

Technical Memorandum of PWRI No. 1872

MOVEMENTS OF DEBRIS FLOWS

November 1982

Slope Failure Division
Erosion Control Department
Public Works Research Institute
Ministry of Construction

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MOVEMENTS OF DEBRIS FLOWS

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EDMONTON ALBERTA

CANADA

Fall 1982

ABSTRACT

The subject of this research is the dynamic behavior of debris flow movements from the initiation to deposition. The phenomena of debris flows have been studied from their deposits by many authors. In recent years, debris flows have been observed and reported by many eyewitnesses in various parts of the world. The analysis of debris flow movements were greatly advanced in the last two decades. In this report, a synthesis of published information is compiled in the form of a state-of-the-art review of the subject of debris flow dynamics. The literature review includes collection of descriptive observational data from debris flow movements in various parts of the world, especially, at Mt. Yakedake, Japan. Initial triggers, velocities, volumes, modes of motion and material characteristics have been summarized.

Generally, the thresholds which generates debris flows can be classified into four types: landslides, erosion of debris due to torrential streams, collapse of a temporary dam with coarse debris, catastrophic glacial meltwater outbursts (jökulhaups), and collapse of crater lakes (lahars). The analysis of plane translational slip was given by Skempton and Delory (1957). The critical slope angle for the occurrence of massive transportation was proposed by Takahashi (1978) using Bagnold's dispersive pressure concept.

Debris flows contain heavy coarse materials, sand, silt and clay, in water. As the result, the properties of debris flows differ from that of Newtonian fluids e.g. water. Several models which were proposed by many authors for the purpose of analysis of debris flows are ; (1) Newtonian fluid, (2) Bingham fluid, (3) Pseudo-plastic fluid, (4) Quasi-plastic fluid (5) Coulomb-viscous model, and (6) Bagnold's model. The Bingham fluid model and Bagnold's model are favoured by many authors. Although those models for debris flows are reviewed in this report, the fundamental constitutive law has not yet been decided upon. Some models may be valid for certain types of debris flows. For example, flows with fine materials behave like Newtonian or Bingham fluids, depending upon their water content. A saturated grain flow lacking fines could be analysed using Bagnold's model. The difficulty in the analysis of debris flow movements originates in the lack of fundamental studies on the behavior of debris materials and accepted methods for generating of debris flows in the laboratory.

The existence of "snout", boulder accumulations at the front part of debris flows, has been reported by many eyewitnesses. "Inverse grading" was observed by authors in the deposits of numerous subaerial debris flows. A few writers have proposed several hypotheses to explain these two features ; (1) Bagnold's dispersive pressure, (2) lift forces, (3) a kinetic sieve mechanism, and (4) buoyancy in a grain mixture.

Deposits from debris flows are classified into two types ; levees and snout accumulations. Mechanisms for their deposition are strictly related to those of flow. A few proposed quantitative analysis and some description related to the deposition processes are reviewed.

Observation of debris flows on Mt. Yakedake in Japan have been made since 1971 by the Ministry of Construction and Kyoto University. Since debris flows occur several times on Mt. Yakedake every year, many facilities and various instruments for their observation have been set up by this observation system, used by many eager investigators for a variety of studies, has been briefly described here. The results of these observation have been arranged and compared with data from other parts of the world.

Finally, collected information about debris flows which occurred in several parts of the world are rearranged and tabulated.

ACKNOWLEDGEMENTS

This research was undertaken and accomplished under the supervision and encouragement of Professor N. R. Morgenstern. I wish to thank Dr. Morgenstern for his encouragement, support and guidance over the past year. I also wish to thank Dr. D. M. Cruden for providing encouragement and guidance in this research.

I would also like to acknowledge other professors whose lectures helped create a background which a geotechnical researcher must possess. Among them Dr. Z. Eisenstein, Dr. P. Kaiser and Dr. D. Sego deserve special thanks.

I wish to extend special thanks to my fellow graduate students who have helped make my study and my life in Canada so enlightening and enjoyable. Special thanks are extended to Mr. P. McLellan for his advice and suggestions for this research.

Finally, I would like to thank Dr. M. Fukuoka, Mr. T. Yasue, and all staffs of P. W. R. I, Ministry of Construction for their encouragement and support for my study in Canada.

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1. INTRODUCTION

1.1 Purpose of this Research

The debris flow, which has been often called as "mudflow" by many authors (Blackwelder 1928 ; Sharpe, 1938 ; Sharpe and Nobles, 1953 ; Curry, 1966 ; Morton and Campbell, 1974 ; and Niyazov and Degovets, 1975) has long been known as a variety of landslide intermedeate between a typical landslide and a water flood (Blackwelder, 1928). The destructive forces that originate in their high velocities and densities and their bouldery contents often caused great damage to both people and property in high population areas (e. g. Ikeya, 1979). With the recent rapid increase in population and development in mountainous areas in all parts of the world, protecting people and property from debris flows has become much more important than in the past.

For the purpose of the prevention of debris flow disastars, the mechanisms of occurrence, movement, and deposition have to be known correctly as far as is possible. In this report a body of published literature is compiled and rearraged with a view to understanding the mechanical behavior of debris flows.

1.2 Definition of Debris Flow

The classification of landslides has been presented by many authors (e.g. Ladd, 1935 ; Sharpe, 1938 ; Coates, 1977 ; and Varnes, 1958 and 1978). The advantages of the Varnes' classification system are that it is well accepted on the North American continent, yet sufficiently general and free of regional bias (Hungur 1981). Moreover, it incorporates many older systems especially that proposed by Sharpe (1938) and its terminology is therefore

Table 1. Slope movement classification after Varnes (1978)

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	FEW UNITS	Rock slump	Debris slump	Earth slump
	TRANSLATIONAL		Rock block slide	Debris block slide	Earth block slide
			MANY UNITS	Rock slide	Debris slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow (deep creep)	Debris flow (Soil creep)	Earth flow
COMPLEX			Combination of two or more principal types of movement		

compatible with a large segment of the literature (Hung, 1981).

The chief criteria used in the classification are the type of movement and the type of material (Table 1). According to this system, the debris flow is a variety of slope movement, rather than a landslide. Debris flows are defined as the flows originating in debris material, which may either proceed as a relatively unbroken block or lead to disruption into many units, each consisting of debris. Debris flows are distinguished from mud flows, a sub-type of earth flows, on the basis of particle size, that is, debris flows contain a relatively high percentage of coarse fragments, whereas mud flows contain at least 50 percent sand, silt, and clay-sized particles. Debris flows are subdivided into typical debris flows, debris avalanches, block stream, solifluction, and soil creep. Block stream, solifluction, and soil creep are distinguished from typical debris flow and debris avalanche by their extremely slow velocities. There is also a type of slope movement which looks like a debris flow or debris avalanche called a debris slide. These three types of slope movement, debris flows, debris avalanches, and debris slides, are more or less similar phenomena and change continuously and reciprocally. Debris flows and debris avalanches are distinguished from debris slides by their higher velocity and higher water content. The difference between debris flows and debris avalanches is not clearly explained in Varnes' classification system, even though each type of movement is presented. In this writer's opinion, debris flows move farther down a slope than in debris avalanches because of higher water contents or existence of longer, and more or less gentler channel.

2. MOVEMENTS OF DEBRIS FLOW

2.1 Generation of Debris Flows

Triggers of Debris Flows

According to many studies, the initiation of most debris flows, is generally associated with four climate conditions; (1) heavy and short-term rainfall (Fryxell and Horberg, 1943; Curry, 1966; Morton and Campbell, 1974; Campbell, 1975; Niyazov and Degovets, 1975; and Mears, 1979) (2) moderate intensity and long-term rainfall (Waldron, 1967; Azimi and Desvarreux, 1974; and Piernon, 1980) (3) Rapid melting of snow or glacial ice (Sharp and Nobles, 1953; Johnson, 1970; and Morton and Campbell 1974) (4) Sudden surface or subsurface glacial lake drainage (Jökulhlaup), (Jackson, 1979) (5) The sudden release of very large quantities of water from crater lakes creating a lahar (e.g. Neall, 1976), and combination of these. Most of debris flows result from unusually heavy rain or from the thaw of snow, but a few do not.

Azimi and Desvarreux (1974) described an example of a debris flow which was not directly connected with heavy rainfall. Water circulation in highly porous debris transported fine particles and gave rise to a progressive clogging of the lower part of a debris fan which perched on a steep slope. The increase in pore pressure resulting from this clogging reached a sufficiently high intensity to reduce the shear strength of the materials and cause an abrupt collapse of the clogged part thus initiating a debris flow. Sometimes a landslide was followed by the debris flow in the upper part of debris.

Jackson (1979) presented an example of debris flows due to a jökulhlaup in the Rocky Mountains. The surging water of the jökulhlaup eroded the slope toe along Cathedral Gully, and triggered slumping, which supplied much of the sediments contained in the debris flows. The causes of a Jökulhlaup is explained by Nye (1976) as following two processes; The first explanation is only applicable to a lake ponded behind glacial ice. When the water level of the lake reaches a critical height, the hydrostatic gradient beneath the glacier decreases continuously from lake surface to glacier toe and drainage is started beneath the glacier. The second explanation is the possibility of through-going fractures within the glacier providing drainage conduits. Such fractures could be caused by sudden movement within the glacier. Jökulhlaup initiation is dependent on long-term climate-glacier interaction (Jackson, 1979)

In general, the Indonesian term "lahar" refers to a flowing mixture of water and debris which is chiefly composed of volcanoclastic materials, and moving down the flank of a volcano. The mechanisms for lahar generation are many and varied.

Neall (1976) proposed five natural genetic grouping; (1) Collapse of crater lakes. This is the most destructive form of lahar and has most commonly occurred in the circum-Pacific region. (2) Mixing of nuées ardentes with water. Nuées ardentes often create debris flows upon mixture with ponded or flowing waters, or with rainstorms. (3) Action of heavy rain. Erupted volcanoclastics are eroded by run off from heavy rainfall. (4) Melting of snow and ice accompanying eruptions, and (5) Phreatic explosions or directed blasts.

Thresholds of Debris Flows

The thresholds which generate debris flows are numerous, complex and varied. Generally, the thresholds are classified into four types ; (1) landslides (soil slips, earth slumps, and rock falls) which are caused by either increases in pore (water) pressure, decreases in the strength of the ground, increases in weight of the ground due to an increased water content, local collapse due to piping, and erosion of the slope toe due to a torrential stream. (Curry, 1966 ; Johnson, 1970 ; John and Rahn, 1976 ; Azimi and Desvarreux, 1974 ; Morton and Campbell, 1974 ; Campbell, 1975 ; Nasmith and Mercer, 1979 ; and Pierson, 1980) (2) Erosion of debris due to torrential streams (Sediments loaded by flooding, created small gullies on the slopes). (Fryxell and Herberg, 1943 ; Waldron, 1967 ; Broscoe and Thomson, 1969 ; Mears, 1979 ; and Pierson, 1980) (3) Collapse of a temporary choking of a channel with coarse debris (dams) by the fluid material collected behind them. (Sharp and Nobles, 1953 ; Broscoe and Thomson, 1969) (4) Jökulhlaup, catastrophic glacial meltwater outburst (Jackson, 1979) (5) Lahar, caused by collapse of crater lakes. (Neall, 1976)

Debris Flows Generated by Landslides

R.H. Campbell (1974, 1975) described the debris flows in southern California which were generated by soil slips triggered by the heavy rainstorms. A post-storm reconnaissance of the area and investigation of downslope effects of shallow failures indicated that, although there were many kinds of landslides from rockfalls to deep rotational slumps, shallow scars resulted from the mass failure of colluvial soil cover of steep hillsides and colluvial fill in the steep ravines were dominant, and the initial movement of slabs of soil and wedges of ravine fill generated many debris flows. The shallow scars are slab or wedge-shaped, with length to thickness ratios generally in excess of 10 : 1 and they are commonly called "soil slips" in coastal California though called "slab slides" by Skempton and Hutchinson (1969).

The initial movements of slabs and wedges of ravine fill caused a reconstitution of the sliding wet masses into flowing, viscous, debris-laden mud, which then flowed down available drainage courses as so called debris flows. He uses the compound term "soil slip-debris flow" to specify debris flows that are known or reliably inferred to have originated from soil slips.

He explained the relation between occurrence of land-slip and heavy rainfall by using the hypothesis of Kesseli (1943) and Haefeli (1948) ; When the rate of infiltration into and through the upper layers exceeds the transmissive capacity of the rocks below, a temporary perched water table is formed. And its head will continue to increase as long as infiltration continues at the high rate. As a result the slope approaches a special condition with seepage flow parallel to the slope surface.

The analysis of the slope stability for the condition, in which the ground-water flow is parallel to the slope at shallow depth, was given by Skempton and DeLory (1957) and it may be written in the form.

$$F = \frac{C' + (r - m\gamma_w)Z \cos^2 B \tan \phi'}{\gamma Z \sin B \cos B} \quad \text{Eqn. 1}$$

Where F is the factor of safety, C' is the cohesion intercept, Z is the vertical depth of the slip surface, B is the slope angle, γ is the unit weight (density) of the soil, γ_w is the unit weight of the water, m is the function of Z such that mZ is the vertical height of the ground-water

table above the slip surface, and ϕ' is the angle of shearing resistance. (Fig.1) R.H. Campbell gives a family of curves of $F=1$, with varying combinations of measured soil parameters γ and $\tan \phi'$. (Fig. 2)

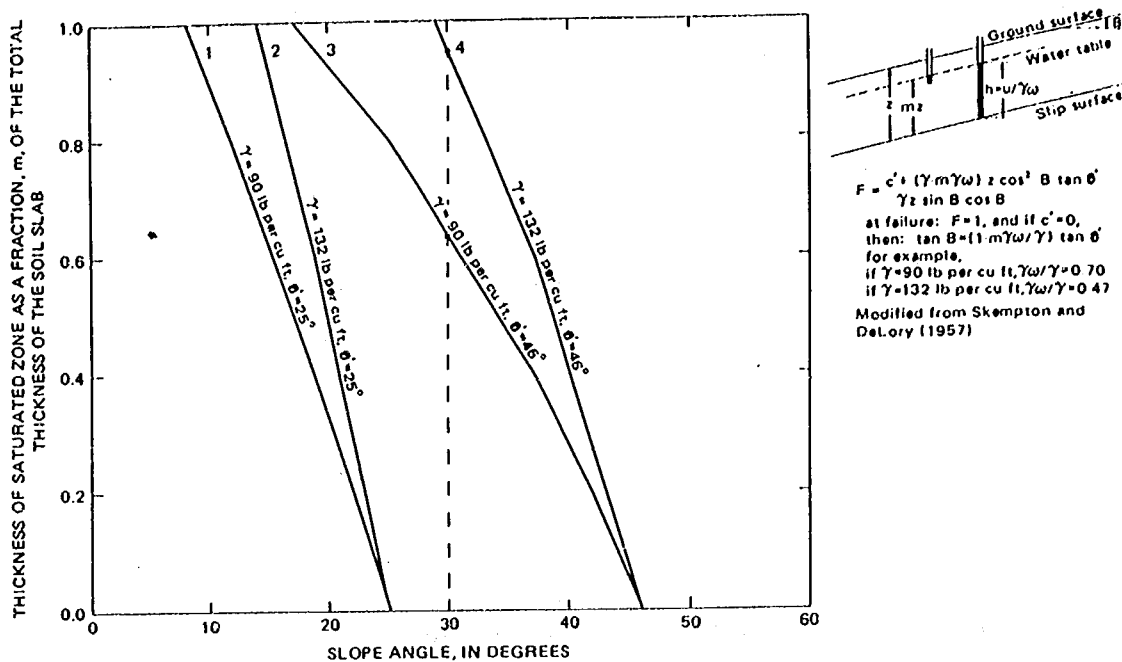


Figure 1. Relation of failure in some typical soils to ground-water content and slope angle. Computed curves for $F = 1$ (failure criterion) at selected values of γ unit weight and ϕ' (angle of shearing resistance). The curves for most natural nonclayey soils lie between curves 1 and 4. Fields to the left and right of each curve are stable and unstable, respectively. (After Campbell, 1975)

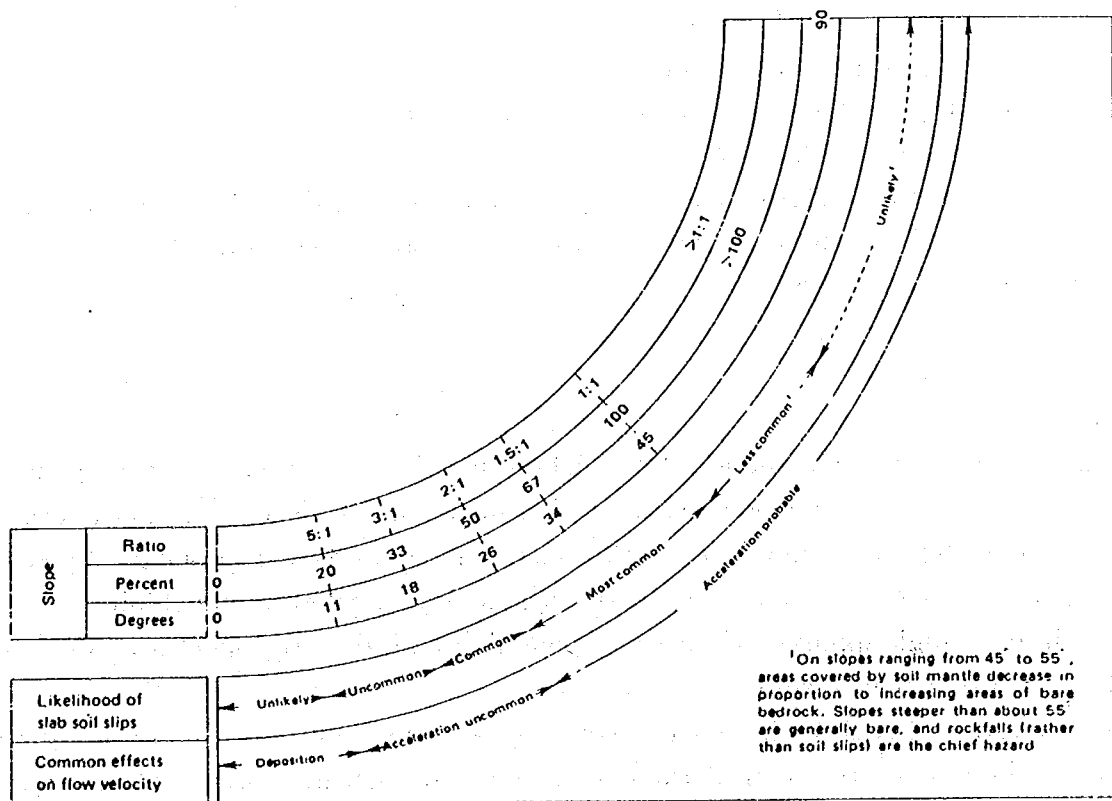


Figure 2. Approximate relations of natural slopes to soil-slip failures. (After Campbell, 1975)

Debris Flows Caused by Eroding of River-bed Sediments by Run-off

Some debris flows are generated by the eroding of river-bed sediments by run-off. Takahashi, T (1978, 1980) advanced Bagnold's (1954, 1956 & 1973) dilatant fluid concept (dispersion of large solid spheres) and proposed two equations which give the critical slope angle for the occurrence of massive debris transport. Debris flows occur under one of three conditions ;

$$\tan \theta \geq \frac{C_*(\sigma - \rho)}{C_*(\sigma - \rho) + \rho} \tan \phi \quad (\text{as Bagnold, 1954, 1973) Eqn. 2}$$

$$\tan \theta \geq \frac{F_0}{F_1} \left(1 + \frac{C}{k F_0 g h_0} \right) \times \frac{(1 - C^2 k^{-2} F_1^{-2} g^{-2} h_0^{-2} + F_0^2 F_1^{-2})^{0.5}}{(1 - C^2 k^{-2} F_1^{-2} g^{-2} h_0^{-2})} \quad \text{Eqn. 3}$$

$$\tan \theta \geq \frac{F_0}{F_2} \left(1 + \frac{C}{k F_0 g a_l} \right) \times \frac{(1 - C^2 F_2^{-2} g^{-2} a_l^{-2} + F_0^2 F_2^{-2})^{0.5}}{(1 - C^2 F_2^{-2} g^{-2} a_l^{-2})} \quad \text{Eqn. 4}$$

where

$$F_0 = C_*(\sigma - \rho) \tan \phi$$

$$F_1 = C_*(\sigma - \rho) + \rho(1 - k^{-1})$$

$$F_2 = C_*(\sigma - \rho) + \rho(1 + h_0 a_l^{-1})$$

C_* = grain concentration by volume in stationary bed.(=0.65)

C = cohesive strength in the debris accumulation

g = gravity acceleration

θ = slope of the debris accumulation

ϕ = internal friction angle in the debris accumulation

a_l = depth measured from surface of bed

h_0 = height of run-off water

σ = density of gravel or boulders

ρ = density of water contained with clay or silt

k = constant (≈ 0.7), $a_l = k h_0$

He carried out a case study (1981) using his equations on the Horadani debris flow in Japan, of 1979 and produced a fairly reasonable results, even though, he used many assumptions for this analysis.

2.2 Analysis of Flows

Introduction

Observations from moving debris flows, debris flow deposits and many experiments have disclosed that debris flows include a variety of unsorted materials and are characteristically longitudinally well graded. Some debris flows have snouts in their frontal part. Since debris flows contain heavy coarse materials, sand, silt and clay in water, they exhibit the property of strength, have high apparent viscosities, have high bulk densities and may flow in either a laminar or a turbulent fashion.

The properties of such highly concentrated dispersions lie between these of Newtonian fluids and those that offer considerable resistance to shearing forces before they flow. (Fisher, R.V., 1971) The analysis of debris flows has been carried out by the following models.

- 1) Newtonian fluid
- 2) Bingham fluid
- 3) Pseudo-plastic fluid
- 4) Quasi-plastic fluid
- 5) Coulomb-viscous model
- 6) Bangnold's model

Newtonian Fluid

The linear viscosity or Newtonian model can be represented in one demension by an equation of the form.

$$\sigma_s = \eta \frac{d\epsilon_s}{dt} \quad \text{Eqn. 5}$$

where η is the coefficient of viscosity, ϵ_s is strain, and t is time. Newtonian fluids have no strength, and the the ratio between the rate of applied strain and the amount of stress is a constant, equal to the coefficient of viscosity. Pure water is a Newtonian fluid.

Gol' din, B.M. and Lyubashevskiy, L.S., 1961 computed the velocity of mudflows by Chezy's formula

$$V = C \sqrt{Ri} \quad \text{Eqn. 6}$$

where R is the hydraulic radius, i is slope, and C is the roughness coefficient, computed by the Manning formula

$$C = \frac{1}{n} R^{\frac{1}{6}} \quad \text{Eqn. 7}$$

Other Soviet authors, Shamov, G.I. and Sribniy proposed the following equations respectively

$$V = 3.15 H^{\frac{1}{6}} d^{\frac{1}{3}} \sqrt{\frac{\gamma_s - \gamma_m}{\gamma_m}} \quad \text{Eqn. 8}$$

$$V = \frac{6.5 H^{\frac{2}{3}} i^{\frac{1}{4}}}{(\phi r_s + i)^{\frac{1}{2}}} \quad \text{Eqn. 9}$$

Where V is the average velocity of the flow (m/sec), d is the diameter of a rock in the sediment (m), H is the average depth of the flow (m), i is the gradient of the flow, γ_s is the specific weight of the rock, γ_m is the specific weight of the mud and rock mass, and ϕ is the ratio of the volume of sediment in a solid body to the water volume, i.e.

$$\phi = \frac{\gamma_m - 1}{\gamma_s - \gamma_m}$$

Considering that $r_s = 2.6$ and $r_m = 1.8$, in the computations it was assumed that

$$\sqrt{\frac{\gamma_s - \gamma_m}{\gamma_m}} = 1.0$$

Then the working formulas of Shamov, G.I. and Sribniy, M.F. will be respectively,

$$V = 3.15 H^{\frac{1}{6}} d^{\frac{1}{3}} \quad \text{Eqn. 10}$$

$$V = 5.15 H^{\frac{2}{3}} i^{\frac{1}{4}} \quad \text{Eqn. 11}$$

As a result of their examination, 3 equations were used for predicting the velocity of mudflows in Crimea. They suggested that Schamov's equation is sufficiently accurate for computation of the velocities of mudflows with coarse rock material and Sribniy's equation is applicable for computing the velocities of mudflows in the absence of coarse rock material.

Nevertheless, the Shamov's equation is not adequate generally, because the slope of river bed is neglected in the equation.

The velocity profile of a Newtonian fluid in a circular channel is (e.g. Johnson, 1970)

$$\dot{\omega} = \frac{R^2 - r^2}{4\eta} \gamma \sin \delta \quad \text{Eqn. 12}$$

where $\dot{\omega}$ = velocity of small flow element

R = radius of circular channel

r = radius of small flow element

η = the coefficient of viscosity

γ = the unit weight of the material

δ = slope angle of channel

Bingham Fluid

Bingham combined plasticity and viscosity models in such a way that the behavior of the combination is similar to that of a dashpot and a friction block in parallel. The equations

$$\sigma_s = K + \eta_b \dot{\epsilon}_s \quad \text{Eqn. 13}$$

$$\dot{\epsilon}_s = 0$$

define the Bingham model, where σ_s is shear stress, η_b is the coefficient of viscosity, $\dot{\epsilon}_s$ is rate of shear strain, and K is the yield strength.

A Bingham plastic exhibits strength and does not flow until its yield strength is exceeded, but its viscosity is constant once flow begins.

Jhonson, A.M., 1970 proposed the use of the Bingham model for the analysis of debris flows. He adopted the semicircular channel as being most nearly suited the determination of the properties of slurries in experiments and analysis.

The rheological model for a Bingham substance flowing in a circular channel is

$$|\sigma_s| = K + \eta_b \frac{d\dot{\omega}}{dr} \quad : (|\sigma_s| \geq K) \quad \text{Eqn. 14}$$

$$(\tau = \tau_o + \eta \cdot \dot{\gamma})$$

where $\sigma_s = \tau$ = shear stress

$K = \tau_o$ = yield stress of slurry

$\eta_b = \eta$ = the coefficient of viscosity

$\dot{\omega}$ = velocity of small flow element

r = radius of small flow element

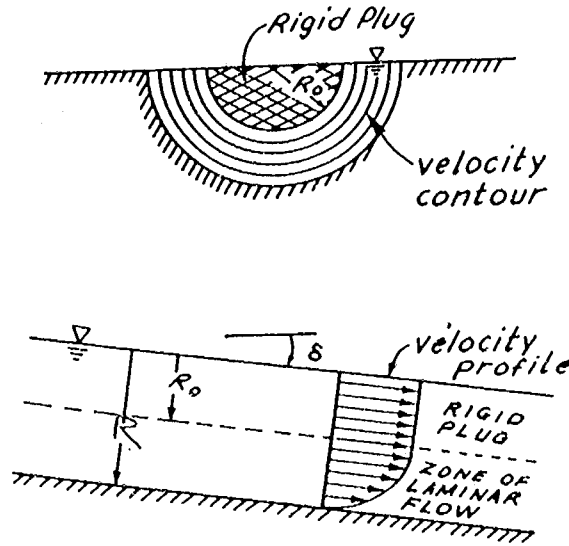


Figure 3. Velocity distribution of Bingham substance flowing in circular channel.
A. Cross-section.
B. Longitudinal section. (After Johnson, 1970)

$$\frac{d\dot{\omega}}{dr} = \dot{\gamma} = \text{shear rate}$$

He derived the velocity distribution in a circular channel.

$$\dot{\omega} = \frac{1}{\eta_b} \left(\frac{R^2 - r^2}{4} \gamma \sin \delta - (R - r)K \right) ; \quad (r \geq R_0)$$

$$\left(V = \frac{1}{\eta} \left[\frac{H^2}{2^2} \gamma \sin \alpha - \tau_o H \right] \right) \quad \text{Eqn. 15}$$

There is an $r^2(H^2)$ term in the above equation so that the velocity distribution is parabolic in form, as is shown on Fig. 3.

The radius of the plug of material which is rigid is given by

$$R_0 = \frac{2K}{\gamma \sin \alpha} \quad \text{Eqn. 16}$$

The velocity of the "plug" can be determined by substituting Eqn. 16 into the equation for the velocity distribution Eqn. 15.

Yano and Daido, 1964 obtained flow curves for clay slurries by a viscometer and applied both the Bingham and pseudo-plastic analysis successfully to laboratory flume experiments. They also formulized the open channel flow equations by deriving expressions for the mean flow velocity for Bingham flow.

$$V = \frac{H\tau_o}{\eta} \frac{a^2 \left(1 - \frac{a}{3} \right)}{2(1-a)} \quad \text{Eqn. 17}$$

where

$$a = 1 - \frac{\tau_o}{\gamma H \sin \alpha}$$

Then they derive resistance coefficients and modified Reynold's numbers and present resistance charts for both laminar and smooth-turbulent flow on their pipe flow experiments.

Pseudo-plastic Fluid

Pseudo-plastic fluids do not have strength, but unlike Newtonian fluids, they display variable viscosities depending upon the rate at which shear is applied.

The rheological equation of a pseudo-plastic fluid is

$$\sigma_s = \left(\frac{1}{A} \dot{\epsilon}_s \right)^{\frac{1}{n}} \quad \text{Eqn. 18}$$

$$[\tau = (\eta \dot{\gamma})^{\frac{1}{n}}]$$

where $\sigma_s = \tau$ = the applied shear stress

$\frac{1}{A} = \eta$ = variable viscosities

$\dot{\epsilon}_s = \dot{\gamma}$ = the rate of shear

Johnson, 1970 derived equations of velocity profile for the flow of pseudo-plastic substances.

$$\omega = \frac{A[(\gamma \sin \delta / 2)]^n}{n+1} [R^{(n+1)} - r^{(n+1)}] \quad \text{Eqn. 19}$$

$$V = \frac{(\gamma \sin \alpha)^n}{\eta (n+1) 2^n} H^{n+1} \quad \text{Eqn. 20}$$

If $n = 1$ and $A = 1/\eta$, eq. 19 reduces to the equation for velocities of a Newtonian substance, eq. 12. In other words the Newtonian model is a special case of the pseudo-plastic model.

Yano and Daido, 1965 proposed an equation by deriving expression for the mean flow velocity for the pseudo-plastic

$$V = \frac{r H^2 \sin \alpha}{(n+2) \eta} \quad \text{Eqn. 21}$$

Quasi-plastic Fluid

Hooke, R.L., 1967 proposed that debris flows behaved as quasi-plastic substances. The response of a quasi-plastic fluid to an applied stress can be represented by

$$\tau - \tau_o = \mu(\tau) \frac{du}{dy} \quad ; [\tau \geq \tau_o] \quad \text{Eqn. 22}$$

where τ = an applied stress

τ_o = the yield strength

$\mu(\tau)$ = the apparent viscosity and μ is a function of the applied stress

$\frac{du}{dy}$ = the rate of shear

A quasi-plastic fluid exhibits intermediate behavior of Bingham fluid and Pseudo-plastic fluid, i.e., it has a yield strength and viscosity values that vary with the rate of shear.

Coulomb-viscous Model

The Bingham model has been modified by the introduction of an apparent Coulomb friction (Morgenstern, 1967; Johnson, 1970; Hampton, M.A., 1972). The Coulomb-viscous

model is a combination of the Coulomb equation, $C + \sigma_n \tan \phi$, and the Newtonian viscous model, $\eta \dot{\epsilon}_s$, and is analogous to the Bingham model, so that

$$\left. \begin{aligned} \tau_s &= C + \sigma_n \tan \phi + \eta \dot{\epsilon}_s & : \tau_s \geq C + \sigma_n \tan \phi \\ \dot{\epsilon}_s &= 0 & : \tau_s \leq C + \sigma_n \tan \phi \end{aligned} \right\} \quad \text{Eqns. 23}$$

where τ_s is shear stress, C is cohesion, σ_n is normal stress, ϕ is angle of internal friction, η is viscosity, and $\dot{\epsilon}_s$ is rate of shear strain. The Coulomb-viscous model and the Bingham model are known generally as plastico-viscous rheological models.

Bagnold's model

Bagnold published in 1954 a study on the behavior of flowing granular materials in Newtonian fluids to investigate the character of the transitional region of the Newtonian viscous behaviour of dispersions of particles at very low concentration and the frictional (Coulomb) behaviour of granular material at high concentration. His experiments were essentially coaxial cylinder viscometer tests on dispersion of solid spheres in liquid. The presence of solid spheres particles in the water really did create normal stress, which he called the dispersive pressure, P , on the surface of the inner cylinder during motion. The presence of solid particles was also manifested by a shear stress, T , called grain shear stress, additional to the fluid drag. This shear stress was related to the dispersive pressure by a ratio.

$$\frac{T}{P} = \tan \alpha \quad \text{Eqn. 24}$$

which was found approximately constant at 0.32 in the fully inertial range, i.e. at high concentrations and velocities ($N > 450$), and at 0.75 in the viscous region ($N < 40$). At the transition region the ratio $T/P = \tan \alpha$ changed gradually from 0.32 to 0.75 (Fig.4). The $\tan \alpha$ is the dynamic analogue of the static friction coefficient (Bagnold, 1956) or the residual angle after shearing, ϕ_r , more commonly termed the angle of repose (Bagnold, 1966).

The linear grain concentration λ is defined by Bagnold as the ratio of grain diameter to the mean free dispersion $= D/S$ and is related to C by

$$\lambda = \frac{1}{(C_o/C)^{\frac{1}{3}} - 1} \quad \text{Eqn. 25}$$

where C_o is the maximum possible static volume concentration (0.74) and C is the volume concentration, i.e. the ratio of the grain-occupied space to the whole space.

Both the stresses T and P were found to increase with the square of the linear concentration, λ , particle diameter, D , and the shear strain rate, $\frac{dU}{dy}$, at high test velocities. At lower velocities the square dependence on the strain rate gradually changed towards a linear one.

These relations give

$$T = P \tan \alpha \propto \sigma (\lambda D)^2 \left(\frac{dU}{dy} \right)^2 \quad \text{Eqn. 26}$$

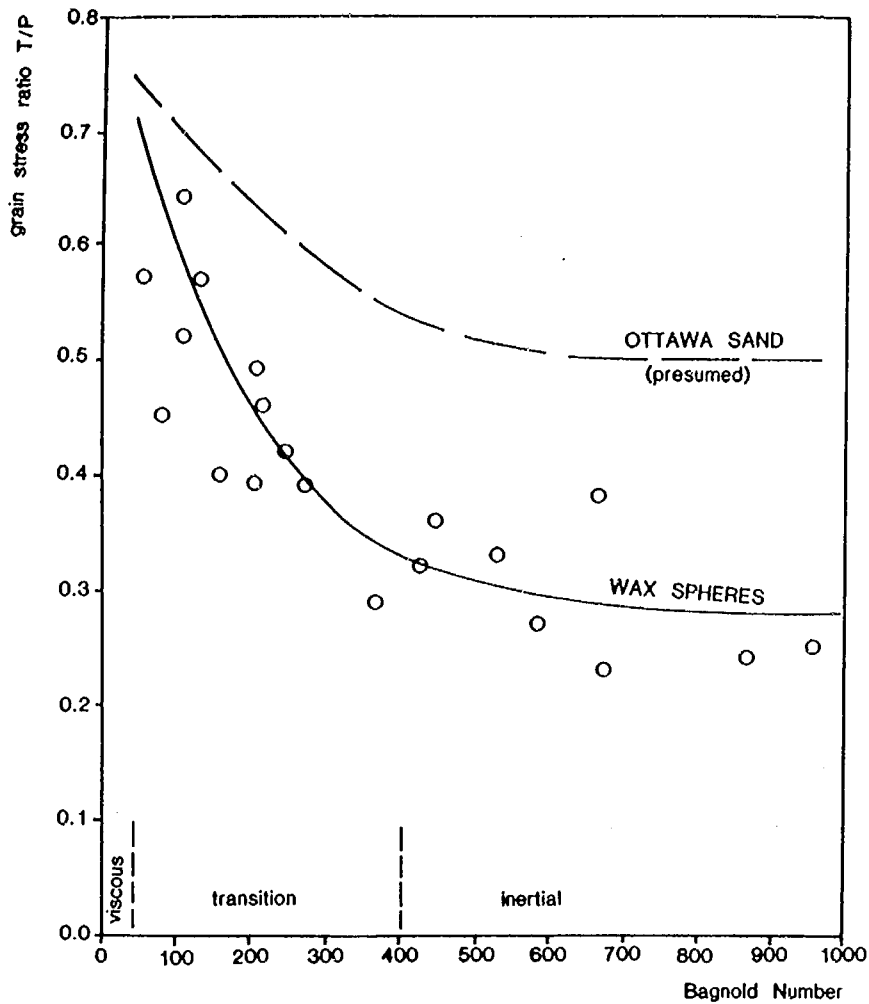


Figure 4. Change of the grain stress ratio (friction coefficient) in the transitional regime
(After Hangr, 1981)

and

$$T = P \tan \phi \propto \lambda^{\frac{3}{2}} \eta \left(\frac{dU}{dy} \right) \quad \text{Eqn. 27}$$

according to whether $\frac{dU}{dy}$ is large or small, i.e. according to whether grain inertia or fluid viscosity dominate, where ρ is the particle density and η is the fluid viscosity.

In attempt to evaluate the relative influence of hydrodynamic and mechanical forces, Bagnold defined a dimensionless number analogous to Reynold's number, equal to the ratio of the inertial stress to viscous stress. The dimensionless number N (later called Bagnold number by some authors) equals

$$N = \frac{\lambda^{\frac{1}{2}} \sigma D^2 dU/dy}{\eta} = \frac{\text{inertia stress}}{\text{viscous stress}} \quad \text{Eqn. 28}$$

in terms of N , the transition from inertia to viscous conditions is seen from Figure 4 to occupy the range from 450 to 40 approx.

For the viscous region he made a more precise measurements of the relation between the whole shear stress, T , and λ , and found the semi-empirical expression.

$$T = (1+\lambda)(1+\frac{1}{2}\lambda)\eta\frac{dU}{dy} \quad \text{Eqn. 29}$$

Bagnold (1954) applied his dispersive stress concept to a dry sand flow. The applied shear stress $T = T$ on any plane y below the upper, free, surface of the sand is $\sigma g \sin\beta \int_y^0 C dy$, where β is the slope angle in the inertia region.

$$T = a_i \sigma \lambda^2 D^2 \left(\frac{dU}{dy} \right)^2 \sin\alpha = \sigma g \sin\beta \int_y^0 C dy \quad \text{Eqn. 30}$$

He assumed the linear grain concentration $\lambda=17$ corresponding $C=0.6$, which is constant with depth. He took $a_i \sin\alpha$ as 0.076 from his the results of the rotating drum experiments. Then he got the velocity profile equation.

$$U = 0.11 \sqrt{g \sin\beta} \frac{y'^{\frac{3}{2}}}{D} \quad \text{Eqn. 31}$$

where y' is measured upwards from the bed. The boundary condition used in the integration is zero bed slip.

Flume experiments were carried out using by a fairly uniform quartz sand of mean grain diameter 0.035mm. The calculated velocities are 50% larger than the measured ones.

Bagnold also applied his dispersive stress concept to a mud flow (debris flow) (1967). The boundary condition used in the investigation is a highly uniform concentration of solids in a liquid which cannot escape, and a zero relative flow or slip between the liquid and the solid. He used the energy conservation law with the unity efficiency per unit bed area.

$$\text{The power supply} = hgS\bar{u}\{\rho' + c(\sigma - \rho')\} \quad \text{Eqn. 32}$$

$$\text{The rate of work done in pushing the bed-load}$$

$$= Ch\bar{u}(\sigma - \rho')g \tan\phi \quad \text{Eqn. 33}$$

, where C is the uniform concentration, h is the depth of the flow, $\bar{u}$ is the common mean flow velocity, S is the slope, σ is the density of bed-load, and ρ' is the density of the fluid. If the power supply $>$ the rate of work, the flow will be maintained, then

$$S > \frac{C \tan\phi}{C + \{\rho' / (\sigma - \rho')\}} \quad \text{Eqn. 34}$$

, which gives the limiting slope needed.

This relation is the same one which was found by the Bagnold in 1954. He rearranged this condition (1973) as for the criterion that the bed remains rigid at the bed slope β , thus becoming

$$\tan\beta < \frac{C_*(\sigma - \rho)}{C_*(\sigma - \rho) + \rho} \tan\alpha \quad \text{Eqn. 35}$$

where $\tan\alpha$ = mean friction coefficient for intermittent contact during saltation.

σ = density of solid.

ρ = density of fluid.

C_* = constant volume concentration of solids with in the bed.

Breitfuss and Scheidegger (1974) proposed a model of Alpine debris flows based on the notion of dispersive pressure occurring in shear flows introduced by Bagnold. They combined Bagnold's dispersive stress equations, the shearing stress, T , and the underwater pressure W of the grains due to gravitational forces. Thus, motion is possible as given by the equation.

$$\frac{T}{P} = \tan \alpha = \frac{G}{W} = \frac{\rho + (\sigma - \rho)C}{(\sigma - \rho)C} \tan \beta \quad \text{Eqn. 36}$$

He set the shearing stress T equal to G , so that in the inertial regime

$$T = 0.0128 \sigma (\lambda D)^2 \left(\frac{dU}{dy} \right)^2 = [\rho + (\sigma - \rho)C] g (h - y) \sin \beta = G \quad \text{Eqn. 37}$$

Upon rearranging and integrated this becomes

$$U = 0.0533 \frac{\sqrt{g}}{D} \frac{2}{3} h^{\frac{3}{2}} \quad \text{Eqn. 38}$$

He checked the flow regime by using the macro-viscous equation, and concluded that the inertia flow regime was indeed realized over (almost) the whole depth of the flow.

Takahashi (1978) presented a number of equations for explaining the mechanism of occurrence, propagation and motion of debris flows using Bagnold's dilatancy (dispersive stress) concept. These were checked by experiments.

He obtained the velocity distribution of debris flows in the same manner as Breitfuss and Scheidegger (1974).

$$U = \frac{2}{5D} \left\{ \frac{g \sin \beta}{a_i \sin \alpha} \left[C_d + (1 - C_d) \frac{\rho}{\sigma} \right] \right\}^{\frac{1}{2}} \left[\left(\frac{C_*}{C_d} \right)^{\frac{1}{3}} - 1 \right] h^{\frac{3}{2}} \quad \text{Eqn. 39}$$

where C_d = grain concentration in debris flow.
 C_* = grain concentration in stationary bed.
 α = friction angle in moving grains.
 β = surface slope of debris flow.

The propagation velocity with the discharge of water supplied from the upstream is

$$\frac{\left(\frac{U}{\sqrt{gD}} \right)^{0.3}}{\left(\frac{q_o}{gD^3} \right)} = \frac{0.693 \sin^{0.2} \beta \left[\left(\frac{C_*}{C_d} \right)^{\frac{1}{3}} - 1 \right]^{0.4} \left[C_d + (1 - C_d) \frac{\rho}{\sigma} \right]^{0.2}}{(a_i \sin \alpha)^{0.2} \left\{ 1 - \frac{[S + (1 - S)C_*]C_d}{C_*} \right\}^{0.6}} \quad \text{Eqn. 40}$$

He supposed some debris flows are generated by the eroding river-bed sediment by surface-flow. He classified beds, which are constituted by uniform layers of loose granular materials, into two types; stationary beds on which the bed material is eroded partially from the upper layer and nonstationary beds on which the whole bed material moves immediately in the critical condition.

On the stationary bed, the front height of a debris flow is given by the equation

$$\frac{h}{h_o} = \frac{U}{U_o} \frac{C_*}{C_* - [S + (1-S)C_*]C_{d\infty} + \left(\frac{h_o}{D}\right)C_{d\infty}\left(\frac{1-U_o}{U}\right)} \quad \text{Eqn. 41}$$

,where h = depth of debris flow.
 h_o = depth of supplied water.
 U_o = imaginary water flow velocity.
 S = degree of saturation in bed in advance to arrival of bore.
 $C_{d\infty}$ = grain concentration in quasi-steady bore front.

On the nonstationary bed,

$$\left. \begin{aligned} h &= \left[2\tan(\theta-r)Bt + \frac{B^2}{U^2} \right]^{\frac{1}{2}} + h_o \\ h &= \left[2\tan(\theta-r)\left(\frac{B}{U}\right)x + \frac{B^2}{U^2} \right]^{\frac{1}{2}} + h_o \end{aligned} \right\} \quad \text{Eqns. 42}$$

where $B = [S + (1-S)C_*]DU + h_o(U_o - U)$
 θ = slope angle of debris bed.
 r = surface slope of nonstationary bed flow.
 t = time.
 x = direction of flow.

Flume experiments were carried out using uniform saturated gravel beds, and the results were in fair agreement with his theoretical results.

Takahashi (1980) proposed equations which give the discharge of a debris flow, Q_T and the grain concentration of debris flow, C_d .

$$Q_T = \frac{C_*}{C_* - C_d} Q \quad \text{Eqn. 43}$$

$$C_d = \frac{\rho \tan \theta}{(\sigma - \rho)(\tan \phi - \tan \theta)} \quad \text{Eqn. 44}$$

where, Q is the water discharge in the debris flow.

Although Bagnold's dispersive stress concept is useful in the analysis of debris flow mechanisms, and many author have used the concept, several problems remain, there may be some fundamental differences between the experiments of Bagnold and natural debris flows. It is unlikely that the particles used by Bagnold, composed of a paraffin and lead stearate mixture, possess the same elastic properties as the rigid quartz and feldspar grains making up most natural sediments. Because the relationship between tangential grain shear stress and grain dispersive pressure is depend on the elastic properties of dispersed solids, $\tan \alpha$ can be expected to vary with grain composition. But Lowe (1976) suggested that the effects of grain composition will be especially significant in dry grain flow, but will tend to disappear in fully viscous dispersions in which the grains interact through a finite thickness of fluid like a debris flow.

In the Bagnold's experiments the grain-fluid mixtures were confined within an annular space of nearly constant volume and the particles were gravity-free for same density of the

interstitial fluid. But natural flows are neither fully confined, nor gravity-free and their characteristics and dynamics differ significantly from his experimental systems (Lowe 1976).

Most of authors (Bagnold, 1954, 1967 ; Breiffuss and Schedegger, 1974 ; Takahashi, 1978) use the boundary condition that λ and D are constant through the flow thickness. But in natural debris flows, solids are sorted longitudinally and inverse grading is occasionally observed, therefore these boundary condition may be in error.

Middleton and Hampton (1976) distinguished debris flow from grain flow. They emphasize that the dispersive stress due to direct grain interaction plays an important role only in the case of grains flow, and that in the case of debris flow, the grains are supported by the matrix strength. The viscosity of the interstitial fluid determines their hydraulic behavior, which means that the dilatant fluid model may be applied to grain flow and the Bingham fluid model may be applied to debris flow. They further claim that only a slight amount of clay in the interstitial fluid will drastically influence grain flow and convert it into debris flow.

Lowe (1976) also suggested that if the clay content of the interstitial fluid exceeds a few percent, the mixture becomes plastic and can no longer be called as a fluid.

Takahashi (1980) calculated the fully-internal flow condition based on the grain-slurry mixture flow, and maintained that the effects of clay are minor and consequently debris flows may be regarded as dilatant flows.

2.3 Accumulation of Debris.

Introduction.

Many eyewitnesses of debris flows described the flow as having a "snout", or boulder accumulation at the distal end followed by a slurry-like muddy water flow. (e.g. Sharp and Nobles, 1953).

"Inverse grading", in which the sequence of grain sizes are from finer particles at the bottom to coarser ones in the upper part of the flow, was observed by a few authors in the deposits of certain subaerial debris flows (Fisher, 1971 ; Mears, 1979). Most other authors have not described nor denied the existence of inverse grading in the deposits of other subaerial debris flows (Fryxell and Horberg, 1943 ; Sharp and Nobles, 1953 ; Curry, 1966 ; Johnson and Rahn, 1970 ; Morton and Campbell, 1974 ; and Pierson, 1980). It can be reasonably stated that inverse grading is not an essential characteristic of subaerial debris flows. A few writers have proposed several hypotheses for explaining inverse grading and frontal accumulations.

- (1) Bagnold's dispersive pressure (Bagnold, 1954 ; Sanders, 1965 ; and Takahashi, 1980).
- (2) Lift force (Fisher and Mattinson, 1968 ; Mattinson and Fisher, 1970 ; and Southard, 1971).
- (3) Kinetic sieve mechanism (Middleton and Hampton, 1976).
- (4) Buoyancy in grain mixture. (Rodine and Johnson, 1976).

Bagnold's Dispersive Pressure

Bagnold (1954) proposed a hypothesis using his dispersive pressure concept for the observed inverse sorting in dry sand flows with mixed-sized grains. Since the dispersive

pressure P should vary as D^2 , grain diameter, for a given shear stress dU/dy , the larger grains should tend to drift towards the zone of least shear, e.g. towards the free surface of a gravity flow, and the smaller grains towards that of greatest shear, i.e. the bed.

Sanders (1965) suggested a mechanism for inverse grading and frontal accumulation of boulders by using Bagnold's inertia grain flows concept.

In inertia-type flow the larger particles tend to move not only towards the top of the flow, but also towards the front of the flow.

Takahashi (1980) applied Bagnold's dilatant fluid concept to the analysis of the mechanics of debris flows. He obtained a equation which gives a longitudinal profile of a snout as following.

$$h + h_{\infty} \ln \frac{|h - h_{\infty}|}{h_{\infty}} = \tan \theta \cdot X \quad \text{Eqn. 45}$$

$$h_{\infty} = \frac{kU^2}{g \sin \theta} \quad \text{Eqn. 46}$$

$$k = \frac{25a_i \sin \alpha}{4 \left[C_d + \left(1 - C_d \right) \frac{\rho}{\sigma} \right] \left[\left(\frac{C_*}{C_d} \right)^{\frac{1}{3}} - 1 \right]^2} \left(\frac{d}{h_{\infty}} \right)^2 \quad \text{Eqn. 47}$$

where h = depth of debris flow.
 h_{∞} = depth of steady debris flow.
 θ = slope angle of debris bed.
 X = distance referring to moving coordinates.
 U = cross-sectionial mean velocity.
 a_i = numerical coefficient.
 α = friction angle in moving grains.
 C_d = grain concentration by volume in debris flow.
 C_* = grain concentration by volume in stationary bed.
 ρ = density of water.
 σ = grain density.
 d = grain diameter.
 k = resistance coefficient.

He imagined the process of boulders accumulation at the front as follows. The larger particles move upwards in the debris and move faster ahead because velocities in the upper layers are faster than in the bottom layers. The larger particles reach the front of the flow, tumble down to the bottom of the flow and are buried in the flow. But soon after that, they appear again on the top of the flow and move ahead. The equation of motion of a particle of diameter d_m which is in steady uniform flow surrounded by spherical particles, of diameter d_m , assuming the mean inter-particle distances are all S , is;

$$\frac{\pi}{6} d_1^3 \left\{ \sigma + \frac{1}{2} (\sigma - \rho) C_d + \rho \right\} \frac{dv}{dt} = -F_1 + F_2 + F_3 - F_4 \quad \text{Eqn. 48}$$

where v = velocity of d_1 particle in the y direction.
 F_1 = y compornent of the submerged weight of d_1 .

$$= \frac{\pi}{6}(\sigma - \rho)gd_1^3 \cos \theta \quad \text{Eqn. 49}$$

F_2, F_3 = dispersive force resulting from the collisions of d_1 with the d_m particles which are one layer above and below respectively.

$$F_3 - F_2 = \frac{2\gamma}{1+\gamma} d_m^3 \frac{\left[\left(\frac{d_1}{2d_m} \right) + \left(\frac{1}{2} + \frac{1}{\lambda} \right) \right]^2 \left(\frac{d_1}{d_m} + \frac{1}{\lambda} \right)^3}{\left(1 + \frac{1}{\lambda} \right)^5} \frac{\pi}{6} (\sigma - \rho) g \cos \theta \quad \text{Eqn. 50}$$

F_3 = drag force.

$$= \frac{1}{2} C_D [(\sigma - \rho) C_d + \rho] \frac{\pi}{4} d_1 V |V| \quad \text{Eqn. 51}$$

V = d_1 velocity in y direction.

C_D = apparent drag coefficient.

Substituting Eqns. 49, 50 and 51 into Eqn. 48 and considering the boundary conditions, the asymptotic velocities are

$$\frac{V^2}{gd_m} = \left| \frac{k_1}{k_2} \right| = \frac{4}{3} \frac{1}{C_D} \frac{(\sigma - \rho) \cos \theta}{[(\sigma - \rho) C_d + \rho]} |k| \quad \text{Eqn. 52}$$

$$\text{in which } k = \gamma^{\frac{1}{3}} \left[\frac{2}{1+\gamma} \frac{(0.5\gamma^{\frac{1}{3}} + 0.5 + \lambda^{-1})^2 (\gamma^{\frac{1}{3}} + \lambda^{-1})^3}{(1 + \lambda^{-1})^5} - 1 \right] \quad \text{Eqn. 53}$$

and is k shown in Fig.5. According to this equation, the larger the d_1 particle than the d_m particle, the faster the upward velocity.

Experiments with (Z size) a grain mixture flow ($d_1 = 22\text{mm}$, $d_m = 5\text{mm}$, and $d_1 = 15\text{mm}$, $d_m = 5\text{mm}$) were carried out and the results agree fairly well with the theoretical results using his equations.

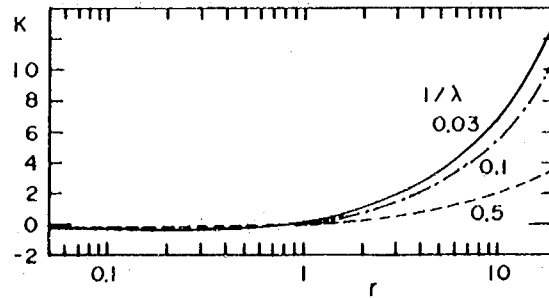


Figure 5. Variations of k versus γ (After Takahashi, 1980)

Lift Force

Fisher and Mattinson (1968) suggested that sediment particles carried in the boundary layer of a fluid flow will be acted upon by a net upward pressure due to the Bernoulli's principle, and the inverse grading is partly developed by the upward force. Southard (1970) showed that such a force is not possible. Mattinson and Fisher (1970) reiterated, however, that there is some kind of force, or forces, operating normal to the direction of flow. Such force is known from numerous experiments, and Southard called it a "lift force" (1971). Southard

(1971) tried to detect and measure the lift force on plastic spheres in laminar open-channel flow in a laboratory. The results suggest that the lift force effect is not important in natural sedimentary processes.

Kinetic Sieve Mechanism

Middleton and Hampton (1976) suggested that the inverse grading in grain flow deposits is product of a kinetic sieve mechanism where by small grains fall downward between large grains during flow, effectively displacing the large grains upwards.

Buoyancy in Grain Mixture

Rodine and Johnson (1976) suggested a mechanism for the transport of coarse clastic material and large isolated blocks in debris flows even on gentle slopes. They showed that clasts can comprise more than 95 % of the volume of debris without significant particle interlocking. The unit weight of the debris, composed of clay, water, and fine-grained particles is nearly equal to the average unit weight of the coarse blocks. Thus large blocks can be suspended by debris with low strength.

2.4 Deposition from Debris Flows

Introduction

Debris flow deposits have been studied by authors from many fields such as engineering, geology, sedimentology, and geomorphology in an effort to sort out their mechanism location, magnitude, shape, texture, and structure. Understanding the mechanism of debris flow deposition helps to avoid or minimize the loss of life and property in terms of landuse controls or evacuation procedures.

Deposits from debris flows are classified into two types, levee deposits and snout deposits. Johnson (1970) called them lateral and medial deposits respectively.

Deposition from a debris flow occurs not only by a decrease of the bed slope but also by an increase in the flow width. A decrease in the bed slope causes a decrease in the driving force of gravity. Increasing of the flow width brings about a lateral spreading of debris, consequently the depth of flow decreases and the resistance force acting along the surface of contact between the debris and the bed increases. When the driving force decreases below the resistance force (or the strength of debris), "freezing" of the debris occurs.

Only a few author have proposed quantitative analyses for the mechanisms of deposition, though many authors have described the process. Since mechanisms of deposition are strictly related to those of flow, the methods of the analysis of flow will be applied in this section.

Bingham Fluid

Johnson (1970) explained the mechanism of deposition from subaerial debris flows by using the Bingham model. He gave the shear stress distribution in a Bingham fluid in a rectangular channel, and pointed out theoretically the existence of a "plug" and "dead regions". These are certain regions of non-deformation, where the applied stress is less than the strength of the fluid. Further, he applied the solution to debris flowing in a rectangular channel for the purpose of explaining the mechanism of deposition.

The plug in the central portion of the flow plays an important role in movement and deposition. The thickness of the plug varies directly with the strength of the material and inversely with the density and slope angle. When a debris flow reaches the apex of the fan, the slope angle decreases rapidly, so that the thickness of the plug increases. When the thickness of the plug equals the thickness of the flow, the flow comes to a stop. This forms deposits in the center of channel, which are called medial deposits by Johnson.

He also explained the process forming lateral deposits, i.e. levees, in natural debris flow deposits, by using this result. When a debris flow moves down in a channel, the dead regions which exist along the edge of the channel remain at the same position as the lateral deposits.

Bagnold's model

Takahashi (1978, 1980, and 1981) applied Bagnold's dilatant fluid concept to the debris flows and proposed some equations for the deposition of debris. Debris flow will reduce the speed, if it reaches the transitional point where the slope angle of the bed, θ , is

$$\tan \theta \leq \frac{(\sigma - \rho)Cd}{(\sigma - \rho)Cd + \rho} \tan \alpha \quad \text{Eqn. 54}$$

, where σ = density of solid
 ρ = density of fluid
 Cd = volume concentration of debris
 α = friction angle in debris

After the debris flow pass the transitional point, the deposition of debris begins, and the distance between the point and the tip of deposition, X_L , is given by

$$X_L = \frac{V^2}{G} \quad \text{Eqn. 55}$$

$$V = U_u \cos(\theta_u - \theta) \left\{ 1 + \frac{[(\sigma - \rho)C_{du}K_a + \rho] \cos \theta_u}{2[(\sigma - \rho)C_{du} + \rho]} \frac{q_t h_u}{U_u^2} \right\} \quad \text{Eqn. 56}$$

$$G = \frac{(\sigma - \rho)gC_{du} \cos \theta \tan \alpha}{(\sigma - \rho)C_{du} + \rho} - g \sin \theta \quad \text{Eqn. 57}$$

, where U = velocity of debris flow
 K_a = coefficient
 q_t = total discharge of debris flow per unit width
 h = depth of debris flow

, and the suffix u means each parameters are observed in upper reach from the transitional point.

The slope angle of deposition, γ , is given by

$$\tan \gamma = \frac{C_*(\sigma - \rho) \tan \phi}{C_*(\sigma - \rho) + \rho \left[1 + 0.52 \left(\frac{q_t}{gd^3} \right)^{\frac{1}{3}} \right]} \quad \text{Eqn. 58}$$

where ϕ = internal friction angle of debris deposit
 d = grain diameter

He concluded after examination of the results of his experiments on the deposition of debris that the distance, x , is almost equal to the maximum width of the deposition (1980),

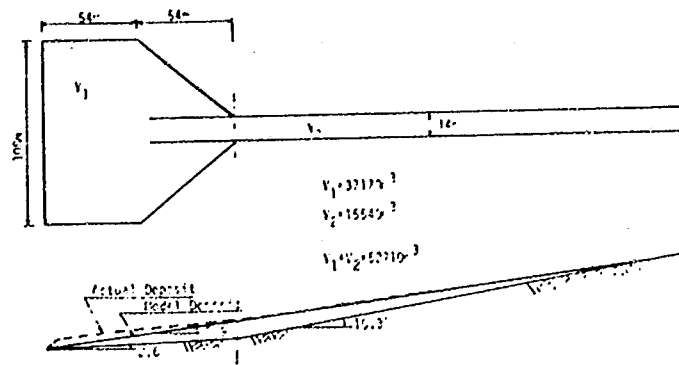


Figure 6. Modeled deposit of debris flow at the mouth of the Hora-dani. (After Takahashi, 1981)

and gave a model shape of deposits for the Hora-dani debris flow of Japan (1981) (Fig. 6).

Lévees

Lévees are often observed on actively forming alluvial slopes, large or small cones, or steep alluvium-floored canyons, and talus fans (Sharp, 1942 ; Sharp and Nobles, 1953 ; Curry, 1966 ; Broscoe and Thomson, 1969 ; Johnson, 1979 ; and Pierson, 1980). Most lévees are sharp linear ridges with steep flanks, and a narrow crest. They consist of boulders, sand, silt, and clay, though they look like bouldery deposit in appearance, and they are often well sorted (Pierson, 1980). Heights of lévees are range from a few inches to 10 feet (10cm—3m) (Sharp, 1942 ; and Curry, 1966). A typical slope face is at an angle of 32 degrees, which is essentially the same as the slope of the face of most moraines (Broscoe & Thomson, 1969).

The process of construction of lévees has been observed by several authors. Sharp (1942) and Curry (1966) explained the process as follows ; The muddy-fluid behind the bouldary surge front pushes up the side of the boulders to the top of the flow, and pushes around the side of the front. Pierson (1980) suggested another process, that is, cobbles and boulders are push outside of the flow by some internal sorting process.

2.5 Conclusions

Several models have been proposed and inspected by many researchers for the purpose analysing debris flow movements. Those models are : (1) Newtonian fluid, (2) Bingham fluid, (3) Psedo-plastic fluid, (4) Quasi-plastic fluid (5) Coulomb-viscous model, and (6) Bagnold's model. From these models, the Bingham fluid and Bagnold's model have been studied extensively by many researchers during this last two decades. Nevertheless, the fundamental questions of how to predict the magnitude, velocity, and reach of debris flow movements still have not been answered. Some models may be valid for certain types of debris flows. For example, flows with fine materials behave like a Newtonian fluid or Bingham fluid, depending on their water content. A saturated grain flow lacking fines could be analysed by using Bangnold's model. The difficulty of analysis of debris flow movements originates in the lack of fundamental studies on the behavior of debris materials and accepted methods for the generating of debris flow in the laboratory. Because debris flows contain heavily coarse materials, sand, silt and clay in water, and the debris materials are merely neither slurries nor mixtures of water and sand or gravel.

3. OBSERVATION OF DEBRIS FLOWS AT MT. YAKEDAKE, JAPAN

3.1 Introduction

Observations of debris flows which occur along the Kamikamihori Valley on the eastern slope of Mt. Yakedake (2458m) (Figure 7) in the Japan Alps have been made since 1971 by the Ministry of Construction in cooperation with the Disaster Prevention Research Institute, Kyoto University.

The debris flows originate in the upper part of the Kamikamihori Valley which is a 1,37 km² catchment area covered by quartzary andesite. Debris flows follow the course of the Kamikamihori Valley for a 2 km length and dump their debris on the alluvial fan where the valley meets the Azusa River.

The debris flows at Mt. Yakedake are triggered by heavy rainfall, and debris flow activity is very frequent. Mt. Yakedake is located near Kamikochi, a famous tourist resort in the mountainous National Park, so it is of easy access. These conditions give us rare sites for the observation of debris flows.



Figure 7. The Location of Mt. Yakedake

3.2 Observation Methods

The observation system has been altered year by year, with continuous improvements of the facilities and an extension of the observation area. Fig.8 shows an outline of the observation system in 1979.

Two types of sensors, "wire sensors" and "contact sensors", are used for purpose of transmitting electric signals from the observation system when the tips of debris flows reach the place where sensors are installed. The "wire sensor" sends a signal when the surge of a debris flow cuts down the wire stretched across the valley bed. The "contact sensor" does similar when the surge of a debris flow contacts the tip of the contact sensor hanging down in the valley. The time when a signal sent is recorded a printer, typing out the time (date,

hour, minute, and second) and the sensor's number.

3.3 Results of Observation

48 debris flows have been observed at Mt. Yakedake from 1970 to 1979, and the obtained information is shown in Table 4. The following results were gained in the analysis of this information.

Rainfall

The debris flows at Mt. Yakedake are triggered by heavy rainfall. Although a little snow remains on the slope of Mt. Yakedake in summer, rapid melting of snow is of no importance for the occurrence of debris flows. The relation between the occurrence of debris flows and rainfall intensity is summarized in Fig. 9 and Fig. 10. It appears that short-term rainfall, for example, a 10 minute rainfall, is more important than longterm rainfall for the occurrence of debris flows. But Pierson (1980) reported that the exceptionally long duration of steady rainfall was the key factor in triggering the debris flows at Mt. Thomas, North Canterbury, New Zealand.

Velocity of Surges

Surge front velocity is dependant on the slope of channel bed, the magnitude of debris flow, the density (grain distribution, water content) of debris, and longitudinal position along the channel (condition of channel bed). Several observed surge front velocities along the valley are shown in Fig. 11. The frequency distribution of surge front velocity is shown in Fig. 12. The velocity ranges from 1.0m/sec to 16.5m/sec, with a mean velocity of about 5m/sec.

The relationship between the maximum velocity and the depth of the snout is shown in Fig. 13. An empirical formula of $V=1.8h$ is obtained from this figure.

Density

The bulk density of several samples of debris is shown in Fig. 14. Samples were collected by setting two types of wide-mouth (12cm diameter and 30cm width) jars on a check dam. The mean density found was 1.71 gf/cm³.

Particle Size

The solid material in the debris fluid ranged from clay to boulders and was extremely poorly sorted. Since it is very difficult to sample coarse material (larger than 10cm diameter) in surges with jars, a photographic analysis method was used for the coarse material. The 35mm photographs of the debris flow of Sep. 4, 1978 were taken every 2 seconds as they passing over the check dam No. 6. The diameters of all particles larger than 10cm were measured and counted in 6 photographs. The cumulative distribution of particle size for coarse material is given in Fig. 15. Further, the areal proportions of matrix, fine material and water, were measured in 6 photographs. The particle size curve for coarse material was combined with that for fine material, which was sampled with jars, taking into account the ratio of coarse material to fine material. A composite cumulative particle size curve was

obtained by this way as shown on Figure 15.

From the composite curves, material collected from the surge of debris flow has an average (D_{50}) diameter of 30 cm. All the material represents a mixture of materials of three groups which are illustrated by three straight lines, a, b, and c, on Figure 15. The material is poorly sorted the standard deviation (σ_t) being 3.5ϕ . The result of comparing this curve to curves from other areas is shown on Figure 16. The Mt. Yakedake debris is coarser than most, although some of other curves were obtained by the analyses of muddy fluids samples without coarse materials.

Volume

The volumes of the debris flows were calculated by using the results from surveying on river-bed (Figure 17).

Impact Force

The impact forces of the debris flows were measured by "pressure mark gauges" (Figure 18) seated on a check dam wall or on large stones. The pressure mark gauge consists of an aluminium plate and a steel cone attached to a steel plate. When the debris flow collides with the steel plate, the sharp apex of the cone penetrates into the aluminium plate, consequently the size of the mark engraved on the plate indicates the impact force. The relations between impact stress measured by such a way and velocity, and maximum particle size are shown in Figure 19.

Vibration

The intensity of ground vibration caused by a travelling debris flow was measured by a pair of vibration gauges set beside the valley. Ground vibration data caused by the debris flow on Sept. 21, 1979 are shown in Figure 20. The arrow indicates the time the debris flow passing by the vibration gauges.

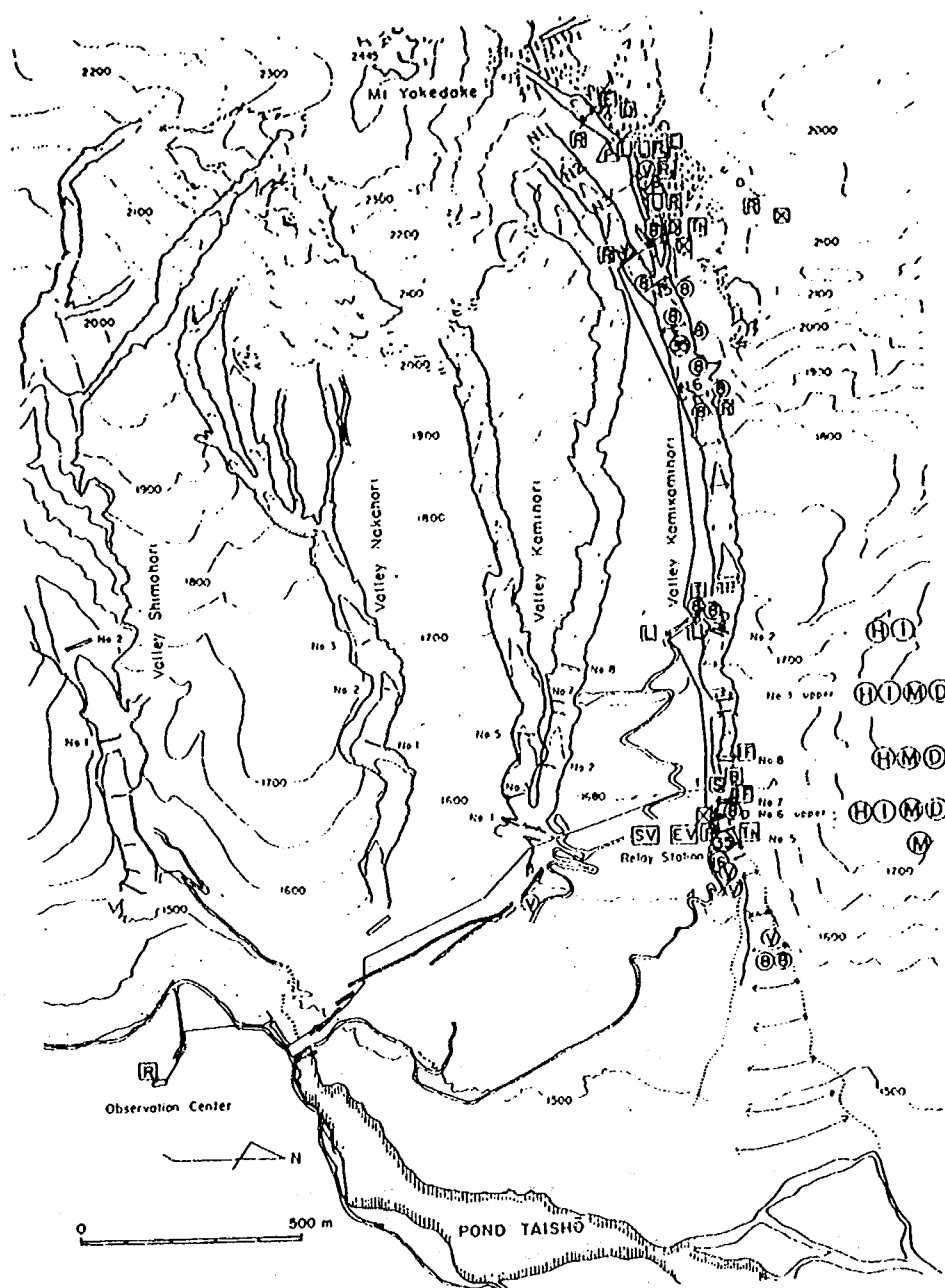


Figure 8. Observation system at the eastern slope of Mt. Yakedake [R] : rain gauge, [Rv] : vector rain gauge, [Rs] : rainfall intensity recorder, [D] : gauging weir, [P] : equipments for debris discharge, [L] : ground water level gauge, [Th] : thermometer, ↔ : wire sensor, I : contact sensor, [S] : seismometer, [IF] : pressure gauge for debris flow, [SV] : space filter speedometer, [EV] : radar speedometer, [T] : tension gauge, (35) : 35 mm interval shot camera, (16) : 16 mm cine camera, (8) : 8 mm cine camera, (8)_D : 8 mm interval shot camera, (V) : video camera, [H] : equipments for flow height, [I] : pressure mark gauge, [M] : mud sampler (cylinder), [D] : debris sampler (box) (After Matsumoto Sabo, 1980)

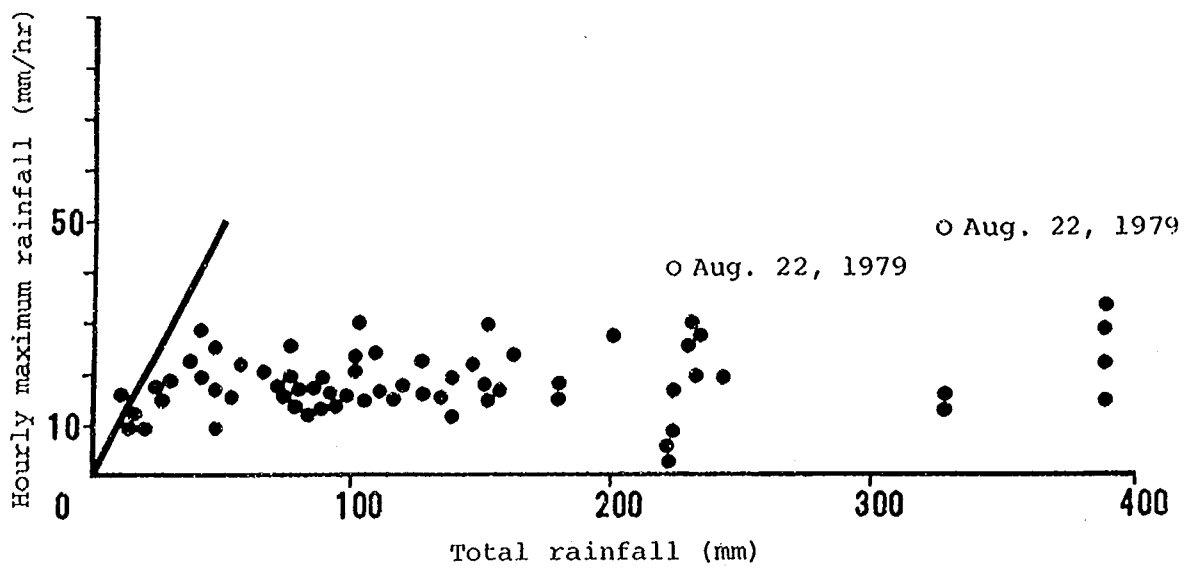


Figure 9. Relation between total rainfall and hourly maximum rainfall when debris flows occurred (After Matsumoto Sabo, 1980)

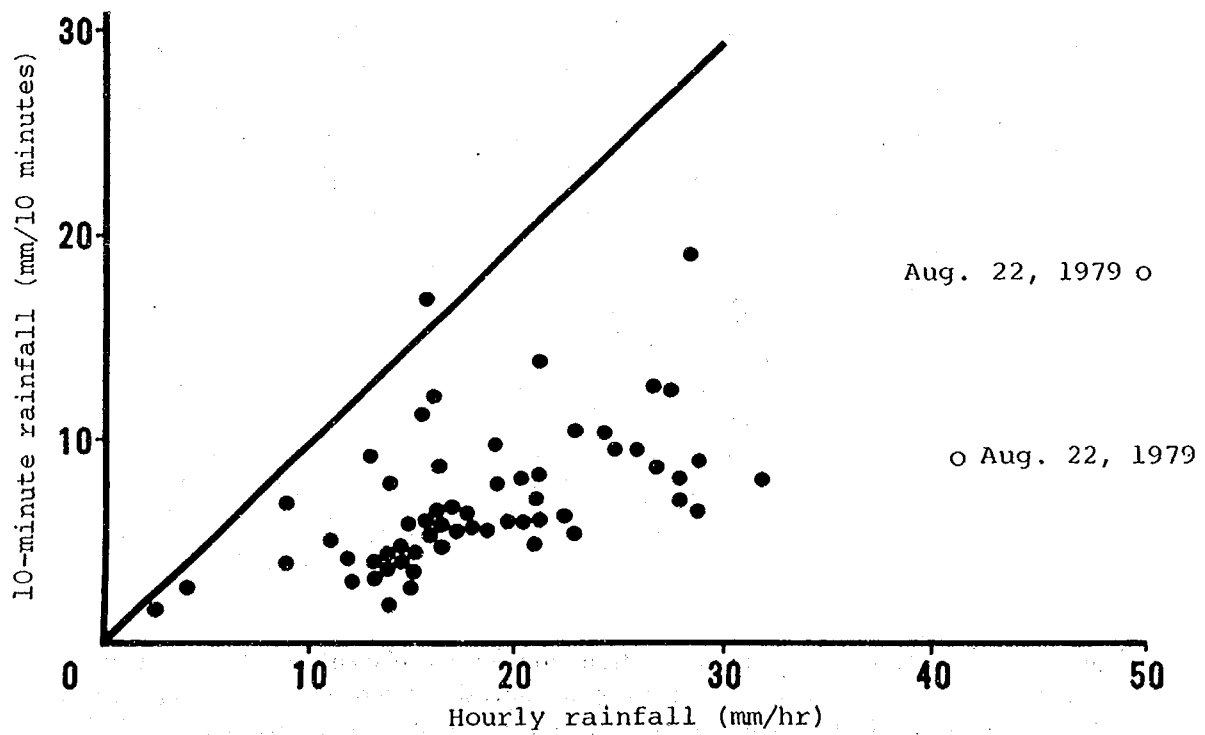


Figure 10. Hourly rainfall and 10-minute rainfall when debris flows occurred (After Matsumoto Sabo, 1980)

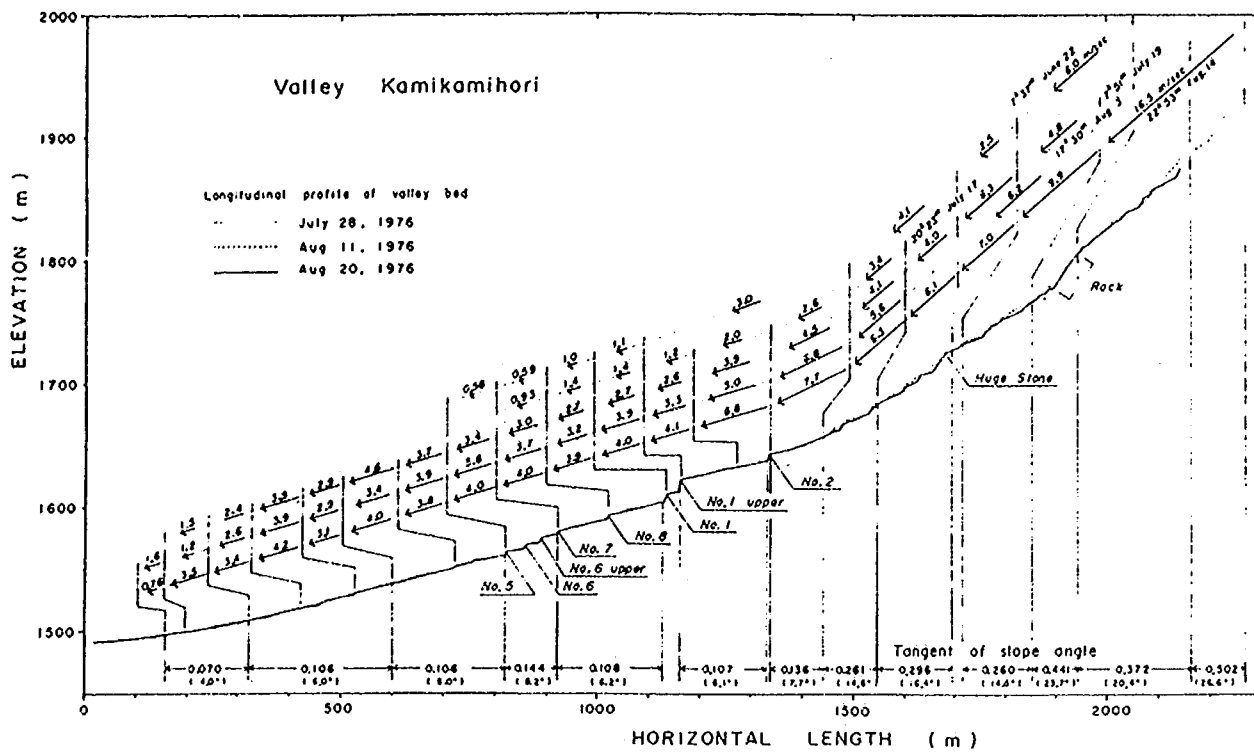


Figure 11. Surge front velocities of debris flows observed along Valley Kamikamihori in 1976 (in m/sec). (After Matsumoto Sabo, 1977)

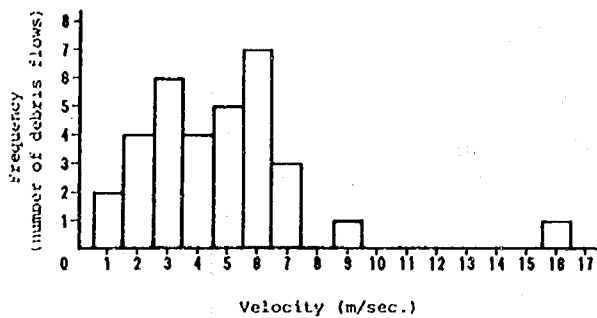


Figure 12. Surge front velocities (After Matsumoto Sabo, 1980)

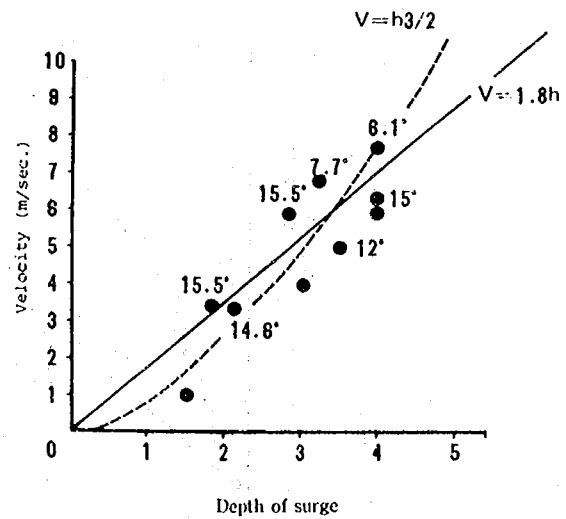


Figure 13. Relation between maximum velocity and depth of surge (After Matsumoto Sabo, 1980)

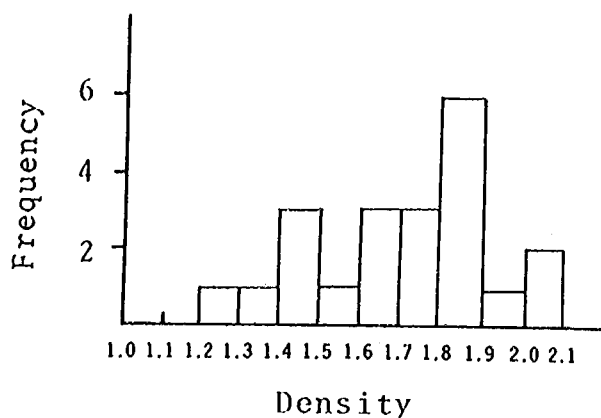


Figure 14. Density of debris flows which occurred from 1978 to 1980

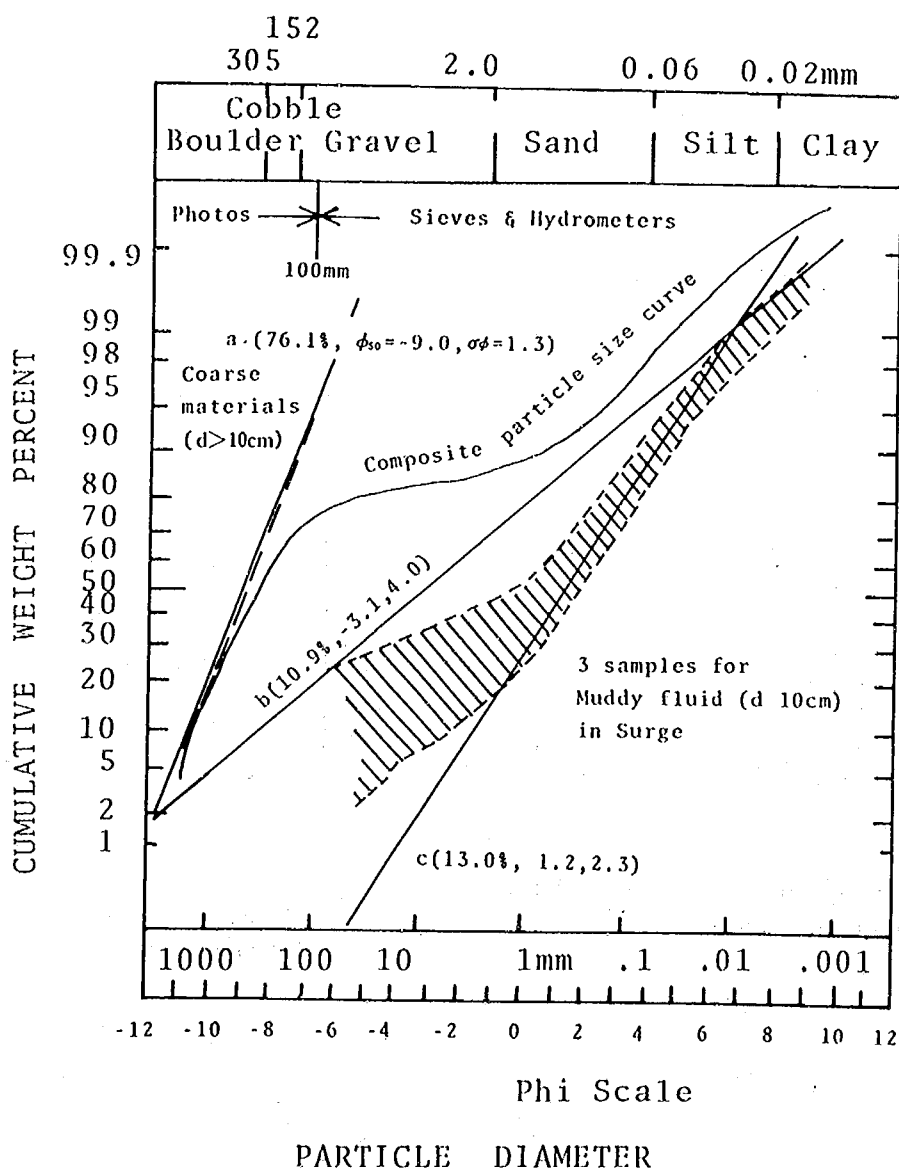
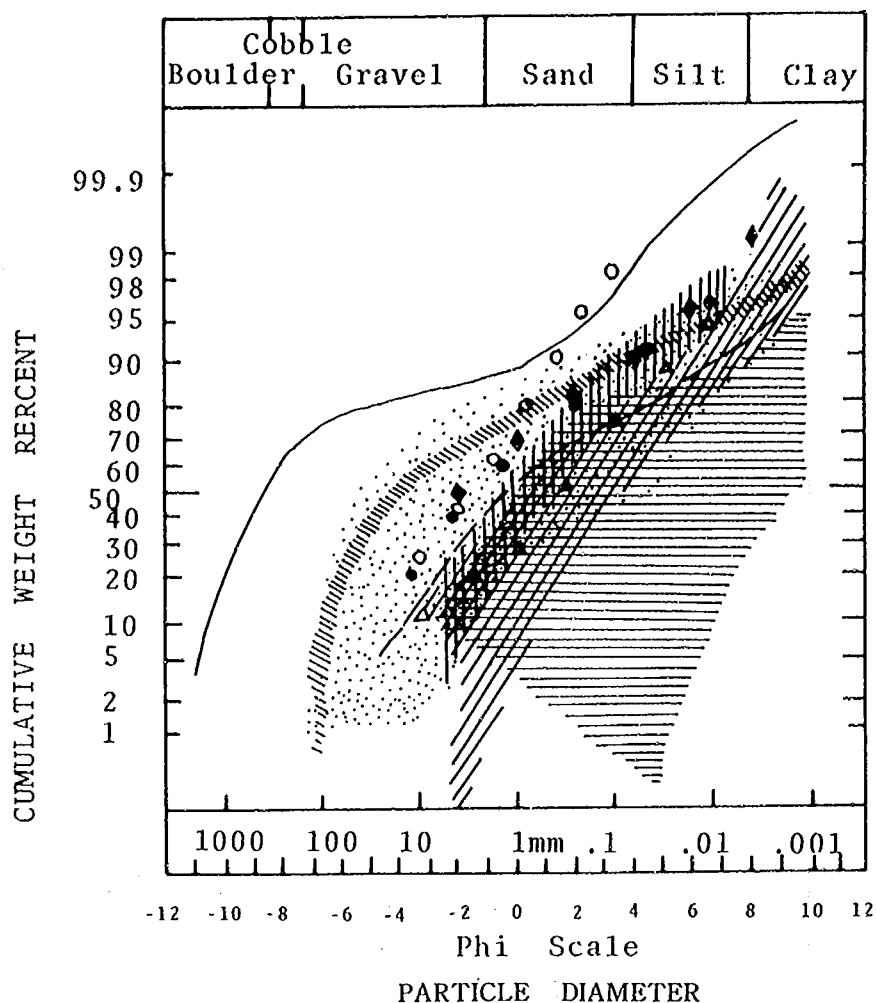


Figure 15. Cumulative distribution of particle size for a debris flow (Sept. 4, 1978) at Mt. Yakedake (After Matsumoto Sabo, 1979)



	Wrightwood Canyon, California	Sharp & Nobles	1953	Debris flow deposits	Entire sample
	Fresno County, California	Bull	1964	Mud flow deposits	Entire sample
	Irazu Volcano, Costa Rica	Waldron	1967	Surges of debris flow	Less than 15cm in dia.
	Steele Creek, Yukon	Broscoe & Thomson	1969	Debris flow deposits	Entire sample
	Mt. Yakedake, Japan	Matsumoto Sabo	1979	Surge of debris flow	Entire sample
	Mt. Thomas, N.Z.	Pierson	1980	Surges of debris flow	Entire sample
	Canadian Rockies	Owens			
○	Quarry				
●	Heath Canyon	Rodine	1974	After Pierson (1980)	
△	Thompson Ck.				
◆	Tenmile Range, Colorado	Curry	1966	Surges of debris flow	Less than 5cm in dia.

Figure 16. Cumulative distribution of particle size for the Mt. Yakedake debris flow (shown as a line) compared to distribution curves and envelopes of curves from other parts of the world.

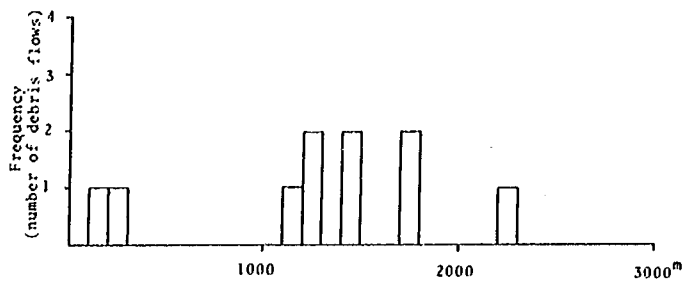


Figure 17. Volume of debris flows (After Matsumoto Sabo, 1980)

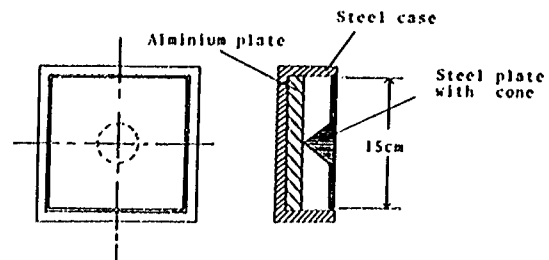


Figure 18. Pressure mark gauge

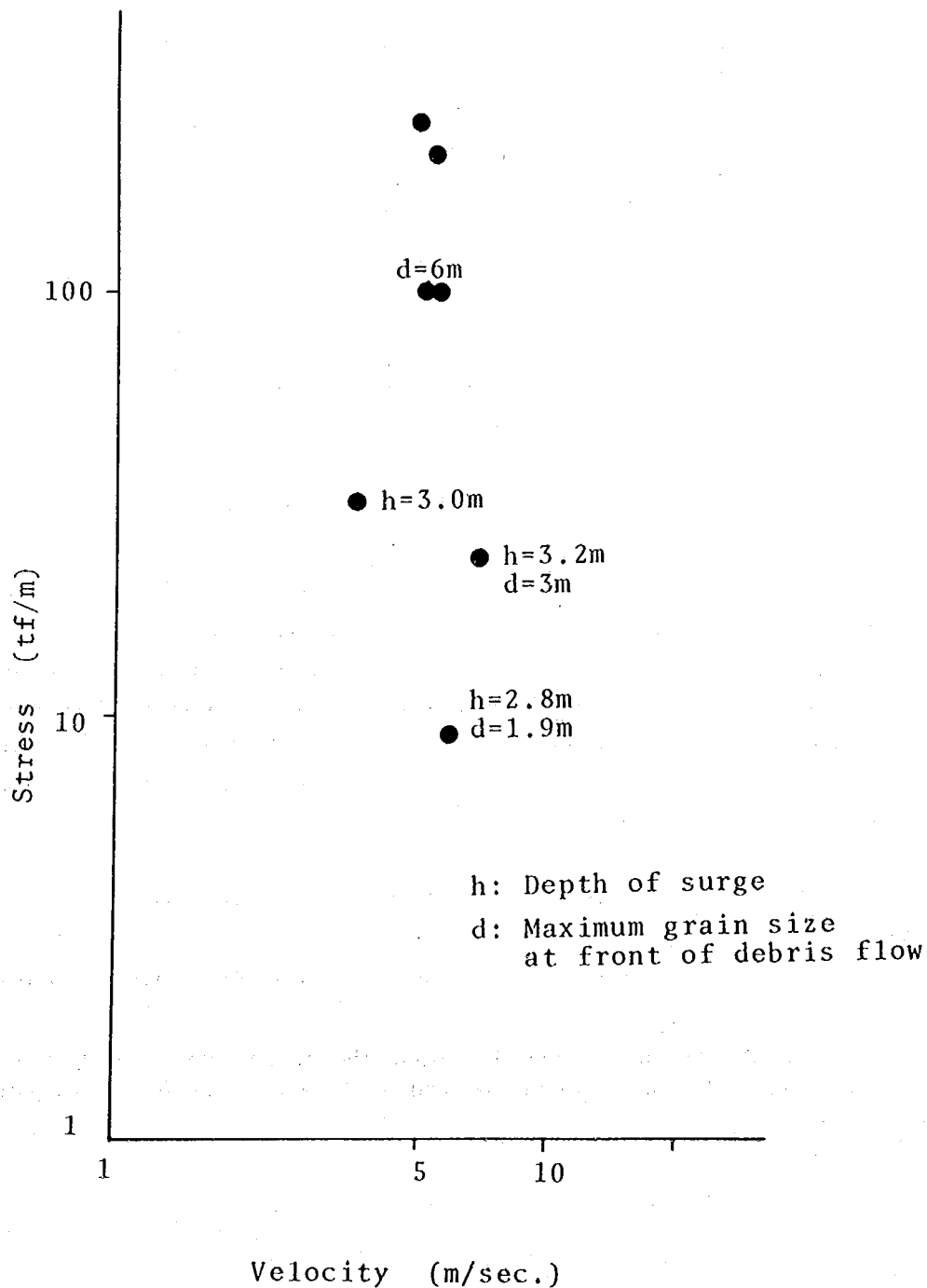
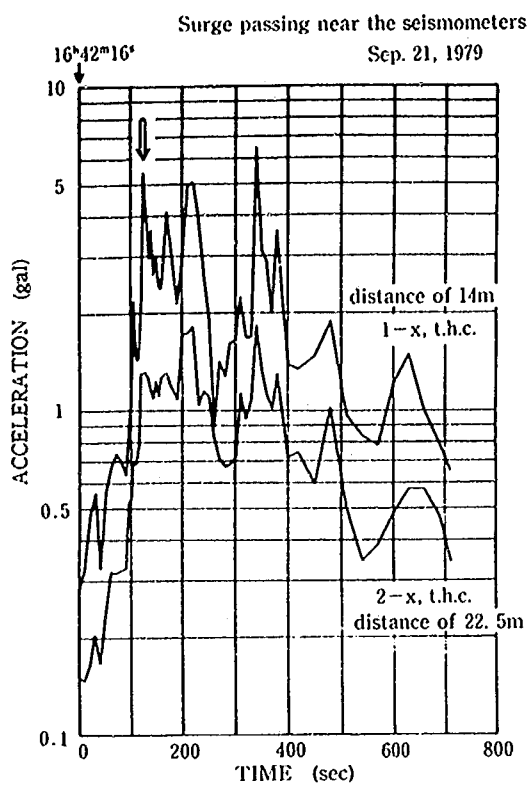
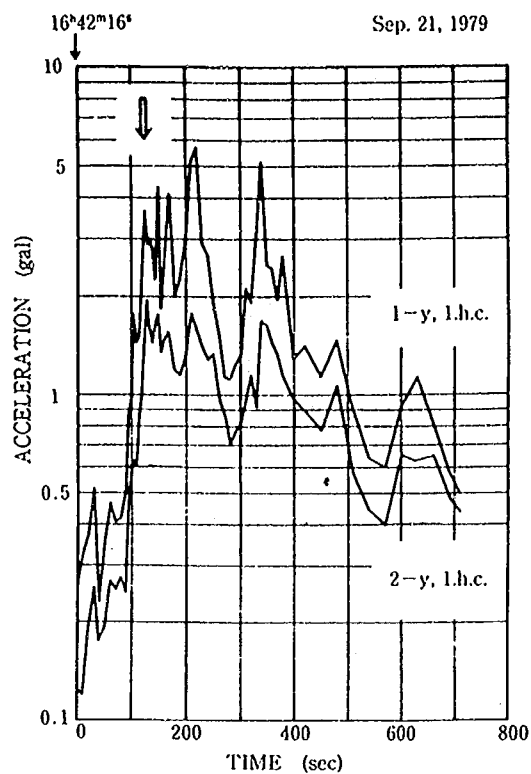


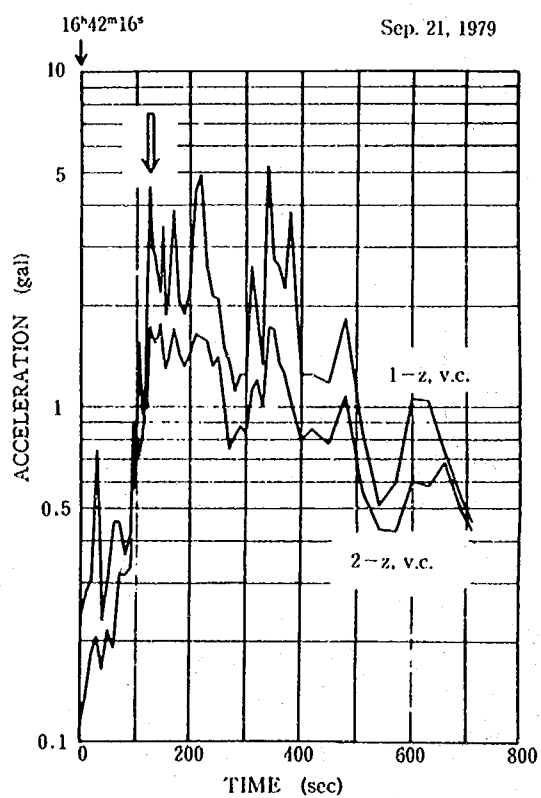
Figure 19. Impact stress, velocity and maximum Particle size (After Matsumoto Sabo, 1980)



Transverse, horizontal component



Longitudinal, horizontal component



Vertical component

Figure 20. Ground vibration caused by travelling of a debris flow on Sept. 21, 1979 (After Matsumoto Sabo, 1980)

Table 3. Comparison of physical characteristics of fluid debris from different areas

Reference	Sample	$\frac{W_t}{V_t}$	$\frac{W_w}{W_s} \times 100$	$\frac{W_s}{W_t}$	$\frac{V_s}{V_t}$	$\frac{V_u}{V_s}$	$\frac{V_v}{V_t} \times 100$	$\frac{V_w}{V_v} \times 100$			Location	Methods of sampling
		Unit Weight	Water content	Weight proportion of solids	Volume concentration of solids	Void ratio	Porosity	Degree of saturation	Coulomb strength	Newtonian viscosity		
		γ (gt/cm ³)	w (%)	a	b	e	n (%)	S (%)	C (kpa)	μ (poise)		Collected
Pierson, T. C. (1980)	Between surges	1.73	67	0.60	0.38	1.63*	62*	109*			Mt. Tohmas	Collected from moving debris flows or muddy flows during surges by wide-mouth (9cm dia.) plastic jars and a bucket.
	During surges	2.09	28	0.78	0.60	0.67*	40*	111*	1.3 to 2.4	2.1×10^3 to 8.1×10^3	New Zealand	
Niyazov, B. S. and Degovets, A. S. (1975)	July 8, 1921	1.5-1.6	86-66*	0.54-0.60*	0.30-0.35	2.3-1.9*	70-65*	100*			Lesser Almatinka River Brain	Deposits of debris in Medeo dam.
	August 7, 1956	1.6-1.7	66-51*	0.60-0.66*	0.35-0.40	1.9-1.5*	65-60*	100*				
	July 15, 1973	2.0	25*	0.80*	0.58	0.83*	42*	100*				
Morton, D. M. and Campbell, R. H. (1974)	Fluid material between surges	1.32	186	0.35	0.20	4.0*	80*	123*			Wrightwood	Collected from moving mudflows by Sampler with 4-inch opening
	Flowing mud during surges	1.62 to 2.13	69 to 16	0.59 to 0.86	0.38 to 0.69	1.63* to 0.45*	62* to 31*	112* to 94*			California	
Johnson, A. M. (1970)	.1917	2.4	7*	0.93*	0.84*	0.19*	16*	100*	1.7 to 5.0		Surprise Canyon California	Bingham viscosity = 7.6×10^2 poise
	Moving debris flow (1965)	2.0	25*	0.80*	0.60*	0.66*	40*	100*	0.6	4.5×10^3	Wrightwood California	
Curry (1966)	Debris flow in 1961	2.53	3*	0.97*	0.93*	0.08*	7*	100*		3×10^4	Tenmile Range, Colorado	Collected from moving debris flow by wide-necked glass liter-sized jars
Sharp, R. P. and Nobles, L. H. (1953)	Debris flow in 1941	2.4	7*	0.93*	0.84*	0.19*	16*	100*		2.1×10^3 to 6×10^3	Wrightwood California	A sample of debris flow
Matsumoto Sabo	Debris flows from 1978 to 1980	Mean 1.71 1.25 to 2.09	50*	0.67*	0.43*	1.33*	33*	100*				

* means assumed value

Table 2. Summary of debris flows from different areas, is put in pocket in back of book.

4. SUPPLEMENTAL DATA

Table 4. List of debris flows at Mt. Yakedake (After Matsumoto Sabo, 1980)

No	Date Year Mon. day. time	Valley	Mag- nitude	Volume of Debris (m)	Rainfall						Weather conditions	Velocity of surge				Depth of surge		Max. section area of flow (m ²)	No. of sampling	Bulk density (g/cm ³)	Boulders in surge		Impact pressure	
					Lower reaches			Upper reaches				Vmax. (m/s)	Vmin. (m/s)	Vave. (m/s)	channel gradient (degrees)	(m)	No. of meas- urement				Dmax (cm)	Dmedium (cm)	Pmax. (tf/m ²)	No. of meas- urement
					10min. (mm)	1hr. (mm)	Ante. (mm)	10min. (mm)	1hr. (mm)	Ante. (mm)														
1	'70. 8.15.18:00-18:30	Kamikamihori	M	—	—	(18.0)	59.0	—	—	—	Typhoon No. 9	—	—	—	—	—	—	—	—	—	—	—	—	
2	'70. 9.18. 9:08	ditto	M	1.500	—	8.0	17.0	—	—	—	Cold front	1.0	—	—	—	1.5	1	6	—	—	140	—	—	
3	'70. 9.28.15:45	ditto	L	1.800	14.0	—	61.0	—	—	—	Autumn rain front	5.0	—	—	12	3.5	1	—	—	—	—	—	—	
4	'71. 7.22.17:00	Kamihori	S	—	7	15.5	59.0	5.5	17.5	72	Cold front	—	—	—	—	—	—	—	—	—	—	—	—	
5	'71. 8.26. —	Kamikamihori	—	—	4.5	13	—	5.5	23	—	Typhoon No. 23	—	—	—	—	—	—	—	—	—	—	—	—	
6	'71. 8.29.13:00	Kamihori	S	200	14	21.5	21.5	6.5	17.5	—	Typhoon No. 25	—	—	—	—	—	—	—	—	—	—	—	—	
7	'71. 9. 6. 4:12	ditto	M	—	—	—	2	14	86	—	ditto	3.3	—	—	5	—	—	—	—	—	—	—	—	
8	'71. 9. 6. 5:20	ditto	M	—	—	—	8	32	115	—	ditto	6.3	4.6	—	11.1	—	—	—	—	—	—	—	—	
9	'71. 9. 6. 5:35	ditto	—	—	—	—	7.5	32	119	—	ditto	—	—	—	—	—	—	—	—	—	—	—	—	
10	'71. 9. 6. 7:20	ditto	L	—	—	—	8	21	174	—	ditto	7.7	—	—	6.1	4	1	—	5	1.5-2.1	—	—	—	
11	'71. 9. 6. 7:23	ditto	L	—	—	—	8	21	174	—	ditto	7.4	—	—	6.1	—	—	—	—	—	—	—	—	
12	'71. 9. 6. 7:30	ditto	M	—	—	—	7	21	176	—	ditto	5.9	—	—	6.1	—	—	—	—	—	—	—	—	
13	'71. 9. 6.10:55	ditto	M	—	6	26	—	7	28	222	ditto	4.6	—	—	6.1	—	—	—	—	—	—	—	—	
14	'72. 8.11.13:05	Kamikamihori	S	—	—	9.0	18.5	—	—	—	Cold front	1.01	—	—	—	—	—	—	—	—	—	—	—	
15	'72. 9.17. 0:05	ditto	S	—	—	11	92	—	—	—	Typhoon No. 20	1.81	0.86	—	14.6-9.3	—	—	—	—	—	—	—	—	
16	'72. 9.17. 0:31	ditto	M	—	—	11	92	—	—	—	ditto	5.1	2.0	—	7.4	—	—	9	1.45-1.73	—	—	267	—	
17	'74. 6.18. 9:00-10:00	ditto	M	—	—	—	—	—	—	—	Cold front	—	—	—	—	—	—	—	—	—	—	—	—	
18	'74. 7.19. 3:49	ditto	M	—	8.0	19	20.5	—	—	—	Stagnant front	3.7	1.9	—	8.3	—	—	—	—	—	—	—	—	
19	'74. 8.11.23:00-24:00	ditto	S	—	4	9	15	—	—	—	Thunderstorm	—	1.9	—	—	—	—	—	—	—	—	—	—	
20	'74. 8.25.22:55	ditto	S	—	5	11.5	25.5	—	—	—	Typhoon No. 14	2.4	1.2	—	16.2	—	—	—	—	—	—	—	—	
21	'75. 7.13. 1:54	ditto	S	—	9	19	93	—	—	—	Baiu front	4.2	—	—	—	—	—	—	—	—	—	—	—	
22	'75. 7.13. 5:12	ditto	M	—	8.5	27	120	—	—	—	ditto	3.3	0.3	—	6.1-7.7	—	—	—	—	—	—	—	—	
23	'75. 7.13. 6:45	ditto	L	1.300	8	28.5	155	—	—	—	ditto	4.0	—	—	—	3.0	3	—	1	1.4	—	38.2	1	
24	'75. 7.13.12:50	ditto	S	300	9.5	26	228	—	—	—	ditto	—	—	—	—	—	—	—	—	—	—	—	—	
25	'75. 8. 6.16:05	ditto	S	—	5.5	18	26	—	—	—	Cold front	5.4	0.5	—	16.0	—	—	—	—	—	—	—	—	
26	'75. 8.23. 9:18	ditto	S	—	6	16	55	—	—	—	Typhoon No. 6	8.9	1.3	—	—	—	—	—	—	—	—	—	—	
27	'75. 8.23. 9:29	ditto	M	—	6	16	57	—	—	—	ditto	1.7	0.5	—	—	—	—	—	—	—	—	—	—	
28	'75. 8.23.15:09	ditto	L	—	9	29.5	98	—	—	—	ditto	6.0	1.5	—	—	4.0	6	8	—	—	215	8		
29	'76. 6.11. 5:20	ditto	M	—	13.0	26.5	127	—	—	—	Baiu front	—	—	—	—	—	—	—	—	—	—	—	—	
30	'76. 6.17. 7:37	ditto	S	—	3.5	12.5	22	4	12	24	Baiu front & Cold front	6.0	0.58	—	20.8-2	—	—	—	—	—	—	—	—	
31	'76. 6.25. 0:19	ditto	S	—	5	21.5	21	6	21	21	ditto	—	—	—	—	—	—	—	—	—	—	—	—	
32	'76. 7.17.20:23	ditto	S	—	5.5	16	16	6	21	19.5	Typhoon No. 9	3.4	0.93	—	14.6	2.1	4	—	—	—	—	—	—	
33	'76. 7.19. 7:51	ditto	L	1.500	9	16.5	14.5	10	19	15	ditto	6.3	1.5	—	15	4.0	4	4	1.97-2.05	—	—	103.6	4	
34	'76. 8. 3.11:30	ditto	L	2.300	5.5	16	93.5	6	15	84.5	Cold front	6.8	1.2	—	7.7-4.0	3.2	1	25	2.08	305	110	24.4	3	
35	'76. 8.14.22:52	ditto	L	—	10.5	23	59.5	10	1	53	—	16.5	0.76	—	24.4-0	—	—	6	2.14	—	—	—	—	
36	'77. 7.15.13:55	ditto	S	—	—	14.5	3.5	12.5	16	3.5	Baiu front	—	—	—	—	—	—	—	—	—	—	—	—	
37	'77. 8. 9. 2:09	ditto	S	—	—	14.5	114.5	3.5	15	109.5	Cold front	2.2	2.1	—	14.17	—	—	—	—	—	—	—	—	
38	'78. 7. 9.17:30	ditto	S	—	—	14.5	14.5	19	28	28	Typhoon	—	—	—	—	—	—	2	1.92	—	—	—	—	
39	'78. 8.17.13:59	ditto	L	1.800	7	9	35.5	12.5	15.5	46	Typhoon No. 11	5.8	0.4	—	15.5-3.9	—	—	4	1.61-1.85	600	—	104.9	7	
40	'78. 9. 4. 7:58	ditto	M	1.300	4.5	15	76	4	14	76.5	Typhoon No. 15	5.9	0.8	—	15.5	2.8	3	11	1.87	190	40	9.33	2	
41	'78. 9.29.19:12	ditto	M	1.200	4.5	14.5	47	5.5	16.5	54.5	Front	3.4	0.5	—	15.5	1.8	3	—	4	1.25-1.87	—	—	—	
42	'79. 8.21.17:11	ditto	S	—	1.5	2.5	26	8	14	76	Typhoon No. 11	2.9	0.45	1.15	19.1-6.9	—	—	2	1.84-2.09	—	—	—	—	
43	'79. 8.22. 4:43	ditto	L	—	2.5	4	77	9.5	13	182	ditto	6.7	1.02	4.7	—	—	—	—	—	—	—	—	—	
44	'79. 8.22. 7:49	ditto	VL	—	10	42	157	18	51	266.5	ditto	—	—	6.1	9.1	—	—	—	—	—	—	—	—	
45	'79. 9.21.16:41	ditto	L	—	10.5	24.5	24.5	12.5	27.5	30	Thunderstorm	4.9	1.54	3.3	10.6-3.5	—	—	2	1.84-2.06	—	—	—	—	
46	'79.10. 1. 0:51	ditto	S	—	6	20	35	4	13.5	24	Typhoon No. 16	3.1	1.45	1.58	3.7-6.9	—	—	—	—	—	—	—	—	
47	'79.10. 1. 1:27	ditto	M	—	6.5	29	61.5	3	18	40	ditto	4.4	1.04	2.4	6.5-9.1	—	—	—	—	—	—	—	—	
48	'79.10. 1. 2:52	ditto	M	—	6.5	22.5	86.5	9.5	25	67	ditto	—	—	—	—	—	—	—	—	—	—	—	—	

5. REFERENCES

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MOVEMENTS OF DEBRIS FLOWS

PWRI TECHNICAL MEMORANDUM

No. 1872

Nov. 1982

Public Works Research Institute

Key Words:

Debris Flow, Bingham fluid
Bagnold's model, Debris Flow movements

Synopsis:

The subject of this research is the dynamic behavior of debris flow movements from the initiation to deposition. A synthesis of published information is compiled in the form of a state-of-the-art review of the subject of debris flow dynamics.



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Table 2. Summary of debris flows from different areas

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⑧	Johnson, A.M. and Rahn, P.H. (1970)	N.A.	USA	Pennsylvania	Small gully near State College.	Relatively humid	1963 1965	120 m long 70 m wide 0.9%	Thick mantle of bouldery loam about 10m in thickness, periglacial colluvium	grams	Periodically	70 40	20 15	40 30	15' 5'	-1965	Rain storm	Small landslides	70	20'	--	--	--	--	--	--	--	--	--	--	40 30	15' 5'	0.11	0.002	80 W 60 L	1	--	--	--	1,600	1,500	Lam	Debris flow			
⑨	Azimi, C. Desvarreux, P. (1974)	Eur.	France		River Ravoire		1965	2730 500 Upper part >1500 Middle part 1500 Lower part 1200 1900	Highly fissured rocks Eocene Flysch (breccias, sandstones, conglomerates, calcareous shales) Mesozoic substratum (Siliceous limestones and clayey shales) Gypsum Limestones and shales		Periodically 1732 1908 : 13 times 1908 : 13 times 1932 : 18 times 1965 and 1966 : 30 times	2730 500	40' 8'	500	--	May 19 and 20 Sept 26, 27 times	High pressure by climb up of springs	Landslide (large)	2000	35'	--	--	--	--	--	--	--	--	--	--	--	500	--	--	--	Width 100m	2	--	--	--	3 x 10 ⁴	--	Alpine			
					Combe Noire		1973		Lower Cretaceous (limestones)			1530 1250	80' 30'	--	August	Ascent of the spring level on the slope	Collapse of the clogged part of debris	1340	37'	--	--	--	--	--	--	--	--	--	--	Vertical fall 760m	--	3.0	--	--	--	--	5000 7000	--	Alpine							
⑩	Morton D. M. and Campbell, R.H. (1974)	N.A.	USA	California	Wrightwood	Semiarid	1969 & 1973	2550 2000	-31'	Intensely fragmented Pelona Schist	Recurring	2550 2000	-17'	1800 1700	9.5' 4'	May to June during 40 days (1969) Spring of 1973	Rapid melting of a heavy snow pack	Small masses of debris fall or slide from the surface of the landslide mass	2550 2250	-40'	--	--	--	--	1.0	0.6 3.75 Intermittently morig flow 0.6'	Bingham viscosity 4x10 ⁴ Newtonian 1x10 ⁴ 6x10 ⁴	--	2.65 Flowing mud 1.62 2.13 1.32'	0.35'	0.38 0.69 0.20'	0.69 0.16 1.86'	Median grain size Upper sample 0.05-0.6mm Lower 0.25-7mm	Snouts 1m in height well-sorted clasts 0.2 - 0.7m in diameter, with an occasional clast up to 1.3m	1800 1700 Vertical fall 750m	5'	3.2	--	--	--	--	Surge : Well Sorting Behind : poor Sorting	--	Lam	Mud flows	
⑪	Campbell, R.H. 1975	N.A.	USA	California	Santa Monica Mountains and vicinity	Semi-arid	1969	--	--	Grass, mustard and sage, chaparral plants (a little)	--	870	--	--	11'	January 18--26 Numerous debrisflows	Heavy rain-storm >5mm/hr Antecedent rainfall >25mm Recurrence intervals 75--150 years	Soil ships	Generally 56' 27' min. 15'	--	--	--	--	--	--	--	--	--	--	General 12' 10'	--	--	--	--	--	Debris trains	--	--	--	Lam	Debris flow					
⑫	Matsumoto Sabo 1975 1981	Eurasia	Japan	Mt. Yakedake	Kamikami-boi Valley	Temperate	1970 1979	1,37 2445 1550	21' 30' 6"	Deposits of volcanic debris flows	Upper reaches relatively rare, Down reaches Coniferous forest	Very active	2200 1700	220 1490	1550 1490	5'	5 times/year	Heavy rain	2200 1700	30' 15'	1560	8.2'	95	12.5	2	3.8	--	--	2.0	--	--	--	Surge Hmax = 3.8'	1500	4'	1.8 Vertical fall 0.3 km	--	--	23000	--	--					
⑬	Niyazov B.S. Degovets A.S. (1975)	Eurasia	USSR		Lesser and Greater Almantika River	--	1921 1950 1956 1973	--	--	Loose clastic moraine deposits in the high-mountain zone (above 3200m) Loose bouldery-gravelly deposits along valley floors and slopes	--	1841, 1921 1950, 1956 and 1973 Three of them-rain-fall Two of them-breach of ice-dammed lake	--	--	--	July 8, 1921 July 8, 1950 August 7, 1956 July 15, 1973	Heavy rainfall >100mm Heavy rainfall 60mm/hr Melting of snow and glacier Melting of snow and glacier	Collapse of moraine Breach of moraine lake and collapse of moraine layer	--	--	--	--	--	--	--	--	1.5-1.6 1.3-1.6 1.7-1.8 2.0	0.30-0.35 -- 0.35-0.40 0.77	--	--	max 3-5m -- -- --	--	--	--	--	--	3-3.2 x 10 ⁴ 0.9 x 10 ⁴ 0.3 x 10 ⁴ --	7.2-10 x 10 ⁴ 2.1 x 10 ⁴ 0.4 x 10 ⁴ 4 x 10 ⁴	Tur Tur -- --	--	--					
⑭	Jackson, L.E. (1979)	N.A.	Canada	B.C.	Kicking Horse valley	Alpine	1978	3450 2700	--	Nearly flat-lying thrust sheets of carbonates and quartzites of Cambrian age	Cathedral Glacier	1925 1946 1958 1962 heavy rain	2700 1980	--	1520 1310	--	September 6 1st flow 2nd flow	Long-term climate-glacier interaction	Catastrophic glacial meltwater outburst or jokulhlaup	--	--	--	--	--	1	1st 0.3 2nd 6	--	--	0.13 0.27	Boulder >2mm = 60-70%	--	--	--	--	--	1.75 x 10 ⁴	--	Jökulhlaup								
⑮	Mears, A.I. (1979)	N.A.	USA	Colorado	Avery Peak	Alpine	1977	0.43 3850 3170	31'	Siltstone Sand stone, and Conglomerate units	--	--	--	--	--	July 24	Intense rainstorms	Sediment load by flood	--	--	--	108 134 est.	--	--	--	--	--	--	--	--	max 4.2x1.5x1.2 Matrix: Sand 59.5% Silt 27.7% Clay 12.8% Boulders 0.25-0.53m aver. dia.	5' 6.5'	--	--	0.6 1.2	Existing	--	Tur	Grain flow							
⑯	Nasmith, H.W. Mercer, A.G. (1979)	N.A.	Canada	B.C.	Northern Vancouver Island	--	1973 1975	0.6 0.5 780 -120	--	Glacial till Sedimentary rocks (argillite and limestone) Volcanic rock	--	-720 -170	35' 15' 50' 15'	120 0	15' 0'	December 15, 1973 November 12, 1975	Hervy rains + melting snow (1-2 m) or snowslides Rain-24hr 1973-120mm 1975-170mm	Small earth slumps	500 700	35' 20' 50' 20'	--	--	--	--	1.6 (on the fan) 5.6 8.3	--	--	--	--	--	--	100 50 120 70 Vertical fall 600m	10' 8' 15' 9'	1.8 1.7	0.02 0.03	max 2 Edge 0.5	--	--	22000 45000	--	Debris flow					
⑰	Pierson, T.C. (1980)	Oce.	N.Z.	North Canterbury	Bullock Creek	Humid-temperate area	1978 middle 0.43 west m (active) 0.46 east m: 0.48	50' 10'	Upfaulted block of highly sheared sandstone and argillite	Tussock grass on the slopes, remnants of beech forest along the valley bottoms	Episodically active for at least the last 2,000 yrs (1923, 41, 45, 51, 60, 71, 72, 73, 74 and 78)	870 500	50' 10' Side slopes 90' 40'	500 250	10' 2' active fan 10' 4'	20 23 April	Rainstorm return period 20yrs. mode rate intensity long duration (10days) 2-hour rainfall 17mm (max).	Small landslides and rills and small gullies on the side slopes	900	50'	400	6'	10-20	Surges -- Currents --	1.0 max 3.0 0.2	2.5-5.0 mean 3.9 5.0 0.8-2.4 mean 1.6	2.1x10 ⁴ to 8.1x10 ⁴ --	1.3 to 2.4 --	2.09 1.73	0.78 0.60	0.60 0.38	0.28 0.67	Extremely poorly sorted. During surges Gravel (>2 mm) 70% Sand 20% Silt 6% Clay 4% Between Surges Gravel 20% Sand 54% Silt 15% Clay 11%	Surges at 20-30 min. intervals	400 300 Vertical fall 600m	5' 3'	3.5	0.16	300 -W 2500 -L- 1.2 max 3m	Observed well-sorted	--	Poorly sorted but front edge well sorted	--	55,000 (Tur)	Lam	Debris flow