The confidence interval calculated based on $\hat{\Pi}$, considers both aspects.

7.3 Results and discussion

7.3.1 Estimation of blocking probability for groups of stems, class A

The estimations of blocking probability for stem class A, with a relative stem length of 80% respect to the bay width (experiments 1, 2, and 9, Table 7.1), can be seen in Table 7.2. The increase of relative head from experiment 1 to 2 decreases the blocking probability of all group sizes. In experiments 1 and 2, $\hat{\Pi}$ ranges in ± 0.10 with the increase of group size, except for groups of 4 and 32 stems. For class A with 5 open bays, groups of 4 stems have higher blocking probability than the other groups.

Table 7.2 – Experimental estimations of blocking probability for class A for different stem group sizes, with 1 and 5 open bays (S.E = Standard Error; CI_W = Confidence interval width).

	Five open bays						**One open bay**		
	H/d = 1.00 (**Exp. 1**)			*H/d* = 1.20 (**Exp. 2**)			*H/d* = 1.20 (**Exp. 9**)		
G_i	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W
1	0.47	0.09	0.31	0.27	0.08	0.28	0.43	0.09	0.31
2	0.47	0.12	0.44	0.33	0.09	0.33			
4	0.63	0.12	0.43	0.50	0.07	0.26			
8	0.41	0.09	0.44	0.31	0.08	0.38			
16	0.42	0.15	0.84	0.31	0.07	0.42	0.50	0.24	1.00
32	0.59	0.13	0.73	0.39	0.06	0.33			

For identical relative heads *H/d*, experiment 9 has higher blocking probabilities than experiment 2. For one open bay, $\hat{\Pi}$ remains apparently constant (± 0.07) with the increase of group size.

For experiments 1, 2 and 9, the normalized value of blockage can be seen as a function of stem group size (Figure 7.1). In experiments 1 and 2 the growing group size influences similarly the blockage estimation, for the tested *H/d* relations. As the group size increases from 1 to 4 stems, blockage increases. From 4 to 8 stems, blockage decreases and then remains partially constant for 16 stems. Groups of 32 stems have a blockage increase of 0.18 in experiment 1 and 0.07 in experiment 2, compared to 16 stems. One may also note that the normalized value of blockage for one and five open bays, with the same relative head, is equal (experiment 2 and 9).

The observations conducted in these experiments and the pictures taken (Figure 7.2), suggest that for groups of 2 and 4 stems, stem-to-stem interactions are few. For larger groups (≥ 16 stems), interactions between stems are more frequent. However, for these tested conditions the change of group size has a weak influence on the blocking probability estimation.

7.3.2 Estimation of blocking probability for groups of stems, class C

The estimation of blocking probability for experiments with stem class C, with a relative stem length of 120% respect to the bay width, (experiments 3, 4, 5 and 10, Table 7.1) can be seen in Table 7.3. An increase of the relative head *H/d* generally decreases the blocking probability with

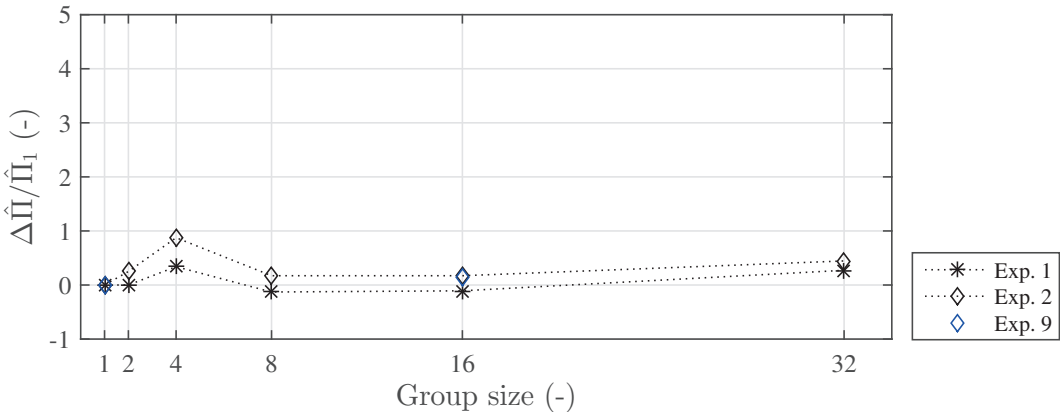
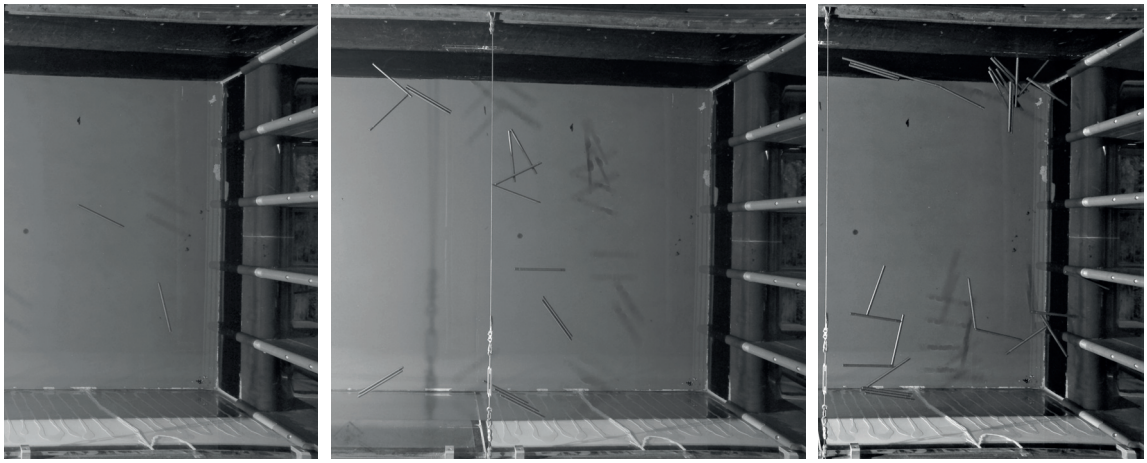


Figure 7.1 – Normalized value of the estimated blocking probability ($\Delta\hat{\Pi}/\hat{\Pi}_1$) for class A as a function of stem group size.



(a) G_2 no stem interactions. (b) G_{16} some stem interactions. (c) G_{32} more stem interactions.

Figure 7.2 – Interactions between stems for different group sizes with class A (experiment 1) (water flows from left to right).

the exception of some groups in experiment 4 (Table 7.3). In the case of experiment 4, groups of 1 and 16 stems have higher blockage in comparison to experiment 3 and 5. Additionally, in experiment 4, groups of 2 and 8 stems have lower blocking probability than in experiment 5 even if the relative head is lower.

The main difference observed in experiments with 2 stems is that in experiment 3 and 5, stems travelled towards the structure in contact to each other while in experiment 4 stems were separated. This may be associated with differences in the moment of supplying the stems that were not noticeable during the experiments.

Table 7.3 – Experimental estimations of blocking probability for class C for different stem group sizes, with 1 and 5 open bays (S.E = Standard Error; CI_W = Confidence interval width).

	Five open bays									**One open bay**		
	H/d = 0.94 (**Exp. 3**)			H/d = 1.00 (**Exp. 4**)			H/d = 1.06 (**Exp. 5**)			H/d = 0.94 (**Exp. 10**)		
G_i	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W
1	0.13	0.06	0.21	0.17	0.07	0.23	0.03	0.03	0.09	0.50	0.09	0.32
2	0.30	0.12	0.42	0.07	0.05	0.15	0.13	0.08	0.27			
4	0.56	0.13	0.50	0.38	0.16	0.59	0.19	0.13	0.44			
8	0.56	0.17	0.78	0.09	0.09	0.31	0.16	0.16	0.52			
16	0.31	- *	- *	0.56	0.13	0.76	0.08	0.06	0.24	0.71	0.11	0.61
32	0.55	0.07	0.42	0.42	0.07	0.40	0.15	0.10	0.45			

*The method fails as the 3 experimental repetitions resulted in 5 stems blocked from a group of 16.

Comparing experiment 3 to 10, one open bay has higher blocking probability than five bays for the same relative head (Table 7.3). In both experiments the estimated blocking probability increased for bigger group sizes.

In experiment 3, $\hat{\Pi}_1$ = 0.13 (1 stem) and $\hat{\Pi}_4$ = 0.56 (4 stems) resulting in a change of blocking probability equal to 0.43. In experiment 5, $\hat{\Pi}_1$ = 0.03 and $\hat{\Pi}_4$ = 0.19 resulting in a change of probability equal to 0.15. Hence, $\hat{\Pi}$ tends to increase with more stems but the relation is not linear.

It is noticeable that groups with 4 and 32 stems (for experiment 3, 4 and 5) have a similar blocking probability (± 0.04). In experiment 5 for an increasing group size, $\hat{\Pi}$ remains practically constant compared to a group composed by 2 stems (± 0.06).

The normalized value of blockage can be seen as a function of the stem group size in Figure 7.3. Experiment 4 has the lowest variation of the normalized value of blockage. This low variation of the normalized value may be related to the high blocking probability for an individual stem. For experiments 3 and 5, the process of blockage is equally influenced by the change of group size for both H/d relations. In the case of one open bay and five, the normalized value of blockage is lower for one open bay with the same H/d relation.

During the experiments it was observed that stems of experiments 3 and 5 have more stem-to-stem interactions and create agglomerated groups of stems (Figure 7.4a and c). In experiment 4, groups travel towards the structure with less interactions among stems (Figure 7.4b). As previously mentioned, experiment 4 shows unexpected behaviours and it may be related to some differences that were not noted when supplying the stems during the experiments.

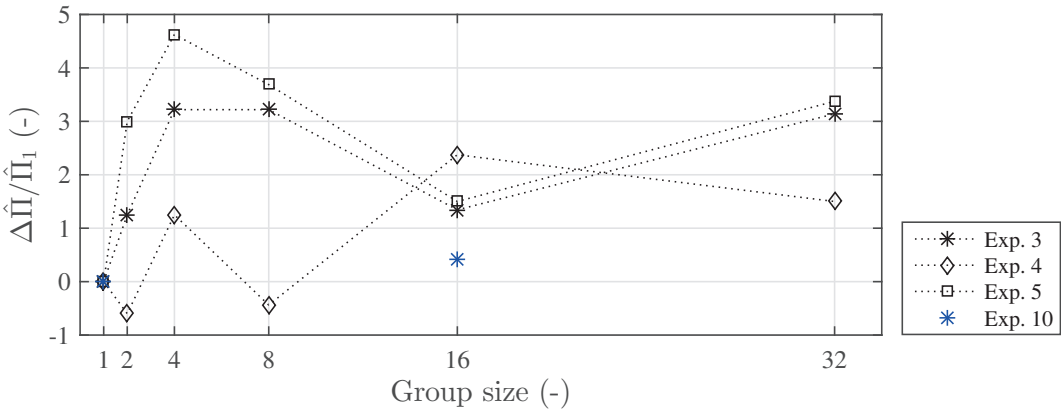
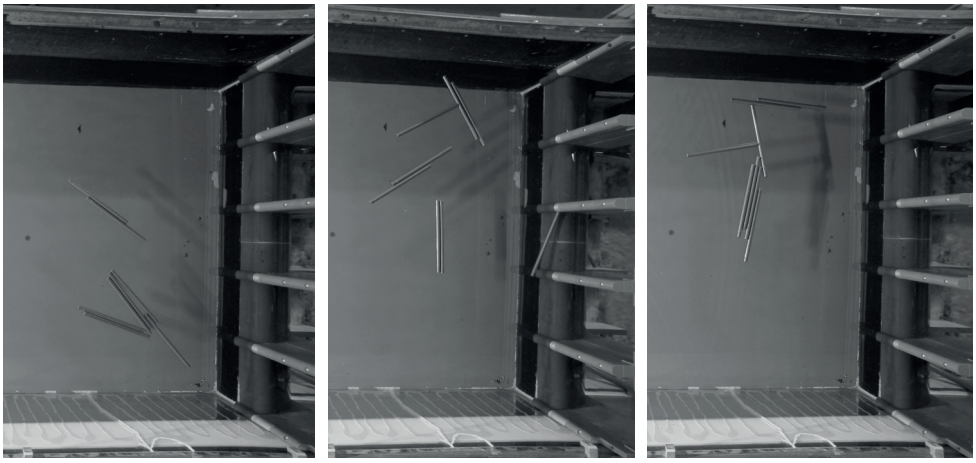


Figure 7.3 – Normalized value of the estimated blocking probability ($\Delta\hat{\Pi}/\hat{\Pi}_1$) for class C as a function of stem group size.



(a) Experiment 3 (b) Experiment 4 (c) Experiment 5

Figure 7.4 – Interactions between stems for equal group sizes and different relative head, with class C (water flows from left to right).

7.3.3 Estimation of blocking probability for groups of stems, class E

The estimation of the blocking probability for experiments with stem class E, with a relative length of 200% with respect to the bay width (experiments 6, 7, 8 and 11, Table 7.1) can be seen in Table 7.4. The estimated blocking probability, for all group sizes, decreases for an increasing relative head (Table 7.4). Comparing experiment 6 and 11, for equal *H/d*, the blocking probability decreases for one open bay. In experiment 11, $\hat{\Pi}$ remains practically constant when increasing the group size (± 0.04).

In experiments 6 and 7, when increasing the group size from a single stem to 8 stems, blocking probabilities increase. Overall, experiments 7 and 8 show that stem groups have higher blocking probability than an individual stem, for these tested conditions. At experiment 6, when increasing

Table 7.4 – Experimental estimations of blocking probability for class E for different stem group sizes, with 1 and 5 open bays (S.E = Standard Error; CI_W = Confidence interval width).

	Five open bays									**One open bays**		
	H/d = 0.76 (**Exp. 6**)			H/d = 0.84 (**Exp. 7**)			H/d = 0.96 (**Exp. 8**)			H/d = 0.76 (**Exp. 11**)		
G_i	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W	$\hat{\Pi}$	S.E	CI_W
1	0.87	0.06	0.21	0.40	0.09	0.30	0.13	0.06	0.21	0.60	0.09	0.30
2	0.90	0.05	0.18				0.53	0.12	0.44			
4				0.66	0.13	0.51	0.22	0.13	0.46			
8	0.97	0.03	0.10	0.66	0.16	0.71	0.25	0.05	0.24			
16	0.83	0.08	0.39	0.50	0.10	0.56	0.17	0.04	0.24	0.56	0.10	0.56
32	0.80	0.09	0.47	0.74	0.03	0.16	0.44	0.14	0.80			

the groups size from 8 to 32, the blocking probability decreases. Experiment 7 has a lower $\hat{\Pi}$ for groups of 16 stems compared to 8 and 32 stems.

The normalized value of blockage can be seen as a function of stem group size in Figure 7.5. The normalized value of blocking probability in experiment 6 is lower than 0.10 when increasing the stem group sizes as that combination of parameters tested already has a high $\hat{\Pi}$ (higher than 0.80).

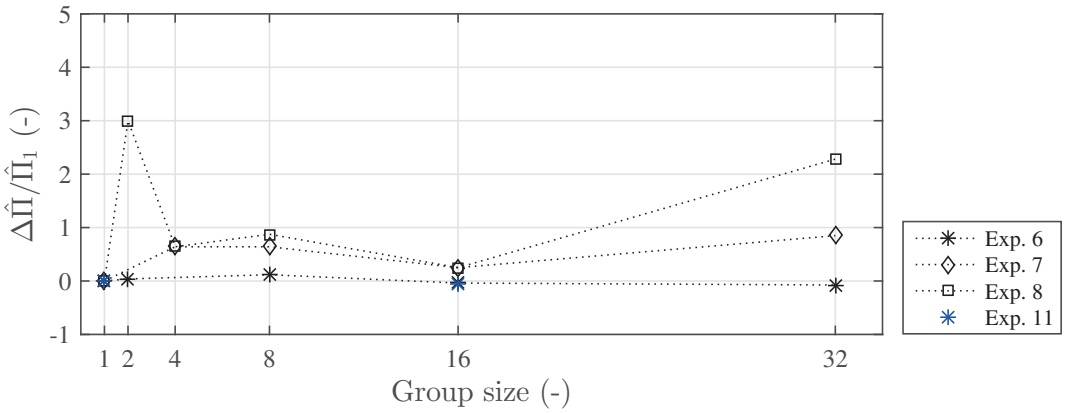


Figure 7.5 – Normalized value of the estimated blocking probability ($\Delta\hat{\Pi}/\hat{\Pi}_1$) for class E as a function of stem group size.

For experiment 7 and 8, the normalized value of blockage for groups of 4 and 16 stems is equal even with a different H/d. The normalized value of blockage for experiments 6 and 11, considering a group of 16 stems is also equal. This suggests that the group size influence on the blocking probability with different bay scenarios is constant.

7.4 Conclusions

As observed with the individual experiments, the behaviour and interactions between LW and hydraulic structures involves random processes. The influence of the number of supplied stems

(group size) on the estimated blocking probability at an ogee crest weir with piers was evaluated. Nonetheless, results show the intrinsic variability of the process. A descriptive analysis of the experiments performed has been presented, focusing in how different sizes of stem groups can change the blockage probability. Herein, the stem density was not a studied variable.

The results allowed to quantify the blocking probability of individual stems and groups of stems, and by comparison, understand the influence of different group sizes for varied LW and hydraulic conditions. Although the standard error in the estimations for some cases reached 0.17, the average value of the standard error was 0.09 and was considered acceptable in light of the random nature of the blockage process. If more experimental repetitions were performed, higher accuracy could be achieved.

An increasing stem group size can increase the blocking probabilities, when compared to an individual stem, for a relative stem length larger than the bay width and certain relative heads. If the blocking probability of a single stem is higher than 0.80, a larger group size will not necessarily increase the blocking probability.

Regarding the influence of the number of open bays on the blocking probability of stem groups, for the same H/d, five open bays were found to have lower blocking probability than one open bay for relative stem lengths L/b equal or lower than 1.20. For $L/b \geq 2.00$, this relation is inverted for equal H/d relation.

For class A experiments ($L/b = 80\%$) the increasing stem group size does not influence significantly the blocking probability when compared to an individual stem except for groups of 4 stems. The same applies for class E ($L/b = 200\%$) when $\hat{\Pi} \geq 0.80$ due to low values of H/d. In many cases where $L/b \geq 120\%$ (class C and E), although not in all, there is a marked effect of the stem group size for the blocking probability when compared to an individual stem.

As observed for the individual stem experiments, with 5 open bays, increases of the relative head H/d decrease the blocking probability $\hat{\Pi}$ for all the relative stem lengths tested L/b. Only for $L/b = 120\%$ (experiment 4), some stem groups do not decrease the blockage probability with a head increase. Overall, experiment 4 with class C had an unexpected behaviour. A difference in the supply method probably occurred that affected the behaviour of the stems considerably. Some slight discrepancies can also be observed in experiment 8 but the global behaviour is aligned to the other experiments.

For stems relatively larger than the bay width, a marked increase of $\hat{\Pi}$ when increasing the stem group size from 1 to 4 stems has been found. The blockage probability for groups of 4 stems could be the double than the blocking probability of an individual stem for constant H/d. Nevertheless, increasing the stem group size from 4 to 16 stems was found not to influence significantly the blocking probability. A slight tendency of decrease for $\hat{\Pi}$ when increasing the group from 4 to 16 stems has been observed. A slightly increasing trend when going from groups with 16 to 32 stems is seen for $\hat{\Pi}$.

8 Head increase due to stem blockage

8.1 Overview

In the previous chapters, the main focus was to understand which parameters and in what manner they influence the blocking probability of stems at an ogee weir. Herein, the main focus is the effect certain characteristics of a stem blockage can have on the head upstream of a spillway and the quantification of the head increase.

From Chapter 2 it is recalled that woody jams are complex and porous accumulations of heterogeneous material (Manners et al., 2007). A jam is defined as three or more pieces of large wood in contact (Wohl et al., 2011), where one piece that was previously mobile has been "trapped" (Dixon, 2016).

In the first part of this chapter (Section 8.2), experiments include an heterogeneous group of 200 artificial stems (i.e. a stem batch) to quantify blocking probability and head increase. Two different heads were evaluated with systematic experiments. The analysis of photographs to evaluate influential characteristics of a jam in terms of head increase are discussed.

In the second part of this chapter (Section 8.3), measurements of head increase are presented for cases were blockage was artificially arranged. A simplified equation to estimate the normalized head increase, as a function of the relative occupied area by stems, is presented.

8.2 Blocking probability and head measurements

8.2.1 Methodology

Experiments were conducted to test how an heterogeneous group of 200 artificial stems (i.e. stem batch) blocks at an ogee weir with piers and what consequences it can have on the head in the reservoir upstream of the structure.

An estimation of transported woody volume is important for hazard evaluation but difficult to

determine. Although some methods exist to predict potential transported volumes, they highly depend on field data or knowledge from past events. Hence, the stem batch was composed by an arbitrary number of 200 stems (Table 8.1) with a stem volume of 0.012 m^3. The batch composition followed the distribution of large wood sizes from the accumulations measured in Switzerland during the year 2005 (Bezzola and Hegg, 2007). The same batch was used for all the experiments. The characteristics of the stem class and stem density can be seen in Table 3.2 from Chapter 3.

Table 8.1 – Batch composition with artificial stems.

	Stem density [-]			
Class	ρ_{s1}	ρ_{s2}	ρ_{s3}	ρ_{s4}
A		30	40	15
B		39		
C	20	20		
D		18		
E		6	6	6

Initially, a discharge was fixed and the water surface elevation above the ogee crest was measured without stems. An ultrasonic distance sensor (± 0.3 mm) was installed 2.60 m upstream of the weir sufficiently upstream not to be influenced by the structure (measurement position greater than $5 \cdot H_d$ as seen in Quintela (2005)). Consecutively, a batch of artificial stems was supplied to the flume with the mechanical equipment described in Chapter 3. Once stems would block it was waited 5 minutes and a new flow depth measurement was taken. The stems that passed the weir were collected, quantified and classified. After 10 minutes, another flow depth measurement was taken. If more stems had passed, the quantification was updated. Finally, all stems were removed and the procedure repeated.

For supplying the batch, stems were placed in stacked horizontal layers, mixing classes and densities (Figure 8.1).

Figure 8.1 – Stem batch arranged to be supplied with the mechanical equipment.

Two experiments were conducted. For experiment 1, an initial head $H = 0.028$ m was defined and 30 repetitions were performed. For experiment 2, $H = 0.030$ m and 25 repetitions were performed. The initial head will be further referred with the subscript *0* to indicate it is the head before stems were supplied (H_0). A configuration of five open bays and a nose configuration N_2 (protruding 0.04 m from the weir into the reservoir) was chosen in line with the previous chapters.

8.2.2 Results and analysis

Estimation of the blocking probability for a batch of 200 stems

The blockage probability for the batch was estimated as the number of stems blocked divided by the number of stems supplied (200). In Figure 8.2, the bars express the blocking probability of the batch and the normalized value of head increase per experimental repetition.

The head increase is compared against the initial head (H_0) with a normalized value expressed as $\Delta H / H_0$ where $\Delta H = H_t - H_0$. The different flow depth measurements obtained after 5 and 10 minutes are expressed with H_t where t is the time of measurement.

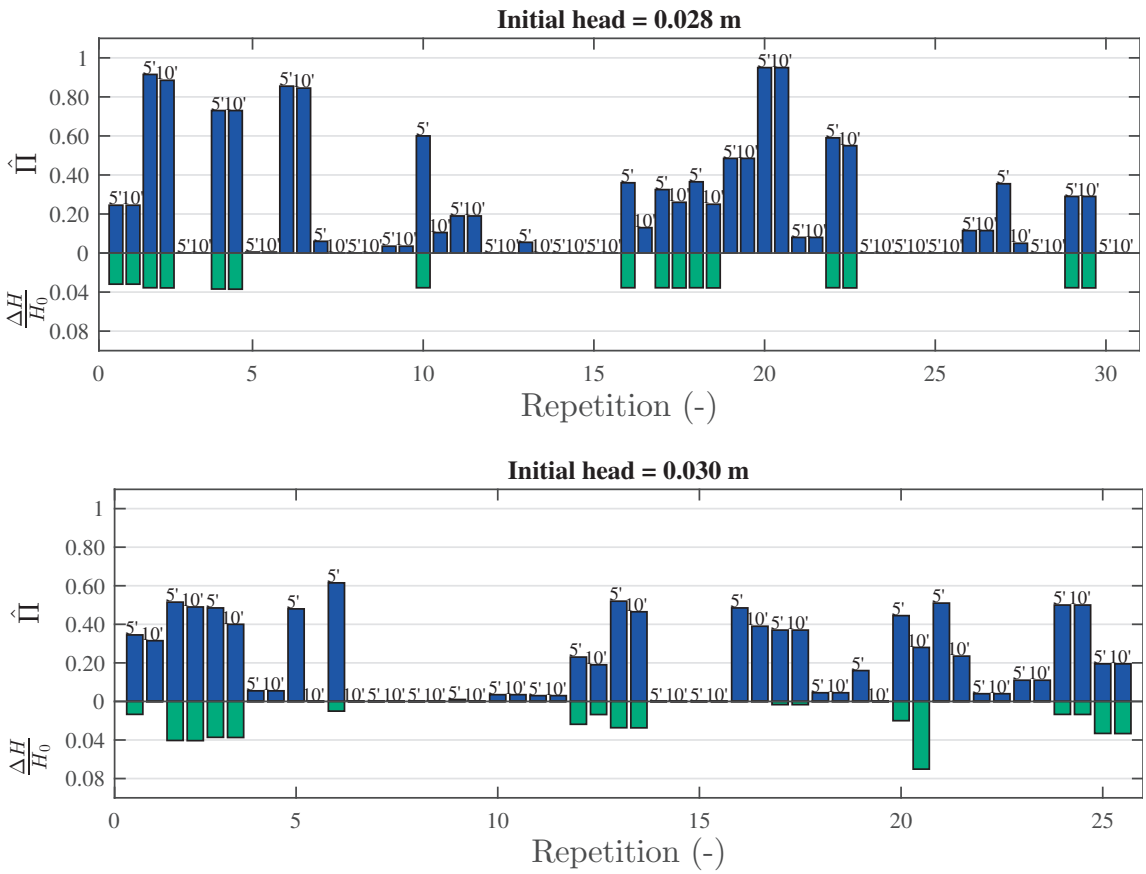


Figure 8.2 – Experimental results of blockage ($\hat{\Pi}$) and head increase ($\Delta H / H_0$) for a batch of stems (Exp. 1 and 2).

The time gap between measurements was adopted to evaluate the stability of blockage in time. It was observed that a jam upstream of the structure, after 5 minutes, was not always stable due to the movement of stems in the vicinity of the structure. If stems were manually blocked or supplied closer to the structure, the situation could be different. The stability of a jam was visually evaluated because the flow velocity was small and it could be detected weather stems continued to move or not.

Under the tested conditions, a batch of 200 stems with H_0 = 0.028 m had low blockage probability $\hat{\Pi}$ = 0.20 (averaging 30 repetitions; standard deviation of 0.09). For H_0 = 0.030 m, $\hat{\Pi}$ = 0.16 (averaging 25 repetitions; standard deviation of 0.08). Therefore, less than 40 stems of the batch are more likely to block than higher numbers of stems at the spillway inlet for these scenarios.

A summary of the experimental results can be seen in Table 8.2 with the measurements taken after 10 minutes. In both experiments, more than 60% of repetitions resulted in 40 stems or less blocked from the complete batch ($\hat{\Pi} \leq 0.20$). With this number of blocked stems, the upstream head remained constant (except for H_0 = 0.030 m, repetitions 12 and 25, Fig. 8.2).

Table 8.2 – Summary of the results frequency divided in intervals of blocking probability ($\hat{\Pi}$) plus the number of experiments that resulted in head increase (ΔH) (measurements after 10 minutes of blockage).

	Exp. 1 H_0=0.028 m		**Exp. 2** H_0=0.030 m	
$\hat{\Pi}$	Frequency	N° $\Delta H \geq 0$	Frequency	N° $\Delta H \geq 0$
0.00-0.20	20 (67%)	0 (0%)	16 (64%)	2 (13%)
0.21-0.40	4 (13%)	3 (75%)	6 (24%)	3 (50%)
0.41-0.60	2 (7%)	1 (50%)	3 (12%)	3 (100%)
0.61-0.80	1 (3%)	1 (100%)	0 (0%)	0 (0%)
0.81-1.00	3 (10%)	1 (33%)	0 (0%)	0 (0%)
Total	30 (100%)	6 (20%)	25(100%)	8 (32%)

For $\hat{\Pi}$ ranging from 0.21 to 0.40 (Table 8.2), at least in 50% of the cases, H increased at the reservoir. Considering $\hat{\Pi} \geq 0.41$, for H_0 = 0.028 m, 3 out of 6 results showed head increase. For H_0=0.030m, 3 out of 3 results showed head increase.

From Table 8.2, with low blocking probability ($\leq$ 0.20) a head increase will likely not occur. Nevertheless, when a higher blocking probability occurs, a head increase is more likely to occur. For the evaluated conditions, one maximum value of $0.2 \cdot 10^{-2}$ m of increase, for repetition number 20 with H_0 = 0.030 m was recorded (Figure 8.2).

In repetition 20 of experiment 2, one bay was blocked by stems parallel to the flow direction. A second layer of stems, perpendicular to the flow, was positioned above the first layer of stems (Figure 8.3). The mix of different stem classes and densities created a congested occupation of the bay.

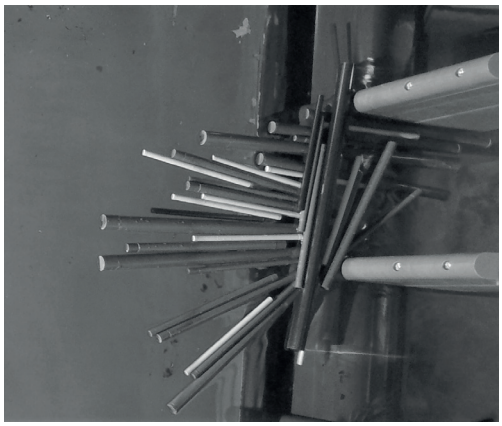


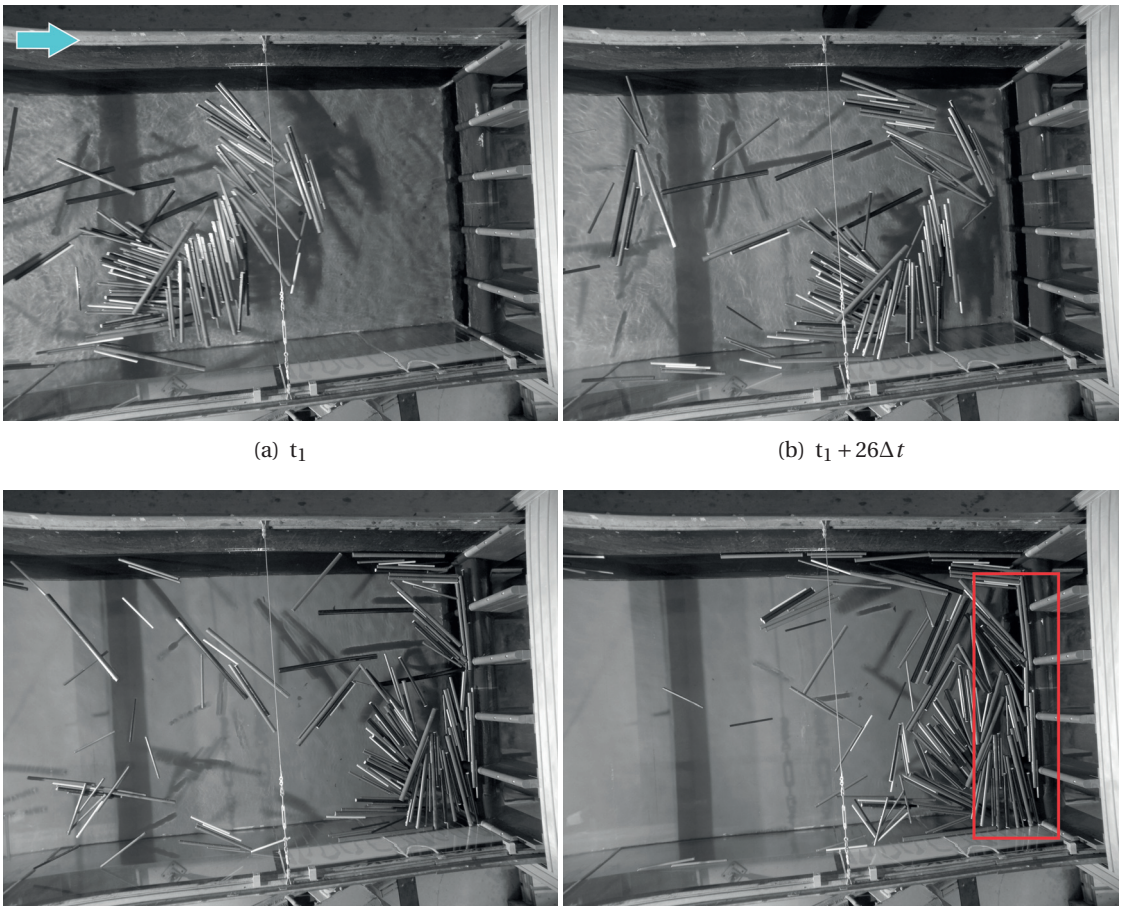
Figure 8.3 – Blockage for repetition 20, experiment 2 (H_0 = 0.030 m).

Due to the supply method of the batch, stems were able to move above each other in several vertical layers (Figure 8.4). These multilayer groups of stems were observed to influence the blockage process. The different combinations and interactions amidst stems gave various geometries of jams and thus different characteristics of the blockage (Figure 8.4).

Figure 8.4 – Example of a multilayer jam seen from upstream of the spillway.

During the experiments it was noted that the first stems that block at the weir tend to determine the shape and composition of the jam, thus becoming key elements that control the blockage process. When stems block perpendicularly to the flow direction, there are high chances that the remaining stems from the batch will block upstream. This type of blockage can evolve into a "carpet" of stems, floating relatively perpendicular to the flow direction upstream of the piers (Figure 8.5). In such cases, with the tested conditions, the flood capacity of the weir remained practically undisturbed as the pier nose kept the jam distant from the weir.

When stems turned close to the pier and aligned parallel to the flow, a re-arrangement of the surrounding stems occurred. While stems were turning, the stems nearby could be moved towards the weir, creating a congested blockage parallel to the flow direction. This behaviour was

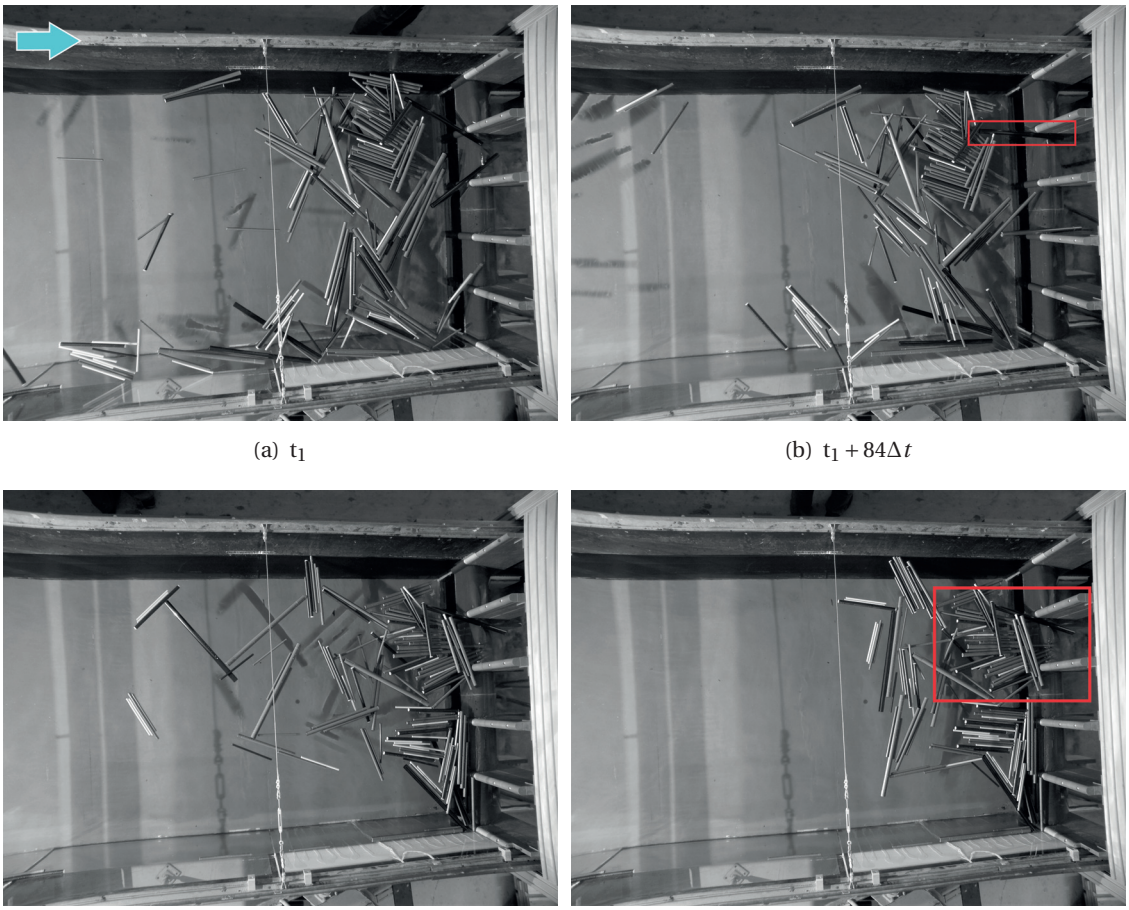


(a) t_1 (b) $t_1 + 26\Delta t$

(c) $t_1 + 76\Delta t$ (d) $t_1 + 420\Delta t$

Figure 8.5 – Experiment 1, repetition 20 ($\Delta H / H_0 = 0$) for different time steps $\Delta t = 0.5s$.

observed in repetition 4 of experiment 1, where one stem of class E ($L/b = 200\%$) with the highest stem density blocked parallel to the pier (Figure 8.6b, second pier from above) and several stems aligned parallel to the flow direction (Figure 8.6c), occupying the complete bay width (Figure 8.6d, second bay from above). In that case, a head increase occurred for the tested condition.



(a) t_1 (b) $t_1 + 84\Delta t$

(c) $t_1 + 340\Delta t$ (d) $t_1 + 536\Delta t$

Figure 8.6 – Experiment 1, repetition 4 ($\Delta H / H_0 = 0.037$) for different time steps $\Delta t = 0.5s$.

Head increase for a blocked batch of 200 stems

With this information, an analysis to find a common characteristic between the different jams and the head increase was pursued. A geometrical characteristic present in all jams to describe them was sought. The determination of a jam characteristic horizontal length or the porosity of the 3 dimensional jam shape, was not possible. The lack of transversal observations of the jam dimension and the variable distance of the jam to the weir did not allow to make assumptions about the depth and exact volume of the blockage. Each experiment was a particular case in which shape and composition of blockage was different, as normal in such stochastic process. Therefore, with the available pictures and notes taken of the jam composition per experiment, a simplified analysis relating the volume of blocked stems to the head increase was performed.

By knowing the stem geometry and having quantified the jam composition per class, a **blocked volume** was calculated by multiplying the stem individual volume by the number of blocked stems. Figure 8.7 shows the normalized value of head increase ($(H_{10'} - H_0)/H_0$) as a function of

the normalized value of blocked volume (volume blocked/volume supplied). Relative differences in the hydraulic head start to appear for blocked volumes greater than approximately 0.20. Nonetheless, a relation between head increase and normalized blocked volume could not be established. In fact, the maximum normalized head increase was obtained for a normalized blocked volume of 0.27, whereas absence of head increase was observed for a normalized blocked volume of almost 1.

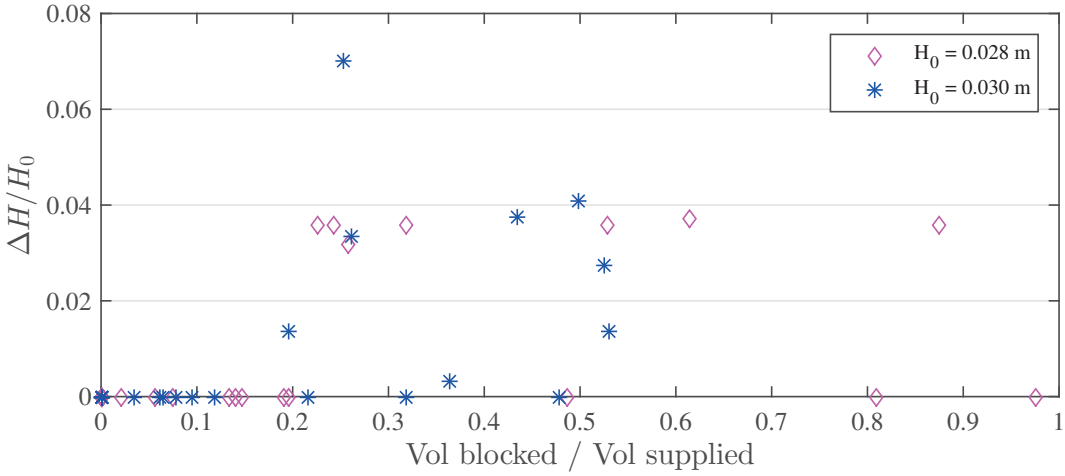


Figure 8.7 – Normalized head increase value ($\Delta H / H_0$) as a function of the normalized blocked volume (after 10 minutes).

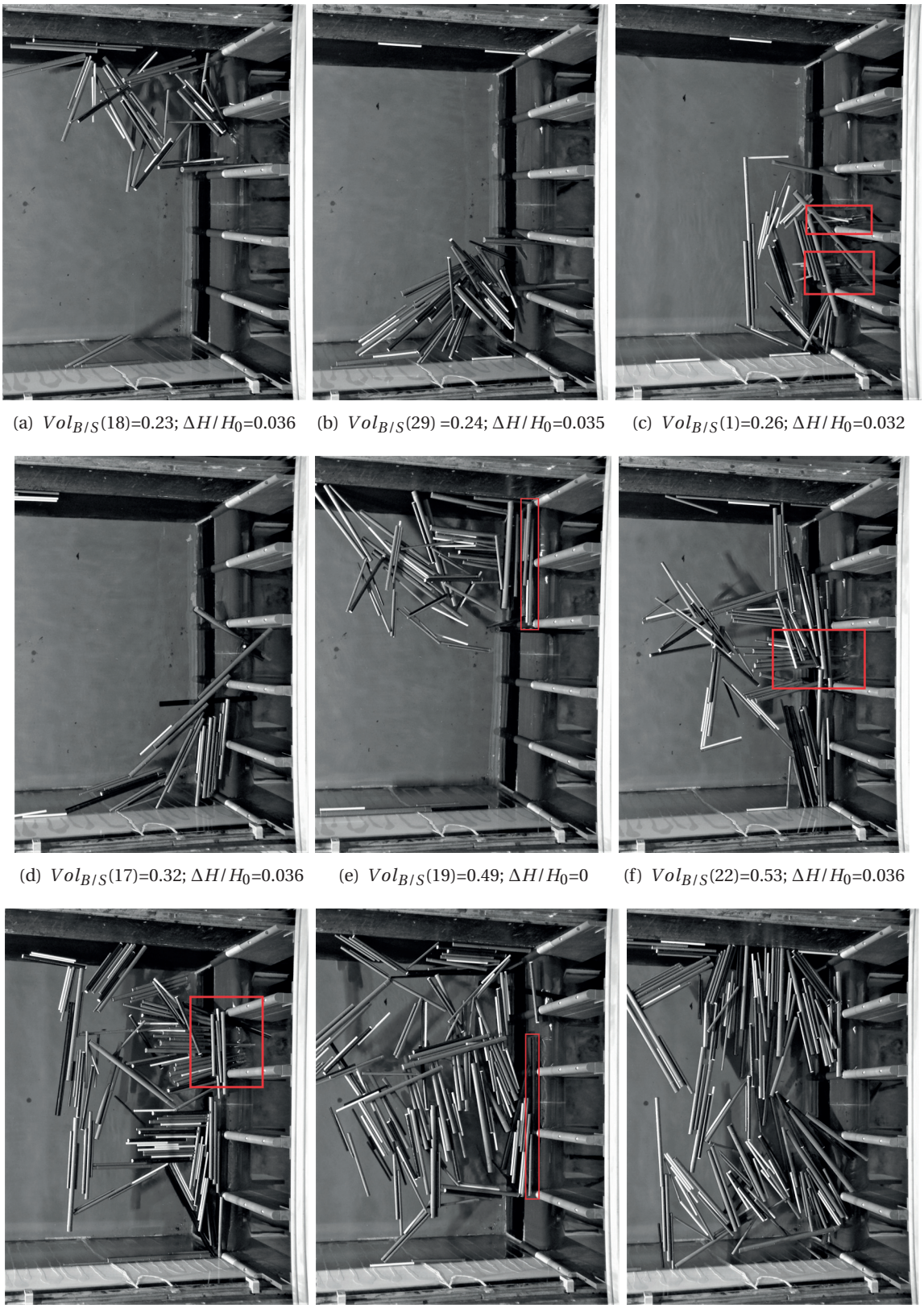
For comparison, the **jam shape** (two-dimensional) was evaluated throughout the pictures taken. In Figure 8.8 the experiments with a normalized blocked volume higher than 0.20 are displayed for $H_0 = 0.028$ m. In the figure caption, the repetition number can be found inside the parenthesis. Pictures are arranged by increasing blocked volume.

In Figures 8.8e and 8.8h (repetition 19 and 6), blockage started with stems of class E ($L/b = 200\%$) blocked perpendicular to the flow direction but no head increase was noted. A carpet of stems upstream of the structure was created without touching the weir.

In Figures 8.8c, 8.8f and 8.8g (repetition 1, 22 and 4) a bay had stems blocked parallel to the flow direction, touching the ogee crest and a head increase was measured.

In the Figures 8.8a, 8.8b, 8.8d, and 8.8i, stems aligned oblique to the flow direction and created 2 layers jams. Stems from class D and E ($L/b = 150$ and 200%) were key members in those jams and were touching the ogee crest, having a group of smaller stems above or upstream.

In Figure 8.9 the experiments with a normalized blocked volume higher than 0.20 are shown for $H_0 = 0.030$ m. In Figures 8.9d and 8.9f (repetition 17 and 16), class E stems ($L/b = 200\%$) were blocked perpendicularly to the flow direction and the majority of stems did not touch the ogee crest. No head increase was observed in that condition. Nonetheless, Figure 8.9i (repetition 24) had a similar type of blockage and a small head increase was measured. In Figure 8.9a (repetition

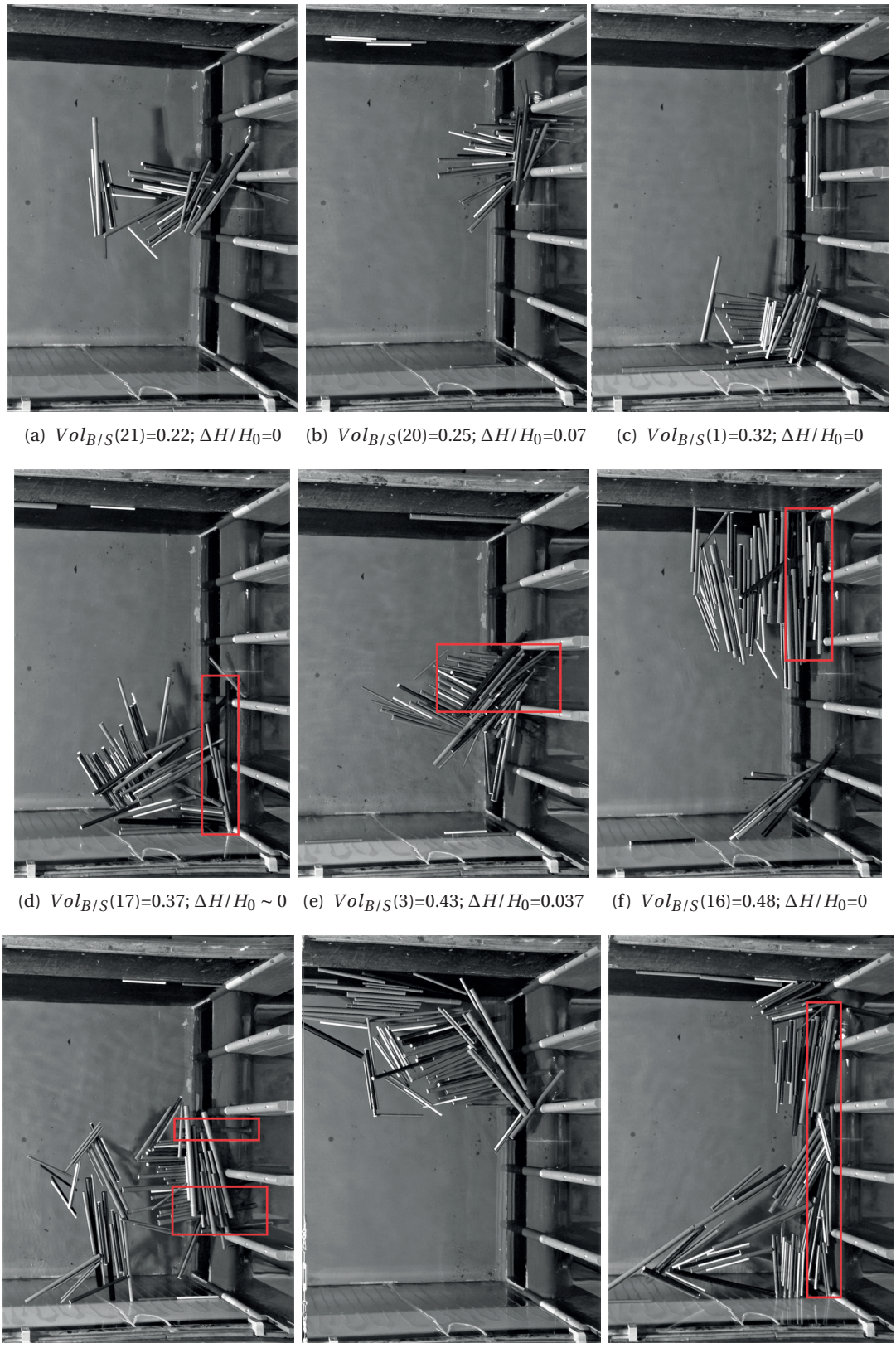


(a) $Vol_{B/S}(18)$=0.23; $\Delta H/H_0$=0.036 (b) $Vol_{B/S}(29)$ =0.24; $\Delta H/H_0$=0.035 (c) $Vol_{B/S}(1)$=0.26; $\Delta H/H_0$=0.032

(d) $Vol_{B/S}(17)$=0.32; $\Delta H/H_0$=0.036 (e) $Vol_{B/S}(19)$=0.49; $\Delta H/H_0$=0 (f) $Vol_{B/S}(22)$=0.53; $\Delta H/H_0$=0.036

(g) $Vol_{B/S}(4)$=0.61; $\Delta H/H_0$= 0.037 (h) $Vol_{B/S}(6)$=0.81; $\Delta H/H_0$=0 (i) $Vol_{B/S}(2)$=0.88; $\Delta H/H_0$=0.036

Figure 8.8 – Experiments with relative blocked volume larger than 20%, for H_0=0.028m.



(a) $Vol_{B/S}(21)$=0.22; $\Delta H/H_0$=0 (b) $Vol_{B/S}(20)$=0.25; $\Delta H/H_0$=0.07 (c) $Vol_{B/S}(1)$=0.32; $\Delta H/H_0$=0

(d) $Vol_{B/S}(17)$=0.37; $\Delta H/H_0 \sim 0$ (e) $Vol_{B/S}(3)$=0.43; $\Delta H/H_0$=0.037 (f) $Vol_{B/S}(16)$=0.48; $\Delta H/H_0$=0

(g) $Vol_{B/S}(2)$=0.49; $\Delta H/H_0$=0.041 (h) $Vol_{B/S}(13)$=0.52; $\Delta H/H_0$=0.027 (i) $Vol_{B/S}(24)$=0.52; $\Delta H/H_0$=0.014

Figure 8.9 – Experiments with relative blocked volume larger than 20%, for H_0=0.030m.

21), class E stems were blocked in an oblique direction respect to the flow and had a two layers jam of smaller stems upstream. The larger stems were touching the spillway crest but a head increase was not measured.

Figure 8.9b shows repetition 20 that was previously discussed. A similar blockage can be seen in Figure 8.9e (repetition 3) where a complete bay blocked with stems parallel to the flow direction and a head increase was measured. Figure 8.9g (repetition 2) involved stems blocked parallel to the flow direction but in two separate bays. For that case, the jam was composed by two layers of stems and the lower one was aligned with the flow direction, touching the spillway crest; a head increase was measured.

Figure 8.9h (repetition 13) shows a two layers jam caused by class D and E stems (L/b = 150 and 200%). Some smaller stems were aligned with the flow direction and submerged due to stems of class E above them. This type of blockage caused a head increase, although the distance from the jam to the crest seems considerable. On the other hand, Figure 8.9c (repetition 1) shows a mix of blockage that would be expected to cause a head increase but did not. The majority of the stems were aligned to the flow direction and blocked one complete bay with a smaller distance to the crest than in Figure 8.9h.

To analyse the **jam composition**, the ratio of blocked to supplied stems per class (after 10 minutes of blockage) was calculated. The difference between the class with the higher blockage and the class with the lower blockage was computed. For example, if in one repetition class A had 100% blockage and class C 30%, it resulted in 70% difference. For experiments with H_0 = 0.028 m, in only 4 repetitions one class blocked more than 20% in comparison to the other classes (Figure 8.10). The cases were: repetition 4, where class B blocked more than class E; repetition 10, where class E blocked more than class C; repetition 18, where class D blocked more than class E; repetition 22, where class B blocked more than class D.

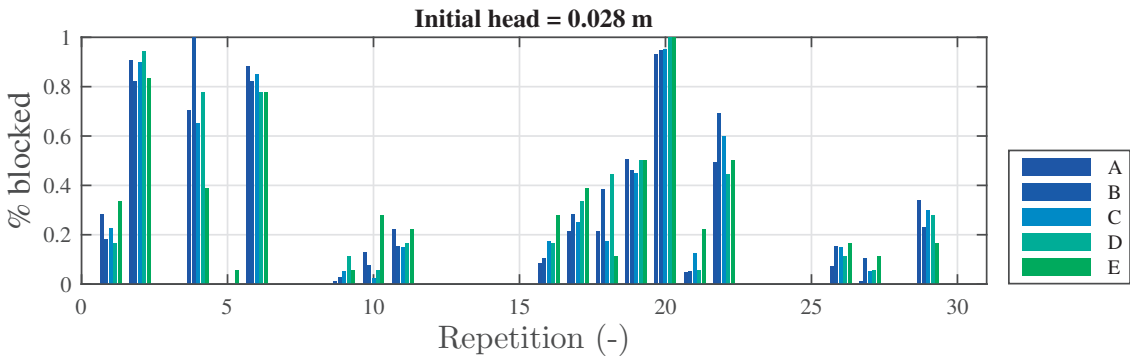


Figure 8.10 – Ratio of blocked stems for each class as a function of the number of experimental repetition, H_0 = 0.028 m.

In the cases of repetition 4 and 22, a higher number of relatively short stems blocked and the jam blocked one complete bay. For both cases, a head increase occurred. As more stems from a smaller class were involved in the jam, perhaps the porosity of the blockage was decreased. If the

spaces between stems were occupied by smaller stems a head increase could develop.

For H_0 = 0.030 m, in 8 repetitions the difference between classes was higher than 20% (Figure 8.11). The cases were: repetition 1, where class B blocked more than class A; in repetitions 2, 3 and 12, class D blocked more than class E; repetition 13, where class C blocked more than class A; repetition 16, where class E blocked more than class A; repetition 20, class A blocked more than class B; repetition 24, class B blocked more than class D.

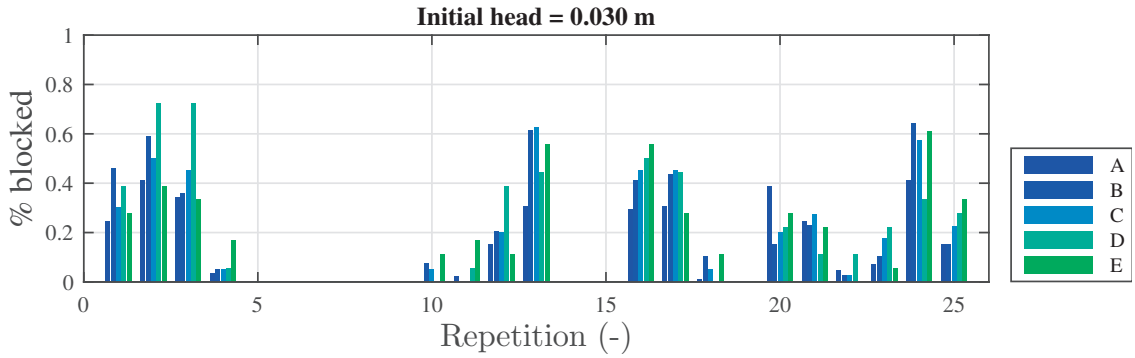


Figure 8.11 – Ratio of blocked stems for each class as a function of the number of experimental repetition, H_0 = 0.030 m.

From those cases, only in repetition 1 and 16 a head increase was absent. At repetitions 2, 3 and 20 a head increase occurred and the spillway bays were blocked with stems parallel to the flow direction. In repetitions 2 and 3, class D had the highest percentage of blocked stems nonetheless smaller classes were also present creating an heterogeneous jam. On the contrary, in repetition 20 class A had the highest percentage of blocked stems from the batch. From the pictures it was observed that the jam was homogeneous in size and heterogeneous in density of blocked stems (different stem colour).

For the cases of repetition 13 and 24, the bigger difference in the stem classes blocked belongs to the stems composing the carpet created upstream of the main blockage. For repetition 13 the jam was mainly composed by stems of class B (L/b = 100%), C (L/b = 120%), and E (L/b = 200%) but stems have a considerable distance to the ogee weir. For repetition 24, the main composition of the jam is also class B, C and E but stems are closer to the weir, possibly creating a multilayer carpet close to the weir.

8.3 Head increase due to artificially blocked stems

8.3.1 Methodology

Herein the methodology has been changed in comparison to the blocking probability experiments. Stems were manually positioned at the spillway inlet to measure their influence on the head increase. By manually placing the stems at the weir, the number of stems blocked was

controlled, constant and systematically arranged for comparison of results. In Table 8.3, the program for the experimental campaign can be seen. Only five open bay scenarios were studied and nose configuration N_2 (protruding 0.04 m from the weir into the reservoir) was used in continuity with the previous chapters.

Table 8.3 – Experimental program for evaluating head increase due to artificially blocked stems.*

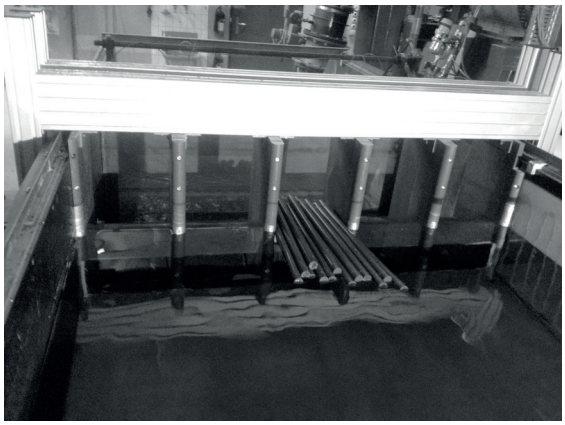
Exp N°	Class	d [m]	Density ρ_s	H_0 [m]	Open bays	Group size	Repetitions
1	A	0.010	0.59	0.010	5	1,2,4,8,16,32	3
2	A	0.010	0.59	0.012	5	1,2,4,8,16,32	3
3	C	0.016	0.56	0.015	5	1,2,4,8,16,32	3
4	C	0.016	0.56	0.016	5	1,2,4,8,16,32	3
5	C	0.016	0.56	0.017	5	1,2,4,8,16,32	3
6	E	0.025	0.54	0.019	5	1,2, -,8,16,32	3
7	E	0.025	0.54	0.021	5	1, -,4,8,16,32	3
8	E	0.025	0.54	0.024	5	1,2,4,8,16,32	3

*Experiments were executed by Selene Hewes during a semester project at LCH-EPFL, supervised by Prof. Anton J Schleiss and Paloma Furlan.

Four different scenarios were considered in which the position of the artificially blocked stems was changed. Always working with five open bays, stems were positioned parallel to the flow direction in the central bay only (Figure 8.12a) and disperse in five bays (Figure 8.12b). Additionally, stems were positioned perpendicular to the flow direction in the central bay (Figure 8.12c) and dispersed (Figure 8.12d). The positions were defined based on visual observations during previous experimental campaigns. Results with stems blocked parallel to flow direction (in the central bay) are discussed in this section as it was the most frequent type of blockage observed in the experiments of Chapter 7. The remaining results can be found in Appendix B.

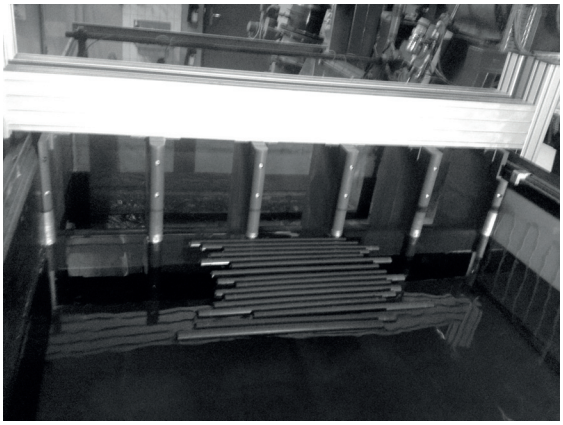
The water surface elevation above the ogee crest was taken with a point gauge (± 0.5 mm) and an ultrasonic distance sensor (± 0.3 mm) at 2.60 m upstream of the weir. Ratios of head H to stem diameter d (H/d, relative head) ranged between 0.76 to 1.20. Heads varied from 0.010 m to 0.024m and may be affected by scale effects (Chapter 3.3.3).

The initial flow depth upstream of the weir was measured without stems so as to obtain H_0. Subsequently, the stem groups were manually placed at the central bay, parallel to the flow direction. It was waited 5 minutes and a new measurement of flow depth was taken immediately afterwards. The procedure was performed three consecutive times. Due to the slight movement of stems, there were cases in which flow depth measurements were taken before 5 minutes as, on the contrary, they would pass the weir. In this regard, the experimental procedure is less systematic than the previous experiments remaining as an exploratory work of the head increase process.

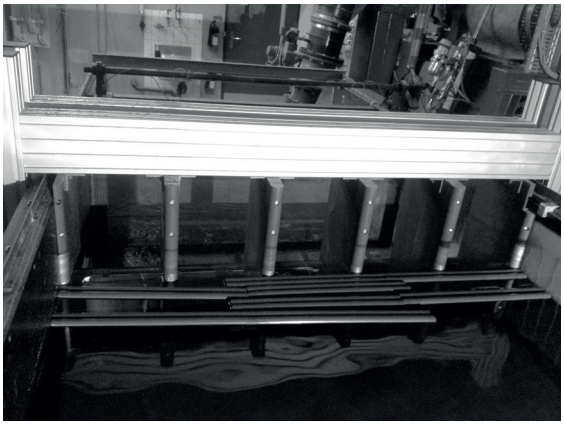


(a) Stems parallel to flow direction, central bay occupied.

(b) Stems parallel to flow direction, all bays occupied.



(c) Stems perpendicular to flow direction, central bay occupied.



(d) Stems perpendicular to flow direction, all bays occupied.

Figure 8.12 – Examples of how the stems were artificially blocked. Groups of 16 stems. Courtesy of Selene Hewes.

8.3.2 Results and analysis

The results obtained in the experiments are presented in Table 8.4, where ΔH represents the difference between the initial head and the new head measurement with stems blocked at the weir $\Delta H = H_t - H_0$. The result presented is the averaged value of the 3 independent measurements taken.

A normalized value of the head increase was calculated as $\Delta H / H_0$ where H_0 is the initial head. Figure 8.13 shows the normalized head increase as a function of the group size for all the stem classes evaluated. An increasing number of artificially blocked stems, increases the normalized head value.

Table 8.4 – Experimental measurements of head increase due to different stem group sizes artificially blocked [m · 10^{-2}].

Class	**Group size**	**Exp. 1** (H/d = 1.00)		**Exp. 2** (H/d=1.20)			
		H_0	ΔH	H_0	ΔH		
A	1	0.96	0.01	1.20	0.00		
	2	0.99	0.03	1.19	0.00		
	4	1.00	0.03	1.19	0.03		
	8	0.99	0.02	1.21	0.04		
	16	0.98	0.05	1.21	0.09		
	32	1.00	0.14	1.21	0.12		
		Exp. 3 (H/d=0.94)*		**Exp. 4** (H/d=1.00)		**Exp. 5** (H/d=1.06)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
C	1	1.50	0.00	1.61	0.01	1.72	0.00
	2	1.50	0.00	1.60	0.01	1.71	0.03
	4	1.50	0.00	1.59	0.02	1.71	0.06
	8	1.50	0.07	1.60	0.04	1.71	0.12
	16	1.50	0.20	1.59	0.13	1.70	0.16
	32	1.50	0.17			1.73	0.18
		Exp. 6 (H/d=0.76)		**Exp. 7** (H/d=0.84)*		**Exp. 8** (H/d=0.96)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
E	1	1.91	0.05	2.10	0.00	2.41	0.01
	2	1.93	0.02			2.40	0.04
	4			2.10	0.00	2.41	0.10
	8	1.93	0.15	2.10	0.20	2.39	0.16
	16	1.89	0.20	2.10	0.25	2.40	0.34
	32	1.88	0.17	2.10	0.20	2.41	0.29

* Measurements taken only with point gauge

Based on the small magnitude of head increase for groups with 1 and 2 stems, these measurements are not considered in the subsequent analysis, as they are within the range of the possible measurement error of the equipment.

Considering the parallel position of stems respect to the flow direction, the area occupied by stems at the weir could be estimated (Figure 8.14). With the stem dimensions and the group size, the transversal area of the cylinders multiplied by the number of stems G_i gives the space filled with stems.

Furthermore, the transversal area occupied by stems was related to the bay width and the flow depth at the weir crest in normal conditions (without stems). This relation was defined as an occupation ratio, estimated with Equation 8.1,

$$O_R = \frac{\pi d_s^2 G_i}{4} \cdot \frac{1}{h_0 b} \tag{8.1}$$

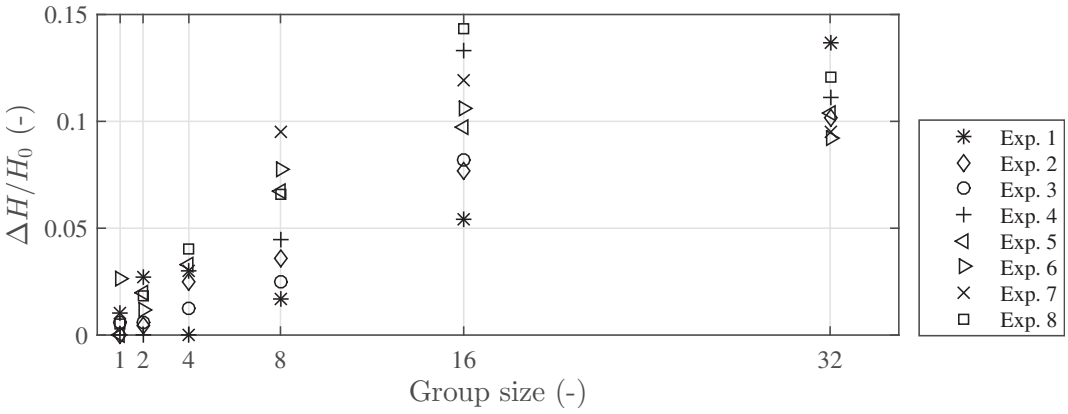


Figure 8.13 – Normalized head increase ($\Delta H/H_0$) as a function of group size artificially blocked, experiments from Table 8.3.

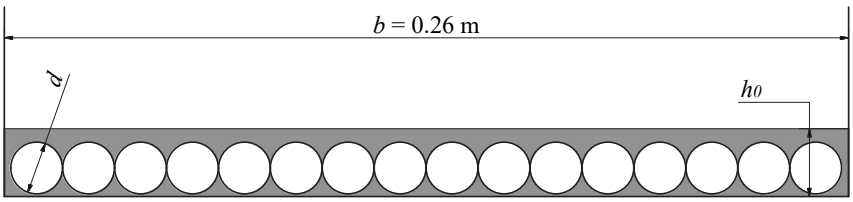


Figure 8.14 – Schematic view of one bay with stems aligned to the flow direction.

where d_s is the stem diameter [m], G_i is the stem group size [-], b is the bay width [m] and h_0 is the flow depth at the crest in normal conditions (no blockage) [m]. For the geometry of an ogee weir equipped with piers, the flow depth at the crest was considered approximately as 0.80 H_0 (Chow, 1959, USACE, 1987), where H_0 is the total upstream head relative to the crest elevation. As stems were positioned parallel to the flow direction, the stem relative length (L/b) is not expected to influence considerably the head increase.

Figure 8.15 shows the relation of the estimated occupied ratio and the normalized head increase for experiments with groups of 4 stems or more. A trend of head increase is noticed for occupied ratios up to 100% and a more constant trend for greater values of occupation. Nonetheless, there are some measurements that fall outside the trend. Two cases of zero head increase for an occupied area of 20% and 36% were noted. In those two cases, the measurements were taken only with the point gauge and had therefore, a different accuracy. These two experiments were removed in the further analysis.

As presented in Chapter 3.3.1 for normal discharge conditions (no blockage),

$$Q = C_Q L_Q H_0^{3/2} \tag{8.2}$$

where Q is the discharge over an uncontrolled ogee crest [m^3/s], C_Q is a discharge coefficient, L_Q the effective crest length [m], and H_0 is the total upstream head relative to the crest elevation [m].

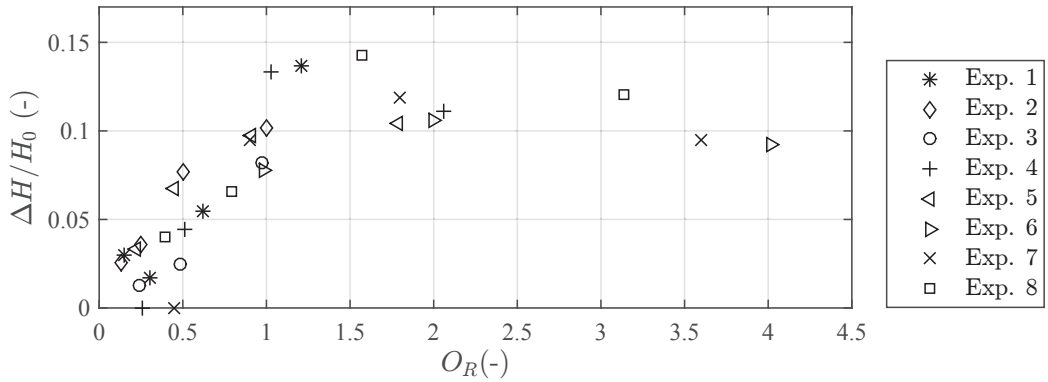


Figure 8.15 – Normalized head increase as a function of occupation ratio for one bay including group stem sizes $G_i \geq 4$.

The effective crest length available in the case of spillways with piers must consider the necessary modifications of the pier width and reduction coefficients due to the presence of piers, as a function of the head. The net crest length is the gross spillway width less the combined thickness of the crest piers. As the head used for these experiments is small, the reduction coefficient was outside the ranges covered in literature thus only the net crest length was used (USACE, 1987).

In the case of inlet blockage due to accumulations of stems, for a constant discharge Q, the equation can be expressed with a modification of the effective crest length (L_Q) and the related discharge coefficient (C_Q) (Equation 8.3).

$$Q = C'_Q L'_Q H'^{3/2} \tag{8.3}$$

From the situation of five open bays without blockage, the crest length is estimated as $L_Q = 5b$. For the case where the inlet is blocked by stems, the crest length can be modified as follows,

$$L'_Q = 5b - \alpha_s b \tag{8.4}$$

where α_s is the ratio of the equivalent bay width with blocked stems (b') over the bay width ($\alpha_s = b'/b$). This ratio can range between 0 (absence of blockage) and 5 (a blockage of all bays). For example, $\alpha_s = 1.00$ means that a complete bay was blocked with stems. The following equation is obtained.

$$\frac{L'_Q}{L_Q} = 1 - \frac{\alpha_s}{5} \tag{8.5}$$

From Equations 8.2 and 8.3, for constant discharge,

$$\frac{Q}{Q} = \frac{C_Q L_Q H_0^{3/2}}{C'_Q L'_Q H'^{3/2}} \tag{8.6}$$

hence,

$$\left(\frac{H'}{H_0}\right)^{3/2} = \frac{C_Q L_Q}{C'_Q L'_Q} \tag{8.7}$$

$$\frac{H'}{H_0} = \left[\frac{C_Q}{C'_Q}\left(\frac{5}{5-\alpha_s}\right)\right]^{2/3} \tag{8.8}$$

Considering the increase of head throughout ΔH,

$$\frac{H'-H_0}{H_0} = \left[\frac{C_Q}{C'_Q}\left(\frac{5}{5-\alpha_s}\right)\right]^{2/3} - 1 \tag{8.9}$$

Assuming that C_Q is approximately equal to C'_Q:

$$\frac{\Delta H}{H_0} = \left(\frac{5}{5-\alpha_s}\right)^{2/3} - 1 \tag{8.10}$$

Figure 8.16 shows the measurements of head increase as a function of the occupation ratio of stems up to 100% occupation of one bay. The measurements taken for groups of 1 and 2 stems, and the two cases of zero head increase for occupied areas of 20 and 36% were removed. The dashed line shows Equation 8.10, assuming $\alpha_s = O_R$.

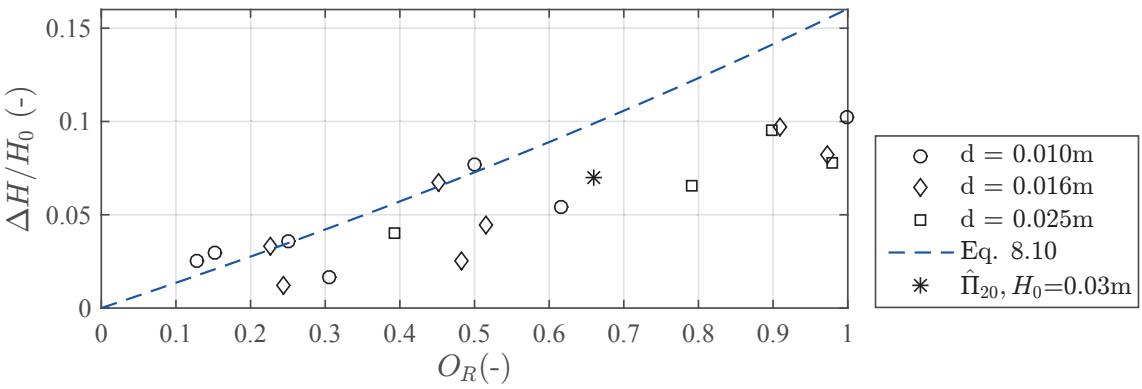


Figure 8.16 – Normalized head increase ($\Delta H/H_0$) as a function of occupation area ratio (O_R) with Equation 8.10.

Figure 8.16 shows that Equation 8.10 provides a conservative estimate of the normalized head increase, particularly for large occupied areas. The experimental results suggest an upper limit of approximately $\Delta H/H_0 = 0.10$ whereas, the theoretical curve would give a conservative value of 16%. From the experiments, if 25% of the bay area is occupied by stems, a head increase up to 4% may be expected (Figure 8.16). If the occupied area is about 50%, then the head can increase up to 8% (Figure 8.16).

Applying Equation 8.10, for $\alpha_s = 0.10$ results in $\Delta H/H = 0.01$ and $\alpha_s = 0.30$ results in $\Delta H/H =$

0.04. For a case of one complete bay closed ($\alpha_s = 1.00$), the normalized head could result in 16%.

8.4 Discussion

From the first two experimental conditions (Section 8.2.1), the tested heads resulted in low blocking probability ($\hat{\Pi} \leq 0.20$) for a batch of 200 artificial stems. If the shape and roughness of the stems would be changed to a more natural geometry and material, the blocking probability would probably increase, as seen in Gschnitzer et al. (2015).

Based on the tested conditions, the volume of large wood blocked at a spillway inlet influences the head upstream of the weir for volumes blocked greater than 20% of the volume supplied. To evaluate the possibility of a head increase, it is necessary to include the geometrical characteristics of the jam such as distance to the crest and orientation plus stem jam composition. When large stems ($L/b \geq 150$) block parallel or oblique to the flow direction, touching the ogee crest, a tendency for head increase was noted. When the jam includes a wide range of stem sizes and densities, there are higher chances for a head increase. For a reservoir flow approach and with the pier nose tested, a carpet of stems upstream of the piers is not likely to develop a head increase.

It is important to underline that different protrusions of the pier nose were not systematically evaluated. If the protrusion of the pier nose is decreased, it is possible that a carpet of floating stems upstream of the weir crest affects the head. In the majority of the cases with blockage and no head increase, the distance between the pier nose and the weir crest avoided stems to modify the free flow capacity of the ogee crested weir. Therefore, increasing the pier nose protrusion may be considered a safety measure against large wood blockage at weirs equipped with piers.

The possible frequency of head increase for a reservoir flow approach was calculated based on the experiments with a batch of large wood presented in Section 8.2.1 (Figure 8.17). With the pier nose separating a carpet of stems upstream of the ogee crested weir, the frequency of not having a head increase was higher than 0.60. However, for some cases of blockage a head increase was measured with a lower frequency. The chances of a head increase for the type of batch supplied and for a reservoir flow approach are relatively low (< 0.20).

It can also be analysed how certain large wood volumes blocked may influence the head increase upstream of the weir. Figure 8.18 presents the frequency of head increase measurements as a function of the relation of stem volume blocked and supplied. It is noticeable that low normalized volumes blocked (< 0.20) have low chances of leading to a head increase (frequency lower than 0.05). For greater volumes blocked, a head increase was in general observed although a clear trend was not observed.

Nonetheless, each experimental repetition resulted in different scenarios. LW blocking is a random process and its effect on the discharge capacity may vary from one case to another (Yang and Johansson, 2009). The composition of the jam varied significantly from repetition

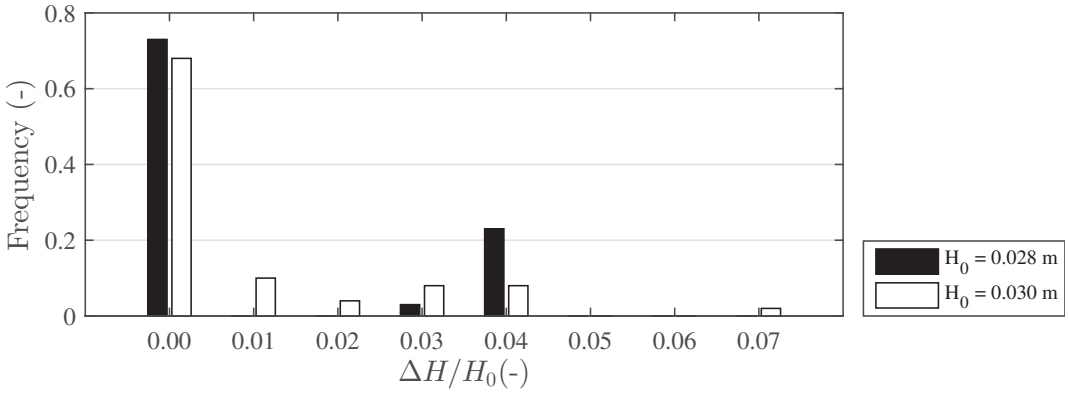


Figure 8.17 – Frequency of head increase measurements ($\Delta H/H_0$) for a batch of 200 of artificial stems with a reservoir flow approach.

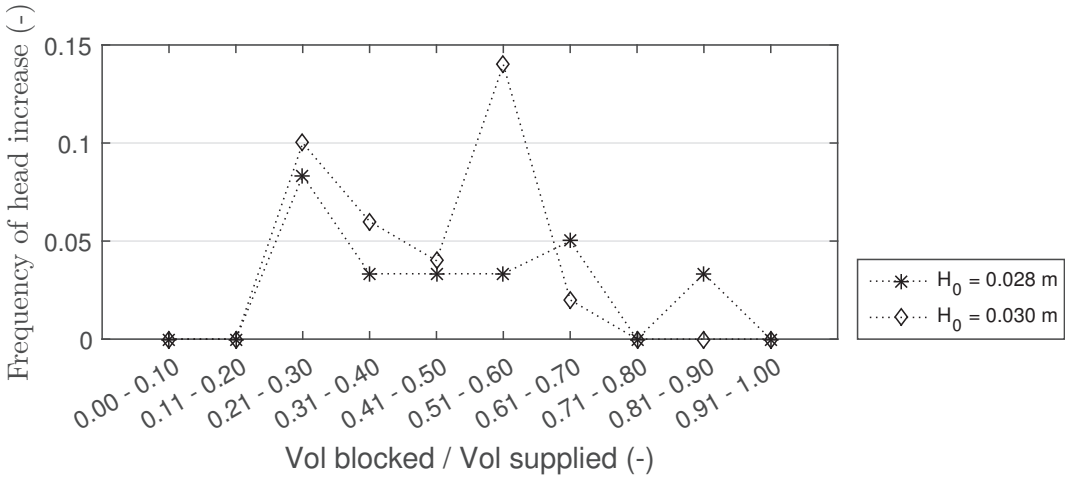


Figure 8.18 – Frequency of head increase as a function of blocked volumes of stems.

to repetition and between the two experiments. To overcome this constrain, head increase observations were performed with artificially blocked stems. For those experiments, different initial head and compositions of stem groups were evaluated and directly linked to the head increase.

Equation 8.10 was evaluated for one of the results from section 8.2. From Figure 8.3, the stem class was visually recognised and the stems blocked parallel to the flow direction were counted. The occupied area included: 8 stems of class A; 2 stems of class B; 4 stems of class C; 3 stems of class D and 3 stems of class E. An approximated occupied area of 66% was calculated. The expected head increase with Equation 8.10 is 9% which is relatively close to the 7% normalized head increase measured experimentally (Figure 8.16). The photographs of other experimental results for blocking probability estimations are being analysed to continue with the evaluation of Equation 8.10.

8.5 Conclusions

Interactions between large woody jams with spillway inlets is frequent at reservoirs in forested areas. The composition and shape of those jams can be a determining parameter when evaluating the jam effect for the rating curve of the structure.

The jam volume was found to be an important estimator to predict head increase but highly linked to the geometrical shape and position of the jam. Accumulations of stems against the weir crest can decrease the discharge capacity of the structure, increasing the upstream head. Herein, the influence of different jam configurations were related to the changes on the head at the reservoir. When large stems in comparison to the opening of a bay block at the ogee crest, smaller stems tend to block also and this can lead to a head increase.

Experimental scenarios of large volumes of stems blocked without causing a head increase have been linked to the position of the jam at the structure and its shape. A carpet of floating stems was not found influential, under the tested conditions, for a head increase. Nonetheless, additional experimental tests are needed to describe the three dimensional shapes of LW jams for reservoir approach flow conditions.

A simple equation to estimate a conservative value of the normalized head increase due to stems blockage was theoretically obtained (Equation 8.10).The equation corroborates the trend observed in the experiments with artificially blocked stems. However, this novel formulation continues to be evaluated with experimental results.

9 Conclusions

9.1 Main conclusions

The main results of this research are summarized herein, accomplishing the research objectives presented initially. To meet the objectives, the blocking probability of large wood and the resulting head increase at an ogee crest spillway equipped with piers was experimentally investigated. The evaluation of the influence of experimental repetitions for estimating accurate blocking probabilities allowed to define a required number of experimental repetitions. With a systematic approach it was possible to identify and quantify the influence of hydraulic and large wood characteristics on the blocking probability. Finally, is was characterized the effect of blocked stems at the spillway for head increase measurements on the reservoir.

The required **number of experimental repetitions** was successfully defined with a statistical justification and in accordance to experimental efforts, assuring accurate estimations of blocking probabilities.

- A reliable number of repetitions n, as a compromise between statistical accuracy and experimental efforts, was found to be $n \geq 30$ (with 90% confidence). With this number of repetitions, estimations of blocking probabilities with standard errors smaller than 0.10 were achieved for individual and group stem experiments.

- The application of the Wald and the Clopper-Pearson methods are recommended to estimate confidence intervals for a binomial proportion.

- The number of experimental repetitions can be decreased based on the stem group size. For larger stem group sizes the standard deviation of experimental results was found to decrease, for identical number of repetitions. Less experimental repetitions were needed for achieving errors smaller than 0.10 for blocking probability estimations. It was found that for groups of 2 and 4 stems the number of repetitions could range between $10 \leq n \leq 30$; for groups of 8, 16 and 32 stems the number of repetitions could be n equal to

10. Nonetheless, if it is decided to use $n < 30$, statistical evaluations of the accuracy are advisable.

- As a good mathematical practice, it is necessary to report an order of accuracy for blocking probability estimations $\hat{\Pi}$ since providing an estimate without any information of how close it is of π is inconclusive.

The **influence of large wood characteristics and hydraulic conditions, on the blocking probability** of large wood at ogee crest spillways equipped with piers, was quantified.

- **Stem density (ρ_s):** Stem density was found to influence the blocking of individual stems when the stem length is equal or larger than the bay width ($L/b \geq 1$). An increasing stem density was found to increase the blocking probability for such cases. Furthermore, this parameter should always be included in studies involving large wood. Individual stems with a density close to water density have a high blocking probability ($\hat{\Pi} \geq 0.73$) and can be considered as key elements to trigger stem jams.

- **Stem diameter relative to the head (*H/d*)**: Increasing H/d was found to decrease the blocking probability in the case of individual stems and groups. In the case of individual stems, $H/d \geq 1.20$ generally lead to a blocking probability equal or lower than 0.20. For stem batches the increase of head was also found to decrease the blocking probability. The relation between head and blocking probability is not linear and varies according to the tested conditions.

- **Number of open bays**: For the same H/d ratio, it was found that five open bays had lower blocking probability than one open bay, in the case of individual stems with stem density much lower than the water density. For the same H/d in the case of stem groups, five open bays were found to have lower blocking probability than one open bay for relative stem lengths equal or lower than 1.20. However, this relation is not linear and the variation of the blocking probability was different according to the tested conditions.

- **Stem length relative to bay width (*L/b*)**: For a constant H and stem density similar to the density of average dry wood in Europe, when increasing the L/b relation for individual stem experiments, blocking probabilities were found to increase. However, the isolation of the L/b parameter for analysing its influence on the blocking probability was not possible as H/d was not constant for each stem class and this has proven to be a highly influential variable in the blocking process of LW.

The influence of the **stem group size** G_i (number of stems) supplied on the blocking probability compared to individual stem experiments was quantified for partially constant stem density.

- Increasing stem group sizes, compared to an individual stem, was found to change the blocking probability only when the relative stem length is greater than the bay width ($L/b \geq 1$) and $\hat{\Pi} \leq 0.80$.
- A marked increase of $\hat{\Pi}$ when increasing the stem group size from 1 to 4 stems has been found. The blockage probability for groups of 4 stems could reach up to the double of the blocking probability for an individual stem with constant H/d.
- Increasing the stem group size from 4 to 16 stems was not found significantly influential for the blocking probability. However, $\hat{\Pi}$ tends to slightly decrease from 4 to 16 stems and then tends to slightly increase from 16 to 32 stems.

The resulting **head increase** in the reservoir, when a blockage of large wood at the spillway inlet is present, was quantified.

- It was found that the head increase in the reservoir is linked to the jam volume, its geometrical shape, position and composition. Equal jam volumes could lead to different head increase measurements.
- The position of key stems inside a jam was found critical to determine the jam shape and its influence on the head increase.
- For a reservoir flow approach, a carpet of floating stems was in general not found relevant concerning head increase possibilities.
- A simple theoretical equation was obtained to estimate the normalized head increase due to stems blockage. Such simplified formulation was found to represent fairly well the trend of head increase measured for artificially blocked stems.

9.2 Practical recommendations

The accumulation of large wood at hydraulic structures like bridges, weirs and spillways can lead to increased upstream water levels, structural loadings and modifications of the inundated areas. These effects can lead to unforeseen situations. When large wood entrapment and transportation processes start, it is difficult to estimate their impact on structures. Thus proper quantifications of the blocking probability of structures like spillways and the resulting head increase are needed. This research project has demonstrated the influence of some large wood characteristics and hydraulic conditions on the blocking probability of large wood and quantifications of the resulting head increase.

The influences found of LW and hydraulic characteristics on the blocking probability of stems, in addition to the innovative statistical study, may contribute to the improvement of hydraulic modeling of large wood (experimentally and numerically). By analysing blocking probabilities

of large wood a generalized linear model (GLM) was started, in Chapter 5, which can be further developed to become a predictor of potential hazards.

Knowledge on the type of forest in the catchment area of a reservoir is crucial and case-by-case studies need to be done. In agreement with Godtland and Tesaker (1994), spillway bays should have a width of at least 0.80 of the stem length to have a blocking probability lower than 0.20. If possible, based on the results obtained in Chapter 5, the spillway should be operated with a head at the weir crest greater than 0.20 times the expected stem diameter (considering a small number of arriving trees without branches). This may decrease the blocking probability to probabilities lower than 0.20. It is preferable to avoid that wood with high density (waterlogged large wood) reaches the spillway inlet as it has higher blocking probability and may trigger woody jams when blocked. Five open bays, as tested, generally have lower blocking probability than a single open bay for a small number of approaching stems.

As a preventive measure for head increase at a reservoir, piers which are protruding into the reservoir are recommended. The required distance between the pier nose and the weir crest should be evaluated case-by-case. When a floating carpet of stems is blocked upstream of the piers without touching the weir crest, generally, it does not affect the discharge capacity of the weir. Therefore, a protruding pier nose may keep the free flow capacity of an ogee crested weir.

If a blockage of large wood occurs at an ogee crested spillway equipped with piers, Equation 8.10 can help to evaluate, conservatively, a normalized head increase in the reservoir. If estimations of the occupied area by stems can be made or assumptions of the modified crest length, then by using Equation 8.10 a normalized head increase estimation can be done. For a case of one complete bay occupied by stems ($\alpha_s = 1.00$), the experiments resulted in a normalized head increase of approximately 10% whereas, the theoretical equation would give a conservative value of 16%. Furthermore, this theoretical equation could be used for evaluations of up to five bays occupied by stems. Nonetheless, this research has shown that a head increase in the reservoir is highly linked to the blocked volume of large wood, the jam shape and composition. Also, the location of the spillway may influence the blockage. The movement of stems for a reservoir flow approach is erratic but stems tend to align to the flow direction close to the weir. If the space for stems to turn freely is not available, blockage may be increased.

9.3 Outlook

The present study provides a contribution in the domain of large wood blocking probability and head increase estimations due to blocked stems. Nevertheless, the random behaviour of large wood and the blocking process is still not fully understood. In this context, the following points may require further investigations:

- The investigation of large wood related processes has advanced rapidly in the last decade with experimental and numerical hydraulic modeling. Herein a mathematical model was

started and can be continued. If further combinations of parameters are evaluated, more probability distributions can be obtained to enlarge the applicability of the model. A stochastic approach needs to be considered for future evaluations of LW blockage. This has to be foreseen when designing the experiments, considering the statistical needs applicable for such challenge.

- Visual records of experiments to create a 3 dimensional overview of the process could be attempted to have a full coverage of the inlet blockage. In that case, results can be studied with conditional probability analysis where interactions in time between the LW pieces modify the blocking probability for stem groups (instead of considering results as binomial with only the final number of blocked stems from the group). The dynamic and random behaviour of large wood can be evaluated in time, measuring the instantaneous evolution of such complex process. This type of approach could complement numerical models.

- Different pier nose protrusions where foreseen, however the challenges of the LW random behaviour restricted the number of parameters that could be evaluated. A typical case was analysed with a nose protrusion into the reservoir that retains jams upstream the weir crest. Other pier nose protrusions should be systematically tested to evaluate how the distance of a jam to the weir crest affects the head increase. This can improve the guidelines for design of spillways equipped with piers. Additionally, different bay opening scenarios should be analysed considering different degrees of opening of the gates to search if gate manoeuvres would allow to guide or unblock large wood from the reservoir.

- Evaluation of increasing blocked volume of large wood at the spillway would be useful to determine critical moments of head increase in the reservoir. An increasing blocked volume would help to understand the evolution and effect of arriving large wood to a reservoir. Also by changing the composition of the wood volume and the stem characteristics, the porosity of the blockage and how it influences the head increase can be explored.

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A Measurements of flow velocity for evaluation of baffle design.

This Appendix contains the flow velocity measurements recorded with a flow probe with a propeller in 36 points (Figure A.1) along a cross-section 2 m downstream of the baffle. These measurements were conducted to evaluate the efficiency of the baffle designed. Measurements were performed for 3 different discharges (Q_1 = 67 l/s, Q_2 = 131 l/s, Q_3 = 183 l/s). The system of coordinates taken for the measurements is shown in the lower left corner of the figure.

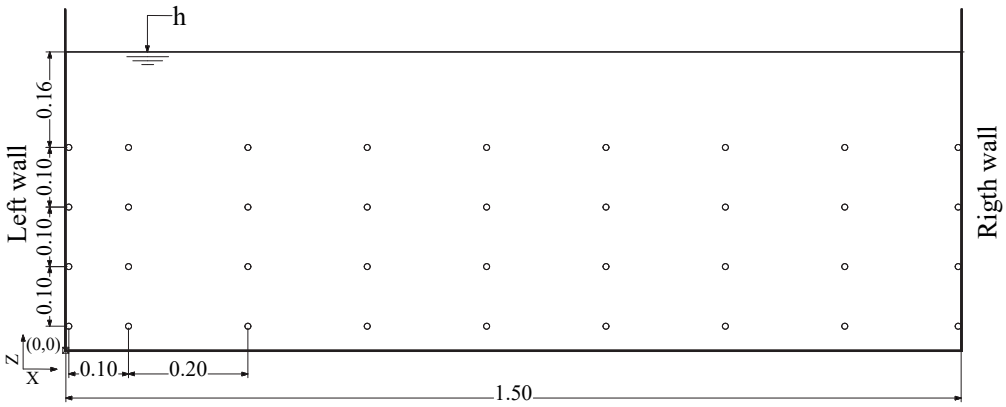

Figure A.1 – Scheme of the cross-section of measurement points (dimensions in m).

Herein are presented the measurements from Chapter 3.3.4.

Appendix A. Measurements of flow velocity for evaluation of baffle design.

Initial condition

Discharge (l/s) = 67
h (m) = 0.51

	Velocity (m/s)			
x \ z	**0.35**	**0.25**	**0.15**	**0.05**
0.00	0.05	0.08	0.14	0.07
0.10	0.14	0.11	0.10	0.17
0.30	0.12	0.17	0.10	0.13
0.50	0.16	0.14	0.09	0.09
0.70	0.10	0.13	0.07	0.16
0.90	0.13	0.09	0.07	0.09
1.10	0.08	0.05	0.03	0.03
1.30	0.04	0.03	0.06	0.03
1.50	0.01	0.04	0.02	0.02

Max velocity (m/s) = 0.17

	Relative difference (%)			
x \ z	**0.35**	**0.25**	**0.15**	**0.05**
0.00	47	36	115	55
0.10	47	12	54	6
0.30	21	36	46	19
0.50	63	8	31	42
0.70	0	0	0	0
0.90	37	28	0	42
1.10	21	64	62	84
1.30	63	80	8	84
1.50	89	72	69	90

Discharge (l/s) = 131
h (m) = 0.55

	Velocity (m/s)			
x \ z	**0.39**	**0.29**	**0.19**	**0.09**
0.00	0.20	0.26	0.26	0.23
0.10	0.26	0.33	0.29	0.20
0.30	0.35	0.30	0.26	0.27
0.50	0.37	0.26	0.21	0.31
0.70	0.16	0.25	0.19	0.22
0.90	0.07	0.11	0.11	0.11
1.10	0.06	0.19	0.12	0.08
1.30	0.07	0.06	0.09	0.07
1.50	0.06	0.06	0.04	0.10

Max velocity (m/s) = 0.37

	Relative difference (%)			
x \ z	**0.39**	**0.29**	**0.19**	**0.09**
0.00	22	6	37	5
0.10	63	33	50	7
0.30	119	20	37	26
0.50	128	6	8	44
0.70	0	0	0	0
0.90	59	57	42	49
1.10	63	22	39	65
1.30	59	76	55	67
1.50	63	76	79	56

Discharge (l/s) = 183
h (m) = 0.58

	Velocity (m/s)			
x \ z	**0.42**	**0.32**	**0.22**	**0.12**
0.00	0.30	0.21	0.31	0.27
0.10	0.37	0.36	0.41	0.24
0.30	0.45	0.41	0.34	0.34
0.50	0.39	0.38	0.36	0.42
0.70	0.32	0.30	0.24	0.24
0.90	0.13	0.14	0.15	0.10
1.10	0.09	0.13	0.09	0.08
1.30	0.10	0.15	0.09	0.13
1.50	0.13	0.08	0.10	0.10

Max velocity (m/s) = 0.45

	Relative difference (%)			
x \ z	**0.42**	**0.32**	**0.22**	**0.12**
0.00	5	29	29	13
0.10	17	22	71	2
0.30	41	37	42	40
0.50	24	27	48	73
0.70	0	0	0	0
0.90	59	53	40	60
1.10	71	56	65	67
1.30	70	49	65	48
1.50	59	73	60	60

Metallic grid

Discharge (l/s) = 67

h (m) = 0.51

	Velocity (m/s)			
x \ z	**0.353**	**0.253**	**0.153**	**0.053**
0.00	0.04	0.03	0.05	0.02
0.10	0.04	0.08	0.08	0.03
0.30	0.10	0.09	0.11	0.07
0.50	0.10	0.11	0.11	0.08
0.70	0.11	0.12	0.12	0.09
0.90	0.12	0.12	0.11	0.09
1.10	0.11	0.12	0.11	0.09
1.30	0.10	0.09	0.08	0.07
1.50	0.07	0.06	0.03	0.03

Max velocity (m/s) = 0.12

	Relative difference (%)			
x \ z	**0.353**	**0.253**	**0.153**	**0.053**
0.00	67	78	61	82
0.10	67	30	35	65
0.30	10	22	9	24
0.50	10	9	9	12
0.70	0	0	0	0
0.90	10	4	9	0
1.10	0	0	9	0
1.30	10	26	35	24
1.50	38	52	74	65

Discharge (l/s) = 131

h (m) = 0.55

	Velocity (m/s)			
x \ z	**0.395**	**0.295**	**0.195**	**0.095**
0.00	0.08	0.08	0.07	0.08
0.10	0.11	0.13	0.15	0.08
0.30	0.18	0.17	0.17	0.12
0.50	0.18	0.17	0.18	0.16
0.70	0.20	0.19	0.20	0.16
0.90	0.19	0.19	0.19	0.18
1.10	0.17	0.18	0.19	0.17
1.30	0.12	0.15	0.14	0.14
1.50	0.08	0.09	0.08	0.08

Max velocity (m/s) = 0.20

	Relative difference (%)			
x \ z	**0.395**	**0.295**	**0.195**	**0.095**
0.00	63	61	64	48
0.10	45	34	26	52
0.30	10	11	15	26
0.50	13	11	8	0
0.70	0	0	0	0
0.90	8	0	3	13
1.10	15	5	5	6
1.30	43	24	31	10
1.50	63	55	59	52

Discharge (l/s) = 183

h (m) = 0.58

	Velocity (m/s)			
x \ z	**16**	**26**	**36**	**46**
0.00	0.10	0.09	0.10	0.10
0.10	0.13	0.17	0.20	0.14
0.30	0.21	0.22	0.22	0.19
0.50	0.24	0.23	0.24	0.21
0.70	0.26	0.26	0.28	0.26
0.90	0.25	0.24	0.27	0.25
1.10	0.23	0.24	0.26	0.22
1.30	0.16	0.21	0.20	0.17
1.50	0.14	0.15	0.10	0.13

Max velocity (m/s) = 0.28

	Relative difference (%)			
x \ z	**0.425**	**0.325**	**0.225**	**0.125**
0.00	63	67	65	61
0.10	49	37	29	47
0.30	18	15	20	25
0.50	8	13	13	18
0.70	0	0	0	0
0.90	4	8	2	4
1.10	12	8	5	16
1.30	37	21	27	33
1.50	47	44	64	51

Appendix A. Measurements of flow velocity for evaluation of baffle design.

Metallic grid with geotextile (final design)

Discharge (l/s) = 67

h (m) = 0.51

	Velocity (m/s)			
x \ z	**0.352**	**0.252**	**0.152**	**0.052**
0.00	0.03	0.03	0.03	0.02
0.10	0.09	0.09	0.09	0.05
0.30	0.11	0.11	0.12	0.09
0.50	0.09	0.09	0.09	0.10
0.70	0.10	0.11	0.09	0.10
0.90	0.09	0.08	0.08	0.10
1.10	0.11	0.11	0.13	0.09
1.30	0.09	0.10	0.10	0.08
1.50	0.06	0.06	0.06	0.05

Max velocity (m/s) = 0.13

	Relative difference (%)			
x \ z	**0.352**	**0.252**	**0.152**	**0.052**
0.00	74	76	67	80
0.10	11	19	0	55
0.30	16	5	28	10
0.50	11	19	6	5
0.70	0	0	0	0
0.90	11	29	17	5
1.10	16	0	39	15
1.30	5	10	6	25
1.50	42	48	39	50

Discharge (l/s) = 131

h (m) = 0.55

	Velocity (m/s)			
x \ z	**0.395**	**0.295**	**0.195**	**0.095**
0.00	0.09	0.10	0.07	0.07
0.10	0.13	0.14	0.13	0.07
0.30	0.20	0.21	0.20	0.15
0.50	0.14	0.15	0.13	0.17
0.70	0.18	0.17	0.17	0.19
0.90	0.14	0.15	0.14	0.18
1.10	0.21	0.21	0.20	0.20
1.30	0.14	0.15	0.17	0.14
1.50	0.09	0.11	0.09	0.09

Max velocity (m/s) = 0.21

	Relative difference (%)			
x \ z	**0.395**	**0.295**	**0.195**	**0.095**
0.00	51	41	58	66
0.10	29	18	24	63
0.30	14	21	18	21
0.50	20	15	21	13
0.70	0	0	0	0
0.90	20	12	15	5
1.10	20	24	21	3
1.30	23	12	3	26
1.50	51	35	45	53

Discharge (l/s) = 183

h (m) = 0.58

	Velocity (m/s)			
x \ z	**0.424**	**0.324**	**0.224**	**0.124**
0.00	0.09	0.11	0.10	0.10
0.10	0.14	0.18	0.21	0.12
0.30	0.26	0.25	0.25	0.21
0.50	0.19	0.19	0.18	0.23
0.70	0.24	0.21	0.23	0.26
0.90	0.20	0.19	0.19	0.23
1.10	0.29	0.29	0.28	0.29
1.30	0.19	0.23	0.20	0.18
1.50	0.14	0.17	0.15	0.12

Max velocity (m/s) = 0.29

	Relative difference (%)			
x \ z	**0.424**	**0.324**	**0.224**	**0.124**
0.00	62	49	56	62
0.10	43	12	7	56
0.30	9	22	11	19
0.50	21	10	22	13
0.70	0	0	0	0
0.90	17	10	16	13
1.10	23	39	24	10
1.30	21	10	11	33
1.50	40	17	36	56

B Supplementary measurements of head increase due to artificially blocked stems.

In Chapter 8, measurements of head increase were presented for cases were blockage was artificially arranged. Stems were artificially blocked at the weir in different positions and the head increase was measured. In Table B.1, the program for the experimental campaign can be seen. Only five open bay scenarios were studied and nose configuration N_2 (protruding 0.04 m from the weir into the reservoir) was used.

Table B.1 – Experimental program for evaluating head increase with artificially blocked stems.*

Exp N°	**Class**	d [m]	**Density** ρ_s	H_0 [m]	**Open bays**	**Group size**	**Repetitions**
1	A	0.010	0.59	0.010	5	1,2,4,8,16,32	3
2	A	0.010	0.59	0.012	5	1,2,4,8,16,32	3
3	C	0.016	0.56	0.015	5	1,2,4,8,16,32	3
4	C	0.016	0.56	0.016	5	1,2,4,8,16,32	3
5	C	0.016	0.56	0.017	5	1,2,4,8,16,32	3
6	E	0.025	0.54	0.019	5	1,2, -,8,16,32	3
7	E	0.025	0.54	0.021	5	1, -,4,8,16,32	3
8	E	0.025	0.54	0.024	5	1,2,4,8,16,32	3

*Experiments were executed by Selene Hewes during a semester project at LCH-EPFL, supervised by Prof. Anton J Schleiss and Paloma Furlan.

Four different scenarios were considered in which the position of the artificially blocked stems was changed. Always working with five open bays, stems were positioned parallel to the flow direction in the central bay only (type 1 blockage, presented in Chapter 8) and disperse in five bays (type 2 blockage). Additionally, stems were positioned perpendicular to the flow direction in the central bay (type 3 blockage) and dispersed (type 4 blockage). The positions were defined based on visual observations during previous experimental campaigns. The head increase measurements of stems blocked parallel to flow direction in the central bay were discussed in Chapter 8. Herein the measurements for the other types of blockage are presented.

Table B.2 shows the results obtained for the artificially blocked stems parallel to the flow direction, occupying five open bays. The stem groups were separated into smaller groups to occupy the

five open bays. To artificially block these smaller groups was more challenging and there was a slight movement of stems. Thus, measurements of head had to be taken before 5 minutes. The measurements herein presented may be less accurate however, a general trend can still be observed.

Table B.2 – Experimental measurements of head increase for artificially blocked stems parallel to the flow direction, disperse in five bays (type 2 blockage) [m · 10⁻2].

Class	**Group size**	**Exp. 1** (H/d = 1.00)		**Exp. 2** (H/d=1.20)			
		H_0	ΔH	H_0	ΔH		
A	1						
	2	0.99	0.01	1.19	0.01		
	4	1.00	0.02	1.19	0.03		
	8	0.99	0.03	1.21	0.04		
	16	0.98	0.10	1.21	0.10		
	32	1.00	0.16	1.21	0.10		
		Exp. 3 (H/d=0.94)*		**Exp. 4** (H/d=1.00)		**Exp. 5** (H/d=1.06)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
C	1						
	2	1.50	0.00	1.6	0.02	1.71	0.03
	4	1.50	0.00	1.59	0.02	1.71	0.07
	8	1.50	0.07	1.60	0.03	1.71	0.11
	16	1.50	0.10	1.59	0.10	1.70	0.17
	32	1.50	0.33			1.73	0.21
		Exp. 6 (H/d=0.76)		**Exp. 7** (H/d=0.84)*		**Exp. 8** (H/d=0.96)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
E	1						
	2	1.93	0.02			2.40	0.09
	4					2.41	0.09
	8	1.93	0.16	2.10	0.20	2.39	0.21
	16	1.89	0.37	2.10	0.28		
	32	1.88	0.53	2.10	0.60	2.41	0.63

A normalized value of the head increase was calculated as $\Delta H / H_0$ where H_0 is the initial head. Figure B.1 shows the normalized head increase as a function of the group size for all the experiments. An increasing number of artificially blocked stems, increases the normalized head value. This type of blockage lead to increases in the normalized head almost of 30% for groups of 32 blocked stems with the highest L/b relation. Equally than in Chapter 8, due to the small magnitude of head increase for groups with 1 and 2 stems, these measurements are not considered as they are within the range of the possible measurement error of the equipment.

The area occupied by stems at the weir was estimated based on the stem dimensions and the group size. The transversal area of the cylinders multiplied by the number of stems G_i gives the space filled with stems. By relating this to the area occupied by water at the weir in normal conditions (without stems), an occupation ratio can be estimated with Equation 8.1.

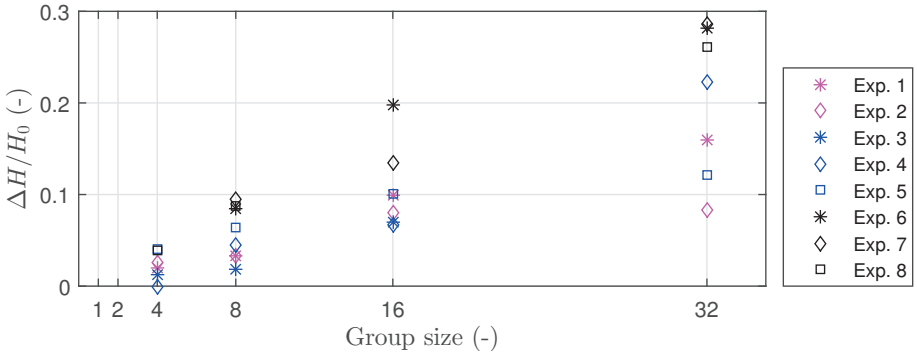

Figure B.1 – Normalized head increase in function of the group size, stems blocked parallel to the flow direction disperse in five bays (type 2 blockage).

Figure B.2 shows the normalized head increase as a function of the occupied area by artificially blocked stems.

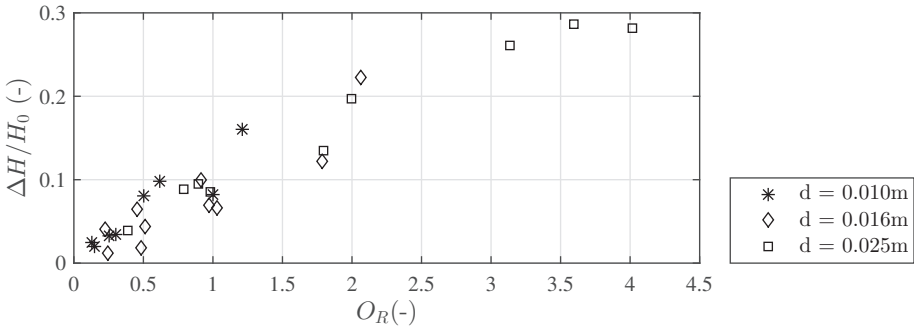

Figure B.2 – Normalized head increase as a function of occupied area, stems blocked parallel to the flow direction disperse in five bays (type 2 blockage).

The figure shows that the normalized head increase has a similar behaviour than for one central bay blocked (Chapter 8). However, due to the movement of stems when manually blocked, these results are only considered qualitatively.

Table B.3 shows the results measured for blockage type 3, where stems were artificially blocked perpendicular to the flow direction only in the central bay. As stems from class A were shorter than the bay width (L/b = 80%), it was not possible to block these stems between two piers in the central bay. Therefore, only experiments with class C (L/b = 120%) and E (L/b = 200%) are presented.

Figure B.3 shows the normalized head increase as a function of the group size for all the experiments.

Appendix B. Supplementary measurements of head increase due to artificially blocked stems.

Table B.3 – Experimental measurements of head increase for artificially blocked stems perpendicular to the flow direction in one central bay (type 3 blockage) [m · 10⁻2].

Class	**Group size**	**Exp. 3** (H/d=0.94)*		**Exp. 4** (H/d=1.00)		**Exp. 5** (H/d=1.06)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
C	1	1.50	0.00	1.61	0.00	1.72	0.00
	2	1.50	0.00	1.60	0.01	1.71	0.00
	4	1.50	0.00	1.59	0.03	1.71	0.00
	8	1.50	0.00	1.60	0.00	1.71	0.03
	16	1.50	0.00	1.59	0.00	1.70	0.00
	32	1.50	0.00			1.73	0.00
		Exp. 6 (H/d=0.76)		**Exp. 7** (H/d=0.84)*		**Exp. 8** (H/d=0.96)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
E	1	1.91	0.02	2.10	0.00	2.41	0.02
	2	1.93	0.00			2.40	0.06
	4			2.10	0.00	2.41	0.00
	8	1.93	0.02	2.10	0.00	2.39	0.00
	16	1.89	0.01	2.10	0.00	2.40	0.04
	32	1.88	0.00	2.10	0.00	2.41	0.08

* Measurements taken only with point gauge

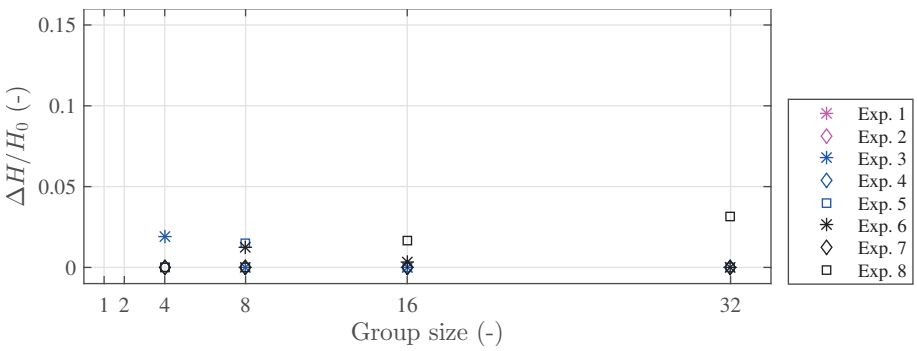

Figure B.3 – Normalized head increase as a function of group size, stems blocked perpendicular to flow the direction in the central bay (type 3 blockage).

In this type of blockage, stems were positioned against the pier nose. The distance between stems and the weir crest was 0.08 m due to the pier nose configuration used (Figure B.4). Under these conditions, would seem reasonable to have close to zero head increase as stems are barely interacting with the weir. However, a head increase of 3% was measured.

Figure B.4 – Example of 8 stems from class C artificially blocked perpendicularly to the flow direction in the central bay.

Table B.4 shows the results measured for blockage type 4, where stems were artificially blocked perpendicular to the flow direction disperse in five bays. Only experiments with class C (L/b = 120%) and E (L/b = 200%) are presented as stems from class A were shorter than the bay width.

Table B.4 – Experimental measurements of head increase for artificially blocked stems perpendicular to the flow direction disperse in five bays (type 4 blockage) [m · 10⁻2].

Class	**Group size**	**Exp. 3** (H/d=0.94)*		**Exp. 4** (H/d=1.00)		**Exp. 5** (H/d=1.06)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
C	1						
	2	1.50	0.00	1.60	0.00	1.71	0.01
	4	1.50	0.00	1.59	0.00	1.71	0.04
	8	1.50	0.00	1.60	0.00	1.71	0.00
	16	1.50	0.00	1.59	0.00	1.70	0.05
	32	1.50	0.00			1.73	0.00
		Exp. 6 (H/d=0.76)		**Exp. 7** (H/d=0.84)*		**Exp. 8** (H/d=0.96)	
		H_0	ΔH	H_0	ΔH	H_0	ΔH
E	1			2.10	0.00		
	2	1.93	0.00			2.40	0.06
	4			2.10	0.00	2.41	0.01
	8	1.93	0.01	2.10	0.00	2.39	0.00
	16	1.89	0.00	2.10	0.00	2.40	0.03
	32	1.88	0.00	2.10	0.10	2.41	0.04

* Measurements taken only with point gauge

Figure B.5 shows the normalized head increase as a function of the group size for artificially blocked stems perpendicular to the flow direction and disperse in five bays. Compared to Figure B.3, the majority of head increase measurements were close to zero. However, one measurement of 4% was recorded.

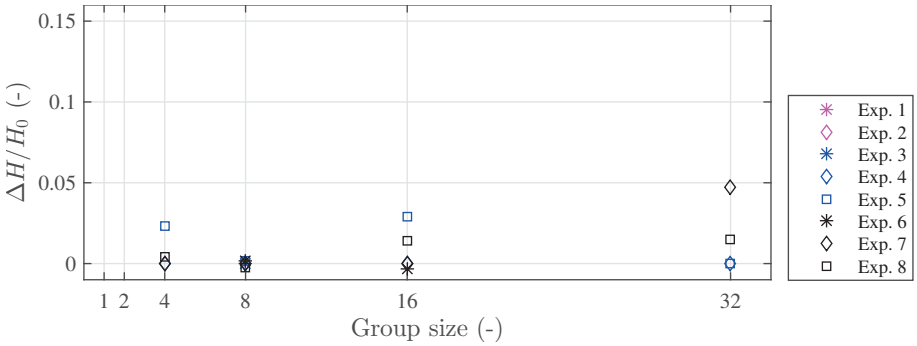

Figure B.5 – Normalized head increase in function of group size, stems blocked perpendicular to the flow direction disperse in five bays (type 4 blockage).

For experiments with blockage type 3 and 4 (stems perpendicular to the flow direction in the central bay and disperse in five bays respectively), stems were not touching or interacting directly with the weir crest. It can be qualitatively concluded that the stem presence in the vicinity of the weir crest rarely to some head increase under the tested conditions. Considering the uncertainty linked to the experimental measurements taken, the maximum head increase expected could be close to 5%. To improve this type of analysis, stems should be fixed in the blocked position to assure reproducibility of experiments and accuracy in measurements.

C Full set of experiments conducted for estimations of blocking probability.

Herein all the experiments for blocking probability estimation performed are presented. The number of repetitions and the blocking probability estimated allow to calculate confidence intervals and accuracy with any method. The result for each experimental repetition and pictures of the experiments are available upon request.

Table C.1 – Complete experimental program with blocking probability result.

Exp N°	**Class**	**Density** ρ_s	***H/d***	**Open bays**	**Nose type**	$\mathbf{G}_i$	**Repetitions**	$\hat{\Pi}$
1	A	0.59	1.10	1	N2	1	30	0.60
2	A	0.59	1.40	1	N2	1	30	0.10
3	A	0.59	1.50	1	N2	1	30	0.00
4	A	0.59	0.90	5	N2	1	30	0.47
5	A	0.59	1.00	5	N2	1	30	0.60
6	A	0.59	1.20	5	N2	1	30	0.27
7	A	0.59	1.20	5	N2	1	30	0.13
8	A	0.59	1.50	5	N2	1	30	0.00
9	A	0.59	0.90	5	N2	2	15	0.47
10	A	0.59	1.10	5	N2	2	15	0.33
11	A	0.59	0.80	5	N1	4	30	0.48
12	A	0.59	0.90	5	N2	4	8	0.63
13	A	0.59	1.10	5	N2	4	8	0.50
14	A	0.59	0.90	5	N2	8	4	0.41
15	A	0.59	1.10	5	N2	8	4	0.31
16	A	0.59	1.10	1	N2	16	3	0.56
17	A	0.59	0.90	5	N2	16	3	0.42
18	A	0.59	1.10	5	N2	16	3	0.31
19	A	0.59	0.90	5	N2	32	3	0.59
20	A	0.59	1.10	5	N2	32	3	0.39
21	A	0.79	1.20	1	N2	1	30	0.37
22	A	0.79	1.40	1	N2	1	30	0.20

Table C.1 Continuation.

Exp N°	**Class**	**Density ρ_s**	***H/d***	**Open bays**	**Nose type**	**G_i**	**Repetitions**	$\hat{\Pi}$
23	A	0.79	0.80	5	N3	1	60	0.75
24	A	0.79	1.00	5	N2	1	30	0.53
25	A	0.79	1.20	5	N2	1	30	0.20
26	A	0.79	1.10	1	N1	8	20	0.32
27	A	0.79	0.90	5	N2	8	30	0.55
28	A	0.79	0.90	5	N2	8	60	0.66
29	A	0.99	1.40	1	N2	1	30	0.03
30	A	0.99	1.00	5	N2	1	30	0.63
31	A	0.99	1.20	5	N2	1	30	0.17
32	A	0.99	1.20	1	N3	4	23	0.08
33	B	0.56	1.00	1	N2	1	30	0.73
34	B	0.56	1.25	1	N2	1	70	0.63
35	B	0.56	1.25	1	N2	1	30	0.07
36	B	0.56	0.75	5	N2	1	30	0.73
37	B	0.56	0.83	5	N3	1	60	0.43
38	B	0.56	1.00	5	N2	1	30	0.33
39	B	0.56	1.25	5	N1	1	60	0.08
40	B	0.56	1.25	5	N2	1	30	0.00
41	B	0.56	1.25	1	N2	2	46	0.37
42	B	0.56	0.92	5	N3	2	52	0.49
43	B	0.56	1.00	5	N2	2	60	0.63
44	B	0.56	1.00	1	N2	16	15	0.31
45	B	0.56	1.00	5	N2	32	60	0.48
46	C	0.43	0.94	1	N2	1	30	0.50
47	C	0.43	0.81	5	N3	1	70	0.66
48	C	0.43	0.94	5	N2	1	30	0.27
49	C	0.43	1.06	5	N2	1	30	0.03
50	C	0.43	0.94	5	N2	4	8	0.25
51	C	0.43	0.94	5	N2	16	3	0.38
52	C	0.43	0.94	5	N2	16	60	0.33
53	C	0.56	0.75	1	N2	1	30	0.60
54	C	0.56	0.94	1	N2	1	30	0.60
55	C	0.56	0.94	1	N2	1	30	0.50
56	C	0.56	0.56	5	N2	1	30	0.97
57	C	0.56	0.75	5	N2	1	30	0.63
58	C	0.56	0.81	5	N1	1	60	0.20
59	C	0.56	0.94	5	N2	1	30	0.17
60	C	0.56	0.94	5	N2	1	30	0.13

Table C.1 Continuation.

Exp N°	**Class**	**Density ρ_s**	***H/d***	**Open bays**	**Nose type**	**G_i**	**Repetitions**	$\hat{\Pi}$
61	C	0.56	1.00	5	N2	1	30	0.00
62	C	0.56	1.06	5	N2	1	30	0.03
63	C	0.56	1.25	5	N2	1	30	0.00
64	C	0.56	1.56	5	N2	1	30	0.00
65	C	0.56	0.75	5	N2	2	69	0.67
66	C	0.56	0.88	5	N2	2	15	0.30
67	C	0.56	0.94	5	N2	2	15	0.07
68	C	0.56	1.00	5	N2	2	15	0.13
69	C	0.56	0.94	5	N2	4	8	0.56
70	C	0.56	0.94	5	N2	4	8	0.38
71	C	0.56	1.00	5	N2	4	8	0.19
72	C	0.56	0.88	5	N2	8	4	0.56
73	C	0.56	0.94	5	N2	8	4	0.09
74	C	0.56	1.00	5	N2	8	4	0.16
75	C	0.56	0.88	1	N2	16	3	0.71
76	C	0.56	0.94	5	N2	16	3	0.31
77	C	0.56	0.94	5	N3	16	10	0.48
78	C	0.56	0.94	5	N2	16	3	0.56
79	C	0.56	1.00	5	N2	16	3	0.08
80	C	0.56	0.94	1	N1	32	4	0.63
81	C	0.56	0.88	5	N2	32	3	0.55
82	C	0.56	0.94	5	N2	32	3	0.42
83	C	0.56	1.00	5	N2	32	3	0.15
84	C	0.97	0.94	1	N2	1	30	0.73
85	C	0.97	0.94	5	N2	1	30	1.00
86	C	0.97	1.06	5	N2	1	30	0.77
87	C	0.97	0.94	5	N2	4	8	0.97
88	C	0.97	1.06	5	N2	4	60	0.33
89	C	0.97	0.94	5	N2	16	3	1.00
90	D	0.63	0.80	5	N2	1	30	0.70
91	D	0.63	0.90	5	N1	1	70	0.21
92	D	0.63	1.00	5	N2	1	30	0.27
93	D	0.63	1.25	5	N2	1	30	0.00
94	D	0.63	0.95	5	N1	32	14	0.46
95	E	0.40	0.96	1	N2	1	30	0.07
96	E	0.40	0.72	5	N3	1	60	0.52
97	E	0.40	0.76	5	N2	1	30	0.43
98	E	0.40	1.00	5	N2	1	30	0.00

Table C.1 Continuation.

Exp N°	**Class**	**Density ρ_s**	***H/d***	**Open bays**	**Nose type**	**G_i**	**Repetitions**	$\hat{\Pi}$
99	E	0.54	0.72	1	N2	1	30	0.43
100	E	0.54	0.88	1	N2	1	58	0.69
101	E	0.54	0.96	1	N2	1	30	0.13
102	E	0.54	1.08	1	N1	1	40	0.10
103	E	0.54	0.64	5	N2	1	30	0.97
104	E	0.54	0.72	5	N1	1	60	0.62
105	E	0.54	0.76	5	N2	1	30	0.87
106	E	0.54	0.80	5	N2	1	30	0.40
107	E	0.54	0.80	5	N2	1	30	0.80
108	E	0.54	0.82	5	N1	1	60	0.28
109	E	0.54	0.92	5	N2	1	30	0.13
110	E	0.54	1.00	5	N2	1	30	0.10
111	E	0.54	1.00	5	N2	1	30	0.03
112	E	0.76	0.96	1	N2	1	30	0.37
113	E	0.76	0.76	5	N2	1	30	1.00
114	E	0.76	0.76	5	N1	1	20	0.95
115	E	0.76	1.00	5	N2	1	30	0.20
116	E	0.76	1.08	5	N1	1	70	0.01
117	E	0.99	0.96	1	N2	1	30	1.00
118	E	0.99	0.76	5	N2	1	30	1.00
119	E	0.99	1.00	5	N2	1	30	0.97
120	E	0.54	0.72	5	N2	2	15	0.90
121	E	0.54	0.92	5	N2	2	15	0.53
122	E	0.54	0.80	5	N2	4	8	0.66
123	E	0.54	0.92	5	N2	4	8	0.22
124	E	0.54	0.72	5	N2	8	4	0.97
125	E	0.54	0.80	5	N2	8	4	0.66
126	E	0.54	0.92	5	N2	8	4	0.25
127	E	0.54	0.72	1	N2	16	3	0.50
128	E	0.54	0.72	5	N2	16	3	0.83
129	E	0.54	0.80	5	N2	16	3	0.50
130	E	0.54	0.92	5	N2	16	3	0.17
131	E	0.54	0.72	5	N2	32	3	0.80
132	E	0.54	0.80	5	N2	32	3	0.74
133	E	0.54	0.92	5	N2	32	3	0.44

Paloma Furlan

Curriculum Vitae

Personal information

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Education

Oct 2014 ∼ *Nov 2018* **PhD Candidate - H2Doc Program**, *EPFL - IST*, Switzerland - Portugal.
Joint degree program between École Polytechnique Fédérale de Lausanne and Instituto Superior Técnico. Temporary thesis title: "Blocking probability of large wood and resulting head increase at ogee crest spillways". Supervised by Prof. Anton J. Schleiss (EPFL) and Prof. Jorge Matos (IST).

2007–2013 **Diploma in Civil Engineering**, *National University of Cordoba*, Argentina.
Five years bachelor degree. Final grade: *7.42/10*. Final project title (Graded: *10/10*): "Simulación numérica de flujo en confluencia (Numerical simulation of a river confluence)". Supervised by Prof Cecilia Pozzi Piacenza and Dr Horacio Herrero.

Professional experience

Nov 2015 – Oct 2016 **Scientific assistant on applied research project**, *Laboratory of Hydraulic Constructions, EPFL*, Switzerland.
Project for BG consulting engineers - SBB CEVA with Dr Giovanni De Cesare (LCH) and Ing Khalid Essyad (BG) as leaders of the project. Construction and design validation for a physical model of a self-priming siphon. The siphon is used to control groundwater levels without energy requirements for the structural safety of a tunnel. Assistance in the experimental campaign, evaluation of results and adaptations to the original design. Numerical simulations of physical model elements for design purpose (Flow3D).

Jun – July 2015 **Scientific assistant on applied research project**, *Laboratory of Hydraulic Constructions, EPFL*, Switzerland.
Project for Forces Motrices Hongrin-Léman (FMHL) with Dr Giovanni De Cesare (LCH) as leader of the project. Numerical simulation with Flow3D of inlet/outlet structures from Hongrin-Léman pump storage scheme. Evaluation and optimization of the fish screen position after the augmentation of the scheme capacity.

Fev – June 2014 **Jr executive engineer**, *EDISUR SA*, Argentina.
Management and organization department. Support for urban sewage network design. Management and development of surveying and subdivisions for new housing projects and neighbourhoods. Follow-up of projects in governmental entities and external companies.

Fev 2011 – June 2014 **Undergraduate research assistant**, *Centre for Water Research and Technology (CETA), UNC*, Argentina.
Position achieved after competition based on qualifications at the research institute of the National University of Córdoba (UNC). Numerical simulations of turbulent flows with OpenFOAM on natural river confluences and open-channels. Pre and post-processing data with Paraview. Assistance with experimental work. Translation of the OpenFOAM user's manual.

2011 – 2014 **Draughtsman**, *Independent professional*, Argentina.
Technical plans and diagrams for diverse industries: Molino Passerini SAIC, Gelatinas Córdoba ICSA, Indupas SA, Cuenca del Sol SA, Molinos Salvay SRL, Agronegocios Fast SH, COR-MIS, DyG Snacks, Mirgal SA, Nueva Dalmacia SA. House blueprints and technical guidance for a private client.

Academic experience

Oct – Dec 2017 **Teaching assistant**, *Laboratory of Hydraulic Constructions, EPFL*, Switzerland.
Teaching assistant in SIE project "Experiments with artificial driftwood to study blockage at spillway inlet".

Oct 2014 – Sept 2016 **Teaching assistant**, *Laboratory of Hydraulic Constructions, EPFL*, Switzerland.
Teaching assistant in "Hydraulic structures and schemes I"; "River eco-morphology". Assistant in semester projects "Participation à des essais en cours au Laboratoire"; "Analyse d'extension et optimisation des systèmes hydroélectriques complexes en Suisse".

2009 – 2012 **Student tutor**, *School of Civil Engineering, UNC*, Argentina.
Guidance and assistance for incoming students of Civil Engineering at the National University of Córdoba.

Non-profit experience

2010 – 2013 **Elected undergaduate representative**, *School of Civil Engineering, UNC*, Argentina.
Member of the directive board of the School of Civil Engineering at the National University of Cordoba, with participation in the committees and vote. Main task: scheduling management and interlocutor of 3rd, 4th and 5th year of Civil Engineering.

2010 – 2013 **Vocal of directive board and Director of events secretary**, *OVEI*, Argentina.
Co-founder and elected member of the directive board for the non profit Organization of Students International Travels (OVEI - Organización de Viajes Estudiantiles Internacionales). Elected director of the events secretary.

Publications

Peer reviewed journal:

- **Furlan, P**; Pfister, M; Matos, J; Amado, C, & Schleiss A.J. (2018). "Experimental repetitions and blockage of large stems at ogee crested spillways with piers", *Journal of Hydraulic Research*, doi:10.1080/00221686.2018.1478897
- De Cesare G., Essyad K., **Furlan P.**, Khuong V.N. and Mulligan S. (2018). "Experimental study at prototype scale of a self-priming free-surface siphon", *Advances in Hydroinformatics*, Springer Water, pp. 899-912, doi:10.1007/978-981-10-7218-5_64

- **Furlan, P**; Pfister, M; Matos, J; Amado, C, & Schleiss A.J. (submitted). "Blockage probability modeling of large stems at ogee crested spillways with piers", *Water Resources Research*.
- **Furlan, P**; Pfister, M; Matos, J; Amado, C, & Schleiss A.J. (submitted). "Statistical accuracy for estimations of large wood blockage in a reservoir environment", *Environmental Fluid Mechanics*.

Conference proceedings:

- **Furlan, P**; Pfister, M; Matos, J & Schleiss AJ (2018). "Spillway blockage caused by large wood in reservoirs". *Proceedings of 9th International Conference on Fluvial Hydraulics, River Flow 2018*, 5-8 September, Lyon-Villeurbanne, France. doi: 10.1051/e3sconf/20184002037
- **Furlan, P**; Pfister, M; Matos, J & Schleiss AJ (2018). "Influence of density of large stems on the blocking probability at spillways". *Proceedings of the 7th IAHR International Symposium on Hydraulic Structures*, 15-18 May, Aachen, Germany. doi: 10.15142/T3664S(978-0-692-13277-7)
- **Furlan, P**; Pfister, M; Matos, J; Schleiss, A.J (2017). "Entrapment of driftwood at ogee crest spillways with piers: influence of woody debris characteristics on blocking probabilities". *Proceedings of the Colloque CFBR-SHF, Hydraulique des barrages et des digues*, November 29–30, Chambéry, France. Société Hydrotechnique de France. Pag. 42-49.
- **Furlan, P**; Pfister, M; Matos, J & Schleiss AJ (2017). "Blocking probability of driftwood at ogee crest spillways with piers: influence of woody debris characteristics". *Proceedings of the 37th IAHR World Congress*, August 13–18, Kuala Lumpur, Malaysia. Pag. 2357–2364
- De Cesare G., Essyad K., **Furlan P.**, Khuong V.N. and Mulligan S (2017). "Experimental study at prototype scale of a self-priming free surface siphon". SimHydro 2017: Choosing the right model in applied hydraulics, 14-16 June 2017, Sophia Antipolis.
- Pozzi Piacenza, C; Herrero, H; **Furlan, P**; Ragessi, M.I; Márquez Damián, S; López,G; Pedocchi, F; García, C.M (2013). "Simulación numérica y experimental del flujo en una confluencia. (Numerical and experimental simulation of flow in a confluence)" *XX Congreso sobre métodos numéricos y sus aplicaciones – ENIEF 2013*, November 19-22, Mendoza, Argentina. CD format.
- Pozzi Piacenza, C; **P. Furlan**; Herrero, H; Ragessi, M.I; Márquez Damián, S; García, C.M (2013). "Evaluación numérica del comportamiento hidrodinámico en confluencias fluviales (Numeric evaluation of hydrodynamic behaviour in river confluences)". *Sexto simposio regional sobre hidráulica de ríos – Ríos 2013*, November 6-8, Santa Fe, Argentina. CD format.

R&D

- Research assistant at "Experimental characterization of turbulent flows in fluvial and marine complex environments". Funded by Secretaria de Ciencia y Tecnología (SECyT), National University of Cordoba. Period 2012 – 2013.
- Research assistant at "Experimental characterization of flow structures on complex turbulent flows". Funded by Secretaria de Ciencia y Tecnología (SECyT), National University of Cordoba. Director: Dr Fabián López. Period 2010 – 2011.

Languages

Excellent	Spanish (**Native**), English (FCE, Un. of Cambridge)
Very good	French (B1+, Language Centre of EPFL)
Good	Portuguese (B1, Language Centre of IST), Italian (A2+, Un. Camerino)

Computer skills

Tools	MS Office, LaTeX, Linux.
Programming	OpenFOAM (C++), Matlab, R.
Data analysis	ParaView, Flow3D, InfoStat (UNC).

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