Journal of Hydrology (N.Z.) Vol. 29, No. 1, 1990

DEBRIS-FLOW SURGES — EXPERIMENTAL SIMULATION

Timothy R.H. Davies

Department of Natural Resources Engineering, Lincoln University, Canterbury, New Zealand.

ABSTRACT

Debris flows are a significant hazard in hilly or mountainous regions. Their destructive nature results from the pulsing flow and its ability to transport large boulders. Analysis of the highly unsteady, non-uniform pulsing flow is not feasible, so a laboratory moving-bed flume was used to study the development, behaviour and characteristics of high-concentration grain-in-fluid waves. These waves behaved similarly to reported debris-flow pulses. Observation of velocity and concentration profiles within the waves suggests that wave behaviour is mainly controlled by larger grains provided the background slurry of fine grains in water is sufficiently dense; that the front of a pulse is highly erosive while the tail is probably less erosive or depositional; and that the maximum height of a pulse is controlled by the velocity gradient within the flow. As grain flow within the waves is complex, a single analytical explanation is unlikely to be satisfactory; both slow and rapid shear regions exist, and useful theoretical input into debris flow hazard assessment is a distant prospect. A comprehensive database of debris flow behaviour is needed so that empirical models can be evaluated and refined. The best prospect for eventual explanation and prediction of debris flow behaviour is numerical simulation of individual grain dynamics, in combination with empirical models.

INTRODUCTION

In recent years there has been a growing recognition that debris flows may be the most important geomorphic modifiers of many steepland valleys and fans. This has resulted in a dramatic increase in the number of studies of debris flows, and in greatly increased interest in the debris flow research programmes of Japan, Russia and China. Debris flows are among the most intense erosion phenomena known (Eisbacher, 1982) and are destructive and dangerous where they affect human life and works. In order to predict the occurrence and effects of debris flows, some understanding of their behaviour is required; to date such predictions have been largely empirical and hence restricted in their applicability. Many analyses assume, among other things, steady uniform flow; this assumption is grossly inappropriate for a phenomenon characterised by extremely unsteady and non-uniform pulsing flow.

The objective of this report is to explore the characteristics of the debris waves that occur in most destructive debris flows. The apparatus developed to achieve this is rather unusual, so its principle, limitations and potential are explained in some detail. The experimental debris waves are then described and discussed, and the implications of these results for the mechanics of field debris flows are outlined.

THE DEBRIS FLOW PROBLEM

A typical debris flow consists of a series of waves, comprising a small percentage of water mixed with a larger percentage of solids (clay, silt, sand, gravel and boulders), moving rapidly down a steep channel. These waves are often superimposed on "normal" flood flow in the channel, though flow may cease altogether before and between waves. Debris flow waves up to 5 m high, moving at up to 13 m/s and having a bulk density of up to 2.5 T/m^3 have been reported; an event may consist of a single wave, or up to several hundred. Instantaneous discharges of up to 2000 m^3/s from a 47 km^2 catchment have been measured (Li *et al,* 1983).

The practical difficulties of preventing damage from debris flows are enormous. Because the flow is highly non-uniform and carries huge volumes of sediment, maximum flow depths exceed those of normal water flood flow, and bridge, channel and culvert flow capacities can easily be exceeded. The high density of the flow material, and its ability to carry large boulders, give it a high destructive potential. Normal flood protection measures are commonly quite inadequate (Hungr, Morgan and Kellerhals, 1984).

Studying and measuring debris flows in the field is also difficult. They occur at the height of high-intensity storms in highly eroded, unstable steeplands where access is rarely easy. It is unusual even to see a debris flow, let alone be in a position to measure it. Chinese, Japanese and Russian workers (e.g., Li and Luo, 1981; Okuda *et al.,* 1980; Yesenov and Degovets, 1979) have recorded events in places where they occur frequently, but even here the data acquired have been restricted to relatively easily-measured variables such as surface velocity, surface level and the properties of the sampled flow material. Crucial variables such as vertical velocity distribution, total flow depth (with possible severe bed scour and/or fill during the passage of a wave) and vertical variation of material composition have not yet been measured in a moving debris flow.

The common alternatives to field measurement of a phenomenon are to reproduce it under controlled conditions at reduced scale in a laboratory, and to analyse it on the basis of accepted theory. The former is feasible in principle, since debris flows have been reported to occur in the field at a very small scale (Pierson, 1980a), but the pulsing nature of the flows requires, even at laboratory scale, a very long channel to allow full development and measurement of the waves. Even then, obtaining data from the moving wave would be very difficult, as would be correcting the data for the effect of the channel sidewalls, or choosing a material mixture so that the small-scale flow behaves in the same way as a large field debris flow. Scaling up laboratory results to apply to the full-scale flows would be a tentative procedure at the present stage of knowledge.

Theoretical analysis of a phenomenon requires an adequate physical description of the behaviour involved, and this is not presently available for debris flows. Hence, while a variety of analyses have been put forward, the field data are not sufficiently precise to allow these to be adequately tested, and most of the theories seem to roughly fit the available facts. Use of these theories for predicting debris flow behaviour thus depends heavily on empirical data.

The basic problem of debris flows, then, is to obtain an adequate description of the behaviour and characteristics of a debris flow wave.

THE NATURE OF DEBRIS FLOWS

A debris flow is fundamentally different from a 'normal' flow of water which transports sediment. In the latter, sediment grains move in response to the gravity-driven flow of water past them. In a debris flow, water and solids form a single heterogeneous fluid in which all components are acted on by gravity to maintain the flow, and there is no significant segregation of any component; water and grains of all sizes are more or less uniformly distributed throughout the flow. An important consequence is that preferential deposition of large solids from a debris flow does not occur; under conditions which would reduce the transport capacity of a water flow and cause sediment deposition, a debris flow will slow down *en masse* with no preferential deposition of solids (Benda, 1985; Costa and Jarrett, 1981), hence the mainly erosive nature of debris flows as reported by Tan Bingyan (1985). All components of debris flows move at the same velocity, or distribution of velocities. These two characteristics are important in simulating debris flows using the moving-bed apparatus described below.

The important characteristics of debris flow waves are their height and speed, which dictate the extent and severity of the damage they cause in a channel. The experiments described in this report are therefore interpreted in the light of the need to predict these factors.

DEBRIS FLOWS — CURRENT KNOWLEDGE

Recent review papers (Johnson and Rodine, 1984; Costa, 1984; Innes, 1984; Takahashi, 1981a) show that despite variations of climate, topography, geology and vegetation, debris flows show certain consistent features. For example (Davies, 1985, 1986), there are distinct differences in flow behaviour between flows with bulk densities less than about 1.5 T/m^3 and those greater than about 1.8 T/m^3; the former behave more or less like ordinary water floods (except that the fluid is a mud slurry) and coarse grains are moved like normal bedload, at the base of the flow and in contact with the bed. The latter, by contrast, have highly intermittent, pulsing flow; the flow in the pulses appears laminar, coarse grains are present at all levels within the flow, and severe vertical erosion of the channel occurs, while flow between the pulses is similar to that of the lower-density flows (Pierson, 1980b).

These two types of flow can be classified as follows (Davies, 1986, 1988):

Type 1: low density, continuous flow, transporting coarse grains as bedload;

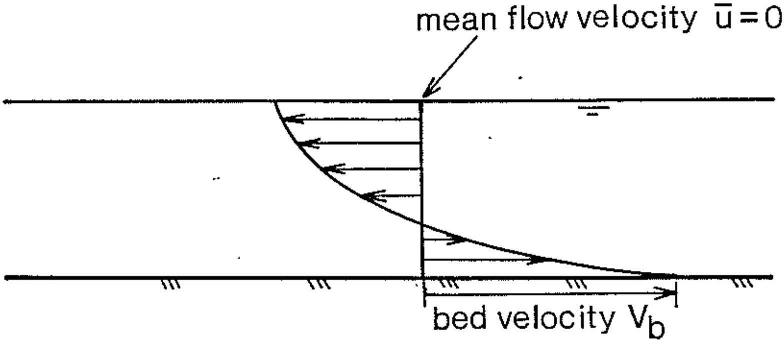
Type 2: high density, pulsing flow, coarse grains present throughout flow.

In addition a third type can be identified from Japanese reports:

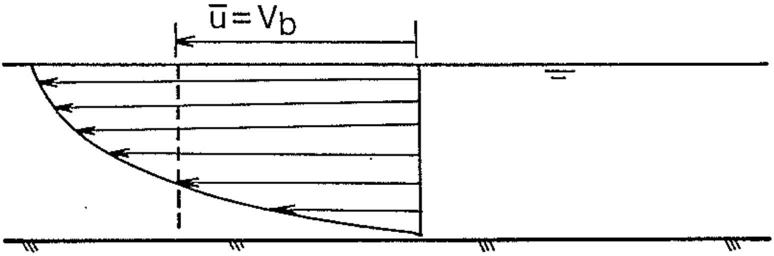
Type 3: high density, single pulse, no fines in flow; this type has been analysed in some detail by Takahashi (1978; 1980; 1981a, b).

Debris flows generally occur following intense bursts of rainfall during long-duration storms (Okuda *et al.*, 1980; Pierson, 1980b; Ikeya, 1976; Niyazov and Degovets, 1975; Curry, 1966) falling onto steep, rapidly-eroding land. The necessary conditions are saturated, steep, shattered bedrock, very intense rainfall and plentiful sediment available in stream beds.

Several attempts have been made to explain the ability of debris flows to



Moving-bed channel



Conventional channel

FIG. 1—Velocity profiles in conventional and moving-bed channels.

transport large boulders. Proposed mechanisms have included the cohesive strength of a flowing slurry, excess pore-water pressures, and dispersive intergranular stresses resulting from grain collisions. Davies (1986) shows the first two of these mechanisms to be unrealistic and postulates, on the basis of the third, that the main features of type 2 debris flows — pulsing flow and transport of large boulders — result from macroviscous grain collisions in the dense, highly-viscous background slurry. Free-surface roll waves appear to amplify and regularise the random pulsations produced by the instability of the macroviscous flow.

In a subsequent report Davies (1988) suggests that the essential property of the macroviscous flow is that coarse material is not preferentially deposited when the energy of the flow decreases; rather, the whole flow slows down, with coarse material remaining in transport. It is this non-depositional character of debris flows that makes the moving-bed apparatus described below suitable for their study. Although the analysis of Bagnold (1956) allows the onset of (macroviscous) pulsing flow to be predicted, the highly non-uniform and unsteady nature of

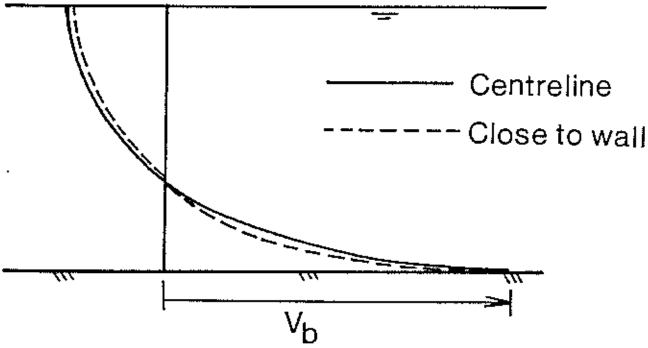


FIG. 2—Effect of sidewall on velocity profile in moving-bed channel.

the developed pulses precludes any realistic theoretical prediction of their characteristics, and laboratory investigation seems at this stage to be the best approach. A moving-bed apparatus allows moving waves of a grain flow to be studied with ease since the waves remain stationary while the bed moves upchannel past them.

APPARATUS

Principle and Constraints

The apparatus used in this study is a moving-bed channel of the principle previously used by Iwamoto and Hirano (1981) to study debris flows, and by Bagnold (1974) and Gulliver and Halverson (1985, 1987) for clear-water flows. In this apparatus the bed moves upchannel at a constant velocity between stationary walls, while the flow material (grains in fluid) remains statistically stationary with respect to the walls. It has been shown for water flows that the vertical velocity distribution in such a channel is identical in shape to that of a fully-developed "conventional" open channel flow, while the length of channel needed to establish this flow is very short. Flow in a moving bed channel is thus a simple Galilean transformation of normal fixed-bed flow; the mean flow velocity relative to the walls is zero, and relative to the bed is equal and opposite to the velocity of the bed. The relationships between mean flow velocity, depth, slope and bed roughness are equivalent in both types of channel. Figure 1 illustrates the velocity profile of the moving-bed channel in comparison with that of a normal channel.

The major advantages of the moving-bed principle for fluid flows are:

(i) The short length of channel required to establish the fully-developed velocity profile;

(ii) The small volume of fluid needed, so that expensive exotic fluids can be used much more cheaply than with a conventional flume-sump-pump-pipework system; and

(iii) The small effect of the sidewalls on cross-channel velocities. Since the mean flow velocity relative to the walls is zero, and with turbulent flow (particularly rough turbulent flow) the vertical velocity profile is quite flat, the effect of wall friction is very small compared with that of a conventional channel.

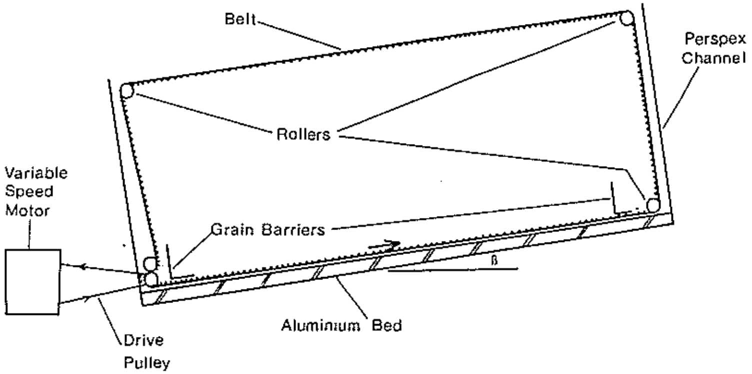


FIG. 3—Diagram of main features of a moving-bed flume.

The moving-bed channel can thus be much narrower than a conventional channel while still representing flow conditions in a wide channel. The main wall effect in the moving-bed channel is close to the bed, where flow velocities are high relative to the wall; in general the effect of wall friction is to increase velocity gradients in a vertical at the bed, and reduce them farther away from the bed (Fig. 2).

All material, fluid and solid, initially within the experimental length of a simple moving-bed channel must remain within this length. With some additional complexity it may be possible to superimpose a mean fluid flow (up-channel or down-channel) but the advantages of the moving-bed principle are progressively lost as this additional velocity increases. It would be very difficult to arrange for sediment to move along the channel, and hence to enter and leave the channel at its ends. Therefore normal bedload transport, in which the sediment moves at a mean velocity much lower than that of the water, cannot be represented in the moving-bed channel. Suspended sediment also poses the same problems because of the requirement (Bagnold, 1963) that similar sediment be present as bedload, but washload can be realistically modelled.

Because a debris flow consists of solids and water *all of which move at the same mean velocity,* the moving-bed channel is suitable for investigating such events. Similarly, because deposition of sediment is not possible in the moving-bed channel (any deposited sediment is remobilised as soon as it reaches the grain barrier at the upper end of the channel), this apparatus is suitable for studying non-depositing debris flows.

A final constraint is that any wave phenomenon which is stationary with respect to the channel walls represents a wave of unchanging shape moving steadily downstream in a field channel. While this is probably not the case with many debris flow waves it is a reasonable starting-point and a justifiable simplification for a preliminary investigation.

Description

The moving-bed apparatus used in this investigation (Fig. 3) had a useful working-section length of 2 m and a channel width of 50 mm. The sidewalls

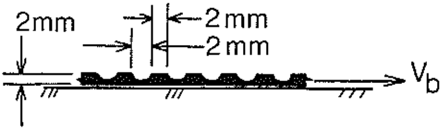


FIG. 4—Longitudinal section of a moving-bed belt.

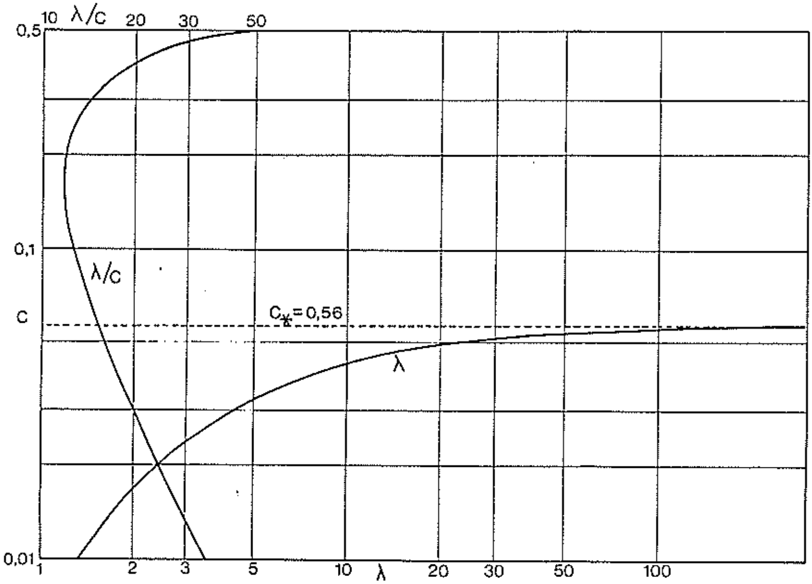


FIG. 5—Linear (λ) vs volumetric (C) concentrations of P.V.C. grains.

were made of transparent 6-mm thick perspex. The channel bed was formed by the grooved side of a corrugated nylon belt, the grooves of which were perpendicular to the belt length and of the cross-section shown in Figure 4. The belt ran with its smooth side in contact with the smooth, plane aluminium bed of the flume, and was driven by a variable-speed electric motor and controller. A system of smooth rollers conducted the belt around its circuit above the channel bed, and belt tension could be adjusted by varying the position of one of these rollers. The ends of the flume were closed to retain fluid, and a system of perspex strips prevented fluid from dripping into the experimental channel section from the belt returning above it.

To retain solid grains within the experimental channel reach and prevent them from jamming in the lower rollers, perforated steel plates were seated in vertical grooves in the sidewalls so that their lower curved ends were in sliding contact with the top of the belt grooves.

The solid grains used in this study were 4 mm long cylinders cut from 4-mm diameter dark green P.V.C. rod; about 10% of them were painted white to act as tracers. A small number of 8-mm long red grains were cut from 8-

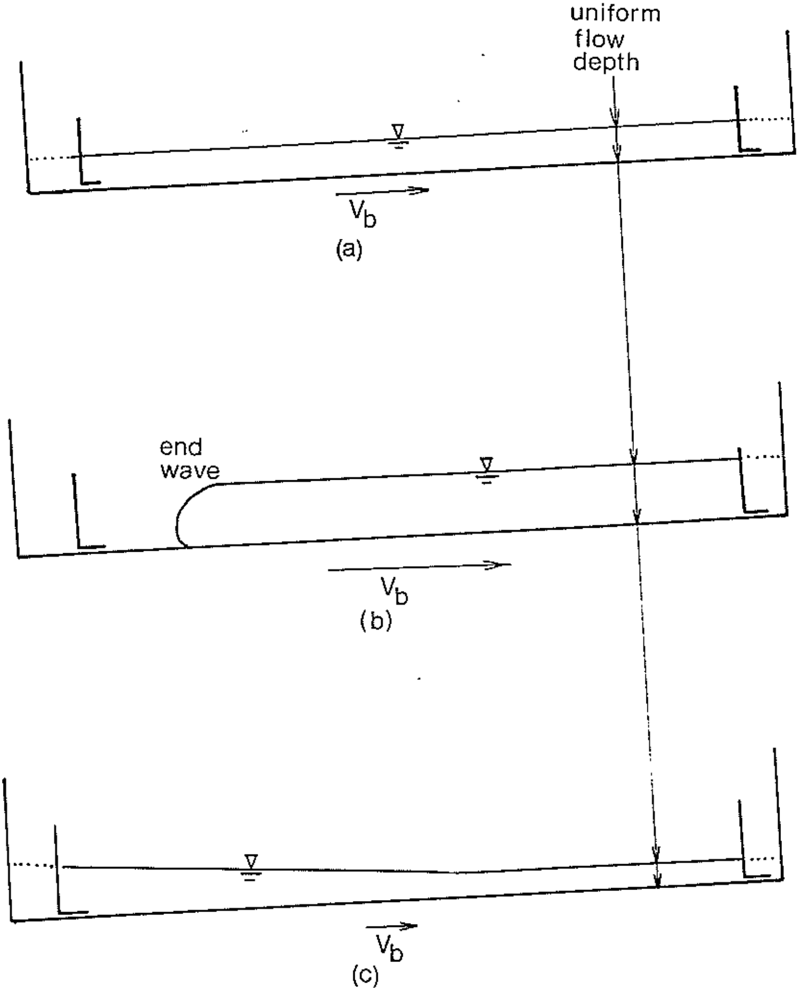


FIG. 6—Shape of flows in moving-bed channel at various belt speeds.

mm diameter P.V.C. rod to study the behaviour of larger grains in a flow of small grains.

The specific gravity of all these grains was close to 1.4, and the maximum natural volume concentration C_* was about 56% (Fig. 5). The fluid used in most of the tests was tap water at room temperature.

Channel slopes ranged from 5° to 19° (8.7% to 34.4%) while bed speeds ranged from 0.25 m/s to 1.17 m/s.

The moving bed had a series of marks on its edge so that the instantaneous bed speed could be recorded by rapid-sequence photos, taken by a 35-mm motor-driven camera with a clock in the field of view. Most of the necessary experimental

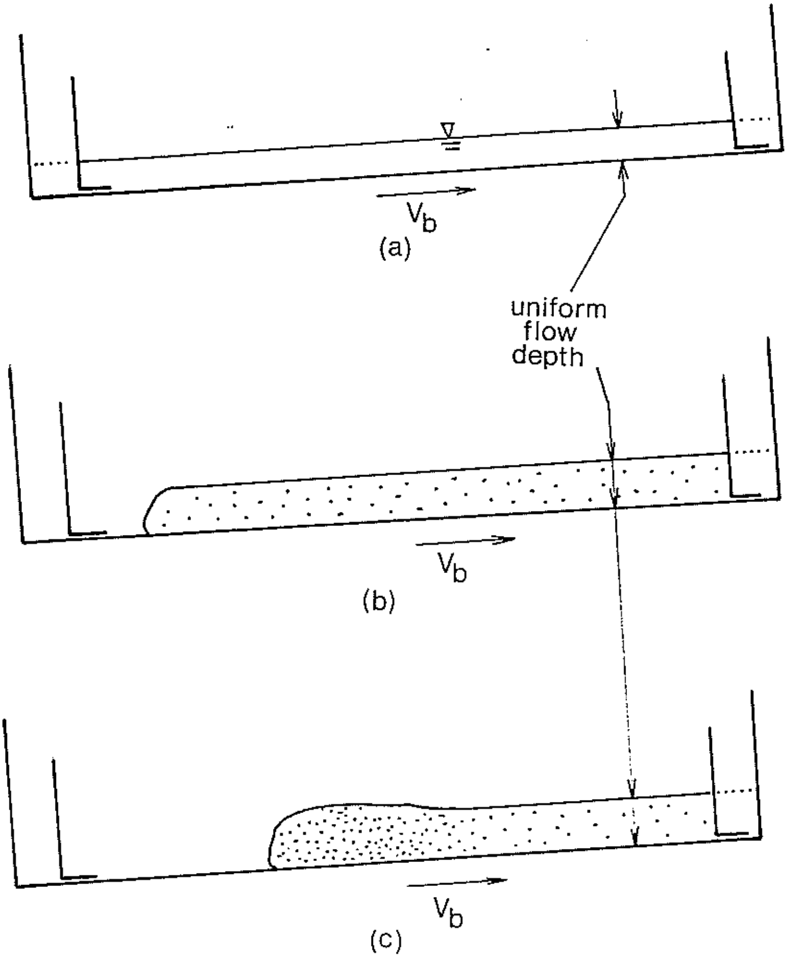


FIG. 7—Effect of added grains on flow shape.

data (bed speed, channel slope, wave size and shape, grain concentrations, local grain velocities, depth of uniform flow) were recorded on photographs for later analysis. A series of video films was used for tracing individual particle trajectories in the waves.

Behaviour

In the moving-bed channel with slopes greater than about 5°, it was very easy to establish a stationary grain-water wave at any bed speed. This unexpected result, caused by the nature of the apparatus, is explained by first considering how the flow parameters change with boundary conditions.

Fig. 6a shows a uniform flow established in the channel at a given slope and bed speed. Note that the volume of fluid in the system is limited, and end effects are negligible. Upon increasing the bed speed, and thus the mean flow velocity of the water relative to the bed, the depth of uniform flow increases to re-establish equilibrium between gravitational and resistance forces. The limited volume of water available cannot fill the whole length of the channel at this new depth, and so the flow extends over only part of the channel length, with an end-wave at the lower end of the flow (Fig. 6b). Conversely, reducing the bed speed gives a lower depth of uniform flow, and the surplus water forms a pool at the lower end of the channel (Fig. 6c). By adjusting the volume of water in the channel it is possible to control the length of the uniform flow reach, so that at any speed and slope an end-wave is present within the channel, with uniform flow upchannel and a dry bed downchannel of it.

A similar effect is obtained by adding solid grains to the flow. A greater flow depth is needed to transport grains in a uniform flow than is needed for a uniform flow of water without grains, so adding grains causes the flow depth to increase; adding sufficient grains will cause an end wave to appear in the channel (Fig. 7a, b). Adding further grains causes the uniform flow depth to increase still further, but there is a limit to the concentration of grains which a uniform flow of given speed and slope can carry; if this is exceeded, the excess grains move to the lower end of the flow and cause the end wave to increase in height, forming a bulbous wave of high concentration (Fig. 7c). It is this bulbous end wave, and its behaviour, which is studied in the series of experiments described herein.

It might be questioned whether the development of debris flow waves is similar to that of moving-bed end waves. Introducing sediment grains to a fixed-bed channel at concentrations in excess of the capacity of uniform flow causes the whole flow to slow down where the concentration is high, due to increased intergranular friction (remember that no deposition is possible and grains and flow move at the same speed). Flow then builds up behind this slower-moving region and recedes in front of it, causing a breaking wave similar to the stationary breaking end-wave of the moving-bed channel.

RESULTS

With No Grains in Flow

At low slopes it was possible to establish a steady, uniform clear-water flow which appeared equivalent in every way to a normal stationary-bed open channel flow, as described by Bagnold (1974) and Gulliver and Halverson (1985, 1987). At slopes steeper than about 5° (at which most of the present tests took place) the Froude number of the flow was sufficient that roll-waves formed and amplified as they moved down the channel. The absolute mean flow velocity between roll-waves was towards the upper end of the channel, while that in the waves themselves was towards the lower end of the channel. The flow was uniform at a scale much larger than that of the roll-wave wavelength.

With Grains in Flow

As grains were gradually added to the flow, the flow characteristics altered:

(i) A small number of grains had a negligible effect on the flow. The grains

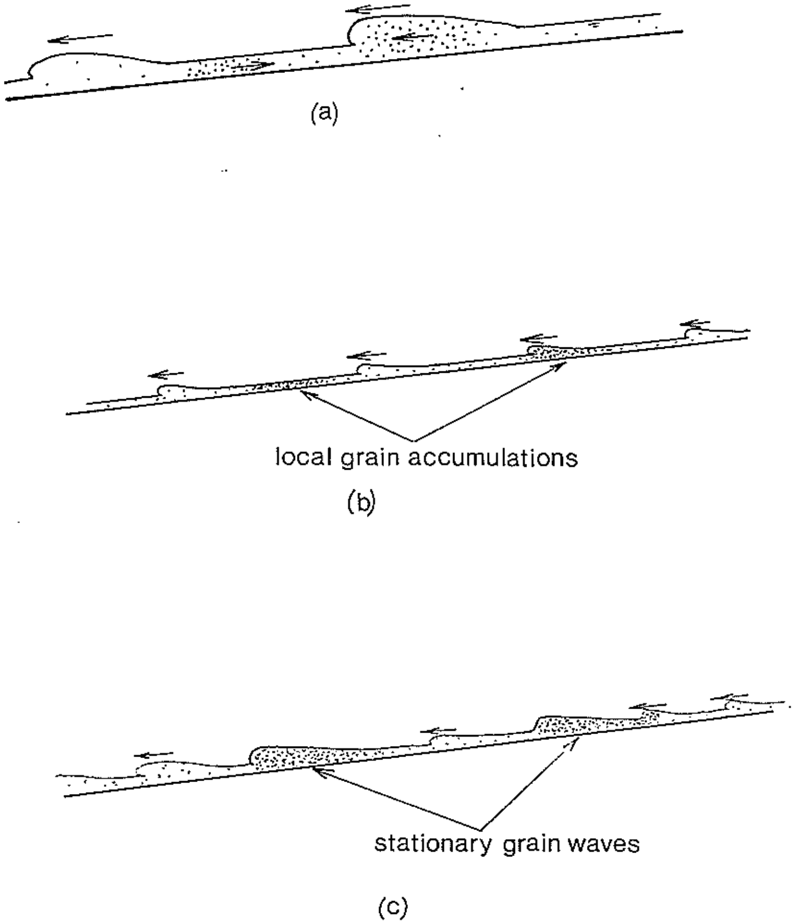


FIG. 8—(a) Roll waves with grains in flow (b) Development of local stationary grain accumulations (c) Development of stationary grain waves.

dispersed throughout the channel length; individual grains were moved downchannel by each roll-wave, and retreated upchannel again in the shallower flow between rollwaves (Fig. 8a).

(ii) As the concentration of grains increased, roll-wave amplitude increased. A roll-wave tended to collect grains as it moved downchannel, increasing its bulk. At some point, however, some grains ceased to move with the roll-wave and were left behind, while the wave, its grain content much reduced, moved away down-channel. Grains thus tended to accumulate at certain locations along the channel (Fig. 8b).

(iii) With still more grains added, these grain accumulations became large enough to form stationary grain waves through which the roll-waves moved, quite

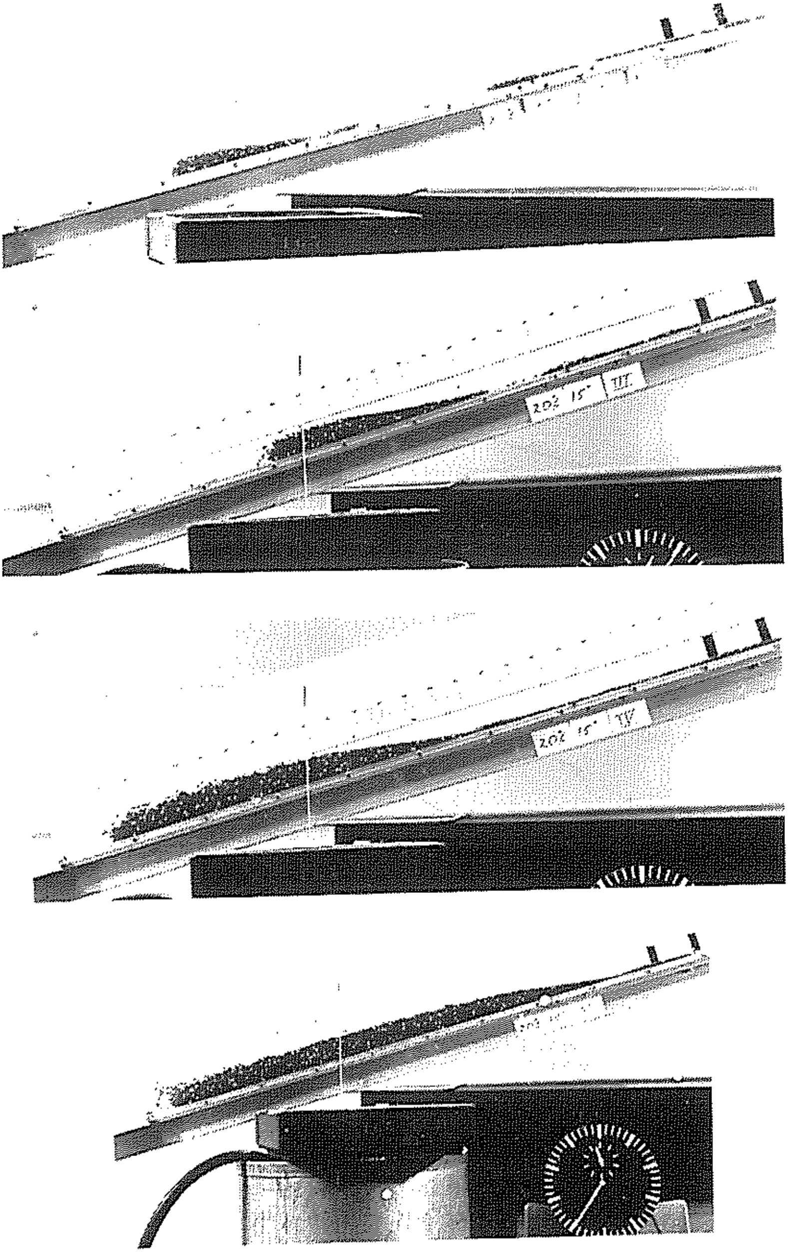


FIG. 9—Development of wave shape with increasing grain volume.

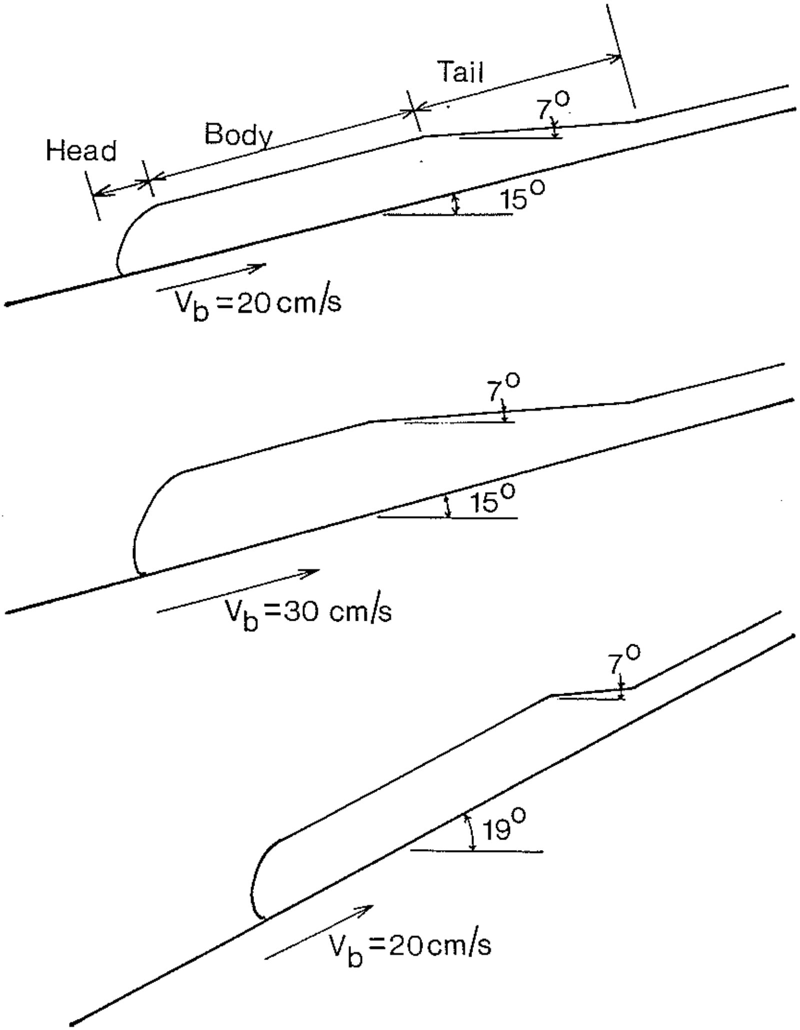


FIG. 10—Wave shape at various slopes and belt speeds.

independently of the end-wave which formed at the lower end of the flow region (Fig. 8c). These stationary waves were unsteady due to the effect of roll-waves moving into them from upchannel. It is clear that a grain-fluid flow of this nature is liable to intrinsic and substantial non-uniformity, suggesting that the pulsing of debris flows is probably an intrinsic phenomenon.

(iv) Further addition of grains resulted in more and more grains moving down

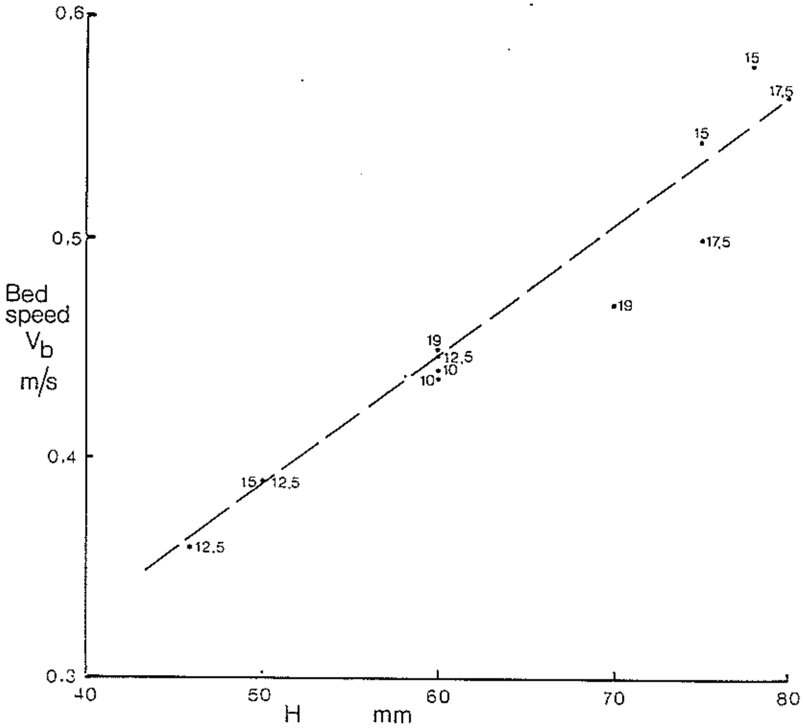


FIG. 11—Surge wave height H as a function of bed speed and slope (numbers beside points denote channel slope in degrees).

through the local accumulation waves, and collecting at the lower end of the channel to form a substantial high-concentration end wave. While small this wave was very similar to intermediate accumulation waves, but when larger it developed different characteristics. A typical sequence of end-wave shapes developed as grain volume increases is shown in Figure 9, while Figure 10 shows how variations in channel slope and bed speed affect the shape of the wave.

The major consistent features of the end-waves are:

(i) A uniform depth "body" extends from the sharply curved front or "head" to a uniformly sloping "tail" at the upchannel end of the wave.

(ii) With decreasing grain volume the head is located closer to the tail.

(iii) The depth of the body varies directly with bed speed and only very slightly, if at all, with slope (Fig. 11); it is not significantly affected by grain volume (Fig. 12).

(iv) The angle made by the surface of the tail with the horizontal is very consistent at 7° ± 0.5°, and does not vary significantly with bed slope, bed speed or grain volume.

Hence, for a given grain volume, the wave tail will be shorter as bed slope increases at constant speed (Fig. 10). At constant bed slope, speed variations

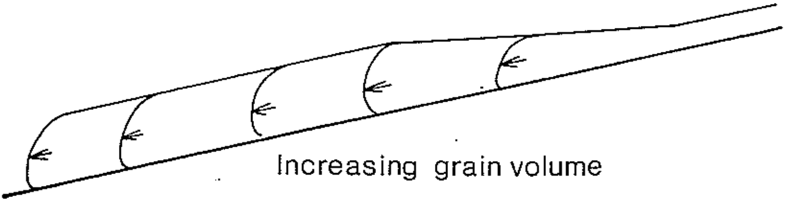


FIG. 12—Wave geometry with increasing grain volume and constant bed speed.

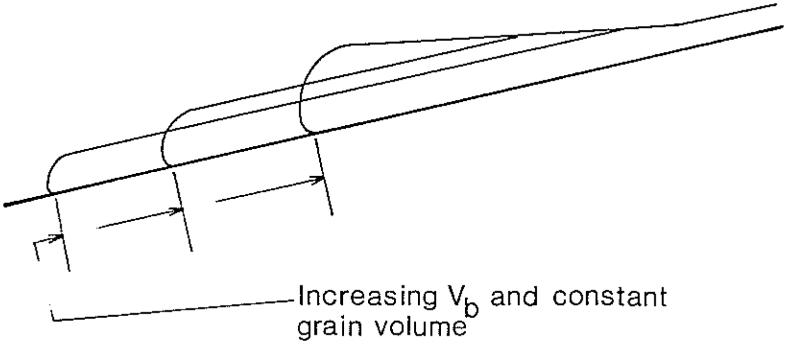


FIG. 13—Wave geometry with increasing bed speed and constant grain volume.

do not affect wave shape as long as the volume of grains present is insufficient to form a body. If a body does form the tail will lengthen as speed increases, corresponding to the increase in body height; however, this increase in height causes the body to become shorter with a fixed volume of grains, and a speed could eventually be reached at which no body forms (Fig. 13).

The regular shapes shown in these figures are an idealisation in some cases; for example, with very large grain volumes at high slopes, the body surface is perceptibly curved in long section, rather than being flat and of uniform depth. Nevertheless, as an initial approach to a complex situation the simplifications of Figures 10–13 are justified.

Velocity Distributions

By tracing grain motion on video films, and using short time-exposure ($\frac{1}{4}$ - $\frac{1}{30}$ sec.) photographs, it was possible to measure velocities in all parts of the flow. The grains thus recorded were adjacent to the channel sidewalls. Observation of grains at the surface of the flow "body" revealed no variation of grain velocity with position across the channel, and thus the wall grain velocity distribution is indeed representative of that within the flow "body". A slight reduction in surface velocity at the walls was noticed in the "tail", so velocity profiles obtained by these methods are somewhat distorted there. As the inferences drawn from these profiles are qualitative, however, this is not a serious problem.

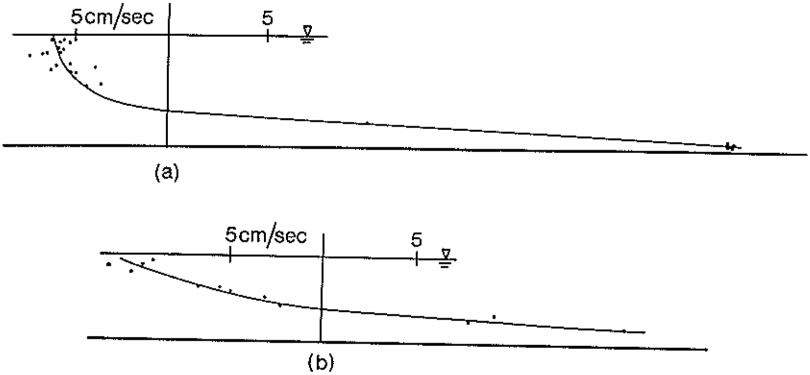


FIG. 14—Velocity distribution in (a) body, and (b) tail of wave.

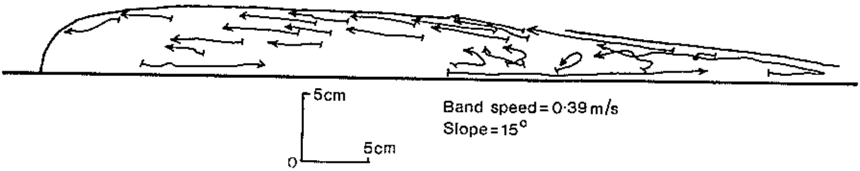


FIG. 15—Path lines of grain movement. Length of each line shows grain movement during 1 second.

Typical velocity distributions in the body and tail regions are shown in Figure 14, while path lines, as recorded on video film, are shown in Figure 15. Notable features are:

(i) The velocity is relatively uniform in the upper part of the body; shearing of grains here is very slow.

(ii) The velocity gradient is high in the lower part of the body and the tail.

(iii) The velocity distribution in the tail is fluid-like with substantial grain shearing everywhere.

(iv) The velocity of surface grains in the tail is double that of the body.

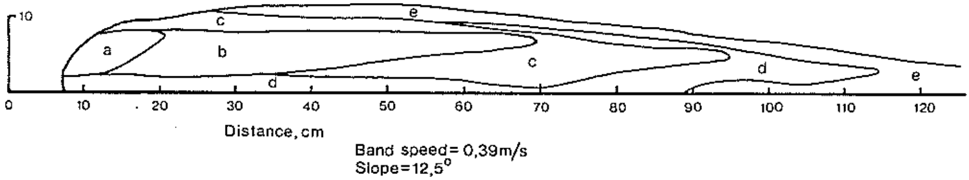
The path lines show the following features:

(i) Nearly all tracer grains in the tail and body of the flow move upwards (away from the bed) with time; only in the head is substantial and consistent downward motion seen.

(ii) Grains paths in the tail show major perturbations reminiscent of fluid turbulence. By contrast, grain paths in all parts of the body show only weak, or no, perturbations.

Grain Concentrations

Figure 16 shows the distribution of local grain concentrations as taken from a short-exposure ($\frac{1}{250}$ sec.) photograph. Again, these data refer to conditions at the sidewall, and as cylindrical grains in contact with the wall tend to align



Zone	Grain Concentration
a	$> 1{,}2\overline{C}$
b	$1{,}1-1{,}2\overline{C}$
c	$1{,}0-1{,}1\overline{C}$
d	$0{,}9-1{,}0\overline{C}$
e	$0{,}8-0{,}9\overline{C}$

$\overline{C}$ = Mean Grain Concentration

FIG. 16—Concentration distribution of grains in wave.

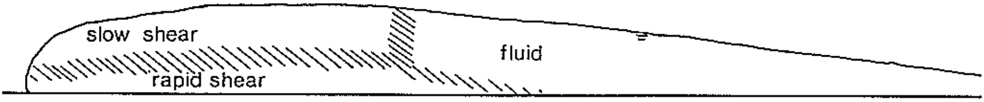


FIG. 17—Flow zones.

themselves with their major axis either perpendicular or parallel to the wall, concentrations measured at the wall could differ from those within the flow where grain orientations are more variable. Concentrations within the flow are probably lower than those at the wall because of the greater voids ratio in more randomly-arranged grains; and also more variable, because local aggregations of similarly-oriented grains are possible.

Bearing these reservations in mind, Figure 16 shows:

(i) Consistently low concentrations in the vicinity of the bed and the flow surface;

(ii) A "core" of higher concentration at mid-depth decreasing from the head to the tail of a wave.

Behaviour of Large Grains

About 50 larger grains were introduced to investigate their motion. It has often been noted that only the front of a debris flow contains a high proportion of large boulders. The large grains in the present tests tended to accumulate at the front of a wave, and to remain there, if the maximum height of the wave was less than about 25 mm (or 3 times the diameter of the large grains). If the wave height was greater than 25 mm the large grains dispersed uniformly throughout that part of the wave where the depth was greater than 25 mm, and did not enter the region (tail) of smaller depth. In very deep waves, therefore, where a large part of the wave was more than 25 mm deep, the small number of large grains present appeared only rarely at the front of the flow.

Flow Zones

Three distinct zones of flow were apparent in the experimental waves (Figure 17):

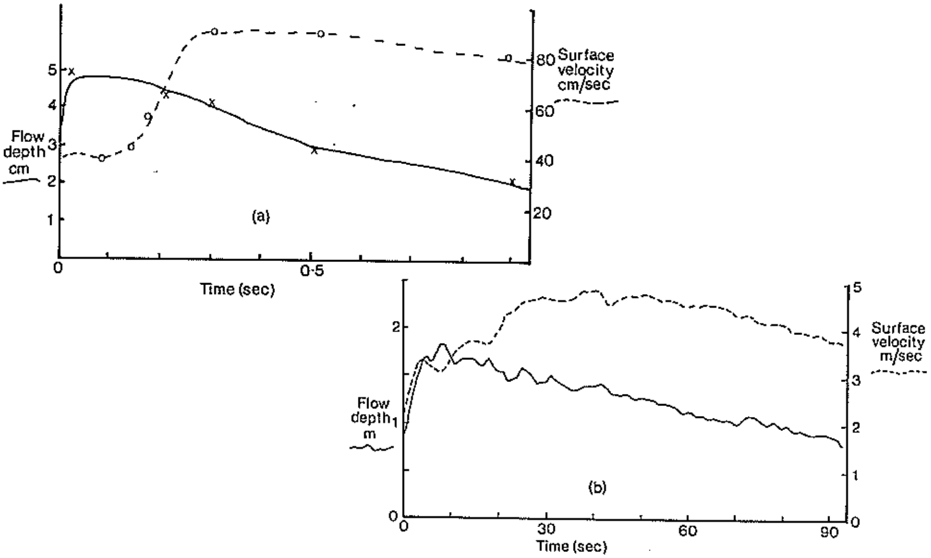


FIG. 18—Behaviour of (a) Laboratory, and (b) Field debris flow (Suwa *et al*, 1984).

(i) In the upper part of the head and body, grain velocity was close to the mean velocity, and grains sheared (slid) past each other very slowly, remaining in contact for substantial lengths of time (~ 1 sec.). At the surface of this zone no fluid was visible, the fluid surface being about 1 grain diameter (4 mm) below the top grain surface. The complete lack of any cross-channel variations in velocity in the surface layer gave the body the appearance of a solid, non-shearing plug when viewed from above.

(ii) In the tail of the wave grains sheared quite rapidly past each other in fluid-like flow, even at the surface, and grain motion was much less regular than in the body. Water was visible at the surface of the flow, and grains continually protruded momentarily through the fluid surface at all locations, giving a "boiling" appearance. The transition between this and the previous zone occurred distinctly within a few grain diameters.

(iii) The base of the head and body was a region of very high shear in which grain velocities relative to the bed increased rapidly with height above the bed.

DISCUSSION OF RESULTS

Comparison with Field Data

In order that this study be relevant to debris flows, the behaviour of the grain waves must resemble that of debris flow waves. This is difficult to demonstrate quantitatively because of the lack of data from debris flow waves, but one useful description is that of Suwa *et al* (1983, 1985). This description, from a video film of a wave at Mt Yakedake, Japan, on 5 September 1983, gives details of changes in surface velocity, surface elevation and surface composition as the wave passed below the camera. These results (Fig. 18) can be compared with a typical laboratory wave. The qualitative similarities between the field and laboratory waves are:

(i) The distinct increase in surface velocity as the "dry" surface of the front part of the wave passes and is replaced by the "wet" surface of the tail.

(ii) The relatively constant surface elevation in the "body" of the wave and the steadily decreasing depth in the "tail";

(iii) The change from "dry" to "wet" surface appearance in moving from the "body" to the "tail".

These similarities support the assumption that the major features of debris flow waves occur also in the P.V.C. grain-in-water laboratory waves. This in turn supports the hypothesis (Davies, 1986) that the main features and behaviour of debris flows can be explained by the shearing of large grains in a fluid (slurry). The nature of the slurry is not crucial (i.e., it can be a Newtonian fluid, a Bingham plastic, or a power-law fluid) provided only that its apparent viscosity is sufficient to cause the shearing of large grains to be macroviscious. Tattersal and Banfill (1983) came to a similar conclusion regarding the rheology of wet concrete, whose flow behaviour is much simpler than that of a cement paste in which the coarse aggregate shears. Many debris flows (Davies, 1986) show a strongly bimodal grain-size distribution and in the Jiangjia Ravine flows, the slurry grains are mostly less than 0.1 mm and the coarse grains greater than 1 mm in diameter.

Instability of Uniform Flow

At channel slopes greater than about 5° both clear-water and grain-water flows showed either free-surface instability in the form of roll waves, or non-uniformity in the form of stationary waves, or both. The roll-wave phenomenon for clear-water flow is fairly well understood (Berlamont and Vanderstappen, 1981) and has been explored analytically for high-concentration sediment-transporting flows by Takahashi (1983). It appears (Davies, 1986) that the clear-water relationships hold at least approximately for the extreme case of debris flows.

The development of local, more-or-less stationary, grain accumulations within the channel (as distinct from end-waves) appeared to result from locally high grain concentrations causing the local downchannel motion of grains (with respect to the bed) to slow down, with more grains accumulating from upchannel at this location. Davies (1988) has shown that, in principle, a non-depositing macroviscous flow would be unstable in this fashion; the criterion for the occurrence of macroviscious, transitional or inertial flow of grains in a fluid is given by Bagnold (1954) as $G^2 < 100$, $100 < G^2 < 1500$, or $G^2 > 1500$ respectively, where

$$G^2 = \frac{\sigma D^2 T}{\lambda \eta_a^2} \qquad (1)$$

where σ = grain density, D = grain diameter, T = grain-transmitted shear stress, λ = linear grain concentration and η_a = apparent fluid viscosity.

However, with the fluid and sediment conditions of this study, Bagnold's (1954) criterion for macroviscous flow G^2 as given by eq.(1) is about 20,000, rather than < 100, indicating inertial flow. Therefore the instability observed in these tests could not be due to macroviscous flow. The test flow was, however, non-depositional, which suggests that the instability of high-concentration grain-in-fluid flows could result from their being non-depositional. If this were the case the macroviscous flow hypothesis advanced by Davies (1986) would be a particular case of a hypothesis involving non-depositional flows; in conventional channels such flows must necessarily be macroviscous, but in the moving-bed channel this is not the case.

The lowest slope at which local grain accumulations occurred was 7.5°. Bagnold (1954, p.63) gives the following expression for the maximum slope of a uniform macroviscous flow:

$$\tan \beta = \frac{\tan \alpha_v (\sigma - \rho)C}{\rho + (\sigma - \rho)C} \qquad (2)$$

in which α_v is the angle of internal friction of a mass of grains, σ = grain density, ρ = fluid density and C is the volume concentration of grains. Since the maximum concentration of the P.V.C. grains in shearing was 0.56 (Fig. 5), the maximum value of β in this study would be about 7° if (2) applied to non-depositing, rather than only macroviscous, flows. If the channel slope is greater than this, it is impossible for the bed and flow surfaces to be parallel and hence uniform flow is impossible. As seen earlier, the surface slope of the "tail" of grain-fluid waves was remarkably constant at about 7°; it is also frequently reported (e.g., Benda, 1985; Mizuyama, 1981; Ikeya, 1981) that, as channel slopes decrease in the region of 7°, field debris flows cease to be erosive and become depositional. Since a macroviscous flow is essentially non-depositional this would seem to indicate a change from eroding (non-depositional) to depositional conditions as slopes become less than about 7°, which is supported by Bagnold's (1954) calculation of a slope angle of 6° for macroviscous flow of cobbles in a mud slurry of ρ = 2.0 T/m^3. Clearly, the maximum value of β for macroviscous flow changes but little in different grain-fluid situations, presumably because both α_v and the maximum value of C also vary only slightly for different grain-fluid combinations.

The field and experimental evidence thus supports the concept that the non-uniformity of debris flow behaviour has its origin in the occurrence and instability of non-depositing macroviscous flow. An additional factor encouraging the development of an initially slight nonuniformity to a series of isolated pulses is the tendency of coarse grains to jam across the width or depth of a channel at high concentrations. Bagnold (1955), Savage and Sayed (1984) and Walton (1983) show this to be important where the channel width or depth is less than about 10 grain diameters, as will be the case for debris flows with large boulders. Such a jam in a region of locally high concentration will form a temporarily stationary or slow-moving dam, and will rapidly accentuate the non-uniformity of the flow.

Characteristics of Stationary Waves

Geometric Shape. The wave evolution sequence shown in Figures 12 and 13 implies the following:

(a) At a given bed speed the depth of the wave body has a unique value which is independent of bed slope.

(b) With increasing bed speed the body depth increases.

(c) The maximum depth of the tail is equal to the body (if any) and head depths.

(d) The tail slope is constant at about 7° below the horizontal, and does not vary with bed speed or slope.

At a given bed speed there appears to be a limit to the depth of flow in the tail, and the body depth, being uniform, is equal to this maximum tail depth. This upper limit occurs when the flow at the very front of the tail becomes "slow", and grain shearing becomes very slow, instead of the fluid-type flow prevailing in the tail (Fig. 17). It seems appropriate to seek an explanation for wave shape in terms of the circumstances under which this transition of flow type occurs.

The criterion for the type of shearing which occurs in a grain flow is given by eq.(1), in which the grain shear stress T is strongly related to the velocity gradient du/dy. It seems reasonable to suppose that du/dy will also affect the transition from fluid-type flow in the tail of a wave to slow-shear flow in the body. In the tail of a wave, the flow depth increases downchannel since the channel slope β is greater than 7°. With a fixed bed speed, the local mean values of du/dy will decrease towards the front of the tail as flow depth increases. If the change to slow shear flow occurs at some critical value of du/dy, then at a given bed speed the transition should always occur at the same depth, irrespective of slope, and hence the body depth should be linearly related to bed speed and not at all related to bed slope. Figure 11 confirms both of these deductions. With a bed speed of 500 mm/s the body depth is 70 mm; in laminar flow the maximum velocity in a vertical is 1.5 times the mean velocity, hence the mean velocity gradient in a vertical $du/dy = 1.5 \times 500/70 \simeq 11$/sec. at the transition. This figure is of the same order as that inferred from measured surface velocities and estimated flow depths in field debris flows (Mizuyama and Uehara, 1980; Suwa *et al,* 1983) and is lower than that in the between-pulse flows reported by Pierson (1981) at Mt Thomas, New Zealand.

The evolution of a grain end-wave as successively more grains are added to a flow may be visualised as follows:

(a) When sufficient grains are added, an end wave develops comprising a short tail section and a head.

(b) With more grains again, the length and maximum depth of the tail increase. The minimum mean value of du/dy in the tail decreases accordingly.

(c) When the tail has grown sufficiently deep that du/dy at its downchannel end is about 11, the grain shear at the front of the tail becomes slow and a "body" begins to form.

(d) Addition of still further grains causes the length of the body to increase, but its depth is limited by that of the tail and remains substantially constant.

The relatively constant body depth H for a given bed speed, irrespective of bed slope, implies that while du/dy cannot be less than about 11 in the fluid-like tail flow, it also cannot be much less than this in the body flow. The velocity profile in the body region (Fig. 14) is quite distinct from that of the tail; no explanation for this is suggested because the problem requires more detailed treatment of grain-flow mechanics.

Grain Motion — Velocity Profiles and Path-lines. Figure 14 shows that, in the upper part of the flow, the velocity gradient in the body is less than that in the tail, while in the lower part of the flow the opposite is true. The point in the profile at which the local velocity equals the mean velocity is at the

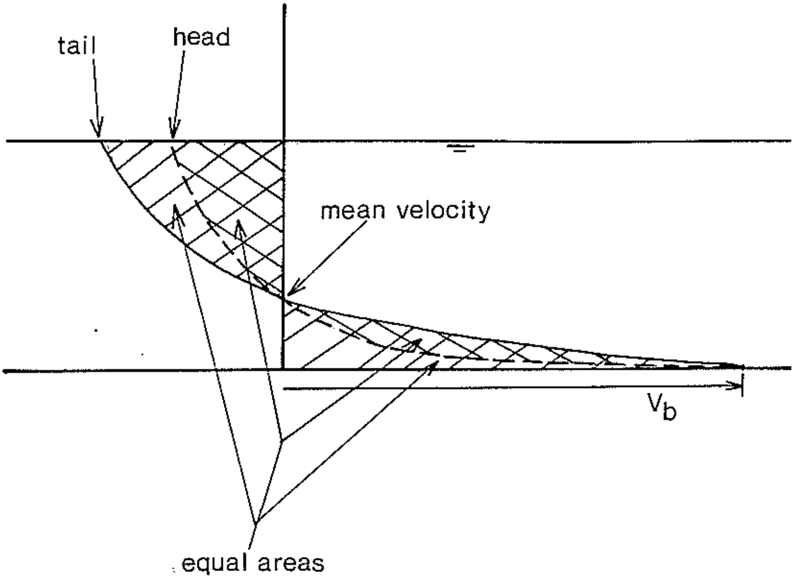


FIG. 19—Idealised velocity profiles.

same height above the bed in both body and tail regions. By idealising these profiles somewhat (Fig. 19) it is seen that the near-bed velocity gradient, and hence bed shear stress, must be greater beneath the body than beneath the tail, thus greater scouring of a channel bed can be expected during the passage of the head and body of a debris flow than during passage of the tail.

The very small velocity gradient in the upper part of the body, together with the visual appearance of the surface, explains why, in a field situation, a rigid plug flow is often reported in debris flows (e.g., Johnson, 1970). The present tests, however, support the conclusion of Iwamoto and Hirano (1981) that slow shear occurs throughout the body region and no rigid plug is present. This conclusion is supported by the viscometer experiments of Phillips (1988) using field debris-flow materials. Rigid-body effects do not occur in debris flows and cannot be invoked to explain their characteristics.

The lack of a rigid plug seems at first surprising since, at the concentrations measured in the flow body, the grain mass could be expected to resist shearing to a significant extent by virtue of intergranular friction. Close observations of grains in motion in this region showed a significant amount of high-frequency, small amplitude up-and-down motion, probably the result of vibrational energy being transmitted from the underlying high-shear region. Such vibration is known to reduce internal friction considerably (Davies, 1982; Bjerrum *et al*, 1961), hence the shear strength of the grain mass becomes very small and the mass shears in response to quite low stresses.

Relatively low grain concentrations have often been reported at the bed and surface of grain flows (e.g., Savage, 1984) and simulations (Campbell and Brennen, 1985). At the bed the inability of grains to penetrate the solid boundary, plus the very high shear rate and hence very energetic grain collisions, causes a low concentration. Close to, and at, the flow surface the overburden pressure is low or zero and grains are able to disperse much more easily than is the case lower in the flow, hence again concentration is lower here also (Fig. 16).

The decrease in grain concentration towards the rear of the wave corresponds to the observed change from slow semi-rigid shearing at the front to more rapid, fluid shear at the tail. The highest concentrations occur in the head, in spite of the somewhat higher grain velocities here as shown by path-lines (Figure 15), and must be associated with the highly non-uniform grain flow conditions.

Flow Regions and Types. The regions of the wave in which different types of flow occurred were visually quite distinct; that, together with the obvious changes of velocity profile between the body and tail, implies that sharp, rather than gradual, transitions separate the flow regions.

In the slow shear flow of the upper body it was noticeable that grains in motion tended to form quite long chains, 5 to 10 grains long, aligned often at a moderate angle (~ 20°) to the channel bed. Such a phenomenon has been predicted by Savage (1984) in dry grain flow and has been observed by Campbell and Brennen (1985) in a computer simulation of dry grain flow. Its appearance in the slow grain-in-fluid shear may have significant implications for the theory of grain flows.

Knowledge of slow shear flows, such as occur in this region, has been summarised by Tüzün *et al* (1983). The two most promising approaches to analysis of slow shear flows are theory and kinematic modelling, but there is no general agreement on the basic principles of this type of flow. Severe experimental difficulties have bedevilled studies of slow shear flow, and it may well be that the moving-bed channel offers a better opportunity to observe the phenomenon.

The high-shear zone underlying the slow shear region is a necessary transition, given that there is at the bed a layer of grains which has a low velocity relative to the bed. The thickness of the high-shear layer is consistently close to 25 mm or 5 to 6 grain diameters; this has also been found in other studies (Tüzün *et al,* 1983) and a theoretical explanation has been proposed by Bridgewater (1980).

The tail of the wave, as has been mentioned, is a region of fluid-like flow, and the velocity profiles are reminiscent of laminar flow. The surface of the flow is disturbed by momentarily protruding grains and by some unsteadiness due to rollwaves entering the region from upchannel.

Behaviour of Large Grains. When 8-mm diameter grains are present within a shearing body of 4-mm diameter grains, the large grains tend to be carried up to the surface of the flow, and thence forward to the front of the flow by the higher surface velocity, if the flow depth is less than about 25 mm. With a deeper flow than this, the tendency is very much weaker. Hence in shallow waves the large grains accumulate at the front of the wave, whereas in deeper waves they are more or less uniformly dispersed throughout the flow.

This behaviour may be related to the variations of flow type present between deep and shallow waves. A shallow wave, less than about 25 mm deep, does not exceed the depth of the high shear zone (about 6 grain diameters) which underlies any slow shear zone, so no slow shear zone is present and the wave consists only of a head and a tail. Hence as soon as a large grain moves rearwards from the head close to the bed it tends to rise through the fluid flow, reaching the surface and being convected back to the front of the wave again. In a deeper wave, by contrast, there will be a slow-shear body region present behind the head, through which a large grain will find it more difficult to rise, and such a grain thus travels much farther back in the wave before reaching the surface.

The reason for the tendency of large grains to rise to the surface of a body of smaller shearing grains has been suggested by Bagnold (1956) and Takahashi (1978) to be the excess dispersive pressure experienced by a larger grain in inertial shearing conditions, which will tend to force the grain towards the surface in the direction of decreasing shear rate. A kinetic sieving process which causes grain segregation independently of flow regime has also been suggested by several authors, most recently by Suwa, Okuda and Ogawa (1983, 1985), and has been demonstrated in simulations of oil-shale flows by Walton (1983). Wood (1986) describes a similar process: "During vibration any upward movement of the larger grains will result in fines entering the space beneath, a process which ultimately drives the larger particles to the surface." In the present grain flows such a process could clearly occur more easily in the rapid-shear areas than in the semi-rigid slow shear zone of the upper body.

Field studies of the motion of large rocks in debris flows show that their diameter can be of the same order as the flow depth (Oliferov, 1970; it is not explained how flow depth was measured) and that they do *not* appear only at the front of a flow (Watanabe and Ikeya, 1985). There is thus a certain probability of the front of a debris flow containing large boulders, and this probability will increase as the boulder size increases in a flow of given depth. This point is important since the impact force due to a mudflow can be increased by a factor of six or so if boulders are present at the front of the flow (Watanabe and Ikeya, 1985).

IMPLICATIONS FOR DEBRIS FLOWS

The experiments described herein show many similarities between the grain-fluid waves and debris flow waves observed in the field. The experiments suggest aspects of debris flow behaviour and processes which are difficult to study in field situations, such as velocity profiles and zones of different flow types. However, the experimental situation is at best an *analogy* of a field debris flow, not a theoretically justified model, and it is not wise to extrapolate results from the laboratory to the field unless there are strong independent indications that the extrapolation is justified. The laboratory waves are idealised in that they travel at constant velocity relative to the bed in a uniform channel and are unchanging in shape and size with time — all characteristics that are unlikely to occur in the field.

Nevertheless, the behaviour and nature of the laboratory waves have some significant implications for improving the understanding of debris flows.

(a) The most significant general implication is that the occurrence and major characteristics of debris flow waves can be explained by shearing of large grains in an intergranular fluid slurry, and that the nature of this slurry does not strongly affect the wave behaviour so long as shearing of the large grains is macroviscous, causing the flow to be non-depositional. Thus, provided the slurry density and apparent viscosity are sufficiently large, it does not matter whether the slurry behaves as a Newtonian, Bingham or power-law fluid; wave behaviour is controlled by the large grains. The major features of the experimental waves — their evolution, shape, size, velocity distribution and reaction to various stimuli — result from the shearing behaviour of the large grains, and it is implied that the same will be true of field debris flows.

(b) The form (longitudinal section), surface appearance and surface velocity of laboratory waves correspond at least qualitatively with those of debris flow waves. This suggests that the maximum height of a debris flow wave is limited by the same factor that limits the laboratory wave height, namely the value of du/dy below which slow shear flow occurs. If this is the same in both situations at du/dy ≃ 11/sec. (field data of Mizuyama and Uehara (1980) suggests that this may be approximately true) then

$$v \simeq 11\ H \qquad (3)$$

where H is the maximum wave height and v the mean flow velocity. If in addition an empirical depth-velocity relationship for debris flows is available (e.g., Mizuyama and Uehara, 1980; Hungr *et al,* 1984; Costa, 1984), then the two equations can be solved simultaneously to give limiting values of v and H. Knowing H, the wave shape for various volumes of flow material can be predicted knowing the channel bed slope and assuming that the tail surface slopes at 7° to the horizontal. This method of prediction is extremely approximate, but any estimate for H is of value in assessing the potential damage from a debris flow. The unsteady behaviour of real debris flow waves will differ qualitatively from that predicted on the above basis — for example, if a wave is slowed by an obstacle in the channel, steady flow theory predicts that the wave height will decrease; in fact, during deceleration the wave will become higher due to faster-moving material accumulating from upstream.

(c) The prospect for developing a straightforward and realistic analytical explanation of debris flows is not good. Even the highly simplified and idealised experimental waves described herein involve processes (e.g., slow shear flow) which cannot at present be described analytically, hence debris flows, with unsteady flow, changing wave shape, irregular channel and a wide range of grain sizes and shapes, seem unapproachable at present. However, the present work demonstrates the nature of this complexity, allowing better judgement of the appropriateness of simplified predictive methods.

Such methods, then, must be developed if prediction of debris flow hazards is to be rationally possible. Being non-fundamental they must be based on good field data describing debris flow behaviour, and this is an area in which a concerted effort is needed if substantial progress is to be made. Field data are extremely difficult to collect, but the techniques developed at Jiangjia (Li *et al,* 1983) and Mt Yakedake (Okuda *et al,* 1980) can yield high-quality, if restricted, descriptions of field events. Pierson (1985) discusses the problems involved in setting up and running a measuring station including the use of in-channel pressure sensors from which a vertical velocity profile can be inferred. One technique not yet attempted in debris-flow channels is the use of previously-buried vertical scour chains to indicate the maximum depth of scour and subsequent fill which occurs during the passage of a debris flow. These have been used very successfully in gravel-bed rivers, but their recovery following a debris flow is problematical. Given the extreme uncertainty about the location of the base of fluid flow during a debris flow, however, and the lack of other alternatives, the use of scour chains should be attempted.

(d) Successes have been achieved in granular mechanics using computer simulations of grain flow (Campbell and Brennen, 1985; Walton, 1983). Computer simulations may have considerable potential for predicting the motion and characteristics of field debris flows. The basis of such simulations lies in calculating individual grain motions following collisions, and keeping account of these motions for a large number of grains. The number of calculations involved is very large, but the calculations themselves are relatively simple. Simulations can add to the basic method such field complications as irregular channel boundaries, irregular grains, etc. To date, computer simulations have been restricted to two-dimensional situations and dry flows; extension to three dimensions would greatly increase computer memory requirements. A reasonably realistic debris-flow comprising irregularly-shaped coarse grains of a range of sizes shearing in a dense slurry in an irregular channel could be simulated, given the rapid developments in computer technology during the past few years.

CONCLUSIONS

1. The major features of debris flow waves are present in the small-scale waves of P.V.C. grains in water reported herein.
2. The height of a steady-state grain flow wave is limited by the occurrence of slow shear flow when the mean velocity gradient in a vertical reaches a lower critical value which may be of the order of 10 $\sec^{-1}$ or less.
3. More than one type of flow is present within a grain flow wave; even in the simple, idealised waves of these experiments the presence of slow shear flow makes analysis very difficult, and it appears that no analytical solution for debris flow problems is feasible at present. The most promising future prospect for "analytical" prediction seems to be computer simulation on a grain-by-grain basis.
4. At present, prediction of the hazards to be expected from debris flows must be based on empirical field data. There is a severe shortage of such data, and strenuous efforts should be made to improve the quality and quantity of the data available.
5. The moving-bed channel is an extremely useful way of studying wave phenomena and is ideal for the homogenous non-depositing character of debris flows.

ACKNOWLEDGEMENTS

I thank Prof. Dr D. Vischer, of the Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH-Zürich, Switzerland, for providing experimental facilities and technical assistance; the Eidgenössische Anstalt für das forstliche Versuchswesen, Birmensdorf, Switzerland, for financial support, and Lincoln University, New Zealand, for sabbatical leave support. I record my gratitude to Dieter Rickenmann, Martin Jaeggi, Kolumban Hutter and Chris Phillips for encouragement and ideas. Anonymous reviewers have helped a lot in improving this paper.

REFERENCES

Bagnold, R.A. 1954: Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proc. Royal Soc. London, 225a:* 49–63.

Bagnold, R.A. 1955: Some flume experiments on large grains but little denser than the transporting fluid. *Proc. Inst. Civil Eng., Pt. 3, Paper No.6041:* 174–205.

Bagnold, R.A. 1956: The flow of cohesionless grains in fluids. *Phil. Trans. Royal Soc. London, 249A:* 235–297.

Bagnold, R.A. 1963: The nature of saltation and of 'bed-load' transport in water. *Proc. Royal Soc., London, 332A:* 473–504.

Bagnold, R.A. 1974: Fluid force on a body in shear-flow; experimental use of 'stationary flow'. *Proc. Royal Soc. London, 340A:* 147–171.

Benda, L.E. 1985: Delineation of channels susceptible to debris flows and debris floods. *Proc. Int. Symp. on Erosion, Debris Flow and Disaster prevention, Tsukuba, Japan:* 195–202.

Berlamont, J.E.; Vanderstappen, N. 1981: Unstable turbulent flow in open channels. *J. Hydraul. Div., ASCE, 107:* 427–449.

Bjerrum, L; Kringstad, S; Kummeneje, O. 1961: The shear strength of fine sand. *Proc. 5th Int. Conf. Soil Mech. and Found. Eng. 1:* 29–37.

Bridgewater, J. 1980: On the width of failure zones. *Geotechnique, 30:* 533–536.

Campbell, C.S.; Brennen, C.E. 1980: Computer simulation of granular shear flows. *J. Fluid Mech., 151:* 167–188.

Costa, J.E. 1984: Physical Geomorphology of Debris Flows. in *Developments and Applications of Geomorphology,* ed. J.E. Costa and P.J. Fleischer. Springer.

Costa, J.E.; Jarrett, R.D. 1981: Debris flows in small mountain stream channels of Colorado and their hydrologic implications. *Bull. Assoc. Eng. Geol., 18:* 309–322.

Curry, R.R. 1966: Observation of alpine mudflows in the Tenmile Range, Central Colorado. *Bull. Geol. Soc. Amer., 77:* 771-776.

Davies, T.R.H. 1982: Spreading of rock avalanches by mechanical fluidization. *Rock Mech., 15:* 9–24.

Davies, T.R.H. 1985: The mechanics of large debris flows. *Proc. Int. Symp. on Erosion, Debris Flow and Disaster Prevention,* Tsukuba, Japan, 215-218, 1985.

Davies, T.R.H. 1986: Large debris flows: a macroviscous phenomenon. *Acta Mechanica, 63:* 161-178.

Davies, T.R.H. 1988: Debris flow surges — a laboratory investigation. *Mitteilung* Nr. 96, VAW, ETH-Zurich, Switzerland.

Eisbacher, G.H. 1982: Mountain torrents and debris flows. *Episodes 4:* 12–17.

Enos, P. 1977: Flow regimes in debris flow. *Sedimentology 24:* 133–142.

Gulliver, J.S.; Halverson, M. 1987: Open channel flow measurements in a moving-bed flume. *Proc. 21st Congr. IAHR, Melbourne:* 16–18.

Gulliver, J.S.; Halverson, M. 1987: Measurement of large streamwise vortices in open-channel flow. *Water Resour.Res. 23, 1:* 115–123.

Hungr, O.; Morgan, G.C.; Kellerhals, R. 1984: Quantitative analysis of debris torrent hazards for design of remedial measures. *Can. Geotech. Jnl. 21:* 663–667.

Ikeya, H. 1976: *Introduction to Sabo Works.* Japan Sabo Association, 168 p.

Ikeya, H. 1981: A method of designation for area in danger of debris flow. *Proc. Int. Symp. on Erosion and Sed. Transport in Pacific Rim Steeplands, IAHS Publ. No. 132:* 576–588.

Innes, J.L. 1984: Debris flows. *Progress in Phys. Geog:* 469–501.

Iwamoto, M.; Hirano, M. 1981: Mechanical characteristics of debris flow. *Proc. XVII IUFRO World Congress, Japan:* 11p.

Johnson, A.M. 1970: *Physical Processes in Geology.* Freeman Cooper and Co: 577 p.

Johnson, A.M.; Rodine, J.D. 1984: Debris Flow in: *Slope Instability* ed. D. Brunsden and D.B. Prior, Wiley: 257–361.

Li Jian; Yuan Jianmo; Bi Cheng; Luo Defu 1983: The main features of the mudflow in Jiang-Jia Ravine. *Zeit. Geomorph., 27, 3:* 325–341.

Li Jian; Luo Defu 1981: The formation and characteristics of mudflow and flood. *Zeit. Geomorph., 25, 4:* 470–484.

Mizuyama, T. 1981: An intermediate phenomenon between debris flow and bed load transport. *Proc. Int. Symp. on Erosion and Sed. Trans. in Pacific Rim Steeplands,* IAHS Publ. *No. 132:* 212–224.

Mizuyama, T.; Uehara, S. 1984: Observed data of the depth and velocity of a debris flow. *Shin-Sabo, 37, 4:* 23–26 (in Japanese).

Niyazov, B.S.; Degovets, A.S. 1975: Estimation of the parameters of catastrophic mudflows in the basins of the lesser and greater Almatinka Rivers. *Sov. Hydrol., 2:* 75–80.

Okuda, S. *et al.* 1980: Observations on the motion of a debris flow and its geomorphological effects. *Zeit. Geomorph., Supplband 35:* 142–163.

Oliferov, A.N. 1970: Transport of large rocks by mudflows. *Soviet Hydrology, 2:* 121–123.

Phillips, C.J. 1988: Rheology of Debris Flow Material. Unpubl. Ph.D. Thesis, Lincoln College, University of Canterbury, Christchurch, N.Z.

Pierson, T.C. 1980: Erosion and deposition by debris flows at Mt Thomas, North Canterbury, New Zealand. *Earth Surf. Proc., 5:* 227–247.

Pierson, T.C. 1981: Dominant particle support mechanisms in debris flows at Mt Thomas, New Zealand, and implications for flow mobility. *Sedimentology, 28:* 49–60.

Pierson, T.C. 1985: Field techniques for measuring debris-flow dynamics. *Proc. Int. Symp. on Erosion, Debris Flow and Disaster Prevention, Tsukuba, Japan:* 203–208.

Savage, S.B. 1984: The mechanics of rapid granular flows. *Adv. Appl. Mech., 24:* 289–366.

Savage, S.B.; Sayed, M. 1984: Stresses developed by dry cohesionless granular materials sheared in an annular shear cell. *J. Fluid Mech., 142:* 391–430.

Suwa, H., Okuda, S.; Ogawa, K. 1984: Size segregation of solid particles in debris flows, part 1. *Annuals, Dis. Prev. Res. Inst. Kyoto Univ., 272B-1:* 409–423 (in Japanese).

Suwa, H.; Okuda, S.; Ogawa, K. 1985: Size segregation of large boulders in debris flow. *Proc. Int. Symp. on Erosion, Debris Flow and Disaster Prevention, Tsukuba, Japan:* 237–242.

Takahashi, T. 1978: Mechanical characteristics of debris flow. *J. Hydraul. Div. ASCE, 104:* 1135–1169.

Takahashi, T. 1980: Debris flow on prismatic open channel. *J. Hydraul. Div. ASCE, 106:* 381–296.

Takahashi, T. 1981a: Debris Flow. *Ann. Rev. Fluid Mech., 13:* 57–77.

Takahashi, T. 1981b: Estimation of potential debris flows and their hazard zones; soft countermeasures for a disaster. *Natural Disaster Sc., 13:* 57–89.

Takahashi, T. 1983: Debris flow and debris flow deposition. *Advances in the Mechanics and Flow of Granular Materials, 2:* 699–718.

Tattersall, G.H.; Banfill, P.F.G. 1983: *The Rheology of Fresh Concrete.* Pitman, London, 356 p.

Tan Bingyan, 1985: The activity of debris flow in Chinese loess region and its prevention. *Proc. Int. Symp. on Erosion, Debris Flow and Disaster Prevention, Tsukuba, Japan:* 187–190.

Tüzün, U., *et al.* 1983: The flow of granular materials — II. Velocity distributions in slow flow. *Chem. Eng. Sci., 37, 12:* 1691–1709.

Walton, O. 1983: Particle-dynamics calculation of shear flow. In: *Mechanics of Granular Materials,* ed. J.T. Jenkins and M. Satake, Elsevier: 327–338.

Watanabe, M.; Ikeya, H. 1981: Investigation and analysis of volcanic mud flows on Mt Sakurajima, Japan. *Proc. Symp. on Erosion and Sediment Transport Measurement, Florence, IAHS Publ. No. 133:* 245–256.

Wood, P.A. 1986: Fundamentals of Bulk Solid Flow. *Report No. ICTIS/TR31, IEA Coal Research, London.*

Yesenov, U.; Degovets, A. 1979: Catastrophic mudflow on the Bol'shaya Almatinka River in 1977. *Soviet Hydrology 19. 2:* 158–160.