Experimental Study of the Use of Stakes to Prevent Driftwood and Natural Debris from Blocking Bridges

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Historically, Japanese bridges have been protected from blockage by stakes that control the passage of driftwood. It is important to clarify the function of these stakes; for example, stakes can be used to prevent debris accumulation near a pier. However, no design codes have been established for the optimal placement of stakes to prevent blockage. Furthermore, no studies have been conducted to compare the blockage prevention performance of stakes at different distances, or how their gradient with respect to the riverbed affects debris accumulation. We performed a laboratory-based experiment to observe the effects of stakes on the flow of driftwood within rivers. We found that driftwood passed between piers after rotating around the stakes. We conclude that bridges would be better protected by vertical stakes, which take advantage of this mechanism.

Key words: bridge, driftwood, experiment, natural debris, stake

1. INTRODUCTION

Many areas experience damage by debris flow and driftwood every year in Japan. This damage is the result of debris from mountain forests and landslides due to local downpours, caused in part by global warming [*Fujita*, 2012]. Recent disaster reports have indicated that blockage by driftwood contributed to damage and flooding around bridges [*e.g., Ishino et al.*, 2006; *Izu-Oshima Disaster Research Committee*, 2014]. There have been a number of studies concerning bridge damage and countermeasures to prevent the accumulation of driftwood [*Nakagawa et al.*, 1992; *Goto et al.*, 2001; *Shimizu et al.*, 2007; *Shibuya et al.*, 2011]. In some studies [*e.g., Adachi and Daido*, 1957; *Ishikawa et al.*, 1989], mechanisms were proposed to explain the formation of driftwood blockage at bridges and in narrow channels. *Adachi and Daido* [1957] found that the variables determining whether a bridge is blocked by driftwood were the density of flowing driftwood, surface flow velocity, and the relationship between bridge pier interval and driftwood length. *Ishikawa et al*. [1989] proposed a model to predict driftwood blockage rates based on the Froude number, channel width, and driftwood length and diameter; numerical predictions of driftwood behavior have been conducted in several studies [*Nakagawa et al.*, 1992; *Goto et al.*, 2001; *Shimizu et al.*, 2007; *Shibuya et al.*, 2011]. *Ishikawa et al*. [2007] proposed the installation of steel within bridge beams as a countermeasure to prevent bridges from being blocked.

Historically, stakes installed before bridges that control the direction of driftwood flow have been used to protect bridges from blockages, for example, at Togetsu Bridge in Arashi-yama and Uji Bridge in the Ise Shrine (**Fig. 1**). Stakes also prevent other types of natural debris from blocking the bridges; Takebayashi [2014] described how stakes functioned during a 2013 flood (**Fig. 2**). Many bridges have narrow intervals between piers; these require protection from blockage by driftwood and other natural debris. Traditional stakes are considered effective countermeasures against blockage by debris. However, design codes for the stakes have not been established; thus, the arrangement of stakes differs between bridges.

At Togetsu Bridge (**Fig. 1**), one stake is installed at every other pier. At other bridges, such as Uji Bridge

Fig. 1 Traditional Japanese technique to prevent damage to historical bridges using stakes, Upper: Togetsu Bridge, Arashi-yama, Kyoto; lower: Uji Bridge, at the Ise shrine, Mie

Fig. 2 Stakes at Togetsu Bridge during a 2013 flood [*Takebayashi*, 2014]

(**Fig. 1**), stakes are installed at every pier.

Furthermore, no study has been conducted to compare the effectiveness of different arrangements of stakes in preventing blockages, or how their gradients with respect to the riverbed affect debris accumulation. We thus conducted laboratory flume experiments to observe the effects of stakes on the behavior of driftwood flowing in rivers. Based on our experimental results, we propose an effective plan for the use of stakes in preventing blockages.

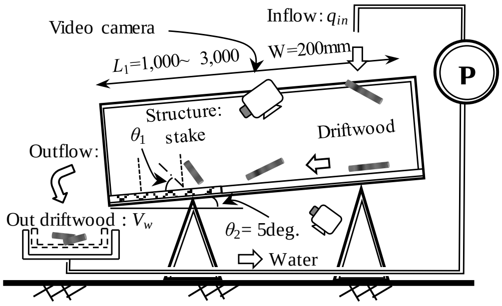

Fig. 3 Schematic diagram of the experimental flume

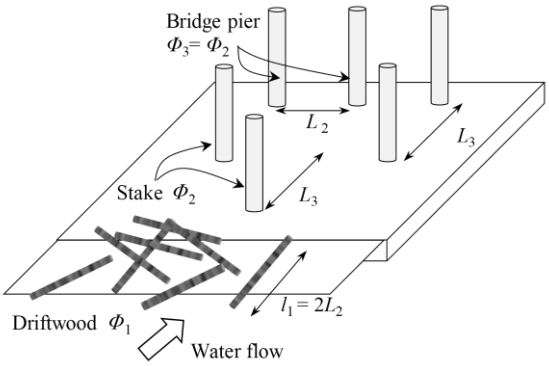

Fig. 4 Schematic diagram of the experimental set-up

2. DRIFTWOOD CONTROL EXPERIMENT

We supplied water and driftwood to the upper part of a flume and observed the mechanisms of driftwood control by the stakes (**Fig. 3**).

2.1 Outline

Fig. 4 shows the experimental set-up; the experimental waterway of fixed bed, which was within the flume, was 20 cm high, 20 cm wide, and 300 cm long. We counted the small pieces of driftwood blocked by the stakes or piers, which were installed at the downstream edge of the flume (**Fig. 4**). The driftwood and water were supplied to the upper point at a rate of q_{in}. The driftwood was Φ_1 in diameter, 10 cm in length, and had a dry density of 0.75. The flume was inclined at an angle of 5° [*Ishikawa et al*., 1989]. The riverbed was covered in stones, such that the flow was stable, as in a real river. The stakes and piers were cylindrical, with a diameter

Table 1 Combinations of parameters used in the experiments

CASE	Φ_1 (mm)	L_1 (mm)	V_w	Direction of flow	Type	θ_1 (°)	L_3	q_{in} (ℓ/s)
1-1	3	1,000	1/s *50s	Horizontal	Without stake			1.0
1-2								2.3
1-3		2,000						1.0
1-4				Vertical				
2-1		1,000		Horizontal	B	90	$1.0*l_1$	
2-2		2,000						
2-3							$1.5*l_1$	
2-4								2.3
2-5							$1.0*l_1$	
2-6							$0.5*l_1$	
2-7					Without stake			
2-8					A	90	$1.0*l_1$	
2-9							$1.5*l_1$	
3-1			50		No structure			
3-2					B	90	$1.5*l_1$	
3-3		3,000						
3-4					Without stake			
3-5			1/s *50s		B	45	$1.5*l_1$	
3-6						135		
4-1	1	2,000			Without stake			

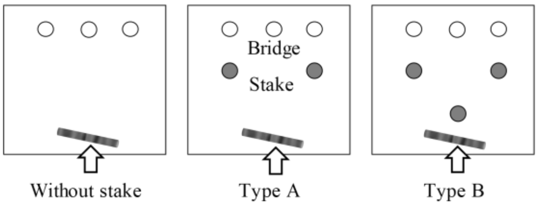

Fig. 5 Stake configurations tested in this study

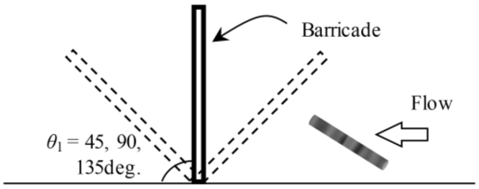

Fig. 6 Angle between the stakes and the riverbed

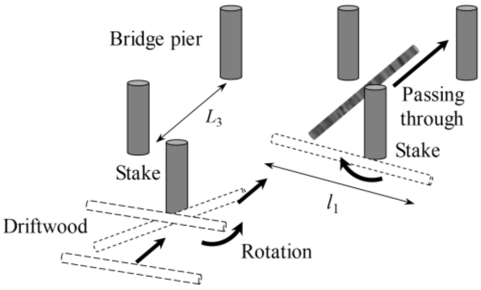

Fig. 7 Driftwood build-up prevention mechanisms

of 1 cm (**Fig. 4**). The experiment was easier to control using cylindrical stakes instead of prism-shaped stakes because flow around prism-shaped stakes is disordered. We used a pier interval, L_2, of 5 cm, which was half the length of the driftwood, l_1, 10 cm. *Ishikawa et al*. [1989] reported that driftwood can easily block the spaces between stakes when the driftwood is longer than the distance between stakes.

Table 1 shows the parameters that we controlled during the experiments. We observed the effect of stakes on driftwood flow as we varied the driftwood diameter, Φ_1, the distance between the stakes, and the supply point, L_1, the driftwood supply rate, V_w, the direction of driftwood flow, and the arrangement of the stakes (**Fig. 5**), the incline of the stakes against the riverbed, θ_1 (**Fig. 6**), the distance between the piers and stakes, L_3, the driftwood length, l_1 (**Fig. 4**), and the upstream water supply rate, q_{in}.

As shown in **Fig. 5**, we proposed a new, houndstooth-shaped stake arrangement, which we called Type B. In the Type A arrangement, we placed stakes at alternating piers, after the arrangement at Togetsu Bridge (**Figs. 1** and **2**). The maximum driftwood volume concentration ratio was approximately 0.3. When the supply water discharge rate was 1.0 l/s, the water height was 1.1 cm and the Froude number was 1.3. When the supply water

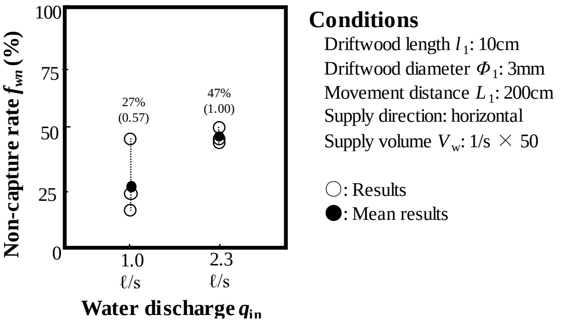

Fig. 8 Effect of water discharge on the non-capture rate, f_{wn}

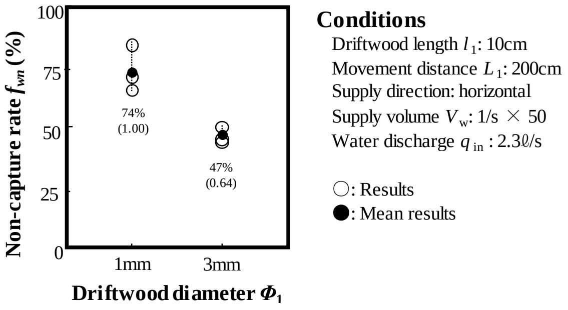

Fig. 11 Effect of driftwood diameter on f_{wn}

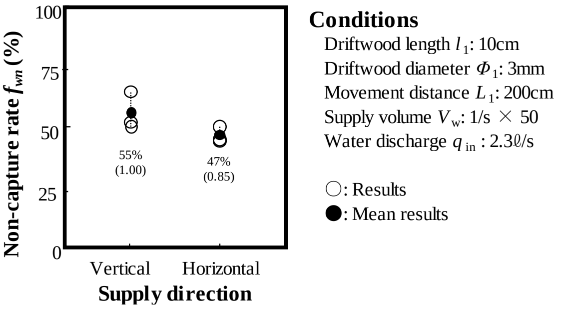

Fig. 9 Effect of the direction of driftwood supply on f_{wn}

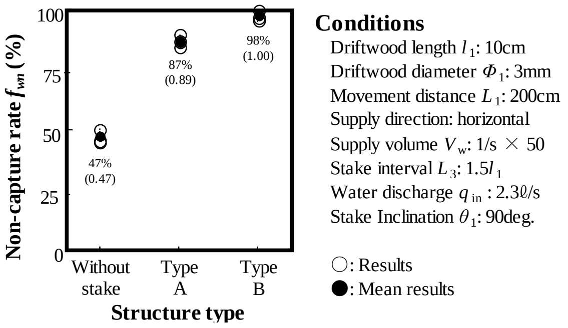

Fig. 12 Effect of stake arrangement on f_{wn}

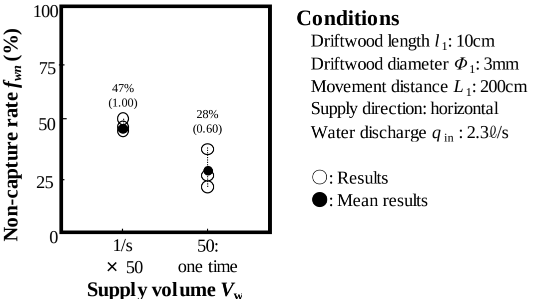

Fig. 10 Effect of driftwood supply volume/speed on f_{wn}

discharge rate was 2.3 l/s, the water height was 1.9 cm and the Froude number was 1.4.

Fig. 7 shows the mechanisms by which the stakes might control the flow of driftwood under the bridge. We believe that driftwood rotates around the stakes, enabling it to flow between the piers. The experiment was repeated three times under each condition and was recorded using video cameras **(Fig. 3**).

2.2 Effect of stake arrangement on driftwood control performance

The non-capture rate, f_{wn}, which is the rate at which driftwood pieces passed between the bridge piers, is given by:

$$f_{wn} = {}^{V_{wout}}\!/_{V_{out}} \qquad (1)$$

where V_{wout} is the number of driftwood pieces that passed under the bridge and V_{out} is the number of driftwood pieces supplied.

Fig. 8 shows the relationship between the supplied water discharge rate from upstream q_{in} (**Fig. 3**) and f_{wn}. f_{wn} increased with q_{in} and water flow speed (**Fig. 8**). In fast-flowing areas, we observed that driftwood passes between bridge piers by rotating smoothly around the stakes, whereas driftwood pieces did not rotate around the stakes in slow-flowing areas, and so were captured by the stakes or piers. Some results for slow-flowing areas agreed with those from fast-flowing areas, which suggests that the capture of driftwood is a probabilistic process.

Fig. 9 shows the relationship between the driftwood supply direction and f_{wn}. In particular, we studied driftwood orientated perpendicular and parallel to the direction of flow. The driftwood orientation did not have a significant effect on f_{wn} (**Fig. 9**). We observed that the driftwood rotated irregularly, such that some driftwood pieces started

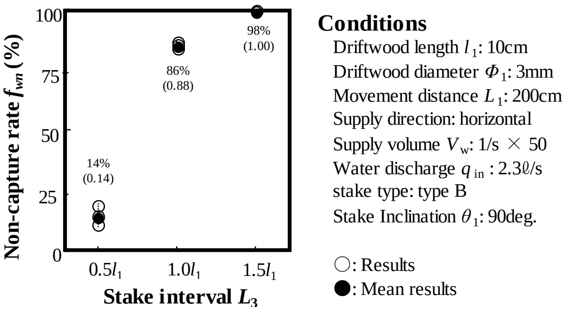

Fig. 13 Effect of the distance between the stakes L_3 on f_{wn}

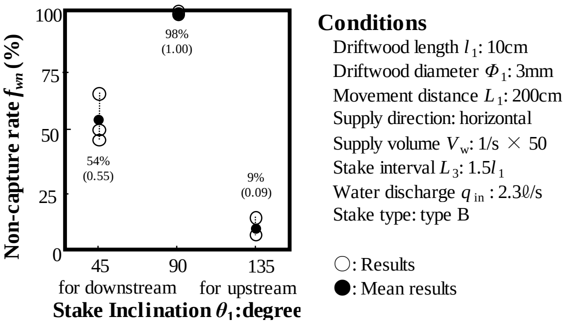

Fig. 14. Effect of the incline of stakes to the riverbed θ_1 on f_{wn}

to be orientated in the direction of water flow.

Fig. 10 shows the relationship between driftwood supply volume/speed and f_{wn}. We introduced one piece of driftwood per second for 50 seconds, and 50 pieces of driftwood simultaneously. When all driftwood was released at once, it was captured easily. f_{wn} was affected by differences in driftwood density, as was shown in a previous study [*Adachi and Daido*, 1957]. However, the results of experiments in which all driftwood was released at once were very similar to those in which driftwood was released slowly (**Fig. 10**).

Fig. 11 shows the relationship between driftwood diameter Φ_1 and f_{wn}. f_{wn} decreased with Φ_1 (**Fig. 11**). [*Ishikawa et al.*, 1989] suggested that there is a relationship between the driftwood capture rate in a narrow flume, the Froude number, and driftwood diameter and length. We observed experimentally that fast-flowing water, as seen when the Froude number is larger, enabled driftwood captured by stakes or bridge piers to be released by rotation around the stakes. Additional research is required to confirm this release mechanism.

Fig. 12 shows the relationship between stake arrangement and f_{wn}. We tested no-stake, Type A, and Type B (**Fig. 5**). The stakes enabled driftwood to pass easily through the bridge piers by rotating around them (**Fig. 7**). The presence of stakes approximately doubled the driftwood capture rate. Furthermore, the Type B arrangement was more effective than that of Type A (**Fig. 12**). We observed that some driftwood that had passed through stakes without contact in the Type A arrangement was captured by bridge piers.

Fig. 13 shows the relationship between L_3 (**Fig. 4**), and f_{wn}. A wide stake interval enabled driftwood to rotate around the stakes easily [Fig. 13]. We concluded that driftwood could not rotate around the stakes if the distance between them was insufficient, that is, when the stakes were separated by more than 1.5 times the driftwood length.

Fig. 14 shows the relationship between θ_1 [Fig. 6] and f_{wn}. The driftwood rotated more easily around the stakes when it was perpendicular to the riverbed. We observed that driftwood was not able to rotate easily around the stakes when the stakes pointed upstream or in the direction of the water flow.

We propose that, to control driftwood accumulation at bridges, stakes should be installed vertically in a houndstooth formation (Type B), with a separation distance L_3 of 1.5 times the driftwood length, l_1.

3. CONCLUSION

To understand the traditional technique of using stakes to prevent driftwood from blocking bridges, we varied the stake arrangement and performed experiments to evaluate their effect on driftwood accumulation. We then proposed an effective stake design based on our experimental results.

We observed that driftwood rotates around the stakes, and then passes between the bridge piers. Driftwood accumulation prevention performance was affected by water flow speed, driftwood density, inclination of the stakes with respect to the riverbed, and stake installation interval. We proposed a new houndstooth-shaped stake configuration, which should act as an effective countermeasure against blockages by driftwood and other floating debris. In the future, additional experiment that is changed the length of driftwood is needed.

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