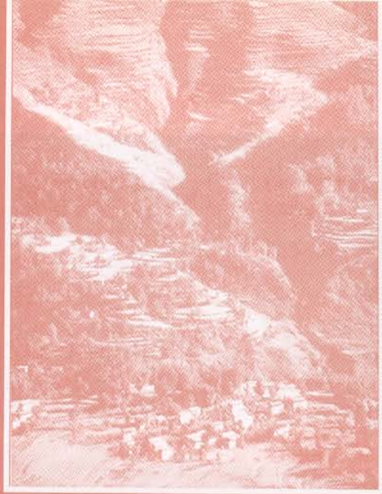


Understanding the dynamic landscape

This chapter examines the factors affecting slopes and what makes them unstable. This starts with the underlying geological conditions and works through geomorphology, climate and materials to the implications of slope instability for road engineering. This chapter covers the following topics.

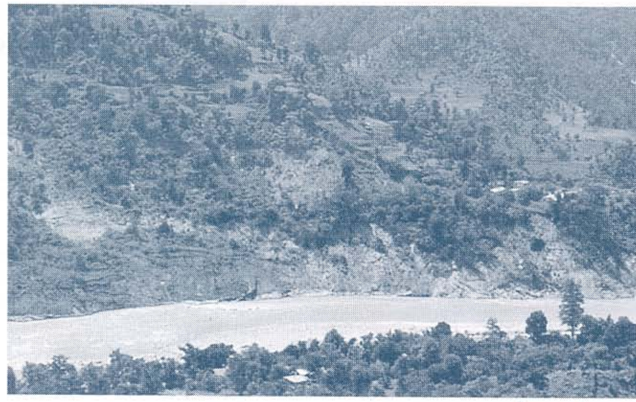
- The underlying geology of Nepal (2.1)
- The ways in which mountain slopes evolve (2.2)
- Engineering aspects of slopes and rocks (2.3 and 2.4)
- Soils and materials (2.5).
- The role of climate and water (2.6).
- Forms and mechanisms of instability (2.7).
- Practical aspects of site investigation (2.8).
- Site treatment (refer to the *Site Handbook*).

The mountain slopes of the Himalayas are large and complex. Their instability is well known, but the causes and mechanisms are often poorly understood. Sometimes it is not possible to do anything about them.

Figure 2.1 summarises the main factors affecting the slopes. These, in turn, may be influenced by many other factors, all of which produce certain effects on slopes: for example, the amount of rainfall in any particular location is determined by a wide range of site features to do with location and topography. The rest of this chapter addresses these in detail.

2.1 THE GEOLOGICAL FRAMEWORK OF NEPAL

The stability of Nepal's mountain slopes is determined largely by the geology that makes up their structure. In order to understand the principles of slope stabilisation, it is necessary to know how the slopes were formed, what they are composed of and how they are evolving. This section introduces these topics, and helps to provide a background to the site assessment procedures described in the *Site Handbook*.



Large deep-seated landslides can occur on a number of different planes, such as has happened in this example of a rotational faiture at Mulghat, Dhankuta District. A number of scars are visible to the left of the buildings

Geological synopsis

The physical environment of Nepal is dominated by a major mountain-building process caused by the collision of two continents.The meeting of two continental plates is not smooth, of course. The movement occurs in a series of jerks, or earthquakes. Great chunks of rocks have been pushed upwards, bending (folding) and breaking (faulting) in the process. As the mountains have arisen, so the forces of nature, particularly water and gravity, have started to cut them down again.

The two continental plates are still moving together, at the rate of a few centimetres per year, and so the mountains are still growing. There is a time lag between the growth and the wearing away of the mountains; hence nature has a substantial backlog of slopes to reduce.

It is on these slopes that Nepal is situated, and on which we are trying to build and maintain our roads. Nepal is situated in the central part of the Great Himalayan Arc, which extends for about 2,400 km from the Punjab Himalaya in the west to the North Eastern Frontier Area or Assam Himalaya in the east. The middle strip of 820 km constitutes Nepal.

The Earth's crust is composed of a layer of cool, brittle rocks, about 30 to 40 km thick where the main continents occur. These effectively float on the surface of the semi-molten rocks of the mantle below. Very slow, viscous flow in the mantle causes sections of the crust to move relative to each other over immensely long time periods. One large section (or 'continental plate'), known as the Indian Shield, has been moving towards and underneath another section, known as the Tibetan Plateau, for approximately the past 40 million years.

The continents meet through a series of thrust faults, where one rock type is pushed on top of another. It is assumed that the height of the Himalayas is attributed to a great thickness of crust rocks underneath them, since the northern part of the Indian Shield plate must now be underlying the southern part of the Tibetan Plateau plate. The principle of isostasy[1] means that the lighter but now thickened crust rocks, where are effectively floating on the viscous mantle below, rise higher than the surrounding areas of crust.

The southerly edge of the original Tibetan plate rocks can be seen as the Mahabharat range. The northern edge of the Indian Shield rocks are not visible, since they have been covered by huge volumes of sediments: these comprise the Churia, Bhabar and Terai, and lie on top of the older Indian rocks. The Churia have in turn been uplifted, distorted and eroded during the more recent part of the process.

The rate of geological evolution is not always constant. There appears to have been a very active tectonic regime from the late Tertiary to the present (*i.e.* from about 10 to 20 million years ago). This has given rise to the crushed, folded and fractured rocks, and at the same time has been combined with a period of relatively rapid sub-tropical weathering. Combined with the effects of monsoon storms on the near-surface hydro-geology, these factors explain why the mountains are so unstable today.

The physiographic north-south cross-section is similar throughout the Himalaya; therefore a simple geo-tectonic zonation, which is applicable to the whole orographic belt, is also valid for Nepal. These divisions are also well correlated with the zonal distribution of the geological formations and the structural arrangements along the Himalayan trend. The zonation is longitudi-

[1] Isostasy is the state of equilibrium, which is thought to exist in the Earth's crust, where equal masses of matter underlie equal areas, whether of continental or oceanic crust rocks, to a level of hydrostatic compensation.

Figure 2.1. Summary of the main factors affecting slope stability

← More stable	Less stable →	What can be done to resolve it
Slope		
Geology		
[Opposite does not occur]	Major disturbance (faulting, folding)	Nothing can be done
Older, more consolidated rocks	Younger, less consolidated rocks	Nothing can be done
Shorter slopes	Longer slopes	Slopes can sometimes be broken up by building large check dams or retaining walls.
Geomorphology		
Undisturbed ridges	Unstable valleys	Nothing can be done
[Opposite does not occur]	River cutting (down- and under-)	Large scale river training works are sometimes worthwhile
[Opposite does not occur]	Gravity and colluvium formation	Large retaining walls sometimes retard colluvial movements
Rocks		
Hard and cohesive rocks	Weak rocks	Nothing can be done under normal Nepalese conditions
Stable minerals (weather slowly)	Unstable, easily weathered minerals	Nothing can be done
Undisturbed rock masses	Fractures	Physical support can sometimes be provided
Hard, unweathered rocks	Weathering	Support, anchoring and reinforcement can sometimes be provided
Materials		
In *situ* and consolidated	Moved and unconsolidated	Materials can be anchored, supported and reinforced
Angular, inter-locking fragments	Rounded & poorly bound fragments	Materials can be anchored, supported and reinforced
Slow soil development	Fast soil development	The surface soil can be reinforced with plant roots
Low infiltration soil	High infiltration soil	Drainage can be improved to encourage runoff
High hydraulic conductivity	Low hydraulic conductivity	Drainage can be improved
Cohesive surface	Uncohesive surface layer	The surface layer can be armoured and reinforced with plant roots
Vegetated surface	Unprotected surface	All unprotected areas can be vegetated by bio-engineering
Water		
Low rainfall	High rainfall	More drainage can be given
Drier location	Damper location	Drainage can be improved
Low intensity rainfall	Intense rainfall	Preventative slope treatment can be increased

Combinations of these destabilising factors form the following main types of failures

Failure type	Main curative action required
Erosion	Surface armouring is required. Mainly done using bio-engineering, but check dams may also be needed.
Planar (translational) landslides	Support, anchoring and reinforcement are needed. Usually achieved by civil and bio-engineering works combined.
Shear (rotational failure)	Drainage, support, anchoring and reinforcement are needed. Usually achieved by civil and bio-engineering works combined, with the main support achieved by a heavy retaining wall.
Debris flow	Drainage and reinforcement are needed. Usually achieved by civil and bio-engineering works combined
Rock failures	Support is required. This can usually only be done using civil engineering techniques.

nally arranged from south to north as shown in Figures 2.2 and 2.3.

Trans-Himalaya or Tibetan Tethys Himalaya

The Tibetan Tethys Himalaya reaches to altitudes of about 5000 metres above sea level. In this zone, the Tethys sediments of the Palaeozoic to the early Cenozoic ages (*i.e.* from about 400 to only 50 million years old) are spread over an area underlain by granite bodies. The sedimentary rocks are highly fossiliferous. The Tibetan Tethys

Figure 2.2: The physiographic sub-divisions of the Himalayas

Zones		Faults	Rock Types
Trans-Himalaya			Tibetan Tethys (ancient marine) sediments: fossiliferous sandstones, claystones and others
Higher Himalaya			Gneisses, granitic rocks, schists and dolomites
		Main Central Thrust	
Lesser Himalaya: (middle mountain)	Midlands		Relatively soft rocks (gentler slopes, thicker soils): granitic gneisses, limestones and phyllites
	Mahabharat range		Relatively hard rocks (steeper slopes, thinner soils): quartzites, dolomites and schists
		Main Boundary Thrust	
Sub-Himalaya: (or Siwaliks)	Churia		Unconsolidated sandstones, shales, mudstones and **conglomerates**
	Inner Terai		Alluvial (boulder, gravel, sand, silt and clay)
		Main Frontal Thrust (or Himalayan Frontal Thrust)	
Terai:	Upper piedmont alluvial plain (Bhabar)		Alluvial (boulders, gravels and sands), gently sloping (5-8°)
	Lower piedmont alluvial plain (Terai)		Alluvial (silts and clays), very gently sloping (2-3°)

Note: 'piedmont' literally means 'foot of the mountain'. A piedmont alluvial plain is formed by the coalescence of numerous alluvial fans where rivers and streams discharge from mountains.

zone is bordered to the north by the Indus-Tsangpo Suture (a line of join or meeting), which stretches along the Indus and Tsangpo rivers. This fault zone signifies the collision trace of the Indian subcontinent with Eurasia. The width of the zone is approximately 40 km. The Thak khola area in Mustang is considered as the type example of this area in Nepal. So far it is the only geological division not touched by a part of the road network.

Higher Himalaya

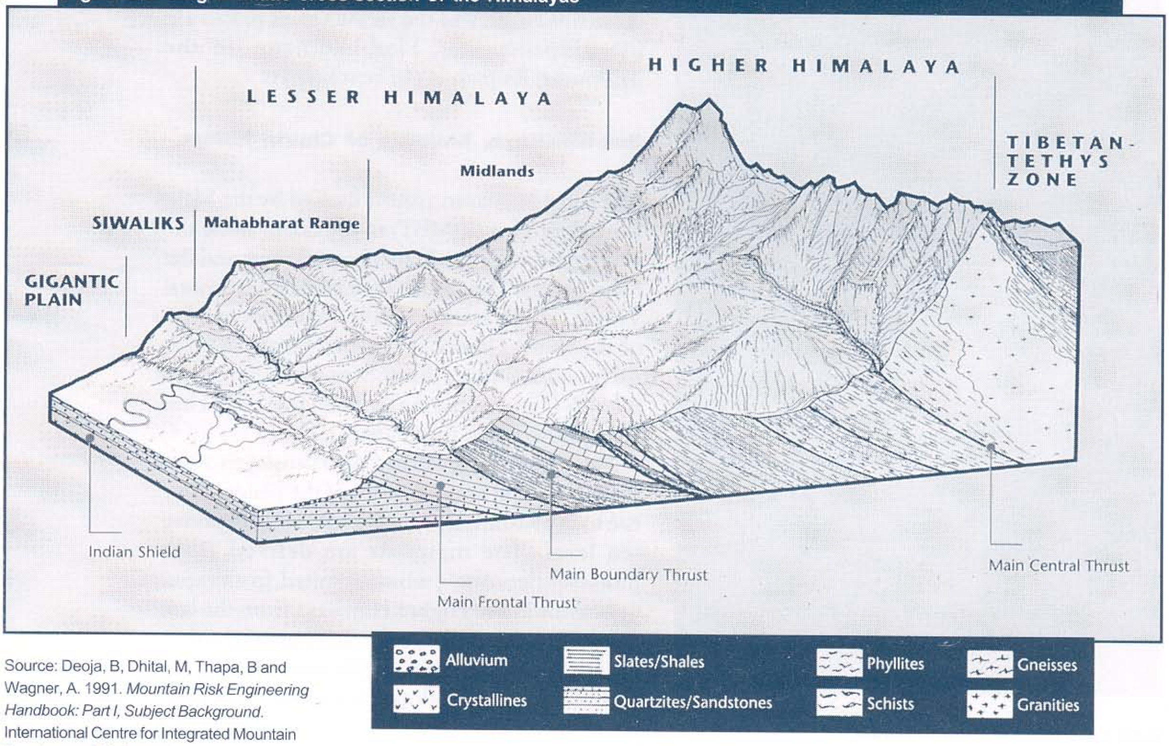
The Higher Himalayan zone ranges from 2000 to more than 8000 metres. There are altogether 14 mountain peaks higher than 8,000 metres and, of these, the Nepal Himalaya contains eight (*i.e.* Mount Everest or Sagarmatha, Kanchenjunga, Lhotse, Makalu, Dhaulagiri, Manaslu, Cho-Oyu and Annapurna I). The upper parts of these mountains are formed by Tethys (ancient marine) sediments, which are underlain by the central crystalline rocks. The whole range consists mainly of high-grade metamorphic rocks, such as schist and gneiss. This zone is characterised by sharp peaks and deep gorges: the Kali Gandaki valley is the deepest gorge in the world.

Trans-Himalayan terrain in the upper Kali Gandaki (Thak khola) Valley. Although this area is now at very high altitudes, these rocks were laid down under an ancient sea, and now comprise the main Tibetan plateau

Both the Higher Himalaya crystalline basement rocks and the Tibetan Tethys sediments thrust on the Lesser Himalayan rocks along the Main Central Thrust (MCT).

Few roads have been built in this zone. The most notable is the Arniko Highway, which uses the Bhote Koshi gorge to cut right through the Higher Himalaya at a relatively low altitude.

Figure 2.3: Diagrammatic cross-section of the Himalayas



Source: Deoja, B, Dhital, M, Thapa, B and Wagner, A. 1991. *Mountain Risk Engineering Handbook: Part I, Subject Background.* International Centre for Integrated Mountain Development, Kathmandu.

[1] Gondwanaland was the southerly of the two ancient continents, which once comprised the Earth's two big land masses (the other was Laurasia). The Indian Shield was once part of Gondwanaland.

Lesser Himalaya or Middle Mountains

The Lesser Himalayan zone lies to the south of the Higher Himalayan zone. It is bordered by the Main Central Thrust (MCT) fault in the north, and the Main Boundary Thrust (MBT) fault in the south. This zone is characterised by medium- to low-grade metamorphic rocks, as well as some igneous and sedimentary rocks. Most of the Lesser Himalayan rocks are barren of fossils except for a few occurrences of stromatolites (fossilised coral), but the Gondwana[1] sediments of the Palaeozoic to the early Tertiary age (*i.e.* from about 400 to only 50 million years old) possess a large number of fossils.

It can be further subdivided physiographically into the Midland and the Mahabharat Range.

Typical Midland terrain in the Lesser Himalayan (Middle Mountain) Zone. Relatively soft rocks give rise to gentler slopes suitable for cultivation

Midland zone

This lies immediately south of the Higher Himalayan zone. It consists of relatively low-lying hills, river valleys and tectonic basins. Its altitudes range between approximately 1000 and 3000 metres. The width is around 30 km. The Midland is represented by a rather dissected topography with predominantly dendritic, centripetal and sub-parallel drainage patterns. Residual soils are found on the ridges, while colluvial soils and talus deposits are present along the slopes. It consists mainly of metamorphic and igneous rocks. Due to the presence of soft rocks such as phyllite, the Midland is amenable to terrace cultivation; furthermore, it has a temperate climate. Since it is favourable for both cultivation and shelter, a dense population is concentrated within

Rato mato forms a distinct terrain type in many lower-altitude areas in the Lesser Himalaya

this zone and many major roads have been constructed to serve its numerous towns and villages.

Among the tectonic valleys, the most notable are Panchkhal, Banepa, Kathmandu, Pokhara and Mariphant.

Mahabharat range

This rises up to 3,000 metres above sea level and extends from the east to the west of Nepal with only minor breaks, in river valleys such as the Sapta Koshi, the Sapta Gandaki, the Karnali, and the Mahakali. It bears rocks from Pre-Cambrian to the early Palaeozoic age (*i.e.* from 2,000 or 3,000 to about 500 million years old) in different places, with Gondwana sediments as well. The rocks consist mainly of quartzite, granite, schist, marble and limestone. Most of the high peaks are found either on granite or limestone. The range is characterised by dendritic, radial and rectangular drainage patterns. These harder rocks give rise to steeper, more rugged slopes with thinner soils and less available water. This accounts for the relatively sparse population in the Mahabharat. Roads between the Midland and the Terai have to cross this range, and the ascents to its passes are often spectacular. Simbhanjhang on the Tribhuvan Rajpath is the best known.

Sub-Himalaya, Siwaliks or Churia Range

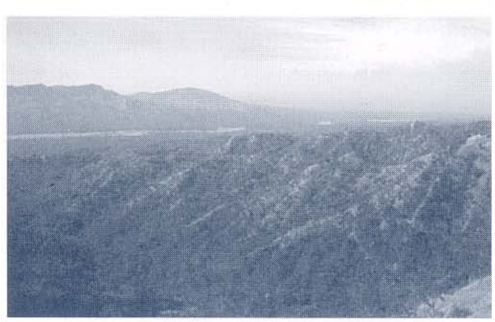
The sub-Himalayan zone is limited by the Main Boundary Thrust (MBT) to the north along the southern foot of the Mahabharat Range; and the Main Frontal Thrust (MFT) or Himalayan Frontal Thrust (HFT) to the south at the southern edge of the Siwalik Group. The Lesser Himalayan (middle mountain) rocks thrust over the sediments of the Sub-Himalayan zone (*i.e.* the Mahabharat has been pushed over the Churia).

The Churia hills of the Sub-Himalayan zone are the first hill range in front of the plains. They rise to approximately 1,000 to 1,200 metres above sea level. The materials are derived from molasses deposits[1], which resulted from rapid upheavals in the Higher Himalaya from the late Tertiary to the early Quaternary age (*i.e.* within the last 10 million years). Trellis, parallel, sub-parallel and rectangular drainage patterns, susceptible to flash floods, are characteristic features of this region. The topography is rugged, with numerous gullies and mounds of talus or scree. Streams are dry most of the time, but become hazardously active during the monsoon, leading to intense erosion, flash floods, debris flows and sedimentation.

The Churia hills make a continuous distinct range from east to west, except that in a few areas they merge with the Mahabharat Range. In some places they form Dun Valleys, which are intermontane basins.

With the exception of the Dun valleys, the Churia are generally too rugged, unstable and inhospitable to support much habitation. Roads

[1] Molasse is a Swiss geological term to describe certain depositional materials found in fold mountain belts. Molasses are a continental (*i.e.* non-marine) deposit formed in marginal troughs and inter-montane basins during and after major tectonic movements. They are often cemented with calcareous and clay-rich materials.



The unconsolidated rocks of the Sub-Himalaya of Churia Range give rise to inhospitable terrain, which remains largely forested

The Terai forms an extensive alluvial plain to the south of the Himalayas

passing through the Churia always have slope stability problems. All the south-north roads cross the Churia range at some point, and some road sections, such as between Chisopani and Surkhet, run through this terrain for very long distances.

The Siwalik Group has thrust over the Terai plain along the Main Frontal Thrust (MFT) fault. The MFT is not a continuous line, but rather it is in an echelon (stepwise) pattern. As with the Main Central and Main Boundary Thrusts, it is still active.

The Siwalik Group is divided into three major units: the Upper, Middle and Lower Siwaliks.

Lower Siwaliks

These consist of irregularly alternating beds of fine-grained, grey-coloured sandstones, variegated mudstones and pseudo-conglomerates. Sandstones are moderately hard, and cemented mostly by calcite. The upper part of this unit is composed of sandstones and variegated mudstones in roughly equal amounts. The thickness of individual beds of sandstones and mudstones varies from 1 to 10 metres, and 1 to 2 metres respectively.

Middle Siwaliks

This unit is further subdivided into two sub-units: the Lower Member and the Upper Member.

The Lower Member is represented by fine- to medium-grained, thick-bedded, compact, fairly hard, greenish grey to light brownish grey, micaceous sandstones, interbedded with greenish grey or brownish yellow to purplish grey mudstones and shales. In places, thin lenses of pseudo-conglomerates have been recorded, especially in the upper horizons. The size of the pebbles varies from 5 to 20 cm. Plant and animal fossils are preserved in both mudstones and sandstones.

The Upper Member is composed of medium- to coarse-grained pebbly sandstones with rare grey to dark grey mudstones, and occasionally silty sandstones and conglomerates. The thickness of the individual beds varies from 1 to 15 metres.

Upper Siwaliks

This zone is composed predominantly of gravel and conglomerate beds. Individual conglomerate beds of 2 to 8 metres thickness lie between the medium- to coarse-grained, brownish grey sandstones and occasionally siltstones. The size of the pebbles varies from several to 100 millimetres. The rock is loosely packed and consists of pebbles of quartzite, dolomite, marble, limestone, granite and Lower Siwalik sandstone and shale. The matrix is calcareous or clayey.

The Terai Plain

The Terai forms the main outwash plain below the Siwaliks and the middle mountains. It extends right across the south of the Himalayas, although in Nepal it is interrupted in places by outlying Siwalik ranges, which extend to the Indian border. To the south, it forms the great plain of the Ganges. It is an alluvial formation of sediments and composed mainly of gravels, sands and silts, of late Tertiary and Quaternary origin (*i.e.* within the last 10 million years). A striking feature is the abrupt shifting of river channels.

The Terai plain ranges in elevation from about 60 to 400 metres above sea level. The width varies between 10 to 50 km and forms a nearly continuous belt from east to west. It is divided into three parts: the Bhabar zone, middle Terai, and southern Terai.

Bhabar zone

This lies immediately south of the Churia range and is made up of alluvial fan deposits of boulders and pebbles sloping down towards the south. The southern margin of the Bhabar zone is marked by a spring line, which gives rise to many streams. The water table in the Bhabar zone lies at a considerable depth, and hence most stream courses are dry throughout the year except during the monsoon. The depth of the water table also explains why it is almost always unpopulated.

Middle Terai

The Middle Terai lies at the south of the Bhabar zone, immediately after the main alluvial fans. The area is composed of cobbles and sand on undulating terrain, with isolated pockets of waterlogged soils and marshes.

Southern Terai

This area lies further south and stretches along the Nepal - India border. It is the lowest terrain of Nepal and in some places, the altitude is less than 70 metres above sea level. It is composed of clays and silts with some sand layers. The water table is shallow and accessible using a hand pump throughout the year, making habitation possible.

In the Terai and Bhabar, bridging is the most problematic issue facing highway engineers. Slope stability problems related to roads are confined to embankment protection.

Regional geological structures

The main structures define the limits of the physiographic sub-divisions. There is often local instability on slopes where roads cross them, and so they are mentioned here as areas with potentially greater engineering problems.

Main Central Thrust (MCT)

The MCT is a conspicuous tectonic boundary throughout the Himalayas. The thrust dips gently northward along its east-west direction, and runs sub-parallel to the Himalayan zone. Augen gneisses (i.e. those with large minerals, usually feldspars, around which the foliation is wrapped) occur continuously throughout the MCT zone: these represent important geological and petrological evidence of tectonic development. The rocks of the Higher Himalayan zone have slipped and spread across the MCT towards the south, producing nappes[1] and klippens[2] on the Lesser Himalayan rocks in the Midland zone.

Main Boundary Thrust (MBT)

The MBT is a longitudinal structure that sharply separates the terrigenic sedimentary rocks of the Sub-Himalaya (Siwaliks) from the low-grade metasedimentary rocks of the Upper Nuwakot Group

The steeper,more rugged Mahabharat Range rises above the gentler slopes of the midlands

of the Lesser Himalaya (middle mountain). The MBT dips at 40-70° towards the north. It is conspicuously marked in aerial photographs and is well exposed in many places. In places it is cut by several NE-SW trending transverse faults.

Mahabharat Thrust (MT)

The MT nowhere appears as a clear-cut break like the MBT, but rather as a narrow transitional zone displaying reverse metamorphism. The underlying low-grade metamorphic rocks (quartzites and phyllites) of the Nuwakot Complex rapidly pass upwards into the overlying high-grade metamorphic rocks (garnetiferous schist) of the Kathmandu Complex[3]. The zone is characterised by coarse-grained garnetiferous schists that appear as cataclastic gneiss[4], due to the intense shearing and mylonitisation[5].

Main Frontal Thrust (MFT) or Himalayan Frontal Thrust (HFT)

The MFT dips north and brings the Siwaliks above the Terai plain. The Thrust plane can be traced out most easily in the Kailali and Koshi areas. This thrust is seismically very active.

Mahabharat Synclinorium

The Mahabharat synclinorium[6] consists of a huge, doubly-plunging syncline and numerous smaller anticlines[7] and synclines[8] trending WNW-ESE. Both the flanks are steep (dip >60°). Kathmandu valley forms the core of the synclinorium, which extends southwards as far as Hetauda. The northern flank (which extends to Trisuli) is generally steeper, in places almost vertical or even slightly overturned. The synclinal closure is perfectly developed in the western area (where it ends at Kuringhat), but in the east the

1 Nappe is a French geological term that describes a sheet of rocks, which has slid right over another series of rocks as a result of extreme folding due to a thrust fault.

2 A klippen is a series of nappes, and is also a term derived from Alpine geology.

3 In general, low-grade metamorphic rocks were formed under conditions of low temperature and strong pressure, especially stress; high-grade metamorphic rocks were formed under conditions of high temperature and high pressures, especially hydrostatic.

4 Cataclasis is a process of dislocation-metamorphism where bands are formed through the distortion of minerals within the rock.

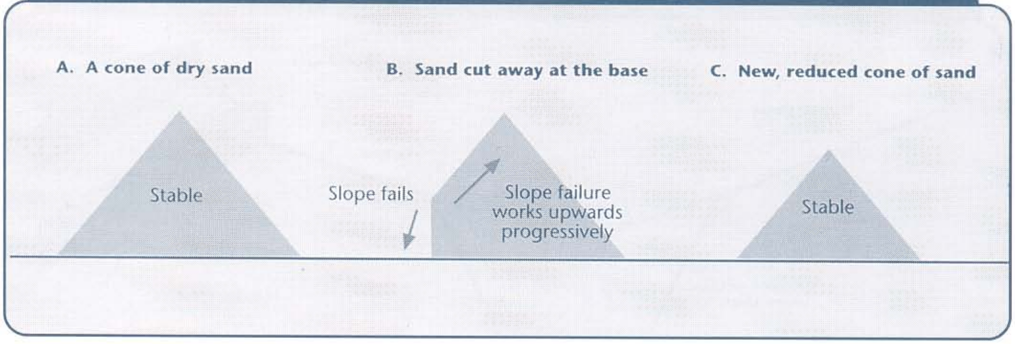
5 Mylonite is a fine-grained rock formed through extensive cataclasis.

6 A synclinorium is a huge trough, in form resembling a syncline, each limb of which consists of a number of small folds.

7 The arch or crest of a fold in rock strata.

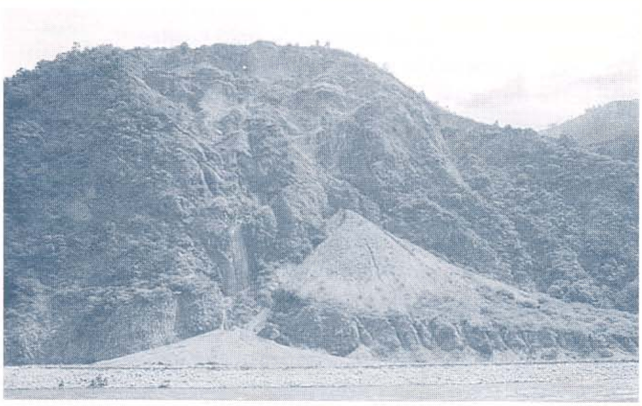
8 A syncline is the trough or inverted arch of a fold in rock strata.

Figure 2.4: Slope evolution with the analogy of a pile of sand



synclinorium narrows down to the single long-stretched syncline of Sindhuli Garhi.

This assessment of the geological zones and structures shows how the mountains come to be there. The next section looks at the way that the rocks are being carved by water and gravity into the complex system of slopes, valleys and ridges which cut across these features.



Many landslides result from a complex mix of erosion and deposition processes. Successful treatment relies on a good understanding of the various processes at work on the site

2.2 THE EVOLUTION OF MOUNTAIN SLOPES

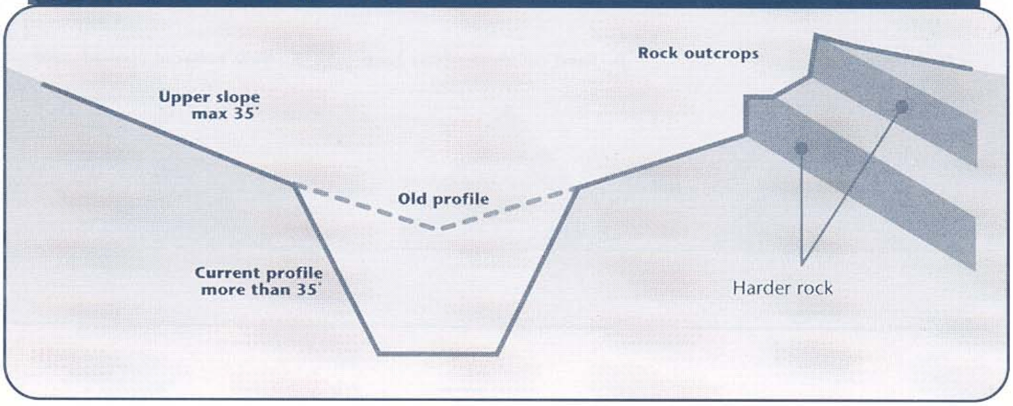
Few people appreciate the far-reaching effects that geomorphic (land-forming) processes have upon all aspects of land management in Nepal, especially highway engineering. This section describes briefly why the mountains are so unstable, and why roads can so easily trigger slope failures, with particular reference to the main middle mountains.

Within the major geological sub-divisions of the Himalayas, numerous geomorphological processes are at work. While movements of the continental plates are creating mountains, other forces of nature are wearing them down again. This is a constantly evolving pattern, and it is important to understand that any form of infrastructure built on mountain slopes will be subjected to damaging forces.

One of the major effects of the continental collision and the faulting and folding of great masses of rocks as a result, is that the rocks have been badly disturbed. They have been distorted, weakened and fragmented. Geological changes take place over a very long period, so that adjustment can take many thousands or even millions of years. When we look at a mountain, we see something which appears solid and permanent; but in geological time it is a temporary feature in the process of formation and removal.

The Middle Mountains consist of long slope components, separated by major breaks of slope. Ignoring irregularities produced by natural slope variation and rock outcrops, the slope components between the main breaks are almost straight. This fact is more obvious if the slope is viewed from a distance of a kilometre or more.

Figure 2.5: Typical major valley cross-section



The reason for this is that they are constantly and rapidly having to adjust to the effect of undercutting at the toe by streams.

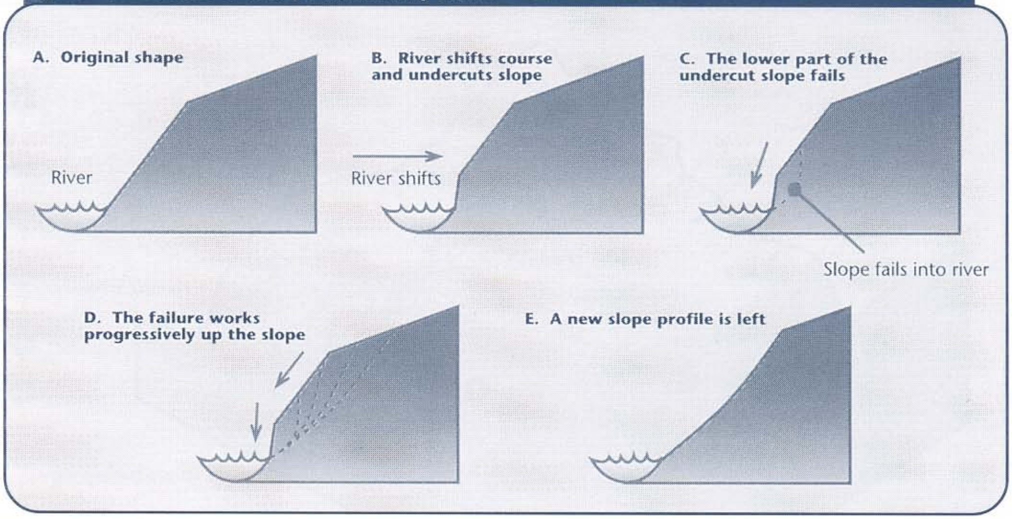
A simple analogy to explain this is a pile of dry sand. In its undisturbed state the sand forms a cone, but if the toe of the cone is scooped away, slope failure occurs and travels upwards from the base towards the apex (see Figure 2.4, page 49). The failure plane is a straight slope, parallel to the cone surface. If scoops are removed from the base of the cone regularly round the circumference, the cone will become covered with failures. Irregularities will develop on the side slopes depending upon whether the local slope is original surface, moved material, or headscar. But overall the straight-sided shape will persist. Eventually, if sufficient scoops are removed, the sand pile will become lower, though the angle of the cone will remain constant and the sides will remain straight.

The mountain slopes have developed in much the same way. The original straight-sided form was established long ago in the geological past by rivers as they cut down into the rising mountain chain. Uplift continues even today (through the mountain-building processes described in section 2.1), and downcutting in the valleys is still active (see Figure 2.5). The effect of river downcutting is to undercut the hillslope and leave the base unsupported, causing slope failure. The slope above the headscar now becomes unsupported, and in time this too will fail, and the landslide steadily elongates uphill.

The tension in the slope is indicated by cracks in the ground above the headscar. If the slope is near its critical angle of stability, a minor disturbance at the base can cause shallow slope failure to occur for many tens of metres above. Rock structure and the presence of springs create numerous points of local instability on the ridge flanks. Bedding planes and joint planes that are oriented roughly parallel to the hillside form inherent slide surfaces that readily shed their overburden of weathered material. Springs create very weak zones in the soil layer that slump out and leave the slope above unsupported. These local processes continue alongside the longer-term and more widespread process of slope reduction by landslides working uphill from the valley floors (Figure 2.6). The middle mountains region has evolved so rapidly that most slopes can be considered to be near their critical angle of stability. In this meta-stable state, only very minor disturbance may be required to destabilise them. Many Churia slopes are the same, but the less consolidated materials are even more fragile.

How is it that the mountains of the Himalayas, which are composed of rock, can be compared to a pile of sand? The answer lies in the weatherability of the rocks. The mountains consist for the most part of metamorphic and poorly consolidated sedimentary rocks. All are highly folded, which has produced numerous cracks (joints) throughout the rock mass. The monsoon rains, coming at the hottest time of the year, create a highly active chemical weathering environment, which vigorously attacks the rock fabric to a depth of several metres. Water penetrates all the joints and micro-fractures in the rock. The minerals, which in many cases have a

Figure 2.6: Evolution of a slope undercut by a river



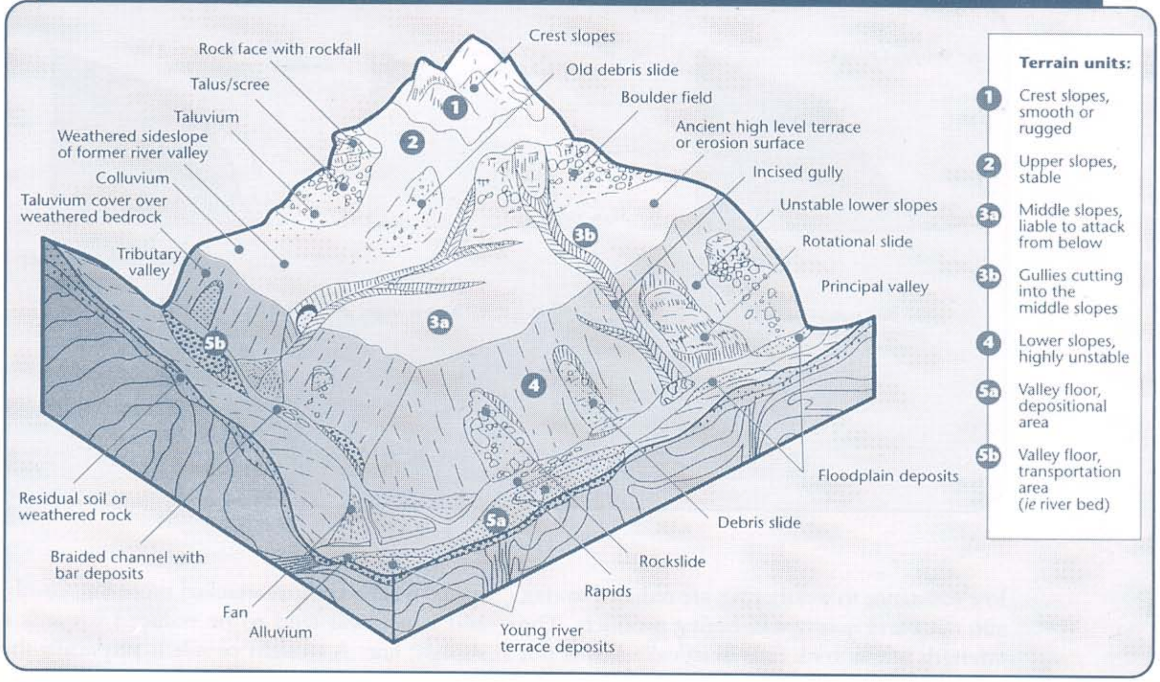
low resistance to weathering, are reduced to clay, silt, mica and quartz weathering products. The strength of the rock falls drastically and is not helped by the closely-spaced fracture planes. The weathered layer is not able to avoid shearing when part of the slope is over-steepened. Landslides on a hillslope tend to advance headwards until they run out at the top of the slope (Figure 2.6e).

Mountain slopes rarely achieve a truly straight profile because of variations in rock type, structure and weathering environment. But any 'high spots' will tend to be attacked more vigorously, and hence will tend to be reduced towards a straight line. A straight profile is physically the most stable configuration. Of course, there are many places where hard rocks resist the 'straightening' process and stand out as outcrops or major breaks in slope. The quartzites found in the Mahabharat Range are examples of a strong and chemically very stable rock that forms major ridges. But it is also highly fractured and brittle, which gives it poor resistance to earthquakes.

After a slide, the weathered layer quickly forms

Relatively gentle outwash fans remain stable long enough for elaborate agricultural terrace systems to be created

Figure 2.7: Schematic cross-section of a typical mountain-valley slope in the middle mountains



(After Fookes et al, 1985 and Transport Research Laboratory 1997).

again. The exposed head scar and slide plane commonly consist of partially weathered rock. These become subjected to weathering until a debris layer builds up, ready to fail when the slope is disturbed once more. The hillslopes gradually become covered in a mantle of soil and partially-weathered rock debris up to a few metres deep. Dormancy may last for a few years or a hundred years: some slides are continually active for many years and never seem to recover. Over thousands of years so many landslides occur that they begin to join up, to a point where almost no slope remains that has not slipped at some time in the past.

The final element in the evolution of mountain slopes is time. If river levels remain static for a long period (many thousands of years) the slope angles will be reduced to gentler grades and the whole landscape becomes more stable. The history of Himalayan geomorphology is one of a continuous succession of periods of rapid down-cutting, alternating with static periods when a certain amount of adjustment towards a more stable state was achieved (*i.e.* slope angles had been reduced). In the present landscape of the Middle Mountains, five principal slope elements can be identified, from the ridge crests at about 2000 metres to the major river beds at about 500 metres (Figures 2.7 and 2.8). Recognising them in the field gives the observer an immediate impression of whether geotechnical problems are likely to be awesome or merely moderate.

2.3 SLOPES AND ROAD ENGINEERING

The role of vegetation and small-scale engineering works could be questioned in the face of the regional mass movements that are the essential feature of Himalayan geomorphology. It is true that for deep failures and major landslides, such methods are inadequate for slope control. But much of the instability is shallow-seated, and much begins in a small way and spreads only if unchecked. These sites can be stabilised with low-cost methods, and if a road is located on a fairly stable alignment it should be possible to maintain the stability with minimal investment.

The five terrain units in Figures 2.7 and 2.8 have very different stability limits, and each has its own range of typical failure mechanisms,

Figure 2.8: A generalised slope model for the middle mountains, with instability types

Terrain unit	Slope (approx.)	Type of mass-movement	Mechanisms and agencies controlling failure	Engineering features and low-cost remedial treatments
1 Ridge top (a) Hummocky crest	15°-45°	Erosion	Gully erosion in deep, cohesionless soils. Erosion on overgrazed slopes: piping.	Unstable ground usually easy to avoid. Arrest erosion in shallow gullies with small atchments with check dams or by backfilling with rubble. Stabilise eroding slopes with bio-engineering methods. Protect slopes below culvert outfalls.
(b) Rock ridge	45°-90°	Plane failure in rock	Gravitational displacement of steep rock with near-vertical or steeply inclined planes of discontinuity, weakened by weathering.	Avoid unnecessary disturbance by hand excavation. Blasting is not recommended, as it will cause rock joints to open further. Clear loose blocks from face.
2 Upper slope (not always present)	15°-25°	Gully erosion, rotational slips, piping	Stream erosion in deep, cohesionless soils, often deforested but grassy. Small rotational slips occur on the steep gully sides forming accumulations of debris that move downhill as earthflows in the gully bed. Piping occurs at the interface between granular soils and less-permeable lower layers.	Unstable ground usually easy to avoid. Arrest further erosion with horizontal vegetative methods. Provide culverts with energy dissipaters to protect outfalls. Rubble may be laid to load toes of *small* rotational slides on gully flanks. Larger slides may prove impossible to stabilise cheaply and should be avoided.
3 Mid slope (a) Slope	20°-30°	Gully erosion	Generally stable but uncontrolled irrigation waters can create problems. Large scale gully erosion, once started, is difficult to arrest with consequent loss of agricultural land.	Bare slopes can be stabilised with bio-engineering methods. Cross drainage should incorporate irrigation requirements for local farmers.
(b) Valley	20°-30°	Gully erosion advancing into large 'valley catchment' slips (with subordinate surface creep, rotational slips and earth flows)	Streams can set up gully erosion that advances headwards into slope. Stream banks are subject to rotational slips.	Cross at most stable situation, utilising solid rock outcrops to key foundations. Culverts need to be correctly designed, equipped with debris racks to avoid blockage, and energy dissipaters to protect culvert outfalls, carried a long way down slope.
4 Lower slope (a) Slopes on debris and completely weathered rock	30°-45°	Active debris slides and erosion (may advance uphill into mid-slope)	Oversteepening of slope caused by rapid dissection of river valleys in recent geological past. Combination of steep slopes, large water catchments and dormant landslips creates many unstable situations.	Avoid active and dormant landslides if possible. Seek stable slopes and excavate minimally, taking utmost precautions to dispose of spoil. Provide adequate cross drainage measures as above.
(b) Hard rock	45°-75°	Rock falls Rotational slips.	Gravitational displacement along steeply inclined rock planes. Weak metamorphic rocks can become saturated and fail rotationally.	Avoid overblasting of solid rocks. Avoid wet, weak metamorphic rocks.
5 River Valley (a) Terrace	Top 0°-15° Sides 25°-50°	Erosion and piping Rotational slips Collapse failure	Unconsolidated, layered terrace deposits of different ages are susceptible to erosion and river scour at base. Some piping occurs.	Avoid areas of sub-surface seepage and piping.
(b) Flood plain and river bed	0°-5°	Scour	Heavy stream flows in monsoon shifts gravel bars and wears away river banks.	Avoid except for bridge crossings.

although all mechanisms do occur on all units except 5(b).

- Unit 1, the ridge top, may have steep and unstable sides, and would normally be avoided altogether except when crossing over to the opposite hill flank.
- Unit 2, the upper slope, is the most stable as it consists of short, moderately-angled slopes. But it is not always present in the landscape, and if present, is vulnerable to encroachment from below by failures on Unit 3 or Unit 4 slopes.
- Unit 3 slopes are reasonably stable but are often wet and often affected by instability from cross-cutting valleys (3b) or from Unit 4 slopes below. Soils are usually several metres thick. Unit 3 slopes usually present large, more or less continuous areas for exploitation by road alignments to traverse or climb.
- Unit 4 slopes consist mostly of old landslide scars and are usually highly unstable. They are mantled in landslide debris and have many rock outcrops: they are not farmed but are covered in forest or degraded forest. Road alignments should be kept to a minimum on these slopes, although individual hill spurs have of necessity to be used for stacked loops to pass from Unit 3 to the valley floors. Good alignment of the road is of paramount importance, avoiding the worst areas at all costs. When the alignment is settled, design and construction of the cut section, drainage works and slope protection must be carried out with the utmost care.
- Unit 5 slopes, the terraces and valley floors, present few serious hazards to engineering apart from flooding and scour from the river. But terraces rarely afford exploitable routes because they are invariably discontinuous along the valley, cut off by the main stream as it swings across the valley from side to side.

The road at Anboo-Khaireni crosses the base of a semi-stable colluvial slope

2.4 ENGINEERING GEOLOGY

The next stage in understanding the characteristics of mountain slopes is to examine the rocks themselves. The strength and other characteristics of rocks also determine in part the nature of slope failures, and the ways in which we need to treat them.

The main types of rocks

Rocks are divided into three principal classes, as follows.

Igneous rocks
Rocks that have solidified from molten or partly molten material originating from a magma[1].

Sedimentary rocks
Rocks resulting from the consolidation of loose sediments, or from chemical precipitation from solution at or near the earth's surface.

Figure 2.9: The main rock types of the Lesser Himalaya (Middle Mountains).

IGNEOUS ROCK	SEDIMENTARY ROCKS	METAMORPHIC ROCKS
Granite	Mudstone	Slate
	Shale	Phyllite
	Siltstone	Schist
	Conglomerate	Gneiss
	Sandstone	Quartzite
	Limestone	Marble
	Dolomite	

[1] Magma is the molten material that exists below the solid rock of the Earth's crust, and sometimes reveals itself on its emission from a volcano. It does not always reach the surface, however, and may cool and solidify underground, among older rocks.

Figure 2.10: Diagnostic properties of the main rock types of the Lesser Himalaya (Middle Mountains)

Rock type	Main diagnostic features
Igneous rock	
Granite	Hard, coarse, grainy texture, mixture of essential minerals of quartz, feldspar and mica (muscovite and biotite); no cementing material
Sedimentary rocks	
Mudstone	Clay minerals, massive (no lamination), smells like mud and is soft enough to be scratched by a fingernail
Shale	Like mudstone, but is formed from laminated layers
Siltstone	Silt size minerals, sharp edges, shining with mica flakes
Sandstone	Sand size grains held together by a cementing material, scratches a hammer or knife (*i.e.* it is harder than steel)
Conglomerate	Distinct rounded to subrounded fragments of grain to pebble size, held together by a cementing material
Limestone	Mostly grey, fine to crystalline variety, can be scratched by a hammer or (knife), effervesces strongly on the addition of dilute hydrochloric acid (HCl); used for road ballast and concrete; the raw material of cement
Dolomite	Similar to limestone, but the addition of dilute HCl gives effervescence only when it is in powder form (*i.e.* a feeble effervescence); used for road ballast and concrete
Metamorphic rocks	
Slate	Dark grey, thin foliation (splits easily); used for roofing and formerly for writing
Phyllite	Foliated (less perfectly cleaved than slate), light grey, clear joint set, small secondary quartz grains, dark minerals
Schist	Foliated, with an undulating or bulging surface (flow cleavage) due to mineralisation, coarser grain size than phyllite
Gneiss	Alternate bands of light (quartz, feldspar) and dark minerals of fairly coarse grain, highly foliated; used as the grinding stone in water mills
Quartzite	Banded, hard (scratches a hammer or knife; *i.e.* it is harder than steel), mostly consisting of mineral quartz, no cementing material; when struck by a hammer, it gives a metallic sound; used for slabs
Marble	Crystalline (sugary texture), effervesces highly on the addition of HCl; used as a facing stone

Metamorphic rocks

Any rocks derived from pre-existing rocks by mineralogical, chemical or structural change, especially in the solid state, in response to marked changes in temperature, pressure and the chemical environment at depth in the Earth's crust; that is, below the zone of weathering and cementation.

Most of the mountain roads of Nepal pass through the rocks of the Sub-Himalaya (Siwalik or Churia) and Lesser Himalaya (Mahabharat Range and Midlands).

The main rocks of the Sub-Himalaya are all sedimentary, and consist of mudstones, sandstones and conglomerates.

The main rocks of the Lesser Himalaya can be sub-divided among the three classes, as shown in Figure 2.9. The diagnostic features of each are given in Figure 2.10.

Principal mineral groups in rocks and their weathering

Minerals are naturally occurring crystalline chemical compounds. Rocks are aggregations of minerals.

The mineral constituents of a rock may have very different chemical compositions and properties. For example, a fresh gneiss sample may contain the following mineral groups:

- dark minerals;
- light minerals (milky);
- dark mica;
- white or light mica (platy, translucent);
- quartz (sugary, translucent but can be milky).

Rocks are affected by weathering. Weathering is defined as *'the physical and chemical alteration of minerals into other minerals by the action of heat, water, and air'* and takes place constantly in nature. Higher temperatures and water contents increase the rate of weathering: when these occur at the same time, as they do during the summer monsoon rains, the rate of weathering can be relatively rapid.

A weathered rock sample will show some or all of the following features:

- softness (*i.e.* minerals can be rubbed off by hand);
- discoloration;
- loosening of grains;
- intact white mica;
- intact quartz.

The relative order of susceptibility to chemical weathering in the common mineral groups

Figure 2.11: Rock weathering grades

Weathering grade	Description
1a	Fresh rock. No visible sign of weathering. Rings when struck with a hammer.
1b	Faintly weathered. Discoloration on major joint surfaces. Rings when struck with a hammer.
2	Slightly weathered. Discoloration of all discontinuity surfaces or throughout rock. Rings when struck with a hammer.
3	Moderately weathered. Up to 50 percent of rock material decomposed and/or disintegrated to soil. Rock can be a continuous mass, or core stones. Rings when struck with a hammer.
4	Highly weathered. More than 50 percent of rock material decomposed or disintegrated to soil. Rock mass is discontinuous.
5	Completely weathered. All rock material decomposed and/or disintegrated to soil. Original mass structure still largely intact. Gives a dull thud when struck with a hammer.
6	Residual soil. All rock material converted to soil. Mass structure and material fabric destroyed.

Source: Geological Society Engineering Group Working Party, 1977. The description of rock masses for engineering geology. *Engineering Geology* 10 (4): 355-388.

is as follows:

- dark minerals — Least resistant to weathering (*i.e.* these weather the most)
- light minerals
- dark mica
- white mica
- quartz — Most resistant to weathering (*i.e.* these weather the least)

This means that a careful investigation of the minerals of a rock, and the degree of weathering to which they have been subjected, can reveal considerable information about the inherent strength of the rock. In a site investigation, this is valuable information in predicting possible slope instability. A hand lens is used to investigate the condition of the minerals.

In a soil, weathering has proceeded much further and the following features may be observed:

- particles are much smaller;
- clay minerals (fines) are present: these are new minerals derived from the weathering products of rock;
- quartz and white mica remain, as they are the most resistant to weathering.

The most intensively weathered soils are rato mato, the red clay loams found in many parts of the Middle Mountains, usually at lower altitudes. These are very old, probably greater than 100,000 years, and indicate a landform which is, or must have been, relatively stable if it has permitted such prolonged weathering.

The overall effect of weathering is to soften and weaken rocks. Many rocks have been weathered so much that in engineering terms they are described as 'residual soils'. The most common of these are the soft rocks (phyllites and gneisses), which are found throughout the middle hills. Since these characteristics are universal, a standard classification system for rock weathering can be used, as given in Figure 2.11. Because of the geological disturbances of Himalayan mountain building, it is relatively rare to find rocks of weathering grade 1 in Nepal.

The degree of weathering of the rock often controls the strength of the rock. A highly weathered rock may fail through the rock body rather than along the joints or fractures (see next section). However, rock strength is due to both:

- the degree of weathering of the body of the rock;
- the spacing and weakness of fractures.

Rock fractures

Fractures are an important feature of many rocks. Most fractures are approximately parallel to each other and constitute what is called a 'set'. They may be closely or widely spaced. Most rocks contain several fracture sets. The presence of fractures is the main cause of failure of rock slopes.

Note that rocks may split:

- along widely-spaced planes, following the grain of the rock;
- along many closely-spaced planes, following the grain of the rock;
- across the grain of the rock at a regular spacing and orientation: these fractures are called joints[1].

The grain of the rock is caused by layers of minerals, in different proportions or of different textures.

Friction along the interfaces between the blocks governs the shear strength of the rock. Shear strength is reduced when contact along the interfaces is lost.

Rock strength is related to the number and weakness of fractures. Open-jointed rocks are very weak because:

- water movement and weathering take place preferentially along the joint planes;
- there is a loss of frictional resistance along the interfaces.

Strong rocks have fewer fractures, or have closed and cemented fractures.

In sedimentary rocks, there is usually one set of joints parallel to the dip and another parallel to the strike. The dip is the line of maximum slope lying in a rock plane. The angle of dip is measured with a clinometer and the bearing of dip is measured with a compass. The bearing can be any figure from 000° to 360°. It is always written as a 3-figure number, *e.g.* 048, to distinguish it from the inclination, which cannot exceed 90°. A reading for the angle of dip which appears to be greater than 90° means that the slope is in fact dipping in the opposite direction. Conventionally the bearing of dip is written first, followed by the angle, *e.g.* 115/35.

[1] Joints are cracks in rock masses, formed along a plane of weakness (the joint plane) and where there has been little or no movement, unlike a fault.

Disturbed rocks are very common and fractures are frequently visible, as on this gueiss in Eastern Nepal

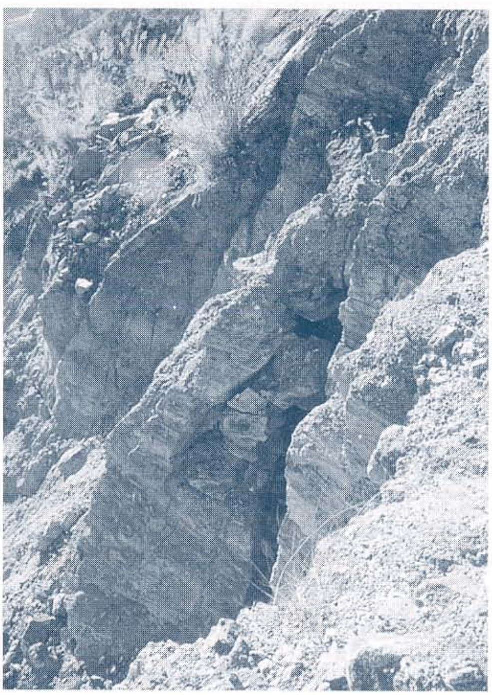
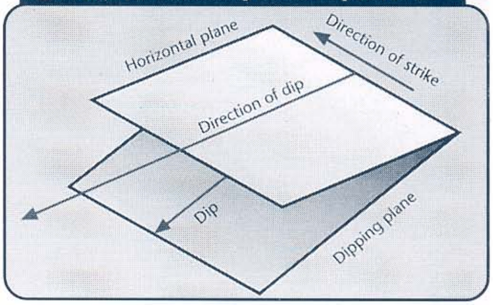


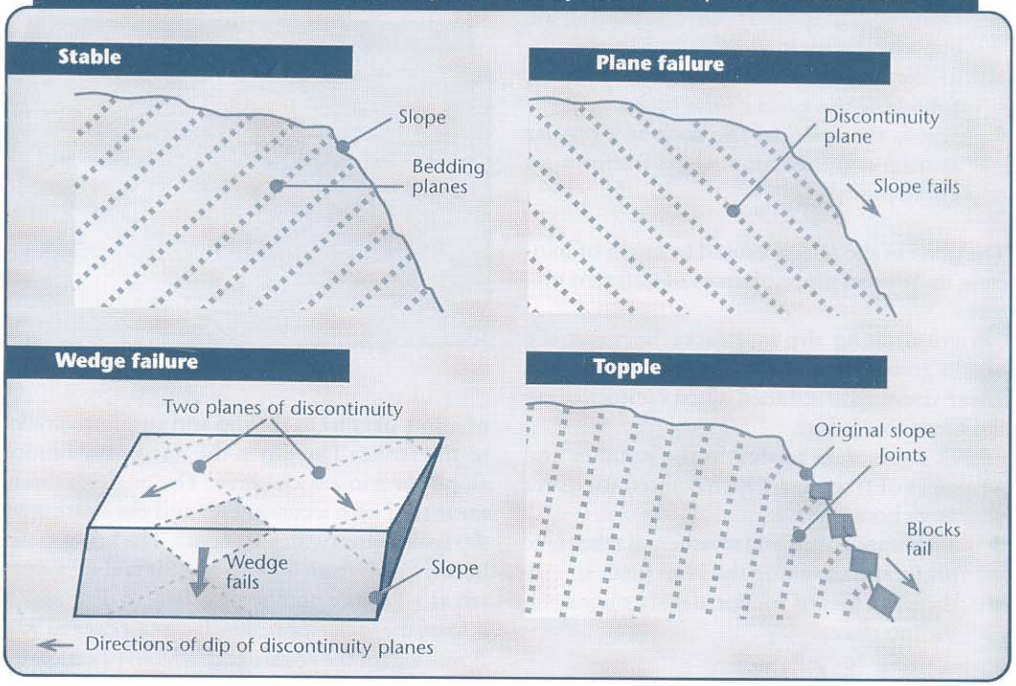
Figure 2.12. The relationship between dip and strike



The strike is the horizontal line contained in the plane of bedding, foliation, or jointing. It is perpendicular to the dip, just as a contour is to the maximum slope of the ground. The bearing of strike is measured with a compass. The figure is always given as a reading less than 180°. In practice strike is measured first because a horizontal line needs to be established in order to find the maximum inclination of the dipping plane. A dip of 115/35 would have a strike of 025°. This is shown diagrammatically in Figure 2.12.

Measurements of the dip and strike of rock joints and other fractures are a necessary part of detailed field site assessments in steeply sloping terrain. When combined with measurements of slope, they can provide useful information on the stability of the slope. Figure 2.13 shows examples of the relationship between the slope and discontinuities. Certain types of failure, such as translational landslides, are sometimes directly and clearly related to the slope and a major discontinuity such as a weak bedding plane being sub-parallel. Where there are several significant planes of discontinuity, such as two intersecting joint planes, wedge failures can occur; but

Figure 2.13: Examples of structural stability and instability related to slope and discontinuities



these are not so clearly visible in the field.

A useful way of plotting potential slope instabilities on the basis of field investigation is through the use of stereographic projection. This determines the angular relationship between planes in a slope, and clearly shows either why a slope has failed, or whether it is likely to fail in the future. This method is described in the ICIMOD *Mountain Risk Engineering Handbook*[1].

2.5 SOILS AND MATERIALS

In some locations, the rocks forming the original slope have been altered, disturbed and mixed so much that they have lost most of their original characteristics. The result is a material, which in engineering terms can cover anything not defined as a pure rock. Some materials have been altered sufficiently to be classed as a soil[2]. Whatever their state, all soils and altered materials have their own characteristics when subjected to geomorphological processes. For this reason, they must be examined separately in any consideration of slope stability.

Considering the topographic variations, there are relatively few distinct soil types in the Sub-Himalaya (Siwaliks) and Lesser Himalaya (Middle Mountain). This is because slope movement usually prevents the continuing development of soil profiles in any one place. Rocks break down under sub-tropical weathering into their constituent minerals and immediately begin to move downhill. The constant movement prevents a mature soil profile from developing: instead, the mineral particles become thoroughly mixed and produce a soil that typically consists of fragments

[1] Deoja, B, Dhital, M, Thapa, B and Wagner, A. 1991. *Mountain Risk Engineering Handbook: Part I, Subject Background*. International Centre for Integrated Mountain Development, Kathmandu

[2] Soil may be defined as 'the collection of natural materials occupying parts of the Earth's surface that may support plant growth, and which reflect pedogenetic processes acting over time under the associated influences of climate, relief, living organisms, parent material and the action of man'.

Figure 2.14: The main soil-forming factors

Soil-forming factor	Effects on soil development
Parent material	Parent material is the starting ingredient from which a soil develops. It is made up of minerals from degrading or deposited rock debris, and organic material derived mostly from plants. A study of the underlying strata does not always determine the main mineral composition of a soil, especially in the case of soils on active alluvial plains. Soil chemistry tends to be dominated by the mineralogy of the rocks forming the main part of the parent material. For this reason the plant-growing character of many soils is often governed by the original composition, especially the degree of acidity or alkalinity.
Climate	Climate governs the type and rate of soil formation, and the type of vegetation that can grow in the area. In general, warm and humid soils develop faster than dry or cold ones. This is seen in Nepal by the darker soils at higher altitudes, where cooler temperatures slow down the decomposition rate of organic matter and improve the soil in a number of ways. At the warmer, lower altitudes, the release of plant nutrients from both mineral and organic constituents can be very rapid during the monsoon. The climate also determines the micro-climate in the soil voids, greatly affecting the extent of microbiological activity. The result of these differences in Nepal is that at higher altitudes soils can be more fertile, better to work and more resistant to erosion. Despite this, the warmer climate at lower altitudes allows faster bio-chemical processes, so that plants still grow faster despite lower soil fertility.
Organisms	The organisms affecting soils can be classed as: higher plants; vertebrates, particularly mammals; micro-organisms (bacteria, fungi, algae, etc); mesofauna (worms, insects, etc.); and man. In general, the plants cycle matter from the soil and harness other matter from the atmosphere, while the animals alter it within the soil. This usually forms a very complex symbiotic relationship, whereby both plants and animals can live together in a mutually beneficial way. In newly developing soils, such as those common in Nepal, the system is very dynamic and has often not reached an equilibrium.
Topography	Topography is a significant determinant of geomorphology. This has been examined in considerable detail in relation to Nepal in the sections above. It includes important considerations such as the length of time in which soil development can take place in a given location; whether material is being removed or deposited; and so on.
Time	Soil formation is a slow process, especially in cooler locations. Some soils, such as **rato mato**, have taken many thousands of years to develop. Time also accounts for changes in the soil, which occur as a result of the interactions of the other factors.

of rock in a silty matrix of low plasticity. The resulting mixed soil without horizons (layers) is called colluvium. Plasticity is low because although weathering may have been rapid enough to break the rock down, it has not continued for long enough to reduce the weathering products to plastic clay minerals. Because the fragments are angular and the matrix lacks clay, colluvium is very permeable. This makes it very susceptible to infiltration and liquefaction during heavy rain, and therefore any attempt to stabilise a slope composed of this material must consider its likely behaviour carefully.

In the process of downhill movement, the fragments from the parent rocks also become mixed together. The fragments found in a soil thus may come from one parent rock, or from rocks of quite different type, depending on the outcrops on the slope above. Rocks rich in quartz tend to produce sandy soils. Metamorphosed sandstones produce a sandy, silty soil containing coarse, hard, irregular pieces of the original rock. Platy, splitting rocks such as phyllites weather to a finer material, but the derived soil usually also contains fragments down to a few millimetres in size of unweathered or partially weathered phyllite. Most rocks contain some light mica, which remains unweathered in the soil profile, though it breaks up into tiny particles.

The action of movement downhill causes stones to rub against each other, rounding off the corners, but the fragments in colluvium retain a noticeably angular shape. Debris flows (wet, flowing landslides) hasten the process of rounding and produce soil particles of wide size ranges, varying from boulders down to fines, all mixed together.

When colluvium reaches the valley bottom it is moved along by the river. The material becomes separated, the fines moving in suspension and the larger fragments rolling and bouncing along the river bed. If this material is deposited, it is called alluvium. The movement by water is much more dynamic than steady movement down hill, causing:

- separation of the particles according to size;
- breaking of the weaker rock fragments such as phyllite and highly weathered gneiss;
- rounding of the harder fragments (boulders, cobbles and gravels) to a spherical shape.

The most noticeable and easily recognisable characteristics of alluvium in mountain valleys are that:

- the fragments are clearly rounded, many almost spherical;
- it has a sandy texture and lacks fines;
- it usually shows signs of horizontal layering, due to steady deposition as the river flow rate declines after a surge.

Alluvium often contains fragments of weak rock and weathered rock. As mentioned above, these are quickly broken up during transport. Their presence in an alluvial deposit therefore indicates that the material has only recently been introduced into the river bed and has not travelled very far or been travelling for very long. Alluvium that is rich in such fragments cannot be used in engineering construction. When an alluvial deposit is selected as a source of material for crushing as aggregate, the hard cobbles often have to be picked by hand out of the river bed.

The rounded nature of the coarse fraction of river deposits generally makes them suitable for aggregate only after crushing, to increase their angularity and mechanical interlock. The presence of mica in the sand fraction can weaken concrete. Sand selected for high strength concrete, for example in bridge works, often needs to be washed to remove the mica.

Slopes cut through unconsolidated alluvial deposits can be highly unstable and very difficult to treat. This accounts for many intransigent stability problems in coarse Churia deposits.

Soil formation and soil types

An understanding of the development of soils is essential when examining the landscape and the kind of plants that will grow in it. Soil is the mixture of organic and mineral elements that forms at the surface of the Earth. It is essentially a living entity, since it contains many living organisms, especially microscopic ones, and it changes over time as a result of the influences working on it. One definition of soil is: '*soil is the space – time continuum forming the upper part of the Earth's crust*'. This apparent lack of specificity emphasises the fact that soil is infinitely variable and changeable. A more thorough definition is 'the collection of natural materials occupying parts of the Earth's surface that may support plant growth, and which reflect pedogenetic processes acting over time under the associated influences of climate, relief, living organisms, parent material and the action of man'.

Soils are formed from the interactions of five series of factors: parent material, climate, organisms, topography and time. These are explained further in Figure 2.14.

The soils of Nepal tend to be dominated by the effects of the extreme topography of the mountains, including their downstream effects on the piedmont alluvial plains. Some soils have been further developed by terracing, whether for dry farming (bari) or paddy farming (khet).

Mountain soils are affected most by the slope processes. On steeper slopes they are generally colluvial in origin, whereas on gentler slopes they may have developed from *in situ* materials. The five main types of hillslope soils are described briefly in Figure 2.15.These are only the main soil types, however. There are innumerable variations among these, particularly as a result of the variations of climate and their effects on the moisture of the soils and the weathering and decomposition rates.

In valley bottoms, as well as in the Bhabar zone and the Terai, the soils are dominated by active alluvial deposition. The frequency of deposition has often been so great that the soil is composed of distinct layers ranging from a few millimetres to perhaps 0.5 metre in thickness. These can have very different properties, depending on the source of the main parent materials. It is common to find layers of fine silt above or below horizons of coarse sands and, in the mountains, even of large cobbles. Buried surface horizons are also common. These are distinguishable by a darker colour and the presence of decaying fibrous roots. They result from the burying of a layer which formed the surface for long enough for plants to grow and improve the soil slightly.

Because of the numerous layers in alluvial soils, the hydrology can be very complex at the micro-level. In the Bhabar zone in particular, there can be such localised variation that soil pro-

Figure 2.15: The main mountain hillslope soils (Mahabharat and Middle Mountain)

Soil class	Description
Forest soils	
Colluvial soils	Highly active soils on steeper slopes. Formed from parent materials derived from higher up the slope. Characterised by mixed particles of angular shape, uncompacted and highly porous. Usually have a relatively high proportion of stones. There are two main phases. (a) Transportational. These are formed on steep side slopes. They are generally thin and the material is in the process of moving down the slope. Some are completely skeletal in nature, such as recent landslide debris. (b) Depositional. These are formed in cones at or near the base of steeper slopes. They are much deeper, often five metres or more, but are so stony that they are often extremely dry and infertile despite the location (which would normally be considered moist and fertile). The accumulation of debris is often too rapid for a well developed topsoil to form. The stone fragments forming the bulk of the soil tend to be hard if they have been transported this far, and therefore are relatively resistant to weathering.
Well-developed hill soils	Stable soils on gentler slopes. Mostly free of stones and providing good rooting conditions to plants. There are three main phases. (a) Deep soils derived from the weathering of softer rocks *in situ*. Frequent on weathered gneisses and other soft rocks. The soil merges gradually with the underlying strata. The relative hardnesses vary laterally as well as with depth, and it is often difficult to distinguish between soil and weathered parent material. Often highly erodible. Usually a low stone content. (b) Soils derived from the weathering of harder parent materials *in situ*. Common on ridge tops and gentle spurs on quartzites and other hard rock types. They are shallower (often less than a metre in depth) and have more stones in the profile. Between the stones, however, the soil has a finer texture and is much better developed than colluvial soils. The transition to rock is clearly defined. (c) Soils formed on ancient river terraces or old erosion levels. Deep and relatively well developed, but the main soil parent material has come from up valley or up slope. A low stone content unless they have developed on a deposit of stony alluvium, in which case they can contain a high proportion of rounded cobbles.
Rato mato (literally 'red soil')	A reddish clay loam soil often referred to as a laterite (but not displaying the features of a true laterite, which has much higher contents of iron or aluminium oxides). Usually deep and stone free. Heavy and difficult to cultivate. Highly erodible. Clay caps tend to form if the soils are exposed to the sun through the removal of vegetation. Occur at low altitudes. Poorly developed topsoils. Despite the rapid erosion now common on many rato mato, these soils have been subjected to prolonged weathering and demonstrate the presence of a stable landform.
Agricultural soils	
Bari terrace soils	Soils that are frequently cultivated and which have been terraced. As a result of the terracing, the rooting depth is extremely variable. The topsoil is ploughed at least once per year and so it is normally loose and friable. Well aerated. Usually a relatively low organic matter content, although compost and straw is present in some.
Khet (paddy) terrace soils	Soils that have been terraced and are cultivated for at least one crop of rice per year. The prolonged flood irrigation means that they are poorly aerated and show signs of iron reduction (pale grey mottling). Textures vary, usually according to the characteristics of the parent material (*i.e.* they tend not all to be fine-textured as in the Terai). Some are cultivated in the winter for a dryland crop, and these tend to be better aerated and friable for part of the year. Generally higher organic matter contents than bari soils, as a result of greater compost and mull applications.

files only 20 metres apart are completely different. Layers of fine silt and clay can reduce water percolation through the soil, resulting in a localised perched water table. This can have a drastic effect on sensitive plants, particularly trees: a plantation can appear patchy as a result of this localisation, with some plants suffering waterlogging only metres from others that are healthy or even suffering drought stress.

Alluvial soils tend to be more fertile than hill soils. There is also a variation here, often related to the textural class, with the coarser soils being noticeably less fertile.

2.6 CLIMATE AND MOISTURE

In assessing sites for bio-engineering, the effect of climate on plant growth is fundamental. It is also a very localised phenomenon. An appreciation of climate can, in addition, provide further understanding of the potential frequency of slope failures and major erosion events.

The monsoon climate

The climate of Nepal is tropical monsoonal, except for parts of the north of the country that are in the rain shadow of the Himalayas, which have a cold semi-desert climate and which are not discussed here.

However, the national climate is modified everywhere by high relief. The local climate experienced by each mountainside is governed by four factors:

1. monsoon rainfall;
2. seasonal variations of temperature;
3. temperature variations due to altitude; and
4. local topographic influences (slope and aspect), which affect both temperature and rainfall.

Rain can occur as a result of several causes. Convection rain is usually the result of intense heating of the land; in Nepal, this gives rise to most of the pre-monsoon thunderstorms. Orographic rain results from a humid air mass rising over a mountain range. Cyclonic rain occurs where warm air is caused to rise through the convergence of air masses in a low-pressure area: this can occur outside the monsoon when the relics of tropical cyclones penetrate from the Bay of Bengal. Variations in monsoonal rainfall are often related to cyclonic depressions within the monsoon air. Frontal rain is less common in Nepal, since it usually occurs where a front of warm, moist air rises over drier, colder air; most of the movements of air masses are seasonal in Nepal, unlike the situation in more dynamic climates.

The tropical monsoon[1] climate is dominated by the summer south-west monsoon rains, which affect the whole of South Asia. It seems to be controlled by a seasonal shift of the westerly jet stream in the upper atmosphere: this moves to the north of the Tibetan plateau, usually in late May, in response to the increased heating during the northern hemisphere summer. The equatorial low pressure trough moves northwards at the same time, increasing in intensity by thermally-induced low pressure, which results from the heating of the land surface. This gives rise to an area of low pressure over northern India and Nepal, and allows moist, low level air to move from the south-west, off the Indian Ocean, under higher level easterly winds.

By the time it reaches Nepal, the rain-bearing wind has been deflected so that it approaches from the south-east, blowing in from the Bay of Bengal. It brings abundant rain from June until September. The duration of the monsoon and amount of rain varies across Nepal, the western one-third of the country being drier than the east. Monsoonal depressions move from SE to NW, on average at the rate of two per month, bringing heavier bursts of rain. The monsoon is longest and wettest in the far east of the country.

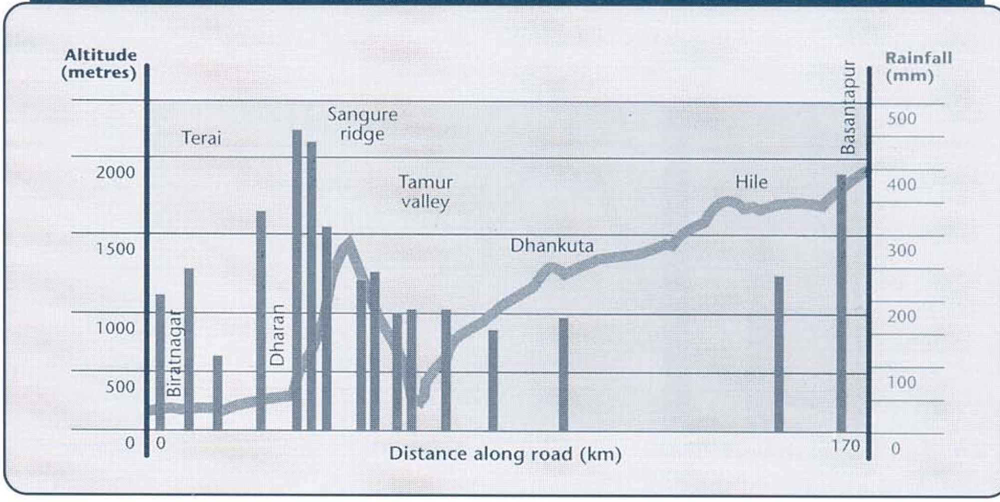
As the summer draws to a close and the area becomes cooler, the westerly jet stream re-establishes its southerly path, usually in October, restoring cooler conditions in the space of a few days. During the winter, the situation is dominated by high-level westerly winds. Air subsiding below these blows outwards from the continental interior of Asia. In Nepal, these appear as dry, cool, northerly winds, very light in the lee of the Himalayas. The dry months of the winter are often relieved in the west by showers that can provide up to one-fifth of the annual total: these originate in depressions from the west.

Rains outside the monsoon are much less likely to trigger slope instability, although there have been important exceptions to this rule, such as the disastrous debris flow at Bagarchhap in Manang District in November 1995. More important is the potential contribution of rainfall to plant growth. In cooler areas, there is sometimes enough winter rainfall to allow forestry planting during the dormant season, although this is rare on harsh bio-engineering sites. Pre-monsoon storms often allow established plants to start growing well before the monsoon sets in.

Heavy rainfall in November and December is rare. The monsoon itself is often preceded by thunderstorms during April and May which, although lasting for no more than a few hours, can be very heavy. The climate therefore shows a very marked dry season lasting from mid-October until May, during which plants in many locations experience severe drought. The total amount of rain, and the incidence of large thunderstorms, vary considerably from year to year.

[1] The name monsoon is derived from the Arabic word *mausim*, meaning season, which explains its application to a climate with large-scale seasonal reversals of the wind regime.

Figure 2.16: Comparison of terrain altitude and rainfall on the jogbani-Basantapur road



Although there are reasonably good rainfall records for Nepal, data for rainfall intensity are scarce.

Although it can rain continuously for days at a time, the monsoon is generally characterised by periods of rain lasting for a few hours, broken by dry spells of similar length. If the sky clears between showers, the heat of the sun can rapidly evaporate surface water. Half an hour of sunlight is often enough to dry a road surface and to bake a soft crust on exposed soil surfaces. Monsoon rain is often very intense.

The intensity of rainfall is very variable and poorly recorded. Short bursts of heavy rain appear to be common: rates of 100 mm/hr for five or 10 minutes seem to occur in many places each year. Longer bursts of heavy rain, such as 100 mm/hr for one hour are much less frequent. Rain of this intensity is very erosive, however, especially if the soil profile had already become well wetted. The burst of rainfall saturates the upper part of the soil profile, which liquefies and flows downhill in a destructive slurry.

Prolonged heavy rain storms, of the order of 200 to 300 mm/day for two days or more appear to occur almost every year somewhere in the southern Himalayas. It is these longer periods of rain that take the soil past saturation point and give rise to the biggest and most widespread slope stability problems. Guidelines for the estimation of these storms are available.[1]

On unprotected slopes, erosion can take place under almost any rain storm. The early rains are often the most damaging, however, especially when heavy storms occur early in the season, before plants have been able to establish. On freshly made slopes, poor compaction (usually due to a lack of water during construction) can give rise to loose, weak and highly erodible materials. This is why bio-engineering can play such an important part in protecting slopes.

Local effects on climate

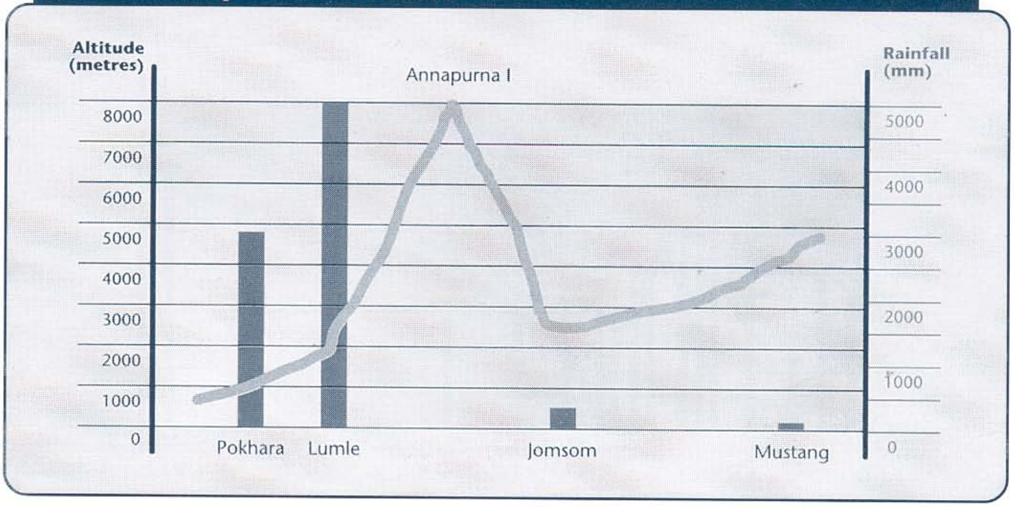
High relief and localised rainshadows greatly affect the distribution of rainfall, which varies considerably over short distances. An idea of the complexity is shown in Figure 2.16, which compares terrain altitude with monsoon (five-month) rainfall totals at 16 raingauge stations on the Jogbani-Basantapur road corridor in eastern Nepal.

Local climate is extremely difficult to predict because of the interaction of the dominating factors, and the extent to which their effects really are very localised indeed. The general pattern is that mountain ridges cause the rain bearing winds to rise and cool, allowing the moisture to condense and precipitate. Behind these ridges the air is more stable (until a higher ridge forces it to rise again): as a result, it rains less in these locations and forms a 'rainshadow'. At the same time, the steepness of the slopes means that sunlight is far more intense on some aspects than others.

The main factors determining site moisture and temperature are given in the paragraphs

[1] There is a chapter on this subject in TRL Overseas Road Note 16, *Principles of low cost road engineering in mountainous terrain* (chapter 8, *Hydrology and hydraulic design*, pages 82 to 96).

Figure 2.17: Schematic diagram showing the effects of the Annapurna Himal in Creating an extreme rain shadow



below, and summarised in Figure 1.16 (see p28).

Aspect. Aspect determines the amount of direct sunlight (insolation) that a site receives. There is a simplistic but frequently very clear distinction between south-facing (warm and dry) and north-facing (cool and damp) slopes. Slopes facing east and west are not quite so straightforward. In general, west-facing sites tend to be drier than east-facing sites. The reason for the main rule is that the air temperature is higher in the afternoon than the morning, and so there is more evaporation from slopes exposed to the sun at that time. Also, many areas have early morning mist, which reduces the effects of the sun. At low altitudes, however, east-facing slopes can be very dry. In areas of higher rainfall, the south-facing slopes tend to receive more rainfall during the monsoon, even if they dry out more during the dry season.

Altitude. Although the topographic environmental lapse rate[1] directly relates altitude to temperature, the relationship is complicated by air movements and ground warming. Even in the shade, southerly aspects can be warmer on sunny days than northerly aspects. The temperature affects the evaporation rate. Higher terrain is also susceptible to greater rainfall as a result of the orographic effects, and high ridges tend to be shrouded in clouds for lengthy periods. Hence ridges tend to have more moisture.

Topographical location. The location of any site on a major mountain slope has an effect on the accumulation and retention of moisture. Gullies and other areas where moisture tends to accumulate, and which are shaded for longer from the sun, tend to be damper than exposed spurs, ridges and steep side slopes.

Regional rain effects. In general, the east of Nepal is wetter than the west. This is apparently the case more in the hills than the Terai. The Terai weather stations show broadly similar rainfall levels across the country; the mean temperatures are also similar, but in the west the seasonal variation is greater, with hotter summers and cooler winters. This has the effect of causing greater drying during the later dry season. In the mountains the effects seem to be more pronounced, but this can only be inferred from the dominant vegetation types since the meteorological records are so localised. The Annapurna Himal, lying to the south of the main trend of the Himalayas, forms a major orographic barrier which causes greater rainfall in the area on its southern flanks.

Rain shadow effect. Rain shadow is the effect found behind major ridges. Moisture-laden air cools as it rises on the fronts of the ridges, so that the moisture condenses and precipitates out; behind the ridges, the air is stable and passes over with relatively little precipitation. This is very common throughout Nepal and can occur on a

[1] The topographic environmental lapse rate is the static reduction of temperature with height. It is generally considered to be 6.5°C per 1000 metres of altitude. However, the exact rate is determined partly by atmospheric moisture, as well as by the movement of air. It also varies seasonally.

Figure 2.18: Environmental factors indicating site moisture characteristics

SITE MOISTURE FACTOR	TENDENCY TOWARDS DAMP SITES	TENDENCY TOWARDS DRY SITES
Aspect	Facing N, NW, NE and E	Facing S, SW, SE and W
Altitude	Above 1500 metres; particularly above 1800 metres	Below 1500 metres; deep river valleys surrounded by ridges
Topographical location	Gullies; lower slopes; moisture accumulation and seepage areas	Upper slopes; spurs and ridges; steep rocky slopes
Regional rain effects	Eastern Nepal in general; the southern flanks of the Annapurna Himal	Most of Mid Western and Far Western Nepal
Rain shadow effect	Sides of major ridges exposed to the monsoon rain-bearing wind	Deep inner valleys; slopes sheltered from the monsoon by higher ridges to the south
Winds	Sites not exposed to winds	Large river valleys and the Terai
Stoniness and soil moisture holding capacity	Few stones; deep loamy* and silty soils	Materials with a high percentage volume of stones; sandy soils and gravels
Dominant vegetation	*e.g.* amliso, nigalo, bans, chilaune, katus, lali gurans, utis	*e.g.* babiyo, khar, dhanyero, imili, kettuke, khayer, salla

* Loam is the name given to a soil with moderate amounts of sand, silt and clay, which produce a texture that is neither too gritty and loose nor too fine and clay, and is therefore conducive to plant growth.

range of scales. It can often be seen even on relatively small Churia ridges, but is much more apparent on the bigger lekhs of the Mahabharat and Middle Mountain formations. The extreme example is caused by the Annapurna Himal: Lumle, on the flank facing the rain bearing wind, receives an annual mean of 5,170 mm; Jomsom, about 70 km away in the lee of the massif, receives an average of only 250 mm per year. This is shown diagrammatically in Figure 2.17.

Winds. Winds are uncommon in the mountains except in the big river valleys. Here, during the afternoons, warm, dry winds tend to flow from the south, up the major river valleys. This is because the air warms in the sun but is laterally restricted by the valley sides; the result is a current generated which flows up the valley as an anabatic wind. In the Terai, warm, dry winds are common during the dry season, especially from the east. Both of these wind types can increase the evaporation significantly.

Stoniness and soil moisture holding capacity. The capacity to hold moisture is limited in many mountain soils by the high stone content. This reduces the pores in which moisture can be stored.

Dominant vegetation. This is a responsive, not determining factor. The main vegetation in an area is often a good indication of the site moisture characteristics (see Chapter 1, section 1.6).

It is important to note that the effects of total rainfall are completely different from those of intensity and duration. Low- rainfall sites can have a large proportion of their monthly rainfall in one prolonged storm, which can give rise to slope failures. Damaging high- intensity rainfall, as well as relatively prolonged storms, can occur anywhere, even in the driest rain-shadow areas. For this reason, total rainfall has a much clearer impact on vegetation cover than it does on slope stability.

Site moisture levels

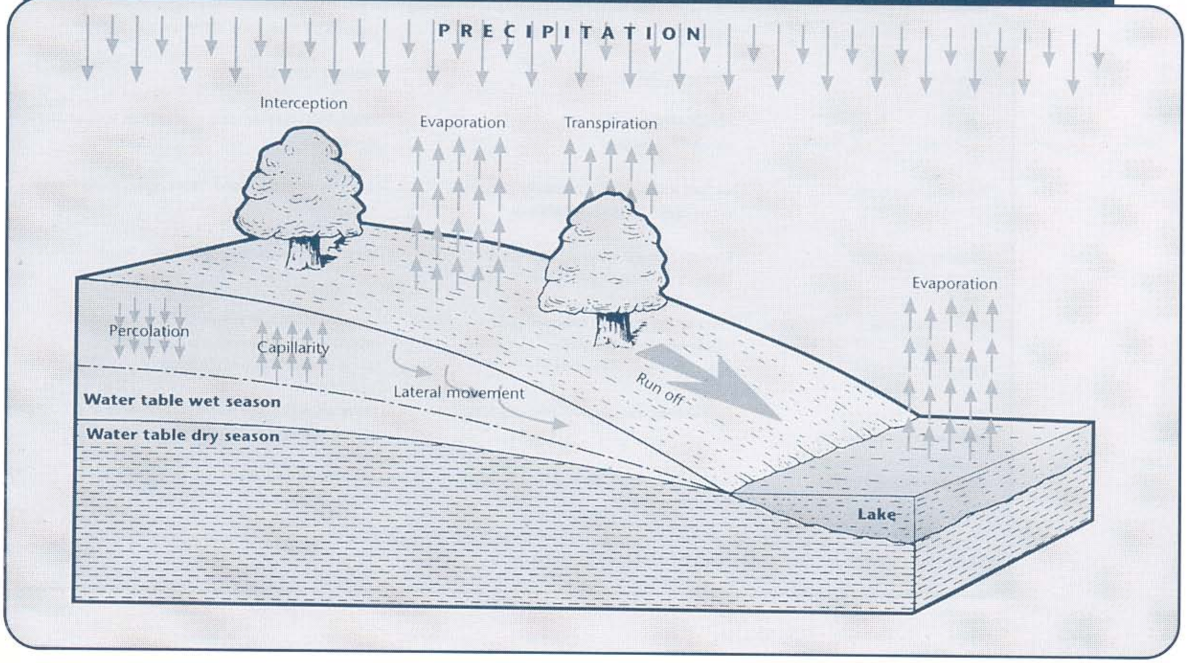
The main features of rainfall in Nepal are that:

- the summer monsoon rains bring 80 to 90 percent of the yearly rainfall; and
- the distribution of rainfall is severely affected by topographical and other factors.

As a result, the main factors making sites more moist are:

- exposure to rain-bearing winds;
- topography causing uplift of the wind; and
- shade from the sun (*e.g.* north-facing slopes);

Figure 2.19: Simpilified diagram of the moisture cycle under humid conditions



Source: Fitz patrick, E A. 1980. Soils: their Classification and Distribution Longman, London.

while those making sites drier are:

- rain shadow effect;
- exposure to the sun (*e.g.* south-facing slopes);
- higher site temperatures;
- soils with low infiltration rates; and
- dry winds in big river valleys.

Rainfall severely affects plants because water is essential for growth. The variations of rainfall, temperature and evapotranspiration can be measured. Their effects on soil water balances are shown in Figure 2.19. The interaction between them in Nepal is described in Figure 2.20.

Moisture and plants

The growth of plants in Nepal is controlled as much by the availability of water as by seasonal variations in temperature. The water balance tends to swing from a super-abundance of water in the monsoon to a severe deficit in the spring months. Much of the water precipitated during the monsoon runs off, evaporates or sinks deep into the ground beneath the rooting zone. The storage capacity of the best soils is estimated to be only about 150 mm in the top metre of soil where it is available to tree seedlings; in poor, stony soils it is much less.

When the monsoon arrives, the water quantity in the soil quickly rises to field capacity, well in excess of plant growth requirements. At this time transpiration is suppressed, despite temperatures greater than 20°C, because the relative humidity is very high (70 - 95 percent).

At the end of the monsoon, when the soil is fully charged with water, plants will grow freely until the forces of transpiration are resisted by soil suction. At this point the plants begin to experience water stress and continue to do so until the soil water is replenished by rain at the beginning of the next monsoon. During winter, when temperatures are lowest and days are shortest, water deficit is not a problem; but as temperatures rise during the spring, water stress for young plants can be acute. The greatest stress is experienced during March and April, but the level of stress is modified by the length and abundance of the rainy season. The wide range of temperatures and rainfall brought about by interactions between season, altitude and topography, means that the best guide to determining plant growth conditions at a site is to observe the state of the ground and to make use of plant types that grow in the vicinity.

Figure 2.20: Major factors affecting site moisture, where they are important and how to recognise them

Major factors affecting site moisture	Example where this is the most important factor	How this factor can be identified in the field
More moisture		
Exposure of the site to rain-bearing winds	On many higher ridges in the Mahabharat and middle mountain areas, *e.g.* along roads from Sindhuwa to Basantapur, Mude to Charikot and Sahajpur to Dadeldhura, and the Shivapuri Lekh above Kathmandu.	Higher ridge areas with good forest cover that excludes the drier tree types. Species such as chilaune, katus, banjh, gurans, utis and nigalo bans are found. If cultivated, there are often many fodder trees growing on the terrace risers and the land is relatively fertile.
Effect of topography in causing uplift of wind and condensation of moisture leading to rain	Southern side of the Mahabharat lekh, *e.g.* on the roads above Dharan, between Hetauda and Simbhanjyang, above Surkhet, and around Lumle on the Pokhara-Baglung road.	Major hill slopes (usually > 1000 metres) with no high topography to the south. Dense forest such as lampate, chilaune-katus and banjh-gurans.
Shade from the sun: north-facing slopes stay moister (also east-facing slopes to a lesser extent)	Most north- and east-facing slopes in the middle mountains, *e.g.* between Dhankuta and Hile, Balaju and Nagarjun, Kakani and Ranipauwa, and the eastern side of the Dauney Hills in Nawalparasi and many other north-facing Churia slopes.	Cool, damp slopes with a lot of shade, usually north-facing. Often growing utis trees. If cultivated, there are often many fodder trees growing on the terrace risers and the land is relatively fertile.
Less moisture		
Rain shadow effect: ridges shield the lower land behind them	Deep valleys in the lee of large ridges, *e.g.* the Tamur valley between Dharan and Dhankuta, the west Seti valley near Dipayal	Deep, sheltered valleys surrounded by high ridges. Hot, dry climate with species such as sugar cane, khayer, bel and khar.
Exposure to the sun: south-facing slopes become much drier (also west-facing slopes to a lesser extent)	Most south- and west-facing slopes in the middle mountains, *e.g.* around Dhading in the Trisuli valley. Most south-facing slopes on lower ridges, where topography is inadequate to cause significant uplift of the wind, *e.g.* western side of the Dauney Hills in Nawalparasi and many other south-facing Churia slopes.	Hot, dry slopes facing directly into the midday and afternoon sun. Dry forest types such as sal, salla, or shrubs such as dhanyero or tilka; poor bari land with maize or khar.
Higher site temperature	Lower altitude sites are generally warmer and drier than higher ones, *e.g.* although some parts of the Churia get more rain, evaporation in higher temperatures makes it drier than some higher ridges.	Vegetation and agricultural crop patterns vary significantly with temperature. Examples are numerous and well known throughout Nepal.
Soils with low rates of infiltration resulting in high runoff	Hill sal forest areas on rato mato, *e.g.* around Panchkhal on the Arniko Highway, and khayer forest on clay soils in the Bhabar zone near Kohalpur.	Clay soils with low infiltration rates, often with a problem of gullying. Often not cultivated and growing a poor forest cover of sal, khayer, salla.
Dry winds in big river valleys	The bottom few hundred metres of big river valleys, *e.g.* the Kali Gandaki near Baglung.	Dry sal or khayer forest types, cacti and xerophytes such as kettuke. If any cultivation, it is restricted to poor maize or khar bari.

Infiltration

Infiltration is the process whereby water enters the soil through the surface. It is influenced by the following factors.

- Intensity of rainfall: the faster that rain falls, the greater the chance that some will run off rather than infiltrate.
- Slope angle: the steeper the slope, the greater is the chance that water will run off.
- Soil texture: the finer the soil particles, the slower will be the penetration of water.
- Vegetation cover: vegetation helps to break up the soil and make it more porous, thus increasing infiltration; but it is necessary to look at the micro level: a short grass cover creates a very different effect from a few large trees with nothing in between.
- Surface openness or compaction: the less open or more compact the surface, the lower will be the infiltration; some soil surfaces are covered by caps of clay or algae.
- Stoniness of the material: the more stony, the less porous is the material and the more water will run off.
- Compaction of the material: the more

Figure 2.21: Aspects of water infitration into soils

(a) Average infiltration rates (IR) by soil texture

SOIL TEXTURE (MM/HR)	REPRESENTATIVE IR (MM/HR)	NORMAL RANGE OF IR
Clay	0.5	< 0.1 - 8
Silty clay	2	0.3 - 5
Clay loam	8	2 – 15
Loam	10	1 – 20
Sandy loam	20	10 - 80
Sand	50	20 – 250

(b) Indicative infiltration rates (IR) based on agricultural criteria.

CLASS	INFILTRATION CATEGORY	IR (MM/HR)	COMMENTS
1	Very slow	< 1	Suitable for rice
2	Slow	1-5	Marginally suitable for rice up to 3 mm/hr
3	Moderately slow	5-20	Unsuitable for rice
4	Moderate	20-60	
5	Moderately rapid	60-125	
6	Rapid	125-250	
7	Very rapid	>250	

(c) Average rainfall and infiltration measurements, Dharan-Dhankuta road

SITE	COVER	RAINFALL (MM/HR)	INFILTRATION (MM/HR)	INFILTRATION % OF RAINFALL
DDR 3+800	Canopy (old debris)	106	74	70
DDR 7+300	Bare (fresh debris)	56	48	86
DDR 19+000	Canopy (old debris)	117	94	80
	Bare (old debris)	113	75	66
DDR 19+400	Canopy (old debris)	28	24	85
	Bare (old debris)	28	15	53

Sources: (a) and (b) Landon, J R. 1991. *Booker Tropical Soil Manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. Longman Scientific and Technical, Harlow.
(c) Clark, J. E. 1992. *Principles of Bio-engineering with Reference to East Nepal*. PhD Thesis, Cranfield University.

Note: The rice suitability qualifications in table (b) assume that options are available. On Nepalese hill slopes, the areas of land that can be irrigated and are climatically suitable for rice cultivation do not always coincide with soils displaying low infiltration rates. For this reason, some khet land has huge infiltration losses and can seriously change the ground-water hydrology for some distance down the slope. The figures given in table (c) are averages presented for comparative purposes only; there are considerable ranges hidden by these data. Canopies are mostly of grasses and other herbaceous vegetation. These measurements were made under simulated, not natural, rainfall.

Liquefied debris from a large landslide is deposited wherever the gradient allows. In this case, the natural deposition site was the point at which the road crossed the month of the valley

Figure 2.22. Approximate relationships between texture, structure and hydraulic conductivity

Texture	Structure	Indicative hydraulic conductivity (mm/hour)	(m/day)
Coarse sand, gravel	Single grain	> 500	> 12
Medium sand	Single grain	250 - 500	6 - 12
Loamy sand, fine sand	Medium crumb, single grain	120 - 250	3 - 6
Fine sandy loam, sandy loam	Coarse, sub-angular blocky and granular, fine crumb	60 - 120	1.5-3
Light clay loam, silt, silt loam, very fine sandy loam, loam	Medium prismatic and sub-angular blocky	20 - 60	0.5- 1.5
Clay, silty clay, sandy clay, silty clay loam, clay loam, silt loam, silt, sandy clay loam	Fine and medium prismatic, angular blocky, platy	5 - 20	0.1- 0.5
Clay, clay loam, silty clay, sandy clay loam	Very fine or fine prismatic, angular blocky, platy	2.5-5	0.05-0.1
Clay, heavy clay	Massive, very fine or fine columnar	<2.5	<0.05

Source: Landon, J R. 1991. *Booker Tropical Soil Manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. Longman Scientific and Technical, Harlow.

compact the material, the lower will be the infiltration rate; newly filled materials or recently cultivated bari can have very high infiltration rates.

The variability of infiltration in soils is demonstrated by the general data given in Figure 2.21(a) and (b). These can be compared with the actual measurements made by Clark (1992) on colluvial debris slopes in East Nepal given in Figure 2.21(c). These demonstrate that colluvial debris has moderate to high infiltration rates and that runoff will only occur under heavy rainfall.

Percolation and hydraulic conductivity

Percolation is the downward or lateral movement of water through soil. The rate of water percolation is measured as hydraulic conductivity.

The Law of Darcy (1856) is applied to soil to define its hydraulic conductivity. Saturated hydraulic conductivity is a constant (K) referring to the flow of a fluid through a saturated conducting medium. It is defined as follows:

$$q = K A \frac{h}{L}$$

Where: q = volume rate of flow across a plane normal to the direction of flow;

K = hydraulic conductivity, which is the volume rate of flow through a sample of unit cross-sectional area under the influence of a unit hydraulic potential or head gradient;

A = cross-sectional area through which flow takes place;

h = hydraulic head expended in moving water from one side of the sample to the other;

L = length of the sample in the direction of the flow.

No soil is sufficiently uniform that it could be measured perfectly by this means, however, and so only approximations can be made. In addition, observations are extremely difficult to make in the field. Figure 2.22 gives general approximate relationships between the texture and structure of soils, and their hydraulic conductivities. In the case of loose colluvial soils with large voids between the abundant stone fragments, percolation may be rather higher than is suggested here. Also, soil profiles do not necessarily have the same characteristics throughout their depths. This is particularly likely with alluvial soils, where a sandy surface horizon may be underlain by a fine-textured horizon with a much lower rate of hydraulic conductivity.

On hill slopes, failure may be induced through variability between the infiltration rate of the surface layer and the hydraulic conductivity of the underlying material. This might occur where recently deposited, porous material overlies more compacted 'original ground'; or where colluvial debris transported from above overlies a firmer material. In either case, the low internal drainage rate of the lower layer may allow the higher layer to reach saturation relatively quickly on account of its high infiltration rate. This can lead to a shallow debris flow. In treating such a slope, drainage would therefore be critical.

Other aspects of water movement

Water can move over the surface of the ground, into the surface to a depth of a few centimetres, further down into the soil profile, and deep into rocks. All these pathways can lead to instability in various forms.

Conditions that lead to overland flow are:

- when the soil has a capping (compacted surface): a soil cap will prevent infiltration even if the soil itself is highly permeable;
- when the rate of precipitation exceeds that of infiltration (when the soil is not saturated);
- when the soil is saturated;
- when impermeable rock or impermeable soil is at the surface;
- slope, to a limited extent, can determine whether or not overland flow takes place: if the slope is very steep, water will flow over it however permeable the surface is; however, for most practical situations slope does not *cause* overland flow, although it certainly influences the *rate* of overland flow.

The result of water flowing over the surface can be either flow without any damage to the surface if it is adequately protected; or erosion if it is not.

Nepalese soils and rocks are generally very permeable, containing voids and many fractures. These allow water in to various depths, all of which can cause instability of various kinds.

When water infiltrates into the soil, it enters the voids and starts to fill them up. As a result, pore water pressure starts to rise. Pore water pressure is the pressure acting on soil grains by water held in the pores. Pore water pressure can be positive or negative. It is negative when the voids are only partially filled with water (this state is also known as soil suction). Pore water pressure becomes neutral just before the point at which the voids become completely filled with water. Pore water pressure becomes positive at the point when all the air has been expelled from the voids and the water phase in the soil-water mix becomes continuous. At that point, the water phase effectively becomes a column and hydrostatic pressure, equivalent to the height of the column, is exerted within the pores. The pressure is transferred to the soil grains.

If the hydrostatic pressure is sufficiently high it will force the grains apart and the mixture will start to behave as a liquid. Hydrostatic pressure developed near the soil surface, as when the upper layer becomes saturated during heavy rain, causes the soil to flow.

When pore water pressure becomes positive along the walls of a fissure underground, a 'pipe' develops. A pipe is an enlarged fissure that forms underground in fine-grained, non-cohesive soil, especially silty or fine sandy soils. Enlargement of the fissure takes place when water, flowing along the fissure or into the fissure from the side walls, detaches particles of soil and carries them away in suspension. Pipes that have not broken through to the surface can still sometimes be detected by the presence of an elongated hollow of subsided ground pointing down the slope. The trench may be above the head of a gully and in the same alignment as the gully, indicating that water is moving into the gully head as ground water through a pipe.

If water travels downwards to the bottom of the soil profile it commonly becomes halted in its path by the impermeable surface of the rock beneath. It then migrates downhill along the interface until it emerges as a spring at a point where the soil becomes shallower or the rock outcrops at the surface.

Pore water pressure may become positive at the base of the soil profile, resulting in a deep translational landslide (the commonest deep type) or a circular failure.

If water goes deeper than the soil profile, it goes into the bedrock.

Water movement through rocks is controlled by:

- the permeability of the rock;
- the angle of bedding; and
- the number, orientation, openness and continuity of fractures.

Figure 2.23. Material types and likely failures

TYPE OF MATERIAL	UNDERLYING CAUSE OF FAILURE	LIKELY MECHANISM OF FAILURE
Debris	Surface water Ground water	Erosion or liquefaction Shear failure
Soft rock	Weathering	Plane or shear failure or disintegration
Hard rock	Weathering	Plane failure
Alternating hard and soft rock	Weathering	Differential weathering plus plane failure

In horizontal rocks it will move sideways, slowly, along the surface of an impermeable layer. In tilted beds it will move more rapidly down the slope. If the rock is fractured, the water will continue to go deeper. Hydrostatic pressure is exerted within the open joint systems of rocks in exactly the same way as in soils. If the water cannot escape as spring water, high pressure can develop and force the joints apart. This is the cause of many rock slides.

In practice, although rocks have been weakened physically by folding and faulting, and chemically by weathering, it is actually water that provides the mechanism of failure by exploiting those weaknesses.

Although this debris fan has been inhabited and cultivated for many years, it remains at serious risk of destruction from this tributary of the Tamur Kosi River

2.7 INSTABILITY

The combination of dynamic terrain, steep slopes, weak rocks and water is, inevitably, instability. This Section examines the actual mechanisms of instability and considers what can be done about them.

The stability of a slope is described in terms of the factor of safety. A factor of safety of 1 means that the slope is at the dividing line between being stable or unstable. If the factor of safety is more than 1, the slope is stable. If it falls below 1 it will be unstable.

Unstable slopes are always in a state of change, either towards a more stable or a less stable condition. Most failures are active for at least several years before they settle down. Only in a few cases will the life progression be known or be capable of being estimated.

Slope materials and components

The materials forming a slope can be categorised as:

- debris, which is not rock as such, since it also includes soil and other mixed materials;
- soft rock, which may be rock that is naturally soft *e.g.* mudstone, or hard rock that has become soft through weathering; and
- hard rock.

These are expanded in the paragraphs below.

Debris. Material deposited as a result of a slope movement. The group includes soil of any type, soil and rock fragments, and rock fragments wholly. The category 'debris' does not indicate a definition of particle size distribution or other physical characteristics. This is because the constituents of debris can range from boulders down

Figure 2.24. The four zones of a landslide

Landslide zone	Location and description
Zone of cracking	Above the slide and sometimes around its sides, visible as tension cracks and subsidence.
Zone of failure	The head scar (crown) and failure surface, which may occupy only a relatively small area at the top of the slide.
Zone of transport	A damaged slope, scarred by the passage of debris on its way downslope. This part of the slope may be stable, and may recover on its own.
Debris pile	The detached, mobile material, either on its way down or in a cone at the bottom.

to silt and clay, in any proportion, and these features would be separately noted in a soil classification carried out on the material.

Unconsolidated debris. Material deposited by a slope movement that has taken place within the last year. Debris which has been deposited recently has a low bulk density and consequently is susceptible to infiltration and failure by liquefaction. This form of failure has the potential to destroy any of the low cost systems designed to catch material moving down the slope, and to fill or over-flow even the biggest of structures.

Consolidated debris. Material deposited by a slope movement that took place more than one year ago. The term applies to old landslide debris and colluvium, which are much more resistant to erosion, liquefaction and internal shear than fresh debris.

Soft rock. Soft rock is *in situ* rock, usually of weathering grade 5, (*i.e.* it makes a dull thud when struck with a hammer). Failure occurs both along rock planes (plane failure) and through bodies of rock (shear failure). Disintegration failure may occur if rock is extremely permeable.

Hard rock. Hard rock is *in situ* rock of weathering grades 1 - 4, (*i.e.* the rock rings when struck with a hammer). Failure occurs only along pre-existing rock planes, by plane failure. Hard rocks have internal strengths much greater than the frictional strength along their fracture planes.

Alternating hard and soft rocks. Bedded rocks in alternating layers, whose susceptibility to weathering is contrasting. Alternating hard and soft rocks, although strictly falling within two rock groups, are included as a material type because the layers influence each other in a way that is different from each rock type alone. Failure is by differential weathering. These alternating bands are particularly common in the Churia ranges.

These material groups and the most likely underlying causes and mechanisms of failure are shown in Figure 2.23. Note that the underlying cause of failure is usually quite distinct from the triggering factor for slope movements. The triggering factor is usually water, but is occasionally an earthquake.

A landslide has distinct parts (see Figure 2.24). Recognising and assessing these individually helps the engineer to understand the character of the landslide and, in particular, its severity.

Types of instability

There are many types of erosion and instability found in Nepal. the most common ones are shown in Figure 2.25. They and others are described in more detail in the paragraphs below.

Erosion. Erosion is the removal of particles from the surface by flowing water. An arbitrary depth limit of 25 mm can be adopted for erosion: this depth refers only to the initial removal of particles and is used to distinguish erosion from mass movements; if particles are continually washd away, the surface will be progressively lowered, giving rise to the forms of erosion described below. For example, a gully 2 metres deep can be developed by the steady removal of particles from its base and sides to a depth of no more than 25 mm at a time.The process which causes this is still erosion.

There are numerous terms to describe erosion, and the most common ones are explained below. When it comes to the protection of critical roadside slopes, the distinctions are largely academic.

Figure 2.25. Common types of erosion and slope failure

MECHANISM	DESCRIPTION	DEPTH
Erosion on the surface	Rills and gullies form in weak, unprotected surfaces. Erosion should also be expected on bare or freshly prepared slopes.	Usually in the top 0.1 metre, but can become deeper if not controlled.
Gully erosion	Gullies that are established in the slope continue to develop and grow bigger. Large gullies often have small landslides along the sides.	Usually in the top 0.5 metre, but can become deeper if not controlled.
Planar sliding (translational landslide or debris slide)	Mass slope failure on a shallow slip plane parallel to the surface. This is the most common type of landslide, slip or debris fall. The plane of failure is usually visible but may not be straight, depending on site conditions. It may occur on any scale.	Frequently 0.5 metre or less below surface, but can be up to 3 metres or more (or along a local discontinuity).
Shear failure (rotational landslide)	Mass slope failure on a deep, curved slip plane. Many small, deep landslides are the result of this process. Large areas of subsidence may also be due to these.	Usually > 1.5 metres deep.
Slumping or flow of material when very wet	Slumping or flow where material is poorly drained or has low cohesion between particles and liquefaction is reached. These sometimes appear afterwards like planar slides, but are due to flow rather than sliding. The resulting debris normally has a rounded profile.	Frequently 0.5 metre or less below surface.
Debris fall or collapse	Collapse due to failure of the supporting material. This normally takes the form of a rock fall where a weaker band of material has eroded to undermine a harder band above. These are very common in mixed Churia strata.	0.5 to 2 metres in road cuts; deeper in natural cliffs.
Debris flow	In gullies and small, steep river channels (bed gradient usually more than 15°), debris flows can occur following intensive rain storms. This takes the form of a rapid but viscous flow of liquefied mud and debris.	The flow depth is usually 1 to 2 metres deep.

Even the smallest gullies can damage roads

Natural or geological erosion: the wearing away of the Earth's surface by water, wind or ice under natural environmental conditions of climate and vegetation, undisturbed by man.

Normal erosion: the gradual erosion of land used by man which does not greatly exceed natural erosion.

Accelerated erosion: erosion which is much more rapid than normal, or natural or geological erosion, primarily as a result of the actions of man or animals.

Splash (or rainsplash) erosion: the spattering of small soil particles caused by the impact of rain drops on wet or weak soils; the loosened particles may or may not be subsequently removed by surface runoff.

Sheet erosion: the removal of a fairly uniform layer of soil from the land surface by runoff water (or overland flow).

Rill erosion: erosion whereby numerous small channels of the order of tens of millimetres in depth are formed.

Gully erosion: the process whereby water accumulates in narrow channels and, over short periods, removes the soil from this narrow area, often

Shallow planar failures on long steep slopes can give rise to large volumes of debris. Althought the debris in this example is about 5m deep, the depth of the failure itself is less than 1m

to considerable depths.

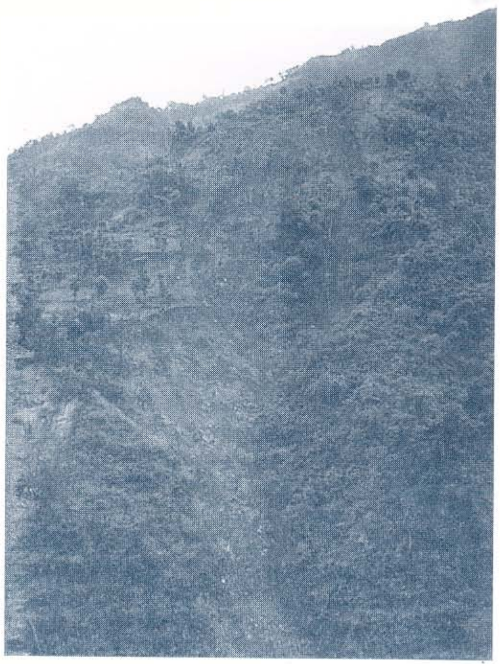
The exact conditions under which each of these occur varies greatly. Sheet erosion is uncommon on roadside slopes, but can be found on extensive bare soils with compacted surfaces. More common is the development of rill or gully erosion through the channelisation of surface runoff (when it occurs) at the micro level. Once drainage lines start to form rills on weak materials, they can enlarge rapidly into gullies.

Gullies. Gullies begin as very shallow, narrow incisions in the slope (rills). If a gully is deeper than 2 m, its sides fail in ways similar to a normal hill slope. Hill slope protection measures are then appropriate on the gully sides, as well as the gully floor requiring its own protection.

Erosion by piping. This is the removal of fines along an underground channel. Percolating ground water in permeable fine soils of low plasticity can remove fines along a fissure to a point where an underground stream is formed. The roof of this stream cavern can enlarge upwards towards the surface and eventually collapse to create an open, elongated chasm or pit.

Planar sliding or translational landslides. These are the most common form of slide in Nepal. In these a 'slab' of material of more or less uniform thickness slides off the surface. Translational slides are typically rectangular in plan, with a straight head scar and straight sides running parallel down the slope. They are frequently quite shallow (*i.e.* one metre deep or less). They can be caused by ground water pore pressure along a slide plane, or by weathering or undercutting of the slope. They can be shallow or deep, according to the structure of the superficial layers.

Shear failure or rotational landslide. Here, a rotational movement of material occurs, forming a spoon-shaped scar on the hillside which is roughly circular in plan. The debris forms a bulge near the toe. Slumps are commonly caused by high ground water pore pressures deep in the



Under very heavy rainfall, weak colluvial materials on steep slopes can reach a critical point of saturation. The material then liquefies and slides, giving rise to shallow failures

Extreme rainstorms can lead to alarming scales of debris flow. The average boulder size is about 2m diameter in this example from Palung, in 1993

hillside, and the slip circle usually goes several metres deep.

In practice in Nepal, deciding if there is a rotational or a translational mode of failure is usually extremely difficult. Many slides are a compound of the two types, in which a rotational component at the head degenerates into a translational component below. This is because coarse, non-plastic debris masses cannot sustain a circular slip plane except at the crown. Deciding which mode is dominant is useful because rotational failures indicate a deep failure plane and may therefore be more difficult to stabilise than a translational slide.

Debris flow. These are caused by the liquefaction of material, usually by the action of heavy rainfall upon a permeable soil surface. The soil literally flows down the slope. The failure plane is usually shallow, sometimes only a few centimetres deep. However, the fluid mass is very difficult to control or stop. Deep flows, which can travel a long way, are very destructive and potentially pose a high risk to life and property.

Plane failure in rock. Any mass movement whose failure plane or planes is controlled principally by fracture planes in rock, and whose debris consists chiefly of rock fragments. The weathering grade of the rock is 1 - 4 (the rock rings when struck with a hammer: see Figure 2.11, page 56). Failure types commonly include plane failure, wedge failure, and toppling (rockfall).

Disintegration. Tensile failure in very soft rock or consolidated soil. This is a special type of rock failure, found in massive or sparsely-jointed, permeable, weatherable rocks (e.g. porous sandstones) and in dense soils and unconsolidated materials that stand in a vertical or near-vertical face. Upon landing the material breaks up into a pile of loose debris, consisting mostly of loose rock mineral particles, such as sand containing a few boulders of weathering grade 4 or 5 (see Figure 2.11, page 56). All traces of rock structure or stratification are destroyed in the fall. For this reason the mechanism is distinguished from a fall of hard rock, which is considered a plane failure. The cause is weathering. Saturation and weathering cause the rock to fail by planar or arc-like shearing throughout the mass. Sometimes this is partially controlled by weakly-developed joint planes. Strictly, the mechanism is a 'fall', but the form of failure is distinctive. The mechanism is typical of thick beds of soft Siwalik sandstone and terrace deposits. It is very difficult to cure.

Differential weathering. Weathering of rock layers whose susceptibility to weathering is strongly contrasting. This failure occurs typically in alternating thin beds of hard and soft rock, such as sandstone and mudstone or siltstone. These formations are characteristic of the Middle Siwalik rocks of Nepal. The cause is a combination of weathering and erosion of the soft rock layers, and plane failure of the hard rock layers. The soft rocks erode back from the face to leave the hard rocks sticking out. Eventually the hard rocks overhang so far that they break off along vertical fractures. The process then starts again and the whole face retreats. This mechanism is very common in the Churia ranges.

Causes of failure

The causes of failure are numerous, but mainly come down to the action of water in some way.

Surface water. This gives rise to erosion, or soaking of the surface to cause shallow sliding. It results from water infiltrating from the surface. The failures caused are shallow, and there is usually clear evidence of the source or presence of water.

Ground water. Ground water causes increased pore water pressure at depth. This gives rise to a failure plane deeper than in surface water failures. In some geological conditions, a considerable amount of ground water can occur but is barely visible as a seasonal spring. Water percolating down through the ground from khet (paddy) terraces and leaking kulos (irrigation leats) can have a major effect a long way down the slope.

Weathering. Rock shear strength is reduced by weathering, as constituent minerals are broken down into weathering products and clay minerals. Physical bonds between rock constituents are weakened or broken. The rock can fail along weakened fracture planes or through its body. Weathering takes place over geological rather than human time, but the effects in weakening rocks can take many years to result in a failure.

Undercutting. A slope is undercut by a flowing stream or by the opening up of a road cutting. Incision (downcutting) or lateral scour by streams is a major cause of slope failure. The initial failure can work rapidly up slope.

Addition of weight. Weight is added usually in the form of landslide debris from a failure higher up the slope, or by the dumping of spoil.

2.8 SITE INVESTIGATION

A rapid procedure for site investigation is given in the *Site Handbook* companion to this volume (Section 1.2, page 15). It is recommended that it should normally be followed. A proforma and guidance notes are given in the *Site Handbook*, Annex A (page 126). In cases of more serious instability, however, a more thorough investigation may be required. That is described in this section, with the procedural guideline and check list required given in Annex A of this volume.

The various aspects of a site which should be investigated are considered in the paragraphs below, with explanations of the kind of problems that may occur.

Because of the range of failures that can occur, it is important to try to identify what is occurring in the ground. For example, as Figure 2.26 shows, cracking in the original hill slope above the road cut slope might be the result of one of three different possibilities, one of which is far more serious than the others.

Many of the investigation criteria involve relatively arbitrary quantifications (such as the length of slope affected by the failure). The reason for this is that these provide indications of the seriousness of the failures and are important in determining the priority and scale of rehabilitation work.

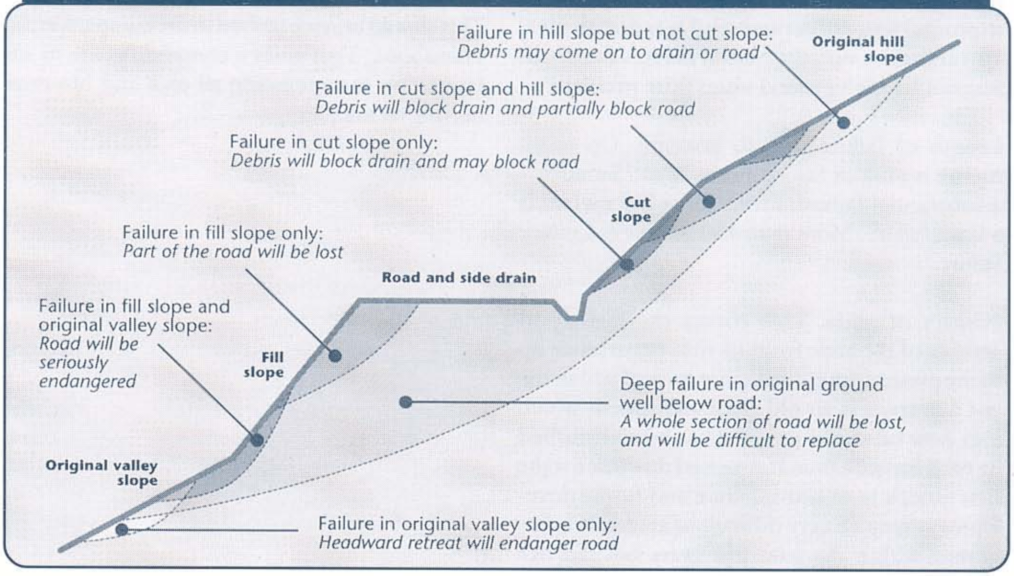
Location of slide. The initial criterion is to determine whether the failure is off the road alignment but within the Department's responsibility, above the road so that debris may come on to the road, below it so that it may be undermined, between road sections, or whether the slide failure plane passes beneath the road. The main options are given in Figure 2.26.

Type of slope affected. If the failure affects the road cutting but not the hill slope, then the slide has probably been caused by road construction; if it affects the hill slope but not the road cutting, then the slide has probably not been caused by road construction: it may be natural or induced by man, but there is a risk of enlargement up slope and deposition of debris on to the road and into the drainage system. If the slide affects the road cutting and the hill slope, it has probably been caused by road construction and is enlarging up the slope. If it is in the embankment, fill or spoil slope, then the slide has been caused by road construction and threatens the carriageway: there is a risk of erosion or liquefaction if the fill is uncompacted.

Slope conditions above slide (or above road, if road is at top of slide). If it is at the crest of a ridge, or on a gentle slope (less than 35º), then the slide is unlikely to enlarge much up the slope. If it is a stable, undisturbed hill slope, the slide can be stabilised easily. On an unstable hill slope with cracked ground, another landslide or topography that collects water, more instability can be expected: there is a high risk to any stabilisation measures. If there is a cut-off drain or take-out drain, there is a high risk of leakage from a cracked drain. Where there is an irrigation channel (kulo), there is a very high risk of major erosion if the channel should leak or be damaged.

Slope conditions at base of slide or below slide (or below road if road is at base of slide). Where the road is intact, instability is from above only. The road may be buried but the road itself will not be disrupted by the slide plane. If the road is disturbed, then it is not at the base and so the slope condition at the base must come

Figure 2.26. Possible failure planes around a road on a hill slope



under one of the next three categories. If there is a stable, undisturbed hill slope, the slide can be stabilised easily. Where there is an unstable hill slope with cracked ground, a landslide or topography that collects water, there is a very high risk to the carriageway; remedial action is urgently required, still with a high risk of major damage. If there is a stream, there is a risk of scour and undercutting of the slope.

General type of failure. Erosion, rilling or gullying up to 2 metres deep caused by surface water is only a minor instability. Gullies more than 2 metres deep with a substantial watercourse have a probability of a significant amount of debris being brought down. Mass movements (slides, flows or falls) are deeper failures requiring more substantial works.

Material forming the original (failed) slope. Debris, which is material deposited as a result of a slope movement, may be unconsolidated or consolidated, depending on whether it is less than or more than a year old. Other possible materials are soft rock, hard rock and bands of alternating hard and soft rocks.

Failure mechanism. Erosion is the removal of particles from the surface by flowing water: this can be in the form of rills, gullies or pipes. Slides, within the soil or along the soil/rock interface, cover any mass movement of soil or debris down slope. Flows are caused by the liquefaction of material, usually by the action of heavy rainfall upon a permeable soil surface. Plane failures in rock are any mass movement controlled principally by fracture planes in rock, and whose debris consists chiefly of rock fragments. Disintegration is a tensile failure in very soft rock or consolidated soil. Differential weathering occurs in rock layers whose susceptibility to weathering is strongly contrasting.

Causes of failure. Surface water causes erosion, or soaking of the surface to cause shallow sliding. Ground water causes increased pore water pressure at depth, leading to failure planes deeper than in surface water failures. Rock shear strength can be reduced by weathering as constituent minerals are broken down. Slopes can be undercut by a flowing stream or by the opening up of a road cutting. Weight can be added usually by the dumping of spoil or by landslide debris.

Depth of failure. Up to 25 mm is a shallow surface failure caused by erosion. From 25 to 100 mm is a shallow mass failure, probably due to the liquefaction of surface layers. From 100 to 250 mm is a deeper mass failure that can involve water contributed both from infiltrating rain water and rising ground water. From 250 to 1000 mm is a deep mass failure probably due primarily to ground water pore pressure. Deeper than 1000 mm comprise very deep mass failures due to, or assisted by, high ground water pore pressure.

Length of failure (top to bottom). Up to 15 metres is a minor failure. From 15 to 75 metres is a substantial failure. From 75 to 150 metres is a large failure. More than 150 metres is a major failure.

History of slide. This covers the history of activity of the slide from its first occurrence up to the present time. if it has not moved within the last 5 years, it is an old slope movement which may now be stable, unless it has been disturbed by road construction. If it moved this year for the first time, it is an active failure and future development may be very difficult to assess. If it has moved within the past five years but did not move this year, it is a recent failure, but at present is inactive. If it moves every year at a diminishing rate by the initial mechanism, it is a continual failure, but holds distinct possibilities for improvement by remedial works. If it moves every year by the initial mechanism at a constant or worse rate, it is a continual failure which may be out of control and have little possibility for improvement.

Life progression of slide. The evolution of the slide from its current condition into the future. If a stable slope has formed, or will stabilise naturally, it may have been a single failure to a stable rock plane or stable slope configuration, which is a relatively rare situation. If further movement is expected by movement at a shallower depth than that of the original failure, then the instability is going through post-slide adjustment. If a repeated movement is expected, by the initial mechanism or another equally serious, full stability may not be achieved for some years.

2.9 SITE TREATMENT

This should be as described in the companion *Site Handbook*. That gives a complete guide to site treatment, incorporating all civil and bio-engineering techniques.