

LARGE WOOD ACCUMULATION PROBABILITY AT A SINGLE BRIDGE PIER

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ABSTRACT

During flood events, transported large wood (LW) can accumulate at river infrastructures, reduce the flow cross-section, lead to backwater rise and eventually to flooding of the adjacent area. In addition, LW accumulations can damage the river infrastructure itself. To predict the risk of LW accumulations, the estimation of the accumulation probability is essential, especially for an integrated flood hazard assessment. Previous studies on LW accumulation probability focused mainly on the influence of a bridge deck or on the effect of bridge pier shapes. The results are partially contradictory, and the existing design equations for LW accumulation probabilities are only available for bridge decks. Therefore, a series of flume experiments was conducted to analyze the LW accumulation probability as a function of (1) the approach flow conditions, (2) the bridge pier roughness, and (3) the LW characteristics, involving various log lengths, LW with and without branches, and uncongested versus congested LW transport. The LW accumulation probability increases with increasing log length, decreasing approach flow velocity, and for congested LW transport. The approach flow Froude number, the water depth, the bridge pier roughness, and the availability of branches had a negligible effect on the accumulation probability. The results for uncongested LW transport were summarized in a novel design equation to estimate the accumulation probability at a single bridge pier and to identify critical bridge cross-sections prior to a flood event. To upscale the experimental results, and to improve the general process understanding, innovative prototype tests will be conducted in spring 2017.

Keywords: Accumulation probability; Flood protection; Flood risk assessment; Large wood (LW); River engineering.

1 INTRODUCTION

Large wood (LW), herein defined as single logs with a diameter $d_L \geq 0.1$ m and a length $L_L \geq 1.0$ m (Keller and Swanson, 1979; Wohl and Jaeger, 2009; Ruiz-Villanueva *et al.*, 2016a), is a beneficial part of river ecosystems. LW can originate from various sources, including hillslopes, timber wood storages, and the fluvial corridor. Single logs and LW accumulations enhance the diversity of morphological structures, species, and flow conditions (Figure 1a). The connectivity between the channel and the floodplain, or between water, sediments, and nutrients highly improves due to LW in rivers (Wohl *et al.*, 2016). During flood events, LW can be mobilized and transported, possibly resulting in accumulations at river infrastructures like bridges or weirs (Figure 1b). Due to such LW accumulations, the flow cross-section reduces, leading to backwater rise. This may result in flooding of the adjacent area, thereby intensifying the flood hazard. The interaction between LW and sediment transport is relevant for the accumulation process and its consequences. On the one hand, LW accumulations can increase sediment deposition, whereas on the other hand, they can cause local scour at bridge piers, inducing structural damages or even failure. The estimation of the accumulation probability is therefore crucial for an integrated flood hazard assessment, as it directly affects the damage potential. The present study focuses on quantifying the LW accumulation probability at a single bridge pier for various approach flow conditions, bridge pier and LW characteristics.



Figure 1. LW accumulation at (a) the River Thur, Switzerland, and (b) a bridge pier in Tyrol, Austria.

2 LITERATURE REVIEW

The LW accumulation probability p is mainly affected by the orientation of transported logs, the type of transport, and the LW characteristics (i.e. LW dimensions, logs with and without branches). As stated by Braudrick and Grant (2001), the orientation of transported logs relative to the flow is influenced by the transversal velocity distribution within a channel, usually with the largest flow velocity located in the channel centerline. Logs transported parallel to the flow experience an equal flow velocity over their entire length, leading to a steady transport state. In contrast, a rotational force is exerted on non-parallel oriented logs, as the flow velocities at both log ends are unequal. For large transport distances, the logs therefore tend to orientate parallel to the flow and are transported along the channel thalweg. Braudrick *et al.* (1997) conducted flume experiments on log deposition processes for approach flow depths $h_o = 0.15 \dots 0.30$ m, and log lengths $L_L = 0.20$ m and 0.40 m. For single LW transport, they observed log deposited mainly in the shallowest areas and orientated non-parallel to the flow. Therefore, both transport orientations for LW occur in channels: parallel and non-parallel to the flow.

Two types of LW transport can be defined in rivers: uncongested and congested (Braudrick *et al.*, 1997). For uncongested LW transport, single logs move independently without contact. In contrast, congested LW transport represents a single mass movement of logs, e.g. as a LW carpet. The transport types are related to the dimensionless input rate, i.e. the ratio of the volumetric log input rate to the approach flow discharge Q_{LW}/Q_o . For increasing Q_{LW}/Q_o , congested LW transport is predominant and characteristic for low-order streams. The different observed transport mechanisms are rolling, sliding, and floating (Haga *et al.* 2002).

LW accumulation bodies are initiated and stabilized by a long piece of wood, the so-called "key member" or "key log" (Nakamura and Swanson, 1994). According to Manners *et al.* (2007), an accumulation consists of approximately 45% of key logs, 25% of LW, 15% of logs with $d_L = 0.01 \dots 0.1$ m, and 15% fine material (e.g. branches, leaves, and soil). Therefore, longer logs play a decisive role for the accumulation probability.

Bezzola *et al.* (2002) conducted flume experiments on the LW accumulation probability p_D at a bridge deck (subscript D). The bridge deck geometry was kept constant, while the flume was adjusted to model rectangular and various trapezoidal cross-sections. The approach flow conditions were defined by the approach flow Froude number $F_o = 0.3 \dots 1.1$, and the ratio of the approach flow depth to the bridge clearance height $h_o/H_B = 0.5 \dots 1.0$. The model LW consisted of logs and rootstocks, and was transported both in an uncongested and congested manner. The experiments were repeated three times. Based on their results, p_D is mainly a function of the LW dimensions (length and diameter) in combination with the cross-sectional geometry, whereas the approach flow conditions (h_o/H_B , F_o) are of minor effect. The maximal $p_{D,max} \approx 80 \dots 100\%$ was observed for congested LW transport including rootstocks in trapezoidal cross-sections, compared to $p_{D,max} = 30\%$ for a rectangular cross-section. In the case of single rootstocks, $p_{D,max} \approx 50 \dots 70\%$ for trapezoidal cross-sections, compared to $p_{D,max} = 25\%$ for a rectangular cross-section. The minimal probability $p_{D,min} \approx 0 \dots 20\%$ was observed for uncongested logs. The results for uncongested transport were combined in design equations.

The effect of different bridge deck types on p_D for uncongested transport was studied by Schmocker and Hager (2011) for approach flow conditions $h_o/H_B = 0.9, 1.0, 1.07$ and $F_o = 0.3 \dots 1.2$, and model LW consisting of single logs and rootstocks. One test run consisted of $N = 8$ repetitions. Increasing accumulation probability was observed for increasing log dimensions, decreasing F_o , and decreasing freeboard ($1 - (h_o/H_B)$). Given a plain bridge deck without railings, for single logs, and for $h_o/H_B = 0.9$, p_D was always zero, whereas $p_D = 30 \dots 100\%$ for $h_o/H_B = 1.07$. Bridge decks with a truss or railings resulted in higher p_D . Design equations for p_D were defined for single logs and single rootstocks.

The LW accumulation probability at bridge decks including a circular bridge pier was investigated by Gschnitzer *et al.* (2013). Similar to previous studies, their findings indicate an increasing p_D for increasing log length, congested transport, logs with branches, and increasing h_o . The results of Gschnitzer *et al.* (2013) were not summarized in a design equation.

The LW accumulation probability p_P at a single bridge pier (subscript P) was tested by Lyn *et al.* (2003) for various approach flow conditions (h_o , F_o , and approach flow velocity v_o). The model LW consisted of logs with and without branches. Within one test run, 70 single logs were inserted 6 m upstream of the bridge pier in random orientation. The tests were repeated 50 times to improve statistical significance. In contrast to Schmocker and Hager (2011), no governing effect of F_o was found, but p_P increased with decreasing v_o and h_o . If more than six logs with branches accumulated, the branches improved the interrelation between the single logs, thereby increasing the accumulation stability. These accumulations, therefore, attached better to bridge piers, resulting in higher p_P compared to accumulations of logs without branches, which tend to resolve.

De Cicco *et al.* (2016) studied the influence of different bridge pier shapes on p_P . Flume experiments were conducted for uniform logs, steady flow conditions ($F_o = 0.3$ and 0.5), congested LW transport, and a fixed channel bed. To model congested LW transport, 25 logs with various lengths were inserted randomly ~3 m upstream of the bridge pier. The tests were repeated ten times. The results are contrary to previous studies, as p_P increased with increasing F_o for all tested pier shapes. For $F_o = 0.5$, the maximum $p_{P,max} = 90\%$

was observed for a squared pier. In contrast, a trapezoidal pier exhibited $p_{P,max} = 40\%$ for $F_o = 0.3$. Given an ogival pier, p_P was zero for all tested F_o .

3 OBJECTIVES

The knowledge on LW accumulation probability is still limited and the results are partially contradictory (Table 1). In addition, the required test repetitions N to obtain statistically significant accumulation probabilities p were defined from $N = 3 \dots 50$. The existing design equations for p are only valid for bridge decks. Systematic studies on the accumulation probability at bridge piers p_P exist, however, the results are not parameterized. Given the hazard potential of transported LW during flood events, further research on the accumulation process is required. This study is part of the interdisciplinary research project *WoodFlow* on LW management in rivers – a practice oriented research project in Switzerland (Ruiz-Villanueva *et al.*, 2016b). The main objectives of this study are to analyze the LW accumulation probability as a function of (1) the approach flow conditions, (2) the bridge pier roughness, and (3) the LW characteristics, involving various log lengths, LW with and without branches, and uncongested versus congested LW transport. A novel design equation is presented to assess the accumulation probability p_P for uncongested LW transport.

Table 1. Governing parameters on LW accumulation probability determined in past studies.

Type	Reference	Approach flow Froude number F_o	Approach flow depth h_o	Approach flow velocity v_o	LW dimensions	LW with branches	Congested LW transport	Cross-section / pier geometry	Number of repetitions N
Bridge deck	Bezzola <i>et al.</i> , 2002				X		X	X	3
	Schmocker and Hager, 2011	X	X		X				8
Bridge pier	Gschnitzer <i>et al.</i> , 2013		X		X	X	X		8
	Lyn <i>et al.</i> , 2003		X	X		X	X		50
	De Cicco <i>et al.</i> , 2016	X						X	10

4 EXPERIMENTAL SETUP

The experiments were conducted in a 10.7 m long, 1.0 m wide, and 0.8 m deep tilting flume at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich (Figure 2a). The 2.0 m long intake is equipped with a flow straightener to generate undisturbed inflow. The channel has a fixed bed ($k_{St, Prototype} \approx 30 \text{ m}^{1/3}/\text{s}$) and side walls made of glass and PVC. The inflow discharge Q_o was measured with an electromagnetic flow meter and regulated with a valve to a maximum of 265 l/s. The channel slope can be varied between $0 \leq S_o \leq 15\%$. The approach flow conditions (subscript o) were regulated by adapting the S_o , Q_o , and a downstream flap gate. They are characterized by h_o , $v_o = Q_o/(Bh_o)$, and $F_o = v_o/(gh_o)^{1/2}$, with B = channel width, and g = gravitational acceleration (Figure 2b). An Ultrasonic Distance Sensor (UDS) was used to measure h_o with an accuracy of ± 1 mm. To avoid viscosity and surface tension effects, Reynolds number $R = v_o \cdot 4R_h/\nu > 10^4$ (Hughes, 2005) and $h_o \geq 0.05$ m (Heller, 2011) were selected, respectively, where $R_h = Bh_o/(B+2h_o)$ = hydraulic radius, and ν = kinematic viscosity of water. The flow is in the rough turbulent regime for $R > 10^4$; therefore, the viscous force is independent of R (Hughes, 2005). The tests were performed according to Froude similitude with a model scale of $\lambda \approx 20$. A single circular bridge pier with a diameter $d_P = 0.05$ m was placed 5 m downstream of the inlet in the channel centerline. For the majority of the experiments, the material of the bridge pier was aluminum (i.e. smooth bridge pier). F_o varied between 0.2, 0.5, 0.8, and 1.2 to model common flow conditions during flood events ranging from subcritical to over-transcritical flow. For a selected range of approach flow conditions, the effects of a rough bridge pier, LW with branches, and congested LW transport on p_P were tested.

4.1 Model large wood

The model LW consisted of natural wood logs with and without branches. The log lengths varied between $L_L = 0.10$ m, 0.20 m, and 0.40 m, corresponding to ratios $d_P/L_L = 0.50, 0.25, \text{ and } 0.125$. The log diameter $d_L = 0.015$ m was kept constant and the branches were 0.04...0.05 m long and 0.004 m thick. Two different types of logs with branches were used for the experiments: The "2D" type corresponds to logs with alternate branches on two sides, whereas the "3D" type has alternate branches on four sides (Figure 2c). The model LW was not watered and always fully floating during tests. Hence, the transported logs did not interact with the channel bed. The tensile strength and the elasticity of the model LW were overestimated due to the usage of natural wood. In nature, transported logs may break when hitting the bridge pier, thereby decreasing the accumulation probability. This was not observed during the experiments.

4.2 Test program and procedure

The LW accumulation probability was examined within five test series (Table 2). To model the worst-case scenario of p_P , all logs were added non-parallel to the flow 1 m upstream of the bridge pier. Given the experimental randomness, the required repetitions to obtain statistically significant accumulation probabilities were studied in test A1. The reproducibility was evaluated by repeating four tests twice (A2-A9). Test series B studied the effects of the approach flow conditions and L_L on p_P (B1-B38). Various combinations of v_o and h_o were investigated for each value of $F_o = 0.2, 0.5, 0.8,$ and 1.2 . For subcritical flow (B1-B35), L_L was varied to 0.10 m, 0.20 m, and 0.40 m, whereas for over-transcritical flow (B36-B38), L_L was kept constant to 0.20 m. In test series C-E, the experiments were conducted for selected approach flow conditions. The bridge pier roughness was increased to model concrete material (i.e. rough bridge pier), with an equivalent sand roughness of $k_{s, Prototype} \approx 3$ mm (C1-C4). The effect of branches was studied using two different types of logs with branches (D1-D7). Test series E focused on the impact of congested LW transport on p_P (E1-E11). For these experiments, a bulk of 3 or 5 logs were added simultaneously to the flow 1 m upstream of the bridge pier. The test program comprises of a total of 3,160 individual test runs and 4,360 added logs.

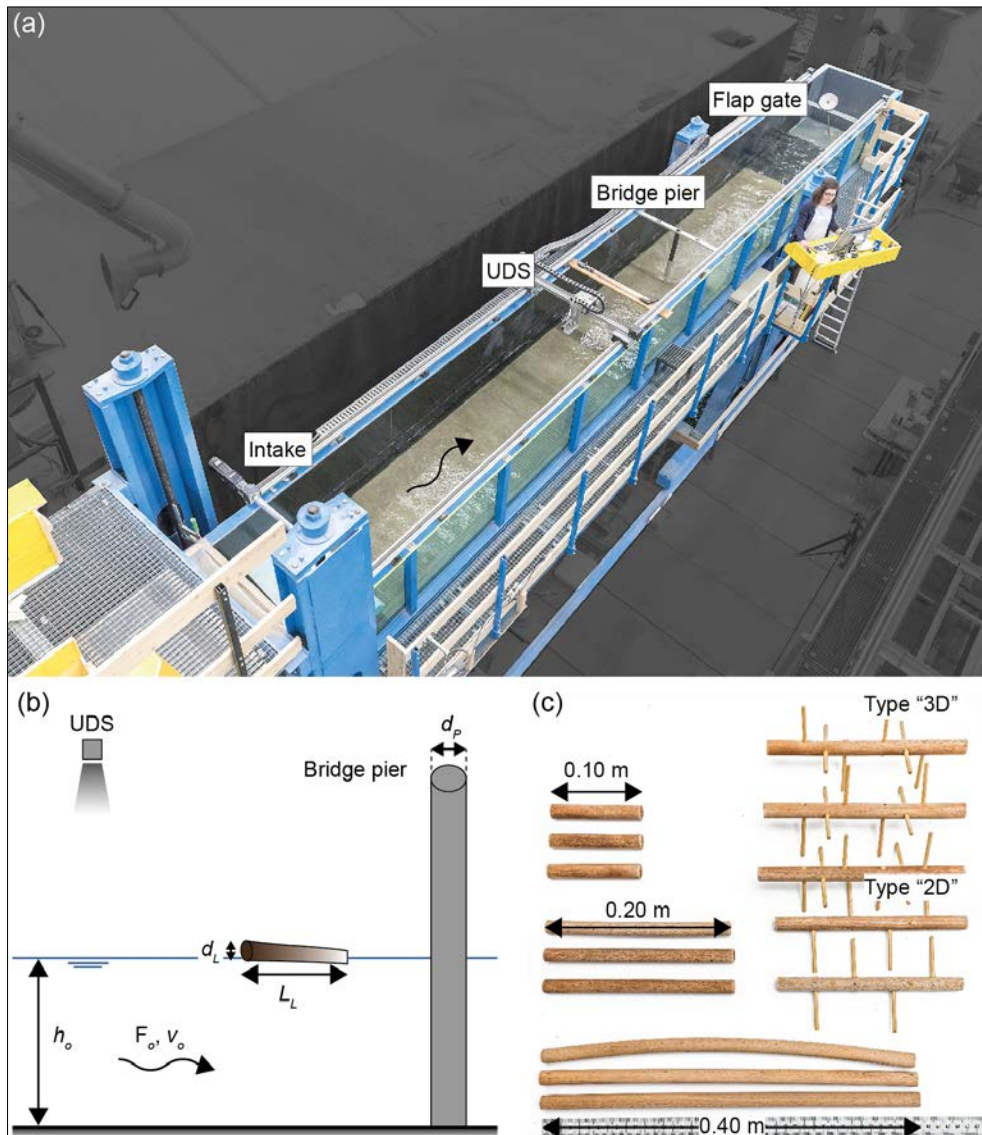


Figure 2. (a) VAW model flume, (b) experimental setup with notation, and (c) model LW.

5 EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Test repetitions and reproducibility

To obtain statistically significant results for the LW accumulation probability p , the required number of test repetitions N is essential. In previous studies, N was defined in a wide range ($N = 3 \dots 50$, Table 1), without quantifying the standard deviation σ of p . For the current study, the required N_{req} was investigated in test run

A1 (Table 2). A single log with $L_L = 0.20$ m was inserted into the flume $N = 300$ times for $F_o = 0.2$, $h_o = 0.15$ m, and $v_o = 0.24$ m/s. Figure 3a shows p_P and the corresponding σ as a function of N . The standard deviation σ increases to a maximum of $\sigma \approx 0.20$ for $N = 6$, and decreases to $\sigma = 0.05$ for $N = 300$. The accumulation probability p_P depends on the corresponding N and varied between 0% and 50%, converging to $p_P = 34\%$ for $N = 300$. To guarantee statistically significant results, a maximum standard deviation of $\sigma = 0.10$ was defined. This results in test repetitions of $N = 40$, which is just reasonable regarding test effort. Selected tests were repeated $N = 60$, if $\sigma \geq 0.10$ for $N = 40$. The test reproducibility was investigated with various L_L for four approach flow conditions (A2-A9). In Figure 3b, p_P is plotted as a function of N for tests A6-A7, and B26. All three tests converged to a final value $p_P \approx 25\%$ with $\sigma = 1\%$. Test reproducibility was consequently confirmed. Note that if N is selected to $N \leq 20$, a value used in previous studies, the accumulation probability would range between 0% and 67%.

Table 2. Test program.

Tests	Tested effect	F_o [-]	h_o [m]	v_o [m/s]	R [-]	L_L [m]	Type of LW (Fig. 2c)	N [-]	Pier type
A1	N_{req}	0.2	0.15	0.24	85,310	0.20	Regular (Reg.)	300	s
A2-3		0.2	0.05	0.14	19,830	0.10		40	
A4-5	Reproducibility	0.5	0.05	0.35	48,618	0.20	Reg.	40	s
A6-7		0.8	0.05	0.55	77,601	0.40			
A8-9		0.2	0.20	0.28	120,525	0.20			
B1-3			0.05	0.14	19,830	0.10, 0.20, 0.40		40	
B4-6		0.2	0.10	0.20	50,310	0.10, 0.20, 0.40		40	
B7-8	0.15		0.24	85,310	0.10, 0.20 ^{a)} , 0.40		40		
B9-11	0.20		0.28	120,525	0.10, 0.20, 0.40		40		
B12-14			0.05	0.35	48,618	0.10, 0.20, 0.40		40	
B15-17		0.5	0.10	0.48	125,543	0.10, 0.20, 0.40		40	
B18-20	Approach flow conditions and log lengths		0.15	0.60	211,826	0.10, 0.20, 0.40		40	
B21-23			0.20	0.69	302,745	0.10, 0.20, 0.40	Reg.	40	s
B24-26		0.05	0.55	77,601	0.10, 0.20, 0.40		40		
B27-29		0.8	0.10	0.80	200,541	0.10, 0.20, 0.40		40	
B30-32	0.15		0.96	339,991	0.10, 0.20, 0.40		40		
B33-35	0.20		1.10	302,745	0.10, 0.20, 0.40		40		
B36			0.05	0.84	116,519			40	
B37		1.2	0.10	1.19	300,566	0.20		40	
B38			0.15	1.46	512,364			20 ^{b)}	
C1			0.05	0.35	48,618			40	
C2	Pier roughness	0.5	0.10	0.48	125,543	0.20	Reg.	40	r
C3			0.15	0.60	211,826			40	
C4			0.20	0.69	302,745			40	
D1			0.05	0.35	48,618		2D	60	
D2-3	Branches	0.5	0.10	0.48	125,543	0.20	2D, 3D	60	s
D4-5			0.15	0.60	211,826			60	
D6-7			0.20	0.69	302,745			60	
E1-2			0.05	0.35	48,618		3xReg., 5xReg.	40	
E3-5	Congested LW transport	0.5	0.10	0.48	125,543	0.20	3xReg., 5xReg., 3x3D	40	s
E6-8			0.15	0.60	211,826			40	
E9-11			0.20	0.69	302,745			40	

Note: R = Reynolds number $\approx 19,800 \dots 512,400 > 10^4$,
 N_{req} = required repetitions,
s = smooth bridge pier,
r = rough bridge pier,
^{a)} ... corresponds to Test A1, and
^{b)} ... test run stopped after $N = 20$, as $p = 0\%$ for $N = 1 \dots 20$.

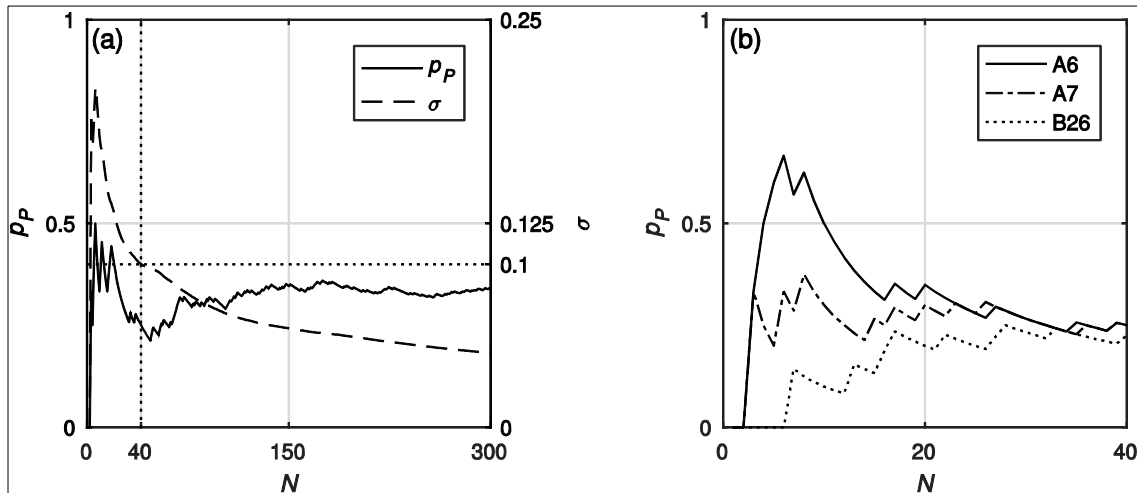


Figure 3. Test results of (a) p_P and σ as a function of N for test A1, (b) p_P as a function of N for reproducibility tests A6, A7, and B26.

5.2 Approach flow conditions and log length

Figure 4a shows p_P as a function of v_o for all tested L_L , and $F_o = 0.2 = \text{const.}$ (B1-B11, A1). The accumulation probability for $v_o = 0.14$ m/s was $p_P = 22\%$ ($L_L = 0.10$ m), 43% ($L_L = 0.20$ m), and 65% ($L_L = 0.40$ m), demonstrating a governing effect of the log length. A longer log is more probable to contact the bridge pier compared to shorter logs, resulting in higher p_P for increasing L_L (Figure 5).

For constant F_o , p_P was decreasing with increasing v_o for all tested L_L (Figure 4a). The tests B12-B38, corresponding to constant $F_o = 0.5, 0.8,$ and 1.2 , confirmed this trend. For small v_o , logs tended to accumulate as soon as any of their parts touch the bridge pier. In contrast, logs transported with high v_o may touch the bridge pier, but resolve due to the increased turbulence, waves, and impact force. Based on test series B, the LW accumulation probability is $p_P \leq 15\%$ for a threshold value of $v_o \geq 0.80$ m/s.

In Figure 4b, p_P is plotted versus h_o , for $L_L = 0.10$ m, 0.20 m, and 0.40 m, and $v_o \approx 0.30$ m/s (A1, B7-B14). The accumulation probability p_P was constant for various h_o . If logs are transported fully floating, they do not interact with the channel bottom. Hence, the effect of h_o on p_P is negligible for a given velocity and log length. As described above, a major effect of the log length on p_P is observed.

In summary, the accumulation probability increases with increasing log length and decreasing approach flow velocity, whereas no effect of the approach flow depth was observed. A constant approach flow Froude number resulted in a large range of accumulation probabilities for a given log length ($p_P = 20\% \dots 43\%$ for $L_L = 0.20$ m; Figure 4a). Consequently, no governing effect of the approach flow Froude number on the accumulation probability can be concluded, and the approach flow velocity must be used as the decisive parameter for the design equation (Section 5.4).

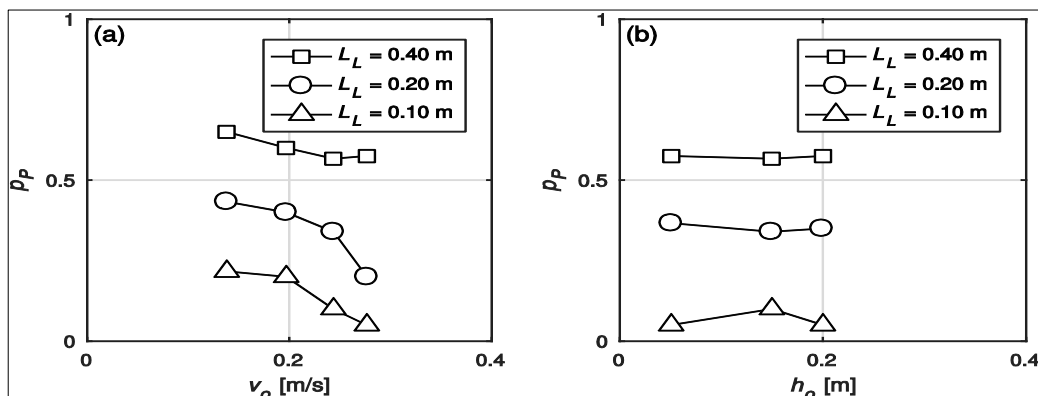


Figure 4. Accumulation probability p_P versus (a) v_o for various L_L with $F_o = 0.2 = \text{const.}$ (B1-B11, A1), and (b) h_o for various L_L with $v_o \approx 0.30$ m/s (A1, B7-B14).

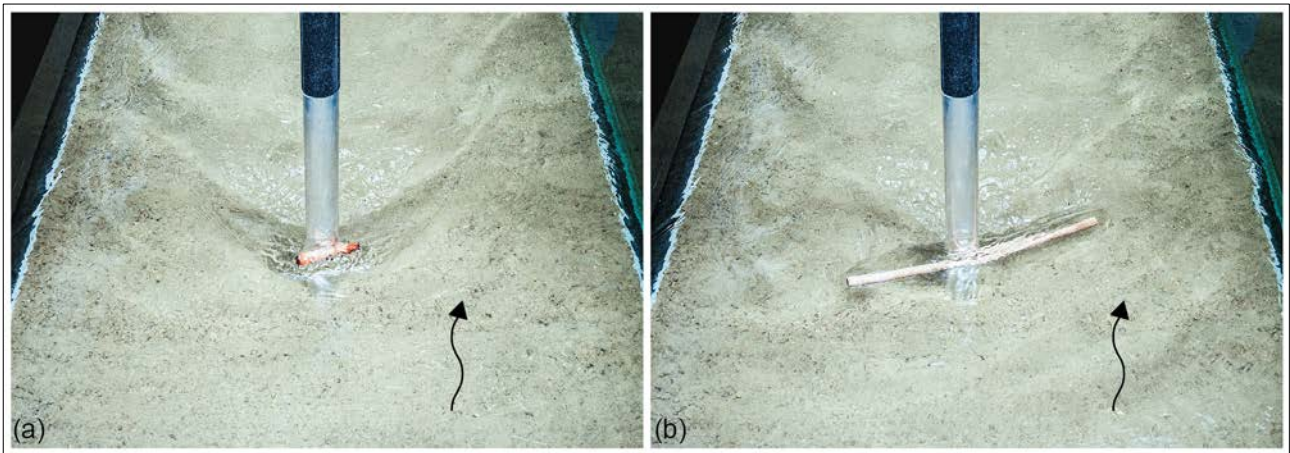


Figure 5. Plan view of LW accumulation with (a) $L_L = 0.10$ m (Test B18), and (b) $L_L = 0.40$ m (Test B20).

5.3 Bridge pier roughness and LW characteristics

In Figure 6a-c, p_P is plotted versus v_o for $L_L = 0.20$ m, and $F_o = 0.5 = \text{const}$. Similar to Figure 4a, p_P was decreasing with increasing v_o for constant F_o , and for all tested bridge pier and LW characteristics. Therefore, a governing effect of v_o on p_P can be deduced, whereas various p_P result for the same F_o .

The effect of a smooth versus a rough bridge pier on p_P is shown in Figure 6a (Test series B vs. C1-C4). For all tested v_o , p_P was slightly higher for the rough bridge pier. However, the difference between smooth and rough pier was 5...10%, and consequently within the range of test reproducibility. Therefore, the tested bridge pier roughness in the present model has no governing effect on p_P .

The influence of uncongested LW with and without branches on p_P is shown in Figure 6b. Regular logs are compared with the two log types with branches (2D and 3D; Test series B vs. D1-D7). No experiments with alternate branches of the type 3D were conducted for $v_o < 0.50$ m/s ($h_o < 0.10$ m), since the branches touched the channel bed and were not fully floating. For $v_o = 0.50 \dots 0.60$ m/s, p_P was 5% to 10% higher for LW with branches (2D and 3D) compared to regular logs, whereas p_P was 5% lower for $v_o = 0.35$ m/s. Again, the differences were within the range of test reproducibility. Similar to the findings of Lyn *et al.* (2003), the effect of branches on p_P is negligible for uncongested LW transport.

Figure 6c compares p_P of uncongested with congested LW transport for the addition of 3 or 5 regular logs, as well as for 3 logs with 3D branches (Test series B vs. E1-E11). For all v_o , p_P was 15% to 40% higher for congested LW transport compared to uncongested. Due to the branches, the interrelations between the single logs improve, leading to an increased stability of the accumulation body, as described in Section 2 (Figure 7). Therefore, the 3 logs with 3D branches result in the highest p_P for all v_o .

In summary, the accumulation probability increases with congested LW transport, whereas only a minor effect of the bridge pier roughness and LW branches for uncongested LW transport was observed.

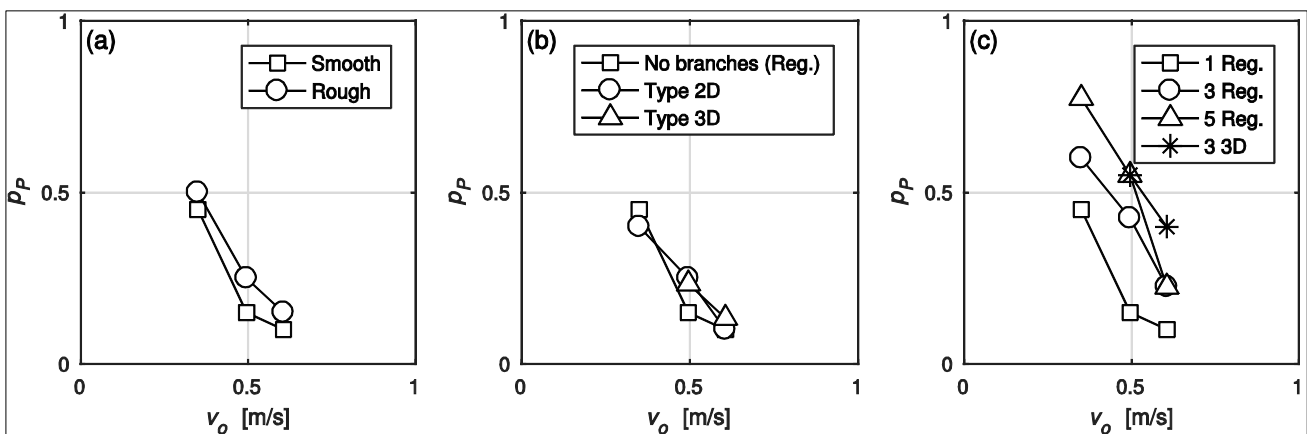


Figure 6. Accumulation probability p_P versus v_o , for (a) smooth versus rough bridge pier (Test series B vs. C1-C4), (b) logs with versus without branches (Test series B vs. D1-D7), and (c) uncongested versus congested LW transport (Test series B vs. E1-E11).



Figure 7. (a) Side view of LW accumulation with a rough bridge pier (Test C3), and (b) plan view of LW accumulation for congested logs with 3D branches (Test E8).

5.4 Normalized accumulation probability for uncongested LW transport

The two governing parameters for p_P of uncongested LW transport were identified as v_o and L_L , or the ratio d_P/L_L , respectively. In addition, these parameters were confirmed with a dimensional analysis. The p_P can therefore be described by the normalized LW accumulation probability parameter

$$LW_p = \left(\frac{v_o^2}{2gL_L} \right)^{0.60} \left(\frac{d_P}{L_L} \right)^{0.75} . \quad [1]$$

According to Eq. [1], L_L exhibits the largest effect on p_P , with an exponent of -1.35 , followed by v_o with an exponent of 1.20 . For the present test range (Test series A and B, Table 2), the LW accumulation probability for single logs at a single bridge pier can be described by the following relationship for $0 \leq LW_p \leq 0.45$ ($R^2 = 0.81$):

$$p_P = e^{-36 LW_p} . \quad [2]$$

Figure 8 shows p_P as a function of LW_p for uncongested LW transport, and Eq. [2]. The Root Mean Squared Error (RMSE) of Eq. [2] is 0.09. As the experimental setup represents a worst-case scenario for p_P (non-parallel log placement directly upstream of bridge pier), the application of Eq. [2] is considered a conservative estimation. The maximum accumulation probability $p_{P,max} = 65\%$ results for $v_o = 0.14$ m/s, $L_L = 0.40$ m, and $LW_p = 0.006$. For $v_o \geq 1.0$ and $LW_p \geq 0.125$, p_P tends to zero.

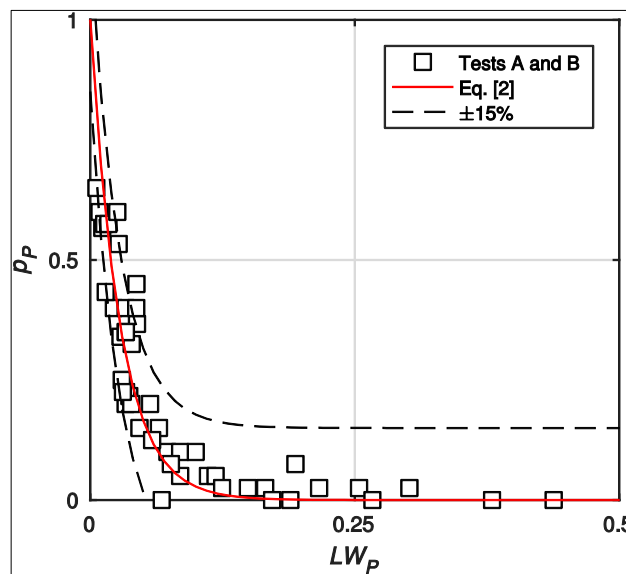


Figure 8. Normalized LW accumulation probability at a single bridge pier for Test series A and B, Eq. [2] (red line), and $\pm 15\%$ (--- line).

6 CONCLUSIONS

A series of flume experiments were conducted to evaluate the LW accumulation probability at a single bridge pier. The physical experiments involved flow conditions typical for flood events, various LW and bridge pier characteristics, and uncongested versus congested LW transport. As a first step, the required number of repetitions to obtain statistically significant accumulation probabilities was defined to $N \geq 40$. Test reproducibility was successfully demonstrated for various flow conditions.

The LW accumulation probability increased with increasing log length, decreasing approach flow velocity, and for congested LW transport. The approach flow Froude number and flow depth generally had a negligible effect on the accumulation probability. For uncongested LW transport, the bridge pier roughness and logs with branches indicated a minor effect on the accumulation probability. The results for uncongested LW transport were summarized in a novel design equation to estimate the accumulation probability at a single bridge pier. Hence, the results of this study are a first relevant step to improve the hazard evaluation of a catchment area. The estimation of the LW accumulation probability is essential for the identification of critical bridge cross-sections prior to a flood event. In addition, the physical experiments on LW accumulation probability with a single bridge pier can be useful to validate numerical models (e.g. Ruiz-Villanueva *et al.*, 2014). As a next step, experiments will be conducted to investigate the effect of multiple bridge piers and a moveable river bed on the LW accumulation probability.

7 OUTLOOK: FIELD TESTS

To validate the experimental results and to ensure their applicability under prototype conditions, field tests (subscript F) will be conducted in cooperation with the Zurich Office of Waste, Water, Energy, and Air (WWEA) in spring 2017. The objective is to compare the results of the field tests with the scale model tests on accumulation probability for uncongested LW transport at a single bridge pier. According to the hydrological estimations, adequate approach flow conditions are expected between April and May 2017. Based on the required cross-section and approach flow conditions, the River Glatt in Zurich, Switzerland, was selected as a suitable location (Figure 9). During these field tests, 60-80 logs with $L_L = 3 \dots 5$ m and $d_L = 0.15 \dots 0.20$ m will be added ≈ 20 m upstream of the circular bridge pier ($d_{P,F} \approx 1.0 \dots 1.5$ m) non-parallel to the flow. The approach flow conditions vary between $v_{F,max} \approx 1.3 \dots 1.5$ m/s, and $h_{F,max} \approx 1.0 \dots 1.5$ m. The surface flow field will be measured using airborne velocimetry. The logs will be removed from the river ≈ 250 m downstream of the bridge pier with an excavator. Given the limited numbers of investigations on LW accumulation probability at a bridge pier, these field tests are essential to improve the general process understanding. The field experiments will improve the current design equation and give insights on possible scale or model effects.



Figure 9. (a) Plan and (b) side view of the field test site at the River Glatt in Zurich (Switzerland) to study LW accumulation probability at a single bridge pier.

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