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Debris flow behaviour – an integrated overview

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Abstract Many facets of debris flow behaviour have been researched recently, but no integrated description of the whole phenomenon has been attempted. Our observations of instability in a stationary deposit of flow material, and of active nick-point recession during a debris flow, allow an integrated, process-based explanation of debris flows to be proposed.

INTRODUCTION

This report attempts a process-based explanation of the complete debris flow phenomenon, from the hillslope instability that starts it to the flow of the final surge into the downstream river. This description results from the authors' three-week field visit to the Dongchuan Debris Flow Observation Station at Jiangjia Gully, China, in July 1990, where intensive discussions took place with the staff of the station and with visiting experts.

The "complete" debris flow process involves three distinct landscape units (Fig. 1): a steep, actively eroding gully wall (or zero-order basin); a steep, narrow degrading gully (or first-order stream); and a less steep, wider, alluvial-bedded valley or channel (second- or higher-order stream). We observed the first two of these units in New Zealand, at Mount Thomas and Tarndale (Phillips, 1989); while the third unit was dramatically seen at Jiangjia Gully, China (Li & Luo, 1981).

SLOPE PROCESSES

Gullyside-slopes in debris flow catchments are typically unvegetated, and over-steepened (40°-90°) by basal stream-bed incision; very unstable, so that even in fine weather stonefalls and rockfalls occur; and associated with faulting and crush zones, often with deep-seated as well as shallow failure surfaces. Slopes

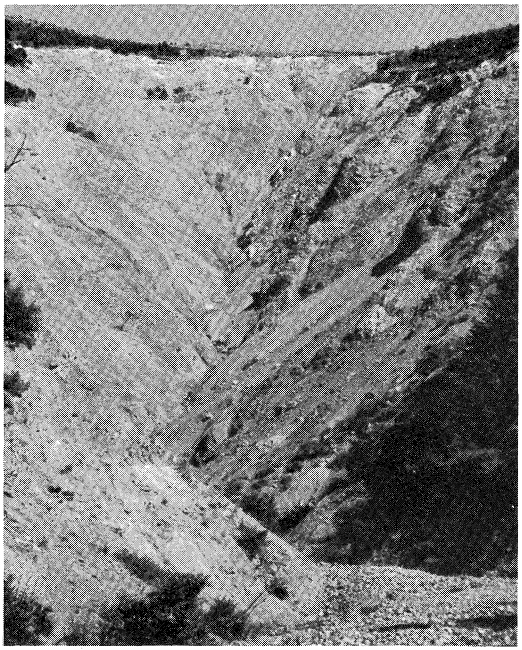

Fig. 1 Mt Thomas gully.

may be up to 1000 m in slope length.

During intense rain, especially when the regolith is saturated, small surface slope failures are common, and both fine and coarse material can literally pour down the side-slopes into the gully bed as a slurry. This material enters the stream channel unsteadily, in batches of a few cubic metres up to several hundreds of cubic metres at a time, at locations that change with time.

GULLY PROCESSES

The gully bed is steep (greater than 10°) and very rough. In places, fine or coarse material scree deposits will have encroached across the gully bed since the last flow event in the gully. When a rainstorm begins, it is probable that substantial quantities of sediment will almost immediately be delivered to the gully bed, in the form of more or less dense slurry which can immediately flow down the steeper gully reaches, and slow down or stop where the gully slope decreases. As rainfall continues this process will become more widespread, and if the rain does not become very intense the overall result of the storm will be to cause material to accumulate in the lower, less steep gully reaches.

Slurry movement in the gully beds picks up and incorporates loose material already lying there, increasing the volume of moving material and often slowing down or temporarily stopping the flow when large rocks are encountered. Further slurry builds up behind this temporary dam until there is enough static pressure to move the rock-jam, or overtop it, whereupon the enlarged mass of rocks and slurry flows down the gully, again entraining loose bed material. Flow thus consists of a series of surges, with coarse material at the head and progressively finer slurry towards the tail. Between surges the streamflow ranges from water high in suspended fines to a thick oily-looking slurry of fines in water.

If the rainfall intensity is sufficient, the surges become energetic enough to entrain the stationary accumulation from a previous surge and form a much larger surge. This can move much faster and scour more material from the gully bed and sideslopes, and can proceed much further down the gully before channel widening (depth reduction) and/or gully slope decrease slows and stops it. Under these circumstances a major event can occur, and substantial quantities of coarse slurry travel to the gully exit and onto the channel or fan surface beyond.

The crucial criterion for such an event is that surges initiated high in the steep gully reaches are sufficiently energetic to remobilize slurry deposits in the lower gully bed. If these deposits have dried and compacted since emplacement, however, it is likely that they can only be remobilized by headward recession of a downstream nick-point to form a deep, narrow canyon (Fig. 2).

Over a long time period, covering several major and many minor events, we expect that the upper gully alternates rapidly between infilled (by delivery of slope material) and scoured (by virtually every rainstorm); while the lower gully bed level will vary much more slowly, being deeply scoured by major events while slowly infilling with slurry deposition from minor events (Figs 2 and 3).

CHANNEL PROCESSES

The channel reach at Jiangjia is from 25 to 500 m wide, depending on location and time (i.e. whether or not the valley bottom is incised), and slopes at about

Fig. 2 Incised channel (1982).

Fig. 3 Infilled channel.

17% (10°) over a 5.5 km length to its confluence with the Xiaojiang River. The channel bed material is fluvially winnowed or washed old debris flow deposit, ranging from -70 to 10 ϕ (100 mm to 0.001 mm) with occasional boulders of 1 m diameter. Between debris flow events the channel is occupied by a braided, gravel-bed river of about 25 m overall width.

Descriptions of flow behaviour in this channel reach have outlined the following sequence of events at a given cross section (Li & Luo, 1981):

(a) Following the onset of rain, streamflow first rises to about 5 $m^3\,s^{-1}$, then suddenly decreases.

(b) A series of small surge waves occurs, initially of thin mud, that lay a "muddy blanket" over the braided gravel channel bed, as each successive surge travels farther downstream.

(c) Following the mud waves, a series (10-100 in number) of large (several metres high) rapid (10 $m\,s^{-1}$ or so) waves of dense ($\sim$ 2.0 $t\,m^{-3}$) slurry occurs, with the appearance of wet concrete. Between waves the slurry becomes stationary, or nearly so. The interval between waves is about 1-5 minutes, but can be remarkably constant.

(d) As the rainstorm dissipates, the waves become smaller and less dense and are followed by re-establishment of muddy stream flow; the channel bed becomes braided again.

Several questions remain unanswered about this remarkable sequence of events:

(i) How do the large, regular waves originate? It is inconceivable that they are simply gully-generated surges flowing down the channel, because of their regularity and since an individual channel surge wave may have a volume of many thousands of cubic metres.

(ii) How do these waves behave as they move down the channel? Do they reduce in size, or grow? Is their frequency of occurrence constant along the channel?

(iii) Why do the waves not erode the channel banks severely, since they appear to be capable of rapid bed erosion?

(iv) Why does the channel streamflow reduce prior to a series of debris flow waves?

To explain these phenomena it is necessary first to consider debris flow rheology.

DEBRIS FLOW RHEOLOGY

Debris flows comprise an intimate mix of coarse, angular grains of all sizes from about 1 mm to 1 m, in a thick slurry of fines (< 1 mm) in water. The volume concentration of solids can be up to 70% or 80%, and the bulk density can be greater than 2.0 t m^{-3}. The material looks and flows like wet concrete. Its flow appears to be laminar in the fluid-mechanical sense, that is, local turbulence can be induced by a disturbance of the wave-front, but is very rapidly damped out by the viscosity of the fluid, and the undisturbed flow is very smooth and free of eddies. Investigations of the rheology of wet concrete, debris flow material and dense suspensions in general suggest that the flow curve is of the general form shown in Fig. 4 (Davies *et al.*, 1991); note that

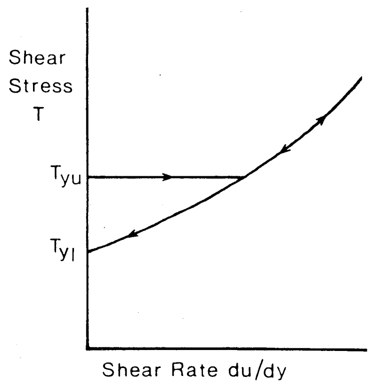

Fig. 4 Flow curve for debris flow material.

this only covers shear rates up to about 10, because the majority of debris flows fall within this range (Phillips, 1989). This flow curve indicates that if the shear stress on a body of fluid exceeds the yield stress, the fluid will suddenly begin to move at a relatively high shear rate; this is exactly the type of behaviour that could give rise to the observed appearance of a low wave in a stationary deposit as described below. Also, in slowing down under reducing shear stress, the material would come to a very gradual halt, again in line with our observations at Jiangjia.

SCENARIO OF SURGE-WAVE INITIATION AND EVOLUTION

Following intense rain, the contributing gullies will each deliver to the main channel a series of surges of varying volume, density, grain-size and fluidity. Since the slope of the main channel is substantially less than that of the gullies, and the width much greater, these surges will probably halt due to their internal friction before travelling far along the channel. Surge activity will effectively dam the channel, causing streamflow to cease downstream. In time the whole channel bed in the region of the headwater gully exits is likely to become filled with stationary surge material, with further surges continually entering the large body of stored slurry.

Observation of debris flow waves in Jiangjia Ravine in late July 1990 revealed that instability exists in the ***stationary*** slurry between the passage of major waves, as evidenced by the spontaneous appearance of very small, solitary full-width surface waves that grow rapidly as they move downstream; within 100 m of travel waves typically had increased in amplitude to about 1 m, travelled at about 5 m s^{-1} and clearly incorporated the underlying slurry as they passed (Fig. 5). A tentative explanation of this phenomenon was suggested by Davies *et al.* (1991). We postulate that the stationary slurry deposited from gully surges can spontaneously generate such waves, particularly as further surges will still be entering the channel slurry and disturbing it.

These surge waves will move to the downstream end of the stationary slurry deposit and over the rough, fluvial bed downstream. They cannot entrain material from the relatively compact stream bed, however; rather, they ***lose*** material in laying down a "mud blanket" over which subsequent waves move. Hence the foremost wave becomes smaller and slower; it is soon overtaken by the next wave in the sequence, which in turn deteriorates and is overtaken. The wave ***group*** velocity is about 2 m s^{-1}, from Jiangjia data, whereas individual wave front velocities range between 5 and 10 m s^{-1}; since the velocity of streamflow is also of the order of 1-3 m s^{-1}, it follows that the reduction in streamflow at any given section due to surges damming the flow upstream will be followed quite soon by the first muddy waves passing that section.

When a few muddy waves have passed a section, the following eaves are much larger and denser, and very regular – we observed five such early large waves spaced ***exactly*** 50 s apart. Since wave initiation is very likely to be random in time, some regulating mechanism must be at work. We observed that large waves overtake small waves, incorporating them in the process (Fig. 5(c)) – in this respect they behave very much like roll-waves in water, which rapidly increase in amplitude and regularity with travel distance. The roll-wave hypothesis of Takahashi (1983) and Davies (1986) thus seems likely to describe the evolution, if not the initiation, of slurry waves. We therefore expect that farther down the channel waves will be less frequent, more regular and bigger than those higher in the channel. This remains to be tested, but depositional evidence certainly supports downstream wave growth.

During the later stages of the event, traces of the original fluvial bed are

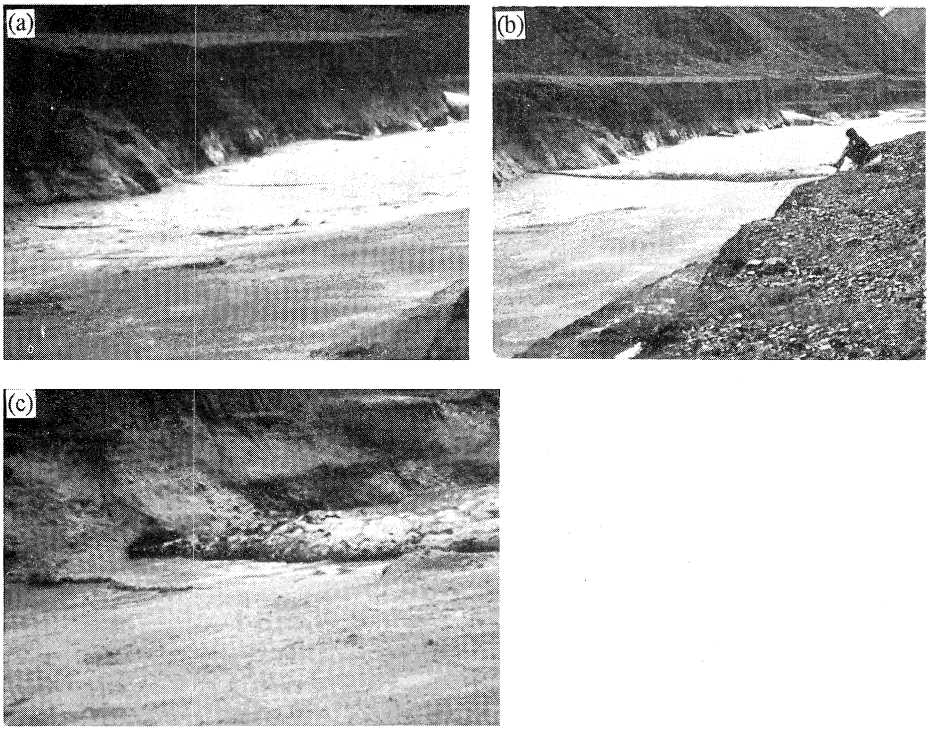

Fig. 5 (a) Incipient wave; (b) wave growing; (c) wave 1 m high.

visible at the edges of the channel, not substantially scoured by all the previous wave activity – hence Davies' (1986) insistence that the head of a debris flow is the active scouring part is certainly untrue for channelized debris flows, though it might still be valid in gully-head reaches.

It seems likely that the locus of wave-generation moves downstream as rainfall decreases and sediment input to the channel ceases. Streamflow will now dilute the in-channel slurry, reducing the yield strength, and wave generation can occur at lower slurry depths and lower slopes.

NICK-POINTS

During the later, less dense wave phase, we observed deep ($\sim$2 m), narrow ($\sim$5 m) scour holes in the bed of a straight channel reach. These were acting as nick-points and being rapidly ($\sim$1 m min^{-1}) eroded headward by the passage of waves. They were being cut into old, dry-looking bed material, clearly not a deposit of the present flow (Fig. 6). The result was a long, deep narrow trough being cut headward in the centre of the channel. We hypothesize that deep bed scour occurs at bends where intense turbulence caused by the bend is able to erode old, compact bed material; between surges scour-holes are

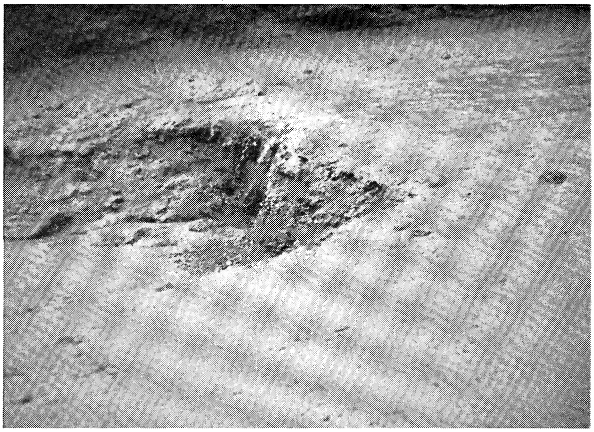

Fig. 6 Nick-point.

filled with easily-scoured slurry. The later, lower and more fluid waves form a turbulent overfall at the scour-hole and excavate the bed more deeply. We later noted a series of such nick-points retreating up the main observation reach, apparently related to a series of bends. This process explains how debris flows can cut deep, narrow canyons in old deposits, obviously by bed erosion, while being unable to widen the channel by lateral scour. The flow falling over the nick-point impinges almost vertically on the bed; vertical momentum destruction causes bed shear orders of magnitude greater than that which can be exerted on the sides by the velocity gradient in a flow parallel to the bed.

When the dilute slurry flow is later replaced by turbulent waterflow, this is able to meander and attack the sides of the narrow trough in the channel, undercutting them to widen the channel substantially (Fig. 7). The event we saw lowered the whole bed width by about 0.5 m, and this was all accomplished after the main wave sequence had finished.

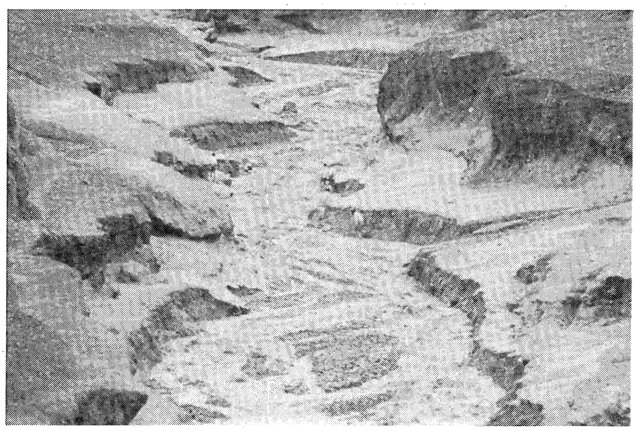

Fig. 7 Streamflow channel.

CONCLUSIONS

(a) Large debris flow surges can be initiated by instability of stationary material in the channel bed.
(b) Debris flows can erode vertically by nick-point retreat, without significant lateral erosion.
(c) The scenario presented is a plausible basis for the complete debris-flow phenomenon.

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