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WOODY DEBRIS ACCUMULATION DURING THE FLOOD EVENT IN THE NAYOSHI RIVER, TSUWANO TOWN, JAPAN.

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ABSTRACT

A significant amount of woody debris deposition was caused during the flood event along the Nayoshi River. The field survey showed two types of woody debris deposition; one is the deposition of individual wood pieces and the other is accumulation or jam of woody debris. Furthermore, two kinds of the woody debris accumulation were found on the field along the river and at the bridges without piers. The statistical analysis of individual wood pieces shows that the mean of the length was 3.4 m in Site 2 and 3.5 m in Site 3. Their probabilistic distribution was log-normal. A comparison of the scale of wood pieces and bridges shows that the wood pieces were longer than the depth from the riverbed to the bridge deck and were as long as the bridges. A flume experiment was also carried out to explore the formation of woody debris accumulation by modeling a bridge without pier. The results present that woody debris accumulation at the model bridge is determined by shaded area of an obstruction in a channel. An empirical equation for predicting the volume of woody debris accumulation at an obstruction is also proposed.

Keywords: Flood, large woody debris, driftwood, debris blockage, jam.

1. INTRODUCTION

The Nayoshi river basin in Tsuwano Town, Shimane Prefecture, Japan was hit by a heavy rain on July 28, 2013. This heavy rain caused landslides and debris flow along a headwater stream in the mountain areas. These resulted in flood with a significant amount of sediment and wood. Various geometric features of river, such as river curvature, and hydraulic structures, such as bridges, produced woody debris accumulations and overflows at several river sections during the flood event. The flooding water deposited a large amount of sediment and wood on the fields along the midstream river reach.

After the flood event, we conducted field surveys along the Nayoshi River in order to examine the characteristics of woody debris accumulation. The field surveys found two types of woody debris deposition; one is the deposition of individual wood pieces and the other is accumulation or jam of woody debris. The woody debris accumulation was found on the field along the mid-river reach and at the bridges without piers.

Research on woody debris accumulation during flood is important from the viewpoint of flood defense. The mobility and the accumulation of woody debris in rivers have recently become the focus of the attention of many researchers in the fields of geomorphology and river engineering.

Rusyda et al. (2013a and 2013b) carried out field investigations into woody debris 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. Rusyda et al. (2014) also performed laboratory experiments in order to investigate the relationship between a woody debris accumulation and an obstruction in the river. Two model bridges with a single pier based on usual bridges in the Yabe River was used as an obstruction. The field investigations and the laboratory experiments clearly showed the dependence of volume of a woody debris accumulation on the shaded area of an obstruction.

There are several previous field studies (*e.g.* Abbe and Montgomery, 1996; Abbe and Montgomery, 2003; Diehl, 1997) and laboratory flume experiments (*e.g.* Braudrick et al. 1997; Braudrick et al. 2001; Bocchiola et al. 2006; Bocchiolla et al. 2008; Schmocker and Hager, 2011) on behavior of woody debris in rivers. For example, Abbe and Montgomery (1996) and Braudrick et al. (1997) found that woody debris tends to deposit on the outside of bends and on bars, where flow depth decreases. Diehl (1997) proposed that the potential for woody debris accumulation depend on basin, channel and bridge characteristics. He also stated that trees undermined by bank erosion is primarily source of the woody debris in rivers. Then, Schmocker and Hager (2011) presented that the bridge deck characteristics had a significant effect on woody debris accumulation during the 2005 flood event in Switzerland. However, little is known about the characteristics of woody debris accumulations during a flood event.

The purpose of the present study is to investigate the characteristics of woody debris accumulation in the Nayoshi River. First, we examine statistical characteristics of the wood pieces deposited along the Nayoshi River. Second, we make laboratory experiments on woody debris accumulation at the model bridges. Finally, we discuss the formation of woody debris accumulations in the Nayoshi River.

2. STUDY AREAS AND RESUME OF FLOOD DISASTER

2.1 Study areas

The study area is along the Nayoshi River in Tsuwano Town, Shimane Prefecture, Japan (Fig. 1). The length of the main river is L = 8.70 km and the river basin area is 17.5 km². The main debris flows occurred in the four mountain torrents and moved into the main river. The field survey was done at four sites of the study area (Fig 2). There are four bridges without piers in this study area. The river bed slope is about 1.4° (i=2.4/100) at Site 1 and 2 (Fig. 3)

Figure 1. Study sites.

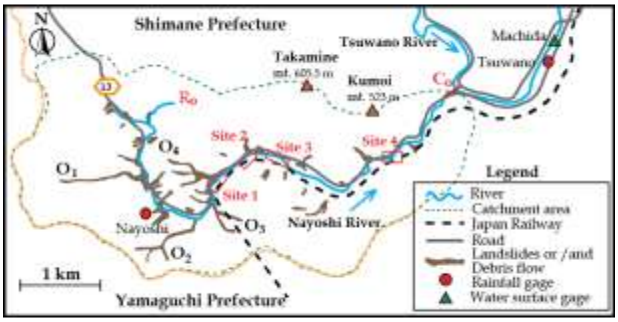

Figure 2. Map of the Nayoshi River Basin.

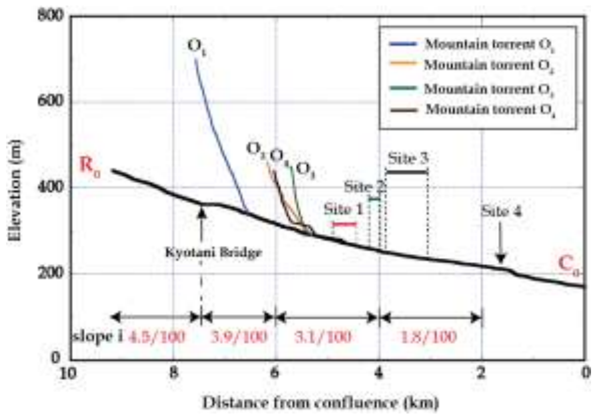

Figure 3. Longitudinal profile of the Nayoshi River.

2.2 Resume of flood disaster

Heavy rain hit Tsuwano Town on July 28, 2013. Figure 4 presents the rainfall condition at Nayoshi Rainfall Station. The accumulated rainfall was 411 mm from 2 a.m. to 10 a.m on July 28 and the largest hourly rainfall was 92 mm from 5 a.m. to 6 a.m. in the early morning.

The heavy rain resulted in many landslides, debris flows, river bank erosion in the river reach and inundated houses and roads in the plain area. Field survey found 42 landslides on the right-hand side and 39 landslides on the left-hand side of the river. The landslides conveyed a significant amount of wood and sediment into the river. Then, the floodwater transported the wood and sediment to the downstream reach of the river.

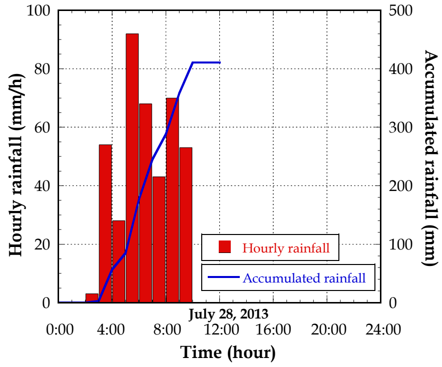

Figure 4.Rainfall situation at Nayoshi Rainfall Station.

Figure 5.The front view of the channel at Site 1.

2.3 Peak discharge during flood event

Based on the channel condition after the flood event, the peak discharge of river flood in Site 1 is evaluated. Manning equation given in Eq. [1] is used to estimate the peak discharge along the channel during the flood event.

$$Q = A\frac{1}{n}R^{\frac{2}{3}}i^{\frac{1}{2}} \quad [1]$$

where A = wetted area (m²); n = roughness coefficient; R = hydraulic radius (m) and i = channel slope.

The bottom length and the above length of the channel is 7.7 m and 11.4 m, respectively. Then, the depth of right-hand side is 4.1 m and the depth of left-hand side is 4.7 m (Fig. 5). By using the dimension, the wetted area and wetted perimeter can be found. The roughness coefficient of the river bed can be assumed around 0.03 to 0.04 because of wood and sediment in flood flow. Therefore the peak discharge is assumed around Q=300 m³/s.

3. FIELD INVESTIGATION OF WOODY DEBRIS DEPOSITION

Field survey along the Nayoshi River was performed on October 26 to 27 and November 1 to 4, 2013. A significant amount of woody debris was deposited on the fields and trapped by the bridges. Most woody debris was deposited on the right hand side of the Nayoshi River.

Figures 6 and 7 provide photos of the deposition of individual wood pieces and the accumulations of wood pieces produced by geomorphologic change of the fields.

Figure 8 also shows the accumulations of wood pieces trapped by the bridge, respectively.

For convenience, the accumulations of wood pieces are termed 'woody debris accumulation' in this paper. There were 125 and 161 individual wood pieces deposited on the fields at Site 2 and 3, respectively. 2 woody debris accumulations were formed by bridges without piers. Furthermore, 13 accumulations were found on the field of various geometric features.

Figure 6. Situation of individual wood pieces at Site 3 (taken from the left side of the river).

Figure 7. A front view of a woody debris accumulation on field at Site 3 (taken from left side of the river).

Figure 8. A back view of a woody debris accumulation at bridge without piers at Site 2 (taken from upstream of the river).

3.1 Individual wood pieces

The geometrical dimensions of individual wood pieces were quantified. Length measurements were made from the base of the attached root-ball (if present) to the furthest end of the wood pieces. Diameter is measured at mid-point of each wood piece.

Figure 9 shows the relationship between length and diameter of each wood piece at Site 2 and 3. Here, we selected individual wood pieces longer than 1 m.

Individual wood pieces at Site 3 has the largest frequency of length 1 m < x < 2.7 m (Fig. 10) and of the diameter 10 cm < x < 15 cm (Fig. 11). These frequency distributions are compared with log normal distribution in the figures.

The average length of the individual wood pieces at Site 2 was approximately 3.4 m and the average diameter of the pieces was about 15 cm. The average length and diameter of the individual wood pieces at Site 3 was approximately 3.5 m and 18 cm, respectively (Table 1).

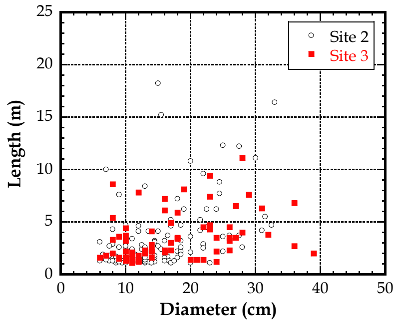

Figure 9. Relationship between diameter and length of each wood piece deposited on the field.

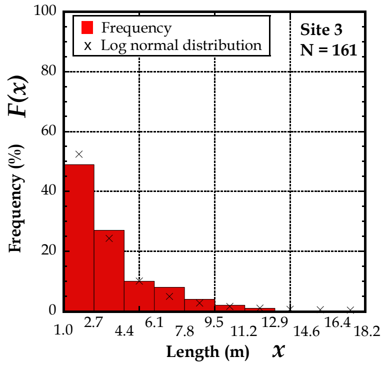

Figure 10. Frequency distribution of length of each wood piece.

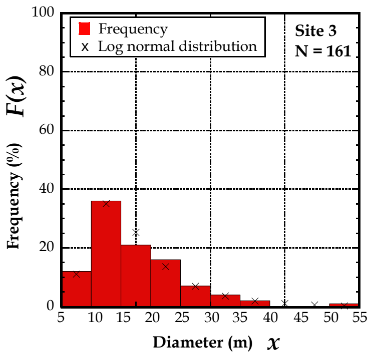

Figure 11. Frequency distribution of diameter of each wood piece.

Table 1. Statistical characteristics of individual wood pieces.

	SITE 2 (N=125 Pieces)		SITE 3 (N=161 Pieces)	
	L (m)	Dia (cm)	L (m)	Dia (cm)
Maximum	18	33	12.7	53
Minimum	1.1	6	1.1	6
Mean	3.4	15	3.5	18
Coefficeint of Variation	0.9	0.4	0.7	0.4

Table 2. Statistical characteristics of woody debris accumulations on fields.

	Site 1	Site 2	Site 3
Number of Accumulation	3	2	8
Number of selected wood pieces	30	12	73
Mean of the pieces length (m)	6	7.8	5.8
Mean of the pieces diameter (cm)	20	26	22
Mean of apparent volume of accumulations (m^3)	130	91	85

Table 3. Statistical characteristics of woody debris accumulations at bridges without piers.

	Site 1	Site 2	Site 4
Number of Accumulation	1	1	-
Number of selected wood pieces	9	5	8
Mean of the pieces length (m)	7.6	10.4	7.0
Mean of the pieces diameter (cm)	23	27	22
An apparent volume of an accumulation (m^3)	479	232	-

Table 4. The comparison of physical quantities of bridge without piers and the average length of wood pieces at the bridge.

Site	L_b (m)	H_b (m)	L_w (m)	L_b / H_b	H_b / L_w
1	13.1	1.8	7.6	1.72	0.23
2	10.8	1.6	10.4	1.03	0.15
4	14.7	2.1	7.0	2.1	0.3

3.2 Woody debris accumulation

The geometrical dimensions of woody debris accumulations on the fields and at bridges were measured by using measurement tool to quantify an apparent volume of the accumulation. Some photos were taken from the front view and the side view of the accumulations.

Representative wood pieces in the accumulations were selected in order to measure their scale. Furthermore, longest wood pieces in the accumulations were selected as a reference. The number of wood pieces in the accumulation was also counted to estimate the volume of an accumulation.

3.2.1 Woody debris accumulations on the fields

Thirteen accumulations were found on the field; three accumulations were at Site 1, six accumulations at Site 2 and eight accumulations at Site 3.

Figure 12 shows the relationship between length and diameter of each selected wood piece in the accumulations.

Figure 13 presents the comparison of the length and diameter of longest wood pieces in each accumulation. The length of longest wood pieces is larger than 10 m. Most longest wood pieces is larger than 0.2 m in diameter.

3.2.2 Woody debris accumulation at bridges

There are two woody debris accumulations at bridges without piers. One is at a bridge at Site 1 and the other at a bridge of Site 2. The apparent volume of the accumulation at Site 2 is smaller than that of the accumulation at Site 1 (Table 3).

Each scale of the bridge is defined in Fig. 14. Scales of the bridge and the trapped driftwood were compared, as shown in Figs. 15 and 16. Each bridge at Site 1 and 2 is longer than the trapped wood pieces. The bridge at Site 4 is as long as the trapped wood pieces. The depth of bridge from riverbed represents 'clearance under bridge'. Fig.16 shows that 'clearance under bridge' is not enough for flowing wood pieces. Thus, the ratio of the clearance of the bridge to the length of wood pieces was from 0.15 till 0.3 (Table 4).

3.2.3 The net and apparent volume of woody debris accumulation

The net volume of woody debris accumulations was obtained by multiplying the average volume of each wood piece and the number of pieces in each accumulation. The apparent volume of woody debris accumulations was also estimated by front-back view and left-right side view of photos. Their volume ratio is 0.2 on average (Fig. 17).

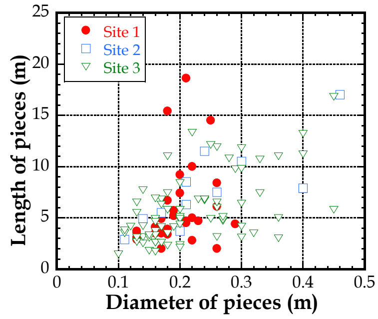

Figure 12. Relationship between diameter and length of selected pieces in each field accumulation.

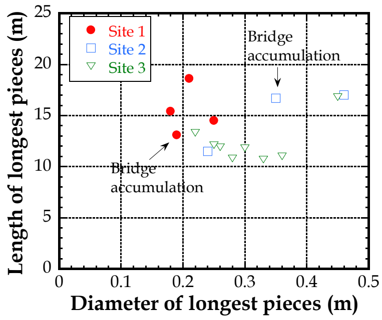

Figure 13. Relationship between diameter of longest pieces and the length of longest pieces in each field accumulation.

Figure 14. The scales of bridge without piers.

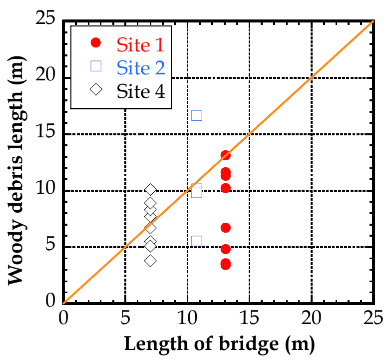

Figure 15. Comparison of wood piece length and bridge length.

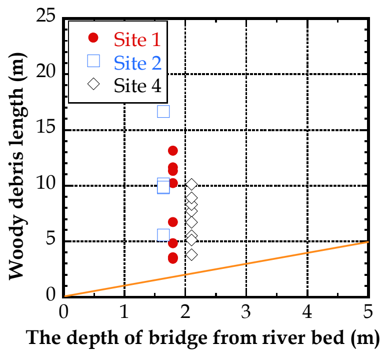

Figure 16. Length of wood pieces versus the depth of bridge from riverbed.

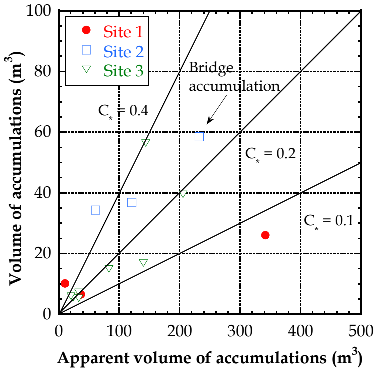

Figure 17. Relationship between apparent and net volume of woody debris accumulations.

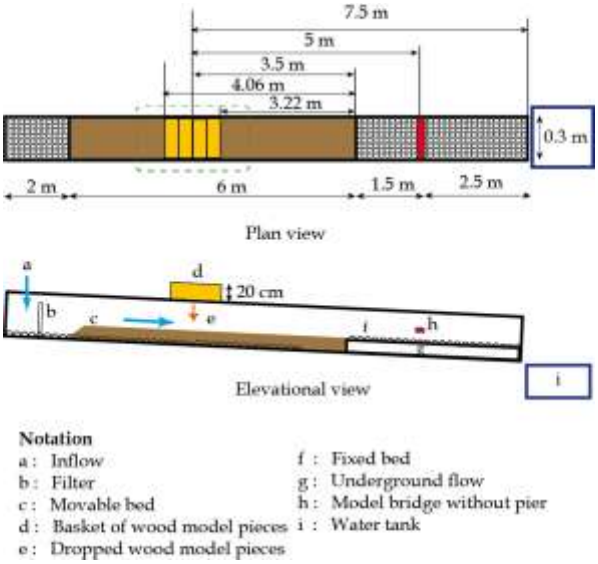

Figure 18. Experimental flume.

4. FLUME EXPERIMENT ON WOODY DEBRIS ACCUMULATION

4.1 Experimental method

4.1.1 Hydraulic model

A rectangular flume with a smooth acrylic board on both lateral side was used for our laboratory experiments. The flume was 30 cm wide, 32 cm high and 12 m long. Figure 18 shows a schematic diagram of the flume.

The flume slope was adjusted to 0.6/100. Inflow flow rate per unit width were about q = 300 cm²/s at the upstream end. The flume bed was divided into movable and fixed part. The movable and fixed bed part were filled with almost uniform sediment grains; the grain density was 2.65 g/cm³, the representative diameter D_{50}=3.6 mm, the standard deviation s=1.28.

A model bridge without piers was installed on the fixed bed part 2.5 m distant from the downstream end. Wooden cylinders pieces were used as the model of floating woody debris. An experimental apparatus for releasing the model wood on the flow surface was placed at the station 5 m upstream from the model bridge.

4.1.2 Model bridge

The model bridge without pier made of smooth acrylic board was used as an obstruction. The plan, front and side views are shown in Figure 19. The reduced size of the prototype was 1/120.

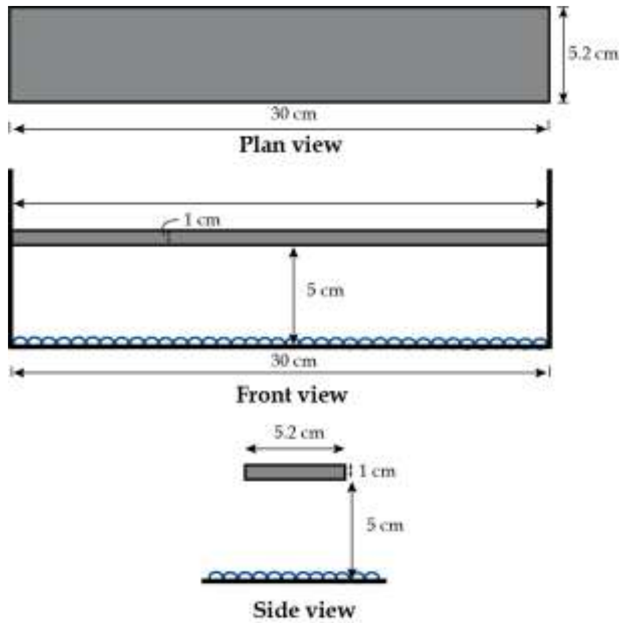

Figure 19. A model bridge without pier.

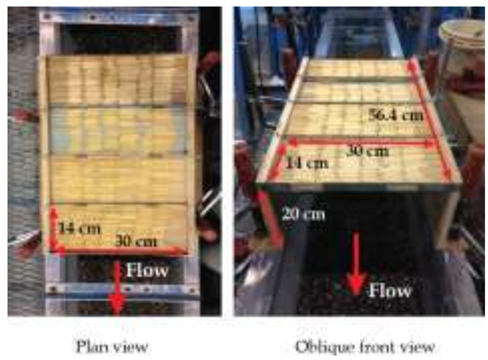

Figure 20. A basket used to drop wood pieces into the flume.

4.1.3 Model wood

A model of floating woody debris was simulated by cylinder wood pieces (Diameter, D = 2.0 mm and Length, L = 7.0 cm). The wood dimension was corresponded to the wood dimension used in Rusyda et al., (2014). 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 basket. The wood density was 0.65 g/cm³. The wood pieces releases on the flow surface by opening the bottom of the basket. This instant release of the wood pieces was modeled after the woody debris inflowed by landslides on valley slopes. Figure 20 shows the plan and oblique views of the basket. There are four spaces in the basket. The number density of the pieces 200 pieces/(30 cm*14 cm) in one space.

4.1.4 Test procedure

Clear water was supplied from a water tank at the upstream flume end. The mixed flow of sediment and water transported downstream along flume bed. The mixed flow was almost clear due to less sediment transport.

The flow was in almost steady state in around 1.0 minute after the arrival of flow front at the model bridge. At the same time wood pieces in the basket were dropped on the flow surface. The congested wood pieces transported to the model bridge in the flume. The model bridge trapped some wood pieces and formed an accumulation (Fig. 21). The other pieces washed away through the model bridge.

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

In order to investigate behavior of wood pieces at the model bridge, four video cameras were placed in the vicinity of the flume. The first video camera was installed on the tops of the flume. The second and the third video cameras were put on the right-hand flume side and in front of the model bridge, respectively. The fourth video camera was set up near the downstream flume end.

Table 5 presents the experimental condition. Eleven runs were performed. The duration of each run was around 15 minutes.

Table 5. Experimental condition

No	Discharge	Number of released wood pieces
1	296	600
2	301	400
3	298	800
4	294	600
5	300	600
6	300	400
7	298	800
8	299	400
9	299	200
10	301	800
11	300	600

Figure 21. A front view of a typical woody debris accumulation formed at the model bridge after stopping the inflow.

4.1.5 Measurement of characteristic quantity of woody debris accumulation

The number of wood pieces trapped and accumulated at the model bridge during and after the experimental runs was counted. For the evaluation of the apparent volume of an accumulation, plan and cross-sectional views of the accumulation was captured by the cameras.

4.2 Experimental results

4.2.1 Woody debris accumulation at a model bridge

A scatter diagram was used to determine the relationship between the number of trapped wood pieces and that of the released wood pieces (Fig. 22). The fraction of trapped wood pieces is plotted against the overall number of wood pieces in Figure 23.

As can be seen from the figure, the wood fraction trapped by the model bridge with a pier (Rusyda et al., 2014) increases with the overall number of released wood pieces. Whereas, the wood friction trapped by the model bridge without pier increases significantly with the overall number of released wood pieces. The friction seem to slightly decrease from the overall number of released wood pieces larger than 600 pieces. The trapping wood by the model bridge without pier requires a sufficient number of wood pieces dropped on the flow surface. Critical condition for trapping the wood pieces by the model bridge without piers is N_c= 200. Here N_c denotes the number of wood pieces for critical condition.

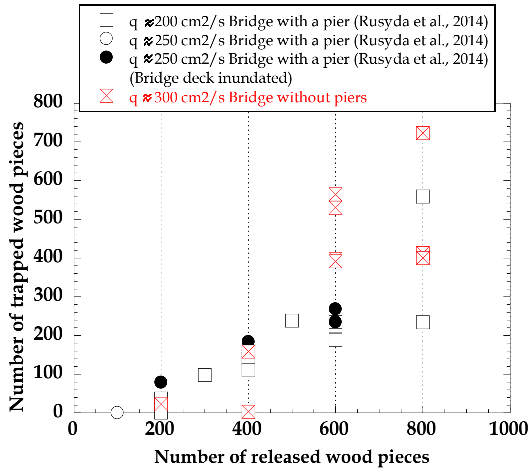

Figure 22. The number of wood pieces trapped by the model bridge during water flow.

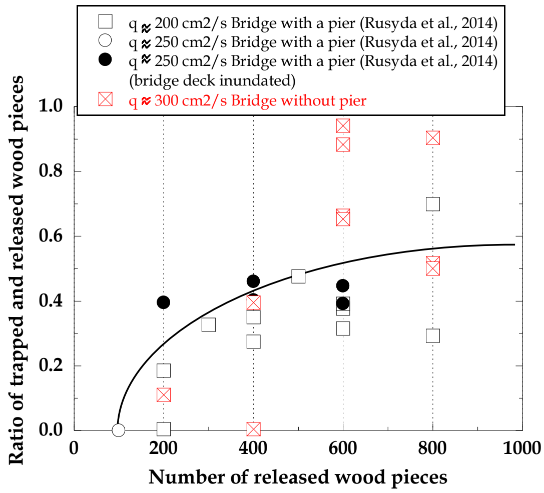

Figure 23. The number ratio of wood pieces trapped by the model bridge and released at station 'd' during water flow.

4.2.2 Relationship between woody debris accumulation and an obstruction

Rusyda et al. (2013a and b) and Rusyda et al. (2014) introduced 'shaded area' of an obstruction from the viewpoint of hydraulics to discuss the relationship between a woody debris accumulation and a bridge. In the river, a bridge is an obstruction to floating woody debris during flood event. According to the previous studies, we also propose 'shaded area' (A_o) defined as frontal area of the model bridge projected onto a plane perpendicular to flow direction (Fig. 24); it was determined as follows :

$$A_o = L_y D_z \qquad [2]$$

where L_y = length of an accumulation and D_z = bridge thickness.

The apparent volume V_{wd} of woody debris accumulation is plotted against 'shaded area' A_o of the obstructions in Figure 25. This figure also shows the field survey results from the work of Rusyda et al. (2013a and b) and flume experiment results from the work of Rusyda et al. (2014). They proposed the following relationship:

$$V_{wd} = CA_o^{\alpha} \quad [3]$$

where C = 2.5 and $\alpha = 3/2$.

This equation is found also valid for the relationship of woody debris accumulation and an obstruction in this field survey and laboratory experiments. Therefore, the volume of woody debris accumulation can be predicted by evaluating the shaded area of an obstruction.

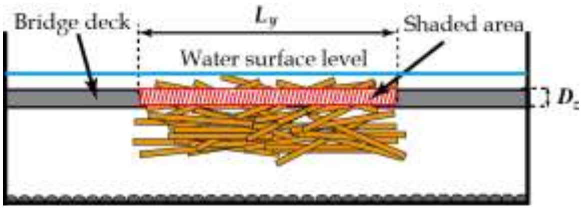

Figure 24. The definition of the 'shaded area' of an obstruction, such as the case of a woody debris accumulation formed by bridge deck.

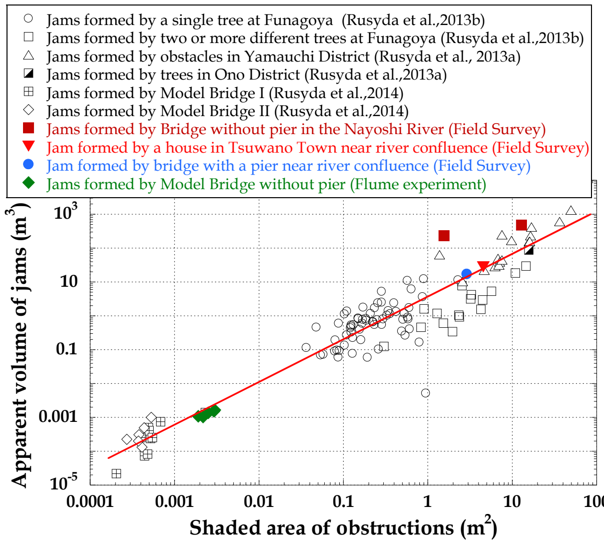

Figure 25. Volume of woody debris accumulation versus shaded area of obstructions in real river and laboratory flume.

5. DISCUSSION

One of the main purposes of this study is to investigate the characteristics of woody debris accumulation at a model bridge without pier in laboratory flume. We also examined characteristics of the deposition of individual wood pieces in Tsuwano Town.

The mean length and diameter of the deposition of individual wood pieces on site 2 is 3.4 m and 15 cm. The individual wood pieces in site 2 is shorter than that in Ono district (Table 6). We supposed that the characteristics of trees covered the mountain areas influences a wood input rate and wood dimension in a river during a flood event.

Table 6. The comparison of statistical characteristics of individual wood pieces in Tsuwano Town and Ono District in Yame City, Japan.

	SITE 2 (N=125 Pieces) in Tsuwano Town		ONO DISTRICT (N=88 Pieces) Rusyda et al.,(2013a)	
	L (m)	Dia (cm)	L (m)	Dia (cm)
Mean	3.4	15	7.1	20
Coefficeint of Variation	0.9	0.4	0.59	0.4

In addition, our laboratory experiments show a woody debris accumulation can be formed by a model bridge without pier. By using the photos of front view and top view of the typical woody debris accumulation, we can estimate the orientation of each wood pieces in the accumulation. The orientation of wood pieces in the accumulations was be varied depend on their position. For example, for 800 released wood pieces, the wood pieces in contact with the model bridge seems to stand up straightly. We supposed that they become a barrier for following wood pieces. Most followed wood pieces are parallel to the model bridge.

Interestingly, for 800 released wood pieces, the orientation of the majority of followed wood pieces in the accumulations is consistent with Rusyda et al. (2014) who performed laboratory experiments by using two model bridges with a pier. However, the orientation of wood pieces in contact with the bridge without pier is different from that of the bridge with a pier due to the difference of the characteristics of the bridges (Figs. 26, 27, 28 and 29).

Our laboratory experiments only focus on a model wood as a log, whereas it might be important to include a root-ball as well. In fact, the inclusion of the root ball would enable us to more understand the behavior of woody debris in a river during a flood event.

Figure 26. A top view of an accumulation at a bridge without piers.

Figure 27. A top view of an accumulation at a bridge with a pier.

Figure 28. A front view of an accumulation at a bridge without piers.

Figure 29. A front view of an accumulation at a bridge with a pier.

6. CONCLUSIONS

The results obtained in this study areas as follows:

1. Individual wood pieces of the length 1 m < x < 2.7 m and of the diameter 10 cm < x < 15 cm has the largest frequency;
2. The average length of the individual wood pieces in site 2 was approximately 3.4 m and the average diameter of the pieces was about 15 cm. The average length and diameter of the individual wood pieces in site 3 was approximately 3.5 m and 18 cm, respectively;
3. The majority length of selected wood pieces in woody debris accumulation on fields ranged from around 10 m to 15 m and the majority diameter of them ranged from around 0.2 m to 0.4 m;
4. The ratio of the depth of bridge from riverbed and the average length of wood pieces (L_w) was from 0.15 till 0.3;
5. Most wood pieces in the accumulation at a bridge are shorter than length of the bridge (L_b). In contrast, most of them are longer than the depth of bridge from riverbed (H_b);
6. The volume of woody debris accumulation is estimated by 0.2 times the apparent volume in average;
7. An empirical equation for predicting the volume of woody debris accumulation at an obstruction is proposed;
8. For 800 released wood pieces, the wood pieces in the wood debris accumulation at the model bridge that in contact with the bridge seems to stand up straightly and the majority of followed wood pieces are parallel to the model bridge.

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