13 Behaviour and Characteristics of Debris Flows

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A debris flow is a rapid mass movement of loose soil, rocks, and organic material along with entrained air and water forming a slurry that flows downhill. Debris flows are one of the major causes of natural disasters in mountain areas; they claim many lives and cause extensive damage to property. Debris flows usually occur unexpectedly. Their sudden breakout, rapid scouring, and filling in may cause serious damage in downstream areas. The prevention and control of debris flows is an important task to safeguard economic development and human lives in mountainous areas.

Debris flows have widely varying characteristics depending on the nature of a basin or watershed and the rainfall conditions. Understanding the fundamental mechanics of debris flows is the key to mitigating their hazards. Mitigation is achieved by designing structural control measures or setting up non-structural systems.

This paper, based on studies done in China, describes the types, characteristics, dynamics, and fundamental mechanics of debris flows, as well as the type of damage they cause to roads and other structures, settlements, and farmland. Five different ways of classifying debris flows are described based on the viscosity, composition, triggering factors, origin, and scale. The differences between debris flows and other similar phenomena such as landslides and floods are summarised.

Definitions and Classification

Debris flows are a rapid mass movement of loose soil, rocks, and organic material (earthen material) along with entrained air and water to form a slurry that flows down ravines and other slopes in mountainous areas. Essentially it is a two-phase flow: the liquid phase contains a mixture of water and fine-grained sediments, whereas the solid phase contains coarse sediments (Qian and Wang 1983, Wu 1992). A debris flow is an intermediate phenomenon between a sediment-laden water-flow (flood) and a landslide, but there are significant differences between these and debris flows.

Debris flows and sediment-laden water flows have different structural characteristics. Debris flows have the structural characteristics of mixed loose solid materials. They have an initial static shear strength τ_0, whereas sediment-laden water flows have no structure, i.e., $\tau_0 \approx 0$. Generally if the unit weight of a flow is more than 1.3 t/m^3 it is classified as a debris flow, if the value is below 1.3 t/m^3 it is classified as a flood. Another difference is that debris flows occur in mountainous areas so the bed gradient (or flow gradient) is usually more than 1%. A flow with a large amount of suspended material along a gradient of less than 1% is usually classified as a water flow with a hyper-concentration of sediment.

Debris flows and landslides have different flow characteristics. A debris flow flows with the characteristics of water. It has a velocity gradient of $d_{\mu c}/d_{\gamma}$. A landslide has a sliding plane between the slide mass and the underlying ground mass but it has no velocity gradient. Debris flows can also be distinguished from landslides according to their saturation levels. If a solid flow is saturated or over-saturated then it is classified as a debris flow, if unsaturated it is classified as a landslide.

There are many different types of debris flow. They can be classified in various ways using such factors as viscosity, composition, triggering factor, origin, scale, location, or source of solid materials.

Figure 13.1: **Low viscous debris flow in the Jangjia Ravine, Dongchuan, Yunnan**

Figure 13.2: **Viscous debris flow in Xiaojiang River valley, Dongchuan, Yunnan**

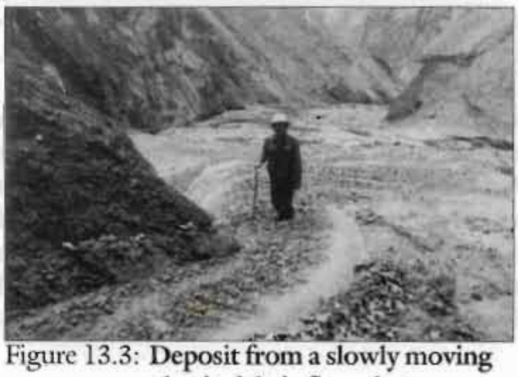

Figure 13.3: **Deposit from a slowly moving plastic debris flow that originated in the upper part of the Jangjia Ravine, Dongchuan, Yunnan (deposit located where the person is standing)**

Classification based on viscosity

Low-viscous debris flow — Water plays the main role in low-viscous debris flows, their characteristics are similar to those of floods. The ratio of solids to water C_v ranges from 0.18-0.55; the unit weight γ_c from 1.30-1.90 t/m^3; and the initial static shear τ_0 should be less than 1.0 Pa. In this kind of debris flow, the mass is free flowing and mostly turbulent. Coarse-grained sediments and blocks of rocks move as bed load, and silting occurs when the velocity suddenly decreases or the flow becomes static (Figure 13.1).

Viscous debris flow — In viscous debris flows, water and solid materials play a more or less equal role. The ratio of solids to water C_v ranges from 0.50-0.78; the unit weight γ_c from 1.80 to 2.30 t/m^3, and the initial static shear τ_0 from 1.0-20.0 Pa. The mass is free flowing and has turbulent, laminar, sliding, and creep flow characteristics. Except for a few larger boulders, solid particles are mostly found as suspended load. Earth and water are not separated when the flow stops. This is also a two-phase flow but, except for a few big stones, should be regarded as a pseudo one-phase flow (Figure 13.2).

Plastic debris flow — In plastic debris flows, the solid material plays the main role. The characteristics are similar to those of a landslide. The ratio of solids to water C_v is >0.75, the unit weight γ_c is >2.25 t/m^3, and the initial static shear τ_0 is >20.0 Pa. The flow is difficult and arrested; most are sliding flows or creep flows. All solid material is in the form of suspended load and earth and water are not separated when the flow stops. This should also be regarded as a pseudo-one-phase flow (Figure 13.3).

Classification based on composition

Water-and-rock flow — Water-and-rock flows are mainly made up of large rock fragments and fine sediments. Less than 5%, and generally less than 2%, of the total mass is made up of cohesive grains (Figure 4, curve D). These are all low-viscous or fluid debris flows with a unit weight of 1.3-1.8 t/m^3.

Mud-and-rock flow — In mud-and-rock flows, the grain size in the debris flow mass ranges from colloids of less than 0.001 mm to boulders more than 20m in diameter. More than 5% of the total mass is made up of cohesive grains (<0.005 mm) (Figure 13.1, curves B and C). Most of these kinds of flows are viscous or plastic debris flows.

Mud flows — In mud flows, the debris flow mass is mainly made up of cohesive grains and sediment with a few rock fragments (Figure 13.4, curve A). Most mud flows are low viscous to viscous debris flows with a unit weight of 1.5 to 1.8 t/m^3.

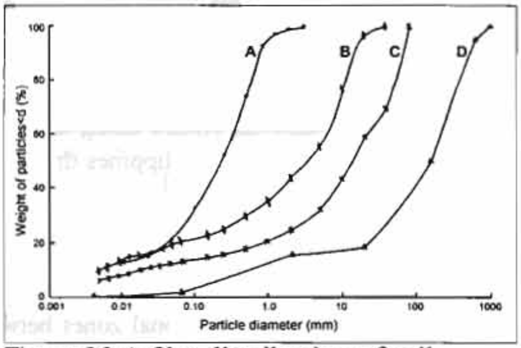

Figure 13.4: **Size distribution of soil particles in debris flows: A - mud flow; B & C - mud and rock flow; D - water and rock flow**

Classification by triggering factor

Rainstorm-induced debris flows — Eighty per cent of debris flows in the world are rainstorm induced.

Ice-and-snow-melt debris flows — Debris flows caused by melting of ice and snow are mainly found in high and very high mountain areas. Debris flows caused by melting glaciers are called glacial debris flows.

Dam-failure debris flows — This kind of debris flow is caused by the failure of natural or man-made dams and includes debris flows caused by glacial lake outbursts and by the failure of landslide and debris flow dams.

Classification based on origin

There are three main types in terms of origin.

Runoff-erosion type — Strong runoff caused by rainstorms can mobilise loose earth on slopes to form debris flows. These are called hydraulic debris flows; most are low viscous.

Gravity-sliding type — This type is mainly caused by landslides and other mass movements. Loose solid materials on a slope saturated with water slide down into ravines as debris flows (Li et al. 1984). These are called sliding debris flows and are mostly plastic or viscous.

Mixed type — Mixed debris flows can occur as a result of a combination of the processes mentioned above. Such flows are usually viscous or low viscous depending on the water content. Some begin as the runoff-erosion type (low-viscous flow) but become gravity-sliding type when large quantities of sliding material join in. Some start as gravity-sliding type (viscous) and become low viscous debris flows after being joined by a lot of low-viscous flow or rainstorm runoff.

Classification by scale

For engineering purposes, debris flows can be classified according to their scale as shown in the table on page 206.

Table 13.1: **Classification of debris flows according to scale**

	Mini-scale	Small-scale	Medium-scale	Large-scale	Very large scale
Peak discharge (Q_c) One time outflow (W_c)	$<1\ m^3/s$ $<10^2\ m^3$	$1\text{-}10\ m^3/s$ $10^2\text{-}10^4\ m^3$	$10\text{-}10^2\ m^3/s$ $10^4\text{-}10^5\ m^3$	$10^2\text{-}10^3\ m^3/s$ $10^5\text{-}10^6\ m^3$	$>10^3\ m^3/s$ $>10^6\ m^3$

Geographical Distribution

More than 60 countries are affected by debris flows. They mainly occur in mountainous areas that have steep topography, active tectonic movement, and heavy rainstorms, and are particularly prone to occur in areas where there has been recent seismic or volcanic activity. Debris flows occur across the semi-humid and semi-dry temperate areas of the Alps, the Caucasus, the Tianshan Mountains, the Qiliashan-Qingling Mountains, and the Himalayas (including the Gangdisi, Kunlun, and other mountains); in the areas of high humidity and rainstorms of the Rocky Mountains, the Madri Mountains and the Andes along the Pacific coast; and in the mountains of Japan, the islands to its south, and the Philippines through to the Indonesian islands.

Two-thirds of China is mountainous and debris flow activities have been recorded in 28 of China's 33 provinces. The distribution of debris flows in China is mainly influenced by topography, geological structure, lithology, climate, and human activities. There are a number of debris flow ravines distributed along the deep-cut transitional zones between the three major topographical steps, i.e., the Qing-Tibet Plateau in the west; the Yungui, Chuanxi, and Huangtu Plateaux, and Sichuan and Chaidamu basins in the centre; and the low mountains, hills, and plains in the east. Eighty per cent of debris flow ravines are concentrated in the two transitional zones between these three steps. Within these areas, the main active and catastrophic debris flow ravines are concentrated along the large rivers that flow along the major fault lines, i.e., the Boduzangbu River fault in Tibet, the Daying River and Xiaojian faults in Yunnan, the Xiangshu River and Anning River faults in Sichuan, and the Bailong River fault in Gansu. These fault regions are also associated with strong earthquake activities.

High-frequency viscous debris flows occur most often in the soft rock outcrops along fault zones. The soft rocks most prone to debris flows are:

- mudstone, shale and coalstone, slate, and schist;
- volcanic rocks such as andesite, rhyolite, and volcanic ash;
- semi-cemented rocks such as gravel, sand, silt, and sub-clay;
- loose Quaternary deposits; and
- granite with thick weathered shells.

The most famous high-frequency viscous debris flow ravines are the Guxiang ravine in Tibet, Jiangjia ravine in Yunnan, Huoshao ravine in Gansu, and Heishahe and Majing ravines in Sichuan. All occur in areas underlain by soft rocks.

In the last half-century, the incidence of debris flows has greatly increased in regions where the environment is being seriously degraded. For example, the Xiaojing catchment area in Yunnan has lost more than half of its forest area, and the vegetation has been reduced to between 2.5 and 8% cover. As a result, the number of debris flow ravines has increased from 38 at the beginning of the 1950s to 101 at present.

Types of Damage

Because of their sudden outbursts, debris flows usually cause great economic loss and heavy casualties. In China, it is estimated that debris flows cause economic losses of 1-1.5 billion Yuan

(US $120-180 million) and kill 300-500 persons every year. The main forms of damage are described below.

Filling — Debris flows carry a large amount of coarse particles and dense silt and clay slurry. After reaching gentler gradients, the solid mass in viscous debris flows is deposited in the debris flow channel and surrounding areas. The depth of deposition can vary from as little as 10 cm to more than 10m. Structures, farmland, and water conservancy structures may be buried (Figure 13.5).

Figure 13.5: **A tunnel along the Dongchuan railway line was silted up by debris flow in**

Impact — The solid mass in debris flows, which often contains big rocks, exerts a strong dynamic pressure and impact force when moving at high speeds. The dynamic pressure can reach as high as 50 t/m^2 and the impact force up to 15,000 t/m^2. Bridge piers or other structures lying along the course of debris flows are often sheared and broken.

Erosion — Debris flows have a great potential to erode narrow ravine sections that have a slope gradient of more than 3%. A single event could deepen such a channel by 5 to 20m, breaking the foundations of bridge piers, houses, and other constructions in the ravine or on the banks (Figure 13.6). The great eroding power of the flow can burst river dykes, check dams, and sediment-trapping dams.

Figure 13.6: **Central pier of a railway bridge damaged by a debris flow, Dongchuan, Yunnan**

Up-rushing and overtopping at a bend — When the mainstream line of a debris flow reaches a bend or meets a bank at an angle, the fast flowing inertia of the flow can cause it to up-rush as high as 10m or more. A few stones may up-rush to 20m or more, filling or bursting constructions on the bank or slopes (Figure 13.7).

Figure 13.7: **Splash and up-rush of debris flow at the Debris Flow Research and Observation Station in the valley of the Jiangjia Ravine, Dongchuan**

Blocking, filling, or extruding of the mainstream line — When a large-scale debris flow enters a main watercourse, the water flow is unable to carry the debris, and the mainstream becomes filled up, extruded, or blocked. This can often cause serious damage to water navigation and diversion works. When the mainstream is dammed, the area immediately upstream will form a lake, submerging villages, farmland, and com-

Table 13.2: **Damming of the Xiaojiang River by debris flows from Jiangjia Ravine (1919-present)** (Kang et al., 1980)

Year	Period of damming (days)	Height of dam (m)	Length of impoundment (km)
1919	48	10-11	>10
1937	40	NK	>10
1949	30	NK	NK
1954	>20	10	9
1961	10	9.5	NK
1964	10	NK	NK
1968	180	10	>10

NK = not known

munication lines. When these dams fail, the large outburst discharge usually causes catastrophic damage downstream (Table 13.2).

Increase in mainstream sediment — Large quantities of debris flow mass entering a mainstream will rapidly increase the sediment budget of the stream and widen and fill up riverbeds. The capability of water to transport sediment is decreased as is the capacity for flow-relief. Surface runoff will give way to underground flow below the sediments, causing streams to dry up in the dry season. The sediment deposits lead to an increase in flood hazards during the wet season and water scarcity in the dry season.

In steep middle and high mountain valleys there may be some areas with gentler slopes. Debris flow fans sometimes form in such areas. During the dormant periods of debris flow, local people regard these areas as suitable sites for settlement. There are many towns, villages, and factories located on such sites. Two-thirds of the towns in the western mountainous areas of Sichuan Province are built on the fans of ancient debris flows. Most of the roads and railway lines pass along debris flow fans. If debris flows reactivate, these towns, villages, farmlands, and communication lines will be threatened. More than ten towns built on ancient debris flow fans in the western mountainous areas of Sichuan have been seriously damaged in this way during the last 50 years. During the rainy season, half of all cases of interruption of roads in the mountainous areas of China are caused by debris flows. Many mines, and especially open mines, located in unsuitable places also create harm to villages through mine debris flows.

Conditions for Formation

Specific geomorphic, geological, meteorological, and environmental conditions lead to the formation of debris flows; variation in these factors leads to differences in the actual processes involved. The three main conditions for the formation of debris flows are steep topography, the availability of large quantities of loose solid material, and adequate water.

Steep topography — This provides the required potential energy and can be considered as the 'starting motor' for a debris flow. The specific factors that control the initiation and nature of a flow are the slope gradient, the ravine gradient, and the relief. The larger the values, the more readily a debris flow will occur. Debris flows begin most easily when the slope angle is more than 35^0, the gradient of the ravine bed is more than 18^0, and the height difference of relief is more than 400m.

Loose solid materials — Earth and water are the two main components of a debris flow mass. In plastic and viscous debris flows, solid material is the main component. The lithology and tectonic activities in an area essentially control the nature and amount of loose solid materials. In most debris flow ravines, landslides are the main source of loose solid material.

Abundant water — Water is an important component of a debris flow. Abundant quantities of water from heavy rainfall or ice and snowmelt are needed for their formation.

Composition, Structure and Rheological Properties

Composition of debris flows — The mass of a debris flow is made up of solid matter (sometimes called simply 'earth') and water. The solid matter includes boulders, sand, silt, and clay in varying proportions. Plastic and viscous debris flows have a similar composition of solid matter in the debris flow forming area. However, as a debris flow passes down a ravine, the proportion of large fragments often decreases and the amount of fine sediment increases, often quite rapidly so that the fluid properties change from plastic to low viscous flow.

Structure of debris flows — The structure of a debris flow mass refers to the nature of the interlocking arrangements between the earth grains; whether they are cohesive grains, sandy grains, or boulders and water. This determines the characteristics and rheological properties of the debris flow mass. There are three basic kinds of structure (Wu 1981):

- a network structure in a fine grained slurry mass formed by the fine cohesive grains and electrolytic water;
- a net-grained slurry with a network structure and sandy grains; and
- a frame structure made up of coarse slurry and large fragments.

Frame structure is the word used to describe the arrangement of large fragments (rocks, stones) in a viscous debris flow. There are four subtypes based on the proportion of large fragments: suspended, bared (propped), superimposed, and interlocked (Figure 13.8). In the suspended type, each fragment is surrounded by slurry. In the beared and superimposed types, bulky fragments restrain and support each other to some degree. There may be collisions as well as friction resistance among fragments, which can result in turbulent flow. In the interlocked type, individual large fragments are in contact while flowing. Although the collision effects between fragments may not be strong, the friction resistance is very large. When the ravine-bed has a steep gradient and/or a lubricating layer of slurry is formed on the ravine bed, incomplete sliding flow or creeping flow may occur.

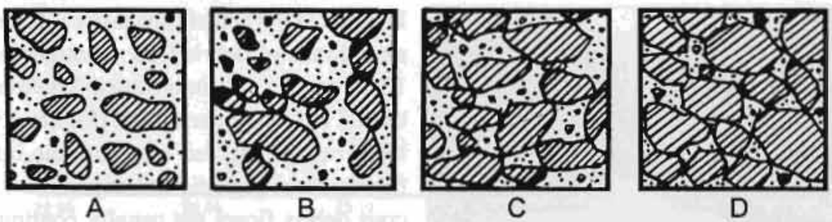

Figure 13.8: **Frame structure of a debris flow containing coarse slurry and large fragments: A - suspended type; B - bared type; C - superimposed type; D - interlocked type**

Flow patterns

The characteristic flow pattern of a debris flow lies halfway between those of a sediment-laden water flow and a landslide. The flow can be classified as turbulent (Figures 13.9, 13.10), laminar

(Figure 13.11), creeping (Figure 13.12), or sliding (Figure 13.13). Low-viscous debris flows have mainly turbulent and laminar flow patterns; plastic debris flows mainly creeping and sliding patterns; and viscous debris flows all four flow patterns. Different flow patterns have different rheological and movement equations.

Figure 13.9: **A viscous turbulent debris flow in the Jiangjia Ravine, Dongchuan Yunnan**

Figure 13.10: **Front of a viscous turbulent debris flow surge, August 13, 1991**

Figure 13.11: **A highly viscous laminar debris flow in the Jangjia Ravine, Dongchuan, Yunnan**

Figure 13.12: **A creeping debris flow in the Jiangjia Ravine, Dongchuan, Yunnan**

Figure 13.13: **A sliding debris flow with interruption between two surges**

In terms of the actual flow process there are three main kinds of debris flow: continuous (Figures 13.14 and 13.15), intermittent/continuous (Figure 13.16), and intermittent (Figure 13.17). The latter can be divided into periodic intermittent flow and non-periodic intermittent flow. Low-viscous debris flows are usually continuous (Figure 13.14). Most viscous debris flows are periodic intermittent flows, but if the supply of saturated earth materials from the upper reaches is large they can become continuous flows (Figure 13.15). A typical example was recorded in the Jangjia Ravine where at around 23.25 hours on the 14th June 1984 the flow changed from intermittent to continuous (Figure 13.18). Plastic debris flows are usually non-periodic intermittent flows with one or more intermittences. The transitional types of debris flows are classified between low-viscous and viscous and are mostly intermittent.

Figure 13.14: **A continuous low viscous (fluid) debris flow**

Figure 13.15: **A continuous viscous debris flow**

Figure 13.16: **Intermittent/continuous flow with a 'head', 'body' and 'tail'**

Figure 13.17: **Intermittent flow**

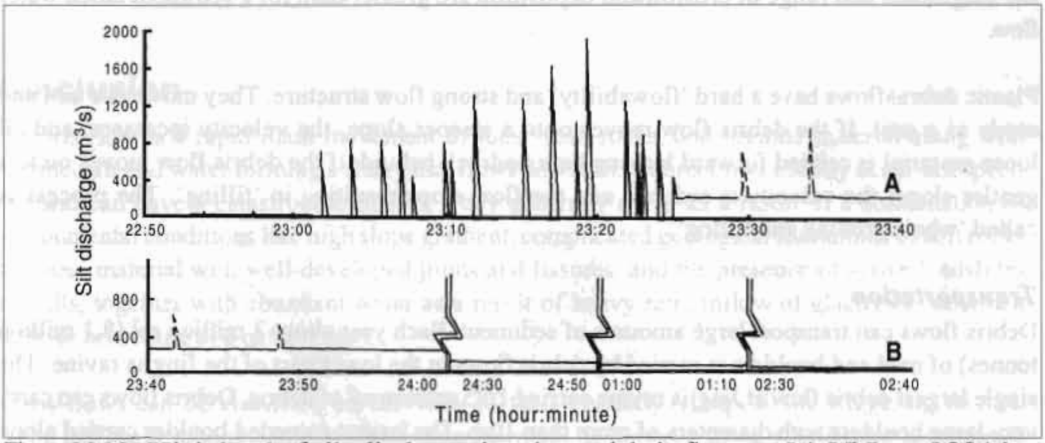

Figure 13.18: **High level of silt discharge in a large debris flow on 14-15 June 1984 in the Jangjia Ravine, Dongchuan, Yunnan**

Dynamics

Because of their high unit weight and high velocity, the magnitude and dynamics of debris flows are different from those of sediment-laden water flows. Debris flows have large impact forces that can erode, fill, up-rush, and overtop at channel bends. Debris flows also have vibrating and abrasive effects. These dynamic actions can transform landscapes within a few hours or even minutes in a way that sediment-laden water flow can only do over periods of several years. Some of the major effects are described in the following.

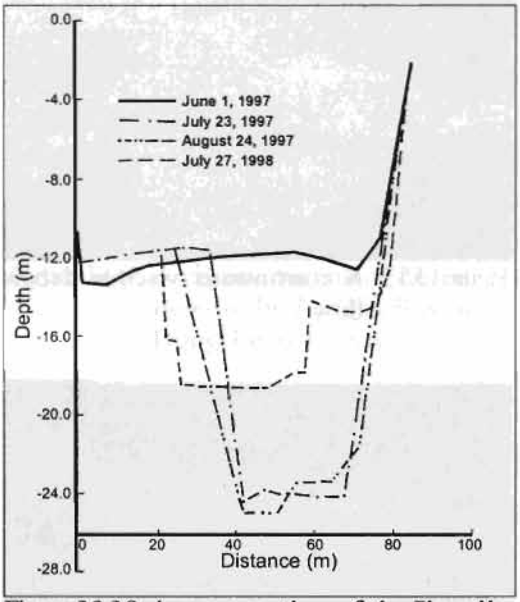

Figure 13.19: **A cross section of the Jiangjia Ravine showing topographical changes caused by debris flows on four occasions between June 1997 and July 1998**

Erosion

Scouring and deposition by debris flows is often extensive; for example, between June 1997 and July 1998, a debris flow in Jingjia ravine eroded the ravine by more than 20m (Figure 13.19) then filled the depositional area to a depth of more than 3m. This debris flow has deposited about 38m on the debris flow fan during the last 40 years. Debris flows, especially viscous and plastic ones, have two special forms of erosion and depositional features: one-single-grain up and down, and eroding and filling.

The one-single-grain up and down type of erosion process is similar to that produced by a sediment-laden water flow. With the change of velocity, grains move up and down in the flow eroding anything they come into contact with. In contrast to a flood, the medium of flow is fine-grained slurry not water. A debris flow has a higher unit weight, higher rigidity coefficient, and higher yield strength than a sediment-laden water flow, and the sediment transport ability is also higher. Thus the magnitude and range of erosion and deposition are greater than for a sediment laden water flow.

Plastic debris flows have a hard 'flowability' and strong flow structure. They move as a unit and erode as a unit. If the debris flow moves onto a steeper slope, the velocity increases, and all loose material is carried forward leaving bare bedrock behind; if the debris flow moves on to a gentler slope, the velocity is reduced and the flow stops resulting in 'filling'. The process is called 'whole eroding and filling'.

Transportation

Debris flows can transport large amounts of sediment. Each year about 3 million m^3 (8.1 million tonnes) of mud and boulders is carried by debris flows in the lower part of the Jingjia ravine. The single largest debris flow at Jingjia ravine carried 1.95 million m^3 of debris. Debris flows can carry very large boulders with diameters of more than 10m. The largest recorded boulder carried along the Jingjia ravine was 22m in diameter.

As with the flow process itself, there are three types of sediment transport: continuous; intermittent/continuous; and intermittent. There are also two main types of transport flow: two-phase and pseudo-one-phase.

In two-phase flow transport, the medium of transport is a uniform slurry composed of material with grain sizes of less than 0.2 mm diameter and electrolytic water. Particles larger than 0.02 mm, and pebbles and boulders are transported as suspended load or bed load. All low-viscous debris flows have two-phase flow transport.

In pseudo-one-phase flow transport, all solid material regardless of size is mixed with and moves with the same velocity as water. All plastic debris flows are pseudo-one-phase flows because all the particles are suspended.

Deposition

Debris flows have three main modes of deposition: gradational deposition; integral bulk deposition; and bedded deposition

In gradational deposition, the particles in the flow settle out gradually from large size to small size as the velocity of the flow decreases. This is the main depositional pattern of low-viscous debris flows. In a low-viscous debris flow, all of the sediments larger than 10 cm will settle out when the bed gradient is less than 1%; the debris flow changes into a hyper-concentrated sediment flow.

Integral bulk deposition occurs when a debris flow moves down a slope and then comes to rest as a result of a decreasing gradient in the gully bed or increasing resistance. The composition of the deposited material is the same as that of the debris flow body. This is the typical deposition pattern for a plastic debris flow. Generally, integral bulk deposition occurs when the initial static shear strength of the debris flow body (τ_o) is larger than the drag force (τ_c) or when the gradient of the gully bed is less than 3%.

Bedded deposition is a transitional mode between gradational and integral bulk deposition. It is similar to gradational except that a few isolated big boulders are also deposited. When the drag force of the flow (τ_c) is smaller than the resistance of the bed surface (τ_f), the debris flow settles down layer by layer on the valley bed. This is the major depositional pattern of viscous debris flows.

Conclusion

A debris flow is a rapid mass movement of loose soil, rocks, and organic material along with entrained air and water forming a slurry that flows downhill. Debris flows usually occur unexpectedly and can have a catastrophic impact. They generally occur as a result of a combination of environmental conditions like high slope gradient, complicated geological formations of soft rocks and loose material with well-developed joints and fissures, and the presence of active landslides and falls, together with abundant water as a result of heavy rain, inflow of glacier or snowmelt water, or breaching of a natural dam.

Debris flows can be classified on the basis of their viscosity, composition, triggering factors, origin, and scale, amongst others. Their characteristics lie between those of sediment-laden flows (or floods) and landslides. The movement patterns include both intermittent and continuous flow and their action can be classified as turbulent, laminar, creeping, or sliding. Because of their high unit weight and velocity, the magnitude and dynamics of debris flows are different from those of common sediment-laden water flows. Debris flows have large impact forces and vibrating and abrasive effects. These dynamic actions can transform landscapes within a few hours or even minutes in a way that sediment-laden water flows can only do over periods of several years. All larger debris flow catastrophes are due to the dynamic effects of such phenomena. Understanding the behaviour and characteristics of debris flows will help in the proper design of control measures to mitigate the hazards posed by debris flows to roads, settlements, farmland, and other structures.

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