Risk reduction measures of large wood accumulations at bridges

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Received: 13 November 2018 / Accepted: 4 October 2019 / Published online: 19 October 2019
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Abstract
Bridges with and without piers are prone to large wood (LW) accumulations during floods, possibly resulting in an upstream backwater rise, local scour, or destabilization of the structure. To reduce the flood hazard, measures are required that decrease the accumulation probability $p$ of LW. This paper presents a literature review on existing measures to reduce $p$ at bridges. In addition, a series of flume experiments was conducted to examine structural measures at bridge piers regarding their accumulation risk reduction effect. The objective was to test the efficiency of (1) LW fins and (2) bottom sills including various configurations. The resulting $p$ was then compared to the setup without measures. The tested configurations of a LW fin did not decrease $p$. Bottom sills, in contrast, are a promising measure to reduce $p$ for a defined range of boundary conditions. The installed sills lead to enhanced turbulence and increased surface waves. The best results to reduce $p$ were obtained with two consecutive sills, leading to an average reduction of $p$ by 30%. In contrast to retaining LW with retention structures, LW can be safely guided downstream, thereby preserving its relevant ecological role in rivers. However, the efficiency of bottom sills strongly depends on the approach flow and the sediment transport conditions.

Keywords Accumulation probability · Flood protection measures · Flood risk assessment · Large wood (LW) · River engineering

1 Introduction

Previous floods in Alpine regions have demonstrated the hazardous impact of increasing large wood (LW) transport [11, 16, 25]. LW is thereby defined as logs with a diameter $\geq 0.1 \text{ m}$ and length $\geq 1 \text{ m}$ [9]. River infrastructures, in particular bridges, are prone to LW accumulations.
accumulations. Due to these LW accumulations, backwater rise and local scour increase, potentially leading to inundations or structural damages. To decrease the flood hazard due to LW transport, a thorough LW management concept is required. The Swiss approach to LW management is to convey LW downstream wherever possible and to retain LW only when necessary, thereby accounting for the trade-off between ecological benefit and natural hazard of LW. Retention racks or nets are a common method to retain LW [6, 13, 23]. However, the intended LW accumulation leads to backwater rise and possible local scour at the retention structure [20]. In contrast, measures that safely guide LW downstream may preserve the relevant ecological role of LW in rivers [29]. An example is a LW fin, with the objective to orient approaching logs parallel to the flow, thereby decreasing the accumulation probability (e.g. at the River Sihl in Zurich, Switzerland; Fig. 1). This study presents a literature review on measures at bridges to convey LW downstream (Sect. 2), with a special emphasis on bridge piers. The results of flume experiments on the efficiency of existing and new structural measures at bridge piers to reduce accumulation probability are presented in Sect. 4, including recommendations for the engineering application. This study was conducted in the frame of a doctorate at the Laboratory of Hydraulics, Hydrology, and Glaciology (VAW) [19] and is part of the interdisciplinary research project WoodFlow [15].

2 Literature review

In general, the risk of LW accumulations at river infrastructures can be mitigated using active or passive measures. Active measures are either maintenance works within the catchment area (i.e. forest maintenance, removal of deadwood, or bank erosion prevention) or structural measures such as retention structures and countermeasures to ensure the safe downstream conveyance of LW. Passive measures include organizational tasks such as early warning systems or evacuation plans, and strategic tasks including the designation of hazard zones and land use planning (Fig. 2). In addition, temporary measures are required during floods to remove LW using e.g. excavators. The two strategies of active
and passive measures are comparable to existing frameworks regarding flood protection in Switzerland [3]. In densely populated areas with a short warning time, passive measures are often no solution. This paper, therefore, focuses on active measures at bridges to convey LW downstream. An overview on measures at dam spillways is summarized in [17] including a hazard assessment diagram. The characteristics of LW retention structures are well documented in [6, 13, 14, 20, 23, 27].

The objective of structural measures for a safe downstream conveyance of LW is the prevention of LW accumulations. According to Bradley et al. [2] the following measures are suitable to enable or improve the downstream conveyance of LW:

- Rectifier—LW fin: A rectifier orients transported logs parallel to the flow direction (e.g. longitudinal alignment of LW). A LW fin is installed as an extension upstream of the bridge pier and has been installed at various Rivers in Switzerland (e.g. Figs. 1 and 3).
- Rectifier—LW deflector: A LW deflector has the same purpose as a LW fin and orients the transported logs parallel to the flow direction. It is located upstream of the river infrastructure. The shape of a deflector may differ between ‘V-shaped pointing against flow direction’ or ‘circular’ (i.e. a pole; Fig. 4a, [10, 12]). The efficiency of a rectifier and different shapes were tested at VAW for a case study at the bypass tunnel

### Large wood accumulation risk reduction measures

| Active | Passive |
|--------|---------|
| **Maintenance measures** | **Organizational measures** |
| - forest maintenance | - early warning systems |
| - removal of deadwood | - evacuation plans |
| - bank erosion prevention | |

| Structural measures | Strategic measures |
|---------------------|--------------------|
| - LW retention structures | - hazard zones |
| - LW downstream conveyance | - land use planning |

Fig. 2 LW accumulation risk reduction measures. (adapted from [10, 23])

Fig. 3 LW fin as a countermeasure to orient transported logs in flow direction, a side view and b plan view. (not drawn to scale; adapted from [2])
Campo Vallemagia ([10, 26], Fig. 5). A circular and V-shaped rectifier was positioned upstream of the bypass tunnel inlet. The results of the flume experiments showed that the rectifier loosens up the LW carpet (i.e. congested LW transport) and orients single logs (i.e. uncongested LW transport) in flow direction. The shape of the rectifier was of minor importance. Lyn et al. [12] investigated the efficiency of a vertical cylindrical deflector positioned $\approx 0.40$ m upstream of the bridge pier (Fig. 4a). The vertical cylindrical deflector reduced the accumulation probability at the bridge pier. However, logs were also retained at the deflector itself. Considering the accumulated logs at the deflector, accumulation probability amounted to 52% compared to only 22% without a deflector. Therefore, the deflector did not orient logs in flow direction, but rather induced an accumulation.

- Instream river training structures: These structures are placed on the channel bottom to alter the flow by inducing secondary currents so transported logs are not accumulated at the bridge pier. Common structures are micro groins (i.e. submerged sills), so-called Iowa vanes, spurs, or meandering ramps. Micro groins may cover the entire or partial river width and are placed inclined or declined to the flow direction. The various structures, their function, and applicability are summarized in Werdenberg et al. [28].

Fig. 4 Schematic view of countermeasures to reduce accumulation probability; a deflector and b submerged groin-like structure. (not drawn to scale; adapted from [12])

Fig. 5 LW deflector in front of the bypass tunnel Campo Vallemagia, Switzerland. (adapted from [10])
According to Lyn et al. [12], submerged groin-like structures decreased $p$ for selected flow conditions (Fig. 4b). The study was rather qualitative, though.

**Sweeper:** A sweeper consists of a polyethylene device mounted on a column and attached at the upstream side of the bridge pier. The vertical height of the sweeper is adjusted according to the current flow depth. The sweeper rotates due to the motion of water, thereby deflecting transported LW (Fig. 6a). It has been implemented in several US states. However, monitoring data on the efficiency of this structure is missing.

**Design features:** According to Bradley et al. [2], new river infrastructures should be designed to reduce the risk of LW accumulation, including:

- Sufficient dimensions of the freeboard (i.e. vertical distance between water surface level and bottom edge of bridge),
- Alignment of bridge piers to the flow direction and adequate spacing between two or more bridge piers to avoid LW accumulation, and
- Design of superstructure to prevent LW accumulation at the bridge deck.

Lange and Bezzola [10] summarized possible measures to ensure a safe downstream conveyance of LW at bridges. In general, the following recommendations were made to prevent LW accumulations at river infrastructures:

- **Cross-section dimensions:** The bridge width should be at least two times the expected log length.
- **Bridge dimensions:** The clearance height of the bridge (vertical distance between river bed and bridge bottom edge) should be at least 1.7 times the dimension of the expected rootstocks.

Furthermore, they differentiated between permanent and temporary measures. The characteristics of permanent measures are:

1. Sufficient river cross-section,
2. Smooth design of the bridge bottom and casings at the front, i.e. upstream side of the bridge (Fig. 7),

![Fig. 6](image_url)  
**Fig. 6** Active measures to enhance LW conveyance a double-stacked installation of a LW sweeper at the Mississippi River, USA (adapted from [2]), b movable bridge at the River Saltina in Brig, Switzerland (adapted from [10])
3. Prismatic design of river cross-section in the vicinity of the bridge (e.g. avoidance of jutting abutments), and
4. Longitudinal alignment of LW (compare Figs. 3, 4, 5).

Temporary measures include solutions during a flood such as LW removal using an excavator. Another possible measure is the installment of movable bridges. During a flood, the flow cross-section can be enlarged, thereby improving the downstream conveyance of LW. A movable bridge was installed in Switzerland (Canton Valais) after a flood in 1993 with extensive LW transport (Fig. 6b). The efficiency of this measure was proven during a flood in 2010 [10].

According to Schmocker and Hager [22], a baffle bridge (Fig. 8a) considerably favors LW passage without damage. The accumulation probability for rootstocks at a baffle bridge was almost halved compared to a truss bridge (Fig. 8b). Franzetti et al. [4] presented a protection structure for a bridge at the River Po in Italy. The bridge is characterized by two narrow parallel rows of piers. The measure consists of a plate mounted at the upstream side of the bridge piers and is built on pillars. The efficiency of the measure regarding bridge scour reduction was evaluated with model tests and extended by field observations after measure implementation. Quantitative results on the efficiency of the measure in prototype are missing, as the monitoring device to investigate the resulting scour with the measure is under development. The efficiency of this measure is unclear, as the additional piers are prone to increase the accumulation probability.

Measures to ensure the safe downstream conveyance of LW are necessary to reduce the accumulation risk at bridges, especially at cross-sections with piers. For the engineering application, robust and cost-effective measures are required. The presented measures above have been mainly tested for specific case-studies or have been implemented at river cross-sections with only minor monitoring. The actual reduction of the LW accumulation probability was rarely quantified. Based on the literature review, it can be hypothesized that LW rectifiers and the concept of instream river training structures may be best
suitable to convey LW downstream and reduce accumulation probability. Therefore, the efficiency of LW fins and bottom sills (similar concept as instream river training structures) was investigated using physical modeling to improve and evaluate the engineering application.

3 Methodology

The risk reduction of LW accumulations was examined for two types of structural measures: A = LW fin mounted upstream of the bridge pier and B = bottom sill mounted on the channel bottom. The test setup is illustrated in Fig. 9. The experiments were conducted for a selected range of approach flow conditions and LW characteristics with a model scale factor of $\lambda = 20$. Similar to the experiments on LW accumulation probability by Schalko et al. [21], a single circular bridge pier with a diameter $d_p = 0.05$ m was placed 5 m downstream of the channel inlet in the channel centerline. The logs were added perpendicular to the flow (log orientation angle to the flow $\gamma = 90^\circ$) 1 m upstream of the bridge pier to model the most-conservative accumulation probability [21]. Two types of LW transport were studied: uncongested (1 log) and semi-congested (3 logs at the same time). It was noted, whether or not the log accumulated at the bridge pier, and then the log was extracted from the flume. This procedure was repeated 40 times to obtain statistically significant accumulation probability with a reproducibility of $\pm 10\%$ [5, 18]. The accumulation probability was calculated as the sum of accumulated logs divided by the number of added logs. The resulting accumulation probabilities $p$ were then compared to those of the pier without structural measures (Reference tests ‘Ref’) presented in Schalko et al. [21].

The tilting channel at VAW is 10.7 m long, 1.0 m wide, and 0.8 m deep and has side walls made of glass and PVC. The 2.0 m long intake is equipped with a flow straightener to remove secondary currents generated by the pumps. The channel has a fixed bed (Manning’s roughness coefficient $n \approx 0.033$ $s/m^{1/3}$) and the channel slope can be varied between $0 \leq \theta_o \leq 15\%$. The downstream flow conditions are regulated with a flap gate.

The model flume is equipped with two pumps of a combined maximum discharge capacity of $Q = 265$ l/s and measured with an electromagnetic flow meter (IDM). The approach flow conditions (subscript $o$) are controlled by adapting $J_o$, $Q$, and the downstream flap gate and are characterized by $h_o$, $v_o = Q/(Bh_o)$, and $F_o = v_o/(gh_o)^{1/2}$, with $B$ = channel width, and $g = gravitational acceleration$. An Ultrasonic Distance Sensor (UDS) was placed on an automated traverse to measure $h_o$.

The two structural measures comprise nine different variations (A.1–A.6, B.1–B.3). Measure A is made of polyvinyl chloride (PVC). The PVC fin was 0.01 m wide and 0.20 m high. The experiments were conducted with two different vertical fin angles $\delta_1 = 45^\circ$
(measures A.1–A.4) and 20° (A.5–A.6), resulting in fin lengths of 0.20 m and 0.55 m, respectively. The horizontal fin angle, i.e., fin position to the flow, was varied between \( \delta_2 = 90^\circ \) (in flow direction; A.1, A.5–A.6) and \( \delta_2 = 60^\circ \) (A.2–A.4). For selected experiments, a Λ-shaped aluminum top (≈ 2 mm thick and 40 mm wide) was placed on the fin (Fig. 9a). The Λ-shaped aluminum top exhibited an angle of 150° for measure A.3 and 120° for measures A.4–A.5. The bottom sills are made of PVC, half-cylinder shaped, 0.50 m long and 0.015 m high (Fig. 9b). For measure B.1, two sills were placed as a V-shape pointing in flow direction (i.e., declined) on the channel bottom. Measure B.2 consists of one declined sill, whereas this setup was further adapted for measure B.3 consisting of two
consecutive declined sills with a distance of 0.20 m. For B.3, the distance of the first sill to the bridge pier $\Delta x$ was varied between $\Delta x = 0$ m, $0.15$ m, $0.30$ m. The test program is listed in Table 1, comprising 34 tests and 1840 added logs:

- The efficiency of measure A.1 was examined evaluating $p$ for various $F_o$, two $L_L$, and single versus semi-congested LW transport (M1–M12).
- The experiments with measures A.2–A.6 were conducted for selected $F_o$, $L_L$, and single LW transport (M13–M19).
- For the measures B.1–B.3, the tests were performed for three different $h_o$ with $F_o = 0.50$, $L_L = 0.40$ m, and single LW transport (M20–M34).
- The model tests with B.3 (M26–M34) further include the variation of $\Delta x = 0$ m, $0.15$ m, and $0.30$ m, whereas $\Delta x = 0.15$ m for tests M20–M25.

4 Results

The efficiency of two types of measures for LW accumulation risk reduction at bridge piers was investigated using physical modeling. The measures are A = LW fin mounted upstream of the bridge pier and B = bottom sill mounted on the channel bottom (Fig. 9; Sect. 3). The results are subsequently presented for the LW fin (Sect. 4.1) and the bottom sills (Sect. 4.2), including design recommendations and limitations.

4.1 Large wood fin

A photo series of LW fin configurations to reduce LW accumulation probability $p$ at a bridge pier is illustrated in Fig. 11.

The LW fin was placed against flow direction with a horizontal fin angle $\delta_2 = 90^\circ$ (Fig. 11a, e, f), or with $\delta_2 = 60^\circ$ (Fig. 11b–d). In addition, the vertical fin angle $\delta_1$ varied between $\delta_1 = 45^\circ$ (Fig. 11a–d) and $\delta_1 = 20^\circ$ (Fig. 11e, f). It was hypothesized that transported logs may hit the LW fin, but disperse due to the sharp edges of the LW fin and the small width in comparison to the bridge pier. Due to the LW fin geometry, an accumulated log is more unstable, leading to a decreased $p$. The variation of $\delta_2$ and the $\Lambda$-shaped aluminum top should further foster the imbalance of an accumulated log, so logs are guided
on the sides of the bridge pier. The added blue ink illustrates how the flow is diverted for \( \delta_2 = 60^\circ \) (Fig. 11b and d) compared to \( \delta_2 = 90^\circ \) (Fig. 11a). In the following, \( p \) is compared to the setup without measures, i.e Ref Schalko et al. [21].

The results of \( p \) with measure A.1 (Table 1 and Fig. 9) versus reference tests without measures (i.e. Ref [21]) are depicted in Fig. 12 for \( L_L = 0.20 \) m, \( L_L = 0.40 \) m, uncongested, and semi-congested LW transport. For uncongested LW transport (Fig. 12a, b), \( p \) only deviates for \( v_o = 0.50 \) m/s, in which \( p \) increases for \( L_L = 0.20 \) m from 16% for the reference test

Table 1 Test program for measure A.1–A.6 and B.1–B.3 on LW accumulation risk reduction with \( d_L = 0.015 \) m and \( N = 40 \)

| Test | Type | \( \delta_1 \) [°] | \( \delta_2 \) [°] | \( \Lambda \)-top | \( \Delta x \) [m] | \( F_o \) [-] | \( h_o \) [m] | \( v_o \) [m/s] | \( L_L \) [m] | #LW |
|------|------|------------------|------------------|----------------|----------------|-------------|-------------|-------------|-------------|------|
| M1   | A.1  | 45               | 90               | No             | –              | 0.20        | 0.10        | 0.20        | 0.20        | 1    |
| M2   |      |                  |                  |                |                |             |             |             |             |      |
| M3   |      | 0.50             | 0.10             | 0.50           | 0.20          |             |             |             |             | 0.40 |
| M4   |      |                  |                  |                | 0.20          |             |             |             |             |      |
| M5   |      | 0.80             | 0.10             | 0.79           | 0.20          |             |             |             |             | 0.40 |
| M6   |      |                  |                  |                | 0.20          |             |             |             |             |      |
| M7   |      | 0.20             | 0.10             | 0.20           | 0.20          |             |             |             |             | 3    |
| M8   |      |                  |                  |                | 0.20          |             |             |             |             | 0.40 |
| M9   |      | 0.50             | 0.10             | 0.50           | 0.20          |             |             |             |             |      |
| M10  |      |                  |                  |                | 0.20          |             |             |             |             | 0.40 |
| M11  |      | 0.80             | 0.10             | 0.79           | 0.20          |             |             |             |             |      |
| M12  |      |                  |                  |                | 0.20          |             |             |             |             | 0.40 |
| M13  | A.2  | 45               | 60               | No             | –              | 0.20        | 0.10        | 0.20        | 0.20        | 1    |
| M14  |      |                  |                  |                | 0.20          |             |             |             |             | 0.40 |
| M15  | A.3  | 45               | 60               | Yes            | –              | 0.20        | 0.10        | 0.20        | 0.20        | 0.50 |
| M16  | A.4  | 45               | 60               | Yes            | –              | 0.20        | 0.10        | 0.20        | 0.20        | 0.50 |
| M17  |      |                  |                  |                | 0.20          |             |             |             |             | 0.40 |
| M18  | A.5  | 20               | 90               | Yes            | –              | 0.50        | 0.10        | 0.50        | 0.50        | 0.40 |
| M19  | A.6  | 20               | 90               | No             | –              | 0.50        | 0.10        | 0.50        | 0.50        | 0.40 |
| M20  | B.1  | –                | –                | –              | 0.15          | 0.71        | 0.05        | 0.50        | 0.40        | 1    |
| M21  |      |                  |                  |                | 0.50          |             |             |             |             | 0.40 |
| M22  |      | 0.36             | 0.20             |               |               |             |             |             |             |      |
| M23  | B.2  | –                | –                | –              | 0.15          | 0.71        | 0.05        | 0.50        | 0.40        | 0.36 |
| M24  |      |                  |                  |                | 0.50          |             |             |             |             |      |
| M25  |      | 0.36             | 0.20             |               |               |             |             |             |             |      |
| M26  | B.3  | –                | –                | –              | 0.00          | 0.71        | 0.05        | 0.50        | 0.40        | 0.36 |
| M27  |      |                  |                  |                | 0.50          |             |             |             |             |      |
| M28  |      | 0.36             | 0.20             |               |               |             |             |             |             |      |
| M29  | B.3  | –                | –                | –              | 0.15          | 0.71        | 0.05        | 0.50        | 0.40        | 0.36 |
| M30  |      |                  |                  |                | 0.50          |             |             |             |             |      |
| M31  |      | 0.36             | 0.20             |               |               |             |             |             |             |      |
| M32  | B.3  | –                | –                | –              | 0.30          | 0.71        | 0.05        | 0.50        | 0.40        | 0.36 |
| M33  |      |                  |                  |                | 0.50          |             |             |             |             |      |
| M34  |      | 0.36             | 0.20             |               |               |             |             |             |             |      |
to 33% for measure A.1. In contrast, $p$ decreases for $L_L = 0.40$ m from 53% for the reference test to 35% for measure A.1. However, for uncongested LW transport, the mean difference in $p$ between A.1 and the reference test is 8.3%, and consequently within the range of test reproducibility ($\pm 10\%$). For semi-congested LW transport (Fig. 12c, d), the mean difference in $p$ is higher with 14.6%. Given $v_o = 0.50$ m/s, $p$ increases for $L_L = 0.20$ m from 43% for the reference test to 63% for measure A.1, while $p$ decreases for $L_L = 0.40$ m from 67% for the reference test to 43% for measure A.1. As no systematic trend can be determined, it can be deduced that measure A.1 has no governing effect on $p$. In contrast to the hypothesis, logs accumulated at the LW fin similarly to the bridge pier.

In Fig. 13, $p$ is plotted as a function of $v_o$ for measures A.2–A.6 (Table 1 and Fig. 9) versus reference tests for selected approach flow conditions, $L_L$, and uncongested LW transport. For measures A.2 and A.3 (Fig. 13a), $p$ is similar to the reference test for $v_o = 0.20$ m/s and $L_L = 0.20$ m ($p$ deviates by 2.5%). For $v_o = 0.50$ m/s, $L_L = 0.40$ m, and measure A.2, $p$ is $\approx 8\%$ lower compared to the reference test. As the deviations are within the reproducibility range, no governing effect can be concluded. Based on the model tests, neither the variation of $\delta_2$, nor a $\Lambda$-shaped aluminum top lead to a
significant reduction of $p$. This supports the findings by [21] that the pier, i.e. fin shape is of minor importance to reduce $p$.

The Λ-shaped aluminum top was adapted to be sharper for measure A.4 and tested for $v_o = 0.20–0.50$ m/s and $L_L = 0.40$ m. According to Fig. 13b, $p$ decreases by $\approx 13\%$ for $v_o = 0.50$ m/s, but is similar for $v_o = 0.20$ m/s, resulting in an average deviation of only 6%. The effect of $\delta_i$ (measures A.5 and A.6), i.e. a longer LW fin, on $p$ is also illustrated in Fig. 13b. The resulting $p$ are higher or equal with A.5 and A.6 compared to the reference tests. Therefore, the variation of $\delta_i$ does not reduce $p$.
In summary, the various LW fin configurations (geometry, orientation, Λ-shaped aluminum top) did not significantly affect the stability of accumulated logs and contradicted the proposed hypothesis. The accumulation probability could not be decreased. According to Lyn et al. [12], a vertical cylindrical deflector reduced \( p \) (Fig. 4a), but logs were still retained at the deflector itself. However, LW retention at a LW fin or deflector may reduce the impact force of accumulated logs acting on a bridge pier. Furthermore, it can prevent structural damages of the bridge pier by reducing scour.

Possible scale effects may exist due to the roughness of the LW fin as well as the Λ-shaped aluminum top in model compared to prototype. A Λ-shaped aluminum top in prototype may be smooth enough for logs to be guided on the sides of the bridge pier. According to [21], a smoother pier decreases \( p \), as the friction between pier and log is smaller due to the smaller roughness coefficient between wood and aluminum compared to wood and concrete (\( \eta = 0.6 \) for aluminum compared to \( \eta = 0.9 \) for concrete [24]). Rootstocks may also affect the resulting accumulation probability. However, the efficiency of a LW fin to guide rootstocks downstream was not part of the present study.

4.2 Bottom sills

The bottom sill configurations are illustrated in Figs. 9b and 14. The different setups are listed in Table 1 (Sect. 3) and include a cross-sill (B.1; Fig. 14a), single and double declined sills (B.2 and B.3; Fig. 14b–f). For the double declined sills (B.3), the distance \( \Delta x \) between sill and pier was varied to \( \Delta x = 0 \) m, \( \Delta x = 0.15 \) m, and \( \Delta x = 0.30 \) m (Figs. 14 and 15). Due to the bottom sills, the flow around the pier may become more turbulent and surface waves increase. These flow conditions lead to a more unstable accumulated log (e.g. moving or tilting log), thereby reducing accumulation probability. In addition, similar to the concept of “instream river training structures” (Sect. 2), the bottom sills are supposed to alter the flow by inducing secondary currents so transported logs do not accumulate at the pier. Based on our model test observations, the flow is diverted normal to the bottom sill, so depending on the position of the bottom sill, logs may turn and are then guided at the side of the pier. In Fig. 14c, dye was added to visualize the flow, indicating a prominent flow alteration due to the declined bottom sill. In Fig. 15a, prominent surface waves can be observed downstream of the bottom sills compared to a rather smooth water
Fig. 14 Measures for LW accumulation risk reduction with $h_o = 0.10$ m, $v_o = 0.50$ m/s for (a) B.1, (b) B.2, (d) B.3 with $\Delta x = 0$ m, (e) B.3 with $\Delta x = 0.15$ m, (f) B.3 with $\Delta x = 0.30$ m, and for (c) B.2 with $h_o = 0.20$ m, $v_o = 0.50$ m/s.

Fig. 15 Measure B.3 with $\Delta x = 0.30$ m, $v_o = 0.50$ m/s, (a) $h_o = 0.05$ m and (b) $h_o = 0.20$ m.
surface in Fig. 15b. Our observations of the flow field indicate that the prominence of surface waves may depend on $h_o$ for a given sill height and flow velocity.

The accumulation probability $p$ is plotted in Fig. 16 as a function of $F_o$ for $v_o = 0.50 \text{ m/s}$ and $L_L = 0.40 \text{ m}$ with measures B.1–B.3 versus a reference test [21]. Note that the dashed line represents $p$ versus $F_o$ based on the findings by [21], i.e. $p$ at a cylindrical bridge pier without any measures. Accumulation probability $p$ is similar for a wide range of $F_o$ and a constant $v_o$. Given $p_{\text{Ref}} = 53\%$ for $F_o = 0.20–0.70$, accumulation probability decreases due to B.1 by 8.3%–25.8% with an average decrease of 16.6% (Fig. 16a). For B.2, $p$ decreases in a similar range (3.3%–23.3%) with an average reduction of 12.5% (Fig. 16a). Both measures indicate the largest reduction of $p$ for $F_o = 0.71$, corresponding to $h_o = 0.05 \text{ m}$. For measure B.3 (Figs. 15 and 16b), the effect of various distances to the bridge pier $\Delta x$ on $p$ was tested. On average, $p$ decreases by 17.5% for $\Delta x = 0.00 \text{ m}$, by 20.3% for $\Delta x = 0.15 \text{ m}$, and by 29.1% for $\Delta x = 0.30 \text{ m}$. The average decrease in $p$ due to measures B.3 is higher than the reproducibility range ($\pm 10\%$). The best results to reduce $p$ were obtained with B.3 and $\Delta x = 0.30 \text{ m}$. Given $\Delta x = 0.30 \text{ m}$ and $F_o = 0.50 (h_o = 0.10 \text{ m};$ Fig. 14f), $p = 10\%$ compared to $p_{\text{Ref}} = 53\%$. According to Fig. 16, the efficiency of bottom sills strongly depends on $F_o$ and $h_o$, respectively. The efficiency further tends to increase with increasing $F_o$ and $\Delta x$ or decreasing ratio of sill height (subscript $S$) to flow depth $h_S / h_o (h_S / h_o = 13.3$ for $h_o = 0.20 \text{ m}, h_S / h_o = 6.6$ for $h_s = 0.10 \text{ m},$ and $h_S / h_o = 3.3$ for $h_o = 0.05 \text{ m}$).

Bottom sills are consequently a promising measure to reduce $p$. The efficiency of this measure can be described by two governing effects:

1. Increased turbulence: The installed sills lead to increased turbulence in the vicinity of the bridge pier. Depending on the sill position with respect to the bridge pier (i.e. $\Delta x$), increased turbulence occurs right in front of the bridge pier (Fig. 15b). The flow velocity fluctuations can lead to varying hydraulic forces acting on the log. These variations cause a rotating movement of the log and log detachment. Accumulated logs become unstable and disperse faster compared to flow conditions without a bottom sill.

2. Flow diversion: The slightly shifted arrangement of the sills compared to the pier centerline diverts the flow normal to the sill, generating a transversal flow component (Fig. 14c). Therefore, approaching logs are rotated normal to the bottom sill, i.e. parallel to the flow, which reduces accumulation probability $p$ by a factor of $\approx 6$ [21]. However, depending on the initial log orientation, logs may orient normal to the flow and accumulate at the pier.

![Fig. 16](image-url) Accumulation probability $p$ versus $F_o$ for $v_o = 0.50 \text{ m/s}$ and $L_L = 0.40 \text{ m}$ with a Ref [21] versus B.1–B.2 (M20–M25), and B Ref [21] versus B.3 (M26–M34); note that - - - is $p$ as a function of $F_o$ according to [21]
In contrast to a LW fin, $p$ decreases due to the bottom sills. The presented experiments demonstrate that bottom sills exhibit the required mechanisms for a robust and efficient countermeasure to decrease $p$. As the efficiency of bottom sills depends on the approach flow conditions, the design has to be determined for a respective river topography and designated flow conditions. The flume experiments were conducted with a fixed bed, thereby neglecting the effect of a movable bed. Scour or deposition changes the sill geometry and consequently affects the wood diversion efficiency. The sill can further have a negative effect on the pier stability as the increased turbulence may lead to larger scour depths. Moreover, the construction of a fixed sill in the middle of the river in prototype may pose several challenges. Therefore, similar to “instream river training structures” (Sect. 2), bottom sills should be implemented at a test reach to evaluate the efficiency in prototype.

## 5 Conclusions and outlook

The objective of this study was to examine and evaluate existing and new structural measures at bridges regarding their accumulation risk reduction effect. A series of flume experiments was conducted focusing on the efficiency of a LW fin and bottom sills upstream of bridge piers. The resulting accumulation probability $p$ was then compared to the setup without measures [21]. The findings can be summarized as follows:

- According to the literature review, casings or movable bridges are a practical measure to decrease accumulation probability $p$ at bridge decks.
- The cross-section and bridge dimensions (e.g. freeboard, bridge clearance height, bridge width) should be designed based on the expected LW dimensions.
- The accumulation probability $p$ at a cross-section with a pier can be reduced by increasing the axial spacing between piers.
- The tested configurations of a LW fin did not decrease accumulation probability $p$. For selected approach flow conditions, a LW fin may even increase accumulation probability $p$ at the bridge pier. Based on the tested parameter range, LW fins cannot be recommended as an efficient measure to reduce accumulation probability $p$. However, LW fins avoid direct impact of logs at the pier.
- Experiments with bottom sills showed a general influence on turbulence and surface waves. They are a promising measure to reduce accumulation probability $p$ for a defined range of boundary conditions. The best results to reduce LW accumulation probability $p$ were obtained with two consecutive sills (measure B.3), leading to an average reduction of accumulation probability $p$ by 30%. The efficiency of bottom sills strongly depends on the approach flow conditions ($F_o$ and $h_o$) and distance to the bridge pier.

During extreme floods with high LW transport, LW may still accumulate despite measures that are supposed to ensure the safe downstream guidance of LW. Therefore, a combined approach of LW downstream conveyance measures and LW retention structures are required to enable a robust and efficient LW management.

To further improve the effectiveness of bottom sills, additional experiments with a movable bed, thereby quantifying the effect of scour and deposition, are deemed necessary. In addition, a combined approach of hydraulic and numerical modeling as well as field tests improves the process understanding of LW accumulations and flood risk assessment in order to derive reliable measures.
Acknowledgements

The first author is financially supported by the Swiss Federal Office for the Environment (FOEN) within the WoodFlow project, grant 15.0018.PJ / O192-0202.

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