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SUMMARY

This report includes an overview of landslide hazard and risk practices in India. It is produced by Department of Civil Engineering and Earth Sciences, Indian Institute of Technology Roorkee, india.

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A Report

on

Overview of Landslide Hazard and Risk Practices in India

by

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Overview of Landslide Hazard and Risk Practices in India

Department of Civil Engg. & Earth Sciences
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Manoj K. Arora
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Abbreviations

The abbreviations appearing in the document have the following meaning:

ANN	Artificial Neural Network
BIS	Bureau of Indian Standard
BMTPC	Building Materials and Technology Promotion Council
CRED	Centre for Research on the Epidemiology of Disasters
CF	Certainty Factor
CRRI	Central Road Research Institute
CBRI	Central Building Research Institute
CSIO	Central Scientific Instrumentation Organisation
CWC	Central Water Commission
DST	Department of Science and Technology
DGPS	Differential Global Positioning System
EWS	Early Warning System
FM	Favorability Modeling
FF	Favorability Function
FMECA	Failure Modes, Effects and Criticality Analysis
GoI	Government of India
GSI	Geological Survey of India
GIS	Geographical Information System
GPS	Global Positioning System
GPR	Ground Penetrating Radar
HH	High Hazard
HDP	High Damage Potential
HR	High Risk
HP	Himachal Pradesh
IMD	India Meteorological Department
InfoVal	Information Value
IRC	Indian Road Congress
ITC	International Institute for Geo-Information Science and Earth Observation
ICG	International Center for Geohazards
ITBP	Indo-Tibetan Border Police
LHZ	Landslide Hazard Zonation
LSZ	Landslide Susceptibility Zonation
LiDAR	Light Detection and Ranging
LHEF	Landslide Hazard Evaluation Factor
LH	Low Hazard
LNRF	Landslide Nominal Risk Factor
LNHF	Landslide Nominal Hazard Factor
LHI	Landslide Hazard Index
LaSirF	Landslide Safe Route Finder
LDP	Low Damage Potential
LR	Low Risk

LRA	Landslide Risk Assessment
MHA	Ministry of Home Affair
MCT	Main Central Thrust
MBT	Main Boundary Thrust
m-LNHF	Modified LNHF
MPBE	Multiple Position Borehole
MoSRTH	Ministry of Shipping, Road Transport and Highways
MOR	Ministry of Railways
MDP	Medium Damage Potential
MR	Moderate/Medium Risk
MH	Moderate/Medium Hazard
NGO	Non Governmental Organization
NDM	National Disaster Management
NDMA	National Disaster Management Authority
NH	National Highway
NRSC	National Remote Sensing Center
NGF	National Geotechnical Facility
NIDM	National Institute of Disaster Management
RMR	Rock Mass Rating
RDSO	Research Designs and Standard Organization
SAR	Synthetic Aperture Radar
SoI	Survey of India
SPBE	Single Point Borehole Extensometer
SMR	Slope Mass Rating
TEHD	Total Estimated Hazard
UN/ISDR	United Nations International Strategy for Disaster Reduction
UK	Uttarakhand
VLH	Very Low Hazard
VHH	Very High Hazard
VLDP	Very Low Damage Potential
VHDP	Very High Damage Potential
VLR	Very Low Risk
VHR	Very High Risk
WIHG	Wadia Institute of Himalayan Geology

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National Vision

"The national vision is to build a safer and disaster resilient India by developing a holistic, proactive, multi-disaster and technology driven strategy for Disaster Management. This will be achieved through a culture of prevention, mitigation and preparedness to reduce the impact of disasters on people. The entire process will centre stage the community and will be provided momentum and sustenance through the collective efforts of all government agencies supported by Non-Governmental Organisations (NGOs)."

[National Disaster Management Guidelines, 2007]

1. INTRODUCTION

In recent times, there has been a sudden spurt in the development activities in Indian mountainous region, which has been mainly responsible for manifold increase in the incidences of landslides. The natural ecosystem of the mountainous terrains like Himalaya is often characterized by unfavorable geological, topographical and seismic conditions. Therefore, the hill slopes are to be evaluated in detail considering basic parameters controlling the stability of the hills in order to minimize the geo-environmental hazards. In this context, the landslide mapping, hazard and associated risk evaluation form important aspects of mitigations practices in India.

Landslide is a major geological hazard, which poses serious threat to human population and various other infrastructures like road and rail routes, and civil structures like dams, buildings and other structures in the hilly terrain. Landslides also occur very often during other major geohazards such as earthquakes, floods and volcanoes.

Expansion of urban and tourism developments in hills result in ever increasing number of residential and commercial properties that are often threatened by landslides. Since the land routes are often disturbed by landslides, they cause major hurdles in mobilizing relief and reconstruction efforts also. It is thus essential that the research and development regarding landslide analysis and their control should get priority and the construction activities in mountainous regions should be planned based on the principle of sustainable development.

1.1 Hazards, Risks and Disasters

A hazard refers to the probability of occurrence of a potentially damaging phenomenon like landslide. In the event of a landslide, it may lead to damages in the form of loss of life or injuries as well as damages to civil structures and properties. The risk studies mainly involve assessment of damages even before the event occurs so that suitable precautions are adopted. When these damages are of extremely high order, they are termed as disasters.

1.2 Status of Natural Disasters in India and the World

From time immemorial, humans have been facing the impact of natural hazards such as earthquakes, landslides, avalanches, floods, cyclones, droughts and volcanic eruptions of varying magnitudes. The statistics reflect that natural hazards account for up to 4% of the total annual deaths globally, not to ignore huge economic losses and migration of people. In fact, the impact of natural hazards and disasters on humans and the environment continues to rise throughout the globe. However, a study shows that this impact is not uniformly distributed. It is heavily tilted towards developing countries such as India, partially due to increased population and also due to lack of preparedness (NDM Guidelines B, 2009). Some typical examples of natural hazards in recent past can be listed as (Science Plan on Disasters, 2008),

i) two tropical storms in Bangladesh in 1991 that caused more than 130,000 lives
ii) the landslides in Nepal in 2002 that affected 265,000 homo sapiens
iii) the Sumatra earthquake of 2004, followed with tsunami claiming more than 250,000 lives and huge economic losses
iv) the massive China earthquake of May 12, 2008 claiming about 70,000 lives.
v) Extensive floods in Pakistan and India in July-August claiming thousands of lives and damaging huge properties.

India, due to its unique climatic conditions and its closeness to geodynamically active areas, has always been vulnerable to a large number of natural disasters. For example,

i) about 60% of the Indian region is fraught with earthquakes of moderate to very high magnitude
ii) more than 12% of the landmasses is affected by floods and river erosions
iii) about 68% of the cultivable area is susceptible to drought
iv) landslides and avalanches regularly haunt the Himalayas and the Nilgiris mountainous regions.

In addition, just like other countries in the western world, India has also become vulnerable to a number of man-made disasters such as nuclear, biological and chemical disasters, and terrorism in recent years (NDM Guidelines A, 2007; Sharda, 2007).

Nevertheless, socio-economically weak community in less developed countries is inflicted more with the impact of natural disasters than the others due to their proximity to the vulnerable habitats which are not prepared to resist the impact. Thus, whereas developed countries may suffer more from economic losses (Schuster 1996), casualties due to natural disasters are greater in less-developed countries such as India (Divoli et al., 2007). The brutality of these disasters in the country can be gauged from the following statistics (Sharda, 2007),

i) during 1990-2000, in a year, an average of about 4344 people lost their lives and about 30 million people were affected by disasters.
ii) during 1994 -1998, economic losses were estimated to be Rs. 286780 million, which climbed to Rs. 474640 million during 1998-2003

However, amongst all the natural disasters, either alone or in association, landslides appear to be major concern in inflicting loss of life, injury, and property damage, particularly in India. This is true since many of the natural disasters such as earthquakes, volcanoes, avalanches, sever storms, heavy rainfall and cloud burst themselves lead to large scale landslides in a region. For example, in Central America, a single storm or earthquake can trigger thousands of slope failures (Harp et al., 1981, 2002). Historical records also suggest that the highest number of lives lost to a single landslide event happened to be in the earthquake-triggered landslide disaster in Kansu Province of China in 1920. Another well known landslide event of the last century was an earthquake-triggered debris avalanche in 1970 on the slopes of Mt. Huascaran, Peru, which advanced with an average speed of 320 km/hr, killing more than 18000 people. Similarly, in Europe, the 1963 Vaiont reservoir slide in North-Eastern Italy, resulted in 2000 casualities (NDM Guidelines B, 2009).

Due to recent heavy rainfall, in July - August, 2010, flash floods and cloud bursts during monsoon in the north and northwest Himalayan region, a number of rainfall induced landslides have reactivated in the region causing road blockages, casualities and damage to properties.

Schuster (1996) also cited that landslides constituted 4.89% of the natural disasters that occurred worldwide during the years 1990 to 2005 (www.em-dat.net). The official figures of United Nations International Strategy for Disaster Reduction (UN/ISDR) and the Centre for Research on the Epidemiology of Disasters (CRED) for the year 2006 also states that landslide ranked third in terms of number of deaths among the top ten natural disasters, as approximately 4 million people were affected by landslides (Kumar et al., 2008). This trend is expected to continue in future due to increased unplanned urbanization and development, continued deforestation and increased regional precipitation as a result of changing climatic conditions in the landslide prone areas.

Thus, landslides indeed form a significant component of the natural disasters that affect most of the hilly regions round the globe. Looking at the recent studies on global landslide disasters, some of the highest landslide risk related disaster zones can be found in Colombia, Tajikistan, India, China, and Nepal, where more than 1 person per hundred sq. km. area is killed every year (NDM Guidelines B, 2009).

In India, disasters caused by landslides are common in mountainous regions, particularly, the Himalaya, which are the tallest among mountain chains of the earth, almost five and a half mile high encompassing an area of half a million square kilometer in its mighty sweep (Bhandari, 1986). The landslide incidences in the Himalaya have been of great concern to the society due to loss of life, natural resources, infrastructural facilities, etc. and also posing problem for future urban development. For example, an estimate shows that, on an average, the damage caused by landslides in the Himalayan range costs more than US$ one billion besides causing more than 200 deaths every year (Naithani, 1999).

1.3 Government of India Initiatives on Natural Disasters

In India, as per NDM Guidelines A (2007), the natural disasters have been categorised as L0, L1, L2 and L3, depending on the ability of various agencies/authorities to tackle them,

L0: denotes normal times which are expected to be utilised for close monitoring, documentation, prevention, mitigation and preparatory activities.

L1: specifies disasters that can be managed at the district level, however, the state and centre will remain in readiness to provide assistance if needed.

L2: specifies disaster situations that may require assistance and active participation of the state, and the mobilisation of resources at the state level.

L3: disaster situations arise from large-scale disasters where districts and the State may not have the capacity to respond adequately and require assistance from the Central Government for reinstating the State and district machinery.

Until recently, the disaster management was generally considered as a post-disaster rehabilitation and relief exercise. Three major disasters in the recent past, namely the Malpa Landslide of August 1998, the cyclone of Orissa in 1999 and the Bhuj Earthquake in 2001, led to a significant shift in the disaster management scenario in the country (Sharda, 2007). The Government of India (GoI) has also felt concerns on frequent loss of life and property due to natural hazards.

As a result, a review of disaster management mechanism is being carried out by the GoI. Recognizing the inclusion of hazard mitigation activities in the planning process, the GoI decided for a significant change in policy from simple relief-centric activities a concrete disaster management process including all essential components on mitigation, prevention, and preparedness. The GoI constituted a number of committees that will focus on a wide range of aspects related to disasters, as listed in NDM Guidelines B (2009),

i) to assess natural hazards and their risks
ii) to develop early warning systems
iii) to evolve techniques for hazard mitigation
iv) to generate public awareness about the causes, effects, and safety measures to be adopted, and
v) to undertake rescue, relief, and rehabilitation measures

The terms of reference of 12th Finance Commission were changed and it was re-mandated to look into the requirements of disaster mitigation and prevention, apart from the routine attention paid by it to the matters related to relief and rehabilitation The 10th Five Year Plan of India has now an exclusive chapter on disaster management (Sharda, 2007).

The GoI, in January 2004, declared the Ministry of Home Affairs (MHA) as the nodal ministry for the coordination of various activities under disaster management programme and the GSI as the nodal agency for landslide studies. Subsequently, the Disaster Management Act, 2005, (DM Act) was enacted on 23 December 2005, and the NDMA was formed, a statutory body under the Chairmanship of the Prime Minister (NDM Guidelines B, 2009).

1.4 Objective of the Report

In spite of the availability of some data on spatial and temporal distributions of landslides, the information on the number of causalities, types of damage, and the triggering mechanisms remain deficient. Due to this paucity of information, a proper landslide hazard assessment at the national level has always been a challenge.

This report presents an overview of landslide hazard and risk assessment practices in India and on landslide triggering mechanisms in Lower Himalayas, with a focus on climate driven triggers.

2. LANDSLIDE HAZARDS IN INDIAN CONTEXT

India, due to its delicate and varied geological character, diverse climatic patterns, and pressures on mountain and coastal developments due to ever-increasing population has constantly been fraught with natural and human-induced landslide hazards in different parts of the country. Landslides and avalanches in India incur huge economic losses in almost all the States and Union Territories hampering various developmental activities of the country (Bhandari, 2006). Therefore, in India, landslides have been identified as a significant natural hazard.

Landslides affect large parts of India, especially the Himalayas, the Northeastern hill ranges, the Western and Eastern Ghats, the Nilgiris and the Vindhyas. About 15% of Indian terrain is vulnerable to landslide hazard. Out of this, 80% is spread over the Himalayas, Nilgiris, Ranchi Plateau and Eastern and Western Ghats and the rest in north eastern region (Kumar et al., 2008). According to a government report, there have been 500 casualties due to landslides during 1998 to 2001 alone, communication and transportation links were affected for weeks and a large area of agricultural land was destroyed.

2.1 Distribution of Landslides in Various Physiographic Divisions of India

Physiographically, India can be divided into 3 major divisions (Figure 1),

i) Peninsular region
ii) Indo-Gangetic alluvial plains
iii) Himalayan region

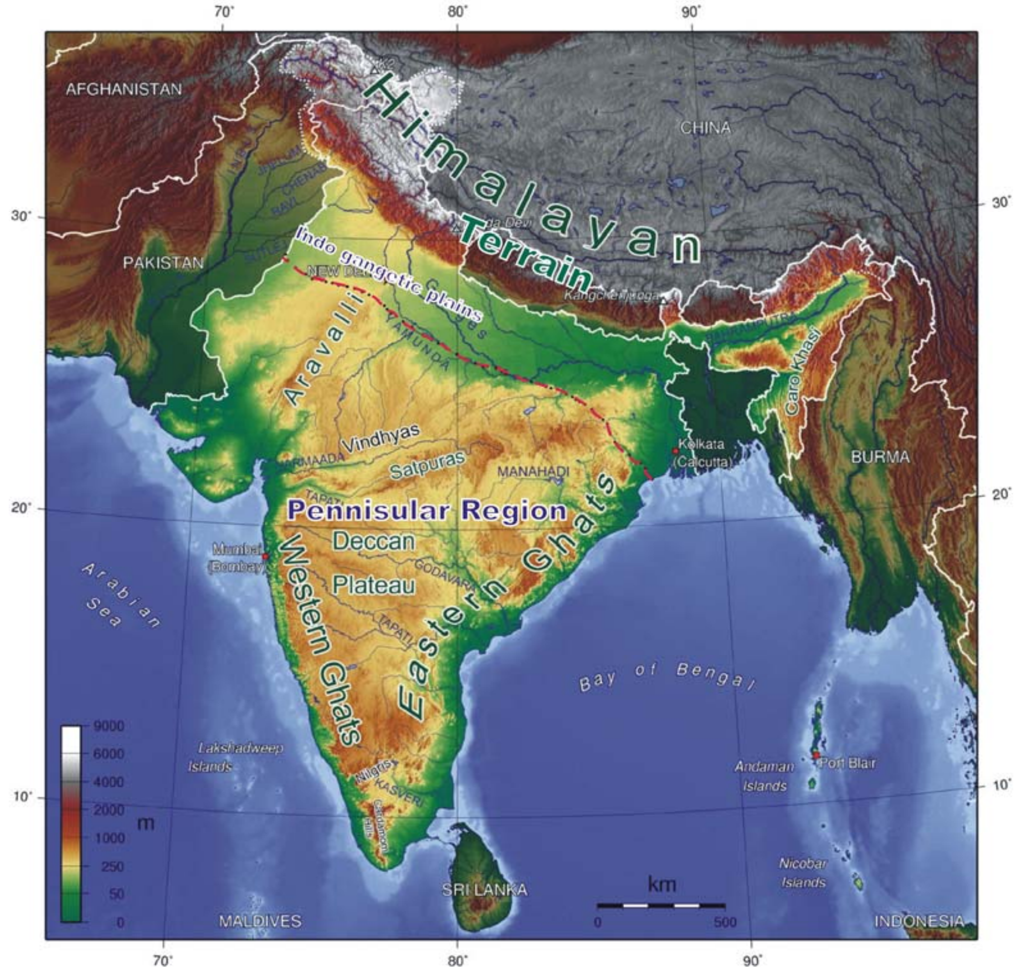

Figure 1. Physiographic divisions of India

2.1.1 Peninsular region

This region generally faces the lowest level of natural hazards including landslides. This part is considered to be tectonically stable as compared to other regions. The region consists of hard and massive crystalline Pre-Cambrian rocks. The topography, in general, is characterized by undulating and moderate slopes supporting thick vegetation. The landslide phenomenon in Eastern coastline is comparatively less. This region is considered to be moderate from the point of landslide occurrence.

The Western coastline of Kerala is often considered as a critical zone for mass movements (Thampi et al., 1995). The region experiences several types of landslides especially during the monsoon seasons. This includes rock falls, rock slips, slumps, creeps, debris flows and in a few cases, rotational types of slides (Sekhar et al., 2009). These landslides are mainly caused by the increase in strain due to percolating rain water in rocks fissures, causing rocks to fracture and slide down the slope. The Western Ghats experience landslides of medium to small sizes locally due to unfavorable geological and adverse hydrogeological conditions. The undercutting by the Arab sea is also another important factor inducing landslides.

A few key landslides that caused huge damages are worth noting. One of them is the Amboori landslide of November 2001 in the State of Kerala, which killed 23 people (Bhandari, 2006). Landslides have been observed along the steep slopes overlooking the Konkan coast in the Western Ghats. These are also quite the Nilgiris, with the Runnymede landslide, the Glenmore slide, the Conoor slide and the Karadipallam slide, to name a few. The main cause of occurrence of these landslides is the unplanned construction activities in the Nilgiri region. During October-November 1978 itself, about 90 lives were lost due to landslides in this region.

2.1.2 Indo-Gangetic Alluvial Plains

This region is characterized by low level plains with very broad undulating topography. As a result, it has the minimum probability for landslide occurrence. However, this region dominantly suffers from heavy flood hazards every year.

2.1.3 Himalayan Region

In the Himalaya alone, one can find landslides of every type - big and small, long and short, quick and creeping, ancient and new (Bhandari, 2006).

The Himalayan region comprises of the most unstable ecosystem, characterized by highly weathered, jointed, fractured and sheared rocks, accompanied by heavy annual precipitation and youthful stages of river, which constantly modify the slope characters. For centuries, formidable snow avalanches did hurtle down the slopes in the higher Himalaya causing extensive damages.

In addition, since the terrain is in its youthful stage of development with its steep topography, adverse seismic and hydrogeological conditions, the region is more prone to all types of natural disasters particularly landslides. The entire terrain is marked by hundreds of landslides. In addition to the natural landslides, due to massive development activities in the recent times in this areas, the reactivated landslides are also included in this number.

Apart from landslides, other natural hazards like earthquakes (Kangra, H.P., 04.04.1905, Intensity: 8.0; Assam, 23.10.1943, Intensity: 7.2; Uttarkashi, U.K., 20.10.1991, Intensity: 6.6; Kashmir, 8.10.2005, Intensity 7.4) and flash floods due to cloudbursts followed with subsequent river and road blockades are often reported. Zones of faults and thrusts in which rocks are shred and shattered are particularly prone to slope instability. The structural discontinuities and presence of weak planes not only reduce the potential strength but also serve as pathways for percolation of water. Valdiya (1980) noticed that rocks of the narrow belt on the junctions of the Great Himalaya-Main Central Thrust (MCT), Lesser Himalaya-Main Boundary Thrust (MBT) and Outer Himalaya, have experienced irreparable hazards since ages. In Balia valley of Nainital district, Nainital fault controls most of the slope instability processes. A continuous fringe or apron of gigantic fans and cones of landslide debris, both ancient and recent, can be seen within a 5-20 km wide MCT belt. The Kaliyasaur landslide in the Alaknanda valley appears to be related to the Srinagar Thrust (Pande, 2006).

In view of these conditions, among the three physiographic divisions, the Himalaya is considered to be a region of high hazard as far as landslides are concerned. Further, the Himalaya is also notoriously economically backward area. Therefore, majority of the people resort to terrace farming to grow cash crop in a bid to get better returns from the land, which has made the area more ecologically fragile. This has also resulted in water seeping into the rocks the mountains, which in the long run may break up the inter-locking ecosystem binding the mountains (Pande, 2006).

Landslides in North-Northwest Himalayan region

The landslide of an unprecedented dimension was the great tragedy of July 1970 in Alaknanda valley, Uttarakhand State that resulted from the massive floods in the river Alaknanda, upon breach of a landslide dam at its confluence with river Patal Ganga (Bhandari, 2006).

In August 1977, a major landslide occurred in Khaila village and destroyed sheds and houses, killing 44 persons and destroying about 150 acres of standing crops. In August, 1979, a major gravitational slide of the steep mountain slopes between Rauntigad and Tawaghat regions seriously affected several villages situated on the above slopes. Two major landslide events occurred in Okhimath in August 1998. A total of Rs. 41 million worth of property was destroyed and 101 lives perished (Pande, 2006). Some other burning examples of landslides that have caused large-scale human tragedies, resources damage and associated environmental-social hazards in the Garhwal Himalaya are the Malpa landslide in 1998, the Phata landslide in 2001, the Budhakedar landslide in 2002 and the Uttarkashi landslide in 2003. Details on some of these landslides have been provided in subsequent sections, with a brief mention of two major landslides of recent years given below.

A few years ago, the Malpa rock landslide (Figure 2) tragedy of 18 August 1998, hit the newspaper headlines as it instantly killed 220 people and wiped out the entire village of Malpa on the right bank of river Kali in the Kumaun Himalaya of the State of Uttarakhand (Bhandari, 2006).

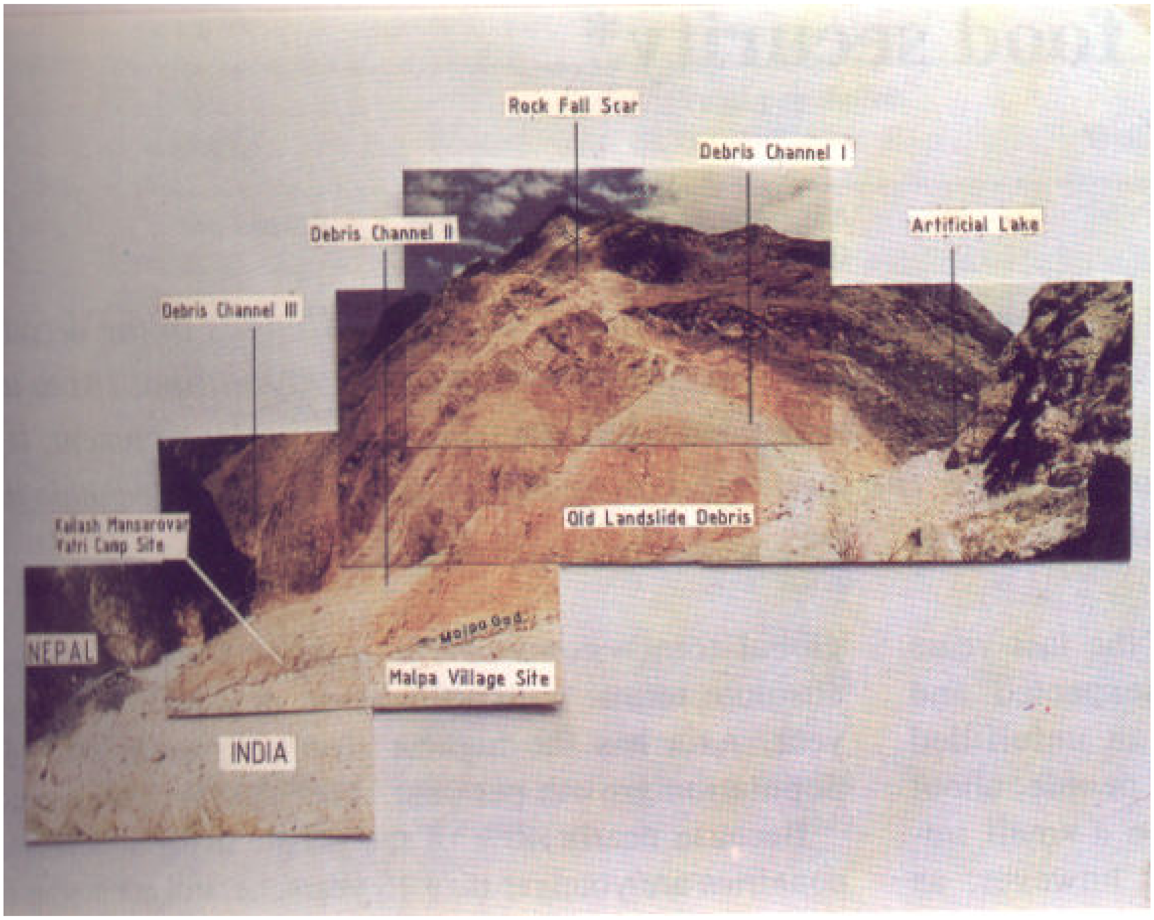

Figure 2. An aerial view of Malpa landslide

The town of Uttarkashi situated at the base of Varunavrat mountain and on the right bank of Bhagirathi river in the Uttarakhand Himalaya, witnessed a serious landslide crisis (Figure 3), which started on 23 September 2003 and continued for 3 weeks with the gravest situation on 1 October 2003. A large-scale damage was caused to the residential areas and infrastructure facilities such as power sub-station and the Rishikesh–Gangotri National Highway (NH) around the small township of Uttarkashi (Kumar et al., 2008).

Figure 3. A panoramic view of Varunavat landslide, Uttarkashi

Landslides in Northeastern Region

The northeastern region is also badly affected by landslide problems of inexplicable variety. Landslides in the Darjeeling district of the State of West Bengal and in other States namely Sikkim, Tripura, Meghalaya, Assam, Nagaland and Arunachal Pradesh have been causing lots of problems and losses. The Darjeeling floods of 1968 destroyed vast areas of Sikkim and West Bengal by a spate of landslides that occurred over a three-day period with precipitation ranging from 500 to 1000 mm. The highway to Darjeeling remained cut off at 92 places resulting into total disruption of the communication systems. Similar happenings can be regularly observed in region along the North Sikkim highway (Bhandari, 2006).

2.2 The Need for Landslide Hazard Assessment

In recent years, the assessment of landslide hazard has become a topic of major interest for both geoscientists and engineering professionals, as well as for the community and the local administrations, primarily due to an increased awareness of the socioeconomic significance of landslides (Brabb and Harrod 1989), increased pressure of development and urbanization on the environment all across (Aleotti and Chowdhury 1999), and a number of catastrophic events in the country (Divoli et al., 2007).

Due to the insufficient knowledge on temporal and spatial occurrences of landslide processes and the event frequency, which is vital for making quantitative estimates of landslide hazard, calibration of predictive models, and validation of temporal predictions cannot be done judiciously (Brunsden et al., 1995) thereby hindering the proper evaluation of landslide hazard at the national level.

3. LANDSLIDES: DEFINITION, TERMINOLOGY AND FACTORS

Landslides are the natural processes, which occur and recur in specific geo-environmental conditions. Although, landslides principally occur in mountainous regions, these can be triggered at places such as surface excavations for highways, buildings and open pit mines. Some of the landslides can be rapid which can occur in seconds, whereas others may be slow which can take hours, weeks, or even longer to develop. Typically, these may occur at places where they have occurred before, on the steep slopes, on the benches, where drainage is causing a problem and at places with weak geological conditions exist.

3.1 Definition and Types

In general, landslide can be defined as (Varnes, 1984),

"All varieties of mass movements on slopes, including some such as rockfalls, topples and debris flows that involve little or no true sliding."

Different criteria may be used for classifying landslides such as form of sliding surface, type of materials involved, rate of movement, type of movement, age and state of activity. The most commonly used classification is the one proposed by Varnes (1978) and Cruden and Varnes (1996), which is based on two important parameters namely the type of movement and the type of material involved (Table 1). A detailed description on types of landslides can be found in Anabalgan (2007).

Table 1. Types of landslides (modified after Varnes, 1978)

Type of movement			***Type of material***		
			Bedrock	***Debris***	***Soil***
				Predominantly coarse	***Predominantly fine***
Falls			*Rock fall*	*Debris fall*	*Earth fall*
Topples			*Rock topple*	*Debris topple*	*Earth topple*
Slides	**Rotational**	**Few units**		*Debris slump*	*Earth slump*
	Translational	**Many units**	*Rock block slide* *Rock slide*	*Debris block slide* *Debris slide*	*Earth block slide* *Earth slide*
Spreads			*Rock spread*	*Debris spread*	*Earth spread*
Flows			*Rock flow*	*Debris flow*	*Earth flow*
Complex movements			*Combination of two or more principal types*		

The landslide types can also be understood in terms of the context and situation by knowing the slope history at different times, as given in Bhandari (2006),

i) Old landslides dormant for decades or centuries, including those which are known to be dormant for decades under a thick cover of vegetation, without showing any signs of instability or activity.

ii) Old landslides which are known to be dormant for decades but are feared to activate due to neglect of slopes, ongoing developmental activities or such other reasons.

iii) Landslides only a few years old, but with no recurrent activity observed since then.

iv) Old landslides, which appear to be dangerously big, but their activity levels remain unstudied and their slope history is unknown.

v) Recent landslides with clear evidence and/unquestionable potential for repetitive activity and enlargement.

vi) Known landslides, periodically treated with partial, inadequate, temporary and non-engineered remediation.

vii) Recent small landslides, with evidence of self-healing.

viii) Landslides, old or recent, under effective (engineered) control.

3.2 Danger, Hazard and Risk

A systematic study of landslide involves,

i) identification and description of danger

ii) evaluation of hazard probability

iii) assessment of the risk.

The definitions of danger, hazard and risk and other related terms can be found in Fell et al. (2008) and Technical Committee of the International Society of Soil Mechanics and Geotechnical Engineering (http://www.engmath.dal.ca/tc32/2004Glossary_Draft1.pdf),

The landslide hazards may be analyzed on mega-regional scales (>1:100000), regional scales (1: 25000 to 1: 50000), semi detailed scale (1:5000: 1: 10000) or detailed scales (1: 1000 – 1: 2000). The studies on mega-regional scale are useful for understanding the pattern of distribution of hazards in a country or a portion of a country. Nevertheless, they can not be effectively used for planning purposes. The regional scale studies are carried out using empirical approaches covering fairly large areas. The output maps can be used for effective planning on District level or general location of major satellite townships and other such purposes. In case of landslide studies on detailed scales, analytical methods are employed and different segments of a slope are covered in detail. These site specific are useful to identify the required control measures as well as to design them based on the realistic estimates of analysis carried out earlier.

Assessment of risk is essential for planning landslide hazard management practices.

3.3 Factors Responsible for the Occurrence of Landslides

A landslide is seldom attributed to a single causative factor. A number of factors contribute to slides, including geology, gravity, weather, groundwater, wave action, and human actions. It is of fundamental importance to identify these causative factors for landslide occurrences in a region, which often is difficult. It is also usually hard to establish the relationships between various causative factors. The great variety of slope movements reflects the diversity of factors that may disturb the slope stability.

Nevertheless, it may be possible to demarcate landslide susceptible areas by identifying and analyzing the factors that have caused landslides in the past (Aleotti and Chowdhury, 1999). It is of primary importance to understand the conditions, under which mass movements are caused and the factors that trigger the movements. Only a systematic study makes it possible to recognize the extent of danger and to propose adequate remedial measures. In general, the factors causing landslides can be categorized into natural and anthropogenic factors (Figure 4), which have been briefly described here.

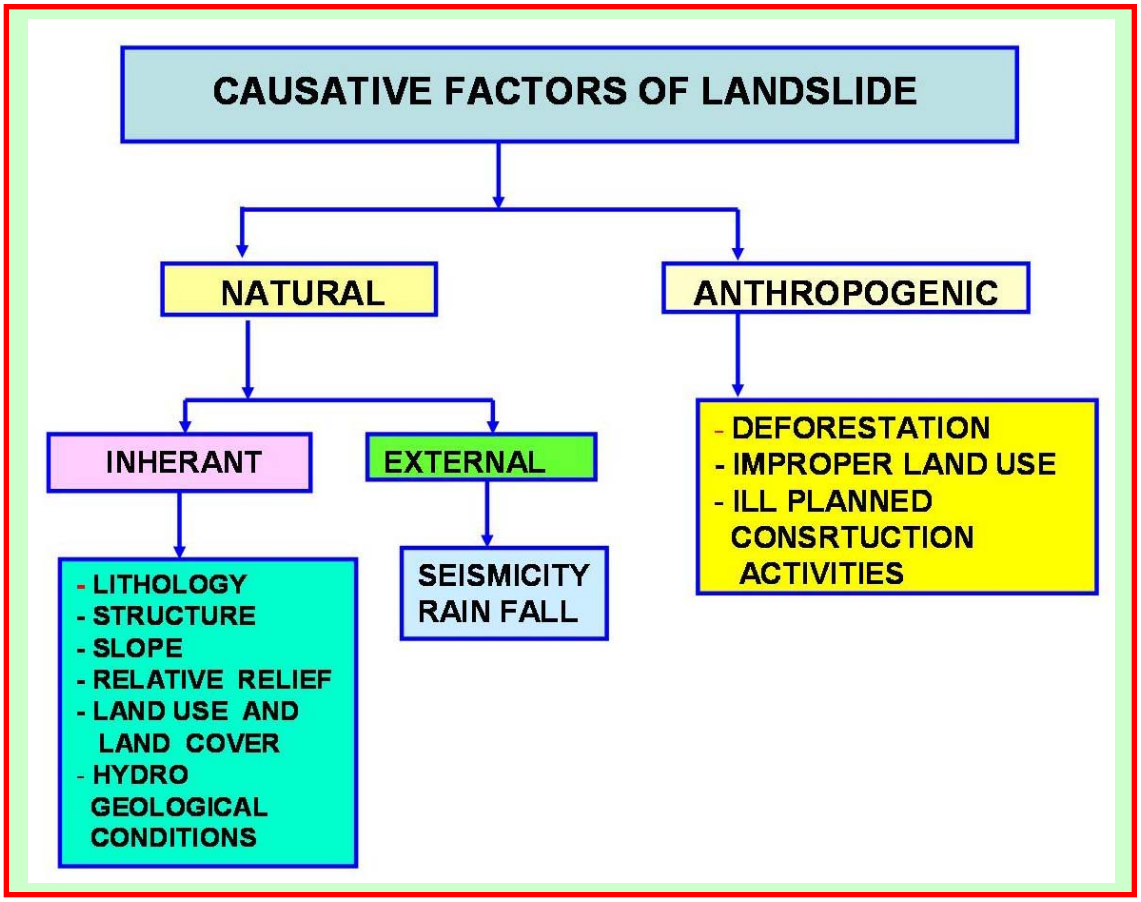

Figure 4. Flowchart showing causative factors of landslide

3.3.1 Natural Factors

Natural factors can be grouped into inherent and external factors.

Inherent Factors

The inherent factors represent the inherent characteristics of hill slope. These factors include geology, slope gradients, local relief, hydrogeological conditions, as well as land use and land cover.

Lithology

It is an important geological parameter as it is related to the basic characters of the slope forming materials. There are two fundamental types of slope forming materials – loose, unconsolidated materials and in-situ rocks. The unconsolidated materials, except older fluvial materials, in general, have least shear strength and are more prone to failure. Particularly, if they are charged with water, they show high potential to failure. The rocks are in general more stable as compared to unconsolidated materials. The lithological characters related to failure potential are related to their erodibility response to the processes of weathering and erosion. For example, igneous rocks, such as granite, are hard and massive and hence show greater resistance to erosion. Moreover, they have interlocking crystals, which is mainly responsible for their increased angle of shearing resistance. On the contrary, the terrigenous sedimentary rocks are more vulnerable to erosion and hence more landslides are seen on these rocks. The granular metamorphic rocks like Quartzite are more stable due to similarity of properties with igneous rocks. However, other metamorphic rocks like phyllites and schists are more prone to landslides. Mechanical and chemical weathering affects the strength of rock mass, which is also one of the contributory factors of landslide.

Structure

Structure includes primary and secondary discontinuities in the rocks such as bedding, joints, foliations, faults and thrusts. The disposition of the structural discontinuities in relation to slope inclination and direction has a great influence on the stability of slopes. Since the landslides by definition are gravitational failures, the presence of preexisting adverse discontinuities are essential for rock failures to occur. In general, if the discontinuities dip at an angle less than that of the slope and more or less in the same direction of the slope, the possibilities of failure are more. The more the frequency of joints, the size of the resultant rock wedges will be small promoting more failure potential.

Slope morphometry

It defines various slope categories based on the occurrence of slope angles. The distribution of slope categories is dependent on the geomorphological history of the area. The angle of slope of each unit is a reflection of a series of localized processes and controls, which have been imposed on the slope. In general, more the angle of slope, the failure potential will be more. However, it is the shear strength, that is, combination of cohesion (C) and angle of internal friction (Φ) of slope forming materials, and is the guiding factor in assessing the stability of the slopes. For example, the older fluvial materials, which have high Φ values, are stable even at higher slope angles of more than 45°. The coarser igneous rocks tend to have more Φ values, but the finer rocks have more of C values. The meandering river courses in Himalaya often causes steep to very steep slopes on the outer periphery of the meanders, where the slopes become unstable.

Relative relief

The relative relief refers to the local height of the slope between the ridge top and valley floor in a slope facet. It has an important role in forming the size of the unstable wedges. The slope having higher relative relief may form unstable rock wedges of big size with more probability of failures.

Land use and land cover

Land cover is an indirect indication of the stability of hill slopes. The thickly vegetated forest areas are less prone to erosion and are generally more stable. However, the barren and sparsely vegetated lands are more prone to erosion and instability. Forest cover smoothers the action of climatic agents on the slope and protects them from weathering and erosion. A well spread-out root system increases the shearing resistance of the slope materials. However, the growth of plants and other vegetation in the pre-existing plane of joints of the rocks may also cause excess stress on joint walls due to increase in size of roots. This phenomenon may push the slope materials out and cause landslides

Similarly, the land use also is an indication of slope behavior. For example, the agricultural lands represent areas of repeated water charging for cultivation purposes and cause intermittent pore pressure on slope materials. Moreover, the agriculture is generally practiced on low to very low slopes though moderately steep slopes are also not spared at places. Hence, these areas are considered as stable slopes. The deforestation on slopes, particularly the soil slopes, is one of the well known factors in inducing landslides as it exposes barren soil to erosion and destabilization.

Hydrogeological conditions

Hydrogeological conditions indicating the subsurface flow pattern is an important parameter in establishing the stability of hill slope. Because the subsurface water in hill is mainly channeled along the structural discontinuities of the rocks, it does not have a uniform flow pattern. Rain and snowmelt water penetrates into joints and fractures of rocks, thus increasing the pore water pressure within rocks. This, in turn, may also decrease shear resistance of rocks causing instability. Saturated clayey soils, when dry up get desiccated and shrunken, which result in cracking of surface. The surface water readily percolates through these fractures and the increased subsurface water content may lead to plastic deformation. Water trapped in rock fissures and joints freezes causing increase in volume. The freezing and thawing actions, which are common in higher Himalaya is one of the important causes of slope instability. This imparts a tremendous amount of pressure on the rock walls, leading to widening of joints and fractures. Freezing of water on the surface impedes drainage of slope and thus increasing pore water pressure.

In case of subsurface water, it is only the shallow water close to the surface that is important from the point of landslides as they can sufficiently reduce strength of surface materials. The subsurface water flowing at deeper levels which are not day-lighted on surface is not important to be considered.

External Factors

The external factors are the outside factors, which can not be studied on a hill slope. They usually affect a larger area and hence are called regional factors. These factors include concentrated rain fall and earthquakes. Since many a time these factors are responsible for initiation of landslides, they are also known as triggering factors.

Seismic shocks and vibrations

The seismic shocks produced by earthquakes, vibrations due to large-scale explosions and heavy machines may affect the equilibrium of slopes by evoking a temporary change in stress levels due to oscillations of different frequencies. These vibrations induced stresses often produce catastrophic landslides. In water saturated clay and fine sands, the displacement or rotation of grains can result in sudden liquefaction of soils initiating a landslide.

Reports of earthquake-induced landslides surface virtually after every earthquake in hilly areas. Himalaya, situated in the moderate (Intensity: 6.0) to great (Intensity: 8.0) seismic zones are geodynamically very sensitive and vulnerable. The earthquake releases a considerable amount of strain energy. This energy adds a lot to the shear stress in a slope instability mechanism. On an average, nearly 200 earthquakes of smaller magnitudes occur every year in the

Uttarakhand State alone. Most of them are undetected by the local communities. There are several examples of earthquake triggered landslides, viz. a major landslip occurred in 1880 at Sher-ka-danda ridge of Nainital hills after an earthquake (Pande, 2006).

There are many other examples of earthquake-induced landslides in India. The Assam earthquake of 1950 caused landslides in more than 15 thousand square km area of the Northeastern Himalaya. The Uttarkashi earthquake of 1991 and its aftershocks triggered hundreds of landslides, which have been compiled in Table 2 (Bhandari, 2006).

Table 2. Uttarkashi earthquake induced landslides

Area	Type of slides
Tehri_Uttarkashi	Rock masses were found to be dislodged
Uttarkashi-Kanaudia Gad	A number of landslides occurred in the terrain composed of river borne material as well as rock outcrops
Gangari-Aghora	Many cases of rock dislodgments and two major landslides
Dharasu-Barkot	Rock dislodgements
Uttarkashi-Kishanput Sukinidhar	Many cases of rock dislodgments and landslides. Cracking in river banks that caused collapsing of high retaining walls
Bhaldiyana-Sukinidhar	A number of rockslides and rock dislodgments
Dhanutri-Kamand	A number of landlsides mostly in overburden material
Kund-Gauri Kund	Rock dislodgments and a few landslides
Tilwara-Chirbatia	Some rock dislodgments

Similarly, a number of landslides were reported after the Chamoli earthquake in 1999 also. There were about new 20 landslides of different dimensions observed in various parts of Chamoli region and about 6 landslides were found to be reactivated (Ravindran and Phillip, 2002).

The magnitude 7.6 Muzzafarabad earthquake of October 8, 2005 triggered hundreds of landslides and rock avalanches. Translational and rotational landslides, shallow rockslides and debris flows have been reported (Bhandari, 2006).

Concentrated rainfall

The concentrated rain fall in a region may lead to cloud burst, and is another important external factor triggering the landslides. This phenomenon may lead to a sudden increase in pore water pressure, decrease in the shear strength of the slope materials and at the same time increasing effective total weight. This may lead to sudden failures. Often this phenomenon is responsible for debris flow and consequent extremely high damages in Himalaya. When sustained rainfall occurs in an area, this leads to disintegration of slope materials consisting mainly of debris. This leads to debris flow down the slope. When this phenomenon is associated with gullies, then the steep slopes below may lead to terrific effects of erosion and large scale damages.

It is a general observation that the landslides mostly occur during monsoon season after a heavy spell of rain. The clayey and marly materials shrink during dry spell, but swell under moist conditions, creating situation conductive to mass movement, including earth-flows. The Himalayan region is sometimes visited by incessant rain that continues for more than a week at a stretch. The examples are commonly observed in the terrain of crystalline rocks in the Champawat-Almora-Ranikhet-Masi and Pauri-Lansdowne belts. Landslides of 1880, 1898, 1924, 1939 and 1943 took place after the heavy rainfall. Tawaghat-Khela landslides in Pithoragarh district followed heavy rainfall. Sirvari landslides (17-18 July, 1986) reveals a similar story. The landslides ravaged basin area of two small tributaries of Alaknanda brought a large volume of boulders on 20 July 1970. Block slides in limestone, dolomite and quartzite resulting from heavy rainfall are quite common in Nainital, Mussoorie-Gohna Lake area (Birahi valley), Pakhi-Belkutchi-Patalganga (Alaknand valley), Satpuli and Marora (Nayar valley) and in the Kapkot-Tejam-Jaulgibi belt (Pande, 2006).

3.3.2 Anthropogenic factors

These factors originate from intermingling of the mankind with the earth surface and include deforestation, improper land use, poorly planned construction activities, urbanization etc.

Deforestation

Plant roots have the tendency to bind soil and thus they are helpful to retard slope instability unless the failure plane is very deep i.e. beyond the root zone. This factor contributes for many Himalayan landslides, as intensive deforestation is reported in many parts of the Himalaya.

Improper land use

The improper land use can be gauged from the following activities,

- Agricultural practices on steep slopes,
- Irrigation on steep and vulnerable slopes,
- Overgrazing and
- Quarrying for construction materials without considering condition of the terrain

Poorly planned construction activities

Often, improper selection of the site or lack of terrain capability evaluation before the placement of infrastructures such hill roads and canals may cause landslides. Moreover, overloading of slopes or removal of lateral support by human interference is a prime concern for slope failures in many areas.

The use of explosives to blast the surfaces of the mountains while constructing roads has brought its own brand of havoc. A study on establishing relationship between the Mussoorie-Tehri road construction and the subsequent landslides in the region, revealed that landslides caused more devastation in deforested rather than forested areas. The study found that 148 landslides took place on slopes where the tree cover was less than 40% and 118 landslides took place where the tree cover was more than 60%. It was found that the landslide debris in afforested area was only 12 m^3 as compared to 26 m^3 of debris in deforested areas. Similarly, 30000 to 40000 m^3 of soil was excavated in carving out 1 km of road in the Himalayas – a figure that eloquently reveals the extent of damage that even relatively harmless activity like road construction does to the local ecology. To make matters worse, most roads are constructed without proper field survey methods. Such roads invariably cause new landslides or reactivate old ones. At present, about 44000 km long roads are spread over the Himalayan region. It has been calculated that 550 m^3 of debris per km of road is produced annually by landslides and rockfalls, causing enormous amount of sediment to slide down the slopes. Most of the roads in Himalayan region have been unscientifically constructed. For example, Panar-Ghat road sections (Distt. Pithoragarh) is constructed parallel to North Almora Thrust. Similarly, Ratighat-Garampani road runs parallel to fault line. At 147 km on Haridwar-Badrinath road (Garhwal Himalaya) a multitier slide, having combination of surficial and deep-seated movement of fragmented rock, had occurred (Pande, 2006).

Urbanization also brings the severe problem of garbage and sewage disposal. The discharge of sewerage and the choking of gullies, which function as natural drains, lead to dangerous seepage, making mountain surfaces that much weaker.

3.3.3 Relationship Between Factors

It is usually hard to establish the relationships between various causative factors. However, it may be possible to demarcate landslide susceptible areas by identifying and analyzing the factors that have caused landslides in the past (Aleotti and Chowdhury, 1999). Nevertheless, from the perspective of landslide hazard and risk assessment, the categorization of factors, as given in Figure 4, need to be understood in terms of internal or preparatory factors, and in terms of external or triggering (Crozier, 1986; Siddle et al., 1991). Internal factors assume a state which will allow the normal fluctuation of external factors to be sufficient to trigger a landslide. Although, internal factors may change over a long period of time to reduce the resistance/shear stress ratio, there is always an external factor which triggers the movement. The internal factors represent the inherent attributes of the ground which make the slopes susceptible to landslides. These causative factors need to be selected judiciously for a landslide hazard and risk assessment study, which will also depend on the study area, the scale of mapping, the reliability as well as accuracy of the data (Aleotti and Chowdhury, 1999).

4. LANDSLIDE HAZARD ASSESSMENT

In recent years, the landslide hazard assessment has become a major topic of interest to both geoscientists and engineering professionals, as well as for the community and the local administrations in India. This interest has further increased due to all-round awareness of the socioeconomic significance of landslides (Brabb and Harrod 1989), augmented pressure of development and urbanization on the environment, and a number of catastrophic events in the country.

Typically, a natural hazard can be defined as the probability of occurrence within a specified period of time and within a given area of potentially damaging phenomenon. In specific terms, it refers to the division or zoning of land surface into areas and ranking of these areas according to degrees of actual or potential hazard from landslide or other mass movements on slopes (Varnes, 1984). Thus, the area is categorized into very high, high, moderate or medium, low and very low hazard zones resulting into the production of landslide hazard zonation (LHZ) maps.

The LHZ maps are an important source of information to the developmental planners as tools for the efficient management of land and its resources. Therefore, these need to be presented in a form comprehensible to them. In addition, LHZ maps are key entities for the assessment of damage potential, and for the quantification of risks due to landslides. It is also true that the forecasting of a landslide for early warning may also depend on the accuracy of landslide hazard map of a region. Over the years, a number of LHZ maps have been prepared throughout the world, and to a certain degree they often indicate areas susceptible to future problems (Varnes, 1984).

The aim of LHZ mapping is to determine the spatial and temporal extents of the landslide hazard. At this stage, it may be expedient to distinguish between landslide hazard and landslide susceptibility. A landslide susceptibility map divides the landslide prone region into different zones according to the relative degree of susceptibility to landslides. This requires the identification of those areas that are, or may be affected by landslides, and the assessment of the probability of such landslides occurring within a specific period of time. However, since the observation on the time domain of landslide occurrence through zonation mapping has always been a difficult task, the time-dependent factors such as rainfall and earthquake are not taken into account in landslide susceptibility zonation (LSZ). Therefore, from conceptual and operational limitations, LHZ map is often considered as a LSZ map, which defines spatial prediction of landslides in terms of landslide susceptibility, which, in turn, is a function of landslide and landslide related internal or preparatory factors, as listed before. The aim of LSZ is to identify places of landslide occurrence over a region on the basis of a set of physical parameters. When zonation takes into account triggering factors such as earthquakes and rainfall in addition to the preparatory factors, it refers to LHZ. Thus, the LSZ maps do not directly incorporate the time and magnitude of landslide occurrences. However, since LSZ has been conceptually accepted as LHZ, it is popularly referred to as LHZ in India. The terms LHZ and LSZ have, therefore, been used interchangeably in this report.

A typical landslide hazard assessment process involves following steps,

i) Creation of landslide inventory
ii) Selection of mapping scales depending upon end-user requirements
iii) Selection of mapping unit
iv) Identification of the causative factors
v) Creation of thematic database
vi) Application of different methodologies for LHZ map preparation
vii) Landslide risk assessment
viii) Detailed landslide investigation/mapping and monitoring

4.1 Creation of Landslide Inventory

In order to estimate future landslide occurrences, it is necessary to understand the conditions and processes of landslide control, and information on existing landslides in a given region. A map or data layer showing distribution of existing landslides serves as the fundamental data for understanding various conditions and processes. Not only the geographical location and type of landslides but also their relationships with other key parameters such as material of slope, slope and its direction, land use land cover, climate and hydrology, form the basis for a landslide inventory. Thus, an inventory of past, existing and new landslides, which also takes into account the mapping of the state of activity and the mode of failure of landslides in the region, is required (Kumar et al., 2008).

Development of inventory or databases of existing landslide incidences and their updation in different parts of India have been considered as essential input for assessing the status of hazard (Sharda, 2007). The main purpose of a landslide inventory map and database is the documentation of all the known landslide incidences, including stabilised, dormant, reactivated, and the most recent slides. Hence, in a typical landslide inventory, the landslides may be listed as,

i) Active landslides
ii) Dormant landslides
iii) Old landslide zones

Thus, a landslide inventory database may include data about its geographical location, date of occurrence, its historical record, rainfall, and seismicity during the landslide event, the dimension and type of the landslide, the volume of material dislodged, the nature and extent of the damages caused/likely to be caused by further sliding, the type of triggering factor (e.g., earthquake, cloudburst, anthropogenic interference, toe erosion by streams or rivers, etc.), the tentative causative factors leading to slope failure etc. The field photographs of landslides, which portray the physical appearance of the landslide in the region, should also be included. However, it may not always be possible to prepare a complete landslide inventory database as it involves the collection of enormous amount of data from the field, which practically may be impossible.

In recent years, landslide inventories have been prepared and updated by utilizing data from aerial photographs and high spatial resolution remote sensing images obtained from satellites such as IKONOS and Quick Bird launched by USA, and CARTOSAT - 1 and 2 launched by India. A few countries like Australia, Italy and New Zealand have taken a lead in preparing landslide inventory databases in this direction. Approaches, ranging from visual interpretation of landslides from high spatial resolution remote sensing data and their fused products to digital image interpretation or automatic classification of remote sensing images have been adopted. The stereo-capability of CARTOSAT satellite sensors is not only useful for estimation of terrain height but also for landslide inventory mapping, as they provide three-dimensional visualisation. The Light Detection and Ranging (LiDAR) data can be used to prepare landslide inventories in the forest areas of hilly regions, to refine the landslide boundaries prepared during field investigations and for three-dimensional visualization at high resolution. The Synthetic Aperture Radar (SAR) interferometric techniques can also be a viable solution to map subtle movement due to landslides, which also is a key information to reflect history of landslides in a landslide inventory.

In India, there seems to be apparent lack of landslide inventory database. Although, different regions of Geological Survey of India (GSI), are involved in preparation of these inventories and have published inventory of landslides of the northwest Himalayas in 2005 (Gupta, 2005), the preparation of a comprehensive and user-friendly national landslide inventory database has yet to be taken up for continuous updating of the landslide scenario in India. This can only be achieved by networking different agencies, research and academic institutions engaged in this task. The field investigations for database creation need to be ably supported with geomatics tools and vice versa.

The field investigations, mainly from the point of view of geotechnical characteristics have been undertaken at some of the landslides in Lower Himalayas. These include Kaliasaur landslide along National Highway (NH) -58 near Srinagar, Uttarakhand, the Sher-Ka-Danda landslide at Nainital, B2 and Lanta Khola landslides in Sikkim, the Powari landslide on NH-21 in Himachal Pradesh, and the Patalganga landslide on NH-58 near Pipalkoti, Uttarakhand.

4.2 Selection of Mapping Scales

The choice of the mapping scale affects the selection of the appropriate approach for landslide hazard assessment (Aleotti and Chowdhury, 1999). Thus, for example, a geotechnical investigation based approach may be suitable for studies concerning individual landslides or landslide affected small areas. The mapping scale for a landslide susceptibility zonation study controls the selection of different causative factors and the level of detailed mapping.

Maps at 1:50000 to 1:100000 scales may be appropriate for national and regional studies since these are only indicative and do not provide adequate details. A mapping scale of 1:25000 to 1:50000, generally referred to as macro-scale and is preferred for delineation of landslide susceptibility zones in hilly regions, river basins, transportation routes etc. Large-scale maps at 1:5000 to 1:10000 scales, also referred to as meso-scale are required for detailed studies at the local and municipality level (NDM Guidelines B, 2009). Mapping at scales larger than the meso-scale will typically be required for site-specific studies.

Thus, the scale of landslide hazard assessment can be defined either on regional basis, community basis or a site basis (Chau et al., 2004). However, three basic factors may be considered to decide upon the scale of LHZ mapping (Aleotti et al., 1996a),

- i) the purpose of the study
- ii) the extent of the study area and
- iii) the availability of data

4.3 Selection of Mapping Unit

It is also important to define a mapping in the field so that the status of various factors may be evaluated. A mapping unit is a land surface that is homogeneous within itself but shows heterogeneity with adjacent units (Hansen, 1984). The selection of a suitable mapping unit for landslide hazard assessment is governed by a number of factors. These include,

- i) type and degree of details of landslides to be studied
- ii) the scale of mapping
- iii) the quality, resolution, scale and type of input data
- iv) the availability of analysis tools such as field investigations, remote sensing and/or GIS

For example, in a raster-based GIS approach for LSZ mapping, the region may be divided into regular grids of pre-defined size depending on the data availability. These grid-cells or pixels serve as the mapping units of reference (Carrara, 1983; Bernknopf et al., 1988; Pike, 1988; van Westen, 1993, 1994; Mark and Ellen, 1995). In this approach, each pixel in the study area is assigned a value of importance or weight corresponding to each causative factor and the weights are integrated in GIS environment to generate an LHZ map.

However, adoption of uniformly spaced mapping units in the form of regular grids of pre-defined size may not ensure the homogeneity of the stability conditions. The weights assigned may not culminate to reliable output in view of heterogeneous conditions within unit itself.

4.4 Identification of Causative Factors

A comprehensive knowledge of the terrain is a pre-requisite to identify various problems related to slope conditions, including existing and the potential instability of slopes in future. Depending upon the terrain conditions, one or the several causative factors, as described in Section 3.3 may be identified and considered. The scale of mapping will govern the collection of data pertaining to these factors through a number of varied sources such as field surveys, topographical, geological and other maps, aerial photographs and remote sensing images.

4.5 Creation of Thematic Database

In this step, a number of thematic maps are prepared by compiling and collating the data on causative factors such as geology, geomorphology, land use, land cover etc., and also the distribution of existing landslide processes. Extensive use of available maps, past statistical and census records, field and Global Positioning System (GPS) surveys, aerial photography, satellite remote sensing and GIS is made to create the thematic layer database.

The most important inputs required for carrying LHZ mapping at both the macro and meso scales have come from topographical and geological maps, remote sensing images, and seismological data in the case of earthquake induced landslides. In India, the custodians of these data sources are the Survey of India (SoI), GSI, National Remote Sensing Center (NRSC) and Indian Meteorological Department (IMD). The SoI provides topographical maps at scales from 1:25000 to 1:250000 scales and is also expected to take up the task of generating topographic/contour maps at the scale of 1:5000 or 1:10000 for the landslide affected hilly regions of India. These agencies play a major role in providing data and hence are expected to be an integral part of any programme on landslide hazard management and risk assessment in the country.

4.6 Methodologies for LHZ Mapping

As stated earlier, the landslide hazard refers to probability of occurrence of a landslide event on a particular slope. The landslide hazard may be distributed on varying degrees in different parts of an area. A LHZ map divides the land surface into zones of varying degree of stability based on an estimated significance of causative factors in inducing the instability (Anbalagan,1992). The LHZ maps are useful for the following purposes,

i) The LHZ maps identify and delineate unstable hazard prone areas so that environmental regeneration programs can be initiated adopting suitable mitigation measures.
ii) The maps help the planners to choose favorable locations for siting development schemes.
iii) They maps are useful as input parameter for assessment of risk of landslides.

The LHZ maps may also be used during the preliminary stages of geotechnical investigations, when a rapid hazard assessment technique is needed. The methodology of preparation of these maps therefore needs to be systematic, practicable and simple so that the practicing engineers, geologists and planners may understand and use them effectively. In this context, different techniques have been developed in the past, which can be broadly grouped into two categories,

i) parameter based zonation techniques
ii) inventory based zonation techniques

Nevertheless, the literature suggests a variation in LHZ mapping methodologies used by different agencies in India and abroad. Several methodoloies for LHZ mapping have been proposed and are based upon some widely accepted assumptions (Varnes, 1984; Carrara et al., 1991; Hutchinson and Chandler, 1991; Hutchinson, 1996; Turner and Schuster, 1996), which can be stated as,

i) The past and present are the keys to the future. This implies that landslides in future will more likely to occur under similar geological, geomorphological, hydrogeologic and climatic conditions, which were and are responsible for the occurrence of past and present landslides. Hence, experiences on existing landslides will be more helpful for landslide susceptibility assessment.

ii) Landslides with distinct geomorphological features can be identified, classified and mapped both through field surveys and remote sensing image interpretations (Rib and Liang, 1978; Varnes, 1978; Hansen, 1984; Hutchinson, 1988; Dikau et al., 1996).

iii) Landslides are controlled by identifiable inherent and external factors, known as causative factors, which can also be mapped from field surveys and remote sensing image interpretations (Dietrich et al., 1995).

An systematic organization of different LHZ mapping methodologies is given in Figure 5. These LSZ methodologies have been sufficiently reviewed in Hansen (1984), Varnes (1984), van Westen (1994), Carrara and Guzzetti (1995), Hutchinson (1996), Mantovani, et al. (1996), Aleotti and Chowdhury (1999), Guzzetti et al. (1999) and Saha et al. (2005). However, for the completeness of this report, a brief overview of these has been provided in this section.

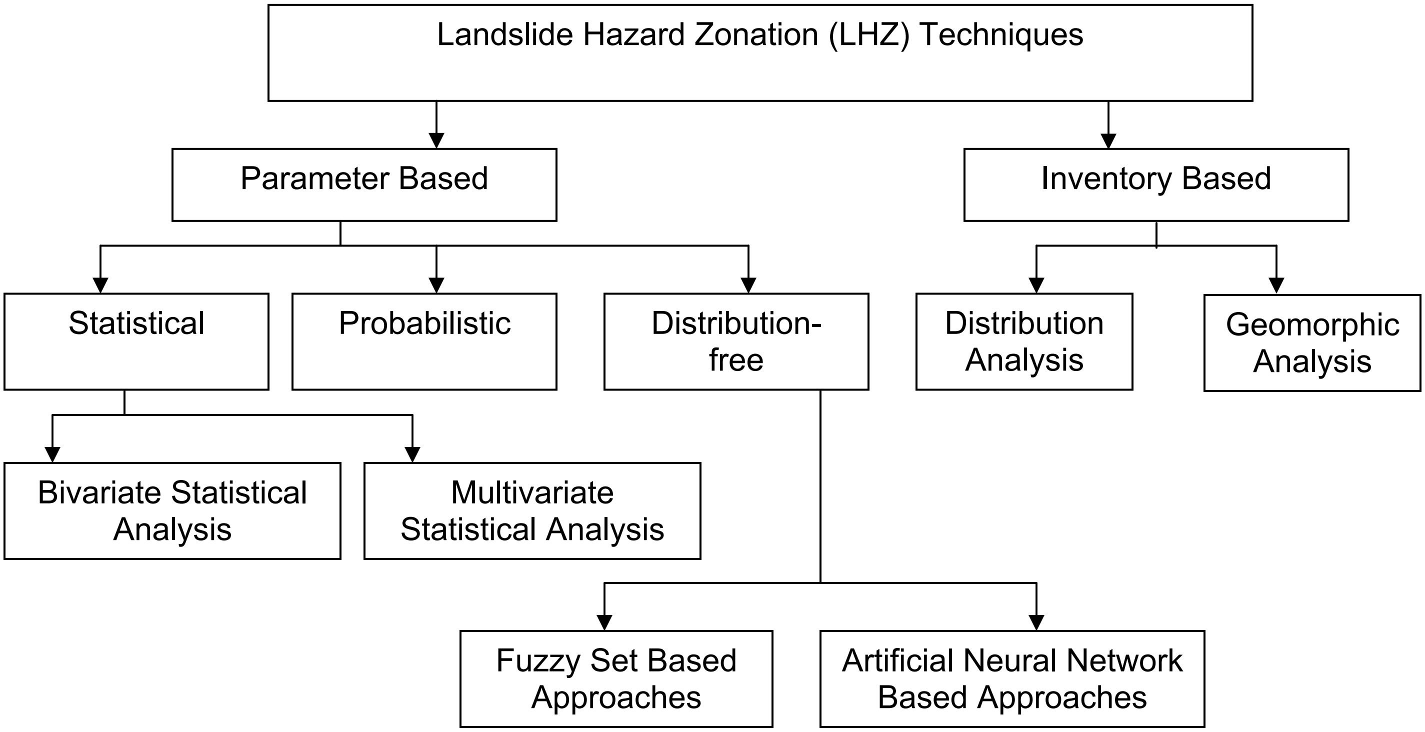

Figure 5. A systematic organization of LHZ techniques

4.6.1 Parameter Based Zonation Techniques

These techniques are typically adopted for regional level LHZ mapping or macro-zonation and are essentially based on certain selected parameters, known as causative factors that are important from the point of view of occurrence of landslides. In these techniques, the qualitative conditions are quantified based on a logic based ranking system. Though different factors are considered by different authors, it is quite logical to use the basic causative factors, which are responsible for instability in all types of terrains. If local factors are used, the utility of the techniques will only be limited to a particular area. The basic causative factors have been discussed in detail in Section 3.3.

As stated, the causative factors include inherent and external causative factors. Since the inherent causative factors are inherent characteristic of a slope, they are obviously best choice for LHZ purposes. They can be studied and evaluated on the slope itself. These factors are universal in nature and hence their choice will provide stability to system of study. In view of universal character of the selected factors, the outputs of one area can be easily compared with the other area in different geological setting Anbalagan (1992).

The parameter based zonation techniques essentially involve the following steps,

i) Selection of parameters/factors for LHZ mapping purpose
ii) Selection of a mapping unit
iii) Formulation of a weight rating assignment system
iv) Unit wise study of status of factors and their distribution
v) Awarding appropriate rating based on existing field conditions
vi) Preparation of thematic data layers pertaining to causative factors
vii) Preparation of landslide hazard zonation map

Selection of Parameters for LHZ Mapping

As indicated earlier, it is logical to use the basic inherent causative factors, which can be studied on a slope and their condition evaluated. In view of their universal characters, their choice is more than justified. However, it is also a known fact that the external parameters, which are referred as the triggering factors, must be considered. However, if the basic character of the factors is examined, they are regional in nature as they occur over large areas and not confined to one single slope facet. Their intensity does not vary much from one facet to another adjoining facet within a geographical domain say within a valley. Even if minor variations are there, these cannot be measured unless enormous number of measuring units is placed. In other words, the inclusion of the external parameters may have not have impact on the final output within a valley or geographical domain. Only when the results are compared with other domains, the final result may vary depending upon the local conditions. In view of this, it may be safe to conclude that a scheme based on the basic inherent causative factors may provide realistic results.

Early efforts on LHZ mapping considering lithology and slope as the causative factors were made by Blanc and Cleveland (1968) and Radbruch-Hall and Varnes (1973) in California, Bowman (1972) in Australia, Dobrovolny and Schmoll (1974) in Alaska, Radbruch-Hall and Crowther (1976) in United States, Rodriguez Ortiz et al. (1978) in Spain and Obermeir (1979) in Virginia.

Brabb et al. (1972) first introduced the landslide frequency analysis with respect to litho units (geology) and slope categories by a simple superimposition method and produced an LHZ map. Varnes (1984) prepared an LHZ map considering slope, soil thickness, land use practice and drainage as the causative factors. Takei (1982) prepared a debris flow susceptibility map in Japan considering rock types, fracturing, weathering characteristics, drainages, vegetation cover, valley slopes and historical records of large landslides as the contributory factors. In New Zealand, Eyles (1983) identified different types of erosion and their severity based on lithology, structure, slope and topography.

Selection of Mapping Unit

As stated in Section 4.3, it is important to select a mapping unit, which can be defined as surface area within which the stability conditions remain more or less homogeneous. The grid based sampling unit has some limitations. Moreover, in grid based sampling units, the data from output map will be in the form of grids, which at times may be difficult to transfer to the ground.

Anbalagan (1992) advocated the use of slope facet as the smallest unit of mapping. The slope facet is a part of hill, which is delimited by ridges, spurs, streams, river and other water courses, within which the stability conditions remain more or less homogeneous. Since the ridges, spurs, drainages or rivers are topographical features, they can be easily identified in the field and in the topographical maps. This makes entire job of field investigations including assignment of weights as well as preparation of various maps, simple to perform.

Formulation of a weight rating assignment system

The weight rating system is usually designed in many different ways on the basis of studying the impact of each selected parameter or factor, for their importance in inducing the instability. Anbalagan (1992) has suggested a landslide hazard evaluation factor (LHEF) rating system that incorporates all the causative factors as listed in Table 3. The LHEF rating scheme may be more relevant as it is based on an empirical approach using important inherent causative factors of slope instability such as lithology, structure, slope morphometry, land use and land cover, relative relief and hydrogeological conditions. In this scheme, the external factors such as rainfall and seismicity have not been included.

Table 3. Maximum LHEF rating for causative factors for macrozonation

S.No	Causative Factor	Max. LHEF rating
1	Lithology	2.0
2	Relationship of structural discontinuities with slope	2.0
3	Slope morphometry	2.0
4	Relative relief	1.0
5	Land use and land cover	2.0
6	Hydrogeological condition	1.0
	Total	**10.0**

The maximum weight for individual factor has further been sub-divided into a number of categories to form a detailed LHEF rating scheme. This helps in understanding the impact of categories within a factor on the occurrence of landslides in a region. This scheme can then be used for calculating total estimated hazard (TEHD) for individual facets. The total estimated hazard (TEHD) value indicates the net probability of instability of a slope facet. It is calculated slope facet-wise, because adjoining slope facets may have entirely different stability conditions. The TEHD value of an individual slope facet is obtained by adding the ratings of each causative factor, obtained from the LHEF rating scheme for that slope facet. Thus, TEHD value = sum of ratings of categories of all causative factors. These TEHD values are then arbitrarily categorized into different landslide hazard zones (Table 4)

Table 4. LHZ on the basis of Total Estimated Hazard (TEHD)

S.No.	TEHD value	Description of zone
1	< 3.5	Very low hazard (VLH)
2	3.5 – 5.0	Low hazard (LH)
3	5.1 – 6.0	Moderate hazard (MH)
4	6.1 – 7.5	High hazard (HH)
5	>7.5	Very high hazard (VHH)

A typical procedure for landslide hazard zonation on macro-level is given in the form of a flowchart (Figure 6).

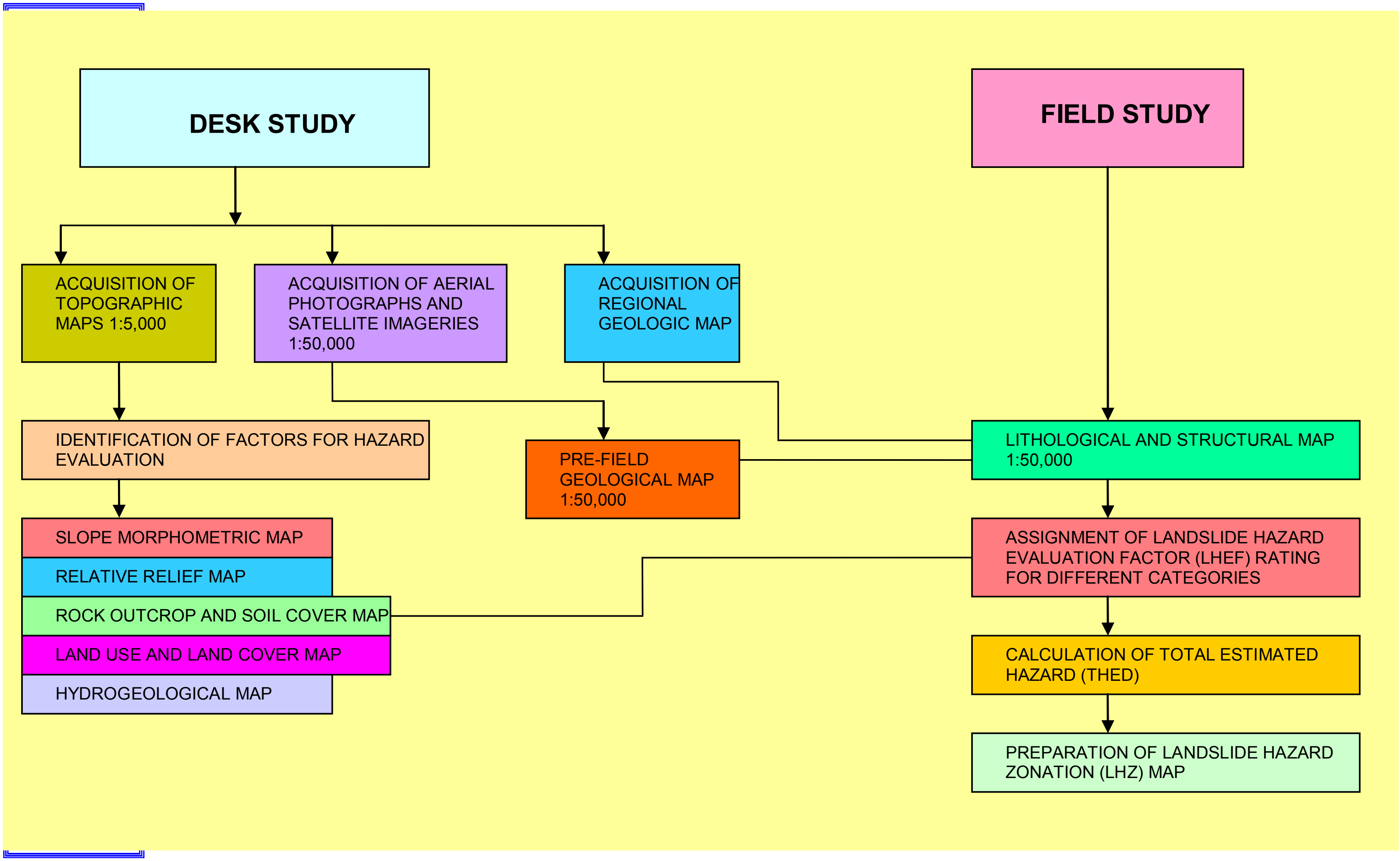

Figure 6. A typical procedure for LHZ mapping

Thus, the success of the parameter based techniques depends on the preparation of quality thematic database and the judicious assignment of weights and ratings to the causative factors and their categories respectively. The thematic database prepared on the basis of field surveys may be time consuming, laborious and uneconomical with data collected over long time intervals.

During the last two decades, LHZ mapping has also been carried out based on manual interpretation of a variety of thematic data layers and their superimposition (Seshagiri and Badrinarayana, 1982; Anbalagan, 1992; Choubey and Litoria, 1990; Pachauri and Pant, 1992; Gupta et al., 1993; Sarkar et al., 1995; Mehrotra et al., 1996; Virdi et al., 1997; Turrini and Visintainer, 1998). In recent times, due to the availability of a wide range of remote sensing data together with data from other sources in digital form and their analysis using GIS, it has now become possible to prepare a digital database of different thematic data layers corresponding to the causative factors responsible for the occurrence of landslides in a region (Gupta and Joshi, 1990; McKean et al., 1991; van Westen, 1994; Nagarajan et al., 1998; Gupta, 2003). The integration of these thematic data layers with weights assigned according to their relative importance in a GIS environment leads to the generation of an LSZ map. Several studies (e.g., Carrara et al., 1991; van Westen, 1994; Lakhera and Champatiray, 1996; Nagarajan et al. 1998; Gupta et al., 1999; Rautela and Lakhera, 2000; Saha et al., 2002; Sarkar and Kanungo, 2004; Saha et al., 2005; Kanungo et al., 2007; Pareekh et al., 2010; Chauhan et al., 2010), have been reported in this regard.

However, whether a conventional or a GIS based thematic database is used, the weights are typically assigned on the basis of the experience of the experts on the subject and about the study area. The assignment of weights may vary from one expert to the other and also from one region to the other. The subjectivity in assigning weights to each thematic data layer and to its categories is the major limitation of this approach. Also, there may be a difficulty in extrapolating a model developed for a particular area to other areas.

In order to minimize subjectivity in the weight assignment process, quantitative approaches, which aim to define objective ways of quantifying the relative importance of various causative factors, can and have been deployed to produce an LHZ map. A number of methods have been developed, which are summarized in the following sections.

Statistical Analysis

The statistical analysis requires comparison of the spatial distribution of existing landslides in relation to different causative factors (Aleotti and Chowdhury, 1999). GIS tools are quite useful in this analysis. Statistical approaches may be bi-variate and multivariate.

Bi-variate Statistical Analysis

In bi-variate statistical analysis, each individual thematic data layer is compared with the existing landslide distribution layer. The weight value of each category of causative factors is assigned based on landslide density. This involves the overlay of landslide distribution layer on each of the thematic data layers, and calculation of respective landslide density values. Different analysis tools such as frequency analysis (Pachauri and Pant, 1992, 1998; Sarkar et al., 1995; Mehrotra et al., 1996), information value (InfoVal) (Yin and Yan, 1988; van Westen, 1997; Lin and Tung, 2003; Saha et al., 2005), landslide nominal risk factor (LNRF) (Gupta and Joshi, 1990) and land hazard evaluation factor (LHEF) (Anbalagan, 1992) can be adopted.

The frequency analysis involves determination of normalized frequency distribution of landslides per unit area in each category of individual factors. This is achieved by overlaying the landslide layer on each thematic data layer manually or in GIS environment. These frequency values are used as the ratings of the respective categories of causative factors. Constant or arbitrary weights are assigned to the causative factors. These ratings and weights for the factors and their categories are integrated to produce the LSZ map.

The Information Value (InfoVal) for LSZ mapping considers the probability of landslide occurrence within each category of thematic data layer. The rating of a particular category of a thematic data layer is determined as,

$$W_i = \ln\left(\frac{Densclas}{Densmap}\right) = \ln\frac{Npix(S_i)/Npix(N_i)}{\sum_{i=1}^{n} Npix(S_i) \Big/ \sum_{i=1}^{n} Npix(N_i)} \tag{1}$$

where, W_i denotes the weight given to the i^{th} category of a particular thematic data layer; *Densclas* denotes the landslide density within the category; *Densmap* denotes the landslide density within the thematic data layer; $Npix(S_i)$ denotes the number of pixels, which contain landslides, in a category; $Npix(N_i)$ denotes the total number of pixels in a category and n is the number of categories in a thematic data layer. The thematic data layers are overlaid and the ratings in the form of InfoVal are added to prepare a landslide hazard index (LHI) map, which is later categorized into different landslide hazard zones to prepare an LHZ map.

Another approach, known as the landslide nominal risk factor (LNRF) approach, was developed by Gupta and Joshi (1990), which determines the rating of each category of thematic data layers. The LNRF is determined using the following equation,

$$LNRF_i = \frac{Npix(S_i)}{\left(\sum_{i=1}^{n} Npix(S_i)\right) \Big/ n} \tag{2}$$

where, $Npix(S_i)$ denotes the number of pixels containing landslides in i^{th} category and n is the number of categories present in the particular thematic data layer. A higher value of LNRF (i.e., LNRF >1) implies more susceptibility to landslides than the average; an LNRF value <1 indicates less susceptibility to landslides; whereas, an LNRF value =1 indicates a category with an average landslide susceptibility. The LNRF values were regrouped broadly into three classes for each thematic data layer, and were assigned ratings 0, 1 and 2 for LNRF<0.67 (low hazard), 0.67<LNRF<1.33 (medium susceptibility) and LNRF>1.33 (high hazard) respectively. The thematic data layers were overlaid and the values were added to prepare an LHI map. The LHI values were classified into three susceptibility zones: low, medium and high.

However, it has been observed that regrouping of LNRF values into ordinal numbers (0, 1, 2) leads to coarsening of approach and reduction in the relative importance of various categories. Therefore, Saha et al. (2005) proposed a modified LNRF approach known as modified landslide nominal hazard factor (m-LNHF), where the computed ratings were directly used without any regrouping.

The bi-variate statistical approaches are based on the observed relationships between each category of factors and the existing landslide distribution in the area. Although, the bi-variate statistical approaches are considered to be a quantitative approach for LHZ mapping, a certain degree of subjectivity exists, particularly in the weight assignment procedures for different causative factors. In all cases, constant weights or arbitrary weights have been assigned to the causative factors for LHZ mapping.

Multivariate Statistical Analysis

Multi-variate approaches consider relative contribution of each thematic data layer to the total susceptibility within a defined area. The procedure involves several important steps (Aleotti and Chowdhury, 1999),

i) Identification of percentage of landslide affected areas in each pixel and their classification into stable and unstable zones,
ii) Preparation of an absence/presence matrix of a given category of a given thematic data layer,
iii) Multivariate statistical analysis (e.g., discriminant and regression analyses)
iv) Reclassification of the area based on the results and their classification into hazard classes.

These approaches involve analysis of large volume of data and therefore may be time consuming. External statistical packages are generally used to support the GIS packages. The statistical analyses most frequently used for LHZ mapping are the discriminant analysis (Carrara, 1983; Carrara et al., 1990) and the multiple regression analysis (Bernknopf et al., 1988; Yin and Yan, 1988; Jade and Sarkar, 1993; Wieczorek et al., 1996; Atkinson and Massari, 1998; Chung and Fabbri, 1999; Clerici et al., 2002).

Carrara (1983) applied both the analysis techniques for LHZ mapping in Southern Italy for predicting actual and potential landslide susceptibility. In this study, a group of geological-geomorphological factors, directly or indirectly correlated with slope instability, were used in the discriminant functions and in the regression equation. It was reported that lithology and its interaction with slope angle contributed significantly in predicting the percentage of unstable areas. However, the result of these statistical approaches underlined the need of other factors capable of improving the efficiency of the approach.

Yin and Yan (1988) analysed 21 categories of different factors based on data collected from field investigation and landslide mapping. Regression analysis was used to establish different degrees of instability for the preparation of LHZ map of the area. Clerici et al. (2002) applied conditional analysis approach for LHZ mapping which simultaneously took into account all the factors contributing to instability. The landslide density of each pixel was computed in correspondence to different combinations of causative factors and an LHZ map was prepared based on the landslide density values. It was observed that this approach was difficult to implement and required complex operations. Further, to achieve satisfactory results, the procedure had to be repeated few times changing the combination of factors and their categories.

Probabilistic Approach

In this approach, the spatial distribution of landslides is compared in relation to different causative factors within a probabilistic framework. The probabilistic approaches are based on the observed relationships between each category of factors and the existing landslide distributions in the area within a probabilistic framework. The thematic data (continuous and categorical) can be transformed into continuous data, by considering the degree of relationship between the landslides and the categories of each thematic data layer. Some of the methods based on this approach include conditional probability model, weight of evidence method under Bayesian probability model, certainty factor method under favorability mapping model, etc.

Favourability modeling (FM) may be considered as an adequate compromise, offering a valid quantitative method, where subjectivity or expert knowledge can be incorporated in the analysis, particularly when data are not sufficient or reliable. With FM, thematic data can be transformed into continuous data, by considering the degree of relationship between the landslides and the categories of each thematic data layer. Each continuous or non-continuous category can be transformed into a value, called favourability value. The certainty factor (CF) may be one of the possible proposed favorability functions (FF) to handle the problem (Shortliffe and Buchanan (1975); Heckerman (1986). The range of CF values varies from -1 to 1. A positive value means an increasing certainty in landslide occurrence, whereas a negative value corresponds to a decreasing certainty in landslide occurrence. By integrating the CF values of the categories of thematic data layers, an LHZ map can be prepared. The CF model has been considered and experimentally investigated in a number of studies (e.g., Chung and Fabbri, 1993, 1998; Chung and Leclerc, 1994; Binaghi et al., 1998; Luzi and Pergalani, 1999; Remondo et al., 2003; Lan et al., 2004).

Chung and Fabri (1999) proposed a conditional probability model for LSZ mapping. Five different procedures namely direct estimation, Bayesian estimation under conditional independence, regression model, modified Bayesian model and modified regression model were adopted for estimating conditional probability of landslide hazard. GIS-based existing landslide distribution layer and various thematic data layers were used to prepare the LHZ map. The LHZ maps were validated by comparing with the later landslides. It was observed that multivariate regression analysis generated better results than other probability methods.

Lee et al. (2002a, 2002b) applied Bayesian probability model using the weight-of-evidence method of Bonham-Carter (1994) for LHZ mapping. Using the location of landslides and topographic factors, the method was used to calculate the weights (positive and negative) and contrast (difference of positive and negative weights) for each category of different causative factors. The contrast was used as the rating of each category. The contrast is positive for a higher influence on landslide occurrences and negative for a lower influence on landslide occurrences. The ratings of the thematic data layers were summed to calculate the LHI values, which were categorized into different zones to prepare an LHZ map. van Westen et al. (2003) also used the weights of evidence approach to generate statistically derived ratings for all categories of thematic data layers. On the basis of these ratings, a judicious choice of relevant thematic data layers was made for preparation of an LHZ map.

The application of probabilistic prediction model based on likelihood ratio function for LHZ mapping was discussed by Chung and Fabri (1998) and Lee and Min (2001). The existing landslide locations and different thematic data layers were used to implement the model. The probability frequency distribution functions of the landslide affected and non-affected areas should be distinctly different. The likelihood ratio function, which is the ratio of the two frequency distribution functions, can highlight this difference. For each category of thematic data layers, two empirical distribution functions for the landslide affected and non-affected areas were computed and the likelihood ratio for all the categories were determined. The LHZ map was prepared using the likelihood ratio values as the ratings of the categories.

Although, the probabilistic approaches are considered to be a quantitative approach for LHZ mapping, a certain degree of subjectivity in the weight assignment procedures for different causative factors exists.

Distribution-free Approaches

Generally, qualitative approaches are highly based on experts experience and knowledge and can be considered as subjective (conventional). On the other hand, the quantitative approaches, such as statistical (bi-variate and multivariate) and probabilistic approaches, can be considered as more objective due to their data-dependent character. However, success of these approaches is highly affected by the number, quality and reliability of data (Ercanoglu and Gokceoglu, 2004). Therefore, to overcome these limitations, some new approaches such as fuzzy logic, artificial neural networks (ANNs), etc. may be adopted for LSZ mapping on a regional scale. Recently, fuzzy set theory, neural networks and combined neural and fuzzy approaches have been used to generate LHZ maps.

Chi et al. (2002b) discussed the effectiveness of fuzzy set theory for landslide hazard mapping. The relationships between input causative factors and past landslides in terms of likelihood ratio functions of each thematic data layer were computed and used as fuzzy membership values. These membership values were able to highlight the difference between areas affected by past landslides and areas not affected by past landslides. Fuzzy inference networks using a variety of different fuzzy operators, especially combination of fuzzy OR and fuzzy Gamma operator were used for data integration to prepare the LHZ map. It was observed that fuzzy Gamma operator with high value could effectively integrate most datasets for LHZ mapping. Tangestani (2003) utilized land hazard evaluation factor (LHEF) rating scheme of Anbalagan (1992) for determination of fuzzy membership values and fuzzy gamma operator for thematic data layer integration to generate the LHZ map.

Gorsevski et al. (2003) demonstrated that LHZ mapping can be achieved through an integration of GIS, fuzzy *c*-means and Bayesian modeling approaches. In the modeling approach, the optimal number of categories was derived by iterative classification for a range of categories or from the expert knowledge. The fuzzy *c*-means classification provided significant amount of information about the character and variability of data and proved to be a useful indicator for landslide hazard mapping. The probabilities were revised with Bayes theorem after the categories with similar characteristics were grouped together by fuzzy *c*-means approach. It was observed that the LSZ mapping using the integrated fuzzy/Bayesian approach produced better spatial prediction of existing landslide locations than qualitative models.

Ercanoglu and Gokceoglu (2004) developed a model based on fuzzy relation concept for preparation of LHZ map. The landslide distribution layer was analyzed in relation to the categories of various thematic data layers to compute the fuzzy membership values for each category. By integrating the fuzzy membership values, the LHZ map was prepared. The fuzzy relation concept is an objective approach for determination of fuzzy ratings of different categories based on actual landslide data. Hence, this approach introduces relativity new concept in rating determination. However, other quantitative approaches such as statistical and probabilistic ones consider the actual landslide data for determination of rating in a crisp manner without employing the relativity.

Arora et al. (2004) proposed an ANN black box approach for LHZ mapping. This approach determines the weights objectively in an iterative process, but the weights in this case remain hidden. The neural network training and testing datasets were prepared using the attributes of various thematic data layers representing the input neurons and the existing LHZ map representing the single output neuron. After successful training and testing of different neural network architectures, the best architecture for this specific problem was selected based on the highest training and testing accuracies. The adjusted connection weights of the best network were used to generate the LHZ map of the area. The distribution of landslide susceptibility zones derived from ANN showed similar trends as that observed with the existing landslide locations in the field.

Gomez and Kavzoglu (2005) also used ANN black box approach for LHZ mapping. In this process, a multilayer perceptron with back propagation learning algorithm was used. A wide range of causative factors and the existing landslide distribution layer derived from digital elevation model, remote sensing imagery and documentary data were used for neural network training and testing. After the training and testing of neural network, an LHZ map was generated for the whole area. It was observed that the predictions were close to reality, indicating a satisfactory performance of the model.

Yesilnacar and Topal (2005) prepared landslide hazard maps using logistic regression analysis and ANN approaches. For this purpose, 19 different thematic data layers were used. The connection weights of neural networks were used to determine the weights for the chosen input thematic layers. The landslide hazard map produced using the ANN approach predicted higher percentage of landslides, especially in high and very high zones than the logistic regression analysis method.

Elias and Bandis (2000) proposed a neuro-fuzzy approach for LHZ mapping. Fuzzy linguistic rules were used to assign fuzzy membership values to different categories of thematic data layers. The fuzzy membership values were used to provide data to the input neurons for neural network model. A single output neuron with values from 0 to 1 was considered to represent the degree of landslide susceptibility based on actual landslide data. The trained neural network was also used for another area to generate the LSZ map. It was observed that the predictions were close to reality, indicating a satisfactory performance of the model.

Lee et al. (2004) attempted the development, application and assessment of a combined probabilistic and artificial neural network for LHZ mapping. Landslide locations and causative factors were used for analyzing landslide susceptibility. A probabilistic method was used for determination of rating of each category and an ANN approach was used for determination of weights of causative factors. The rating of each category was determined using the likelihood ratio function (Lee and Min, 2001). The weight of each factor was determined after artificial neural network training (Hines, 1997). After successful training of the neural network, the weights of the factors were determined based on the weight matrices analysis for all the training datasets. The normalized average value of ten different weights for a particular factor was considered as the weight of the corresponding factor. The LSZ maps were prepared by integrating the ratings of the categories only and also by integrating the ratings and the weights together.

The above studies clearly demonstrate the usefulness of a variety of methodologies for LHZ mapping across the globe. However, it may not be irrelevant to state at this juncture that geomatics tolls shall play a major role in developing any methodologies for the preparation of LHZ maps. No doubt, these tools have been and will continue to be used extensively everywhere in the world, including both developed and developing countries. For example, in India, the notable use of GIS technology coupled with advanced parametric and non-parametric techniques for LHZ mapping in Lower Himalayas can be found in Gupta and Joshi (1990), Saha et al. (2002), Saha et al. (2004), Kanungo et al., (2006), Pareekh et al. (2010), Chauhan et al. (2010) etc.

4.6.2 Inventory Based Techniques

The inventory based approaches are typically used for large-scale landslide hazard zonation mapping, and are based on data collected during preparation of landslide inventory, as detailed in Section 3.1.

Distribution Analysis

Distribution analysis is a straightforward approach for LHZ. In most of the studies, the landslide inventory maps, provided the basis of analysis. The landslide inventory provides a spatial distribution of existing landslides represented on a map either as the affected areas (polygons) or as point events (Wieczorek, 1984). In another alternative, the landslide distribution was represented as a density map (Wright and Nilsen, 1974). Espizua and Bengochea (2002) prepared susceptibility and risk zonation maps based on an inventory of landslides generated through field surveys and interpretation of aerial photographs. Landslide susceptibility and risk zones were mapped in view of the natural hazards and the degree of loss to elements at risk along roads and routes because of a given magnitude of landslide.

However, the landslide inventory maps do not provide information on the temporal changes in landslide distribution. Therefore, a modification in the inventory maps was done in the form of landslide activity maps, which were based on multi-temporal aerial photo interpretation (Canuti et al., 1979). These activity maps were found to be useful to study the effect of temporal changes in land use on landslide activity.

The distribution analysis methodologies, although, are very time consuming, cumbersome and costly, but maps based on these approaches may be useful in providing first hand information on the landslide activities of the area.

Geomorphic Analysis

Geomorphological mapping of landslide hazard is a direct, qualitative method that relies on the ability of the investigator or expert to estimate actual and potential slope failures (Guzzetti et al., 1999). In this methodology, the LHZ is carried out directly in the field by scientists/geomorphologists, based on their experience in the subject, about the area and in other similar situations, without describing any rules which have led to this assessment. The LHZ maps are directly evolved from detailed geomorphological maps.

A number of studies on geomorphological mapping of landslide hazard has been carried out since 1970s (e.g., Carrara and Merenda, 1976; Kienholz, 1978; Fenti et al., 1979; Ives and Messerli, 1981; Kienholz et al., 1983, 1984; Zimmerman et al., 1986; Rupke et al., 1988; Seeley and West, 1990; Hansen et al., 1995; Soeters and van Westen, 1996; van westen et al., 2000; van Westen et al., 2003).

One of the most comprehensive projects reported in the literature was the French Zermos maps (Humbert, 1977) which involved analysis of active and inactive landslides with respect to the factors responsible for landslide hazard and then extrapolation of similar physical conditions for preparation of LHZ maps. The Zermos map of the Moyenne Vesubie region, France, prepared by Meneroud and Calvino (1976) showed four zones of instability defined on the basis of five factors, namely lithology, structures, slope, morphology and hydrology. Another Zermos map prepared by Landry (1979) identified seven classes of susceptibility on the basis of the factors such as geological nature of the soil and sub-soil, slope angle, drainage and local history of landslides.

Hearn (1995) developed an LHZ map at 1:10000 scale compiled directly from the field based geo-morphological features. Soeters and van Westen (1996) and van Westen et al. (2003) reported LHZ mapping based on the geomorphological criteria for slope instability. The geomorphological method allows a rapid assessment of landslide hazard in a region. However, the main disadvantages of this method are (Leroi, 1996),

i) the use of subjective decision rules that govern the landslide occurrences
ii) the difficulty in updating the hazard assessment as new data becomes available
iii) the requirement of extensive field surveys

4.7 Landslide Risk Assessment

A natural hazard is usually assessed in terms of the probability of a landslide event occurring within a defined time period and area, whereas risk is a measure of the probability and severity of the damaging event. In general, risk can be defined as (Lee and Jones, 2004),

> ***"the potential for adverse consequences, loss, harm or detriment by the hazard to human and the things that humans value".***

In a more scientific way, risk has also been defined as (Royal Society, 1992),

> ***"a combination of the probability or frequency of occurrence of a particular hazard and the magnitude of the consequences of occurrence."***

The above definition is quite useful as it identifies the importance of a phenomenon (i.e., landslides in the present case) in generating risk and the significance of consequences in the assessment of risk. A complete risk management process comprises two components, risk assessment and risk treatment.

There is a range of risk assessment procedures varying from quantitative to qualitative estimations of risk, with the latter based majorly on expert's judgments. Suitability of either qualitative or quantitative assessments depends on both the desired accuracy of the outcome and the nature of the problem. Generally, for a large area, there is scarcity of available data for any quantitative analysis. Therefore, a qualitative risk assessment may be applicable. On the other hand, for specific sites, a detailed quantitative risk assessment may be required. Hence, risk assessment varies from a general indication of the threat across a region, to specific statements on levels of risk at a particular site.

Thus, LRA can be carried out at different stages in the decision-making process, starting from developmental planning on a regional scale to the evaluation of a particular site on a local scale. An LRA map at regional scale portrays the areas with different levels of threat to human beings and the things that value to them. This information can be used to establish land use plans, developmental activities and patterns of building regulations. The site-specific risk assessment can provide information on the location of the hazard, the value of land and property on this location, and an analysis of the risk to life, property that may result from landslide event. Hence, similar to LHZ maps, the landslide risk assessment (LRA) maps can be prepared at various scales,

i) on regional scales of 1: 50000 to 1: 25000
ii) on semi-detailed scales of 1: 5000 to 1:10000
iii) on detailed scales of 1: 1000 to 1: 2000).

The techniques related to risk assessment mapping at various scales are limited due to complexity of the process involved. Risk refers to the nature of damage likely to be caused if the failure occurs. The damage may be in the form of loss of life and injuries and/or loss of land and properties. For example, a major landslide in a remote area may cause less damage as compared to a smaller landslide in a thickly populated area. Hence, the risk is function of hazard probability and damage potential, as given in Anbalagan and Singh (1996).

Thus, the assessment of risk has two components namely hazard probability and damage potential. Hazard probability can be directly obtained from LHZ maps. Here, selection of mapping unit is an important criterion, which may be facet-wise or a grid based. Unlike a hazard zonation map, in risk assessment, the boundaries are flexible in nature. Initially, the LHZ boundaries are used for the risk assessment also. In case of facet wise LHZ, the study starts with VHH and HH facets. Considering that the event occurs, the probable boundary of the damage prone area has to be delineated. For example, if a human settlement is located on a stable VLH slope below a steep cliff, the major risk due to failure may lie mostly outside the hazardous slope. Hence, the overall boundary of the risk gets widened to encroach into the VLH slope also. This way the risk assessment has to start from VHH and HH facets to further involving MH and other low hazard slopes. In this context, the major component of the works lies with VHH and HH slope facets.

The variable nature of the boundaries of risk categories makes them difficult to mark judiciously. The following factors may be considered while marking the boundaries.

i) the topography of the area, particularly the slope facet in which the hazard occurs and the adjoining facets
ii) the nature of failure
iii) the geological factors controlling the pattern of instability
iv) the possible intensity of other external factor to aggravate the nature of damage

4.7.1 Regional Risk Assessment

The spatial distribution of landslide risk may be obtained by integrating landslide probability and vulnerability of population or property at spatial level in a GIS environment (Leone et al., 1996). The resulting map can be subdivided into areas of different risk zones.

The probability of landslide occurrences depends on both the inherent factors and triggering (external) factors. However, the triggering factors may change over a very short time span and are thus very difficult to estimate. If triggering factors are not taken into account, LSZ maps may be used to define the likelihood or probability of occurrence of a landslide event.

Vulnerability may be defined as the level of potential damage, or degree of loss, of resources at risk, subjected to a landslide of a given intensity (Fell, 1994; Leone et al., 1996; Wong et al., 1997). Vulnerability assessment involves the understanding of the interaction between a given landslide and the affected resources. Generally, the vulnerability to landslide may depend on the volume and velocity of sliding, the distance of transportation of slided material, the resources at risk, their nature and proximity to the landslide (Finlay and Fell, 1995). The assessment of vulnerability is somewhat subjective and may be largely based on historic records. The appropriate vulnerability factor may be assessed systematically based on expert's opinion and may be expressed at a scale of 0 to 1. The vulnerability of resources at risk can be taken as resource damage potential.

For regional risk assessment, a number of qualitative LRA methodologies can be used, which can be listed as (Lee and Zones, 2004),

i) Risk registers
ii) Relative risk scoring
iii) Risk ranking matrices
iv) Relative risk rating
v) Failure modes, effects and criticality analysis (FMECA)

Risk registers

A risk register is a document which keeps all the records of the known risks due to landslides in an area or at a particular site and also the decisions taken in monitoring and managing these risks. This register can serve the purpose of historical landslide data base. This is also useful in screening out the areas with minor or negligible landslide problems for planning developmental activities and also prioritizing landslide problems at an early stage of a project. Details on risk register concept and historic landslides can be found in several studies (e.g., Lee et al., 1998a; Lee, 1999; Lee and Clark, 2000 and Lee and Zones, 2004).

Relative Risk Scoring

In most cases, evaluation of risk in absolute terms is inappropriate due to the difficulties in assigning exact values for the hazard, for resources at risk and their possible consequences. Hence, it is expedient to assess the relative risk potential at different sites posed by particular hazards based on subjective appraisal.

The relative risk scoring approach uses the definition of risk as a function of hazard probability and adverse consequences. The landslide hazard probability and adverse consequence elements (resources at risk) are represented by relative scores or rank values and the risk is the product of these scores. The risk numbers thus produced are then used to classify each site within an arbitrarily defined scale of risk classes. This allows some comparison between different sites and provides a basis for taking management decisions. The details of this approach along with examples are given in Lee and Zones (2004).

Boggett et al. (2000) used the relative risk scoring approach to evaluate the problems of rockfalls and rockslides in South Shore Cliffs, Whitehaven, UK and identified the required remedial works. McDonnell (2002) developed and implemented a similar approach at a World Heritage site of basalt cliffs in Northern Ireland. The cliffline was divided into different sections and the risk within each section was calculated. The relative risk score was considered as a cumulative effect of the hazard score, visitor concentration score and visitor perception score. The hazard score was obtained by summation of four different components such as stability number (indicates hazard potential and obtained from slope stability analysis), slope angle, presence or absence of springs and water seeps, and presence or absence of dumped material. The resources at risk at this heritage site were visitors only. Thus, the concepts of visitor concentration score and visitor perception score were introduced. The perception score reflected visitor's awareness about the landslide hazard. The relative risk scores for all cliff sections were obtained and categorized into different risk classes.

Chau et al. (2004) presented landslide risk for Hong Kong as a function of hazard and exposure. Landslide hazard was represented by the LSZ map and the exposure was represented by population data as per 2001 census survey. The classification of the population was made based on the criterion that all the population classes have equal area (i.e., numbers of pixels). The class numbers of the susceptibility and population classes were normalized with respect to maximum class number in each category to obtain the index values. These normalized values represented the hazard index and exposure index. These indices of each pixel were multiplied to obtain the risk values of the area and the risk values were categorized to prepare the risk map of the area.

Risk Ranking Matrices

In this approach, risk is represented in the form of a risk matrix where subjective ranking of different risk levels is defined based on the likelihood of landslide hazard measured against the increasing severity of adverse consequences. This is fully based on expert's opinions to make appropriate assessments of the likelihood of landslide events and adverse consequences.

van Dine et al. (2002) used the concept of risk ranking matrices for a qualitative risk assessment of a forest land at Perry Ridge under British Columbia Ministry of Forests. The probability of landslide hazard was rated as high, moderate, low, very low or none based on the past occurrence of landslides, independent of their sizes. The consequences were rated as high, moderate or low based on the resources at risk (people, property and water supply). Three different risk ranking matrices were developed, one for each of the resources at risk. The very high, high, moderate, low and very low risk zones for different combinations of hazard and consequences to resources were assessed based on the risk ranking matrices.

Cardinali et al. (2002) used both relative risk scoring and risk ranking matrices approaches to describe the landslide risk assessment of parts of Umbria, Central Italy. The study area was divided into a series of landslide susceptibility zones and the risk within each susceptibility zone was determined as a function of susceptibility and vulnerability. Landslide hazard for each susceptibility zone was defined in terms of landslide frequency and intensity. Levels of hazard were defined using a two-digit coding, one each for landslide frequency and intensity. Such coding system was used to determine whether the hazard was due to high frequency of landslides or intensity or both. Estimates of vulnerability of each type of resource at risk were based on the relationship between intensity and type of landslide and the likely damage due to the landslides. Three different levels of damage such as aesthetic, functional and structural were envisaged. A risk matrix was prepared using the coding system of landslide hazard and different levels of damage. Here also, a unique coding value termed as specific risk index was used in the risk matrix instead of qualitative terms such as low, medium and high. In order to provide a measure of total risk, the specific landslide risk indices for each susceptibility zone were categorized into one of the landslide risk zones such as very high, high, moderate and low.

Relative Risk Rating

Relative risk rating approach adopts method similar to those used in the relative risk scoring and risk ranking matrices approaches. It is a descriptive approach in which a range of risk categories are defined, each with a certain degree of hazard and level of consequence. According to Palmer et al. (2002), this approach has proved its usefulness in situations where the resources at risk are uniform or broadly similar throughout an area, but have spatial variation in the degree of hazard. This technique also provides a means of identifying the relative risk throughout the area.

In this approach, the area is divided into different units based on the ground characteristics, such as, geology, landform, soil, topography, etc. information on the distribution, nature and frequency of landslides, various resources at risk. The expected levels of consequences within each unit are then gathered. Risk categories are assigned to each unit based on the hazard and consequence conditions within it.

Failure Modes, Effects and Criticality Analysis (FMECA)

The FMECA approach provides a structured framework for the qualitative analysis of various components of an engineered slope using engineering judgement to generate scores or rankings. The details of this approach are discussed in Lee and Jones (2004). However, this technique is applicable only for the risk assessment of structural failures in an engineered slope. The FMECA approach has been used as a risk assessment tool in the dam industry (Sandilands et al., 1998; Hughes et al., 2000) and coastal slopes (Lee, 2003).

The above literature reveals that the risk register approach is heuristic in nature and utilizes field records of risks related to landslide occurrences. Other approaches namely relative risk scoring, risk ranking matrices and relative risk rating are quite similar to each other. In these approaches, linguistic coding of various resources at risk with respect to their damage potential is done. The risk assessment matrix has also been generated in terms of linguistic coding only.

Recently, fuzzy set theoretic approaches have also been applied for the preparation of LRA maps at regional level.

4.8 Detailed Landslide Mapping, Investigation and Monitoring

Specific landslides in very high and high risk zones are identified from the regional level risk assessment maps for detail studies. This requires mapping of and monitoring of landslides on regular basis so that suitable mitigation measures can be adopted.

4.8.1 Landslide Mapping and Investigation

The detailed mapping of landslides is generally carried out on 1:1000 to 1:2000 scales to understand the stability of individual slopes. The mapping and landslide investigations can be carried out using analytical and observational methods. Analytical methods represent detailed study of unstable slopes on different scales. These will require inputs on soil and rock properties, which need be collected from field and laboratory measurements. These can also be estimated through ‘back analysis’ wherein a known slope is analysed assigning a suitable factor of safety with various combinations of strength parameters, which are then judiciously chosen.

Once the strength parameters are known, the stability equations can be framed considering the resisting and disturbing forces to work out the factors of safety. It is also called as microzonation approach and may include finite element analysis and modeling of slopes.

The detailed analytical investigations have to be carried out in a systematic way in order to account for all the parameters responsible for instability. The investigation/analysis involves the following steps (Anbalagan et al. 2007),

i) preparation of geological map and sections
ii) identification of mode of failure
iii) estimation of shear strength parameters of slope forming materials
iv) calculation of Factor of Safety (F)

Preparation of Geological Map and Sections

Initially, topographical map of the area under consideration is prepared at 1:1000 to 1:2000 scales with contour intervals of 1 to 2 m. The topographical map is used as a base map to prepare the geological map of the area. A number of geological sections, at least 3 to 5 in number are prepared for individual slopes – one at centre and other two close to flanks. The number of sections can accordingly be increased depending on size of slope, heterogeneity of slope forming material and importance of the affected area.

Identification of Mode of Failure

Identification of mode of failure is important to choose relevant analytical method for calculating factor of safety (F) of the slope. Possible mode of failure is identified considering type of slope materials involved in the slide. The geological materials can be broadly classified into two categories viz. (i) in-situ rocks and (ii) overburden soil and debris. Rotational mode of failure commonly occurs in soil and debris, while translational and toppling mode of failures are common in in-situ rocks. Different modes of failure are identified, for which F value can be calculated.

Estimation of Shear Strength Parameters of Slope Materials

These can be determined using different methods such as rock mass classification schemes like rock mass rating (RMR) system of Bieniawski (1979), empirical correlations by Barton and Choubey (1977), Barton and Bandis (1981), tri-axial shear test on intact rock samples, block shear test and back Analysis.

Back analysis can be carried out for both rock and soil slopes including debris slopes. It gives the most realistic estimate of shear strength parameters for slope forming materials. For this, initially the mode of failure has to be identified. Here, F of a slope is considered to be unity, i.e. the slope is on the verge of failure (critically stable). Based on ground observation like tilted trees, open ground cracks, break in slope profile at the upper part and other such features (Figure 7), a particular slope is judiciously selected and the philosophy of this approach is to back calculate the shear strength parameters of the rock mass/ overburden under this near failure condition. Generally, the value of angle of internal friction (Φ) can be obtained for various types of slope materials from standard tables. Hence, the value of cohesion (C) can be obtained. In fact, for a series of values of Φ, corresponding values of C are obtained. Based on engineering judgment, a suitable combination of C and Φ is chosen. This is a very useful and nearly accurate method for obtaining shear strength properties of slope materials in field conditions.

It describes the status of stability of a particular slope and is based on the concept of limiting equilibrium, i.e. the condition at which forces tending to induce sliding are exactly balanced by those forces resisting sliding. So, F can be defined as the ratio of total force available to resist sliding to total force tending to induce sliding. In other words,

$$\text{Factor of Safety} = \frac{\text{Total resisting force along plane of separation}}{\text{Total mobilising force available to induce failure}} \tag{3}$$

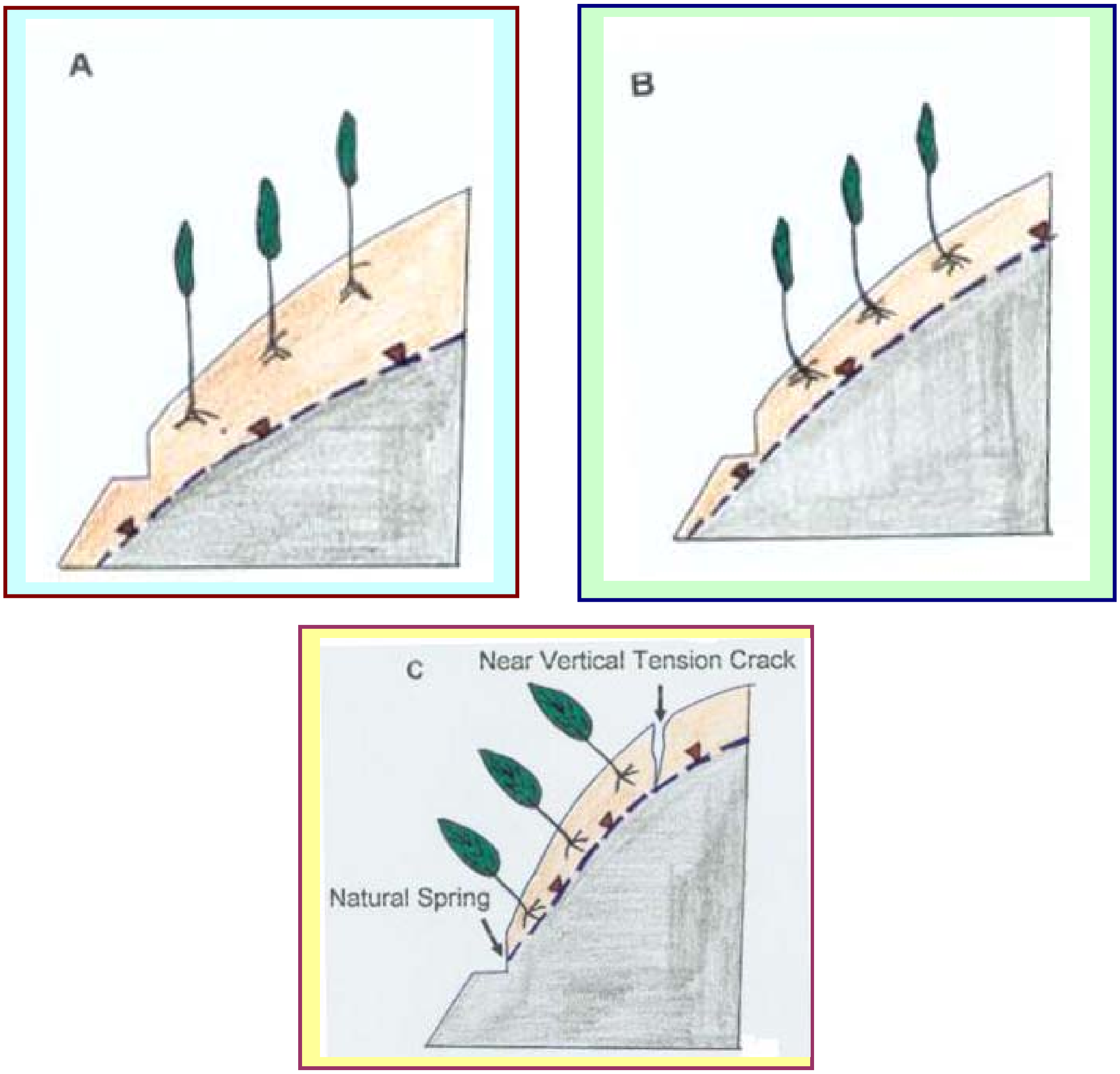

Figure 7. Ground observation as indicative of stability condition of concerned slopes. A: Stable slope – vertical trees (F>1.5), B: Slightly bent trees – slope still stable (1.5>F>1), C: Notable bending of trees – tension crack near crest – emergence of spring point on cut face – critically stable slope (F≈1) – ideal for carrying out Back Analysis to ascertain shear strength parameters of slope material (Dashed blue line – phreatic surface)

Calculation of Factor of Safety

When the slope is on the verge of failure, a condition of limiting equilibrium exists in which the resisting and driving forces are equal and in this condition, it is considered that F = 1. When the slope is stable, the resisting forces are greater than destabilizing forces and value of factor of safety will be greater than unity. Following same logic, the slopes having F < 1**,** are considered to be unstable. Once the mode of failure and shear strength parameters are obtained, stability equations are worked out analytically by considering the resisting and mobilizing forces along the discontinuity to determine F of particular slope.

4.8.2 Landslide monitoring

Monitoring of landslides is also an important component of landslide studies. It includes the measurement and analysis of landslide dynamics and also study of changes in the factors that may cause landslides. Typically, landslide monitoring needs to be carried out in real-time or at relatively close intervals of measurement of temporal and spatial variability of mass movements at the surface and beneath the surface, micro-topography, soil moisture, ground water levels, and precipitation.

The process of landslide monitoring typically consists of selection of a specific site depending upon the severity of the type of movement, location, hazard, and risk value of slope failure, selection of proper monitoring methods. The methods can be surface and subsurface measurements of the landslide activity.

The slope is instrumented through a set of instruments useful in understanding the stability conditions of the slopes. These equipments include extensometers, inclinometers, piezometers, crakemeters and rain gauges along with other related equipments. The instruments cover relatively small area and hence the overall cost of the landslide monitoring may increase.

The data obtained has a greater significance as it provides actual deformation patterns with time, which can be quantitatively utilized for planning stability measures. Repeated instrumental monitoring at regular intervals provides data related to slope deformation patterns and real time observations are also done to transmit data using modern telecommunication systems. Instrumental monitoring of the slopes can be broadly classified into two categories,

i) Surface monitoring using precision leveling of survey pillars or pedestals distributed within landslide area
ii) Subsurface deformation monitoring of slopes using instruments such as extensometers and inclinometers.

In addition, piezometers are also generally embedded within the ground to obtain information related to pore water pressures. Since rain water is a major inducing factor of landslide, rain gauges are also installed on slopes to obtain pattern of precipitation. In fact, the instruments used for surface monitoring and subsurface monitoring can be used simultaneously in order to obtain correlative results (Anbalagan et al., 2007).

Surface Monitoring

The surface monitoring may be carried out by precision leveling, Total Station surveys, and now-a-days using Differential GPS control surveys within the landslide area. The survey pillars or pedestals of suitable sizes, used as reference or control points, are generally constructed made of reinforced cement concrete. Sometimes, iron/ wooden pegs are also used. The pillars are embedded within the ground with their numbers marked on top. These pillars are aligned along a number of rows running along the slope. In fact, these pillars can be spaced at regular intervals of 5 m to 10 m level difference. The rows can be spaced at 10 m to 50 m depending upon the size of the landslides. A typical sketch of the location of survey pillars in landslide monitoring study is shown in Figure 8. The coordinates of individual pillars are recorded at different time intervals to obtain rate of movements. The elevation difference between the pillars and their lateral distance are the important parameters which should be monitored with time. The observations may be taken once in a week to a month. If the monitoring does not show any significant movement, the period of observation can be increased.

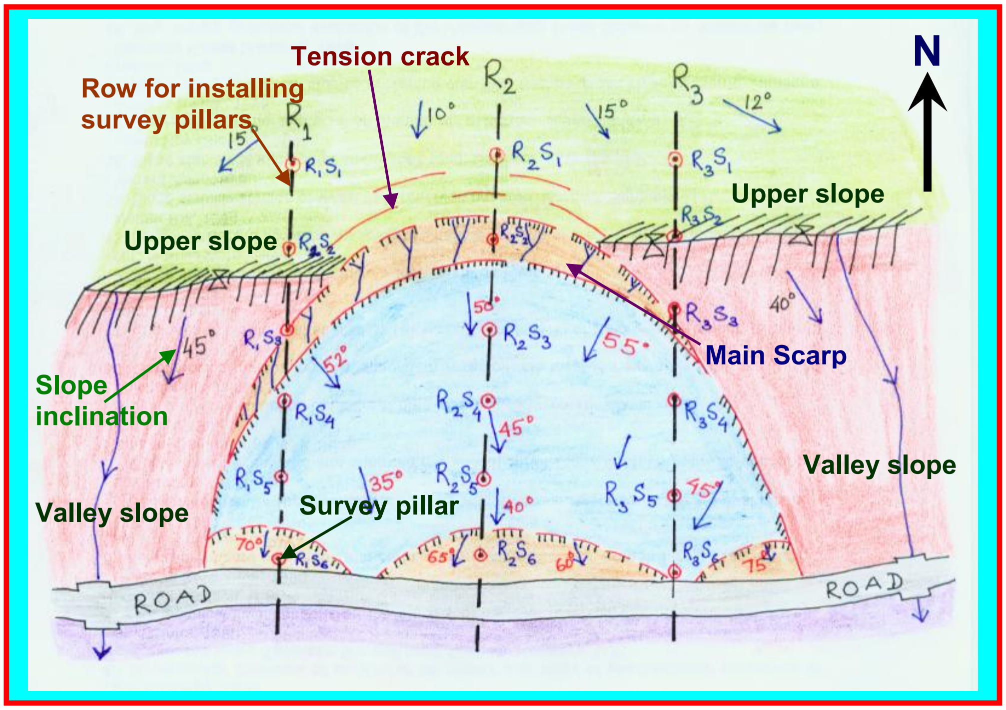

Figure 8. Surface monitoring

Subsurface Monitoring

The subsurface monitoring is carried out using a set of instruments to monitor various aspects related to slope movements and also to understand relationship between the factors often responsible for instability. These instruments include extensometers, inclinometers, tiltmeters, crack monitors and piezometers, in addition to automatic rain gauges on surface. These instruments may be especially useful where movement is known to be occurring, but at a slow rate. The objective here is to quantify this movement and to locate the surface of failure.

An immediate need may be to have an advance warning on the onset of movements which may take place rapidly. Large rockfalls or steep slope movements may fall in this category. Automatic monitoring is essential for this purpose. Extensometers and tiltmeters have also been used with some success.

A description of some of the equipment, which are used for sub-surface monitoring in India, is provided here.

Inclinometers

In the hilly terrains, inclinometers are used for monitoring landslides/ slopes, to detect zones of movement and establish whether movement is constant, accelerating, or responding to control measures. Inclinometers are basically of two types; vertical inclinometer and horizontal inclinometer. Inclinometers generally consist of an casing, a horizontal probe, control cable, pull cable, and a readout unit (Figure 9). The casing is installed in a horizontal trench or borehole with one set of grooves oriented vertically.

Figure 9. An Inclinometer

The probe, control cable, pull-cable, and readout unit are used to survey the casing. Grooves inside the casing control the orientation of the probe and provide a surface from which repeat measurements can be obtained. Apart from trenches and boreholes, casing can be embedded in fills, can be cast into concrete, or can be attached to structures. It is a special purpose grooved pipe that,

i) provides access for the inclinometer probe, allowing it to obtain subsurface measurements of tilt
ii) controls the orientation of the inclinometer probe
iii) deforms with the adjacent ground or structure.

Tiltmeter

A tiltmeter (Figure 10) is used to monitor the change in movement of slopes in hilly terrains. It provides pattern of slope movement and early warning of potential slide/ damage. In landslide investigations, applications of tiltmeters include, monitoring deflection and deformation of retaining walls, monitoring stability of structures in landslide prone areas, monitoring behavior of structures under load, documenting effects of nearby landslides and providing early warning of potential damage.

Figure 10. A Tiltmeter installed underground

A tiltmeter consists of a tilt sensor housed in a compact waterproof enclosure. The tilt sensor is a precision bubble-level that is sensed electrically as a resistance bridge. The bridge circuit outputs a voltage proportional to tilt of the sensor. If a slope moves, tiltmeter can determine the direction of movement, delimit the areas of deformation and in many cases reveal the pattern of movement like slumping, creep and settlement. Continuous monitoring through tiltmeter ensures those events that may go undetected by periodic manual monitoring. Modern tiltmeters easily fulfil the demand for measurement with higher precision and automated surveying. Used together with inclinometers, both instruments constitute an effective observational approach for affected slopes. When tiltmeter is read manually, changes in inclination are found by comparing the current reading to the initial reading. Besides, tiltmeters may also be connected to a data logger, which can obtain frequent readings, perform calculations and trigger alarm if tilt or the rate of change exceeds preset limits.

Tape Extensometer

Tape extensometers can be used to measure closure between points up to 30 m apart, with an accuracy of 0.05 to 0.2 mm. This instrument is comprised of a precision stainless steel measuring tape with equally spaced (at 5 cm intervals) punched holes. To take readings, the free end of steel tape is hooked to a remote reference point and the instrument is hooked to the nearest point. The steel tape is pulled out and the instrument is fixed at one of the perforations on the tape. The main body incorporates a tape-tensioning device coupled to a sliding scale and dial gauge arrangement. The micrometer drum on the instrument is rotated to provide a fixed amount of tension to the tape. The dial gauge reading after tensioning and the visible pin-hole position on the tape at the instrument nose indicates the reading for the site.

Borehole Extensometer

Borehole extensometers are used to measure rock displacement which may take place as a consequence of movements in natural slopes. The borehole extensometers can be broadly categorized into two types; single point borehole extensometers (SPBE) and multiple position borehole extensometers (MPBE).. The borehole extensometer which is consisted of a single rod or wire extending between the anchor and the reference head is called SPBE. Extensometer having more than two rods or wire (up to a maximum of about eight) is termed as MPBE (Figure 11). The instrument is grouted in borehole leaving a reference head on wall surface of the structure. Readings are periodically taken by the sensor on all the points in reference head. The difference between initial and final readings indicates the movement of hill slope during the period.

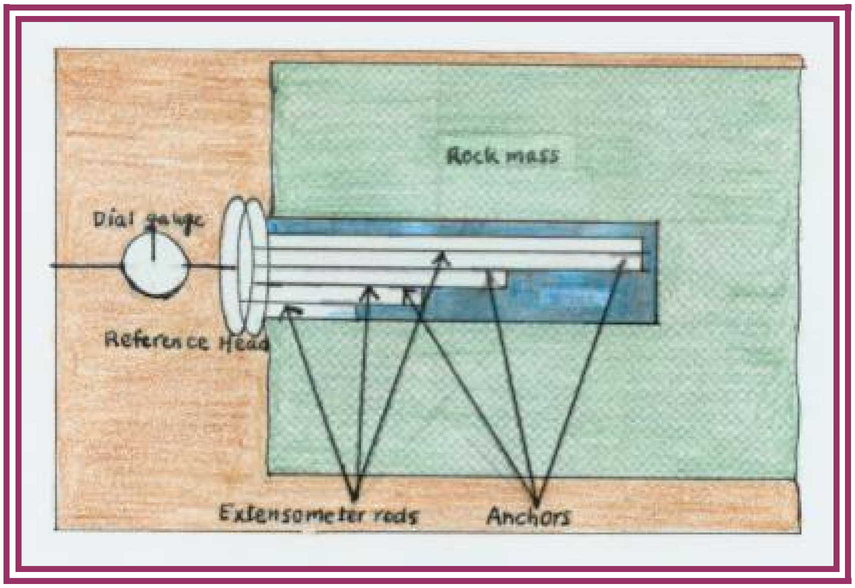

Figure 11. Multiple Position Borehole Extensometers (MPBE)

Piezometer

In landslide and slope studies, piezometers (Figure 12) are used to measure pore water pressure in hill slopes. Depending upon the quantum of subsurface water, pore water pressure increases proportionately. The piezometer readings may indicate the nature of pore pressure build-up in subsurface. The sudden increase in pore water pressure can be correlated to heavy rainfall or any subsurface source with the help of piezometers. The piezometers are generally installed within a bore hole inside the slide materials. In developing early warning system (EWS), the role of piezometers is often very important as rapid failures are generally associated with sudden increase in piezometer readings.

Figure 12. A Piezometer

5. CURRENT STATUS OF LANDSLIDE STUDIES IN INDIA

The landslides and avalanches in India have been causing huge economic losses and hampering developmental plans of the country (Bhandari, 2006). The landslides can easily be regarded as the most significant natural hazard (Sharda, 2008) in the country. Proper landslide hazard management requires actions taken to lessen the risk posed by them.

The landslide hazard management in India has uptill now been based on ad-hoc solutions to counter area specific problems. Recently, GoI has taken significant steps in setting up a number of task forces for landslide hazard zonation and risk assessment studies, geotechnical investigations etc. Several institutes, as listed Appendix A, have been approached to come under the umbrella of these task forces so that a coordinated effort can be made to mitigate the problem of landslide hazards in the country as a whole. The role of these task forces will be,

i) to review the existing methodologies of LHZ and LRA
ii) to demarcate the regions as per priority for detail studies
iii) to recommend plans for generation of LHZ maps at various scales

All these institutions have been active in landslide hazard studies and hazard management in the country.

After the Indian Ocean Tsunami of December 2004, the GoI passed the Disaster Management Act on 23rd December 2005, which had the provision of creation of National Disaster Management Authority (NDMA) headed by the Prime Minister, to lead and implement an integrated approach to disaster management in the country. The NDMA has prepared a draft of **National Guidelines on Landslides** to direct the activities envisaged for mitigating the landslide risks at all levels. The objective is to provide and encourage the use of scientific information, maps, technology, and guidance in mitigation techniques, emergency management, land use planning, and development and implementation of government policy to reduce losses from landslides throughout the country. A brief overview the NDMA guidelines are presented in the next section.

5.1 National Disaster Management Guidelines on Landslides

In India, no specific rules exist within the constitutional frame work of India to define the nature of hazards and legal consequences in the event of occurrence as well as extent of compensation and other related details. Nonetheless, landslide hazard and risk assessment have been incorporated by the Bureau of Indian Standards (BIS) in the form of Indian Standard codes.

The NDMA guidelines (NDM Guidelines B, 2009) include both regulatory and non-regulatory frameworks with defined time frames for various activities such as national and state disaster management plans and policies for landslides. The specific objectives of NDMA guidelines are,

i) to institutionalise the landslide hazard mitigation efforts
ii) to make the society aware of the various aspects of landslide hazard in the country
iii) to prepare the society to take suitable action to reduce both risks and costs associated with this hazard.

5.1.1 Structure of the Guidelines

In the guidelines, nine major areas, as listed below, have been identified for systematic and coordinated management of landslide hazards,

i) Landslide hazard, vulnerability, and risk assessment

ii) Multi-hazard conceptualisation
iii) Landslide remediation practice
iv) Research and development; monitoring and early warning
v) Knowledge network and management
vi) Capacity building and training
vii) Public awareness and education
viii) Emergency preparedness and response
ix) Regulation and enforcement

Successful implementation of the guidelines would require consideration of the following operational issues, as listed in the document,

Technical/Scientific

i) Integrating landslide concerns in the development of disaster management plans at different levels i.e., national, state, district, municipal/panchayat.
ii) Networking of knowledge based institutions dealing with landslide studies for effective implementation of national landslide agenda.
iii) Innovation in the management of multiinstitutional and multi-disciplinary teams.
iv) Switching over from piecemeal remediation of landslides to simultaneous and holistic implementation of control measures.
v) Participation of the private and insurance sectors in disaster management plans.
vi) Establishment of a disaster knowledge network (a network of networks) and a mechanism for dissemination of information at the national level.
vii) Mechanism for international linkages, cooperation and joint initiatives.
viii) Formation of expert committees for distribution of workload, evaluation of any project proposal, recommendation for funding the project, scrutiny of the project report, approval for implementation of the suggested

remediation measures and assessment of the efficacy of the recommendations after their implementation.

Legal Issues

i) Techno-legal regime for introduction of sound slope protection, planned urbanisation, regulated land use and environment friendly land management practices.

ii) Zero tolerance against deliberate environmental violence and unhealthy construction practices.

iii) Laws governing new constructions and alteration of existing land use on problematic slopes and in landslide prone areas.

The National Executive Committee will coordinate preparation of the national disaster management plan incorporating the disaster management plans prepared by the Central and State governments for landslide affected States and districts, which will be approved by the NDMA. The plan will be based on the schedule of activities in the guidelines designed for effective landslide hazard mitigation in the country. The complete guidelines on landslides and snow avalanches can be accessed from the website http://ndma.gov.in/ndma/guidelines/LandslidesSnowAvalanches.pdf.

Nevertheless, some excerpts from these guidelines, as per the requirement of this report, are reproduced in the following,

Scale of analysis specified in the document

Typical scales of analysis specified in the document are,

i) National or regional (1:1M to 1:100000)

ii) Macro-Scale (1:25000 to 1:50000)

iii) Meso-Scale (1:5000 to 1:10000)
iv) Mapping at a scale larger than the meso-scale for site-specific studies.

Type of landslides

As regard to the type of the landslide, the document refers to the creation of a landslide inventory, according to the type of the landslide. The landslide inventory map and database will be prepared to document all known landslide incidences, including stabilised, dormant, reactivated, and the most recent landslides. The database is expected to include data about the location, date of occurrence, rainfall, and seismicity during the event, the dimension and **type of the slide**, the volume of material dislodged, the nature and extent of the damages caused/ likely to be caused by further sliding, the type of triggering factor (earthquake, cloudburst, anthropogenic interference, toe erosion by streams or rivers, etc.), the tentative causative factors leading to slope failure, and the limit of the run-out distance.

Basic documents and data required for hazard assessment

The document enlists the most important inputs required for carrying LHZ mapping at both the macro and meso scale as; topographical and geological maps, remote sensing products, and seismological data in the case of seismogenic landslides. A mechanism is required to be put in place to communicate the seismic and rainfall data in real-time to the national landslide hazard database centre.

Methodology

The document states that the approaches to landslide hazard mapping being used by different agencies in India are at variance with each other. The on-going mapping programmes therefore should continue to make the best use of the prevailing state-of-the-art technologies, at the same time making a determined effort to arrive at national level recommendations through a process of workshops and rigorous peer review.

The LHZ maps produced by the various organisations, institutions and individuals in the country are either qualitative or semiquantitative. In either case, landslide inventory has not been used as the basic input data. These studies have conventionally been carried out on manual interpretations of various thematic maps and their super-imposition. During recent years, the availability of a wide range of high resolution remote sensing data in digital form has been immensely helpful in the preparation, interpretation, and analysis of data in the GIS environment. As a result, it has become possible to prepare different thematic maps corresponding to different causative factors responsible for the initiation of landslides, more accurately and within a shorter period.

Hazard matrix / hazard level categorisation

An LHZ map requires the division of an area into several zones, indicating the progressive levels of the landslide hazard. The number of zones into which a territory is divided is generally arbitrary. Commenting on the time domain of landslide occurrence through zonation mapping is a difficult task.

Risk matrix / risk level categorization

As per the NDMA document, the landslide risk zonation has so far not been attempted in India. Most of the organisations and institutes in our country carry out LHZ mapping which is significantly different from landslide risk zonation. The four data inputs required for risk zonation are environmental factors, triggering factors, historic landslide occurrence and elements at risk. The historic information on landslide occurrence is by far the most important input as it gives insight into the frequency of the events, the types of landslides, and the volume and extent of damage. As the required information is not readily available, quantitative landslide risk assessment becomes a difficult task. The information of triggering factors is quite site-specific and can only be modelled properly using deterministic models, which require considerable input on the geotechnical characterisation of the terrain (soil depth, cohesion, friction angle, and permeability). Temporal probability is determined either by correlating the data on landslide occurrence with that of triggering factors, or through dynamic modelling.

Nevertheless, investment decisions on different projects usually depend upon the level of risk and the corresponding risk reduction initiatives. Therefore, considering the importance of landslide risk zonation mapping, a proposal has been recently drawn up by the BIS to frame guidelines for landslide risk zonation mapping.

Regulation and enforcement

The State governments of landslide affected areas in consultation with the NDMA will establish the necessary techno-legal and techno-financial mechanisms to address the problem of landslide hazards in their respective states. This is to ensure that all stakeholders responsible for regulation and enforcement adopt landslide safe land use practices and provide for safety norms with regard to slope stability in landslide affected areas, in particular, and hilly areas in general.

Indian Standard Codes

Considering the interest of public safety, the BIS will place all Indian standards related to landslides in the public domain including the Internet for free download. A periodic revision of the codes and standards relating to landslides will be undertaken by drafting groups within a fixed time-frame of five years or even earlier on a priority basis.

Other than the BIS, there are a number of other bodies that develop design codes and guidelines in the country, e.g., the Indian Roads Congress (IRC), Ministry of Shipping, Road Transport and Highways (MoSRTH), Research Designs and Standards Organisation (RDSO), and Ministry of Railways (MoR). Codes developed by these organisations will also be updated and made consistent with current state-of-the-art techniques on landslide safety.

A description of the existing BIS codes related to landslide studies is given in the next section.

5.2 Bureau of Indian Standard Codes Related to Landslides

The following Bureau of Indian Standard (BIS) codes related to landslides are available,

i) BIS Code No. – IS:13365 (Part3):1997

Quantitative classification system of rock mass – Guidelines Part 3: Determination of Slope Mass Rating

ii) BIS Code No. - IS :14496 (Part2): 1998

Preparation of landslide hazard zonation maps in mountainous terrains – Guidelines – Part 2: Macrozonation

The other related BIS Codes related to corrective measures of unstable slopes are as follows.

i) Retaining wall for hill area – Guidelines - Part 1: Selection of type of wall

ii) Retaining wall for hill area – Guidelines - Part 2: Design of Retaining/Breast walls

iii) Retaining wall for hill area – Guidelines - Part 3: Construction of Dry stone walls

The BIS is also in the process of preparation of IS Codes on Risk assessment as well as design of other types of retaining walls/Toe walls.

However, the BIS Codes are in the form of guidelines and hence can not be considered as binding on legal matters. They can be cited in the legal proceedings for issues related to landslides as additional evidence. In case of legal proceedings related to individual's case, presently circumstantial evidences are considered more important as compared to BIS Codes. Nonetheless, the BIS codes can be cited as the correct procedural guidelines in legal cases. The details of some of these codes are given in the following,

5.2.1 BIS Code on Landslide Hazard Zonation (LHZ)

The BIS code on `Preparation of landslide hazard zonation (LHZ) maps in mountainous terrains' deals with LHZ preparation of scales of 1:25000 or 1:50000 (Macrozonation). The purpose of this document is to standardize the technique related to LHZ mapping within the country so that various organization involved in the geological mapping, landslide investigations, implementation of development schemes and research on landslides can make use of the technique. The technique is based parameters like lithology, structure, slope morphometry, relative relief, land use and land cover and hydrogeological conditions. A landslide hazard evaluation factor (LHEF) rating scheme is used for awarding rating for different conditions as observed in the field. This rating scheme is quantitative scheme using qualitative field conditions. The code describes in detail step by step procedures for preparation of this map. The smallest unit of mapping is a slope facet. The information related to stability of slopes are collected and analyzed facet-wise for awarding ratings. The total estimated hazard (TEHD) is calculated facet-wise and classified in different categories like very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH). Each hazard is shown in different symbols.

This technique is being extensively used by Geological Survey of India, which is engaged in the LHZ mapping of the entire country. In fact, this technique provides only preliminary information related to slope instability, which can be used for planning of schemes and further details studies of unstable slopes, wherever required.

The code also provides an example with different figures for the better understanding of the code. Development schemes can be planned confidently within LH and VLH slope facets as adverse conditions are not generally anticipated within them. Development schemes in moderate hazard slope facets require caution as they may contain local pockets of instability. It may be advisable to avoid planning of development schemes in HH and VHH slope facets if possible. But if not avoidable, they need to be studied in detail to understand the nature of instability and to adopt proper remedial measures before implementation of schemes.

5.2.2 BIS Code on Slope Mass Rating

The IS Code on Slope Mass Rating (SMR) deals with preliminary assessment of stability of rock slopes. Particularly this method is effectively applicable to rock cut slopes like terraces for building construction on hills, roads on hilly terrains and other such cut slopes. The approach is based on modification of Rock Mass Rating (RMR) system using adjustment factors related to discontinuity orientation with reference to slope as well as failure mode and excavation methods. Basically there are three modes of failure observed in the rocks namely plane failure, wedge failure and toppling failure. Computation of SMR requires data collection related to orientation discontinuities from the field. Based on the stereographic plotting of structural readings of discontinuities, the mode of failure can be identified. The purpose of this document is to carry out rapid hazard assessment studies along rock cut slopes and natural rock slopes to assess the nature of hazard in order to adopt control measures or plan further detailed investigations. It is mainly used by geologists engaged road investigations and State organizations as well as researchers.

The scheme identifies four factorial adjustment ratings depending on the relation between the orientation of the discontinuity and slope angle in addition to the method of excavation. The estimated factorial ratings are added to the already assessed RMR to get the final value of SMR. The values of SMR have been divided into five categories from the point of view of stability conditions namely very bad (SMR < 20), bad (SMR 21-40), normal (SMR 41-60), good (SMR 61-80) and very good (SMR > 80). The stability conditions improve from very bad to very good. Since the code concerns only preliminary investigations, the outcome need to be studied carefully for planning further detailed studies on those slopes, where they are essential to be carried out. The code also indicates some of the general remedial measures for different categories of SMR values.

The code can be used for effective safe design of rock cut slopes, which is indicated by good to very good values of SMR. In some cases, normal values of SMR are also considered safe. This approach is a fast and rapid hazard assessment technique and comparatively large areas can be covered in short time intervals. Hence it is useful to assess the stability of cut slopes of roads, terraces and other slope cuts.

5.2.3 BIS Code on Retaining Wall for Hill Area

The IS Codes related to retaining walls are now available in three parts though more additions are planned to be published in due course. The part 1 discusses particularly the parameters to be considered for the correct selection of type of wall. The code provides a classification of retaining walls based on the construction material and mechanics of behavior of walls. In general the choice of a particular retaining wall depends on type of slope material, water seepage conditions, hill slope angle, foundation conditions, slope of back fill and seismicity of the area as well as local resources and local skill. These conditions have been elaborated in the code.

The part 2 deals with general design criteria of retaining and breast walls. The common details like top width, base width, back fill material and importance of drainage provisions are discussed. The code also discusses safe bearing capacity for different types of soil. The code also indicates desired factors of safety (F) for different conditions such as against overturning (F – 2.0 for static loads and 1.5 with seismic forces) and against sliding (F – 1.5 for static loads and 1.0 with seismic forces). The details related to depth of walls, stepping of base of wall on rock slope, dip of the base wall towards hill slope, negative batter on the back side of the wall, drainage and erosion control in the toe area are discussed.

The part 3 deals specifically with dry stone masonry wall, a type of wall which is more commonly constructed during road and other excavations for toe stability. The code discusses about various conditions, which should be satisfied while designing the wall. The code discusses about type material to be used in the construction and it recommends that flat stones between 225 mm x 100 mm x 75 mm and 600 mm x 200 mm x 300 mm can be used for construction. The code recommends a base slope angle between 1 (vertical) in 6 (horizontal) and 1(vertical) in 3 (horizontal). It recommends a top width of 60cm. The courses of stones should be placed systematically and leaving no gaps within. The backfill should be done with hand picked rubbles for a width of about 500 mm. The top 30 cm should be filled with locally available soil to prevent ingress of surface water into the slope. In high walls use of reinforced cement concrete bonding elements are recommended. More codes related to the design of various other types of retaining walls are in progress.

The BIS is also considering a risk assessment technique based on two important parameters namely nature of landslide hazard and nature of damages like to be caused in the event of a landslide. The code may be accepted only after larger circulation around India to various organizations to obtain comments and incorporating all those relevant comments suitably.

5.3 A Concise Account on Landslide Works by Key Agencies in India

As cited in the NDMA guidelines, one of the earliest studies on landslides in the country has been carried out by GSI. These include the study of the Nainital landslide by Sir R.D. Oldham in 1880 and C.S. Middlemiss in 1890, the study of the Gohana landslide in 1893 in the Himalayan region that resulted in the formation of a 350 m high landslide dam across the Birehiganga (NDM Guidelines B, 2009). Till date, GSI has carried out studies on more than one thousand five hundred incidences of landslides.

In the case of LHZ mapping, the GSI has prepared LHZ maps with scales ranging from 1:25000 to 1:50000 covering about 45000 km^2 in the landslide prone hilly tracts. The LHZ mapping has also been carried out with similar scales, covering about 4000 km along the important National and State Highways. Besides, the GSI has also prepared detailed LHZ maps of five landslide affected townships in different parts of the country at scales of 1:5000 and 1:10000.

Facet based LHZ methodology was initiated at Indian Institute of Technology Roorkee (erstwhile University of Roorkee) since 1980s. The work is still continuing over different parts of the Uttarakhand Himalayan region, incorporating progressive improvements. Several institutions have adopted facet based LHZ mapping. In addition, several advanced methodologies based on objective weight ranking systems have also been attempted at IIT Roorkee to produce landslide hazard zonation and risk assessment maps at regional level in the Himalayan region.

The major activities of Central Road Research Institute (CRRI) include geological and geotechnical investigations of landslides, landslide hazard potential and risk analysis, instrumentation, monitoring, and prevention of landslides. The CRRI has published a number of reports on landslide correction techniques, application of geo-textiles, deep trench drains, and promotion of jute based geo-textiles, etc. The CRRI is also responsible for creation of a partial landslide inventory database of over 200 landslides in different parts of the country.

The Central Building Research Institute (CBRI) has prepared LHZ maps in parts of Garhwal, Sikkim, and the Darjeeling Himalayan region using different techniques and has also monitored some landslides. Some of the work has been carried out in collaboration with IIT Roorkee. The institute has also attempted implementation of control measures at some landslides in the State of Uttarakhand, Himalaya.

The Central Scientific Instrumentation Organisation (CSIO), a national instrumentation laboratory, has installed an instrumentation network for landslide monitoring at Mansa Devi, Haridwar in 2006, to be discussed later.

The Wadia Institute of Himalayan Geology (WIHG) has carried out LHZ mapping in parts of the Sutlej valley.

A Landslide Hazard Atlas of India containing small scale maps was published jointly by the Building Materials and Technology Promotion Council (BMTPC) and the Anna University in 2004.

The National Remote Sensing Center (NRSC) has prepared LHZ maps on a scale of 1: 25000 along various pilgrimage routes and important highways in Uttarakhand and the Himachal Himalayan region. Remote sensing and GIS techniques were extensively used in preparation of this atlas, which was published in two volumes in 2004. The NRSC has also carried out a high resolution aerial survey of the Varunavrat landslide and has provided detailed maps on the contour, slope, etc.

The NRSC, GSI and International Institute for Geo-Information Science and Earth Observation (ITC) are collaborating on developing landslide risk assessment models for the North-Western and North-Eastern Himalayan regions and also the Western Ghats. A collaborative project on LHZ for NH-17 (from Mumbai to Goa) by the GSI and NRSC is in progress. With the availability of high resolution images, it is possible for the NRSC to monitor landslides and also keep an eye on the occurrence of new landslides and formation of landslide dams in highly inaccessible areas.

The Department of Science and Technology (DST) of the Ministry of Science and Technology took intense interest in landslide studies in India by disbursing financial grant to the research ventures related to landslides. An Expert Committee comprising of eminent Scientists was constituted to process applications for research projects related to landslides and to provide financial help for the projects in November 1988. The Expert Committee is reconstituted every two years. The DST has so far supported more than 100 research projects on landslides totaling about Rs. 250 million, to a number of academic and scientific institutes to carry out landslide hazard mapping in parts of the Sutlej Valley in Himachal Pradesh, the Kumaon and Garhwal areas in Uttarakhand, the

Konkan Railway Region from Panvel to Ratnagiri, the Nilgiris, and the North-Eastern States of Manipur, Nagaland, Mizoram, Sikkim, and Arunachal Pradesh.

The DST through a research work carried out by Saha et al., (2004) at IIT Roorkee has also developed software/brochures for the Landslide Safe Route Finder (LaSirF) to provide safe navigation while constructing new communication lines/roads in hilly areas. In addition, the DST has brought out many publications on landslides and related issues like the coordinated national programme on Landslide Hazard Mitigation, and a Field Manual for Landslide Investigations, etc. Periodically, it also organizes awareness programmes / courses / workshops for government agencies/Non-Governmental Organisations (NGOs) and communities.

The DST is also in the process of establishing a National Geotechnical Facility (NGF) in Dehradun, in collaboration with the International Center for Geohazards (ICG) and the Norwegian Geotechnical Institute. The facility aims to acquire the state-of-the-art facilities in geotechnical sciences and to provide a platform for building capacities in geotechnical investigations and research.

The Central Water Commission (CWC) is the prime organisation for assessing the hazard potential of landslide dams in the country and its vicinity.

The National Institute of Disaster Management (NIDM), which works under the control of the National Disaster Management Authority (NDMA), is responsible to develop training modules, formulate and implement human resource development plans, organise training programmes covering the management of natural hazards including landslides, develop educational material for disaster management, and provide assistance to State governments and State training institutes in the formulation of State level policies and plans for disaster management.

5.4 Progress on Creation of Landslide Inventory Database in India

It has been long felt that a comprehensive inventory of landslides covering various aspects is prepared for engineers and planners, which can be used for proper planning, designing, landslide mitigation and management of highway network. The CRRI has attempted to create and engineering database on landslides based on Relational Database Management technique. It includes information on a variety of data related to geography, geology, geotechnical characteristics of different landslides. The design of their database consists of five tables; main information, general information, geotechnical information, causes of landslide and remedial measures. The main information contains the landslide number, name and location of landslide. The general information contains landslide number, history of landslide, width of landslide along the road, sliding length, area affected, loss of life, loss of property, average annual rainfall, rainy season and snow fall. The geotechnical information includes, geotechnical, geophysical and geological data (e.g., type of movement of the slide body, slope angle, material, rock characteristics, soil type, soil properties, presence or absence of any tension cracks, seepage of water, drainage pattern, vegetation density etc. The cause of landslide table indicates various factors which might have been responsible for the occurrence of the landslide. This includes various fields such as external load on the slope, any vibrating action, increase of water content on slope material, weathered disintegrated nature of the slope material, presence of unfavorable joint places, etc. The remedial measures table contains data in the form of measures proposed to stabilize the slide, recommending agency, measures adopted to stabilize the slope, adopting agency, and the present status of slide. To retrieve any information from the database, queries can be generated for each of the field.

CBRI has also made an inventory of landslides on Rishikesh-Badrinath and Rishikesh-Kedarnath routes in the Garhwal Himalaya. The field surveys through electronic distance measurements and extensometer observations have helped in differentiating stable areas from the unstable areas (Bhandari, 2006).

These databases, however, is partial in nature. Many such databases need to be created for the benefit of the society. These databases should also be updated from time to time and may be made web-enabled for their easy access by different stake holders.

5.5 A Portrayal of Some Individual Landslides in India

Some of the major landslides occurred in different parts of India and their impact during 1984 – 2010 are given in Table 5.

A brief information on some of landslides occurring in various regions, as defined in Section 2.1, is also given in the next sections.

Table 5. Some of the major landslides in India

SN	Date	Location	Impact
1	July 1984	Mundakay, Kerala	14 Killed
2	June 1985	Kumpanpara Kerala	9 Killed
3	October 1990	Nilgris	36 people killed and several injured. Several buildings and communication network damaged
4	July 1991	Kappikalam, Kerala	11 killed
5	July 1991	Assam	300 people killed, road and buildings damaged, Millions of rupees
6	November 1992	Nilgiris	Road network and buildings damaged, Rs.5 million damage estimate
7	June 1993	Aizawal	4 persons were buried
8	July 1993	Itanagar	25 people buried alive 2 km road Damaged
9	August 1993	Kalimpong, WB	40 people killed, heavy loss of property
10	August 1993	Kohima, NL	200 houses destroyed, 500 people died, about 5km road stretch was damaged
11	November 1993	Nilgris	40 people killed, property worth several thousands damaged
12	January 1994	Kashmir	National Highway 1A severely damaged
13	June 1994	Varundh ghat, Konkan	20 people killed, breaching of ghat road damaged to the extent of 1km. At several places
14	July 1994	Bison valley, Kerala	7 killed
15	May 1995	Aizwal Mizoram	25 people killed road severely damaged
16	June 1995	Malori Jammu	6 persons killed, NH 1A damaged
17	September 1995	Kullu, HP	22 persons killed and several injured about 1 km road destroyed
18	July 1997	Pazhampallichal, Kerala	9 killed
19	August 1998	Okhimath	69 people killed
20	August 1998	Malpa, Kali river	205 people killed road network to Mansarovar disrupted
21	January 1999	Pamba, Kerala	25 killed
22	November 2001	Amboori, Kerala	39 killed
23	September 2003	Varunavrat, Uttarkashi	Heavy loss of infrastructures
24	July 2004	Joshimath–Badrinath	Washed away nearly 300 meter long road between Joshimath and Badrinath, 17 killed
25	August 2004	Tehri	9 killed
26	July-August, 2010	Uttarkhand Region	Widespread landslides due to flash floods, heavy loss of property and lives

5.5.1 Landslides in Peninsula Region

A brief description of some landslides in the peninsula region, as compiled in Sekhar et al. (2007), is given in the following,

Mundakay landslide

This was one of the biggest landslides that occurred in the Arunamala hills of Wayanad district in a reserved forest area affecting a total area of 32.3 hectare. The type of the landslide was rotational, which ultimately transformed to a huge debris flow along the Arunapuzha stream. This landslide could be put in the category of rainfall-induced landslide, since the region received 340 mm rainfall on the day of the landslide. No traces of anthropogenic factors could be found.

Adivaram debris flows

In 1993, a set of small debris flows were initiated in terraced rubber plantations. Their cumulative effect was greater than any one natural hazard in the State of Kerala. In fact, it was these debris flows which was an eye opener to many and led to the development of a regional landslide hazard assessment methodology by Thampi et al. (1998), which is presently followed in the State.

Amboori landslide

Amboori landslide has been considered as the most awful natural disaster that has been reported from Kerala in the recent years. Amboori landslide originated due to anthropogenic activities in the form of unsustainable land-use practices, casual developmental activity and unplanned housing. The landslide type was a debris flow. The approximate volume of material in this debris flow was gauged at 5000 m^3. The lithology of the area comprised of highly migmatised metapelitic sequences banded with charnockites and gneisses. A high intensity rainfall preceded by an above average seasonal rainfall was identified as the main cause of the landslide. A number houses were destroyed.

Marappalam Landslide

This landslide occurred in a densely wooded area, near Mettupalayam town on State Highway-8 on Mettupalayam-Ooty section in the year 1993. The Coonoor river flows with a aconvex bend towards the toe of the slide. The slope forming material comprises colluvium or saprolite with a veneer of soil. Factors such as thick sapprolite zone, intense precipitation for a short duration of time, permeability characteristics of slope forming material led to the occurrence of debris slides in this region. The triggering mechanism was inferred due to water charging the interface of bed rock and soil and consequential increase in pore pressure due to torrential downpour of 282 mm rain the area experienced the day before the slide.

5.5.2 Landslides in the Himalaya

The description of landslides in this region has been chronologically arranged starting from Jammu and Kashmir, Himachal Pradesh, Kumaun and Garhwal Himalaya, Uttarakhand. The matter presented here has been compiled from Pande (2006) and other web resources.

Nashri landslide

This is an old and notorious landslide located between Batote and Ramban on the NH-1A. The area around Nashri slide comprises Lower Murrees, built up of alternate beds of sandstones and shales. The sandstones are highly fractured and the shales seem to dominate the landslide activity. The landslide was characterized as a retrogressive slump slide resulting from softening and toe erosion by the Nacchar nallah. Heavy annual rainfall and snowfall cover changed the drainage frequently and appeared to be the major causes of regularly activating the landslides at Nashri.

Khuni Nala Blockslide cum rockfall

The Khuni nala (i.e., drain) blockslide cum rockfall landslide is located on NH-1A between Ramban and Banihal. Almost every year the site is fraught with landslides of varied intensities destroying vital bridges and disrupting the traffic and the communication system. The slope comprises highly jointed Precambrian Salkhala gneisses with thin bands of sericitic phyllite and micaceous schist. The probable cause of the landslide occurrence is the nala itself due to its very steep gradient (40^o to 50^o) and highly slideprone geological formation. Planar slides and rockfalls developed above the subway primarily due to adverse joint pattern of the rock formation.

Thangi Slide

The Thangi slide, located on NH-22 on the right bank of Sutluj river, is a recurring landslide that disrupts the traffic and transport on the highway after every snowfall melting. It is a composite slide-cum-wedge failured rockfall type landslide in the upper part and debris type landslide in the lower part. The rocks are highly jointed, low dipping mica schist of lower Haimanta Group, which have become very weak due to chemical weathering. The lower and middle slopes are covered with old glacial debris, which have become unstable due to toe erosion by Satlej river and also due to cutting for road widening. High density of joints and fractures has created channels for water seepage, moistening the slopes and thus reducing the shear strength of the material.

Khadra Dhang

Khadra Dhang landslide, located on NH-22 along the right bank Satlej river, is a type of translational debris slide, originally initiated in 1960s but is currently active also. The slopes are mainly covered with semi consolidated old glacial debris on weathered granitic gneisses. Although, the material along the slope is dry but seepages and springs create pore water pressure thereby reducing the shear resistance of the material. As a result, glacial debris became dangerously unstable converting it into slurry. This along with over steep slope resulted into this landslide.

Pangi Slide

Pangi slide, located on NH-22 in embankment part of the lower valley slopes along Pangi Nala, is a rotational debris type landslide in the upper part and translational planner type landslide in the lower part. The rock types are biotite gneiss and garnetiferous mica schist of Vaikrita Group covered with old scree and boulders of gneisses. Regular freezing and thawing of joints reduces the cohesive strength of the rocks, which has resulted into a number of cracks. The presence of seasonal seepages also indicates building up of pore water pressure and toe cutting by the Pangi Nala have made the slopes unstable. The cause of landslide may also partially be attributed to the uncontrolled blasting for the construction of highway.

Powari Landslide

The Powari landslide zone can be regarded as the zone of the largest landslides located on the lower slope along the right bank of Satlej river between Powari and Peo towns. A major landslide is reported to have occured about 15 years ago after the construction of approach road from Powari to Kalpa. The type of landslide is a composite one, which represents a combination of debris fall along upper part, rotational slump in middle slope and debris slide at the toe. The saturated overburden consisting of old glacial debris, rich in mica, are responsible for the slope failure. An irrigation canal passing along the upper part of the slope contributes water to a number of seepage zones located within the slumped mass. This, together with snowmelt resulted in the build up of pore water pressure over a long period of time and gradual decrease in shear resistance and also pulverized overlaying micaceous rich old glacial debris and slope material. Additionally, the excavation of slopes for the hairpin bends road construction from Powari to Peo and continuous toe erosion by Satlej river appeared to have triggered the landslide.

Barua Slide

The Barua landslide is located on the left middle slope in the Bapsa valley about 5 km southeast of Karcham. The landslide occurred in 1987-88 but has been repeatedly activated. The location of the landslide is close to the Karcham and Vaikrita thrusts. Seasonal snowmelt from upper slope in old glacial material had build up pore water pressure and thus reduced the shear strength. The removal of toe to widen the road and already moistened glacial material and seasonal seepage from upslope contributed to the occurrence of this landslide. A number of houses as well as orchards and fields were damaged.

Urni Rockfall

The Urni rockfall is located on the right bank of river Satlej on NH-22 in highly jointed Wangtu gneisses. The upper slopes are covered with old glacial debris and open forest, whereas the lower slopes are barren. Though, no seepage or springs are visible in the slide zone, seasonal seepage from snowmelt usually takes place through the joints. This together with opening of joints due to uncontrolled blasting to widen the NH-22 reduced the shear strength of the rock mass and led to rockfalls along the wedge joints.

Nachar Slide

The Nachar landslide in the lower middle slope on left bank of Satlej river is located on NH-22 road in highly jointed region of sheared granite-gneiss of central Crystallines (Jutogh Groups). There is one seepage zone present in the landslide zone and one seasonal stream on the other flank of the slide. Five sets of closely spaced fractures and joints developed due to tectonic activity and uncontrolled blasting broke the rock into blocks and acted as easy passages for water seepage. The seepage through these joints and fracture and upper slope debris over a long period of time reduced the shear strength of the rock. Thus, the adverse rock dip and slope relationship and seepage of water from upper slopes resulted into a complex rockfall cum debris slide.

Soldan Khad Slide

The slide is located along the right bank of the Soldan Khad, a tributary of Satlej river. The lower valley slope in terrain is composed of highly sheared and crushed rocks of Wangtu gneissic complex. The slopes are covered with old glacial and landslide debris. Due to flash floods in September 1988 as a result of cloud burst, lot of debris was brought down within 24 hours, which caused heavy loss of human and cattle lives, property and orchard fields. The landslide can be put in the category of composite type with rotational debris slump in the upper part and translational slide in middle and lower parts.

Jakhri Slide

The Jakhri landslide on the left valley slopes of the Sutluj valley is located on NH-22 in highly weathered and sheared mica gneisses of Jutogh/Wangtu Gneiss complex covered with fluvio-glacial and colluvial debris. The sparsely vegetated lower valley slope became dangerously unstable due to the construction of link road for Jakhri Hydel project site. This led to the reactivation of the old landslide debris. The first landslide occurred in July, 1992 after the monsoon rainfall. The landslide of greater intensity occurred in Feb, 1993 following heavy winter rains. The slipped mass temporarily blocked the river Satlej and a lake was formed within 48 hours. The type of landslide is a translational debris slide. Continued seepages from the agricultural field, seasonal rainfall and snowmelt into already wet old debris and rocks over a long period of time resulted in decrease in shear resistance.

Malpa landslide

In 1998, a rock avalanche of formidable consequence struck the village Malpa in Pithoragargh district bordering China and Nepal, situated on the right banks of the river Kali river, in the districts of Pithoragarh of the Kumaon Himalaya. A massive landslide triggered by heavy rains swept off the entire Malpa village. The lithology of the area around Malpa represents an intricate system of folding, thrusting, metamorphism and igneous action. The great Himalayan belt of Kumaon is occupied by Pre-Cambrian metamorphites of Central Crystalline with isolated, but sizeable amounts of metasediments, gneisses, schists, graniotes, quartzites and amphibolites. The slopes are generally high and steep and the MCT (Main Central Thrust) is known to pass through near the village. The mountain slopes were generally high and steep and the rocks were of fractured nature. River Kali passes along this rock bed, which perhaps caused the widening of the rock fissures. On the rock bed and along the fracture, the whole village and many construction works were located on the banks of the river Kali. The river water thrust on the fractured rock and the drainage, and the excessive construction work together were the most contributing factors for the avalanche. Several houses of Malpa village situated close to a steep gorge were slipped into the river Kali. Several people, including a batch of 60 pilgrims on its way to holy Kailash Mansarovar journey and eight personnel of the Indo-Tibetan Border Police (ITBP), were feared killed.

Sher-ka- Danda Landslide

There have been two landslides on the Sher-Ka-Danda slope in Nainital. The first landslide took place in the year 1867 after persistent rainfall for 3 days. The massive debris that resulted from the 1880 landslide permanently filled a portion of the Nainital lake. The Krol and Trac formations the slope, comprises mainly the limestone/dolomite, calcareous shale and phyllites. The slope cover consists of the debris of previous landslides which include shale, slate and limestone embedded in the matrix of silt and clay, the proportion of which is found to increase with depth. The presence of a longitudinal fissure along the full length of the ridge at the top is considered to be the tensional opening due to the slow gliding of the entire slope along deep seated cleavage planes or shear zones dipping towards the lake. Samples from the slope were obtained and they were analyzed to understand the sub-slope characteristics and determine the causes of the landslide probability. Microscopic examination of the collected samples indicated that the rock cuttings were generally fresh and free from any sign of alteration.

The Karmi landslide

In July 1983, the Karmi region of Central Himalaya witnessed a calamitous landslide caused by a cloudburst and heavy rain. The toe of the slope of the landslide, filled with debris, on the flank of stream has developed slip zones, which become active during heavy rains. Geologically, the area is composed of part of both the calc-zone of Tejem and the Loharkhet group. The rock types comprise mainly of limestone and slates of the calc-zone, and the younger rock units of the Loharkhet group consisting of quartzite, chlorite schists and subordinate amphibolites which lender of chemical weathering. Some houses of Karmi village, situated on the right flank of the Karmi Nala were washed away by the flooded overflow of the channel and about 150 people were killed.

The Alaknanda valley tragedy

Major landslides and floods have been known to occur in the Aaknanda river and its tributaries, every 10 or 20 years. The Alaknanda tragedy occurred in July 1970, along the river Alaknanda. A landslip fell into the lake of Gudiyar, which supplies one of the feeders of Birahi river, and drove out half of the lake, instantaneously causing the river to overflow and even flooding the Alaknanada. The impact of flooding was so huge that it carried away two large wooden bridges, and swept away many persons. The valley can geologically be described as consisting of three major lithological units; Dudhatoli group, Garhwal group and Central Crystalline. The Dudhtoli group constituted by moderately metamorphosed phyllites and quartzites. Garhwal group consists of quartzites, shales, schists and carbonate rocks with met-volcanic intrusions. The Central Crystalline group consists of schists, gneiss and granites. The probable cause of the landslide were reported as the unusual cloud burst, which resulted into the formation of a landslide dam at the constriction of the river Patalganga simultaneously choking the river Alaknanda.

Harmony landslide

Along Karnaprayag-Gwaldam road in Chamoli district, a major landslide occurred near Harmony village in 1986 (Figure 13). Since its occurrence, the affected road stretch causes traffic disruption each year mainly during monsoon. Anbalagan et al. (2008) carried out detailed study on 1:1000 scale and stability analysis of the area. A number of geological sections prepared. On the basis of the field studies, the slide was identified as a circular type of failure. Stability analysis and determination of Factor of safety (F) was done, by using Circular Failure Charts method (Hoek and Bray, 1981) as well as by analytical studies. On the basis of the studies, suitable control measures like regarding of slope, providing retaining walls drainage measures to drain out the subsurface water as well as biological control measures to improve geoenvironmental balance of the area were suggested.

Figure 13. The Harmony landslide

Berinag landslide

Berinag village witnessed heavy landslide in 1996. The primary cause of the landslide was the unstable slope of the area. A secondary cause of slop instability was poor environmental management in the upper reaches of the village and mismanagement of the drainage system. In this area, the vegetation cover is very poor, which plays an important role in slope stability. In most part of the landslide area, deforestation has led to severe shallow landslide. A number of casualities occurred and half of the village was buried under landslide debris.

Okhimath landslide

In August 1998, huge rainfall lashed the Himalaya and led to a landslide in Okhimath area. Rubbles, debris and boulders fell into the Madmaheshwar river, a tributary of the Mandakini, and caused the formation of an artificial lake. Apart from natural factors such as the high level of seismicity in the region and the heavy rainfall in 1998, the anthropogenic factors such as deforestation, indiscriminate construction of roads and buildings, mining and excavation activities were also responsible for the occurrence of the landslide. The deforestation led to soil erosion and lowered winter retention. The effect of these activities was so catastrophic that it led to the landslides in the area, killing 69 villagers.

Kaliasur Landslide

The Kaliasaur landslide is the most persistent and regularly occurring landslide. It is located on the Haridwar-Badrinath road. It first occurred in 1920. After which the moderate to heavy landslide activities were reported in 1952, 1963, 1964 and 1965. The rock formation in the landslide area belongs to the Garhwal group of rocks, namely, white and light green quartzite inter bedded with maroon shales. The rocks appeared to have been folded into a plunging overturned anticline on the western side of the slide zone with a plunge towards the northeast. Another anticline appeared to be on the eastern side of the slide zone with a plunge towards the south.

In this area, the river Alaknanda occupies a deep sinuous gorge with a crest of sinuosity located near the slide zone. The slopes on the left side of the river are steep whereas the slopes on the right side are gentle. The slide zone is located on the left side of the river, which supports the main road. This area contains a number of smaller scree zones, along with areas where quartzites are exposed.

Kaliasaur landslide (Figure 14) is essentially a multi-tier, retrogressive landlside in a complex rock formation with clear evidence of fault planes testifying to the intense tectonic activity in the geological past. Evidence of sliding at the interface of quartzites and maroon shales must presumably have been the starting point. Road construction activity in general and repeated back cuttings required for restoring the road width, year after year, combined with poor drainage to create recurring debris slides in the colluviums cover. The river action at the slope toe aggravated the instability.

Figure 14. Frontal face of the Kaliasur landslide

Varunavrat Landslide, Utttarkashi

The town of Uttarkashi situated on the base of Varunavratt Mountain and on the right bank of Bhagirathi river, Himalaya, observed a series of landslides for 2 weeks starting from 23 September 2003. However, its intensity was felt on 1 October 2003, when several residential areas and infrastructure were damaged albeit no loss of human and animal lives was reported due to the timely and combined efforts of the local administration in warning and evacuating the people. Uttarkashi town lies between two major thrusts, namely MCT zone and the North Almora Thrust. The MCT zone, which is vulnerable to landslides, is bounded by the Vaikrita Thrust in the north and the Munshyari Thrust in the south. The landslide falls in the high hazard zone of the LHZ map compiled in the atlas of NRSC. The two major causes were stated as; high density of joints/fractures and lineaments in and around the slide-affected zones and the presence of an inferred fault near the crown, a lineament between the crown and toe portion of the landslide and nearness of the Mandwa–Ujeli fault. Moreover, during the night prior to 23 September 2003, a very heavy rainfall occurred which triggered the landslide around this structurally vulnerable zone.

Details of some examples of existing landslides in the Garhwal Himalaya, during the field recent campaign in May 2010, by the investigators are given in the following,

Birahi Ganga landslide

Birahi Ganga landslide is located along the NH-58 near iron bridge over Birahi Ganga river, approximately 7 km form the Chamoli town towards Joshimath, in Uttarakhand. A photograph of the frontal face of the landslide is shown in Figure 15.

The Birahi Ganga landslide comes under the category of rock slide. The approximate dimensions of this slide are 90 meters (length along the road), 75 meters (height) and 4 meters (width of debris flow). The landslide might have occurred a few years ago and appears to have reactivated due to road widening and construction. Due to this landside, NH-58 has been hugely affected and an approximately 3400 sq. meter of the pine forest area has been lost. The bedrock material consists of highly jointed and fractured schists. The average orientation of the joint plane is N55°E/25°SE. In this site, topography and joint planes are dipping in the same direction. Rainfall and subsequent weathering activity may further reactivate the landslide. As a result, the crest may go further upwards increasing the area under rockslide. Some remedial measures have been taken to control the landslide. A retaining wall of approximately 3.5 m height along the landslide has been built. However, a part of the wall has been damaged (approximately 40 m long) due to reactivation of rock slide.

Figure 15: Frontal face of the Birahi Ganga landslide

Kandey Landslide

The landslides near Kandey village situated approximately 10 km from Chamoli district near Gopeshwar. A photograph of the frontal face of the landslide is shown in Figure 16. This landslide is a debris slide with approximate length and height of the order of 300 m and 350 m respectively. It is an active landslide, and the activities are still going on. Approximately 80000 sq meter of the area near the crest of the landslide followed by a long debris flow channel falling on Balasuti River (a tributary of Alaknanda River) is affected. The debris are composed of quartzite and schists. As per the villagers, the landslide is very old (>70yrs) and still active mostly in the monsoon season. The crest portion of the landslide has been visited by our team and found that intensive agricultural activity (paddy) has been carried out in the region above the crest of the main landslide. There is no remedial measure has been taken so far to control the landslide. Due to this landslide the Kandey village may be highly affected in coming years.

Figure 16: Frontal face of the Kandey landslide

Landslides near Nell village

The landslides near Nell village situated approximately 7 km from Chamoli town. A photograph of the frontal face of the landslide is shown in Figure 17. The visited area is affected by a series of rockslide and debris slide stretching almost 3 kilometers, most of them are reactivated during Chamoli earthquake in 1999. Only one debris slide of this series located close to Nail village in the extreme north has been visited. The debris slide is approximately 120 m wide and 70 m high. The debris are composed of quartzite and schists. The landslide is still active and water flowing during monsoon triggers the further reactivation of the slide. GPS measurement shows that approximately 9700 sq meter of the area near the crest of the landslide are affected. The length of the landslide tail is approximately 250 meters. The landslide tail is connected to another two major landslide which are not approachable. A series of retaining wall construction have been seen in this particular slide.

Figure 17: Frontal face of a landslide near Nell village

5.6 Progress in LHZ mapping at Regional Level in India

The landslide hazard zonation on macro (1:50000 or 1:25000) scales and meso (1:10000 or 1: 5000) scales has been taken up by Geological Survey of India. The methodology standardized by BIS has generally been followed to carry out landslide hazard zonation mapping in different parts of the country. However, after covering some areas following these BIS guidelines, it was felt that certain parameters need modification, which are under review. As of now, the landslide hazard zonation mapping has been completed covering about 49000 sq km in different States and 4700 km along National and State Highways (Sharda, 2008).

CBRI has carried out landslide hazard zonation in parts of Alaknanda and Bhagirathi valleys as also in the Darjeeling Himalayas and in east and south districts of Sikkim (Bhandari, 2006).

Landslide zonation mapping in parts of Ravi Basin, Himachal Pradesh; Yamuna Basin, Uttarakhand; Imphal Town, Manipur; Kohima City Nagaland and Kolasib and Cachar districts, Mizoram and Manipur, have continued.

Landslide hazard zonation on macro-scales include Guwahati Urban Area; Coonoor Area, Nilgiri district, Tamilnadu; Thodupuzha Area, Idukki district, Kerala; along NH-39 between Kohima and Imphal, Nagaland and Manipur; between Imphal and Nungba along NH-53, Manipur; Lunglei area, Mizoram.

The other efforts in this field include LHZ mapping in Chamoli and Almora districts in Ramganga basin; around Ranikhet in Uttarakhand; around Shimla in Himachal Pradesh; part of Mumbai-Goa Highway and area around Malshej Ghat area in Maharashtra.

In addition to above, THE LHZ mapping on meso-scales (1:10,000 or 5,000 scales) has been taken up by GSI in some States. These include area around Lunglei Town, Mizoram; Kurisumala, Kottayam district, Kerala and area around Vaishnodevi Shrine, Jammu and Kashmir.

NRSC in 2001 published an Atlas on Landslide Hazard Zonation majorly based on the interpretation of remote sensing data and limited field checks along pilgrimage routes in the Himalaya. However, the geotechnical and geoengineering aspects were not fully covered to enable precise solutions for arresting or retarding the mass movement.

DST is also in the process of producing an LHZ atlas based primarily on the projects sponsored by the department. It will include LHZ maps in East Sikkim Himalaya, Sikkim, North East Himalaya, Satjuj Valley, HP, Mandakini Valley from Kund Chatti to Soneprayag, Sukhindarg area, Kumaun Himalaya, Tawaghat-Sobala region, Kumaun Lesser Himalaya, Chamoli, Nilgris, Uttarkashi, Maneri, Bhatwari, Gangnani, Dabrani and Lunglei District, Mizoram. All these maps, are based on weight rating systems assigned to various causative factors, namely, lithology, structure, slope, relative relief, hydrogeological, and landuse/land cover. A range of methods have been used to produce the LHZ maps of different parts of the country, which will be included in this Atlas.

5.6.1 A Chronology of Examples on LHZ mapping in the Himalaya

Mazumdar (1980) attempted a hazard zonation mapping in terms of physico-mechanical properties of the rocks underlying the slope and intensity of rainfall.

Sheshagiri and Badrinarayan (1982) took initiative in the preparation of landslide zonation map of Nilgiri area. They used factors like clay factor, slope angle and land use for the landslide hazard zonation. The LHZ map of the Nilgiri area thus mainly indicated hazard prone slopes. The map was used in the planning for roads in the area.

Anbalagan (1992) used facet based LHZ technique for preparing LHZ map of Kathgodam - Nainital area. Extensive use of aerial photographs was made for collecting pre-field data. The technique has been successfully applied in different parts of Kumaun and Garhwal Himalaya of India.

Similar type of technique with different parameters was followed by several authors at different times (e.g., Seshagiri and Badrinarayana, 1982; Choubey and Litoria, 1990; Pachauri and Pant, 1992; Gupta et al., 1993; Sarkar et al., 1995; Mehrotra et al., 1996; Virdi et al., 1997; Turrini and Visintainer, 1998) for LHZ mapping in other parts of the country. For example, Turrini et al. (1994), carried out LHZ mapping of Alpago area of Northern Italy using LHEF rating technique of Anbalagan (1992). Satisfactory results were obtained. It was however felt that the relative relief could be omitted whereas other factors coule be kept intact. The use of remote sensing and GIS in the pre-field stage of investigations was also recommended.

Gupta et al. (1993) presented the landslide hazard zonation map of the area round Shivpuri in Garhwal Himalaya. Gupta and Anbalagan (1997) carried out landslide hazard zonation of Tehri dam reservoir. It was indicated that some of the high hazard zones on the left bank of river Bhagirathi, where suitable control measures are suggested to be implemented after detailed studies.

An integrated remote sensing and GIS based analysis for landslide hazard zonation was carried out by Gupta et al. (2002) in the Bhagirathi valley of Garhwal Himalaya. A number of thematic data layers pertaining to causative factors, namely landuse/land cover, thrust buffer, photo-lineament buffer, lithology, drainage buffer, slope angle, relative relief and also an existing landslide distribution data layer were created. The LHZ was carried out using the relative weight rating system approach by first computing the landslide hazard index and then classifying the LHI values into various hazard zones. The percentage of landslide areas in each hazard zone was determined and analysed.

Saha et al. (2004) implemented two bivariate statistical methods namely InfoVal and modified LNRF for the generation of LHZ map in a raster based GIS environment. The study area covered a small region of about 550 km^2 in the

Himalayas. Geologically, the region comprises the Lesser Himalayas and the Higher Himalayas (Valdiya, 1980), and consists of sandstones, limestones and granite-augen gneiss. Structurally, the region is complex due to the presence of various thrusts, faults and intense deformations. A number of thematic data layers on specific themes related to the factors affecting the occurrence of landslides, viz. landslide distribution, relative relief, slope, aspect, structural features, lithology, landcover and drainage density were generated from topographical maps, remote sensing data, geological map and the field surveys. The weights obtained from both the methods were integrated to generate a Landslide Hazard Index (LHI) map in GIS. The LHI values were categorized into various hazard zonation classes based on success rate curve method to produce two LHZ maps (Figures 18 and 19). The LHZ map generated using InfoVal method does not show any ghost effect and appears relatively homogeneous throughout the area thereby does not show any influence of major structural zones and discontinuities. The proposed M-LNRF method based on a statistical criterion resulted in more logical boundaries of various hazard zones with different percentages of areas (e.g., VH (11%), H (28%), M (26%), L (26%), VL (10%)).

Sarkar and Kanungo (2004) suggested an integrated approach for landslide susceptibility mapping using remote sensing and GIS on the basis of studies carried out in Darjeeling Himalaya. A part of the Darjeeling Himalaya was selected for the model execution. IRS satellite data, topographic maps, field data, and other informative maps were used as inputs to the study. Important terrain factors, contributing to landslide occurrences in the region, were identified and corresponding thematic data layers were generated. These data layers represent the geological, topographical, and hydrological conditions of theterrain. A numerical rating scheme for the factors was developed for spatial data analysis in a GIS. The resulting landslide susceptibility map was validated by correlating the landslide frequencies of different classes. It showed a close agreement with the existing field instability condition. The effectiveness of the map was also confirmed by the high statistically significant value of a chi-square test.

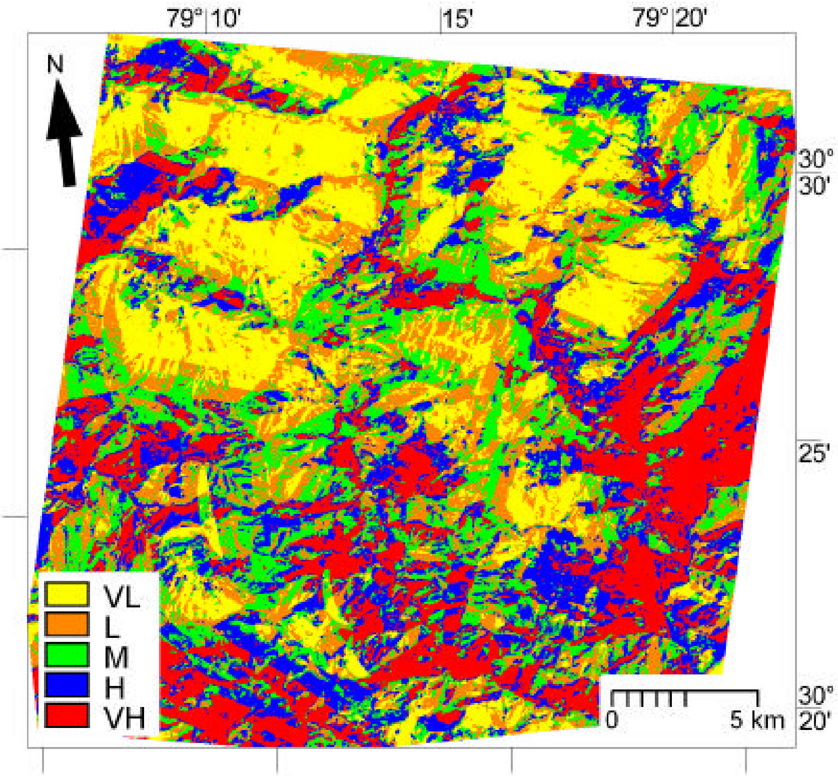

Figure 18. LHZ map prepared using InfoVal method

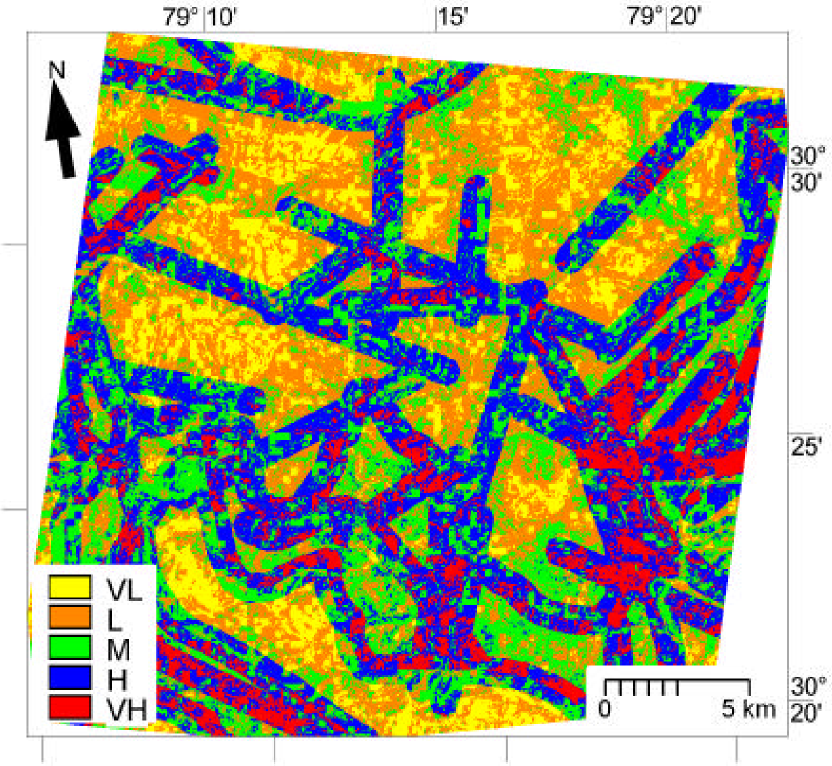

Figure 19. LHZ map prepared using modified LNRF method

Prasad et al. (2006) studied the causative factors of landslides in Mandakini valley from Kumd Chatti to Soneprayag. The mapping of landslide zones was based on aerial photo-interpretation followed by field checks. A number of landslides were mapped in the field. A LHZ map based on subjective weight rating system was prepared. It was concluded that structural state of the bed rocks and the heavy precipitation were the major causes of the landslide in the selected study area. Slope geometry, topography, vegetation, drainage conditions, material properties, down cutting and undercutting of slopes by the streams and spacing of the streams were other key factors. It was also observed that the in this study area, landslides were controlled by activities along active lineaments.

Pachauri et al. (2006) carried out landslide hazard zonation and terrain analyses in Garhwal Himalaya. The entire study was grouped into three stages; classification of the terrain, landslide hazard zonation and risk assessment. The techniques used for the classification were based upon the homogeneity of the slope characteristics so as to prepare a facet classification map. Data on facet category, distance from the North Almora thrust, vegetation density, distance from the nearest ridge top, slope aspect and altitude were collected. A weighted rating system was applied to various factors to produce a landslide susceptibility map. The methodology was effectively used for understanding the relationship of the landslide with active faults.

Anbalagan and Singh (2006) used the LHZ mapping technique in application of route location in hilly terrains. Presently the GSI is engaged in preparation of LHZ map of the hill regions of the entire country on 1:50000 using LHEF rating scheme. The reports of GSI are confidential and are available for limited use only. These may be thrown open for public use soon.

LHZ in Satlej river valley of Himachal Pradesh was attempted by Virdi et al. (2006). The valley had seen intensive landslide activity and other mass movements due to rapid expansion of road network, development projects and increasing urbanisation. The LHZ maps were prepared based on the empirical evaluation of geological, geomorpological, hydrological, anthropogenic and other causative factors. On the basis of slope direction, the area was divided into facets. Weights were assigned to each facet based on the relationships between occurrences of landslides and various causative factors. The LHI for each facet was computed, which were then categorised to produce the LHZ map of the area.

Mehrotra et al. (2006) also produced an LHZ map in parts of Sikkim Himalaya. Various factors viz. geology and structure, slope, drainage, landuse etc. were considered to create thematic database with the help of remote sensing data, topographical maps and field surveys. LHZ was prepared based on numerical weight rating system.

Sakia et al. (2006) also generated a LHZ map of Guwahati area by considering geotechnical parameters, relative relief, lithology, forest cover, slope etc. The data pertaining to these factors were collected from field as well as laboratory analyses. Here also, the facet based approach was used for preparation of landslide hazard zonation map.

Tiwari et al. (2006) carried out LHZ along a route in Lunglie district of Mizoram on the basis of significance of geo-environmental factors including instability. The facet based methodology was used here.

Singh (2006) performed LHZ in Itanagar, capital of Arunachal Pradesh by considering geological, hydrological, slope, neotectonic, anthropogenic factors

Kanungo et al. (2006) developed an approach for LSZ mapping leading to upto risk assessment through the use of advanced approaches and their implementation within the domain of remote sensing and GIS. Four different approaches, namely, conventional weighting approach, ANN black box approach, fuzzy set based approach and combined neural and fuzzy approach for LSZ mapping were used. The study area was located in Darjeeling Himalaya, which lie within the Lesser- and Sub-Himalayan belts. Database from IRS-1C LISS-III and sensors, SoI topographic maps at 1:50,000 scale, published geological map by GSI, extensive field data on landslides and land use/land cover was prepared. Various thematic data layers pertaining to causative factors, namely, slope and aspect, lithology, lineament buffer, drainage buffer, land use land cover, and existing landslide distribution data layer were prepared. In subjective-weight rating approach, the success rate curve method for segmentation was also adopted to fix the boundaries of landslide susceptibility zones statistically and to minimise subjectivity in arbitrarily selecting the natural boundaries of different zones. In ANN black box approach, a feed forward multi-layer ANN with one input layer, two hidden layers and one output layer was designed. The input layer contained 6 neurons each representing a causative factor. The output layer contained a single neuron corresponding to existing landslide locations. It is found that VHS and HS zones together occupied 34.6% of total area and contained 50.7% existing landslide area. There is lot of similarity between LSZ maps prepared using conventional weighting approach and ANN black box approach. This may be due to the fact that the conventional one was used as the reference map for generating the ANN black box based LSZ map.

In the fuzzy set based approach, ratings of each category of a given thematic layer were determined using the concept of fuzzy relation. The cosine amplitude similarity method was used to determine the membership degrees of categories by establishing the strength of relationship between the existing landslides and the categories. By assigning the ratings of the 35 categories, 35 images of fuzzy relations were generated. The corresponding fuzzy relation images for various categories of a thematic layer were integrated together to generate a fuzzy relation image for that thematic layer. A total of 6 fuzzy relation images were created. The integration of these images was performed to obtain landslide susceptibility index (LSI) using arithmetic overlay operation. The range of LSI values o were divided into five landslide susceptibility zones using success rate curves method. The spatial distribution of existing landslides in the LSZ map showed that VHS zone occupied 6.1% of total area and contained 41.0% of existing landslide area. Further, HS and VHS zones together occupied 28.8% of the total area and contained 66.1% of existing landslide area.

LHZ using combined neural and fuzzy approach involved three main stages; determination of weights of thematic layers through ANN connection-weight analysis, determination of ratings for categories using cosine amplitude similarity concept and integration of ratings and weights in GIS to generate an LSZ map. The arithmetic integration of six thematic data layers representing the ratings of the categories (obtained from fuzzy set based approach) and weights for the layers was done to obtain the LSI for each pixel. Here also, the success rate curve method was used to classify the LSI values into five different susceptibility zones to produce the LSZ map. In this LSZ map, VHS zone occupied only 2.3% of the total study area and contained 30.1% of landslide area. Further, VHS and HS zones together occupied 22.5% of the total area and contained 62% of existing landslide area. This LSZ map showed preferential distribution of higher landslide susceptibility zones along structural discontinuities (lineaments), which should indeed be the case.

The study also conducted a comparative evaluation of the LSZ maps using landslide density analysis, error matrix analysis and difference image analysis. Amongst all the maps, the LSZ map produced from combined neural and fuzzy approach was considered to be the best LSZ map (Figure 20) of the area.

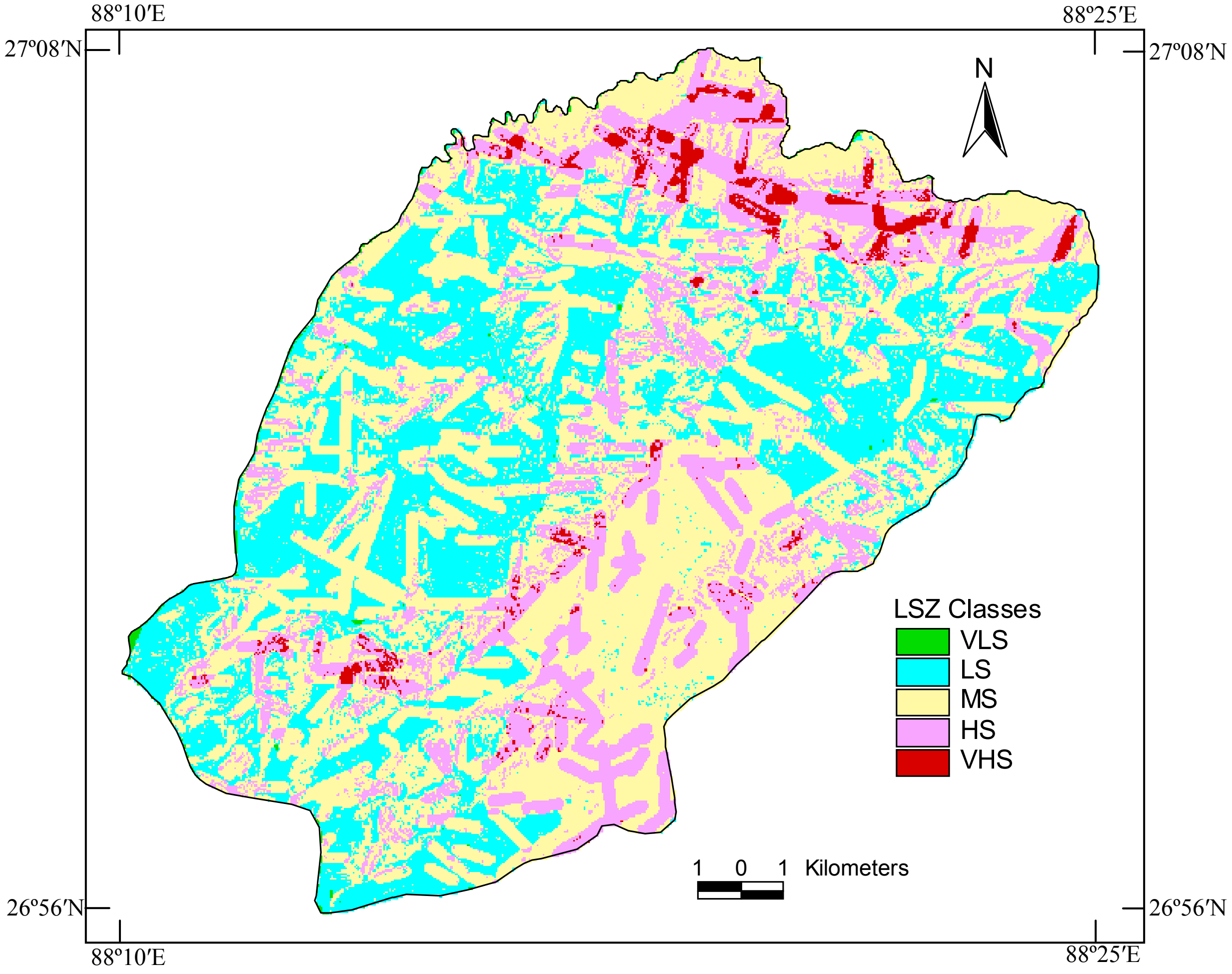

Figure 20. LSZ map prepared from Neuro-fuzzy technique

Biswas et al. (2007) applied a GIS based technique for preparing of landslide hazard zonation map along Shivpuri – Vyasghat road section, Garhwal Himalaya.

Chakraboti et al. (2008) modified the regional scale LHEF rating scheme for preparation of Landslide hazard zonation (LHZ) mapping on meso-scale for systematic town planning in Nainital. The importance of the individual parameter has been considered in a more detailed way to bring more details of the hazard categories. This technique is being considered at present for preparation of a BIS code.

Deva and Srivastava (2006) suggested a grid-based approach for classifying the terrain into five categories using three factors that include lithology, ruggedness number and land use/land cover.

Pachauri (2007) based on the LHZ mapping carried out in Chamoli area of Uttarakhand concluded that facet-based LHZ is very effective tool for landslide mapping in high relief areas in Himalayas and is cost effective.

Champatiray et al. (2007) suggested a fuzzy-based method for landslide hazard zonation in active seismic zone of Himalaya.

Chauhan et al. (2010a) implemented a logistic regression model for Landslide Susceptibility Zonation of Chamoli area part of Garhwal Himalayas, India. Logistic regression model estimates the relative contribution of these categories causing slope failures and establishes a relation between the categories and landslides. Then based on a statistical test, significant or the most influential categories are selected, and finally the model assigns the probability of landslide susceptibility. The thematic data layers pertaining to each causative namely slope, aspect, relative relief, lithology, structural features, drainage density and landuse/landcover existing landslide distribution in the area were created in GIS. The areal extent of landslide susceptibility zones, percentage of observed landslides and landslide density in these zones showed that 71.13% of observed landslides fall in 21.96% of predicted Very High and High susceptibility zone, which in fact should be the case. Most of the area that falls into predicted very high and high hazard zone is concentrated around chamoli, which is the major town of Uttarakhand and is the base station of various tourist locations.

Chauhan et al. (2010b) also proposed a new LHZ technique based on ratings derived from artificial neural networks for preparation of an LHZ map in the Chamoli area. Based on the same causative factors, the LSZ maps from conventional ANN black box approach and the proposed approach were prepared (Figures 21 and 22). A very large area of about 29% was classified as very high susceptible zone in ANN black box model which did not show any defined pattern and was distributed overall in the map, whereas LSZ map obtained from ANN derived ratings was able to confine very high susceptible zone largely concentrated around Chamoli area. Thus, a realistic landslide hazard zonation was shown by the proposed approach.

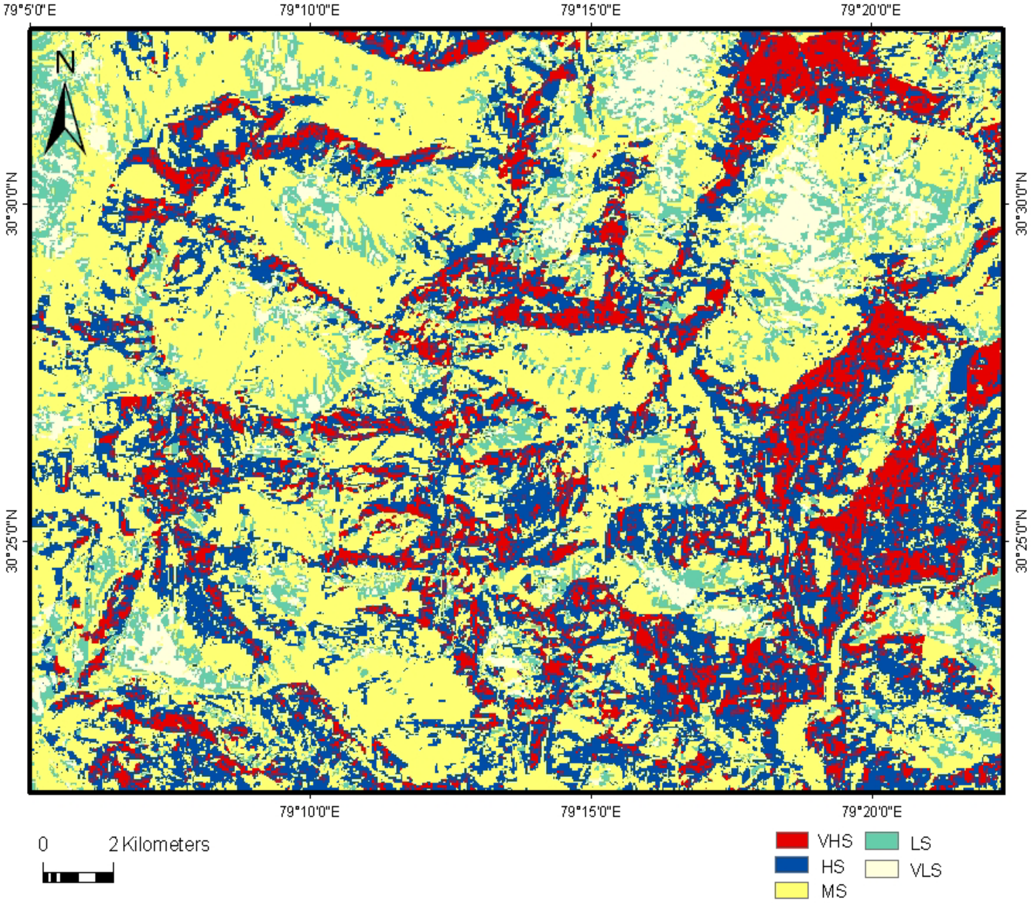

Figure 21. LSZ using ANN black box approach

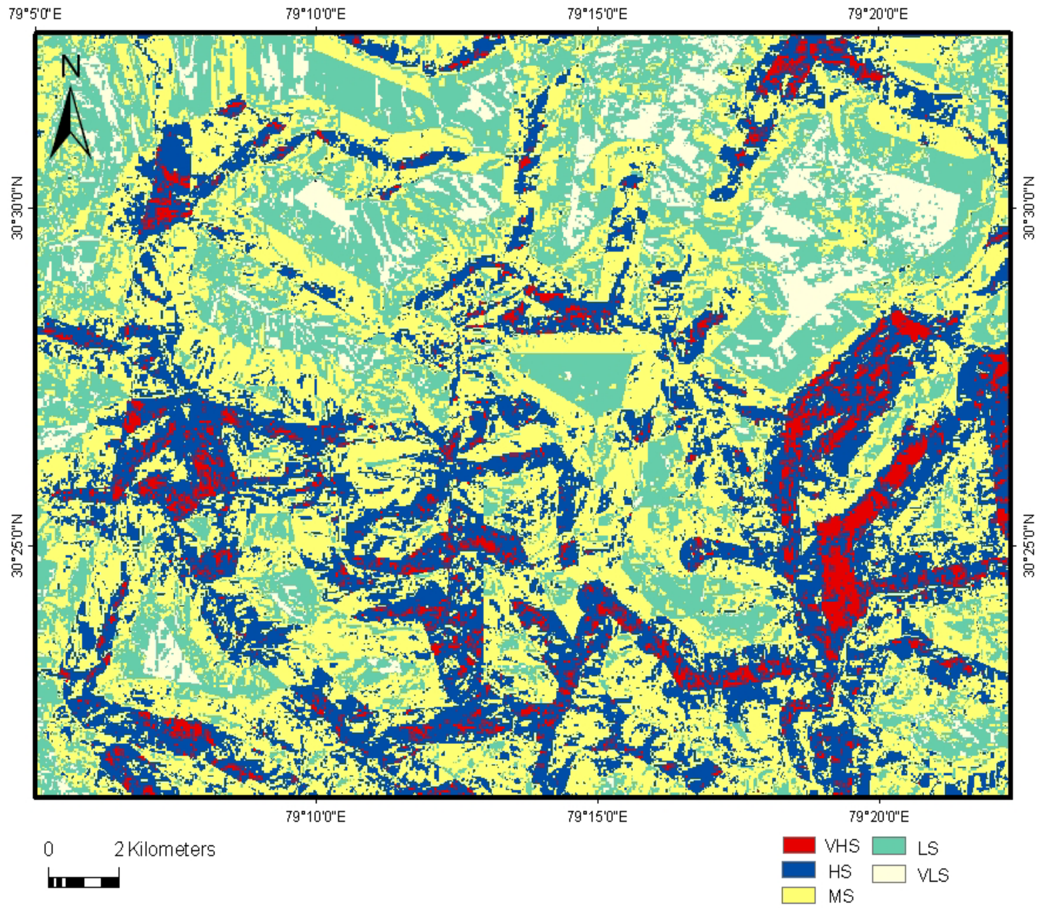

Figure 22. LSZ using ratings derived from ANN

Pareekh et al. (2010), in addition to static causative factors, considered the influence of earthquakes in distribution of landslide hazard zones in the Chamoli region, which falls in seismic zone IV as per the IS Code 1893 – 2001 (IS: 1893). In the Garhwal seismotectonic block, a total of 83 seismic events of magnitude ≥ 4 have been recorded from 1842 to 1996. Uttarkashi (Oct 20, 1991) and Chamoli (March 29, 1999) are most recent examples of devastating earthquakes of magnitude larger than 6. These earthquakes caused new landslides and reactivated the older ones. The methodology included prepraration of pre and post Chamoli earthquake Landslide Hazard Zonation maps in GIS environment. From the pre and post earthquake LHZ maps a difference map was created (Figure 23). The difference map showed the shift from one landslide zone to another, after the occurrence of the earthquake. It clearly depicts that after the occurrence of the earthquake, the areas of moderate to very high hazard zones increased. It was also observed that the area in very low and moderate hazard zones was severely affected by Chamoli earthquake. The areas for low hazardous zones decreased showing the increased severity of the hazard in seismic shaking conditions.

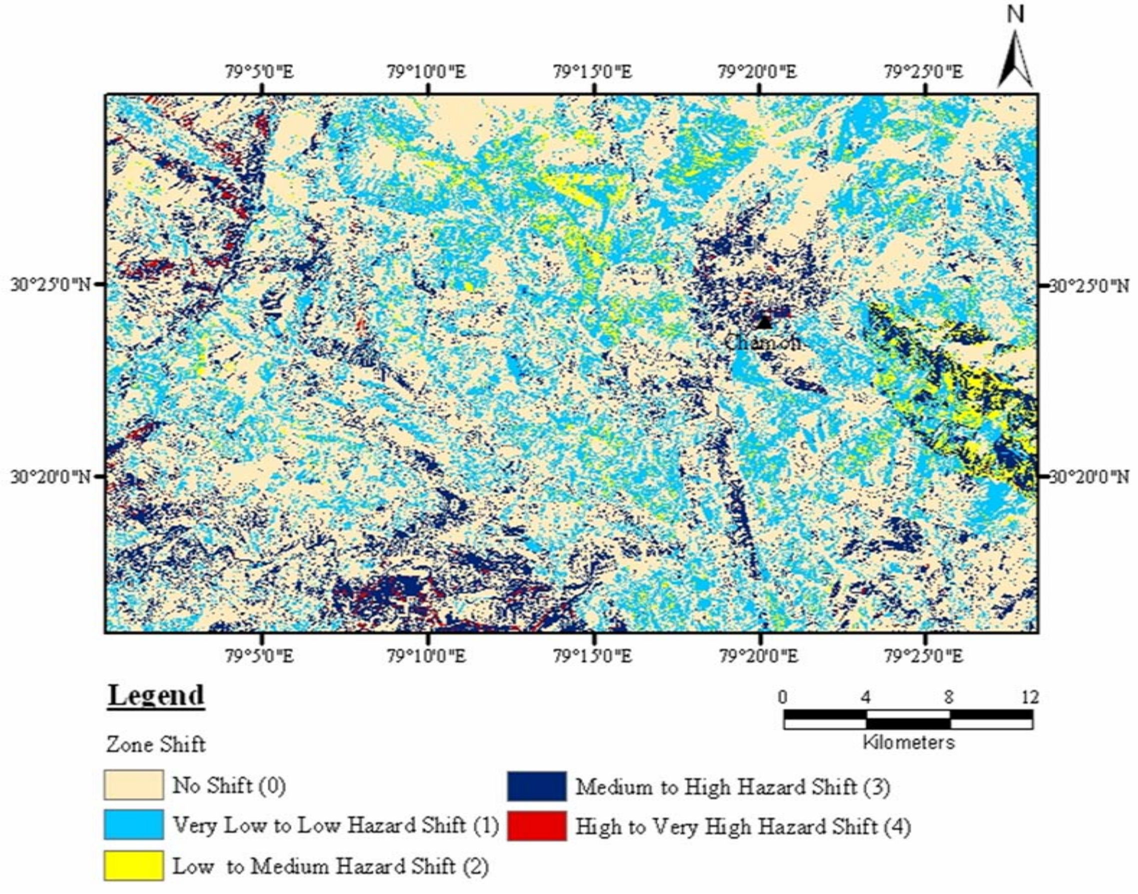

Figure 23. Shift phenomenon in LHZ zones (computed from before and after earthquake)

5.7 Landslide Risk Zonation in India

Landslide risk zonation has so far not been sincerely attempted in India. Most of the organisations and institutes in the country have culminated LHZ mapping only. The four data inputs required for risk zonation are environmental factors, triggering factors, historic landslide occurrence and elements at risk. The historic information on landslide occurrence is by far the most important input as it gives insight into the frequency of the events, the types of landslides, and the volume and extent of damage. Landslide inventory maps, derived from historical archives, field data collection, interviews of the affected community and image interpretation are essential. Since, these data are not readily available, landslide risk assessment has become very difficult. Information on triggering factors consists of earthquake and rainfall records, which have to be converted into magnitude-frequency relations of those aspects that actually trigger landslides, e.g., earthquake acceleration or groundwater depth. These parameters are very site specific and can only be modelled properly using deterministic models, which require considerable input on the geotechnical characterisation of the terrain (soil depth, cohesion, friction angle, and permeability). Temporal probability is determined either by correlating the data on landslide occurrence with that of triggering factors, or through dynamic modelling. On the other hand, the spatial probability can be obtained either through dynamic modelling or by analysing the relation between the locations of past landslide events with a set of environmental factors.

Anbalagan and Singh (1996) suggested and implemented the LRA approach in mountainous terrain of Kumaun Himalayas, India, using a risk assessment matrix. Risk was considered as a function of hazard probability and damage potential. The damage potential was evaluated as very low (VLDP), low (LDP), moderate (MDP), high (HDP) and very high (VHDP) in terms of loss of life and/or injuries as well as loss of land and property (Table 6). For example, damage potential of resources damage to >50 dwellings or damage of very thick vegetated area or damage of >2000m of road, is treated as VHDP.

Table 6. Damage potential of different resources at risk

Damage potential (DP)	Number of dwellings likely to be damaged	Land use land cover categories	Length of road damage (m)
VLDP	<2	Barren	<100
LDP	2-5	Sparsely vegetated	101-500
MDP	5-10	Mod. Vegetated/ agricultural land	501-1000
HDP	10-50	Thickly vegetated	1001-2000
VHDP	>50	Very thickly vegetated	>2000

The hazard probability of slope facets such as very low (VLHP), low (LHP), moderate (MHP), high (HHP) and very high (VHHP) was obtained from the LSZ map. These datasets on damage potential and hazard potential were integrated manually based on a slope facet concept and a risk assessment matrix was formed with a five fold classifications such as very low risk (VLR), low risk (LR), moderate risk (MR), high risk (HR) and very high risk (VHR). The procedure of preparing landslide risk assessment (LRA) is shown in Figure 24.

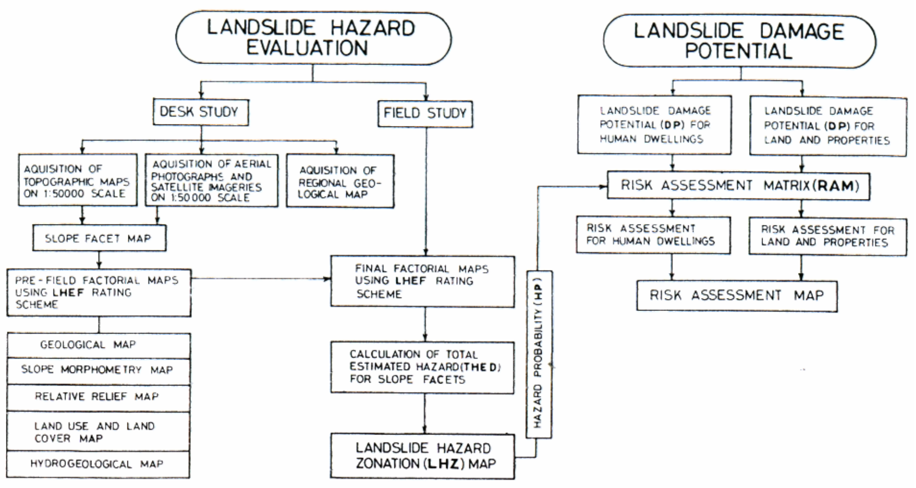

Figure 24. Procedure of preparing landslide risk assessment (LRA) map

The LRA map of Sukhidang area indicates the level of risk in various localities as very high risk (VHR), high risk (HR), moderate risk (MR), low risk (LR) and very low risk (VLR) indicated by different symbols (Figure 25). The risk assessment map indicates that some of the slopes deeply undercut by a river adjoining the habitations show high risk zones.

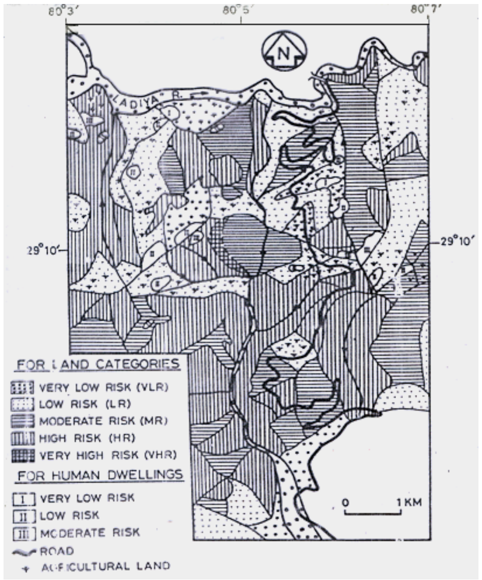

Figure 25. Landslide risk assessment map of Sukidang area, Himalaya

Rautela and Lakhera (2000) prepared the vulnerability map of parts of Himalayas in Sirmur district, Himachal Pradesh, India, using 1991 census data and an LHZ map. The population of the area (1991 census) was categorized into five classes and was used to formulate the vulnerability coding of populations to devastation caused by landslides (Table 7). In this case, only population data was used for vulnerability studies, but not other resources/infrastructures were considered.

Table 7. Vulnerability (Vul) coding of population classes to devastation caused by landslides

Landslide hazard classes	**Population class**				
	Sparse	**Low**	**Moderate**	**High**	**Very high**
Least	Low Vul	Low Vul	Low Vul	Low Vul	Moderate Vul
Low	Low Vul	Low Vul	Low Vul	Moderate Vul	Moderate Vul
Moderate	Low Vul	Moderate Vul	Moderate Vul	High Vul	High Vul
High	Moderate Vul	Moderate Vul	High Vul	Very High Vul	Very High Vul

In recent times, Kanungo et al. (2007) suggested two new approaches for landslide risk assessment wherein landslide risk was considered as a function of landslide potential or susceptibility and the resource damage potential. These approaches were named as,

i) LRA using danger pixels
ii) LRA using Fuzzy Concept

5.7.1 LRA Using Danger Pixels

Danger pixels can be defined as pixels those appear to be under real risk due to landslides. The steps involved in this approach, LRA using danger pixels, are given in Figure 26. Danger pixels are considered as those pixels which lie in VHS and HS zones in a given set of four LSZ maps prepared from different methodologies. For generating a danger pixel map, the VHS and HS zones in each LSZ map were merged together and the remaining landslide susceptibility zones (MS, LS and VLS) were masked out. The danger pixel map represents pixels that appear to be under real danger from landslide point of view. The resource map is an image with different numerical attributes for different resource categories (i.e., land use land cover and roads). As barren land is not an important resource category from damage point of view, pixels allocated to barren land are ignored for landslide risk assessment. Hence, the remaining resource categories (habitation, road, agriculture, tea plantation, thick forest and sparse forest) were considered under risk due to landslides. The danger pixel map and the resource map have been multiplied to generate the LRA map.

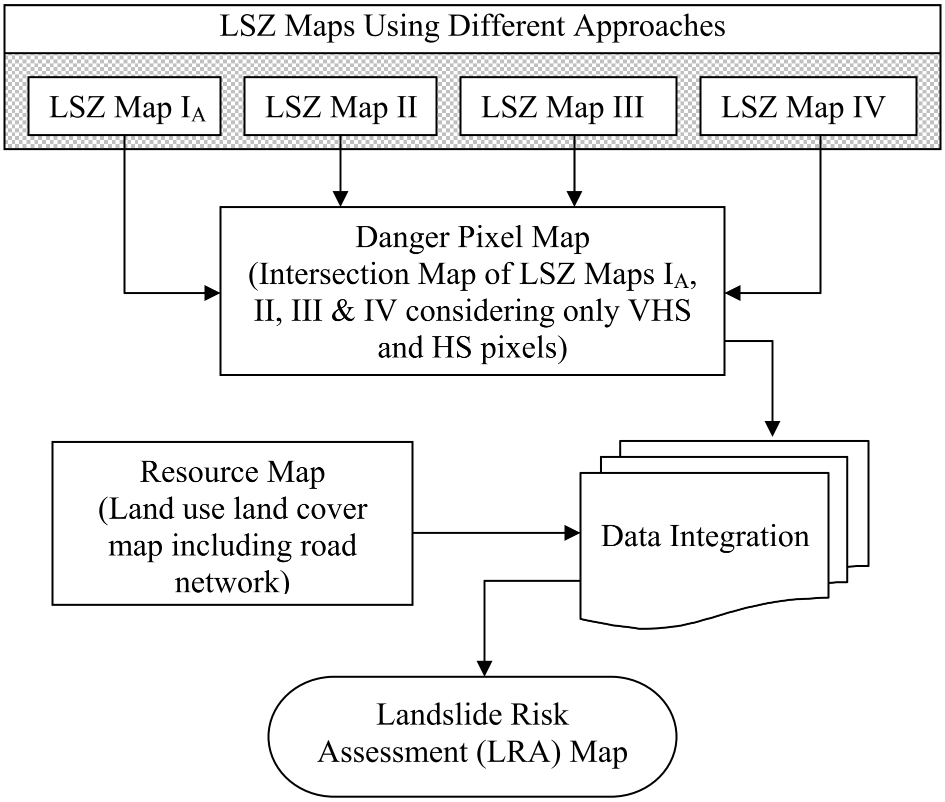

Figure 26. Steps for landslide risk assessment (LRA) using danger pixels.

5.7.2 LRA Using Fuzzy Concept

This approach is an extension of risk ranking matrices approach of Anbalagan and Singh (1996). According to them, the landslide potential and the damage potential of various resource elements have been categorized into qualitative terms such as very low, low, moderate, high and very high. Also, the risk ranking matrices have been developed in qualitative terms. However, in this approach, the landslide potential and the damage potential of various resource elements can be quantified in terms of fuzzy membership values as per their relative importance to risk assessment. Thus, the risk assessment matrix can be generated with numerical values, which can be classified into different risk zones. This approach is a combination of risk scoring and risk matrix. The best LSZ map can be used as an input layer to provide landslide potential. Further, land use land cover map including the road network has been used as the input layer to correspond to the resource map, which has been used to derive information on resource damage potential.

The fuzzy membership values for landslide susceptibility zones and different land use land cover categories have been assigned on the basis of a linguistic scale derived from expert's judgment. These two layers in terms of their fuzzy membership values have been multiplied in GIS to generate a LRA map which has been classified into different risk zones. The steps for LRA using danger pixel approach are shown in Figure 27.

The LRA map produced from danger pixel concept does not infer the degree of severity of risk to different resource categories due to landslides. However, the LRA Map II produced from fuzzy concept depicts different degrees of severity of risk from VHR to VLR for various resource categories due to landslides.

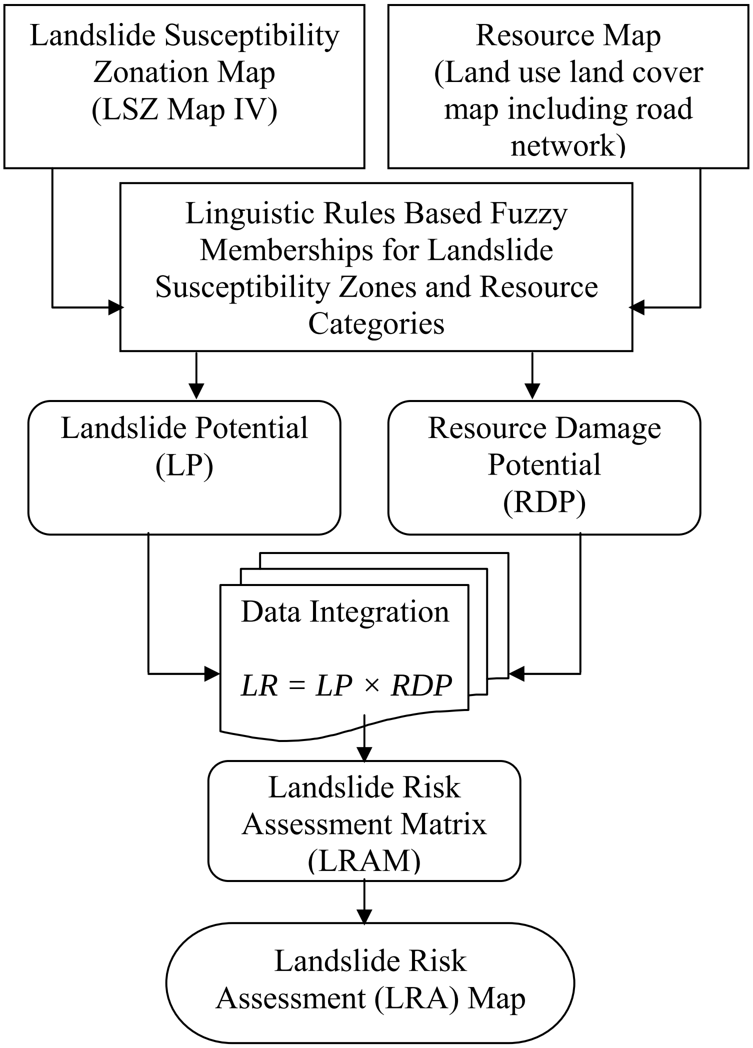

Figure 27. Steps for landslide risk assessment (LRA) using fuzzy concept

These two approaches were applied by Kanungo et al. (2007) to carry out risk assessment in Darjeeling Himalaya. The LRA map produced from danger pixel approach is shown in Figure 28.

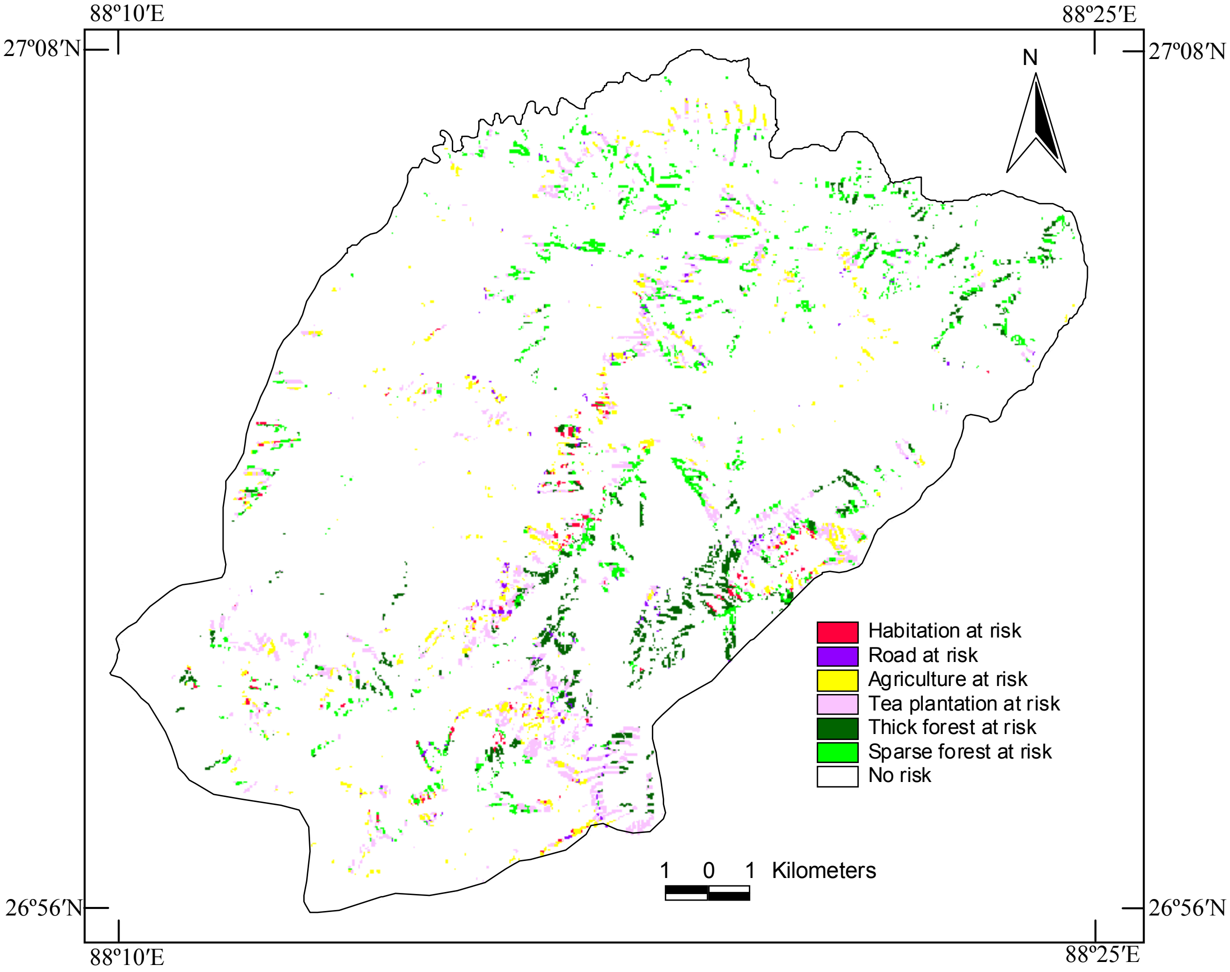

Figure 28. Landslide risk assessment map using danger pixels

This LRA map showed spatial distribution of different resource categories that appeared to be under real danger due to landslides. It was observed from the LRA map that the habitation around Darjeeling and Ghum were under risk due to landslides. A portion of road from Sonada to Ghum is also under risk due to landslides. Mostly the tea plantation in the southern part and thick forests in the southeastern part of the study area were under risk due to landslides. However, the LRA map produced using danger pixels does not infer the degree of severity of risk to different resource categories due to landslides. Another LRA map produced using fuzzy concept is shown in Figure 29.

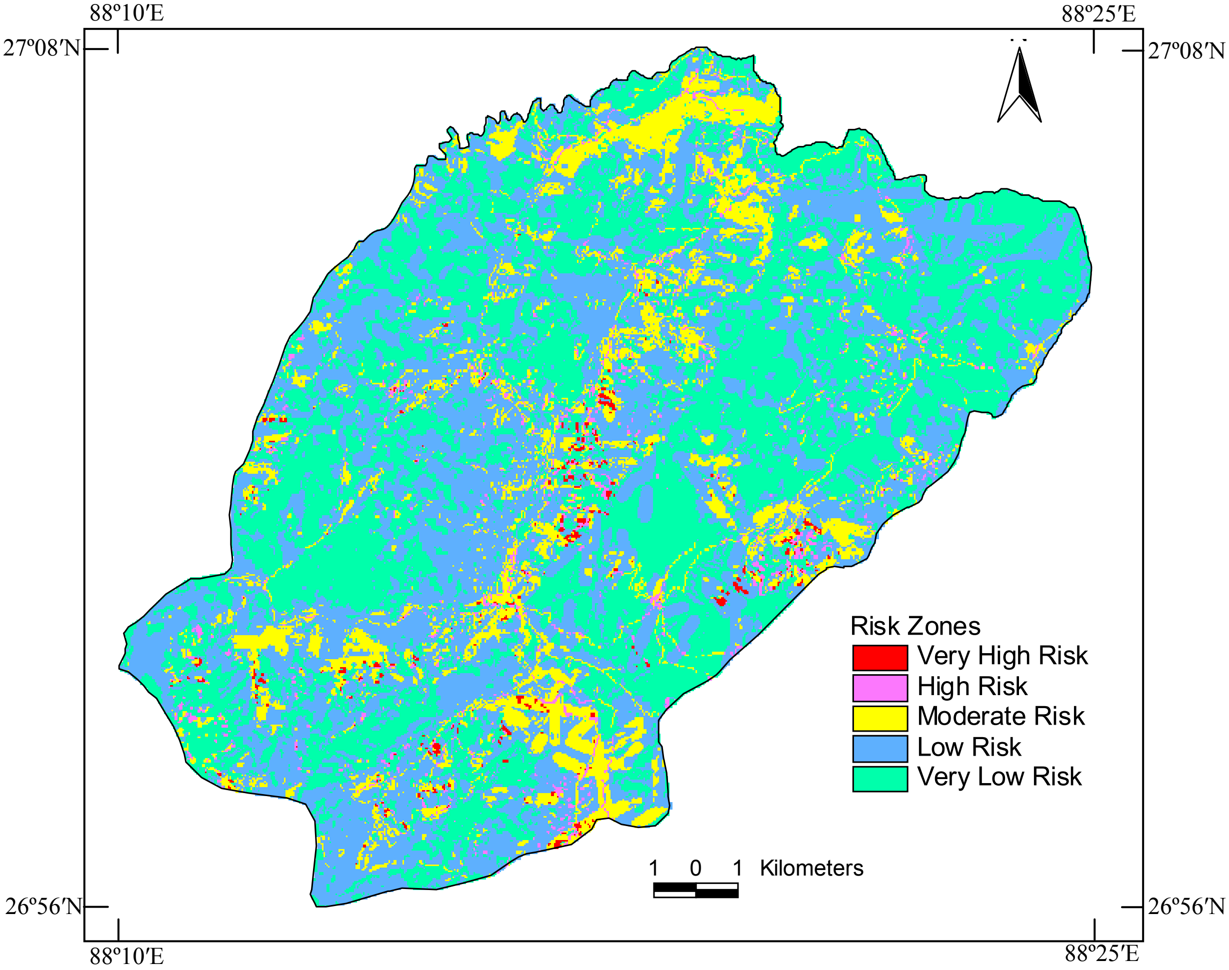

Figure 29. Landslide risk assessment map using fuzzy concept.

In this approach, LSZ map, prepared using the fully objective combined neural and fuzzy approach was used as an input to provide landslide potential. Further, the resource map was used as another input layer to derive information on resource damage potential. The LRA Map revealed that landslides pose very high risk to selected sites of habitation in Sonada, Darjeeling and northeastern part of Tiger hill, and HR to a section of road from Sonada to Ghum. The LRA Map produced from fuzzy concept depicts different degrees of severity of risk from VHR to VLR for various resource categories due to landslides.

5.8 Detailed Landslide Investigation, Monitoring and Early Warning Systems

In India, as stated earlier, there appears to be no concentrated and cohesive effort on detailed landslide investigation, mapping and monitoring of landslides.

The earliest known example is available from 1880, when the Britishers installed a system of surface monitoring of Nainital hill slopes in Sher-ki-danda area. They installed a line of pillars and monitored the position of the pillars by precision leveling. In view of importance of the Nainital area, the practice was continued till 1947 till Independence of the State. Later though the practice started after a time gap, it continued with many time gaps upto 1960. The data are available with Public Works Department. Later the practice was discontinued though the Sher-Ki-Danda hill slopes still unstable. A well planned monitoring and probably leading an Early Warning System (EWS) is need of the hour in Nainital area.

The landslide instrumentation initiatives have also been taken by CRRI in early 1970s, Bhandari (1980). Hydraulic standpipe piezometers were used for pore pressure measurements. Electrical resistivity method was used to determine slip surface of landslide at Snowdon in Shimla. Water level indicators were used to monitor relative ground subsidence and a crack cum tilt measurement device was developed and used for measuring progression of crack widths and tilts of structural members in buildings affected by landslides.

A landslide monitoring laboratory equipped with the latest equipment was also established at CBRI during that time. Most of the landslide instrumentation related to monitoring of pore water pressures and surface and subsurface displacements. Several innovative devices were gradually added to supplement EDM observations.

In Tehri, extensometers were installed on the hill slope just above T4 diversion tunnel of the Tehri dam according to the old reports of the GSI. The data was very useful to understand the behavior of the slope just above the diversion tunnel. The monitoring helped to understand that the slope had attained stability with the type of treatments done on the slope. Similarly, the Konkan Railways installed extensometers and piezometers on the cut slopes excavated for locating the rail lines. They are still being monitored.

CSIO in collaboration with CBRI through a DST sponsored project had also instrumented an active landslide, near Mansadevi temple, Haridwar.

A few works have been reported. Some of them are briefly narrated here.

5.8.1 Detailed Landslide Investigation

The detailed landslide investigations are site specific and are carried out on scales of 1:1000 to 2000. This is also called micro-zonation approach. The sites are often chosen from LHZ maps, where the high hazard (HH) and very high hazard (VHH) slope facets are the most potential ones for detailed study. The sites also can be chosen based on intense field studies from the surficial indications of slope movements. The priority of selection for study is obviously based on the immediate utility of the results. The sites in the vicinity of important Engineering projects such hydroelectric projects, colony and industrial complexes, roads and other such projects demand more attention. Funds are also readily available for such projects.

The preparation of LHZ maps at the micro scale is yet to be practiced in India. There seems to be neither a code nor a standard methodology for LHZ mapping at this scale. There are a few instances when it was attempted by the GSI, in the Nainital area, Mirik, and Gangtok, based on the BIS guidelines on macro scale mapping only. A review of these maps indicates that the overburden that forms considerable slope forming material in the case of the Himalaya has not been taken into consideration. Therefore, the assessment made of slope-stability status may not be realistic. For LHZ mapping at the meso scale, two additional factors, namely slope erosion and geotechnical properties of slope material, have been added to the list for macro scale LHZ mapping.

A few studies have been carried out for detail landslide mapping and monitoring in different parts of India. These include landslide hazard evaluation along cut slopes of roads in Garhwal Himalaya by Chakraborty and Anbalagan (1997), slope stability analysis of Mouzhu landslide by Kumar and Singh (2005), an appraisal of Mao landslide, Manipur by Singh (2005), landslides incidences along NH-53 by Okendro et al., (2005), a study of frequently recurring landslides on NH-39, Nagaland by Kumar et al. (2005), geotechnical investigation of Phikomei landslide by Singh et al. (2005), geomorphic studies and effects of rock mass strength on slope stability in different landslide prone areas of Meghalaya by Rai (2006),

Anbalagan et al. (1992) used the modified SMR approach for carrying out stability analysis of Lakshmanjhula – Shivpuri road section. They used stereographic projection for identifying the nature of failure pattern. On the basis of analysis, they provided location based information on nature of stability, type of failure and general type of support system required at the site. Anbalagan and Chakraborty (2008) carried out slope stability studies along Uttarkashi – Bhatwari road section of Garhwal Himalaya. Wherever rock cut slopes are encountered along the road, modified SMR technique was used for analyzing the stability conditions.

NTPC landslides on the approach road to Gunga adit

The approach road from Dabrani to Gunga adit is one of three important approaches for the construction of main tunnel. The roads in front of the adit had four hairpin bends over a distance of 1.5km. The road developed major cracks along the route and resulted into slides at many places (Figure 30). Anbalagan (2009) studied problem, mapped the entire area on 1:1000 scale, prepared many geological cross sections. The area has granitic gneisses exposed on the slopes. A thin to thick cover of debris is present over the rocks. During heavy rain, the top debris got saturated and under high the pore pressure development, the debris got slided. The stability analysis with talus mode of failure was done at the site. A number of measures including regarding the slope, reinforced gabion wall structures at the toe, well designed drains along the road on the hill side and biotechnical measures were suggested. The measures were implemented in 2009 and the road is functioning without problems during the current year.

Figure 30. The NTPC landslide

5.8.2 Landslide Monitoring

Landslide monitoring has been practiced only at few landslide sites and that too in partial manner in India. Considering the incidence of a huge number of landslides in the Himalaya, it may also not be possible to undertake monitoring of each individual landslide. Moreover, the Himalayan conditions demand that a new generation of monitoring instruments is introduced to perform multiple functions. For example, a device for surface movement measurements could be such that it monitors low orders of movements during the period quiescence whereas it monitors high orders when the slide is active (Bhandari, 2006).

Brief details on some of the typical landslide sites monitored in India are given in the following,

Instrumentation and monitoring of landslides at Powari, Himachal Pradesh

Rao et al. (1995) of CRRI were the first to conduct a study on instrumentation and monitoring of landslide at Powari, in Himachal Pradesh State. The Powari Landslide area is located is located on NH-22. The Powari landslide is a part of an old landslide which reactivated in 1987 due to a number of factors. It first occurred in the month of May 1987, again reactivated in December, 1987. After a gap of one year, it again activated in January 1989 three times. Since then the landslide is recurring every year particularly in rainy season.

The 1975 Kinnaur earthquake in the region severely affected the geology of this region. The four lithotectonic units such as, Rampur Formation, Jutogh formation (outer crystalline), Vaikarita formation (inner crystalline) and Lower Haimanta Formation, have been recognized along the Sutlej valley. The outer crystalline unit includes low grade metamorphic rocks whereas the inner crystalline unit comprises of high grade metamorphic rocks like schists, gneisses and migmatites.

Earlier studies suggest that the upper margin of the slide is bounded by a prominent, near vertical head scarp, which is composed of fractured gneissic rocks. The central part of the slide has low relief and is composed of debris material. The left and right parts of the slide area are composed of highly weathered rocks and debris material. Large as well as small tension cracks and subsidence have been observed in the central part of the slide. Thus, instrumentation plays a vital role in monitoring the stability of slope and also in collecting factual information on the performance of structures located on the slope. Instrumentation is utilised to measure subsidence or settlement of slopes, lateral displacement, tilting of structures and pore water pressures.

At the Powari landslide, instruments such as Casagrande open stand pipe peizometer, digitilt inclinometer and rain gauges were installed. Using these instruments, the variation in peizometric levels, magnitude and direction of surface and sub-surface movements and the effect of the infiltration of rain water on slope were observed.

For surface movement studies, a scheme of instrumentation involving wodden pegs, thedolite, plane table, clinometer compass etc. were used. 30 wooden pegs were installed in the potential slide zone. Initial position of these pegs were plotted on the contour map with help of conventional surveying. The theodolite was used to determine the lateral shift in the position of peg whereas clinometer compass was used to determine the change in the direction of shift. The survey was conducted twice, first in July 1994 and then in Oct. 1994. Almost all the pegs were indicative of lateral and vertical movements towards NE directions. The extent of lateral movement varied from 0.05 m to 0.60 m and vertical movement from 0.10 m to 0.60 m. These movements clearly indicated the unstable zone of the slide area.

Sub-surface movement studies were carried out with the help of inclinometers installed at two borehole locations on the slopes. Inclinometer is used for monitoring of slope movement normal to the axis of casing pipe. Cumulative deflections for uphill and downhill locations were found to be 30.72

mm and 74.24 mm respectively. The rate of movement for the uphill slope and downhill slope locations was found to be very slow to extremely slow. It was also observed that rate of the movement was higher during snow melting and rainy seasons.

Later, an instrument aided monitoring of a Powari landslide on NH-22 along Satlej river has been attempted by Kumar et al. (2006), to infer the change in the nature, magnitude, surface and sub-surface rate and direction of the landslide movement in two years. Geological and geotechnical investigations were followed with instrumentation. The scheme of instrumentation involved theodolite and plane table surveys, clinometer measurements, compass and tape measurements, for detecting the surface movements. The inclinometer was used for quantitative measurement of lateral movement of the slope as well as direction of movement, and rate of lateral movement. The study showed that the slide area consisting of overburden is unstable and prone to slips and slides occurring periodically, particularly in the event of rainfall.

Chanmari landslide in north-eastern Himalaya

Bhasin et al. (2002), under a joint institutional co-operation programme between India and Norway, carried out landslide investigations in and around the capital city of Gangtok. Emphasis was placed on four landslides that have caused significant damage to life and property. These were Chanmari landslide, Tathangchen landslide, Six-mile landslide and Burdang landslide. These landslides were characterised as composite, in which different types of movement occur in different areas of the displaced mass. The slope movements in the Chanmari landslide and the six-mile landslide involved a combination of earth slide and debris flow. The Tathangchen and the Burdang landslide were characterised as composite rock slide-debris flow, in which the slope movements were initiated by sliding on the bedding or schistosity of the rock mass followed by flow of the displaced material.

The instrumentation and monitoring of Chanmari landslide was carried out. The Chanmari area lies in the eastern part of Gangtok and is inhabited by several thousand people. This area has been prone to landslides since the 1960s. Recently, the movements on the slope have been dominated by earth slide and debris flow. The rock is basically quartz mica schist that was found to be weathered in the upper part of the hole, but fresh in the lower part. The subsurface flow that caused the slope failure at Chanmari was presumably shallow in nature, as evidenced by the shallowness of the failure surface. The pore-water suction in the layer closest to the ground was probably depleted soon after the intense rainfall, and shallow sub-surface flow probably increased rapidly. One cannot rule out the possibility of deep subsurface flow because a large area around Chanmari is undergoing downslope creep. Therefore, an instrumentation program consisting of settlement pillars (survey monuments) and piezometers was initiated for monitoring ground movement and for determining the variation of pore pressure with climate, respectively.

Because the stability of the slope is dependent on the pore-water pressure in the ground, a programme of pore-water pressure measurements at Upper Chanmari (northern part of Chanmari) using four piezometers is currently underway. Around the surface of the landslide area a network of measuring points (movement pillars made of concrete) were erected to record the movement in the ground. The conventional geodetic method using a theodolite was used to measure the movement of the ground relative to a chosen stable area in bedrock. Monitoring of the landslide is to be carried out at regular intervals with greater frequency of readings during rainy periods. The results obtained from these instruments will be correlated with landslide activity; this will form an important part in decision making in regard to abandoning homes or closing roads.

Instrumentation and monitoring at Amparav landslide area, Uttarakhand

Gupta et al. (2009) of CRRI conducted an in-depth study of Amparav landslide to suggest the remedial measures with suitable engineering designd to control the slide. Instrumentation and monitoring was one of the components of the investigations with the aim to acquire surface as well as sub-surface landslide movements, which may be useful to understand the failure mechanism of the landslide under study.

The Amparav landslide area falls under the Kumaun division of the Uttarakhand State on NH 87, in the Upper Shiwaliks in the vicinity of Main Boundary Thrust. The area falls under the highest seismic zone and consists of the sedimentary rocks, which are soft and probably immature. The average slope in the area is 16^o whereas the upper rocky area has approximately 40^o average slope. The slides in the region were found to be of varied failures specifically talus and, plane/block failures, as observed during reconnaissance survey of the area.

To check the movements in the plane/block failure zone, movement gauges, developed in CRRI workshop, were installed. The movement gauge is capable of recording linear upto 30 cm (extension or contraction) as well as angular movements upto 90^o (clockwise or anticlockwise). A total of 5 movement gauges were fixed up in different rock beds across the bedding plane. In addition, the area of landslide zone was painted with red and yellow color lines and each rock block was marked by a unique number. The observations were taken in subsequent field trips. Most of the movement gauges were lost due to plane/block failure. Only one movement gauge was intact showing no movement. Painted colored lines were partially missing without any sign of any displacement in its remaining part. Thus, it was inferred that either there was no movement or there were abrupt movement of rock blocks. It was then decided not to install any other gauges to monitor the surface or subsurface movements.

A couple of piezometers were installed at the site of circular/rotational failure and in the paddy fields to monitor the pore water pressure fluctuations. The data were collected at regular time intervals for a year. It was found that the pore water pressure fluctuations were nominal. Thus, no significant effect of pore water pressure on landslide activities was found.

Design of control measures at Kaliasaur landslide, Uttarakhand

Kumar et al. (2010) of CRRI presented a report on investigation of Kaliasaur landslide and design of control measures for its long term stability. Differential Global Positioning System (DGPS) surveys were conducted for monitoring of the landslide.

Kaliasaur Landslide is located on NH-58 in the Rudraprayag District of Uttarakhand. The history of the landslide dates back to 1920 and since then, the slide has been experiencing frequent recurrences. The slope exists as a bare face of quartzite rock on which debris accumulated at the base of the slide. Geologically, the area belongs to Lesser Himalayan division, the rocks of which come under one of the stratigraphic groups called "Garhwal Group". The area is comprised of Uttyasu Quartzite. Fall of rock blocks due to intersection of discontinuities was found to be quite common. Folding observed in the quartzite was associated with displacement at places. Displacements observed in the immediate vicinity of the volcanic intrusions suggested faulting associated with the time of intrusion.

To monitor the movement of the slide using DGPS survey, 35 specially designed pedastals were installed in the landslide body in addition to 30 that were already installed. The initial positions of the pedestals installed on the slope before the monsoon were obtained through DGPS survey and were plotted on the contour map. The positions of these pedestals were again determined after the monsoon, which was followed by third time monitoring. Out of 65 pedestals, only a few showed significant movement ranging from 1.74 m to 3.69 m. It was noticed that the pedestals installed within the slide boundary did not provide of the movement except at two locations, which were on the loss debris deposition. Rest of the pedestals, which showed movement, were located near and around the crown part indicating the active movement above the crown. None of the pedestals showed upward tilting, therefore, no indication of deep seated movement was inferred. From the data at two time intervals, it was difficult to conclude about the type, magnitude and direction of the movement. Prolonged DGPS surveys need to be carried out for effective monitoring.

Mansadevi Landslide near Haridwar

Haridwar landsldie is a classic example of slope stability problem encountered on the byepass road of Haridwar town. Siwalik rocks of Outer Himalaya are exposed in the area. They consist of alternating bands of sandstone, siltstone and claystone of Middle Siwalik rocks. Sandstones are thickly bedded with intercalations of other rock types. The slope at the landslide site has debris cover for 2 -3 m. The in-situ rocks are seen along the stream cut faces. It was seen that the failure was mainly restricted to debris cover at the top along its contact with the rocks below. During rainfall, the subsurface seepage water formed a temporary phereatic surface up to the contact below. The pore water pressure generated due to water saturation is mainly responsible for the failure at the site. Hence it is typical case of talus failure. A collage of pictures of the landslide site is shown in Figure 31.

Figure 31. Mansadevi landslide and its impact

An attempt to monitor the landslide under a project sponsored under CSIR network programme by Planning Commission of India, by two Institutions namely CBRI and CSIRO for over a period of more than 3 years was made. After initial field investigations by CBRI, the monitoring instruments like inclinometers 2 piezometers, 10 joint meters, strain gauges, crack meters and other such instruments were used. The instruments were powered by a solar panel and monitored round the clock.The studies indicated definite and marked movements of the slope during rains. The movements and the piezometer reading corroborated to show that seepage pressure is more active during the movements of the slope. Since the project had limited objectives of slope monitoring, further advanced early warning could not be attempted.

These example case studies clearly suggest the lack of initiatives taken in monitoring landslides in India. Instruments ranging from conventional surveying to the recent DGPS surveys, have been utilized for estimation of surface and sub-surface movements of the landslides. The monitoring can also be carried out using specialized techniques such as, terrestrial photogrammetry and LIDAR surveys, ground penetrating radars (GPR) and ground and space based SAR Interferometry.

In future, as an alternatively, the use of differential SAR Interferometry can be used to monitor landslide dynamics at regional and on per landslide basis. Persistent Scatterer (PS), and differential interferometery techniques can be used for the correlation between landslide morphology, motion and topographic analysis, and have been used in some countries for landslide monitoring. Efforts in this direction have been started in India, and in particular at IIT Roorkee, through joint collaboration on geohazards between DST, India and Norwegian Research Council, Norway.

5.8.3 Landslide Early Warning Systems

The term early warning includes a number of sequential tasks,

i) planning and instrumentation of unstable slopes and landslides

ii) monitoring of landslides
iii) fixing of early warning alert thresholds
iv) decision making
v) dissemination of early warning alerts

There seems to be no standard readymade mechanisms for early warning systems in India. Only a few instrumentation, monitoring methods and data processing systems are available but that too in disintegrated fashion. As mentioned earlier, the methods have been designed to tailor a particular landslide according to its type, magnitude, hazard potential of the landslide, and the purpose of the early warning alert. The mechanism of evolving an early warning system has to be given due focus in India.

Thus, not even a single early warning system has so far been installed on any of the landslides in India. Centre for Disaster Mitigation and Management at Vellore is under progress some schemes of early warning against Landslides. The scheme for early warning against rockfalls and rapid motion landslides is based on wire fence actuated signals. For landslides of repetitive kind, multiple indicator approach is utilized. The integrated use of automated equipment for sub-surface information coupled with surface monitoring with the help of Geomatics tools and IT based real time monitoring will hold a great promise as tools for early warning against certain types of landslides (Bhandari, 2006).

6. CONCLUSIONS

This report is a short and snappy account of the landslide hazard and risk practices in India. The material presented in this report has been collected from a number of published reports on the subject, as available on the Internet and also obtained from different agencies/organizations involved in the works related to the subject under consideration. Based on this information, the following conclusions can be drawn,

i) The impact of disasters, in general, is heavily tilted towards developing countries such as India, partially due to increased population and also due to lack of preparedness.

ii) India, due to its unique climatic conditions and its closeness to geodynamically active areas, has always been vulnerable to a large number of natural disasters.

iii) Disasters caused by the landslides are quite common in mountainous regions, particularly, the Himalaya, which are the tallest among mountain chains of the earth

iv) Reports of earthquake-induced landslides surface virtually after every earthquake in the Himalaya, which are situated in the moderate to very high seismic zones and are geodynamically very sensitive and vulnerable.

v) The Himalayan region is frequently visited by incessant rain that continues for more than a week at a stretch resulting into cloud burst and flash floods due to which the region is heavily fraught with landslides during the monsoon season causing huge damages to properly and casualities.

vi) In order to include hazard mitigation activities in the planning process, the Government of India has decided for a significant change in policy from simple relief-centric activities a concrete disaster management

vii) There seems to be apparent lack of proper landslide inventory database in India. The existing databases are partial in nature. Many such databases need to be created for the benefit of the society. These databases should also be updated from time to time and may be made web-enabled for their easy access by different stake holders.

viii) The National Disaster Management Authority (NDMA) has prepared a draft of National Guidelines on Landslides to direct the activities envisaged for mitigating the landslide risks at all levels.

ix) Landslide hazard and risk assessment have been incorporated by the Bureau of Indian Standards (BIS) in the form of Indian Standard codes. The methodology standardized by BIS has generally been followed to carry out landslide hazard zonation mapping in different parts of the country. However, after covering some areas following these BIS guidelines, it was felt that certain parameters need modification, which are under review.

x) The Geological Survey of India (GSI) has been regarded as the nodal agency for the preparation of LHZ maps in different parts of the country. Many other organizations and institutes have also been active in producing LHZ maps at different scales utilizing a number of conventional and advanced methodologies.

xi) The Department of Science and Technology (DST) of the Ministry of Science and Technology has taken intense interest in landslide studies in India by disbursing financial grant to the research ventures related to landslides

xii) National Remote Sensing Center (NRSC) in 2001 published an Atlas on landslide hazard zonation primarily based on the interpretation of remote sensing data and limited field checks along pilgrimage routes in the Himalaya. However, the geotechnical and geoengineering

xiii) DST is also in the process of producing an LHZ atlas based primarily on the projects sponsored by the department

xiv) Landslide risk zonation has so far not been sincerely attempted in India. Most of the organisations and institutes in the country have culminated LHZ mapping only.

xv) There appears to be no concentrated and cohesive efforts on detailed landslide investigation, mapping and monitoring of landslides. Most of the studies have been conducted on individual basis by different agencies without any proper coordination.

xvi) There seems to be no standard readymade mechanisms for early warning systems in India. Only a few instrumentation, monitoring methods and data processing systems are available but that too in disintegrated fashion.

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Appendix A

Institutes in India Engaged in Landslide studies

Several institutions, directly or indirectly, have been involved in landslide related studies in India. A partial list is given below. There may be many more institutes and organizations.

i) Bureau of Indian Standards (BIS)
ii) Centre for Earth Science Studies (CESS)
iii) Centre for Water Resources Management and Development (CWRDM)
iv) Central Building Research Institute (CBRI)
v) Central Road Research Institute (CRRI)
vi) Defence Terrain Research Laboratory (DTRL)
vii) Department of Mines
viii) Department of Science and Technology (DST)
ix) Department of Space (DoS)
x) Geological Survey of India (GSI)
xi) Indian Institute of Remote Sensing
xii) Indian Institute of Technology Bombay (IITB)
xiii) Indian Institute of Technology Roorkee (IITR)
xiv) National Disaster Management Authority (NDMA)
xv) National Institute of Technology, Calicut (NIT-C).
xvi) National Remote Sensing Center (NRCS)
xvii) National Transportation Planning and Research Centre (NTPAC)
xviii) Wadia Institute of Himalayan Geology (WIHG)