# UNDERSTANDING THE FORMATION OF WOODY DEBRIS JAMS AT BRIDGE PIERS

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## ABSTRACT

Woody debris accumulations at bridge piers can significantly increase the risk of flooding and bridge failure due to increased afflux upstream of bridges, additional structural loads and exacerbated scour. Despite the importance of this problem, limited research has been conducted on the topic. In this study, we experimentally analyse the process of accumulations of woody debris (modelled with twigs and natural sticks) at single piers exposed to flow and a continuous debris supply. Results show that these debris jams follow a three-phase growth: *unstable* (where growth occurs rapidly but debris are easily disengaged); *stable* (growth assumes a less pronounced trend and debris are less likely to be escaped); *critical* (the accumulation begins to oscillate about the pier and ultimately drifts away, i.e. fails). The dimensions of the accumulation at failure were observed to plot as well-defined functions of the flow and debris characteristics. In particular, while the cross-sectional and longitudinal dimensions of the accumulations were observed to decrease with increasing flow, the vertical component displayed an opposite trend. These results provide a worst-case scenario that can be useful for engineering bridge design and flood risk assessment.

**Keywords:** Bridge pier, Flood risk, Woody debris, Debris jam, Bridge clogging

## 1 INTRODUCTION

The stability of fluvial bridges have long been a major concern for scientists and engineers. Bridge piers modify the flow field, inducing structural lateral loads and localised scour. The accumulation of woody debris at bridge piers significantly exacerbates these effects. Namely, woody debris jams cause important flow constrictions, affecting the neighbouring flow field (Daniels and Rohads, 2004; Pagliara and Carnacina, 2012), increasing the upstream water levels (Diehl, 1997; Lagasse et al., 2010) and intensifying pier scour (Lagasse et al., 2010). Diehl (1997) estimated that more than 30% of bridge failures in the United States is related to the accumulation of woody debris at piers.

Large Wood Debris (LWD) can be mobilised by several processes, especially bank erosion and buoying fallen trees on the floodplains (Diehl, 1997; Lyn et al., 2003; Lagasse et al., 2010), conveyed during flooding events. Obstacles within the LWD path, such as a bridge pier, are likely to entrap oncoming logs, possibly initiating a build-up process that leads to an LWD pile (Diehl, 1997). It has been reported that accumulations are generally begun by a key-element, i.e. a large and sturdy log (Diehl, 1997). This key-element becomes a source of recruitment for smaller debris, which allow the debris pile to expand (Manners et al., 2008, Lagasse et al., 2010). In-situ observations suggest that an inverted half-cone (Diehl, 1997; Lagasse et al., 2010) is the most typical jam shape.

In spite of the importance of debris to bridge stability and flooding, scientific studies aimed at understanding the potential size that might be reached by these debris jams are extremely limited. Most studies on LWD have been mainly based on field surveys (e.g. Diehl, 1997), where the actual evolution of the accumulation is rarely observed. Consequently, river bridge design and flood risk assessment guidelines either do not consider drift accumulations or suggest arbitrary design raft size (Diehl, 1997). Only a few and relatively recent experimental studies (e.g. Lyn et al., 2003; Bocchiola et al., 2008, Rusyda et al., 2014) have attempted to investigate the build-up phenomenon, although they have been limited in scope and have not analysed the fundamental relationship between LWD accumulation process and flow conditions.

The aforementioned issues associated with debris accumulations could be included in engineering design and flood risk assessment if the potential dimensions and coefficient of drag of the debris jam could be estimated. Developing predictive techniques for the dimensions of LWD accumulations would allow the estimation of debris-induced effect on the flow through momentum conservation principles by considering the drag force exerted on the debris jam:

$$F_D=\frac{1}{2}\rho C_D A v^2, \qquad [1]$$

where $F_D$ is the drag force, $\rho$ is the water density, $C_D$ is the drag coefficient, $A$ is the accumulation area normal to the flow and $v$ is the approaching flow velocity.

The aim of this study is to analyse the growth and potential size of LWD accumulations at bridge piers. A total of 322 laboratory experiments were performed, in which natural sticks were introduced upstream of model piers in order to naturally form the debris accumulations. We first examined how debris accumulations grow over time, identifying clear patterns that were observed in all experiments. We then analysed the influence of debris length and pier size on the dimensions of formed jams for the idealised situation of uniform size debris supply. Finally, we compare accumulations obtained with uniform size debris against those that were formed by using a non-uniform length distribution of debris elements and assuming the accumulation was initialised by a key-element.

The results of these tests enabled a detailed analysis of the time evolution and critical dimensions of debris jams observed under a range of flow conditions and debris characteristics. Our findings help clarify the process by which debris accumulate at bridge piers and provide practical guidance for estimating the potential dimensions of debris accumulations.

## 2 DIMENSIONAL ANALYSIS

A dimensional analysis was carried out in order to derive a relationship among the variables that are relevant to the woody debris accumulation phenomenon. Assuming that all variables are interdependent (and assuming the channel boundaries are far enough to have negligible influence on the phenomenon) the following functional relation is proposed:

$$f\left(\rho,\mu,v,h,g,D,L,d,\rho_L,W,H,K\right)=0, \qquad [2]$$

where $\rho$=water density, $\mu$=water dynamic viscosity, $v$=approaching flow velocity, $h$=water depth, $g$=gravity acceleration, $D$=pier width, $L$=single debris length, $d$=single debris diameter, $\rho_L$=debris density, $W$=accumulation width, $H$=accumulation height and $K$=accumulation length ($W$, $H$ and $K$ are indicatively sketched in Figure 1).

Applying Buckingham π-theorem to the functional relation [2] and using $\rho$, $v$ and $L$ as repeated variables yields

$$g\left(Fr_L,Re_L,\frac{h}{L},\frac{L}{D},\frac{d}{L},\frac{\rho_L}{\rho},\frac{W}{L},\frac{H}{L},\frac{K}{L}\right)=0, \qquad [3]$$

where $Fr_L$ and $Re_L$ are respectively the Froude and the Reynolds number with characteristic length $L$ (the length of individual debris elements). Eq. [3] can be further simplified under certain assumptions. The flow is fully-developed turbulent and in this condition influence of the Reynolds number can be neglected (Wallerstein et al., 2001; Bocchiola et al., 2008). In addition, water depth $h$ has been observed as non-influential if the debris accumulation is well above the river bed by Lyn et al., (2003). This was also observed in some of our preliminary experiments. Under these assumptions, the functional relation [3] can be simplified as

$$g\left(Fr_L,\frac{L}{D},\frac{d}{L},\frac{\rho_L}{\rho},\frac{W}{L},\frac{H}{L},\frac{K}{L}\right)=0. \qquad [4]$$

The dimensionless variables in [4] were then used in the design of the experiments and data analysis.

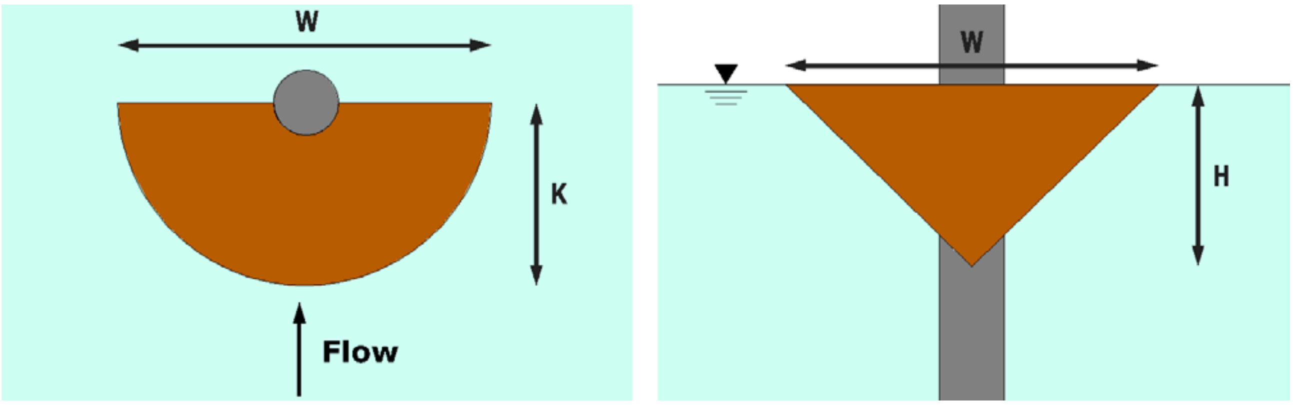


**Figure 1**. Sketch of an idealised woody debris jam indicating the main geometrical variables used in our analysis: width *W*, height *H* and length *K*. Left: plan view. Right: cross-section.

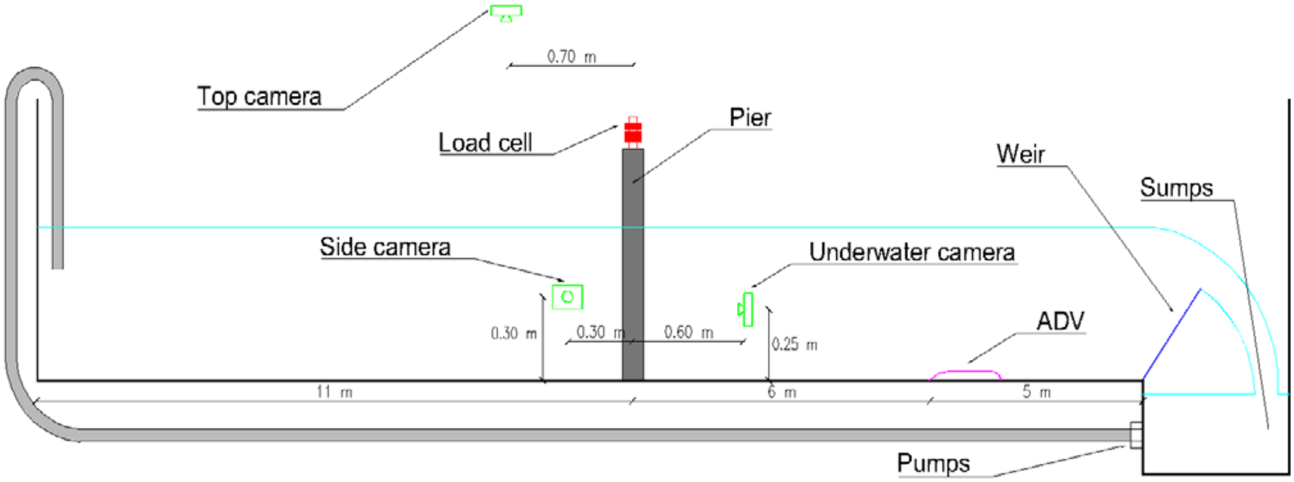


**Figure 2**. Sketch of the University of Southampton Hydraulics lab flume and the set-up used for woody debris experiments (not to scale).

## 3 EXPERIMENTS

Experiments were performed in a 22 m-long and 1.375 m-wide glassed-wall flume at University of Southampton. Figure 2 shows a sketch of the flume and the set-up adopted for the experiments. A circular pier was placed at the flume centreline, 11 m downstream the inlet. The pier was held from the top, at which point a load cell was connected to measure the force exerted on the pier over the course of the experiments. Flow conditions were constantly monitored by a multi-cell and multi-beam ADV placed 6 m downstream of the pier. The position of the ADV was selected in order to avoid debris-induced backwater effects on the measurements. Three cameras were installed in order to capture the time evolution of all the relevant geometric characteristics of the debris jam. The first camera was mounted on the top of the flume, the second on the side and the third was submerged 60 cm downstream of the pier.

The experiments consisted in dropping natural sticks individually (oriented parallel to the flow) at a constant frequency (approximately 20 sticks per minute) 7 m upstream of the pier. Debris were modelled using twigs and sticks collected from fallen branches or trees. Their density of debris elements was kept approximately constant by drying them after each experiment. Furthermore, debris diameter *d* was constant for each type of debris. We used two different types of debris, namely uniform and non-uniform size. Uniform size sticks had the same length *L* for all individual elements. Non-uniform sticks were used to mimic the supply of debris in natural channels, where a variety of debris dimensions is usually found (e.g. Sedell et al., 1988; Manners et al., 2008) and are typically non-normally distributed. We used a log-normal probability density function for relative lengths (relative to the highest length or key-element, as previously described):

$$p(\chi)=\frac{1}{\chi\sqrt{2\pi}\sigma}e^{-\left(\frac{\ln\chi-\mu}{\sqrt{2}\sigma}\right)^2}, \quad [5]$$

where $\chi$ is the ratio between a debris length and the key-element length. Adopting for [5] mean and standard deviation respectively $\mu$=-1.3039 and $\sigma$=0.7367, obtains a curve that is comparable to Sedell et al., (1988). Figure 3 shows a series of 100 sticks used for the non-uniform debris length experiments for one particular length *L* of the key-element.

We used three different piers, having diameters of 25, 50 and 100 mm. Five groups of experiments were conducted with 5 different combinations of *D* and uniform *L*, and 13 groups for the non-uniform debris length. For each group, a large number of experiments have been performed covering a range of flow discharges from 0.08 to 0.42 $m^3$/s. In total, 322 experiments were carried out. Table 1 indicates the variables adopted for each group.

## 4 RESULTS

### 4.1 Accumulation growth

The analysis of the accumulation temporal growth has shown a common behaviour for all jams. This growth can be conceptually classified into three different phases, hereafter referred to as *unstable*, *stable* and *critical*. These three stages are illustrated by the examples shown in Figure 4, where the dimensionless accumulation width *W/L*, height *H/L* and length *K/L* are plotted over the course of three uniform size debris experiments (having the same length *L* but different $Fr_L$).

**Table 1**. List of experiments. A1 to A5 are uniform size debris, B1 to B13 are non-uniform size debris.

| Group | Debris length (mm) | Pier diameter (mm) | L/D | Number of flow conditions |
|---|---|---|---|---|
| **A1** | 375.0 | 100 | 3.75 | 18 |
| **A2** | 250.0 | 50 | 5.00 | 21 |
| **A3** | 312.5 | 50 | 6.25 | 21 |
| **A4** | 375.0 | 50 | 7.50 | 19 |
| **A5** | 375.0 | 25 | 15.00 | 18 |
| **B1** | 500.0 | 100 | 5.00 | 17 |
| **B2** | 625.0 | 100 | 6.25 | 18 |
| **B3** | 375.0 | 50 | 7.25 | 15 |
| **B4** | 437.5 | 50 | 8.75 | 16 |
| **B5** | 500.0 | 50 | 10.00 | 18 |
| **B6** | 562.5 | 50 | 11.25 | 18 |
| **B7** | 625.0 | 50 | 12.50 | 18 |
| **B8** | 687.5 | 50 | 13.75 | 17 |
| **B9** | 750.0 | 50 | 15.00 | 18 |
| **B10** | 437.5 | 25 | 17.50 | 16 |
| **B11** | 500.0 | 25 | 20.00 | 18 |
| **B12** | 625.0 | 25 | 25.00 | 18 |
| **B13** | 750.0 | 25 | 30.00 | 18 |

The unstable phase occurs at the initial stage of the accumulation growth, when a few members (or the key-element) are entrapped by the pier and begin to recruit other oncoming debris. During this phase, the accumulation grows at a quick rate. In addition, debris elements can be easily mobilised and disengaged from the jam, resulting in frequent size variations.

After the accumulation has built a framework sufficient enough to entrap other members, the jam growth follows a less pronounced trend and becomes more stable. This slower pace of growth is likely to be the result of the cubic relation between volume and linear dimensions. During this phase, the accumulation size typically reaches its maximum dimensions, which can last for a longer time compared to the other phases. Moreover, at this stage the accumulation assumes the typical half-cone shape that has often been reported from field observations available in the literature.

Finally, at the critical phase the accumulation begins a rotational oscillatory movement about the pier. This pivoting eventually results in the accumulation being completely disengaged from the pier (hereafter referred to as *failure*). Figure 5 shows an example of the accumulation failure. All experiments were stopped after the failure of the debris accumulations.

4.2 Accumulation potential size

The maximum dimensions reached by woody debris jams at the beginning of the critical phase have shown a strong dependency on both flow conditions and debris length. Figures 6 and 7 show the maximum dimensionless width, height and length obtained for each experiment against $Fr_L$ for respectively uniform and non-uniform debris. These figures show that when $Fr_L$ is low, values of $W/L$ and $K/L$ are the highest, whereas $H/L$ is smallest. With increasing $Fr_L$, width and length rapidly decrease, while height increases.

It is also clear that for the range of values tested in this study the ratio $L/D$ seems to have no significant impact on the debris build-up. Although L/D values ranged from 3.5 to 15 (for uniform debris) and between 5 and 30 (for non-uniform debris), results shown in Figures 6 and 7 are all clustered within a narrow band irrespectively of $L/D$. A similar conclusion can be reached for the ratio $d/L$. The debris diameter $d$ was kept constant and $L$ was varied in all experimental groups, but the curves show no indications that this factor can have an influence within the range of values studied.

**Figure 3**. One particular set of 100 sticks used in the experiments with non-uniform debris.

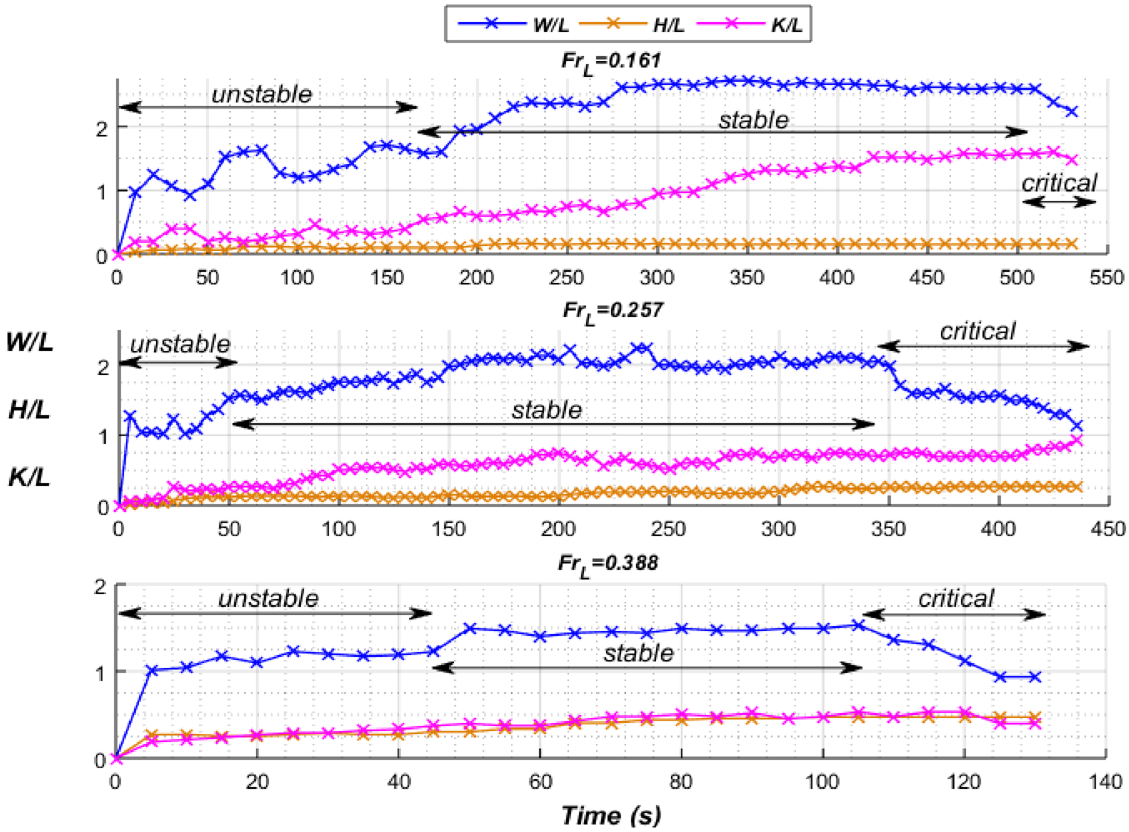


**Figure 4**. Time evolution for uniform size stick experiments (group A4) at three different values of $Fr_L$. On the vertical axis: dimensionless jam size variables *W/L*, *H/L* and *K/L*. Growth phases are indicatively reported. The last data point corresponds to the instant in which accumulation failure and dislodgement from the pier occur.

## 5 ANALYSIS AND DISCUSSION

Our results provide the first robust evidences of the formation, growth and failure of debris accumulations at bridge piers. While a few features observed in these experiments are consistent with the hypotheses suggested by Diehl, (1997), Manners et al., (2008) and Lagasse et al. (2010), the failure process (i.e. the *critical* phase which occurred for all jams) has not been previously reported in the literature. Only Lyn et al. (2007) observed that some debris piles were no longer in place between two site visits, and in one instance they supposed that a jam could have been dislodged from a pier and then re-accumulated at another downstream pier, although there was neither evidence of this nor a link to the failure mechanism. Our experiments unveiled

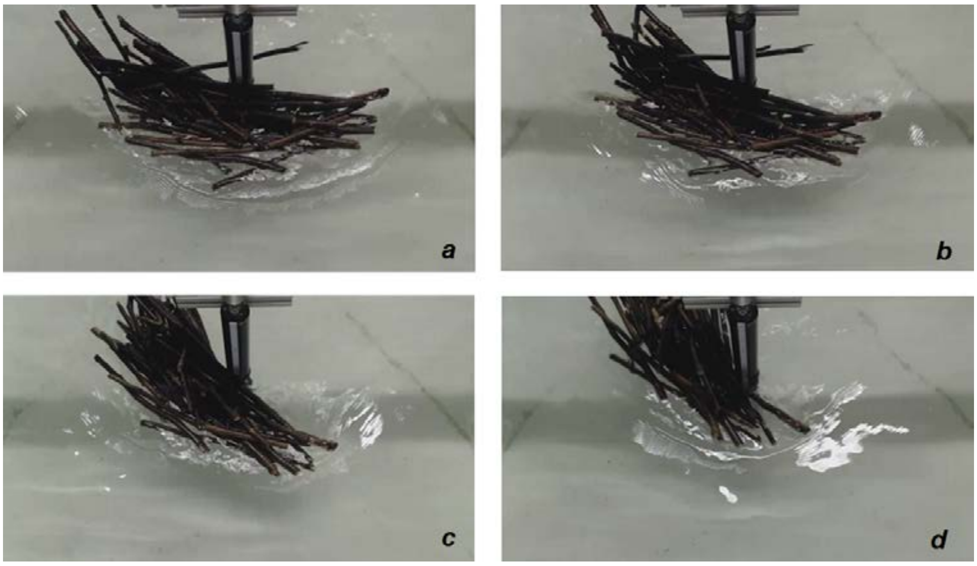


**Figure 5**. An example of accumulation failure for a non-uniform size debris jam from the beginning of the oscillation (a) to the final dislodgement (d).

that the lifetime and the size of a woody debris jam are limited by the critical condition after which the jam is completely removed from the pier. The critical condition provides an opportunity to define metrics representing the potential dimensions that can be reached by debris accumulations. The three dimensionless variables thus defined have shown a clear dependency the parameter $Fr_L$, indicating that any attempt to describe LWD accumulations must be linked to these variables. The results of our experiments with non-uniform debris and at low $Fr_L$ show that an accumulation can reach a width up to 40~50% larger than the length of the key-element. This contradicts previous field-based observations that suggest a maximum width equal to the key-log. In addition, our results show that a jam is more likely to reach the river bed at high $Fr_L$.

Our experimental results unveiled substantial differences between the dimensions of debris jams formed by debris of uniform and non-uniform lengths. The former reach a size that is much larger than the latter at the same $Fr_L$. Consequently, idealised experiments adopting a constant size of debris will overestimate the actual size that a LWD pile can reach, as debris supply in natural environments is typically non-uniformly distrbuted. At low flow conditions, the width of formed accumulations was as high as 3 times the length of the uniform debris elements, but only 1.5 times the length of the key-element in the non-uniform experiments.

Data from our experiments can be used for engineering practice in flood risk analysis and bridge design as a first approximation for the potential size of accumulations that might be achieved at a bridge pier, for given flow and debris size characteristics.

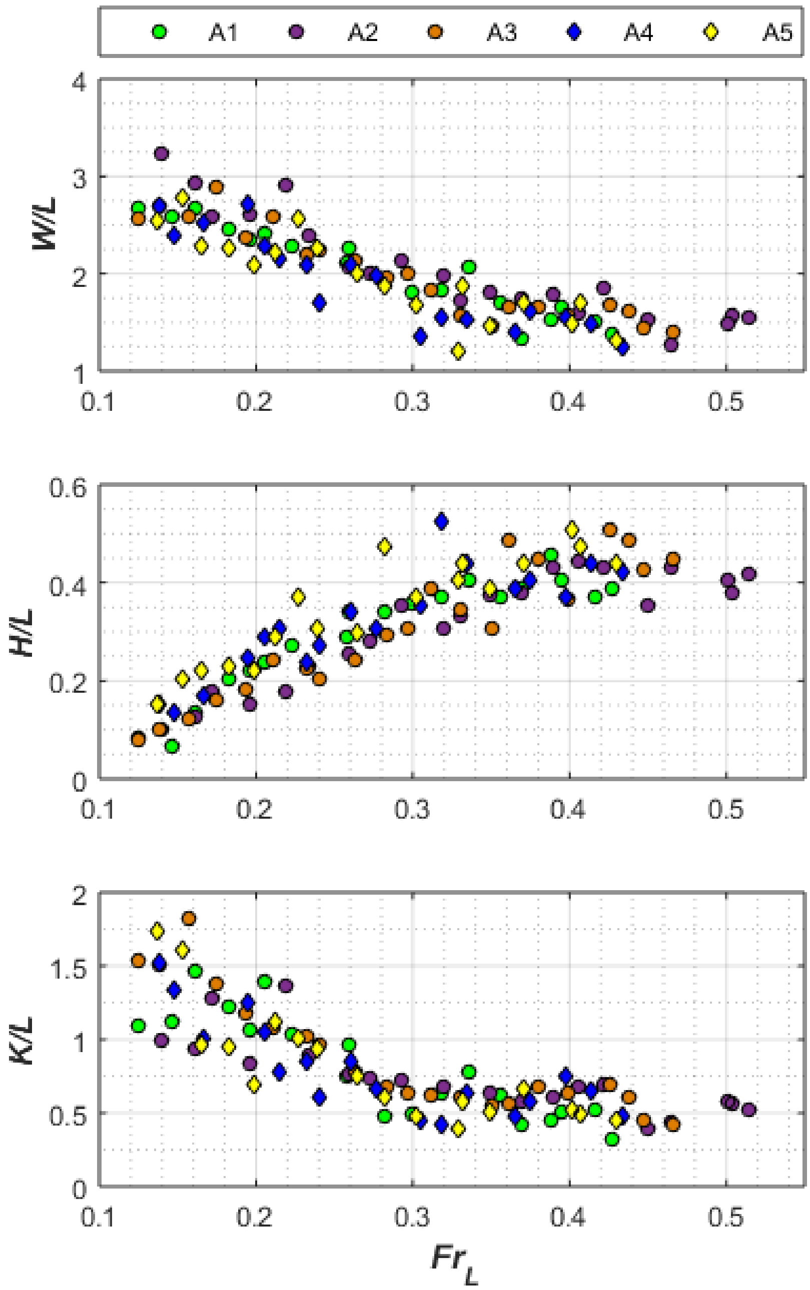


**Figure 6**. Dimensionless accumulation size variables against $Fr_L$ for uniform size debris.

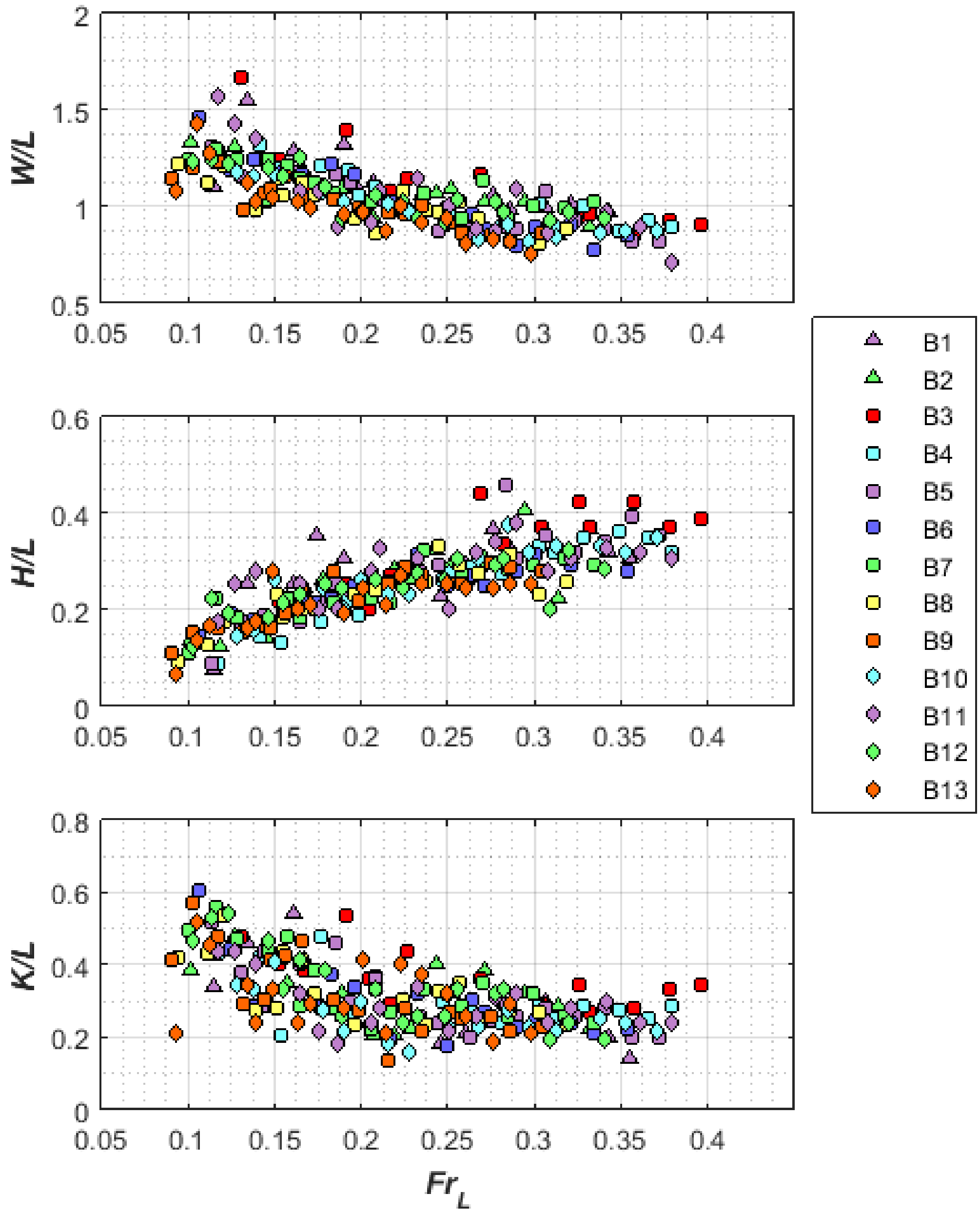


**Figure 7**. Dimensionless accumulation size variables against $Fr_L$ for non-uniform size debris.

## 6 CONCLUSIONS

A set of experiments on woody debris accumulations at bridge piers has been carried out. Results have shown a three-phase behaviour that these jams assume during their lifetime. The critical phase is of a particular interest, since at the beginning of this stage accumulations typically reach their maximum size and begin to oscillate about the pier until they are disengaged and drifted away. This phase was found in all experiments we conducted.

Furthermore, debris jams were highly dependent on the variable $Fr_L$, which contains flow conditions and debris length. When $Fr_L$ is low, debris pile width and length are highest, whereas height is minimal. When $Fr_L$ is high, width and length are smallest and height is highest.

Experiments with idealised debris of uniform size formed accumulations that were much larger than those with a non-uniform distribution of lengths that tries to mimic the supply of debris in natural channels. Therefore, non-uniform debris would ensure a more accurate analysis, although uniform debris can still be used to provide important insights into the accumulation process.

These results are the first attempt to predict the expected accumulation size for given flow conditions and debris length. Also, these findings can be used to estimate the potential dimensions of debris accumulations at bridge piers, which can be particularly useful for bridge design and flood risk assessments purposes.

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