Chapter 2: Landslides and Debris Flows

Landslides and debris flows are among the major causes of flash floods in the Himalayan region as the rock, earth, debris, and mud that they transport can be deposited across river beds to form an unstable barrier to river flow – a landslide dam – which may fail catastrophically leading to sudden downstream flooding. It is easy for landslide dam lakes to form in the steep and narrow valleys found in high rugged mountain areas because only a relatively small amount of material is needed to block such valleys (ICIMOD 1991a). Thus one way of mitigating flash floods is to take measures to reduce the occurrence of landslides and debris flows. For this, it is first necessary to understand how they form.

What is a Landslide?

A landslide is defined as the movement of a mass of rock, earth, or debris down a slope (Cruden 1991). A debris flow is effectively a type of landslide in which the mass is saturated or oversaturated with water, thus forming a slurry which flows down the slope. A debris flow is actually an intermediate form between a landslide and a sediment laden flood, with the characteristics of mixed loose solid material (Wu and Li 2001). Debris flows are differentiated from floods by the higher unit weight of flow (>1.3 tonnes/m^3) and gradient ($>1\%$).

Classification of landslides

Landslides are classified in many different ways. Varnes' (1978) classification is one of the most commonly used; it is based mainly on the nature of the source materials and the type of movement involved. The main types of landslide are summarized in Table 1, illustrated in Figure 1, and described briefly in the following section.

Fall. A fall is a sudden movement of material that detaches from a steep slope or cliff. It occurs as a single free fall or a series of leaps and bounds down the slope. Depending on the material involved, it can be a rock fall, soil fall, debris fall, earth fall, boulder fall, or other fall. Falls take place on slopes of 45° to 90°.

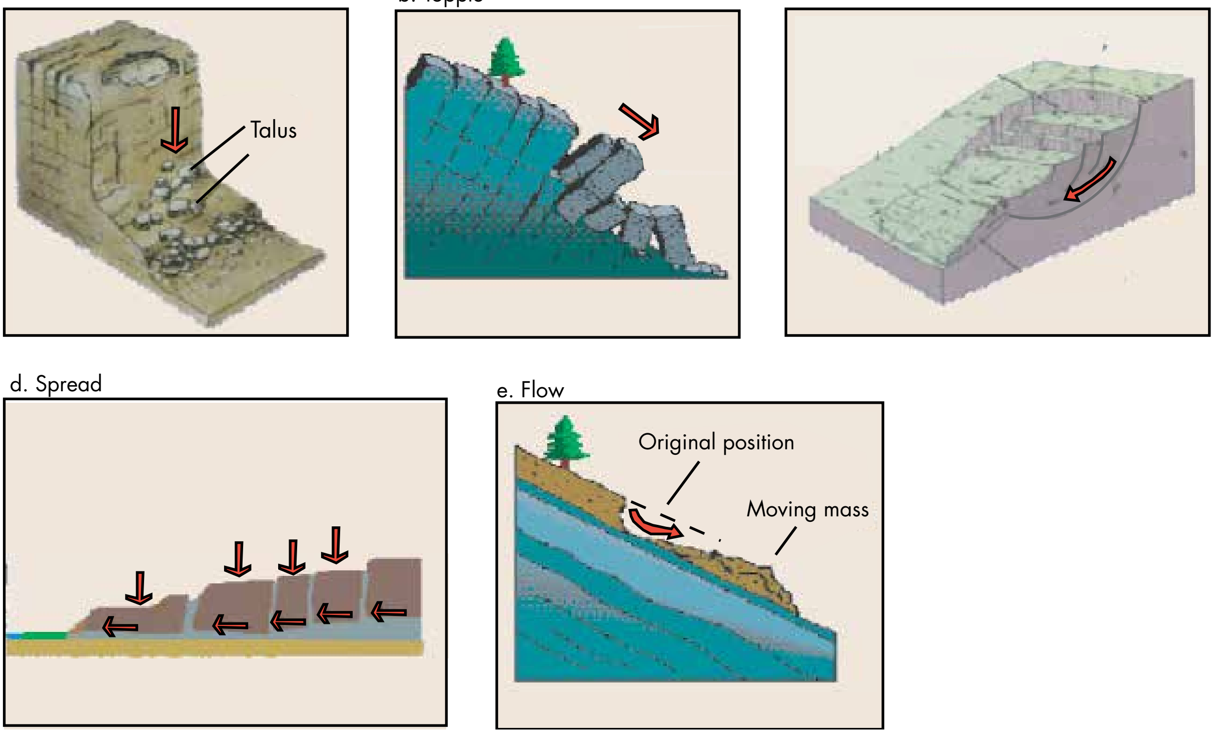
Topple. A topple occurs when a block of rock tilts and rotates forward on a pivot or hinge point and separates from the main mass or surface, falling to the slope below and subsequently bouncing or rolling down the slope. A topple can be triggered by gravity, water, ice, or wind, and the rate of topple can vary from very slow to extremely rapid.

Table 1: Types of landslide (abbreviated classification of slope movements)

Type of movement	Type of material		
	Engineering soil		Bedrock
	Predominantly fine	Predominantly coarse	
Fall	Earth fall	Debris fall	Rock fall
Topple	Earth topple	Debris topple	Rock topple
Slide (rotational/translational)	Earth slide	Debris slide	Rock slide
Lateral spread	Earth spread	Debris spread	Rock spread
Flow	Earth flow	Debris flow	Rock flow
Complex	Combination of two or more principal types of movement		

Source: abbreviated version of Varnes' classification (Varnes 1978)

Figure 1: Types of landslide



Slide. A slide is a down slope movement of rocks or soil occurring mainly on surfaces of rupture or relatively thin zones of intense shear strain. There are two major types of slide: rotational and translational. Rotational slides occur most frequently on the surface of homogeneous slopes, whereas translational slides take place on more or less plane surfaces.

Spread. A spread is an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material (Cruden and Varnes 1996). It occurs when a large block of soil spreads out horizontally after fracturing from the original base. Spreads usually occur on gentle slopes of less than 6°.

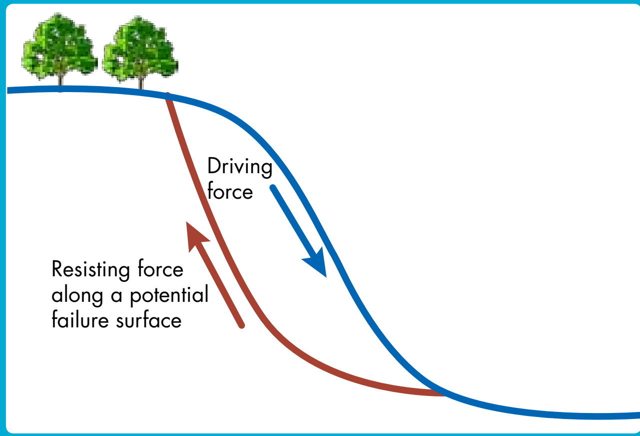
Flow. A flow is in effect a liquefied landslide containing a high proportion of unconsolidated, saturated material suspended in water. Flows can carry material ranging in size from clay to boulders, and may contain woody and plant debris such as logs and tree stumps. Flows can be of different types according to the materials they contain and the speed of flow, including mudflows, earth flows, debris flows, creeps, and debris avalanches. The rate of flow may vary from slow to very rapid (from 5 km/hr to 40–50 km/hr or more in extreme cases) and the flow can cover several kilometres. The flow starts when unconsolidated material becomes saturated and can be triggered by intense rainfall, glacial melt, and earthquakes and precipitated by shallow landslides or in some cases by the collapse of a riverbed. Debris flows are relatively common in steep mountain areas with high rainfall. They are extremely destructive of life and property because of the mass and high speed of flow (Takahashi 2007). They can cause significant erosion of the substrates over which they flow, thereby increasing their sediment charge and further increasing their erosive capabilities (Nettleton et al. 2005).

Complex movement. A complex movement is a combined process of two or more of the types of movement mentioned above. Large-scale movements are usually complex, as in a rock/debris avalanche, for example.

Mechanism of Landslide Formation

A landslide is a by-product of slope instability. Slope stability is the state of balance between driving forces and resisting forces acting on the earth's surface (Figure 2). The driving force tends to pull materials down a slope whereas the resisting force holds the material where it is. When the driving force exceeds the resisting force, the slope becomes unstable and the materials on the slope will start to move. This can result from an increase in the driving force, a decrease in the resisting force, or a combination of the two.

Figure 2: Forces acting on a slope



Driving force (shear stress)

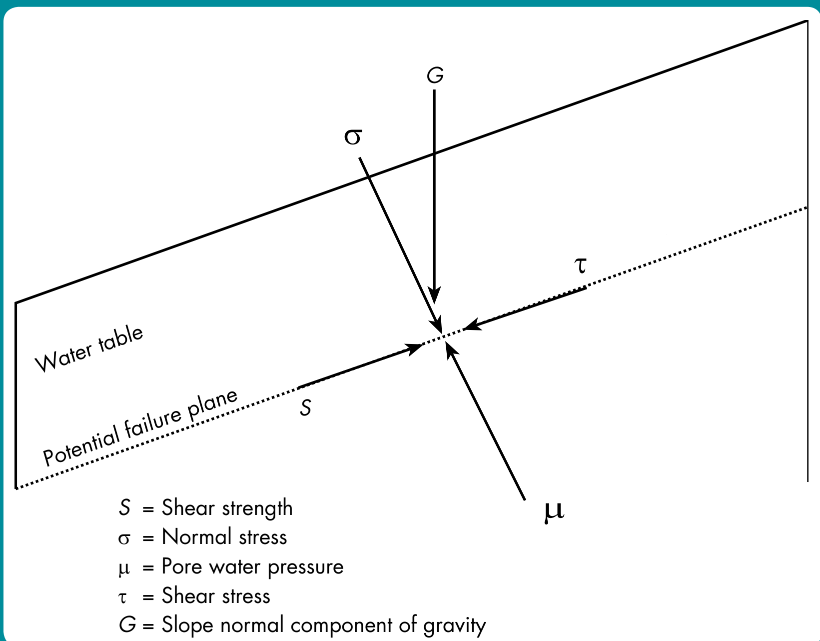
The driving forces on a slope make up the shear stress or driving stress (τ). The main force contributing to shear stress is gravity. The slope angle, type of material, water content, earthquakes, and anthropogenic activities can all contribute to the effect of gravity. The driving force increases with increasing steepness.

Resisting force (shear strength)

The resisting forces on a slope make up the shear strength (*S*). These forces develop as a result of the internal friction caused by interlocking of molecular particles. The resisting forces depend upon the shear strength of the slope materials, which is a function of cohesion and internal friction (shear strength = cohesion + internal friction). Cohesion (*C*) is the innate 'stickiness' of a material: the strength of attraction or bonding of molecules. For example, clay and granite are both cohesive whereas dry sand is non-cohesive. Internal friction refers to the friction between grains within a material and is expressed in terms of the coefficient of friction or angle of internal friction (ϕ). It depends on how slick the grains are and is a function of the type of material and how strongly the grains are pressed together by gravity, which is expressed in terms of the slope normal component of gravity or normal stress (σ). Water plays an important role in reducing the resisting force.

The forces acting on a point along the potential failure plane are illustrated in Figure 3.

Figure 3: Force diagram for thin to thick translational slides



Factor of safety

The factor of safety, FS, for a rock slope is the ratio of the total force resisting sliding (resisting forces) to the total force tending to induce sliding (driving forces) (Li et al. 2001) along an assumed or known rupture surface. In other words, it is the ratio between the shear strength and the shear stress:

$$FS = \frac{\text{Shear strength (resisting force)}}{\text{Shear stress (driving force)}}.$$

FS < 1 indicates unstable slope conditions, FS = 1 indicates that the slope is at the point of failure, and

FS > 1 indicates stable slope conditions. According to Vazirani and Ratwani (1980) the factor of safety against sliding should be not less than 1.5.

In order to assess the potential of failure on a slope, it is important to calculate the factor of safety.

The equation for the factor of safety is given by

$$FS = \frac{C + (\gamma - m\gamma_w)\, z \cos\beta \tan\phi}{\gamma z \sin\beta}$$

where
C = the cohesion of the material,
γ = the unit weight of the material,
m = the proportion of the slab thickness that is saturated,
γ_w = the unit weight of water,
z = the thickness of the slope material above the slide plane,
β = the slope of the ground surface in degrees assumed to be parallel to the failure plane, and
ϕ = the internal angle of friction in degrees.

The model relies on several simplifying assumptions. The values take into account factors such as the level of the water table, the depth of the failure surface, and soil weight but do not account for the impact of adjacent factors such as upslope development or downslope modifications of the hill slope or accentuating factors such as ground vibrations or acceleration due to earthquakes.

The shearing resistance of a soil can also be determined in the laboratory using the direct shear test, triaxial shear test, unconfined compression test, or Vane shear test.

Factors Contributing to the Development of Landslides

A landslide is the result of slope failure. The causative and triggering factors include anything that leads to an increase in the shear stress (driving force) on the slope, a decrease in the shear strength (resisting force), or a combination of the two. The factors can be geological, morphological, physical, and/or human (Cruden and Varnes 1996). They are generally divided into natural factors and man-made (anthropogenic) factors. The major natural factors include high relief and steep slopes, soil type, vegetation cover, river bank erosion, heavy precipitation, earthquakes, folding and faulting, and weathering. In particular, unconsolidated deposits, strongly weathered and fractured rocks, and earth become saturated during heavy rainstorms and are then very prone to slide on a steep slope. The major anthropogenic factors are inappropriate land use and poor watershed management practices such as deforestation, extension of agriculture on steep slopes, intensive agriculture or unsuitable crops, and overgrazing; poor water management; unplanned settlements; and poorly planned construction of roads, trails, and other infrastructure.

Debris flows are characterized by high water content. The causative factors for debris flows include the above, but of these the most important are steep slope, loose rock and soil materials, clay minerals, saturated soils, and especially rainfall or snowmelt generated runoff of sufficient intensity and duration to initiate slope movements (Brooks et al. 2005; Tognacca et al. 2000, cited in Brien et al. 2008).

Mitigation Measures

The first approach to mitigating flash floods is to reduce the likelihood of occurrence of landslides and debris flows, and thus the creation of landslide dams. This means taking measures to reduce the likelihood of slope failure. Slope failure mitigation measures can be divided into three categories: control, restraint, and other (JICA 2006). The most common measures are summarized in Table 2 and discussed briefly below. Specific techniques are described in detail in Chapter 4 (Bioengineering Measures) and Chapter 5 (Physical Methods).

Control measures

Control measures are applied to prevent or reduce the occurrence of landslides by modifying the natural conditions that contribute to their formation such as topography, groundwater, surface water, and other conditions. These measures can be implemented gradually over a long period. The major types of control measure are drainage, slope protection, and reforming the slope through soil removal.

Increasing the efficiency of surface water drainage can help to limit the infiltration of water into the soil and thus reduce the landslide potential. The two main approaches are drainage collection and drainage connection to remove the collected water. It can also be useful to limit water entering the ground from water bodies such as ponds, irrigation channels, and paddy fields by making the banks and bottom of these water bodies water resistant or impermeable with materials such as plastic sheeting, clay, asphalt, and concrete.

Groundwater control measures are designed to remove groundwater from the slope and prevent more water flowing into the mass from outside. This can mean draining surface water and shallow sub-surface water up to 3 m below the surface as well as draining water from deeper layers by boring. Where the slip surface is in the shape of a valley, drainage wells can be dug at the bottom of the valley and water can be drained out to the wells through a borehole. A drainage tunnel can be built to remove deep underground water, where a large volume of underground water flows near the slip surface.

Slope protection measures involve using vegetation (bioengineering) or artificial structures to stabilize the slope and cover the surface to reduce infiltration and increase cohesion. Bioengineering methods are one of the main approaches used to mitigate debris flows, as minimizing runoff above the slope and binding loose materials on the slope through a network of roots have the highest priority. Bare slopes without vegetation are more prone to debris flows than slopes covered by vegetation (Li and Clarke 2007).

The slope can also be reformed to maintain the balance of the landmass, most commonly by removing the sliding mass from the upper part, sometimes replacing it at the foot of the slope. Such measures require skilled engineering and can sometimes trigger a landslide, so careful investigation and planning is required before implementation.

Table 2: Mitigation measures

Purpose	Drainage		Surface drainage/groundwater drainage
Control	Slope protection with vegetation		Bioengineering
	Slope protection using structures	Spraying	Spraying mortar Spraying concrete
		Plastering	Plastering with stones or blocks Spraying concrete
		Crib work	Pre-cast crib wall construction Cast-in-place crib work
	Removal of unstable soil mass		Excavation
Restraint	Improvement of slope shape		Excavation
	Construction of retaining walls		Stacked blocks and stone masonry Concrete leaning walls Concrete gravity walls Concrete crib retaining walls
	Pile construction		Piling
	Anchoring		Anchoring
	Counterweight filling		Counterweight filling
Other	Protection methods		Catch walls
	Rock fall prevention		Rock fall prevention measures Rock fall check measures
	Avalanche control		Avalanche trapping measures
	Other construction		Fencing Installing gabions Temporary protection measures

Source: DWIDP/JICA 2004b

Restraint measures

Restraint measures are structural ways of reducing the likelihood of landslides. The most common measures are construction of retaining walls, anchoring, and pile construction. These techniques have high construction costs and require specific technical skills; careful investigation and understanding is needed before designing such measures.

Retaining walls can be installed to hinder the small or secondary landslides that often occur at the toe of larger landslides. Retaining walls are effective against small landslides but cannot resist direct landslide driving forces. They are usually installed in combination with other measures such as bases of embankment structures and walls for drainage of horizontal borings. Different types of walls are discussed in more detail in Chapter 5.

Anchors use the tensile force of anchor bodies to stabilize the slope. Steel wires or bars are inserted throughout the sliding landmass and cemented into the bedrock in order to join the sliding landmass and bedrock together. Anchor work can be used on moderate to steep slopes. The advantage of anchors is that a large restraint force can be obtained from a relatively small element. Large restraint forces can be obtained by increasing the number of anchors.

Steel piles can be used in a similar way as anchors to tie the sliding landmass to the bedrock below in order to restrain movement. Steel piles of 200–600 mm diameter are designed to resist both shearing and bending stress. Piles are generally filled with concrete.

The lowest, or toe, area of a landside can be prevented from moving by piling up extra material, and slope stability can be increased by reducing erosion at the toe. This method is widely implemented because of its reliability and immediate effect and is sometimes combined with soil removal from the upper part.

Other measures

Other protection measures include installing catch walls on lower slopes to slow landslides, measures to prevent rock falls that might trigger a landslide, and various types of fencing and other measures to protect installations from the impact of landslides. These measures also include sabo dams, which are designed to reduce the load carried downstream by a debris flow. Sabo dams are discussed in more detail in Chapter 5.