Log jam formation at bridges and the effect on floodplain flow: A flume experiment

Takaaki Okamoto1 | Hiroshi Takebayashi2 | Michio Sanjou3 | Ryuta Suzuki4 | Keiichi Toda1

1Department of Civil Engineering, Kyoto University, Kyoto, Japan
2Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
3Civil and Earth Resources Engineering, Kyoto University, Kyoto, Japan
4Nagasaki Office of River and National Highway, Ministry of Land, Infrastructure, Transport and Tourism, Nagasaki, Japan

Correspondence
Takaaki Okamoto, Department of Civil Engineering, Kyoto University, Kyoto 615-8540, Japan.
Email: takaaki.okamoto@water.kuciv.kyoto-u.ac.jp

Abstract
During localized torrential rains, a large amount of driftwood can be entrained into the river leading to decreased discharge capacity and increased water levels. In August 2012, driftwood accumulated at the bridge in Shizugawa River in Uji, Japan and a house was washed away by the floodplain flow. For disaster prevention, it is important to know the flow characteristics of the floodplain flow. However, detailed information to accurately characterize the floodplain flow around bridges is usually not available. In this study, three kinds of flume experiments were performed. First, we conducted the driftwood accumulation and porous board tests at the model bridge to evaluate backwater rise and blockage ratio of driftwood accumulation (to further conduct PIV measurements). After a large amount of driftwood accumulated at the bridge, the water overflowed the banks and floodplain flow occurred. Next, we examined the effect of the surface hydraulics on driftwood accumulation process by PIV. Then, we measured the velocity of floodplain flow by PIV, in which the accumulation was modeled using a porous board. The results revealed the effect of driftwood accumulation on floodplain flow. The obtained velocity distribution of floodplain flow is useful to estimate the erosion damage location by floodplain flow.

KEYWORDS
backwater rise due to driftwood accumulation, blockage ratio of driftwood accumulation, effect of surface hydraulics on accumulation process, PIV, velocity of floodplain flow

1 INTRODUCTION

During localized torrential rains, a large amount of driftwood is entrained into a river channel. Driftwood accumulation at a bridge leads to backwater rise and flooding of nearby areas (Ruiz-Villanueva, Bodoque, Diez-Herrero, and Blade (2014), Lucía, Comiti, Borga, Cavalli, and Marchi (2015), Comiti, Lucía, and Rickenmann (2016)). In August 2012, heavy rain hit Uji, Japan. The driftwood jam blocked Shizugawa River and the high-speed floodplain flow caused the severe damage to the houses on the surrounding floodplain (Okamoto, Takebayashi, Kaneko, Shibayama, and Toda (2016)). Therefore, for disaster prevention, it is important to know the backwater rise due to the driftwood accumulation at bridges and the flow characteristics of floodplain flow.

Many researchers have focused on the transport of driftwood. Braudick and Grant (2001) examined the transport...
and deposition of large driftwood in rivers by flume experiments. Their experiments indicated that driftwood was deposited where the channel depth was less than the buoyant depth. Bocchila, Rulli, and Rosso (2008) observed the statistical linkage between driftwood jam size and transport distance of logs.

Wohl and Jaeger (2009) investigated the relations between the longitudinal distribution of driftwood and channel width, bed gradient and total stream power by using field measured data. Ruiz-Villanueva, Bladé, Diez-Herrero, Bodoque, and Sánchez-Juny (2014) developed two-dimensional modeling of the transport of driftwood and deposition pattern of wood. In addition, the increase in water level and the change in flow velocity due to a driftwood accumulation were reproduced by the model.

An empirical equation for predicting the blocking probability of driftwood at a river infrastructure (bridges or weirs) has been proposed. Lyn, Cooper, Yi, Sinha, and Rao (2003) examined the effect of flow velocity and flow depth on the blocking probability of logs at a central pier. Bocchila, Rulli, and Rosso (2006) indicated that the blocking probability of logs and their trapping mechanism, “bridging two rods” or “leaning against a single rod”, depended on the log length and flow conditions. Bocchila et al. (2008) revealed that the blocking probability was higher for single logs than that for driftwood jams. Schmocker and Hager (2011) observed that the blocking probability of logs at the bridge deck increased with flow depth and decreases with an increasing Froude number. Pfister, Capobianco, Tullis, and Scheiss (2013) indicated that the blocking probability at piano key weirs was highly influenced by the log diameter and upstream head.

Schalko (2017) revealed that the blocking probability at the pier increased with increasing log length and with decreasing approach flow velocity. According to her results, the Froude number had negligible effect on the blocking probability. De Cicco, Paris, Ruiz-Villanueva, Solari, and Stoffel (2018) conducted a review about the factors influencing the driftwood blocking at bridge piers and summarized the experimental and numerical modeling approaches used to analyze the accumulation process.

Several studies have been conducted to examine the backwater rise due to the driftwood accumulation. Schmocker and Hager (2013) and Schalko, Schmocker, Weitbrecht, and Boes (2018) conducted driftwood accumulation tests at a debris rack to evaluate the governing parameter on the resulting backwater rise. Schalko et al. (2018) indicated that the backwater rise increased with increasing approach flow Froude number, driftwood accumulation length, organic fine material and compactness of the accumulation and with decreasing mean log diameter. Panici and de Almeida (2018) examined the formation and growth of the driftwood jams at bridge piers and revealed a clear dependency of the accumulation length on flow characteristics and log length distribution.

There are few studies published on blockage ratio of driftwood accumulation, effect of surface hydraulics on accumulation process and floodplain flow around a bridge. When a driftwood jam blocks a river, the flow depth increases upstream of the river and floodplain flow occurs around a bridge (Uji, Japan in 2012 and Shiso, Japan in 2018, Figure 1). In Uji, the floodplain flow in Shizugawa River flowed into the surrounding floodplain and consequently the house was washed away (Figure 1).

Three kinds of the flume experiments were conducted in this study. First, we conducted the driftwood accumulation tests at the model bridge to evaluate the backwater rise. After a large amount of driftwood accumulation at the bridge, the water overflowed the banks and floodplain flow occurred. The values of flow depth for driftwood accumulation tests were compared with those for porous board tests and we evaluated the blockage ratio of the driftwood accumulation to further conduct PIV measurements. Next, we measured the flow velocity upstream of the bridge pier by PIV after the single log was trapped and examined the effect of the surface hydraulics on accumulation process. Then, we measured the velocity of the floodplain flow by PIV, in which the accumulation was modeled using a porous board. The results revealed that the obtained velocity distribution of floodplain flow is useful to estimate the erosion damage location by floodplain flow.

2 | EXPERIMENTAL PROCEDURES

2.1 | Driftwood accumulation experiments

Figure 2 shows the setup of the driftwood accumulation experiment and the coordinate system. The experiments were conducted in a 10 m long and 0.4 m wide glass-made flume. The $x$-axis is in the streamwise direction, with $x = 0$ at the upstream edge of the model bridge. The $y$-axis is in the vertical direction, with $y = 0$ at the floodplain surface. The $z$-axis is in the spanwise direction, with $z = 0$ at the channel wall. Furthermore, $U$, $V$, and $W$ are the time-averaged velocity components in the streamwise, vertical and spanwise directions, respectively; $u$, $v$, and $w$ are the corresponding turbulent fluctuations.

Floodplain models (1/80 scale: composed of hard vinyl chloride) were placed on both sides of the channel, as shown in Figure 2. The width of both floodplains is $B_f = 0.1$ m and the width of the main-channel region is $B_m = 0.2$ m. The bank height is uniform in the streamwise direction ($D = 0.1$ m). The model railing bridge (0.04 m height) was mounted 4.0 m from the upstream edge of the floodplain and 0.09 m above the channel bottom. The bridge is
composed of a railing (0.04 m height), a deck and two rectangular piers (0.01 m width). The bridge roadway is 0.2 m long, 0.05 m wide and 0.01 m thick. Bridge-pier spacing is $BR = 0.06$ m. The model bridge was fixed to the floodplains.

Wooden dowels were used to model logs. The density of the wooden dowels was $0.5 \text{ g/cm}^3$. The model log length varied between $l = 0.06$ and 0.12 m and its diameter is $d = 0.006$ m. The floating wood length in an actual river is $4.0–10.0$ m (Figure 1d). The wooden dowels were soaked in water for 2 hr prior to a test.

First, we evaluated the blocking probability of a single model log at the bridge. The experiment was carried out by adding a single model log to the approach flow. The angle of supplied model logs was randomly varied. The release point for the dowels was at 4.0 m upstream from the model bridge ($x = -4.0$ m). If the single model log was trapped by the bridge piers, it was removed before the next test. The test was repeated 40 times for each case.

Next, we investigated the backwater rise due to driftwood accumulation. 270 wooden dowels were supplied...
continuously to the flow for each case (the total number of supplied model logs: \( n_d = 270 \)). The model logs were added randomly over the channel width. Over the entire test duration, we measured the temporal development of flow depth \( H \) in the main-channel at a point 0.1 m upstream of the bridge (\( x = -0.1 \) m) using a manual point gauge (±0.5 mm) to examine the backwater rise due to the driftwood accumulation at the bridge. To evaluate test repeatability, ten times tests (Test 1–10) were conducted for each case.

Then, we evaluated the blockage ratio of the driftwood accumulation to further conduct PIV measurements. The end-of-test values of flow depth \( H_{\text{max}} \) for driftwood accumulation tests were compared with those of flow depth \( H_p \) for porous board tests and we evaluated the blockage ratio of the driftwood accumulation. The model logs accumulated at the bridge were removed prior to the porous board tests. A porous board (0.15 m high, 0.2 m wide, 0.003 m thick with a 0.003 m hole-diameter) was placed upstream of the bridge in the main-channel (Figure 2c). The blockage ratio of the porous board \( \lambda_b \) is calculated as follows:

\[
\lambda_b = \frac{A_b}{A}
\]

where \( A_b \) is the shaded area of the porous board and \( A \) is cross-sectional area in main-channel (\( A = B_m D \)). The blockage ratio of the porous board \( A_b/A \) was varied between 0.2 and 0.91. We measured the flow depth in main-channel \( H_p \) throughout the porous board tests at 0.1 m upstream of the bridge using a point gauge for \( Fr = 0.26, 0.43, 0.6, \) and 0.78.

### 2.2 Velocity measurements upstream of bridge pier

To investigate the effect of the surface hydraulics on the first accumulation process, the flow velocity upstream of the bridge pier was measured by PIV, as shown in Figure 3. The experiments were conducted in a 10 m long and 0.2 m wide glass-made flume. The instantaneous velocity components \( (u, v) \) on the \( x-y \) vertical plane (0.15 × 0.15 m) were calculated by a PIV algorithm (Okamoto and Nezu (2013), Sanjou, Okamoto, and Nezu (2018)). The 0.002 m thick LLS (laser light sheet) was generated by 3.0 W YAG-laser using a cylindrical lens. The illuminated flow pictures were taken by a high-speed CCD camera (1,024 × 1,024 pixels) with 500 Hz frame-rate and 60 s sampling time. The fluid tracers were Nylon-12 particles of 80 μm diameter and 1.02 specific density. A LLS was vertically projected from the channel bed. To examine the effect of the accumulated driftwood on the surface hydraulics, the single model log (\( l = 0.12 \) m) was added to the flow. After the log was trapped by the pier, we measured the flow velocity (\( n_d = 1 \)).

### 2.3 Velocity measurements of floodplain flow

To examine the velocity distribution of the floodplain flow, we measured the flow velocity on the floodplains by vertical PIV and horizontal PIV, as shown in Figure 4. The experiments were conducted in a 10 m long and 0.4 m wide glass-made flume. According to the preliminary experiments (measurements of drag force exerted on the model house on floodplain, Okamoto et al., 2016), the results revealed that the flow characteristics of floodplain flow depended on the flow depth upstream of the bridge. When the resulting backwater rise (flow depth \( H_p \)) using a porous board was similar to the experiments with the driftwood accumulation, the values of the drag force exerted on the house on floodplain using a porous board consisted with those using model logs. Thus, the porous board was placed upstream of the bridge in the main-channel to mimic a blocked river due to driftwood accumulation at a bridge. The blockage ratio of the porous board was varied based on the driftwood accumulation tests in Section 2.1 (\( A_b/A = 0.56, 0.65, \) and 0.74).

For vertical PIV, a LLS was vertically projected from the water surface. The position of the LLS was varied in the spanwise direction (\( z/B_m = 0.1, 0.2, 0.3, 0.4, \) and 0.45 on right bank and \( z/B_m = 1.55, 1.6, 1.7, 1.8, \) and 1.9 on left bank). The illuminated pictures were taken by the same
CCD camera. The location of the PIV measurement was changed in the streamwise direction, starting 0.7 m upstream of the bridge ($x = -0.7$ m) and extending to 0.7 m downstream of the leading edge of the bridge ($x = 0.7$ m). The velocity components ($\hat{u}, \hat{v}$) on the $x$-$y$ vertical plane ($0.15 \times 0.15$ m) were calculated.

For horizontal PIV, we measured the flow velocity on the floodplains and in the main-channel. The LLS was horizontally projected near the free surface ($y / H_f = 0.9$). The velocity components ($\hat{u}, \hat{w}$) on the $x$-$z$ horizontal plane ($0.2 \times 0.2$ m) were calculated by a PIV algorithm. Downstream of the bridge ($x/B_m \geq 0$), the flow depth in the main-channel is smaller than the bank height ($H < D$), as shown in Figure 4b. The LLS does not pass through the floodplain models. Therefore, we could not measure the flow velocity in the main-channel downstream of the bridge.

### 2.4 | Hydraulic conditions

Table 1 shows the hydraulic conditions of the driftwood accumulation experiments (CaseD series). The model log length ($l = 0.06, 0.09, \text{and} 0.12$ m) and the flow discharge $Q$ were varied. $U_m$ is the initial bulk mean velocity. $H_m$ denotes the initial flow depth in the main-channel (Figure 2b). $Fr = U_m / \sqrt{gH_m}$ denotes the approach Froude number.

Table 2 shows the hydraulic conditions of porous board tests and the velocity measurement experiments. For CaseP series (Porous board tests), the end-of-test values of flow depth $H_{max}$ for driftwood accumulation tests were averaged in ten times repeated tests and compared with those of flow depth $H_p$ for porous board tests. We evaluated the blockage ratio of the driftwood accumulation to further conduct PIV measurements. The blockage ratio of the porous board ($A_p/A = 0.2–0.91$) and flow discharge $Q$ were varied.

For CaseS series (Surface hydraulics), the flow velocity upstream of the bridge pier was measured by PIV before the addition of the model log ($n_d = 0$) to investigate the effect of the surface hydraulics on accumulation process. After the

### Table 1 | Hydraulic conditions (driftwood accumulation)

| Method       | $Q$(l/s) | $U_m$(m/s) | $H_m$(m) | $l$(m) | $d$(m) | $l/d$ | $B_R$(m) | $l/B_R$ | $D$(m) | $Fr$ |
|--------------|----------|------------|----------|--------|--------|-------|----------|---------|-------|------|
| Driftwood accumulation | 3.0      | 0.21       | 0.07     | 0.60   | 0.006  | 10    | 0.06     | 1.0     | 0.1   | 0.26 |
| CaseD6-1     | 5.0      | 0.36       |          |        |        |       |          |         |       |      |
| CaseD6-2     | 7.0      | 0.50       |          |        |        |       |          |         |       |      |
| CaseD6-3     | 9.0      | 0.64       |          |        |        |       |          |         |       |      |
| CaseD6-4     | 3.0      | 0.21       | 0.09     | 15     | 1.5    |       |          |         |       |      |
| CaseD9-1     | 5.0      | 0.36       |          |        |        |       |          |         |       |      |
| CaseD9-2     | 7.0      | 0.50       |          |        |        |       |          |         |       |      |
| CaseD9-3     | 9.0      | 0.64       |          |        |        |       |          |         |       |      |
| CaseD9-4     | 3.0      | 0.21       | 0.12     | 20     | 2.0    |       |          |         |       |      |
| CaseD12-1    | 5.0      | 0.36       |          |        |        |       |          |         |       |      |
| CaseD12-2    | 7.0      | 0.50       |          |        |        |       |          |         |       |      |
| CaseD12-3    | 9.0      | 0.64       |          |        |        |       |          |         |       |      |
| CaseD12-4    | 3.0      | 0.21       | 0.12     | 20     | 2.0    |       |          |         |       |      |
single log was trapped by the pier, we measured the flow velocity upstream of the pier ($n_d = 1$).

For CaseF series (Floodplain flow), the PIV measurements of floodplain flow were conducted, in which the blockage ratio of the porous board $A_b/A$ was changed based on the driftwood accumulation and porous board tests ($A_b/A = 0.56$, $0.65$, and $0.74$). Prior to a flood (without the porous board), the water in the main-channel did not overflow the banks. The bulk mean velocity was $U_m = 0.5$ m/s (which corresponds to $U_r = 4.5$ m/s [prototype scale in an actual river]) and the approach (initial) flow depth in the main-channel was $H_m = 0.07$ m.

### Table 2

| Case | $Q$ (l/s) | $U_m$ (m/s) | $H_m$ (m) | $D$ (m) | $A_b/A$ | Fr | $l$ (m) | $n_d$ | Method |
|------|----------|-------------|-----------|---------|---------|-----|---------|-------|--------|
| CaseP-1 | 3.0 | 0.21 | 0.07 | 0.1 | 0.2-0.91 | 0.26 | — | — | Porous board test |
| CaseP-2 | 5.0 | 0.36 | — | — | 0.2-0.91 | 0.43 | — | — | Porous board test |
| CaseP-3 | 7.0 | 0.50 | — | — | 0.2-0.91 | 0.60 | — | — | Porous board test |
| CaseP-4 | 9.0 | 0.64 | — | — | 0.2-0.91 | 0.78 | — | — | Porous board test |
| CaseS-1 | 7.0 | 0.50 | 0.07 | 0.1 | — | 0.60 | 0.12 | 0 | Flow upstream of bridge pier/PIV |
| CaseS-2 | 7.0 | 0.50 | — | — | 0.60 | 0.12 | 1 | — | Flow upstream of bridge pier/PIV |
| CaseS-3 | 7.0 | 0.50 | — | — | 0.60 | 0.12 | 2, 3 | — | Observation of trapped logs |
| CaseF-1 | 7.0 | 0.50 | 0.07 | 0.1 | 0.56 | 0.60 | — | — | Floodplain flow/PIV |
| CaseF-2 | 7.0 | 0.50 | — | — | 0.65 | 0.60 | — | — | Floodplain flow/PIV |
| CaseF-3 | 7.0 | 0.50 | 0.74 | — | 0.60 | — | — | — | Floodplain flow/PIV |

### Figure 5

Photographic examples of the driftwood accumulation for CaseD12-1 ($Fr = 0.26$) and CaseD12-3 ($Fr = 0.6$), number of supplied driftwood ($l/B_R = 2.0$, $n_d = 100$)

3 | RESULTS

#### 3.1 Driftwood accumulation at a bridge and backwater rise

The driftwood accumulation tests were performed to evaluate the accumulation probability, backwater rise and blockage ratio of the driftwood accumulation. Figure 5a,b shows the example photographs of the driftwood accumulation for CaseD12-1($l/B_R = 2.0$, $Fr = 0.26$) and CaseD12-3($l/B_R = 2.0$, $Fr = 0.6$), respectively. After the first group of model logs is added to the flow, some logs touch a pier, turn and span between two piers. The other logs pass through the bridge. The blocking probability of logs is $P_b = 0.225$ prior to the initial blockage for $l/B_R = 2.0$, $Fr = 0.6$ ($P_b = 0.075$ for $l/B_R = 1.5$, $P_b = 0.0$ for $l/B_R = 1.0$). The blocking probability $P_b$ mainly depends on the log dimension and flow velocity (Schalko, 2017). Once one or two logs are trapped, the blocking probability significantly increases and the driftwood accumulation starts.

For CaseD12-1 (low Froude number case), the logs accumulate near the free surface and the driftwood accumulation expands upstream. For CaseD12-3 (high Froude number case), the driftwood accumulation length is small, but the accumulation resulted in an increase in the water level upstream from the bridge. Figure 6 shows the temporal development of the flow depth in the main-channel $H$ at 0.1 m upstream of the bridge ($x/B_m = -0.5$) for CaseD12-3($Fr = 0.6$). The flow depth values are normalized by the initial flow depth $H_m$. For CaseD12-3($l/B_R = 2.0$), at the start of the driftwood accumulation, the flow depth increases rapidly with the number of trapped logs (Schmocker and Hager (2013)). After 70 logs are added to the flow ($n_d = 70$), the flow depth increases slowly. After the addition of 200 logs ($n_d = 200$), the flow depth reaches the almost constant value. This implies that after a large amount of logs accumulates at the bridge, the
flow depth increases and the flow velocity upstream of the bridge decreases. The incoming logs do not sink under the trapped logs. Consequently, the driftwood accumulation expands upstream (blockage ratio of the accumulation increases slowly). Due to the random accumulation process, the increase rate of the flow depth varies between the repeated tests (Test1-10). However, the end-of-test values of the flow depth \( H_{\text{max}} \) are almost same for Test1-10.

Figure 7a shows the end-of-test value of the flow depth in the main-channel \( H_{\text{max}} \). The values of the flow depth in ten times repeated tests are averaged for each case. Maximum and minimum values of \( H_{\text{max}} \) for the repeated tests are also indicated.

For CaseD6 \( (l/BR = 1.0) \), some logs touch a pier, but do not span two piers. Consequently, all logs pass through the bridge and the values of \( H \) remain constant. The values of \( H_{\text{max}} \) for \( l/BR = 2.0 \) are larger than those for \( l/BR = 1.5 \). This implies that the increase in the blockage ratio \( A_p/A \) of the driftwood accumulation is determined by the log dimensions and the approach Froude number. The values of \( A_p/A \) are larger for high Froude number cases than those for low Froude number cases. For high Froude number cases \( (Fr \geq 0.6) \), some logs are trapped near the channel bed (0.01 m from the channel bed). This implies that the incoming logs sink under the water surface and the driftwood accumulation blocks nearly the entire flow depth region (Figures 8a,b). For low Froude number cases \( (Fr \leq 0.26) \), the sinking motion of the logs is not observed. (Figure 8a).

### 3.2 Effect of surface hydraulics on accumulation process

To evaluate the contribution from the surface hydraulics to the driftwood accumulation process, the flow velocity upstream of the bridge pier was measured by PIV. Figure 9a shows the time-averaged velocity vectors \( (U, V) \) upstream of the bridge pier before the addition of the single model log \( (n_d = 0) \). The Froude number is \( Fr = 0.6 \). The contour of the time-averaged vertical velocity \( V \) is also depicted by the
rainbow in Figure 9a. The x-axis is normalized by the main-channel width $B_m$.

Under the water surface (at $y/H_m = 0.0$–0.7), the downward flow ($V < 0$) occurs upstream of the pier. In contrast, the upward flow is observed near the water surface (at $y/H_m = 0.9$–1.0). Figure 10 shows the photographs of the driftwood accumulation for CaseS-2 and CaseS-3 ($n_d = 1, 2, 3$; $Fr = 0.6$). After the single log ($n_d = 1$; $l/BR = 2.0$) is added to the flow, the log is trapped by the pier. However, the trapped log does not sink under the water surface due to the upward flow.

Figure 9b shows the time-averaged velocity vectors ($U$, $V$) upstream of the bridge pier after the addition of the single log ($n_d = 1$). Once the single log (Log1) is trapped, the region of the negative vertical velocity ($V < 0$) increases and the strong downward flow occurs near the trapped log. After the second log (Log2) is added to the flow ($n_d = 2$), incoming Log2 presses trapped Log1 downward and the trapped log is transported toward the channel bed by the downward flow (Figure 10). Consequently, Log1 is trapped near the channel bed (0.01 m from the channel bed) and the blockage ratio of driftwood accumulation increases. When a number of logs are supplied to the flow, it is also observed that the incoming logs sink under the trapped ones.

### 3.3 Occurrence condition of floodplain flow around a bridge

To investigate the occurrence condition of floodplain flow around a bridge, Figure 11 shows the flow depth $H_f$ on the right bank at the bridge edge ($x/B_m = 0.0$) for CaseP-3 and CaseP-4. For $Fr = 0.6$, the flow depth is $H_f = 0$ when $A_p/A \leq 0.49$, indicating that the water in the main-channel does not overflow the banks. When $A_p/A \geq 0.49$, the water in the main-channel overflows the banks ($H > D$) and the flow depth increases linearly. The occurrence condition of floodplain flow depends on the Froude number. For $Fr = 0.78$, floodplain flow occurs around the bridge when $A_p/A$ exceeds 0.3.

Figure 12 shows the contours of the water level $y_w$ on the horizontal plane for $Fr = 0.6$ and $A_p/A = 0.65$. $y_w = 0$ is at the floodplain surface. Upstream of the bridge ($x/B_m \leq 0$), the water level $y_w$ is almost constant in the streamwise direction and the difference between the left and the right banks cannot be observed.

Downstream of the bridge ($x/B_m \geq 0$), it is also observed that the values of the water level $y_w$ at $z/B_m = 0.4$, 1.6 (near the floodplain edge) are lower than those at $z/B_m = 0.1$, 1.9 (far from the floodplain edge). These results imply that the floodwater on both banks returns to the main-channel for $x/B_m \geq 0$. The values of the water level $y_w$ on the banks
positions are $z/B_m = 0.3$ and 0.1 on the right bank. The Froude number is $Fr = 0.6$ and the blockage ratio of the porous board is $A_p/A = 0.65$. The flow velocity slightly increases in the streamwise direction for $x/B_m \leq 0$ (upstream of the bridge). The flow velocity values rapidly increase downstream for $x/B_m \geq 0$ (downstream of the bridge). This is because the flow depth $H_f$ decreases rapidly downstream, as shown in Figure 12. The peak velocity value is observed at $x/B_m = 1.5$ and reaches over $U/Um = 1.6$ ($U = 0.8$ m/s corresponds to $U_p = 7.1$ m/s [prototype scale in an actual river]). The region of $x/B_m = 0.0$–1.5 on the bank is estimated as the flood-hazard area. In Uji, Japan, in 2012, the flood damage was small upstream of the bridge and the house downstream of the bridge was washed away by the floodplain flow (Figure 1b). In Shiso, Japan, in 2018, the floodplain flow eroded the bank around the bridge and the erosion depth increases downstream (Figure 1c). In contrast, for $x/B_m > 2.0$, the flow depth $H_f$ decreases slightly and the floodplain flow returns to the main-channel. Consequently, the flow velocity decreases downstream.

To estimate the flow discharge on the left and right banks, we integrated the (local) flow discharge per unit width in the spanwise direction. Figure 15 shows the spanwise distribution of the flow discharge per unit width $ΔQ(z) = H_f(z) \cdot \langle U \rangle(z)$ at $x/B_m = 0$ (upstream edge of the bridge). The Froude number is $Fr = 0.6$ and the blockage ratio of the porous board is $A_p/A = 0.65$. The depth-averaged streamwise velocity $\langle U \rangle(z)$ and flood-flow discharge per unit width $ΔQ(z)$ are calculated as follows:

$$\langle U \rangle(z) = \frac{1}{H_f(z)} \int_0^{H_f(z)} Ud\gamma$$

$$ΔQ(z) = H_f(z) \cdot \langle U \rangle(z)$$

The values of $ΔQ(z) = H_f(z) \cdot \langle U \rangle(z)$ are not uniform in the spanwise direction. For the right bank, the values of $ΔQ(z)$ become larger at $z/B_m = 0.2$ and 0.3 (at a point located at...
a small distance from the bridge). This indicates that on the right bank, the flow velocity slightly decreases at $z/B_m = 0.4$ and 0.45 (near the bridge) and increases at $z/B_m = 0.2$ and 0.3. These results provide suggestive evidence that in an actual river, high-speed flow causes bank erosion in a location situated at a small distance from the bridge in the spanwise and downstream directions (Figure 1c).

Using the approximate curve (polynomial approximation), we integrated the (local) flood discharge per unit width and successfully evaluated flood discharge on the floodplain. The flood discharge on the left and right banks is calculated as follows:

**Figure 12** Contours of time-averaged streamwise velocity on floodplain on vertical plane ($A_b/A = 0.65$, $Fr = 0.6$)

**Figure 13** Contours of time-averaged streamwise velocity on horizontal plane ($A_b/A = 0.65$, $Fr = 0.6$)

**Figure 14** Contours of time-averaged streamwise velocity on floodplain on vertical plane ($A_b/A = 0.65$, $Fr = 0.6$)

**Figure 15** Spanwise distribution of flow discharge per unit length on floodplain for $A_b/A = 0.65$ and $Fr = 0.6$
At the start of the driftwood accumulation, the flow depth rapidly increases with the number of trapped model logs. After the addition of 200 logs, the flow depth reaches an almost constant value. This indicates that after a large amount of logs accumulates at the bridge, the incoming logs do not sink under the trapped logs. Consequently, the driftwood accumulation expands upstream and the blockage ratio of the accumulation slowly increases.

2. The results reveal that the blockage ratio of the driftwood accumulation is determined by the driftwood dimension and the approach Froude number. The blockage ratio of the driftwood accumulation is found to be $A_l/A = 0.65$ for CaseD12-3($l/B_{m} = 2.0$) and $A_l/A = 0.56$ for CaseD9-3($l/B_{m} = 1.5$). The values of $A_l/A$ are larger for high Froude number cases than those for low Froude number cases. For low Froude number cases ($Fr \leq 0.26$), the incoming logs sink under the water surface and the accumulation expands upstream. Final accumulation shape is described as a driftwood carpet. For high Froude number cases ($Fr \geq 0.6$), the incoming logs sink under the water surface and the driftwood accumulation blocks the almost whole flow depth region.

3. We examined the effect of surface hydraulics on the accumulation process. Once a log is trapped, the strong downward flow occurs near the trapped log. The incoming logs press the trapped log downward and the log is transported toward the channel bed by the downward flow. Consequently, the blockage ratio of driftwood accumulation increases.

4. The results of the PIV experiments revealed that the velocity of floodplain flow is low upstream of the bridge. In contrast, the floodplain flow velocity rapidly increases downstream of the bridge ($x/B_{m} = 0.0-1.5$). This result has the same tendency with the erosion damage location by floodplain flow in Uji, 2012 and Shiso, 2018, Japan.

5. Using the approximate curve, we integrated the flow discharge per unit width and successfully evaluated the discharge of floodplain flow in the blocked river. The results revealed that the flow discharge on both banks $Q_f (=Q_L + Q_R)$ increases with an increase of the blockage ratio of the porous board. For $A_l/A = 0.65$, 20.8% of the total flow discharge runs into the floodplains in the blocked river.

The derived blockage ratio values of driftwood accumulation can be used to model the accumulation at a bridge in numerical simulation of flooding due to log jam. The obtained velocity distribution of floodplain flow can be useful for a flood risk assessment tool. Downstream of a bridge, the houses are at risk of collapse and being washed away when a river overflows its banks. It is necessary to estimate...
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NOTATIONS

\( A = B_h D \)  
cross-sectional area of main-channel
\( A_b \)  
shaded area of porous board
\( A_p / A \)  
blockage ratio of porous board (=\( \lambda_b \))
\( B_f \)  
main-channel width
\( B_m \)  
end-of test value of flow-depth in main-channel
\( B_R \)  
bridge pier spacing
\( d \)  
model log diameter
\( D \)  
bank height
\( Fr \)  
approach Froude number( = \( U_m / \sqrt{g H_m} \))
\( H \)  
flow-depth in main-channel (increases with driftwood accumulation)
\( H_f \)  
flow depth on floodplain
\( H_m \)  
initial flow-depth in main-channel
\( H_{max} \)  
end-of test value of flow-depth in main-channel
\( H_p \)  
flow-depth in main-channel for porous board tests
\( l \)  
model log length
\( n_d \)  
number of model logs (supplied to water)
\( P_b \)  
blocking probability of model log
\( Q_C \)  
flow discharge on both banks
\( Q_L \)  
flow discharge on left bank
\( Q_R \)  
flow discharge on right bank
\( Q_M \)  
flow discharge in main-channel
\( Q \)  
total flow discharge
\( \Delta Q \)  
flow discharge per unit width
\( U \)  
time-averaged velocity component in the streamwise direction
\( V \)  
time-averaged velocity component in the vertical direction
\( W \)  
time-averaged velocity component in the spanwise direction
\( \langle U \rangle \)  
depth-averaged velocity on floodplain
\( U_m \)  
initial bulk-mean velocity in main-channel
\( U_p \)  
flow velocity in proto-scale
\( x \)  
streamwise coordinate
\( y \)  
vertical coordinate
\( y_w \)  
water level
\( z \)  
spanwise coordinate

ORCID

Takaaki Okamoto  
https://orcid.org/0000-0001-6801-4335
Michio Sanjou  
https://orcid.org/0000-0002-8146-9788

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