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Drift accumulation at river bridges

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ABSTRACT: Drift seriously increases the destructive power of a flood event. Drift accumulations and blockages at river bridges are a widespread problem leading eventually to total bridge failure. Limited knowledge is currently available on drift blocking processes during flood events. The main purpose of this experimental study was to analyze driftwood blocking at a bridge deck depending on the: (1) drift dimensions; (2) freeboard below bridge deck; (3) flow characteristics; and (4) bridge design. The model tests included the accumulation of both single logs and single rootstocks at bridge decks. The test flow conditions represent a major flood event, with the freeboard tending to zero and the drift is able to touch the bridge deck. A total of four bridge types without piles were investigated, namely the reference bridge consisting only of the bridge roadway, a truss bridge, a railing bridge, and a baffle bridge. The results indicate the significant effects of freeboard, the approach flow Froude number and the bridge design on the drift accumulation process.

Keywords: Bridge failure; Drift accumulation; Flood; Hydraulic modeling; Risk management

1 INTRODUCTION

In the present work, drift is defined as any type of wood laying or floating in a river. Other terms used in the literature are e.g. driftwood, floating debris or Large Woody Debris (LWD).

1.1 *Drift supply*

Drift is part of each river and most drift is wood from the river vicinity. Trees fall into the rivers due to age, wind and side erosion (Keller and Swanson 1979, Diehl and Bryan 1993). Especially in steep mountain areas, landslides, debris flows and avalanches can transport large amount of drift (Bezzola and Hegg 2008). During periods of low discharge, the drift is mostly stable and exhibits no actual danger. In contrast, drift influences a number of geomorphic and biological processes of a fluvial system (Shields and Gippel 1995, Gurnell et al. 1995, Stewart and Martin 2005, Andreoli et al. 2007). Drift provides valuable habitats for a wide range of both flora and fauna, offers shelter for fish, increases the hydraulic roughness of the river and effectively traps and stores sediments (Young 1991, Gippel 2005).

1.2 *Drift entrainment and transport*

Especially during flood events, drift is entrained in a river and transported downstream due to increasing discharges and flow depths. The drift initiation has been investigated by e.g. Braudrick and Grant (2000, 2001), Bocchiola et al. (2006a). and Haga et al. (2002). Log entrainment is primarily a function of the log angle relative to the flow direction, log density, the log diameter, the presence/absence of rootstocks and both the flow depth and flow velocity. Logs longer than the bankfull width tend to be stable and are removed only during large flood events. Once the drift is transported, three distinct wood transport regimes were observed, namely uncongested, congested and semi-congested (Braudrick and Grant 2001). The transport distance of drift depends mainly on the channel cross-section and the presence of obstacles (Bocchiola et al. 2006b). For mountain rivers wider than the tree height, wood can be transported over long distances and therefore reach populated areas and lead to major problems.

1.3 *Drift deposition*

Transported drift either deposits due to insufficient stream power or accumulates at obstacles and narrow cross-sections (Lang and Bezzola 2006). At decreasing flow depths, drift is deposited in shallow water zones, on banks and at the river shore (Gurnell et al. 2000a,b, Braudrick and Grant 2001). The accumulation of drift in the river itself, e.g. at large boulders, was investigated by Faustini and Jones (2003), Bocchiola et al. (2008) and Manners and Doyle (2008). They observed that the accumulation probability of drift increases with its length and decreases with the Froude number. An accumulation is more likely if bridging against two obstacles occurs.

Of special interest for this study is the drift accumulation at river bridges or weirs (Fig. 1). Especially during flood events, transported wood dramatically increases the destructive power of floods and seriously endangers bridges. Drift accumulations at bridges reduce or even jam the entire river cross-section. Most observed drift accumulations fall into two classes, namely: single-pier accumulation and span blockages (Diehl 1997). Given the high flow depths during flood events, drift can further get blocked at the bridge deck itself. All accumulations may result in an increase of the upstream water level and flooding of nearby infrastructure. Blocking of a cross-section can decrease the sediment transport thereby increasing backwater in addition. Drift impact on bridges can seriously damage the structure or even lead to a total failure. Further, due to increased flow velocities and turbulence in the bridge vicinity, drift accumulations contribute to scour (Melville and Dongol 1992). An overview on drift-related problems is found in Diehl (1997), Bradley et al. (2005) and Lang and Bezzola (2005).

The evaluation of about 100 bridges subjected to drift-related damage during the 2005 flood event in Switzerland indicated that both bridge design and river morphology have a major effect on the drift accumulation risk (VAW 2008). Exposed structural elements like trusses, railings or supply cables, and pipes under bridges increase the risk of drift accumulation considerably. ‘Smooth’ bridge designs and adequate river morphology often assure the safe passage of transported drift. Therefore, systematic drift blockage test were conducted at the *Laboratory of Hydraulics, Hydrology and Glaciology* VAW, Swiss Federal Institute of Technology ETH, Zurich. The tested flow conditions represent a major flood event, e.g. a 100-year flood or higher, as the freeboard tends to zero and interaction between drift and the bridge deck is possible.

Figure 1. Drift accumulation at (a) railway bridge in Sarnen and (b) weir Perlen in Lucerne, during 2005 flood event in Switzerland, flow direction from left to right

2 EXPERIMENTAL SETUP

2.1 *Model channel*

The hydraulic experiments were conducted in the rectangular VAW river engineering channel. The channel is 13 m long, 0.60 m wide, 0.60 m high and has a discharge capacity of $Q = 150$ l/s. The channel is considered hydraulic smooth and a flow straightener at its intake generated undisturbed inflow. Various flow conditions can be established by varying both the approach flow discharge Q and the channel bottom slope S_o. The approach flow depth h was measured using an ultrasonic level sensor of ±1 mm accuracy.

The model bridges were mounted at a height of $H = 0.15$ m above the channel bottom and 8.30 m from the intake. The bridge deck was 0.60 m long, 0.10 m wide and 0.010 m thick. Four bridge types were investigated, namely the reference bridge consisting only of the bridge deck, a truss bridge, a railing bridge and a baffle bridge (Fig. 2). Both the railing and the truss bridges were mounted on the reference bridge, the baffle of radius 0.002 m was attached to the upstream bridge face.

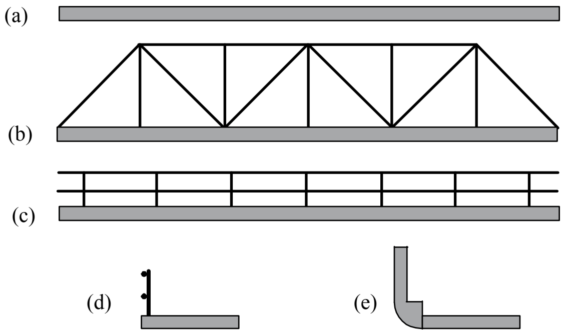

Figure 2. Investigated bridge types: Frontal view of (a) reference bridge, (b) truss bridge, (c) railing bridge and cross-sections of (d) railing bridge and (e) baffle bridge

As no interaction between the drift and the channel bottom occurred in the approach flow section, it was assumed that the drift moves with the flow velocity. The hydraulics of drift flow below the bridges may therefore be characterized by the approach flow Froude number $\mathsf{F} = V/(gh)^{1/2}$, with h = flow depth, $V = Q/(Bh)$ = approach flow velocity, Q = approach flow discharge, B = channel width or bridge length and g = acceleration of gravity (Fig. 3). Eleven different flow conditions were tested, involving three values of the relative approach flow depth h/H = 0.90, 1.00 and 1.07 and four of F = 0.3, 0.5, 0.8, 1.2. For $h/H = 1$, the water surface just reaches the lower bridge deck, for h/H = 1.07 the water surface is at the upper bridge deck. For F = 1.2 the relative approach flow depths of h/H = 1.0 and 1.07 could not be tested, as the bridge generated a backwater rise leading to transitional flow. A relative approach flow depth of h/H = 0.93 was therefore tested additionally for F = 1.2. All eleven flow conditions were tested for each of the four bridge types.

2.2 *Model drift*

Five different logs and eight different rootstocks were used as model drift. The logs (subscript L) were natural without branches and varied in length L between $(1/4)B$ = 0.15 m and $1.5B$ = 0.90 m and in diameter D_L between 0.015 and 0.02 m (Fig. 4). Both real and artificial rootstocks were used. The imitations consisted of a round disc or two crossed bars representing the rootstock and an attached dowel representing the log. The rootstock (subscript R) dimensions involved maximum (subscript M) D_{RM} and minimum (subscript m) D_{Rm} rootstock diameters, and length L of the attached log (Fig. 4). The maximum rootstock diameter ranged from 0.12 to 0.22 m and was therefore of the same order as the bridge clearance H = 0.15 m. The stability of the model drift is not properly scaled in the experiments. If drift accumulates at bridges during a flood event, it can break into smaller pieces due to increased dynamic forces. A drift blockage can therefore appear and break again without causing major damage. This was not observed during the present tests as the stability of the model drift was too large.

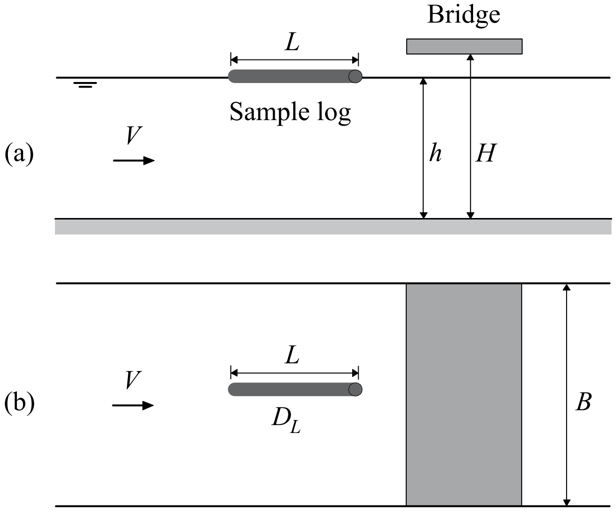

Figure 3. Experimental setup: (a) side view (b) plan, notation

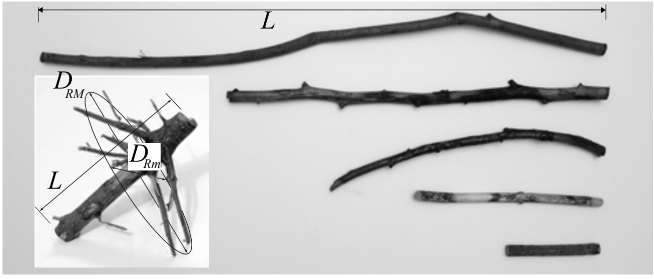

Figure 4. Examples of logs and rootstock used, notation

2.3 *Test procedure*

Channel flow conditions were established first. Each test was carried out by adding a single piece of drift to the approach flow, 5 m upstream of the model bridge. The drift either passed the bridge or got stuck and was then removed before the next test. The logs were added randomly, but aligned themselves immediately in flow direction. The rootstocks were added with the attached log ahead. The tested drift was initially dry and therefore floated entirely on the water without contact to the channel bottom. The drift was not dried between a test series, given the short test duration of only some minutes.

Each test involving a certain single drift piece and bridge type at a certain relative flow depth and F was repeated 8 times. From preliminary observations this was found to be about the smallest repetition number for statistically relevant results. Combining 11 flow conditions, 4 bridge types and 13 wood types, with 8 repetitions for each wood type, resulted in a total of 4,576 individual tests.

3 OBSRVATIONS AND RESULTS

3.1 *Bridge choking*

Drift accumulation at the model bridge had a major effect on the flow characteristics, similar to sediment aggregation (Diehl 1997). A stuck model drift resulted in a reduction of cross-sectional area and therefore led to a backwater rise, especially for rootstocks combined with supercritical approach flow. Figure 5 shows a series of a rootstock blocking test with $h/H = 0.90$ and $\mathsf{F} = 1.2$ for the railing bridge. The natural rootstock is blocked in the railing (Fig. 5a), leading to a hydraulic jump upstream of the bridge (Fig. 5b). The hydraulic jump moves upstream and the originally supercritical flow breaks down. Note that the rootstock in Fig. 5 is fairly large as compared to the bridge. Normally several pieces of drift are required, e.g. a drift cluster, until a rise in the upstream flow level occurs. Bridge chocking was never observed for single logs, given the small reduction of cross-section below the bridge. However, once a single log is blocked the risk of additional drift accumulation and backwater rise increases significantly. Observations during recent flood events indicate that the backwater rise is a frequent problem leading to overtopping of the upstream river levees (VAW 2008).

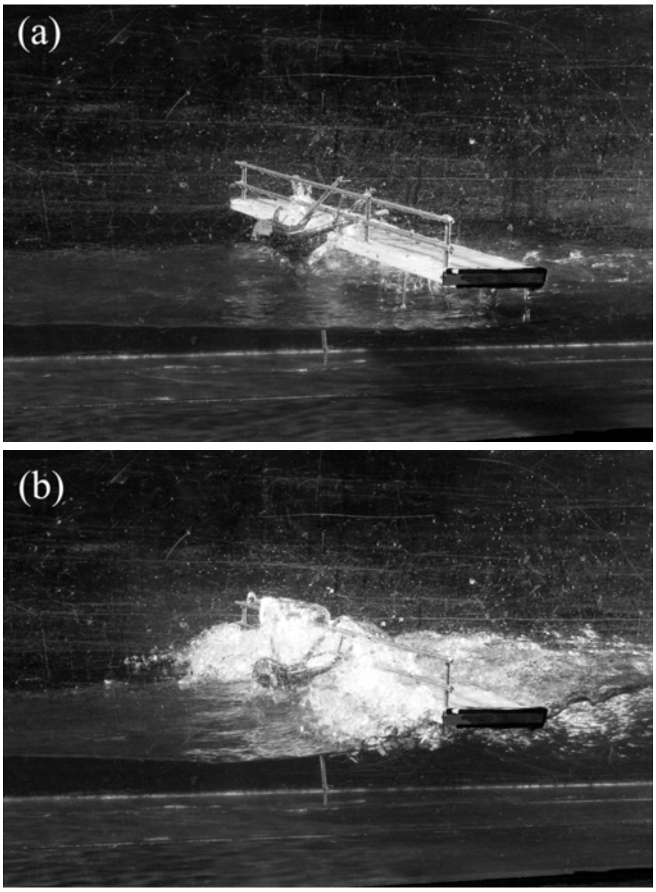

Figure 5. Bridge choking process due to a blocked rootstock with $h/H = 0.90$ and $\mathsf{F} = 1.2$

3.2 *Blocking processes*

Various blocking processes were observed in the experiments. Given the absence of piles, logs only accumulated if they had a chance to touch the bridge deck. Small logs hit the bridge and got blocked at the deck itself or at the bridge construction (especially railing and truss bridge). The longest logs occasionally spanned between the bridge deck and the channel side wall. Rootstocks got mostly blocked between the bridge deck and the channel bottom, due to their three-dimensional expansion (Fig. 6). The effect of both the flow condition and the bridge design on the blocking process is discussed below.

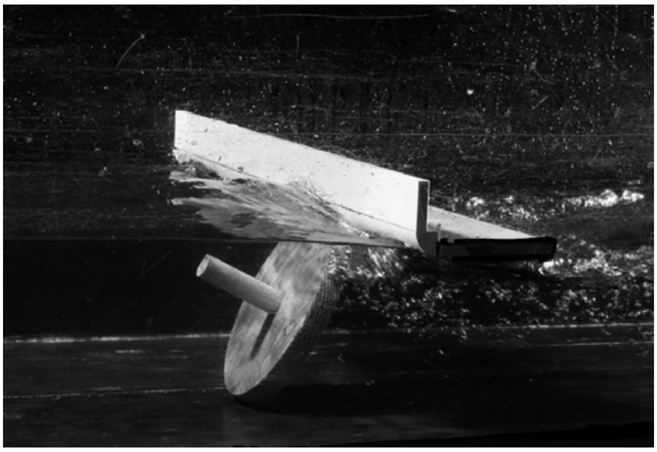

Figure 6. Blocking of a artificial rootstock at baffle bridge

3.3 *Blocking probability*

For a statistical interpretation of the experiments, two test cases were distinguished. Either the sample drift passed the bridge section resulting in a blocking probability of $P = 0$, or it got stuck with a blocking probability of $P = 1$. Drift typically passing over the reference bridge counted as stuck with $P = 1$. As each test was repeated 8 times, 9 possible probabilities of $P = 0$, 1/8, 2/8, …and 1 resulted. The chosen test repeatability was a compromise between justifiable test effort and accurate probability interpretation. Note that the results provide an estimation for the blocking probability and are subjected to variations, given the complex and turbulent processes of drift blocking.

To relate the blocking probability P to the governing parameters, a relevant log and rootstock size were determined. The log length L was used as relevant log size. Regarding rootstocks, the results indicated, that the length of the attached log does not exhibit a particular effect on the blocking process and the minimum rootstock diameter had a minor effect. The relevant rootstock size was therefore defined as

$$D_R = (D_{RM}^{\;2} \cdot D_{Rm})^{1/3} \qquad (1)$$

Given the bridge setup without piles and high flow depths, the effect of the attached log may be underestimated. For small flow depths, an attached log can exhibit a major effect regarding entrainment, transport distance and deposition within streams (Haga *et al.* 2002, Bocchiola *et al.* 2006a,b). The blocking probability P was then related to L/B for single logs and D_R/H for single rootstocks, respectively. In this study, L/B ranged between 0.25 and 1.5, and D_R between 0.66 and 1.33. Figure 7 shows typical results for the reference bridge, for various F and h/H. Note that for $\mathsf{F} = 1.2$ only $h/H = 0.90$ and 0.93 were tested. For these flow conditions, no blocking of single logs was observed, as the logs did not touch the bridge deck. The results for single logs are therefore limited to $0.3 \leq \mathsf{F} \leq 0.8$. For single rootstocks and $\mathsf{F} = 0.3$, the results indicated no trend at all. For all h/H tested, the blocking probability ranged between 0 and 1. This is mainly due to the small approach flow velocity resulting in no definite rootstock transport and a highly random blocking process as compared with higher Froude numbers. The results for single rootstocks are therefore limited to $0.5 \leq \mathsf{F} \leq 1.2$. The coefficients of determination R^2 for straight line fits are stated in the plots; they are noted to be relatively low, thus directing to a highly turbulent phenomenon and the large number of complicated effects present in the blocking process.

The blocking probability generally increases with both L/B or D_R/H and h/H. For $h/H = 0.90$, the blocking probability for single logs is $P = 0$ for all Froude numbers. This results from the fact that the freeboard prevents contact between the logs and the bridge deck. Once the logs get the chance to touch the bridge deck, the blocking probability increases with increasing log length. An increasing Froude number is seen to lower the blocking probability. The maximum blocking probabilities observed for single logs are $P_{LM}(\mathsf{F} = 0.3) = 1.0$, $P_{LM}(\mathsf{F} = 0.5) = 0.88$ and $P_{LM}(\mathsf{F} = 0.8) = 0.75$. The results for single rootstocks indicate similar trends. Due to the lateral expansion of a rootplate, rootstocks already get blocked for $h/H = 0.9$. An increase of h/H and D_R/H results in an increase of the blocking probability.

Drift passes a bridge better at high approach flow Froude numbers. Drift transported with a low Froude number blocks the bridge as soon as any of its parts touches the bridge structure. For high Froude numbers, a stuck drift may be freed again due to waves and large vertical flow components. However, assuming that drift gets stuck easier at the bridge deck if hit with a high velocity (especially for the truss bridge), this finding is somewhat astonishing but reflects the significance of turbulence.

These observations were made for all investigated bridge types. Due to their comparable design, the blocking probabilities for the reference, truss and railing bridge demonstrate almost equal results. The effect of the baffle bridge is discussed below.

3.4 *Effect of bridge characteristics*

Observations during recent flood events in the Alps indicated that the bridge deck design had a significant effect on drift accumulations. Drift often got stuck in open constructions and at truss bridges. ‘Smooth’ designs and baffle bridges favor a harmless drift passage. This aspect was investigated using various model bridge types. Figure 8 compares the blocking probability P of both single logs and rootstocks for the truss and the baffle bridges for $\mathsf{F} = 0.80$ and $h/H = 0.90$, 1.0, 1.07. The baffle bridge leads to a decrease of the blocking probability for both logs and rootstocks. For logs and $h/H = 0.90$, no blocking was observed for both bridge types. Whereas P for single logs increases to about 0.60 for the truss bridge subjected to $h/H = 1.00$ (Fig. 8a), no blocking occurs at the baffle bridge (Fig. 8b). For $h/H = 1.07$, the maximum blocking probability for the tested drift is 0.75 (truss) in comparison to 0.38 (baffle).

The probabilities of single rootstocks indicate similar results (Fig. 8c, d) with an even major decrease of P for the baffle bridge. The blocking probability P for $h/H = 1.0$ decreases from 0.75 (truss) to 0.25 (baffle) and for $h/H = 1.07$ from 0.75 (truss) to 0.20 (baffle). Due to the round and smooth front shape, a baffle bridge significantly decreases the risk of drift blocking. In addition, for flow depths exceeding the upper bridge deck, the baffle accelerates the flow beneath the bridge and therefore favors drift transport. The truss bridge in turn exhibits perfect conditions for drift blocking, especially if the drift reaches the open construction.

After the 2005 flood event in Switzerland, several bridges were rebuilt with a baffle or a baffle was added to the current construction (Fig. 9). Other bridges were modified by covering open cable conduits with concrete casings. However, this solution requires an increase of the side banks as well, to prevent water from flowing around the bridge. The additional forces due to the water impact and the dynamic pressure have to be considered for bridge design. This improved design has to prove itself during future flood events given that almost no prototype experience was collected so far. The proposed design is cost-effective and relatively simple to apply to existing bridge constructions.

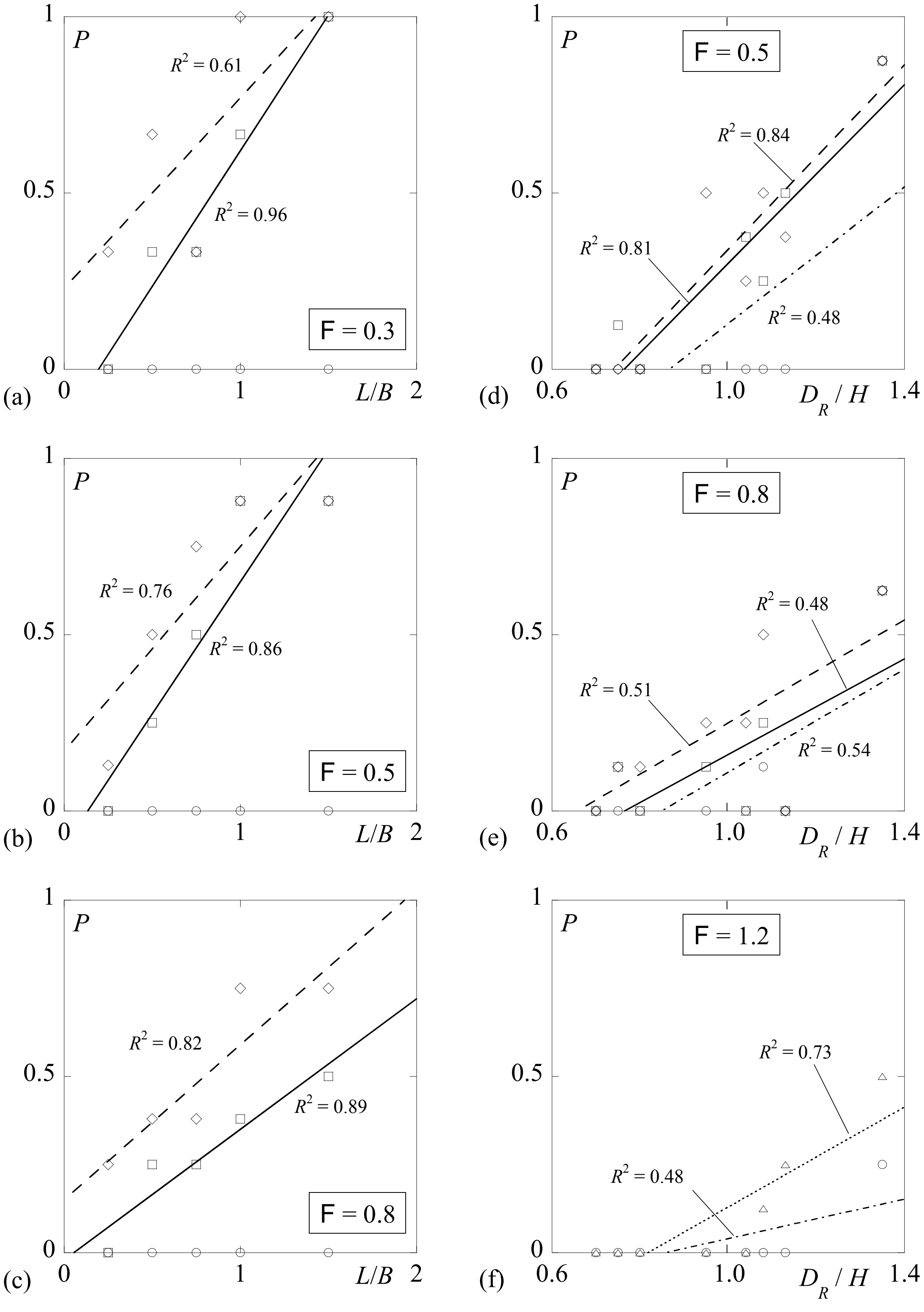

Figure 7. Blocking probability P versus L/B (single logs) and D_R/H (single rootstocks) for various F and h/H = 0.90 (○, - · -), 0.93 (△ , • • •), 1.00 (□,——), and 1.07 (◇ , - - -) for reference bridge.

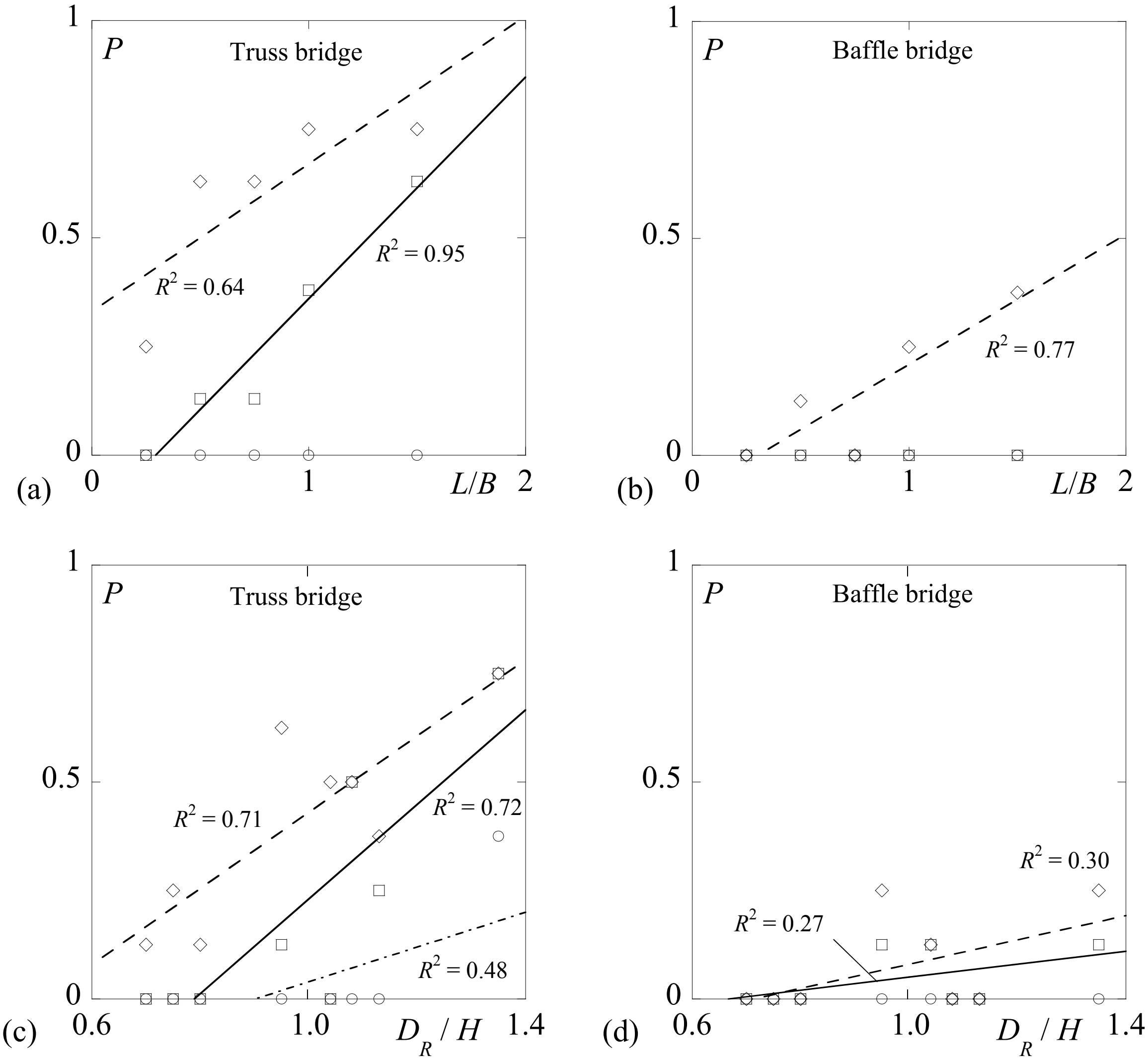

Figure 8. Blocking probability P versus L/B (single logs) and D_R/H (single rootstocks) for $\mathsf{F} = 0.8$, $h/H = 0.90$ (○, - · -), 1.00 (□,——), and 1.07 (◇, - - -) and (a, c) truss and (b, d) baffle bridges.

4 CONCLUSIONS

The main goal of the present model experiments was to evaluate the important factors affecting the blocking probability at bridge decks during flood events. A series of systematic drift blocking tests included both single logs and single rootstocks and a range of drift dimensions, approach flow Froude numbers, freeboards and typical bridge designs. The tests indicate that the blocking process depends on various factors and therefore certain randomness must be accepted for drift blocking tests.

The blocking probability was demonstrated to increase with the relative approach flow depth and the drift dimension. Single rootstocks exhibit a larger blocking probability than single logs, mainly due to their bulky shape and the higher degree of freedom. The blocking probability increases significantly as the freeboard tends to zero and the probability for drift to touch the bridge is increased.

The blocking probability for both logs and rootstocks decreases with increasing Froude number. A high degree of turbulence may ‘free’ accumulated drift by waves and large vertical flow components. An increased blocking risk was especially observed for truss and railing bridges, whereas a baffle bridge favors drift passage without damage. A ‘smooth’ bridge design decreases therefore the blocking probability as the drift is not stuck in open structural elements. This positive effect of the baffle increases with the Froude number, given the accelerated flow and a flushing effect across the bridge section.

However, a more specific analysis of the results has to be carried out, to allow for an application as a risk assessment tool. An estimation of the blocking probability prior to a flood event can increase the benefit of hazard maps or emergency action plans. So far, the derived results are limited to bridge deck accumulation and transcritical flow conditions. Further research is required to account especially for pile and drift accumulations under small flow depths. The river geometry and the presence of sediment load are additional aspects to be considered. In addition, the derived equations only account for single drift blocking, as in case of a flood event, numerous drift is transported.

Figure 9. New baffle bridge at River Chirel, Switzerland

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