A Topple denotes the overturning or tilting of a block of rock on a pivot or hinge. Finally, it separates from the main mass resulting in a fall or slide.

The term **slide** is applied to a mass movement process in which a distinct surface of rupture or zone of weakness separates the slide material from the more stable, underlying material. The slide materials can be broken up and deformed or they can remain fairly cohesive and intact. A cohesive landslide is called a **slump.** A **rotational slide** is one in which the movement is more or less rotational about an axis that is parallel to the contour of the slope. A **translational slide** is a mass movement on an approximately planar surface.

Spreads are failures caused by liquefaction: the process whereby water-saturated sediments transform into a liquid state. The movement of **flows** resembles that of a viscous fluid; slip surfaces are almost absent. Flow can take place as one or more lobes that move at different rates depending upon the viscosity of the material and the slope angle.

The most common natural hazards occurring in the Himalayas are mass movements (landslides, debris flows, and mud flows), earthquakes, and floods. Landslides in the Himalayas are often complex, as there is usually more than one factor contributing to sliding.

Factors Causing Landslides

There are several factors that directly or indirectly cause slope instability. For landslide assessment, it is necessary to carefully study the past and present factors responsible for instability. Under normal conditions, the shear stress along the slope is in equilibrium with the shear resistance of the slope. But it is often modified by various internal and external factors and, as soon as the shear stress along the slope exceeds the shear resistance, landslides and other mass-wasting phenomena set in and the slope is modified to the new values of equilibrium (Záruba and Mencl 1982).

Factors that are more or less long-lasting and inherent in the constituent rock and soil can be called the primary causes of failure. The basic factor is the force of gravity. There are also many other factors. Some of the important ones are: rock and soil type and strength, rock structure (folding, faulting, jointing, foliation, bedding (Hoek and Bray 1981), soil depth, porosity, and permeability.

The factors that are either variable or very short-lived can be called the secondary causes or triggers. They are seismicity, intensity of precipitation, land use, natural slope conditions, rock and soil weathering conditions; presence or absence of gullies, streams, and rivers; and groundwater conditions.

A short description of the important landslide-causing factors common in the Nepal Himalayas is presented below.

Geology

Lithology

Lithology is one of the primary factors causing landslides. The rocks in the Himalayas range from granite, gneiss, and schist in the Higher and Lesser Himalayas to soft sandstone, mudstone, and conglomerate in the Siwaliks. The most common types of mass rock movement in the Himalayas are rockslides, rockfalls, rock toppling, and wedge failure. Short descriptions of the common rocks are given below (Dhital 1991).

Fractured Slate: This type is found in a large portion of the Midlands and breaks easily into long pencil-shaped or small flat polygonal chips which cleave off the bed even in the dry season. Slate is susceptible to wedge failure, gully erosion, and toppling.

Interbedded Quartzite/Sandstone and Shale: These types of rock are found north of the MBT as well as in the inner part of the Lesser Himalayas. The anisotropy inherent in the interbedding of resistant quartzite or sandstone with weak slate or mudstone contributes significantly to mass movement. Huge rockslides and smaller wedge failures are common.

Interbedded Limestone/Dolomite and Slate: The most common types of mass movements on these rocks are rockslides parallel to the bedding/joint planes and wedge failures. Thick beds of dolomite fail along the discontinuity planes. On the other hand, rockfall is likely if the slope is steep.

Massive Limestone, Dolomite, Marble, or Quartzite: Under normal conditions, these rocks are quite stable, but, when strongly jointed, wedge failure or rockfall is possible.

Interbedded Soft Sandstone and Mudstone: This type of rock is found in the Siwalik Zone. Occasionally, it forms high cliffs. Large-scale wedge failures and plane rockslides often occur in the wet areas and areas with deep gully erosion.

Massive Granite, Gneiss, and Crystalline Rocks: These rocks are found in the Lesser and Higher Himalayan zones. Generally, these rocks are quite stable. They form steep cliffs and narrow gorges. Rockfalls, rock avalanches, boulder gliding, talus cones, and wedge failures are seen at higher altitudes and along fault zones.

Phyllite and Quartzite Alternation: Generally, a thick succession of the phyllite and quartzite alternation is found in the Midlands. Large anticlines and synclines with numerous small-scale folds also occur in this rock unit. The main mass movements associated with this rock unit are debris slides, wedge failures, and gully erosion. Large-scale rotational slides may occur in the weathered or crushed zones.

Deeply Weathered Residual or Colluvial Soils: After rock weathering and disintegration, various kinds of soils are formed on slopes. Generally, translational and rotational slides are common on these soils. If the slope is gentle (less than 25 degrees), it may be quite stable. However, depending upon the intensity of precipitation, gully erosion may occur and badlands may develop.

Alluvial Soil: Alluvial soil is found along the river banks and in the proximal areas. It is of two types: the old consolidated (cemented) river terrace type and the recent terrace type with loose gravel and fines. Often, in the old terraces, vertical joints develop which may fail by toppling and fall. On both types of terraces, deep gully erosion and rotational and translational slides also occur.

Rock Structure

The geological structure of the Himalayas is such that there are several roughly east-west trending major thrusts and faults with several weak and crushed zones (Plate 2). In such areas, numerous small and big landslides occur along these linear structures. On the other hand, the orientation of folds, bedding, foliation, and joints in the rock also play a vital role in landsliding (Plate 3). Active faults are common in the Nepal Himalayas. The MFT, MBT, and other active faults (Fig. 3) are characterised by the parallel alignment of many small and large landslides.

Weathering

Mechanical and chemical weathering change the strength parameters of the rock and soil considerably. In many landslide events, chemical alterations, such as hydration and ion exchange in clay, are thought to have contributed to triggering off landslides (Záruba and Mencl 1982). Chemical weathering in rocks along the discontinuities may reach tens of metres below the surface and thus weaken the rocks considerably. Himalayan rocks, especially in the warm-temperate and subtropical climatic zones, are usually deeply weathered The weathering grades of rocks applicable for engineering practices are presented in Table 6.

Table 6: Weathering Grades of Rocks

Grade	Degree of Weathering	Description
VI	Residual Soil	The rock is discoloured and completely changed to a soil in which original rock fabric is destroyed. There is a large change in volume.
V	Completely Weathered	The rock is discoloured and changed to a soil but original fabric is mainly preserved. There may be occasional small core stones. The properties of the soil depend in part on the nature of the parent rock.
IV	Highly Weathered	The rock is discoloured. Discontinuities may be open, discoloured surface, and original fabric of discontinuities may be altered. Alteration penetrates deeply but core stones are present.
III	Moderately Weathered	The rock is discoloured, discontinuities may be open and show discoloured surfaces with alteration starting to penetrate inwards. Intact rock is noticeably weaker, as determined in the field, than the fresh rock.
II	Slightly Weathered	The rock may be slightly discoloured, particularly adjacent to discontinuities, which may be open and will have slightly discoloured surfaces. The intact rock is noticeably weaker than the fresh rock.
I	Fresh	The parent rock is not discoloured and there is no loss of strength or any other weathering.

Geotechnical Properties of Soil

The geotechnical properties of soil are the main factors contributing to soil slope failures. Soil composition, depth, shear strength (which depends on density, cohesion, plasticity, dilatancy, and angle of internal friction), porosity, permeability, grading, packing, moisture content, and organic material content are some of the important geotechnical parameters for soil study. The Unified Soil Classification System (USCS) is often applied in soil classification and studies in engineering practices.

Genetically, the soils on the hillslopes of the Himalayas can be classified as colluvium and as residual soils, in addition to the alluviums found along the river and stream banks in the form of terraces. Along many of the major river valleys, alluvial soils are present on the hill slopes - much higher than the present river levels due to the upliftment of the Himalayas. All these types of soils are often silty gravel and occasionally clayey silt. Debris slides are observed in coarse-grained soils with steeper (35-45 degrees) slopes and rotational slides are characteristic of fine-grained and thick soils with gentler slopes (less than 35 degrees).

Groundwater

Flowing groundwater exerts pressure on soil particles thus impairing slope stability. Abrupt changes in the water level, as might occur in reservoirs, cause the porewater pressure on slopes to increase and this, in turn, may lead to the liquefaction of sandy soils. Groundwater can wash out soluble cementing substances and thus weaken the intergranular bonds and reduce the mechanical strength of the ground. Flowing groundwater flushes out fine particles in fine sand and silt and the strength of the slope is reduced by the cavities formed in the process (Záruba and Mencl 1982).

Perched groundwater exerts upthrust on overlying beds. The most important aspect of porewater pressure on rock and soil is that it reduces the normal stress but does not affect the shear stress of the material.

Precipitation

Rainfall is one of the main factors controlling the frequency of landslides. The magnitude of the influence depends upon climatic conditions, the topography of the area, the geological characteristics of the slope, and the porosity and permeability of rocks and soils. The variation in the soil depth and the nature and frequency of discontinuities on the rock may also play their roles.

Rain and meltwater penetrate joints and produce hydrostatic stress in rocks. Rain increases the porewater pressure on soils and, consequently, decreases the shear resistance. Rainfall measurements have shown that recurrent slope movements occur during periods of exceptionally high rainfall (Záruba &Mencl 1982).

The relationship between the amount of rainfall and frequency of landslides has been studied by many authors. In Nepal, Karmacharya (1989) studied the relationship between total annual precipitation recorded in the *Gorkhapatra*, a daily newspaper, and the frequency of landslides during the period from 1971 to 1980 and found a strong correlation between them.

More detailed studies on the relationship between rainfall and landslide events are available on the Darjeeling Himalayas in India. The area lies close to Eastern Nepal. Froehlich et al. (1990) observed that short-distance overland flow and slope wash began in the tea plantation area when the rainfall exceeded 50mm with a 0.5mm/min intensity. Shallow slides or slumps on steep slope segments began to occur, mainly along undercut sections of roads or rivers, when 24-hour rainfall events exceeded 130-150mm, or on occasions of continuous rain over a three-day period in excess of 200-240mm.

Li (1990) studied the landslides induced by heavy rainstorms in the eastern part of the Sichuan Basin, about 240km NNW of Chengdu, China, in 1982. Three hundred and ten landslides in four different areas of the country, including 85 major landslides, were studied in detail. Li concluded that, if the cumulative precipitation of the area is 50 to 100mm in one day and daily precipitation more than 50mm, somewhat small-scale and shallow slides will occur. When cumulative precipitation within two days is from 150mm to 200mm and daily precipitation about 100mm, the number of landslides will increase with precipitation. And, when cumulative precipitation exceeds 250mm in two days, with an average intensity of more than 8mm/hour in one day, the number of large landslides increases abruptly (Li 1990, p27).

In Japan, rainfall of from 150 to 200mm, with an intensity exceeding 20 to 30mm/hour, is considered to be critical (Cotecchia 1978). In southern Italy, old landslides are immediately reactivated after every strong storm. In the Western Alps and their forehills, the most frequent critical rainfall is 100-200mm/day (Cotecchia 1978).

In the Higher Himalayan Zone, the water freezing in the fractures and discontinuities increases in volume and tends to widen them. As a result the rock becomes vulnerable to sliding.

Monsoon and Rainstorm (Cloudburst) Events in Nepal

The climate of Nepal is essentially controlled by monsoon winds and the physiography. The monsoon winds result from an inland low pressure that develops in summer, and they are accentuated by a northward migration of air from the southern hemisphere. These are south to southwesterly winds which carry moisture from the Indian Ocean to Nepal (Nelson et al. 1980). The wet season is from June to September. Generally, in Nepal, the precipitation decreases from east to west during the summer monsoon, whereas the winter monsoon shows the reverse trend. Approximately 80 per cent of the total annual rainfall occurs between June and September (Fig. 6), with relatively limited precipitation from November to February. Rains brought by these winds are characterised by strong seasonality, variation in the amount of precipitation, and high intensity at lower altitudes.

The regional climate (Fig. 7) is strongly influenced by the mountain ranges. A distinct rainshadow area is created by the Great Himalayan Range (Fig. 1). Generally, the Inner Himalayan valleys are very dry. The local climatic pattern is strongly controlled by the slope aspect. The south-facing slopes have a higher insolation rate, resulting in higher evaporation rates. This, in turn, is reflected in the greater sparsity of vegetation on the south-facing slopes than on the north-facing slopes (Nelson et al. 1980).

Measured values of mean annual precipitation in Nepal range from approximately 250mm in the stations north of the Great Himalayas to over 3,000mm in numerous other stations. The mean annual precipitation in the 114 stations considered was 1,627mm (Alford 1992). It is not uncommon for 10 per cent of the total annual precipitation to occur on a single day and for 50 per cent of the total to occur during 10 days of the rainy season (Alford 1992). Such uneven distribution plays an important role in triggering landslides.