

The main features of the mudflow in Jiang-Jia Ravine

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with 6 figures, 6 photos and 4 tables

Zusammenfassung. Das Bergland von Südwest-China ist ein Gebiet, wo durch Starkregen verursachte mudflows sehr häufig sind. Oft verursachen diese katastrophale Schäden an Siedlungen und Feldern. Der größte und verheerendste mudflow kommt im Wildbachbett des Jiang-jia vor. Obwohl das Einzugsgebiet nur 47,1 km² beträgt, werden Schlamm-Abflußmengen bis 2420 m³/s erreicht. Die schweren Schäden treten seit mindestens 300 Jahren auf. In der Regenzeit (Mai bis Oktober) treten jährlich Dutzende von Schlammströmen auf, die ein Volumen von $3-5 \times 10^6 \text{ m}^3$ /Jahr erreichen. Auf der Basis von mehr als 15 Beobachtungsjahren werden statische und dynamische Kennzeichen von mudflows beschrieben.

Summary. The mountainous area of southwest China is a region where mudflows generated by heavy rainfall are rather common and frequently cause catastrophic damage to the local settlements and fields. Jiang-jia Ravine has the largest and most hazardous mudflow in this area. Its catchment is only 47.1 km², but the maximum mudflow discharge can reach 2420 m³/s. It is known that the mudflow has been causing damage for at least 300 years. In the wet season (May–October) each year, the mudflow may occur from several to several dozen times, and the total volume transported reaches $3-5 \times 10^6 \text{ m}^3$ every year. We describe the static and dynamic features of the mudflow and its deposits on the basis of observations made over more than 15 years.

Résumé. Dans les régions montagneuses du sud-ouest de la Chine, des coulées de boue provoquées par des pluies intenses sont très communes et provoquent fréquemment des dommages catastrophiques aux villages et aux terres agricoles. La "Jiang-jia Ravine" est le siège des coulées les plus vastes et les plus dangereuses de la région. Leur bassin s'étend sur 47,1 km² seulement mais le débit maximum des coulées peut atteindre 2420 m³/s. Il est bien connu que les coulées ont causé des dégâts il y a 300 ans. Pendant la saison humide (mai–octobre) de chaque année les coulées peuvent avoir lieu à de très nombreuses reprises et le total du volume transporté atteint $3 \text{ à } 5 \times 10^6 \text{ m}^3/\text{an}$. La morphologie et la dynamique des coulées sont décrites sur base d'observations s'étalant sur plus de 15 années.

Introduction

Jiang-jia Ravine lies in the middle reach of the Xiao Jiang River in the Dongchuan District of Yunnan Province (fig. 1). It lies alongside the Dachao River basin which is also characterized by mudflows. We have already described these (LI JIAN et al. 1979, 1981), but the scale of the mudflows and the damage caused, is far greater in the Jiang-jia Ravine than for the Dachao River.

The sedimentary and mechanical characteristics of the mudflow

The Jiang-jia Ravine mudflow is a kind of plastic viscous liquid with a high proportion of solid matter (table 1). It is very different from a debris flow dominated by sand and gravel. The complex mechanical composition gives a high density, high viscosity, and large shear strength (table 2). This material acts as a plastic-viscous system with mutual saturation of solid and liquid. In some of the tributary valleys of the Ravine the solid content may rise to 85 % and the ratio of water to soil by weight may reach 1:6 or more. These mass movements resemble earth flows and more down steep channels under the influence of gravity.

Table 1 The mechanical composition of the mud (cumulative percentages).

Gran diameter (mm)	0.001	0.005	0.01	0.05	0.1	0.25	0.5	1.0	3	5	7	10	20	40	80
%	1.30	2.00	5.80	14.00	15.57	17.60	19.35	22.11	28.94	36.44	41.13	48.57	65.05	83.01	96.74

The grain size of the solid material is very heterogeneous, ranging from fines (< 0.005 mm) to giant boulders 5–8 m in diameter, a size ratio of 7×10^6 . It is this mechanical composition which controls both the flow and the sedimentary features of the resulting deposits. Preliminary analysis suggests that the mud matrix involves all the material under 3 mm diameter, and that larger gravel particles float in this mud. The capacity of the mud for buoying up coarser material, and thus transporting it, is increased by turbulence, while forces of dispersal also occur as the gravels interact: in this way even the huge boulders are carried along with apparent ease. Further the various types of clay mineral, and the content of positive ions in the mud as well as its temperature all affect its ability to support large boulders. The limited experiments we have been able to carry out do not establish the role of these large particles in the mobile flow.

Our measurements show a bimodal distribution on the sediment size histogram (fig. 2). This distribution is distinct both from normal river-bed sediments in the area, and from the geological materials which outcrop in the upper reaches of the basin, and is reminiscent of glacial moraine. The material cannot simply accumulate as a result of mechanical failure of the upper slopes, but must undergo more complex weathering and mixing. Its recognition is significant for Quaternary Studies, for in the past such deposits have been confused with glacial moraine, in China at least.

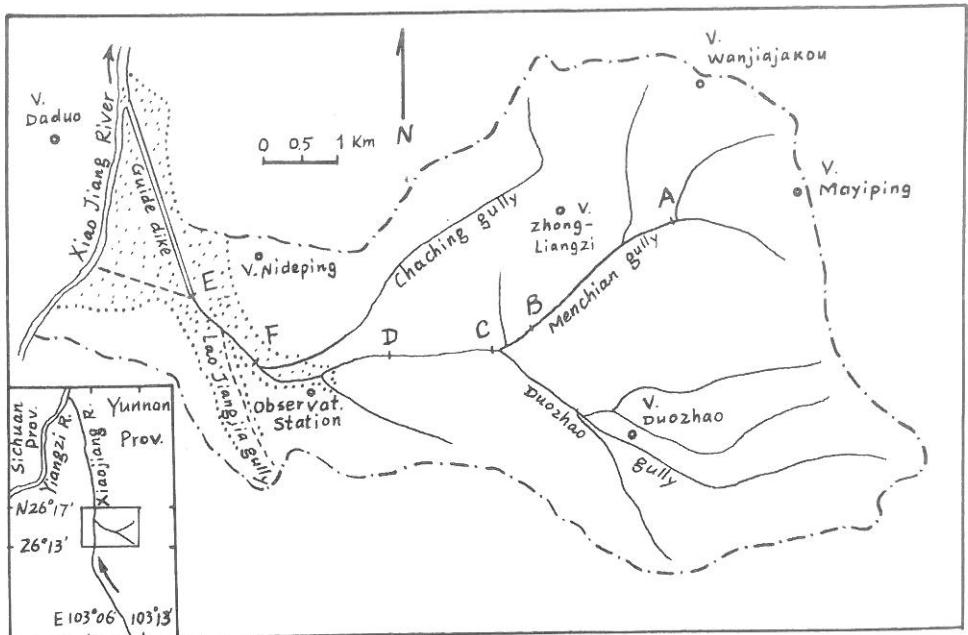


Fig. 1. The basin of Jiang-jia Ravine.

Table 2 Measured values for the mudflow of July 16, 1974.

Parameter	number	unit
Density (γ)	2.30	g/cm^3
Median of granular diameter (d_m)	3.92	mm
Shear strength (τ)	4.33	dyn/cm^2
Viscosity (η) (measured on remoulded material calculated from field data)	15.5 (1736)	poises
Percentage solids	89.0	%

The density of the mudflow material is one of the most important parameters, setting it apart from other substances. The value in this Ravine is generally in the range $1.9\text{--}2.3 \text{ g/cm}^3$. Mudflows with such a high density which occur as often as ten times every year are very rare, in China and throughout the world. There is a consistent relation between the mudflow density and the mean diameter of the grains in the fluid mud matrix. It is given by the equation

$$\gamma = A \cdot d_m^B$$

where γ — density of the mudflow
 d_m — mean value of grain diameter of the mud matrix
 and A, B are constants¹

¹ Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica (1977): A preliminary study of rheological characteristic of slurry mudflow's fluid.

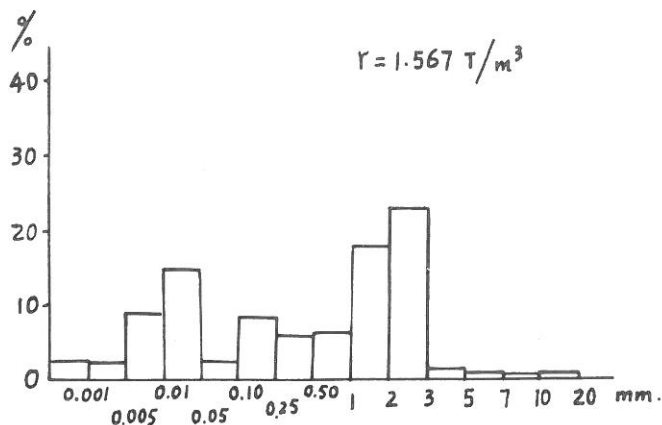
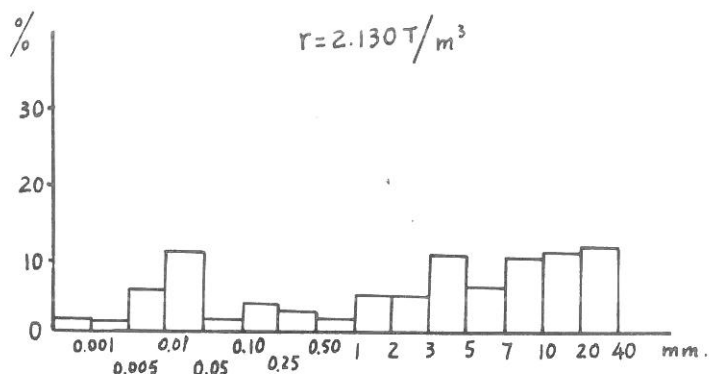


Fig. 2. Histogram of mechanical composition of mudflow.

The constants vary from one basin to another; for the Jiang-jia Ravine the values are $A = 1.65$, $B = 0.188$

According to the data based on both static and dynamic observations made for years in the Field Station and laboratory, the conclusions which can be drawn are as follows:

- a) The density of the flowing material increases gradually from turbid water (1.10 g/cm^3) at the beginning to a value of 2.25 g/cm^3 or so at the end of the mudflow bursting. The value during the duration of mudflow bursting (in the form of a wave or surge) is usually stable and between $2.10\text{--}2.37 \text{ g/cm}^3$, but it reduces quickly down to the initial turbid flood value as soon as the mudflow stops.

- b) As a flood changes into a mudflow, the density at the point of transition is about 1.60 g/cm^3 or so. That is to say when:

$\gamma < 1.60 \text{ g/cm}^3$ continuous flow of muddy floodwater
 $\gamma \geq 1.60 \text{ g/cm}^3$ mudflow in waves

- c) During the motion of mudflow, a large amount of river bed material can be dug, moved and carried by the moving mudflow mass along its path; this material is strongly and turbulently mixed and gradually becomes incorporated into the mudflow.

粘度2-3Pas

Making use of values of shear strength from remoulded material, the viscosity of the mudflow in the Jiang-jia Ravine has been measured in the laboratory as 20-30 poises. But using the data from field observation in the research station of Jiang-jia Ravine in the formula $\eta = \frac{\gamma g i h^2}{2v}$ the viscosity of the mudflow can be calculated to be equal to 1500 poises. Here density of the mudflow, $\gamma = 2.13 \text{ g/m}^3$; i (inclination of the river bed of the research station) = 0.06; h (depth of the mudflow) = 1.40 m; v (velocity of the mudflow) = 8.0 m/s; g (acceleration of gravity) = 980 cm/sec²; and η (viscosity of mudflow) = 1534 poises. A viscosity of 2.1×10^3 to 6×10^3 poises has been measured by H. CAMPBELL (1974) for a mudflow in the Wrightwood District (USA) where the ratio between water and solid was 15-20 : 80-85.

As for the shear strength of the mudflow in the Jiang-jia Ravine, it may be approximately expressed by the Bingham formula $\tau = \tau_0 + \eta \frac{dv}{du}$ where τ - the shear stress of the mudflow; τ_0 - the critical shear stress under which the mudflow cannot move; η - viscosity of the mudflow; and $\frac{dv}{du}$ - gradient of velocity in different layers of mud. The value of the shear strength of the mudflow in Jiang-jia Ravine River reached 2000-3000 dynes/cm² which is far higher than those in other districts.

It is worth pointing out that owing to its great viscosity and the high initial shear strength of the mudflow, the critical equilibrium of the mudflow mass on the slopes can be destroyed only after an appreciable external force has been applied to overcome the resistance of internal friction.

Observation in the field and experiment in the laboratory have shown that the static characteristics of the mudflow, such as density, viscosity and shear strength influence the dynamic features of it, therefore their values and the relationships among them have become an important aspect of research on the mudflow and its prevention.

The bursting process of mudflow and its dynamic features

On the basis of observations at the research station in Jiang-jia Ravine (1965-1979), the most important feature of the mudflow movement is that it bursts, usually in the form of successive waves or arrays from beginning to end² (table 3, fig. 3, photo 2).

² It is an intermittent flow, every one of which is in a wave form and just like fig. 4a.

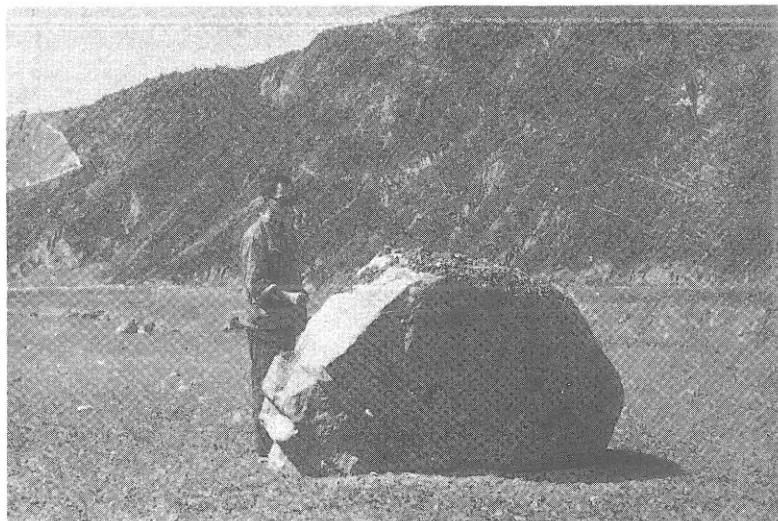


Photo 1. Big stone carried by mudflow on July, 5, 1978 to the constructed deposition size (near F in fig. 1) and deposited mudflow mass.

Table 3

(June, 27–28, 1966)

parameter	unit	Number
Time		23:09,27–04:03,28
Total duration	hr	4.91
Height (depth) of head Surge (h)	m	max 4.00
velocity (v)	m/s	max 13,1
	m ³ /s	min 3.19
Discharge (Q)		max 2420
		min 152
Volume of one wave	m ³	max 24600
		min 655
Number of waves		126
Lasting time of one wave	sec	max 63
		min 5
Total volume of mudflow	m ³	362,000
Density (r)	g/cm ³	2.22
Content of Solid	%	88
mean value of granular		
diameter of mudflow mass (dm)	mm	6.80
Max diameter of debris	m	6.2
density of Solid	g/cm ³	2.76
Viscosity of mud (η)	poises	15.0 (1510) ²
Shear strenght of mud (τ)	dyn/cm ²	2120



Photo 2A. Moving mudflow wave.



Photo 2B. Three small mudflow waves one after another.

As seen from fig. 3, the waves trains occur for a period of time and there is not any flow before the first surge of the mudflow or between successive groups of waves. Interruption of normal flow in the valley is achieved quickly as soon as the discharge of the flood in the valley comes to $4-6 \text{ m}^3/\text{sec}$. The duration of cessations of flow generally last several minutes. The longest interval may reach 25–30 minutes. A sense of silence sets in, to be broken as a distant sound like thunder marks the next convulsion of the contributing gullies, and then the surges (waves) of the mudflow rush down one after another until the episode is ended (fig. 3,4).

A small burst lasts ten to thirty minutes with 3–5 waves and a big one can last more than ten hours with more than a hundred waves. The biggest height of the mudflow surge is 2–3 metres in the wide and even river bed, and 5–7 metres in a narrow gully. If the mudflow is retarded at a channel bend, the leading waves will surge up by some metres. According to our observations, the largest discharge was of $2420 \text{ m}^3/\text{s}$ (27 June, 1966); the longest duration of the bursting was more than twelve hours (21 July, 1966); and the greatest number of successive waves (arrays) was 310.

The longest pause between two waves is 15–20 minutes. Based on field observations each mudflow-wave is noted on fig. 4. The head presents a tongue-like form in plan (photo 2A). The maximum velocity is at the front or head of the surge. The velocity in the median line of the wave is always higher than that of both sides and

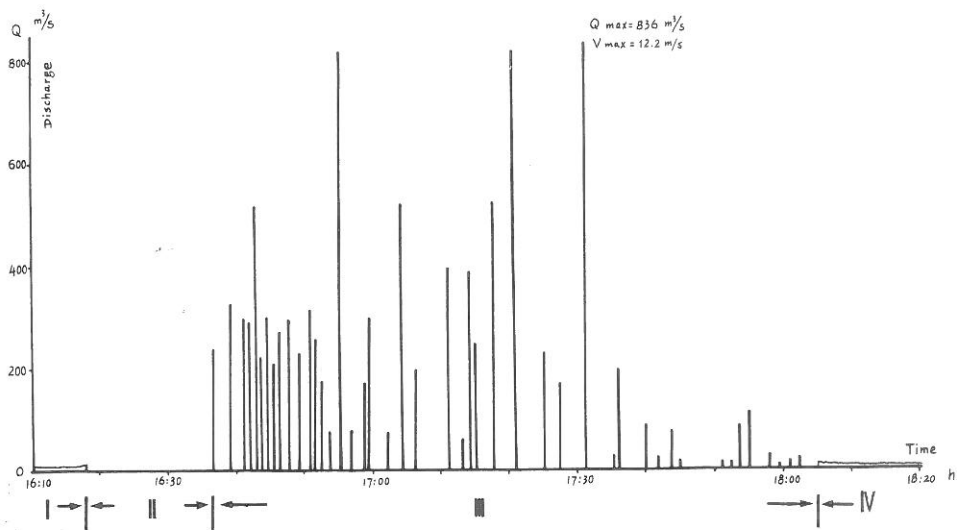


Fig. 3. Process of mudflow bursting in Jiang-jia Ravine (on July, 23, 1966). – (I) – The normal water discharge (flood) before bursting mudflow ($4-6 \text{ m}^3/\text{sec}$); (II) – Cessation of water flow before bursting mudflow (16:18 – 16:37), there is not any flow in the valley; (III) – Process of bursting mudflow, it is an intermittent flow, each phase of which is in a wave form and just like figure 4a. It lasts one hours and 29 minutes with 45 waves. Between successive waves there is no flow in the valley; (IV) – Beginning of normal water discharge (flood).

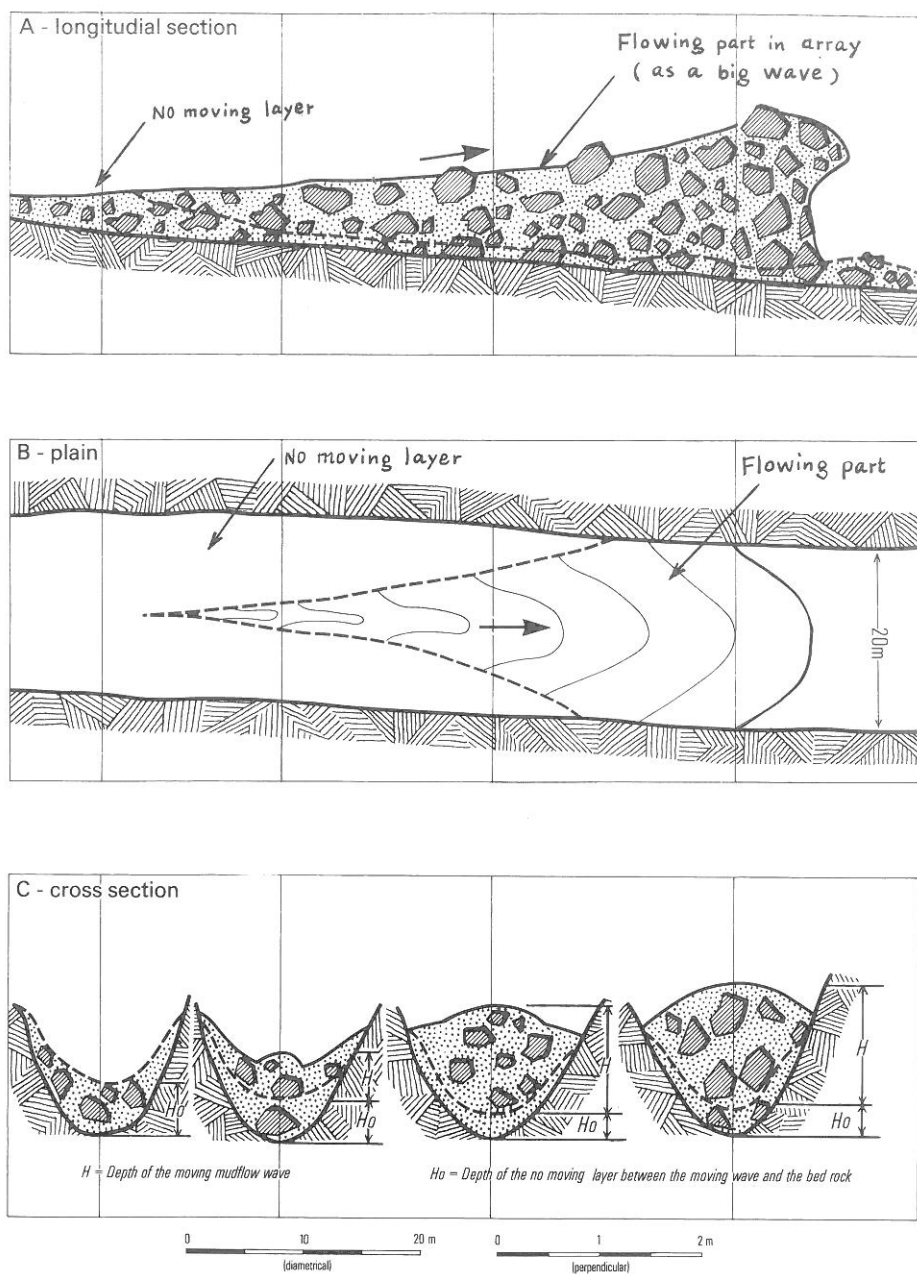


Fig. 4. Illustration of wave form of a viscous mudflow.

comes to zero at the tail where it gradually narrows and almost changes into a thread (figs. 4a, b). As shown in successive cross sections, the mudflow has a convex surge head, a horizontal middle reach and a concave tail. The outline of the bed with mudflow layer of about 40–50 cm thick above it could be seen at the place where the mudflow is interrupted (fig. 4c). The general length from the head to the tail of the wave (fig. 4a) is 20 m (a small one) to 100 m (a large one). A wave lasted as much as 20–60 seconds. It is perhaps best described by an analogy; the whole wave (surge) seems to be a creeping giant serpent with a huge head and slender tail. When it meets an obstacle its kinetic energy causes it to rush up to 5–8 m. The mud, together with big and small stones, is thrown into the air (photo 3). The impact force of the head reaches as much as $10\text{--}50\text{ tons/m}^2$.

The moving waves of mudflows (grouped in arrays) are very similar to each other. The splattering wave is at the front and the posterior parts display laminar flow. So the fluid mass of each moving wave constitutes a complete flow system and an undivided body. In this case stones of 0.5–0.6 metres size floated on its surface. It is completely different from the movement of gravel and stones in a river in flood (MORTENSEN & HÖVERMANN 1958).

Why should the mudflow always surge in the form of a train of waves? It seems that this characteristic of this kind of viscous mudflow depends upon the physical nature of the material and the rheological features of the fluid mass. It is obvious that this kind of viscous mass cannot flow unless the mud is deep enough to get over its yield strength in shear, i.e. the shearing stress due to gravity is greater than the shear resistance that the fluid mass offers. To reach this critical value it needs time in which the energy can be accumulated and converted.

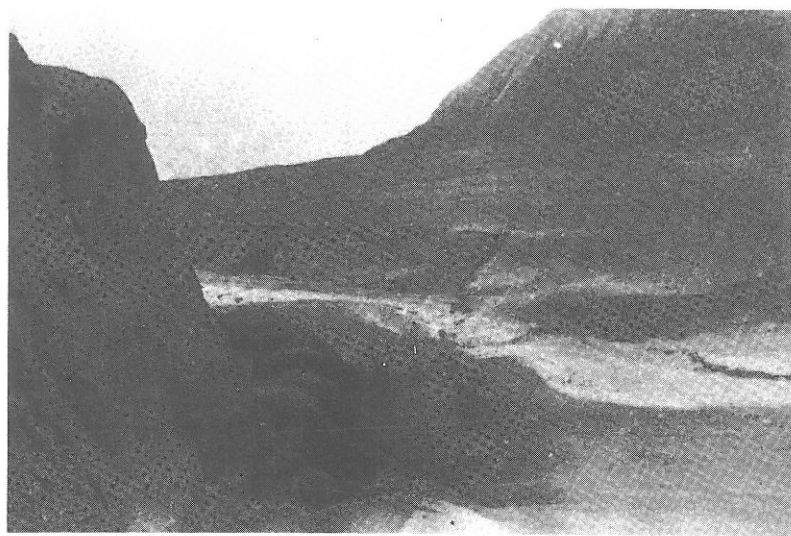


Photo 3. Mudflow wave before cliff. The surge of it rises up to 5 metres and the mud with stones is thrown into the air.

We have also noted that the first wave moving over the river-bed is unusual as the rough bed offers a considerable resistance to movement. As a result the first wave on the 'dry', rough bed moves down very slowly. There is no obvious spray splattering in its front. Because the mudflow adheres to the rough surface of the bed it loses material along the way, and becomes thinner and thinner. Finally the wave stops to form a pronounced tongue form with a margin about 10–20 cm thick. Then further waves advance over the initial deposits for some distance and then stop as before. This pattern of mudflow moving and adhesion can be defined as the 'pavement' because it seems to pave the way on the rough bed for the following surges of mudflow. As far as the field observation goes, a later wave might extend beyond the prior one by 50–60 metres. Therefore it needed dozens of waves and also a long time to reach the observing section from the confluence of the Duozhao and Menchian tributaries (fig. 1C). It also follows that many of the smaller mudflows do not reach the surveyed section. Consequently the counted numbers of the mudflows bursting past the surveying section has tended to be fewer than might be observed further up the valley.

After this initial pavement process, the advancing waves moved more freely on the fresh and smooth surface of the mud, reaching velocities as high as 15 m/sec. The layer of fresh material which adheres to the bed could be 40–50 cm thick in the channel and even over 20 cm on the slopes as steep as 10–20° (fig. 4, a c).

Jiang-jia Ravine is a gully with water flowing throughout the year. Its minimum discharge prior to the wet season is about 0.2–0.3 m³/s. The peak value of the flood discharge cannot be measured because there is no 'flood' (in the conventional sense) in summer. Calculations using the hydrological hand book of Yunnan Province show that the highest flood discharge which might be recorded in the basin is 100–150 m³/s. Thus the maximum discharge of the mudflows is 20 times and more larger in volume than that of the predicted river flood, and several hundred times more than that of water in the river bed before the mudflow bursts. Such a large ratio has never been reported from other countries. Yet, despite these figures, in the summer season during heavy rainfall the cessation of water flow (before and during bursting mudflow) occurs frequently even though this basin has a drainage area of 40–50 km². The longest period without flood is as much as 20–30 minutes, and this seems to be a typical feature of these viscous mudflow gullies.

The velocity of the mudflow in Jiang-jia Ravine has been examined from the head of the surge (fig. 4a). The maximum value measured was 15 m/s and in general lay in the range 4–7 m/s. The velocity of the mudflow surge in Jiang-jia Ravine can also be determined using the data obtained from the surveyed section in a formula:

$$V = 13.5 \left(\frac{d}{h}\right)^{0.062} \left(\frac{C}{\gamma}\right)^{0.025} \sqrt{ghi}$$

- where
- V – velocity of mudflow surge cm/s
 - d – median of granular diameter cm
 - h – height (depth) of the surge cm
 - C – percentage viscous grains (< 0.005 mm) %
 - γ – density of mudflow g/cm³
 - g – acceleration of gravity cm/s²
 - and i – inclination of river bed at the surveying section %

Table 4 The variation of incision and deposition in Jiang-jia Ravine. $\left(\frac{-6. \text{Variation value (m)}}{(1870), \text{Altitude, a.s.l. (m)}} \right)$

Date of measurement	Observation sites (see fig. 1)				
	A	B	C	D	E
1957	(1876)	(1604)	(1516)	(1374)	(1162)
Feb. 1962					+ 19 (118)
June 1965					+ 5 (1186)
April 1966	- 6 (1870)	+ 52 (1656)	- 2 (1514)	+ 16 (1390)	- 2 (1184)
Nov. 1966	- 1 (1869)	- 44 (1612)	+ 12 (1526)	+ 5 (1395)	+ 4 (1188)
July 1967	+ 7 (1876)	+ 4 (1616)	+ 6 (1532)	- 1 (1394)	+ 6 (1194)
Oct. 1969	- 16 (1860)	- 16 (1600)	- 8 (1524)	- 3 (1391)	
May 1933		- 4 (1596)	- 6 (1518)	- 13 (1404)	+ 12 (1206)
Nov. 1974		+ 0.3 (1596.3)	+ 2 (1520)	+ 5 (1409)	- 1 (1205)
July 1977	- 6 (1854)	+ 2.5 (1598.8)	- 5 (1515)	- 5 (1404)	+ 15 (1220)
Total 1957-1977	- 22	- 5.2	- 1	+ 30	+ 58

The erosion and deposition of mudflow

The conspicuous features of mudflow in erosion and deposition are that its erosion action is very intensive, the deposition process of it is surprisingly quick, and at the same time it has a great variation (table 4, fig. 5). One mudflow event can carry $0.3-0.4 \times 10^6 \text{ m}^3$ of mudflow material away from the upper part of the basin in a few minutes to 1-2 hours. The annual output reaches up to $4-5 \times 10^6 \text{ m}^3$. The diameter of the largest boulder carried may be 7 m and with a volume over 30 m^3 . It is obvious that such an enormous quantity of the solid mass in motion must cause great change on the upper, lower and at the confluence into Xiao-jiang River. The mudflow can transform the appearance of the basin and its neighbouring region in few minutes, or at most 1-2 hours, making it one of the most active geomorphic processes known (BRUNSDEN 1979). Erosion and deposition by mudflows is going on in many mountain regions of China; it demands serious attention.

³ XU JUNMING, PO MIAOSHEN & LI RUSONG: Investigations of mudflow in Jiang-jia Ravine, 1966 (unpublished).



Photo 4. View of erosion in upper part of Menchian Gully.

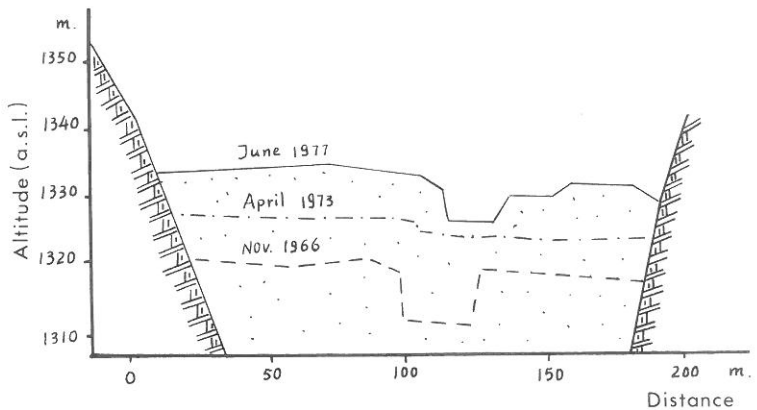


Fig. 5. Deposition process on the cross section of the research station of Jiang-jia Ravine.

In the basin of Jiang-jia Ravine the upper part is rapidly denuded by erosion while the lower reach shows rapid deposition (photo 4, 5A, B)³. It is common that the upper reach including the underlying rock (consisting of shale) is cut down to 3–5 metres, even 8–10 metres in one event. As a consequence we have measured erosion in Jiang-jia Ravine as up to 20 000–24 000 tonnes/km² a year (fig. 6). In other words it is common that a layer of 2–3 metres in the middle section and 5–6 m in the lower parts of the Ravine is deposited in a single event (table 4, fig. 5). As is seen from table 4, during 1957–77 the deposition had built up to as much as 58 metres near the mouth of the guide dike (fig. 1E). The bed of Daidi gully (fig. 1A) had been



Photo 5A. Deposition of mudflow in the wide part of the gully (near F in fig. 1).

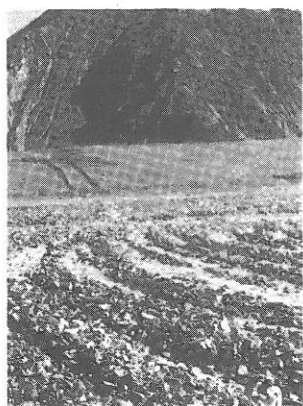


Photo 5B. Fresh mudflow deposition in a form of ring.

cut down by 22 metres in the same period. These values emphasise the role the mudflow has played in modelling the earth's surface! The force exerted by the mudflow is far greater than river flow even in flood, or even that of a large contemporaneous and active glacier. At home and abroad there are many other examples showing that mudflows present an astonishing capacity for transport and damage to the local environment (Lanzhou Institute of Glaciology & Cryopedology 1972).

We have been able to show that the alluvial features of this mudflow involve a general tendency for the upper part of the basin to be eroded while the lower part has deposition dominant. But in any one event it is possible for the incision and deposition to appear in any reach of the basin, even on some gently sloping sections.

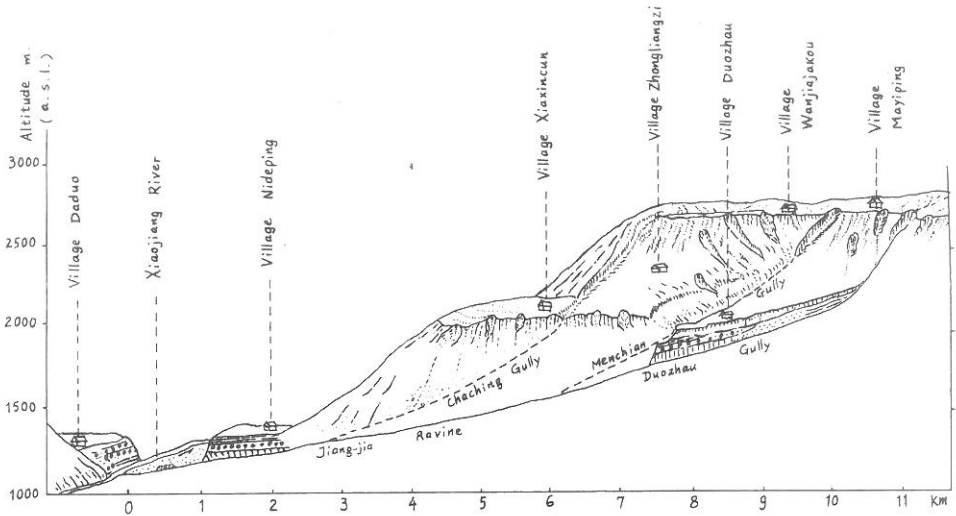


Fig. 6. The longitudinal profile of Jiang-jia Ravine and its erosive pattern.

Indeed it has frequently been observed that some parts of the river bed had been incised by 5–8 metres by a single event on one day, only to be buried by another during the next night (photo 4).

When deposition occurs in the upper part, it is always caused by a particularly viscous mudflow with great cohesion. But such deposition is ephemeral and later destroyed by the more common erosional events.

All our observations emphasise the great contrast in behaviour between a mudflow and a stream in a similar-sized basin. Water discharge always increased downstream i.e. $Q_{up}^w \leq Q_{low}^w$. For a mudflow it is commonly the case that discharge reduces as it proceeds down the Ravine, i.e.

$Q_{up}^m \geq Q_{low}^m$ where Q_{up}^w , Q_{low}^w , Q_{up}^m , and Q_{low}^m are discharges of water and mudflow in the upper and lower streams along the same valley. This feature of mudflows is very significant especially whenever attempts are made to control the mudflow.

The phenomenon of aggradation was observed on a concreted-stone dam 5 metres high at the confluence with the Chaching Gully (fig. 1F) in 1974. It showed completely different behaviour from a river flood. The deposition of the mudflow in the valley extended from the dam about 4 km upstream with a thickness of 4–5 metres until the confluence of the Duozhao and Menchian tributaries (fig. 1C). The total deposition reached more than $0.7 \times 10^6 \text{ m}^3$ while the normal volume of the reservoir of the dam is only $5 \times 10^4 \text{ m}^3$. The slope of the newly deposited surface along the valley was only 60–70 % that of the former bed. These data have provided input in designing an engineering system to exert effective action in protecting and controlling the mudflow (photo 6A, B).



Photo 6A. The deposition size with earth-dams designed to catch the mudflow mass.



Photo 6B. View of the fluid mudflow in the constructed deposition size, when the mudflow is bursting (the density of it is $2.0\text{--}2.3\text{ g/cm}^3$).

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