Effect of river bed slope and particle size distribution on washing out condition of trees in rivers

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Abstract: *In previous studies, washing out of trees can be evaluated using Breaking or Overturning Index(BOI) and Washing-Out Index(WOI). However, the applicability of those indices were only validated some middle-stream rivers where the bed slope is not so steep. For validating the indices at different river condition from past studies, this survey carried out at 7 rivers with different bed slopes. Accordingly, a relationship between WOI and particle size distribution became clear. Bed slope is found to have no influence on the critical condition of BOI, but particle size distribution can affect the critical wash-out condition for WOI.*

Keywords: *tree trunk breakage, tree wash out, breakage or overturning index(BOI), wash-out index (WOI), particle size distribution of river bed materials*

1. INTRODUCTION

Forestation inside a river (Johnson, 1994) sometimes causes a problem, not only because it reduces river flow capacity downstream, but because debris by floods, i.e., broken tree trunks and branches, increase the drag force on bridge piers in rivers. The debris attached to and accumulates around a pier causes a large scour hole around it and sometimes breaks the pier (Melville and Dongol, 1992). In addition, excessive forestation by a single tree species or an invasive exotic tree species sometimes affects the biodiversity of a river ecosystem (Stokes, 2008). For rejuvenation of a gravel bed river, it is necessary to get the information on how floods affect the formation of a plant community in a river. In particular, the characteristics of sand deposited by the flood event (i.e., particle size, nutrient content) (Oswalt and King, 2005), flood disturbance frequency (Gilvear and Willby, 2006) and intensity (Vervuren et al., 2003), and bed degradation due to flooding (Kamrath et al., 2006) are reported to be important factors that affect the plant community.

Considering the above situation, it is necessary to know the wash-out and breaking conditions of river vegetation due to floods. Conditions of plants uprooted by strong wind or flooding have been analyzed mainly in terms of drag moment acting on the plants (TRCRD, 1994; Gardiner et al., 2000) or bed shear stress (dimensionless shear stress) (Temple, 1980; Egger et al., 2007). Recently, Tanaka and Yagisawa (2009) conducted field investigation in Tamagawa river for a flood in 2007 and reported breaking and washing out of trees can be evaluated using Breaking or Overturning Index(BOI) and Washing-Out Index(WOI), respectively. However, the applicability of those indices was only validated for some middle-stream rivers where the bed slope is not very steep.

Therefore, the objective of this study was to clarify the effect of river bed slope and particle size distribution of river bed materials on critical value of BOI and WOI. To fulfill the objective, field investigations were conducted in the Arakawa River, Miyagawa River (in Mie Pref), Miyagawa River (in Gifu Pref.), Fujigawa River, Kamanashigawa River, Ooigawa River and Abegawa River for finding out the breaking and wash-out conditions of trees by floods.

2. MATERIALS AND METHODS

2.1. River flow analysis

The basic equations included in the hydrodynamic model are the conservation of fluid mass equation and momentum equations (Reynolds equation). The basic governing equations in Cartesian coordinate are shown as follows:
Continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{1}$$

Momentum equations in x and y directions:

$$\frac{\partial M}{\partial t}+\frac{\partial Mu}{\partial x}+\frac{\partial Mv}{\partial y}=-gh\frac{\partial Z_s}{\partial x}-\frac{\tau_{0x}}{\rho}-\frac{f_x}{\rho}+\frac{\partial}{\partial x}\left(-\overline{u'^2}h\right)+\frac{\partial}{\partial y}\left(-\overline{u'v'}h\right) \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial Nu}{\partial x}+\frac{\partial Nv}{\partial y}=-gh\frac{\partial Z_s}{\partial y}-\frac{\tau_{0y}}{\rho}-\frac{f_y}{\rho}+\frac{\partial}{\partial x}\left(-\overline{u'v'}h\right)+\frac{\partial}{\partial y}\left(-\overline{v'^2}h\right) \tag{3}$$

where t is the time; h is the water depth; u and v are the depth-averaged velocities in x and y directions, respectively; $M=uh$ and $N=vh$ are the flux in x and y directions, respectively; τ_{0x} and τ_{0y} are the bed shear stress in x and y directions, respectively; f_x and f_y are the drag forces per unit area in x and y directions, respectively; $-\overline{u'^2}$, $-\overline{u'v'}$, and $-\overline{v'^2}$ are depth-averaged Reynolds stresses; g is the gravitational acceleration, h is the water depth, ρ is the fluid density; and Z_s is the water level. Depth averaged Reynolds stresses are calculated by the same method with Hosoda (2002) as follows:

$$-\overline{u'^2}=2D_h\left(\frac{\partial u}{\partial x}\right)-\frac{2}{3}k \tag{4}$$

$$-\overline{uv'^2}=D_h\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \tag{5}$$

$$-\overline{v'^2}=2D_h\left(\frac{\partial v}{\partial y}\right)-\frac{2}{3}k \tag{6}$$

$$D_h=\alpha h u_* \tag{7}$$

where, D_h is the kinetic eddy viscosity, k is the depth averaged turbulent energy, α is constant (α is set as 0.3 in this study), u_* is the friction velocity. k is given as shown below equation (Nezu and Nakagawa(1993)).

$$k=2.07{u_*}^2 \tag{8}$$

For grid transformation from the Cartesian coordinates to generalized coordinate system, the method by Hosoda et al. (1996) was applied. Finite volume method was used to solve the partial differential equations. The applicability of the model was validated for river flow (Tanaka and Yagisawa 2009).To analyze the moment acting on a tree, M, we considered the drag force, F, including the tree stand structure (Tanaka et al., 2006) was considered as shown in Eqs. (9) and (10), and bed shear stress, τ, was evaluated by Eq. (11).

$$(f_x,\ f_y)=(u,v)\times\frac{1}{2}m\rho C_{d-ref}d_{BH}\sqrt{u^2+v^2}\int_0^h\frac{d(z)}{d_{BH}}\frac{C_d(z)}{C_{d-ref}}dz=(u,v)\times\frac{1}{2}m\rho C_{d-ref}d_{BH}\sqrt{u^2+v^2}\int_0^h\alpha(z)\beta(z)dz \tag{9}$$

$$M=\frac{1}{2}\rho C_{d-ref}d_{BH}\left(u^2+v^2\right)\int_0^h z\alpha(z)\beta(z)dz \tag{10}$$

$$(\tau_{0x},\ \tau_{0y})=(u,v)\times\frac{\rho g {n_b}^2\sqrt{u^2+v^2}}{h^{1/3}},\quad \tau=\sqrt{{\tau_{0x}}^2+{\tau_{0y}}^2} \tag{11}$$

where z (m) is the vertical axis from the ground where trees are vegetated, m (number of trees/m^2) is the tree density per unit area, C_{d-ref} is the reference drag coefficient (=1 considering a circular cylinder in this study), $C_d(z)$, $d(z)$ is the drag coefficient, cumulative width of tree trunks, and branches (m) at height z, respectively, d_{BH} is the tree trunk diameter at breast height (m), n_b (m$^{-1/3}$s) is the Manning roughness coefficient without vegetation, $\alpha(z)$ is an additional coefficient expressing the vertical tree structure, and $\beta(z)$ is an additional coefficient representing the effect of leaves and the inclination of branches (for details, see Tanaka et al. (2006)).

2.2. Study area and field investigation

Before and after typhoon No.9 on 2007, field investigation was conducted on gravel bars (AR and KU) in Arakawa River, Japan. For other rivers represented in Figure1, field investigations were conducted before and after typhoon No.12 and 15 on 2011. In each site, (1) particle size distribution of river bed material (d_{50} and d_{90}), (2) tree characteristics (as like trunk diameter at breast height (d_{BH}) and tree

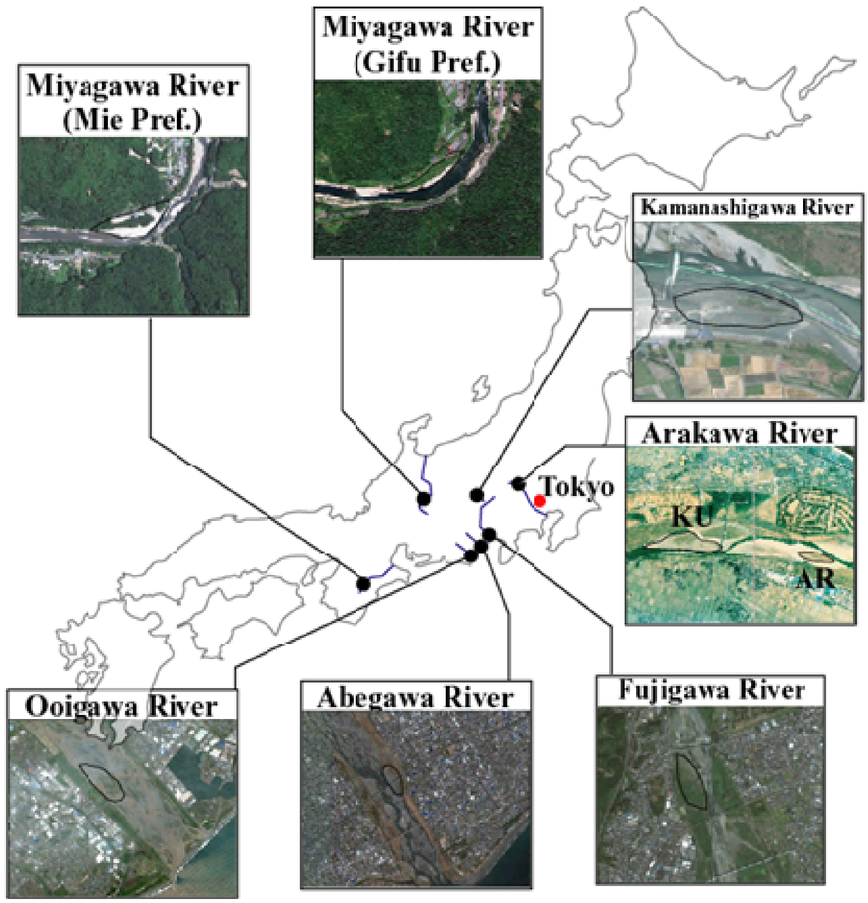

Figure 1 Locations of studied rivers/study areas

Table 1 Characteristics of investigated rivers

River	Distance from river mouth (km)	River bed slope	Particle size of river bed material		Tree characteristics	
			d_{50} (cm)	d_{90} (cm)	Trunk diameter at breast height d_{BH} (cm)	Tree height H_t (m)
Miyagawa River (Mie Pref.)	72 - 78	1/16 - 1/175	18 - 100	20 - 129	2 - 85	2 - 23
Miyagawa River (Gifu Pref.)	58 - 75	1/76 - 1/132	20 - 53	26 - 66	2 - 88	2 - 21
Kamanashigawa River	81	1/97	8 - 21	12 - 36	5 - 17	4 - 7
Ooigawa River	2	1/156	6 - 13	9 - 21	4 - 18	3 - 6
Fujigawa River	2	1/156	9 - 23	11 - 35	6 - 20	3 - 9
Abegawa River	4	1/284	4 - 13	6 - 19	4 - 17	2 - 6
Arakawa River	78 - 80	1/375	2 - 11	3 - 14	2 - 15	2 - 13

height(H_t)), (3) trees breaking or washed out situation due to flood and (4) maximum trace water depth at each flood event (H_{max}) were measured. Particle size distributions of river bed materials at each site were determined. d_{50} and d_{90} were estimated by two methods in this study. One was to take a photo of the river bed and conduct image analysis to determine the particle size distribution when the particle size is large and the screening test cannot be used. The second was to sample bed materials from the river bed surface to 5 cm depth and screen them by using five sieves with 31.7 mm, 19.1 mm, 9.52 mm, 5.66 mm, and 4.00 mm mesh to obtain the particle size distribution. In this study, second method was applied only few locations in Arakawa River.

2.3. Critical shear stress estimation for d50 and d90

To evaluate the shear stress acting on the grain, τ_{*i}, the non-dimensionalized Shields parameter that are usually used for considering 'the gravity force (slope direction)' over 'the weight of the grain in water' were used as below:

$$\tau_{*i} = \frac{\rho g H I_b}{(\rho_s - \rho) g d_i} = \frac{H I_b}{\left(\frac{\rho_s}{\rho} - 1\right) d_i} \tag{12}$$

where ρ_s and ρ are the density of the particles and water, respectively; g is the gravitational acceleration; d_i is the grain diameter at which i% volume passes through the sieve, and I_b is the bed slope. The critical shear stress of d_{50} for the initiation of motion, τ_{*c50} can be approximated from the Shields diagram as:

$$\frac{\tau_{*c50}}{(\rho_s - \rho) g d_{50}} = 0.06 \tag{13}$$

To calculate the effects of the grain size distribution, the critical shear stress of each grain size i, τ_{*ci}, as proposed by Egiazaroff (1965), was:

$$\frac{\tau_{*ci}}{(\rho_s - \rho) g d_i} = \frac{0.1}{\left[\log_{10} 19 (d_i / d_m)\right]^2} \tag{14}$$

where d_m is the medium grain size τ_{*50} and τ_{*90} are derived by substituting d_i = d_{50} or d_{90} in Eq. (12), respectively. τ_{*c90} is derived by substituting d_i = d_{90} in Eq. (14).

2.4. Definition of the Breakage or Overturning Index (BOI) and Wash Out Index(WOI)

In this study, BOI and WOI were defined same with Tanaka and Yagisawa(2009) as shown in below equations.

$$BOI = \frac{d_{BH\,\max}}{d_{BH}} \tag{15}$$

$$WOI = \frac{\tau_{*90}}{\tau_{*c90}} \tag{16}$$

Where d_{BH} is the tree diameter at the flood event, d_{BHmax} is the maximum d_{BH} that the flood can break the trunk, τ_{*90}, τ_{*c90} is non-dimensionalized shear stress and non-dimensionalized critical shear stress of d_{90}, respectively.

3. RESULTS

3.1. Comparison of simulated and observed water levels for the September 2007 flood in Arakawa River

Contour maps of the simulated velocity and water depth at the peak discharge of the flood are shown in Figure 2(a). The inundations of flood areas “A (island at KU)” and “B (flood plain)” in Figure 2(c) were reproduced well in the simulation (Figure 2(b)). However, it was difficult to confirm that the result of the simulation was good enough to evaluate the situation of the flood as a two-dimensional expression. Therefore, validation of the numerical simulation was conducted by comparing the calculated and observed peak water levels (Figure 2(d) and (e)). The maximum water level at the flood event was determined by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT) by measuring the height at which debris was attached. The peak water level in the flood simulation was used as the maximum value at each calculation grid, and the calculations agreed well with the observed peak water level as a whole.

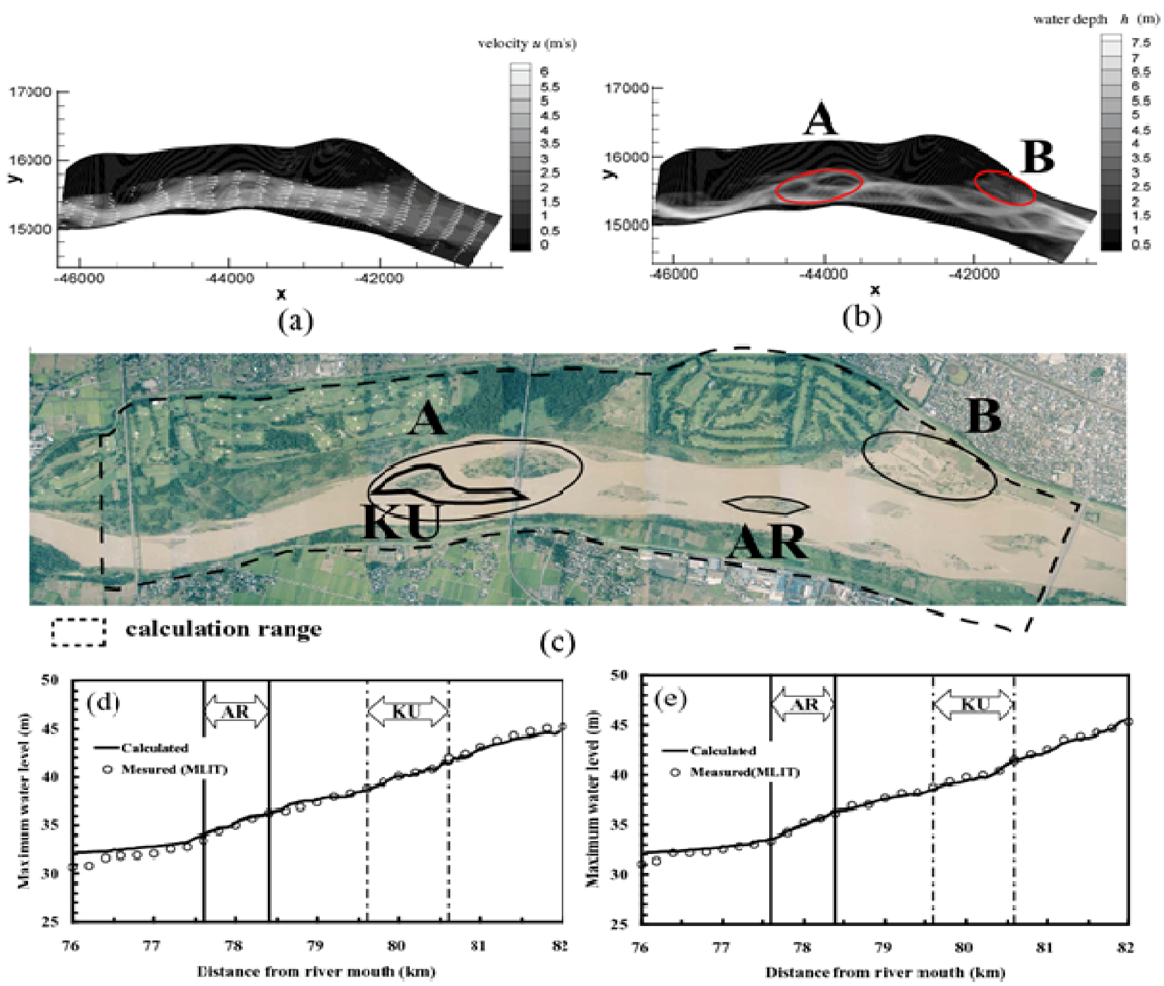

Figure 2 Flow situations of Arakawa River between 76 km to 82 km at the maximum discharge of the September 2007 flood: (a) contour and vector map of simulated velocity, (b) contour map of simulated water depth, (c) aerial photo (provided by Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan). (d) and (e) show comparison of simulated and observed maximum water levels along the Arakawa River during the September 2007 flood on the right bank and left bank, respectively. *x* and *y* represent the axes in the orthogonal coordinate system. The two elements in Figure 3(c) representing the inundated areas are “A (island at KU)” and “B (flood plain)”.

3.2. Effect of river bed slope and particle size distribution of river bed material on BOI and WOI

Figure 3(a) shows the comparison between BOI values obtained from drag moment by numerical simulation for Arakawa River and destruction situation of trees due to a flood observed from field investigation. In this study, 4 regions (Region A-D) were defined depending on BOI and WOI values as shown in Figure 3(a). The most of broken trees due to the 2007 flood were categorized in Region B. In contrast, most of trees not received damage were plotted in Region A. However, some data representing broken trees were plotted in Region A. Regarding these data, it was confirmed by the field investigation after the flood that these trees were broken due to attach the large amount of debris. In numerical simulation, the effect of attached debris on the increment of drag force acting on trees was not considered. Therefore, it is supposed BOI values of these trees were underestimated.

Figure 3(b) shows the comparison between WOI values calculated for the flood event and washed out situation of trees observed from field investigation in the Arakawa River. Some data representing overturned trees were plotted in Region C and D. If WOI exceeds 1, most of trees can be washed out in the region BOI > 1. However, not washed out trees were also categorized in Region C even when WOI exceeds 1. This result indicates that critical value for WOI increases with decreasing BOI in

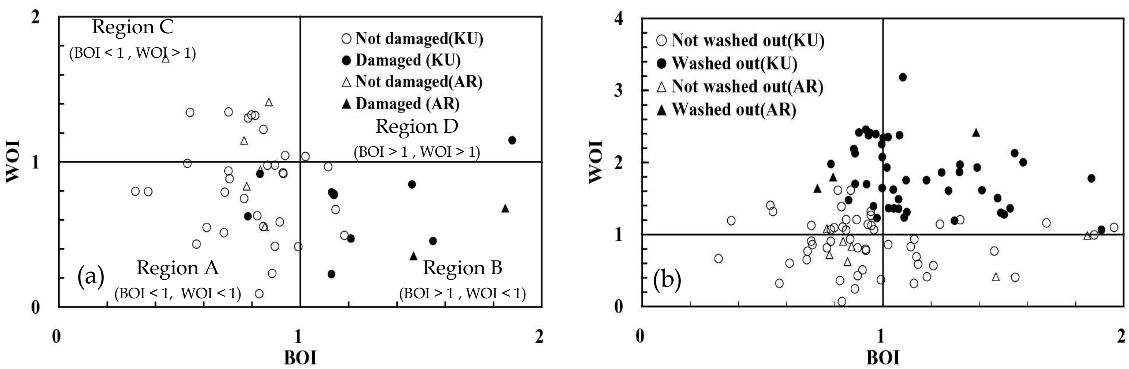

Figure 3 Tree damage situation in relation to the critical value of trunk breakage(BOI) and washed out of trees(WOI) based on the results of numerical simulation for Arakawa River (a) BOI , (b) WOI

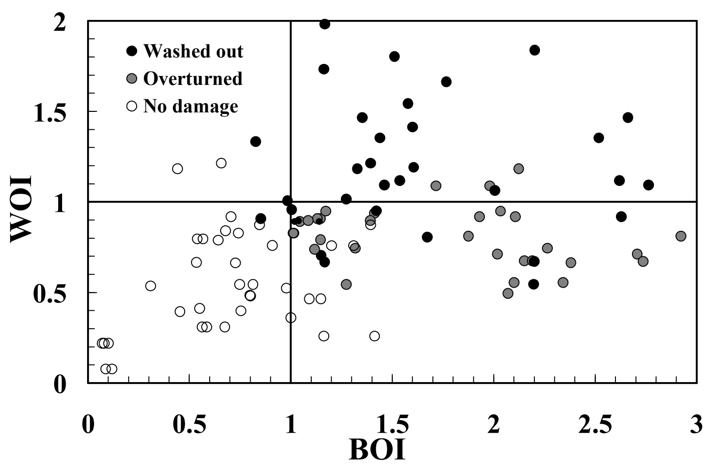

Figure 4 Tree damage situation in relation to the critical value of trunk breakage(BOI) and washed out of trees(WOI) based on the results of field investigations for Miyagawa River (Mie and Gifu Pref.), Fujigawa River, Kamanashigawa River, Ooigawa River and Abegawa River

Region C. In case of small BOI, to break the tree roots become difficult. Therefore, it is thought that the trees were not washed out.

In Figure 4, BOI and WOI values of investigated rivers except for Arakawa River are plotted. In comparison with BOI value for overturned tree and not one, BOI can distinguish well whether trees are broken or not. Similar tendency can be obtained from Arakawa River case (Figure 3(a)). These results indicate that BOI is not affected by river bed slope and particle size distribution. On the other hand, unlike with result of Arakawa River (Figure 3(b)), some washed out trees can be plotted In Region B. It is supposed that large fluid force acted on upper ground part of trees and uprooting of tree-roots occurred even when d_{90} did not move.

4. DISCUSSION

For elucidating the effect of particle size distribution of river bed material on critical value of WOI, relationship between d_{90}/d_{50} and WOI are summarized in Figure 5. In this figure, WOI values plotted in Region B of Figure 4 are represented. Dotted line and line were decided by WOI values for downward limit of washed out trees and upper limit of remained trees, respectively. According to these two lines, it can be found that critical value of WOI increase with increasing d_{90}/d_{50}. When the large size particles are mixed with the small one, movement of the small particles should be prevented by sheltering effect of large particles. Therefore, river bed materials become hard to move with the increase of d_{90}/d_{50}. This result suggests that effect of d_{90}/d_{50} on critical condition of washing out trees needs to be considered in Region B.

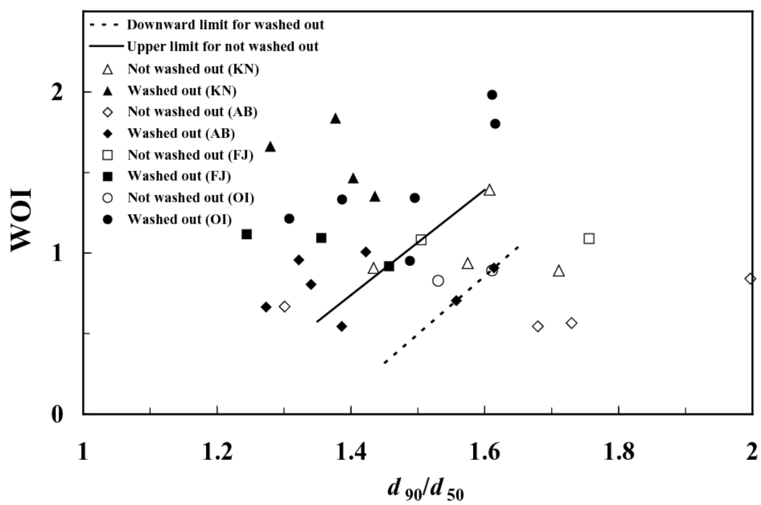

Figure 5 Effect of particle size distribution (d_{90}/d_{50}) on the critical value of WOI
KN : Kamanashigawa River, AB : Abegawa River, FJ : Fujigawa River, OI : Ooigawa River

5. SUMMARY

The following conclusions and recommendations were obtained by this study:

1) Bed slope is found to have no influence BOI, but particle size distribution affects the critical wash-out condition for WOI.
2) Critical value of WOI increases with decreasing BOI in Region C.
3) Effect of d_{90}/d_{50} on critical washout condition of trees needs to be considered in Region B.

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