Proceedings of the 7th International Conference on Civil Structural and Transportation Engineering (ICCSTE'22)
Niagara Falls, Canada – June 05-07, 2022
Paper No. 173
DOI: 10.11159/iccste22.173

A Fundamental Study on the Interaction between Driftwood and Free-Surface Flow in an Open Channel

Terunori Ohmoto [1], Hirotaka Une [2]
[1] the Center for Water Cycle Marine Environment and Disaster Management / Kumamoto University
3-52-31,Kurokami, Kumamoto, Japan
ohmoto@kumamoto-u.ac.jp; une@tokuyama.kosen-ac.jp
[2] Department of Civil Engineering and Architecture/ National Institute of Technology, Tokuyama College
Gakuendai, Shūnan, Japan

Abstract **-** In this study, a high-resolution, high-speed camera was used to capture driftwood velocity, while PIV (particle image velocimetry) and PTV (particle tracking velocimetry) were used to measure free-surface velocity. The effects of channel slope, driftwood length and driftwood shape on the relative velocity between driftwood and free-surface flow were examined on the basis of an equation relating to driftwood motion and the experimental results. The study revealed that in cases where the driftwood angle is small, the velocity of a cylindrical piece of driftwood becomes higher than the free-surface velocity as channel slope and driftwood length increase. It was also found that the product of driftwood length and channel slope is proportional to the square of driftwood and free-surface velocity.

Keywords**:** drift wood, free-surface flow, cylindrical wood, spherical wood , PIV, high speed camera

1. Introduction

Debris flow, accompanied by a collapse of stream bed deposits triggered by a localized torrential rainfall, causes an outflow of not only large volumes of water and sediment, but also of a considerable amount of driftwood. The heavy rains of July 2017 in the northern part of Kyushu,Japan caused many extensive hillslope failures and landslides in the areas along the Akatani and Otoishi Rivers. The water-borne transportation and deposition of large volumes of sediment and driftwood inflicted devastating damage in the valley bot-tom plain, leaving 42 persons dead or missing and destroying 336 houses.

The heavy rains of 2012 in the northern part of Kyushu, Japan were of a similar magnitude, leaving 32 persons dead and destroying 363 houses. The heavy rains of 2017, however, were made more devastating by the mobility and destructive power of the driftwood.

One of the most damaging floods that Kyushu has ever experienced was the West Japan Flood of 1953 (West Japan Flood Research Group, 1957), 3) which left 1,028 persons dead or missing, including 488 in Kumamoto Prefecture and 297 in Fukuoka Prefecture. Damages and suffering in the areas along the Shira and Chikugo river, Japan were particularly serious.

In Kumamoto Prefecture, the flood, which is also known as the "June 26 Flood," left the built-up area of the city of Kumamoto filled with newly deposited volcanic ash (locally called "Yona"). Driftwoods also came loose in the Mt. Asosan area. The flow of debris and entrained driftwoods which ware caused by a hillslope failures in Minami Aso rushed into the Shira River, washing away houses and wooden bridges downstream. At the reinforced concrete Kokai Bridge, located 14.5 km upstream from the mouth of the river, the river bed rose and driftwood blocked the river channel. This reduced the discharge capacity of the channel, causing an outflow of a tremendous amount of driftwood from a 50-meter-long section of the left bank. In July 1990, the Ichinomiya Debris Flow of Kumamoto Prefecture caused protected-lowland inundation along the Furue River of the Asodani area and caused the death of eight persons.

It is well known that driftwood aggravates flood and debris flow damage, thus causing considerable human suffering. Implemented control measures using open-type check dams and driftwood detention basins have not been sufficiently effective (Harada et al., 2017).

Review by Ruiz-Villanueva, V. et al.(2015) brought a comprehensive qualitative and quantitative summary of recent advances regarding the different processes involved in large wood dynamics in fluvial systems including wood budgeting and wood mechanics.

The factors controlling large wood motion were also analysed by Braudrick and Grant (2000, 2001) who studied the influence of different log characteristics (orientation, size, density, and presence of roots) on large wood mobility, comparing a theoretical approach with the results of flume experiments and field observations. In addition, they examined some dynamics of wood transport in streams through a series of flume experiments and observed three distinct wood transport regimes: uncongested, congested and semi-congested. During uncongested transport, logs move without piece-to-piece interactions and generally occupy less than 10 per cent of the channel area. In congested transport, the logs move together as a single mass and occupy more than 33 per cent of the channel area. Semi-congested transport is intermediate between these two transport regimes.

This study focuses on driftwood–fluid interaction in a driftwood-carrying flow in order to investigate the water-borne movement characteristics of driftwood.

Previous studies on driftwood include one by Matsutomi and Tanabe(2006) in which a piece of driftwood was placed into an experimental flume. The results of this experiment were that the distance of movement necessary for reaching a driftwood's steady state is not greater than 20 times the driftwood length, and that the passage probability distribution of driftwood in the direction transverse to flow showed a normal distribution pattern, with its variance increasing as the drift distance increased.

Concerning the behavioral stability of driftwood, Sanjo and Okamoto (2016) measured pitching and yawing moments to determine the static and dynamic stability of driftwood. On the basis of an experiment conducted on the percentage of driftwood trapped by a bridge, the behaviours of the percentage of driftwood trapped by a bridge and of backwater were also evaluated.

Regarding the mechanism of driftwood motion, Mizuhara (1973,1974) conducted a series of experiments involving stroboscopic photogrammetry and reported, among others, that the velocity of driftwood relative to flowing water in a steady state is proportional to roughly the square of 0.5 to 0.6 times the driftwood weight and channel slope. They also found that if the channel slope remains constant, the final relative velocity of driftwood is hardly affected by the flow rate.

Yet, despite all the work done in the area, no study has ever tried to measure driftwood velocity and free-surface velocity simultaneously. Furthermore, few experimental studies have been made on the relative velocity between driftwood and free-surface flow.

In this study, a high-resolution high-speed camera was used to capture driftwood velocity with high accuracy, while PIV (particle image velocimetry) and PTV (particle tracking velocimetry) were used to measure free-surface velocity. The effects of channel slope, driftwood length and driftwood shape on the relative velocity between driftwood and free-surface flow were examined on the basis of an equation relating to driftwood motion and the experimental results.

2. Experimental Apparatus and Method

The flume used in the experiments conducted in this study is a 15 m long, 60 cm wide and 40 cm high variable-slope recirculating straight flume, as shown in Figure 1. The sidewalls are made of tempered glass, making photographing and laser beam irradiation from the sidewalls possible. Figure 1 illustrates the open channel flume used in the experiments. In the experiments, the flow rate was fixed at 14 l/s, and the slope was varied among four values: 1/60, 1/100, 1/300 and 1/500. Table 1 shows the hydraulic conditions.

The driftwood pieces used in the single-piece experiment were three types of Mempisang wood bar-shaped pieces. They had a specific gravity of 0.7, a diameter of 0.6 cm and a length of 5 cm, 10 cm or 15 cm. Three types of giant dogwood spherical pieces had a specific gravity of 0.8 and a diameter of 1 cm, 2 cm or 3 cm. In the multi-piece experiment, three types of bamboo strips were used with lengths of 5, 10 or 15 cm, and a specific gravity of 0.7. To prevent the driftwood pieces from absorbing water over time, which would change their specific gravity changes, the driftwood

No.	1	2	3	4
Discharge Q(l/s)	14	14	14	14
Channel slope I_o	1/60	1/100	1/300	1/500

Table 1: Hydraulic conditions

Flow depth H(cm)	2.6	2.8	4.0	5.2
Mean flow velocity U_m(cm/s)	90	83	58	45
Froude number $U_m/(gH)^{1/2}$	1.78	1.59	0.93	0.63

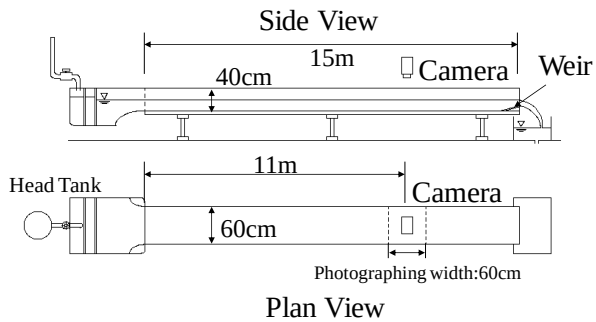

Fig. 1: Experimental channel

pieces were coated with waterproofing compound. In the multi-piece experiment, the driftwood pieces were placed into the flume after immersing them in a surfactant solution to enhance dispersibility. In all cases, driftwood pieces were put into the flow at the center of the channel at a distance of 2 cm downstream from the upstream end of the open channel.

PIV (particle image velocimetry), one of the most widely used non-contact image pro-cessing techniques, was used for measuring flow velocity. In the 1/300 and 1/500 slope cases, image data was recorded on the computer hard disk as 125-fps (frames per second) 1024×1024-pixel black-and-white video image data; and in the 1/60 and 1/100 slope cases as 250-fps, 1024×1024-pixel black-and-white video image data. The measurements covered the region within ±10 cm from the midpoint of the width of the channel in the cross-channel direction, with the spatio-temporal average in this region being taken as free-surface velocity. During the experiment, nylon particles with a diameter of 100 □m and a specific gravity of 1.02 were placed in the water as tracers. To eliminate the influence of the conditions under which driftwood pieces are placed into the water and of the side-walls, drift analysis was performed in the downstream section between 11 m and 11.6 m from the upstream end of the channel, as well as within ±10 cm from the midpoint of the channel width.

In the single-piece experiment, the average velocity of driftwood was measured from the number of frames (time) needed by the center of gravity to move a certain distance. On the channel bed in the measurement section, the midpoint of the channel, and the points at a distance of ±10 cm from the midpoint of the channel width in the cross-channel direction, were marked with small white-paint dots at 10 cm intervals.

3. The Characteristics of Driftwood and Free-surface Velocity

Figure 2 shows an example path of motion of a 10-centimeter-long piece of driftwood of Case No.2 of Table-1 captured at 10/250 second intervals. The driftwood is shown in this case to be making translational movements in the direction of flow at a constant angle of 17°.

Figures 3 show the results of the simultaneous measurements of free-surface and drift-wood velocity on a channel slope of 1/60 in the 10 cm driftwood-length case. Free-surface velocity measurements are shown in the colored contours, with warm colors indicating higher velocities and cold colors indicating lower velocities.

It can be seen that, driftwood velocity tends to be higher than free-surface velocity, and that driftwood tends to make free-surface velocity higher locally.

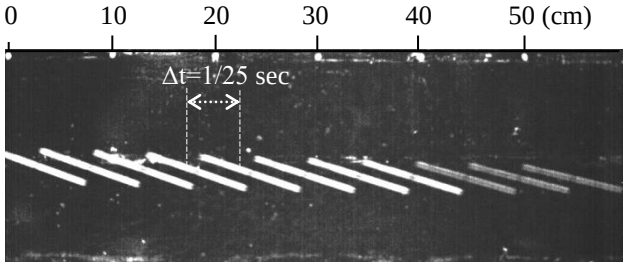

Fig.2: Motion pictures of driftwood captured at 1/25sec in case of No.2 in Table 1.

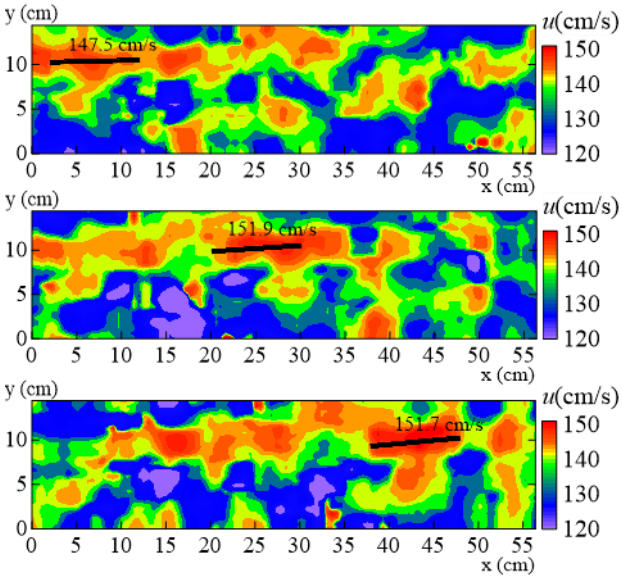

Fig.3: Simultaneous measurements of free-surface and driftwood velocity on a channel slope of 1/60 in the 10 cm driftwood-length case

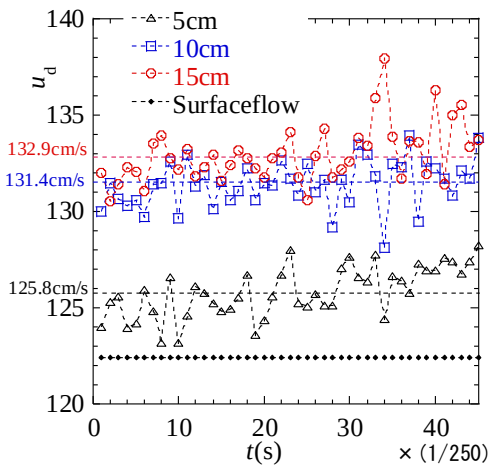

Figure 4. Time series of the driftwood velocities in case of No.2 in Table 1.

The instantaneous structures of open channel flow were analysed on the basis of direct numerical simulation (DNS) (Hayashi et al., 2000). Analysis revealed that in the near-surface region, there were no semi-periodic long streamwise streaks similar to the streaks observed in near-wall regions in the direction of flow. However, the presence of upward flow regions, called "splats", and sinking regions, called "anti-splats", were observed locally, meaning that intermittent structures called "surface-renewal eddies" and "patch eddies" were formed. Such structural differences between the near-wall and near-surface regions are thought to have something to do with the presence or absence of shear, which is a difference between the two types of regions.

In the experiment conducted in this study, the Froude numbers were relatively large, and the banded structures, due to the shear in the near-bottom region, affected the free-surface flow regime. It was therefore not possible to confirm the existence of clearly discernible structures consisting of pairs of splats and anti-splats.

Figure 4 shows the time series of the velocities of 5 cm, 10 cm and 15 cm driftwoods captured at 1/250 second intervals on a channel slope of 1/100. Figure 4 also shows the spatio-temporal average of free-surface velocities. These have been plane-averaged in the measurement section at distances of 11 m to 11.6 m downstream from the upstream end of the channel, as well as within ±10 cm in the cross-stream direction.

It is shown that the velocities of all driftwood pieces are higher than the free-surface velocity. This indicates the possibility that, because driftwood motion was relatively active, driftwood velocity was affected by the flow velocity in the near-bottom region.

4. Factors Affecting Driftwood Velocity

Figures 5 and 6 show the effects of channel slope and driftwood length on the difference in the averages of driftwood velocity and free-surface velocity, respectively.

It is shown that the average velocity of driftwood tends to be higher than that of free-surface velocity. The difference difference tends to increase with channel slope and is proportional to roughly 0.5th power of the channel slope. It can be be seen that the greater the driftwood length is, the greater the average velocity difference becomes.

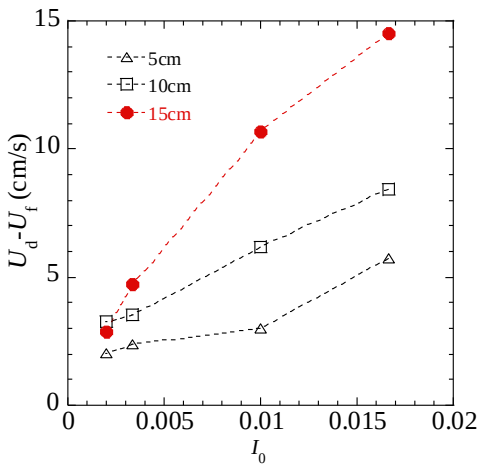

Fig.5: Effect of channel slope on the difference in the averages of drift-wood velocity and free-surface velocity

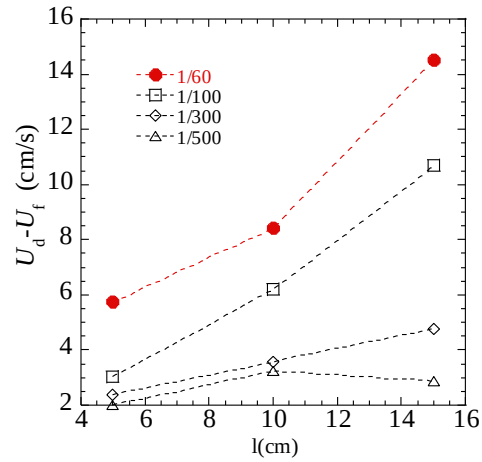

Fig.6: Effects of driftwood length on the difference in the averages of drift-wood velocity and free-surface velocity

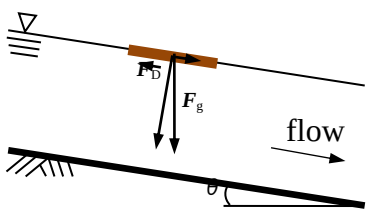

Fig.7: A driftwood motion in uniform flow

4. EQUATION FOR DRIFTWOOD MOTION

The equation for driftwood motion at its center of gravity in Figure 7. is

$$\rho_d V_d \frac{d\boldsymbol{U}_d}{dt_d} = \boldsymbol{F}_A + \boldsymbol{F}_B + \boldsymbol{F}_D + \boldsymbol{F}_G + \boldsymbol{F}_H + \boldsymbol{F}_L + \boldsymbol{F}_p + \boldsymbol{F}_{others} \tag{1}$$

where the subscripts d and f represent the driftwood and fluid, respectively; $\mathbf{U}_d$=the velocity vector of the driftwood; ρ_d=the density of driftwood; V_d=volume of the driftwood; $\mathbf{F}_A$ in the first term on the right-hand side=added mass term; $\mathbf{F}_B$=buoyancy term; $\mathbf{F}_D$=drag force; $\mathbf{F}_G$= Basset term; $\mathbf{F}_L$=lift force; $\mathbf{F}_p$=pressure gradient term; and $\mathbf{F}_{other}$=other external forces including wave resistance.

If it is assumed that a piece of driftwood is in steady motion in a uniform flow field in the equilibrium between gravity and drag, as shown in Figure 7, the streamwise component of driftwood velocity in the direction of flow can be expressed as follows:

$$\rho_d V_d \frac{dU_d}{dt_d} = \rho_d V_d g \sin\theta - \frac{1}{2} C_D \rho_f A_s \left|U_s - U_f\right| (U_s - U_f) = 0 \tag{2}$$

If it is assumed that a cylindrical piece of driftwood is transported downstream in the direction parallel with the flow axis, and the drag of the driftwood surface can be ignored, we have:

$$\begin{aligned} \rho_d \frac{\pi}{4} d^2 \ell g \sin\theta &= \frac{1}{2} C_D \rho_f (\alpha \frac{\pi}{4} d^2) \left|U_d - U_f\right| (U_d - U_f) \\ U_{rel}{}^2 = (U_d - U_f)^2 &= \frac{2}{\alpha C_D} \frac{\rho_d}{\rho_f} g \ell \sin\theta \end{aligned} \tag{3}$$

When the driftwood is transported downstream at driftwood angle Φ relative to the flow axis, then:

$$\begin{aligned} \rho_d \frac{\pi}{4} d^2 \ell g \sin\theta &= \frac{1}{2} C_D \rho_f (h_w \ell \cos\phi) \left|U_d - U_f\right| (U_d - U_f) \\ U_{rel}{}^2 = (U_d - U_f)^2 &= \frac{\pi}{2C_D} \frac{\rho_d}{\rho_f} \frac{g}{\beta \cos\phi} d \sin\theta \end{aligned} \tag{4}$$

where draught$h_w = \beta d$. If the piece of driftwood is spherical and is transported downstream in the direction parallel with the flow axis, then:

$$\begin{aligned} \rho_d \frac{\pi}{4} d^2 \ell g \sin\theta &= \frac{1}{2} C_D \rho_f (h_w \ell \cos\phi) \left|U_d - U_f\right| (U_d - U_f) \\ U_{rel}{}^2 = (U_d - U_f)^2 &= \frac{\pi}{2C_D} \frac{\rho_d}{\rho_f} \frac{g}{\beta \cos\phi} d \sin\theta \end{aligned} \tag{5}$$

where $A_s = \gamma(\pi/4)d^2$.

Figure 8 shows how the product of driftwood length and channel slope affects the square of the difference between driftwood and free-surface velocity. Although the relationship in Eq. 3 is proportional, and it more or less holds true when driftwood length is 10 cm, there are deviations when driftwood length is 5 cm or 15 cm.

When a channel slope of 1/100, a drag coefficient C_D"~3.0" and a specific gravity of driftwood$\rho_d/\rho_f = 0.7$are assumed, Eq. 3 gives calculated values of relative velocity between the driftwood and free-surface velocity of 5.7 cm/s, 8 cm/s and 9.9 cm/s for driftwood lengths of 5 cm, 10 cm and 15 cm, respectively. The measured values of relative velocity actually obtained were 3.0 cm/s, 6.2 cm/s and 10.7 cm/s for driftwood lengths of 5 cm, 10 cm and 15 cm, respectively. Thus, although the calculated values are somewhat greater than the measured values for driftwood lengths of 5 cm and 10 cm, the obtained results on the whole are in general agreement.

When the driftwood is transported downstream at a driftwood angle Φ relative to the flow axis, driftwood length is taken into account in addition to the area projected on the flow area. Hence, the relative velocity of the driftwood, $U_{rel} = (U_d - U_f)$, can be expressed as

$$\begin{aligned} \rho_d \frac{\pi}{4} d^2 \ell g \sin\theta &= \frac{1}{2} C_D \rho_f (h_w \ell \cos\phi) \left|U_d - U_f\right| (U_d - U_f) \\ U_{rel}{}^2 = (U_d - U_f)^2 &= \frac{\pi}{2C_D} \frac{\rho_d}{\rho_f} \frac{g}{\beta \cos\phi} d \sin\theta \end{aligned} \tag{6}$$

where draft $h_w = \beta d$. If ϕ is 90°, relative velocity is not dependent on driftwood length. As shown in Figure 12, driftwood velocity shows agreement with free-surface flow velocity, indicating that there is no longer any dependence on driftwood length.

If a spherical piece of driftwood is transported downstream in a direction parallel with the flow axis, then:

$$\rho_d \frac{\pi}{6} d^3 g \sin\theta = \frac{1}{2} C_D \rho_f (\gamma \frac{\pi}{4} d^2) \left| U_d - U_f \right| (U_d - U_f)$$

$$U_{rel}{}^2 = (U_d - U_f)^2 = \frac{4}{3\gamma C_D} \frac{\rho_d}{\rho_f} g d \sin\theta$$

$$A_s = \gamma \frac{\pi}{4} d^2$$

In the equation shown above, the driftwood velocity tends to increase in relation to the free-surface flow velocity as the diameter of the sphere increases. In Figure 8, however, driftwood velocity tends to decrease, though slightly, as mentioned in the preceding section.

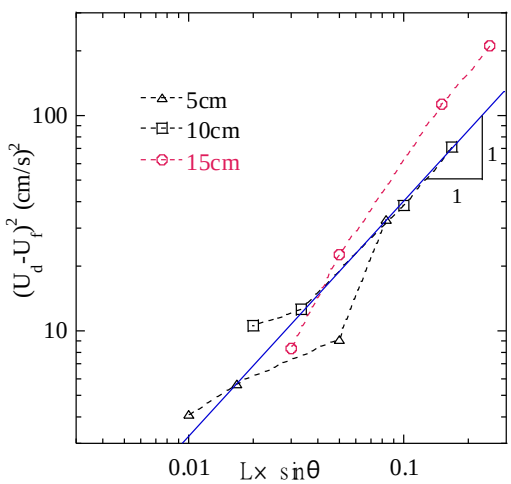

Fig.8: Motion pictures of driftwood captured at 1/25sec in case of No.2 in Table 1.

5. Conclusion

In this study, a high-resolution, high-speed camera was used to capture driftwood velocity, while PIV (particle image velocimetry) and PTV (particle tracking velocimetry) were used to measure free-surface flow velocity. The following conclusions have been reached, on the basis of an equation for driftwood motion and experimental results, concerning the effects of channel slope, driftwood length and driftwood shape on the relative velocity be-tween driftwood and free-surface flow:

1) In cases where the driftwood angle is small, the velocity of a cylindrical piece of drift-wood tends to become higher than that of free-surface velocity as channel slope and driftwood length increase.
2) Compared with the standard deviation of free-surface flow velocity, the channel dependence of the standard deviation of a cylindrical piece of driftwood is negligibly small.
3) In the case of a cylindrical piece of driftwood, the product of driftwood length and channel slope is proportional to the square of the difference between driftwood and free-surface flow velocity.
4) In cases where a piece of driftwood is in steady motion in the equilibrium between gravity and drag in a uniform flow field, the velocity of the driftwood relative to the free-surface velocity can be expressed by Eq. 3.
5) When the driftwood angle is 90°, the velocities of cylindrical and spherical pieces of driftwood are in general agreement with free-surface velocity.

References

[1] Braudrick, C. A., and G. E. Grant, “When do logs move in rivers?, Water Resour. Res., 36(2), 571–583, doi:10.1029/1999WR900290, 2000.

[2] Braudrick, C. A., and G. E. Grant , “Transport and deposition of large woody debris in streams: A flume experiment, Geomorphology,41(4), 263–283, doi:10.1016/S0169-555X(01)00058-7., 2001

[3] Harada N.,Nakamura K.,Kimura I.,Satofuka Y.and Mizuyama T.,, “Debris-wood capture effect controlled by concrete-slit dam under low-gradient flow, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering) Volume 73(4): I_1351-I_1356, 2017.

[4] Hayashi S., Ohmoto T., et al., “The performance of DNS for channel turbulence using regular grid system, Proceeding of Hydraulic Engineering, Vol.44: 593-598, ,2000

[5] Mizuhara K., “Study on the mechanism of motion of the drift wood (I), Journal of the Japan Society of Erosion Control Engineering, Volume 26, No.1: 17-25, 1973

[6] Mizuhara K., “Study on the mechanism of motion of the drift wood (II), Journal of the Japan Society of Erosion Control Engineering, Vol.27, No.2: 6-12, 1974.

[7] Virginia Ruiz-Villanueva, Hervé Piégay, Angela M. Gurnell, Richard A. Marston,and Markus Stoffel1, V. et al.,2015 Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges, Rev. Geophysics., 54, 611–652, doi:10.1002/2015RG000514

[8] Sanjou M. & Okamoto T, “Fundamental study on relationship between stability characteristics of driftwood and blockage property at bridge, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), Volume 72(3): 88-100, 2016

[9] Yano S., Okubo R.,Tsusue A.,Takamura D.,Tomita K.,Kasama K. and Nihei Y., “Analysis on cause of driftwoods generation by 2017 Northern Kyushu Heavy Rain, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), Volume 74(5):I_1063-I_1068, 2018