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Landslide Hazard Management and Control in India

V.C. Thakur

International Centre for Integrated Mountain Development
Kathmandu, Nepal
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Cover Photograph: Two perspectives of the area near Nathpa village, NW Himalayas — rockfall cum debris slide blocking the Sutlej River (background) and translational debris slide on the same site, the imminent hazard to construction activities (inset)

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Preface

The inherently unstable nature of mountain areas of the Hindu Kush-Himalayas is well recognised. The steep slopes, unstable geology, and intense monsoon rains combine to make the Hindu Kush-Himalayas one of the most hazard-prone areas in the world. Although natural hazards of varying intensity have occurred frequently in the past in Hindu Kush-Himalayan countries, more recently there has been an increase in human settlement of hazard-prone areas as a result of population pressure, as well as improvements in accessibility by road and the onset of other infrastructural developments. Consequently, natural and man-made disasters are on the increase and each event affects an even greater number of people than before. Floods and landslides during the monsoon season are the most common natural disasters affecting this region, often resulting in substantial economic and environmental losses and causing great suffering to many people.

Despite all this the present levels of understanding and systematic analysis of these disastrous events are very poor and data bases are non-existent. No monitoring activities are carried out even in cases where such monitoring can be of direct benefit to project-related management activities. Investments in developing practical guidelines for managing such events as well as in forecasting them have been inadequate.

Since its inception, ICIMOD has been promoting the development of a better understanding of natural hazards. Various activities have been undertaken so far. These include several training programmes dealing with mountain risk engineering, focussing on improving road construction along unstable mountain slopes, a review of landslide hazard management activities in China, and field assessment of landslides and flood events in south central Nepal following the extreme climatic events that took place in July 1993.

One of the goals set by ICIMOD in its Mountain Natural Resources' programme is to "Improve the conditions of mountain resources and environments by halting and eventually reversing their degradation." Programme activities envisaged to achieve the above goal are directed to:

- identification of measures to mitigate different types of natural hazards which result in the loss of natural resources;
- promotion of skills and methodologies for natural hazard assessment; and
- improvement of public awareness for better disaster preparedness in mountain areas.

ICIMOD's programme on "Landslide Hazard Management and Control" focusses on these concerns to help protect valuable natural resources from different types of natural hazards. This programme is based on activities already introduced at ICIMOD in 1994 with support from the Government of Japan.

This programme is concerned not only with examining the types and extent of landslide events but also with measures for their mitigation and control; and in addition the skills and methodologies needed for natural hazard assessment.

To improve the knowledge base on Landslide Hazard Management and Control, state-of-the-art reviews were commissioned in four countries of the Hindu Kush-Himalayan Region. These countries are China, India, Nepal, and Pakistan.

Suresh Raj Chalise of the Mountain Natural Resources' Division at ICIMOD coordinated the work carried out on these reviews and the current document entitled "**Landslide Hazard Management and Control in India**" was prepared by Dr. V.C. Thakur of the Wadia Institute of Himalayan Geology. Dr. Thakur has produced a comprehensive document on a topic that is crucial to the development of mountain areas and the well-being of mountain inhabitants.

Abstract

'Landslide Management and Control in India' examines the problem of landslides in a mountain environment in which rising populations and an increase in infrastructural construction have led to augmentation in the probability of landslide occurrence. The various landslide triggers (rainfall erosion, deforestation, earthquakes, overburden of and construction of inappropriate infrastructure, geological causes, etc) and parameters of occurrence are discussed; a number of case histories are given in illustration. Methodologies for Landslide Hazard Zonation and map preparation are discussed, along with landslide hazard rating. Methods of landslide hazard mitigation are covered and an outline for a training programme is proposed as part of the paper's principal recommendations.

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Introduction

A landslide is defined as the movement of a mass of rock, earth, or debris down a slope. Landslides comes under the classification of mass movement. There are many classification schemes for mass movement, but the classification proposed by Varnes (1978) adopted here is elaborated on in Annex 1 of this report. The definition and nomenclature of landslides and a method for reporting a landslide, as suggested by the Commission on Landslides of the International Association of Engineering Geology (IAEG), is given in Annex 2 of this report.

The Himalayas, including Jammu and Kashmir, Himachal Pradesh, Garhwal, Kumaon, Sikkim, the Darjeeling Hills, Arunachal, and the northeastern hill states of Nagaland, Mizoram, Manipur, and Meghalaya, are where the rate of incidence of landslides ranges from high to very high in India. In Peninsular India, the Western Ghats and Nilgiris have high to moderate landslide incidence rates, whereas the Eastern Ghats and the Vindhyan range show low landslide incidence rates. In many cases, landslides occur as a result of other natural hazards like earthquakes, floods, and cloudbursts, bringing catastrophe and destruction. It has been observed that the frequency and intensity of landslides have increased substantially in the last five decades. This increase is mainly attributed to two main causes: deforestation and human activities. The Himalayas have gradually lost a lot of their forest cover in the last hundred years due to exploitation for timber. All the hill states have been opened up for development through road construction and major engineering projects. All these construction activities have intensified the destabilisation of slopes and, added to this, the population pressure has resulted in degradation of the physical environment. According to this author's estimate, in India the cost of restoration work and the associated economic losses due to landslides can be conservatively estimated at IRs.200 *crore* (2 billion) per annum.

The damage to property and loss of lives are enormous when cumulative figures are taken of all the landslides in the country. The 20th July 1970 flash flood, caused by the damming of the Alaknanda River by a landslide and the subsequent outburst of the dam, wiped out the hamlet of Belakuchi, killing 55 persons and flooding a widespread area downstream up to the town of Srinagar. The Tista, Jaldhaka, and Diama rivers of northern Bengal were flooded in 1975 due to landslides, leaving about 4,500 people homeless. In northern Sikkim, the landslides in 1983 caused extensive damage to roads and bridges, killed 35 villagers, and washed away a labour camp. In Jammu and Kashmir, landslides continued to damage the road, causing blockades for several days in 1971, 1972, 1973, 1975, 1977, 1979, and 1986. The Jhakri landslide in the Sutlej Valley, on 25th February, 1993; the Kaliasaur landslide in Alaknanda Valley, on 19th September, 1989; and frequent landslides on the Mussoorie bypass and at Kathgodam-Almora are major landslide events. From 1978 to 1979, 200 landslides were recorded in the Western Ghats and again, in 1983, a large stretch of road was damaged in the Western Ghats. Twenty-five lives were lost in the 1st July (1993) landslide in Itanagar, Arunachal Pradesh, and 40 in the 5th August (1993) landslide in Kalimpong, West Bengal. Available records show that a total of 600 persons were killed by landslides from 1975 to 1995. In the Nilgiri Hills and Western Ghats in southern India, about 100 persons have been killed and about 600 families rendered homeless during the last two decades. More recently, in September 1995, 80 persons were buried alive by a landslide in Kulu Valley, Himachal Pradesh.

The Problem of Landslides

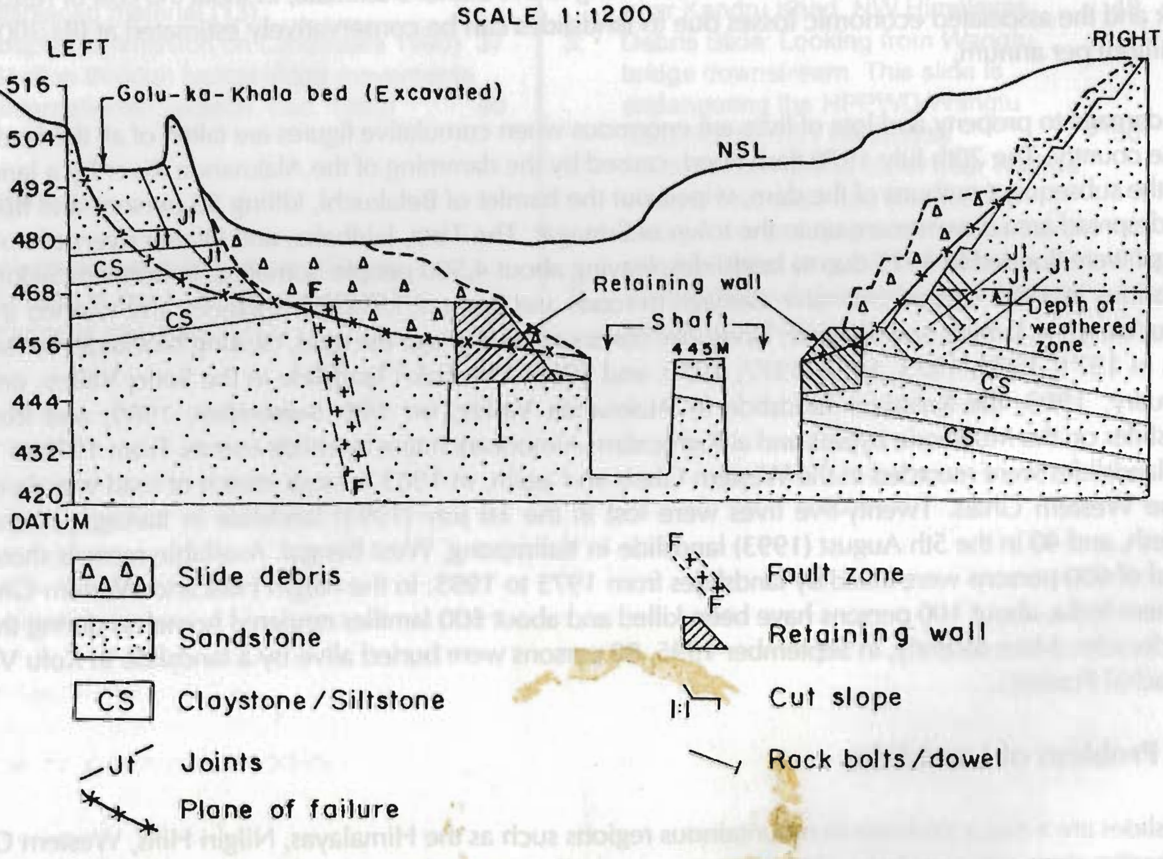
Landslides are a major problem in mountainous regions such as the Himalayas, Nilgiri Hills, Western Ghats, and northeastern region in India, disrupting communication routes, increasing the sediment load of rivers, and resulting in additional expenditure for the state exchequer on landslide control. Landslides take place most frequently during the monsoon rains, as water is an important catalyst for initiating landslides. In the Himalayas, the winter rains and, at high elevations, frost action and snow also contribute to landslides. Inherent geological characteristics of the strata and geometry of the slope control the stability of the slope and, in turn, landslides. Active tectonic movements; such as the movement across faults and uplift of topography, occurring at a rate of 20mm to 50mm per year in the Himalayas; result in weaknesses across certain tectonic zones that are prone to extensive landslides and other types of mass movement. Deforestation, as a result of the felling of trees for timber, and removal of vegetation cover, as a result of development activities such as building roads, dams, and settlements, are also responsible for the increased rate of soil erosion and destabilisation of slopes prone to landslides.

In India, a fairly good network of roads has been constructed in the Himalayas and in the hill states of the Northeastern region in the last five decades. There is also a good system of roads and railways in the Western Ghats and Nilgiri Hills. Disruption of traffic is very common, especially during the monsoon months, and, sometimes, vehicular traffic is blocked for several days as a result of landslides.

There are several instances of landslides being a major problem in the construction of major hydroelectric projects in the Himalayas. Case histories of landslides affecting power projects, such as the Chineni hydel project in Jammu and Kashmir, the Baira-Siul and Giri hydel projects in Himachal Pradesh, and the Beas dam project at Pong in the Punjab, have been described (Krishnaswamy and Jain 1975). In all these cases, control measures were successfully adopted on the advice of geotechnical experts from the Geological Survey of India.

The case history of the powerhouse slide of the Giri hydel project in Himachal Pradesh is illustrated in Figure 1 as an example. During the excavation of the powerhouse pit of the Giri hydel project, landslides occurred, as anticipated, on both the slopes. To stop the sliding, several control measures were suggested, including the construction of a reinforced concrete (RCC) retaining wall; easing of slopes, 1:1, on either bank of the Golu Ka Khala; and, later, grouting and shotcreting the slope faces and rock bolting.

Figure 1: Geological cross-section across Golu Ka Khala Powerhouse area, Giri Hydel Project, H.P., showing geology and control measures (Krishnaswamy and Jain 1975)



There are several instances of the damming of rivers by landslides and subsequent outbursts of the dams, resulting in heavy destruction in downstream areas. This generally happens when a side stream joining the main river suddenly brings a large amount of debris as a result of cloudburst. There have been numerous such outbursts of landslide dams, e.g., the Gohna landslide dam in 1893; the Reni landslide dam in 1968; the Belakuchi landslide dam in Garhwal in 1970; the Parachu landslide dam caused by the Kinnaur earthquake in 1975; and the Jhakri landslide dam across the Sutlej River in Himachal Pradesh in 1993. Making a passage for the river by breaking or partly blasting the way out from the dam is the best way of averting disaster downstream, and this was successfully accomplished with the Jhakri landslide.

Environmental Impact of Landslides on Urban Settlements

Several hill stations were built by the British in India's Lower Himalayan regions, e.g., Dalhousie, Dharamsala, Sigla, Mussoorie, Nainital, and Darjeeling. These hill stations have now grown into medium to large urban settlements and have witnessed rapid growth in recent years. All these towns are located in areas that receive a minimum rainfall of 2,000mm per annum. Landslides and subsidence are an acute problem in Nainital and Simla, but the problem is not so acute in Dalhousie and Dharamsala because of their favourable topography;. the frequency in the latter two urban areas being on average one major landslide in one area every two to three years. Landslides and subsidence in Simla and landslides in Nainital are described below.

Landslides and Slope Stability in Nainital

Nainital is an important hill resort in the Kumaon Hills of Uttar Pradesh. It has a natural lake at an altitude of 1,929.2masl. The lake is two kilometres long and one kilometre wide and is surrounded by hills ranging in height from 2,085m to 2,612m. The hill slopes, in general, are scree strewn and have abundant pine trees. Nainital lies at the southeastern end of a synclinal basin, predominantly comprised of limestone-dolomite, shale-quartzite, and conglomerates of the Krol Group. The overburden is of Recent to Subrecent deposits. The rocks are highly folded and faulted, with a major thrust in the area called the Manora Thrust. The Main Boundary Thrust also passes south of Nainital. The recurrence of large landslides and slips has been seriously limiting the growth of the township, and, in some instances, large infrastructures, such as hotels and buildings, are threatened by landslides. Nainital's local economy is totally dependent on tourism. The further development of tourism infrastructure is constrained due to slope instability. The Nainital Lake, which is the heart of the hill resort, is receiving an increasing sediment load from landslips and landslides, threatening its very existence.

The Sher-Ka-Danda slopes and the Kailakon Balia ravine are the active slide areas in Nainital. The presence of a 1.25km long crack along the slopes of Sher-Ka-Danda, extending from Government House to the Birla Mandir area, has been reported since 1897. Horizontal movement of 1.5m, between 1957 and 1965, was observed on either side of the Sher-Ka-Danda hill cracks. In the Kailakon area, a maximum horizontal cumulative movement of 35m and a cumulative vertical movement of five metres have been recorded in the last 60 years. The annual rainfall varies from 2,600mm to 2,900mm, of which 2,400mm occurs during the three monsoon months. It has been observed that landslides and subsidence occur mainly during the monsoon months. A landslide hazard zonation map showing different areas of instability in Nainital township and Balia Valley is shown as Figure 2 (Valdiya 1987).

Subsidence and Slips in Simla, H.P.

Simla, summer capital of British India and now the capital of Himachal Pradesh state, is located on a ridge at an altitude of 2,012m in the Lesser Himalayas. The area receives an average annual rainfall of 1,600mm, most of which is received during the monsoons. Although small slips and subsidence have been common occurrences, a major subsidence occurred along the ridge in August 1971, following heavy precipitation. The fissures formed by subsidence extended for over 400m in length, showing a vertical displacement of half a metre.

Investigations carried out around the town by the Geological Survey of India (GSI) revealed the presence of a funnel-shaped mantle of overburden with the upper rim of the funnel coinciding with the northern edge of the ridge; most of the portions affected by slips and subsidence lie within the overburden funnel. Control measures carried out included drainage construction to prevent percolation of the surface water into the overburden, and there was no new construction on the affected portions of the hill slope.

Simla, being the state capital of Himachal Pradesh, has witnessed accelerating growth in the last few decades, and it has grown from a town to a city. The thick forest cover of *Deodar* trees on the hill slopes was cut in many places to construct office buildings, houses, and hotels, thereby degrading the hill slopes and triggering landslides. The main reason for the landslide problem in Simla is the poor planning and bad implementation of construction projects without giving due consideration to geological and ecological conditions.

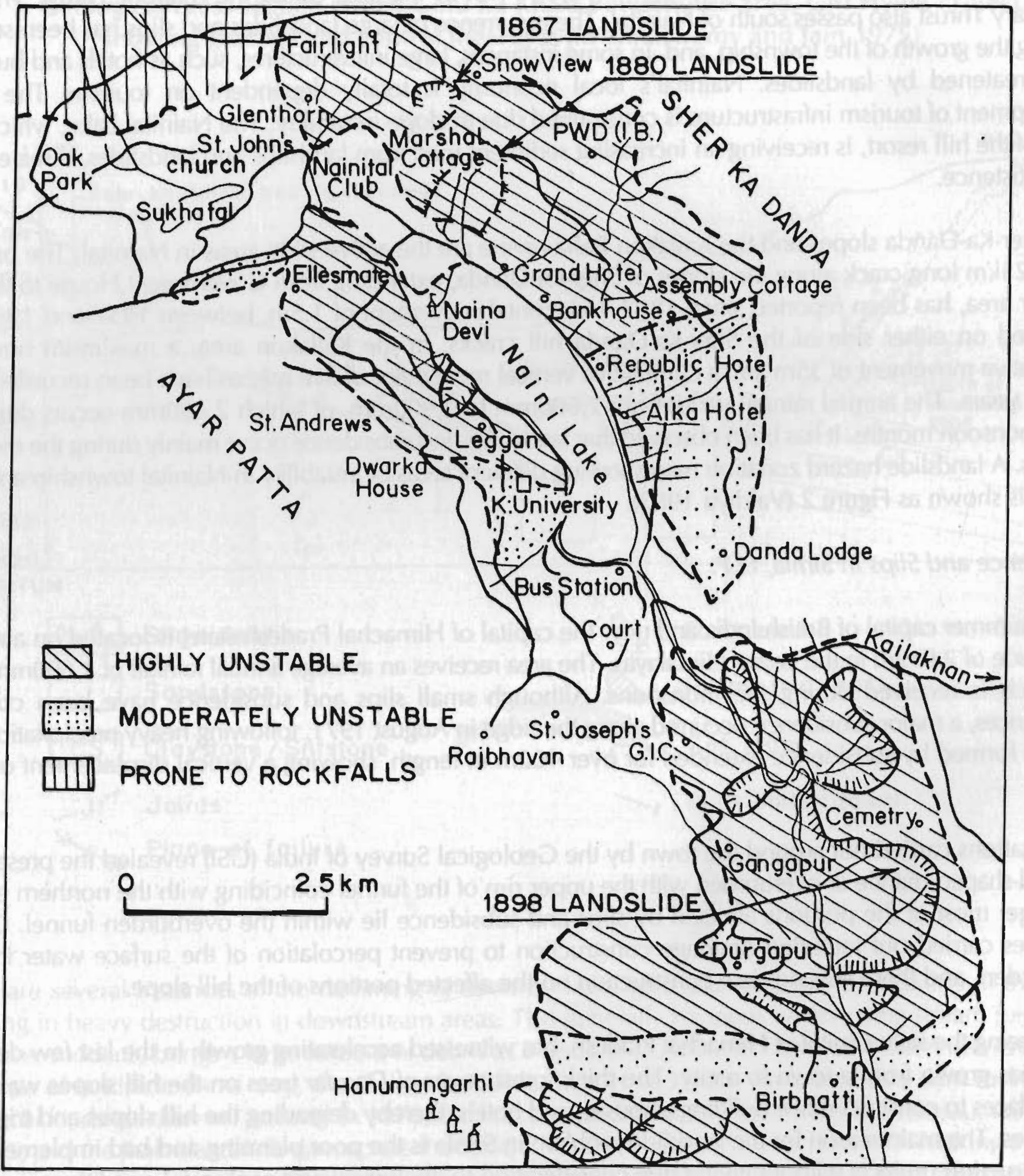
The Landslide Problem in Mussoorie

Mussoorie is another hill station built by the British, located 260km NE of Delhi, at an altitude of 2,000m. The landslide problem here has been triggered by the unabated growth of poorly planned hotels and commercial establishments, which has considerably reduced the vegetative and forest cover of the hill slopes.

Impact on Farms and Agriculture and Infrastructure

The loss of farm and agricultural land as a result of landslides is negligible and often not reported in the Indian Himalayas. However, some villages and farmlands are located on geologically old landslide soil on hill slopes, especially on Lesser and Higher Himalayan terrain.

Figure 2: Major instability zones in the Nainital town slide and the Ballia Valley (Valdiya 1987)



Roads are the most vulnerable infrastructure prone to landslides in the hills. About 90 per cent of landslides occur during the three monsoon months, and the rest (about 10%) take place during the winter rains. In September 1995, there were very heavy rains in the Kulu and Chamba valleys in Himachal Pradesh, severing communication links for about 10 days due to heavy landslides. The maintenance expenditure on landslides and for keeping roads open to vehicular traffic costs the government exchequer approximately 100 *crore* rupees per year for the Himalayan region only.

Other infrastructures that have been affected by landslides are bridges, dams, and powerhouses; but they are mostly only threatened, and remedial measures have been taken to save them. Therefore, it is very important for the major engineering projects in the Himalayas that proper assessment of slope stability is carried out and remedial measures taken in advance to prevent major landslides. Examples of such hydropower infrastructures threatened by landslides have been reported at the Sanjay *Vidyut Bhaba* project in the Sutlej Valley and at Uttarkashi in the Bhagirathi Valley.

Factors Controlling Landslides

About 90 per cent of landslides take place during the monsoon or winter rains in the Northwestern Himalayas. In addition to other landslide destabilising factors, the rains play a vital role in triggering most of the landslides in the Himalayas. From south to north, the Indian Himalayas can be divided into different climatic zones, for example, the tropical, sub-tropical, sub-temperate, semi-arid, and arid zones. The precipitation pattern also varies across these climatic zones. Monsoon precipitation is largely received south of the Higher Himalayas and rainfall may vary from 150mm to 300mm, depending upon the local topography and location. The Himalayan region, e.g., Ladakh and Spiti, lying north of the Higher Himalayan ranges, has an arid to semi-arid climate and receives less than 50mm of monsoon rains. The winter rains that bring snow at higher altitudes are more pronounced in the western than in the eastern Himalayas.

Monsoon Rains and Landslides

On 18th September 1880, a large debris avalanche, including slide material, killed 143 persons in the upper part of Nainital town. It swept the Victoria hotel, some buildings, and the Naina Devi temple into Nainital Lake. This disastrous event took about half a minute and was preceded by several hours of incessantly heavy rain (260-290mm). Prior to this catastrophic event, the development of a 1.25km long crack on the slate-marl succession of Sher-Ka-Danda was observed in 1867 (Middlemiss 1910). On 17th August, 1899, in another event following incessant rain, an enormous mass of infrakrol slates slumped down into the Balia stream, burying a brewery settlement near Nainital.

The road system in Sikkim and the Darjeeling Hills has suffered extensive damage in the past and is still prone to landslides, subsidence, lateral mass movements, and toe erosion. Heavy rains were the principal contributing factor to landslides and mass movement in 1911, 1914, 1968, and 1973. The whole area experiences heavy rainfall, varying from 3,000mm to 6,000mm per year. Also, there are frequent cloudbursts when the intensity of the rainfall is as high as 600mm in a day and, at times, 200mm for a period of two to four hours. The precipitation during cyclonic storms is in the order of 500mm to 600mm per day, and a cyclonic storm continues for two to three days (Soin 1980). The rainfall recorded from 2nd to 4th October 1968 and 11th to 13th October 1973 was 403mm and 461mm respectively.

Types of Damage and Their Causes

Surface sheet erosion is caused by high-intensity short-duration rainfall on steep slopes comprised of weathered and foliated rocks which are already oversaturated. Gully erosion is caused by the inability of natural channels to cope with heavy discharge resulting from high-intensity precipitation and cloudbursts. Soil mass movement involving the flow of loose soil strata is facilitated through percolation of rainwater and can also be triggered by toe erosion. The rock strata, with joints, folds, and unfavourable dip conditions, activated by percolation of water through the weak planes, causes rockfall. Erosion at the toe of the road, slopes, retaining walls, and toe walls is caused by scouring and further facilitated by heavy rainfall. Toe erosion also causes landslides, and it is aggravated where a meandering river hits the base of the hill slope. In the landslip zone, the subsidence observed is caused by the movement of underlying strata by subsoil flow/runoff.

Remedial Measures

Surface/sheet erosion is treated through good surface drainage and compacting of the soil on the slopes. Catchwater drains, surface drains, turfing, benching of slopes, chemical stabilisation, bituminous mulching, and afforestation have been found to be successful means of arresting landslides.

Gully erosion is controlled through catchwater drains, checkdams, check walls, and drop channels. The walls and drains are founded on unerodable strata, and the drain floor is made impervious.

Mass movement of soil in wet conditions is prevented by constructing retaining structures, surface drains on the strata, catchwater drains, and benching to ease the slopes.

The effect of rockfall is reduced by removing the overburden and overhanging rocks. Easing of slopes has been found to be effective, and breast walls have worked where the overburden is not high. Subsidence has been controlled using deep drains, benching slopes, side drains, and formation filling.

Case History of the Naina Devi Landslide in Himachal Pradesh

The Naina Devi temple, an important Hindu pilgrimage site, and the town of Nainital are situated in one of the Siwalik ranges in Bilaspur district, Himachal Pradesh. The temple is located on the highest peak of the Naina Devi *Dhar* (range) and the town is built on the southwestern slopes. The ridge is separated by a saddle, and to the south of saddle lies a broad valley in which houses are located.

Raju and Jalote (1980) reported the Naina Devi landslide. It rained excessively during the monsoon of 1978. A crack was observed in the floor of the temple warehouse on 1st August 1978, following heavy rains on the previous day. On the following days, a number of cracks were observed in the surrounding areas, including the bus stand. Subsidence or vertical displacement of from 15cm to 30cm was observed on 6th August, and an appreciable widening of the cracks was observed on the following days. The lower spur in the valley, adjacent to a small stream, is reported to have slid on 24th August, following heavy rains. This slide damaged the houses located on the spur and blocked the stream's course. On the morning of the 25th, a widening of the fissures at the bus stand was noticed and the ground mass started moving, slowly threatening the structures. All inhabitants abandoned their houses and moved to safer places in the town. The downward movement of the ground started at seven a.m and, in a span of two hours, the whole mass of debris, 143 structures belonging to 46 families, and a portion of the road and some portions of the steps to the temple were carried down the slope over a distance of 150m.

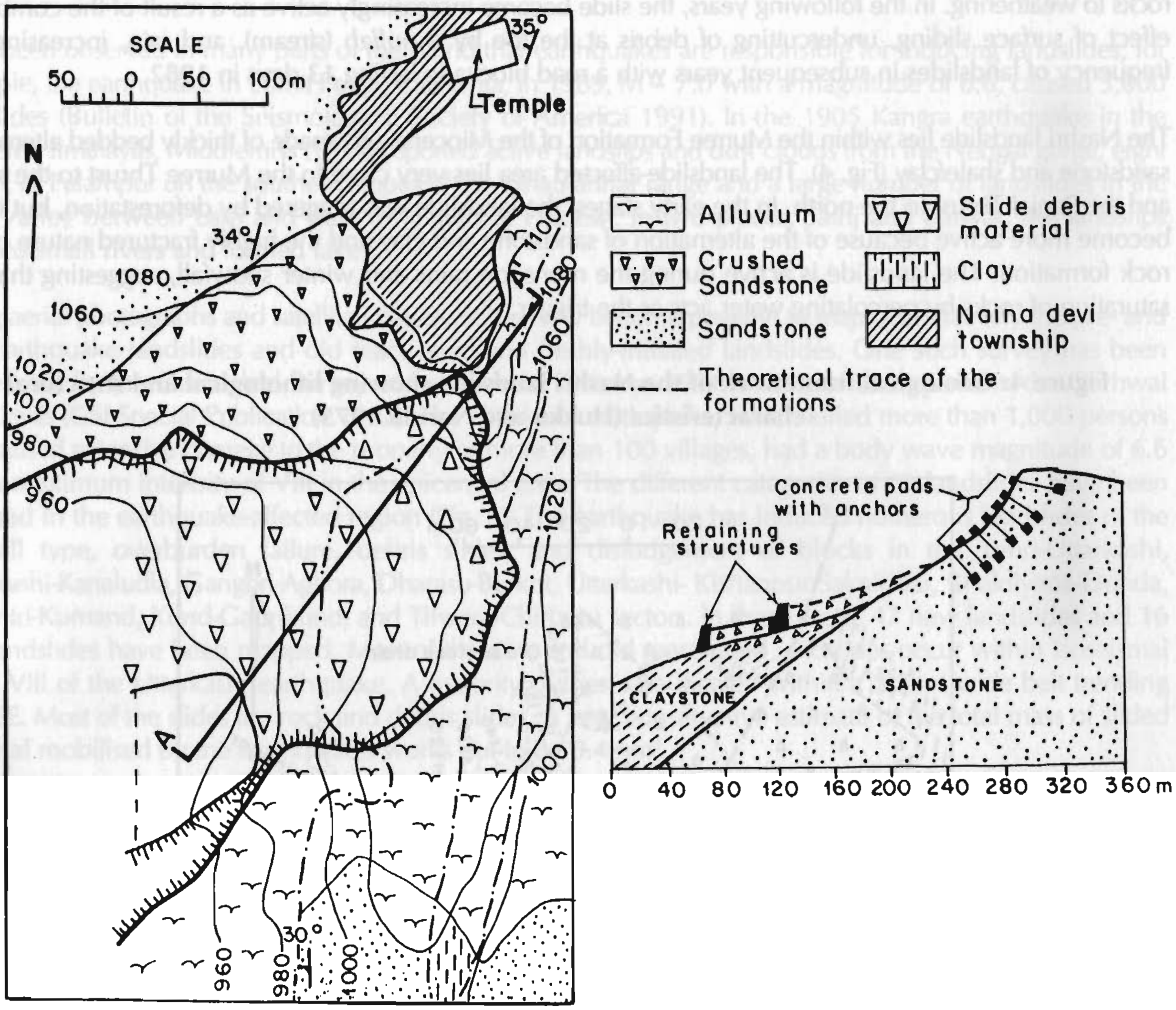
The Naina Devi range, where the temple and town are located, is a linear hill range constituting the southwestern limb of an anticline. The Lower Siwalik formations, comprised of sandstone and claystone, occur on the ridge. The length of the area affected by the slide is 880m and the width is 480m. The slide material is mainly composed of sandstone debris of various sizes, embedded in sandy soil overlying purple claystone. The claystone dips towards the valley at angles ranging from 30° to 35° (Fig. 3). The whole village and the bus stand were originally constructed on this overburden. The area has been stable for a very long time. The landslide was a result of the unprecedented heavy rains that oversaturated the overburden material, resulting in increased weight and porewater pressure and reducing the cohesion and shear strength of the material, especially at the interface of the claystone and overburden.

Remedial measures were suggested by the Geological Survey of India (GSI) team (Fig. 3) in order to stabilise an area of over 20,000sq.m. Retaining structures at locations shown in the figure, with weep holes to allow seepage, were suggested. On steep slopes, where circular failure had occurred in fractured and weathered sandstone, concrete pads with suitable anchors into massive sandstone were suggested. The easing of the slopes, small retaining walls, and proper drainage were recommended for the eastern slopes.

Deforestation and Landslides

Tree roots play an important structural role on hill slopes. The roots, winding through the soil and often penetrating bedrock, add strength to the soil in the same way that steel rods reinforce concrete. When trees

Figure 3: Geological setting of the Naina Devi landslide (upper figure) and remedial measures (lower figure) (Krishnaswamy 1980)



are felled, these roots begin to decay; the hill slope gradually loses its resistance to failure, resulting in landslides. Studies in the Western Cascade Range of Oregon, USA, on clear-felled, unstable, and steep hill slopes, revealed that landslide erosion was 2.8 times greater on such slopes than on comparable forested land (Haigh 1984).

It is estimated, on the basis of satellite imagery, that Uttarakhand, the area covering the hill districts (Kumaon and Garhwal) of Uttar Pradesh, has only 37.5 per cent of its area under forest cover. The deforestation of Uttarakhand has occurred very rapidly in the last five decades, finally reaching alarming proportions and giving birth to the *Chipko* Movement; a movement of the people to save the forests. Deforestation in the Uttar Pradesh Himalayas has also increased floods in the Gangetic plains.

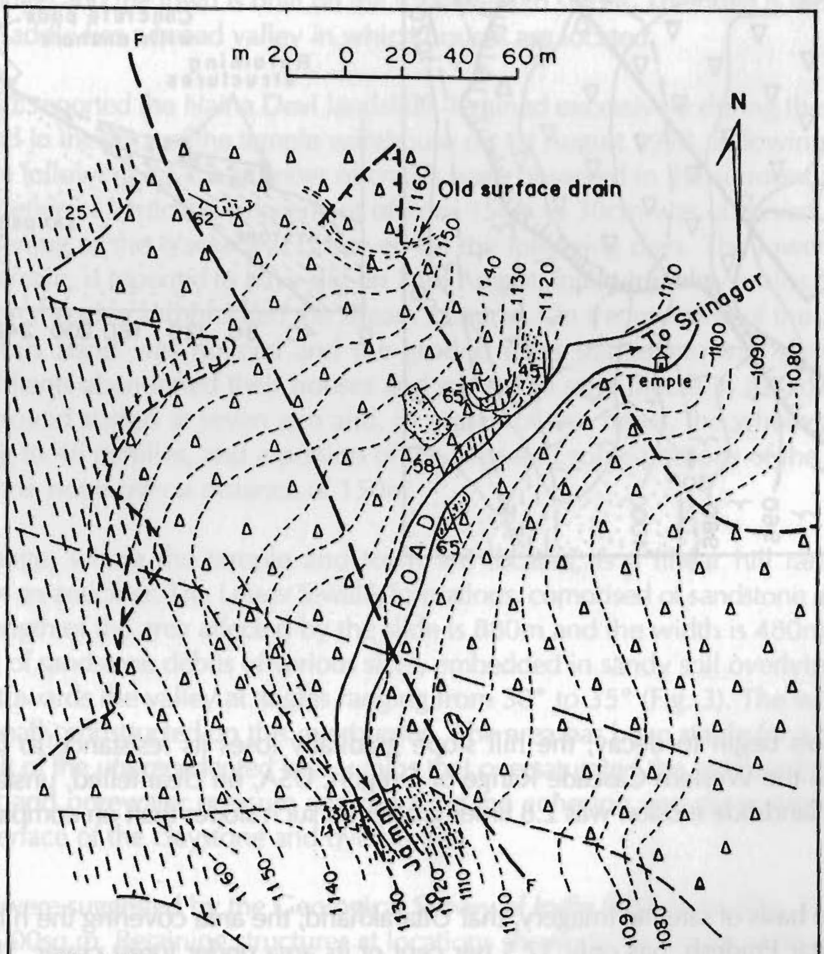
Road construction has been another conspicuous contributor to deforestation, causing massive landslide problems. New hill roads have been built quickly and cheaply across uncharted territory, ancient landslide zones, and active scree slopes. Explosives have been used liberally, and these have opened up fissures in the fractured rock slopes.

Case History of Nashri Landslide

The Nashri landslide is situated 131km from Jammu on the Jammu-Srinagar national highway. This slide has been a major problem for the last 40 years, obstructing vehicular traffic during the monsoon and winter rains. The slide covers an area 400m wide along the road and 1,000m long along the slope. The landslide started in 1953 as a small scar below the road, after a jungle fire destroyed its protective vegetative cover and exposed rocks to weathering. In the following years, the slide became increasingly active as a result of the combined effect of surface sliding, undercutting of debris at the toe by a *nullah* (stream), and rain, increasing the frequency of landslides in subsequent years with a road blockade lasting 13 days in 1982.

The Nashri landslide lies within the Murree Formation of the Miocene age, made of thickly bedded alternating sandstone and shale/clay (Fig. 4). The landslide-affected area lies very close to the Murree Thrust to the south and the Panjal Thrust to the north. In the early stages, the landslide was triggered by deforestation, but it has become more active because of the alternation of sandstone and clay and the highly fractured nature of the rock formation. The landslide is active during the monsoon rains and winter snowfall, suggesting that the saturation of rocks by percolating water acts as the trigger.

Figure 4: Geological framework of the Nashri landslide showing lithological and structural characteristics (Hukku and Narula 1975)



The Central Road Research Institute (CRRI) investigated this slide in June-July 1983, at the request of the Border Road Organisation. The various remedial measures suggested after the investigation include augmentation of surface drainage by constructing a system of catchwater drains, trench drains, chutes, and intercepting drains besides biotechnical stabilisation and installing concrete restraining piles (Fig. 5).

Earthquakes and Landslides

It has been observed in many parts of the world that earthquakes are responsible for inducing landslides; for example, the earthquake in Loma Prieta, California, in 1989, M= 7.0 with a magnitude of 6.6, caused 3,000 landslides (Bulletin of the Seismological Society of America 1991). In the 1905 Kangra earthquake in the Western Himalayas, Middlemiss (1910) reported active landslips and dust clouds from the Neogal gorge, eight km NE of Palampur on the southern slopes of the Dhauladhar range and a large number of landslides in the Beas Valley between Larji and Kulu in Himachal Pradesh. In two places, Sainj and Barwar, the landslips blocked small rivers and formed lakes.

Using aerial photographs and satellite imagery, it has now become possible to map quantitatively the pre- and post-earthquake landslides and old reactivated and freshly-initiated landslides. One such survey has been carried out by the Geological Survey of India for the October 1991 Uttarkashi earthquake in the Garhwal Himalayas (GSI Special Publication 1992). The Uttarkashi earthquake, which killed more than 1,000 persons and caused extensive damage to the property of more than 100 villages, had a body wave magnitude of 6.6 and a maximum intensity of VIII in the epicentral area. The different categories of 63 landslides have been mapped in the earthquake-affected region (Fig. 6). The earthquake has induced numerous landslides of the rockfall type, overburden failure, debris slides, and dislodgement of blocks in the Tehri-Uttarkashi, Uttarkashi-Kanaludia, Gangori-Aghora, Dharasu-Burkot, Uttarkashi- Kishanpur Saknidhar, Bhaldiyana-Dunda, Phauntri-Kumand, Kund-Gaurikund, and Tilwara-Chirbutu sectors. In these areas, 47 new landslides and 16 old landslides have been mapped. Most of the new and old reactivated landslides occur within isoseismal Zone VIII of the Uttarkashi earthquake. A majority of these are located within a 2.5km wide belt trending NW-SE. Most of the slides are rock and debris slides. A very conservative estimate of the total mass of slided material mobilised by the earthquakes works out to be 0.4mm^3.

Geology and Landslides

Lithology and structural characteristics are the two main factors in geology which influence landslides. Lithology means rock type and structural characteristics include geometry and the mechanical properties of joints, bedding planes, faults, and folds. Laban (1979), following an airborne reconnaissance survey of Nepal, concluded that geological structure and lithology accounted for more than 75 per cent of all observed landslides. A similar conclusion was arrived at in part of the Garhwal Himalayas by Joshi (1987). Haigh (1984) observed that instability along the roads in the Garhwal Himalayas was influenced by joints and bedding planes dipping out of slopes. Based on his own study in the Middle Himalayas in Nepal and on reviewing the findings of other workers, Gerrard (1994) concluded that geology and human activities play a considerable role in triggering landslides in the Himalayas.

In the Himalayas, the Main Central Thrust, Main Boundary Thrust, and Himalayan Frontal Thrust are the principal thrust faults which are neotectonically active. All these thrust zones have a predominant influence on landsliding and many of the larger and catastrophic landslides are associated with movements along these thrusts (Nakata 1982, Valdiya 1985).

According to Bartarya and Valdiya (1989), lithology is the most important factor governing landslides in the Gaula catchment area of Nainital in the Kumaon Himalayas, but the localisation of landslides within lithologies is the result of fractures, shear zones, and dip of the beds. In their (Bartarya and Valdiya's) study area, the granites, quartzites, and basic volcanics are most prone to landsliding. The volcanic rocks and quartzite of the Bhowali and Blaini formations have caused 189 landslides; the Amritpur granite, 108 landslides; and the sandstone of the Siwaliks and schist of the Ramgarh Group, 49 landslides. Landslide density also varies with respect to geological formations, e.g., the Amritpur granite has the greatest density of landslides (2.6/km^2), followed by the Infrakrol Formation (2.33/km^2), the Bhowali quartzite (1.58/km^2), and the Siwalik Group (1.12/km^2).

Figure 5: Control measures adopted for the Nashri landslide

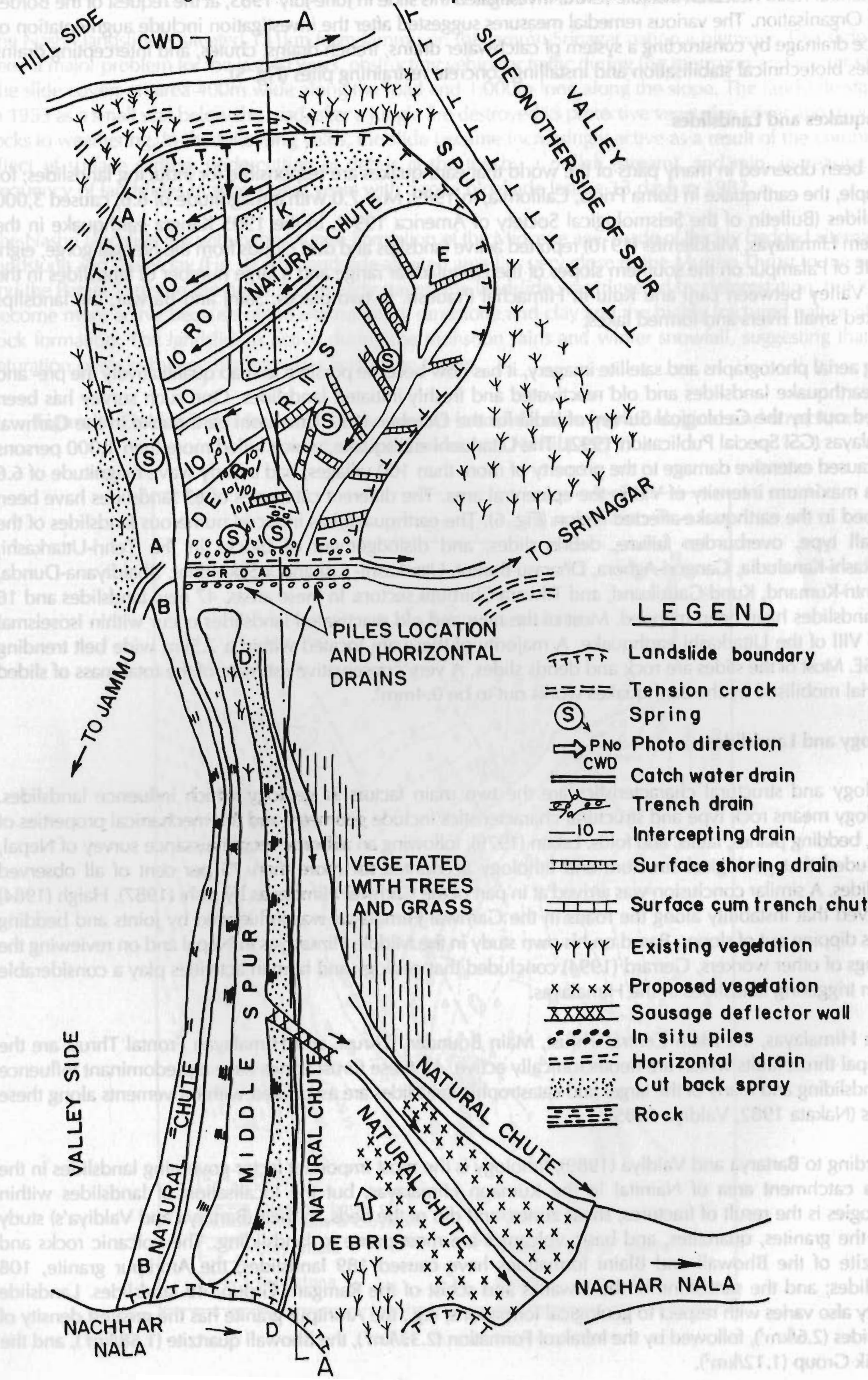
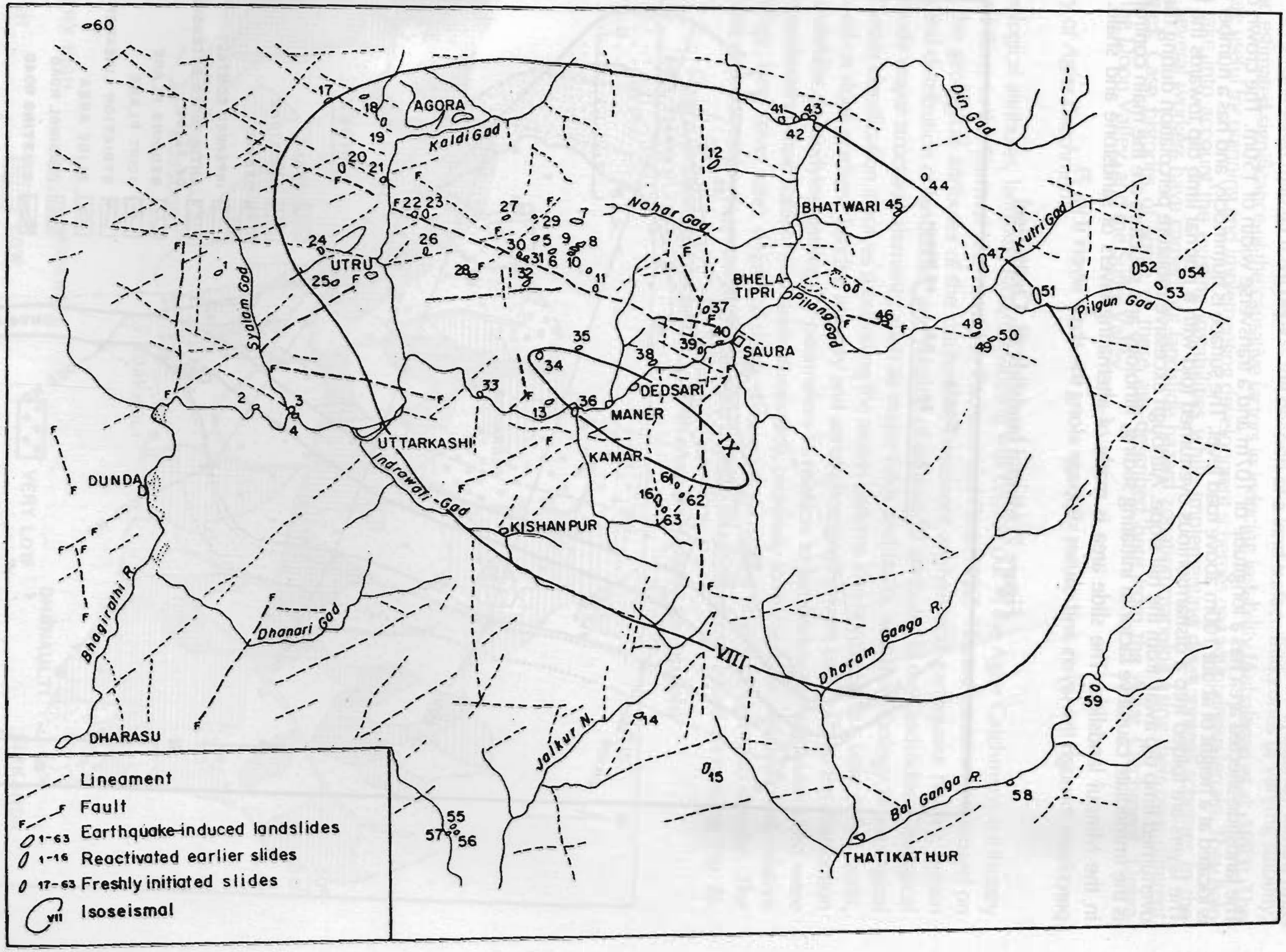


Figure 6: Map showiong October 1991 Uttarkashi earthquake-induced landslides based on pre- and post-earthquake IRS list II FFC imagery and aerial photographs (October 1991 Uttarkashi earthquake, Geological Survey of India 1992)

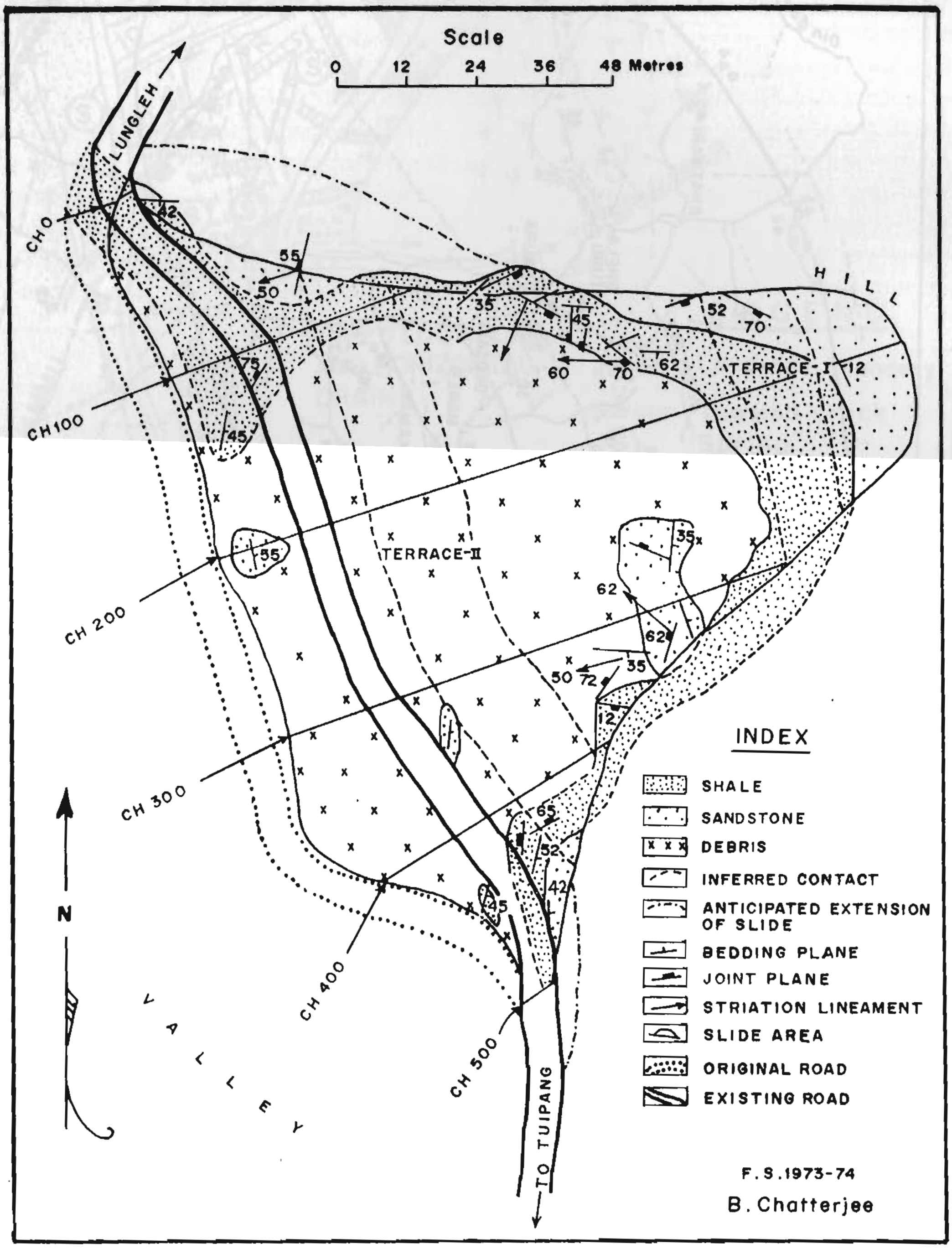


Case History of the Minpui Slide

The Minpui slide is located at milestone 23 on the Lungleh - Tuipang road in Mizoram in the NE region. The landslide was triggered during five days of 140mm of heavy monsoon rains and was preceded by a severe earth tremor (Chatterjee 1975). The slide is activated during the monsoon months.

The landslide-affected area has a longitude of 107m and a transverse width of 150m. The crown of the slide is located at a height of about 100m above road level. The surface is hummocky and has a number of terraces. The layers are folded into a disharmonious overturned fold with a normal limb dip towards the hill and an overturned limb dip away from the hill slope. Although excessive moisture percolation during the monsoon is the immediate causative factor in initiating sliding, lithology and structure are the main controlling factors in the Minpui landslide. The slide area is made of alternating layers of sandstone and shale. Rainwater percolates through the layers and causes slippage along the shale layers (Fig. 7).

Figure 7: Minpui landslide (B. Chatterjee)



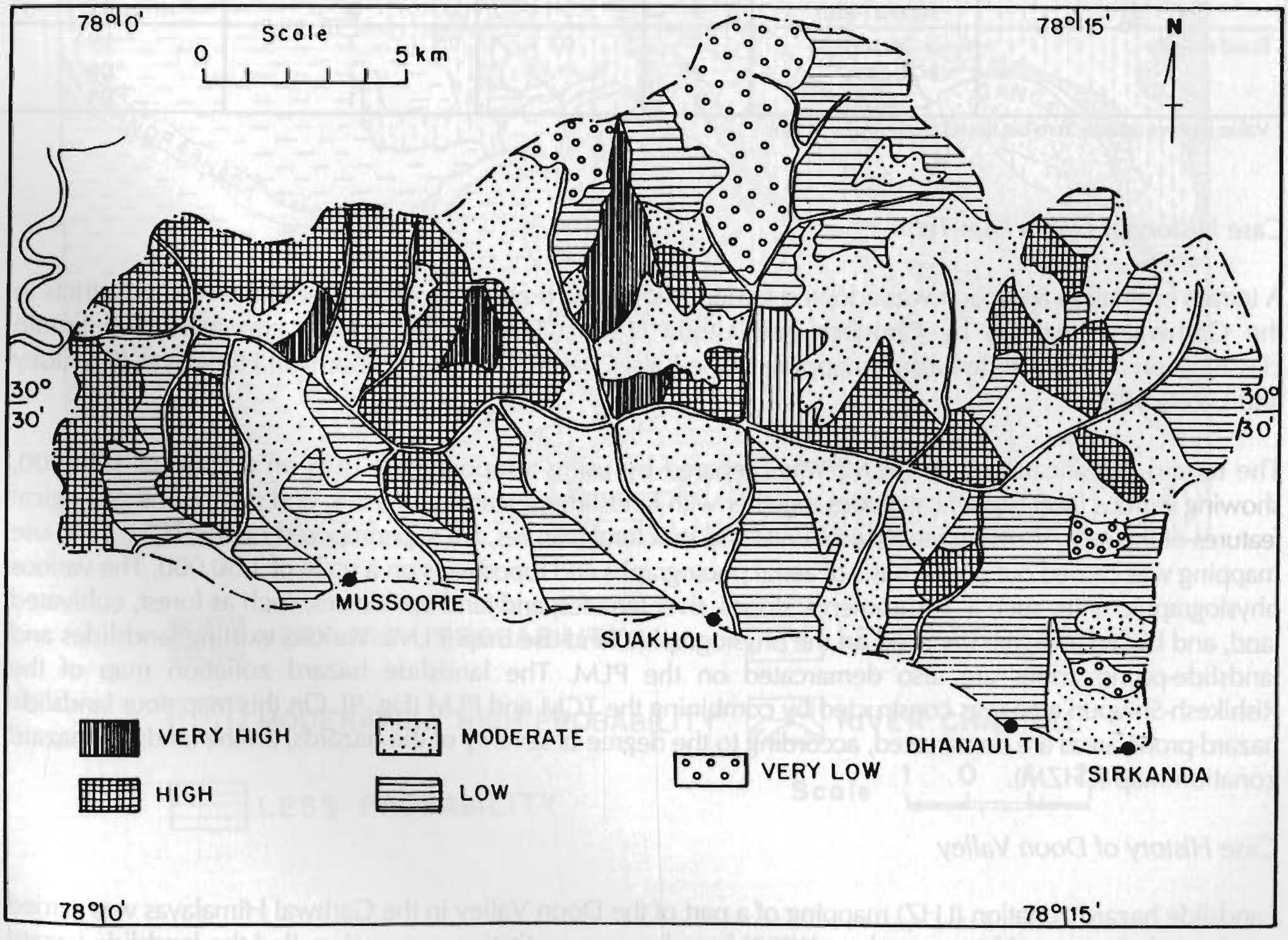
Landslide Hazard Zonation

A landslide hazard zonation map (LHZM) depicts the division of a land surface into zones of varying stability, based on the estimated significance of the causative factors in inducing instability (Anbalagan et al. 1993). The LHZ maps are useful for planning and implementing development schemes on mountainous terrain. They help planners to take into account the existing instabilities while implementing development schemes in the mountains. Several workers have carried out landslide hazard zonation mapping using their own different methodologies. Case histories of some of these are described here from the Aglar Catchment, Dehra Dun-Tehri, the Doon Valley, and the Sutlej Valley.

Case History of Aglar Catchment

Based on geological attributes, landslide hazard mapping was carried out in the Aglar Catchment, a tributary of the Yamuna River in the Garhwal Himalayas, by Pachauri and Pant (1992). Hazard zonation is assessed on the basis of the geological attributes of the catchment, lineament analysis and earthquake history, terrain classification and distribution of landslides, and relation of geological attributes to the landslides. Geological attributes include major structural elements, such as major folds and faults, and the lithology of geological formations. Terrain classification involves subdividing the terrain patterns into homogeneous units called facets, which are based on slope gradient. Landsat imagery and aerial photographs were used to map the distribution of existing landslides. In studying geological parameters in relation to landslides, the attributes used were geotechnical parameters (slope stability and slope kinematics), proximity to major faults, relative relief, relative altitude, lithology, land cover (use), degree of slope, distance from nearest ridge top, and road density. The landslide hazard zonation map was prepared on the basis of a classification system based on ranking (Fig. 8).

Figure 8: Landslide hazard zonation map (ref. above paragraph)



To quantify the zonation, a weighting and rating system was used, as described in Table 1 overleaf.

Table 1: Weighted Landslide Hazard Rating System in the Aglar Catchment (after Pachauri and Pant 1992)

Factor	Class	No.	Weighting	Class rating	Weighted rating
Geological factor	Dip slopes				
	Non-dip	1	11	2	22
	slopes	2		0	00*
Distance from active fault	0-2km	1	10	4	40
	2-4km	2		3	30
	4-6km	3		2	20
	6-8km	4		1	10
	>8km	5		0	0*
Slope angle	> 40°	1	09	4	36
	30-40°	2		3	27
	20-30°	3		2	18
	10-20°	4		1	09
	< 10°	5		0	0*
Relative relief	> 800m	1	08	5	40
	600-800m	2		4	32
	400-600m	3		3	24
	200-400m	4		2	16
	0-200m	5		1	8
Geological formation	Main rock				
Nagthat Krol Blaini	quartzite	1	07	4	28
Chandpur Land cover	limestone	2		3	21
	boulder slate	3		2	14
	phyllite	4		1	7
	Sparse vegetation	1	06	3	18
	Cultivated land	2		2	12
	Forested land	3		1	06
Distance from ridge top	0-900m	1	06	3	15
	900-1800m	2		2	10
	1800-2700m	3		1	05
Road density	> 2km/km²	1	03	3	09
	1-2km/km²	2		2	06
	< 1km/km²	3		1	03

* Value is never actually zero but the relatively lowest in rank.

Case History of Dehra Dun-Tehri

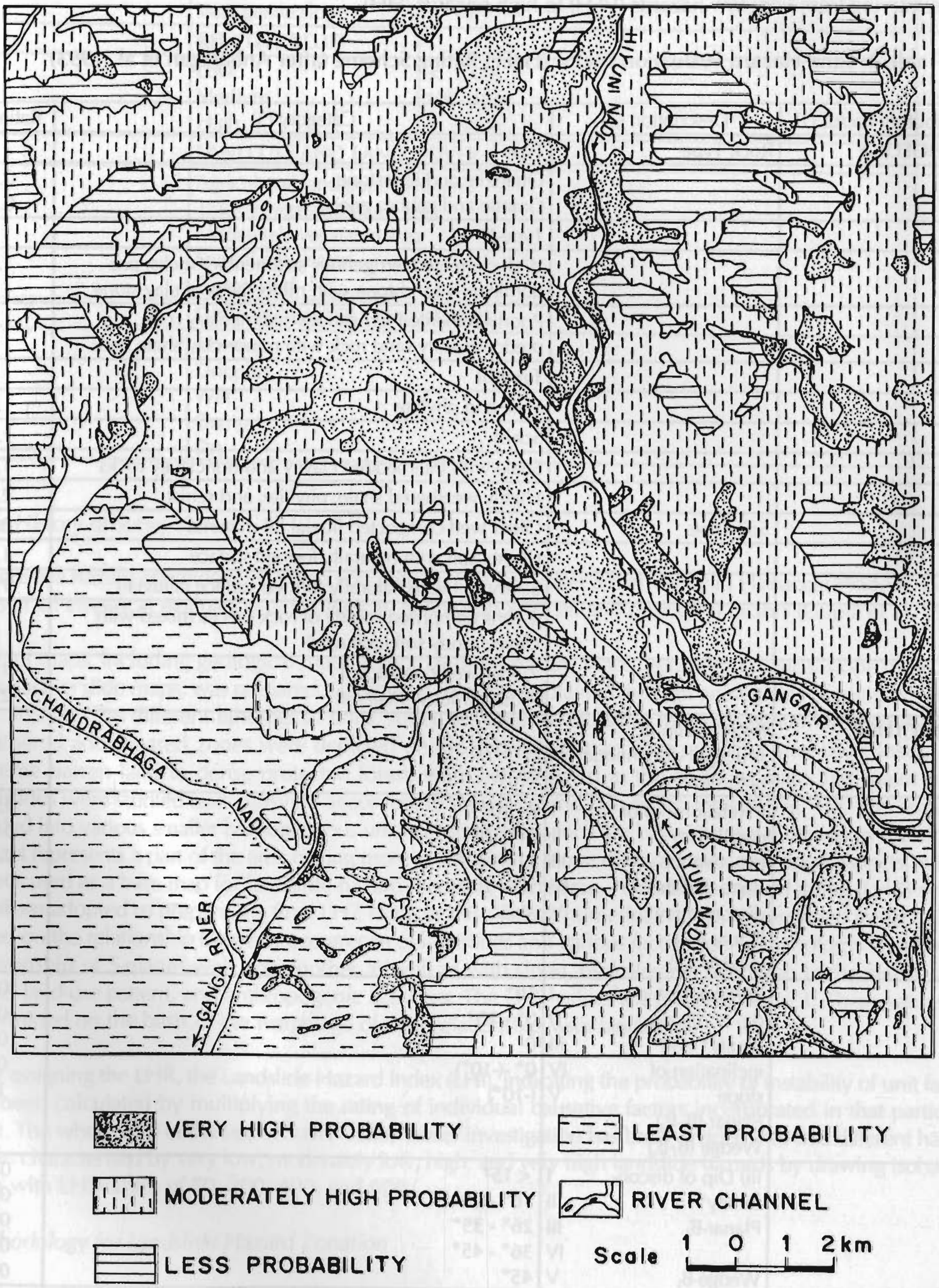
A terrain evaluation approach was adopted for landslide hazard zonation of the Dehra Dun-Tehri districts in the Garhwal Himalayas by Choubey and Litoria (1990). These authors have also attempted terrain classification and landslide hazard mapping in the Kalsi-Chakrata area in the Garhwal Himalayas (Choubey and Litoria 1990).

The terrain classification map (TCM) was prepared by using a topographic map on a scale of 1:50,000, showing various facet (slope) categories together with landslides, escarpments/cliffs, and ridges. The geological features of the area, showing lithological units and structural features, are superimposed on the TCM. Land-use mapping was carried out on the basis of aerial photographs and toposheets on a scale of 1:50,000. The various physiographic units, such as escarpments, slopes, river terraces, and land-use classes, such as forest, cultivated land, and barren area, are depicted on the physiographic land-use map (PLM). Various existing landslides and landslide-prone zones are also demarcated on the PLM. The landslide hazard zonation map of the Rishikesh-Shivpuri area was constructed by combining the TCM and PLM (Fig. 9). On this map, four landslide hazard-prone areas are demarcated, according to the degree of severity of the hazards, on the landslide hazard zonation map (LHZM).

Case History of Doon Valley

Landslide hazard zonation (LHZ) mapping of a part of the Doon Valley in the Garhwal Himalayas was carried out by Anbalagan and his co-workers (1993) based on a quantitative approach called the landslide hazard evaluation factor (LHEF).

Figure 9: Landslide Hazard Zonation map of Rishikesh-Shivpuri area in the Garhwal Himalayas (Choubey and Litoria 1990)



Landslide hazard mapping of the Maldeota-Sahastardhara area of Doon Valley involved, in the first stage of preparation, a series of maps on slope, facet, lithology, structural features, slope morphometry, relative relief, land use, land cover, and hydrology. The maximum LHEF ratings for different categories are determined in these maps on the basis of their estimated significance in causing instability. The rating value was given on the basis of the land hazard evaluation factor described in Table 2. The LHZ map shows four categories of hazards, varying from very low hazards (VLH) to high hazards (HH).

Table 2: Land Hazard Evaluation Factor (LHEF) Rating Scheme (after Anbalagan et al. 1993)

Contributory Factor (1)	Description (2)		Category (3)	Rating (4)
A. LITHOLOGY	Rock Type		**Type-I**	
			Quartzite and limestone Granite and gabbro gneiss	0.2 0.3
			Type-II	
			Well-cemented terrigenous sedimentary rocks, predominantly sandstone with minor beds of clay stone	1.0
			Poorly-cemented terrigenous sedimentary rock, predominantly sand rock with minor clay shale beds	1.3
			Type-III	
			Slate and phyllite	1.2
			Schist	1.3
			Shale with interbedded clayey and nonclayey rocks	1.8
			Highly weathered shale, phyllite, and schist	2.0
	Soil Type		Older well-compacted fluvial fill material	0.8
			Clayey soil with naturally formed surface	1.0
			Sandy soil with naturally formed surface (alluvial)	1.4
			Debris comprised mostly of rock pieces mixed with clayey/sandy soil (colluvial)	
			-Older well compacted -Younger loose material	1.2 2.0
B. STRUCTURE	Relationship of structural discontinuity with slope			
	i) Relationship of parallelism between the slope and the discontinuity* Planar (s-s) Wedge (i-s)	I II III IV V	> 30° 21° -30° 11° - 20° 6° - 10° < 5°	0.20 0.25 0.30 0.40 0.50
	ii) Relationship of dip of discontinuity* and inclination of slope Planar (B_j-B_s) Wedge (B_i-B_s)	I II III IV V	10° 0° - 10° 0° 0° -(-10°) (-10°)	0.3 0.5 0.7 0.8 1.0
	iii) Dip of discontinuity* Planar-B_j Wedge-B_i	I II III IV V	<15° 16° - 25° 26° - 35° 36° - 45° 45°	0.20 0.25 0.30 0.40 0.50
	Depth of Soil cover		5m 6-10m 11-15 16-20m 20m	0.64 0.85 1.30 2.0 1.20

	SLOPE MORPHOMETRY		
	Escarpment/cliff	> 45°	2.0
	Steep slope	36°-45°	1.7
	Moderately steep slope	26°-35°	1.2
	Gentle slope	16°-15°	0.8
	Very gentle slope	< 15°	0.5
	RELATIVE RELIEF		
	Low	< 100m	0.3
	Medium	101-300m	0.6
	High	> 300m	1.0
	LAND USE AND LAND COVER		
	Agricultural land/populated land		0.65
	Thickly-vegetated forest area		0.80
	Moderately-vegetated area		1.2
	Sparsely-vegetated		1.5
	Barren land		2.0
	GROUNDWATER CONDITIONS		
	Flowing		1.0
	Dripping		0.8
	Wet		0.5
	Damp		0.2
	Dry		0.0

Case History of Sutlej Valley

A landslide hazard zonation (LHZ) map was prepared for the upper Sutlej Valley in Himachal Pradesh, on the basis of an empirical evaluation of geological, geomorphological, and biological factors (Gupta et al. 1993).

A set of maps, including geological maps, major land-use pattern maps, geomorphological slope maps, and major active slide maps, was prepared. Geological data were obtained through geological mapping on a scale of 1:50,000. The different lithological units, structural features, old slide material, quaternary deposits, and weathered and sheared zones were depicted on the geological map. Five principal land-use classes, from extreme barren land to dense protected forest, were incorporated in the land-use map. The major active landslides were studied and classified according to their type and rate of movement (Fig. 10). The area was divided into various smaller homogeneous units called facets, which are based on the direction of the slopes. A facet represents a part of the area having more or less similar slope characteristics and slope aspects. A facet map is used as a base map for landslide hazard mapping of the area. A landslide hazard rating (LHR) system has been adopted to prepare the final LHZ map. In this system, numerical values are assigned to each facet, based on the relationship between occurrence of landslides and various factors such as lithology, weathering, relationship of S-planes with one another as well as with slope, hydrological condition of the slope, slope angle, land-use pattern, and anthropogenic activities. The LHR values are given in Table 3. These values are determined on the basis of the weightage of their relationship with landslides.

After assigning the LHR, the Landslide Hazard Index (LHI), indicating the probability of instability of unit facets, has been calculated by multiplying the rating of individual causative factors incorporated in that particular facet. The whole area of the upper Sutlej Valley under investigation has been divided into five different hazard zones characterised by very low, moderately low, high, and very high landslide hazards by drawing isohazard lines with LHI values of 50, 200, 400, and 600.

Methodology for Landslide Hazard Zonation

Under a coordinated programme for the study of landslides, the Department of Science and Technology, Government of India, constituted a group to prepare a standard methodology for landslide hazard zonation. This group has prepared a report (Department of Science and Technology 1994), and the methodology adopted for this report is described here.

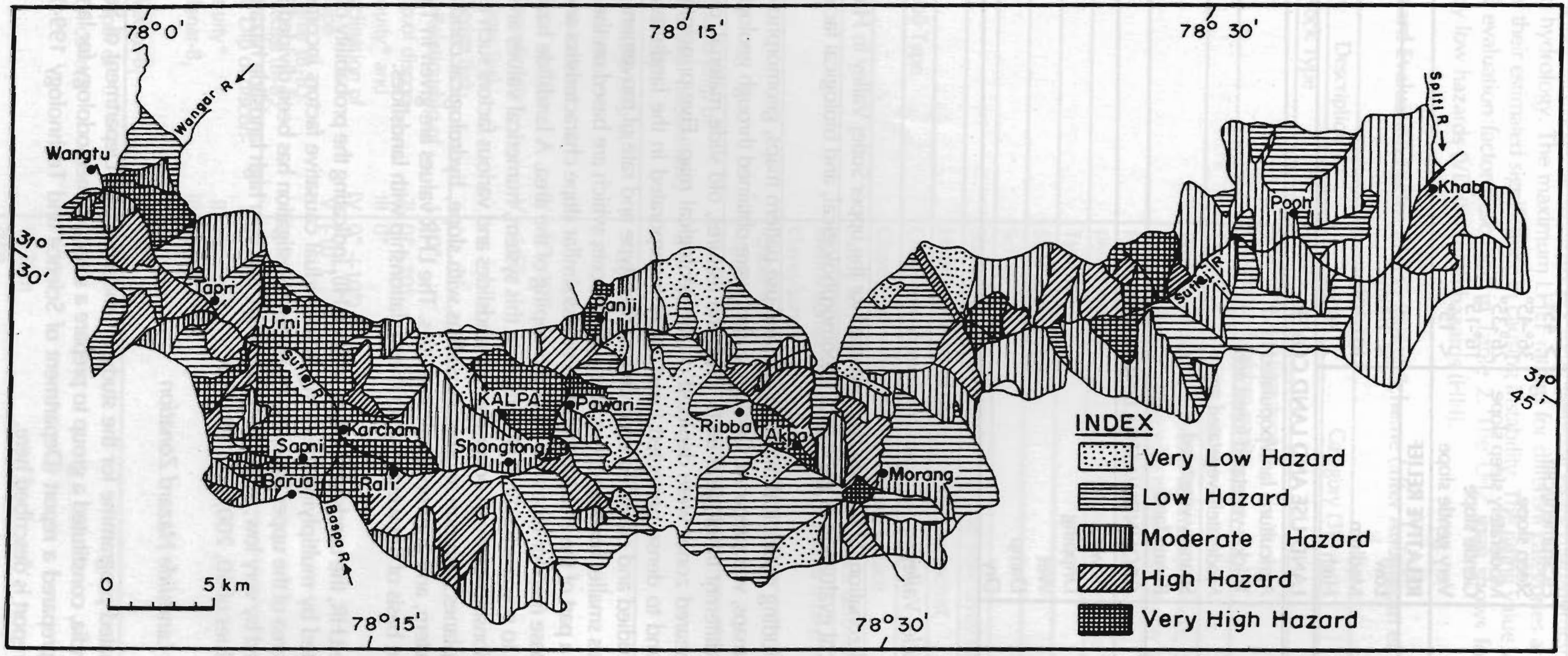


Figure 10: Landslide Hazard Zonation map along Sutlej Valley, Kinnaur District, Himachal Pradesh (Gupta et al. 1993)

Table 3: Landslide Hazard Rating System in the Upper Sutlej Valley of H.P. (after Gupta et al. 1993)

Factor	Class	Weighted Rating
Lithology	Augen gneiss, porphyritic gneiss, granitic gneiss, hard quartzite, migmatites	1
	sandstone, granite	2
	slate, phyllite, mica schist	3
	slate, phyllite, mica schist interbedded with clay	4
	clay, soil, loose material	5
Weathering	Fresh rock	1
	Slightly weathered; absence of any weathered material (Rock fabric is not altered)	2
	Moderately weathered; presence of leached material along joint planes (Rock fabric is altered on the surface only)	3
	Highly weathered; presence of leached material on the surface (rock fabric is altered up to a depth of a few cm)	4
Relationship of planes with one another as well as with the slope	(a) When the intersection of S planes plunges in the direction of the slope plunge of line of intersection	
	0-20	2
	20-40	3
	40-60	4
	> 60	5
	(b) When the intersection of S planes plunges away from slope plunge of line of intersection	
	> 60	2
	40-60	3
	20-40	4
	> 20	5
Hydrological condition	Dry slope	1
	Presence of streams, canals, springs on the lower slope	2
	Toe cutting of lower slope	3
	Presence of streams, canals, springs on the middle slope	4
	Presence of streams, canals, springs on the upper slope	5

Preparation of Thematic Maps

The various factors that contribute to instability are lithology, structure, slope, relative relief, hydrology, land use, and land cover pattern. Different thematic maps can be prepared on a scale of 1:50,000 using aerial photographs, satellite imagery, and field investigation.

Lithological Map

A geological map should show the different lithologies in the area. Lithology is an important factor and includes composition, texture, degree of weathering, and other attributes such as the consolidated or unconsolidated nature of sediments that influence the physical behaviour of rocks. A lithological map should show the geological setting, including the nature and types of rocks present.

Structural Map

Geological structures include major faults, folds, bedding, foliations/schistosity, joints, shear zones, and non-conformity. These structures can be plotted on the lithological map and, in my opinion, there is no need to prepare a separate structural map. The degree of fracturing, shearing, attitude of bedding or jointing in relation to slope, and nearness to active fault zones are also important factors in determining slope stability. Information on structures can be generated through field work, by incorporating already existing information, and also from aerial photographs and satellite imagery.

The seismic status of the region, including past earthquakes, locations of their epicentres, and their intensity zones in the map, can have an added significance for evaluating landslide hazards.

Slope Map

A slope map divides the terrain into small facets of varying slope angles. All facets are to be marked with the slope direction. It is proposed that the slopes be classified into six categories, viz., 15°, 16-25°, 26-35°, 36-45°, 46-60°, and above 60°.

Relative Relief Map

The difference between the highest and the lowest values of contours (altitude) defines the relative relief. A high value for relative relief indicates faster uplift, presence of active faults, and relatively strong competency contrasts of lithologies in the area. Lower reliefs owe their origin to the maturing of the topography and slower uplift. A relief map can be prepared with the help of toposheets. It classifies the terrain into various zones representing the range of relief.

Hydrological Map

First a drainage map of the area is prepared with the help of toposheets. The various basins are demarcated on the drainage map, and the morphometric parameters, particularly the drainage density values of each basin, are determined. Hydro-geological data, such as springs, seepage zones, ponds, and reservoirs, are incorporated in the map. Rainfall data and groundwater levels are also useful additional inputs for the hydrogeological map. The surface indication of groundwater, such as damp, wet, dripping, and flowing conditions, are used for rating purposes.

Land-use and Land-cover Map

The type of land cover and land use affects the stability of the slopes on mountainous terrain. Barren and sparsely-vegetated areas show faster erosion and greater instability than reserve or protected forests. Forests and thick vegetation cover generally reduce the effects of erosion and weathering. A well-spread root system increases the shearing resistance of slope material. Agricultural land may be considered stable due to repeated water charging for cultivation purposes. The rating is given on the basis of intensity of vegetation cover.

A land-use and land-cover map of an area of terrain can be prepared using aerial photographs, satellite imagery, and field investigation. Five categories are classified on the basis of different land-use patterns, e.g., dense forests, moderate forests, sparse vegetation, barren land, agricultural land, and populated areas.

Also, a separate landslide inventory map can be prepared that will depict both the active and old landslides. Since this map can be prepared using aerial photographs, satellite imagery, and field investigation, it is more appropriate that the inventory of landslides is also incorporated in the land-use and land-cover map.

Landslide Hazard Rating (LHR)

An LHR is a numerical scheme based on the major causative factors of slope instability such as geology, slope and relative relief, land use and land cover, and hydrological conditions. The LHR rating for different thematic maps is assigned on the basis of the estimated risks of their causing instability that leads to landslides.

The rating (LHR) number is assigned on a scale of one to 20, on the basis of the evaluation of the nature of features for each thematic parameter (map) as described in Table 4.

Table 4: Assigned Rating of Various Thematic Maps (after DST Report 1993).

Thematic Maps		Features to be studied	Rating (LHR)
Lithology	*	Rock types	20
	*	Extent of weathering	
	*	Soil types	
	*	Thickness of soil cover	
Structure	*	Major thrust and fault (nearness to a tectonically-active zone)	20
	*	Geological discontinuities, including bedding, joints, foliations and fractures, etc and their relationship with slope/aspect	
	*	Effect of seismicity	
Slope and Relative	*	Slope angle	20
Relief	*	Local relief	
	*	Surface drainage (drainage density)	20
Hydrology			
	*	Seepage zones	
	*	Spring points	
	*	Ponds, lakes, water bodies, etc	
	*	Toe erosion	
	*	Rainfall/cloudburst	
	*	Groundwater level	
Land use/Land cover	*	Forest cover	20
	*	Agricultural land	
	*	Barren slope	
	*	Human habitation	
Total			100

Data Analysis

There can be two approaches to the analysis of data required for preparing landslide hazard zonation maps. One approach is the superimposition method which obtains the total landslide hazard rating by overlaying all the factor maps one by one. All the thematic maps are successively overlain and every time the total hazard rating value for each facet is added (a facet is a part of the hill slope which has more or less similar slope characteristics, showing consistent slope direction and inclination). Finally, a map showing various facets of different landslide hazard rating values is obtained. Based on this, the categorisation of the area is carried out in terms of instability.

Another approach to obtaining the total landslide hazard value of the area is to divide each thematic map into square grids of four sq.cm. each and mark all the grids with numbers, which should be the same in all maps. For each grid in each map, the LHR of different factors is marked. Finally, the total landslide hazard rating (LHR) of different grids is obtained by adding the LHR values collected from different maps for each grid. The minimum and maximum values of the LHR will give the range, which may be categorised in terms of instability. Wherever it is not feasible to collect data to determine LHR in four sq.cm.grids, it is better to further divide the area into four equal grids.

Investigators may select any of the two above-mentioned approaches to analyse the data needed for preparing final landslide hazard zonation maps. However, the facet concept has an advantage in that it indicates the smallest mapping unit which has a definite boundary.

Landslide Hazard Zonation

To divide the area into different hazard-prone zones, the range of TLHR obtained is categorised into five divisions in terms of instability, namely, very high, high, moderate, low, and very low, for the purpose of preparing landslide hazard zonation maps. Thus, a final landslide hazard zonation map of the terrain is prepared which will broadly show different areas or zones of the hill slopes, based on the nature of their instability. This map will be useful for better land-use planning of any development activity.

The methodology described above is simple and can easily be adopted by the investigators engaged in hazard zonation mapping. The final hazard zonation map should reflect the intensity of hazard potential of the terrain. The investigator may modify the methodology if necessary, depending upon the conditions of the terrain and geo-environmental factors. It is recommended that a landslide hazard rating system be used for preparing pre-feasibility reports of development projects in hilly areas.

Control Measures

In the past, control measures for landslides were essentially based on individualistic approaches for the qualitative assessment of the situation and experience. In India, in recent years, a more professional and multidisciplinary approach has been followed in terms of control measures involving proper analysis, both in the field and laboratories, of geological conditions, engineering characteristics of soil and rocks, and geomorphological and hydrological statuses. The highly heterogeneous nature of these parameters makes it difficult to obtain a high degree of standardisation in landslide control measures.

The Central Road Research Institute (1992) and the Central Soil and Materials Research Station (1993) have prepared state-of-the-art reports on landslide control or corrective measures currently commonly practised in India. The control measures and case history of some landslides in India, as given in these reports, are described here. The landslide control measures can be classified as: drainage measure, surface treatment, soil stabilisation, positive and self-supporting measures, and geometric methods.

Drainage Measures

Drainage can be surface or sub-surface, both contributing to the destabilisation of slopes. A proper survey of the geohydrological regimes of affected hillsides is a prerequisite for deciding the type and method of drainage to be used. There are several methods available for reducing the potentiality factor for slope stability.

Surface Drainage

The control of surface runoff is the most important factor in stabilising slopes. Surface runoff causes erosion and its percolation through the ground increases porewater pressure within the slope material, both contributing to instability of hillside slopes. Surface drainage is controlled by maximising the runoff from unstable areas and constructing drains. There are several types of drains for collecting and diverting surface runoff, e.g., a) catchwater drains, b) roadside drains, and c) cross drains.

Catchwater Drains

The surface water flowing from hill slopes towards potential unstable areas is the main problem in the drainage of hill slopes during heavy rains. Catchwater drains are constructed to collect and divert the water from the hill slope. The locations of the drains should be decided after studying the geomorphological conditions of the slopes. In the case of large slide areas, a number of interconnecting water drains is more effective. The water from catchwater drains should be diverted into chutes or natural hillside drains. Catchwater drains should be lined and properly maintained, and they can be given a gradient of from one in 50 to one in 33.

Roadside Drains

Roadside drains are provided on the roadsides at the foot of hill slopes to drain out water from the road surface as well as the portion of the hill slopes below the catchwater drains. In the hilly region, where the road is not adequately wide, roadside drains can be built in such a way that they function as drains as well as part of the road surface. Roadside drains are constructed of dry rubble stone masonry and they can be square, semicircular, trapezoidal, triangular, or V-shaped in sections.

Cross Drains

Cross drains are provided where streams cross the roadway. The water from the side drains is taken across by cross drains to divert the water from the road to a water course or valley. Cross drainage should be provided at frequent intervals in order to reduce the volume of water in catchwater and side drains. The number of cross drains, including scuppers, varies from four to eight per kilometre depending upon the nature of the terrain. Cross drains should be provided at every crossing point of natural *nullah*(s) (stream) and water. The cross drainage structures normally used are culverts, scuppers, causeways, and minor or major bridges.

Subsurface Drainage

Subsurface water increases the porewater pressure in subsoil rock material and weakens the fractures and bedding/foliation planes, thereby reducing the stability of the slope mass. Several landslides in the Himalayan region take place as a result of the circulation of subsurface water during the monsoons. Although the removal of water from within a slope by subsurface drainage incurs more expenditure than surface drainage, subsurface drainage is more effective in reducing porewater pressure along weak failure planes. The removal of subsurface water tends to bring about a more stable condition by way of decrease in seepage forces, increase in shear strength, and reduction in pore pressure and driving forces. In dealing with subsurface water, the foremost task is to intercept the subsurface flows above the sliding mass. Subsurface drainage is also useful for slope cuttings and under proposed embankments. Subsurface drainage is carried out by installing horizontal drains, vertical wells, deep trench drains, and drainage tunnels. These drains are meant to remove excess subsurface water and reduce the saturation within hillside slopes.

Horizontal Drains

Horizontal drains are constructed of perforated PVC pipes, 50mm in diameter. The pipes are installed at a negative of 5°to 15° to the horizontal, into a hill or embankment, to drain out the groundwater. These drains serve as additional drainage channels for the hill slopes and facilitate the removal of water from subsoil with poor permeability.

The upper two thirds of the pipe section is perforated or slotted. A lightweight conventional rotary drill is used to make horizontal boreholes into which the slotted PVC pipes are inserted. The groundwater flows into the pipes through perforations/slots. Water drained out from each row of drains is collected in a lined catchwater drain and discharged at a suitable surface-drainage point.

Deep Trench Drains

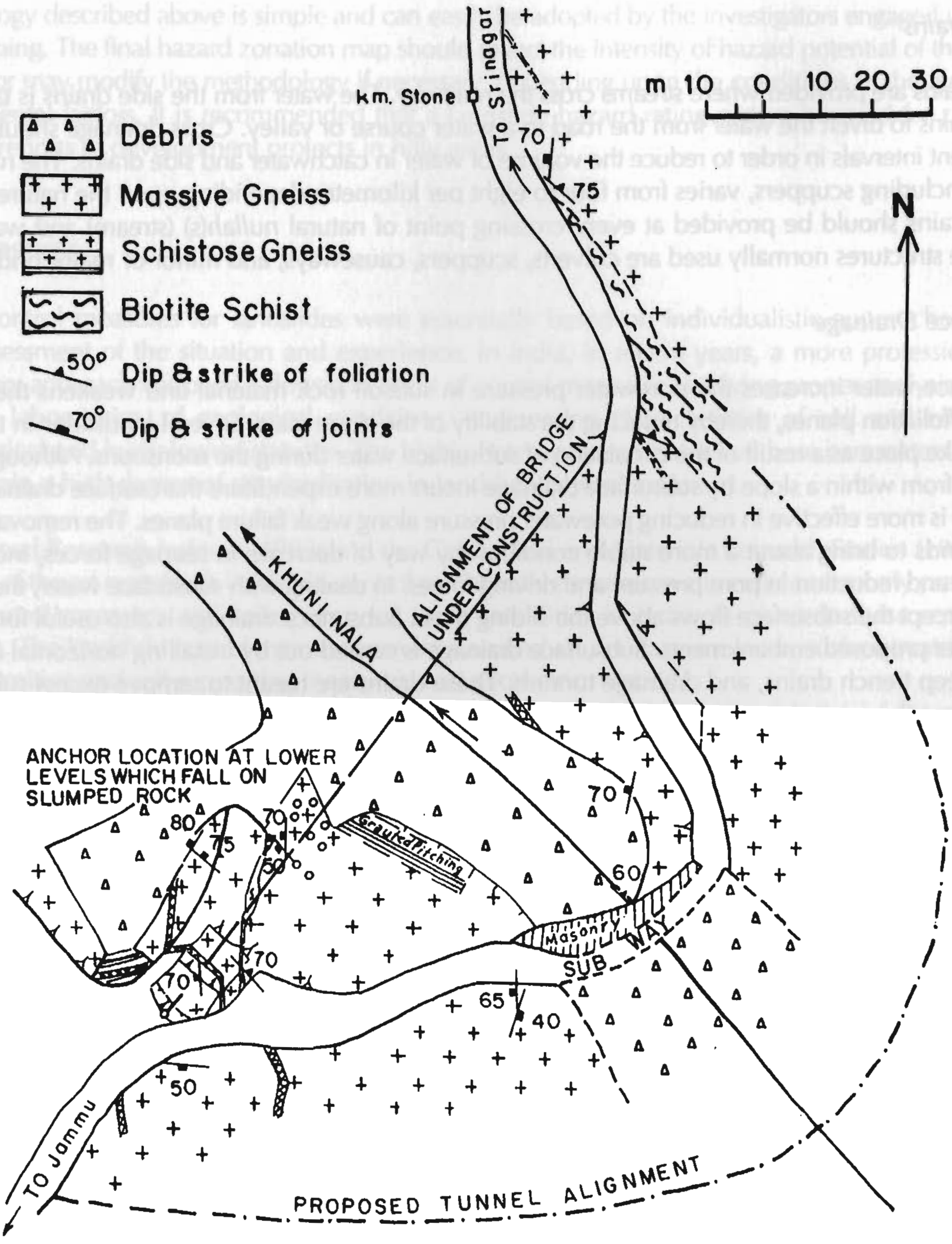
Deep trench drains have limitations in those locations where the subsurface drainage has to be intercepted at depths of less than five to eight metres. Trench drains are normally used where horizontal drilling is not feasible. Deep subsurface trench drains, consisting of a number of interconnected trenches dug into the slope and backfilled with rubble which has good draining properties, can be highly effective in quickly draining saturated slopes.

Filter fabric is an effective means of drainage for landslide control. Clog-proof filter fabric covered drains consist of a permeable gravel core, surrounded by a filter fabric to prevent clogging. The gravel size is either 16-32mm or 35-70mm to ensure a sufficiently high void ratio. The average amount of material needed per metre of drain length is about one cubic metre of gravel and five square metres of filter fabric.

Retaining Walls

Retaining walls are generally erected to stabilise unstable slopes or to support existing landslides (Fig. 11). A substantial amount of manual and skilled work is required to construct retaining walls.

Figure 11: Geological framework of the Khuni Nala landslide and control measures undertaken, including alignment of the bridge along the Jammu-Kashmir highway (CRRI Report 1992)



The foundation of the retaining walls should lie on the hard strata or rock and should be free from scour, frost, and surface water. The base of the foundation must be wide enough to distribute the pressure over the foundation. The stone to be used should be more than 0.14 cubic metres in size, and the width of each stone should be more than 1.5 times its height. The backfill layer immediately behind the wall should be made of stone or some granular material. The soil or granular material between the backfill layer and the hill slope should be rammed and compacted in 150mm layers sloping away and downwards from the back of the wall. Proper drainage facilities should be provided to prevent water from accumulating behind the wall, and an adequate number of weepholes of more than 75mm^2 should be maintained.

Masonry Walls

In the present practice, retaining walls of up to four metres in height are constructed in random rubble-dry stone masonry. Retaining walls above four metres in height are built either in lime or cement mortar masonry or in drystone masonry with 0.6m-wide mortar masonry bands three to four metres apart, laid both in horizontal and vertical directions. The top thickness is usually 0.6m, the front batter one to four, and the back face vertical. Masonry courses are made normal to face batter and the back of the wall can be finished rough.

Sausage Walls/Gabion Walls (SWG)

Timber walls or concrete crib walls and sausage walls are also used as restraining structures. A crib wall is made in a wooden mesh in which drystone masonry is built. Sausage walls are made by forming sausages of steel wire netting of eight SWG with 10cm square or hexagonal holes. The sausages are filled with hard local boulders/stones, and the wire-net is wrapped at the top. This process is carried out on the site where the sausage walls are to be installed. Over the past 25 years, sausage walls have been used extensively on Himalayan slopes. It has been found that sausage walls can withstand a greater amount of deformation than stone masonry, without cracking. They also allow free passage of water.

In the USA and Europe, sausage walls, more commonly called gabions, are assembled from prefabricated geogrids. Geogrids, made of polypropylene, have high resistance to impact and weathering and also possess good strength and elongation characteristics.

Pile Walls

Pile walls are used in place of retaining walls. The main advantage of piles is that they can be installed prior to excavation. Little space is needed and, therefore, less excavation work is required. Piles reduce the danger of slope movements in cuttings and provide an effective means of stabilising existing landslides. Pile walls have some limitations, however, as they are not strong enough to hold back the bottoms of deep cuttings where large horizontal stresses are present.

Anchored Walls

The stability of retaining walls can also be enhanced by using ground anchors (Fig. 12). Gravity walls have limitations where the surface area and the depths of the landslides are large. It has been found that anchored walls are effective where the surface failure is deep.

A deep, pre-stressed anchor is also applied for stabilising soil slopes. Walls with pre-stressed anchors have a major advantage because they actively oppose the movement of the soil mass, rather than behaving passively as in the case of unstressed anchors and gravity structures. Pre-stressed anchors are employed either in combination with retaining structures, or alone, to reduce the driving forces of a landslide and to increase the normal effective stresses on its slip surface.

Buttress Walls

Buttresses are often used as retaining devices on landslides and creep movements on hill roads. Failure of the structure can take place due to foundation failure, shear between the structure and the foundation, and shear through the structure itself. Therefore, rock buttresses are constructed, preferably on solid foundations, to avoid foundation failure. The buttress is constructed with the upper face vertical and the lower face with a slope of 1.5:1.

Concrete Retaining Walls

Concrete gravity walls are very expensive and are used for important structures and in urban areas. These walls have a foundation in the bedrock or good soil below the slip surface. The stability of the whole body of the walls and the stem is considered in the design. The body of the walls is taken to include the mass of soil directly above the heel of the cantilevered wall and earth pressure. Weepholes are generally kept in the wall.

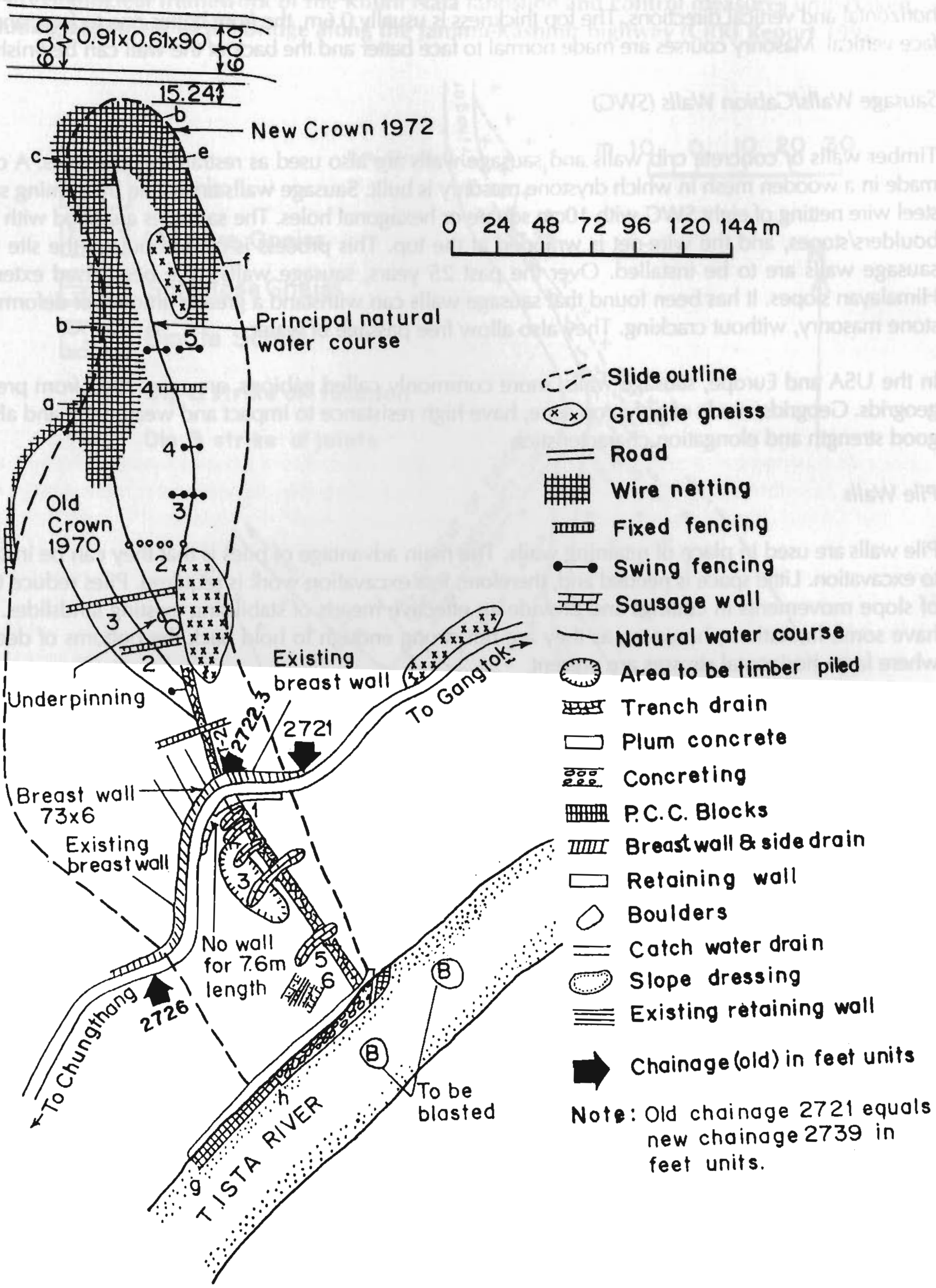


Figure 12: Extensive control measures undertaken to mitigate landslide hazards in the Tista Valley, Sikkim (Bhandari and Gupta 1985)

Self-supporting Measures

Self-supporting methods of landslide control are used primarily to improve the shear strength of the soil. The most commonly-employed techniques are rock bolts, rock anchors, anchored beams and cable lashing, shotcreting, and soil nailing.

Rock bolts are shallow fitting elements and anchors are fixed deep into the slope. A rock bolt helps to stabilise the slope face by exerting force which compresses the joints and prevents loosening by freezing. It also ensures greater stability by functioning as a dowel and increasing the shear resistance along the joints. Bolts are usually grouted along their entire length with cement or other chemical agents.

Anchors are used to control a much larger volume of rock than in the case of rock bolts. Anchors can be used to replace retaining walls and other supporting structures. Tendon and cable anchors are used to provide pre-stressing force. Pre-stressed anchors are used to stabilise a rock slope against the possibility of deep- seated failure. Pre-stressed rock anchors consist of high tensile steel wires or groups of wires inserted into the boreholes drilled into the slope. Pre-stressing force can be applied to the slope through the wire, and this makes the slope stable.

Anchored Beam and Cable Lashing

An anchored beam, made of concrete or steel, is used in any direction across the rock face. Anchored beams minimise the number of bolts required by distributing the support of rock bolts over a wide area of the slope. Cable lashing involves tying or wrapping huge unstable rock blocks with individual cable strands and anchoring these into sound rock slopes on each side.

Shotcreting

Shotcrete is concrete consisting of cement mortar with an aggregate of up to 20mm. Shotcrete is applied by air jet directly to the unstable sections of rock slopes to prevent weathering and spalling of rock surfaces and to provide surface reinforcement between rock blocks. Prior to the application of shotcrete, the slope should be thoroughly scaled of loose rock pieces. Shotcrete is applied in 70mm to 100mm thick layers, and each layer is allowed to set before successive layers are applied. A steel mesh is sometimes bolted to the slope face before shotcreting is carried out. Shotcrete provides a rapid and mechanised solution to rockfall problems. It is very commonly used to stabilise rock slopes in hydroelectric projects.

Soil Nailing

Soil Nailing is a method of reinforcing the ground *in situ* and is applied to retaining structures and natural slope stabilisation. It is primarily a combination of the principles of the New Austrian Tunnelling Method and the Reinforced Earth Method.

Soil nailing is employed in alluvial silts, fine sand, cemented sand, weathered rock material, moraine, and so on, to stabilise cuts ,to improve the safety of existing cuts, and to restore failed slopes/walls.

Geometry Alteration Measures

Altering the geometry of a slope can improve the stability of deep-seated slopes. This can be achieved by removing all unstable materials and, if necessary, replacing them with stronger materials. The common approach is to either remove some of the material from near the top of the unstable zone or to add material at the toe.

This method is used occasionally to control potential landslides but is more suitable for existing landslides. It involves designing a suitable slope, followed by proper surface drainage measures. It is best suited for slides moving downslope towards a road and not for slides that undermine a road on its downward slope.

Surface Protection Measures

Surface protection measures may include planting, turfing, coir netting, and rock revetment, which are effective in preventing soil erosion and, in turn, stabilising the slope.

Planting

Afforestation is more effective for stabilising shallow sheet slides than landslides with deep-lying slide surfaces. It is generally accepted that forest growth helps to dry out the surface layers, and that ramification of the root systems assists the consolidation process. Since trees draw water from the surface beds, the most suitable species for planting on sliding slopes are those that have the highest consumption of water and the highest transpiration rates. Experience has shown that a mixed forest of broad-leaved trees, such as oak, hornbeam, ash, and alder, which may also be grown as coppice in a 30 to 40 years' rotation, is most appropriate for the afforestation of sliding areas. In the absence of binding material in the soil, such as silt or sand, reinforcing material is used to strengthen the root mat system.

Reinforced Vegetation Using Geogrids

'Geogrids' (such as Netlon and Tensar) are extremely flexible, extruded polymer meshes of high tensile strength. They are used for earth reinforcement applications. Forced vegetation, regeneration, and afforestation programmes for enhancement of slope stability are proven methods and are practised widely. Normally, the vegetation growth on a slope depends upon several factors, e.g., retention of soil moisture, slope angle, constituent soil particle size, velocity of surface runoff, type of soil cover, and so on.

Vegetative Turfing

This method consists of preparing a slope area into seed beds by grading it to the extent possible and then broadcasting seeds or planting root strips of locally-available creeping grass with a good network of roots. The vegetation network of a root system penetrates 50-75cm deep into the slope, thereby serving as a soil anchor and providing added resistance to erosion.

Coir Netting

Processed coir yarn is made of coconut husk and is generally woven in meshes of 1", 3/4", and 1/2". If a heavy mesh fabric is firmly laid on graded earth and sown with suitable grass seeds, it gives maximum protection to the soil until the grass takes root and provides a permanent coverage. After the soil is stabilised, the netting decomposes and provides nourishment to the grass growing on the soil medium.

Soil Stabilisation

Lime columns, grouting electro-osmosis, and soil nailing are the methods commonly employed for slope stabilisation.

Grouting

Grouting is used to improve weathered slopes from which rock or boulders may be falling. Proper types of grout and acceptable injection pressure is determined before applying the grout. Strict quality control is required for mixing proportions, water content, grout pressures, and so on during grouting operations. Grouting is a costly remedial measure and is recommended for use only in exceptional situations.

Chemical Stabilisation

Landslides in the case of sensitive clays can be effectively controlled by using chemical methods. The shear strength of sensitive clays is increased by the diffusion of different salts placed in holes drilled in the clay. Lime is mixed with clay using a tool shaped like a giant dough mixer or egg beater.

Case Histories of Landslide Control

The Border Road Organisation and Public Works' Department maintain the main arteries of the road system in the Himalayas. They consult other technical organisations, such as the Geological Survey of India, the Central Road Research Institute, and the Central Water Commission, to devise landslide control and management measures (Fig. 11). Two examples of landslide management are described below (after Soin1980).

Landslide 'A'

The slide 'A' area covers a road length of 550m and extends 245m above and 240m below the road. The main causes of the slide were percolation of water, absence of vegetation on the slope, and undercutting at the toe of the slope due to a meandering river. The slide has been controlled by providing proper drainage and carrying out river training measures. Drains have been constructed to lead the water outside the slide area, chutes on the downstream side to drain out water, and check-walls between the river and the road. The river training works include three spurs and a toe wall with an apron. A breast wall has been erected all along the slide. These measures have helped to stabilise the area affected by the landslide.

Slide 'B'

This slide has affected a road length of 700m; it extends 200m above and 37m below the road level. The slide area is located at the river bend, and sliding has resulted in soil-mass movement in wet conditions, subsidence, and toe erosion. The slide took place after the 1968 floods when one kilometre of the road was breached, damaging the retaining walls and breast walls.

Based on studies carried out by the Geological Survey of India, the Central Road Research Institute, and the Central Power Commission, a new formation was cut and drains were built; benching on slopes was provided; and river training works, spurs, and aprons were constructed at river level. During the 1973 floods, the spurs were heavily damaged. The slide has been controlled by providing drainage above the road, river training works, and restraining structures. Water from above the crown of the slide has been drained out outside the slide area through a drain towards the downstream side. Flow through the *nullah* is channelised to pass over the chutes. The denuded portion of slide is cut into steps and a drain provided over the old step. The intervening step is drained through the perforated bamboo placed three metres inside by excavation and backfilling. To prevent attacks from the flow of the river water, three spurs of crated boulders with heavy toe protection, rising one metre above the highest flood level and with an apron in front, have been provided. These measures have stabilised the slide-affected area.

Landslide Dam and Flooding

The Gona slide of Birehi Valley in the Garhwal Himalayas is a historically famous case. According to R.R. Pulford (Narrative Report on the Gona Lake and Flood Lucknow November 14, 1894), rockfall occurred in September 1893, damming the Birehi Ganges stream in Birehi Valley. However, the catastrophe came to pass only a year later, on August 26, 1895, when the water broke through the dam and damaged the valley, causing heavy destruction downstream in the Alaknanda Valley. Later, in their Survey of the Central Himalayas, Heim and Gansser (1939) reported scree material of limestone and limestone covering about 1.5sq.km with a maximum thickness of 300m. They estimated the volume at about 150 million cubic metres. The lake was four kilometres long and had a maximum width of 0.7km. In their estimate, the height of the rockfall was about 1,000 to 1,200m, and limestone had broken off from a dry rock wall due to stratification. It can be concluded that the rockfall occurred as a result of cloudburst.

A flood of very high intensity occurred in the Alaknanda River and its eastern tributaries in Garhwal on 20th July 1970, causing heavy loss of life and property. Belakuchi village was washed away and communications were disrupted due to the landslides that occurred on the bank of the river and its tributaries. The floods were caused by a cloudburst in the Kuanrikhal area at an altitude of 3,700m, which formed a lake at Birehi, a tributary of the Alaknanda. Later, this lake burst caused devastating floods (Kumar and Shome 1970). Similarly, the 1978 Bhagirathi floods were the result of the breaking of Lake Kandoligad, a tributary of the Bhagirathi.

It has now been established that the flash floods were caused by cloudbursts; they are common occurrences in the Himalayas. In August 1994, three cloudbursts in Kulu Valley, Himachal, swept away three villages causing great loss of life and property. In August 1993, a landslide occurred upstream of Jeori in the Sutlej Valley. A lake was formed, threatening the ongoing construction of the Nathpa-Jhakri power project. Timely action, which involved blowing out a part of the slide-created dam, saved the situation and averted the catastrophe.

Landslide control in the catchment area is an important aspect. It has a direct bearing on floods and the silt load accumulation downstream in the reservoirs of the engineering projects. Investigation of the catchment area is not only important for landslide control but also has great relevance for the siltation rates of reservoirs. A detailed study of the catchment area should include analyses of slope conditions, drainage, structural features, such as faults and joints, predominantly operating subarial processes, density of forest/vegetation cover, and land-use patterns.

Based on their study of slope failure in the catchment area of the Alaknanda and the Bhagirathi, Prasad and Verma (1980) suggest the following landslide control measures.

a. Large-scale afforestation along the valley side: active slide faces must be protected from grazing and excessive felling of trees
b. Protection of the toes of repose slopes by erecting stout embankments and diversion of stream flow from the toe by constructing gabion structures
c. Headward extension of the gullies should be checked by making small dams
d. If a lake is formed at high altitude, the water should be drained out slowly

Institutions Involved in Landslide Research, Training, Warning, Monitoring, and Management

In the past, the Geological Survey of India (GSI) was the only organisation that was called upon to undertake hazard investigation studies in the country. The GSI has geotechnical divisions in its regional headquarters, and the divisions manage the engineering geology aspects of all the engineering projects, including power projects funded by the Government of India. The GSI's services are also sought from time to time by state governments and border road organisations for landslide-related problems.

Since the pace of development in the mountain regions has increased considerably in the last few decades, the impacts of landslide problems have also multiplied as a result of increased human activity. As a result, more organisations are now studying landslide hazards. Although the GSI still provides its consultancy services to government departments, several other institutions provide services for individual cases. Institutions most actively involved in landslide consultancies are the Central Road Research Institute, the Wadia Institute of Himalayan Geology, the Central Building Research Institute, the Central Soil and Material Research Station, the Indian Institute of Remote Sensing, the National Remote Sensing Agency, the Defence Terrain Research Laboratory, Roorkee University, Kumaon University, and the Indian Institutes of Technology in Bombay, Delhi, and Kanpur. These institutions provide specialised expertise to solve difficult slide problems and also carry out their own research and development (R&D) work. Routine landslides are tackled by the respective engineering departments such as the Public Works' Department (PWD), the State Directorate of Geology and Mining from different states, and the Border Road Organisation of the Central Government.

Research and Development Efforts

Landslides are one of the principal natural hazards in the Indian subcontinent, and particularly in the Himalayan region. Considering the increased frequency of landslides, the heavy expenditure involved in controlling slides, and the lack of scientific landslide studies, the Department of Science and Technology (DST) of the Government of India has launched a coordinated programme for the study of landslides. The programme calls for a multidisciplinary and holistic approach using new techniques, such as remote sensing, GIS, and instrumentation, to understand the physical causes of and mitigation measures for landslides.

The objectives of the DST coordinated programme are: a) setting up a database for landslides, b) zonation of landslide-prone areas for risk assessment, c) monitoring of selected high-risk zones, d) development of suitable control measures, e) development of models and a prognostic system, f) documentation and dissemination of data, and g) training of personnel.

The institutions involved in the R&D programme of DST are the Central Building Research Institute, the Central Road Research Institute, the Wadia Institute of Himalayan Geology, the Geological Survey of India, the Indian Institute of Remote Sensing, Roorkee University, the Indian Institute of Technology at Bombay and Kanpur, and the Defence Terrain Research Laboratory.

Under the coordinated programme of the DST, landslide hazard zonation mapping is being carried out in parts of the Sutlej-Beas Valley in Himachal Pradesh, the Garhwal Himalayas, the Kumaon Himalayas, the Western Ghats, Sikkim, Mizoram, and the Nilgiri hills. Other activities of the programme include monitoring of the Powai landslide in Kinnaur district, Himachal Pradesh, through instrumentation, creation of databases, and development of models and a prognostic system. The Powai slide mass movement is being monitored by instruments such as rain gauges, piezometers, inclinometers, and borehole extensometers.

Though considerable R&D efforts are being made and expertise has been developed at various institutions and universities, transfer of expertise to user agencies is still lacking. The Public Works' Department (PWD) and the Border Roads' Organisation are the two main agencies who look after the maintenance of roads. The institutions are called upon from time to time by these agencies to tackle specific landslide problems. However, there is no mechanism for the transfer of expertise from R&D institutions to implementing agencies or for updating knowledge.

Overall Conclusions and Recommendations for a Practical Training Programme

Overall Conclusions

It can be concluded that geology and rain water are the two principal factors that influence the initiation of landslides. Landslides cause serious damage to road networks and other infrastructures every year, mainly during the monsoon rains. Landslide control is essential for keeping communication networks open and running in mountainous regions. This involves heavy and recurring expenditure by the national exchequer. It has also been observed that construction of roads and large projects in the mountains has caused hillslope instability and initiated landslides which, in turn, have accelerated the degradation of the environment.

There are two aspects of landslide control and mitigation that merit serious consideration. Existing landslides need to be arrested using various control measures. A landslide hazard zonation study can delineate areas of poor stability, as well as normal stable slopes, so that mitigation measures can be adopted to prevent landslides. The following recommendations have been made for tackling landslide problems.

a. Preparation of a landslide inventory and creation of a database of the existing landslides, preferably on the basis of the watershed area, using satellite imagery, aerial photographs, and GIS
b. Preparation of landslide hazard zonation maps
c. Monitoring of some problematic and important landslides, using instrumentation
d. Research and development work in control measures, instrumentation, and modelling for risk assessment
e. Training programmes on capacity building for landslide studies and transfer of knowledge to user agencies

Training Programme for Landslides

The study of landslides requires an integrated and interdisciplinary approach to subjects such as geology, hydrology, and engineering. The main aim of the programme should be to impart training on the mapping of geological and hydrological characteristics of the landslide area and to suggest appropriate corrective measures for controlling landslides. In addition, the training should include preparation of an inventory and a database of landslides, using PCs and GIS, and monitoring landslides through instrumentation.

Course Contents

a. Introduction to landslides: nomenclature, reporting etc.
b. Geological mapping of landslide area on a scale of 1:10,000 or even on a smaller scale, including lithological mapping, structural characteristics, and mapping of landslides using aerial photographs and satellite imagery
c. Kinematics of faults, joints and fractures, folds, and foliation
d. Geomorphology should include slope classification and slope analysis
e. Hydrology should include surface runoff and movement of groundwater at a shallow level
f. Stress and strain, mechanical properties of rocks, soil, and rock mechanics
g. Construction of engineering structures, such as retaining walls, gabions, and so on, as landslide control measures
h. Monitoring of landslides and knowledge and use of instruments
I. Use of PCs for database creation and GIS applications
j Field training on some landslides

Duration of the Course : Theory : Two weeks
Field work : One week
Total : Three weeks

Number of Trainees : 20

Minimum Qualification : M.Sc Geology or B.E. Civil (Assistant Engineer/Executive Engineer level)

Specialists Invited for Lectures: Geologist, Geomorphologist, Hydrogeologist, Civil Engineer, Landslide Monitoring Specialist, GIS Specialist

Annex 1

Classification of Mass Movement

The classification proposed by Varnes (1978) is the most commonly used. It was also adopted by the Landslide Committee, Highway Research Board, Washington. It classifies landslides into falls, topples, slides, lateral spreads, and flows. Wherever two or more types of movement are involved, the slides are termed complex. Varnes (1978) has divided the material prone to landslides into two classes, i.e., rock and soil. The soil is further divided into debris and earthfall.

Falls: Falls are abrupt movements of the slope material that separate from steep slopes or cliffs. Most of the movements occur due to free falls or by rolling or bouncing. Depending upon the type of slope material involved, it may be called rockfall, debris fall, and soil or earthfall.

Topples: Topples are blocks of rock that tilt or rotate forward on a pivot or hinge and then separate from the main mass, fall on the slope, and subsequently bounce and roll down the slope. They may be rock topples, debris topples, or soil topples, depending upon the type of material involved.

Slides: These are movements caused by finite shear failure along one or more surfaces of rupture, which are visible or whose presence can be inferred. The two principal types of slide are rotational and translational.

a. Rotational: These slides refer to failures involving sliding movements on the circular or near circular surface of failure. They generally occur on slopes of homogeneous clay, shale, weathered rocks, and soil. The movements are more or less rotational on an axis parallel to the contour or the slope. Such slides are characterised by a scarp at the head which may be nearly vertical. They may be single rotational, multiple rotational, or successive rotational types.

b. Translational: These are non-rotational block slides involving mass movements on more or less planar surfaces. The movement of a translational slide is controlled by weak surfaces such as beddings, joints, foliations, faults, and shear zones. The slide materials range from unconsolidated soils to slabs of rock and debris. Block slides are translational slides in which the moving mass consists of a single unit of rock block that moves down slope.

Spreads: These failures are caused by liquefaction whereby saturated, loose, cohesionless sediments are transformed into a liquid state. Rapid ground motions, such as those caused by earthquakes, are responsible for this phenomenon.

Flows: Flows are rapid movements of material as a viscous mass where inter-granular movements predominate over shear surface movements. These can be debris flows, mudflows, or rock avalanches, depending upon the nature of the material involved in the movement.

Complex Failure: These are slides in which the failures occur due to a combination of the above types of movement.

Classification of Slope Movements (Varnes 1978)

Types of Soil Movement	Bedrock	Engineering	
		Predominantly Coarse	Predominantly Fine
Fall	Rockfall	Debris fall	Earthfall
Topples	Rock topple	Debris topple	Earth topple
Rotational	Rock slump	Debris slump	Earth slump
Few Units	Rock block slide	Debris block slide	Earth block slide
Translational Many Units	Rockslide	Debris slide	Earth slide
Lateral Spreads	Rock spread	Debris spread	Earth spread
Flows	Rock flow (deep creep)	Debris flow	Earth flow (soil creep)
Complex	Combination of two or more principal types of movements		

Some Definitions of Landslides

The Glossary of Geology (Bates and Jackson 1987) defined a landslide as "the downslope transport under gravitational influence of soil and rock material *en masse*. Usually the displaced material moves over a relatively confined zone or surface of shear."

Webster's 3rd International Dictionary gives the definition as "the usually rapid, down slope movement of a mass of rock, earth or artificial fill on a slope."

According to the Working Party on the World Landslide Inventory (1990), a landslide is "*the movement of a mass of rock, earth or debris down a slope.*" This is the informal definition recently adopted by the Working Group and suggested for use in the International Decade for Natural Disaster Reduction (1990-2000).

Landslide Features (Figure A-1)

Crown (1): The practically undisplaced material still in place and adjacent to the highest parts of the main scarp

Main Scarp (2): A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the slide material away from the undisturbed ground

Top (3): The highest point of contact between the displaced material (13) and the main scarp (2)

Head (4): The upper parts of the landslide along the contact between the displaced material and the main scarp (2)

Minor scarp (5): A steep surface on the displaced material of the landslide, produced by differential movements within the sliding mass

Main body (6): The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp (2) and the toe of the surface of rupture (11)

Foot (7): The portion of the landslide that has moved beyond the toe of the surface of rupture (11) and overlies the original ground surface

Tip (8): The point of the toe (9) farthest from the top (3) of the landslide

Toe (9): The lower,usually curved, margin of the displaced material of a landslide, it is the furthest from the main scarp (2)

Surface of rupture (10): The projection of the main scarp (2) surface under the dis-placed material of a landslide

Toe of surface of rupture (11): The intersection (sometimes buried) between the lower part of the surface of rupture (10) of a landslide and the original ground surface

Surface of separation (12): The part of the original ground surface overlain by the foot (7) of the landslide

Displaced material (13): Material displaced from its original position on the slope by movement in the landslide

Zone of depletion (14): The area of the landslide within which the displaced material (13) lies below the original ground surface

Zone of accumulation (15): The area of the landslide within which the displaced material lies above the original ground surface

Depletion (16): The volume bounded by the main scarp (2), the depleted mass (17), and the original ground surface (Cruden 1980)

Depleted mass (17): Part of the displaced material which overlies the rupture surface (10) but underlies the original ground surface

Accumulation (18): The volume of the displaced material (13) which lies above the original ground surface (Cruden 1991)

Flank (19): The side of the landslide. Compass directions are preferable for describing the slide but, if left and right are used, they refer to the slide viewed from the crown

Landslide Dimensions

L_r = The length of the rupture surface: the distance from the toe of the surface of rupture to the crown

L_d = Length of the displaced mass: the distance from the tip to the top

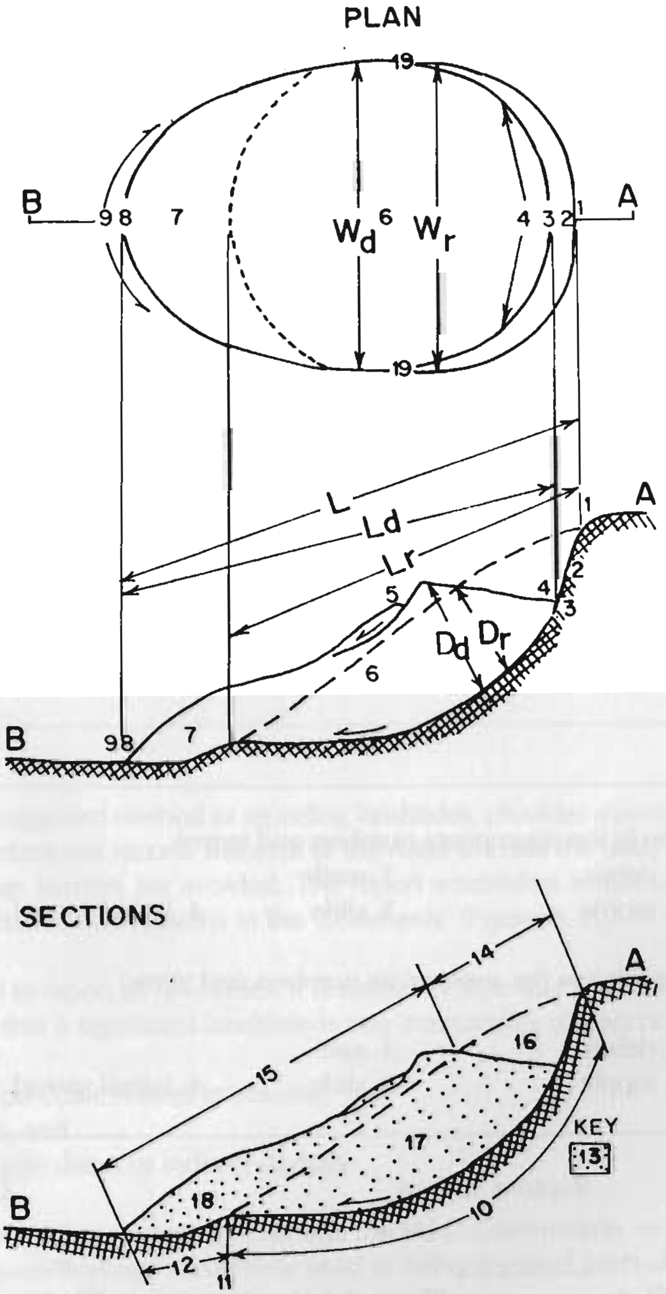
L = Total length: the distance from the tip of the landslide to its crown

W_r = Width of the rupture surface: the maximum width between the flanks of the landslide, perpendicular to the length, L_r

W_d = Width of the displaced mass: the maximum breadth of the displaced mass perpendicular to the length, L_d

D_r = The depth of the rupture surface: the maximum depth of the rupture surface below the original ground surface measured perpendicular to the original ground surface

Figure A-1: Suggested nomenclature for landslides. Cross-hatching indicates undisturbed ground, stipping shows the extent of displaced material (13) (IAEG Commission on Landslides 1990)



LANDSLIDE REPORT

Day month year
Date of Report / / /

Landslide Locality: ____________ National Inventory Number: ____________

Reporter's Name: ____________

Affiliation: ____________

Address: ____________

Phone: ____________

Day month year
Date of Report / / /

Type: First movement (circle the appropriate numbers and terms)

1. rock 2. debris 3. earth
1. fall 2. topple 3. slide 4. lateral spread 5. flow

Second movement (circle the appropriate numbers and terms)

1. rock 2. debris 3. earth
1. fall 2. topple 3. slide 4. lateral spread 5. flow

Geometry:

	Rupture Surface		Displaced Mass
	Length L_r = ______ m		L_d = ______ m
	Width W_r = ______ m		W_d = ______ m
	Depth D_r = ______ m		D_d = ______ m

Damage: Value

Currency ____________

Casualties ____________

Reference:

1.______________________________

____

____

2.______________________________

____

____

3.______________________________

____

____

Comments:______________________________

____

____

____

____

The Landslide Report, a suggested method of reporting landslides, provides a permanent record of details that cannot be coded in the database record. Because of the need to code the data, complex descriptive details which may face language barriers are avoided. The report establishes minimum data requirements while permitting additional, detailed observations in the 'comments' (Figure A-2).

Because it is not practical to report all landslides, it is necessary to create a working definition of a significant landslide. It is proposed that a significant landslide is one that satisfies at least one of the following criteria:

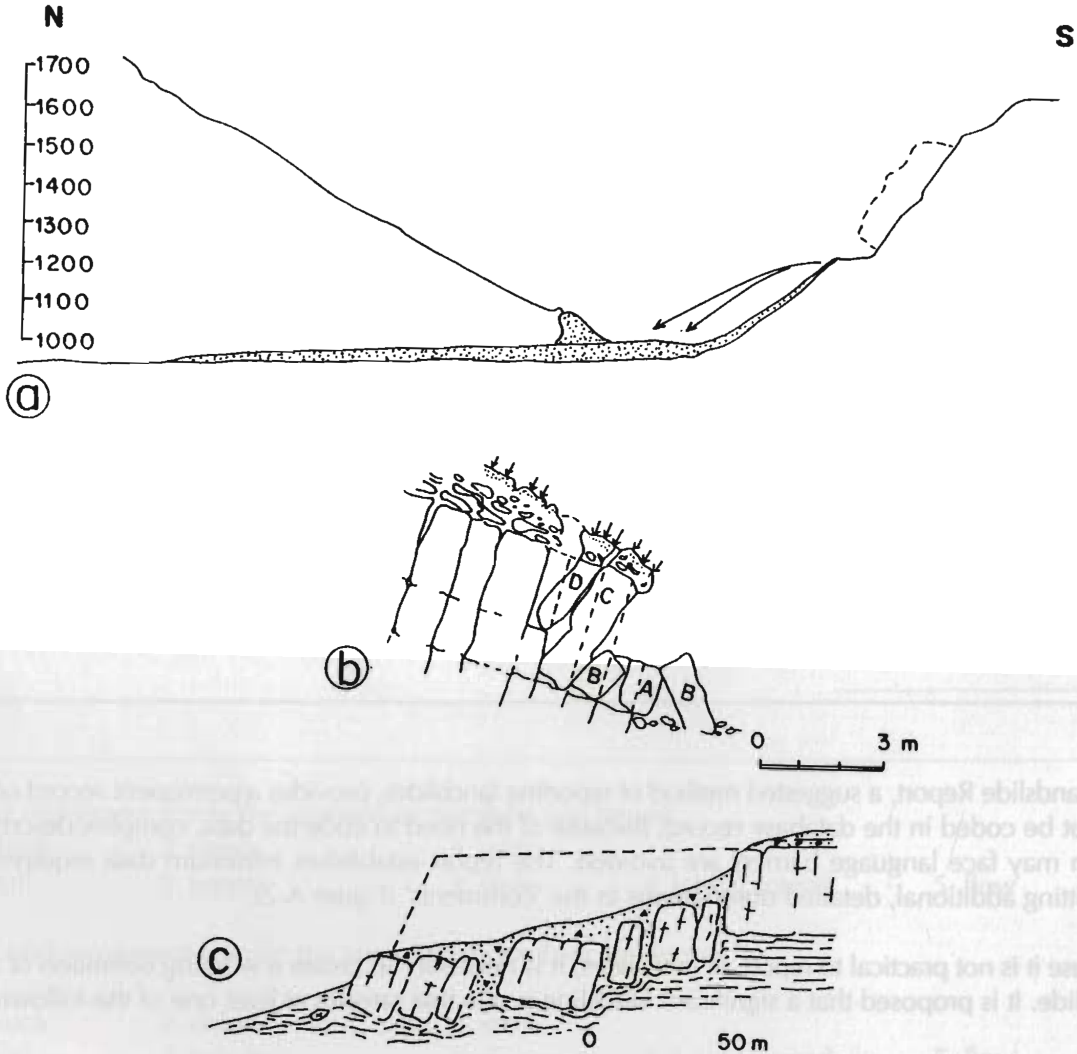
1) is over one million cubic metres in volume,
2) causes casualties, and
3) causes considerable direct or indirect damage.

The report uses terminology from Varnes (1978) and the IAEG Commission on Landslides and Other Mass Movements (1990). This terminology is currently used in many regional and national inventories, including those in Canada, Czechoslovakia, Italy, and the U.S.A.

The Landslide Report is arranged to permit ready coding for computer processing. Consequently, observations are either numeric or of mutually exclusive categories that can be classified numerically. Each category is represented by a number so that information is transcribable on to the electronic database.

References in the Report and descriptive comments will not be transferred to the Landslide Record. However, a separate file of references will be created and represented by numbers in the Record. The comments need not be transferred to the Record but should remain on file with the Landslide Report. Landslide Reports should be maintained in National Centres for public reference.

Figure A-2: Section through typical slope movements (International Geotech. Society 1990)



The specifications of the measurements of an individual landslide in the Report, which include the position, the date, the type,the geometry, and the volume,are described here.

<u>Position</u>

The position of each landslide is to be mapped by its latitude and longitude to the nearest second. This provides a reference point for subsequent mapping and research. On landslides that extend over more than one second, the crown of the landslide should be taken as the reference point. The elevation of the tip of the landslide, the toe of the surface of rupture, and the highest point of the crown above mean sea level should be recorded to the nearest 10m.

Date

The date of occurrence should be recorded. Difficulties arise when the movement is not fast. When the movement is progressive and takes place over an extended period of time, the 'date of occurrence' is when the most rapid displacement took place. If this is not known, the day when displacement last took place should be recorded.

Type

The most widely-used classification is Varnes (1978). Varnes' classification is based on two criteria: the type of movement and the material involved. Material is classified as either bedrock or engineering soil. Soils are divided into debris or earth. The latter is fine-grained material in which at least 50 per cent consists of sand, silt, and clay-sized particles. There are five main types of movement: falls, topples, slides, spreads, and flows. A sixth group includes all complex failures in which one of the five main types of movement is followed by another. Some movements may exhibit more than two types of movement in sequence. Most movements are complex. Varnes (1978) suggested the construction of names for the movements which reflected their complexity.

Consider the Elm landslide in which the displaced rock mass fell, shattered, and flowed as debris. This was a rockfall-debris flow (Varnes 1978, p.21). The complex type of movement can be accommodated in the report by describing a second type of movement which follows the first. To aid in the definition of movement type, a brief description is given of each, according to Varnes (1978).

In falls, a mass is detached from a steep slope along a surface on which little or no shear displacement takes place. Materials descend mostly through the air either by free fall, saltation, or rolling.

Topples involve the forward rotation of the displaced mass about an axis at or near its base. Topples may precede or follow falls or slides and are sometimes evident as detached blocks perched precariously on a valley wall.

Slides are movements of a more or less coherent mass along one or more well-defined surfaces of rupture.

In spreads, the dominant mode of movement is lateral extension, accommodated by either shear or tensile fractures.

Flows include a wide range of movements with significant variations in velocity and water content which exhibit spatially continuous deformations. Flows often begin as either slides, falls, or topples on steep slopes which rapidly disintegrate with the loss of cohesion of the displaced material.

Geometry

The length, width, and depth of the rupture surface can often be estimated when parts of the surface of rupture are obscured. They are shown by a subscripted r. The length, width, and thickness of the mass of displaced material are measured directly and are denoted with a subscripted d.

The maximum length of the rupture surface, L_r, is measured from the toe of the surface of rupture to the crown. The other length measure, L_d, is taken from the tip of the displaced material to its top. The total length, L, is measured from the tip to the crown (Varnes 1978). The maximum widths of the surface of rupture, W_r and the displaced mass, W_d, are measured across the original ground surface in directions perpendicular to the lengths L_r and L_d. Depth is the most difficult dimension to estimate. The maximum depth of the surface of rupture, D_r, should be estimated from the original ground surface in a direction perpendicular to it. The thickness of the displaced material, D_d, is measured perpendicular to the surface of the displaced material.

Volume

The volume of the displaced mass in cubic metres should be given to three significant digits. In the Landslide Record, n represents the order of magnitude of the volume. When the displaced mass does not have regular dimensions, the volume can be estimated by fitting a geometric figure. For instance, considering the displaced mass as half an ellipsoid might be appropriate for a rotational slide. In this case, the volume is computed by using the major axes of half an ellipsoid:

$$V = \frac{1}{2}\,\frac{4}{3}\,n\,\frac{1}{2}\,L_d\,D_d\,\frac{1}{2}\,W_d = \frac{1}{6}\,L_d\,D_d\,W_d \quad (1)$$

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Plates

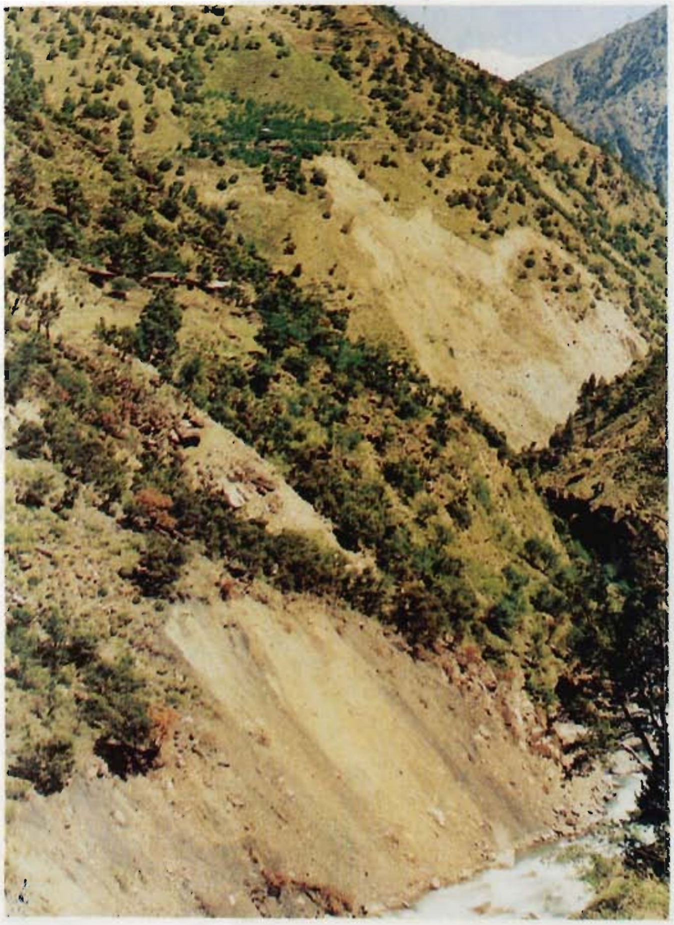

Plate 1: Sapni Slide: Combination of rotational debris slump and translational slide in the Quaternary overburden with graphitic horizons in the lower and middle valley slope of the Baspa River near the Baspa-Sutlej confluence, NW Himalayas

Plate 2: Rockfall : Wedge failure cum debris slide between Wangtu and Nathpa villages near Kandru Khad, NW Himalayas

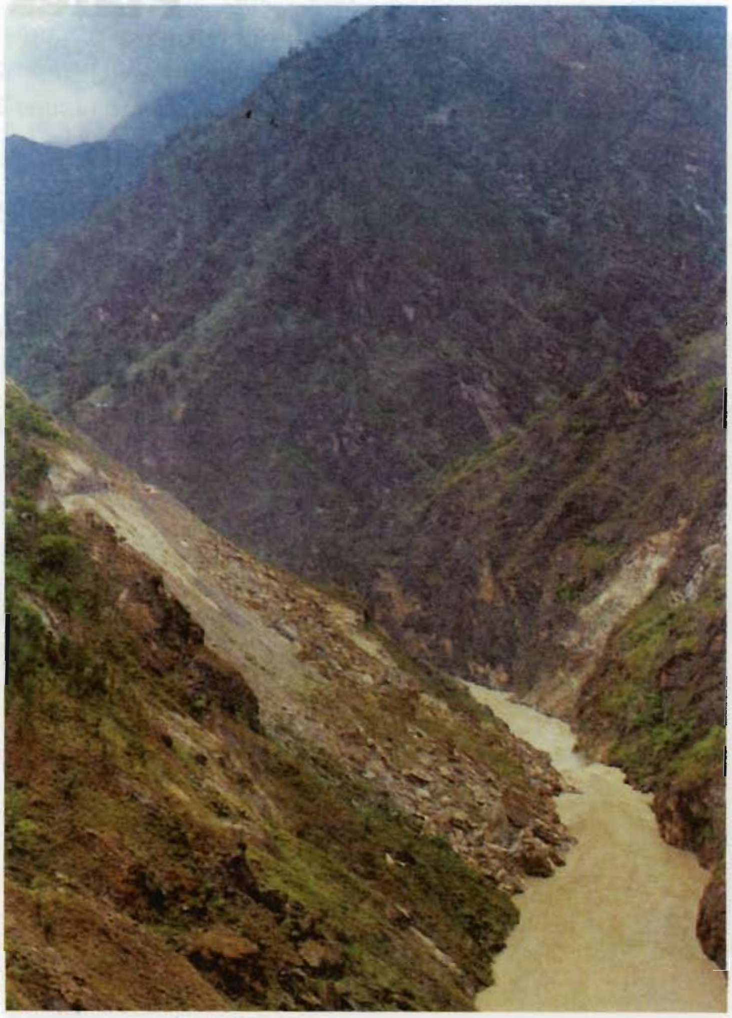

Plate 3: Debris Slide: Looking from Wangtu bridge downstream. This slide is endangering the HPPWD Wangtu Rest House, NW Himalayas

Plate 4: Rockfall cum debris slide: near Nathpa village. This slide has blocked the Sutlej River creating a lake more than one kilometre long, NW Himalayas

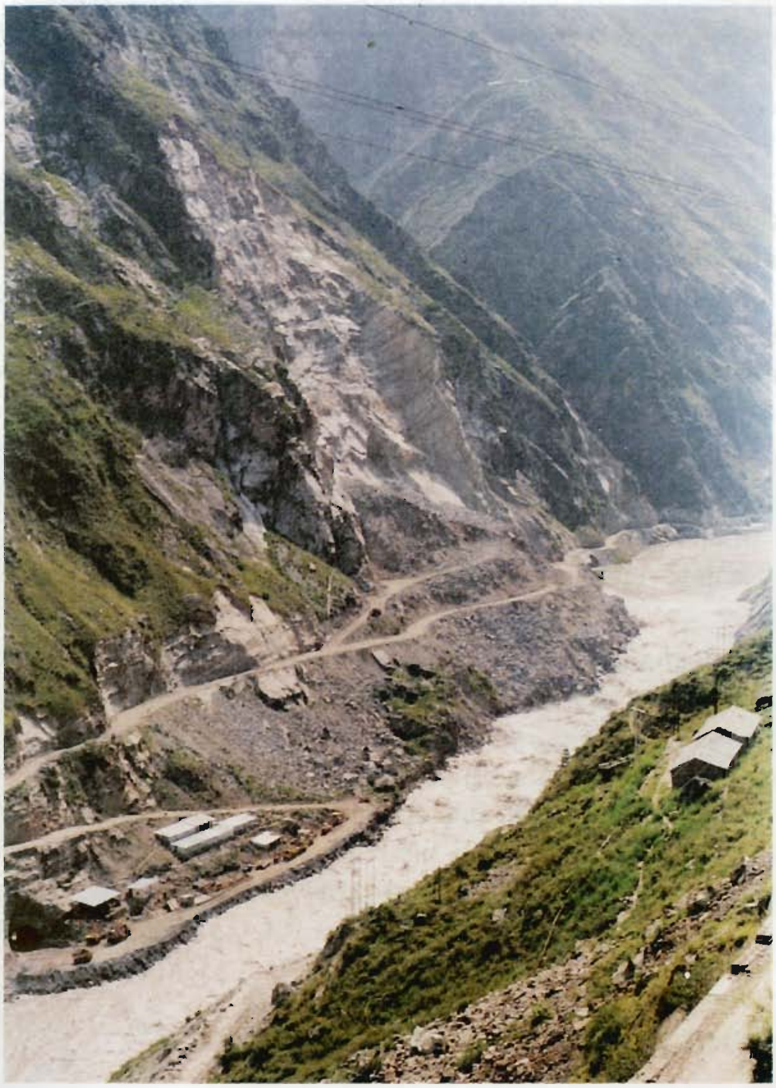

Plate 5: Translational debris slide: near Nathpa village, NW Himalayas

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Other publications on natural hazards are:

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- Landslide Hazard Mapping and Management in China
- Landslide Studies and Management in Nepal
- Climatic Atlas of Nepal

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- ✳ **Afghanistan**
- ✳ **Bhutan**
- ✳ **India**
- ✳ **Nepal**
- ✳ **Bangladesh**
- ✳ **China**
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