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Debris Flow Surges – A Laboratory Investigation

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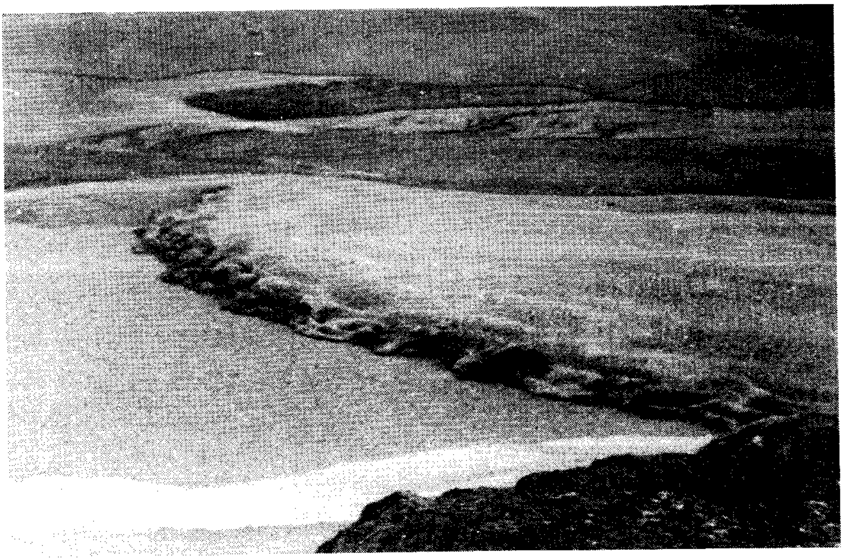

Frontispiece:
Large debris flow surge,
Jiangjia Ravine, China.
$H \sim 3m$, $U \sim 10m/s$.

Vorwort des Herausgebers

Die vorliegende Mitteilung enthält einen Bericht, den Dr. Timothy Davies vom Lincoln College in Neuseeland für uns verfasst hat. Dr. Davies war von August 1985 bis zum Mai 1986 Gast der Eidgenössischen Anstalt für das forstliche Versuchswesen der ETH (EAfV) und führte bei uns eine Anzahl Versuche zur Erforschung von Murgangbewegungen durch. Dabei kam seine Begabung, hydromechanische und sedimentologische Vorgänge in ihrer Grundsätzlichkeit zu erkennen und zu erklären, voll zur Geltung. Seine Aufgabe, eine Ausgangsbasis für unsere Forschungsprojekte und jene der EAfV zu schaffen, hat er so zu unserer vollen Zufriedenheit erfüllt. Dafür danken wir ihm bestens und freuen uns auf die weitere Zusammenarbeit mit ihm.

Wir danken hier auch dem Schweizerischen Schulratspräsidenten für die finanzielle Unterstützung sowie der EAfV für ihren umfassenden Beitrag, wobei wir insbesondere das Engagement von Dipl.Bau-Ing. Jürg Zeller und seinen Mitarbeitern hervorheben.

Möge dieser Bericht auch anderen Forschern dienen, die sich mit Murgängen befassen! Die verheerenden Hochwasserereignisse des Sommers 1987 im Alpenraum haben die Aktualität der Murgangforschung ja eindrücklich belegt.

Prof.Dr. D. Vischer

Zusammenfassung

Murgänge stellen in Gebirgsregionen ein bedeutendes Gefahrenpotential dar. Eine eingehende Analyse der Berichte von Murgangereignissen aus der ganzen Welt zeigt, dass solche Abflüsse schubweise auftreten und sich instationär verhalten, und dass dabei grosse Gesteinsblöcke in einem Brei aus Feinmaterial und Wasser bewegt werden. Die ausserordentliche Schadenswirkung ist bedingt durch das pulsierende Verhalten der Murgänge sowie durch ihre Fähigkeit, grosse Blöcke zu transportieren. Es gab bisher keine befriedigenden Erklärungsansätze für diese Eigenschaften; eine neue Erklärung ergibt sich mit dem Konzept von dispersiven Scherspannungen granularer Materialien, das zum Resultat führt, dass sich keine Körner aus der Strömung absetzen können, und mit der Betrachtung einer Oberflächeninstabilität (Rollwellen). Dieser neue Ansatz wird durch Naturmessungen unterstützt.

Eine Untersuchung des äusserst instationären, ungleichförmigen und schubweisen Abflusses ist sehr schwierig. Mit einer speziellen Versuchsrinne, auf deren Sohle sich ein Förderband aufwärts bewegt, wurden Entstehung, Verhalten und Eigenschaften von Wellen in sehr konzentrierten Korn-Flüssigkeits-Gemischen studiert. Diese Wellen verhielten sich ähnlich wie die Schübe (oder Pulse) von Murgängen. Die beobachteten Geschwindigkeits- und Dichteprofile in den Wellen geben Anhaltspunkte über die inneren Bewegungsabläufe in einem Murenschub. Aufgrund der Beobachtungen kann folgendes vermutet werden: Das Verhalten einer an Feststoffen konzentrierten Welle wird vor allem durch die groben Partikel bestimmt; die Front eines Pulses wirkt sehr erodierend, während der hintere Teil wahrscheinlich weniger erodiert oder sogar Material ablagert; die maximale Höhe (Abflusstiefe) eines Pulses wird durch den Geschwindigkeitsgradienten innerhalb des Abflusses bestimmt.

Die komplizierte Art der Partikelbewegungen innerhalb der Wellen lassen vermuten, dass eine einfache analytische Erklärung dafür kaum genügen kann; es existieren Zonen sowohl langsamer als auch schneller Scherung, und die Aussichten für einen nützlichen theoretischen Ansatz zur Beurteilung der Murganggefährlichkeit scheinen zur Zeit gering. Es besteht daher ein dringliches Bedürfnis nach dem Errichten einer Datenbank über Murenereignisse, damit empirische Ansätze geprüft und verfeinert werden können. Die besten Aussichten für eine detaillierte Analyse des Murgangverhaltens und für Voraussagen darüber versprechen die numerische Simulation der Partikelbewegung von Granulaten, zusammen mit der Anwendung von empirischen Modellen.

ABSTRACT

Debris flows are now recognised as a very significant hazard in hilly or mountainous regions. Collation of descriptive material from many parts of the world shows that debris flows are unsteady, pulsing-flow events, and that they consist of large solids shearing in a slurry of fine solids in water. The extraordinary debris-flow hazard results from the pulsing nature of the flow and its ability to transport large boulders; existing explanations of these phenomena are inadequate, and are superseded by consideration of dispersive grain stresses which lead to non-depositional flow, and free-surface ("roll-wave") instability. Field data support this new explanation.

Analysis of the highly unsteady, non-uniform pulsing flow is not feasible, so laboratory tests using a moving-bed flume studied 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 insights into the internal motion of debris flow pulses. It appears that wave behaviour is largely controlled by the large grains provided the slurry 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.

The complex nature of grain flows within the waves suggests that 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. An immediate need, therefore, is for

collation of a database of debris flow behaviour so that empirical models can be evaluated and refined. The best prospect for detailed explanation and prediction of debris flow behaviour is numerical simulation of individual grain dynamics, in combination with empirical models.

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NOMENCLATURE

C	volumetric concentration of grains
C_b	C for coarse grains
C_*	maximum value of C_b
C_s	C for slurry particles
D	grain diameter
F	Froude number $= v/(gh)^{1/2}$
F_c	critical value of F for roll-wave development
g	gravitational acceleration
G	criterion for macroviscous flow
h	flow depth
H	maximum wave height
Re	Reynolds' number $= vh\rho/\eta$
T	solid-transmitted shear stress
U	surge velocity
$u_{(y)}$	local velocity at height y above bed
v	mean flow velocity
$\mathbf{v}$	grain volume
V_b	bed (belt) speed
y	height above bed
α_v	internal friction angle of grain mass
β	channel slope
γ	bulk density (specific weight) of flow
γ_s	bulk density of slurry
η	dynamic viscosity of Newtonian fluid
η_a	apparent viscosity of non-Newtonian fluid
η_B	Bingham viscosity
η_T	total viscosity of grain-fluid mixture
λ	linear concentration of grains
σ	grain density
ρ	fluid density
τ	shear stress
τ_B	Bingham shear strength of slurry

1. INTRODUCTION:

In recent years there has been a growing recognition in the western world that debris flows are an important contributor to the geographic modification of many steepland valleys and fans. This has resulted in a dramatic increase in the number of studies of debris flow phenomena, and in greatly increased interest in the long-standing research programmes on debris flows in Japan, Russia and China. It is now clear that debris flows can be one of the most intense erosion phenomena known (Eisbacher, 1982) and are correspondingly destructive and dangerous where they can affect human life and works. In order to predict the occurrence and effects of debris flows, some degree of understanding of their behaviour is required; to date such predictions have been largely empirical and hence restricted in their applicability. Most of the analyses that have been attempted are highly idealised in assuming, among other things, steady uniform flow, an assumption grossly inappropriate for a phenomenon, the most striking characteristic of which is the extremely unsteady and non-uniform pulsing nature of the flow.

The objective of the work described in this report is to explore in a preliminary fashion the characteristics of the debris waves that occur in most destructive debris flows, and to indicate promising directions for further research. The apparatus developed to achieve this is rather unusual, and following a preliminary description and analysis of debris flow behaviour its principal limitations and potential are explained in some detail. The characteristics of the experimental debris waves are then described and discussed, and the implications of these results for the mechanics of field debris flows are outlined.

2. THE DEBRIS FLOW PROBLEM:

A typical debris flow event consists of a series of waves of material, comprising a small percentage of water mixed with a much larger percentage of solids (clay, silt, sand, gravel and boulders), which move rapidly down a steep channel as a result of rainfall or snowmelt in the catchment. These waves are often superimposed on "normal" flood flow in the channel though flow may cease altogether before and between the arrival of waves at a section. Debris flow waves have been reported to be up to 5 m high, moving at up to 13 m/s and with a bulk density of up to 2.5 T/m^3; 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 (see Frontispiece).

The practical difficulties of preventing damage from such events are obvious. Because the flow is highly non-uniform and carries with it huge volumes of sediment, maximum flow depths are much greater than would be the case in a normal water flood flow, and channel-side objects are much more susceptible to destruction; bridge 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 by pressure, abrasion and impact. Normal flood protection measures will probably be quite inadequate. The rarity of debris flows, although resulting in a low probability of occurrence in a given time period, means that when one <u>does</u> occur the chance of extreme damage is high because protection measures against such a rare event are not economically justified.

Equally obvious are the difficulties of studying and measuring debris flows in the field. Given that they occur at the height of high-intensity storms in highly eroded, unstable steeplands where access is not easy at the best of times, it is not surprising that even to see a debris flow, let alone be in a position to measure it, is a rarity. Chinese and Japanese workers have been able to record events in places where they occur much more frequently than usual, but even here the data acquired has been restricted to easily-measured variables such as surface velocity, surface level and the properties of the sampled flow material. Crucial variables such as the velocity distribution in a vertical, total flow depth (admitting the possibility of severe bed scour and/or fill during the passage of a wave) and variation of material composition in a vertical have not yet been measured.

The common alternatives to field measurement of a phenomenon are to reproduce it under controlled conditions (and perhaps at reduced scale) in a laboratory, and to analyse it on the basis of accepted theory. The former appears to be in principle a feasible proposition 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 that even at laboratory scale a very long channel would be needed 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, and also choosing the appropriate material mixture so that the small-scale flow behaves in the same way as a large field debris flow; scaling up the laboratory results to apply to the full-scale situation would also be at best a tentative procedure at the present stage of knowledge.

Theoretical analysis of a phenomenon requires at the very least 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 physical data are not sufficiently precise to allow these to be adequately tested, and most of the theories seem to roughly fit the available facts. The use of these theories for predicting debris flow behaviour is thus rather limited, and depends heavily on the use of empirical data rather than fundamental explanation of the phenomena.

The basic problem of debris flows, then, is to obtain an adequate description of the behaviour and characteristics of a debris flow wave; only then can an analysis be sensibly sought.

3. THE NATURE OF DEBRIS FLOWS:

A debris flow is fundamentally different from a 'normal' flow of water which transports sediment. In the latter, the solid sediment grains move in response to the gravity-driven flow of water past them. In a debris flow the 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 deposition of solid grains from a debris flow does not occur; under conditions such as a reduction of slope which would reduce the transport capacity of a water flow, and cause sediment to deposit, a debris flow will slow down en masse without any preferential deposition of solids (Benda, 1985; Costa and Jarrett, 1981). Hence the largely erosive nature of debris flows as reported by Tan Bingyan (1985). A further consequence of the nature of debris flows is that all components of the flow move at the same velocity, or distribution of velocities. These two characteristics are important in allowing a realistic simulation of debris flows using the moving-bed apparatus described below.

In terms of practical needs, 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.

From the above summary it is obvious that, in the writer's opinion, current understanding of debris flows and their processes is extremely limited - so limited, in fact, that any attempt at sophisticated analysis is quite inappropriate because of the lack of physical facts with which to check the analysis. The present work is an attempt to find a physical framework for debris flow behaviour, and the results and discussions are therefore expressed mainly in qualitative, physical terms. The trap of "mathematistry" has recently been described very clearly by Klemes (1986) in the context of hydrology, with the conclusion that with today's advanced analytical and computer methods too much research effort is expended in this direction and too little on physical investigations on which to base advanced analyses. This trap is therefore avoided in this report.

4. DEBRIS FLOWS - CURRENT KNOWLEDGE:

As mentioned above, there are in the literature many reports of debris flows in various parts of the world. Recent review papers (Johnson and Rodine, 1984; Costa, 1984; Innes, 1984; Takahashi, 1981a) summarise these and it is clear that despite many local variations of climate, topography, geology and vegetation, certain features of the flows appear consistently. 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).

In practical terms, the factors which lead to damage to streamside facilities are the surging, intermittent nature of the flow and its ability to transport large boulders. The lower-density, non-surging flow episodes are less destructive; however they may be more significant than the high-density flows in causing river problems farther downstream downstream since, though transporting less sediment per cubic metre of water, they occur much more frequently. The sediment transport capacity of low-density flows is presently under investigation at the V.A.W. with a view to the development of an extension to the recent equation for the bedload capacity of clear-water flows in steep channels (Smart and Jaeggi, 1983). This report concentrates on the surging of the higher-density flows.

4.1 Occurrence:

Not all rainstorms give rise to debris flows, even in regions where flows are common. Debris flows are most often observed immediately following bursts of extremely intense rain which occur from time to time in the course of a long-duration storm (Okuda *et al*, 1980; Pierson, 1980b; Ikeya, 1976; Niyazov and Degovets, 1975; Curry, 1966). It appears that the very intense rain, falling onto a previously saturated landscape with already high river flows, triggers the phenomenon. Exceptions to this are those catastrophic mudflows reported by Niyazov and Degovets (1975) which originated in the collapse of a glacial moraine and release of impounded lake water. Sharp and Nobles (1953) reported snowmelt-initiated debris flows.

It is also clear that a large volume of available sediment is a necessary condition for debris-flow occurrence. Many flows are associated with channels containing a deep bed of widely-graded alluvial material, fed by tributary streams flowing in steep, rapidly-eroding ravines with shattered lithology so that during heavy rain the sediment concentration in streams is high. Availability of sediment in the channel and on hillslopes may thus influence whether or not a particular rainstorm will give rise to a debris flow (Zhang *et al*, 1985).

4.2 Major Features:

Debris flows as reported vary widely in character. Some are barely distinguishable from normal water floods, having merely a very high suspended sediment concentration; their flow is turbulent and steady in the short term, and coarse material is carried as bedload at the base of the flow. These are often referred to as "hyper-concentrated" flows. At the other extreme are the very high-density (bulk densities up to 2.53 T/m^3 have been reported), extremely intermittent flows, in which pulses with large instantaneous discharges are separated by periods of zero flow. There does not seem to be a continuous variation of behaviour between these two extremes, however, and it appears that the sudden onset of pulsing in a previously steady flow is the result of some instability process. For example, Li *et al* (1983) report that in the Jiangjia Ravine, China, increasing flow rates carry sediment normally in increasing quantities until the flow rate reaches about 5 m^3/s, whereupon the flow ceases for up to 30 minutes; thereafter a series of large discrete slurry waves passes down the channel. Following the passage of the last wave, the flow becomes continuous again. It seems clear that the transition from steady to pulsing flow occurs abruptly and reflects a fundamental change in flow mechanics.

In a similar way, it appears to be almost invariably the pulsing flows which carry large boulders along with them; Pierson (1980b) for example, describes pulses in which large rocks appear at the flow surface, while in the turbulent non-pulsing flow between the surges coarse material was carried along at the base of the flow as normal bedload. The ability of a flow to transport large grains throughout its depth, then, is in some way associated with the surging process. Only one report (Li and Luo, 1981) seems to describe a non-pulsing flow of high density, but some ambiguity renders the description unclear; as shown later, in such large channels at very high flow rates, pulse amplitude may tend to reduce with distance downstream.

The other major features of debris flows are summarised in Table 1, in which 3 main types of debris flow are distinguished as follows:

Type 1 low density, continuous flow.

Type 2 high density, pulsing flow.

Type 3 high density, single pulse only.

Type 3 flows have been observed at Japanese field sites and in laboratory experiments, and have been the subject of extensive analysis (Takahashi 1978, 1980, 1981a, b). As will be seen later, the occurrence of only a single pulse may well reflect a different mode of origin for these flows, hence the need to distinguish them from Type 2 flows.

TABLE 1

DEBRIS FLOW CHARACTERISTICS

(after Davies, 1986)

Flow Type Characteristic	1	2	3
Flow	Steady	Pulsing	Single pulse
Appearance	Turbulent	Laminar	Laminar
Sizes present above bed	Fine	Fine + coarse	Coarse + fine
Coarse load	At bed	Throughout depth	Throughout depth
Density	≤ 1.6 T/m^3	≥ 1.8 T/m^3	≥ 1.8 T/m^3
Viscosity	$\simeq$10-100 x water	$\geq$1000 x water	$\geq$1000 x water
Velocity	Low; $\simeq$ 2 m/s	High; $\simeq$ 3-5m/s	High
Effect on bed	Depositional	Very erosive	Very erosive

The density limits given in Table 1 are very approximate, and will probably vary with local circumstances.

5. PREVIOUS EXPLANATIONS OF DEBRIS-FLOW BEHAVIOUR:

The most significant characteristics of debris flows are their pulsing nature and their ability to carry large particles at the surface of, or within, the flow without their sinking to the bed. Previous attempts to explain these phenomena are now discussed.

5.1 Pulsing Flow:

The intermittent nature of large debris flows is also seen in small debris flows and debris slides. In the latter case, observation has shown (Pierson, 1980b; Johnson, 1970; Broscoe and Thompson, 1969; Sharp and Nobles, 1953) that a pulse can be generated by the entry of a debris slide to a stream channel, forming a temporary dam; subsequent mobilisation of this material due to rising water level upstream results in a surge-wave travelling down stream. It seems unlikely, however, that this mechanism can satisfactorily explain pulsing in large debris flows, due to the volume of material which would be needed to dam a large channel full of water. Nor does it seem likely that the entry of realistically-sized debris slides to the channel would occur in such a time sequence that large waves could be generated by superposition of smaller ones. The pulsing of large debris flows seems more likely to be caused by some intrinsic instability of slurry flow in an open channel; certainly Niyazov and Degovets (1975) are of the opinion that mudflow pulsing results from channel processes, and their report of several large pulses resulting from a single initiating event supports this contention.

It is concluded that no detailed explanation for the pulsing of large debris flows has previously been available, but that it is likely to be the result of internal flow processes rather than from external stimulation of an intermittent nature.

5.2 Support of Large Grains:

Three independent mechanisms have previously been proposed to explain the ability of debris flows to carry large rocks which are not in direct contact with the stationary bed of the flow:

(i) The cohesive strength of the fine material in the flow (e.g., Johnson, 1970; Hampton, 1975, 1979; Middleton and Hampton, 1976; Rodine and Johnson, 1976).

(ii) Buoyancy due to excess pore-water pressure within the body of the flow (e.g., Hampton, 1979; Pierson, 1981).

(iii) Dispersive pressure caused by intergranular contact stresses resulting from grains shearing past each other (e.g., Bagnold, 1954, 1956; Takahashi, 1978, 1980).

These mechanisms are now examined in this order.

5.2.1 Cohesive Strength:

It has been shown that, when stationary, debris flow material has substantial yield strength (that is, it can resist an applied stress without yielding) due to the cohesion of the clay particles present (Pierson, 1981; Johnson, 1970) and is thus capable of supporting large grains. In this situation the excess weight of a grain is transferred to the ground below through the unyielding structure of the stationary material.

When the material is in motion, however, then by definition its yield strength has somewhere been exceeded, and a continuous unyielding matrix no longer exists to transfer the grain's weight to the ground. If general shearing is taking place within the flow, then no part of the flow can possess strength, and the imposition of an additional stress - such as placing a boulder in the flow - will result only in further changes in the rate of shear; a grain of excess density cannot then be supported by the flow material. Even if part of the flow is non-shearing, forming a rigid plug that moves with the flow (Johnson, 1970), this plug cannot be supported by any strength of the flowing material between it and the bed. A flowing fluid cannot simultaneously act as a solid. Only if all the flow material forms a rigid plug, which is sliding along the underlying ground without any continuous deformation, can the strength of the material support solids of excess density.

The experiments of Hampton (1975) apparently demonstrated the ability of a flowing Kaolin-in-water slurry to support larger heavy grains in the absence of suspension by turbulence, and in the absence of dispersive stresses between the larger grains. Since the volume concentration of the larger grains was about 10%, however, Hampton's claim that dispersive stresses were avoided cannot be sustained; Bagnold (1955) states that when grain concentrations reach about 10%, grain collisions become "a certainty" because the linear concentration becomes greater than unity, and dispersive stresses will therefore be present. It seems likely, then, that the "competence" of a flowing slurry to support heavy grains demonstrated by Hampton (1975) resulted from dispersive pressure rather than from any strength of the slurry (Hampton, 1979, p.754).

Casual experiment with slurry material shows that, when it is stationary, heavy stones will rest on the surface without sinking; as soon as the body of the slurry is continuously disturbed, however, the stones will sink to the bottom.

It is concluded that the concept of grain support by the cohesive strength of flowing debris is unrealistic.

5.2.2 Buoyancy:

Hampton (1979) and Pierson (1981) both envisaged that grains of excess density could be supported by buoyancy forces greater than those to be expected from the density of the flowing material, if the pressure of pore fluid within the flowing material increased with depth at a rate greater than hydrostatic. Pierson (1981) measured pore pressures in tanks containing stationary debris flow material, and also the rate of change of pore pressure following mixing; he concluded that since excess pore fluid pressures occurred following mixing, and dissipated only slowly (over several hours) grains could be supported by this mechanism for a length of time of the order of the duration of a debris flow. Hampton (1979) sampled the heavy grains present in the upper portions of stationary slurries at unspecified times after mixing, and claimed that the results supported the buoyancy concept.

Once again, the difficulty with this idea lies in transferring a principle, which is legitimate in a stationary slurry, to a flowing body of debris. Certainly, in a stationary body of debris flow material, connections between voids will be small and excess pore fluid pressures will dissipate only slowly; overlying heavy solids can be partly supported by this excess pressure since their excess weight is balanced, and transferred to the bed, by contained stationary columns of high-pressure fluid. In a shearing body of material, however, solid grains of all sizes are continuously moving relative to one another, and voids and their inter-connections will be continuously changing in location and geometry. Thus pore pressures will be able to dissipate rapidly (of the order of seconds or less) because pore fluid is able to move easily in response to a pressure gradient. Again, the flowing material is unable to resist an applied stress, and any pressure gradient will cause additional flow, and hence dissipate. If a rigid plug of debris is moving with the flow, because shear stresses within it are less than its yield strength (Johnson, 1970), then excess pore pressures can exist within it and will dissipate slowly. It is still the case, however, that this pressure cannot be transferred to the lower flow boundary through the shearing layer that exists between the plug and the flow boundaries, since excess pressures will dissipate rapidly in this layer.

It is concluded that the concept of grain support by buoyancy due to excess pore fluid pressures is not realistic.

5.2.3 Dispersive pressure:

Bagnold (1956, 1968), Lowe (1976) and Takahashi (1978, 1980) have proposed that the phenomena of debris flows can be explained by the concept that when solid grains are present within a shearing fluid, contacts between grains result in a tendency for grains to be forced apart, away from each other. The existence of this dispersive pressure is beyond question (Bagnold, 1954; Bailard and Inman, 1979) and the process implies that, under inertial grain shearing conditions (see below), large grains will be forced towards the low-shear region of grain motion, that is, to the surface of the grain layer. The further analyses of Lowe (1976) and Takahashi (1978, 1980) confirm the realism of the concept and its relevance some aspects of debris flow behaviour. It is the more puzzling, therefore, that while other investigators have given the dispersive stress concept brief consideration, they discard the idea in favour of less plausible ideas (Johnson, 1970; Pierson, 1980b).

It may be significant that most studies assume that grain interaction in a debris flow will be inertial in nature. According to Bagnold (1956), grain shearing will be inertial or viscous according as the grain flow parameter G^2 is greater than 1500 or less than 100; G^2 is given by

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

where σ = grain density, D = grain diameter, T = solid-transmitted shear stress ($\simeq$ total shear stress at high grain concentrations), λ = linear grain concentration (= grain diameter/mean radial separation distance) and η_a = apparent dynamic viscosity of intergranular fluid. In inertial grain shearing, momentum is transferred among grains by impulsive contacts, that is, grain momentum resulting from a collision is not all transferred to the intergranular fluid between successive grain contacts. In viscous grain shearing, grain momentum resulting from a collision is entirely dissipated by fluid friction before the next collision. Bagnold (1956) shows that grains will disperse at uniform concentration throughout the flow only if $G^2 \leq 100$, which, if the intergranular fluid is water, sets an upper limit of $D \simeq 50$ microns for grains of quartz density. This appears to explain the existence of slurries of clay particles in water, which do not show a concentration gradient with depth (Bagnold, 1956; Carter, 1975).

It appears, however, that the grain collision conditions in debris flows, in which many grains are very much larger than 50 microns, must be inertial, and the uniform dispersion of large grains through the whole flow depth is not predicted by the dispersive stress analyses of Takahashi (1978, 1980) or Lowe (1976) (although it is assumed by Bagnold (1968)).

None of these mechanisms yet offers any explanation of the pulsing behaviour of large debris flows.

6. PRESENT EXPLANATION:

Type 1 debris flows do not appear to differ from normal streamflow in any fundamental way. Their behaviour can probably be explained, therefore, by the normal processes of sediment transport by water, perhaps modified to account for the reduction of turbulence intensity by the fine material suspended in the flow. The high-density, pulsing Type 2 and 3 flows, however, appear to behave in a very different manner, and a different explanation must be sought. Type 3 (single-pulse) flows have been analysed with some success by Takahashi (1978, 1980) on the basis that such a flow occurs when a rapidly-increasing seepage flow of water first reaches the surface of a sloping sand or gravel deposit. The deposit can clearly contain only a small proportion of fine material, since its permeability must be high in order to allow significant seepage to occur. Experiment and theory, the latter based on Bagnold's inertial flow equations and assuming essentially that the debris flow is equivalent to intense bedload transport in a very shallow flow, shows that a single pulse will result; the association of debris flows in Japan with intense bursts of rain (Okuda et al, 1980) is in accord with this explanation, which cannot however explain the multiple-pulse events recorded in many catchments. Takahashi (1981b) and co-workers (Takahashi, Ashida and Sawai, 1981) have extended their analysis of type 3 flows to derive procedures for identifying hazard zones.

The following explanation of type 2 flows is based on the observed flow characteristics. It is at this stage a hypothesis only, and as such is complementary to, rather than superseding, other theories such as those of Takahashi (1978, 1980), Johnson (1970) and Johnson and Rodine (1984) with which it overlaps. Being developed from the practical aim of explaining and predicting the occurrence and height of debris flow surges, however, it does appear to offer a promising avenue for further investigation, and the experiments described later lend support to the realism of the concept.

The basis of the idea is that although a debris flow consists of a mixture of water and solids of many sizes, it can be realistically modelled as a 3-component system, the components of which are water, fine solids (up to 1 mm diameter) and coarse solids (more than 1 mm in diameter). Further, it seems likely that when a large concentration of fines is present, the fine solids and water will form a slurry in which the solids do not move very much relative to the water, and the whole flow can then be considered as a homogeneous, viscous, dense fluid with coarse grains dispersed in it. This assumption both simplifies the situation by reducing the number of independent components present and increases its versatility by allowing the density and viscosity of the intergranular fluid to vary. The idea has been proposed previously (Davies, 1985, 1986; Shen and Xie, 1985) and is here explored in greater detail.

The mechanics of flows in which high concentrations of coarse grains interact with an intergranular fluid are as yet but poorly understood (Savage, 1984), and in spite of many more recent and sophisticated analyses (e.g., Savage, 1979; Bailard and Inman, 1979; Savage et al, 1983) the pioneering work of Bagnold (1954, 1955, 1956) remains substantially intact as a simple and realistic approach to the problem. From the results of experiments in which various concentrations of neutrally-buoyant beads were sheared in the annular space between two vertical concentric cylinders, the outer of which rotated, Bagnold derived empirical relationships between grain concentration, rate of shear, fluid density and viscosity, shear stress and direct stress exerted by the fluid-grain mixture at the flow boundaries. It was clear from these experiments that when grain concentrations and fluid viscosity were low, or grain size and shear stress were large, the viscosity of the intergranular fluid had little effect on the boundary stresses, which derived mostly from grain contacts; this is Bagnold's "inertial flow" regime. By contrast, with the opposite conditions the stresses are significantly affected by fluid properties, and this is the macroviscous flow regime. As noted earlier, macroviscous flow is only to be expected in large-scale flows of quartz-density solids in water if those solids are very fine; thus all previous explanations of debris-flow behaviour based on dispersive stress have assumed inertial flow. If, however, the intergranular fluid is the slurry of fine grains in water, then its density and particularly its viscosity can be substantially greater than those of water and much larger grains can experience macroviscous shearing conditions in this slurry.

The significance of macroviscous shear in explaining debris-flow behaviour lies in Bagnold's (1956) deduction that large grains in a macroviscous flow of limited depth will be dispersed throughout the flow depth at more or less uniform concentration. This provides a theoretical explanation for the ability of debris flows to transport large boulders which are visible at or near the flow surface. Though not yet demonstrated experimentally, the deduction seems theoretically sound.

<u>The hypothesis is thus proposed, that the ability of a debris flow to transport large rocks depends on the occurrence of macroviscous flow conditions</u>.

Bagnold (1955) further shows that, when shear stress in a macroviscous flow of already high concentration increases (due to an increase in flow depth, or slope, or grain concentration), this increase of shear stress causes the grain-carrying capacity of the flow to <u>decrease</u>. In a normal, bedload-transporting flow such a decrease in capacity would cause large grains to deposit on the bed; since the large grains in a macroviscous flow are uniformly dispersed, however, and in fact form an integral part of the grain-fluid mix which constitutes the flow (moving at essentially the same speed as the intergranular fluid), deposition of the large grains is impossible. The only way in which fewer large grains per unit time can be transported, therefore, is if the velocity of the whole flow (grains and fluid) decreases. Such a decrease will cause more rapidly-moving flow from upstream to accumulate at the section of lower velocity, increasing the flow depth and shear stress there so that the flow capacity is further reduced. The original flow is thus unstable against a small disturbance and will tend to spontaneously develop alternating faster and slower, shallower and deeper reaches, which will move downstream as incipient surges.

The occurrence of macroviscous flow thus appears able to cause both the dispersion of large grains and, because the flow is non-depositional, the pulsing behaviour seen in type 2 debris flows. In the following section this idea is tested with field data.

6.1 Test: onset of pulsing flow

Bagnold (1954) gives eq(1) as the criterion for the occurrence of macroviscous flow. This can be expanded to (Bagnold, 1956)

$$G^2 = \frac{\sigma(\sigma-\rho)gD^2 \cos\beta C_b h}{\lambda\eta_a^2} \qquad \text{(D2)}$$

where ρ = density of intergranular fluid, g = gravitational acceleration, β = bed slope, C_b = volumetric grain concentration, and h = flow depth. If the intergranular slurry has a density of 1.5 T/m^3, then with typical values of h = 0.5 m, D = 0.05 m, β = 6°, C_b = 0.3 and λ = 3 the value of η_a required for macroviscous flow is $\approx$ 5 kg/m/s or about 5,000 times that of water. Laminar flow of the intergranular fluid, treated in this simple analysis as a Bingham fluid, is also a requirement for uniform distribution of coarse grains, and occurs at a Reynolds' number R_e of about 2500 (Zhang Hao et al, 1980; Quian Yiyang et al, 1980);

$$R_e = vh\rho/\eta_a \qquad (3)$$

where v is the mean flow velocity. If the velocity gradient of the flow is about 5 (see below), then under the above conditions $v \simeq 2$ m/s and $\eta_a = 0.6$ kg/m/s. Hence, under these "normal" flow conditions, $\eta_a \simeq 5$ kg/m/s is sufficient to cause macroviscous flow and grain dispersion.

From tests on the rheology of a debris flow, Dai et al (1980) show how the shear strength τ_B and Bingham viscosity η_B vary with concentration (Fig.1; note that τ_B is not the true yield strength of the slurry, but is obtained by back-extrapolation of the linear part of the curve to du/dy= 0) and it is interesting that Wan (1982) and D. Rickenmann (1985, V.A.W., E.T.H.-Zurich, pers comm) find very similar results with Kaolinite slurries. The apparent viscosity η_a of the slurry at a given shear rate can then be found (Fig. 1):

$$\eta_a = \frac{\tau}{du/dy} = \frac{\tau_B + \eta_B\, du/dy}{du/dy} = \eta_B + \frac{\tau_B}{du/dy} \qquad (4)$$

and Fig. 2 shows now η_a varies with slurry concentration C_s and du/dy. Various combinations of C_s and du/dy give $\eta_a = 5$.

Mizuyama and Uehara (1980) have reported the depths and velocities of debris flows in Japan, and their data indicate that in the pulses of debris flows the mean velocity gradient or rate of shear is less than about 5 or 10. Hence one can assume that at the onset of pulsing

$$du/dy \simeq 10 \qquad (5)$$

which from Figure 2 indicates that $C_s \simeq 0.27$ is the slurry concentration at the onset of type 2 flow, corresponding to a

Fig.1

Rheology of fine material slurry
(Dai et al, 1980).

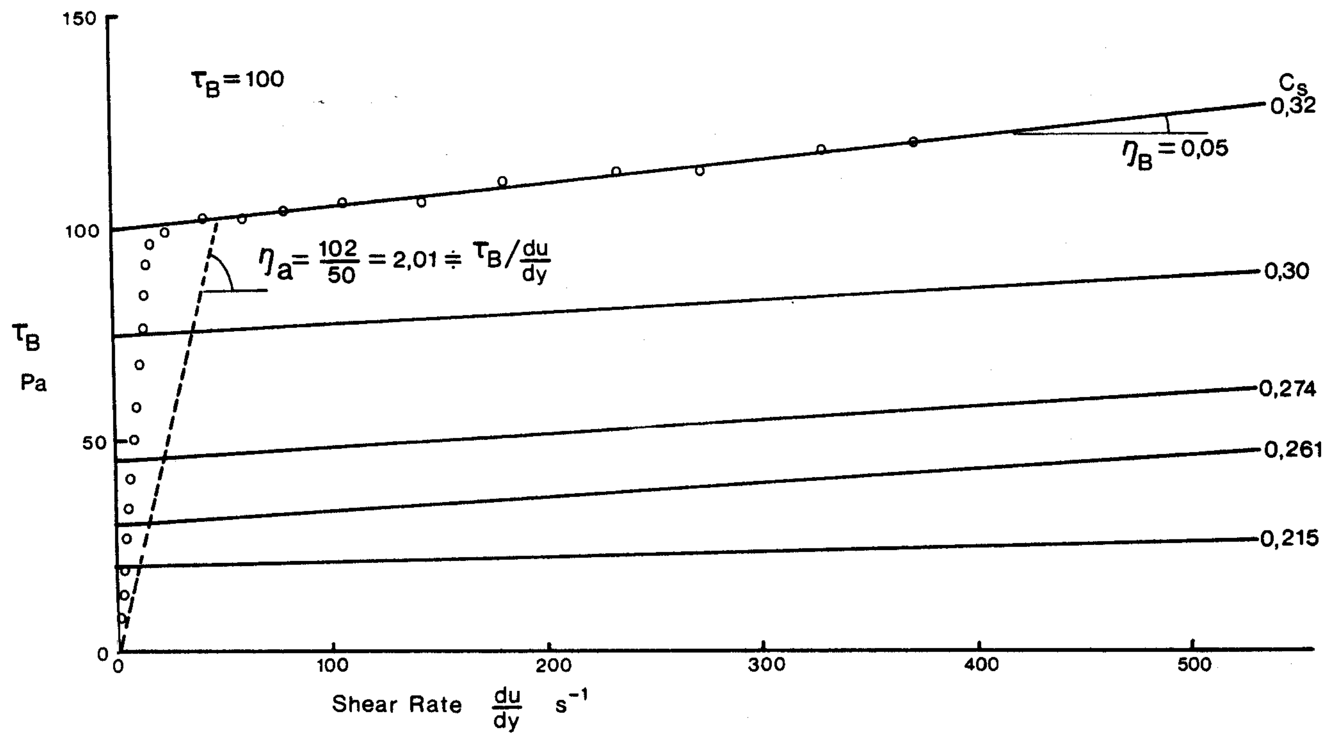
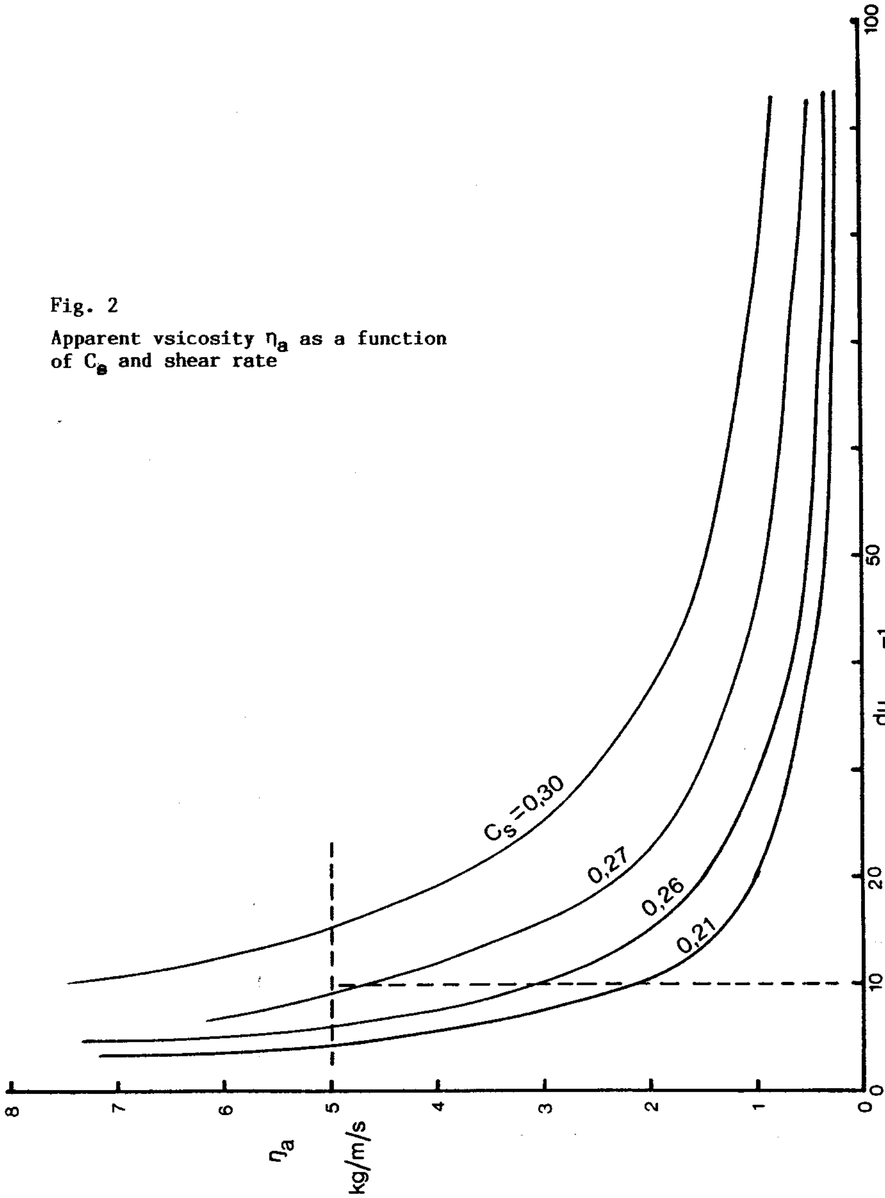


Fig. 2

Apparent vsicosity η_a as a function of C_s and shear rate



bulk density of $\gamma \simeq 1.4$ T/m^3. It should be noted, however, that at such low values of du/dy the idealised Bingham behaviour is unlikely to occur, which will limit the value of η_a to of the order of 10 kg/m/s as du/dy tends to zero.

The near-surface granulometry of some Chinese debris flows is shown in Fig.3. It is seen that at $\gamma = 1.59$, the size distribution of grains is strongly bimodal, showing that coarse grains are distributed throughout the flow as in type 2. At γ = 1.40, there is a slight indication that coarse grains are being dispersed, whereas at $\gamma = 1.38$ the size distribution is unimodal, and no coarse grains are present at the flow surface. It appears that $\gamma = 1.40$ indicates onset of the macroviscous flow, and confirms that in this case $\eta_a \sim 5$ is a realistic criterion for predicting the conditions under which a type 2 flow will occur.

Assuming, then, that for type 2 flows $\eta_a \geq 5$, then from (4)

$$\eta_B + \frac{\tau_B}{du/dy} > 5$$

or, since $\eta_B \sim 0.01$ (Dai <u>et al</u>, 1980; Wan, 1982),

$$\frac{\tau_B}{du/dy} > 5$$

and giving du/dy its likely value of about 5-10, the criterion for the occurrence of type 2 becomes

$$\tau_B \gtrsim 25\text{-}50 \text{ Pa} \qquad (6)$$

Chinese data allows (6) to be tested. In Quinshui Gully, Dachao River, $\tau_B < 10$ Pa and no type 2 pulses occur, whereas in the adjacent Hunshui Gully $\tau_b \sim 30\text{-}50$ Pa and pulses do occur (Li and Luo, 1981). In Jiangjia Gully type 2 flows occur with $\tau_B > 200$ Pa (although there are indications that the <u>slurry</u> τ_B may be less than this, see below), while in a different Hunshui

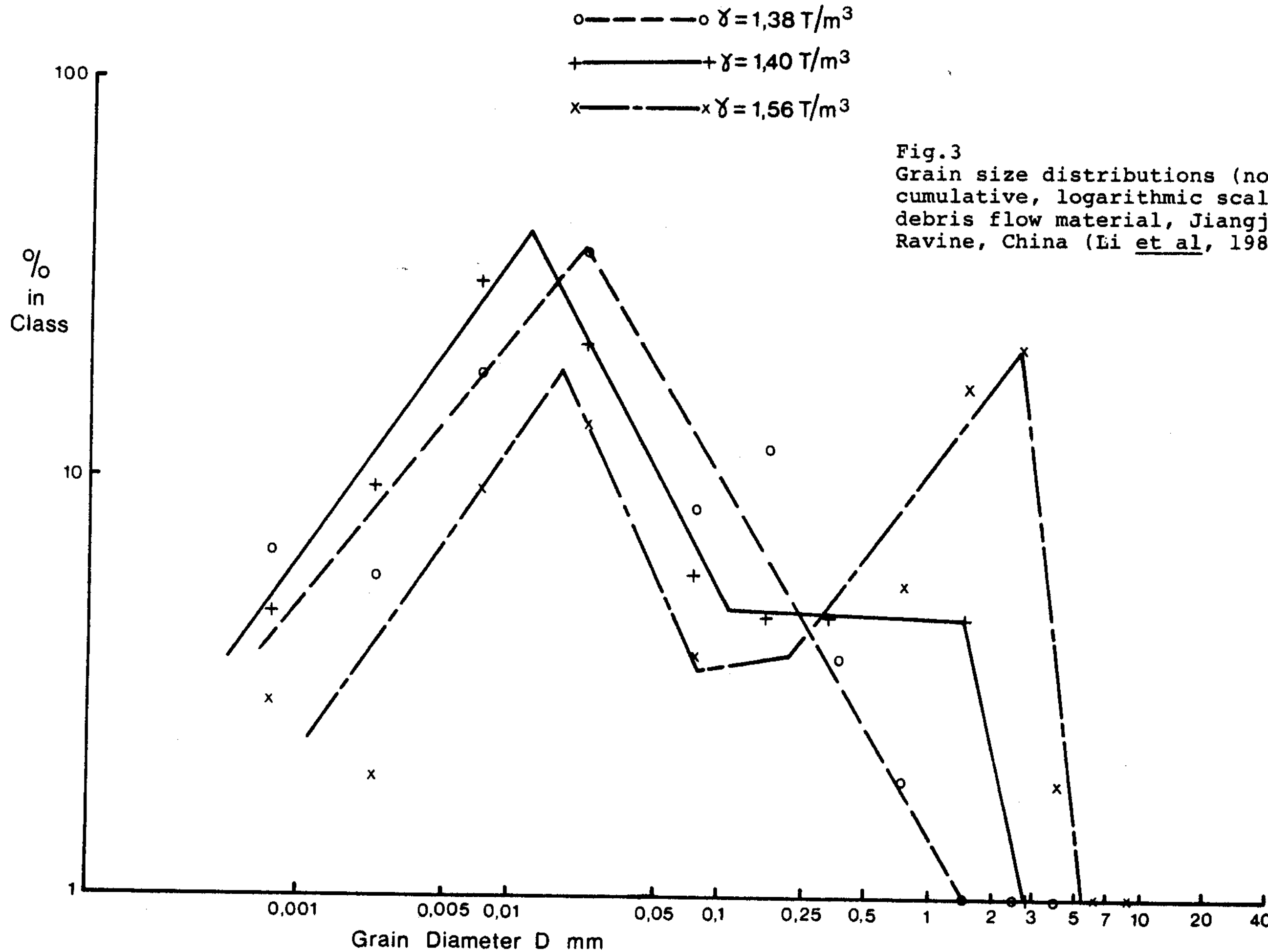


Fig.3
Grain size distributions (non-cumulative, logarithmic scales) of debris flow material, Jiangjia Ravine, China (Li et al, 1983).

gully τ_B ~ 6-20 Pa and turbulent, non-pulsing debris flows occur which may or may not be type 2 (Li et al, 1983; Zhang et al, 1985). The simplified criterion (6) thus seems to work reasonably well, and other published data support it (Pierson, 1980b; Costa, 1984; Johnson and Rodine, 1984). It is emphasised that the criterion is approximate due to the assumptions made in its derivation, but being theoretically based it should not be liable to much variation from place to place. It is convenient to use, requiring only viscometer testing of a field sample of slurry in water from the site to determine τ_B, thus uncertainties about clay and water chemistry are eliminated. It is clear, however, that (6) is not a sufficient criterion for type 2 flows; a further requirement is that enough sediment be available to be mobilised so that C_s can reach 0.25. This condition can be estimated in the field by geomorphological survey, and the third requirement, that sufficient rain must fall to start all these processes, can be evaluated (in principle) from meteorological data.

It thus seems reasonable to associate the onset of macroviscous flow with the presence of large grains in samples taken from the upper layers of a debris flow, indicating a high degree of grain dispersion.

6.2 Development of Surges:

In the steep, narrow gullies in which type 2 flows originate there are many channel boundary nonuniformities able to disturb the uniform flow of a dispersed slurry, and any of these will be able to initiate the instability which gives rise to incipient surge waves as outlined earlier. Such a surge will amplify rapidly and may well jam in a narrow channel due to the bridging of clusters of large grains across the channel, or between the bed and the free surface (see Savage and Sayed, 1984, p.411, and Walton, 1983, pp 332-333, for discussions of grain jamming; Bagnold (1955) also reports such an effect in an experimental flume). A blockage forms a stationary or slow-moving dam, behind which material still in motion builds up until the downstream force is sufficient to overcome the interparticle or particle-boundary friction, and the jammed material is set in motion again, moving away downstream as a surge wave.

Such a surge, with a large depth and a steeply-sloping front, will exert a very high shear stress on the bed and Bagnold (1956) shows that in some circumstances the bed may be scoured by a macroviscous flow to almost unlimited depth. This is in line with the very deep, narrow channels typical of pulsing debris flows in alluvial deposits (Pierson, 1980; Okuda et al, 1980).

Surges such as those described above will clearly occur in a more or less random sequence in small gullies, and some other mechanism is needed to explain how these surges can evolve into the much larger, more regular surge waves in the larger channels downstream described by Li et al, (1983) and Li and Luo (1981). These are up to 5 m high, 50 m wide and travel at speeds of up to 13 m/s, and it is inconceivable that they are the unmodified result of temporary blockages in small gullies, as consideration of the volume of material in a single pulse (up to 24,000 m^3) shows. A different mechanism is needed, and this may be found in the instability of a free-surface flow.

Due to an inherent imbalance between the gravity force driving the flow and the resistance provided by the channel boundaries, open channel flow of a Newtonian fluid is unstable and develops into a series of roll waves if the Froude number, F, exceeds some critical value F_c (Henderson, 1966). F is defined as

$$F = v/(gh)^{1/2} \qquad (7)$$

where v and h are mean flow velocity and depth respectively, and g is the acceleration due to gravity. F_c depends on the cross-sectional shape of the channel and on the Reynolds' number of the flow Re

$$Re = \frac{vh\rho}{\eta} \qquad (8)$$

where ρ is the fluid density.

Experimental and theoretical studies have investigated the occurrence of roll waves with the following conclusions:

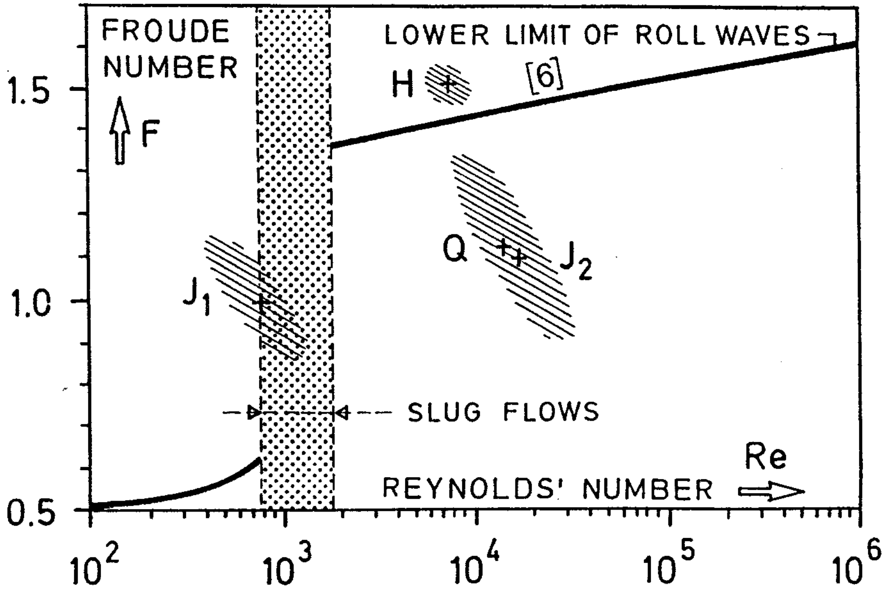
(i) In highly turbulent flow ($Re > 10^5$), F_c is close to 2 in a wide channel (Henderson, 1966).

(ii) As Re decreases towards the turbulent limit of about 1500, F_c decreases towards about 1.3 (Berlamont and Vanderstappen, 1981).

(iii) With $600 < Re < 1500$, flow instability decreases (Mayer, 1959; Ishihara et al, 1960). Slug waves may occur, which result from the development of slugs or patches of turbulent flow separated by laminar flow (Mayer, 1959; Binnie, 1959). These move more slowly than the underlying flow.

(iv) With $Re < 600$, in laminar flow, F_c is about 0.6 in an infinitely wide channel. As the width-to-depth ratio becomes smaller, however, F_c increases; with a width-to-depth ratio of 10, F_c is about 0.8 (Berlamont and Vanderstappen, 1981). Fig.4 summarises the flow conditions needed for roll wave development.

(v) With $F > 1.3$ ($Re > 1500$) the small initial roll waves



H HUNSHUI (INCIPIENT PULSING) J_2 = JIANGJIA (NO PULSING)
J_1 JIANGJIA (INCIPIENT PULSING) Q = QUINSHUI (NO PULSING)

Fig.4
Roll wave diagram with field data.

travel more slowly than the underlying flow (Mayer, 1959); as the waves grow, however, the intervening flow becomes shallower and slower and may vanish altogether (Holmes, 1936).

(vi) Roll waves in laminar flow always travel faster than the flow on which they are superimposed (Binnie, 1959).

(vii) The transverse spacing, amplitude and regularity of roll waves increases downstream (Mayer, 1959).

Because F in natural channels rarely, if ever, exceeds 1.0 when averaged over substantial channel lengths, and because Re in natural channels is usually of the order of 10^5 or so, it is clear that roll-wave instability is unlikely to occur. Roll waves do occur in artificial channels where flow boundaries are smooth and slopes steep (Brock, 1967).

Thus, if flow in a wide natural channel becomes laminar, due to the presence of a high concentration of fine sediment in suspension, conditions are suitable for roll waves to occur if $F \geq 0.6$. If the water surface is strongly disturbed, roll waves would grow in amplitude very rapidly (Mayer, 1959). Such waves can travel long distances while retaining their identity, and will tend to persist as a channel becomes wider and shallower downstream since high width/depth ratios are more conducive to the maintenance of the instability (Berlamont and Vanderstappen, 1981).

It seems unlikely that debris flow pulses can be caused by slug flows since the slug itself is turbulent, by contrast with the viscous appearance of debris flow waves, and turbulence would cause the dispersed grains to fall to the bed (Bagnold, 1956).

The mechanism of roll wave generation and development can thus explain the very large debris flow waves reported by Kang and Zhang (1980), Li et al (1983) and Niyazov and Degovets (1975) in wide valleys a considerable distance downstream of the debris source. Certainly, roll waves in debris flows are visually and geometrically very similar to roll waves in water.

One might reasonably question whether roll waves can in fact occur in a fluid which contains a high concentration of solid particles, since the studies mentioned above referred only to the flow of water. Roll waves have, however, been observed in the flow of sand down a slope through a body of still water (Davies, 1979) and in the grain-in-water experiments described below, so there seems no reason to suppose that the presence of solid grains would prevent roll wave formation. A plug flow, in which the upper part of the flow is rigid, would however prevent any free surface instability, and the presence of roll waves thus indicates that plug flow probably does not occur.

Li et al (1983) note that mudflows in the Jiangjia Ravine, China, begin to pulse when the previously continuous flow rate reaches about 5 m^3/s and the fluid density reaches about 1.6 T/m^3, equivalent to a solids concentration of about 35% by volume. In the 25 m wide channel they describe, a viscosity of about 500 times that of water would be required for flow to become laminar at Re = 500, and this is indeed the order of increase which would be expected with a solids concentration of the order of 35% (Chu, 1980; Dai et al, 1980). Thus, a measure of support is given to the hypothesis that the onset of pulsing corresponds with the occurrence of conditions suitable for the development of roll waves as the flow becomes laminar.

Field data from China (Li and Luo, 1981; Li et al, 1983; Zhang et al, 1985) allow a rough test of the hypothesis that large debris flow pulses are caused by a roll-wave instability. Fig.4 shows the lower limit of roll-wave development in water flows, and it is assumed that this applies also to debris flows. The conditions for the onset of pulsing in Jiangjia Gully are known, as are those for flows apparently at the limit of pulsing in Hunshui Gully, and these both plot close to the theoretical limit for roll-wave development. Non-pulsing flows in Jiangjia Gully and Quinshui Gully have also been measured and plot well within the stable region. The shading in Fig.4 represents the degree of confidence in the assumptions of flow viscosity and velocity which had to be made with these data. The field data thus do not contradict the roll-wave hypothesis, which seems worthy of further investigation. Fig.5(a) shows how random initial disturbances become organised and amplified by the roll-wave mechanism, and Fig.5(b) sketches the possible sequence of events in a debris-flow channel system.

The macroviscous flow criterion thus seems to be realistic as an indicator of when type 2 debris flows can occur, and leads to a conceptual idea of how pulsing flows originate. The further downstream development of pulses may be described by the free-surface instability model.

6.3 Discussion:

A frequently-reported result of debris-flow processes is the concentration of the largest rocks at the front of a flow (Suwa, Okuda and Ogawa, 1985). Takahashi (1981a) and Bagnold (1956) show that such an effect can result from the dispersive stresses

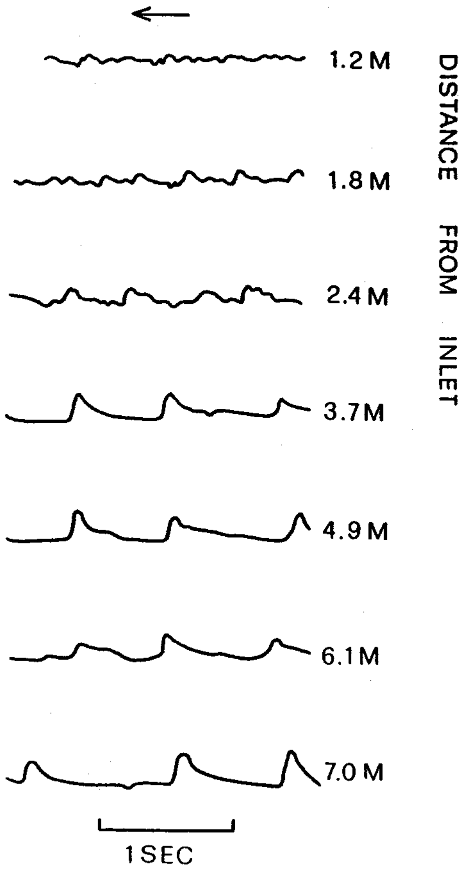


Fig.5(a)

Development of roll waves along a channel (Mayer, 1959)

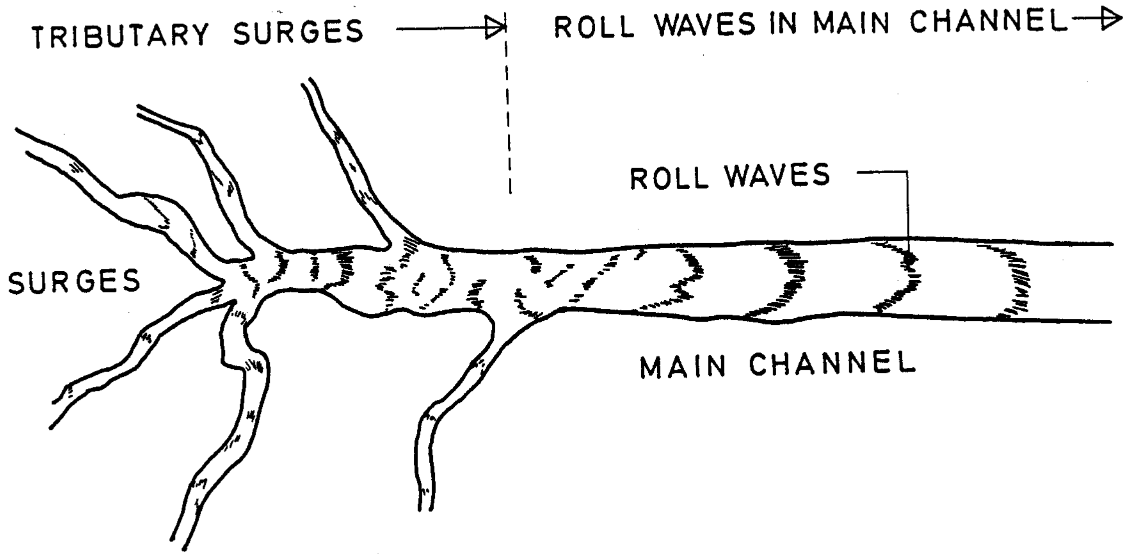


Fig.5(b)
Evolution of roll waves from
tributary surges.

on grains in an inertial flow, which cause the larger grains to migrate to the region of lowest shear, which is at the free surface. This being where the local flow velocity is greatest, the large grains are carried forward to the front of the flow and accumulate there, being somehow resistant to being re-buried by the advancing flow. If the flow is macroviscous, this mechanism is absent because the differential dispersive stress on different-sized grains is no longer effective - hence one would expect large grains to be found equally at all parts of the flow. Another mechanism, that of 'kinetic sieving' (Suwa, Okuda and Ogawa, 1985), is however still active and tends to cause small grains to accumulate at the base of the flow by, crudely, falling through the gaps between the larger grains. Hence the larger grains again tend to move to the free surface. Walton (1983) shows this effect in a computer simulation of the flow of realistically-shaped grains. Although kinetic sieving occurs quite slowly in the presence of a viscous intergranular fluid, it does explain the accumulation of large grains at the front of a macroviscous flow surge. The experiments described later throw more light on the behaviour of large grains.

The shear strength criterion suggested above as an indicator of those catchments in which type 2 debris flows could occur is obviously very approximate - perhaps precise only to within an order of magnitude - and therefore serves as a first-order approximation only. It can be compared with Takahashi's (1983) theoretical development, which resulted in a diagram indicating that type 3 flows can only occur in channels with bed slopes within a certain range, e.g., for $\sigma = 2.65$ T/m^3 and $\rho = 1.00$ T/m^3, the range is between at 15° and 24°. Insofar as most mountain catchments have channel reaches which fulfil this criterion it seems that only when no part of a drainage network exceeds 15° can the possibility of type 3 flows be discounted. However, many reports exist (e.g. Li et al, 1983; Pierson, 1980) of type 2 flows in channels of much lower slopes, hence Takahashi's criterion does not cover type 2 flows. Conversely, since type 3 flows can occur in laboratory channels with $\tau_B = 0$, and in the field with $\tau_B < 25$ Pa (Sawada et al, 1985), the type 2 criterion is not effective for type 3 flows; where the type of flow to be expected is unknown, both criteria should be considered.

There is some controversy over which part of a type 2 flow is erosive, and which depositional in behaviour. Pierson (1985), for example, states that the viscous early part of a surge is depositional, while the more turbulent later part causes the deep erosion characteristic of surging flows. In principle it seems that the deeper, denser, front part ("head") of the surge will cause the deep scour; indeed, if this is in fact the case, and the later part ("tail") is depositional, it may well appear that the opposite is true, because the decreasing flow depth in the tail will cause the surface to fall in elevation despite the increase in bed elevation, giving the impression of scouring. Since it is at present impossible to measure the stationary bed elevation during the passage of a high-density surge, no definite answer to this problem can yet be given, but the experiments described below do support the view that scour is likely to be greater below the front part of the flow.

From existing knowledge of debris flow behaviour, and simple analysis, it is thus possible to explain their occurrence and behaviour in a very preliminary fashion. Extension of the analysis to predicting the characteristics of debris flow pulses is however quite unjustified because of the very unsteady and non-uniform nature of flow in the pulsing situation. For this reason the series of experiments described below was undertaken in order to obtain some idea of the nature and behaviour of debris flow waves.

7. APPARATUS:

7.1 Principle and Constraints:

The form of apparatus used in this study is a moving-bed channel of the principle previously used by Iwamoto and Hirano (1981) in the context of debris flows, and by Bagnold (1974) and Gulliver and Halverson (1985, 1987) for clear-water flows. In this type of apparatus the bed of the channel moves upchannel at a constant velocity between stationary walls, while the flow material 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 indeed. Flow in a moving bed channel is thus a simple Galilean transformation of normal fixed-bed flow, in which 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 will be equivalent in both types of channel. Fig.6 illustrates the velocity profile of the moving-bed channel in comparison with that of a normal channel.

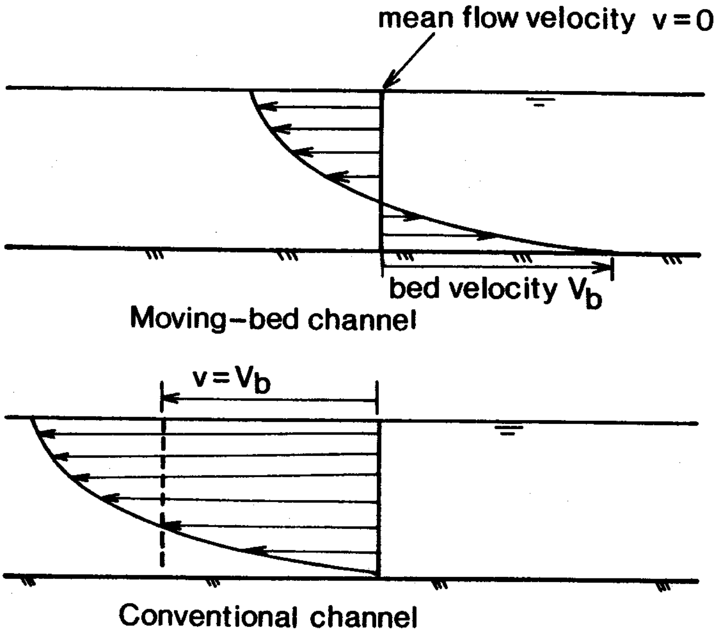


Fig.6

Velocity profiles in conventional and moving-bed channels.

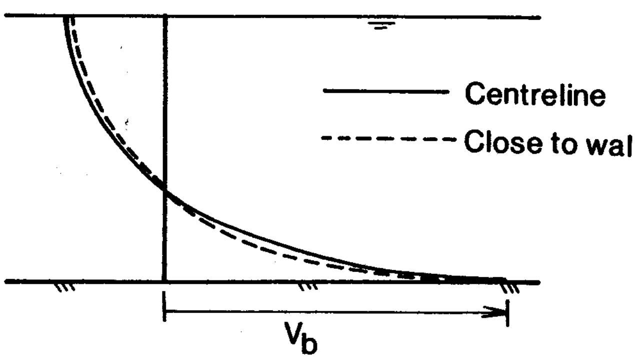


Fig.7
Effect of sidewall on velocity profile in moving-bed channel.

The major advantages of the moving-bed principle for pure 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 in causing a cross-channel velocity profile. 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 a conventional channel. The moving-bed channel can thus be much narrower than a conventional channel while still being representative of flow conditions in a wide prototype channel. The main wall effect in the moving-bed channel is close to the bed, where flow velocities are low relative to the bed and 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.7).

It is an unavoidable constraint of a simple moving-bed channel that all material, fluid and solid, initially within the experimental length of the 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 above 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 it appears that normal bedload transport, in which the sediment moves at a mean velocity much lower than that of the water, cannot easily 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 the investigation of 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 significant constraint inherent in the moving-bed apparatus is that any wave phenomenon which is stationary with respect to the channel walls represents a wave of unchanging shape moving downstream with a steady velocity in a field channel. While this is probably not the case with many debris flow waves in the field it is a reasonable starting-point and justifiable simplification for an investigation of this preliminary nature.

7.2 Description:

The moving-bed apparatus used in this investigation (Fig.8) had a useful working-section length of 2 m, and a channel width of 50 mm. The sidewalls were made of transparent 6 mm thick perspex. The channel bed was formed by the grooved side of a

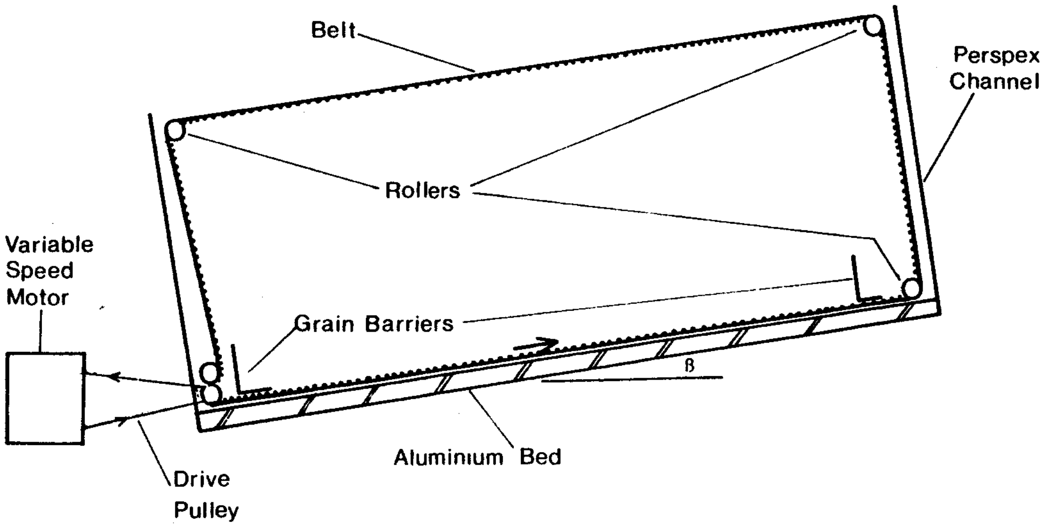


Fig.8

Diagram to illustrate main features of moving-bed flume.

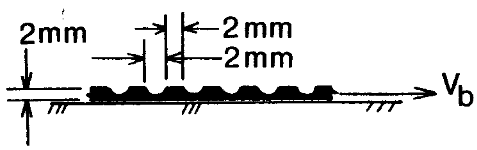


Fig.9

Longitudinal section of moving bed belt.

corrugated nylon belt, the grooves of which were perpendicular to the belt length and of the cross-section shown in Fig.9. The belt ran with its smooth side in contact with the smooth, plane aluminium bed of the flume, and was driven by a toothed drive wheel connected by another toothed belt to a variable-speed electric motor and controller. A system of smooth rollers conducted the belt around its circuit above the channel bed, and the 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 (Fig.10).

The solid grains used in this study were 4 mm long cylinders cut from 4 mm diameter P.V.C. rod; about 10% of them were painted white to act as tracers but were otherwise identical to the rest of the dark green grains. A small number of 8 mm long red grains were cut from 8 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.11). The experimental fluid used in most of the tests was tap water at room temperature; for a small number of tests the fluid dynamic viscosity was substantially increased (by a factor of the order of 100-fold) by dissolving in the water a small

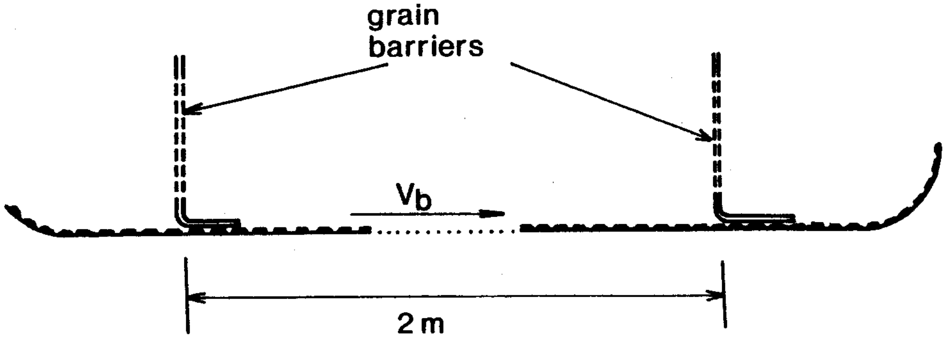


Fig.10

Arrangement of grain barriers at ends of moving-bed channel.

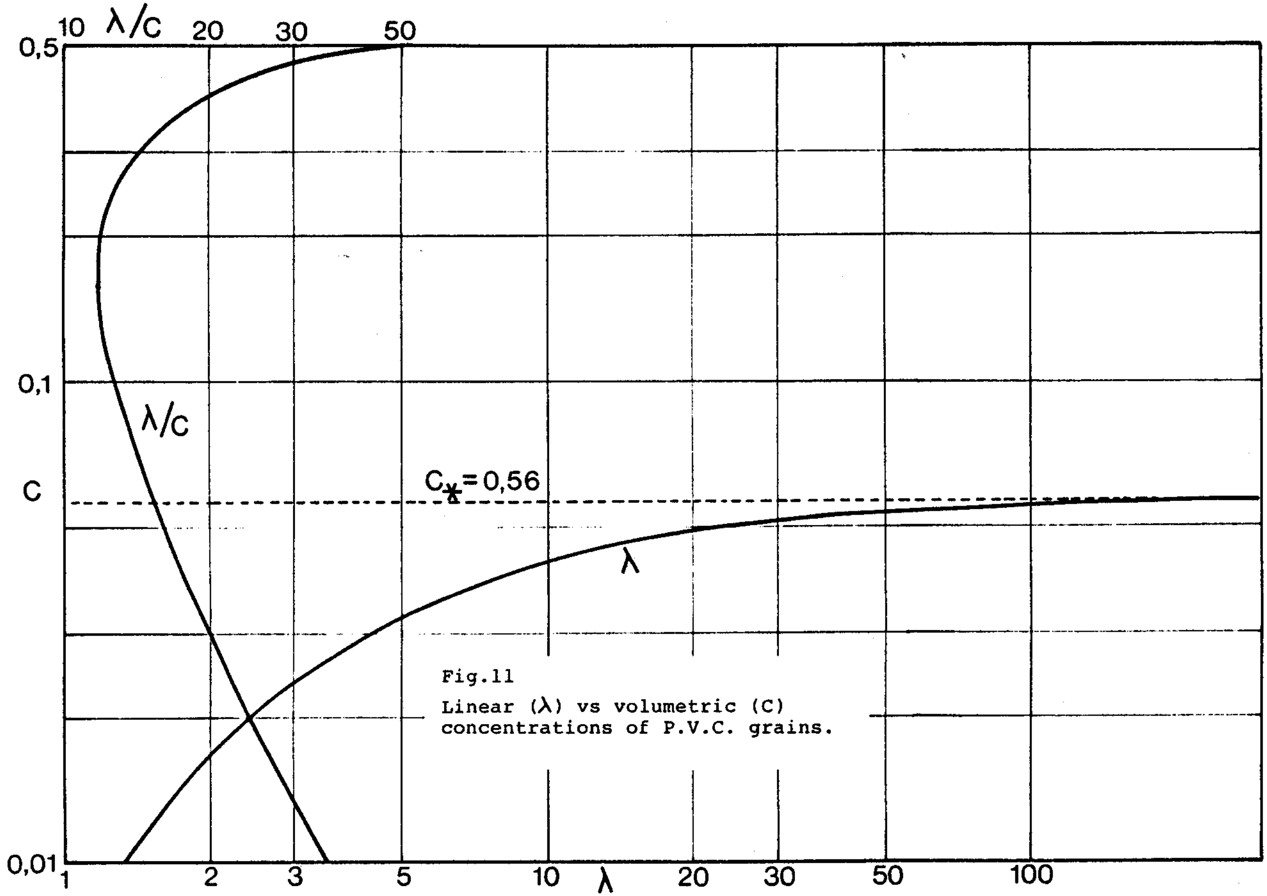


Fig.11
Linear (λ) vs volumetric (C) concentrations of P.V.C. grains.

percentage of cellulose solution. This increases the viscosity by forming long-chain molecules which resist shearing, and causes the fluid to become slightly pseudoplastic, but this latter effect was considered to be of negligible importance in the present work.

The range of channel slopes used was from 5° to 19° (8.7% to 34.4%) while the bed speeds ranged from 0.25 m/s to 1.17 m/s. The volume of grains in the channel was a controlled variable, changes in which caused different types and sizes of wave to form at given values of slope and bed speed.

The moving bed had a series of marks on its edge so that the instantaneous bed speed could be recorded by rapid-sequence photos, with a clock in the field of view, taken by a 35 mm motor-driven camera. In fact most of the necessary experimental 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 also taken and proved invaluable for subsequent reviewing of experimental conditions, and for tracing individual particle trajectories in the waves. A copy of this video tape is held at the V.A.W.

7.3 Behaviour:

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

Fig.12a 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 that 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 in order to re-establish equilibrium between gravitational and resistance forces. The limited volume of water available cannot now 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.12b). 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.12c). 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.13a, 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 down to the lower end of the flow and cause the end wave to increase in height, forming a bulbous wave of high concentration (Fig.13c). It is this bulbous end wave, and its behaviour, which is studied in the series of experiments described herein.

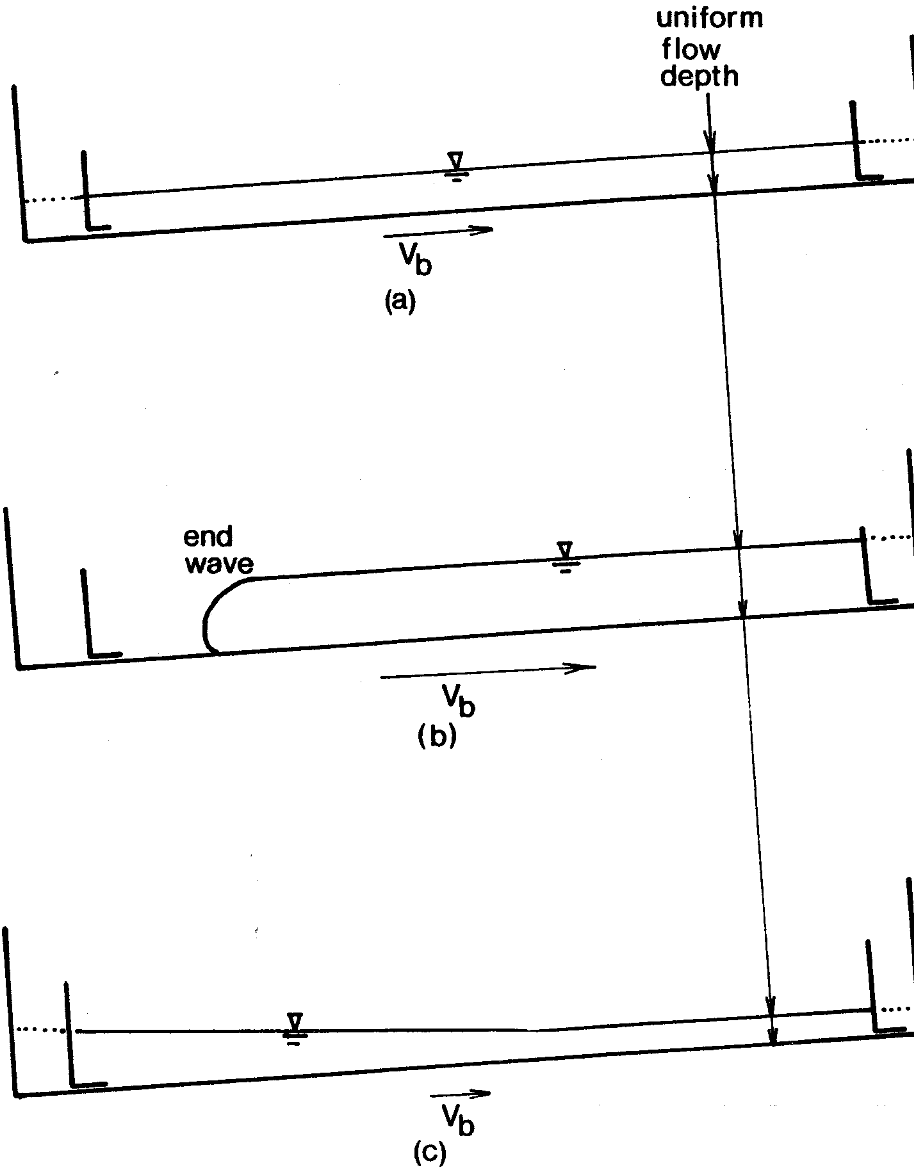


Fig.12

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

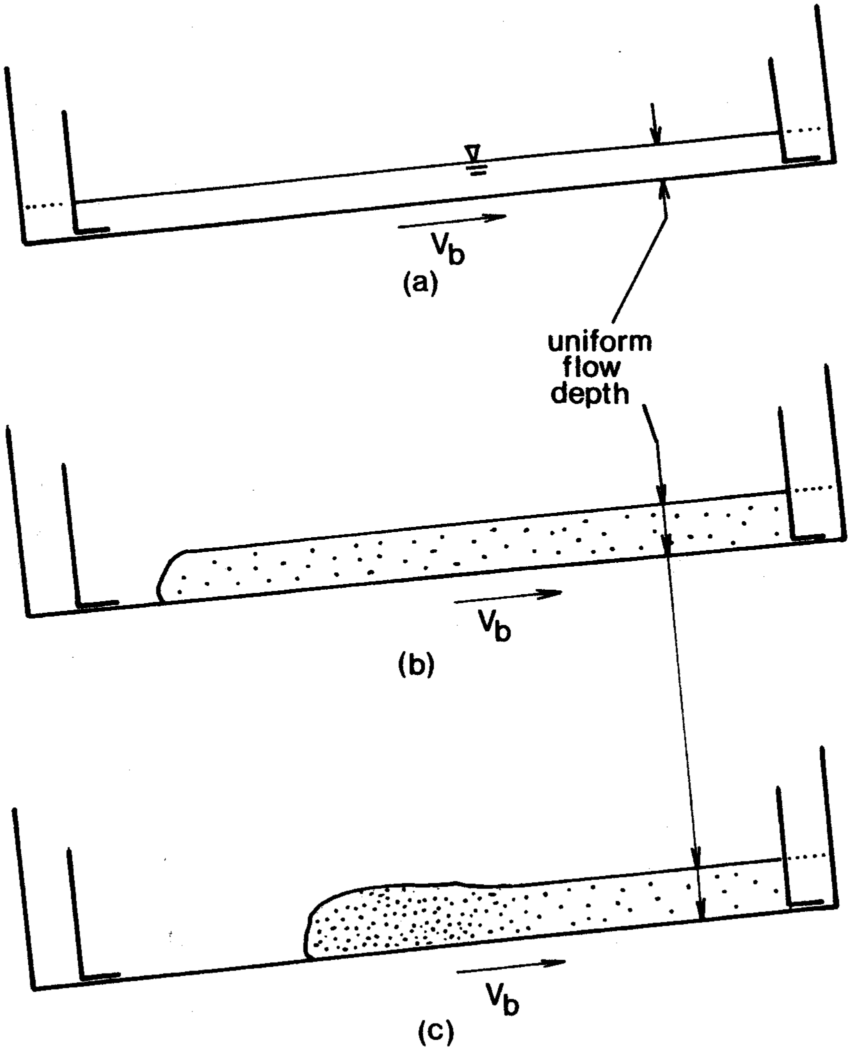


Fig.13

Effect of added grains on flow shape.

It may be questionable whether the way in which debris flow waves develop is similar to the evolution of these moving-bed end waves. Making the transformation from the moving-bed to the fixed-bed situation, introduction of sediment grains to the latter at concentrations in excess of the capacity of uniform flow causes the whole flow to slow down where the concentration is high, due to the increased intergranular friction (remember that (a) no deposition is possible, and (b) 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 which is essentially similar to the stationary breaking end-wave of the moving-bed situation. Slug input tests in the moving-bed channel are described later and support the essential similarities of evolution between debris-flow waves and end-waves.

8. RESULTS:

8.1 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 the slopes (steeper than about 5°) at which most of the present tests took place, the Froude number of the flow was sufficiently high that roll-waves formed and and amplified as they moved down the channel. These were easier to observe than in a conventional channel since they moved more slowly relative to the sidewalls. Although lack of time precluded a study of this phenomenon the moving-bed apparatus is clearly very suitable for such a programme. Note that 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 larger than that of the roll-wave wavelength.

8.2 With Grains in Flow:

As grains were gradually added to the flow, the flow characteristics altered. The following section describes these changes.

(i) With a small number of grains in the system their effect on the flow was negligible. The grains dispersed throughout the channel length, sometimes with a tendency to collect at the upper or lower end, depending on the slope and bed speed. Individual grains were moved downchannel by each roll-wave, and retreated upchannel again in the shallower flow between rollwaves (Fig.14).

(ii) As the concentration of grains increased, their presence tended to cause the amplitude of the roll-waves to increase. There appeared to be a tendency for a roll-wave to collect grains as it moved downchannel, which caused its bulk to increase; at some point, however, the grains for some reason ceased to move with the roll-wave and were left behind, while the wave, its grain content much reduced, moved away downchannel. A result of this process was that grains tended to accumulate at certain locations along the channel (Fig.15).

(iii) With still more grains added, these grain accumulations could become large enough to form stationary grain

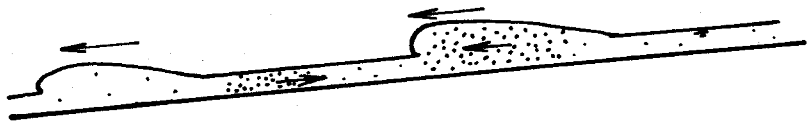


Fig.14

Roll waves with grains in flow.

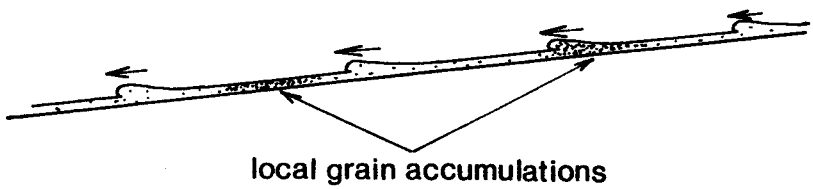


Fig.15

Development of local stationary grain accumulations.

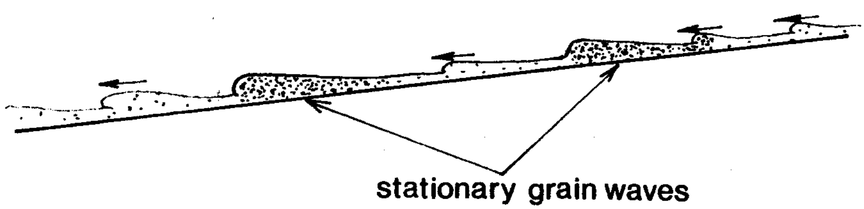


Fig.16

Development of stationary grain waves.

waves, quite independently of the end-wave which formed at the lower end of the flow region (Fig.16). These small waves were rather unsteady in shape and position due to the effect of roll-waves moving into them from upchannel.

The development of these stationary waves may be very significant in indicating an instability of uniform flow, and an instability of the statistical uniformity of the non-steady roll-wave flow, when sufficiently high concentrations of coarse grains are present. The hypothesis proposed earlier suggests that this instability is due to the non-depositional character of the grain-fluid flow. Whatever the reason, 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 downstream through the local accumulation waves, and collecting at the lower end of the flow reach to form a substantial high-concentration end wave. While still small this is very similar to the intermediate accumulation waves, but as it grows further it develops rather different characteristics. A typical sequence of end-wave shapes with increasing grain volume is shown in Fig.17, while Fig.18 shows how variations in channel slope and bed speed affect the shape of the wave.

The major consistent features of the waves are:

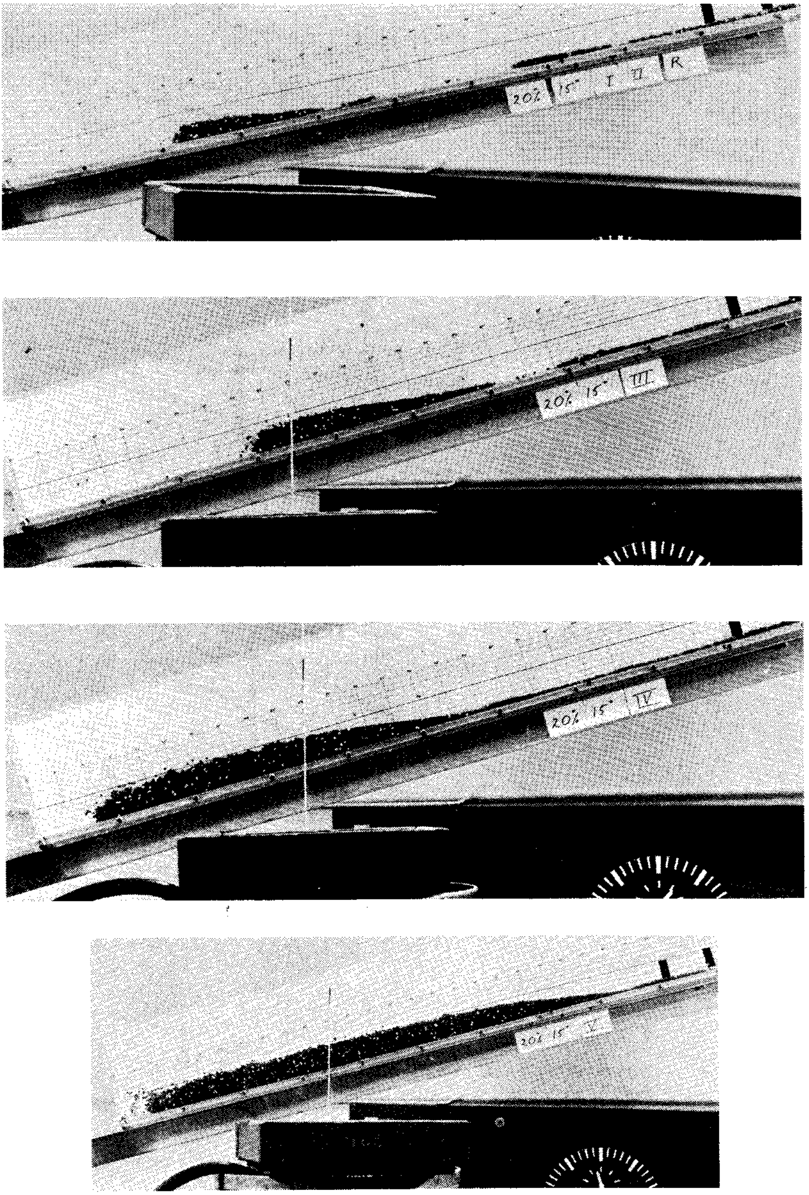


Figure 17.
Development of wave shape
with increasing grain volume.

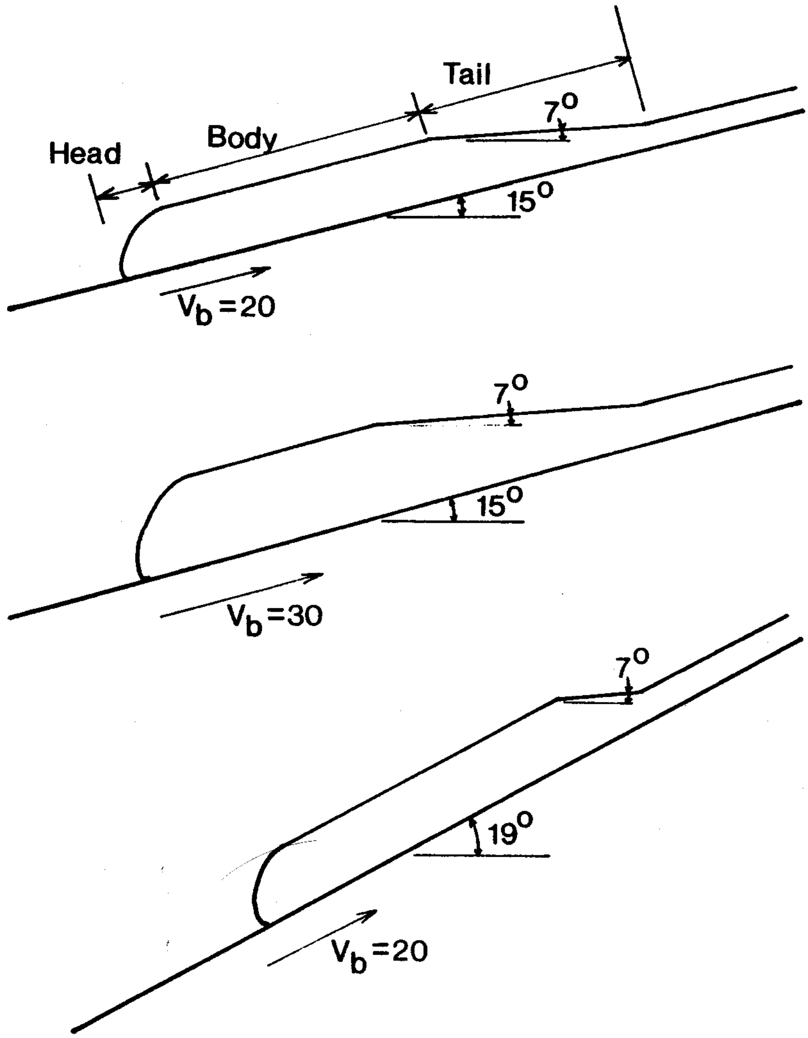


Fig.18

Wave shape at various slopes and belt speeds.

(i) The general presence of a uniform depth "body" extending 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 successively 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.19); it is not significantly affected by grain volume (Fig.20).

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

The outcome of these features is that, with a given grain volume, the wave tail will be shorter as bed slope increases at constant speed (Fig.18). At constant bed slope, speed variations 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 become longer as speed increases, corresponding to the increase in body height; however, this increase in body height causes the body to become shorter with a fixed volume of grains, and a speed could eventually be reached at which no body formed (Fig.21).

Note that 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 quite perceptibly curved in long section, rather than being flat and of uniform depth (Fig.22). Nevertheless, as an initial approach to describing a relatively complex situation the simplifications of Figs.18-21 are justified.

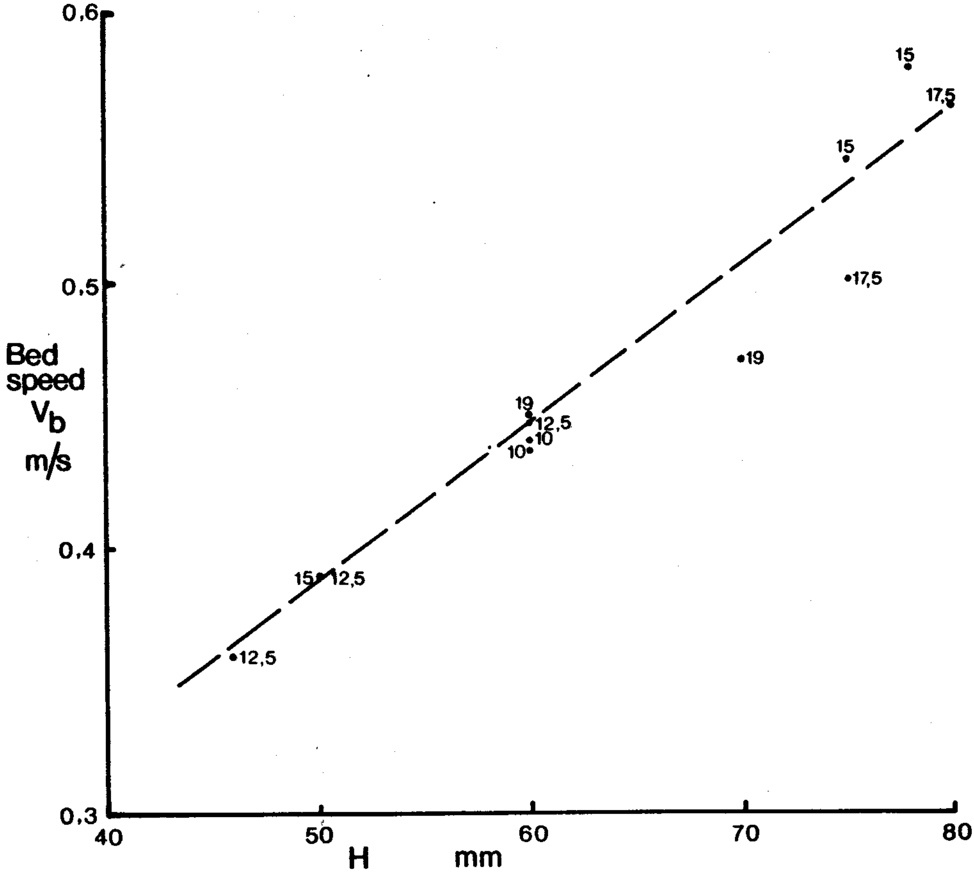


Fig.19
Surge wave height H as a function of bed speed and slope (numbers beside points denote channel slope in degrees).

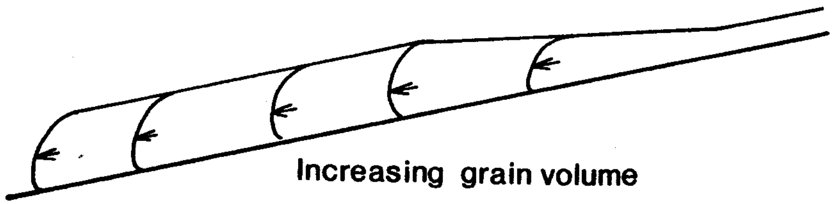


Fig.20

Wave geometry with increasing grain volume.

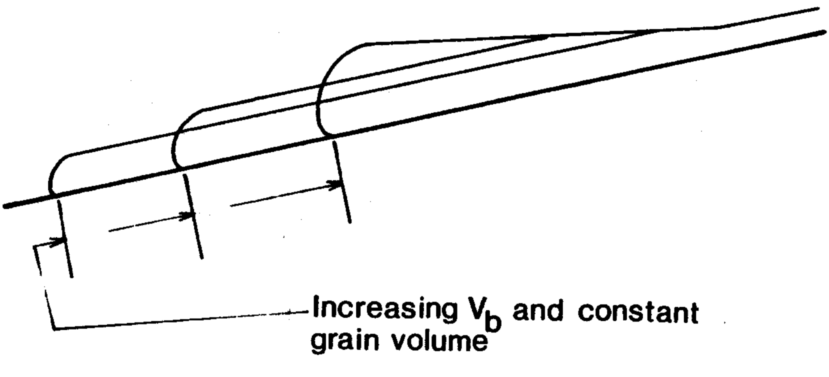


Fig.21

Wave geometry with increasing bed speed and constant grain volume.

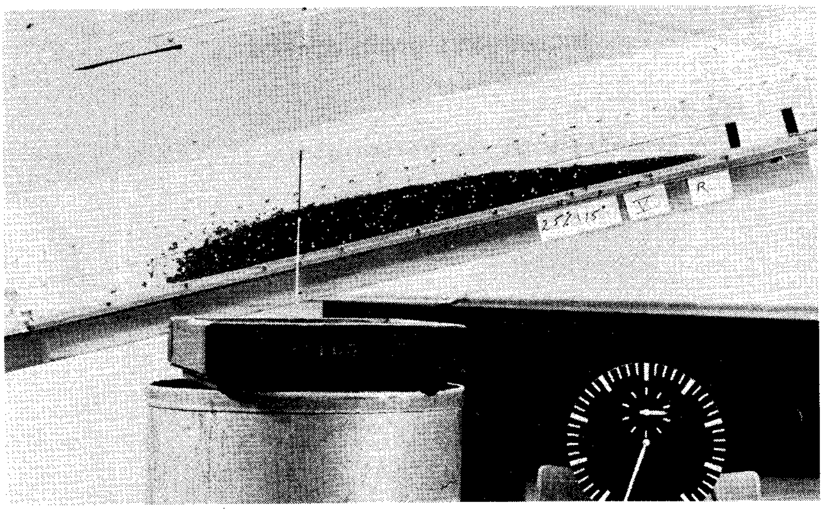


Figure 22.
Photograph of wave with curved upper surface.

At slopes of less than 5° it was possible to establish a truly uniform flow of depth (about 2 cm) much greater than that of the roll-wave "uniform" flows on slopes of 7.5° or steeper, because the Froude number of the flow was too small to allow roll waves to develop. It was apparent, though, that only at a single slope could uniform flow occur with a given bed speed and grain concentration - an increase in grain volume, for example, caused an increase in surface slope at constant bed speed (Fig.23).

8.3 <u>Velocity Distributions</u>:

By tracing grain motion on video films, and using short time-exposure ($^1/4$-$^1/30$ sec.) photographs, it was possible to measure velocities in all parts of the flow. Obviously the grains thus recorded were adjacent to the channel sidewalls, and one must question whether they were representative of grain motion in the interior of the flow; observation of grains at the surface of the flow "body" revealed no variation of grain velocity with position across the channel, which is taken as suggesting that a similar situation obtains within the flow, and that the wall grain velocity distribution is indeed representative of that within the flow "body". A slight tendency for the surface velocity to reduce at the walls was noticed in the "tail", and may indicate that velocity profiles obtained by these methods are somewhat distorted. Since the inferences drawn from these profiles are qualitative, however, this is not a serious problem.

Some typical velocity distributions in the body and tail regions are shown in Figs. 24 and 25, while path lines as

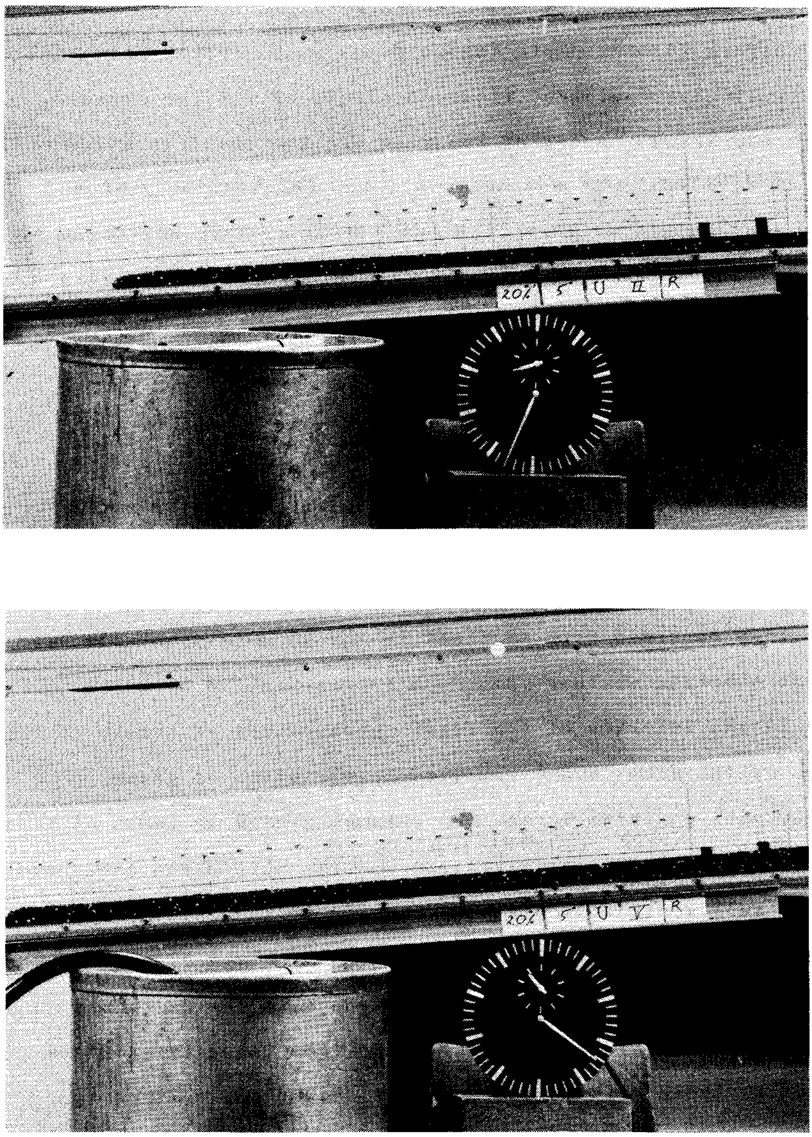


Figure 23.
Increase of surface slope with increase of grain concentration in uniform flow.

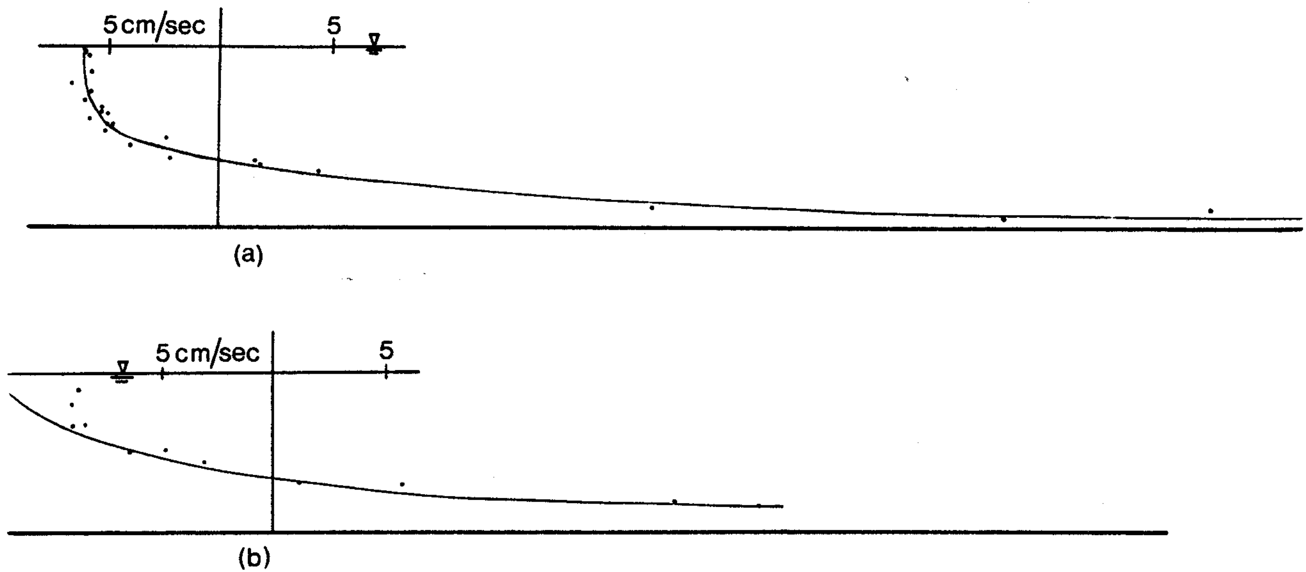


Fig.24
Velocity distribution in (a) body, and (b) tail of wave.

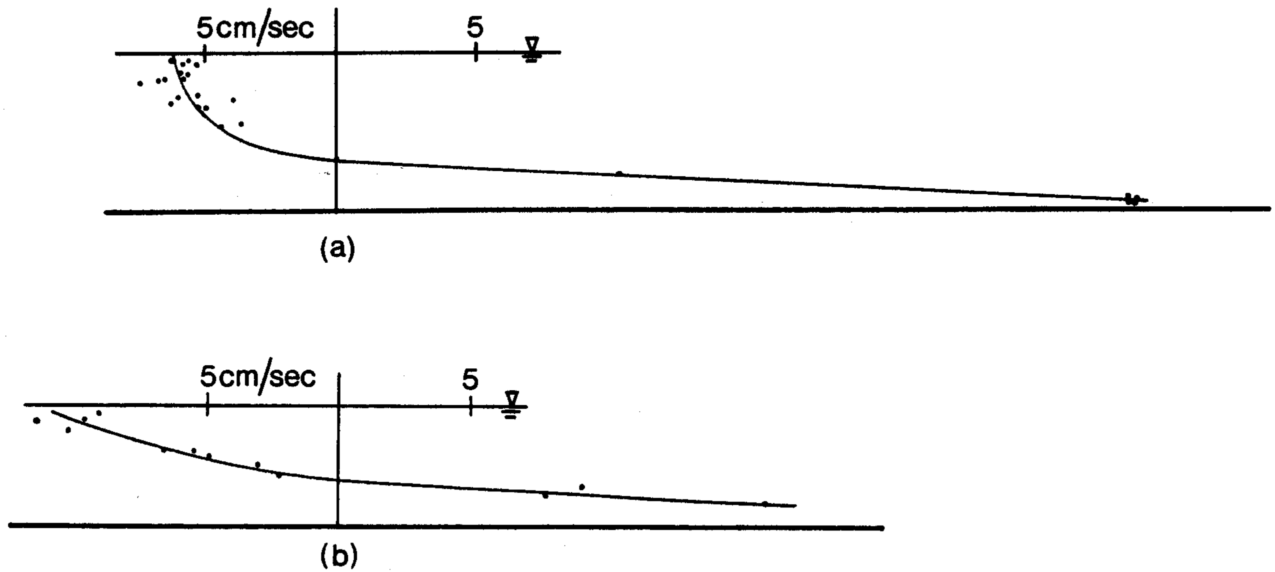


Fig.25

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

recorded on video film are shown in Figs. 26 and 27. Notable features of the velocity distributions are:

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

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

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

(iv) The much greater velocity of surface grains in the tail as compared with the body.

The path lines show the following features:

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

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

8.4 Grain Concentrations:

Fig.28 shows the distribution of local grain concentrations as taken from a short-exposure (1/250 sec.) photograph. Again, this data refers to conditions at the sidewall, and because of the tendency for the cylindrical grains in contact with the wall to align themselves with their major axis either perpendicular or parallel to the wall, the concentrations measured at the wall will probably differ somewhat from those in the interior of the flow where grain orientations are more variable. Concentrations within the flow are probably lower than those at the wall because

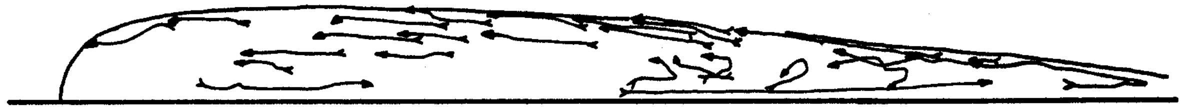


Fig.26

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

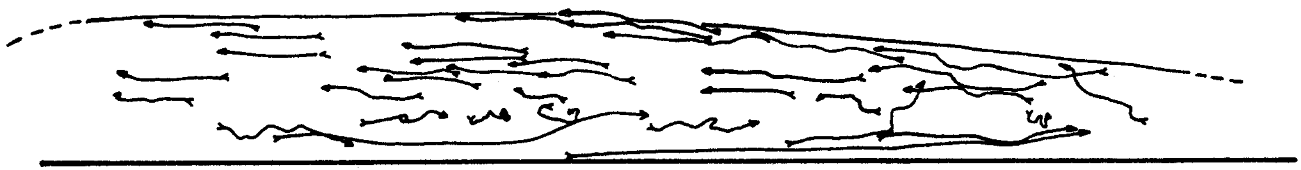
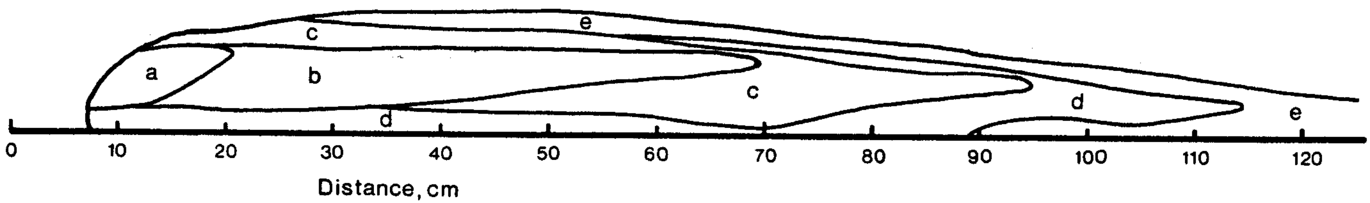


Fig.27

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



Band speed = 0,39 m/s
Slope = 12,5°

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.28

Concentration distribution of grains in wave.

of the greater voids ratio in more randomly-arranged grains, and also more variable, because local aggregations of similarly-oriented grains seem likely to occur.

Bearing these reservations in mind, Fig.28 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;

(iii) no distinct correspondence between the characteristics of the grain concentration and velocity distributions.

8.5 Behaviour of Large Grains:

A small number (about 50) of larger grains was introduced to various flow and wave situations, to investigate their motion. It has often been noted that the very front of a field debris flow contains a high proportion of large boulders while the rest of the flow does not. The large grains in the present tests did indeed show a distinct tendency to accumulate at the front of a wave, and to remain there, as long as 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 this 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) where the depth was less than this. 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 meant that they only rarely appeared at the front of the flow.

8.6 Flow Zones:

Three distinctly different zones of flow were apparent in the experimental waves, each with different flow characteristics (Fig.29):

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

(ii) The tail of the wave was a zone of fluid-like flow in which grains sheared quite rapidly past each other, even at the surface, and grain motion appeared 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 was quite sharp, occurring within a few grain diameters.

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

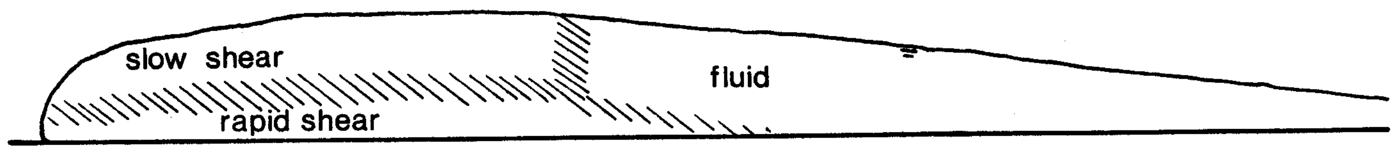


Fig.29
Flow zones.

velocity distributions (Fig.24) show this region to be deeper (~ 25 mm) than was apparent to the eye. There was a region of rather slower shear at the base of the tail, but this merged into the upper part of the tail with no obvious change in flow type so that a distinct flow zone was not obvious here.

8.7 Changes in Fluid Viscosity:

By dissolving a small proportion of cellulose solution (carboxymethylcellulose) in water, the viscosity of the inter-granular fluid was increased substantially - of the order of 100-fold. The major effect of this (Fig.30) was to cause the length of a grain-fluid wave to increase, because the slope of the head became much less steep and the body surface more pronouncedly curved. The maximum height of the wave was not affected. It was also noted that grains no longer protruded momentarily through the surface of the tail, and in fact a thin layer of grain-free fluid was present at the surface as noted under different circumstances by Bagnold (1955).

8.8 Wave on Wet Channel Bed:

Under certain conditions it was found to be possible to establish a grain wave when a thin layer (1-2 mm deep) of water was present covering the bed downchannel of the wave head. This wave was thus moving over a wet channel bed, whereas most of the waves studied moved over an essentially dry bed. This wave always moved slowly upchannel without changing its shape, showing that water was percolating slowly from the uniform flow section upchannel of the wave, through the wave to the wet channel bed in

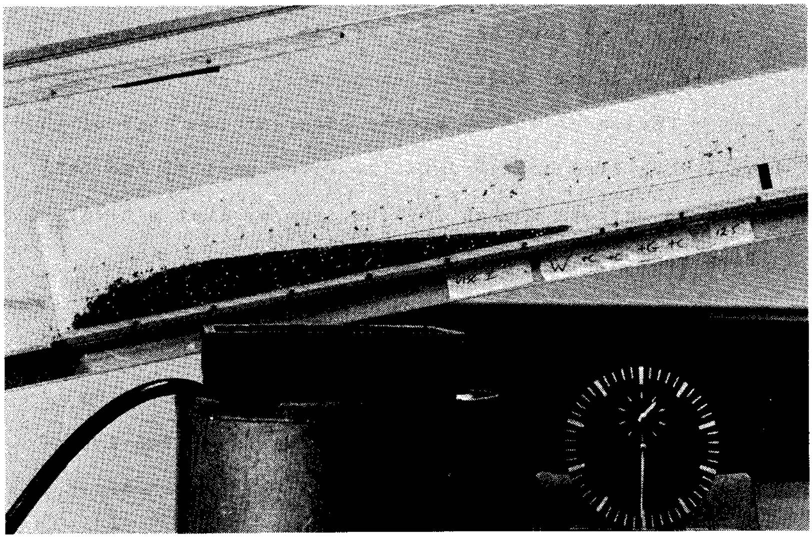


Figure 30.
Effect of increased fluid viscosity on wave shape.

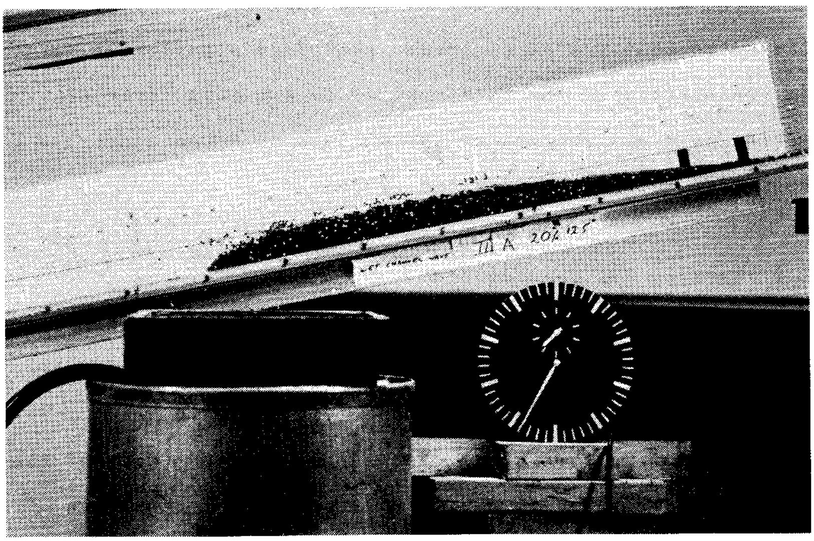


Figure 31.
Shape of wave on wet channel bed.

front of the wave. The wave had a noticeably gently sloping head, but was otherwise very similar in shape to the normal waves for a given bed speed and slope (Fig.31).

8.9 Slug Input of Grains:

In order to study the way in which an equilibrium wave evolved from a sudden local mass input of sediment, tests were carried out in which a volume of grains was tipped onto the moving bed through a shallow (~ 5 mm deep) water flow. The way in which a normal grain wave developed from this input is shown in Fig.32:

(i) The input mass formed a roughly symmetrical heap which was momentarily stationary with respect to the channel walls. This stage was an artefact of the experimental system, in that the grain mass was stationary relative to the walls when introduced, this being easier than matching its along-channel velocity to that of the bed.

(ii) The mass began to move upchannel with the bed, accumulating water on its upchannel side as it did so. This water began to seep into the grain mass, and to exert a downchannel force on it, resisting the upchannel motion.

(iii) Eventually the upper parts of the mass began to be forced to shear downchannel over the lower parts, due to increasing downchannel fluid pressure and to saturation of the pore volume reducing intergranular friction. The grain mass then began to change shape so that the downchannel slope steepened and the upchannel slope became less steep.

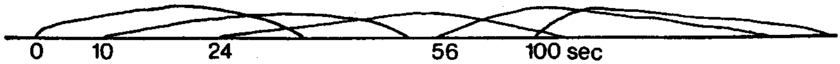


Fig.32

Evolution of slug input of grains to normal wave shape.

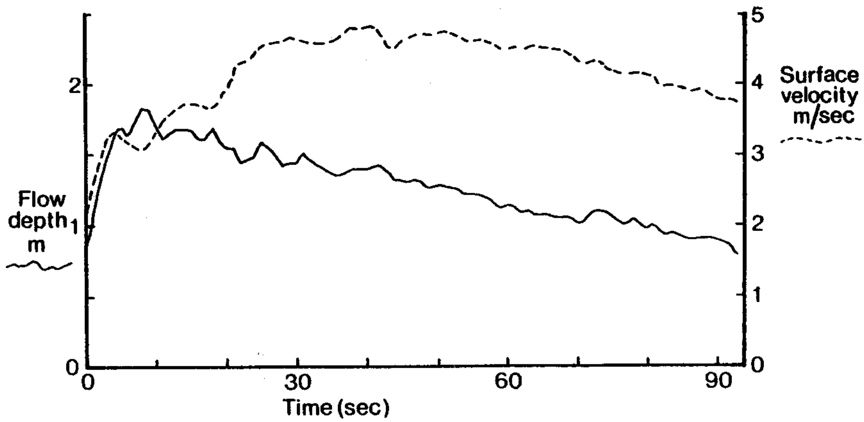


Fig.33

Behaviour of field debris flow (Suwa et al, 1984).

(iv) This process continued, and as shearing increased the upchannel velocity of the wave decreased and it ultimately became stationary with respect to the side-walls and identical in shape to a normal grain-fluid wave; which indeed it was.

9. DISCUSSION OF RESULTS:

9.1 Comparison with Field Data:

In order that this study be shown to have a wider significance than that of a series of demonstrations of the behaviour of a specific small-scale grain-fluid flow situation, it is necessary to show that the behaviour of the grain waves resembles that of debris flow waves to a significant extent. This is difficult because of the lack of detailed descriptions of debris flow waves, but one useful description is that reported Suwa *et al* (1983, 1985). This is taken from a video film record of the passage of a wave at Mt Yakedake, Japan, on 5 September 1983, and gives details of changes in surface velocity, surface elevation and surface composition as the wave passed below the camera. These results are shown in Fig.33, and can be compared with the results from a typical laboratory wave (run 20-15-III) shown in Fig.34. The qualitative similarities between the field and laboratory waves are clear:

(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";

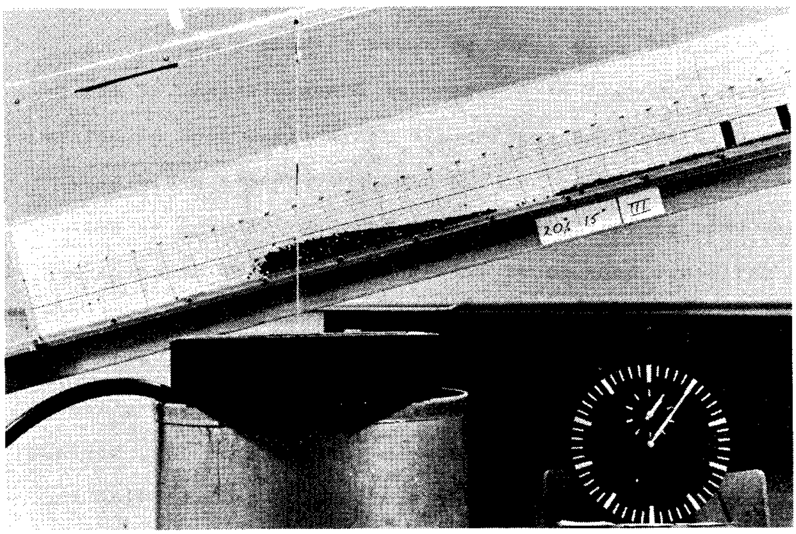


Figure 34.
Wave of run 20-15-III.

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

Although no more quantitative comparison is possible, these correspondences are sufficiently obvious to support the assumption that the major features of debris flow waves occur also in the laboratory waves. This in turn supports the hypothesis that the main features and behaviour of debris flows can be explained by the shearing of large grains in a fluid slurry, and indicates that 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 macroviscous). Interestingly, Tattersal and Banfill (1983) came to a similar conclusion regarding the rheology of wet concrete, whose flow behaviour is much simpler than that of the cement paste in which the coarse aggregate shears. The strongly bimodal grainsize distribution of many debris flows (e.g. Fig.3) shows the presence of two distinct grain populations, and indicates that, at least in the case of the Jiangjia Ravine flows, the slurry grains are mostly less than 0.1 mm and the coarse grains greater than 1 mm in diameter.

The concept that three physical components - coarse grains, fine grains and water - control the occurrence and behaviour of debris flows suggests that a ternary phase diagram might be useful in classifying, or inter-relating, different types of sediment flows such as bedload, hyperconcentrated flows, etc. Fig.35 is a preliminary attempt to explore this idea. On the diagram are shown the (very approximate) limits to the occurrence of laminar and turbulent flows, macroviscous, transitional and

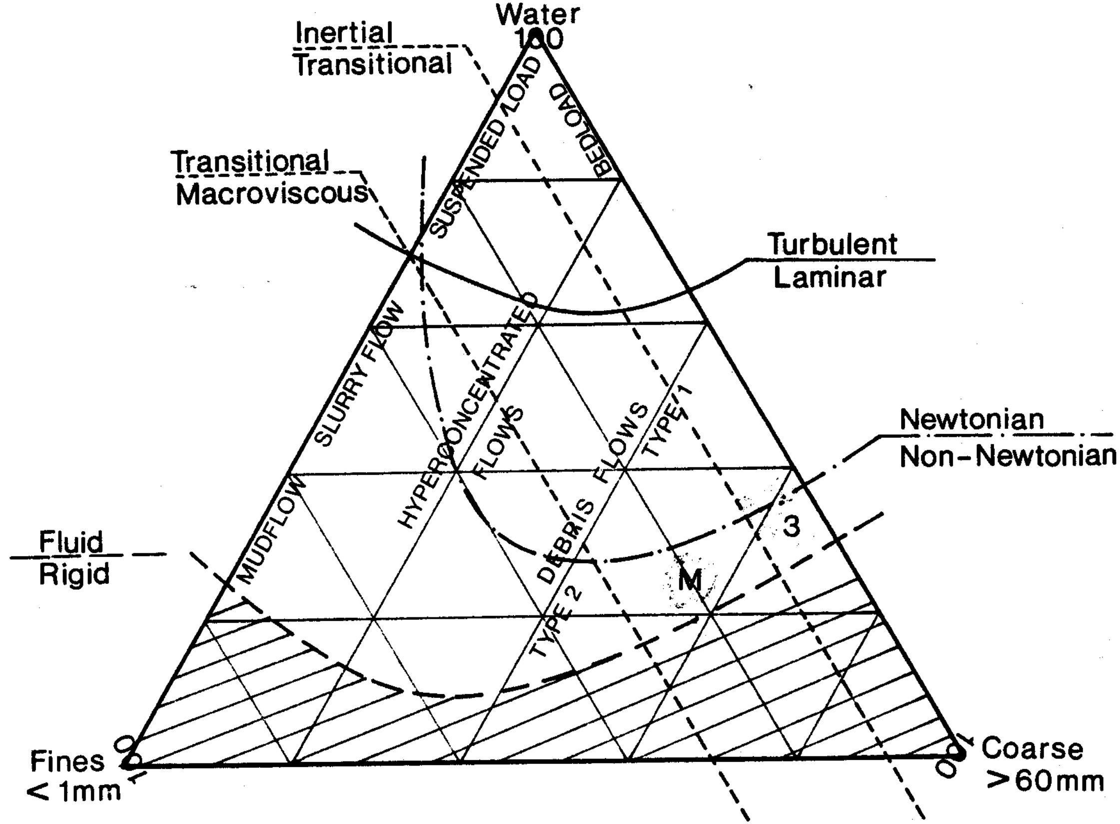


Fig.35
Ternary phase diagram for water-fines-coarse sediment flows. 3 = Type 3 debris flows; M = Mt Thomas debris flows.

inertial flows, Newtonian and non-Newtonian flows, and the rigid zone where no flow is possible due to very high grain concentrations. Flow is assumed to be

(a) laminar or turbulent according as the Reynolds' number (Newtonian fluid) is less than or greater than 500;

(b) macroviscous, transitional or inertial according as $G^2 < 100$, $100 < G^2 < 1500$, or $G^2 > 1500$ respectively;

(c) Newtonian or non-Newtonian according as the fine grain volume concentration C_s is greater than or less than 30% respectively, and the linear concentration λ of coarse grains is less than or greater than 14 respectively;

(d) rigid or non-rigid according as the volume concentration of coarse and fine grains is greater than or less than 70%. Note that the absolute maximum volume concentration of total solids at which flow can occur is then 91% (Appendix 1) giving a flow bulk density of 2.50 T/m^3 if the solids density is 2.65 T/m^3; Curry (1966) reported a bulk density of 2.53 T/m^3 in a "dry" debris flow.

Also shown on the diagram are (again approximate) regions in which various types of flow phenomena occur. Here the confusion of nomenclature which has plagued this topic for many years is a problem, but the physical composition of the material taking part in the phenomena, which is shown by the diagram, clarifies the situation somewhat. It is seen that type 2 debris flows occupy only a small part of the diagram bordering on the rigid zone, and there is a large region occupied by hyperconcentrated flows and type 1 debris flows between "normal" bedload-suspended load flows and type 2 flows. Type 3 debris flows also occupy a small region of no-fines, high coarse-grain concentration flow.

While at present Fig.35 is tentative only, it does appear to be a promising way of visualising the material composition of debris flows and other phenomena, and of describing their relationship to each other.

9.2 <u>Instability of Uniform Flow</u>:

At channel slopes greater than about 5° all flows, both clear-water and with grains, showed either distinct free-surface instability in the form of roll waves, or distinct 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), and it appears (Fig.4) 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 the occurrence of locally high grain concentrations which caused the local downchannel motion of grains (with respect to the bed) to slow down, and thus more grains accumulated from upchannel at this location. There is no reason to believe that roll waves are a necessary component of this mechanism, but this could not be tested in the present apparatus. It was shown earlier that in principle a macroviscous flow would be unstable in this fashion; however, with the fluid and sediment conditions of this study, i.e., σ = 1400 kg/m^3, ρ = 1000 kg/m^3, D = 4 x 10^{-3} m, η_a = 10^{-3} kg/m/s, cos $\beta \sim 1$, $C/\lambda \sim 1/20$ ($0.02 < C < 0.43$, see Fig.11), and

$h \simeq 5 \times 10^{-3}$m, G^2 as given by eq.(2) is about 20,000, indicating inertial flow. Thus the instability observed in these tests could not be due to macroviscous flow. The test flow was, however, non-depositional, which suggests the possibility 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) and further considered herein 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.

Further, 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:

$$\tan \beta = \frac{\tan \alpha_v \, (\sigma - \rho)C}{\rho + (\sigma - \rho)C} \qquad (9)$$

in which α_v is the angle of internal friction of a mass of grains. Since the maximum concentration of the P.V.C. grains in shearing was 0.56 (Fig.11), the maximum value of β in this study would be about 7° if (9) 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 will be seen later, 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 actively erosive and become depositional in nature. 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 $\rho = 2.0$ 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 lends some positive support to 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 an important phenomenon where the channel dimension (width or depth) is less than about 10 grain diameters, as will be the case for large boulders in debris flows. 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.

9.3 Characteristics of Stationary Waves:

9.3.1 Geometric Shape

The wave evolution sequence shown in Fig.17 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. In fact, the upper limit to the tail depth 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.29). 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 be significant in affecting 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 mean and local 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 18 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 x 500/70 $\simeq$ 11/sec. at the transition. It is interesting that 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 reported by in the between-pulse flows reported by Pierson (1981b) at Mt Thomas, New Zealand.

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

(a) With a small number of grains, the grains will be uniformly distributed throughout the flow.

(b) When enough grains are present, local grain accumulations occur within the flow, causing low grain waves. An end wave may also be present depending on the volume of fluid present.

(c) As still more grains are added an end wave develops comprising a short tail section and a head.

(d) 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.

(e) 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.

(f) 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 unique body depth H for a given bed speed, irrespective of bed slope, is a remarkable feature of the grain waves, and implies that while du/dy cannot be less than about 11 in the fluid-like tail flow, it also cannot be much greater than this in the body flow. Presumably the reason for this lies in the detail of the velocity profile in the body region (Fig.24), which is quite distinct from that of the tail; no explanation for this is suggested herein, the problem being one requiring more detailed treatment of grain-flow mechanics than is appropriate here.

The fact that the wave is stationary means that the along-channel forces acting on it (gravity component downchannel and bed-induced shear force upchannel) are in balance. Since the body is of uniform depth the forces on any length of body are also in balance, which means that the body section generates no net force which affects the head or tail; hence the body can vary in length without causing the head or tail to change shape. The head is composed of a similar material to the body, but has a depth less than that of the uniform flow in the body, hence the shear force on its base is greater than the downslope gravity component acting on it and the head delivers a net upchannel force to the body. In the tail, the depth is greater than that of uniform flow in the same material, and the downslope gravity force exceeds the upslope shear force at the base of the flow. Thus the tail exerts a downchannel force on the body which must balance the upchannel force exerted by the head (Fig.36). The grains available to form a wave (i.e., those left over when the grain capacity of the upchannel uniform flow has been satisfied) adjust their distribution in head and tail until a balance of forces occurs and a stationary wave results; this must be a negative feed- back, stabilising process, i.e., if there are too many grains in the head this causes the wave shape to adjust so as to reduce the number of grains in the head.

Note that in a channel of slope less than about 7° the slope of a maximum-concentration non-depositing flow will be greater

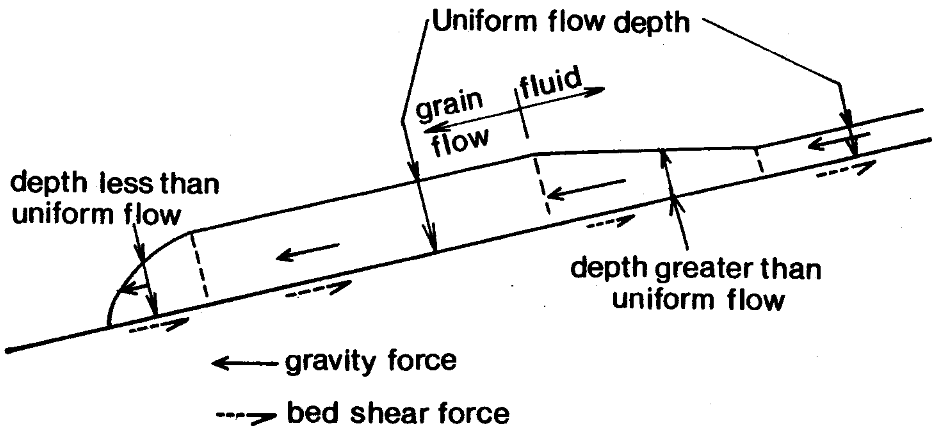


Fig.36
Regions of flow and forces.

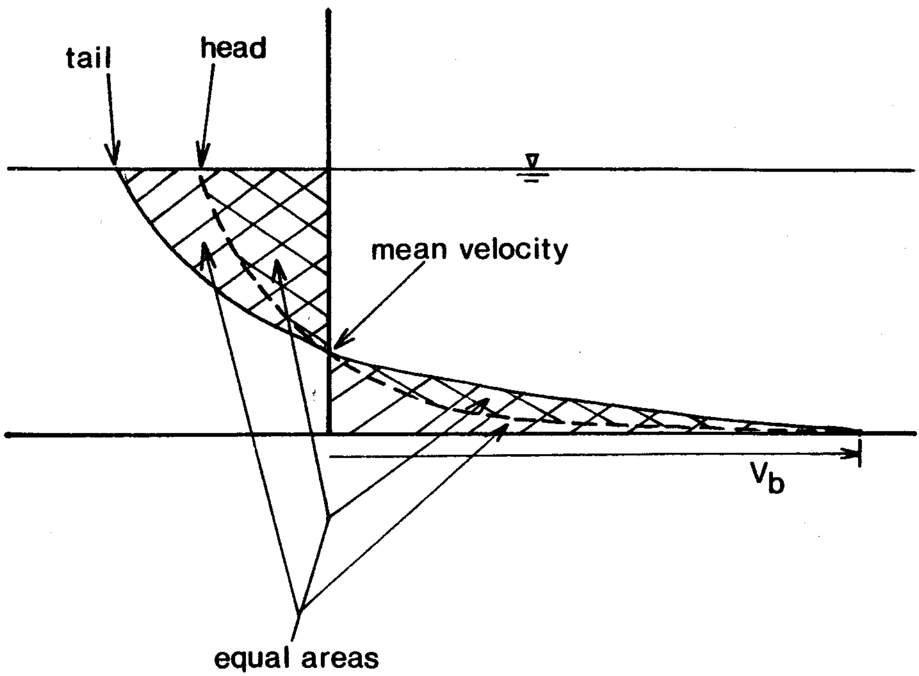


Fig.37
Idealised velocity profiles.

than the channel slope, and the flow depth will decrease, causing du/dy to increase, downchannel. Hence du/dy will not become low enough to cause slow shear flow and a "body" section cannot form. The decreasing flow depth region will simply be bounded downchannel by an end-wave or head, and will merge upchannel with a uniform flow region of lower, uniform concentration (Fig.23).

9.3.2 Grain Motion - Velocity Profiles and Path-lines

Figure 24 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. It is interesting that the point in the profile at which the local velocity equals the mean velocity is at the same height above the bed in both body and tail regions. By idealising these profiles somewhat (Fig.37) 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 considerable scatter in the points from which the velocity profiles are drawn, and the very laborious procedure of deriving the profiles from video film, prevents any theoretical or empirical relationships being derived or flow laws being tested using this data. In future experiments of this nature the use of image analysis techniques should allow sufficient data on grain motion to be collected that such derivations and tests can be made.

The very small velocity gradient in the upper part of the body, together with the visual appearance of the surface, enables one to understand how, in a field situation, a rigid plug flow is often reported in debris flows (e.g., Johnson, 1970). Such a plug is a characteristic of a flowing Bingham plastic material, and such models have been extensively studied in the context of debris flows (Johnson, 1970; Johnson and Rodine, 1984; Enos, 1977). 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; the Bingham model is thus strictly inapplicable, as was earlier deduced from the existence of roll-waves resulting from free-surface instability. 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 there could be expected to resist shearing to a significant extent by virtue of the considerable intergrannular friction present. 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 the internal friction very 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.

The perturbations shown by grain paths in the tail region certainly indicate the presence of turbulent eddies in the flow, probably generated in the higher shear region close to the bed. These in themselves, however, do not mean that flow in the tail is not laminar, because the viscosity of the grain-fluid mix is still sufficient to damp out the eddies very rapidly, thus flow is dominated by viscosity and is laminar. The pathlines do indeed show that following a major transverse excursion a grain path rapidly becomes linear again.

The only perturbations shown by grain paths in the wave body are close to or below the mean velocity height, which is in fact a region of quite rapid shear. In the slow shear region of the upper body grain paths are almost purely linear.

9.3.3 Concentration Variations:

The lack of distinct changes of grain concentration corresponding with the changes of velocity gradient and flow type in the wave probably results from the sampling method used to measure grain concentration. Each point concentration from which the curves of Fig.28 were drawn represents an average measured over an area 1 cm high by 5 cm long, hence any sharp variations at a scale smaller than this will be obscured. There is also some possible imprecision or inconsistency in assigning grains which lie across the boundary between two areas to one of those areas, and it is possible that in some cases grains lying in a plane somewhat distant from a sidewall may have been counted incorrectly.

Relatively low grain concentrations at the bed and surface of grain flows (e.g., Savage, 1984) and simulations (Campbell and Brennen, 1985) have often been reported. At the bed the inability of grains to penetrate the solid surface, 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.

The decrease in grain concentration towards the rear of the wave corresponds to the observed change in flow state 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 (Fig.26), and must be associated with the highly non-uniform grain flow conditions there. No explanation of processes in the head region is offered here, but this region is clearly of great importance to the size and shape of waves. The gradual decrease of grain concentration towards the rear of the tail corresponds to an increase in the mean velocity gradient as the flow depth decreases. Which of these factors are causes and which are effects is not yet clear.

9.3.4 Flow Regions:

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

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 ($\sim 20°$) 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 simulation of dry grain flow, and its appearance in the slow grain-in-fluid shear here 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 by way of plasticity theory and of kinematic modelling, but there is as yet no general agreement on the basic principles of this type of flow. Severe experimental difficulties have been experienced in trying to study slow shear flow, and it may well be that the moving-bed channel principle offers an opportunity to observe the phenomenon more easily than has previously been the case.

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, a factor which has been found to occur in other studies (Tüzün et al, 1983) and for which a theoretical explanation has been proposed (Bridgewater, 1980). The mechanics of flow in this layer are presumably quite different to those of the upper body region, with a very high shear rate close to the bed in which grains collide rather than sliding gently past each other. Depending on grain concentration and shear rate, flow in this region could be macroviscous, transitional or inertial, or all of these regimes could occur successively as the bed is approached from above.

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 waviness due to roll-waves entering the region from upchannel.

The head is a region of strongly nonuniform flow in which grains move down towards the bed before being rapidly accelerated upchannel by the motion of the bed. Grain motion in the head is strongly influenced by intergranular friction as affected by the surface tension of the pore fluid, since the "free surface" of the pore fluid is some distance below the grain surface, and it is known that a mass of damp grains clings together significantly as a result of surface tension. The same phenomenon may affect the surface layer of grains in the body, since here also the fluid level is below the grain surface; thus the lack of shear apparent in this layer when viewed from above could be caused by the real shear strength of the layer due to surface tension. This effect would not be present in a field debris flow. It is therefore possible that the lack of sidewall friction effects deduced from the lack of lateral variation of velocity in the surface layer does not apply lower down in the flow where no surface-tension related shear strength can be present.

9.3.5 Behaviour of Large Grains:

When 8 mm diameter grains are present within a shearing body of 4 mm diameter grains, there is a strong tendency for the large grains 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.

It seems likely that 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 experiences a tendency to rise through the fluid flow and does so, rapidly 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 is thus able to travel much farther back in the wave before reaching the surface.

The reason for a large grain to tend to rise to the surface when in 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 in the direction of decreasing shear rate, that is, towards the surface.

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) states that in a flow of granular solids any difference in grain properties is likely to cause differential grain motion and hence segregation, and describes a process similar to kinetic sieving: "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). On this basis one can only say that there is a certain probability of the front of a debris flow containing large boulders, and that this probability will increase as the boulder size in a flow of given depth increases. 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).

9.3.6 Changes of Intergranular Fluid Viscosity:

The use of fluid of increased viscosity had no effect on the body or tail geometry of a grain-fluid wave, although the irregularity of grain motion in the tail was noticeably reduced and a layer of grain-free fluid was present at the surface of the tail. The head, however, was much shallower in slope and hence much longer than with lower viscosity fluid. Since the upchannel force generated by this head to balance the downchannel force due to the tail is essentially the same as with a lower viscosity fluid (since the tail shape is the same), then the intergranular friction in the viscous-fluid head must be lower because a larger volume of grains is involved. Hence the nature of the pore fluid does affect the grain stresses in the type of shear occurring in the head.

9.3.7 Wave with a Wet Downchannel Bed:

The head of a normal wave riding over a dry downchannel bed is much steeper than that of a wave on a wet downchannel bed.

This is because the wet channel wave has a higher water content at the base of the head, and again reduced intergranular friction, in this case due to reduced surface tension forces holding grains together, requiring a larger volume of grains to provide the force necessary to balance the downchannel tail force.

9.3.8 Slug Input:

The major result of the slug input tests is that the slug moves upchannel until it has accumulated enough water to be able to flow with respect to the bed at the bed velocity. When first introduced, the slug mass is so concentrated that such flow is impossible, and only when grain packing has been reduced by the presence of pore fluid does the mass begin to flow.

A similar effect was noted when a mass of grains was added to an equilibrium wave; the added grains formed a bulge in the wave that moved upchannel until enough water had been accumulated to reduce the grain concentration to that of a normal "body" or "tail" section, whereupon steady state conditions were re-established.

10. IMPLICATIONS FOR DEBRIS FLOWS:

The experiments described herein show many similarities between the grain-fluid waves and debris flow waves observed in the field. It is clear that the experiments give indications as to the nature of 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. It is important to realise, however, that the experimental situation is at best an analogy of a field debris flow, not a theoretically justified model, and it is therefore not wise to extrapolate results from the laboratory to the field unless there are strong independent indications that the extrapolation is legitimate. Even if this is the case, the laboratory waves are very 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, and these are now discussed.

(a) Probably the most significant general implication is that the occurrence and major characteristics of debris flow waves can be explained on the basis of the 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. 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. In particular, 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.

One obvious objection to this implication is the existence, in both field and laboratory situations (Engelund and Wan, 1984) of pulsing hyperconcentrated mudflows without any coarse grains present. In this case the flow behaviour, which is superficially similar to that of debris flows, is controlled by the fine material. Consideration of the rheology of both mudflow and debris flow materials allows this point to be resolved. Engelund and Wan (1984) show theoretically that pulsing flow will occur in a fluid which has a static yield stress higher than the minimum shear stress which occurs during flow (Fig.38). Thus a bentonite clay slurry, in which this criterion was satisfied, flowed with pulses while a kaolinite slurry, in which it was not, did not. In a flow containing coarse grains it is very likely that this criterion will be satisfied because the stress required to set a mass of grains in motion from a static packing state is less than that needed to maintain the motion when the grains have been slightly dispersed by motion. This behaviour was reported by Ukraincik (1980) in a study of the rheology of fresh concrete and has previously been suggested by Davies (1985). The common factor in the behaviour of fine-grained mudflows and coarse-grained debris flows is thus the yield stress and low shear-rate behaviour. Where coarse material is present in high concentrations this dominates the flow and causes pulsing; when it is not, only those slurries with appropriate rheology will pulse (Anderson et al, 1969). In practice, most debris flow slurry material seems to behave in a manner similar to kaolinite and cannot cause pulsing flow without the presence of coarse grains. The criterion of Engelund and Wan (1984) refers only to the ability of the flow to cease moving altogether, forming a temporary dam which is later remobilised as a pulse or wave; the explanation of pulsing flow based on the instability of macroviscous flow proposed earlier requires only that the flow velocity reduces, and does not therefore explicitly involve the yield stress. Both explanations are probably equivalent in many practical situations, and are in effect both similar to the concept of grain jamming as a contributor to rapid amplification of an initial non-uniformity caused by non-depositing flow.

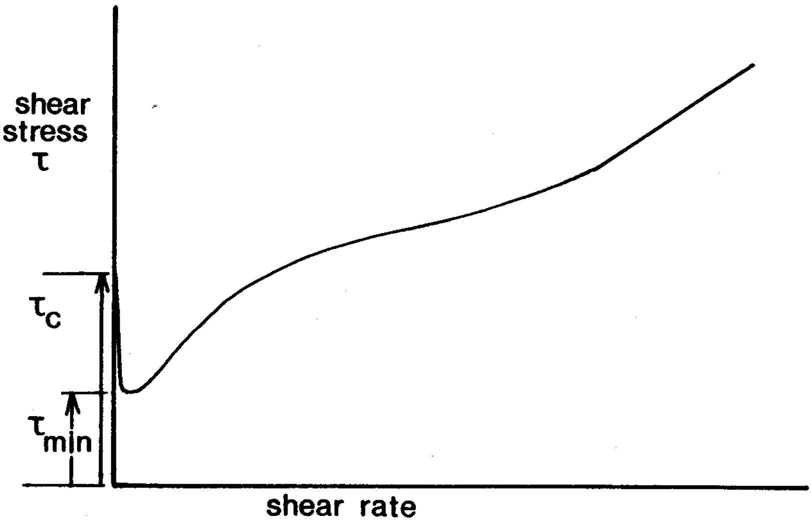


Fig.38
Rheology of pulsing flow material.

(b) It has been shown earlier that the form (longitudinal section), surface appearance and surface velocity of debris flows correspond at least qualitatively with those of the laboratory waves. This allows the proposition 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 (Mizuyama and Uehara, 1980) suggests that this may be approximately true - then

$$v = 11 H \qquad (10)$$

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. Even though this method of prediction is extremely approximate, any estimate for H is of value in assessing the potential damage from a debris flow. It must be emphasised again, however, that the unsteady behaviour of real debris flow waves will differ qualitatively from that predicted on the above basis - for example, if a wave is forced to slow down due to an obstacle in the channel, the steady flow theory predicts that the wave height will decrease; in fact, during the 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 the field situation, with unsteady flow, changing wave shape, irregular channel and a wide range of grain sizes and shapes, seems fundamentally quite unapproachable at present. However, the present work at least allows one to appreciate the nature of this complexity and to better judge 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. As stated in the Introduction, field data is 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) describes a similar measuring station and discusses the problems involved in setting up and running such a facility, including the use of in-channel pressure sensors from which a vertical velocity profile could be inferred. One technique which does not appear to have been 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. In gravel-bed rivers these have been used very successfully, but their recovery following a debris flow must be much more problematical. Given that there is extreme uncertainty about the location of the base of fluid flow during a debris flow, however, and the absence of any other possibility of obtaining such information, the use of scour chains should be attempted.

(d) In view of the successes achieved in granular mechanics by computer simulations of grain flow situations (Campbell and Brennen, 1985; Walton, 1983) it is tempting to suggest that this technique, which is at present in its infancy, has 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. The most important advantage of this technique lies in the potential for adding to the basic method such complications as exist in field situations, e.g., irregular channel boundaries, irregular grains, etc. To date, computer simulations have been restricted to two-dimensional situations and dry flows and extension to three dimensions would greatly increase the computer memory requirements without however complicating the computational procedure unduly. It does not seem unreasonable to envisage such a simulation of a reasonably realistic debris-flow situation comprising irregularly-shaped coarse grains of a range of sizes shearing in a dense slurry in an irregular channel, given the very rapid developments in computer technology which have occurred in the past few years.

11. CONCLUSIONS:

11.1 The occurrence and behaviour of pulsing debris flows results from the presence of high concentrations of coarse grains shearing in a dense, viscous slurry of fine grains in water.

11.2 The occurrence of macroviscous grain shearing conditions is associated with the onset of the main features of debris flows, i.e., pulsing flow and the transport of large boulders.

11.3 The instability of macroviscous flow causes the flow to break up into a series of pulses or waves; this process is assisted by the tendency of coarse grains to jam at high concentrations. These waves can propagate into larger channels by free-surface instability causing the very large waves reported from China.

11.4 The major features of debris flow waves are present also in the small-scale waves of P.V.C. grains in water reported herein.

11.5 The height of a steady-state debris 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 or less.

11.6 More than one type of flow is present within a debris flow wave; even in the simple, idealised waves of the 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.

11.7 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 it is a matter of urgency that strenuous efforts be made to improve the quality and quantity of the data available.

11.8 The moving-bed channel used for the present tests is an extremely useful way of studying wave phenomena and is ideal for the homogeneous non-depositing character of debris flows.

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APPENDIX:

Bulk Density of Slurry-Grain Mixtures:

The bulk material of a debris-flow comprises coarse grains in a slurry of fine grains in water (Fig.A1). Considering a given volume of mixture, the total volume of coarse grains is V_b, of fine grains is V_s and of water is V_w. The total mixture volume is V, so that the volume concentration of coarse grains is

$$C_b = V_b/V$$

and the volume concentration of fine grains making up the slurry is

$$C_s = V_s/(V_w + V_s) = Vs/(V - V_b)$$

The density of both coarse and fine solids is 2.65 T/m^3.

The bulk density γ of the mixture is

$$\gamma = \frac{2.65\ V_b + 2.65\ V_s + V_w}{V}$$

$$= 2.65\ C_b + 2.65\ \frac{V_s}{V} + \frac{V_w}{V} \qquad - \text{(A1)}$$

Now $$\frac{V_s}{V} = \frac{V_s}{V_s + V_w} \cdot \frac{V_s + V_w}{V} = C_s \cdot \frac{V_s + V_w}{V} = C_s\ \frac{(V - V_b)}{V}$$

$$= C_s(1 - C_b) \qquad - \text{(B2)}$$

Also $$V_w = V - (V_s + V_b)$$

so that $$\frac{V_w}{V} = 1 - \frac{(V_s + V_b)}{V} = 1 - \frac{V_s}{V} - C_b$$

$$= 1 - C_s(1 - C_b) - C_b$$

$$= 1 - C_s + C_sC_b - C_b \qquad - \text{(C3)}$$

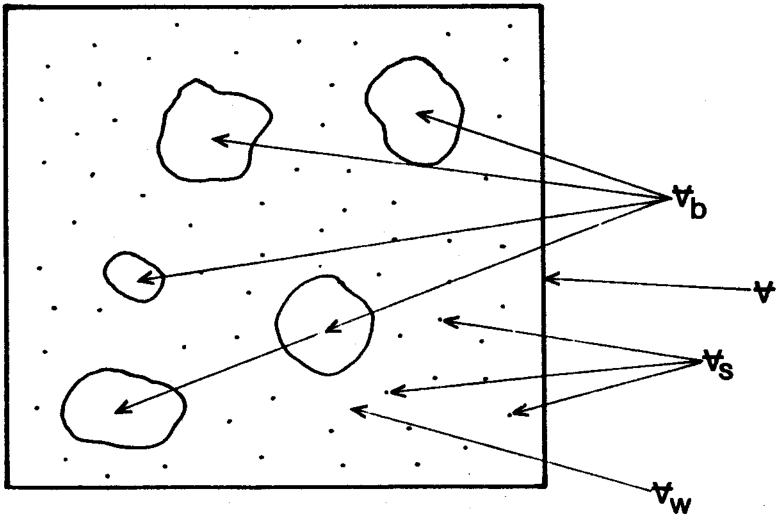

Fig.A1

Constituent materials of debris flow slurry-grain mixture.

Substituting (2) and (3) in (1):

$$\begin{aligned}
\gamma &= 2.65\ C_b + 2.65\ C_s(1 - C_b) + 1 - C_b - C_s + C_sC_b \\
&= C_b(2.65 - 2.65C_s - 1 + C_s) + C_s(2.65 - 1) + 1 \\
&= C_b(1.65 - 1.65C_s) + 1.65C_s + 1 \\
\therefore \gamma &= 1.65(C_b + C_s(1 - C_b)) + 1
\end{aligned}$$

Giving C_b and C_s their maximum conceivable values of 0.7 for natural material gives $\gamma = 2.50$, which compares with the maximum recorded field value of 2.53 (Costa, 1984).

The total volume concentration of solids in water

$$C_T = \frac{\forall_b + \forall_s}{\forall} = \frac{\forall_b}{\forall} + \frac{\forall_s}{\forall} = C_b + C_s(1 - C_b) \text{ from (2).}$$

Hence with $C_b = C_s = 0.7$, $C_T = 0.91$.

Also $\gamma = 1.65\ C_T + 1$