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Log jam formation by an obstruction in a river

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ABSTRACT: The flume experiments were carried out to examine the relationship between a log jam and an obstruction in a channel. Cylindrical wood pieces and bridges with a single pier were used as a model of floating woody debris and an obstruction, respectively. The results reveal that a log jam at the model bridge is determined by shaded area of an obstruction in a channel. An empirical equation for predicting the volume of a log jam at an obstruction was proposed. A log jam at the model bridge caused backwater rise. Backwater rise depends on the number of wood pieces trapped by a model bridge. Dependence of loss coefficient on trapped wood pieces is clearly shown. Loss coefficient is determined by blockage ratio of a jam at a model bridge.

1 INTRODUCTION

Heavy rain hit the Yabe River basin in Yame City, Japan on July 14, 2012. This heavy rain caused landslides and debris flows along the upstream river reach in the mountain areas. These resulted in a flood with a significant amount of sediment and wood (e.g. Rusyda et al., 2013a and 2013b). Floating woody debris was trapped by bridges in the upstream river reach and by riparian trees in the midstream river reach. These resulted in woody debris accumulation, backwater rise and overflow at certain bridges, such as Sokobarai and Miyanoue Bridge in the upstream river reach. Sokobarai and Miyanoue Bridge are usual bridges with a single pier. Therefore, it is important to know the characteristics of woody debris jam formation and backwater rise at such bridges.

A woody debris jam has been studied in terms of geomorphology and river engineering. Rusyda et al. (2013a and 2013b) carried out field investigations into woody debris jams formed by some obstructions during the 2012 Yabe River flood. The obstructions were bridges and riparian trees in the river and houses on the flood plain. They clearly pointed out the dependence of volume of a woody debris jam on the shaded area of obstructions.

A previous field study on woody debris jams in a basin scale was conducted by Abbe & Montgomery (2003). They proposed that a woody debris jam can be formed by sufficient size of riparian vegetation during flood event. The jam becomes a barrier and disperses flood water over the flood plain. A field study on woody debris jams in a river was carried out by Diehl (1997). He found that bridges in Tennessee with one pier in the channel have more possibility to trap floating debris than that of bridges with two piers on the banks and without piers in the channel. The accumulations blocked the channel and produced a significant backwater rise.

A number of flume experiments on woody debris jam formation in rivers were performed (Braudrick et al. 2001, Bocchiolla et al. 2006, Bocchiola et al. 2008, Schmocker & Hager, 2011). For example, Bocchiola et al. (2008) show that the probability of formation of a log jam in streams with complex morphology increases with its length and decreases with its Froude number. Schmocker & Hager (2011) performed experiments on the blocking probability of floating logs at bridge decks. Their results indicated that the blocking probability depends on log dimension, freeboard, Froude number and bridge characteristics. The blockage of logs has a significant effect on backwater rise.

However little is known about the log accumulation at bridges.

The purpose of the present paper is to investigate relationship between a log jam and a structure such as a bridge in river. In this study logs is assumed representative of woody debris in rivers.

2 EXPERIMENTAL METHOD

2.1 *Hydraulic model*

The laboratory experiments were performed in a rectangular flume; it was 30 cm wide, 32.8 cm high and 12 m long with smooth acrylic board on both the lateral sides. A schematic diagram of the flume is shown in Figure 1. The flume slope was set at 1/100 or 0.6/100. Inflow discharges per unit width were about q = 200 cm^2/s or 250 cm^2/s at the upstream end. Movable and fixed parts

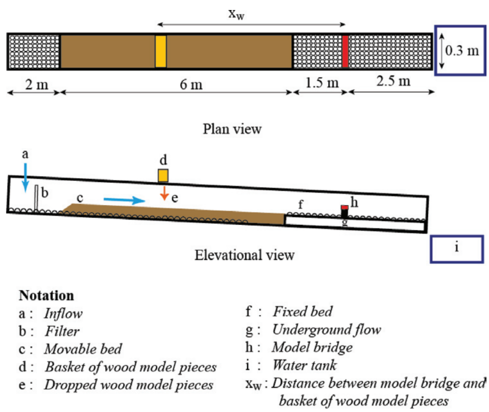


Figure 1. Experimental flume.

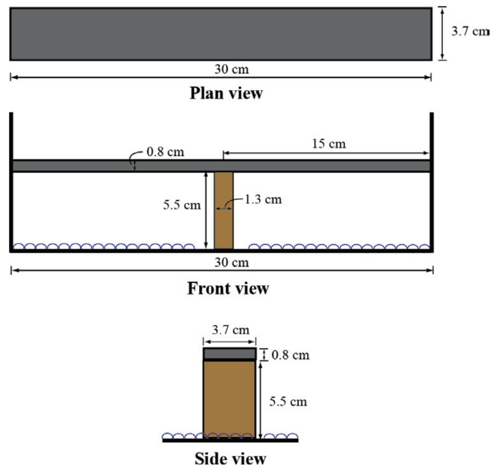


Figure 2. Model of Sokobarai Bridge (Model Bridge I).

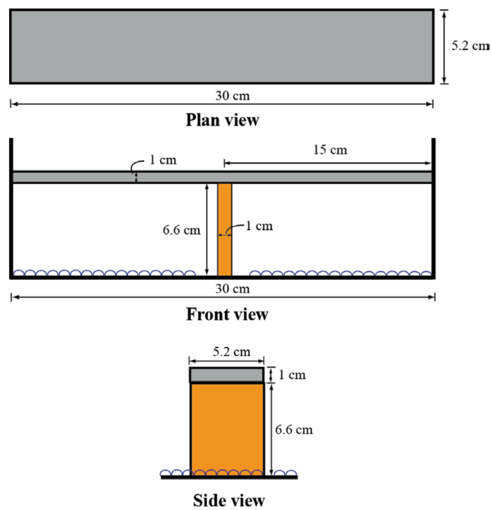


Figure 3. Model of Miyanoue Bridge (Model Bridge II).

were installed on the flume bed. The movable bed part was composed of almost uniform sediment grains; the grain density was 2.65 g/cm^3, the representative diameter d_{50} = 3.6 mm, the standard deviation s = 1.28. The fixed bed part was roughened by the same materials as the movable bed materials. Model bridges were used as an obstruction in the flume. The model bridge was placed on the fixed bed part 2.5 m distant from the downstream end. Pieces of wooden cylinders were used as the model of floating logs. The apparatus for dropping the wood pieces on the flow surface was installed at the station 5 m upstream from the model bridge.

2.2 *Model bridges*

Two different model bridges were used; one was based on Sokobarai Bridge (Model Bridge I) and the other on Miyanoue Bridge (Model Bridge II). The model bridges I and II were composed of deck and single pier. Their plan, front and side views are shown in Figures 2 and 3, respectively. Their reduced size of the prototypes was 1/100 for Model Bridge I, and 1/120 for Model Bridge II.

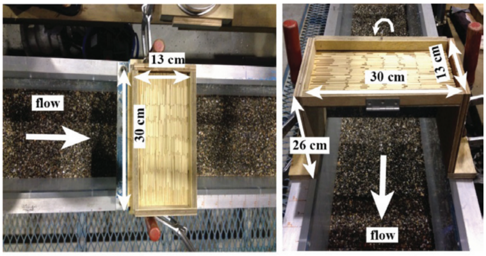
River slope was 1/100 near the Sokobarai Bridge (Model bridge I) and 0.6/100 near Miyanoue Bridge (Model bridge II). Smooth acrylic board was used as the material for the model bridges.

2.3 *Model wood*

Cylindrical wood pieces were used to model logs; Its diameter was D = 2.0 mm and its length was L = 7.0 cm. This satisfies the condition of $L >> D$. Prior to a test, the wood pieces were soaked in water for 10 minutes and then were put in a few baskets. The wood density was 0.65 g/cm^3. A few baskets were mounted on the top of the flume sides 5 m upstream from the model bridge. Opening the bottom of the basket made the wood pieces fall on the flow surface. This instant release of the wood pieces was modelled after the woody debris inflowed by landslides on valley slopes. Figure 4 shows the plan and oblique views of the basket. Number density of the pieces was 100 pieces/(30 cm*13 cm) or 200 pieces/(30 cm*13 cm).

2.4 *Test procedure*

Clear water was supplied from the upstream flume end. The mixed flow of sediment and water moved downstream along the flume bed. Less sediment



Plan view **Oblique front view**

Figure 4. A basket used to drop wood pieces into the flume.

transport was found under this condition. Therefore, the mixed flow was almost clear.

The flow was in almost steady state in around 1.0 minute after the arrival of the flow front at the model bridge. Wood pieces in the basket were dropped on the surface of steady and uniform flow. The densed wood pieces moved down to the model bridge in the flume. Some wood pieces were trapped and accumulated at the bridge (Fig. 5). The others passed through the bridge. The accumulation caused an increase in water level upstream from the model bridge. The measurements of the water level were made during the log accumulation at the model bridge. The same measurements were also made after the removal of the trapped pieces.

Flow discharge was measured by catching the outflow water in a few containers at the downstream end.

Four video cameras were placed in the vicinity of the flume to investigate the behaviour of wood pieces at the model bridge. The first video camera was installed on the top of the flume. The second and third video camera were put on the right and left-hand flume side. The fourth video camera was set up near the downstream flume end.

Table 1 provides the experimental condition. Thirty-four runs were performed. The duration of each run was around 15 minutes.

2.5 *Measurement of water surface level*

The x,y and z coordinates are defined as shown in Figure 6. The x coordinate is in flow direction. Measurements of the water surface level were made at $y = 15$ cm for the longitudinal depth profile and at $x = -5$ cm and (B_b+5 cm) for the transverse depth profile by a point-gauge.

The measurements of the water surface level were made under two different conditions; one is the first stage with log jam at the model bridge, and the other, the second stage, without log jam at the model bridge. Therefore, backwater rise Δh includes the effect of

Figure 5. A front view of a typical log jam formed at model bridge I after stopping the inflow.

Table 1. Experimental condition.

	Channel condition		Wood condition		
No	Slope	Discharge (cm²/s)	x_w (m)	Number of released wood pieces	Bridge type*
1.	1/100	236	2.5	200	I
2.	1/100	197	2.5	200	I
3.	1/100	253	5.0	200	I
4.	1/100	247	5.0	400	I
5.	1/100	238	5.0	50	I
6.	1/100	248	5.0	300	I
7.	1/100	248	5.0	150	I
8.	1/100	195	5.0	800	I
9.	1/100	195	5.0	600	I
10.	1/100	195	5.0	200	I
11.	1/100	195	5.0	400	I
12.	1/100	195	5.0	300	I
13.	1/100	195	5.0	100	I
14.	1/100	247	5.0	800	I
15.	1/100	247	5.0	600	I
16.	1/100	247	5.0	400	I
17.	1/100	247	5.0	200	I
18.	0.6/100	246	5.0	400	II
19.	0.6/100	246	5.0	200	II
20.	0.6/100	246	5.0	100	II
21.	0.6/100	246	5.0	600	II
22.	0.6/100	200	5.0	600	II
23.	0.6/100	200	5.0	400	II
24.	0.6/100	200	5.0	200	II
25.	0.6/100	201	5.0	600	II
26.	0.6/100	201	5.0	400	II
27.	0.6/100	201	5.0	200	II
28.	0.6/100	201	5.0	600	II
29.	0.6/100	193	5.0	500	II
30.	0.6/100	193	5.0	300	II
31.	0.6/100	237	5.0	600	II
32.	0.6/100	237	5.0	400	II
33.	0.6/100	187	5.0	800	II
34.	0.6/100	187	5.0	800	II

*I: Model of Sokobarai Bridge (bridge with a pier) II: Model of Miyanoue Bridge (bridge with a pier).

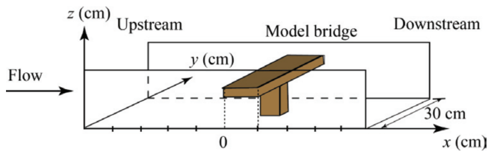


Figure 6. Definition sketch of the *x*, *y* and *z* coordinates near the measurement point.

log jam and the model bridge in the first stage and that of the bridge only in the second stage.

2.6 *Measurement of characteristic quantities of log jam at a model bridge*

The number of wood pieces trapped and accumulated at the bridge was counted during and after the experimental runs. Plan and cross-sectional views of the log jam were taken by the camera. These photos were used for the evaluation of the apparent volume of log jam.

3 EXPERIMENTAL RESULTS

3.1 *Log jam at a model bridge*

Figures 7 and 8 shows the relationship between the number of trapped wood pieces and that of the released wood pieces. The fraction of trapped wood pieces is plotted against the overall number of wood pieces in Figures 9 and 10.

It is found that the wood fraction trapped by the model bridge increases with the overall number dropped on the flow surface. It also increases with the overall number and approaches to their maximum values of 0.4 to 0.5. Trapping wood by the model bridge requires a sufficient number of wood pieces dropped on the flow surface. Critical condition for trapping the wood pieces by the model bridge is $N_c = 100\sim200$. Here N_c denotes the number of wood pieces for the critical condition.

3.2 *Relationship between a log jam and an obstruction*

A bridge is an obstruction to the flowing woody debris during flood events. In order to discuss the relationship between a woody debris jam and a bridge, Rusyda et al. (2013a and b) introduced 'shaded area' of an obstruction from the viewpoint of hydraulics. According to the previous study, we also introduce 'shaded area' (A_o) defined as frontal area of the model bridge projected onto a plane perpendicular to the flow direction; it was determined for two different cases (Fig. 11) as follows:

$$A_o = P_y L_z \qquad \text{for} \quad L_z < P_z \qquad (1)$$

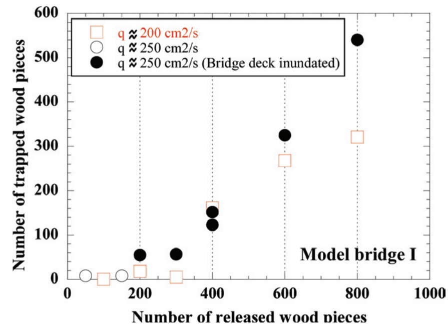


Figure 7. The number of wood pieces trapped by the model bridge I during water flow.

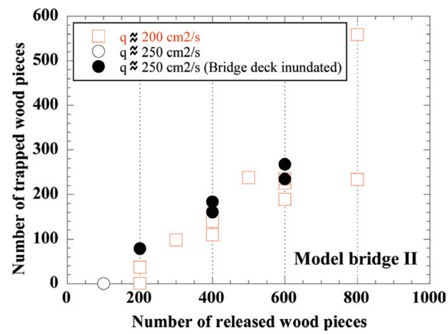


Figure 8. The number of wood pieces trapped by the model bridge II during water flow.

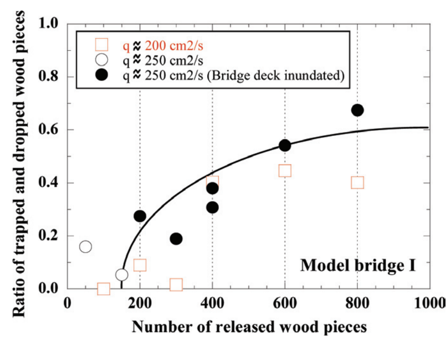


Figure 9. The number ratio of wood pieces trapped by model bridge I and dropped at the station 'd' during water flow.

or

$$A_o = P_y L_z + L_y D_z \qquad \text{for} \quad L_z > P_z \qquad (2)$$

where P_y = width of pier; L_z = depth of jam; P_z = height of pier; L_y = length of jam; and D_z = thickness of bridge deck.

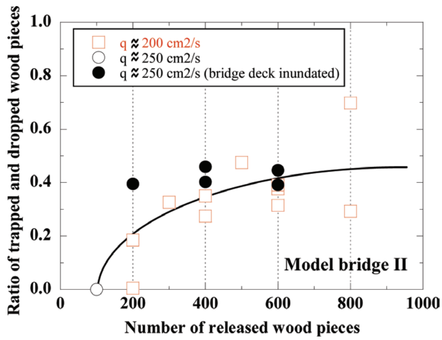


Figure 10. The number ratio of wood pieces trapped by model bridge II and dropped at the station 'd' during water flow.

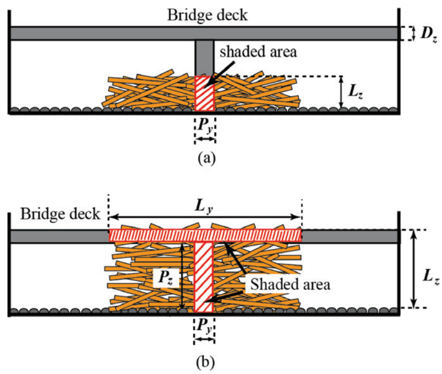


Figure 11. The definition of the 'shaded area' of an obstruction, such as the case of a jam formed by a pier (a) and that of a jam formed by bridge deck and pier.

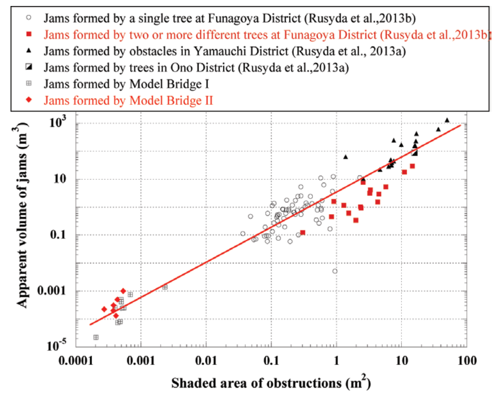


Figure 12. Volume of log jams versus shaded area of obstructions in real river and laboratory flume.

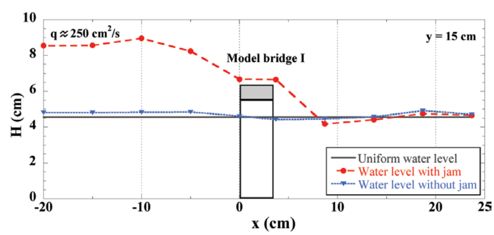


Figure 13. Measurements of water level with and without log jam at model bridge I.

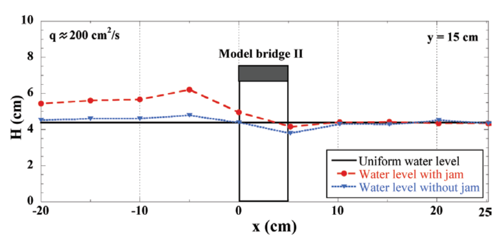


Figure 14. Measurements of water level with and without log jam at model bridge II.

The apparent volume V_{wd} of log jam is plotted against 'shaded area' A_o of the obstructions in Figure 12. This figure also shows the field survey results from the work of Rusyda et al. (2013a and b). They proposed the following relationship:

$$V_{wd} = CA_o^{\alpha} \qquad (3)$$

where $C = 2.5$ and $\alpha = 3/2$. This equation is found valid for the smaller region of shaded area as well as its larger region. Therefore evaluating the shaded area of an obstruction, we can predict the volume of log jam.

3.3 *Backwater rise due to log jam at the model bridge*

The backwater rise with and without log jam at model bridges I and II are illustrated in Figures 13 and 14, respectively. For comparison, water level in the uniform flow state is also plotted in these figures.

Comparing the water levels with log jam and the other water levels, we can find that backwater rise due to the log jam is significantly large. At around $x = 10$ cm, on the other hand, every water level is approximately same. Therefore, an estimate of backwater rise due to log jam is important from the viewpoint of flood defense. Two types of backwater rise occurred through the log jam at a model bridge. The first type is the case when the water level is higher than a model bridge (Fig. 15a). It happened at model bridge I and II during $q \approx 250$ cm²/s. The second type is the case

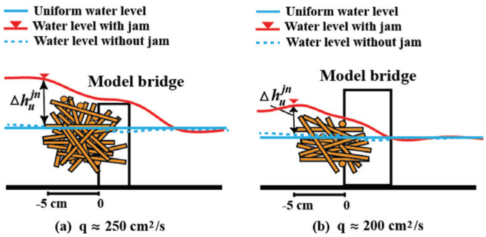


Figure 15. A schematic feature of backwater rise.

when the water level is lower than a model bridge (Fig. 15b). It evidently happened at model bridge I and II during $q \approx 200$ cm^2/s.

In order to identify backwater rise, we introduce the following equations:

$$\Delta h_{ud}^j = h_u^j - h_d^j \tag{4}$$

$$\Delta h_{ud}^n = h_u^n - h_d^n \tag{5}$$

$$\Delta h_u^{jn} = h_u^j - h_u^n \tag{6}$$

where h_u^j = upstream water depth with jam; h_d^j = downstream water depth with jam; h_u^n = upstream water depth without jam and h_d^n = downstream water depth without jam.

Backwater rise of Eq. (4) includes the effect of a model bridge and log jam, while Eq. (6) includes the effect of log jam only and Eq. (5) the effect of a model bridge only.

Figures 16 and 17 show the backwater rise based on Eqs. (4) and (6) versus the number of wood pieces trapped by a model bridge. These figures express that the backwater rise increases with number of trapped wood pieces.

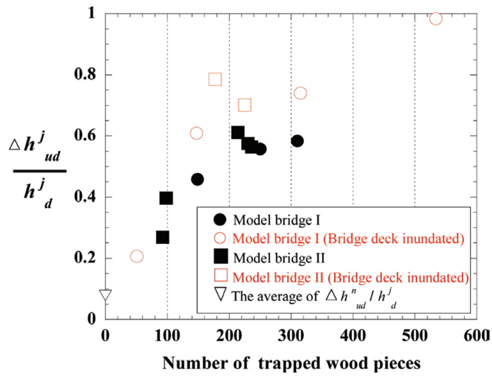


Figure 16. Relationship between the normalized backwater rise and the number of wood pieces trapped by a model bridge.

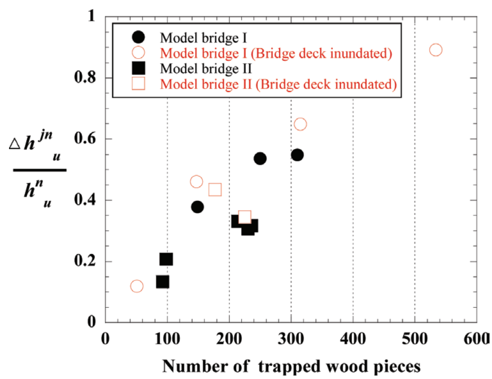


Figure 17. Relationship between the normalized backwater rise and the number of wood pieces trapped by a model bridge.

3.4 *Loss coefficient*

Head loss due to obstructions in a river can be expressed by 'loss coefficients'. 'Loss coefficients' due to log jam and a model bridge can be defined in the following form:

$$f_d^j \equiv \Delta E_{ud}^j / \left((v_d^j)^2 / 2g \right) \tag{7}$$

$$f_d^n \equiv \Delta E_{ud}^n / \left((v_d^n)^2 / 2g \right) \tag{8}$$

Here

$$\Delta E_{ud}^j \equiv \left\{ \frac{(v_u^j)^2}{2g} + h_u^j \right\} - \left\{ \frac{(v_d^j)^2}{2g} + h_d^j \right\} \tag{9}$$

$$\Delta E_{ud}^n \equiv \left\{ \frac{(v_u^n)^2}{2g} + h_u^n \right\} - \left\{ \frac{(v_d^n)^2}{2g} + h_d^n \right\} \tag{10}$$

$$v_u^j = q / h_u^j \tag{11}$$

$$v_d^j = q / h_d^j \tag{12}$$

$$v_u^n = q / h_u^n \tag{13}$$

$$v_d^n = q / h_d^n \tag{14}$$

where f_d^j = loss coefficient with jam; f_d^n = loss coefficient without jam; v_u^j = upstream velocity with jam; v_d^j = downstream velocity with jam; v_u^n = upstream velocity without jam; v_d^n = downstream velocity without jam; ΔE_{ud}^j = energy loss between the upstream and downstream station of the model bridge with jam; ΔE_{ud}^n = energy loss between the upstream and downstream station of the model bridge without jam; g = the gravity acceleration and q = water discharge per unit width.

Figure 18 presents the effect of the trapped wood pieces on the loss coefficient. This figure represents the loss due to a model bridge and log jam. However, every loss coefficient shows almost same value for each number of trapped wood pieces. The role of log jam in the loss coefficient is major, wheras the role of a model bridge in the loss coefficient is minor.

The loss coefficient is plotted against the apparent volume of log jam at a model bridge in Figure 19. This figure indicates the dependence of the loss coefficients on log jam. Furthermore, the apparent volume of log jam determines the blockage ratio of jam (Fig. 20). Here, the blockage ratio of jam is defined as a ratio of the frontal area of jam (A_{wd}) to the total flow area (A_t). Thus, the loss coefficient is depicted versus the blockage ratio of jam in Figure 21. The dependence of the loss coefficients on the blockage ratio of log jam can be found.

The downstream water depth with jam h_d^j is approximately equal to the normal depth h_o. For convenience, we can use the normal depth and velocity as a reference value.

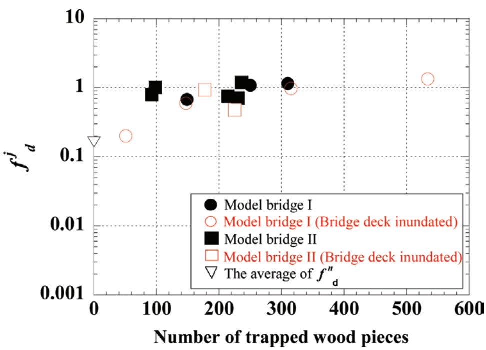


Figure 18. Relationship between the loss coefficient and the number of trapped wood pieces.

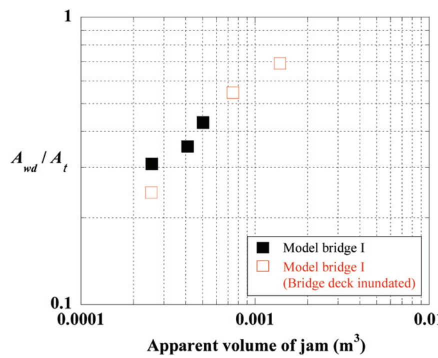


Figure 20. Relationship between the blockage ratio of jam and apparent volume of log jam at a model bridge.

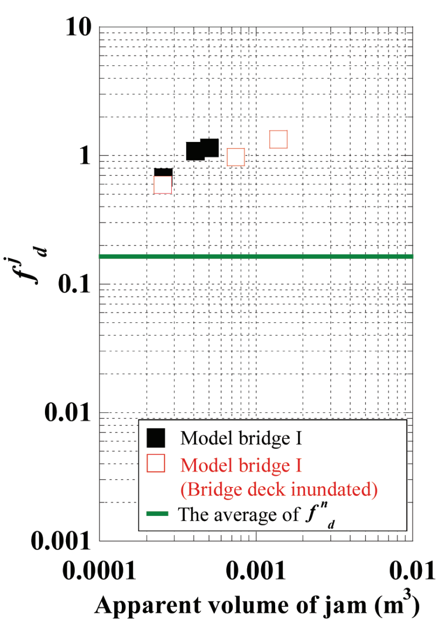


Figure 19. Relationship between the loss coefficient and the apparent volume of log jam at a model bridge.

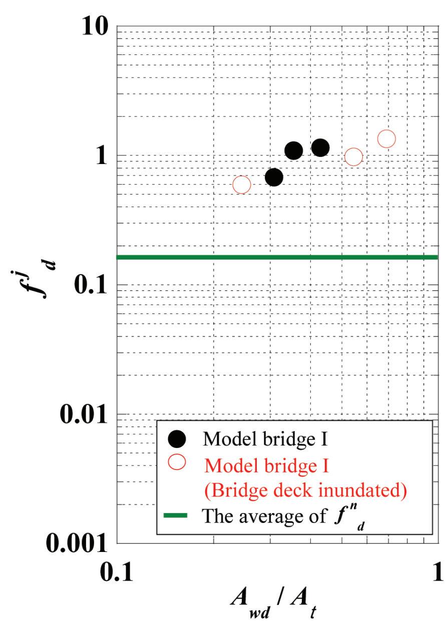


Figure 21. Relationship between the loss coefficient and the blockage ratio of jam.

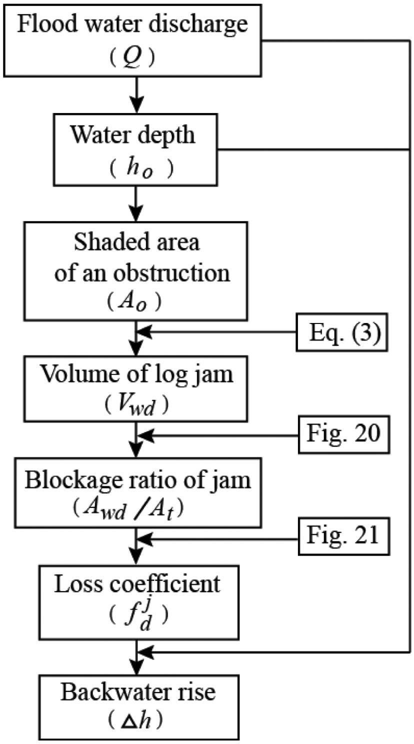


Figure 22. A flow chart for predicting backwater rise.

3.5 *Procedure of estimation of backwater rise due to log jam at a bridge*

Estimating V_{wd} with Eq. (3) and A_t from hydraulic and geometric condition yields the ratio A_{wd}/A_t. From Figure 21, we can determine the loss coefficient. Finally we can predict the backwater rise from the loss coefficient and hydraulic condition (Fig. 22).

4 CONCLUSIONS

The present study neglects fine materials such as branches and leaves but considers logs only as the model of woody debris floating in rivers. The next stage of this study should be extended to the mixed materials of branches, leaves and logs.

The results obtained in this study are as follows:

1. The log jam at an obstruction is determined by 'shaded area' of the obstruction.
2. An empirical equation for predicting the volume of log jam at an obstruction is proposed.
3. Backwater rise depends on the number of wood pieces trapped by a model bridge.
4. The dependence of the loss coefficient on trapped wood pieces is clearly shown.
5. Loss coefficient is determined by blockage ratio of jams.

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