14 Debris Flow Studies in Japan

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Debris flows are a mixture of loose soil, rocks, organic material, and water that moves rapidly downhill destroying everything in its path. Debris flow disasters are common and cause severe damage to life and property in most parts of Japan where they are often called 'mountain tsunami' (or tidal waves). In order to try and mitigate the damage caused by debris flows it is necessary to have a good understanding of their mechanisms. The study of these mechanisms was greatly facilitated when video cameras became available to record the movement. During the last 30 years a great deal of research on debris flows has been carried out in Japan and their characteristics are considerably better known than before. However, investigation is still difficult as the flows generally occur during or just after periods of heavy and concentrated rainfall.

Introduction

The term 'debris flow' is used to describe flows that contain much larger amounts of sediment, principally clay, sand, gravel, and boulders, than an ordinary water flow, and more water than a landslide. They are flows of mixed sediment and water in which the volume of sediment is greater than that of water. A debris flow does not flow as a result of the traction force of running water but because of the effect of gravity on the sediment load. The sediment does not move as individual grains, there is collective transportation in which fine sediments like clay and sand, and larger fragments like pebbles and boulders flow together as a single mass. The evidence for this is the fact that when such flows stop, sediments accumulate with large boulders in front. Very large boulders that could not be transported by water alone are sometimes transported by a debris flow. In 1934 a debris flow in Japan was able to move a 3,000 tonne boulder. Figure 14.1 shows a diagram of debris flow moving through a channel with large boulders at the head.

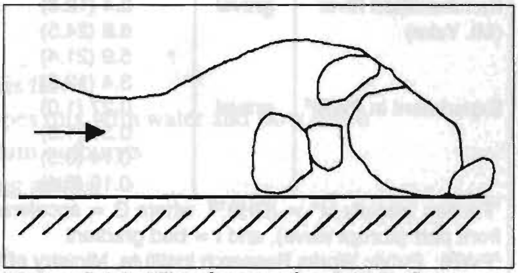

Figure 14.1: The front of a debris flow showing the large boulders at its head

One of the characteristic features of a debris flow is the great power with which they flow. This is the reason why they often cause fatalities and serious damage to infrastructure, houses, and other property. As debris flows have a high density and excessive power, they normally flow straight downwards – even at the bends of river courses where they will sometimes run up onto the opposite slope. However, although the damage they cause can be quite intense and serious, the actual area affected is limited compared to the area affected by a flood.

The characteristic features that differentiate a debris flow from a landslide or a collapse are

- the distance the flow travels — typically much further than a landslide (100 to 1,000m or more);
- the velocity — the flow is faster than a landslide (usually several metres to tens of metres per second); and
- that the sediment and water flow down together as a cohesive body, sometimes containing large boulders.

Velocity and Unit Weight of Debris Flows

The velocities of some actual and experimental debris flows in Japan are given in Table 14.1 and the unit weights of different types of debris flow materials in Table 14.2. The velocity and velocity coefficients and unit weight of mud flows are generally higher than those of gravel-type flows.

Sediment volume

Takei (1980) investigated the relationship between the size of a catchment area and the volume of deposited sediment (Figure 14.2). This type of data has been found very useful in planning to help mitigate debris flow disasters in Japan.

Table 14.1: The velocity of some debris flows in Japan

Place	Type	Velocity at front U_f m/sec (km/hr)	Coefficient of velocity U_f/U^{*1}	Remarks
Nojiri River (Sakura Island)	mud	11.5 (41.4)	11.9	8 April 1975
		13.6 (49.0)	11.1	17 April 1975
		10.0 (36.0)	8.8	4 April 1975
		9.8 (35.3)	7.4	29 April 1975
Experiment in PWRI[2]	mud	10.1 (36.4)	13.1	Sediment concentration 10%
		18.5 (66.6)	19.7	Sediment concentration 10%
		14.8 (53.3)	16.7	Sediment concentration 20%
		14.7 (52.1)	19.2	Sediment concentration 20%
Kamikamihori River (Mt. Yake)	gravel	3.4 (12.3)	1.5	
		6.8 (24.5)	3.3	
		5.9 (21.4)	2.1	
		3.4 (12.2)	1.5	
Experiment in PWRI[2]	gravel	0.27 (1.0)	0.7	
		0.37 (1.3)	1.3	
		0.14 (0.5)	0.4	
		0.10 (0.4)	0.4	

[1]Friction velocity $U^* = (GHI)^{1/2}$ where G = acceleration of gravity, H = water depth/height of debris flow at front part (abrupt wave), and I = bed gradient
[2]PWRI: Public Works Research Institute, Ministry of Construction, Japan
Source: Ikeya (1980)

Table 14.2: Unit weight of debris flow materials

Place	Type	Unit weight (kg/m³)
Mt. Yake, Japan	Gravel	1300
Ura River, Japan	Gravel	1610
Sakura Island, Japan	Mud	1800-1900
Wrightwood, CA, USA	Mud	1720-2230
Wrightwood, CA, USA	Mud	2400
Ten Mile Range, Colorado, USA	Mud	2530

Note: The recorded values depend to some extent on the size of the sediment sampler
Source: Ikeya (1980)

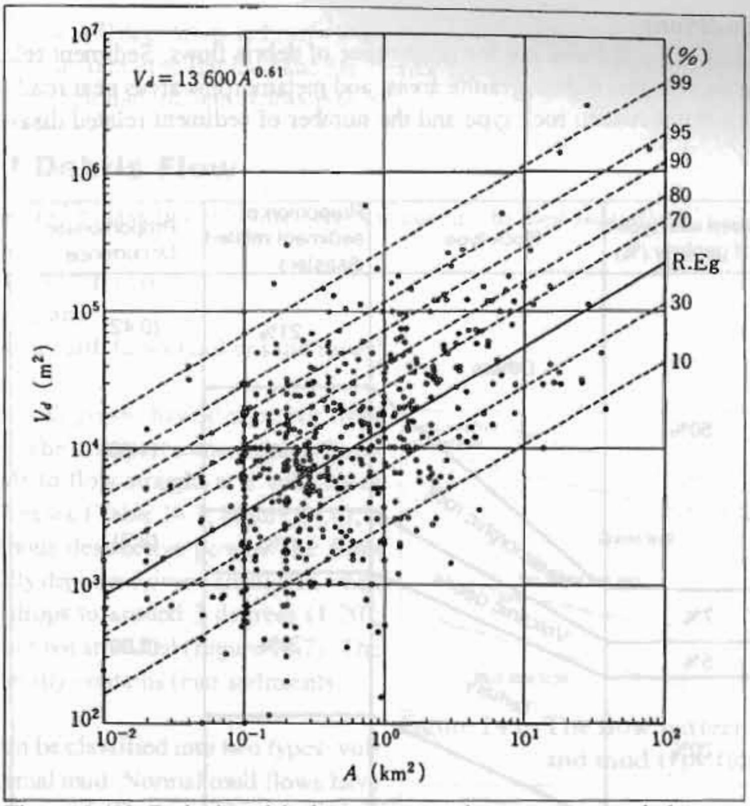

Figure 14.3: Relationship between catchment area and the sediment volume of debris flows

Causes

Ikeya (1974) described three main reasons for debris flows.

- Sediments produced by breaking up of hill slopes mix with water and flow down
- Collapsed sediments dam up a river and the dam outbursts
- A riverbed deposit experiences strong scouring action

Takei (1980) provided a more detailed list of causes.

- High rainfall intensity in a short period of time after a period of continuous rainfall
- High rainfall intensity in a short period of time in an area with new volcanic sediments
- Unstable sediments on steep torrent beds (>20°) become saturated; liquefaction occurs as a result of the impact of surface runoff
- Collapsed materials flow down carrying water and sediment from the torrent bed
- Collapsed sediments block a torrent stream and this natural dam then breaks; the collapsed sediments and water form a debris flow
- Landslide materials turn into a debris flow as a result of liquefaction
- Earthquakes or vibrations from volcanic eruptions cause parts of slopes to break off and the flowing torrent bed sediment liquefies
- Other causes like pyroclastic flow (volcanic eruption), and rapid melting of snow

Geological conditions

Geology is a major factor influencing the occurrence of debris flows. Sediment related disasters frequently occur on volcanic debris, granite areas, and metamorphic areas near roads. Figure 14.4 shows the relationship between rock type and the number of sediment related disasters.

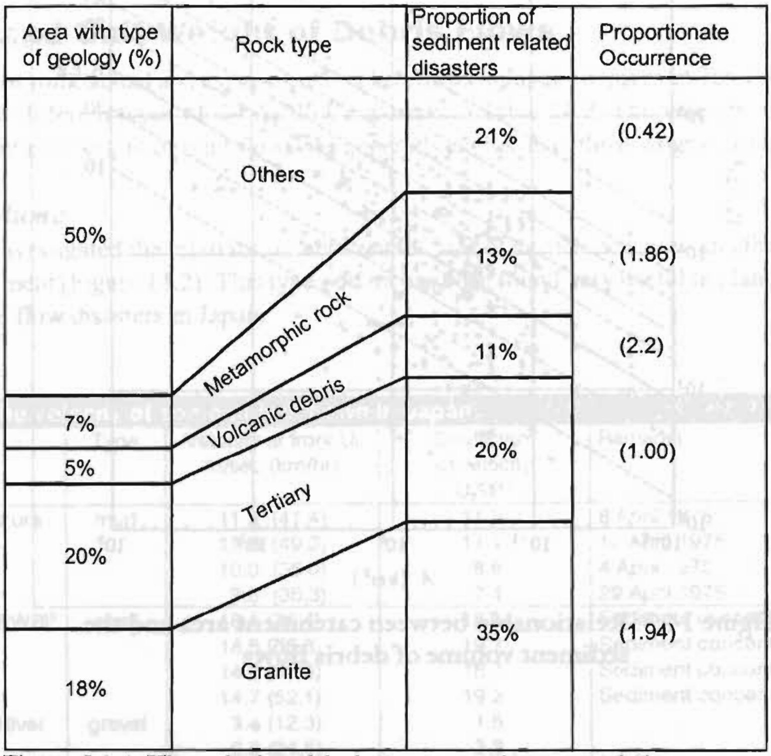

Figure 14.4: **The relationship between rock type and the number of sediment related disasters in Japan**

Generally the following conditions cause a debris flow to come to rest.

- Change in the riverbed slope or width. According to a study by the Public Works Research Institute, Ministry of Construction, Japan, debris flows will come to a virtual halt when the riverbed gradient decreases to less than 10° or is less than half of the preceding gradient, or when the width of the river suddenly increases to 2-3 times the preceding width (Figure 14.5).

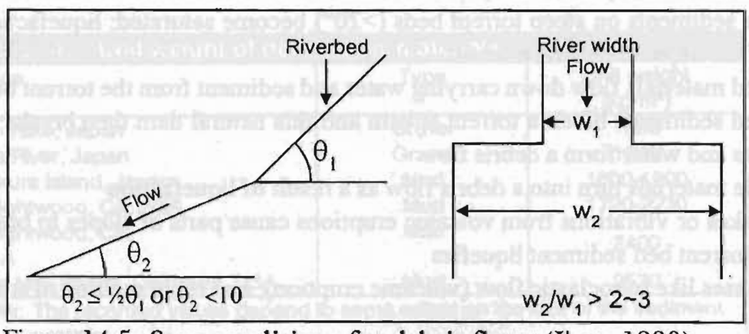

Figure 14.5: **Stop conditions for debris flows** (Ikeya 1980)

- A debris flow will deposit its sediment at the mouth of a valley where a river flows down from a mountainous area onto flat land and the riverbed gradient is around 10° or less. Most debris flows stop when the gradient is less than 4°.

Types of Debris Flow

Debris flows can be classified into three types according to their flow characteristics and type of damage:

- debris flows with gravel;
- mud flows; and
- sediment or earth flows (soil or sand flows).

Debris flows with gravel have distinctive front and rear parts. The front part contains many boulders and tends to flow straight at a velocity of around 3 to 7 m/sec (Table 14.1, Figure 14.6); it has an enormous destructive power. The front part is generally deposited over a small area when the gradient drops to around 3 degrees (1:20); the deposits are not stratified (Figure 14.7). The rear part generally contains finer sediments.

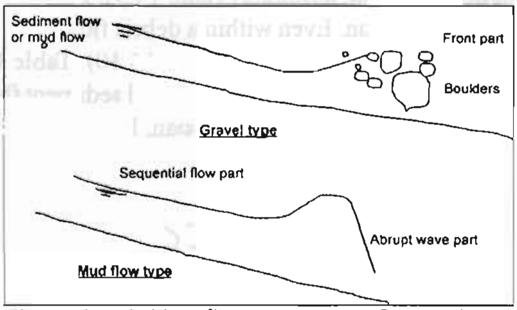

Figure 14.6: **The flow pattern of gravel and mud type flows**

Mud flows can be classified into two types: volcanic and normal mud. Normal mud flows have an abrupt wave — and may not have boulders — at the front (Figure 14.6). The velocity coefficient is several times higher than that of gravel-type debris flows (Table 14.1). The structure of the accumulated material ranges from random to layered depending upon the sediment concentration, discharge, bed materials, and bed gradient (Figures 14.7 and 14.8). The front part has a large striking energy whereas the rear flow has a big abrasive power. In general, mud flows can flow down gentler slopes than gravel-type debris flows, and even on nearly level slopes. Volcanic mud flows occur in active volcanic areas and contain fresh volcanic ash. The infiltration rate tends to be lower in places covered with fresh volcanic ash so that surface run-off is higher. The surface runoff together with the huge amounts of loose fresh ash on a steep slope mean that even rainfall of less than 10 mm in an hour can be sufficient to trigger a flow. Volcanic mud flows are frequent and because of their special characteristics should be considered as a separate category for the sake of disaster mitigation or warning.

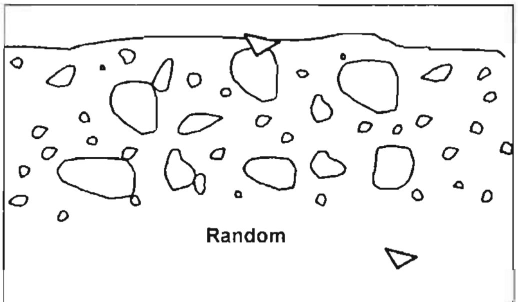

Figure 14.7: **Sediment deposits from a debris flow with gravel showing a random structure**

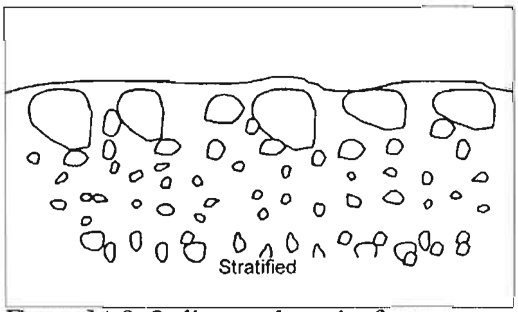

Figure 14.8: **Sediment deposits from a mud flow showing a stratified structure**

Sediment or earth flows (also known as soil or sand flows) are an intermediate type of flow between a mud flow and a debris flow with gravel. They do not flow in the form of mass transport; the individual grains of sand and gravel travel independently. Because of the independent flow, the velocity ranges can be calculated using Manning's formula. Flow surges indicate high velocity and high sediment concentrations (Figure 14.6). The deposits formed by this type of flow are usually stratified.

Figure 14.9 shows an example of comparative particle size accumulation curves for a gravel-type debris flow and a mud flow. There is a big difference in the distribution of grain sizes between the two types of flow.

In general, a debris flow can be differentiated from a sediment flow by the presence of boulders deposited at the terminus (Table 14.3). Further, the deposits have a random structure and there is no stratification. Even within a debris flow, there are different zones, however, with different sedimentation characteristics (Figure 14.10). Table 14.4 shows the accumulation characteristics of the transport zone, debris flow zone, and sediment flow zone in a debris flow that took place in September 1976 at Shoudo Island, Japan. Debris flow deposits are distinguished from colluvium on the basis of the transport distance: if the transport distance is at least five times longer than the length of the deposit the deposit is classified as debris flow, if less then as colluvium.

Debris Flow Surveys

In order to forecast, and try and prevent, debris flow disasters it is important to understand the transport mechanisms and contributing factors. Collection, compilation, and assembly into databases

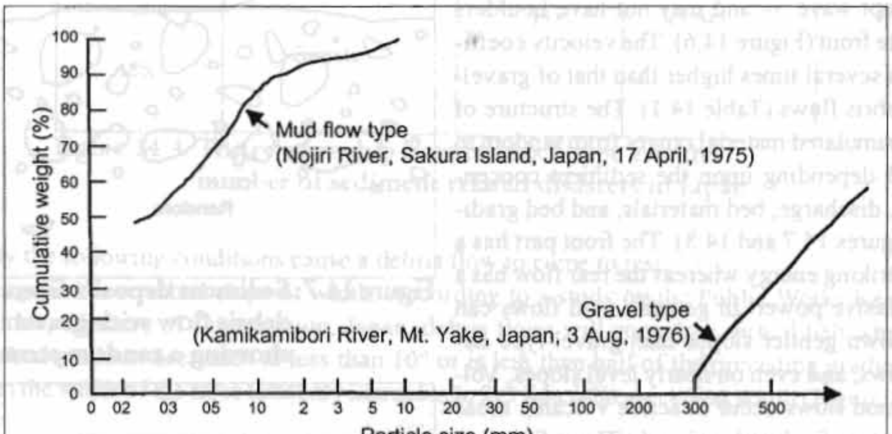

Figure 14.9: **Particle size accumulation curves for mud flows and debris flows with gravel**

Table 14.3: Accumulation characteristics of debris flows and sediment flows

Type	Characteristics of accumulation
Debris flow	• big boulders at the front • convex cross section (see Figure 14.9) • lays down a thick deposit
Sediment flow	• stratified accumulation common • maximum particle size 1.0 to 1.5m, fine-grained soil dominant • accumulation range wide
Flood flow	• distribution of grain size quite uniform; accumulation slope gentle • deposit thin and wide

Table 14.4: **Accumulation characteristics of transport zone, debris flow zone, and sediment flow zone, Shoudo Island, Japan, September 1976**

Description	Transport zone	Debris flow zone	Sediment flow zone	Flood flow zone
Grain size (diameter φ)	bedrock dominant, some gravel	most 1.5m max: 3-4m av: 2m	max: 1m av: 5 cm	max: 10-20 cm av: 0.5 cm
Thickness of accumulation		max: 4m av: 2m	max: 1.5m av: 0.5m	max: 1m av: 0.3m
Surface of accumulation		rough	rough/smooth depending upon landscape and material	smooth
Structure		random	almost stratified	clearly stratified

Source: Ikeya (1980)

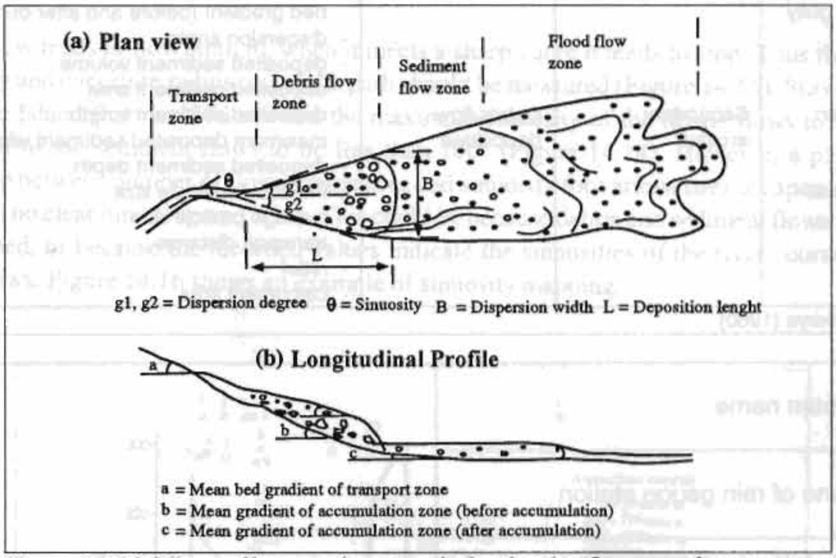

Figure 14.10: **The sediment characteristics in the front and rear parts of a typical debris flow (a) plan view (b) longitudinal profile**

of data related to observed debris flows is an important step towards disaster prevention activities. Engineering structures to prevent (further) debris flows, or mitigate their effects, in an area of risk can be planned using this information. Table 14.5 lists the observations that need to be made after a debris flow has occurred.

Debris flows often occur repeatedly along the same channels. Information about such periodic occurrences should be collected from interviews with local people and by consulting records.

The great majority of debris flows are triggered by rainfall. Rainfall patterns vary depending upon the weather pattern; for example a summer thunderstorm, a typhoon, or monsoon conditions. It is important that as much rainfall data as possible is collected in areas prone to debris flows. These can then be analysed after a debris flow occurs to discover the rainfall conditions that triggered the flow. The data needed are antecedent rainfall (total rainfall during the two weeks preceding the rainfall event that triggered the flow), and total continuous rainfall and maximum rainfall per hour and per ten minutes at the time of debris flow occurrence. The antecedent rainfall affects the moisture in the soil mass and thus determines the likelihood of saturation and liquefaction occurring during a rainfall event. Figure 14.11 shows a typical format for collecting (and plotting) rainfall data related to a debris flow.

Table 14.5: Survey data sheet for debris flows

Place	Phenomenon	Sediment	Necessary data
Hill slope (head of gully)	Landslide or collapse	Collapsed sediment	- slope condition, including geology, gradient, vegetation, soil depth, and so on (preferably before and after collapse) - collapsed sediment volume
Stream bed	Sliding or heavy erosion	Bed materials	- bed gradient - deposited sediment volume - bed material
	Flowage (transport)		- tortuosity - bed width - bed gradient
Mouth of valley or gully	Sedimentation		- bed width (before and after debris flow) - bed gradient (before and after debris flow) - dispersion angle - deposited sediment volume - deposited sediment area
Alluvial fan	Secondary erosion	Debris flow deposition	- deposited sediment length - maximum deposited sediment width - deposited sediment depth
Whole area			- maximum particle size - average particle size - transport distance - relief - catchment area

Source: Ikeya (1980)

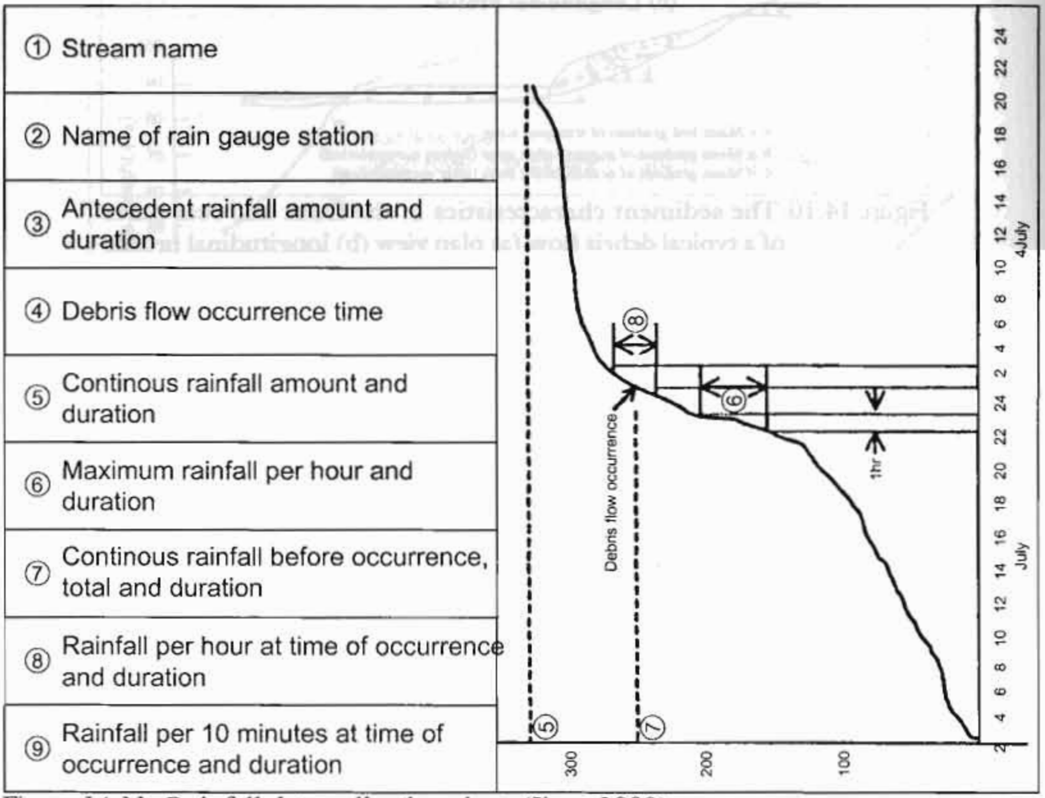

Figure 14.11: **Rainfall data collection sheet** (Ikeya 1980)

The cumulative rainfall is plotted against time (Figure 14.12). This plot can be used to derive the values for continuous rainfall prior to occurrence (CR), initial rainfall (FR), effective rainfall (ER), time of effective rainfall (t), and intensity of effective rainfall (I). The boundary marking the change from initial to effective rainfall is called the inflectional point. Recognising this point can be very useful for forecasting. The relationship between intensity of effective rainfall and effective rainfall, and severity of associated disasters, at various places in Japan is shown in Figure 14.13. The majority of debris flows occur at the time of maximum rainfall intensity.

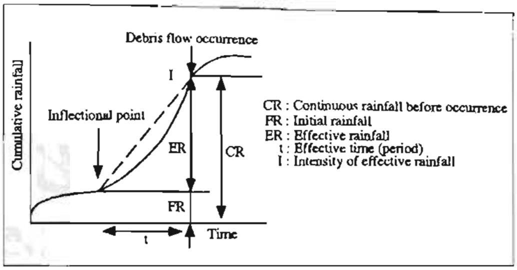

Figure 14.12: **The relationship between time and cumulative rainfall, and debris flow occurrence** (Ikeya 1980)

A debris flow tends to flow straight, when it meets a sharp curve it tends to stop. Thus the degree of sinuosity and curvature radius (m) of the path should be measured (Figure 14.15). Surveys from the Shoudo Island flow in 1976 showed the maximum sinuosity of the debris flows to be about 40°and that of the sediment flows to be less than 100° (Figure 14.14). However, a plot of the relationship between number of flow occurrences and sinuosity for various sites in Japan indicates that there is no clear limit (Figure 14.15). This could be because debris and sediment flows were not differentiated, or because the recorded values indicate the sinuosities of the river courses rather than the flows. Figure 14.16 shows an example of sinuosity mapping.

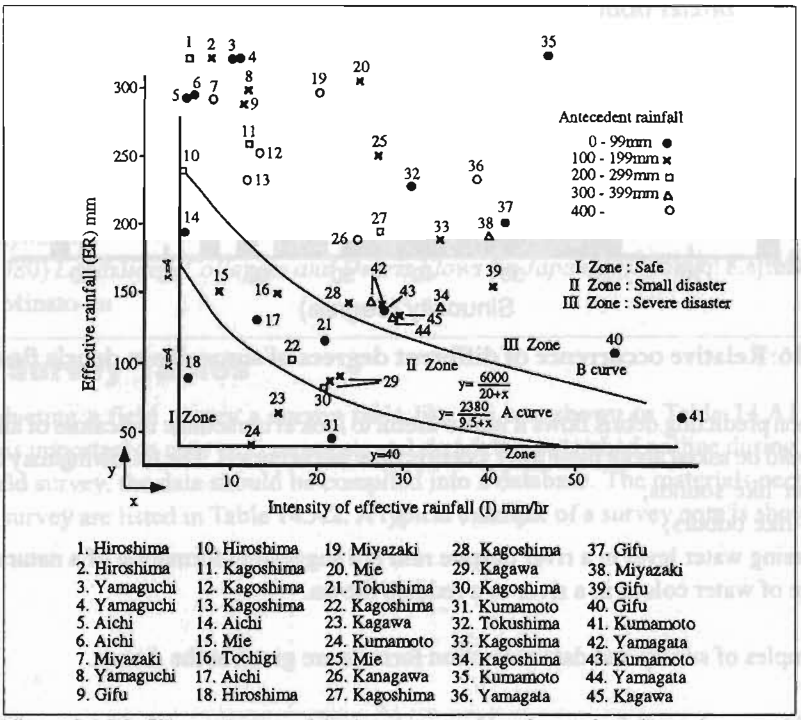

Figure 14.13: **The relationship between effective rainfall and intensity of effective rainfall, and severity of disaster – data from 45 sample sites (Ikeya 1980)**

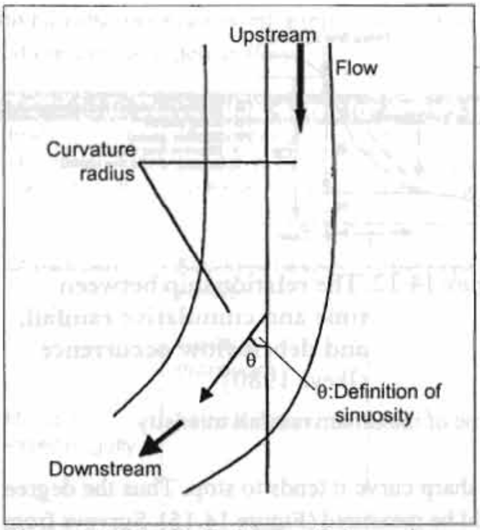

Figure 14.14: **Definition of sinuosity**

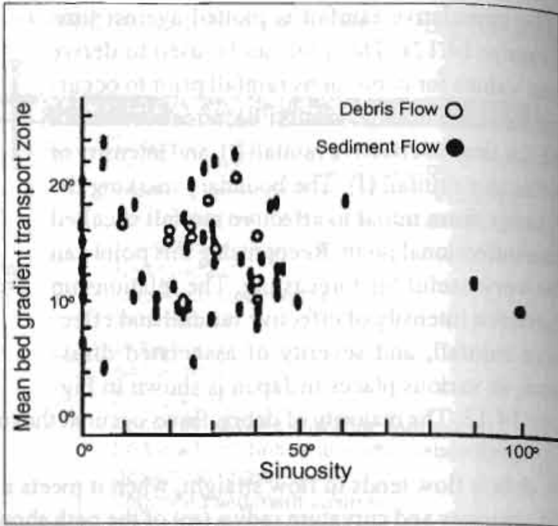

Figure 14.15: **Relation between degree of sinuosity and mean bed gradient in the 1976 Shoudo Island flow disaster**

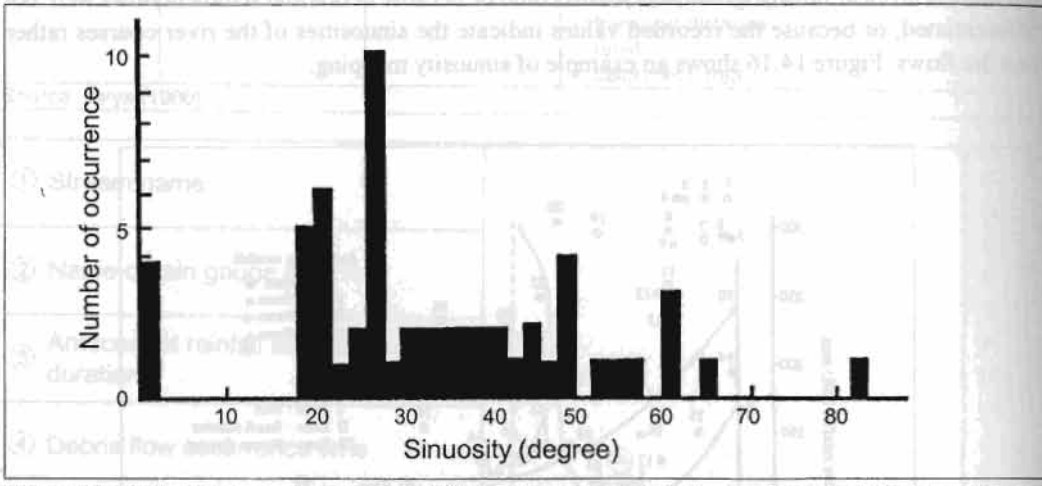

Figure 14.16: **Relative occurrence of different degrees of sinuosity in debris flows in Japan**

Finally, when predicting debris flows it is also useful to look at immediate indicators of an occurrence. People should be asked about these after a debris flow has occurred. The following may be observed:

- thunder like sounds;
- decay-like odours;
- decreasing water level in a river despite rain fall suggesting formation of a natural dam; and
- change of water colour in a river to a reddish brown.

Some examples of survey and data collection formats are given in the Annex.

Final note

Debris flow surveys are best carried out immediately after an event has occurred when the results are still clearly visible. At this time local people are likely to remember the details of the disaster clearly. However, they will also be feeling disturbed and under stress due to the loss of relatives, friends, and property. Investigators must take care to take into account the sensitivities and feelings of those affected when carrying out such surveys.

Conclusion

Debris flows cause serious disasters in many mountain areas in the world, but they are still not fully understood and predicting is difficult. Detailed studies are still required in different places and under different conditions. Data collection is an important first step. This paper describes some characteristics of debris flows and outlines the type of data that need to be collected.

Acknowledgement

This paper is based heavily on the published work of Hiroshi Ikeya of the Public Work Research Institute, Ministry of Construction, Japan. I am thankful to him and the Public Works Research Institute for allowing me to make use of their materials in this paper.

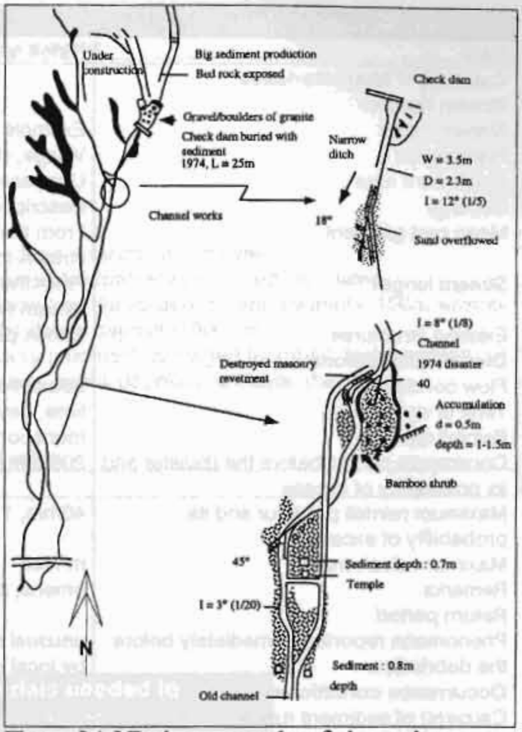

Figure 14.17: An example of sinuosity mapping of a debris flow (Shoudo Island)

References

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Ikeya, H. (1980) *How to Investigate Debris Flow Disasters (in Japanese).* Tokyo: Sankaidou, Bunkyou-ku

Takei, A. (1980) *Landslides, Collapses and Debris Flows (in Japanese).* Tokyo: Kajima Syuppann Kai, Minato-ku

Annex: Survey Tables

Before conducting a field survey a survey table like the one shown in Table 14.A1 should be prepared. It is important to note any comments and sketch the watershed outline during the survey. After the field survey, the data should be compiled into a database. The materials needed to do a debris flow survey are listed in Table 14.A2. A typical example of a survey note is shown in Table 14.A3.

Table A1: Survey table

Data	Notes and examples
Catchment characteristics	
Stream number	
Stream name	Example: Nallu Khola, upstream of Nakhu Khola
Place name	Village, district, zone and region
Catchment area	Upstream of the confluence with main stream (km^2)
Geology	Description
Mean bed gradient	From the head of first degree gully to the confluence with main stream (degrees)
Stream length	From the head of first degree gully to the confluence with main stream (m)
Existing structures	Check dam (CD), bank protection (BP), bridge
Disaster conditions	
Flow condition	debris flow (D), mud flow (M), sediment flow (S), flood flow (F)
Time of occurrence	time, day, month, year
Rainfall type	monsoon, thunder storm, typhoon, frontal rain, other
Continuous rainfall before the disaster and its probability of excess	200 mm, 1:100
Maximum rainfall per hour and its probability of excess	40mm, 1:100
Maximum discharge	m^3/sec
Remarks	omens, past disasters
Return period	
Phenomena reported immediately before the debris flow	unusual sounds, sudden changes in water level (observations by local people)
Occurrence conditions	
Cause(s) of sediment runoff	landslide collapse, breaking of natural dam, scouring of bank/bed, etc or gathered two or three causes
Bed gradient before disaster	degrees
Bed gradient after disaster	degrees
Area of landslide/collapse	m^2
Volume of landslide/collapse	m^3
Slope of landslide/collapse	degrees
Transport conditions	
Mean bed gradient	degrees
Flow width	m
Bed width	m
Scoured depth and volume	depth: maximum and average volume: total (depth x width x length)
Bending, meandering, and sinuosity	Place of bending (distance from a base point), degree of sinuosity, right or left direction from upstream. Example: 500m from B/P1 30° R
Deposition conditions on stream bed	Example: unstable sediments such as boulders and sand between points 5 and 10, bed rock between points 10 and 12 and deposition on L and R banks between points 10 and 11
Vegetation conditions near stream	Example: both banks dense pine forest, both banks thin shrub
Particle size (maximum and average diameter)	cm
Water level of both banks	Use distinctive marks on banks at the bending point
Deposition conditions	
Topography of deposition zone	Oark alluvial fan, valley plain
Beginning point of the deposition (bed gradient and conditions	Example: bed gradient 8°, valley mouth, alluvial fan, change point of bed gradient
Bed gradient before disaster	degrees
Bed gradient after disaster	degrees
Bed width before disaster	m
Maximum deposition width	m
Dispersion angle	degrees ($\varnothing_1 + \varnothing_2$)
Deposition length, L	m
Deposition depth, D (maximum and average)	m

Table A1: **Survey table (cont'd)**	
Data	Notes and examples
Deposition area	m^2
Deposition volume	m^3
Maximum particle size (diameter) (front, middle, and end part)	cm
Average particle size (diameter) (front, middle, and end part)	cm
Damage Conditions	
Human	Number of dead, missing, and injured
Buildings	Number completely/partially destroyed/inundated
Roads	Washed away (m), debris deposit (m) Example: 100m washed away, 150m debris deposit (1000 m^3)
Bridges	Washed away (number), damaged (number) and condition
Cultivated land and forest	Washed away, debris deposit/inundation (ha)
Period of transportation blockage	days
Other	
Total damage	Estimated value
Source: Ikeya (1980)	

Table A2: **Equipment and materials needed to perform a debris flow survey**
Background information
Topographic maps (1/25,000-1/10,000 for location map, 1/5,000-1/2,500 for field survey)
Aerial photographs
Geological maps
Disaster records
Materials for field survey
Camera and film
Field note, pen
Clinometer (clinocompass) to measure strike and dip
Hammer for geological survey
Hand level for bed gradient survey
Range pole
50m measuring tape
3-5m convex rule to measure boulder size and deposition depth
Binoculars
Plastic bags to collect bed materials
Altimeter
Climbing rope
Spade, scoop, etc.

Table A3: **Example of Survey Notes**[1]

Profile at X- section			
1. Survey point (no.)	1	2	3
2. Distance from the base point	100m	120m	150m
3. Confluence of branch	left branch (L4)	right branch (L4-1)	
Geology of both banks			
4 Geology (rock type)	LR sandstone	LR limestone	LR granite
5. Weathering	strong	Little	little
6. Faults, cracks	not known	50cm intervals	1m intervals
7. Depth of surface soil	3-4m	2-3m	1m
Landslide/collapse			
8. Scale of landslide (width, length, depth, strike and dip)	L. B20*l20*d1m NE30°, N70°	No	No
9. Remaining sediment volume	100 m^3	No	No
10. Possibility of expansion	Yes; if heavy rain	No	No
11. Width	45m	20m	15m
12. Gradient	9°	20°	
13. Scouring/accumulation	balance	small S/A	extreme S.
Stream bed			
14. Bending/meandering (sinuosity : degree)		30°, right	
Bed material			
15. Depth av. (max.)	5-6m (8m)	6-7 (8m)	0-0.5m (1.0m)
16. Gradation (maximum size)	sand	gravel (dia. 10cm)	boulder (dia 1.5m)
17. Accumulation structure	random	lamellar	random
18. Stability	rather stable	unstable	very unstable
19. Debris flow zone or bed load transport zone	BL	BL / DF	DF
20. Occurrence, transport, deposition zone of debris flow	dep.	tran.	occ.
Other			
21. Surface water (change)	yes (yes)	yes (yes when rain)	no (yes when rain)
22. Spring water (change)	no ( )	no ()	a little
23. Vegetation (density)	medium/high trees (dense)	medium/high trees (dense)	shrub (thin)
24. Existing structures	Check dam	No	No
25. Land use	bench, terrace	L forest, R grazing	L/R shrub
26. Remarks			

[1]Note: sketches and/or photographs of occurrence, transport, and deposition zones and any other relevant features should be attached.