Resistance of the Debris Flow on the Roughness Boundary

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Abstract

The constitutive equations for debris flows that are presently generally used are arrived at by evaluating the interactions in the flow, the particle to particle displacements and collisions, and turbulence generating within the pore fluid. The other hand, although the beds of mountain rivers are covered with large particles as an armor coat, the existing constitutive equations do not take boundary conditions, such as riverbed roughness, into consideration. When we will discuss about the boundary conditions, we would evaluate the particle-particle and particle-fluid interactions in the closed area of the bed.

Channel experiments under various conditions of riverbed roughness were conducted based on the above concept. To investigate the influence of riverbed roughness on debris flows, the coefficient f' was defined by modifying the coefficient of resistance, f, which is the ratio of the energy gradient to the friction loss. The modified resistance coefficient f' takes the same value when sediment concentration is the same and there is no consideration about boundary condition of riverbed roughness. Experimental results indicate that f' increases as riverbed roughness increases with larger riverbed particle. Moreover, f' increases as the relative flow depth, which is the ratio of the flow depth, h, to roughness height, ks, becomes small and the sediment concentration, c, becomes dense. That is, the excess flow resistance appears due to large riverbed roughness. This suggests it is not adequate to estimate the debris flow behavior if you don't take the boundary conditions due to large riverbed roughness into account.

In these experiments, bottom resistance was also measured using Shear force sensor. Experimental results confirmed that the bottom resistance increases as c thickens or ks becomes high. That is, the rate of each stress ingredient changes with the conditions of riverbed roughness. It is thought that the resistance force from the river bed measured by the shear force sensor should be in balance with the shear stress due to the collisions and frictions.

To evaluate the above detailed influences of riverbed roughness, a two layer model was constructed with an "interface" introduced between the upper layer applied to the existing constitutive equations, and a riverbed roughness layer. The energy dissipation function in the riverbed roughness layer due to the particle-particle displacements and inelastic collisions, and turbulence generating within the pore fluid was formulated. In the formulating of the energy dissipating rate, we take the variation of the relative velocity and times of collisions in unit time of the particles collide with the riverbed roughness into account. The results of calculations using this model agree well with experimental data.

Keywords: debris flow, riverbed roughness, bottom resistance, two layer model

Introduction

The riverbeds of mountain rivers in which debris flows occur are usually covered by an "armor coat" of large particles. Therefore, when a debris flow runs from upstream to downstream, it is thought that the riverbed conditions change, for example the size of the sediment particles in the riverbed. From a dynamic viewpoint, it is thought that the difference in riverbed conditions affects the behavior of the particles near the bottom and so affects the whole river flow.

Research on the constitutive equations of debris flows is carried out based on modeling of the inner interactions among particles, and many constitutive equations have been proposed; e.g., Drew (1983), Egashira, et al (1989), Shen, et al (1982), Takahashi (1977, 1980), Takahashi et al, (1996), Tsubaki et al, (1982), etc. However, there are great differences in the dynamic interpretation of debris flow among researchers, and a common view has not been established. Further, in these constitutive equations, the influence of riverbed roughness has not been taken into consideration, and the size of the particles used for riverbed roughness in the experiments is one of comparable internal particles.

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Egashira, el al. (1989) defined the constitutive equations of debris flows from a mechanical energy conservation law applied to the flow of a broad domain that contains from the bed load to the debris flow, and obtained good results. From a square arrangement model of particles, these constitutive equations are arrived at by evaluating the interaction of particles in the flow considering three mechanisms; particle to particle displacements, inelastic of particle-to-particle collisions, and turbulence generation within the pore fluid. When such a view is applied to the interaction between particles on the riverbed; in considering the collision of particles, the energy dissipation at the time of the inner particles colliding with the larger particles of the riverbed differs from that occurring inside of a fluid; Thus the situation of the flow changes with the conditions of riverbed roughness, such as particle size and density (interval). That is, when we estimate the debris flow, the influence of riverbed roughness should be considered. The problem of the influence of riverbed roughness is an important issue in research into constitutive equations of debris flow.

Based on the above ideas, Suzuki, et al. (2003) conducted channel experiments under various riverbed roughness conditions. The results confirmed that the coefficient of resistance increases as riverbed roughness increases with larger riverbed particles: the coefficient of resistance increases when sediment concentration is dense or the relative flow depth is small. Hence, it is necessary to construct a flow model that can evaluate the influence of riverbed roughness.

In this research, to evaluate the influences of riverbed roughness, a two layer model is constructed with an "interface" introduced between the upper layer applied to existing constitutive equations, and a riverbed roughness layer. Particles interaction in the riverbed roughness layer was evaluated by similar method with Egashira et al.'s constitutive equations. Using Shear force sensor, channel experiments under various conditions of riverbed roughness were conducted to measure bottom resistance. The applicability of the two-layer model was then examined.

Construction of our two-layer model

Existing constitutive equations

For analysis in this research, we refer the constitutive equations of Egashira, et al. (1989, 1997, 2000) and Itoh, et al. (1998)

Momentum conservation equations for a steady longitudinally uniform, one dimensional flow of a sediment-water mixture as shown in **Fig.1** are described;

$$\tau = \int_z^h \rho_m g \sin\theta dz \tag{1}$$

$$p = \int_z^h \rho_m g \cos\theta dz \tag{2}$$

in which h is the flow depth, g is the acceleration due to gravity, θ is the inclination, τ is the shear stress at any distance from the bed, z, p is the isotropic pressure, and ρ_m is the mass density of debris flow;

$$\rho_m = (\sigma - \rho)c + \rho \tag{3}$$

in which σ is the mass density of sediment particles, ρ is the mass density of water, c is the sediment concentration.

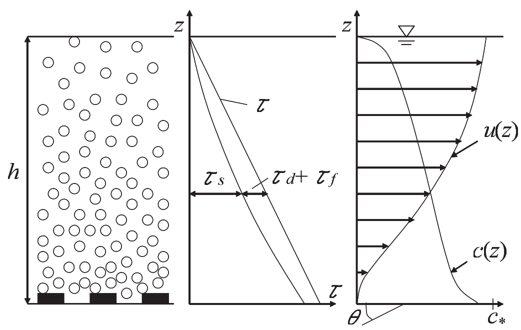

Fig. 1. Definition sketch of a flow over fixed bed

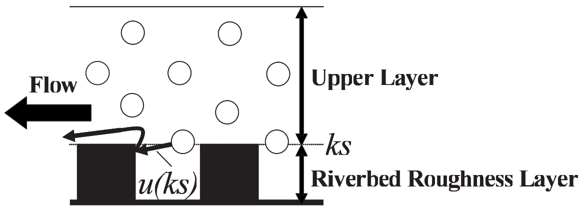

Fig. 2. Schematic picture of the two layer model

Egashira, et al. and Miyamoto proposed expressions for p and τ;

$$p = p_s + p_d + p_f \tag{4}$$
$$\tau = \tau_s + \tau_d + \tau_f \tag{5}$$

in which p_s is the pressure of static interparticle contacts, p_d is the dynamic pressure due to inelastic particle to particle collisions, p_w is the hydrostatic pressure of interstitial water, τ_s is the yield shear stress, τ_d is the stress due to inelastic particle to particle collisions and τ_f is the shear stress supported by interstitial water. They were theoretically formulated the energy dissipation rate caused by particle to particle contacts, inelasticity of particle to particle collisions and turbulent flow of interstitial water, obtaining expressions for each component of eqs.(4) and (5);

$$p_d = k_g e^2 \sigma d^2 c^{1/3} (\partial u/\partial z)^2 \tag{6}$$
$$p_s = \alpha(p_s + p_d) \quad \alpha = (c/c_*)^{1/5} \tag{7}$$
$$p_w = \rho g \cos\theta (h - z) \tag{8}$$
$$\tau_s = p_s \tan\phi_s \tag{9}$$
$$\tau_d = k_g \sigma (1 - e^2) d^2 c^{1/3} (\partial u/\partial z)^2 \tag{10}$$
$$\tau_f = k_f \rho d^2 (1 - c)^{5/3} / c^{2/3} (\partial u/\partial z)^2 \tag{11}$$

in which d is sediment particle diameter, u is the velocity, c_* is volume concentration of the particle layer in a filling state, e is the coefficient of restitution, ϕ_s is the interparticle friction angle, k_g is the empirical constant that is specified as 0.0828. k_f is a parameter of the disorder scale of a particle gap, and is an experiment constant of 0.16–0.25 based on the experimental results in conditions that c is high (c = 0.25∼; Ashida, et al. (1987, 1988)). τ_f was confirmed by Hotta et, al. (1998, 2000) when c is high ($c > 0.28$). However, since the unreasonableness when c is low has been pointed out by Egashira, et al. (1989), and Suzuki, et al. (2003) actually suggested overestimation of τ_f in conditions where c is low and gave a correction value of 0.08, this research also uses this value.

Two-layer model

To evaluate the influences of riverbed roughness, a two layer model was constructed with an “interface” introduced between an upper layer applied to the existing constitutive equations, and a riverbed roughness layer (**Fig.2**). For the roughness layer, it was considered that the energy dissipation mechanisms change with the condition of the roughness, especially in respect to inelastic particle to particle collisions. A comparison with the Miyamoto’s method for τ_d is described below.

In the existing constitutive equations, Miyamoto (1985) drew τ_d, having assumed that particles distribute almost equally in the whole flow, locate in a line at intervals equal to one row on average, and repeat inelastic collisions mutually on a collision angle α_i (**Fig.3**). The dissipation energy at one collision, ϕ_i, is expressed as;

$$\phi = \frac{1}{2}(1 - e^2)\left(\frac{\pi d^3}{6}\right)\sigma(\delta u \cdot \sin\alpha_i)^2 \tag{12}$$

in which δ_u is the velocity differential. When the distance between particles, bd, is given as;

$$bd = \left(\frac{c}{\pi/6}\right)^{-\frac{1}{3}} d \tag{13}$$

The number of collisions per unit time, N, is;

$$N = \frac{\delta u}{bd} = \frac{\partial u}{\partial z} \tag{14}$$

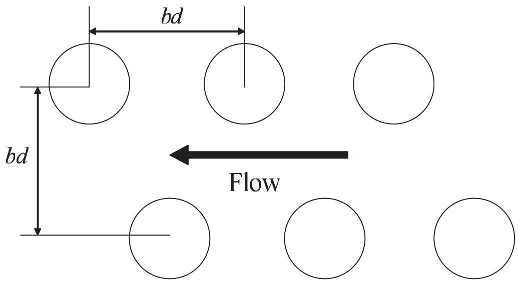

Fig. 3. Model of the granular-water mixture

Since the occupying volume of one particle is $(bd)^3$, energy dissipation per unit time and per unit volume, Φ_d, is expressed as;

$$\Phi_d = \frac{N\phi_i}{(bd)^3} = k_g\sigma(1-e^2)d^2c^{1/3}\left(\frac{\partial u}{\partial z}\right)^3; \quad k_g = \frac{\pi}{12}\left(\frac{\pi}{6}\right)^{\frac{1}{3}}\sin^2\alpha_i \tag{15}$$

The relationship between Φ and τ is;

$$\tau = \frac{\Phi}{(\partial u/\partial z)} \tag{16}$$

Therefore, τ_d is expressed as (10).

On the other hand, in the roughness layer, based on the analysis of video animation it assumed as follows; particles whose speed is $u(ks)$ collide with the roughness, and rebound in the opposite direction, are then pushed back by the flow and speed is once set to 0. Then it returns to the flow speed after that (**Fig.2**). That is, a particle loses all the kinetic energy that it had before the collision. It is thought that particles may also collide with the upper surface of the roughness, but the model was constructed this way for simplicity. Therefore, ϕ_i, N, and Φ_d are expressed as;

$$\phi_i = \frac{1}{2}\left(\frac{\pi d^3}{6}\right)\sigma \cdot u(ks)^2 \tag{17}$$

$$N = \frac{u(ks)}{\beta ks} \tag{18}$$

$$\Phi_d = \frac{N\phi_i}{(bd)^3} = \frac{1}{2}c\sigma\frac{1}{\beta ks}u(ks)^3 \tag{19}$$

in which β is the ratio roughness interval to ks.

Then, if the flow velocity distribution in the riverbed roughness layer is assumed to be a straight line distribution, $\delta u/\delta z$ and τ_d are expressed as;

$$\frac{\partial u}{\partial z} = \frac{u(ks)}{ks} \tag{20}$$

$$\tau_d = \frac{1}{2}c\sigma\frac{1}{\beta}u(ks)^2 \tag{21}$$

τ_s is expressed as in (9), in which, p_s is particle frame stress and should be independent on the roughness conditions; so it is obtained substituting eqs.(4), (7), (8) into eq.(2);

$$p_s = \left(\frac{c}{c_*}\right)^{1/5}(\sigma-\rho)ch\cos\theta \tag{24}$$

In addition, τ_f is applied eq.(11). Therefore, bottom resistance $\tau(0)$ is expressed as;

$$\tau(0) = \left(\frac{c}{c_*}\right)^{1/5}(\sigma-\rho)ch\cos\theta\tan\phi_s + \frac{1}{2}c\sigma\frac{1}{\beta}u(ks)^2 + \rho k_f\frac{(1-c)^{5/3}}{c^{2/3}}\frac{d^2}{ks^2}u(ks)^2 \tag{25}$$

Concentration distribution

Substituting eqs.(4) and (5) with eqs.(6) to (11) into eqs. (1) and (2), and then eliminating $(\partial u/\partial z)^2$, an expression for sediment concentration is obtained;

$$(h-z)\frac{\partial F}{\partial c}\frac{\partial c}{\partial z} = F - c \tag{26}$$

$$F = \frac{f_{pd}\tan\theta}{\left(\frac{\sigma}{\rho}-1\right)}\left[(f_f + f_d - f_{pd}\tan\theta) - \left(\frac{c}{c_*}\right)^{1/5}(f_f + f_d - f_{pd}\tan\phi_s)\right]$$

$$f_f = k_f\frac{(1-c)^{5/3}}{c^{2/3}}, \quad f_d = k_g(1-e^2)\left(\frac{\sigma}{\rho}\right)c^{1/3}, \quad f_{bd} = k_g e^2\left(\frac{\sigma}{\rho}\right)c^{1/3} \tag{27}$$

The formula for the concentration distribution in the two-layer model was arrived at as follows. p_d corresponds to the preservation energy of the inelastic collisions of particles. Therefore, p_d is expressed as;

$$p_d = \frac{1}{2}e^2 c\frac{\sigma}{\rho}\frac{1}{\beta}u(ks)^2 \tag{28}$$

Substituting eqs.(4) and (5) with eqs.(8) to (11), (24) and (28) into eqs. (1) and (2), and then eliminating $(\partial u/\partial z)^2$, an expression for sediment concentration is obtained;

$$(h-z)\frac{\partial F_{ks}}{\partial c}\frac{\partial c}{\partial z} = F_{ks} - c \tag{29}$$

$$F_{ks} = \frac{ks_{pd}\tan\theta}{\left(\frac{\sigma}{\rho}-1\right)\left[(ks_f + ks_d - ks_{pd}\tan\theta) - \left(\frac{c}{c_*}\right)^{1/5}(ks_f + ks_d - ks_{pd}\tan\phi_s)\right]}$$

$$ks_f = k_f\frac{(1-c)^{5/3}}{c^{2/3}}\frac{d^2}{ks^2}, \quad ks_d = \frac{1}{2}c\frac{\sigma}{\rho}\frac{1}{\beta}, \quad ks_{pd} = \frac{1}{2}e^2 c\frac{\sigma}{\rho}\frac{1}{\beta} \tag{30}$$

Flow velocity distribution

Substituting eqs.(4) and (5) with eqs.(6) to (11) into eqs. (1) and (2), and then eliminating $\int_z^h c \cdot dz$, an expression for velocity concentration is obtained;

$$\frac{\partial u}{\partial z} = \left[\frac{g\sin\theta(h-z) - (c/c_*)^{1/5}(\sigma/\rho - 1)g\cos\theta\int_z^h c\cdot dz\cdot(\tan\phi_s - \tan\theta)}{(f_d + f_f - f_{pd}\tan\theta)d^2}\right]^{1/2} \tag{31}$$

The formula of the flow velocity distribution in the two-layer model was arrived at as follows. In a stationary state, external force, τ_{ext}, and $\tau(0)$ should be in balance.

$$\tau_{\text{ext}} = \rho_m gh\sin\theta = \tau(0) \tag{32}$$

$u(ks)$ will be obtained if eq.(25) and c(0) calculated with the formula of concentration distribution are substituted into eq.(32). Since the riverbed roughness layer is a straight line distribution, applying the existing constitutive equations to the upper layer, the flow velocity distribution will be obtained.

Experiments

Experimental devices

The variable slope channel of the Civil Engineering Research Laboratory was used for the experiment (**Fig.4**).

Length is 10m and width is 30cm with glazed sides. In this experiment, the width of the channel was narrowed to 10cm and the bottom of the side of the lower stream of the channel (4.5m) was made as high as 10cm. At the lower stream side (4.5m), a strip of roughness is positioned and the upper stream side (4.5m) is filled with sediment. An ultrasonic sensor (Omron; E4PA-LS50-M1) for measuring the time change of flow surface level is installed at 1m upper from the lower end. The shear force sensor is installed in the pit located at the lower side channel bottom for measuring bottom resistance F_x as shown in **Fig.5**.

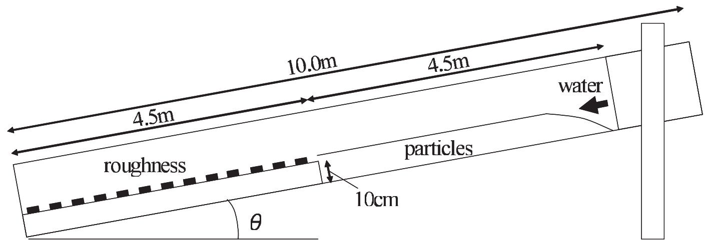

Fig. 4. Experimental Setup

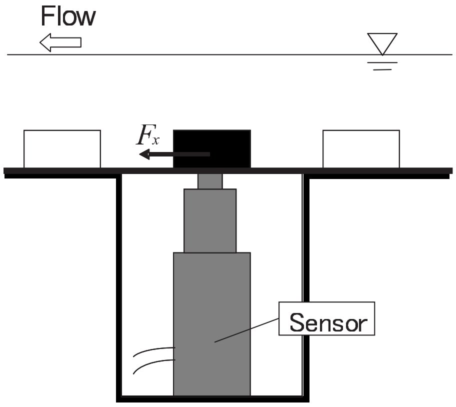

Fig. 5. Shear force sensor

Table 1. Conditions of riverbed roughnesses

	ks (cm)	*w* (cm)	β*ks* (cm)	β
ks2	0.2	0.8	1.6	8.000
ks3	0.3	0.8	1.6	5.333
ks5	0.5	0.8	1.6	3.200

Experiment method

The upper stream side of the channel is filled with particles to a depth of about 10cm. Water is regularly supplied from the upper end and a debris flow is generated. In the stationary state section, the unit width flux Q (cm^2/s) and the flux concentration, c, are measured at the downstream end. Average flow depth, h (cm), is calculated from surface level data obtained by the ultrasonic displacement sensor, and the cross-sectional average flow velocity U (cm/s) is calculated from the relation "$Q = hU$". Time average bottom resistance, $F_x(gw)$, is calculated from the data of shear force obtained by the shear force sensor.

Experimental conditions

Three kinds of strip roughness were used. The material used is wood, and the cross-section is a rectangle. The size and the pitch of strip roughness are shown in **Table 1**; ks is the roughness height (height from the riverbed to the upper surface of the roughness), w is the roughness width and βks is the average roughness interval (**Fig.6**). w and βks are constant. w is 0.8cm and βks 1.6cm. Only ks was changed among 2, 3, and 5 mm, so the roughnesses are called $ks2$, $ks3$, and $ks5$.

In each roughness, the bottom resistance are measured using three forms (**Fig.6**). **A pattern**: Width 3.0cm, length 3.2cm, two strips and two slots (slot means the space between the strips). Total area is 9.6cm^2. Strips and slots are 1:1 in area in the plan view, and this is used to examine the balance of the external force and F_x. **B pattern**: Width 3.0cm, length 4.0cm, two strips and three slots. Total area is 12.0cm^2. Strips and slots are 2:3 in area in the plan view, and this is used to examine the ratio of the resistance of the strips, F_{st}, to the external force, by comparing with **A** pattern. **C pattern**: Width 5.0cm, length 0.8cm, one strip. Total

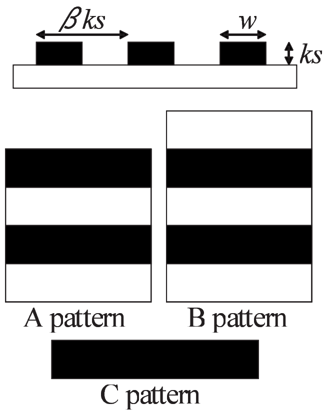

Fig. 6. Schematic picture of the roughness

area is 4.0cm^2, and this is also for examining the rate of F_{st} to the external force; simultaneously the accuracy of the experiments is verified by comparison with the **B pattern**.

The average sediment particle diameter, d, is 0.294cm, and the specific gravity, σ, is 2.65. Due to them being sieved, sediment particles have an almost uniform size. d is the particle diameter when converting into a volume equivalent ball. The channel slope θ (degree) is 13, 15 and 17. The range of the unit width flux of the supplied water is 150–300 (cm^2/s).

Experimental results and discussion

Applicability of the two-layer model to flow resistance

Suzuki, et al. (2003) confirmed that flow resistance increases as riverbed roughness increases with larger riverbed particles: flow resistance increases when c is dense or the relative flow depth, h/ks, is small. In this research, to investigate the influence of riverbed roughness on debris flows, the coefficient f' was defined by modifying the coefficient of resistance, f, which is the ratio of the energy gradient to the friction loss;

$$f = \frac{2gh\sin\theta}{U^2} \tag{33}$$

$$f = \frac{2\rho_m ghU\sin\theta}{\rho_m U^3} = \frac{2}{\rho_m}\cdot\frac{1}{U^3}\int_0^1 \Phi\cdot dz = \frac{25\rho}{2\rho_m}K(c)\left(\frac{h}{d}\right)^{-2} \tag{34}$$

$$K(c) = \frac{\alpha}{1-\alpha}k_g\cdot\frac{\sigma}{\rho}\cdot e^2c^{\frac{1}{3}}\tan\phi_s + k_g\cdot\frac{\sigma}{\rho}(1-e^2)c^{\frac{1}{3}} + k_f d^2\frac{(1-c)^{5/3}}{c^{2/3}} \tag{35}$$

in which internal dissipation energy, Φ, and external energy should be equal(36) in a stationary state, and constitutive equations were substituted for Φ in (34);

$$\int_0^h \Phi_{\text{total}}\cdot dz = \rho_m ghU\sin\theta \tag{36}$$

Since the physical-property values, such as σ and e, are constant when particles are the same, $K(c)$ becomes a function of only c. Then, eliminating (h/d), we obtain f';

$$f' = f\cdot\frac{2\rho_m}{25\rho}\left(\frac{h}{d}\right)^2 = K(c) \tag{37}$$

The value of f' calculated using constitutive equations for debris flow is constant for the same sediment concentration, c. That is, when the influence of riverbed roughness is great, the shifts of f' from $K(c)$ are great.

In **Fig.7(a), (b)**, show the results of experiments and the calculating results using our two layer model. Data are classified by whether h is smaller **(a)** or larger **(b)** than 2.25. Further, c is classified for every 0.03 (or 0.04). The calculation method is as follows. First, 2.0cm **(a)** or 2.5cm **(b)** are substituted into h, and arbitrary c is set up. Next, ks is changed continuously, and $c(z)$ and $u(z)$ distributions are determined for every ks so that c will become the c as set up before. Then f' is calculated using these results.

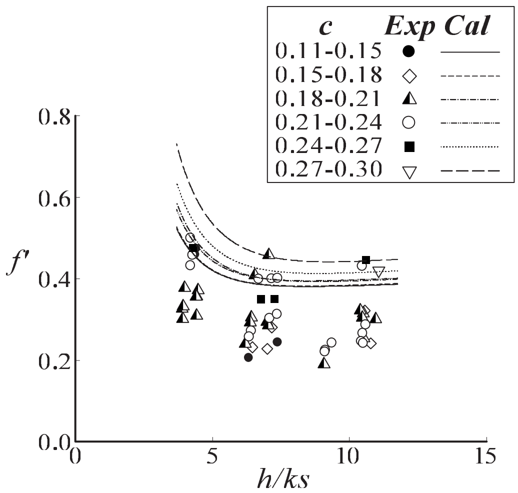

Fig. 7. **(a)** Relationship between relative flow depth and f' (Strip roughness; $1.75 < h < 2.25$)

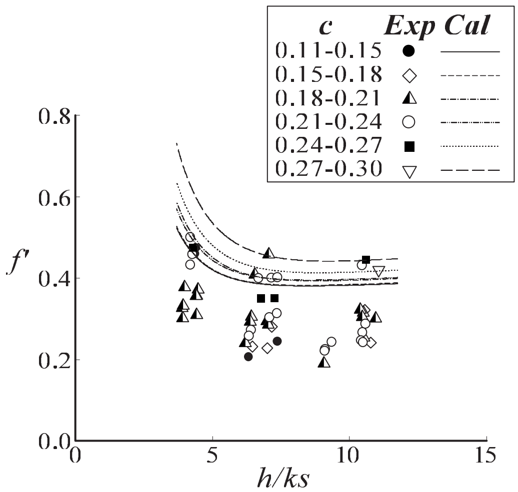

Fig. 7. **(b)** Relationship between relative flow depth and f' (Striproughness; $2.25 \leq h < 2.8$)

When h/ks is higher than 10, the calculated value of f' is almost equal to $K(c)$.

The results of the strip roughness indicate the same tendency as in the case of sand roughness (**Fig.8**; data are from Suzuki, et al. (2003)), f' increases when h/ks is small. Thus by comparing **(a)** and **(b)**, the values of f' of experiments are seen to be small when h is small.

Calculations resulted in the same tendency as in the experimental results being reproduced; that is that f' increases when h/ks is small, there is almost no difference from c in the range of c in this experiment and the values of f' were small when h is small. Additionally, values of f' are a generally a little smaller than the calculations in the case of strip roughness, thought to be caused by the superfluous evaluation of τ_f when c is small, and the difference of parameters such as ϕ_s because the strip roughness is wood. Although further examination will be required, since there is only about 1 or 2mm difference in h, these are fairly appropriate values.

Sand roughness and strip roughness show the same tendency and the tendency can be reproduced by the two layer model, that is, both can be treated in the same framework using parameters such as β and ks.

Balance between bottom resistance and external force

It is necessary to examine whether the total bottom resistance, F_x, and the external force are in balance before examining the structure of the bottom resistance. And it is necessary to examine the position of the base level of $h(z=0)$ where F_x and the external force are in balance. In the above examination, the base level of h is the bottom of roughness.

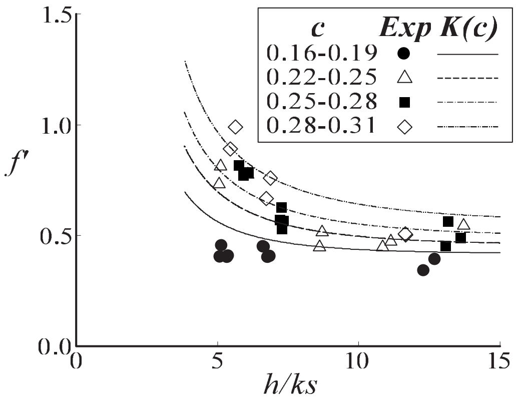

Fig. 8. Relationship between relative flow depth and f' (Sand roughness)

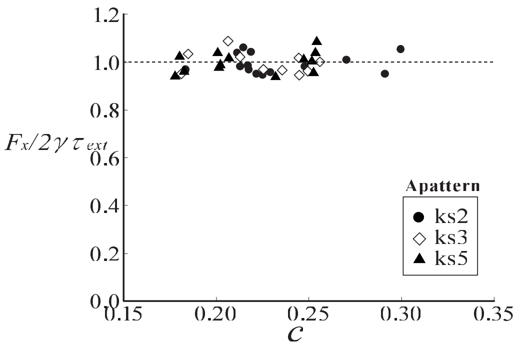

Fig. 9. Relationship between the external force and F_x (Apattern)

Since the strips and slots in the **A pattern** are 1:1, F_x, and the external force, should be in balance. Since the width is 3.0cm, the area of a set of strip (0.8cm) and a slot (0.8cm) is 4.8cm^2. The external force applied to this area is set to $\gamma\tau_{\text{ext}}$;

$$\gamma\tau_{\text{ext}} = 4.8\rho_m gh\sin\theta \tag{38}$$

Since the **A pattern** has 2 sets of strips and slots, the external force is $2\gamma\tau_{\text{ext}}$. The ratio of F_x to $2\gamma\tau_{\text{ext}}$ was examined. In **Fig.9**, the results of calculations using h, whose base level is the bottom of the roughness is shown. It was determined that the ratio is not concerned with ks or c, but that $F_x/2\gamma\tau_{\text{ext}}$ is about 1.0. The results indicate that τ, and τ_{ext} are in balance and the validity of the setup with a base level of h is confirmed.

Bottom resistance structure

It is thought that a change of the resistance of the flow is brought about by the change of the resistance structure at the riverbed. Important phenomena such as erosion and deposition occur in a riverbed; thus it is thought important to clarify the resistance structure at the riverbed.

We examined the ratio of the resistance of a strip, F_{ks}, to $\gamma\tau_{\text{ext}}$, R_{st}, using the results of the **B** and **C patterns**. In this research, R_{st} is considered to be equivalent to $(\tau_s + \tau_d)/\tau$. Since **B** contains strips and slots in a 2:3 ratio, the ratio of the resistance supported by a slot to $\gamma\tau_{\text{ext}}, R_{ch}, R_{st}$ are obtained as follows.

$$R_{ch} = \frac{F_x - 2\gamma\tau_{\text{ext}}}{\gamma\tau_{\text{ext}}} \tag{39}$$

$$R_{st} = 1 - \frac{F_x - 2\gamma\tau_{\text{ext}}}{\gamma\tau_{\text{ext}}} = \frac{3\gamma\tau_{\text{ext}} - F_x}{\gamma\tau_{\text{ext}}} \tag{40}$$

Since the C pattern has only one strip, and the width is 5.0cm, R_{st}, is as follows.

$$R_{st} = \frac{F_x}{8\rho_m gh\sin\theta} \tag{41}$$

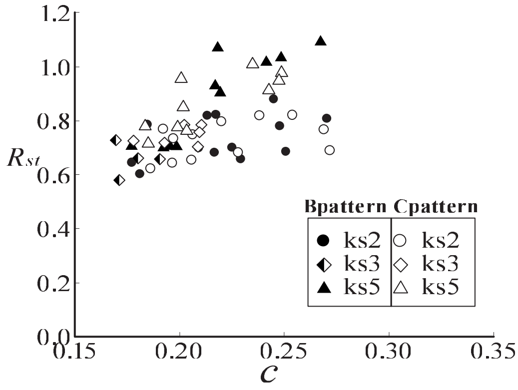

Fig. 10. Relationship between sediment concentration and the ratio of the resistance of the strips to the total bottom resistance (Comparing B patternandCpattern)

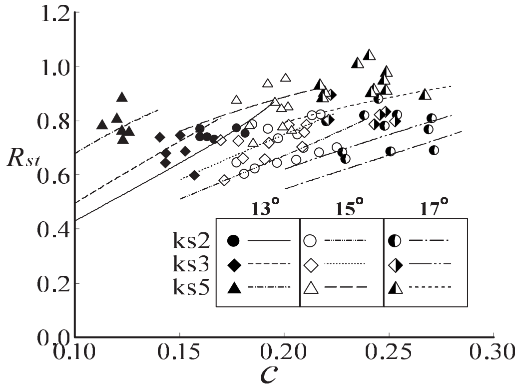

Fig. 11. Relationship between the sediment concentration and the ratio of the resistance of strips to the total bottom resistance (Comparison of experiments and calculation using the two lawyer model)

In **Fig.10**, data from experimental conditions that are the same between A and B are shown. Since both are almost equal, it can be said that experiments are reliable.

Next, all the experimental results for every θ and every ks are shown in **Fig.11**. Additionally, the results of calculations, which correspond with each classification, using the two-layer model are shown. The calculation method is as follows. First, 2.5cm and 0.294cm are substituted for h and d, and an arbitrary ks is set up. The bottom concentration, $c(0)$, is changed continuously, and the c and u distributions are determined. Then, c and $(\tau_s + \tau_d)/\tau$ is calculated using these results ($(\tau_s + \tau_d)/\tau = R_{st}$). The results indicate that R_{st} increases when ks is high even with the same c. It is considered that cause of this is that τ_d increases when ks is large. Although there is some gap when θ is high, it can be said that the results of the calculations using the two-layer model and the experimental results are almost equal.

Conclusions

To evaluate the influences of riverbed roughness, a two layer model was constructed with an “interface” introduced between an upper layer applied to the existing constitutive equations, and a lower riverbed roughness layer. Particle interactions in the riverbed roughness layer were evaluate by the same method as for the existing constitutive equations. Moreover, channel experiments under various conditions of riverbed roughness were conducted to verify the model.

We examined the flow resistance of debris flow. The experimental results demonstrated that sand roughness and strip roughness show the same tendency; such that flow resistance increases when h/ks is small. Further, the tendency can be reproduced by the two-layer model, that is, both situations can be treated by the same framework using parameters such as ks and β.

We also examined the structure of the bottom resistance. The results indicated that the ratio of the resistance of a strip to the total bottom resistance, which is equivalent to $(\tau_s + \tau_d)/\tau$, increases when ks is high even with the same c. The results of calculations using the two-layer model and the experimental results are almost equal. Thus, while clarifying the influence of riverbed roughness, which has not taken into consideration in considering internal resistance structures in conventional approaches, we constructed a model that can evaluate the influence of riverbed roughness.

In future work it will be necessary to consider variations in the speeds of erosion and deposition along with the conditions of roughness, and also to examine applications suitable for this model.

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References

Ashida, K., S. Egashira and H. Sasaki (1987) Occurrence of slope failure and mechanics of debris flow, Annuals, Disas. Prev. Res. Inst., Kyoto Univ., No.30B-2, pp.507–526 (in Japanese)

Ashida, K., S. Egashira and H. Yajima (1988) Mechanics of debris flow, Annuals, Disas. Prev. Res. Inst., Kyoto Univ., No.31B-2, pp.411–422 (in Japanese)

Drew, D.A. (1983) Mathematical model of two-phase flow, Ann. Rev. Fluid Mech., pp.261–291

Egashira, S., K. Ashida, H. Yajima and J. Takahama (1989) Constitutive equations of debris flow, Annuals, Disas. Prev. Res. Inst., Kyoto Univ., No.32B-2, pp.487–501 (in Japanese)

Egashira, S., T. Sato and K. Chishiro (1994) Effect of particles size on structure of sand-water mixture, Annuals, Disas. Prev. Res. Inst., Kyoto Univ., No.37B-2, pp.359–369 (in Japanese)

Egashira, S., K. Miyamoto and T. Itoh (1997) Constitutive equations of debris flow and their applicability, 1st. International Conference on Debris-Flow Hazards Mitigation, ASCE, pp.340–349

Egashira, S., K. Miyamoto and T. Itoh (2000) Bed-load rate in view of two phase flow dynamics, Proceedings of hydraulic engineering, JSCE, No.41, pp.789–794 (in Japanese)

Hotta, N., K. Miyamoto and M. Suzuki (1998) Pore-water pressure distribution of solid-water phase flow in a rolling mill, Journal of the Japan Society of Erosion Control Engineering, Vol.50, No.4, pp.11–16 (in Japanese)

Hotta, N., and T. Ohta (2000) Pore-water pressure of debris flows, Physics and Chemistry of the Earth (B), Vol.25, No.4, pp.381–386

Itoh, T., S. Egashira (1998) Comparative study of constitutive equations on debris flows, Proceedings of hydraulic engineering, JSCE, No.42, pp.913–918 (in Japanese)

Miyamoto, K. (1985) Mechanics of grain flows in Newtonian fluid, Ph. D.-thesis presented to Ritsumeikan Univ., (in Japanese)

Shen,H and N.L. Ackermann (1982) Constitutive relationships for fluid-solid mixtures, Proc. ASCE, Vol.108, No.EM5, pp.748–763

Suzuki, T., N. Hotta and K. Miyamoto (2003) Influence of riverbed roughness on debris flows, Journal of the Japan Society of Erosion Control Engineering, Vol.56, No.2, pp.5–13 (in Japanese)

Takahashi, T. (1977) A mechanism of occurrence of mud-debris flows and their characteristics in motion, Annuals, Disas. Prev. Res. Inst., Kyoto Univ., No.20B-2, pp.405–435 (in Japanese)

Takahashi, T. (1980) Debris flow on prismatic open channel, Proc. ASCE, Vol.106, HY3, pp.381–396

Takahashi, T., Y. Satofuka and K. Chishiro (1996) Dynamical law of debris flows in inertial regime, Annuals, Disas. Prev. Res. Inst., Kyoto Univ., No.39B-2, pp.333–346 (in Japanese)

Tsubaki, T., H. Hashimoto and T. Suetsugi (1982) Grain Stress and Flow Properties of Debris Flow, Proc. JSCE, No.317, pp.79–91 (in Japanese)