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Experimental study on bridges over mountainous streams with blocked piers due to woody debris

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Abstract

When bridges are blocked with woody debris, a high flow depth leads to overflow and causes the flow to spread widely, and some bridges become dangerous. Many studies have examined bridges blocked with woody debris on gentle slopes in the subcritical flow regime. However, there have been few studies on woody debris occurring with debris flows from steep mountainous areas in the supercritical flow regime. Therefore, we conducted laboratory experiments with a two-pier bridge model and considered factors for the blockage of bridges by woody debris. We examined the effects of the bridge clearance, amount of woody debris, and length of the woody debris on bridge blocking. The results show that the woody debris concentration upstream of the bridge and the ratio of the woody debris length to the bridge pier interval affect bridge blocking. When the ratio was less than 1, blocking became unstable. When the ratio was larger than 1, blocking occurred at a lower concentration compared with a ratio of less than 1. When the ratio was less than 1.5, a smaller bridge clearance had an increased possibility of blocking at the same concentration. When the ratio was greater than 1.5, the bridge clearance did not seem to affect the blocking possibility.

Key words：Experimental study, bridge, blocking, woody debris, mountainous streams

1. INTRODUCTION

When bridges become blocked with woody debris, a high flow depth leads to overflow from the bridge, which causes the flow to spread widely.

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Ishikawa et al. (2014) reported that the Izu Oshima sediment disaster in 2013 caused woody debris to block bridges and flooding and deposition in the Motomachi area. Furukawa et al. (2009) reported that the Houfu sediment disaster in 2009 caused woody debris to block bridges and facilitated sediment deposition on national roads. Therefore, bridges may become critical points in the event of debris flows. However, not all bridges become blocked with the accumulation of woody debris because bridge conditions such as shape and installation slope and woody debris conditions such as volume, length, and shape are different.

Many studies have considered bridges blocked with woody debris for gentle slopes in the subcritical flow regime. Drift wood studies have mainly been conducted in reservoir areas because it causes problems when flowing in (e.g. Pfistter et al. 2013, Sumi and Kantoush, 2016). Also in a gentle slope downstream area, such as a river management area, bridge blocking due to the occurrence of woody debris caused problems, prompting many studies to be conducted. Adachi and Daidou (1957) and Matsumoto et al. (2001) conducted channel experiments and focused on the accumulation mechanism and accumulation rate of woody debris. Sakano (2003) performed channel experiments to determine the woody debris, bridge, and hydraulic conditions that lead to a high possibility of woody debris accumulation. Hashimoto et al. (2016) performed a flume experiment based on actual disaster cases and bridge conditions and reported that the volume of woody debris blocking bridges is influenced by the woody debris and area in a channel shielded by the bridge. Previous studies have shown that bridge piers become blocked with woody debris accumulation and stagnation, and that smaller pier intervals increase bridge blockage.

However, in steep slope mountainous torrent areas in the supercritical flow regime, disaster mitigation has mainly focused on sediment disasters, such as landslides and debris flows because damage caused by sediment is much larger than that caused by woody debris (Takahashi, 2007). Engineering works and studies have been conducted mainly on sediment movement and have not focused on the behavior of woody debris or triggering damage as much as on sediment movement. However, Ishikawa et al. (2014) reported that woody debris that occurs from a sediment disaster may cause huge damage in residential areas, and it is important to examine woody debris that has occurred in a steep slope area. Several studies have considered woody debris in steep slope areas. Braudrick et al. (1997) reported that the ratio of the woody debris to the flow discharge defines the accumulation of woody debris and that a higher ratio causes accumulation. Rudolf-Miklau and Hübl (2010) reported and classified the woody debris risk including bridge blocking from steep mountainous areas and summarized the protection method for risk management considering the woody debris source and application area. Some studies focused on countermeasures to protect against woody debris using check dams (e.g. Bezzola et al. 2004) and rope nets (Rimböck, 2004). Piton and Recking (2016) conducted a flume experiment focusing on the design of an open check dam trap function considering sediment and woody debris in a steep slope area. Recently, studies focusing on hazard zoning concerning woody debris occurrence and transportation with GIS have been conducted (e.g. Mazzorana et al. 2009 and Ruiz-Villanueva et al. 2014). However, there are few studies focusing on the bridge blocking process or boundary conditions due to woody debris in a steep slope area. Hasegawa et al. (2015) conducted a flume experiment and showed that bridge blocking occurs more frequently with a low woody debris discharge at high velocity under the same flow depth conditions. Their results imply that the supercritical flow condition causes bridge blocking more frequently than the subcritical flow condition, but their experimental conditions were limited. For example, they only used bridge models with a single pier. Bridges over mountainous rivers can have multiple piers, as shown in **Photo 1** (right), and the pier interval may influence the blocking condition as reported for gentle slopes. In this study, we conducted laboratory experiments with a two-pier bridge model in the supercritical flow regime to determine the factors that affect the occurrence and phenomena of bridges blocked with woody debris.

2. EXPERIMENT CONDITION

The flume had a length of 4 m, width of 0.2 m, slope of 2°, water supply of 3.2 L/s, and Froude number of 3.1. The slope of 2° corresponds to the boundary between a mountainous river and a gentle slope river, and commonly becomes a point where flooding occurs. We set the bridge model 0.5 m upstream from the downstream end (see **Fig. 1**, **Photo 2**, and **Table 1**). For the bridge model, we set up two piers with a span length of 0.062 m and considered two different clearances of 0.02 and 0.04 m (see **Fig. 2**). We changed the number of woody

Photo 1. Bridges blocked with woody debris from debris flows: (left) Izu Oshima disaster (PASCO Co.) and (right) Houfu disaster (Furukawa et al. 2009).

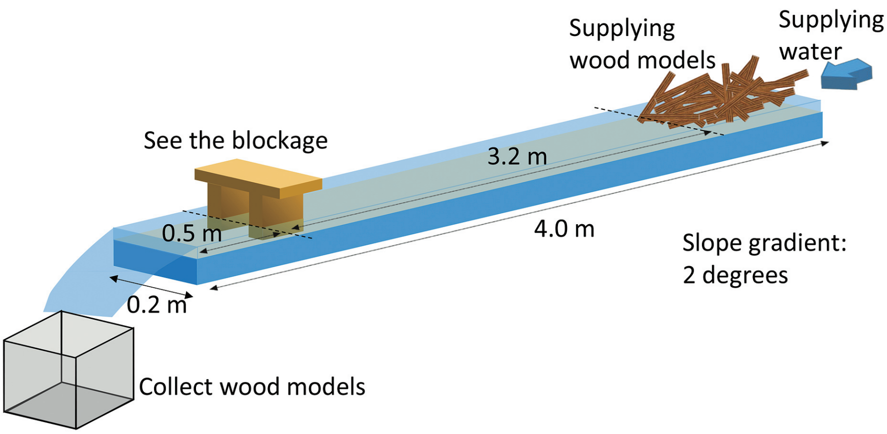

Fig. 1. Overview of experiments.

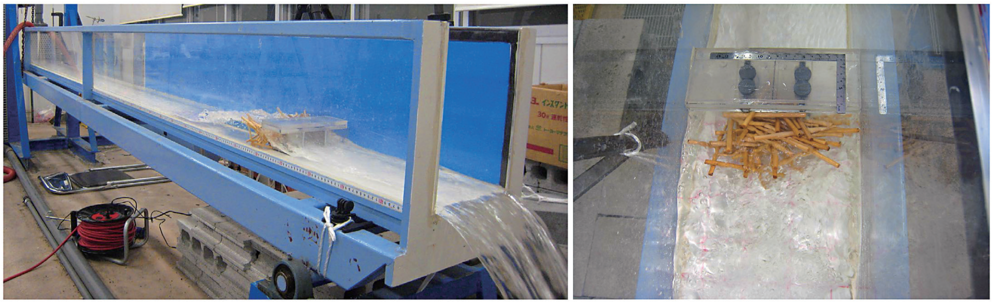

Photo 2. Overview of experimental channel (left) and bridge blocked with woody debris (right).

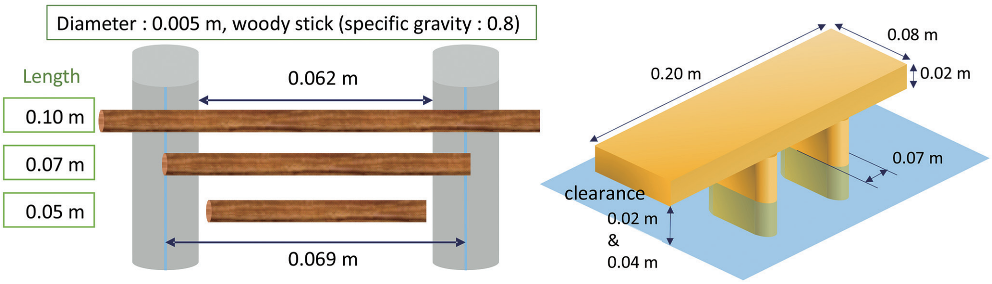

Fig. 2. Woody debris model (left) and bridge model (right).

Table 1. Conditions of the channel experiments.

Slope gradient		2 degrees
Hydraulic conditions	Water discharge	3.2 L/s
	Flow depth	0.014 m
	Froude number	3.1
Model of bridge	Piers	2
	Clearance	0.02 m 0.04 m
Models of woody debris	Length: supplied number at intervals of 10 pieces	0.05 m: 170-300 pieces 0.07 m: 10-160 pieces 0.1 m: 10-80 pieces
	Diameter	0.005 m
	Specific gravity	0.8

debris and length of the woody debris (0.05, 0.07, and 0.1 m; see Table 1) to observe the difference in blockage. To supply the woody debris, we gathered the wood, put it into a dustpan, and dropped it en masse in the channel upstream. We set video cameras at three angles: the side of the channel to see the rise in the water level due to blocking, top of the channel to see the blockage process, and at the downstream end to check how much wood passed through the bridge. We collected the wood from the downstream end. When woody debris occurs with debris flow, it moves a long distance in a steep slope area colliding with wood and sediment, and most branches are torn off and the length of roots and timber are shortened or broken into pieces (e.g. Nakamura and Swanson, 1993). The

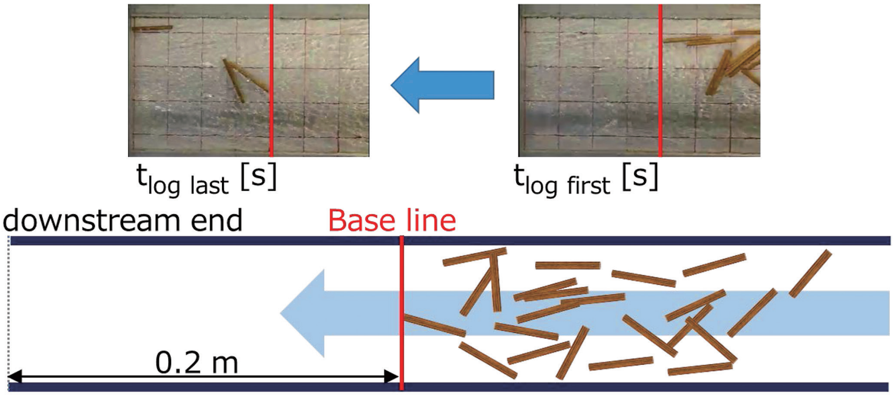

Fig. 3. Method for calculating the woody debris discharge.

condition whereby there are no branches and roots is more dangerous because blocking is less likely to occur compared to when there are branches and roots, and therefore we used woody debris without branches and roots. Furthermore, the condition explains the use of the woody debris supplied from timber cut and abandoned in natural forests. We conducted 10 trials for each woody debris supply condition.

3. EXPERIMENT RESULTS

3.1 WOODY DEBRIS DISCHARGE

Even when the conditions for the amount of woody debris and discharge are the same, the woody debris transportation process differs with the occurrence of phenomena such as spreading or accumulation. Moreover, if there are variations in the woody debris input volume or procedure, the amount of driftwood flowing to the bridge changes. Therefore, we evaluated the amount of woody debris as a time series with the discharge 0.2 m upstream of the bridge as the baseline (see Fig. 3) to avoid the effect of reproducibility due to the input procedure. We checked the time from the front end of the woody debris to pass the baseline (i.e., $t_{log\ first}$ [s]) and the back end to do the same (i.e., $t_{log\ last}$ [s]) and then divided the number of pieces of wood by this time. We defined this value as the discharge of woody debris q_{log} [cm^3/s].

$$q_{log}=\frac{N_{log}V_{log}}{(t_{last\ log}-t_{first\ log})} \qquad (1)$$

N_{log} represents the number of pieces of woody debris, and V_{log} [cm^3] shows the volume of one piece of woody debris. We defined the blocked condition as woody debris remaining at the bridge and causing dam-up at the upstream side.

3.2 BLOCKING FREQUENCY, DAM-UP DISTANCE, WOODY DEBRIS CONCENTRATION ON CASES OF 2-CM CLEARANCE

Here, we show the experimental results of the blocking frequency, dam-up distance, and woody debris concentration on cases of 2-cm clearance.

Fig. 4 shows the relationship between the discharge of woody debris and frequency of blocking, temporary blocking, and non-blocking for each length of woody debris. Temporary blocking means that woody debris blocked the bridge and caused dam-up but became disentangled and flowed down within 120 s. We used 120 s as the index because we found that blocked woody debris at the bridge did not flow down after 120 s from the preliminary experiment. We did not consider the condition whereby woody debris blocked the

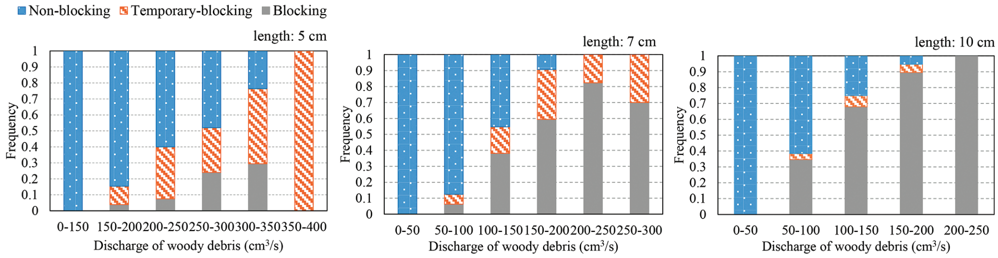

Fig. 4. Frequency of blocking, temporary blocking and non-blocking conditions according to the experimental results (2-cm clearance).

bridge within 120 s but did not cause dam-up as temporary blocking. Since dam-up leads to small velocity and deposition, the risk at the bridge becomes larger due to the blocking even in temporary phenomenon. Therefore, we considered temporary blocking as part of the blocking condition. For all lengths, a larger discharge of woody debris led to blocking, and a smaller discharge led to non-blocking. Blocking seemed to occur at a small discharge with longer pieces of woody debris. Longer pieces of wood reduced the frequency of temporary blocking. At a length of 5 cm, temporary blocking was more frequent than at other lengths. Temporary blocking also occurred more frequently when the discharge condition was increased while the length was fixed at 5 cm. This appeared to be because of the ratio between the woody debris length and bridge pier interval: 0.8 at 5 cm, 1.1 at 7 cm, and 1.6 at 10 cm. When the length is shorter than the bridge pier interval, in the 5-cm wood model cases, single pieces of woody debris could not block the bridge. Even though blocking occurred from several pieces once, collapse due to flow turbulence or wood model movement seemed to occur because the length is short. When the length is longer than the interval, in 10-cm cases, single pieces were sufficiently long to span two piers. Once woody debris caused blocking, the woody debris would not be dislodged easily even if some of the pieces moved because blocking is stable from two supporting points. Wood 7 cm in length is slightly longer than the interval. Therefore, it can span the piers with the single wood model but even with slight movement, it loses one support point easily. Therefore, the blocking that occurred in 7-cm cases seems to be unstable and collapses, indicating a higher frequency of temporary blocking compared to 10-cm wood cases.

Fig. 5 shows the woody debris concentration and occurrence of blocking. Concentration C_{log} was calculated from the woody debris discharge q_{log} and supplied water discharge q_{water}.

$$C_{log}=\frac{q_{log}}{q_{water}+q_{log}} \qquad (2)$$

Considering the temporary blocking case as the blocking condition, the results show that a higher concentration and longer pieces of woody debris caused blocking more frequently. However, under the same concentration and length conditions, both blocking and non-blocking processes showed a wide range of results, especially at smaller ratios between the woody debris length and bridge pier interval (e.g., 0.8). Based on the experimental results, blocking seems to be influenced by several factors of woody debris dynamics. For example, the woody debris flow angle to the bridge, flow course to the bridge, collision and accumulation of wood, and especially the behavior upstream of the bridge seem to affect the blocking process.

Fig. 6 shows the relationship between the accumulation volume of woody debris and the dam-

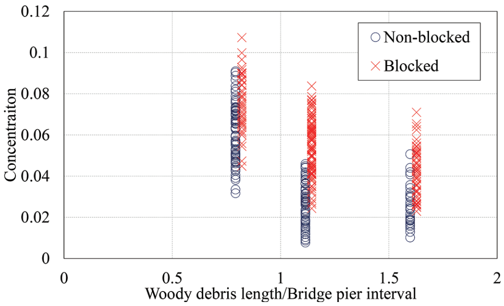

Fig. 5. Occurrence of blocking in the experimental results (2-cm clearance).

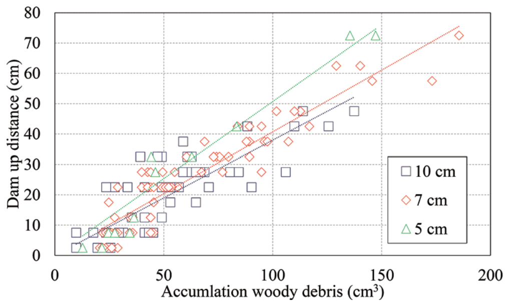

Fig. 6. Relationship between the accumulation of woody debris and the dam-up distance (2-cm clearance).

up distance in the event of blocking. The dam-up distance indicates the slope distance from the bridge upstream to the hydraulic jump. Usually we use an ultrasonic sensor to observe flow depth but it was difficult in our experiment because several pieces of the woody debris protruded from the water surface. Therefore, we used the dam-up distance instead of the dam-up depth because it was easy to obtain and showed us a more accurate value from video. The distance increased with dense woody debris blocking and decreased under the sparse condition. The results show that longer pieces of woody debris caused sparse blocking, and shorter lengths caused dense blocking. This is due to the void difference; shorter length woody debris blocking includes smaller voids compared with longer length woody debris blocking even though the volume of wood is the same. This occurs because shorter length cases, especially 5-cm cases, require more wood pieces to form larger accumulation and cross over two piers or supporting points and cause stable blocking. As shown in **Figs. 4** and **5**, increasing the length caused blocking to be more frequent, but the dam-up distance due to blocking increased with shorter pieces of woody debris.

4. STATISTICAL METHOD

It is difficult to determine the increased tendency to change from the non-blocking to blocking condition using only the experimental results. In addition, the results may be influenced by the number of experiments. Thus, we used a statistical method. We applied logistic regression analysis using the woody debris concentration as the explanatory variable and the occurrence of blocking as the response variable. We compared the blocking probability P based on the woody debris concentration x (see **Fig. 7**).

$$P=\frac{e^{ax+b}}{e^{ax+b}+1} \qquad (3)$$

Here, e indicates the natural logarithm, and a and b are coefficients. **Figs. 8** and **9** show the results of the logistic regression analysis. The conditions under which both non-blocking and blocking occur, as shown in yellow in **Fig. 7**, can be explained by the shape and inclination of the regression curve. When the inclination was steep and the concentration range for P=0.1−0.9 was narrow, the yellow area with both blocking conditions became smaller. Therefore, in both clearance cases, pieces of woody debris 5 cm in length showed a larger yellow range. This indicates that the transition from non-blocking to blocking was larger than that for the 7- and 10-cm lengths.

At different clearances, the regression curves moved to the higher concentration side, and the curve shape became gentler with a 4-cm clearance

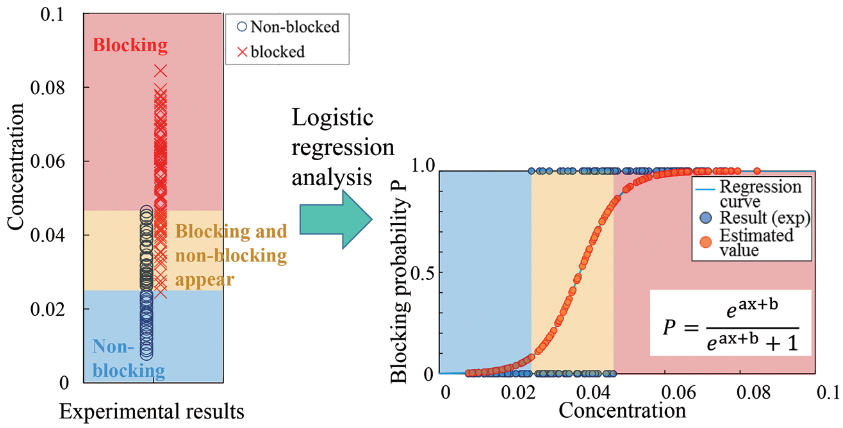

Fig. 7. Method of logistic regression analysis.

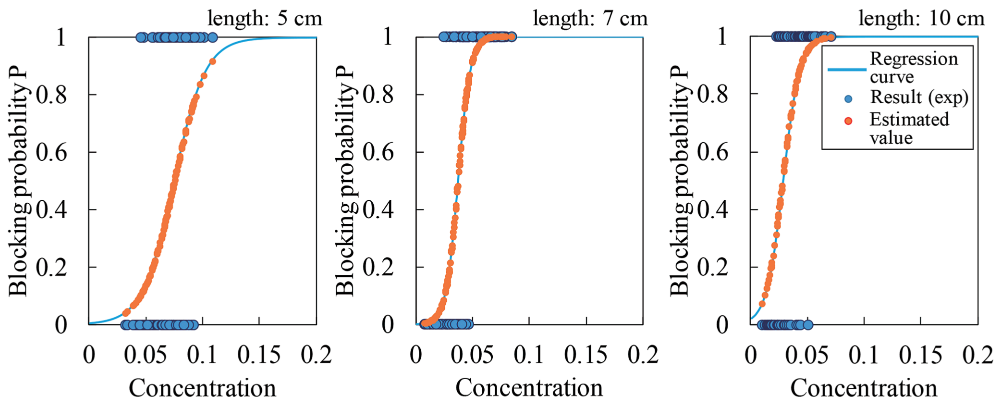

Fig. 8. Results of logistic regression analysis for a clearance of 2 cm.

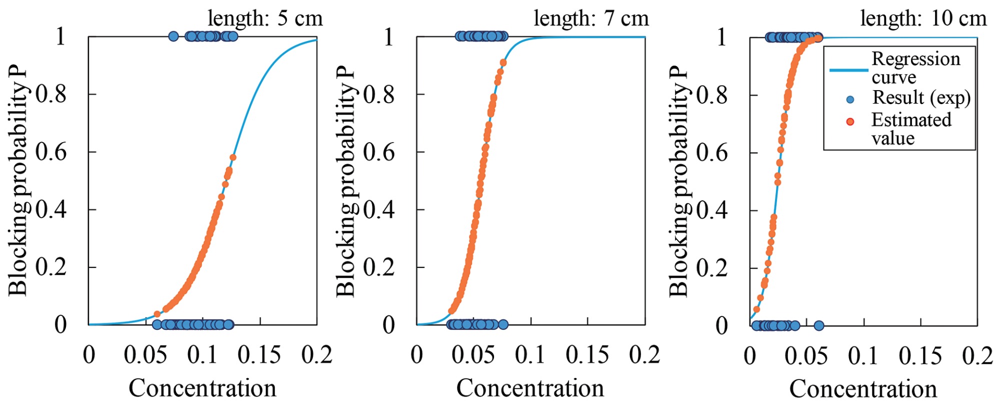

Fig. 9. Results of logistic regression analysis for a clearance of 4 cm.

for woody debris with lengths of 5 and 7 cm. This indicates that larger clearances required higher woody debris concentrations to increase the blocking probability P for woody debris pieces with lengths of 5 and 7 cm. This seems to be because woody debris with lengths of 5 and 7 cm could not induce stable blocking compared to debris with a length of 10 cm owing to the ratio with the pier interval, as shown in **Figs. 4** and **6**. At smaller clearances, the flow surface and the bridge beam distance became smaller, and the contact frequency between each piece of woody debris and the bridge beam or piers increased. Therefore, the 2-cm clearance case required a lower woody debris concentration for the same blocking probability P with woody debris lengths of 5 and 7 cm compared with the 4-cm clearance case.

However, the shape and inclination of the regression curve did not show remarkable changes with 10 cm long woody debris. This length seemed to be sufficient to cross the pier interval and cause both accumulation and blocking, as shown in Figs. 4 and 6. Thus, the clearance had a smaller effect compared to shorter pieces of woody debris.

5. CONCLUSION

We conducted a laboratory experiment with a two-pier bridge model and considered factors that affect the occurrence and phenomena of bridges being blocked with woody debris. The results show that the important factors were the woody debris concentration upstream of the bridge and the ratio of the woody debris length to the bridge pier interval. A higher concentration increased the frequency and possibility of blocking. When the ratio of the woody debris length to the bridge pier interval was smaller than 1, the blocking became unstable compared to larger ratios. A larger ratio (or longer woody debris length) required a lower concentration for blocking than a smaller ratio (or shorter length). When the ratio was less than 1.5, a smaller bridge clearance showed a higher possibility of blocking at the same concentration. When the ratio was greater than 1.5, the bridge clearance did not seem to affect the blocking possibility. The woody debris length and pier interval data can be obtained from field observations. However, woody debris discharge and concentration data are difficult to obtain. Therefore, information on the woody debris concentration and proposed estimation methods are required. Furthermore, this study focused on woody debris shape without branches and roots. The actual possibility of blocking will be higher because some of the roots may remain with woody debris and become entangled more easily. In future, we will conduct further experiments under different conditions. For example, we can change the bridge model to one without piers, which is used frequently for steep mountainous channels, and use pieces of woody debris that include roots, which seem to increase blocking.

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要　旨

流木により橋が閉塞すると，水位上昇による氾濫・堆積が発生して危険になる場合がある。既往研究では常流の緩勾配領域について検討されてきた。しかし，射流の急勾配領域の山間部で発生する流木による橋の閉塞の検討は少ない。本研究では，橋脚２本の橋模型を用いて，橋のクリアランス，流木量，流木長さを変えて水理実験で検討を行った。結果から，橋の上流での流木濃度と流木長さに対する橋脚間の距離の比が閉塞に影響することを示した。比が１よりも小さいと不安定な閉塞が生じ，１を超えると低い流木濃度で閉塞が発生した。比が1–1.5の条件では小さいクリアランスで閉塞確率が高いが，1.5を超えるとクリアランスの違いは閉塞確率に影響しなかった。