

Review

# A Review of Japanese Debris Flow Research

Tamotsu TAKAHASHI

Association for Disaster Prevention Research (138-1, Tanaka Asukai Cho, Sakyo-ku, Kyoto, Kyoto 6068226, Japan)

## 1. INTRODUCTION

The phenomenon of debris flow has been recognized since ancient times in Japan, where debris flow disasters have caused damage and suffering. In steep mountainous areas of Japan, residents have given evocative names to debris flows to warn future generations of their danger. Such names include “Ja-nuke” (the runoff of the king snake), “yama-tsunami” (mountain tsunami), and “yama-shio” (mountain tide). However, because debris flows usually originate on remote high mountain slopes or steep ephemeral gullies and arise during adverse weather conditions, the characteristics and mechanisms of debris flows had long remained poorly understood and the phenomenon was even considered a “phantasmal disaster.”

Scientific investigations of debris flow began in the 1950s and included qualitative discussions of the definition of debris flow. Nomitsu and Seno [1959], Tani [1968], and Murano [1968] defined debris flow as the gravitational motion of a porridge-like mixture of sediment and water, in which the volume of sediment is much larger than the volume of water. Koide [1955] classified debris flow into “yama-tsunami” and “doseki-ryu” types. He defined a yama-tsunami as the pushing ahead of a cohesive earth mass produced by a landslide along a valley and a doseki-ryu as the pushing ahead of sediment accumulated on a gully bed. Thus, a doseki-ryu had no direct relationship to a landslide. Kaki [1954] defined a yama-tsunami as a forward-moving mixture composed of 70% soil and 30% water and a doseki-ryu as a flow composed of 30% soil and 70% water with relatively thin depth. The term doseki-ryu is now widely used in Japanese to refer to debris flow; “doseki” means a mixture of soil and stone, and “ryu” means flow.

Tani [1968] classified three types of debris flow

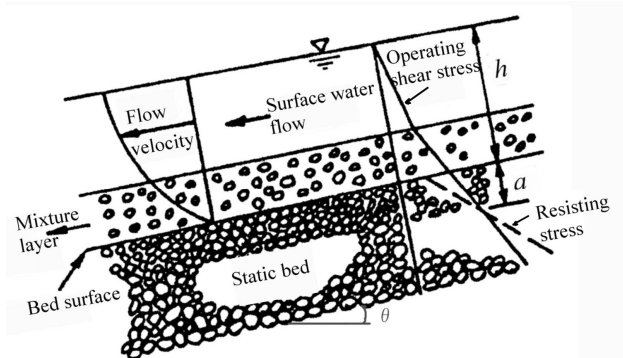
initiation: 1) transformation of a landslide block into debris flow, 2) collapse of a landslide dam, and 3) sediment entrainment into the surface water flow on a gully bed. He also compiled several observed characteristics of debris flow: 1) The lateral surface profile of flow is upward convex, with the front part swelling longitudinally. 2) The flow is dominated by soil and stone rather than water and resembles a moving hill composed of stone, sand, mud, and wood that produces a smoke-like cloud of debris and a bad smell. 3) The sound is like that of thunder or a formation of airplanes.

Yano and Daido [1965] referred to debris flow as “mud flow.” They defined it as a flow of muddy clay and modeled its motion by applying concepts of pseudoplastic fluid and Bingham fluid.

Full investigations were not undertaken until the 1970s. By that time, improvements of major rivers had lessened the risk of large-scale flooding disasters. However, management of minor rivers lagged behind that of major rivers, and the use of slope lands for human activities increased vulnerability to sediment hazards. Before 1964, among human victims of total water-related hazards, 32% were affected by sediment events. Since 1965, this percentage has increased to approximately 50% [Takahashi, 2009]. This situation provides strong motivation for research on debris flow and other sediment hazards.

## 2. DEBRIS FLOW INITIATION CRITERIA

Daido [1971] postulated that debris flow occurs due to the gradient transition in deposited sediment from the gradient of colluvium to that of sediment deposited by stream transport. He called the latter gradient the “aqueous grade” and conducted flume experiments to measure



**Fig. 1** Stress distributions under the effects of surface water flow on a water-saturated bed.

aqueous grades produced under shallow surface water flows 1–3 times deeper than the average grain diameter of the bed. The results indicated an approximate aqueous grade of  $13^\circ$ . Then, selecting an area that had suffered severe debris flow disasters in 1966, Daido [1971] analyzed the topography of ravines by classifying the channel gradients every  $10^\circ$ . This analysis placed the more severely eroded reach (the debris flow source) in the  $20^\circ$  category and the depositing area in the  $10^\circ$  category, confirming his conjecture.

Takahashi [1977; 1978] considered a thick uniform layer of loose granular material of negligible cohesive strength and slope angle of  $\theta$ ; he analyzed the stability of that layer under a surface water flow of depth  $h$ , where the bed was saturated with parallel seepage water. If  $\theta$  satisfies

$$\tan \theta \geq \left\{ \frac{C_*(\sigma - \rho)}{C_*(\sigma - \rho) + \rho} \right\} \tan \varphi \equiv \tan \theta_2, \quad (1)$$

the bed might slip even though the seepage flow does not reach the surface. On the other hand, without overland flow, neither sliding nor flow would occur on a bed that does not satisfy Eq. 1, in which  $C_*$  is the grain concentration by volume in the static debris bed,  $\sigma$  and  $\rho$  are the densities of grains and fluid, respectively, and  $\varphi$  is the internal friction angle of the bed. If the operating shear stress and resisting stress within the bed layer are distributed linearly, the situation depicted in **Fig. 1** will arise when

$$\tan \theta = \left\{ \frac{C_*(\sigma - \rho)}{C_*(\sigma - \rho) + \rho(1 + h/a)} \right\} \tan \varphi \quad (2)$$

is satisfied, where  $a$  is the depth of the intersection of the operating shear stress line with the resisting stress line, and the excess load produced by the solids in the mixture layer illustrated in **Fig. 1** is neglected. The part from the bed surface to depth  $a$  is unstable, initiating the gravitational

motion together with the surface water flow. The smallest  $a$  value to give rise to sediment gravity flow is equal to the representative grain diameter of the bed  $d$ ; if  $a$  is below that value, the grain movement, if any, should be impelled by the fluid dynamic force of the surface flow, which would merely be bed load transport. Therefore, the substitution of  $a = d$  in Eq. 2 gives the critical slope angle  $\theta_1$  for the occurrence of massive sediment transportation.

Moreover, Takahashi experimentally showed that if  $a \geq 0.5h$  was satisfied, the particles entrained in the surface water flow would be dispersed uniformly throughout the entire flow depth; otherwise, particle flow would occur only in the lower part of the flow. Flow with particles densely dispersed in the entire depth can be considered debris flow, and therefore the condition for the emergence of debris flow can be given by

$$\tan \theta \geq \left\{ \frac{C_*(\sigma - \rho)}{C_*(\sigma - \rho) + 3\rho} \right\} \tan \varphi = \tan \tilde{\theta}. \quad (3)$$

Takahashi [1987] later defined “immature debris flow” as the sediment gravity flow arising on a slope steeper than  $\theta_1$  but flatter than  $\tilde{\theta}$ , in which the layer of moving particles encompassed only the lower part of the flow.

Takahashi [1977; 1978] proved this theory by flume experiments and also compiled other experimental data to obtain the following debris flow initiation criteria of  $q_* \geq 2$  or  $h/d \geq 1$  for a bed slope steeper than  $15^\circ$

[Takahashi, 1987], where  $q_* (\equiv q_0 / \sqrt{gd^3})$  and  $q_0$  are the non-dimensional and dimensional surface water discharges per unit width, respectively, and  $g$  is the acceleration due to gravity. Using these criteria, we can assess whether a basin is prone to debris flow. If these criteria are satisfied under a predetermined rainfall condition in any sub-basin within the objective basin, that basin can also be designated as prone to debris flow. The Japanese government adopted this concept in their guidelines for designating debris-flow-prone ravines. Without referring to rainfall, the guidelines consider a debris-flow-prone ravine to be one having an area more than 5 ha and a channel gradient steeper than  $15^\circ$  upstream from the assessment point. These criteria correspond to the characterization of a debris-flow-prone ravine as one in which the representative bed particle diameter is 6.3 cm or

less, and debris flow occurs upstream from the assessment point with an effective rainfall rate of 75 mm/hr. This condition seems reasonable in comparison with many actual data. Furthermore, the criteria suggest that debris flow will occur when the critical condition to initiate debris flow,  $q_* \geq 2$ , is satisfied at the assessment point. The discharge under an arbitrary rainfall condition can be known by applying an appropriate method of flood runoff analysis.

Understanding what rainfall condition may generate debris flow is extremely important for warning and evacuation strategies. With this need in mind, Seno and Funasaki [1974] analyzed data from rainfalls that induced debris flows. They identified possible rain-induced debris flow danger by plotting rainfall on a plane with orthogonal axes of effective rainfall amount and effective rainfall intensity, both determined more or less arbitrarily from hyetograph patterns. Japanese government researchers and engineers used Seno and Funasaki's [1974] method and, after some revisions, developed guidelines for estimating critical local rainfall levels for which warnings or evacuation orders should be issued.

Other researchers have proposed that the amount of water storage in a basin may have a larger direct effect on landslide and debris flow than does rainfall amount. Suzuki *et al.* [1979], and Michiue and Kojima [1980] applied a three-storied tank model, which had been previously used for flood runoff analyses, to the prediction of sediment hazards. Suzuki *et al.* [1979] examined sediment hazard potential in the Rokko Mountains area and found that the results corresponded well with the storage of 35 mm in the top tank of the tank model and 50 mm in the second tank. Meanwhile, Michiue and Kojima [1980] focused on the Kure area and estimated 70 mm as the critical storage, found by summing the storage in the top and the second tanks.

Takahashi [1981] investigated time-varying slope stability under arbitrary rainfall and a slope surface composed of three layers with different infiltration coefficients. He obtained a hyperbolic-type curve for the occurrence of surface landslide on a plane having two orthogonal axes of rainfall intensity and cumulative rainfall. Moreover, he applied the tank model method, which produced a similar hyperbolic-type critical curve on the same plane. By analyzing previously published data, Takahashi [1981] also estimated critical curves for various

places in Japan.

As Tani [1968] pointed out, two other causes of debris flow generation involve transformation of a landslide block. In one type, the cause would be similar to that leading to general landslides, but a landslide is transformed into debris flow while in motion. The block would have to contain many voids and plenty of water. Sassa *et al.* [1980] reported that vertical ground subsidence could trigger rapid movement of a landslide block. When groundwater locally flows in a sandy slope at relatively high velocity, the void ratio of the grain layer along the groundwater path is increased by underground erosion and infiltration. Sometime thereafter, a loose zone is formed and subsides as groundwater levels rise. Subsidence then causes rapid loading that destroys the structure of the grain layer; the overburden pressure is supported by the liquefied layer. Sassa *et al.* [1980] called this type of movement "valley-off" debris flow. In a following study, Sassa *et al.* [1985] also noted that if a landslide block falls onto a torrent deposit, undrained shearing of the bed can occur, resulting in liquefaction. The block then starts to move along the torrent bed like a sleigh. Their hypothesis may well explain the trigger of a debris flow. However, they did not explain how the motion continues and how the destruction of earth block proceeds.

Ashida *et al.* [1983] assumed that dissolution of an entire landslide mass would be completed when the deformation energy reached a certain critical value. They suggested that such energy was produced by friction at the boundary between the ground surface and the earth block. By this theory, the necessary distance for liquefaction can be estimated, presuming that the downslope gradient is steep enough for movement to continue. This theory claims, in general, that a solid earth block will liquefy on a slope steeper than about  $20^\circ$  and longer than a few tens of times the thickness of the block. However, this theory cannot predict the phenomena that appear during the process of block destruction, such as the formation and motion of flow mounds and the occurrence of debris flow following the main block motion.

Takahashi [2001] constructed a model of landslide transformation into debris flow, as illustrated in **Fig. 2**. If a deep-seated landslide occurs due to a rise in groundwater level, at least in the neighborhood of the slip surface, liquefaction proceeds, and the overburden pressure is supported by the liquefied layer. The liquefied layer flows

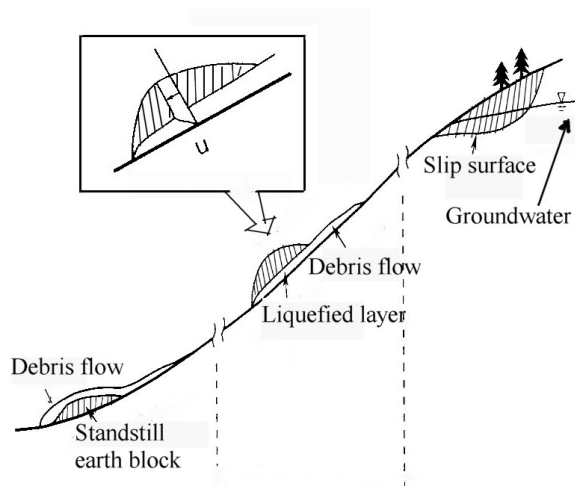


Fig. 2 Example of landslide transformation into debris flow

with a velocity distribution of zero at the bottom and maximum velocity at the top, such that the supported earth block moves faster than the liquefied layer; the liquefied layer is thus left behind as debris flows. The motion of the earth block continues as long as the slope gradient is steep enough, and liquefaction at the boundary between the earth block and the ground continues. Thus, the earth block continues cannibalizing from its body to produce a lasting liquefied layer with an elongated tail forming a debris flow. If the water-saturated part of the earth block has been thoroughly consumed by production of the liquefied layer or if the earth block arrives at a flat area, it will stop. In this case, the debris flow following the earth block will flow over the stopped earth block or detour around it and continue to move downward. Takahashi *et al.* [2003] developed a numerical model to simulate these processes from the initiation of motion to the stopping point. The solid part of the earth mass is represented by a bundle of cohesive cylinders that are separated but that sometimes stick to each other while in motion. These cylinders are supported on the liquefied layer that is successively produced by the fracturing of lower water-saturated parts of the cylinders. The model successfully reproduced an actual debris flow [Takahashi 2007].

Takahashi and Kuang [1988] conducted experiments on the formation and destruction of debris dams with the debris flow initiation due to debris dam destruction in mind. They classified three processes of dam destruction: 1) failure due to overtopping, 2) retrogressive failure, and 3) sudden sliding collapse of the dam body. They then conducted computer simulations for cases 1) and 3). The simulation for case 1) was accomplished by applying the

flow-routing method that will be further described later in this paper. The simulation for case 3) predicted slip surface formation within the dam body in response to water level change behind the dam, using a dynamic programming procedure. The results indicated that the simulations were successful. Abrupt release of stored water behind the dam mingled with the slid dam body and produced debris flow if channel slope was steep enough. In these simulations, overtopping failure occurred for the whole channel width. Takahashi and Nakagawa [1993] modified that method to allow for the case of overtopping at a relatively narrow part of the crest.

### 3. MECHANICS OF FLOW

As mentioned earlier, modeling of debris flow mechanics in Japan began with the viscoplastic model of Yano and Daido [1965]. They noted that conspicuous characteristics of debris flow would be formed by the nature of the interstitial fluid, namely the mud slurry. The serious shortcoming of viscoplastic models is the difficulty of determining crucial parameter values such as the yield strength and apparent viscosity. Laboratory tests usually produce very different values for these parameters than do field observations and cannot account for the changes in parameter values due to the addition or subtraction of water or sediment during motion. According to the author's observations [Takahashi, 1999], typical viscous-type debris flow in the Jiangjia ravine of China lacked the plug that should exist in a viscoplastic fluid flow.

On the other hand, other studies by the author [Takahashi, 1977; 1978] suggested that the main characteristics of debris flow would be produced by the frequent collisions between coarse particles, and the effect of interstitial fluid would be negligibly small. Thus, the author applied Bagnold's constitutive equations in the inertial regime to a stony-type debris flow:

$$a_i \cos \alpha \cdot \sigma \lambda^2 d^2 (du/dz)^2 = C(\sigma - \rho)g(h-z)\cos \theta \quad (4)$$

$$a_i \sin \alpha \cdot \sigma \lambda^2 d^2 (du/dz)^2 = \{C(\sigma - \rho) + \rho\}g(h-z)\sin \theta, \quad (5)$$

where  $a_i$  is a numerical constant,  $\alpha$  is the collision angle,  $\lambda$  is the linear concentration of grains defined by  $\lambda = \{(C^*/C)^{1/3} - 1\}^{-1}$ ,  $C$  is the grain concentration in volume in flow, and  $u$  is the flow velocity at height  $z$ .

If  $C$  is constant throughout the depth, Eqs. 4 and 5 can

be easily integrated under the boundary condition of  $u = 0$  at  $z = 0$ ; the resulting integration of Eq. 5 is given as

$$u = \frac{2}{3d} \left( \frac{g \sin \theta}{a_i \sin \alpha} \frac{\rho_r}{\sigma} \right)^{1/2} \frac{1}{\lambda} \{h^{3/2} - (h-z)^{3/2}\}. \quad (6)$$

Mathematically, the velocity distribution function obtained from Eq. 4 is not the same as that of Eq. 6. This was one aspect of critiques of Takahashi's model. However, this contradiction was produced by the assumption of a uniform concentration distribution. In cases of nearly uniformly distributed grains in the entire depth of flow and high-velocity flow on a rigid bed, both of these velocity functions fit the experimental data well [Takahashi, 1980]. Actually, those two functions are physically equivalent when the following formula is satisfied:

$$C = \frac{\rho \tan \theta}{(\sigma - \rho)(\tan \alpha - \tan \theta)}. \quad (7)$$

The value of  $\tan \alpha$  is approximately equal to  $\tan \varphi$ , and

$$C = \frac{\rho \tan \theta}{(\sigma - \rho)(\tan \varphi - \tan \theta)} \equiv C_\infty \quad (8)$$

was obtained experimentally as the equilibrium concentration of debris flow that proceeded with neither erosion of the bed nor deposition onto the bed.

The velocity distribution on a movable bed, however, has an inflection point near the bed. The velocity distribution pattern in the lower layer is convex upward, whereas that in the upper layer is concave upward; this pattern cannot be explained by Eq. 6, which shows a consistent upward concave curve. This pattern was also noticed by Tsubaki *et al.* [1982], who used it as a critique of Takahashi's model. Tsubaki *et al.* [1982] introduced a new constitutive equation considering the multiple collisions of particles, different from Bagnold's simple binary collision concept. In their theory, shear stress was shown to depend only on the collision stress, but the normal stress was composed of both the collision stress and the enduring contact stress. Their constitutive relationship could well explain the peculiar velocity distribution pattern mentioned above, and Tsubaki *et al.* [1982] claimed that this proved the validity of their theory. But, if normal stresses contain the contact stress, the reason the contact stress is not contained in the shearing stresses as a function of  $p_s \tan \varphi$  should be given, in which  $p_s$  is the normal contact stress.

The peculiar velocity distribution pattern on a movable

bed can be well explained by merely introducing the function

$$\tan \alpha = (C_* / C)^{1/3} \tan \varphi \quad (9)$$

into Eqs. 4 and 5. Moreover, if this function is assumed, these two equations are mathematically closed to be able to give the two unknown variables  $u$  and  $C$  [Takahashi, 1991].

Daido *et al.* [1984] conducted experiments similar to Bagnold experiments and obtained a constitutive equation based on the energy balance concept for simple binary collisions. They concluded that the dynamic stress in the granular phase was one order smaller than that reported by Bagnold. Egashira *et al.* [1989] adopted this result in their stress balance equations that correspond to Eqs. 4 and 5. Because the dynamic stresses were estimated to be one order smaller than those by Bagnold's or Takahashi's models, very large static contact pressure and shearing stress should be included on the left-hand sides of Eqs. 4 and 5, respectively, even in the case of a small solids concentration. But, in solving the equations, they inadvertently introduced the relationship of  $p_c$  to  $p_s$  as a numerical constant, where  $p_c$  is the dynamic pressure due to inter-particle collision, and  $p_s$  is the static pressure due to enduring contact. This assumption describes  $p_s$  as a function proportional to  $p_c$ . Consequently, their stress balance equations have the same forms as Eqs. 4 and 5 except that the numerical coefficients are multiplied to the respective square of the velocity gradient terms on the left-hand side. Therefore, we can conclude that the ratio of  $p_s$  to  $p_c$  was introduced to modify the constitutive relations of Daido *et al.*'s equations to attain a similar magnitude to that of Bagnold, and contrary to their claim, no static stress was considered. Egashira *et al.* [1997] modified the  $p_s$  to  $p_c$  ratio as a function of  $(C/C_*)^{1/5}$ , but this did not correct the essential flaw contained in their theory.

Takahashi and Tsujimoto [1997] discussed the constitutive relations in subaerial granular flow and obtained the following formulae:

$$\tau_c = \frac{4}{5} \sqrt{\frac{1}{15\pi}} \frac{1+e}{\sqrt{1-e}} C^2 (1+\lambda) \sigma d^2 \left( \frac{du}{dz} \right)^2 \quad (10)$$

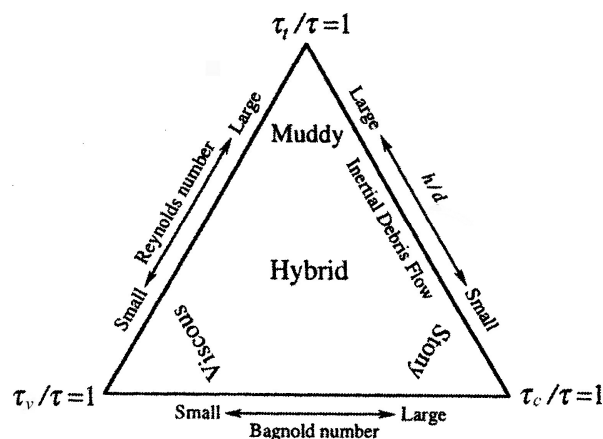
$$\tau_k = \frac{1}{3(1+\lambda)} \sqrt{\frac{1}{15\pi(1-e)}} \sigma d^2 \left( \frac{du}{dz} \right)^2 \quad (11)$$

$$p_c = \frac{2}{15} C^2 (1 + \lambda) \frac{1 + e}{1 - e} \sigma d^2 \left( \frac{du}{dz} \right)^2, \quad (12)$$

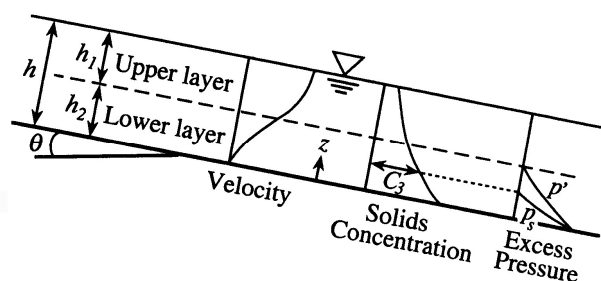
where  $\tau_c$  is the shear stress due to inter-particle collision,  $\tau_k$  is the kinetic stress produced by a particle exchanging movement layers, and  $e$  is the restitution coefficient of particles. The dynamic shear stress is the sum of  $\tau_c$  and  $\tau_k$ . This sum in the range of  $e = 0.4-0.85$  has a similar tendency and similar absolute values with changing  $C/C_*$  as that found in Bagnold's experimental result [Takahashi, 2007]. Therefore, if the sum of Eqs. 10 and 11 is substituted in the left-hand side of Eq. 5, and Eq. 12 is substituted in Eq. 4, we should be able to obtain the theoretical velocity and concentration distributions without using Bagnold's empirical constitutive relations. But, if the flow is on a movable bed, the concentration of solids near the bed would be close to  $C_*$  and the collision and kinetic stresses should be minimal. In this context, we need more strict discussion on the predominant stresses in the flow.

Possible existing shear stresses in flow are  $\tau_s$ ,  $\tau_k$ ,  $\tau_{ss}$ ,  $\tau_{\mu}$ ,  $\tau_y$ , and  $\tau_i$ , and the total shear stress  $\tau$  would be the sum of these stresses, in which  $\tau_s$ ,  $\tau_{\mu}$ ,  $\tau_y$ , and  $\tau_i$  are the static shear stress due to the enduring contact motion of particles, the deformation stress within the interstitial fluid, the yield stress of the interstitial fluid if any, and the turbulent mixing stress, respectively. Flow in which  $\tau_s$  is predominant in the entire depth occurs when the mean solids concentration in the entire cross-section  $C$  exceeds the critical value to form a skeletal structure, and particles move in enduring contact. This is the case of a quasi-static debris flow, a subject that is beyond the scope of this paper. If  $C$  is less than that critical value, except for the layer near the bed,  $\tau_s$  cannot be predominant in the entire depth, and the flow becomes dynamic debris flow. If we write  $\tau_{\mu} + \tau_y = \tau_s$ , then  $\tau_v$  represents the shear stress due to viscoplasticity of the interstitial fluid, and because  $\tau_k$  is the shear stress due to migration of particles, it can be included in  $\tau_i$ . Therefore, under a constant solids concentration, the ratios  $\tau_i/\tau$ ,  $\tau_v/\tau$ , and  $\tau_c/\tau$  should be the controlling factors for the behaviors of the debris flow. From this, Takahashi [2001a] concluded that the three kinds of dynamic debris flows can be classified in a ternary diagram, as shown in **Fig. 3**.

Debris flows in which the stress is dominated by particle collision are called "stony debris flow," those dominated by turbulent mixing stress are called "turbulent muddy debris flow," and those dominated by viscoplastic



**Fig. 3** The existence domains of various types of dynamic debris flows.



**Fig. 4** The general structure of inertial debris flow.

stress are termed "viscous debris flow." In **Fig. 3**, the three sides are represented by the Bagnold number ( $=\sigma\lambda^{1/2}d^2(du/dz)/\mu$ ), the relative depth ( $=h/d$ ), and the Reynolds number ( $=\rho_T U h/\mu$ ), respectively, where  $\rho_T$  is the apparent density of debris flow material,  $U$  is the cross-sectional mean velocity, and the effects of yield stress are ignored.

Debris flows that occur in the domain adjacent to the side representing the relative depth in **Fig. 3** are sometimes called "inertial debris flow" because the inertial stresses ( $\tau_c$  or  $\tau_i$ ) dominate in the flow. The hybrid flow in the inertial debris flow consists of the layer of lower particle collision and contact and the layer of upper turbulent suspension, as illustrated in **Fig. 4**. The ratio of these two layers in the flow depends on the relative depth and the concentration. If the relative depth is small and the particle contact layer occupies the entire flow, the flow is stony debris flow. If the relative depth is large and the turbulent suspension layer occupies almost the entire depth, the flow is a turbulent muddy debris flow. Takahashi and Satofuka [2002] developed a generalized theory of such a flow.

The stress balance equations toward the flow direction and perpendicular to it are written as

$$\tau_c + \tau_k + \tau_s + \tau_t = g \sin \theta \int_z^h \{(\sigma - \rho)C + \rho\} dz \quad (13)$$

$$p_c + p_s = g \cos \theta \int_z^{h_2} (\sigma - \rho)C dz \equiv p', \quad (14)$$

where  $p'$  is the effective pressure transmitted directly from particle to particle, and  $h_2$  is the thickness of the lower layer. If the solids concentration at the bottom of the flow is  $C_*$ , the dynamic pressure  $p_c$  at the bottom must be zero because no flow can exist at such a high concentration as  $C_*$ . Therefore, at the bottom, all the effective pressure  $p'$  should be borne by the static pressure  $p_s$ . If the solids concentration decreases upward, at the height where  $C$  becomes equal to the critical concentration  $C_3$ , then  $p_s$  becomes zero. Therefore, the following function is assumed:

$$p_s = \begin{cases} \frac{C - C_3}{C_* - C_3} p' & ; C > C_3 \\ 0 & ; C \leq C_3 \end{cases} \quad (15)$$

The relationship between  $p_s$  and  $\tau_s$  is assumed to be the following Coulomb's equation:

$$\tau_s = p_s \tan \varphi. \quad (16)$$

The stress balance equation in the upper layer is given as

$$\tau_c + \tau_t = \int_z^h \rho_T g \sin \theta dz. \quad (17)$$

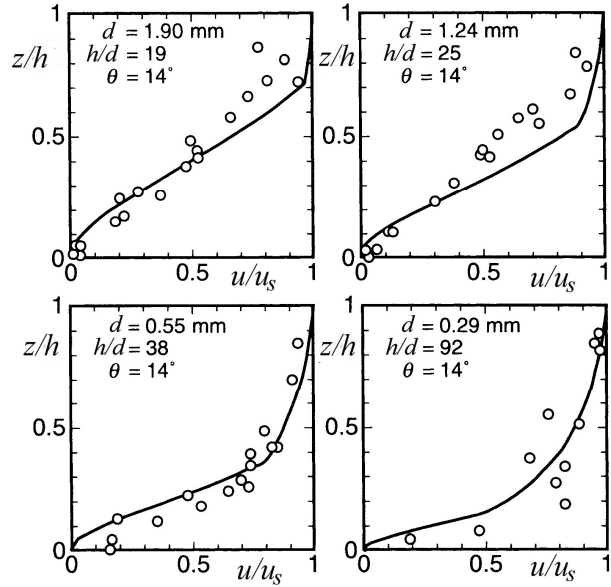
The constitutive equations for  $\tau_c$ ,  $\tau_k$ , and  $p_c$  are given by Eqs. 10, 11, and 12, respectively, and that for  $\tau_t$  is given by

$$\tau_t = \rho_T l^2 \left( \frac{du}{dz} \right)^2, \quad (18)$$

where  $l$  is the mixing length and  $l = \kappa z$  is assumed, in which  $\kappa$  is the von Karman constant.

**Figure 5** compares the results of numerical integrations of this system of fundamental equations with the experimental data reported by Hirano *et al.* [1992], where the velocity is normalized by the surface velocity  $u_s$ . The theoretical as well as experimental velocity distribution curves tend to lower the height of the boundary between the upper and lower layers (the breakpoint on the curve) and to increase the degree of concavity (of the approach to the curve for the logarithmic curve of water flow) as the relative depth increases. Moreover, the theoretical curves well fit the experimental results.

Takahashi [1982] described immature debris flow, which is composed of coarse particles with no particles suspended in the upper layer, and Arai and Takahashi [1986] reported on turbulent muddy debris flow, which is



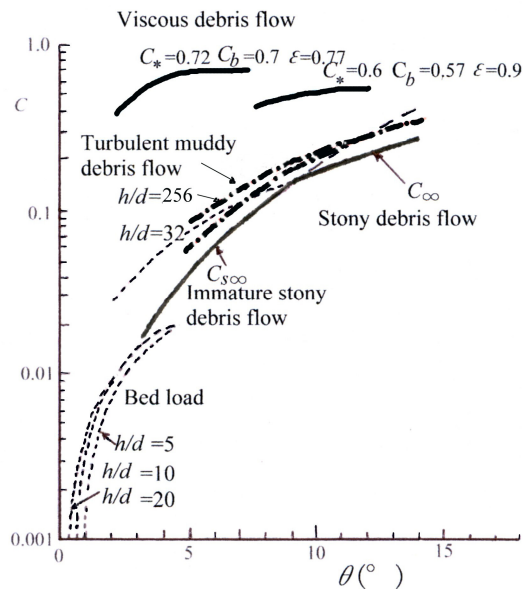
**Fig. 5** Theoretical and experimental velocity distributions.

composed of fine particles and has a thin lower layer. Mizuyama [1980] empirically obtained the equilibrium solids concentration of immature debris flow  $C_{sc}$ . Hirano *et al.* [1992] discussed that the non-dimensional parameter  $N_L \equiv z/d \sqrt{\rho_T / (\sigma F(C))}$  is an important parameter for determining the flow pattern, as shown in **Fig. 4**; they noted that the larger the particle diameter and the particle concentration are, the thicker the lower layer becomes. These investigations are considered to be the lemmas of Takahashi and Satofuka's generalized theory.

Key issues for understanding viscous debris flow are how coarse grains heavier than the ambient fluid can be dispersed in laminar viscous flow, excluding collision effects, and how to estimate the apparent viscosity of the mixture. The strength of the viscoplastic fluid as a model of debris flow material cannot explain the mechanism [Takahashi, 1981a]. Takahashi *et al.* [2000] proposed a Newtonian flow model in which particles are dispersed by squeezing flow among particles. The total shear stress in viscous debris flow is a mixed shear stress due to the effect of fluid viscosity as modified by the presence of grains and cannot be split into grain and fluid elements. Therefore, the stress balance equation is given as

$$\tau = \mu_a \left( \frac{du}{dz} \right) = \rho g h \sin \theta \left\{ \left( 1 - \frac{z}{h} \right) + \frac{\varepsilon}{h} \int_z^h C dz \right\}, \quad (19)$$

where  $\varepsilon = (\sigma - \rho)\rho$ , and  $\mu_a$  is the apparent viscosity of the debris flow material. In this model, particles are deposited



**Fig. 6** Equilibrium particle concentrations versus slope in various kinds of debris flows.

when debris flow arrives at a flat area, and the shearing deformation in flow becomes insufficient to disperse particles. This theory well explains the high equilibrium concentration and velocity within the flow.

The abovementioned generalized inertial debris flow theory and the Newtonian viscous debris flow theory give the equilibrium solids concentrations versus channel slope as shown in **Fig. 6**.

#### 4. CHARACTERISTIC MOVEMENTS OF FLOW

Observations of debris flow in motion began as early as 1970 at the Kamikamihori and Ashiaraidani ravines on the mountainside of Yakedake volcano. However, several years passed without any observations of conspicuous sediment movements. Finally, Okuda and his colleagues from the Disaster Prevention Research Institute (DPRI, Kyoto University) successfully photographed a debris flow in action at the Kamikamihori ravine in 1976. They analyzed these photographs in detail and reached the following conclusions on the nature of debris flow [Okuda *et al.*, 1977]:

- 1) The forefront of the debris flow resembled a bore, and the flow depth suddenly became large from virtually no preceding flow.
- 2) The biggest stones accumulated at the front part, and the forefront contained little water; this part can be

called “stone flow.”

- 3) The flow was greatly elevated along the right (outer) bank, presumably because the photographed section was located slightly downstream from a slight bend in the stream channel.
- 4) The front part of the flow, where large boulders accumulated, lasted only a few seconds; the following part lasted a longer time and looked like a mud flow with gradually decreasing discharge.
- 5) As well as could be estimated from the sharpness of the photographs, the velocity seemed to be distributed laterally and the central part was somewhat like a plug in Bingham fluid flow; the velocity at the central part was the largest, and almost no lateral velocity gradient existed.

Characteristics 1), 2), and 4) are conspicuous in stony debris flow. In particular, the phenomenon of large boulders accumulating toward the forefront of a debris flow has attracted the interest of many researchers, and many mechanisms have been proposed. Takahashi [1980] developed a theory based on Bagnold's concept of dispersive pressure due to inter-particle collision: Because the velocity varies from zero at the bottom to a high value in the upper layer, and the mean velocity is somewhere in between the bottom and surface values, if grain sorting arises in the flowing layer and coarser particles are transferred to the upper part, those particles would be transported forward faster than the mean propagating velocity of the debris flow front; there, they would finally arrive and tumble down to the bed. Takahashi verified this theory in flume experiments. Hashimoto and Tsubaki [1983] also proposed a similar theory based on their multi-particle collision theory mentioned earlier. Yamano and Daido [1985] applied the dynamic sieving concept, in which coarser particles do not move upward; instead, finer particles fall through the voids among coarse particles. Suwa [1988], on the other hand, proposed a theory that did not involve the previously mentioned inverse grading; his theory focused on the faster longitudinal velocity of big boulders than the mean flow velocity. His concept is more likely to fit cases of turbulent muddy debris flows and viscous debris flows; however, for many of these cases, boulder accumulation has not been found. A discrete particle model for analyzing the motion of variously sized individual particles will likely be a powerful method in the future, but difficult problems remain, such as how to

account for the effects of interstitial fluid [e.g., Mizuno *et al.*, 2000].

Ashida *et al.* [1981] investigated the phenomenon of super-elevation found by Okuda *et al.* [1977] and noted as their third main finding above. Ashida *et al.* [1981] reported that super-elevation theory and shock wave theory for super-critical water flow applied well to this phenomenon. The super-elevation remaining as a trace of flow at the river channel bend is often used to estimate debris flow discharge.

A number of wire sensors were installed along the Kamikamihori ravine, and the times at which a debris flow front cut them in sequence were recorded to determine the translation velocity of the debris flow front. The change in the channel bed elevation during the 15 years from 1962 to 1977 was also measured [Okuda *et al.*, 1978]. From that study, the following characteristics were pointed out. In areas where the channel slope was steeper than  $16^\circ$ , debris flow developed by the erosion of the bed. Downstream of that reach, where structures to consolidate the bed were installed, bed erosion was restrained or deposition could even occur. Downstream of this reach, possibly by the deposition upstream and the locally steepened channel gradient, the ability to erode the bed was rejuvenated. Thus, the redeveloped debris flow finally reached the fan area, where, with the decrease in slope gradient, it stopped. The data further demonstrate that the deeper the flow and the steeper the channel gradient are, the larger the velocity of the debris flow becomes. However, the velocity also depends on the solids concentration: the denser the concentration is, the slower the velocity becomes. These facts support Takahashi's [1977] theories of debris flow generation due to surface water runoff and flow mechanics, and they also suggest that erosion and deposition processes that take place as the flow moves down the valley are very important to understanding debris flow motion in a ravine.

A sediment sampler set on a bed consolidation structure captured portions of the forefronts of several debris flows. Sample analyses revealed that the apparent specific densities of water and solid mixtures were between 1.4 and  $1.85 \text{ g/cm}^3$ . A pressure gauge buried on top of this structure measured the flow pressures. These pressures corresponded to equivalent densities of approximately  $1 \text{ g/cm}^3$  and  $1.5 \text{ g/cm}^3$ , respectively, at the forefront where maximum flow depth and particle concentration occurred and at the end of the flow where the material was quite

liquid. These equivalent densities were always less than the density of the hypothetical liquid that considered the entire mixture of water and particles to be a continual fluid. This pressure deficit was largest at the stony front part and decreased toward the muddy rear part [Okuda *et al.*, 1981]. Thus, some parts of the load are not supported by the fluid pressure but are transmitted directly to the bottom, possibly by the effect of particle collisions. This finding verifies the existence of particle dispersive pressure due to particle collisions.

The process of debris flow deposition was also observed on the fan of the Kamikamihori ravine [Okuda *et al.*, 1980]. The behavior of the flow near the fan top was similar to that in the gully upstream because of the restraint on flow within the incised channel. Even in the region farther downstream where the incised channel disappeared, the flow did not widen immediately so as to flow over the entire debris fan; rather, the flow gradually became wider. On a flat gradient of  $4\text{--}5^\circ$ , a large boulder with a major axis of approximately 4 m was observed rolling downward with the greater part of its body protruding. This debris flow flowed more than 500 m down the fan, creating a comparatively flat deposit, referred to as a flat-type debris flow lobe.

Laboratory experiments also demonstrated the slow widening of debris flow deposits on a fan [Takahashi, 1980a]. In this experiment, the debris flow flowed out from a narrow gorge to a wide, flattening area that was laterally horizontal; upon reaching the latter area, the debris flow behaved as if it were still in the gorge. The flow traveled a certain distance before it suddenly stopped forming a debris flow lobe. Then, the succeeding debris flow from the upstream gorge alternated its direction, alternating between moving to the right and to the left. Consequently, at the end of a rather long and sporadic channel-shifting process, as in the case of a large-scale debris flow, the deposit was circular, with a diameter approximately equaling the distance from the outlet to the distal end of the first flow. Previous to that investigation, Takahashi and Yoshida [1979] had conducted some experiments and explored some simple theoretical considerations on debris flow deposits with the change in channel slope. They found that the travel distance  $x_L$  was given by

$$x_L = V_e^2 / G \quad (20)$$

$$V_e = U_u \cos(\theta_u - \theta_d) \left[ 1 + \frac{\{(\sigma - \rho_m)C_u \kappa_a + \rho_m\} \cos \theta_u g h_u}{2\{(\sigma - \rho_m)C_u + \rho_m\} U_u^2} \right]$$

$$G = \frac{(\sigma - \rho_m)g C_u \cos \theta_d \tan \alpha}{(\sigma - \rho_m)C_u + \rho_m} - g \sin \theta_d$$

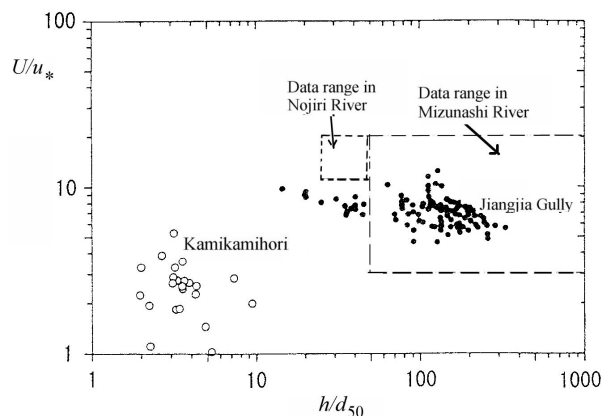
where  $U$  is the cross-sectional mean velocity of debris flow,  $\kappa_a$  is a coefficient similar to the active earth pressure operating at the slope change,  $\rho_m$  is the density of interstitial fluid, and subscripts  $u$  and  $d$  indicate the values upstream and downstream from the change in slope, respectively.

Hirano *et al.* [1991] undertook experiments to clarify the three-dimensional deposition processes using a similar apparatus to that of Takahashi [1980a]. They analyzed the probabilities of stopping distances by dividing the debris flow body into many blocks vertically and horizontally. Such an analysis based on Lagrangian concepts has not been expanded upon since.

Suwa and Okuda [1982] dug bore holes to examine the structures of debris flow lobes. They revealed that the materials on the surface were richer in cobbles and larger in mean diameter than were those in the deeper part, such that the structure of the sediment accumulation in the debris flow lobe was inversely graded. Furthermore, the longitudinal particle size variation in each lobe showed that the concentration of cobbles and the mean particle diameter increased toward the forefront. These characteristics were more evident in the swollen-type debris flow lobe that was deposited at an area near the ravine outlet. Because the swollen-type lobe was formed by the sudden stopping of the debris flow after it flowed out of the ravine, the clear inverse grading within the lobe should reflect the vertical structure in the stony debris flow in the upstream channel.

Researchers from the Osumi Work Office of the Ministry of Land, Infrastructure, and Transport have also conducted observations of turbulent muddy-type debris flow in the Nojiri River of Sakurajima Volcano. The solids concentrations in that flow often exceeded 50% by volume, and solids had median sizes of 0.3–1 mm. Applying the Manning resistance formula to the flow, the resistance coefficient was almost the same as that for plain water flow [Osumi Work Office, 1988]. Hirano and Hashimoto [1993] observed the turbulent muddy-type flows at the Mizunashi River, Unzen Volcano, and obtained data showing similar tendencies to those from Nojiri River.

Takahashi and his colleagues also conducted field observations of viscous debris flows in the Jiangjia ravine,



**Fig. 7** Velocity coefficients versus relative depths in various debris flows.

China, for an 8-year period beginning in 1991. They observed several debris flows and confirmed previously reported characteristics: tens to hundreds of surges (intermittent bore-like flow) repeatedly emerged on time intervals of a few tens of seconds to a few minutes, and in between those surges, flow completely stopped. They also newly identified a feature at the rear part of a surge, where the lateral surface profile became concave upward and thin lateral flow concentrating toward the lowest part of the section appeared. This finding brought into question the applicability of the widely accepted Bingham fluid model or other viscoplastic fluid models [Takahashi, 1999].

**Figure 7** presents the relationship of velocity coefficients  $U/u_*$  and the relative depths  $h/d_{50}$  in various debris flows observed in the field [Takahashi, 2007]. For the data from the Nojiri and Mizunashi rivers, only the distributing areas are illustrated. The velocity coefficients differ between the Jiangjia ravine and Kamikamihori ravine. Stony-type debris flows have larger resistance to flow than do viscous-type debris flows. Note that these two types also have different distribution ranges according to relative depth. The stony-type flow can only occur in a relative depth range of less than approximately 20–30. These distribution ranges of velocity coefficients and relative depths for the respective flow types can be well explained quantitatively by the generalized inertial debris flow model and by the Newtonian flow model mentioned earlier.

## 5. ROUTING ALONG THE RIVER CHANNEL AND SIMULATION OF DEPOSITION AT THE DEBRIS FAN AREA

The debris flow routing along a river channel can be simulated by numerically solving the system of one-dimensional governing equations composed of the momentum conservation equation for the mixture of solids and fluid, the respective mass conservation equations for the liquid phase and solid phase, and the equation for bed elevation change. The solid phase is divided into coarse and fine fractions; the particles in the latter fraction are always suspended in the interstitial fluid to constitute fluid heavier than plain water. The formula for resistance to flow involves the momentum conservation equation; therefore, the difference in the constitutive equations for the three kinds of debris flows should be reflected in the momentum conservation equation. The volume of debris flow that travels downstream will increase with bed erosion or decrease with deposition. Therefore, the erosion and deposition velocity equations should be reflected in the mass conservation equations. Takahashi *et al.* [1987] obtained erosion and deposition velocity equations based on the following concept: if debris flow contained less solids than the equilibrium volume given by Eq. 8, the bed would be eroded, but if the solids concentration was larger than the equilibrium value, solids would be deposited. Substituting these equations into mass conservation equations and using the uniform flow equation for stony debris flow as the momentum conservation equation (kinematic wave approximation), they were able to reproduce the experimental debris flows in a varied-slope channel produced by the water supply from the upstream end or laterally along the channel. This method was applied to cases of arbitrary boundary conditions such as a flood runoff hydrograph under arbitrary rainfall and to various scales of surface landslide that immediately liquefied [Takahashi and Nakagawa, 1991]. Downstream-moving particle segregation processes were also considered by adding the conservation equation for the concentration of each size fraction in an infinitesimal area and the upward and downward motions of respective size classes of particles caused by inter-particle collisions. Thus, the convergence of large particles to the front of a stony debris flow was simulated [Takahashi *et al.*, 1992; 2000a].

In a typical viscous-type debris flow, as the velocity decreases toward the end of a surge, deposition proceeds from the lower to upper parts, and flow stops. Thereafter, when the next surge reaches this point, it entrains the still-soft deposit formed by the last surge; however, toward

the end of the flow, surge deposition again takes place, and the flow finally stops. An event of viscous debris flow repeats these processes tens to hundreds of times. Therefore, to trace the behaviors of viscous debris flow in a transferring reach, the system of governing equations should account for deposition and stoppage mechanisms and the entrainment of the newly deposited layer. Takahashi *et al.* [2000] developed such an analysis method based on the newly introduced Newtonian fluid model.

Concerning debris flow deposition on a three-dimensional terrain, Takei [1982] adopted a stochastic method using a random walk model. Specifically, he used an equation for motion of a point mass to estimate the debris flow velocity from one grid point to another. The direction of flow was decided by the probability proportional to the flow velocities calculated from the elevation differences between the adjacent grid points. However, a disadvantage of a random walk model is that motion is one dimensional; deposition proceeds only one dimensionally even though its longitudinal pattern is complicated, reflecting complex topography.

Takahashi and Tsujimoto [1984] used horizontally two-dimensional momentum conservation and mass conservation equations, in which the terms representing the flow resistance were the so-called two-variable model. For example, the resisting shear stress to  $x$  direction is given as

$$\tau_{bx} = (\sigma - \rho_m)ghC_L \cos \theta_s \tan \alpha + k(D/d)U\sqrt{U^2 + V^2}, \quad (21)$$

where  $D$  is the equivalent roughness height of the fan area,  $k$  is the resistance coefficient, and  $V$  is the velocity component perpendicular to  $U$ . The first term on the right-hand side of Eq. 21 is the Coulomb resistance term, and the second term is the fluid resistance term. Takahashi and Tsujimoto's [1984] calculation result well explained the results of laboratory experiments and the actual debris flow deposition that occurred at Horadani fan in 1979, in which the upstream boundary condition at the fan top was given as a hydrograph obtained from the routing along the channel upstream. However, some confusion remained in Eq. 21. This kind of equation is frequently used to analyze the arrival distance of avalanches, but in the case of stony debris flow, as is clear from Eq. 4, the first term represents the total resisting stress on the bed. That stress is not quasi-static Coulomb resistance stress but rather dynamic shear stress due to inter-particle collisions. We do not need to consider the second term of Eq. 21, even though this

formula is correct if  $k$  is the resistance coefficient for interstitial fluid only, because in this case the second term is negligibly small compared to the first term. Therefore, later, Takahashi and Nakagawa [1992] neglected the second term and rewrote the first term to obtain

$$\tau_{bx} = \frac{\sigma}{8} \left( \frac{d}{h} \right)^2 \frac{1}{\{(C_*/C)^{1/3} - 1\}^2} U \sqrt{U^2 + V^2}. \quad (22)$$

Takahashi *et al.* [1988] added the conservation equation for particle number in flow to the fundamental system of equations for two-dimensional deposition processes and explained the size distribution characteristics on and inside the debris flow lobe mentioned earlier.

Arai and Takahashi [1988] introduced a depositing velocity equation to the fundamental system of equations for the two-dimensional deposition processes in turbulent muddy debris flow. The validity of their theory was then proved by laboratory experiments.

Using the same two-dimensional system of equations previously applied to stony-type debris flow, Takahashi *et al.* [1987a] examined the deposition processes of a huge volcanic mud flow at Mt. Nevado del Ruiz in Colombia. Unlike for the stony debris flow case, the resistance to flow formula was the Manning formula. The flow that reached the Armero fan was supposed to have a structure of coarse particles in the lower part of the flow and only very dense mud in the upper part. Therefore, a threshold stopping velocity was introduced to explain the stoppage of flow after coarse particles were deposited. This method well explained the area and structure of deposition, which was divided into a coarse deposit in the lower layer and a fine mud layer in the upper part. A two-dimensional flooding and deposition model for viscous debris flow that did not use the empirical stopping threshold but instead used a theoretical deposition velocity equation was also developed [Arai and Takahashi, 1999].

## 6. CONCLUSION

This paper has reviewed debris flow research in Japan, focusing on the fundamental mechanics of initiation, flow, and deposition. Qualitative characteristics revealed by geological, geotechnical, and geomorphological investigations have not been included in the present paper. Debris flow control and avoidance by hard and soft countermeasures are crucial. However, due to lack of space, these measures and related mechanical considerations are

not reviewed here. If any important works are not reviewed here, it is because the author has been remiss.

## REFERENCES

- Arai M. and Takahashi T. (1986): The mechanics of mud flow. Proc. JSCE, 375/II-6., pp. 69–77 (in Japanese).
- Arai M. and Takahashi T. (1988): Depositing process of mud flow on gentle slope bed plunging from steep slope. Proc. 6<sup>th</sup> Congress of APD, IAHR, pp. 83–90.
- Arai M. and Takahashi T. (1999): Two-dimensional simulation of the deposition process. In Takahashi T. (ed.), Japan-China joint research on the mechanism and the countermeasures for the viscous debris flow, Disaster Prevention Research Institute, Kyoto University, pp.85–88.
- Ashida K., Takahashi T. and Arai M. (1981): Study on debris flow control: Debris flow in bends of rectangular section. Annuals, DPRI, 24B-2, pp.51–263 (in Japanese).
- Ashida K., Egashira S. and Ohtsuki H. (1983): Dynamic behavior of soil mass produced by slope failure. Annuals, DPRI, 26B-2, pp. 315–327 (in Japanese).
- Daido A. (1971): On the occurrence of mud-debris flow. Bull. DPRI, 21 (2), pp. 109–135.
- Daido A., Miyamoto K., Miwa H. and Nishimoto N. (1984): A consideration on the constitutive equation of a granular flow containing Newtonian fluid in the void in view of energy loss mechanism. Proc. 39<sup>th</sup> Ann. Meeting, JSCE, Part 2, pp.367–368 (in Japanese).
- Egashira S., Ashida K., Yajima H. and Takahama J. (1989): Constitutive equations of debris flow. Annuals, DPRI, 32B-2, pp. 487–501.
- Egashira S., Miyamoto K. and Itoh T. (1997): Constitutive equations of debris flow and their applicability. Proc. 1<sup>st</sup> International Conference on Debris Flow Hazards Mitigation, ASCE, pp. 340–349.
- Hashimoto H. and Tsubaki T. (1983): Reverse grading in debris flow. Proc. JSCE, 336, pp. 75–84 (in Japanese).
- Hirano M. and Hashimoto H. (1993): The field measurement of debris flow in the Mizunashi River and the characteristics of flow. In Hirano M. (ed.) Investigations of debris flows and pyroclastic flows at Unzen, Research Report for Grant-in Aid for Scientific Research, Kyushu University, pp. 9–22 (in Japanese).
- Hirano M., Hashimoto H., Tazaki T. and Miyajima S. (1991): Grains deposition from debris flow due to decrease of channel slope and expansion of the width. Proc. Hydraulic Eng., JSCE, 35, pp. 453–458 (in Japanese).
- Hirano M., Hashimoto H., Fukutomi K., Taguma K and Pallu M.S. (1992): Nondimensional parameters governing hyperconcentrated flow in an open channel. Proc. Hydraulic Eng. 36, pp. 221–226 (in

- Japanese).
- Kaki T. (1954): The experimental research for mud-flow. *J. JSECE*, 19, pp. 1-6 (in Japanese).
- Koide H. (1955): Landslide in Japan. Toyokeizai News Press (in Japanese).
- Michiue M. and Kojima E. (1980): Prediction of cliff failures due to severe rainfall. Proc. 17<sup>th</sup> Symposium of natural hazards, pp. 131-134 (in Japanese).
- Mizuno H., Mizuyama T., Minami N. and Kuraoka S. (2000): Analysis of simulating debris flow captured by permeable type dam using distinct element method. *J. JSECE*, 52(6), pp. 4-11 (in Japanese).
- Mizuyama T. (1980): Sediment transport rate in the transition region between debris flow and bed load transport. *J. JSECE*, 33(1), pp. 1-6 (in Japanese).
- Murano Y. (1968): Sabo Engineering. Asakura Shoten (in Japanese).
- Nomitsu R. and Seno K. (1959): New Potamology. Chijin Shokan, Tokyo, pp. 1-318 (in Japanese).
- Ohsumi Work Office. (1988): Debris Flow at Sakurajima. Ohsumi Work Office, pp.1-64.
- Okuda S., Suwa H., Okunishi K., Nakano K. and Yokoyama K. (1977): Synthetic observation on debris flow, Part 3; Observation at valley Kamikamihorizawa of Mt. Yakedake in 1976. *Annuals, DPRI*, 21B-1, pp. 277-296 (in Japanese).
- Okuda S., Suwa H., Okunishi K., Yokoyama K., Nakano K. and Ogawa K. (1978): Synthetic observation on debris flow, Part 4: Observation at Kamikamihorizawa valley of Mt. Yakedake in 1977. *Annuals, DPRI*, 20B-1, pp. 237-263 (in Japanese).
- Okuda S., Suwa H., Okunishi K., Yokoyama K., Ogawa K., Hmana H. and Tanaka S. (1980): Synthetic observation on debris flow, Part 6: Observation at Kamikamihorizawa valley of Mt. Yakedake in 1979. *Annuals, DPRI*, 23B-1, pp. 357-394 (in Japanese).
- Okuda S., Suwa H., Okunishi K., Yokoyama K. and Ogawa K. (1981): Synthetic observation on debris flow, Part 7; Observation at Kamikamihori valley of Mt. Yakedake in 1980. *Annuals, DPRI*, 24B-1, pp. 411-448 (in Japanese).
- Sassa K., Takei A. and Kobashi S. (1980): Landslides triggered by vertical subsidences. Proc. International Symposium on Landslides, New Delhi, 1, pp. 49-54.
- Sassa K., Kaibori M. and Kitera N. (1985): Liquefaction and undrained shear of torrent deposits as the cause of debris flows. Proc. International Symposium on Erosion, Debris Flow and Disaster Prevention, Tsukuba, pp. 231-241.
- Seno K. and Funasaki M. (1974): Sediment hazards (mainly the hazards due to debris flow) and rainfall amount. *J. JSECE*, 26(2), pp. 22-28 (in Japanese).
- Suwa H. and Okuda S. (1982): Sedimentary structure of debris-flow deposits, at Kamikamihori fan on Mt. Yakedake. *Annuals, DPRI*, 25B-1, pp. 307-321 (in Japanese).
- Suzuki M., Fukushima Y., Takei A. and Kobashi S. (1979): The critical rainfall for the disasters caused by debris movement. *J. JSECE*, 31(3), pp.1-7 (in Japanese).
- Takahashi T. (1977): An occurrence mechanism of mud-debris flows, and their characteristics in motion. *Annuals, DPRI*, 23B2, pp. 405-435 (in Japanese).
- Takahashi T. (1978): Mechanical characteristics of debris flow. *J. Hydraulics Div., ASCE*, 104(8), pp. 1153-1169.
- Takahashi T. (1980): Debris flow on prismatic open channel. *J. Hydraulics Div., ASCE*, 106(3), pp. 381-396.
- Takahashi T. (1980a): Study on the deposition of debris flow (2)-Process of formation of debris fan. *Annuals, DPRI*, 23B-2, pp. 443-456 (in Japanese).
- Takahashi T. (1981): Estimation of potential debris flows and their hazardous zones: Soft countermeasures for a disaster. *J. Natural Disaster Science*, 3(1), pp. 57-89.
- Takahashi T. (1981a): Debris flow. *Annual Review of Fluid Mech.*, 13, pp.57-77.
- Takahashi T. (1982): Study on the deposition of debris flows (3): Erosion of debris fan. *Annuals, DPRI*, 25B-2, pp.327-348 (in Japanese).
- Takahashi T. (1987): High velocity flow in steep erodible channels. Proc. 22<sup>nd</sup> Congress of IAHR, Lausanne, Vol. F.H, pp. 42-53.
- Takahashi T. (1991): Debris flow. Balkema, Rotterdam, 165p.
- Takahashi T. (1999): Mechanics of viscous debris flow. In Takahashi T. (ed.), Japan-China joint research on the mechanism and the countermeasures for the viscous debris flow Disaster Prevention Research Institute, Kyoto University, pp. 64-84.
- Takahashi T. (2001): Process of occurrence, flow and deposition of viscous debris flow. In Seminara G. and Blondeaux P. (eds.), *River, Coastal and Estuarine Morphodynamics*, Springer-Verlag, pp. 93-118.
- Takahashi T. (2001a): Mechanics and simulation of snow avalanches, pyroclastic flows and debris flows. *Special Publications of International Association of Sedimentology*, 31, pp. 11-43.
- Takahashi T. (2007): Debris flow: Mechanics, Prediction and Countermeasures. Taylor & Francis, Leiden, 448p.
- Takahashi T. (2009): Mechanics-based approach toward the mitigation of debris flow disasters. *Landslides, Disaster Risk Reduction*, Springer-Verlag, Berlin, pp. 89-113.
- Takahashi T. and Kuang S. (1988): Hydrograph prediction of debris flow due to failure of landslide dam, *Annuals, DPRI*, 31B-2, pp. 601-615 (in Japanese).
- Takahashi T. and Nakagawa H. (1991): Prediction of stony debris flow

- induced by severe rainfall. *J. JSECE*, 44(3), pp.12–19(in Japanese).
- Takahashi T. and Nakagawa H. (1992): Prediction of flood hydrograph due to collapse of a natural dam by overtopping. *Annuals, DPRI*, 35B-2, pp. 231–248 (in Japanese).
- Takahashi T. and Nakagawa H. (1993): Estimation of flood/debris flow caused by overtopping of a landslide dam, *Proc. 25<sup>th</sup> Congress, IAHR*, Tokyo, III, pp. 117–124.
- Takahashi T. and Satofuka Y. (2002): Generalized theory of stony and turbulent muddy debris-flow and its practical model. *J. JSECE*, 55(3), pp.33–42 (in Japanese).
- Takahashi T. and Tsujimoto H. (1984): Numerical simulation of flooding and deposition of debris flow. *Annuals, DPRI*, 27B-2, pp.467–485 (in Japanese).
- Takahashi T. and Tsujimoto H. (1997): Mechanics of granular flow in inclined chute. *J. Hydraulic, Coastal and Environmental Eng., JSCE*, 567, pp. 57–71 (in Japanese).
- Takahashi T. and Yoshida H. (1979): Study on the deposition of debris flow (1) – Deposition due to abrupt change of bed slope. *Annuals, DPRI*, 22B-2, pp. 315–328 (in Japanese).
- Takahashi T., Nakagawa H. and Kuang S. (1987): Estimation of debris flow hydrograph on varied slope bed. *Erosion and Sedimentation in the Pacific Rim, IAHS Publ.* 165, pp. 167–177.
- Takahashi T., Nakagawa H. and Yamaji A. (1987a): Method for determination of the hazardous area due to debris flow. *Annuals, DPRI*, 30B-2, pp. 611–626 (in Japanese).
- Takahashi T., Nakagawa H. and Sato H. (1988): Formation of debris flow fan by fully developed and immature debris flows. *32<sup>nd</sup> Conf. on Hydraulics, JSCE*, pp. 497–502 (in Japanese).
- Takahashi T., Nakagawa H., Harada T. and Yamashiki Y. (1992): Routing debris flows with particle segregation. *J. Hydraulic Eng., ASCE*, 118 No. 11, pp. 1490–1507.
- Takahashi T., Nakagawa H. and Satofuka Y. (2000): Newtonian fluid model for viscous debris flow, *Proc. 2<sup>nd</sup> Intern. Conf. on Debris-Flow Hazard Mitigation*, pp. 255–267.
- Takahashi T., Inoue M., Nakagawa H. and Satofuka Y. (2000a): Prediction of sediment runoff from a mountain watershed. *Annual J. Hydraulic Eng., JSCE*, 44, pp. 717–722 (in Japanese).
- Takahashi T., Satofuka Y. and Kashimoto S. (2003): Motion of landslide-induced debris flow. In Rickenmann D. and Chen C.L. (eds.), *Debris-Flow Hazard Mitigation*, Millpress, Rotterdam, pp.399–410.
- Takei A. (1982): Prediction of debris flow hazardous area by a stochastic method. In Ashida K. (ed.) *Study on the Prevention and the Mitigation of the Sediment Disaster on an Alluvial Fan*, Research Report for the Grant-in-Aid for Scientific Research, Disaster Prevention Research Institute, Kyoto University, pp.82–91 (in Japanese).
- Tani I. (1968): On debris flow (Yamatsunami). *Water Science*, 60, pp.106–126 (in Japanese).
- Tsubaki T., Hashimoto H. and Suetsugi T. (1982): Grain stresses and flow properties of debris flow. *Proc. JSCE*, 317, pp.70–91 (in Japanese).
- Yamano K. and Daido A. (1985): The mechanism of granular flow of mixed diameter composed two diameters. *Proc. JSCE*, 357/II-3, pp.25–34.
- Yano K. and Daido A. (1965): Fundamental study on mud-flow. *Bull. DPRI*, 14, pp. 69–83.