Reservoir Level Rise under Extreme Driftwood Blockage at Ogee Crest

Loïc Bénet[1]; Giovanni De Cesare[2]; and Michael Pfister[3]

Abstract: Dams are civil structures essential to modern civilization. However, they can be a threat if not properly designed and operated. A particular risk that potentially can lead to dam failure is the blocking of the spillway inlet with driftwood or debris. This study investigated, on the basis of physical modeling, this blocking as well as the related backwater rise and discharge-capacity reduction. Considerable quantities of driftwood were supplied upstream of an ogee weir with piers, and the subsequent reservoir level rise was measured. Particular focus was placed on extreme events in terms of driftwood occurrence (volume) and discharges (design value). It was found that a gated ogee blocked with driftwood performs with a reduced discharge coefficient as long as no countermeasures are taken, such as pier overhang, the removal of piers, or the installation of a rack. The performance of these countermeasures was studied, and criteria were developed to control the perturbing effect of driftwood. **DOI: 10.1061/(ASCE)HY.1943-7900.0001818.**

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Introduction

Every dam-created reservoir has a spillway to limit the reservoir level rise and thus to avoid dam overtopping. Overtopping may have dramatic consequences, namely dam failure, the related inundations of which can cause fatalities and the loss of infrastructure. It is essential for dam safety that spillways are operational under all conditions, particularly during extreme events. Such extreme events might become more frequent if climate change potentially generates stronger local precipitation (ETH 2018). Extreme events are characterized by floods carrying water and, in some cases, driftwood, which typically is entrained into the watercourse by landslides and bank erosion, or anthropogenic debris such as cars or containers.

The accumulation of driftwood or debris at spillway inlets potentially results in a reduced discharge efficiency, so that the reservoir water level rises, such as occurred at the Palagnedra Dam, Switzerland (Bruschin et al. 1981). Every intensively civilized or afforested catchment faces this problem. Measures are necessary (1) to accept a reservoir level increase by providing sufficient freeboard, (2) to protect spillway inlets from driftwood accumulation, or (3) to induce the passage of driftwood over the weir. However, these tasks are rather challenging. The volume of driftwood potentially arriving at the spillway inlet, as well as its local behavior near the spillway inlet and its blocking characteristics, are difficult to quantify (BAFU 2019).

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Driftwood Blockage at Spillways

Le Lay and Moulin (2007) and STK (2017) studied blockage by driftwood of spillway inlets. Hartung and Knauss (1976) studied a spillway consisting of a 15-m-long ogee crest principal inlet and two lateral side bays as secondary inlets with higher crest elevations. The structure was organized to orient driftwood along the flow, break up long trunks, and force them into the downstream spillway tunnel. In addition, floating chains and interceptors were investigated to hold back driftwood in the reservoir and to keep the inlets free.

Godtland and Tesaker (1994) conducted model tests with driftwood on an ogee with and without piers. They indicated that without piers, the passing probability increases with increasing discharge. To avoid blockage, the free vertical opening between the crest and the bridge should be at least 15% of the maximum trunk length L_M, and the relative bay width should be $b/L_M \geq 0.8$, where, b is the bay width and L_M is the length of the largest trunk.

Johansson and Cederström (1995) investigated the passage of trees of various lengths in gated weir fields in a physical model. They found that a single tree approaching a single open gate has the highest probability of passing. If two trees arrive simultaneously or two gates are open, then the passing probability decreases. Furthermore, the probability of passing decreases as the tree length increases. A relative upstream head increase of up to 10% occurred due to blocking.

Hartlieb (2012a, b) conducted physical model tests in a 2.5-m-wide channel, including an ogee weir with piers forming three bays $b = 0.5$ m wide each. Driftwood of different lengths up to $2b$ was supplied either as a single trunk or in batches of five trunks. Hartlieb found that the approach flow velocity is of little significance for the blocking probability, whereas the relative trunk length is relevant. Furthermore, batches have a higher blocking probability than single trunks. For the head increase, the blocking probability is increased with large approach flow Froude numbers as a consequence of a denser driftwood packing at the weir.

Pfister et al. (2013) presented a physical model investigation of piano key weirs (PKWs) and driftwood, including individual trunk tests as well as batch tests. For the individual tests, the blockage probability was a function of the head H and the trunk diameter D. For a reservoir-type inflow, trunks typically pass a PKW if the critical flow depth h_c at the weir is larger than D and block a PKW if $h_c < D$. The batch tests showed that the accumulation typically was loose, so the absolute head increase was small. Venetz (2014) continued the work of Pfister et al. (2013), including a study of channel approach flow upstream of the PKW.

Walker et al. (2018) performed model tests of a radial gated ogee crest spillway with two bays blocked by driftwood. For a full gate opening, they reported a reservoir level rise of 1.5 m and a discharge reduction of 35%. The approach to the bays corresponded to channel flow, proving a compact blocking similar to that from river applications.

Furlan (2019) used the experimental setup presented herein and conducted tests with artificial stems of well-defined characteristics. The outcomes were as follows: (1) driftwood experiments should be repeated at least 30 times for individual trunks to achieve errors smaller than 10%; for groups of 32 trunks, 10 test repetitions generated the same accuracy; (2) trunks with a high density (close to that of water) block more frequently than do light trunks; (3) pronounced weir heads H (i.e., large discharges) tend to reduce the blocking probability; (4) numerous open bays tend to block less than one single open bay under the same head; (5) long trunks ($L/b > 0.8$) block more frequently at bays of a given width than do short trunks; (6) equal test conditions can lead to a different blockage of a key trunk and thus to a different reservoir head increase; and (7) the horizontal extension of a driftwood carpet is not significant for the head increase under reservoir conditions.

Measures to Limit Impact

Structures to reduce the impact of driftwood on the rating curve are numerous and usually are linked to a particular case. Perham (1986) discussed measures to keep racks free of driftwood at powerhouse inlets, including net-type racks and air bubbler systems. Perham reported that a particular floating debris boom had deficient performance and that conventional traveling rack cleaners have an insufficient cleaning capacity during intense debris occurrence.

Godtland and Tesaker (1994) described the case of Vinkelfalet Dam (Norway), in which a bridge along the weir was removed to let driftwood pass. USACE (1987, 1997) and FHWA (2005) include overviews of debris characterization, the estimation of debris quantities, debris impact on structures, trash racks, the removal of floating debris, debris passage at spillways, and the disposal of debris.

Built racks and nets were summarized by Hartlieb and Bezzola (2000) and Lange and Bezzola (2006). Möller et al. (2009) described the concept of a side-weir rack for Matteschwelle in Bern, Switzerland. Pfister (2010) applied the side-weir rack concept at a diversion tunnel inlet, and demonstrated that the upper part of the rack remains free for that setup (so that the rating curve is affected only slightly) if a lateral debris retention basin with a rotational flow is provided.

Schmocker and Hager (2013) presented a physical model study of driftwood accumulation at racks. The results indicated a significant effect of the approach-flow Froude number on the driftwood accumulation process, whereas the driftwood properties had only a minor effect on the resulting backwater rise. Schmocker and Weitbrecht (2013) presented an overview of driftwood risk analysis and retention measures for large alpine rivers.

Schmocker (2017) conducted model tests of a weir with two bays, without measures or with a rack installed slightly upstream of the crest. A wooden board with two openings representing a spillway with two weir fields was placed in the channel. Without a rack and for a natural emplacement of the trunks, a relative head rise of up to 30% was observed due to the blocked bays, and a relative head rise of less than 10% occurred if the rack was provided. When manually compacting the wood at the bay or the rack, a relative head rise of up to 40% was observed, versus 10% for the rack.

Schalko et al. (2018) provided a rack in a channel and supplied a predefined driftwood accumulation. The tests were performed partially with a mobile sediment bed. They predicted the channel flow depth increase due to blocking as a function of the initial flow depth and Froude number, as well as of the wood characteristics. Schalko et al. (2019a) presented a literature review of existing measures to reduce the driftwood accumulation probability at bridges and introduce bottom sills to reduce the accumulation effect.

Lassus et al. (2019) summarized model studies from the literature and conducted numerical simulations. They found overall agreement and specified the discharge reduction at an ogee crest equipped with a rack as 7%–22%, depending on the driftwood density, the rack type, and the reference head.

The present study focused on an extreme driftwood occurrence during a pronounced flood event. Only the reservoir head increase was considered, and a full blockage was assumed. As a reference, a gated ogee was chosen (with fully opened gates), because of its frequent application as a spillway inlet control structure. Physical model tests with quasi-natural driftwood were conducted, including different discharge scenarios and bay configurations. Tests were conducted without and with measures to counteract the hydraulic effect of the driftwood blockage.

Experimental Setup

Physical Model

Systematic experimental tests were performed on a straight channel at the Platform of Hydraulic Constructions (PL-LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL) (Bénet 2019) (Fig. 1). The channel was horizontal, 10 m long, $B = 1.5$ m wide, and 0.7 m high. At the channel end, an ogee crest with a design head of $H_D = 0.15$ m was transversely mounted. Its crest level was $W = 0.42$ m above the channel bottom to eliminate an effect of the approach flow on its rating curve, because $2H_D < W$ (Vischer and Hager 1999). The crest was equipped with 0.04-m-thick and round-nosed piers. They were fixed on a flexible frame so that $n = 1$–5 open bays resulted. All the bays had the same width b for a test, whereas the bay width was varied between 0.175 and 1.500 m between tests. The upstream pier front position either was aligned with the vertical weir front or was overhanging into the reservoir.

The discharge Q was supplied by the in-house pump system and was measured by a magnetic inductive flowmeter (Krohne, Switzerland) up to $\pm 0.5\%$ full-scale. A point gauge fixed approximately 2 m upstream of the weir crest was used to measure flow depths up to ± 1 mm. There, the maximum kinematic head (i.e., for H_D) in the channel was on the order of the measurement accuracy and thus negligible.

A flow tranquillizer was provided 6.0 m upstream of the weir to generate homogenous approach flow conditions, which were validated by Furlan (2019).

An implicit validation of the measured parameters is given in Fig. 2(a), comparing the measured rating curve in terms of discharge coefficient C_d

$$C_d = \frac{Q}{b_e\sqrt{2gH^3}} \qquad (1)$$

versus the relative head χ

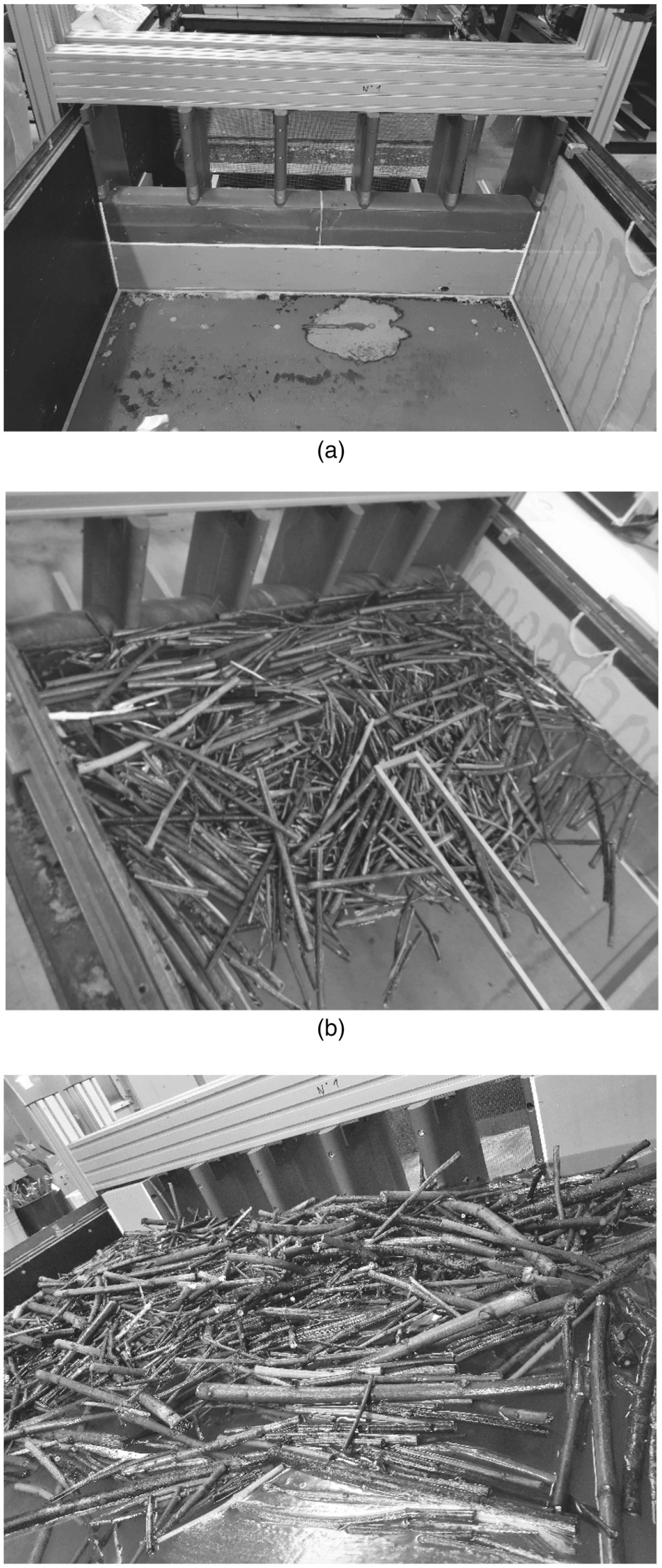


Fig. 1. Physical model (without countermeasures) with five open bays: (a) overview; (b) before Test 10; and (c) during Test 30.

$$\chi = \frac{H}{H_D} \quad (2)$$

for the test setups with a calculated curve (Vischer and Hager 1999). Fig. 2(a) shows preliminary tests without driftwood and

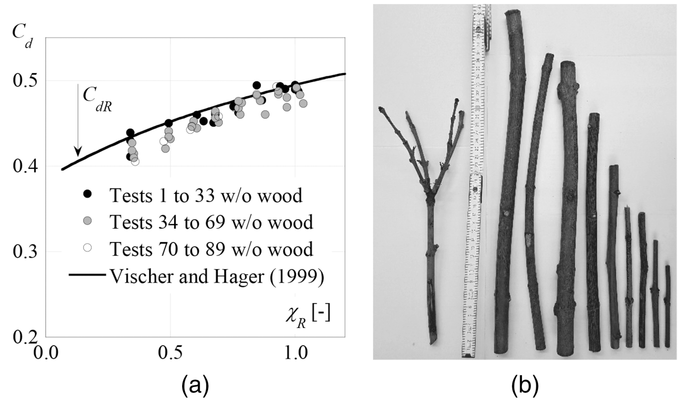


Fig. 2. (a) Measured and predicted ogee rating curve C_d versus χ_R without driftwood, tested without racks; and (b) photo of driftwood and rootstock with rule (cm).

with the model geometries according to those of Tests 1–89. In Eq. (1), $b_e = nb - (n2K_pH)$ corresponds to the effective hydraulic width considering the pier contraction (Vischer and Hager 1999), where K_P is the pier parameter. The model values of C_d reach, on average, 98% of the calculated references with a standard deviation of $\sigma = 0.02$. Scale effect affecting the rating curve are small because $H \geq 0.050$ m for the main tests (Hager et al. 2020, Tables 1–4). Smaller heads of $H \geq 0.017$ m had to be considered for Tests 70–73, 75–78, 82–86, and 99–100. For the driftwood, scale effects were present but not determinant. The trunk shape and surface were natural [Fig. 2(b)], the trunk stiffness was overestimated, and organic fine materials were absent.

Fig. 3 is a definition sketch of the model, showing the ogee crest with the piers. The figure includes some of the countermeasures that were installed during the second test phase, namely the pier overhang and the rack.

Test Procedure

The following test procedure was applied:

1. The tested driftwood volume was homogeneously added to the model in stagnant water [Fig. 1(b)].
2. The smallest discharge (e.g., $Q = 0.028$ m^3/s) was supplied, and blockage occurred. Driftwood that passed the weir was returned to the reservoir so that the blocked volume always was known. Partially, an initial blockage had to be produced manually by positioning a long trunk transversely in a bay.
3. Stable conditions were developed for the measurement of H.
4. The discharge was increased for the next test to the subsequent value (e.g., $Q = 0.085$ m^3/s), and the procedure was repeated.

The following parameters were varied systemically in the model: (1) model discharge 0.005 m^3/s $\leq Q \leq$ 0.171 m^3/s, corresponding to $0.098 \leq \chi_R \leq 1.029$ ($\chi_R = H_R/H_D$, based on reference discharges without driftwood); (2) supplied driftwood volume $1V$, $2V$, or $4V$ (with $V = 0.038$ m^3); (3) model bay width 0.175 m $\leq b \leq$ 1.500 m ($0.40 \leq b/L_M \leq 3.46$), and the number of open bays $n = 1$–5; (4) pier front overhang aligned or overhanging up to 0.080 m; and (5) rack type. Tables 1–4 list the test program and selected parameters.

Driftwood Characteristics

Driftwood was supplied in batches of volumes $1V$, $2V$, and $4V$. The reference volume $V = 0.038$ m^3 was chosen to focus on an extreme event. If applying a geometrical scale factor of $\lambda = 35$ and the Froude

Table 1. Test program and measured model data without countermeasures

Test	Total discharge, Q (m^3/s)	Unit discharge, $q = Q/nb$ (m^2/s)	Head ratio without wood, χ_R	Driftwood volume ($\times V$)	Individual bay width, b (m)	Open bays, n	Measured head with wood, H (m)	Measured discharge coefficient with wood, C_d	Pier front overhang, p (m)	Relative bay width, b/L_M	Unit driftwood volume, $v = \Sigma V/nb$ (m^3/m)
1	0.028	0.022	0.333	1	0.260	5	0.055	0.383	0	0.60	0.029
2	0.085	0.066	0.668	1	0.260	5	0.115	0.387	0	0.60	0.029
3	—	—	—	1	0.260	5	—	—	0	0.60	0.029
1a	0.028	0.022	0.333	1	0.260	5	0.055	0.385	0	0.60	0.029
2a	0.085	0.065	0.667	1	0.260	5	0.116	0.381	0	0.60	0.029
3a	0.164	0.126	1.006	1	0.260	5	0.177	0.387	0	0.60	0.029
4	0.028	0.022	0.335	1	0.260	5	0.054	0.398	0	0.60	0.029
5	0.085	0.065	0.667	1	0.260	5	0.114	0.391	0	0.60	0.029
6	0.165	0.127	1.008	1	0.260	5	0.178	0.385	0	0.60	0.029
7	0.028	0.022	0.335	1	0.260	5	0.056	0.377	0	0.60	0.029
8	0.085	0.065	0.665	1	0.260	5	0.118	0.370	0	0.60	0.029
9	0.164	0.126	1.006	1	0.260	5	0.181	0.374	0	0.60	0.029
10	0.028	0.022	0.333	2	0.260	5	0.057	0.365	0	0.60	0.059
11	0.085	0.065	0.667	2	0.260	5	0.122	0.353	0	0.60	0.059
12	0.165	0.127	1.007	2	0.260	5	0.170	0.412	0	0.60	0.059
13	0.028	0.022	0.333	4	0.260	5	0.056	0.375	0	0.60	0.118
14	0.085	0.066	0.667	4	0.260	5	0.119	0.367	0	0.60	0.118
15	0.165	0.127	1.008	4	0.260	5	0.177	0.388	0	0.60	0.118
16	0.028	0.021	0.326	1	0.335	4	0.056	0.370	0	0.77	0.029
17	0.085	0.064	0.654	1	0.335	4	0.118	0.364	0	0.77	0.029
18	0.166	0.124	0.990	1	0.335	4	0.189	0.345	0	0.77	0.029
19	0.030	0.022	0.341	2	0.335	4	0.057	0.387	0	0.77	0.057
20	0.088	0.066	0.668	2	0.335	4	0.121	0.363	0	0.77	0.057
21	0.170	0.127	1.008	2	0.335	4	0.183	0.372	0	0.77	0.057
22	0.029	0.022	0.334	4	0.335	4	0.058	0.365	0	0.77	0.114
23	0.087	0.065	0.663	4	0.335	4	0.126	0.337	0	0.77	0.114
24	0.170	0.127	1.005	4	0.335	4	0.192	0.345	0	0.77	0.114
25	0.019	0.021	0.334	1	0.175	5	0.052	0.420	0	0.40	0.044
26	0.057	0.065	0.664	1	0.175	5	0.117	0.375	0	0.40	0.044
27	0.111	0.127	1.012	1	0.175	5	0.176	0.394	0	0.40	0.044
28	0.019	0.021	0.333	2	0.175	5	0.052	0.419	0	0.40	0.087
29	0.057	0.065	0.666	2	0.175	5	0.116	0.382	0	0.40	0.087
30	0.114	0.130	1.029	2	0.175	5	0.185	0.375	0	0.40	0.087
31	0.019	0.022	0.337	4	0.175	5	0.054	0.403	0	0.40	0.175
32	0.057	0.065	0.665	4	0.175	5	0.112	0.402	0	0.40	0.175
33	0.112	0.128	1.016	4	0.175	5	0.170	0.418	0	0.40	0.175

similitude, then $1V = 410$ m^3, $2V = 820$ m^3 [e.g., Figs. 1(b and c)], and $4V = 1{,}640$ m^3 of solid wood (the loose batch volume is larger). Table 1 also gives the unit model driftwood volume v, indicating the solid wood volume which arrives per transverse meter of open bay [0.025 m$^2 \leq (v = \Sigma V/nb) \leq 0.175$ m^2 in model dimensions]. For $\lambda = 35$, this corresponded to a range of 31–214 m^3 solid wood /m open bay width in a prototype. A batch of $1V$ was composed of 690 trunks and 20 rootstocks, and the batches of $2V$ and $4V$ were composed of the related multiples. A volume of $4V$ thus included 2,760 trunks and 80 rootstocks.

The length L mixture of the trunks within a batch was inspired by in situ observations of Bezzola and Hegg (2007) and Rickli and Hess (2009), who described driftwood accumulations at weirs after floods in Switzerland. The driftwood accumulations are shown in Fig. 4(a) and compared with the present mixture. A batch of $1V$ included model trunks of length $L_M = 0.433$ m (10 trunks, maximum length), $L = 0.372$ m (15 trunks), $L = 0.367$ m (20 trunks), $L = 0.300$ m (35 trunks), $L = 0.233$ m (50 trunks), $L = 0.172$ m (65 trunks), $L = 0.167$ m (85 trunks), $L = 0.130$ m (110 trunks), and $L = 0.100$ m (300 trunks) [Fig. 2(b)]. The supplied driftwood followed the coarse distribution of Rickli and Hess (2009) in accordance with the present approach of an extreme event. For the trunk diameter D, $L/D = 20$ was assumed. At a scale factor of $\lambda = 35$, prototype trunk lengths of 3.5 m $\leq L \leq$ 15.2 m were reproduced.

Repetition of Experiments

As stated previously, Furlan (2019) recommended repeating identical driftwood tests several times to achieve statistical relevance. The number of required repetitions decreased, however, with the size of the batches. The maximum number of trunks per batch that Furlan tested was 32, for which 10 repetitions were proposed. We tested batches of 690 ($1V$) to 2,760 ($4V$) trunks plus 20–80 rootstocks, suggesting that less than 10 test repetitions were necessary. Tests 1–3 thus were conducted four times [Tests 1–3, 1a–3a, 4–6, and 7–9 (Table 1) all under identical conditions] to compare the outcome in terms of discharge coefficient C_d (derived from the measured H) as a function of the discharge (expressed as χ_R). Fig. 4(b) shows that the data of Tests 1–9 were similar per χ_R. A statistical analysis indicated that the maximum deviation from the mean head H of all measurements per Q was less than $\pm 2\%$. An absolute error below 4% seemed acceptable in the context of driftwood, so all further tests were conducted only once, without repetition. The rating curve without driftwood (Vischer and Hager 1999) is shown in Fig. 4(b).

Table 2. Test program and measured model data with overhanging piers

Test	Total discharge, Q (m^3/s)	Unit discharge, $q = Q/nb$ (m^2/s)	Head ratio without wood, χ_R	Driftwood volume ($\times V$)	Individual bay width, b (m)	Open bays, n	Measured head with wood, H (m)	Measured discharge coefficient with wood, C_d	Pier front overhang, p (m)	Relative bay width, b/L_M	Unit driftwood volume, $v = \Sigma V/nb$ (m^3/m)
34	0.019	0.022	0.337	1	0.175	5	0.052	0.426	0.04	0.40	0.044
35	0.057	0.065	0.663	1	0.175	5	0.103	0.453	0.04	0.40	0.044
36	0.111	0.127	1.012	1	0.175	5	0.174	0.401	0.04	0.40	0.044
37	0.019	0.021	0.331	2	0.175	5	0.054	0.392	0.04	0.40	0.087
38	0.057	0.065	0.665	2	0.175	5	0.104	0.448	0.04	0.40	0.087
39	0.110	0.126	1.007	2	0.175	5	0.168	0.419	0.04	0.40	0.087
40	0.019	0.022	0.336	4	0.175	5	0.053	0.413	0.04	0.40	0.175
41	0.057	0.066	0.669	4	0.175	5	0.105	0.447	0.04	0.40	0.175
42	0.111	0.127	1.013	4	0.175	5	0.169	0.419	0.04	0.40	0.175
43	0.019	0.022	0.337	1	0.175	5	0.053	0.415	0.08	0.40	0.044
44	0.057	0.066	0.669	1	0.175	5	0.103	0.460	0.08	0.40	0.044
45	0.112	0.128	1.019	1	0.175	5	0.157	0.472	0.08	0.40	0.044
46	0.019	0.022	0.334	2	0.175	5	0.052	0.421	0.08	0.40	0.087
47	0.057	0.065	0.667	2	0.175	5	0.102	0.465	0.08	0.40	0.087
48	0.112	0.128	1.016	2	0.175	5	0.156	0.475	0.08	0.40	0.087
49	0.019	0.022	0.334	4	0.175	5	0.052	0.421	0.08	0.40	0.175
50	0.057	0.065	0.668	4	0.175	5	0.103	0.458	0.08	0.40	0.175
51	0.112	0.128	1.018	4	0.175	5	0.155	0.481	0.08	0.40	0.175
52	0.029	0.022	0.334	1	0.335	4	0.054	0.396	0.04	0.77	0.029
53	0.088	0.066	0.667	1	0.335	4	0.106	0.435	0.04	0.77	0.029
54	0.169	0.126	1.003	1	0.335	4	0.174	0.395	0.04	0.77	0.029
55	0.030	0.022	0.337	2	0.335	4	0.054	0.401	0.04	0.77	0.057
56	0.087	0.065	0.663	2	0.335	4	0.106	0.431	0.04	0.77	0.057
57	0.170	0.127	1.005	2	0.335	4	0.169	0.414	0.04	0.77	0.057
58	0.029	0.022	0.335	4	0.335	4	0.054	0.399	0.04	0.77	0.114
59	0.088	0.066	0.668	4	0.335	4	0.105	0.443	0.04	0.77	0.114
60	0.169	0.126	1.004	4	0.335	4	0.162	0.441	0.04	0.77	0.114
61	0.028	0.021	0.326	1	0.335	4	0.052	0.403	0.08	0.77	0.029
62	0.087	0.065	0.664	1	0.335	4	0.103	0.452	0.08	0.77	0.029
63	0.171	0.128	1.011	1	0.335	4	0.155	0.476	0.08	0.77	0.029
64	0.029	0.022	0.333	2	0.335	4	0.053	0.405	0.08	0.77	0.057
65	0.089	0.066	0.669	2	0.335	4	0.105	0.444	0.08	0.77	0.057
66	0.170	0.127	1.008	2	0.335	4	0.156	0.469	0.08	0.77	0.057
67	0.029	0.022	0.334	4	0.335	4	0.053	0.408	0.08	0.77	0.114
68	0.088	0.065	0.665	4	0.335	4	0.104	0.446	0.08	0.77	0.114
69	0.170	0.127	1.006	4	0.335	4	0.156	0.467	0.08	0.77	0.114

Table 3. Test program and measured model data without piers

Test	Total discharge, Q (m^3/s)	Unit discharge, $q = Q/nb$ (m^2/s)	Head ratio without wood, χ_R	Driftwood volume ($\times V$)	Individual bay width, b (m)	Open bays, n	Measured head with wood, H (m)	Measured discharge coefficient with wood, C_d	Pier front overhang, p (m)	Relative bay width, b/L_M	Unit driftwood volume, $v = \Sigma V/nb$ (m^3/m)
70	0.005	0.003	0.099	1	1.500	1	0.018	0.295	0	3.46	0.025
71	0.010	0.007	0.158	1	1.500	1	0.028	0.319	0	3.46	0.025
72	0.015	0.010	0.203	1	1.500	1	0.036	0.327	0	3.46	0.025
73	0.020	0.013	0.244	1	1.500	1	0.041	0.360	0	3.46	0.025
74	0.025	0.017	0.284	1	1.500	1	0.050	0.342	0	3.46	0.025
75	0.005	0.003	0.099	2	1.500	1	0.018	0.296	0	3.46	0.051
76	0.010	0.007	0.163	2	1.500	1	0.028	0.335	0	3.46	0.051
77	0.015	0.010	0.203	2	1.500	1	0.034	0.356	0	3.46	0.051
78	0.020	0.013	0.244	2	1.500	1	0.043	0.337	0	3.46	0.051
79	0.025	0.017	0.282	2	1.500	1	0.051	0.328	0	3.46	0.051
80	0.031	0.021	0.321	2	1.500	1	0.057	0.342	0	3.46	0.051
81	0.036	0.024	0.353	2	1.500	1	0.058	0.387	0	3.46	0.051
82	0.005	0.003	0.098	4	1.500	1	0.017	0.313	0	3.46	0.102
83	0.010	0.007	0.160	4	1.500	1	0.029	0.311	0	3.46	0.102
84	0.015	0.010	0.207	4	1.500	1	0.037	0.324	0	3.46	0.102
85	0.020	0.013	0.246	4	1.500	1	0.042	0.353	0	3.46	0.102
86	0.025	0.017	0.284	4	1.500	1	0.048	0.364	0	3.46	0.102
87	0.030	0.020	0.318	4	1.500	1	0.058	0.327	0	3.46	0.102
88	0.036	0.024	0.355	4	1.500	1	0.061	0.363	0	3.46	0.102
89	0.041	0.027	0.382	4	1.500	1	—	—	0	3.46	0.102

Table 4. Test program and measured model data with rack

Test	Total discharge, Q (m^3/s)	Unit discharge, $q = Q/nb$ (m^2/s)	Head ratio without wood, χ_R	Driftwood volume ($\times V$)	Individual bay width, b (m)	Open bays, n	Measured head with wood, H (m)	Measured discharge coefficient with wood, C_d	Pier front overhang, p (m)	Relative bay width, b/L_M	Unit driftwood volume, $v = \Sigma V/nb$ (m^3/m)
90	0.030	0.022	0.340	1	0.335	4	0.053	0.419	0	0.77	0.029
91	0.088	0.065	0.665	1	0.335	4	0.102	0.459	0	0.77	0.029
92	0.170	0.127	1.008	1	0.335	4	0.150	0.498	0	0.77	0.029
93	0.029	0.022	0.335	2	0.335	4	0.052	0.420	0	0.77	0.057
94	0.088	0.066	0.666	2	0.335	4	0.102	0.460	0	0.77	0.057
95	0.171	0.128	1.010	2	0.335	4	0.151	0.494	0	0.77	0.057
96	0.029	0.022	0.336	4	0.335	4	0.053	0.411	0	0.77	0.114
97	0.087	0.065	0.664	4	0.335	4	0.103	0.452	0	0.77	0.114
98	0.171	0.127	1.009	4	0.335	4	0.151	0.494	0	0.77	0.114
99	0.010	0.007	0.166	4	0.335	4	0.026	0.417	0	0.77	0.114
100	0.020	0.015	0.262	4	0.335	4	0.042	0.391	0	0.77	0.114
101	0.030	0.023	0.341	4	0.335	4	0.053	0.422	0	0.77	0.114
102	0.041	0.030	0.410	4	0.335	4	0.064	0.427	0	0.77	0.114
103	0.051	0.038	0.471	4	0.335	4	0.074	0.429	0	0.77	0.114
104	0.059	0.044	0.522	4	0.335	4	0.081	0.441	0	0.77	0.114
105	0.070	0.052	0.576	4	0.335	4	0.09	0.441	0	0.77	0.114
106	0.080	0.059	0.626	4	0.335	4	0.097	0.451	0	0.77	0.114
107	0.106	0.079	0.751	4	0.335	4	0.114	0.471	0	0.77	0.114
108	0.119	0.089	0.805	4	0.335	4	0.123	0.470	0	0.77	0.114
109	0.138	0.103	0.885	4	0.335	4	0.134	0.480	0	0.77	0.114
110	0.159	0.118	0.964	4	0.335	4	0.146	0.482	0	0.77	0.114
111	0.170	0.127	1.007	4	0.335	4	0.152	0.487	0	0.77	0.114
112	0.019	0.022	0.335	4	0.175	5	0.052	0.423	0	0.40	0.175
113	0.042	0.048	0.550	4	0.175	5	0.085	0.449	0	0.40	0.175
114	0.057	0.065	0.668	4	0.175	5	0.104	0.452	0	0.40	0.175
115	0.080	0.092	0.825	4	0.175	5	0.129	0.476	0	0.40	0.175
116	0.104	0.118	0.968	4	0.175	5	0.151	0.463	0	0.40	0.175
117	0.111	0.126	1.009	4	0.175	5	0.157	0.465	0	0.40	0.175
118	0.019	0.022	0.337	4	0.175	5	0.052	0.426	0	0.40	0.175
119	0.057	0.065	0.665	4	0.175	5	0.101	0.469	0	0.40	0.175
120	0.113	0.129	1.023	4	0.175	5	0.155	0.484	0	0.40	0.175

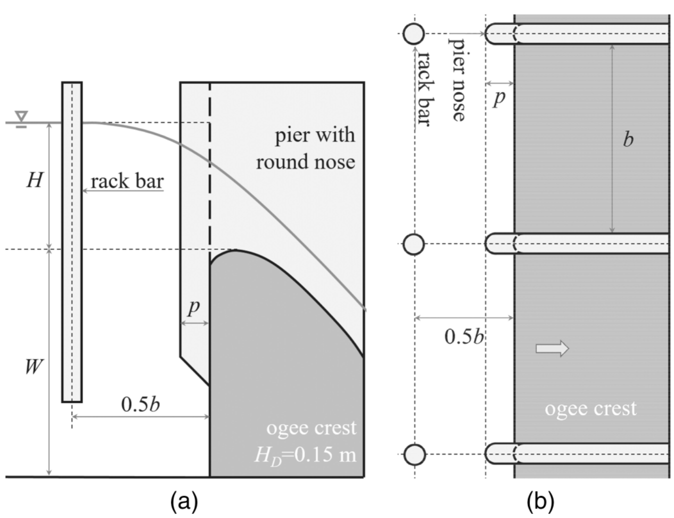


Fig. 3. Definition sketch: (a) vertical section; and (b) plan view.

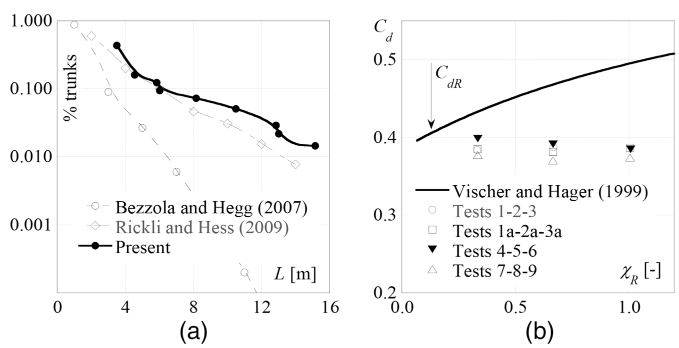


Fig. 4. (a) Characteristics of the present driftwood (upscaled with $\lambda = 35$) and in situ surveys; and (b) C_d versus χ_R of the repetition tests (Tests 1–9).

Reservoir Level Rise without Countermeasures

Tests 7–33 [excluding the repetition tests (Table 1)] were conducted without countermeasures to visualize the effect of the driftwood on the ogee performance. The model was operated as shown in Fig. 1, i.e., (1) the upstream pier front was aligned with the vertical weir front; (2) with $n = 4$ or 5 open adjacent bays of width $b = 0.175$, 0.260, or 0.335 m (corresponding to $b/L_M = 0.40$, 0.60, or 0.77); (3) with discharges of approximately $\chi = H_R/H_D = 0.33$, 0.67, or 1.00; and (4) with driftwood volumes of $1V$, $2V$, and $4V$.

The measured heads H with driftwood blockage are shown as a function of the unit discharge $q = Q/nb$ in Fig. 5(a) and as C_d versus χ_R in Fig. 5(b). The reservoir head increased considerably under a determinant driftwood blockage. On average, the head rose to 114% of the related head without driftwood, and maximally it rose to 121%. None of the varied parameters (unit discharge q_R,

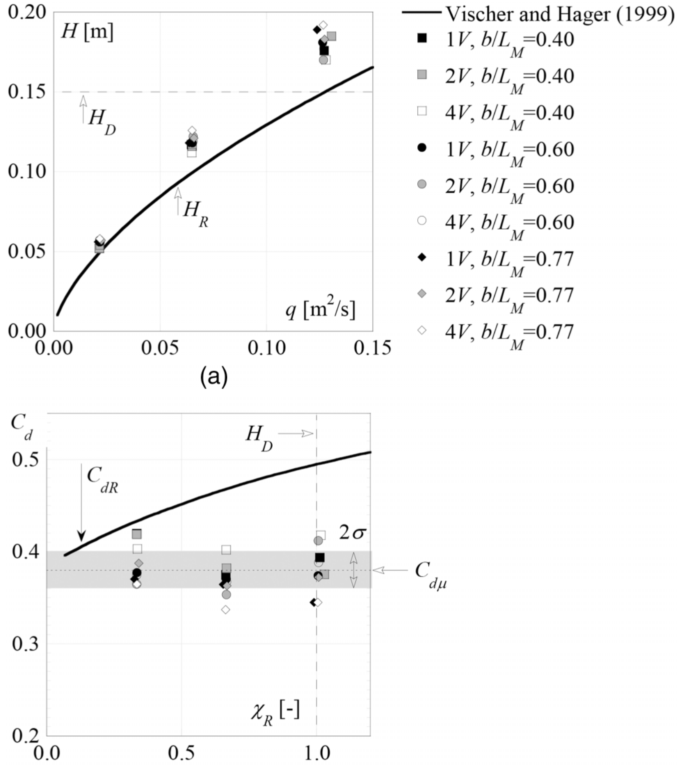


Fig. 5. Data of Tests 7–33 (Table 1, with wood): (a) Hversus q; and (b) C_d versus χ_R (Rating curve without driftwood from Vischer and Hager 1999.)

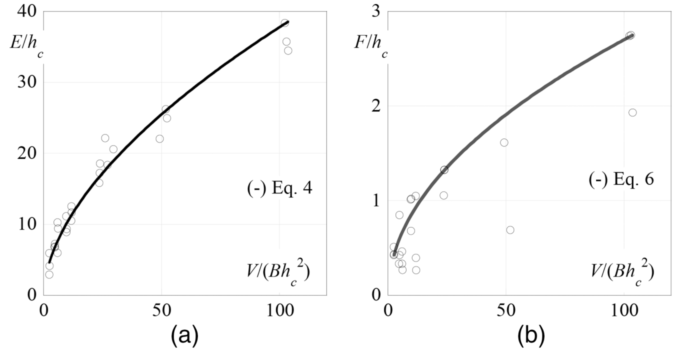


Fig. 6. Normalized carpet characteristics of Tests 7–33 (Table 1): (a) horizontal length E/h_c versus $V/(Bh_c^2)$ [Eq. (4)]; and (b) envelope of blockage height at pier front F/h_c versus $V/(Bh_c^2)$ [Eq. (6)].

wood volume V, and bay width b/L_M) had a dominant individual effect on the head rise, because all measured points quasi collapse per q.

Fig. 5(b) visualizes the effect of the blocked driftwood in a nondimensional way, showing the absence of a systematic effect of χ_R, V, and b/L_M. The trend of the data points was almost horizontal, meaning that C_d was quasi-independent of χ_R (i.e., of q_R). The increased efficiency in function of χ_R at the nonblocked ogee is removed [Fig. 5(b), Vischer and Hager (1999)]. Fig. 5(b) and the blocking process in the model show that

1. Small $\chi_R \approx 0.33$ (small discharges) with comparatively small flow velocities at the pier front (where the blocking is initiated) generated a relatively large C_d, given that the transposed force on the wood was modest. The wood near the piers was distributed horizontally in one or two layers only.
2. At $\chi_R \approx 0.67$, the force transposed to the wood increased with the flow velocity, so that the blocking became denser, leading to a slightly reduced C_d. The wood at the piers formed a dense vertical barrier.
3. For large $\chi_R \approx 1$, the transposed forces continued to rise, but the blockage (the vertical barrier) had already been fully established (here, at $\chi_R \approx 0.67$) and did not change its structure. The additional head with its larger flow cross section again slightly augmented C_d.

There was no systematic reduction in C_d when the driftwood volume increased from $1V$ to $4V$. This means that a complete blockage at the ogee was achieved herein for the lowest tested volume of $1V$. Supplementary driftwood was deposited in the reservoir far from the ogee without having any influence on the ogee near-field flow due to reservoir flow velocities of approximately zero. Schmocker (2017), Furlan (2019), and Schalko et al. (2019b) made similar observations. This confirms that the tested wood volumes were sufficiently large to represent an extreme and full blockage.

When isolating tests associated with the relative bay width b/L_M, a minor effect of the bay width is evident. Interestingly, by trend, narrow bays ($b/L_M = 0.40$) generate a smaller level rise than do wide bays ($b/L_M = 0.77$). We suggest that this is due to a higher wood span width of wide bays, producing higher transposed forces and thus a more pronounced vertical barrier. This may lead to a reduced permeability. Godtland and Tesaker's (1994) criterion of $b/L_M \geq 0.80$ intentionally was never achieved herein because the extreme case of a full blockage was considered.

A statistical analysis of the C_d coefficients was conducted because there was no recognizable dominant trend. From all C_d values of Tests 7–33, the maximum was $C_{dM} = 0.42$, the mean was $C_{d\mu} = 0.38$, the median was $C_d = 0.38$, the minimum was $C_{dm} = 0.34$, and the standard deviation was $\sigma = 0.02$. For practice, the discharge coefficient could be

$$C_d = C_{d\mu} - \sigma = 0.36 \tag{3}$$

This coefficient applies up to the design discharge for a fully blocked ogee with piers and for $b/L_M \leq 0.77$. The comparison of the blocked ogee with the rating curve without driftwood (Vischer and Hager 1999) indicates the additional reservoir level rise due to driftwood blockage.

Apart from the hydraulic efficiency of a blocked ogee crest, as discussed previously based on C_d, the horizontal driftwood carpet extension E (m) on the reservoir surface also might be interesting. The horizontal driftwood extension length was defined normal to the crest axis, originating at the upstream pier front and reaching into the reservoir. The length E was affected by the total supplied driftwood volume V (i.e., $1V$, $2V$, or $4V$), the channel width B, and the discharge (expressed with h_c), as

$$\frac{E}{h_c} = 2.76\left(\frac{V}{Bh_c^2}\right)^{0.57} \tag{4}$$

The coefficient of determination was $R^2 = 0.94$ between Eq. (4) and the measured values [Fig. 6(a)]. The measurement provided only an approximate value of E due to the heterogeneous nature of driftwood. Eq. (4) considers B as the reference width. The data scatter increases if $nb \ll B$, meaning that only a narrow weir width nb is open [herein, $0.58 \leq nb/B \leq 0.89$ (Table 1)] compared with the total channel width $B = 1.50$ m. The unit discharge h_c comprises the hydraulically active weir width nb as

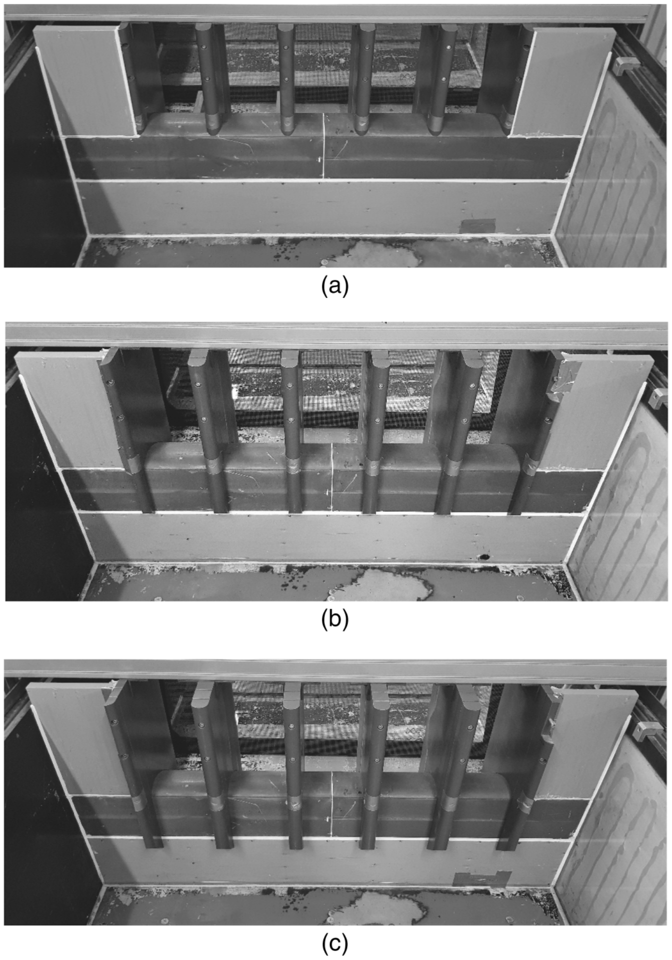


Fig. 7. Model configuration with overhanging piers ($b = 0.175$ m) of (a) $p = 0$ m (upstream pier front aligned with vertical weir front); (b) $p = 0.04$ m (small overhang); and (c) $p = 0.08$ m (large overhang).

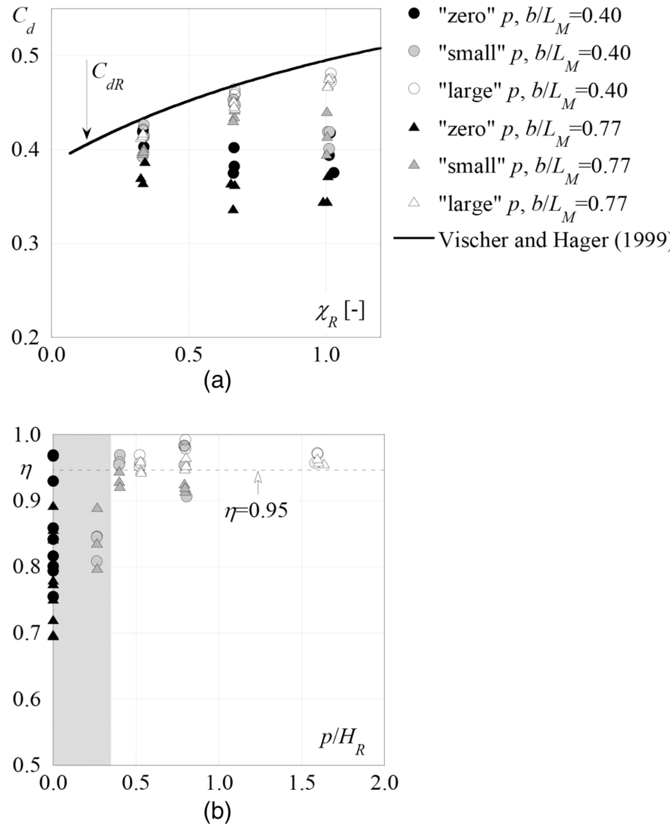


Fig. 8. Effect of pier overhang p (Table 2): (a) C_d versus χ_R; and (b) as function of p/H_R (shaded area denotes affected reach).

$$h_c = \sqrt[3]{\frac{Q^2}{n^2 b^2 g}} \qquad (5)$$

The vertical batch height F (m) (defined between the reservoir water level and the highest trunk at the pier front blockage) also was normalized with Bh_c^2. An envelope following the same structure as Eq. (4) is proposed

$$\frac{F}{h_c} \leq 0.27 \left(\frac{V}{Bh_c^2} \right)^{0.50} \qquad (6)$$

The wooden blockage at the pier front thus vertically rose above the surface of the reservoir, up to F at maximum. The determination of the best fit of the same base equation, but with different coefficients, was $R^2 = 0.62$ [Fig. 6(b)].

Reservoir Level Rise with Countermeasures

Pier Overhang

Tests were performed with overhanging pier fronts protruding into the reservoir (Figs. 3 and 7). The suggested hydraulic effect of this countermeasure is that the driftwood blockage initiated at the pier front is distant from the critical flow section (located near the weir crest and dominating the rating curve).

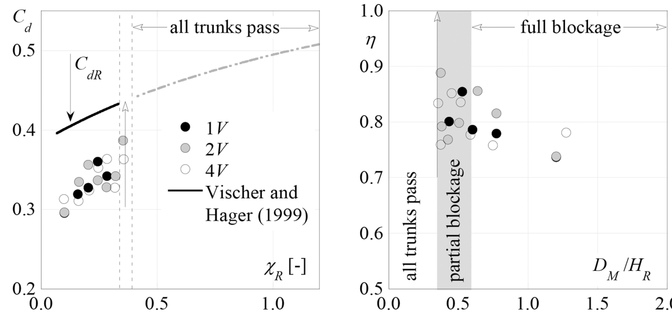
The data included three different overhangs, p: (1) $p = 0$ m (zero overhang) for Tests 16–33, (2) $p = 0.04$ m (small overhang) for Tests 34–42 and 52–60, and (3) $p = 0.08$ m (large overhang) for Tests 43–51 and 61–69 (Table 2). A value of p equivalent to one (0.04 m) or two (0.08 m) pier widths corresponds to classical values to decrease the pier effect on the discharge capacity of the weir (flow contraction). The pier overhang relative to the head without driftwood varied within $0 \leq p/H_R \leq 1.64$. The following parameters were varied: (1) $n = 4$ or 5 open adjacent bays of width $b = 0.175$ or 0.335 m (corresponding to $b/L_M = 0.40$ or 0.77); (2) discharges of approximately $\chi = H_R/H_D = 0.33$, 0.67, or 1.00; and (3) driftwood volumes of $1V$, $2V$, and $4V$.

The data showed a clear positive effect of the pier overhang p. The larger the overhang, the less C_d was affected by the blocked driftwood. Fig. 8(a) shows the rating curve for the three test overhangs. All data of the large overhangs (open symbols) nearly collapsed with the prediction without driftwood (Vischer and Hager 1999), whereas those tests without overhangs (solid symbols) had strongly reduced C_d values. The positive effect of the pier overhang was related to the head H_R expressed as p/H_R [Fig. 8(b)]. Note that

$$\eta = \frac{C_d}{C_{dR}} \qquad (7)$$

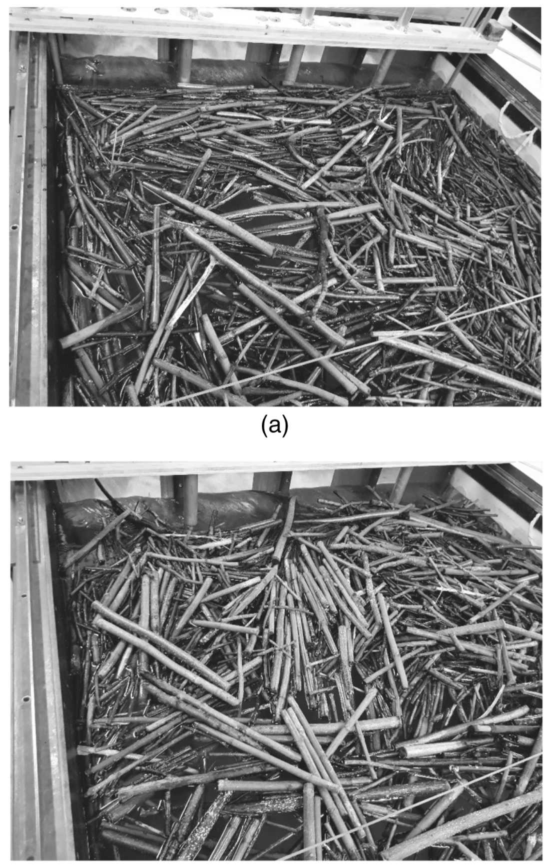
is the discharge coefficient measured with wood divided by the computed reference value without wood (Vischer and Hager 1999). The effect of a full blockage under the herein tested extreme conditions was small (typically $\eta \geq 0.95$) if $p/H_R > 0.35$.

Fig. 9. Physical model without piers during Test 84 (Table 3).



(a) (b)

Fig. 10. Rating curve without piers (Table 3): (a) C_d versus χ_R; and (b) η as a function of D_M/H_R.



(a)

(b)

Fig. 11. Driftwood blockage under otherwise identical conditions (Table 4): (a) Test 98 with full rack; and (b) Test 111 with reduced rack.

Absence of Piers

The absence of piers refers to a physical model without piers (Fig. 9), so that $b = B = 1.5$ m. In reality, this condition herein equated to $B/L_M = b/L_M = 3.46$. Without piers, horizontally floating trunks face no vertical obstacle, so that a blockage is impossible. The driftwood only touches the transversely oriented weir crest, at least for small discharges.

The test procedure (Table 3, Tests 70–89) had to be modified because a full or partial blockage could be maintained only under the smallest discharges. The discharge thus was increased in small steps (roughly +5 L/s each), up to the values at which all the wood passed the crest. Three wood behaviors were identified: full blockage for minimal discharges, partial blockage under small discharges, and the passage of the driftwood under slightly higher discharges. Three wood volumes of $1V$, $2V$, and $4V$ were tested, as well as model discharges up to 0.041 m^3/s (unit discharges of $q = 0.027$ m^2/s).

The discharge coefficient C_d of the fully or partially blocked crest behaved as shown in Fig. 10(a). The C_d value clearly decreased when blockage occurred, as long as $\chi_R < 0.30$–0.35. For larger discharges (higher χ_R), the wood passed, and the C_d value equaled that of the free crest, C_{dR} [Fig. 10(a), Vischer and Hager (1999)]. Pfister et al. (2013) showed that the blocking probability of driftwood on piano key weirs is related to the ratio of the maximum trunk diameter D_M relative to weir head H_R. Fig. 10(b) shows the normalized discharge coefficient η versus D_M/H_R. As in Pfister et al. (2013), three regimes developed: (1) full blockage for $D_M/H_R > 0.60$ with $\eta \approx 0.75$–0.85, (2) individual trunk passage for $0.35 \leq D_M/H_R \leq 0.60$ with $\eta \approx 0.75$–0.90, and (3) a free ogee without blockage for $D_M/H_R < 0.35$ with $\eta \to 1$. Pfister et al. (2013) indicated almost similar limits of $D_M/H_R < 0.35$ for a blockage probability of zero and of $D_M/H_R > 1$ for a blockage probability of 1.

Upstream Rack

Racks were inserted $0.5b$ upstream of the weir (Figs. 3 and 11) for bay widths of $b/L_M = 0.77$ and 0.40. The pier overhang was $p = 0$ m, and relative heads of $\chi_R = 0.17$ to 1.02 were provided.

First, a full rack with one bar per pier exactly positioned upstream of the pier axes was studied [Fig. 11(a), Tests 90–98 and 118–120; Table 4]. This rack acted similarly to overhanging piers because its transverse spacing was b. Second, a reduced rack including only a bar upstream of every second pier was tested [Fig. 11(b), Tests 99–117; Table 4], with a transverse spacing of $2b$. It was suggested that this second arrangement motivates the rotation of the driftwood parallel to the flow so that the trunks would potentially pass the weir without generating a significant reservoir level rise.

All bars were circular in plan view, with a diameter equal to the pier width (e.g., 0.04 m). The bars thus were massive, but this setup

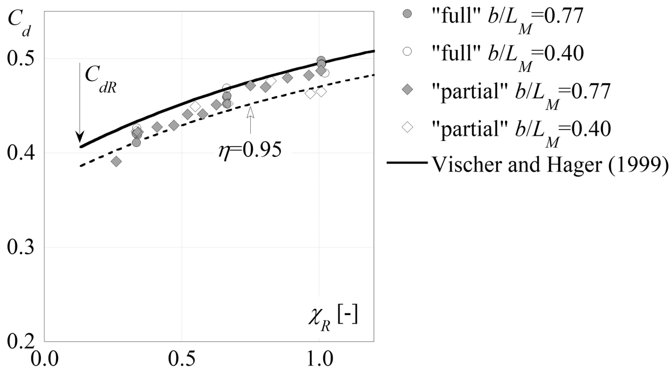


Fig. 12. Ogee rating curve C_d versus χ_R for the model configuration with racks.

allowed a direct comparison of the present results with those of the overhanging piers. Fig. 12 shows C_d versus χ_R for both rack types.

The full rack included tests with driftwood volumes of $1V$–$4V$. The tests indicated that the wood had only a small effect on the discharge capacity, so C_d values larger than 95% of the reference without driftwood were achieved. This is in line with the results of the tests considering overhanging piers. The rack was positioned at $0.57 \leq (0.5b/H_R) \leq 3.35$, which was much farther upstream (in the reservoir) than the minimum distance of $p/H_R > 0.35$ required for an uninfluenced operation in the context of the pier overhang [Fig. 8(b)].

The reduced-rack tests included only the maximum wood volume of $4V$, because the wood volume had no significant effect in previous tests. The rack was positioned at $0.58 \leq (0.5b/H_R) \leq 6.76$, upstream of the minimum distance $p/H_R > 0.35$ required for free operation in the context of the pier overhang [Fig. 8(b)]. The outcome of the reduced-rack tests was inhomogeneous. The presence of the wood partially reduced the discharge capacity, and minima values of 90% of the reference C_d without driftwood were achieved. Some trunks leaned against the pier nose where the rack bar was absent, and thus reached into the critical flow zone on the weir crest, affecting the weir capacity. A systematic rotation of the trunks in the streamwise direction, combined with their passage of the weir, was not observed (Schalko et al. 2019a). This certainly was due to the wood supply mechanism chosen herein, in which the full volume was provided in one single batch. We suppose that a reduced rack could be more efficient and (partially) could orient the trunks if the wood were supplied continuously and in small batches of, e.g., five trunks.

Full racks maintained the discharge capacity expressed by C_d by trend slightly better than did reduced racks. However, fewer data were available for full than for reduced racks. Reduced racks clearly improved the situation up to large discharges ($\chi_R < 0.90$), compared with the setup without countermeasures [Fig. 5(b)], but were less efficient for the design case ($\chi_R \approx 1$).

Conclusions

The following observations were made within the framework of the model tests conducted herein:

- An extreme and instantaneous occurrence of driftwood blocked a gated (with piers) ogee crest. Godtland and Tesaker (1994) stated that such a blockage appears if $b/L_M < 0.80$, i.e., if the bay width b is less than 80% of the L_M of the longest trunks arriving.
- Godtland and Tesaker's (1994) criterion was not tested herein, but the tests confirmed a blockage if $b/L_M < 0.77$. The blockage partially had to be provided manually in the model for $b/L_M = 0.77$, indicating that the blockage limit was approached.
- A blocked gated ogee crest generated a reservoir level rise if no countermeasures were provided. Without countermeasures and for a full blockage, a relatively constant mean value of $C_{d\mu} = 0.38$ was observed in the model. This was independent of the discharge (up to the design discharge), of the relative bay width (for $b/L_M \leq 0.77$), and of the driftwood volume (for extreme volumes). With regard to the variation in the data, which is typical for driftwood, a coefficient of $C_d = C_{d\mu} - \sigma = 0.36$ is recommended for practice [Fig. 5(b)].
- Overhanging piers reduced the negative effect of driftwood on the rating curve. The effect of a fully blocked weir on C_d is quasi-absent ($\eta \geq 0.95$) if the pier overhang p into the reservoir (Fig. 3) exceeds $0.35H_R$ (reference head H_R without driftwood).
- Without piers (nor gates or a weir bridge, i.e., if b/L_M is large), no effect of a driftwood blockage on C_d was observed if the maximum trunk diameter D_M was below $0.35H_R$ [Fig. 10(b), All trunks pass]. A blockage with an individual and sporadic trunk passage was observed for trunk diameters of $0.35H_R$–$0.60H_R$, and a full blockage occurred for diameters exceeding $0.60H_R$.
- A full rack (one bar per pier, respecting the Godtland and Tesaker criterion) positioned $0.5b$ upstream of the weir front almost removed ($\eta \geq 0.95$) the effect of the driftwood blocked at the rack.
- A reduced rack with one bar every other pier did not respect the Godtland and Tesaker criterion. Accordingly, wood reached the ogee crest and partially perturbed the discharge capacity, so that only $\eta \geq 0.90$ was achieved.
- Only an extreme driftwood volume instantaneously arriving at the ogee was tested herein, presenting an extreme scenario. Continuously arriving smaller batches may behave differently. Furthermore, the results presented herein are related to a reservoir approach and an ogee crest only.
- A thorough spillway design including overhanging piers (or a rack), respecting the Godtland and Tesaker (1994) criterion or following an adequate weir regime, reduces the risk related to driftwood blockage. The present study is pertinent for existing structures in which these measures are not yet applied.
- Driftwood contributes to ecological diversity and should thus remain in streams. Ideally, blockage countermeasures should cause the driftwood to pass the spillway without generating any backwater rise.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article (Tables 1–4).

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Notation

The following symbols are used in this paper:

B = total channel width (m);
b = individual bay width (m);

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C_d = discharge coefficient;
D = trunk diameter (m);
E = horizontal driftwood carpet extension normal to weir axis (m);
F = vertical blockage height (above reservoir surface) of driftwood at pier front (m);
g = acceleration of gravity (m/s^2);
H = upstream weir head (m);
h_c = critical flow depth (m);
L = trunk length (m);
n = number of open bays;
Q = discharge (m^3/s);
q = unit discharge (m^2/s);
R = coefficient of determination;
U = upstream channel flow velocity (m/s);
V = driftwood volume (m^3);
W = vertical offset between channel bottom and weir crest (m);
λ = geometrical scale factor;
ρ = water density (kg/m^3); and
χ = relative head.

Subscripts

D = design;
M = maximum; and
R = reference, i.e., without driftwood.

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