LANDSLIDE HAZARD ZONATION MAPPING, CONSIDERING GEOENVIRONMENTAL CONDITIONS, OF PARTS OF BHAGIRATHI RIVER VALLEY, U.P., INDIA

A THESIS

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requirements for the award of the degree
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DOCTOR OF PHILOSOPHY
in
EARTH SCIENCES

By

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OCTOBER, 1996

Gratis

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **LANDSLIDE HAZARD ZONATION MAPPING, CONSIDERING GEOENVIRONMENTAL CONDITIONS, OF PARTS OF BHAGIRATHI RIVER VALLEY, U.P., INDIA** in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the **DEPARTMENT OF EARTH SCIENCES,** University of Roorkee, Roorkee, U.P.,India, is an authentic record of my own work carried out during a period from **April, 1991** to **October, 1996** under the supervision of **Dr. R. ANBALAGAN** .

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other University.

(Gupta)

PANKAJ GUPTA

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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12/7/97 — Signature of Supervisor

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12.7.97 — Signature of External Examiner (A.K. Roy)

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ABSTRACT

The Himalaya, which represents tectonically active mountainous region, is generally characterised by steep slopes, high relief, weathered, fractured and folded rocks, in addition to unfavourable hydrogeological conditions. These factors make the Himalayan terrain more vulnerable to landslides. Moreover, there has been a sudden spurt in the development activities in the last two decades, mainly related to road construction, urbanisation, small scale industries and tourism. These development activities are often implemented without taking into consideration the existing instabilities and thereby increasing the landslide potential. In this connection, the landslide hazard zonation provides useful data on the status of instability of the area. These maps also help the planners in implementing the development schemes with minimum geoenvironmental hazards to the area.

Landslide hazard may be defined as the probability of occurrence of a potentially damaging natural phenomena. A landslide hazard zonation map depicts a division of land surface into zones of varying degree of stability based on an estimated significance of causative factors in inducing the instability.

An attempt has been made to evaluate the geoenvironmental hazards of Tehri and its vicinity by preparing a landslide hazard zonation map. The detailed evaluation of unstable slopes has also been carried out to evolve possible remedial measures.

The Study area is located in the Lesser Himalaya of Garhwal hills between latitudes 30°20' - 30' and longitudes 78°15' - 30' and falls within the administrative limits of Tehri and Uttarkashi districts of Uttar Pradesh. The area extending over 450 sq km approximately, is covered in the Survey of India topomap number 53J/7. The study area partially covers the Tehri dam reservoir also.

Objectives intended in the present study are; preparation of Landslide Hazard Zonation (LHZ) map of the study area, analysis of stability for high hazard slopes and assessment of the geoenvironmental status of the area with particular reference to degradation of hill slopes.

For the preparation of landslide hazard zonation (LHZ) map, the Landslide Hazard Evaluation Factor (LHEF) rating scheme (Anbalagan, 1992) has been adopted. This scheme is based on an empirical approach and includes the major inherent causative factors of slope instability, such as lithology, structure, slope morphometry, land use land cover, relative relief and hydrogeological condition. The reliability of LHZ map is essentially dependent on the rating scheme of causative factor adopted which has been well established in parts of Kumaun (Anbalagan, 1992) and Garhwal Himalaya (Gupta et al., 1993, Gupta and Anbalagan, 1993 and Anbalagan et al., 1993). The external contributory factors, such as rainfall and seismicity are not included, since they are regional in nature and their impact on landslide potential cannot be estimated with particular reference to a slope facet.

The causative factors included in LHEF rating scheme are divided into a number of subcategories. These subcategories of each individual causative factors are arranged in their right hierarchial order and awarded a relative rating. Here the time is indicated in relative terms; for example, a moderate hazard slope is more vulnerable to landslide failures as compared to a low hazard slope but less vulnerable as compared to a high hazard slope.

Procedures taken up initially for LHZ mapping of the study area, incorporate preparation of a slope facet map and pre-field factorial maps for individual causative factors on 1:50,000 scale. This is followed by facet-wise collection of data for causative factors and preparation of final factorial maps using field data. Next, LHZ map is produced through using TEHD value for each facet which is rendered by LHEF rating scheme. The LHZ map of the study area delineates the entire area in five hazard zones.

Assessment of geoenvironmental status of the area with particular reference to degradation of hill slopes is carried out, following and exercise on the distribution of sub-categories corresponding to each individual causative factor, for whole area of study and for all the five hazard zones. Later, order of influence of causative factors has been established by applying Friedman Test and later verified by age's Test. Correlation coefficients between TEHD & causative factors and among causative factors are estimated in order to achieve corresponding relations.

Further, stability analysis of high hazard facets is carried out after identifying potentially unstable high hazard slope facets, collection of structural data, preparation of cross sections and determination of strength parameters. This ultimately leads to calculation of factor of safety for plane, wedge and circular failures of potentially unstable HH slope facets. Finally, general remedial measures has been discussed.

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CHAPTER I

Introduction

□ 1.1 GENERAL

In this International Decade of Natural Disaster Reduction (IDNDR), the mountain hazards receive greater attention for systematic evaluation and mitigation. Among the mountain hazards, the impact of landslides have often resulted in a reaching consequences for the mountain environment in addition to loss of life and properties. Landslides are one of the main source of soil loss in the Himalaya. A single catastrophic slope failure in the Himalayan region could block the water course, which may form a landslide dam for few hours to couple of years (Table 1.1). Since these dams do not have adequate stability factor, they may breach. The height of landslide dams (350 m) have even exceeded the height of the highest man made dam. The complete or partial failures of such dams due to overtopping and/or breaching resulted in flash flood over a wide area in the downstream side.

TABLE 1.1 LANDSLIDE DAMS ON HIMALAYAN RIVERS

YEAR	EVENT
1841	A huge rock mass from Nanga Parbat fell into the Indus and formed a 64 km long lake. Few months later the dam breached.
1846	Due to a massive landslide, the flow of the river Kali stopped for several hours.
1857	A massive landslide blocked the Nandakini river for three days.
1868	A landslide lake near Jhinjhee in the Birahiganga valley breached and killed 73 persons at Chamoli.
1893	Gohana slide hurtled down several thousand metres into the Birahiganga in October 1893 and filled up the river bed to a height of 350 m. The lake formed was 5 km long and 2 km wide. On August 24, 1894, a part of the dam toppled, raising the water level by 50 m at Srinagar. The town of Srinagar was completely destroyed. Two days later, the level of the river Ganga rose by 4 m at Hardwar.
1950	Widespread landslides blocked the Brahmaputra and its tributaries following a major earthquake.
1957	A long lake was formed by the landslide debris brought by the Dronagirinala near Bhaphund.
1968	Floods in Rishiganga created a 40 m high blockade near Reni village. The lake silted up by May 1970 and eventually the blockade was breached in the July 1970 floods. A landslide dam at Labubensi in Nepal on the Burhi Gandak river broke and caused disastrous flooding downstream. Widespread landslides on the Teesta caused death and devastation all over Darjeeling and Jalpaiguri.
1970	The narrow gorge of the Patalganga got chocked and more than 60 m high reservoir was built up. The bursting of this dam resulted in a flood pulse in the Alaknanda valley which triggered off many more landslides. The village of Belakuchi was washed away. Floods in the Birahiganga triggered several landslides causing a major blockade of river with a 10-12 m afflux. The Gohana Tal was completely silted up.
1976	Nandakini river blocked for hours due to massive landslides.
1978	Kanodia Gad, a petty tributary joining the Bhagirathi river upstream of Uttarkashi, spread a debris cone across the main river impounding it to a height of 30 m. Breaching of the landslide caused havoc due to flash floods. A 1.5 km long and 20 m deep lake was left behind by the landslide dam.
1979	River Saraswati was blocked by an avalanche near Mana village. The water level rose up by 2 m.
1981	River Tinnau in Palpa district, Nepal was blocked by a landslide during prolonged rains in September 1981. The breaking of the dam killed 200 people downstream in the Terai region.

(Anonymous 1991)

The mountainous terrains such as Himalaya, though look to be mighty and strong, have inherent weak geological features such as thrust, faults, shear zones, joints, bedding. In addition, the pace of the modern development has been accelerated in the recent times with the construction of roads, buildings, industries and a number of civil structures. These constructions seldom take into consideration the existing slope instability. As a result, the balance of stability gets disturbed paving way for landslides and the attendant damages.

The concept of sustainable development should form a strong foundation for developmental processes in hilly terrains. Sustainable development in mountainous terrain refers to implementation of development schemes taking into consideration the existing instability of the terrain, so that the resultant geoenvironmental hazards are kept to minimum (Anbalagan & Singh, 1996). The systematic investigations should involve the principle of `whole to part', where a large area considered initially for project implementation and followed by carrying out systematic investigations. The investigations involve the following work components.

i) Initially a large potential area for project implementation is studied on regional scale (1: 50,000) mainly to identify the distribution of hazard prone areas.

ii) A number of possible alternative alignments are planned and the one with minimum geoenvironmental hazard is chosen.

iii) The hazard prone slopes along the proposed alignment are evaluated in detail with reference to the proposed project.

iv) Possible precautionary and preventive measures are identified for successful implementation of developmental schemes with minimum environmental degradation.

The first step for achieving sustainable development of the preparation of landslide hazard zonation mapping of the area is to identify the hazard prone zones. "A *landslide hazard zonation (LHZ) map* depicts division of land surface into zones of varying degree of stability based on the estimated significance of the causative factors in inducing instability."

The LHZ maps have an important role in planning and development in mountainous areas, which is useful for the following purposes.

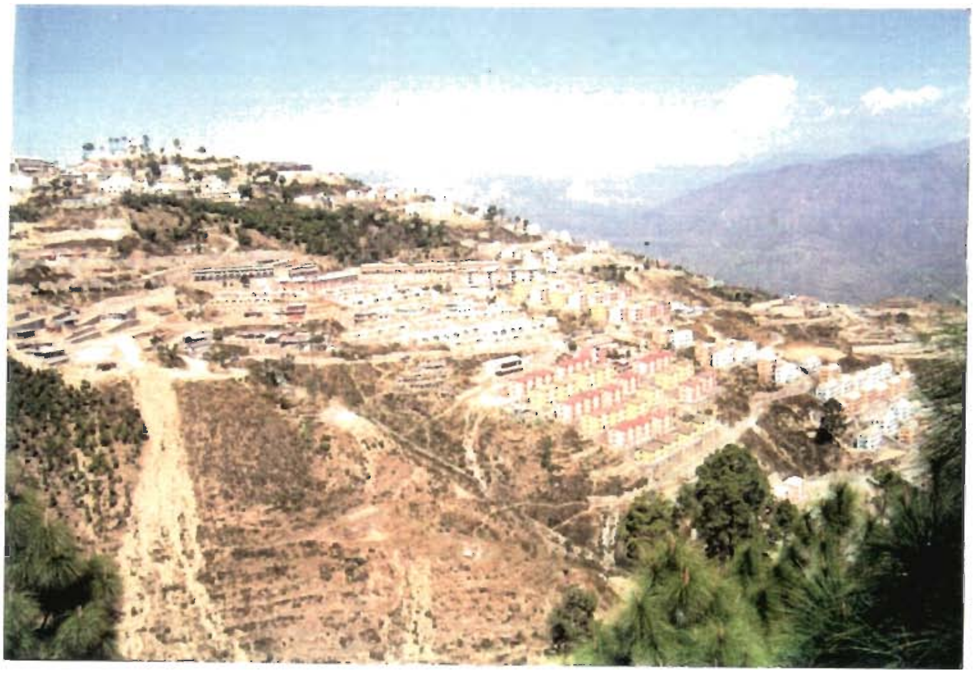
i) Identification and delineation of hazardous area in the mountainous region to avoid the highly unstable zones.

ii) Ecologically sound mitigation measures can be adopted, depending on the nature of the hazardous zones, to check further environmental degradation of the area.

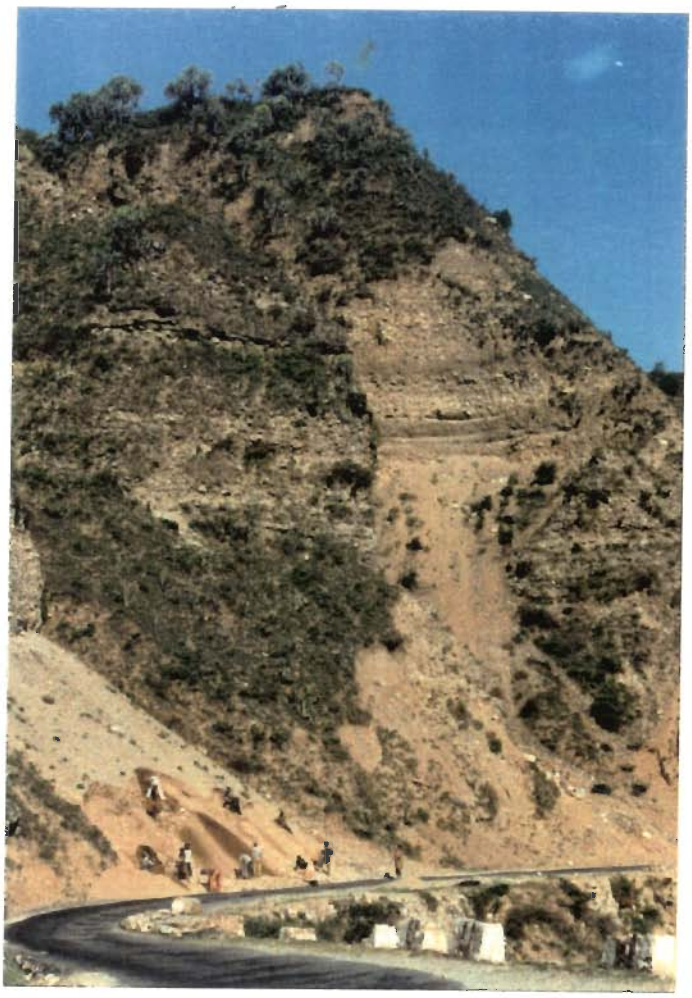
iii) These maps provide input data for preparing risk maps which are helpful in landslide hazard management.

Another important aspect of degradation of mountain environment is related to the population pressure on the available scarce resources. The important consequence of excessive utilization of natural resources by way of cultivation, grazing, fodder, fuel wood and timber is that the carrying capacity of the land has far exceeded in many places. Hence ecological regeneration and other mitigation measures should be implemented in order to control the deterioration of the ecological balance before they are damaged irreversibly.

PLATE 1



Panoramic view of New Tehri town showing initiation of slide on a part of side slope.



Removal of toe support of the slope due to road construction leading to landslides between Bhaldiyana and Uttarkashi.

□ 1.2 THE AREA OF STUDY

1.2.1 Location and Accessibility

The study area is situated in the Lesser Himalaya of Garhwal hills between 30°20′-30′ latitudes and 78°15′-30′ longitudes and is located within the administrative limits of Tehri and Uttarkashi districts of Uttar Pradesh (Fig.1.1). The area of study falls in the Survey of India Toposheet Number 53J/7 and covers about 400 sq km area. Tehri, New Tehri and Chamba are the prominent settlements of the study area. Beside, these localities, very famous temple of Hindu Goddess "Surkaunda Devi" is situated on a highest peak (2770 m) near Kaddukhal. Moreover, Pratapnagar a beautiful tourist place is located to the north of Tehri. The State Highway-54, off-taking from Rishikesh and passes through Chamba, Tehri and further extends upto Dehrasu. The Dehradun - Mussoorie - Chamba road provides access to the southern part of the study area. The Mussoorie - Chamba section of the road located at the top of a northeast - southeast tending ridge, receives snow fall during winters. In addition, the Chamba - Dehradun road under construction will replace the Chamba - Tehri - Dharasu section of the existing State Highway-54 after the construction of Tehri dam. The villages are generally linked with bridle paths and foot paths.

1.2.2 Physiography and Drainage Pattern

Physiographically, the study area, falling in Lesser Himalaya is highly rugged due to high mountains, steep slopes and deep valleys. A physiographic map (Fig.1.2) has been prepared to find out the drainage pattern, ridge network and other features like springs from the Survey of India Toposheet Number 53J/7. There are three major ridges in the study area namely, the Pratapnagar - Banali - Gwar, the Taru - Kanatal

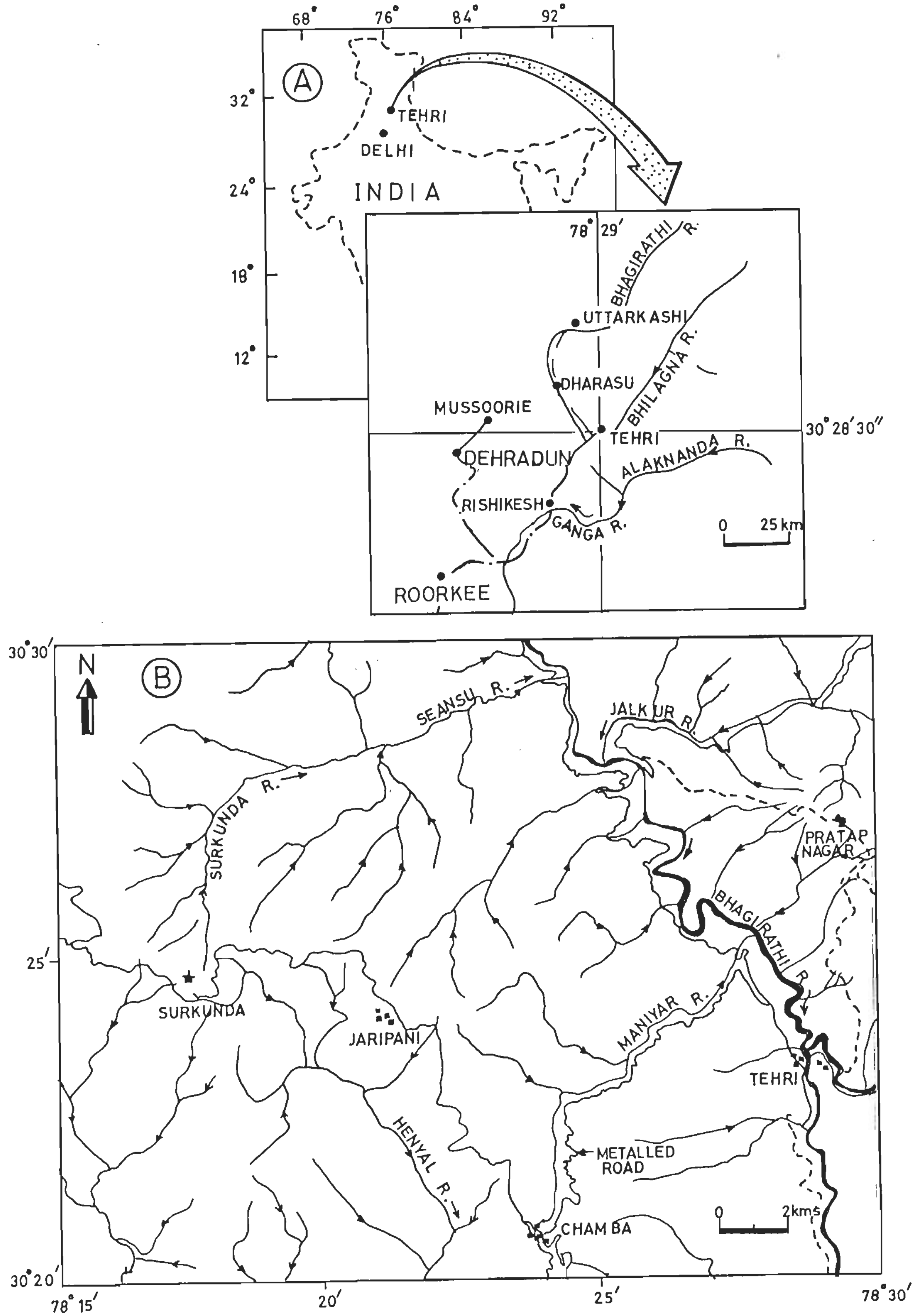


Fig. 1·1 A-LOCATION OF TEHRI AREA
B-AREA OF STUDY

FIG.1·2. PHYSIOGRAPH MAP OF THE STUDY AREA

Dhar- Chamba and Sankari Dhar - Thaul Dhar - Dhang Dhar - Surkanda ridge trending northwest - southeast. The Pratapnagar - Banali - Gwar ridge has a maximum elevation of 2182 m in Pratapnagar. Relatively steeper slopes prevail in its northern region. The ridge has thick to moderate vegetation on its north, whereas in southern region, cultivation is practised. The Taru - Kanatal Dhar- Chamba is the longest ridge in the area and runs roughly in northwest - southeast direction. The ridge has maximum elevation (2770 m) at Surkanda, which is also the highest peak of the study area. Although, the ridge shows moderately steep slopes (26° to 35°) in general, yet at some places steep slopes (36° to 45°) are present. The ridge has thick to moderate vegetation in the northwest region, whereas cultivation is practised in southern region near Chamba town. Sankari Dhar - Thaul Dhar - Dhang Dhar - Surkanda ridge runs in roughly northwest- southeast direction. Later two ridges have Rounstrikhat and Surkanda common places. In general, this ridge shows moderate to steep slopes. Major part of the ridge is covered by the thick to moderate vegetation, whereas, cultivation is practised in few locations. The last two ridges coalesce between Rounstrikhat and Surkanda.

The study area falling in a part of the Bhagirathi river basin includes parts of the Bhilangna, Song and Heunal river sub-basins. The river Bhagirathi flows roughly in a southerly direction on the eastern part of the area. The East flowing, Bhilangna river joins the Bhagirathi river at Tehri. The Song river, a tributary of the Bhagirathi river also flows roughly in a southerly direction. Heunal river originated at the slope of Surkanda hill, flows roughly in southeast direction. In addition, the region is well drained by numerous streams, which are mostly of first and second order in nature.

Dendritic and sub-dendritic patterns are commonly seen in a major part of the region. Sub-parallel pattern is also found at one or two places in the northeast and southwest region. Moreover, radial patterns are developed locally around the hills of Pratapnagar and Surkanda. A number of springs are also present in the region and majority of them are located in the south-eastern part of the study area.

1.2.3 Seismicity

The study area is a part of Garhwal Himalaya and lies within zone IV of the seismic zoning map of India prepared by the Indian Standard Institution (Anonymous, 1976). In the historical records of the seismicity of the Garhwal Himalaya, a violent earthquake of more than VIII occurred on September 1803 in the central portion of the Himalayan range (31.3°-78.8°). This earthquake was highly destructive, and a large part of the population was perished in widespread landslides. In this earthquake, Badrinath temple was severely damaged and the upper portion of Qutub minar in Delhi was also damaged. Earthquake shocks of magnitude 5 to 6 have been recorded for the Garhwal region in 1809, 1816, 1966, 1967, 1968, 1969, 1976, 1979 and 1986 Thakur and Kumar, 1995. The most recent event was the Uttarkashi (body wave magnitude 6.6) earthquake, which struck the Garhwal region for 45 seconds, in the early hours (02.53) of 20th October, 1991. Beside these strong events, many small magnitude earthquake have also occurred in this region.

1.2.4 Vegetation

The study area has a good forest cover. The natural vegetation follows climatic altitudinal zonation in mountainous region, because of temperature variations. The development processes such as, urbanisation, excessive road construction, hydroelectric projects have put pressure on the vegetation, wild life and pastoral lands. In this context, Garhwal Himalaya has been the area, greatly subjected to this pressure, multiplied by intensive cultivation, overgrazing, ruthless felling of trees, new human settlements and population influx which resulted in the reduction of forest cover of this region.

The important plants in the study area are chir pine (Pignus *roxburghii*), Buras (Rhododendron *arboreum*), Oak (Quercus *incana*), Kilmore (Berberis *spp.*), Dhaula (Woodfordia *fruiticosa*), Hinselu (Rubus *ellipticus*), Deodar (Cedrus *Decodara*), Pipal (Fias *religrose*), Neem (Azardirachta *indica*), Barh (Ficus *benghalensis*) etc. A variety of wild animals have been reported in this region. The important ones are tiger, panther, leopard, hyena, Jackal, fox, bear, wild got, rabbit, monkey, languor and several types of birds.

1.2.5 Climate

There are four main seasons in the study area, such as winter, summer, monsoon and post-monsoon. Following is a brief discussion;

The upper reaches of Surkanda and Pratapnagar areas receive light to moderate snowfall during the month of December and January, whereas New Tehri receives occasional snowfall during the peak winters in January. Low altitude areas often experience low to moderate rainfall and hail storm. The region receives good amount of rainfall. The maximum precipitation comes during the monsoon season. In general, the area receives 100 cm to 125 cm of rainfall annually. The temperature shows significant diurnal and monthly variations. The temperature often reaches sub-zero during months of December - January and attains a highest around 32°C in the months of May-June. Relative humidity normally varies from 50% to 85% with the highest during the monsoon.

□ 1.3 OBJECTIVES, METHODOLOGY AND ANALYTICAL TOOLS

1.3.1 Objectives

The present study has been taken up with the following objectives.

i) Preparation of Landslide Hazard Zonation (LHZ) map of the study area.

ii) Analysis of stability of high hazard slopes.

iii) Assessment of the factors causing the degradation of hill slopes.

1.3.2 Methodology

An empirical method, Landslide Hazard Evaluation Factor (LHEF) rating scheme (Anbalagan, 1992) has been modified and used to prepare LHZ map of the area. This scheme is based on an empirical approach using major inherent causative factors of slope instability such as lithology, structure, slope morphometry, land use and land cover, relative relief and hydrogeological conditions. The reliability of LHZ map is essentially dependent on the rating system of causative factor adopted, which has been well established in parts of Kumaun and Garhwal Himalaya of India (Anbalagan, 1992; Anbalagan, 1992 (a); Gupta, Anbalagan and Bist, 1993; Gupta & Anbalagan, 1995; Anbalagan, Gupta and Sharma,1992; Anbalagan, Sharma and Tyagi, 1993; Anbalagan and Singh, 1996 and Anbalagan and Tyagi, 1996). In this scheme, the external contributory factors, such as rainfall and seismicity are not included because they are erratic and regional in nature and their impact on landslide potential cannot be estimated with particular reference to a slope facet. The causative factors included in LHEF rating scheme are divided into a number of sub-categories. These sub-categories of each causative factor are arranged in their right hierarchical order and awarded a relative rating.

In order to achieve above mentioned objectives, the following procedures are used.

1) Preparation of Landslide Hazard Zonation (LHZ) map of the study area.

i) Preparation of a slope facet map of the study area on 1:50,000 scale.

ii) Preparation of pre-field factorial maps of individual causative factors.

iii) Slope facet-wise collection of field data of causative factors.

iv) Preparation of final factorial maps.

v) Calculation of total estimated hazard (TEHD) for each slope facet.

vi) Preparation of LHZ map with the help of TEHD values.

2) Stability analysis of high hazard slopes.

i) Collection of structural data.

ii) Preparation of geological cross-sections.

iii) Determination of strength parameters of slope materials.

iv) Calculation of factor of safety (FOS)

3) Assessment of the factors causing the degradation of hill slopes.

i) Calculation of distribution of subcategories of individual causative factors for the whole area and for each hazard zone.

ii) Calculation of order of influence of causative factors.

iii) Calculation of correlation between TEHD and causative factors and among causative factors.

iV) General evaluation of geoenvironmental condition of the area.

v) Possible remedial measures.

1.3.3 Analytical tools

In the present study, landslide hazard zonation mapping has been carried out by modifying the empirical method 'Landslide hazard evaluation factor (LHEF)' rating scheme of Anbalagan, 1992. Stereographic method has been used to analyse the structural data slope facet-wise. This method has also been used to get the preferred orientations of each set of discontinuities by plotting their poles. An empirical method, namely, Rock Mass Classification System has been used to calculate the geomechanical properties of the rocks. In addition to this, statistical tools for correlation and order of influence have been used. Spearman's correlation formula has been applied to find out the correlation between total estimated hazard (TEHD) and causative factors and among causative factors also. Friedman's test has been applied to find out the order of influence of causative factors for each hazard zone and for the whole area of study and later verified by Page's test

In case of plane failure analysis, the technique given by Hook and Brey, 1981 has been used to calculate the factor of safety (FOS). For other types of failures, computer programs RWEDGE for wedge and BASC & SARC for circular failures, have been used for the analysis.

□1.4 PLAN OF THE STUDY

The research work is presented in six chapters. A glimpse of each chapter is given below:

Chapter I, INTRODUCTION, The chapter begins with a brief discussion on the major landslide dams in the Himalaya. Next, definition of LHZ mapping, its utility and need for identification of hazard prone areas through LHZ mapping have been described. This chapter also includes the profile of the study area embodying location and accessibility, physiography, drainage pattern, seismicity, vegetation and climates. Finally, the chapter concludes with the objectives, methodology and analytical tools.

Chapter II, GEOLOGICAL SETTING, covers mainly regional geology and geology of the study area.

Chapter III, METHODOLOGY, covers mainly international and national status of the landslide hazard zonation (LHZ) mapping. This chapter also includes the technique opted for LHZ mapping of the study area and its merits and demerits. The Landslide Hazard Evaluation Factor (LHEF) rating scheme given by Anbalagan, 1992 has been modified in this work to achieve the objectives.

Chapter IV, LANDSLIDE HAZARD ZONATION MAPPING AND STATISTICAL ANALYSIS, mainly include the factorial maps of all the six causative factors and landslide hazard zonation (LHZ) map. This chapter also includes the distribution of sub-categories of each causative factor in various hazard zones. Moreover, this chapter also contains the statistical analysis for correlation and order of influence of causative factors.

Chapter V, DETAILED INVESTIGATIONS, includes the identification of high hazard slope facets, satisfying the Markland Test, with the possible mode of failure and finally, calculation of Factor of safety of these high hazard slope facets under various dynamic and static conditions.

Chapter VI, CONCLUSIONS AND REMEDIAL MEASURES, covers mainly the discussion on conclusions already indicated in chapter IV & V in order to provide a comprehensive result of the research programme.

CHAPTER II

Geological Setting

The crescent shaped Himalaya crowned by Mount Everest is the world's loftiest and youngest belt of mountains. The landscape of the Himalaya presents the snow-clad peaks, large valley-glaciers, deep gorges, roaring waterfalls in addition to along with dense forest cover. The Himalaya is sub-divided into four longitudinal tectonic-geomorphic zones namely, the Outer Himalaya or the Siwaliks, the Lesser Himalaya or the Lower Himalaya, the Higher Himalaya or the Great Himalaya and the Tethyan Himalaya or Tibetan Himalaya. The present area of study lies in the Lesser Himalaya of Uttar Pradesh (U.P.). The U.P. Himalaya includes eight districts namely, Pithoragarh, Almora, Nainital, Pauri, Chamoli, Uttarkashi, Tehri and Dehradun. The former three districts constitute the administrative division of Kumaun and latter five of Garhwal. The Lesser Himalayan domain is demarcated by thrusts such as Main Boundary Thrust (MBT) and Main Central Thrust (MCT). In addition, the area is characterised by multiple thrusting, repetition of rock-units showing mylonitization. In north, the Main Central Thrust (MCT) has brought up the basement rocks high comprising grade metamorphics to soaring heights of Great Himalaya, the vertical stratigraphic throw being of the order of 20 Km (Valdiya, 1983). The Main Boundary Thrust (MBT) in the south seems to be still geodynamically active, being under - thrusting of the Indian plate under the Himalaya (Valdiya, 1983).

2.1 Kumaun Lesser Himalaya

Valdiya (1980) defines the Uttar Pradesh Himalaya as Kumaun Himalaya. The Kumaun Lesser Himalaya stretches from the Kali river which defines the Indo-Nepal border in the east, to the Tons - Pabar Valleys demarcating the eastern border of Himachal Pradesh.

The Kumaun Lesser Himalaya consists of two ranges, each disposed in NW-SE direction. The southern range passes from Nainital - Lansdowne - Mussoorie, while the northern range extends through Champawat, Devidhura, Ranikhet, Dudhatoli, Nag Tibba and Jaunsar (Valdiya, 1980). Kumaun Lesser Himalaya has been divided into two segments: i) Inner Lesser Himalaya and ii) Outer Lesser Himalaya (Valdiya, 1980). The Inner Lesser Himalaya lies in between the northern Nag Tibba range and the Great Himalayan range, while the Outer Lesser Himalaya lies between northern and southern Nag Tibba Ranges.

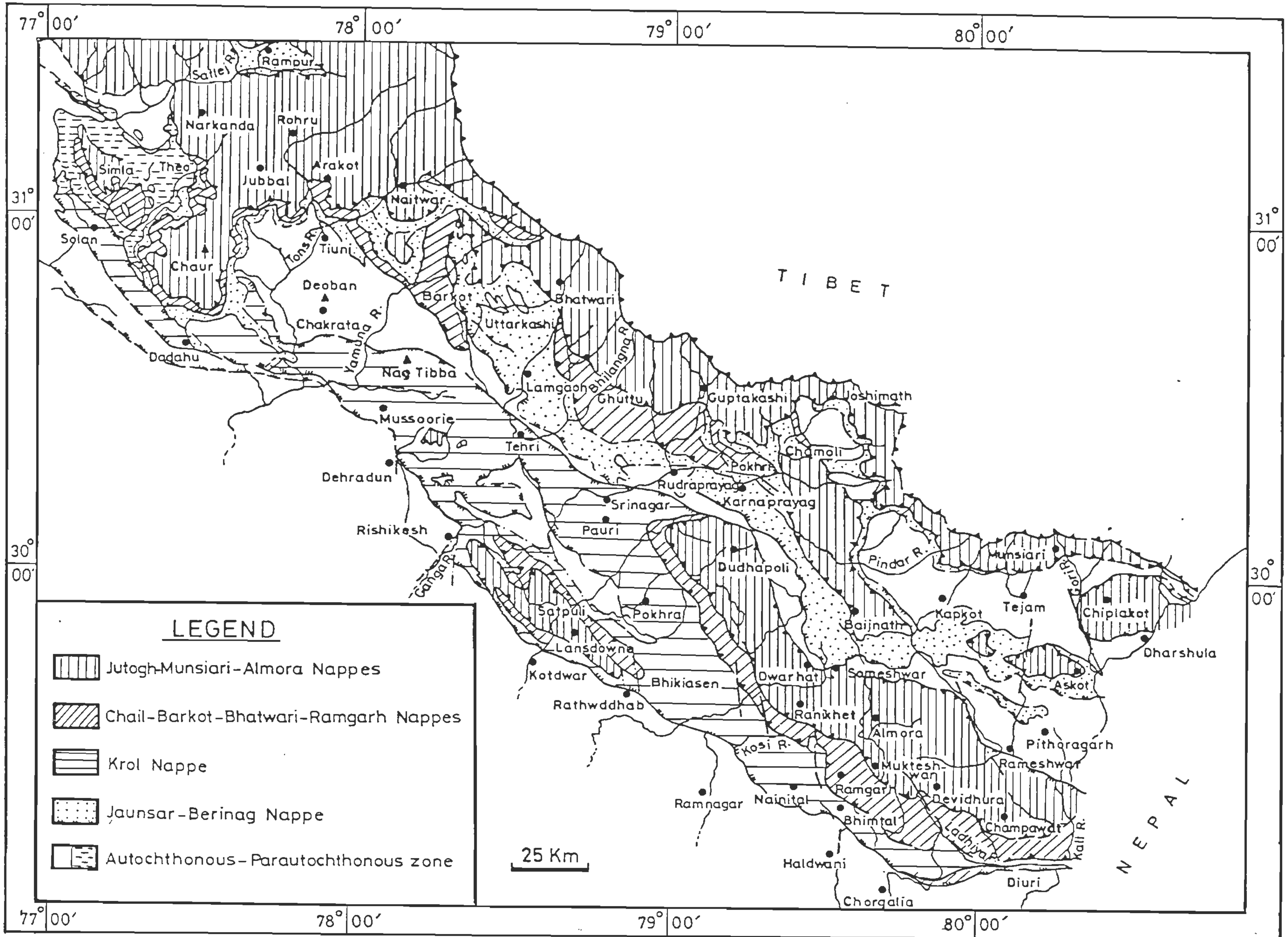


FIG. 2·1 GEOLOGICAL MAP OF KUMAUN LESSER HIMALAYA (VALDIYA, 1980)

2.2 Regional Geology

Four major lithotectonic units, each characterised by distinct lithological composition, stratigraphic succession, structural pattern and magmatic history, have been recognised in Kumaun Lesser Himalaya (Table 2.1 & Fig. 2.1) by Valdiya, 1980, which is being discussed below.

TABLE 2.1 STRATIGRAPHIC SUCCESSION OF THE KUMAUN LESSER HIMALAYA

GROUP	INNER LESSER HIMALAYA	OUTER LESSER HIMALAYA
	FORMATIONS	
Almora	Munsiari	Gumalikhet Champawat Granodiorite Saryu
	---Munsiari Thrust-----	----Almora Thrust-----
Ramgarh	Barkot and Bhatwari	Debguru Porphyroid Nathuakhan
	--Barkot-Bhatwari Thrust--	----Ramgarh Thrust----
Sirmur		Subathu Singtali
Mussoorie		Tal Krol Blaini
Jaunsar	Berinag	Nagthat Chandpur Mandhali
	----Berinag Thrust----	-----Krol Thrust-----
		Subathu
Tejam	Mandhali Deoban	
Damtha	Rautgara Chakrata	Rautgara Chakrata

(Valdiya, 1980)

They are - i) The autochthonous unit of Damtha and Tejam Groups, exposed in the inner belt of the Lesser Himalaya, ii) The Krol Nappe of the Outer Lesser Himalaya constituted of Jaunsar and Mussoorie Groups, whose equivalent in Inner Lesser Himalaya being represented by Berinag Nappe, iii) The Ramgarh Nappe and its extensions and iv) The Almora Nappe made up of medium-grade metamorphics and intruded by syntectonic and highly deformed granitic suites.

The Inner Lesser Himalaya reveals the autochthonous Precambrian sedimentary Groups. The Lower Damtha Group at its base consists of the Chakrata Formation of turbidite flysch. This Formation is gradually succeeded by an assemblage of slate-quartzite of Rautgara Formation. The Rautgara includes a vast proportion of intrusive of dolerites and basalts. The Damtha is conformably succeeded by Tejam Group, comprising the Deoban and Mandhali Formations. The Deoban Formation is characterised predominantly by dolomites with prolifically developed branching stromatolites. This Formation grades upwards into the pyritous-carbonaceous slates, marl and interbedded calcite, marbles of the Mandhali Formation.

The Tejam Group has been thrusted over by a huge pile of quartzite and basic volcanics of the Berinag Formation in the Inner Lesser Himalaya. Across the Tons river in the west, the Berinag joins with the Nagthat Formation of the Jaunsar Group.

In the Outer Lesser Himalaya, the autochthonous Damtha in the north and Siwalik in the south have been thrusted over by a 6000 m thick sedimentary successions forming the Krol Nappe. The lithostratigraphic units involved in the Krol Nappe include the impersistently occurring Mandhali Formation at the base, Chandpur and the Nagthat

Formations of the Jaunsar Group; Blaini, Krol and Tal Formations of the Mussoorie Group constituting the top. The Mandhali consists of black and green phyllites, plastically deformed marble and a variety of quartzites at its base. The Chandpur is a metaflysch formation made-up of olive green and grey phyllite and metasiltstones. The Nagthat Formation consists of quartzites with subordinate slates and includes synsedimentary basic volcanics. The Blaini Formation begins with a persistent horizon of conglomerate intercalated with greywackes and siltstones which pass into carbonaceous slates and varicoloured limestone. The succeeding Krol Formation consists predominantly of carbonates; limestones, marls and slates in the lower parts and dolomites in the upper part. The Tal Formation is fossiliferous at the top. The Bryozoa bearing profusely oolitic and sandy limestone, unconformably overlying the Tal Formation constitute the Singtali Formation. This Formation is covered with a veneer of slates, limestones and greywackes of Subathu Formation

The third lithotectonic unit comprises the Ramgarh Group which is constituted of two lithological units, the Nathuakhan Formation and Debguru Porphyroid. The Nathuakhan Formation is invaded at the base by Debguru Porphyroid which is a vast and thick suit of spectacularly porphyritic granite grading into quartz-porphyry. The upper unit, Nathukhan Formation is constituted of olive green and grey phyllites interbedded with quartzwacke.

The fourth and the upper most lithotectonic unit consists of a vast sheet of medium grade metamorphics intruded by syntectonic granodiorite-granite suite. This is the Almora Nappe which builds the upper part of Nag Tibba Range extending from the Kali valley through Champawat and Ranikhet to Dudhatoli in Pauri-Garhwal. The basal

Saryu Formation consists of Phyllonites, Chlorite-sericite-biotite schists, garnetiferous sericite schist and flaggy quartzites. This unit has been intruded by the Champawat Granodiorite or its equivalents such as the Almora and Dudhatoli granites. The upper unit Gumalikhet Formation is composed of the carbonaceous phyllites, generally grading into graphite schists. The root of the Almora Nappe is the Munsiari Formation constituting the base of the Great Himalaya.

2.3 GEOLOGY OF THE STUDY AREA

A number of workers carried out geological studies in the study area and its vicinity. This includes Kumar and Dhaundiyal (1976), worked on the stratigraphy and structure of "Garhwal Synform" in the Garhwal and Tehri Garhwal regions of Uttar Pradesh. Saklani (1979) studied the lithology and structure of northern Tehri between the Bhilangna and Jalkur rivers whereas Jain (1987) carried out structural, lithological and sedimentological studies in south-eastern Uttarkashi between the Jalkur and Bhilangna rivers. The Geology of the study area described here is mainly based on the work of Valdiya (1980).

The rocks exposed in the study area lie in the Inner as well as in the Outer Lesser Himalaya. The Inner Lesser Himalaya, in the study area is represented by the rocks of Rautgara Formation of Damtha Group, Deoban Formation of Tejam Group and Berinag Formation of Jaunsar Group. On the other hand, the rocks exposed in the Outer Lesser Himalaya belong to the Chandpur and Nagthat Formations of Jaunsar Group and Blaini, Krol and Tal Formations of Mussoorie Group.

The stratigraphy succession of the study area is shown in the Table 2.2 and the distribution of different Formations belonging to the various Groups is shown in Fig 2.2

TABLE: 2.2 STRATIGRAPHIC SUCCESSION OF THE STUDY AREA

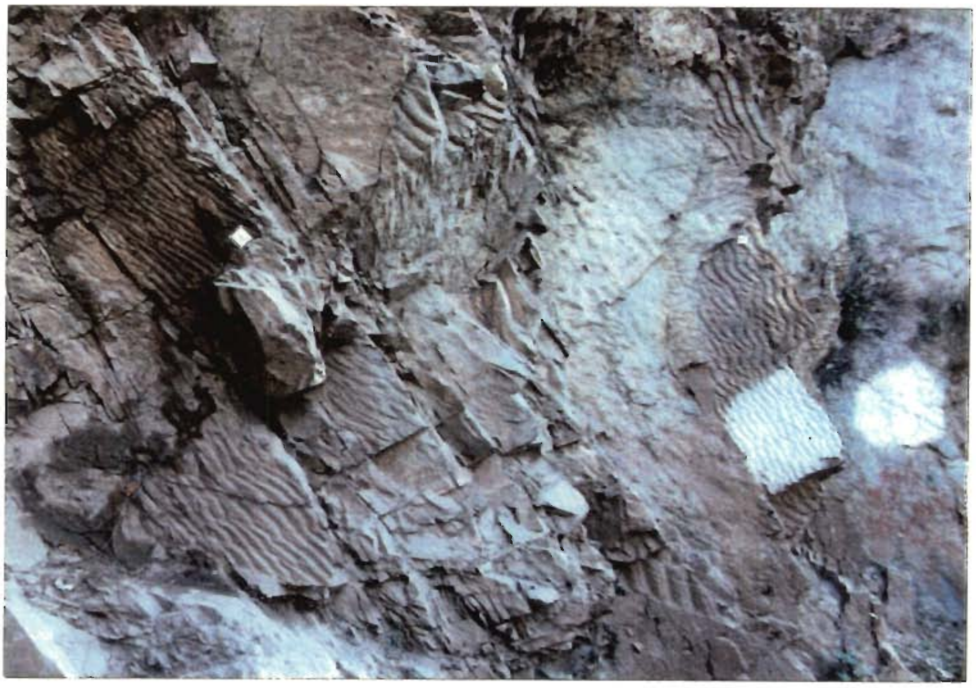
<table>
<tr><th rowspan="2">GROUP</th><th>INNER LESSER HIMALAYA</th><th>OUTER LESSER HIMALAYA</th><th rowspan="2" colspan="2">AGE*</th></tr>
<tr><th colspan="2">FORMATIONS</th></tr>
<tr><td>Mussoorie</td><td></td><td>Tal</td><td>Ordovician(?)-Devonin (500-350my)</td><td></td></tr>
<tr><td></td><td></td><td>Krol</td><td>Cambrian (570-500my)</td><td></td></tr>
<tr><td></td><td></td><td>Blaini</td><td>Eocambrian (650-570my)</td><td rowspan="5">LATE PRECAMBRIAN</td></tr>
<tr><td>Jaunsar</td><td>Berinag</td><td>Nagthat</td><td>-</td></tr>
<tr><td></td><td></td><td>Chandpur</td><td>-</td></tr>
<tr><td>Tejam</td><td>Deoban</td><td></td><td>Middle Riphean</td></tr>
<tr><td>Damtha</td><td>Rautgara</td><td></td><td>>1300my</td></tr>
</table>

*(Valdiya, 1980; Age *Azmi and Joshi)*

2.3.1 Rautgara Formation

The Rautgara Formation is exposed at two places in the northeastern region of the study area (Fig. 2.2). In the extreme northeast, it is separated by Berinag Thrust from the Berinag Formation, while its southern contact is marked by North Almora Thrust (NAT), separating it from the Chandpur Formation. The Rautagara Formation comprises purple, pink and white coloured, well jointed, medium grained quartzites interbedded with medium grained, grey and dark green sublitharenites and minor slates as well as metavolcanics. Some lithounits of the Rautgara Formation show ripple marks indicating deposition under the shallow water conditions (Valdiya, 1980).

PLATE 2



Ripple marks in quartzites of Rautgara Formation exposed along Bhaldiyna - Lambgaun road.

Congolomerates of Blaini Formation, Exposed south of Chamba.

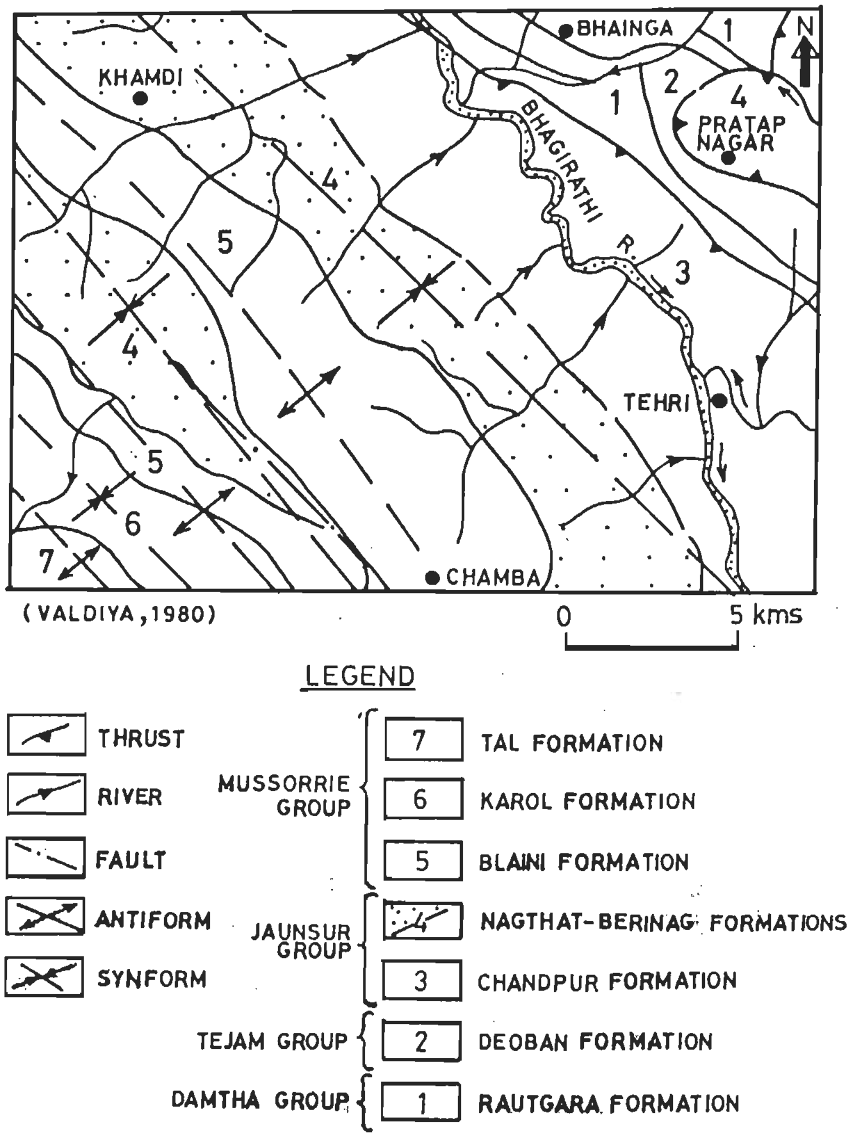


Fig. 2·2 GEOLOGICAL MAP OF THE STUDY AREA

2.3.2 Deoban Formation

The Deoban Formation is also exposed in the northeastern region of the study area (Fig. 2.2). This is sandwitched between the Rautgara and the Blaini Formations having a thrusted contact (Berinag Thrust) with the Berinag Formation. The Deoban Formation occupies topographically higher ridges. and consists of dense, fine grained dolomitic limestone which is white, light pink and blue-grey in colour with minor phyllitic intercalations.

2.3.3 Chandpur Formation

The Chandpur Formation is delimited towards north by a well defined thrust called North Almora Thrust (NAT) trending roughly northwest-southeast and dipping southwest (Fig. 2.2). The rocks of the Chandpur Formation are low grade metamorphosed lustrous and shiny phyllites. These phyllites are olive green and grey in colour interbedded and finely interbanded with metasiltstone and fine-grained wakes. The Chandpur Formation occupies the valley all along the Bhagirathi river.

2.3.4 Nagthat Formation

The Nagthat Formation is exposed roughly at the central and western regions of the study area (Fig. 2.2). The north end of this Formation is restricted by the Chandpur Formation. As a result of folding, the same Formation is once again appears in the western region bounded by Blaini Formation. The same Formation exposed in the western region is restricted by the Blaini Formation of its north and south ends. The rocks of the Nagthat Formation is characterised by white, purple and green coloured quartzites with subordinate intercalations of grey and olive green slates with siltstones.

2.3.5 Berinag Formation

The rocks of the Berinag Formation are exposed in the northeastern part of the study area (Fig. 2.2). The Berinag Formation is separated by the Berinag Thrust at its base. The Berinag Formation consist of white, purple and green coloured quartzites.

2.3.6 Blaini Formation

The rocks of the Blaini Formation are also exposed in the study area (Fig. 2.2). The Formation consists of quartzites, limestones, slates, phyllites and conglomerates with sub-rounded to well rounded clasts (cobble to pebble size).

2.3.7 Krol Formation

Rocks of the Krol Formation are exposed in the southwestern region of the study area with Blaini Formation at its base and the Tal Formation at the top (Fig. 2.2). Krol Formation comprises sequence of limestone with intercalations of grey and greenish grey slates and siltstone.

2.3.8 Tal Formation

Rocks of the Tal Formation are exposed in the southwestern region of the study area (Fig. 2.2). This Formation mainly comprises white and grey coloured limestone with intercalations of pale quartzites and grey slates.

2.4 STRUCTURE

Major as well as minor structures have been observed in the area of study. The major structural features include the North Almora Thrust (NAT) and the Berinag Thrust, exposed in the northeastern region. The southeasterly dipping North Almora Thrust separates the Chandpur phyllites from the Rautgara Formation towards north. The northeasterly dipping Berinag Thrust, also called locally the Pratapnagar Thrust (Valdiya, 1980) separates the Rautgara Formation from the Berinag Formation. A number of antiforms and synforms in the central and southwestern regions, which together form a part of the Mussoorie syncline (Valdiya, 1980) have been observed. In addition, a local fault has been observed in the southwest of Chamba town. The minor structures include the bedding planes, joint planes, foliation planes, small folds and small scale faults.

CHAPTER III

Methodology

The Himalaya, which represents tectonically active mountainous region is generally characterised by steep slopes, high relief, weathered, fractured and folded rocks in addition to unfavourable hydrogeological conditions. These factors make the Himalayan terrain more vulnerable to landslides. Moreover, there has been a sudden spurt in the development activities in the last two decades mainly related to road construction, urbanisation, small scale industries and tourism. These development activities are often implemented without taking into consideration the existing instabilities and thereby increasing the landslide potential. In this connection, the landslide hazard zonation provide useful data on the status of instability of the area. These maps also help the planners in implementing the development schemes with minimum geoenvironmental hazards to the area. This brings out the necessity for Landslide hazard Zonation (LHZ) mapping for prior identification of unstable areas before implementation of any developmental scheme in the mountainous region.

3.1 LITERATURE SURVEY

3.1.1 International Status

Landslide Hazard Zonation (LHZ) mapping is a relatively recent development in landslide investigations. Attempts have been made in different parts of the world for preparing of landslide hazard maps using different parameters.

Nelson et al (1979) made a landslide susceptibility map of central California using slope angle, weak geological units, and past landslides. Varnes (1980) prepared a landslide zonation map adopting slope, soil thickness, landuse practice and drainage as the basic factors. Takei (1982) described methods for making debris flow hazard map taking into account the type of rock, fracturing, weathering characteristics, springs, vegetation and cover, valley slope. Brabb (1984) provided a useful review of development of landslide hazard mapping. Hanson (1984) discussed two principal categories of landslide hazard mapping namely direct and indirect mapping. Kawabani and Saito (1984) used valley density, elevation, slope angle and formations for preparing a quantified landslide risk mapping. Wagner et al (1987) discussed preparation of rock and debris slide risk maps for road alignment purposes, using lithology, structure, slope and geomorphological factors. Koirala and Watkins (1988) described a slope ranking system mainly for adopting preventive measures during excavations. Grainger (1988) suggested a procedure for hazard zonation of coastal landslides with the help of aerial photographs. Barros, Amaral, and Orsi, (1992) presented a method for establishing a landslide susceptibility map using four factors - geology, slope, surfacial deposits and land use. Bertocci, Canuti, & Garzorrio, (1992) gave a methodology for a preliminary analysis and the classification of the hazard areas, based mainly on geomorphological and mechanical characteristics. Chang, (1992) suggested a method for landslide hazard zonation using geology (including lithology and structural attitude), soil (including variety and thickness) or its fundamental properties, and water regime, vegetation cover and landuse, as its derived properties. Olds & Wilson (1992) suggested a risk zoning scheme, developed on the basis of geology, topography and terrain. Sindair (1992) presented a slope condition and risk rating system for slope condition survey and slope design. The parameters, involved are stability condition assessment, erosion condition assessment, slope geometry, topography, vegetation/landuse, drainage and soil/rock type. Turrini et al (1994) gave a modified technique of Anbalagan (1992) for landslide hazard zonation technique. Ives and Messerti (1981) gave a useful technique for mountain hazard mapping. Van Westen (1993) suggested application of Geographical Information System (GIS) in Landslide Hazard Zonation.

However an internationally acceptable quantified approach is yet to be developed as various workers have adopted different approaches for landslide hazard mapping.

3.1.2 National Status

In India, landslide hazard zonation (LHZ) mapping received greater attention of researchers since 1990. A number of workers have proposed schemes for LHZ mapping. There is an acute need to extend the landslide hazard zonation map to cover the entire Himalaya where the pace of implementation of the development programmes have been intensified recently. Sheshagiri and Badrinarayan (1982) prepared a landslide zonation of Nilgiri plateau adopting the approach of Varnes (1980). Gupta and Joshi 1990 evolved a factor called Landslide Nominal Risk Factor

(LNRF) index for hazard zoning of a part of Ramganga catchment using landuse, lithology, distance from tectonic features and azimuth directions. But the most important factors such as relationship of structure with slope, slope angle and hydrogeological factors have not been incorporated. Pant and Pachauri (1989) proposed a technique for land hazard mapping for a small catchment in Garhwal Himalaya, using various geoenvironmental parameters influencing the land hazard. Choubey & Litoria (1990) prepared a LHZ map in Garhwal Himalaya by using Terrain Classification Map (TCM), assuming slope as basic factor. Anbalagan (1992) attempted a quantified approach called Landslide Hazard Evaluation Factor (LHEF) rating system incorporating all the basic inherent causative factors controlling the landslides such as lithology, weathering characters, structural relationship with slope, slope morphometry, relative relief, land use and land cover and hydrogeological conditions. This is the only classification at present, which uses slope facet concept and is based on basic causative factors, which are common in different types of terrain. Bureau of Indian Standards (BIS) has accepted a Indian Standard Code on LHZ mapping (under publication), based on the method of Anbalagan (1992). Anbalagan and Sharma (1992) gave a LHZ mapping technique with special reference to route location in mountainous terrains. Mehrotra et al (1992) prepared a LHZ map of Rishikesh Tehri area, Garhwal Himalaya on the basis of factors such as slope, lithology, landuse, drainage, structural features and occurrence of active and old landslides. Jade & Sarkar (1993) gave a statistical model for hazard assessment of landslides. Anbalagan and Singh (1995) prepared a risk assessment map of Sukhidang area with the help of landslide hazard zonation map by using the factors such as topography of the area, nature of failure and geological factors controlling the nature of failure. The risk assessment map has been divided into five risk zones namely very high risk, high risk, moderate risk, low risk and very low risk.

3.2 TECHNIQUE FOR LANDSLIDE HAZARD ZONATION (LHZ) MAPPING

The methods of analysis of landslides differ widely depending on the objective for which they are prepared. However, they can be broadly classified into three categories namely, analytical, observational and empirical methods.

Analytical: Analytical approach is the detailed study of landslides. It assesses the landslide activity in terms of factor of safety (FOS) using a set of input parameters related to characteristics of slope materials and the mechanics of landslide phenomena. The analytical methods require soil/rock properties. These properties could be estimated through a carefully planned and executed field and laboratory investigation programmes or else to resort to "back analysis" wherein an unstable/stable 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 are set up considering the resisting and disturbing forces to work out the factors of safety. It is also called microzonation approach and includes FEM analysis and modelling of slopes.

Observational: The approach is based on instrumental monitoring of slopes. The slopes are instrumented through extensometers and inclinometers to study the movements with time. Stability is worked out based on the data obtained from these instruments. The result of this approach help to carry out a better analytical study.

Empirical: The empirical approach relates the experiences gained from the earlier investigations to the existing field conditions. On the basis of field experiences, causative factors are identified and their influence in inducing instabilities are studied. The qualitative nature of field conditions are quantified based on relative rating schemes.

Analytical studies are extensively carried out in India and abroad. Well known techniques' incorporating various factors for different types of slip surfaces are available. Several computer programmes are also available for analysis.

The observational studies, in general are costly and time consuming. These are mainly employed in engineering project sites such as river valley projects, road projects and colony projects. The instrumentation covers relatively small areas and hence the overall cost turn out to be exorbitant. However, these provide useful inputs for better analytical studies.

Empirical approach is the recent approach and is becoming much popular these days particularly for rock slopes. The well known RMR and Q systems are based on these approaches. The landslide hazard zonation (LHZ) mapping also falls in this category only. This method is generally cheaper since large areas can be covered in relatively short duration. This macro-zonation approach, categorises the area into very stable. stable, moderately stable, unstable and very unstable. As such, it is useful for preliminary planning of development schemes and help to avoid unstable and very unstable slopes during planning. Even if unavoidable, their recognition in the initial stages help to evolve better preventive measures.

Therefore, keeping in view of above aspects, an empirical LHEF rating scheme (Anbalagan, 1992) has been adopted for the present study. In the present study, the empirical approach of Anbalagan, 1992, which is based on Landslide Hazard Evaluation Factor (LHEF) rating scheme has been adopted for the initial identification of hazard prone areas. The LHEF rating scheme was successfully applied in parts of

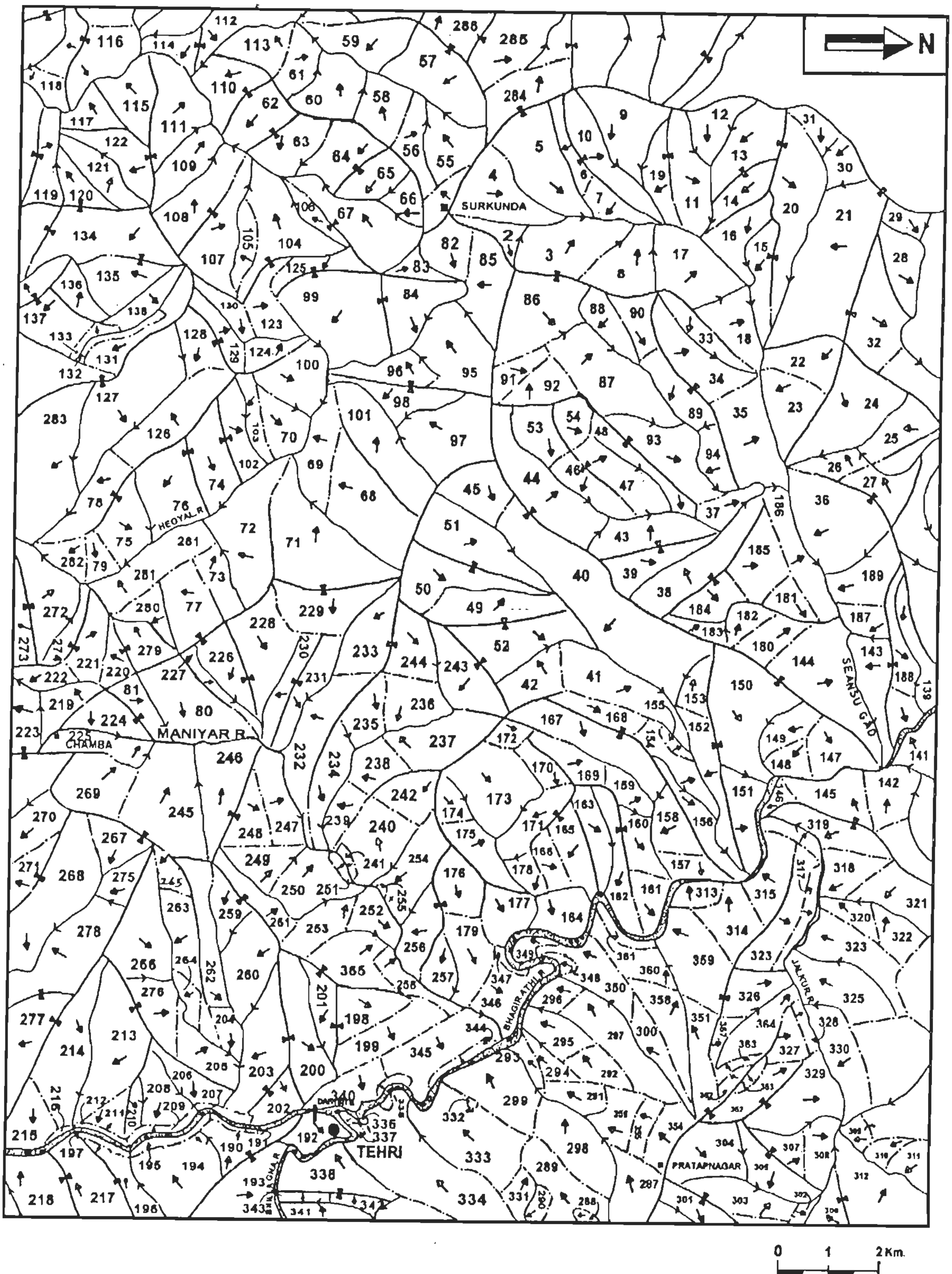
Kumaun and Garhwal Himalaya (Anbalagan, 1992; Anbalagan, Gupta and Sharma 1992 and Gupta et al 1993; Gupta and Anbalagan, 1993 and Anbalagan et al 1993. This LHEF rating is a numerical rating scheme, based on the empirical approach which has been modified in the present study in structure category.

3.2.1 Slope Facet

A slope facet is a part of hill slope which has more or less uniform characters within the slope facet, showing consistent slope direction and inclination. A slope facet map of the study area has been prepared (Fig 3.1). The general direction of a slope facet is shown by an arrow. Initially the topography of the study area is studied carefully on the topomap. The hill slopes are divided into a number of small segments, called slope facets bounded by ridges, spurs, gullies and streams. In the absence of ridges, spurs, gullies and streams, arbitrary lines are used as a slope facet boundary, where a significant change in the attitude of slope is observed. Slope facet may vary in shape and size depending upon the uniformity and nature of the slope.

3.2.2 Landslide Hazard Evaluation Factor (LHEF) Rating Scheme

The causative factors of landslides can be broadly classified into two major categories namely inherent and external. The LHEF rating scheme is based on major inherent causative factors of slope instability such as geology (lithology and structure), slope morphometry, land use and land cover, relative relief and hydrogeological conditions. These factors represent the inherent characteristics of a slope facet and can be evaluated/estimated to a fairly high degree. However some of the other important contributory factors such as rainfall and seismicity are not included in the landslide hazard zonation technique. These factors are external factors, which are regional in



LEGEND

RIDGE LINE
STREAM COURSE
FACET BOUNDARY
SLOPE DIRECTION

FIG.3.1. SLOPE FACET MAP OF THE STUDY AREA

nature and erratic in their occurrences. Therefore, it is difficult to estimate their impact with particular reference to a slope facet. Moreover, when rainfall or seismicity occur over a large area, the degree of impact on the adjoining slope facets may not vary. In fact, the status of ranking arrived on the basis of inherent factors may remain more or less same even after the occurrence of these external factors, that is, a high hazard slope facet may fail early as compare to a moderate hazard or a low hazard slope facet. The reliability of a LHZ map is essentially dependent on the rating system adopted for the preparation of the map. The LHEF rating scheme is based on an empirical approach, which combines past experience as gained from the study of causative factors and their impact on landslides with conditions anticipated in field of study (Anbalagan, 1992) Similar approaches have been adopted in the well-known rock mass classifications such as RMR and Q systems (Barton et al, 1974; Bieniawski, 1979). The maximum LHEF ratings for individual contributory factors are determined on the basis of their estimated relative significance in causing the instability (Table 3.1). The number 10.0 indicates the maximum value of the total estimated hazard (TEHD). A detailed LHEF rating scheme, showing ratings for a variety of subcategories for individual causative factors is given in Table-3.2 and the same is discussed below.

TABLE 3.1 PROPOSED MAXIMUM LHEF RATING FOR DIFFERENT CONTRIBUTORY FACTORS FOR LHZ MAPPING

Contributory Factor	Maximum LHEF Rating
Lithology	2.0
Relationship of structural discontinuities with slope	2.0
Slope morphometry	2.0
Land use and land cover	2.0
Relative relief	1.0
Hydrogeological conditions	1.0
Total	10.0

(ANBALAGAN, 1992)

3.2.2.1 *Lithology*

Lithology includes broadly rock type and soil type. In case of rock type, the erodibility or the response of rocks to the processes of weathering and erosion has been the main criteria in awarding the ratings for subcategories of lithology Further, rocks are divided into three groups type-I, type-II and type-III. The rocks of type-I includes rocks like quartzite, limestone and igneous rocks, which are generally hard, massive and resistant to erosion. In comparison, rocks of type-II includes terrigenous sedimentary rocks, which are vulnerable to erosion and landslides. The rocks included in type-III are phyllites, schists and other soft rocks characterised by flaky minerals which weather quickly and promote instability. Accordingly, the LHEF ratings have been awarded

.

In case, if the rocks are weathered, a correction factor depending on the status of weathering has been included for rock types I & II (Table 3.2). This correction factor is multiplied with the corresponding rating of rock to get the corrected rating.

In case of soil, genesis and age are the main considerations in awarding the ratings. For example, Older alluvium is generally well compacted and has a high shearing resistance. Recent materials such as slide debris are loose and have low shearing resistance.

3.2.2.2 *Structure*

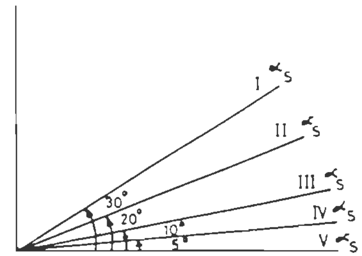
Structure includes primary and secondary discontinuities in the rocks such as bedding, joints, foliations, faults and thrusts. The disposition of structural discontinuities in relation to slope inclination and direction has a great influence on the stability of

TABLE 3.2 LANDSLIDE HAZARD EVALUATION FACTOR (LHEF) RATING SCHEME

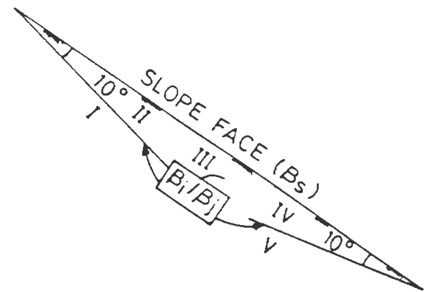
Contributory Factor	Category	Rating	Remarks
Lithology *Rock Type*			**Correction factor for weathering**
	Type-I Quartzite & Limestone Granite & Gabbro Gneiss	 0.2 0.3 0.4	(a) HIGHLY WEATHERED - rock discoloured joints open with weathering products, rock fabric altered to a large extent; correction factor C_1
	Type-II Well cemented terrigenous sedimentary rocks, dominantly sandstone with minor beds of claystone.	1.0	(b) MODERATELY WEATHERED - rock discoloured with fresh rock patches, weathering more around joint planes, but rock intact in nature; correction factor C_2.
	Poorly cemented terrigenous sedimentary rocks, dominantly sandstone with minor clay shale beds.	1.3	(c) SLIGHTLY WEATHERED - rock slightly discoloured along joint planes, which may be moderately tight to open, intact rock; correction factor C_3
	Type-III Slate & Phyllite Schist Shale with interbedded clayey and non-clayey rocks.	1.2 1.3 1.8	**The correction factor for the observed degree of weathering should be multiplied by the fresh rock rating to get the corrected rating.**
	Highly weathered shale, phyllite & schist.	2.0	*For rock type I* C = 4, C = 3 and C = 2 *For rock type II* C = 1.5, C = 1.25 and C = 1.0
			Cont...

Contributory Factor	Category	Rating	Remarks
Soil Type	Older well-compacted fluvial fill material *(Alluvial).*	0.8	
	Clayey soil with naturally formed surface (Eluvial).	1.0	
	Sandy soil with naturally formed surface *(Alluvial).*	1.4	
	Debris comprising mostly rock pieces mixed with clayey/sandy soil (Colluvial)		
	I. Older well compacted.	1.2	
	II. Younger loose material.	2.0	
Structure ***Relationship of structural discontinuity with slope.***			α_j = dip direction of joint. α_i = direction of line of intersection of two discontinuities. α_s = direction of slope inclination. β_j = dip of joint. β_i = plunge of line of intersection. β_s = inclination of slope
Relationship of parallelism between the slope & the discontinuity.*	I < 30°	0.20	* Discontinuity refers to the planar discontinuity in case of planar failure or the line of intersection of two planar discontinuities in case of wedge failure, whichever more is important.
	II 21° - 30°	0.25	
	III 11° - 20°	0.30	
PLANAR - $\lvert\alpha_j - \alpha_s\rvert$	IV 6° - 10°	0.40	
WEDGE - $\lvert\alpha_i - \alpha_s\rvert$	V ≤ 5°	0.50	*Cont...*

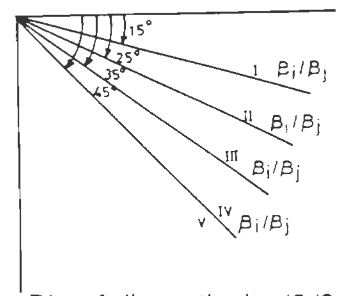
Contributory Factor	Category		Rating	Remark
Relationship of dip of discontinuity and inclination.*				
PLANAR - $(\beta_j - \beta_s)$	I	> 15°	0.65	
WEDGE - $(\beta_i - \beta_s)$	II	0° - 10°	0.85	
	III	0°	1.30	
	IV	0° -(-10°)	2.00	
	V	-10°	1.20	
*Dip of discontinuity**				
PLANAR - β_j	I	≤ 15°	0.65	
WEDGE - β_i	II	16° - 25°	0.85	
	III	26° - 35°	0.30	
	IV	36° - 45°	0.40	
	V	> 45°	0.50	
Depth of soil cover.				
	5m		0.65	
	6 - 10m		0.85	
	11 - 15m		1.30	
	16 - 20m		2.00	
	20m		1.20	
STRUCTURE *Sub-Category*				
	Favourable		<0.9	
	Moderately Favourable		0.9-1.4	
	Unfavourable		>1.4	



Parallelism between the slope and the discontinuity $(\alpha_j/\alpha_i-\alpha_s)$



Relationship of dip of discontinuity and the inclination of slope $(\beta_j/\beta_i-\beta_s)$



Dip of discontinuity (β_i/β_s)

Cont...

Contributory Factor	Category	Rating	Remarks
Slope Morphometry			
Escarpment/Cliff	45°	2.00	
Steep Slope	36° - 45°	1.70	
Moderately steep Slope	26° - 35°	1.20	
Gentle Slope	16° - 25°	0.80	
Very Gentle Slope	15°	0.50	
Relative Relief			
Low	≤ 100 m	0.3	
Medium	101 - 300 m	0.6	
High	> 300 m	1.0	
Land Use And Land Cover			
Agricultural land/Flat Land		0.65	
Thickly Vegetated Area.		0.85	
Moderately Vegetated Area		1.20	
Sparsely Vegetated Area. With Lesser Ground Cover.		1.50	
Barren Land.		2.00	
Hydrogeological Condition			
Flowing		1.00	
Dripping		0.80	
Wet		0.50	
Damp		0.20	
Dry		0.00	

(Modified after Anbalagan, 1992)

slopes. Relationship of structural discontinuities with slope has been considered for LHEF rating in case of structure. In this connection, the following three types of relations are considered important :

1) The extent of parallelism between the directions of the discontinuity, or the line of intersection of two discontinuities and the slope.
2) The difference in the dip of the discontinuity, or the plunge of the line of intersection of the two discontinuities to the inclination of the slope.
3) The steepness of the dip of the discontinuity, or the plunge of the line of intersection of two discontinuities.

The more, the discontinuity or the line of intersection of two discontinuities tends to be parallel to the slope, the greater the risk of failure. Moreover, till the dip of the discontinuity plane or the plunge of the line intersection of the two discontinuities does not exceed the inclination of the slope, the failure potential remains high. When the dip of the discontinuity or plunge of the line of intersection of two discontinuities increases, the probability of failure also increases, because the angle of friction for the discontinuity surfaces may be reached. The above relations of the structural discontinuity with that of slope inclination has been sub-divided into five sub-categories. Accordingly, the LHEF ratings have been assigned for various stability conditions. In order to calculate the structural rating for each slope facet, rating has been read out for the discontinuities from each set of stability conditions and added to get the final structural rating. It should be noted that if the discontinuities are more than one, then LHEF rating has been calculated for all the cases of discontinuities.

The one having maximum LHEF rating for structure is considered for the LHZ mapping. Structure has been divided judicially into three sub-categories namely, favourable (<0.9), moderately favourable (0.9-1.4) and unfavourable. These values indicate the degree of impact of structures in inducing the landslides.

In case of soil cover, chances of failure increases as the depth of soil cover increases up to a certain depth. Beyond that, stability increases due to compaction of soil by its weight. Therefore, in case of soils, the inferred depth is considered for awarding the ratings.

3.2.2.3 *Slope Morphometry*

Slope morphometry is another important causative factor, in the instability of slopes. The slope morphometry maps represent the zones of different slope inclination. The distribution of the slope subcategories is dependent on the geomorphological history of the area. The angle of slope of each unit is a reflection of a series of localised processes and controls, which are imposed on the slope facet. The slope morphometry map is prepared by dividing the large topographical map into smaller units called as slope facets. Five subcategories of slope morphometry are considered in the LHEF rating scheme, namely escarpment or cliff (>45°), steep slope (36°-45°), moderately steep slope (26°-35°), gentle slope (16°-25°)and very gentle slope (≤15°).

It is a known fact that steep slopes have higher chances of slope failure than the gentle ones. Therefore, five sub categories of slope morphometry have been arranged in their hierarchial order and the ratings awarded.

3.2.2.4 *Land use and Land cover*

Land use and land cover is an indirect indication of the stability of hill slopes. Vegetation cover commonly, smothers the action of climatic agents on slopes and protect them from the affects of weathering and erosion. A well spread grass cover provides a blanket to the top layer of a slope and protects it from the direct impact of rain drops as well as checks the infiltration of water into the slope surface, which may subsequently reduces the shear strength of slope material. Similarly, well spread root system increases the shearing resistance of slope material.

Five subcategories of land use and land cover are considered in LHEF rating scheme namely agricultural land or populated plant land, thickly vegetated forest area, moderately vegetated area, sparsely vegetated area with lesser ground cover and barren land.

Barren and sparsely vegetated areas show faster erosion and greater instability as compared to reserve or protected forests, which are moderate to thickly vegetated and generally less prone to mass wasting processes. Agriculture, in general, is practised on terraced fields in hilly region. The agricultural lands represent areas of repeated water charging for cultivation purposes and as such may be considered stable. Based on criteria of intensity of vegetation cover, the LHEF rating were awarded.

3.2.2.5 *Relative Relief*

Relative relief is the maximum height within a slope facet, measured in the direction of slope. There are three sub categories of relative relief in LHEF rating scheme namely low relief (>100 m), medium relief (101 m-300 m) and high relief (>300 m). It is an obvious fact that the chances of slope instability are more with increasing slope height. Therefore, LHEF ratings are given accordingly.

3.2.2.6 *Hydrogeological Condition*

Groundwater does not have uniform pattern in hilly terrain and it is generally channelised along weak planes of rocks. The observational evaluation of the groundwater behaviour in hill slopes is not possible over large areas. Therefore, in order to make quick appraisal, the nature of surface indications of groundwater are considered for hazard evaluation mapping purposes. Surface indications of water such as flowing, dripping, wet, damp and dry are used for LHEF rating purposes. The observation are made after the monsoon, to assess probably the worst hydrogeological conditions of the study area.

3.2.2.7 *Calculation of Total Estimated Hazard (TEHD) Values*

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. Total estimated hazard (TEHD) value = sum of ratings of all causative factors (lithology + structure + slope morphometry + landuse and land cover + relative relief hydrogeological conditions).

On the basis of TEHD values, five categories of landslide hazard zones were identified (Table 3.3). These landslide hazard zones are very low hazard (VLH), low hazard (LA) moderate hazard (MH) , high hazard (HH) and very high hazard (VHH).

PLATE 3

Terraced farming on slopes comprising weathered phyllites between Tehri and Pratapnagar.

Dense vegetation stabilizing in slopes near Pratapnagar.

TABLE 3.3 LANDSLIDE HAZARD ZONATION ON THE BASIS OF TOTAL ESTIMATED HAZARD (TEHD)

Zone	TEHD Value	Description of Zones
I	< 3.5	Very Low Hazard (VLH) Zone
II	3.5 - 5.0	Low Hazard (LH) Zone
III	5.1 - 6.0	Moderate Hazard (MH) Zone
IV	6.1 - 7.5	High Hazard (HH) Zone
V	> 7.5	Very High Hazard (VHH) Zone

(ANBALAGAN, 1992)

3.3 GENERAL PROCEDURE FOR LANDSLIDE HAZARD ZONATION (LHZ) MAPPING

The LHZ mapping technique is a macro-zonation approach showing the probabilities of landslide hazards of an area on 1:50,000 scale. The LHZ mapping comprises mainly two aspects i) desk study and, ii) field study (Fig 3.2). The scope of desk study includes first, preparation of slope facet map on 1:50,000 scale (Fig 3.1). A total 365 slope facets have been prepared for the present study, which covers roughly 450 sq km. A slope facet map of the study area is used as a base map to prepare the prefield factorial maps such as lithological map, structural map, slope morphometry map, land use and land cover map, relative relief map and hydrogeological map. All prefield factorial maps have been prepared slope facet - wise with the help of Survey of India topomap (53J/7) and regional geological maps. These prefield terrain evaluation maps showing the status of causative factors in the study area help to plan and execute the field investigation system execute. In order to obtain maximum information during field investigations, a number of traverses have been made. Traverses have been planned in such a way that not only the maximum number of slope facets but maximum part of an individual slope facet have been covered. During the field study, the data pertaining to various causative factors are arranged and modified wherever required.

After incorporating the obtained field data in all the slope facets, final factorial maps have been prepared. The LHEF ratings have been assigned to each causative factor slope facet-wise and total estimated hazard (TEHD) values were calculated for each slope facet. Finally, with the help of TEHD values of each slope facet, landslide hazard zonation map of the study area is prepared.

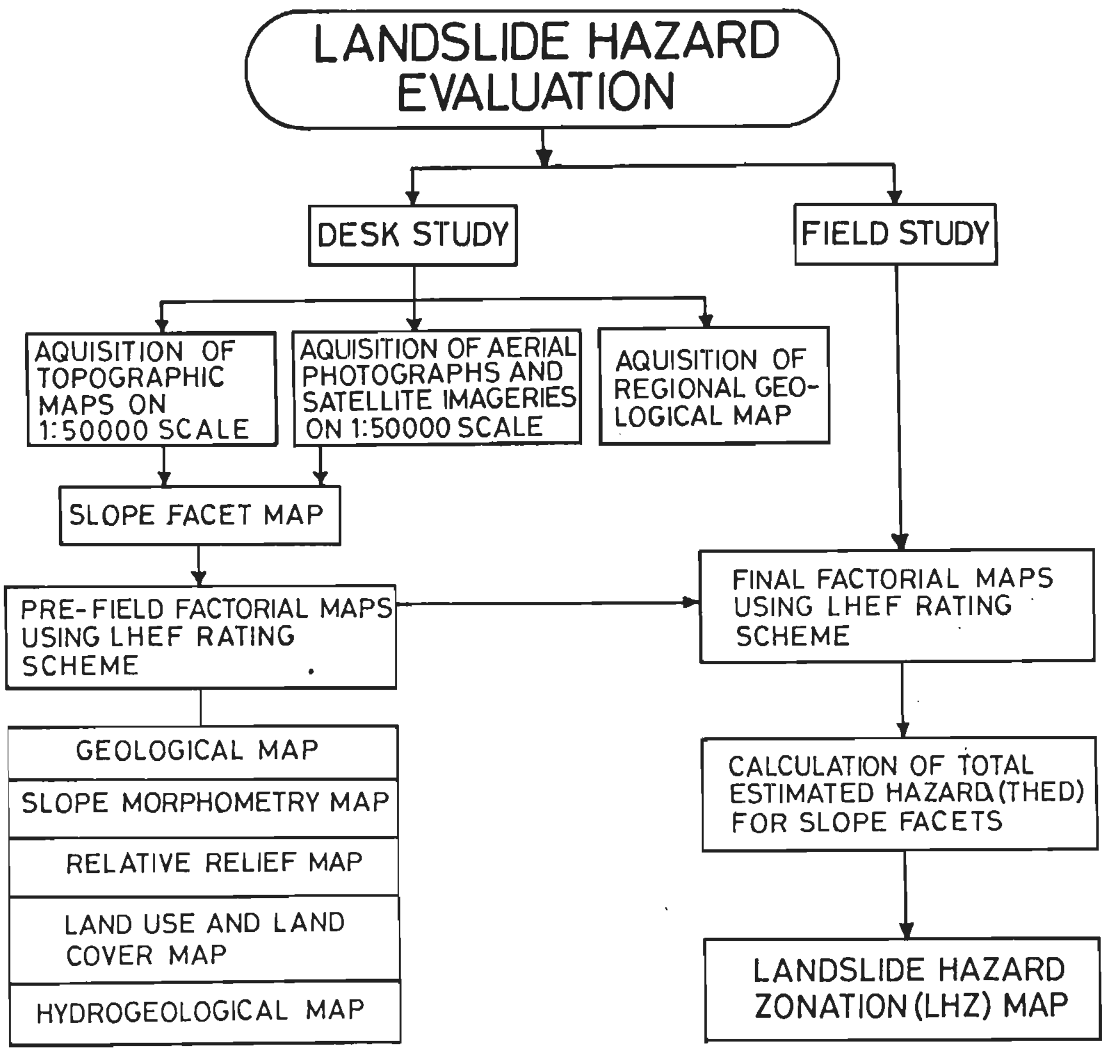


FIG. 3.2 GENERAL PROCEDURES FOR LANDSLIDE HAZARD ZONATION MAPPING
(ANBALAGAN, 1992)

3.4 MERITS AND DEMERITS OF LHEF RATING SCHEME

The landslide hazard evaluation factor (LHEF) rating scheme (Anbalagan, 1992) having some advantages over other schemes.

i) The LHEF rating scheme is more simple and applicable to all types of hilly terrains, as this scheme is based on basic inherent causative factors controlling the landslides.

ii) It is comparatively a rapid scheme at the planning stage of engineering structures.

iii) This is a simple and cheap hazard assessment technique and it does not involve any complicated equipment during the field survey.

iv) The final landslide hazard zonation map is simple and can be easily understandable by the users.

v) The LHEF rating scheme gives the representative output for all the categories of hazard. In case of high hazard category, it gives the 75% to 85% good results.

vi) This technique involves extreme exhaustive field inputs.

vii) During field observations, personal judgements play a vital role. However, it has been found that the variation are generally limited to less than 20%

CHAPTER IV

Landslide Hazard Zonation Mapping and Statistical Analysis

The Himalayan region has been the target of intense development activities in the form of roads, buildings, rope ways, railway lines, canals and other engineering structures in the past few decades. The large scale occurrences of landslides, induced due to development activities, have indicated the necessity to adopt systematic planning in order to keep the induced landslide hazards to a minimum. The systematic investigations should be planned on the principle of `whole to part', where large areas are initially considered so as to arrive at a favourable alignment for implementing the development schemes. The landslide hazard zonation (LHZ) mapping is the first step towards achieving a sustainable development of hilly terrains.

□ 4.1 LANDSLIDE HAZARD ZONATION MAPPING

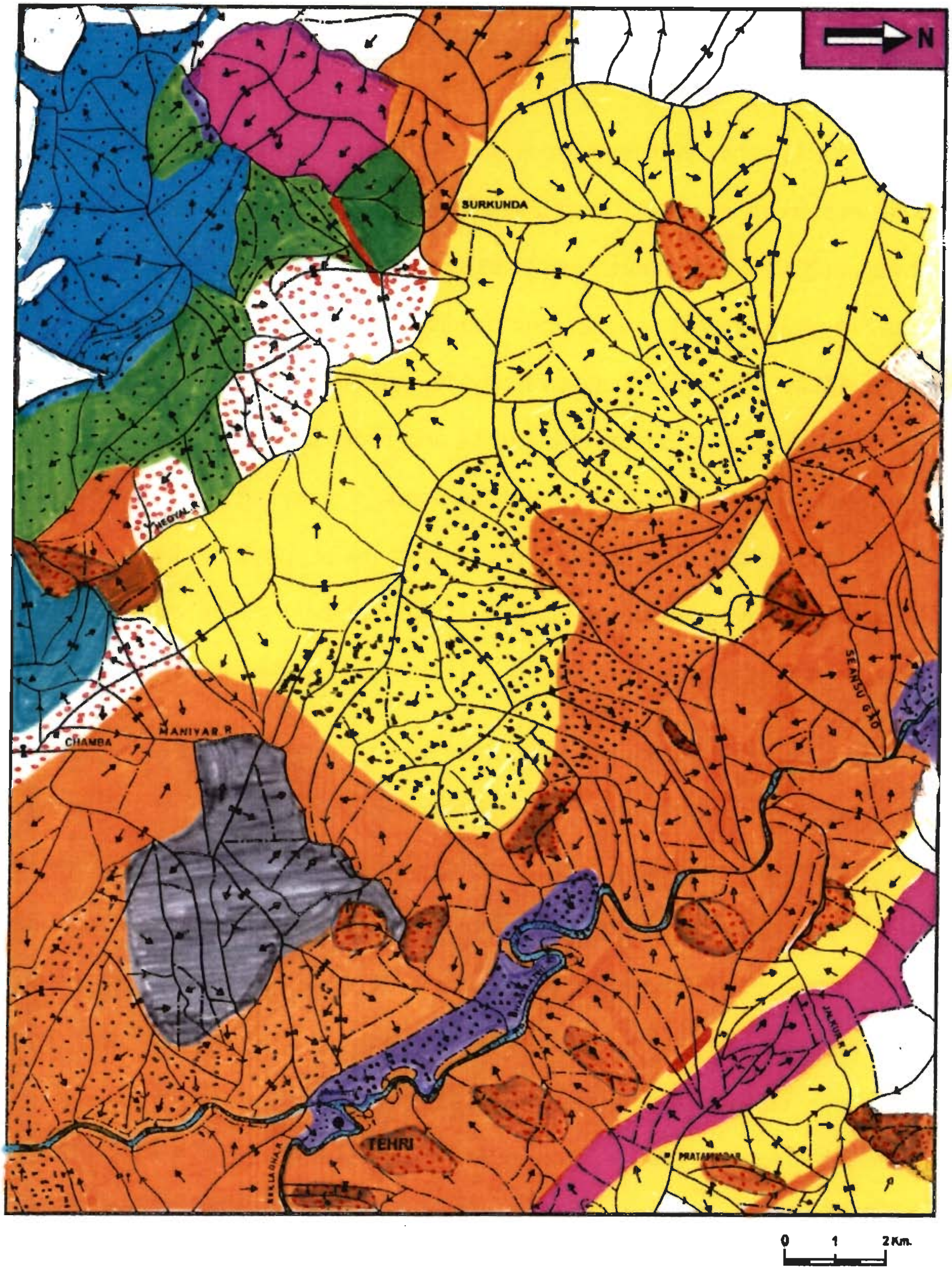
The landslide hazard zonation mapping of the study area has been carried out using a modified landslide hazard evaluation factor (LHEF) rating scheme of Anbalagan, 1992, which has been discussed, in detail in chapter III. A number of prefield factorial maps pertaining to each of the causative factor such as lithological map, structural map, slope morphometry map, land use and land cover map, relative relief map and hydrogeological conditions map covering three hundred and sixty five slope facets of the study area have been prepared. These maps depict the nature and the distribution of the causative factors over the area. Later these maps have modified mainly based on the field studies.

Initially, a slope facet map of the area has been prepared which serves as a base map in order to prepare the prefield factorial maps. These factorial maps have been modified wherever required, after obtaining the field data. For that purpose, a number of traverses have been taken in such a way that all the slope facets in the area of study have been visited for collecting the actual field data. A description of factorial maps is given below.

4.1.1 Lithological Map

Lithology is an important causative factor for the instability of slope facets. A lithological map of the area has been prepared which shows the distribution of various rock types as well as soil types (Fig. 4.1).

During the field investigations different rock types and their weathering status have been studied. In case of soil cover, soils are identified on the basis of soil genesis.



LEGEND

- PHYLLITE
- QUARTZITE
- QUARTZITE WITH MINOR BANDS OF PHYLLITE
- PHYLLITE WITH MINOR BANDS OF QUARTZITE
- LIMESTONE WITH MINOR BANDS OF QUARTZITE & SLATE
- LIMESTONE
- ALTERNATIVE BANDS OF QUARTZITE & PHYLLITE
- SLATE WITH MINOR BANDS OF QUARTZITE
- QUARTZITE WITH MINOR BNANDS OF SLATE & PHYLLITE
- SOIL COVER
- RIVER BORNE MATERIAL
- PHYLLITE WITH MINOR BANDS OF LIMESTONE, CONCLOMARATE AND QUARTIZITE
- SLATE
- METABASICS

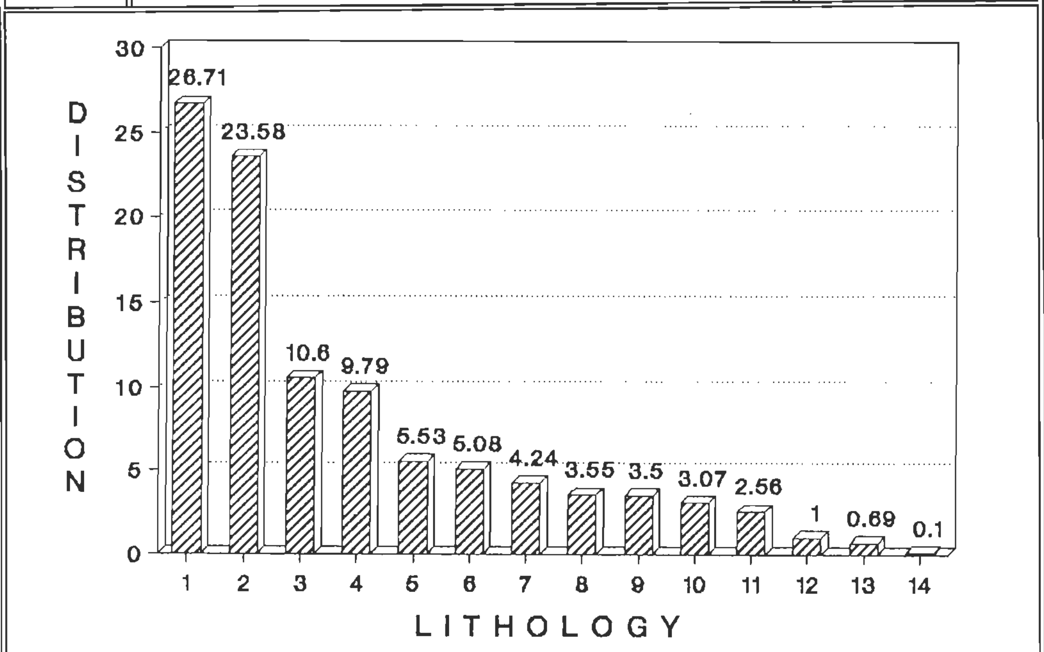
FIG. 4.1 LITHOLOGICAL MAP OF THE STUDY AREA

The contacts between different rock units and soil types have also been observed in order to prepare lithological map (Fig.4.1). The dominant rock types in study area are phyllites (26.71%) and quartzites (23.58%). The other lithological units observed in the area are given below based on their dominance in terms of percentage. These units are quartzite with minor bands of phyllite, phyllite with minor bands of quartzite, limestone with minor bands of quartzite and slate, limestone, alternating bands of quartzite and phyllite, quartzite with minor bands of slate and phyllite, slate with minor bands of quartzite, soil cover, river borne material, phyllite with minor bands of limestone, conglomerate and quartzite, slate, metabasics. The distribution of these rock and soil types has been shown in Table 4.1 as well as in the form of bars.

Phyllite covers the major part of the study area and are exposed mainly on both the banks close to Bhagirathi river. It is also exposed on the left bank of the Maniyar river and at places on the right bank. Phyllites are also exposed along Heoyal river in western and southern regions. It is also exposed as a thin band in the northeastern corner of the region. Phyllites exposed on the left banks of the Bhagirathi and Maniyar rivers are generally weathered close to the surface and support soil cover. This rock is generally vulnerable to weathering and is present in the valley regions. In general, phyllites, which are exposed downstream of the confluence of the River Bhagirathi and Bhillangana, are relatively hard, compact and siliceous in nature. The second most dominant rock exposed in the study area is quartzite. This rock is generally, hard, compact and forms steep slopes on the higher reaches of the region. Quartzites are exposed as a thick band starting from northwest through the central region and extends upto southern part of the area. Quartzites are also exposed in the northeastern region.

TABLE 4.1 DISTRIBUTION OF LITHOLOGY (AREA IN PERCENT) IN THE STUDY AREA

SL. NO.	LITHOLOGY	DISTRIBUTION (Area in Percent)
1	Phyllite	26.71
2	Quartzite	23.58
3	Quartzite with minor bands of Phyllite	10.60
4	Phyllite with minor bands of Quartzite	09.79
5	Limestone with minor bands of Quartzite and Slate	05.53
6	Limestone	05.08
7	Alternating bands of Quartzite and Phyllite	04.24
8	Slate with minor bands of Quartzite	03.55
9	Quartzite with minor bands of Slate and Phyllite	03.50
10	Soil Cover	03.07
11	River Borne Material	02.56
12	Phyllite with minor bands of Limestone, Conglomerate and Quartzite	01.00
13	Slate	00.69
14	Metabasics	00.10



These rocks form two high peaks namely Surkunda and Pratapnagar in the study area. Quartzites with minor bands of phyllite are weak in comparison to quartzites. These rocks are mostly exposed in the central region of the area. Phyllites with minor bands of quartzites, mainly occupy the northern region. These rocks are also exposed on both sides of the Bhagirathi river in the southeastern corner area. Limestones with minor bands of quartzites and slates, exposed in the southwestern region are bedded and hard in nature. Limestones exposed in the western region of the area are generally hard in nature. Alternate bands of quartzites and phyllites are encountered in southwestern region along the right bank of the Maniyar river, a tributary of Bhagirathi river. The thicknesses of quartzite and the phyllite bands are more or less equal. Slates with minor bands of quartzites are exposed in the southern region. The quartzites with minor bands of slates and phyllites are also exposed in southern region along right bank of the Hunal river. The Soil types cover only 3.07% of the study area and are found in all parts of the region. These soil types which form thin cover, are mainly derived by the rivers. Soils in the eastern region on the left bank of the Bhagirathi river have eluvial soil on the surface. River borne materials (RBM) are present at lower levels on both the banks of Bhagirathi river. These older terrace materials form the fertile agricultural lands. Phyllites with minor bands of limestone, conglomerate and quartzite are also seen to the south of the Chamba town. Slates, which contributes less than one percent in the study area are exposed in the western region. Metabasics are seen at two places only. It is exposed in the northern region along the North Almora Thrust (NAT) and in the western part of the study area.

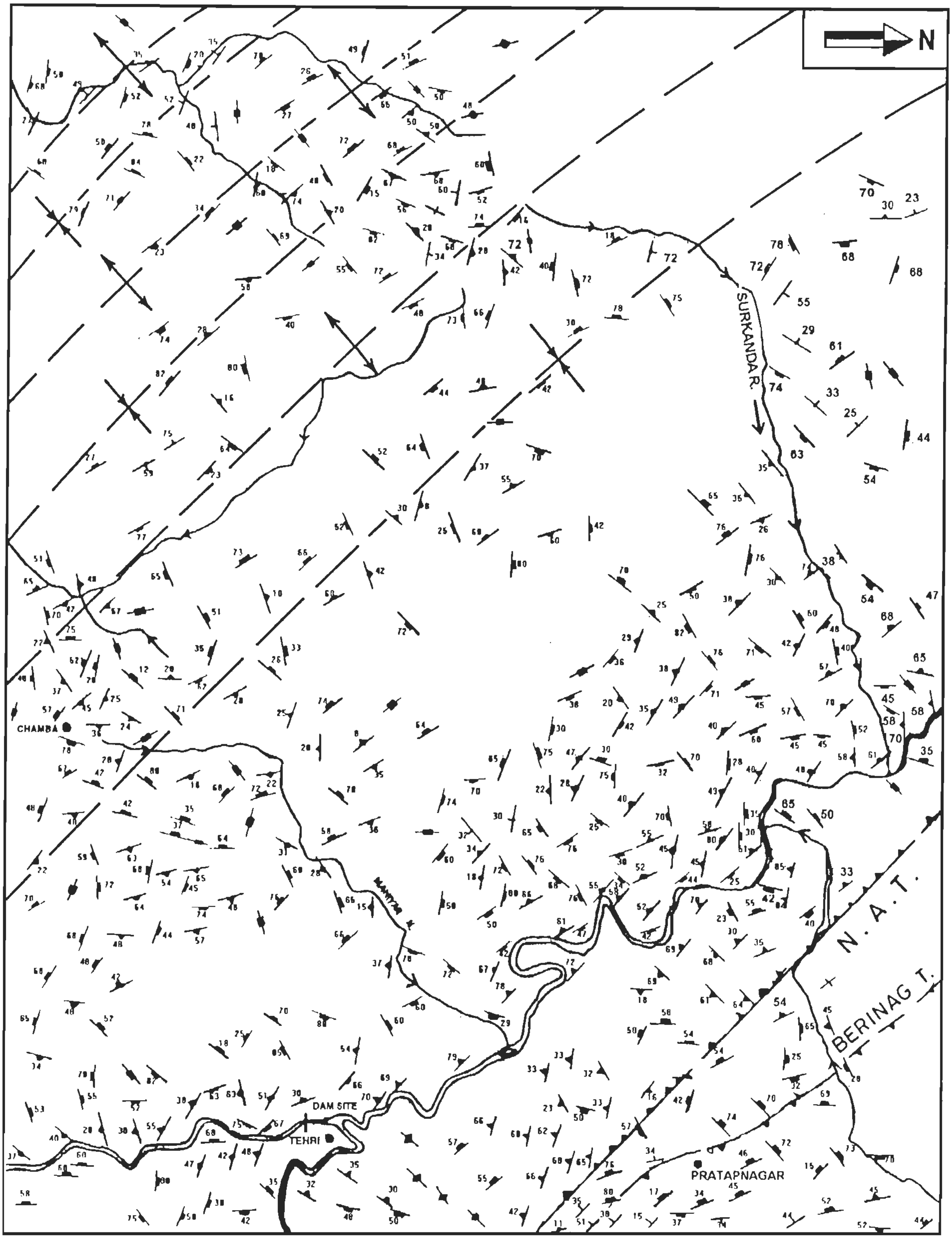
The landslide hazard evaluation factor (LHEF) ratings of causative factor 'lithology' have been calculated for individual slope facet taking into consideration the lithology and its weathering status. Wherever more than one rock or soil types are falling within an individual slope facet, fractional areas have been calculated with respect to slope facet area for individual rock or soil types falling in a particular slope facet. These fractional areas of each rock or soil types have been multiplied by their corresponding LHEF ratings and added together to get final LHEF ratings of lithology for an individual slope facet.

In some cases, where the major rock has intercalations of other rocks within a slope facet (for example quartzite with minor bands of slate and phyllite), the general percentage of intercalations is studied in addition to field conditions, including weathering. Based on the above parameters, the LHEF ratings have been awarded.

4.1.2 Structural Map

The structural map (Fig. 4.2) includes major as well as the minor structures observed in various slope facets. The major structural features of the area include the North Almora Thrust (NAT) and the Berinag Thrust seen in the northeastern region. The Berinag Thrust is also called Pratapnagar Thrust (Valdiya,1980). The area also includes antiforms and synforms in southwestern region, which together form a part of the Mussorrie syncline (Valdiya, 1980).

A number of minor primary and secondary structures such as beddings, joints, foliations and folds have been observed in different rocks. Beddings and joints are well developed in quartzitic rocks. These planes often show long strike continuities. The more or less regular intersections of these discontinuities have rendered the quartzites into rectangular rock blocks of varying size. Foliation planes are dominantly present in phyllites with few set of joint planes. The limestones generally show well developed joints. The structural discontinuities such as bedding, joint and foliation planes have been used for calculation of TEHD considering their disposition in relation to slope



(After Valdiya,1980)

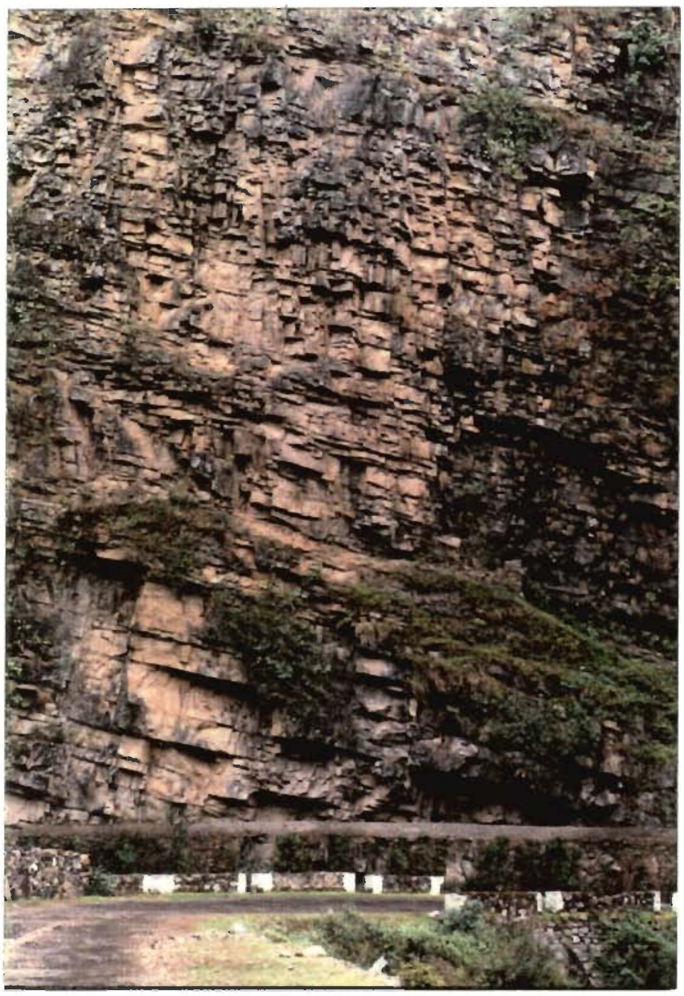
0 1 2

LEGEND

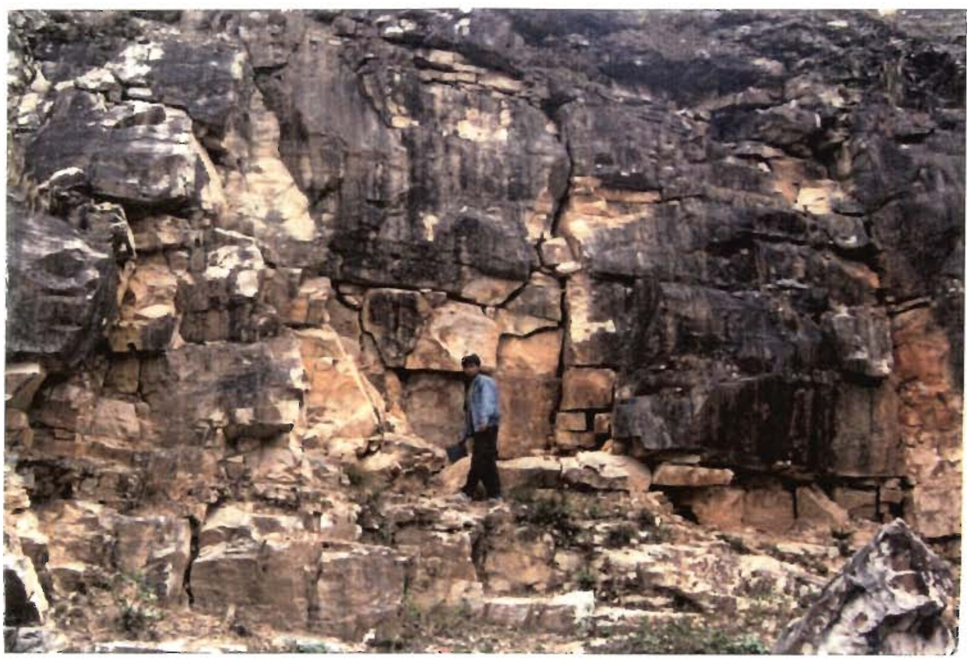
BEDDING PLANE
FOLIATION PLANE
JOINT PLANE
SYNFORM
ANTIFORM
THRUST

FIG. 4 . 2. STRUCTURAL MAP OF THE STUDY AREA

PLATE 4



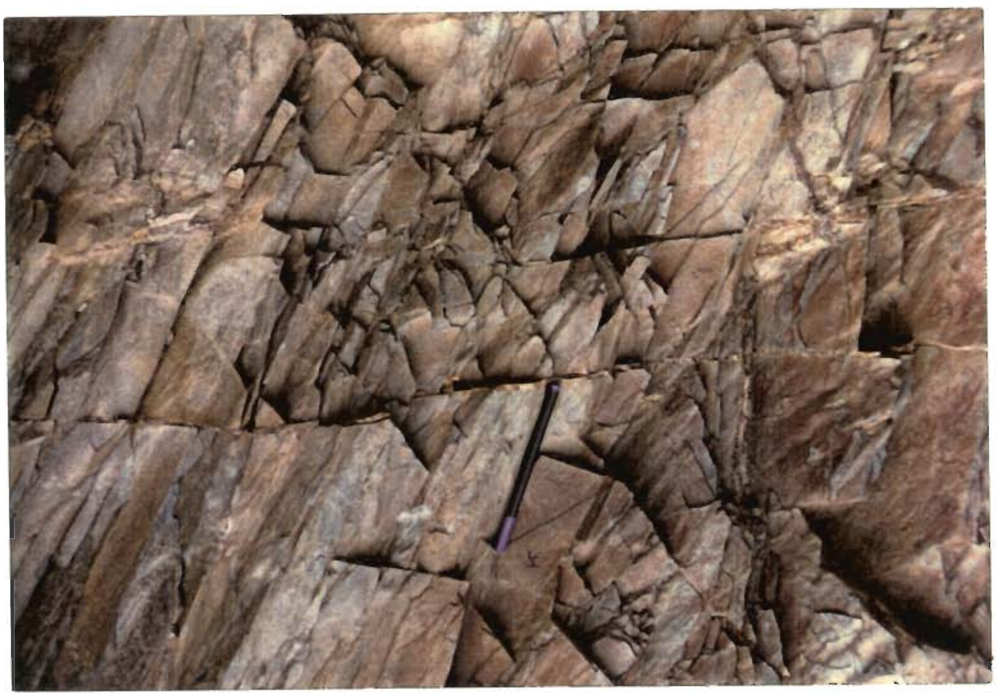
Quartzites of Rautgara Formation showing three sets of joints near Ongad village.



Orthogonal joints in limestone of Deoban Formation near village Chaundhar between Bhaldiyana and Lambgaun.

PLATE 5

Failure along axial plane cleavage joints in an asymmetric antiform in phyllites south of Surkunda.

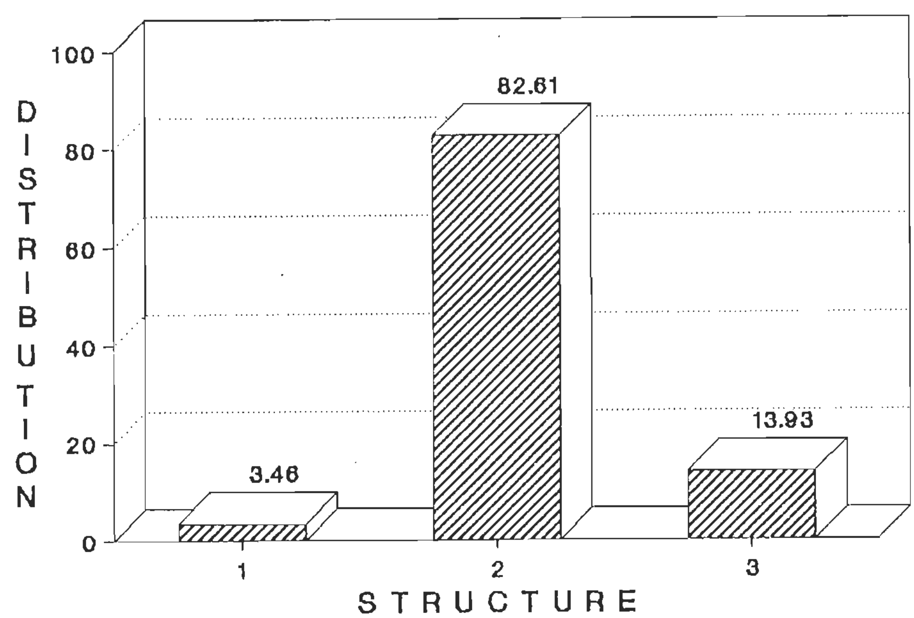


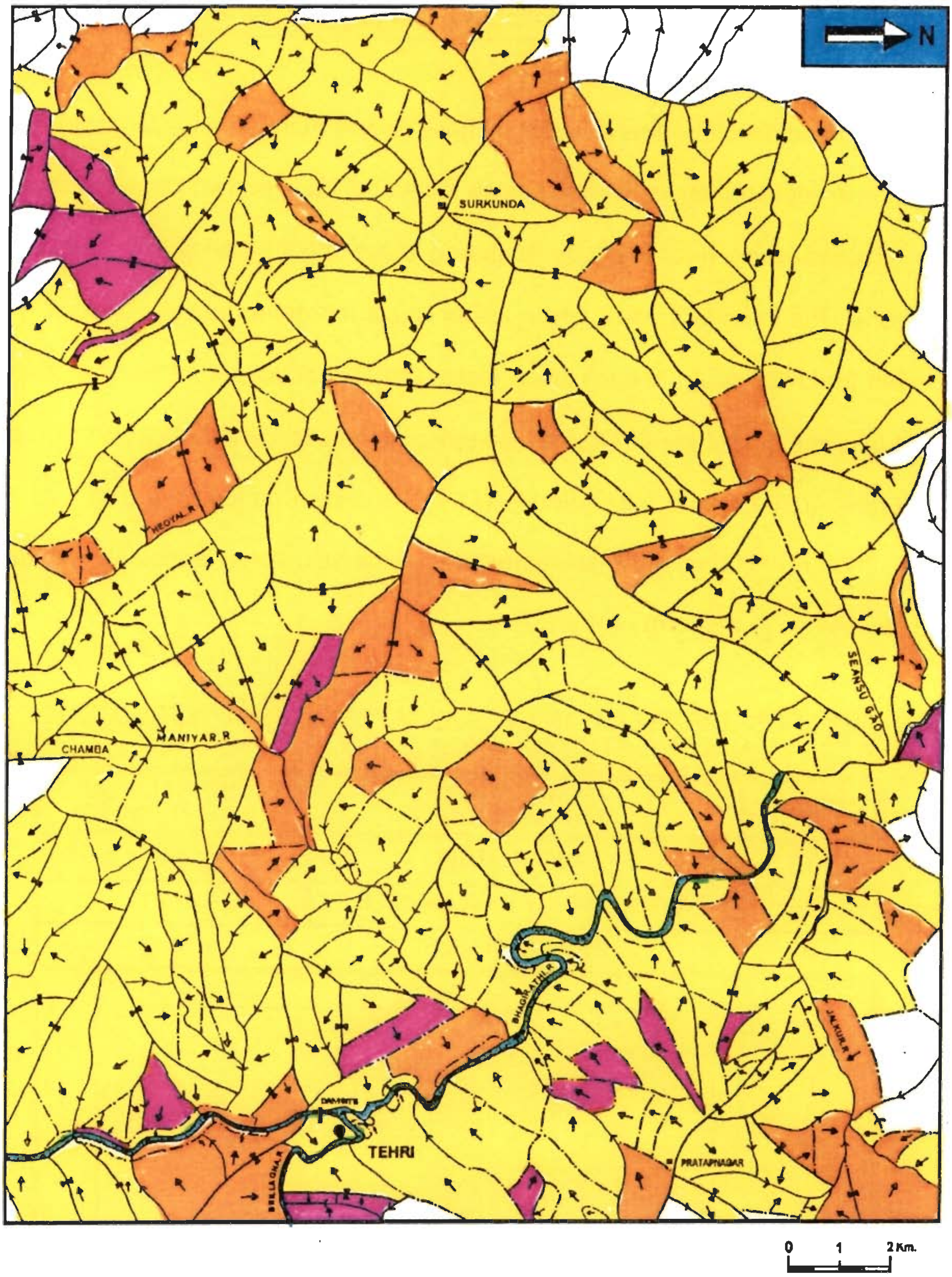
Three sets of joints displayed by phyllites near village Motana between Bhaldiyana and Lambgaun road.

inclination and direction. The attitudes of these discontinuities are plotted on stereonet to get their representatives for each slope facet and the important ones are shown in the structural map (Fig. 4.2). By analysing these model planes with the help of stereonet, the important ones, which are unfavourable from the view of stability are chosen for LHEF rating of each slope facet. The final structural rating of each slope facet falls into one of the three sub-categories namely favourable (<0.9), moderately favourable (0.9-1.4) and unfavourable (>1.4) are shown on the map (Fig. 4.3). The percentage distribution of the sub-categories in the study area is tabulated in Table 4.2. as well as in the form of bars.

TABLE 4.2 DISTRIBUTION OF SUB-CATEGORIES OF STRUCTURE IN THE STUDY AREA

Sl. NO.	STRUCTURE (Subcategories)	DISTRIBUTION (Area in Percent)
1	FAVOURABLE	3.46
2	MODERATELY FAVOURABLE	82.61
3	UNFAVOURABLE	13.93





LEGEND

FAVOURABLE
MODERATELY FAVOURABLE
UNFAVOURABLE

FIG. 4.3 THE DISTRIBUTION OF SUB-CATEGORIES OF STRUCTURE

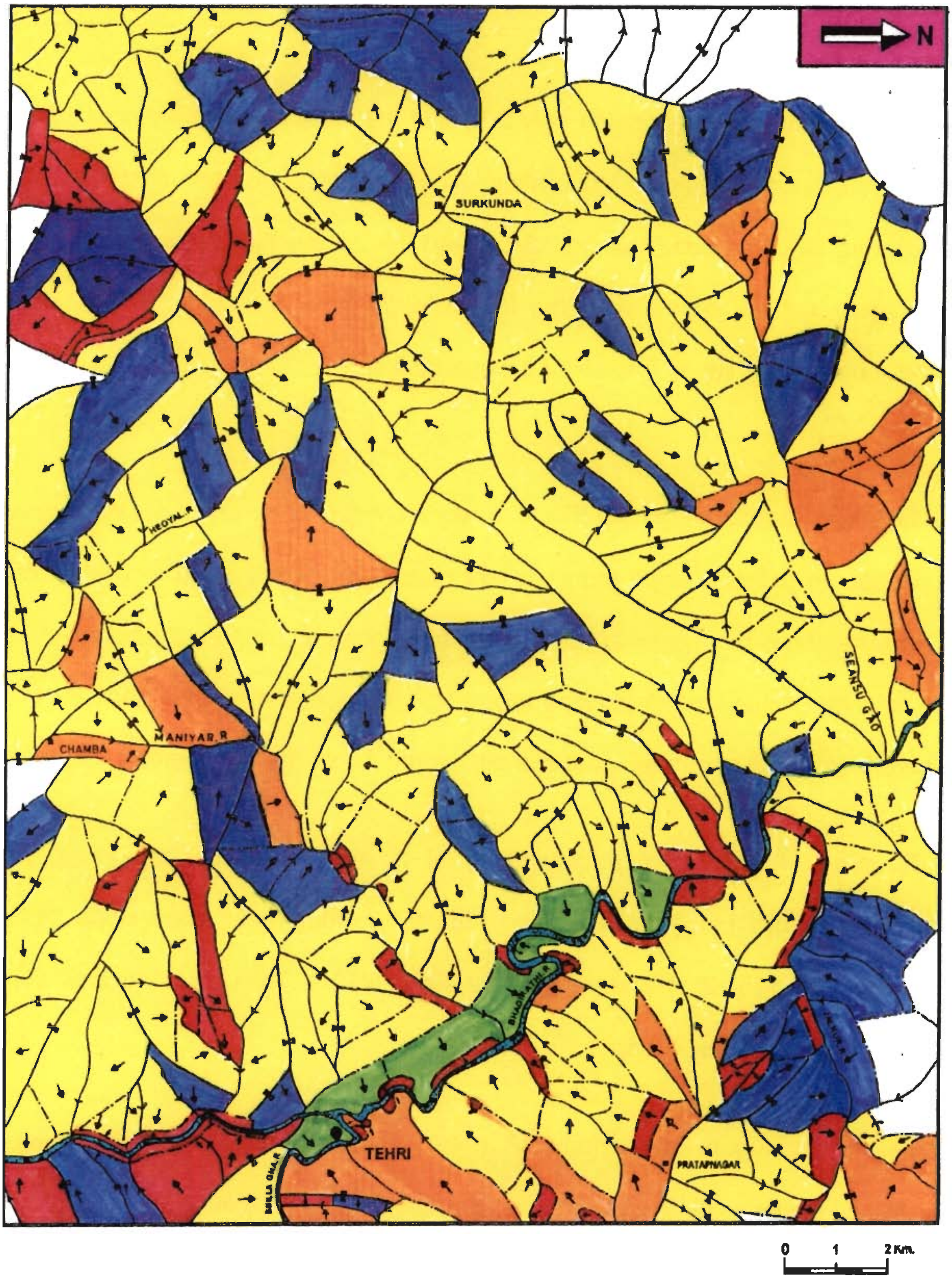
The favourable category cover only 3.46% of the area, mainly present in the eastern and southwestern regions. Moderately favourable category is the most dominant one, covering 82.61% area. It is well distributed throughout the area of study. The third category `unfavourable' covers the 13.93% of the area, is also distributed throughout the area, mainly lies in the isolated slope facets.

4.1.3 Slope Morphometry Map

The Slope Morphometry map (Fig. 4.4) represents zones of different slope inclination. In order to prepare slope morphometry map, the general slope inclination of each slope facet has been calculated. This has been done by counting the contour lines per unit length within individual slope facets from the toposheet. Often the counting has been done in two to three locations distributed within the slope facets.

The area of study has a distribution of all the five slope categories, namely escarpment/cliff (>45°), steep slope (36°-45°), moderately steep slope (26°-35°), gentle slope (16°-25°) and very gentle slope (<15°). Their distribution is shown in Table 4.3 as well as in bars.

The slope category escarpment/cliff (>45°) covers 5.96% of the study area. This category of slopes are mostly seen in small slope facets adjoining Bhagirathi river and Jalkur river. They are seen as isolated patches along other water courses also. A number of slopes inclined at more than 45° angle are also found in the southwestern region in limestone terrain. The steep slopes occupy 15.35% of the study area, where these slopes generally fall in hard rocks. Slopes of this category are also seen in



LEGEND

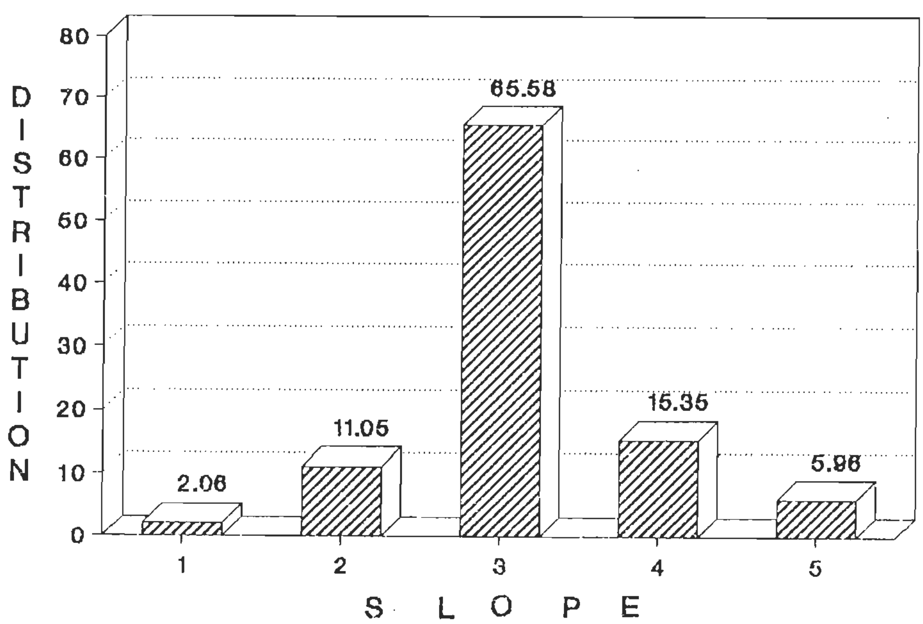
- VERY GENTLE SLOPE (<15°)
- GENTLE SLOPE (16°-25°)
- MODERATELY STEEP SLOPE (26°-35°)
- STEEP SLOPE (36°-45°)
- ESCARPMENT / CLIFF (>45°)

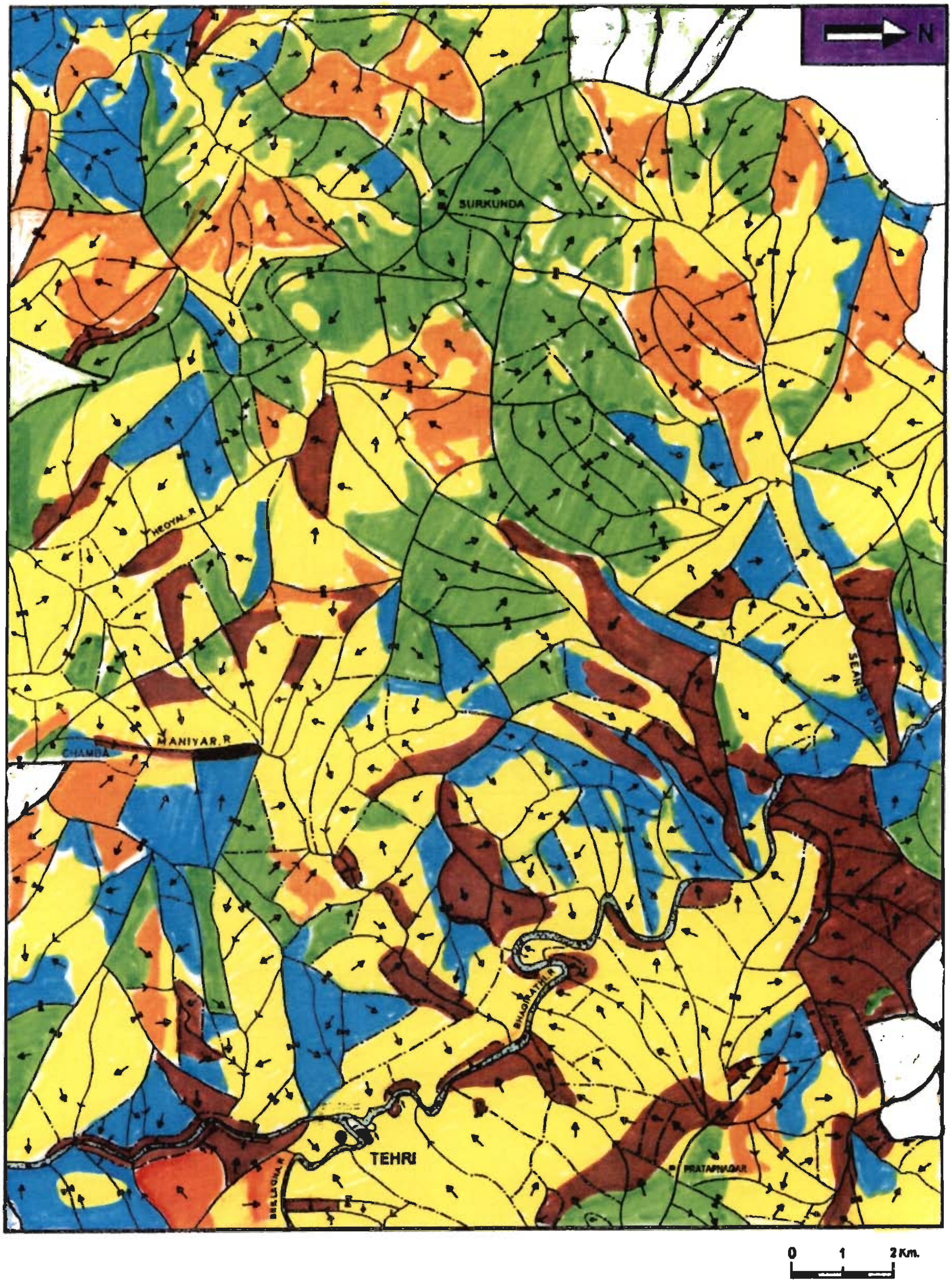
FIG. 4.4. SLOPE MORPHOMETRY MAP OF THE STUDY AREA

southwestern and the some parts of northeastern region, where limestones and quartzites are exposed. Moderately steep slopes form a dominant category and are well distributed throughout the area. The gentle slopes are seen in patches and commonly lie in the northern and eastern regions. The very gentle slopes are seen in the regions of old river terraces forming agriculture land of the region mostly adjoining the Bhagirathi river.

TABLE 4.3 DISTRIBUTION OF SUB-CATEGORIES OF SLOPE MORPHOMETRY IN THE STUDY AREA.

SL. NO.	SLOPE CATEGORY (Subcategories)	DISTRIBUTION (Area in Percent)
1	Very Gentle Slope	02.06
2	Gentle Slope	11.05
3	Moderately Steep Slope	65.58
4	Steep Slope	15.35
5	Cliff/Escarpment	05.96





LEGEND

- AGRICULTURAL LAND / POPULATED FLAT LAND
- THICKLY VEGETATED FOREST AREA
- MODERATELY VEGETATED AREA
- SPASELY VEGETATED AREA WITH LESSER GROUND COVER
- BARREN LAND

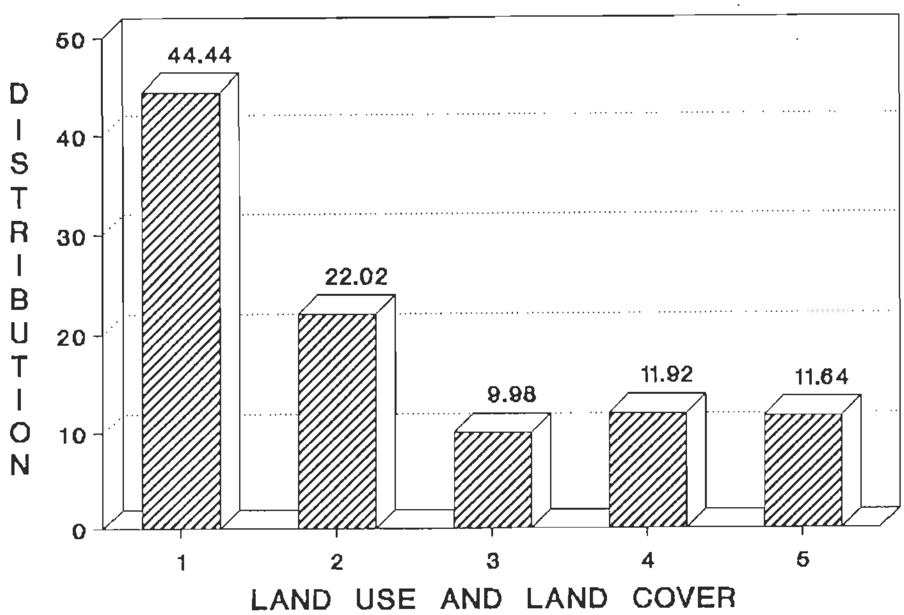
FIG. 4.5 LAND USE AND LAND COVER MAP OF THE STUDY AREA

4.1.4 Land use and Land cover Map

Land use and land cover play an important role in the stability of hill slopes. The vegetation cover commonly provides strength to the slope material and smothers the action of climatic agents on slopes. Land use and land cover map (Fig.4.5) of the area shows the distribution of the sub-categories namely, agricultural land/populated flat land, thickly vegetated forest area, moderately vegetated forest area, sparsely vegetated area with lesser ground cover and barren lands. The percent distribution of sub-categories of land use and land cover are shown in Table 4.4 as well as in the form of bars.

TABLE 4.4 DISTRIBUTION OF SUB-CATEGORIES OF LAND USE AND LAND COVER IN THE STUDY AREA.

SL.NO.	LAND USE & LAND COVER (Subcategories)	DISTRIBUTION (Area in Percent)
1	Agricultural Land/Populated Flat Land	44.44
2	Thickly Vegetated Forest Area	22.02
3	Moderately Vegetated Forest Area	9.98
4	Sparsely Vegetated Forest With Lesser Ground Cover	11.92
5	Barren Land	11.64

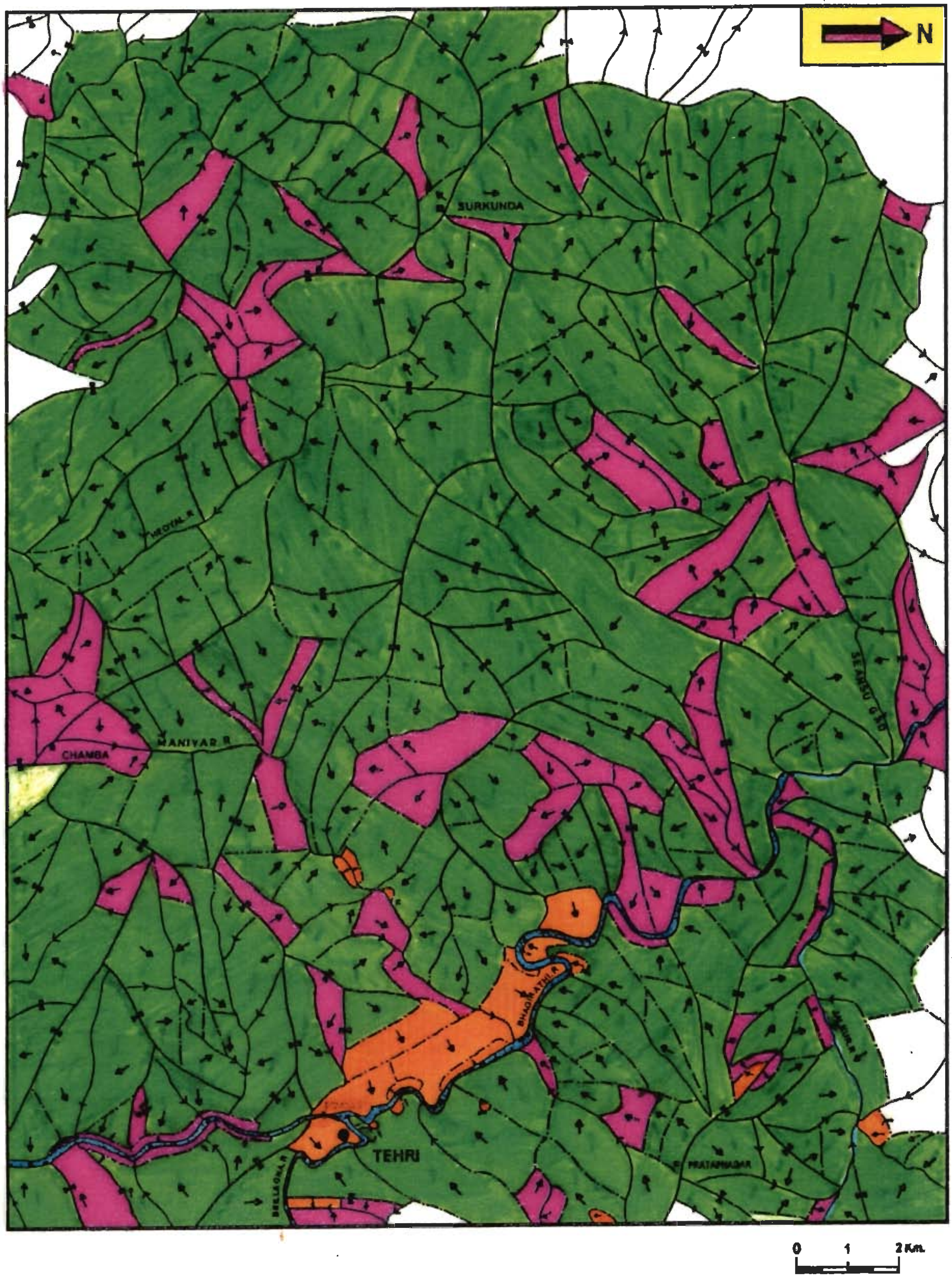


Agricultural land/populated flat land slopes are the most dominant ones covering 44.44% in the region. Agriculture, in general, is practised on gentle to very gentle slopes such as old river terraces, though moderately steep slopes mostly formed by weathered soft rocks, are also used for this purpose. Agricultural field/populated flat lands are mainly seen along the Bhagirathi river and its tributaries such as Bhillangana, Heunal, Jalkur, Maniyar and Seansu rivers. Slopes having thickly vegetated forests are generally observed on high reaches in the western, central and southwestern regions, in addition to isolated patches in different parts of the region. Slopes covering moderately vegetated forests are mainly seen in the northwestern and southwestern areas. Sparsely vegetated slopes and barren slopes occupy more than ten percent each in northern, northeastern and southeastern regions.

Distribution of sub-categories of the land use and land cover for each slope facet has been carefully studied to award LHEF ratings. If more than one type of LULC pattern are seen in a single slope facet, the fraction area of each LULC pattern with respect to slope facet area has been calculated and multiplied by their respective ratings and added to get the actual LHEF rating for the slope facet.

4.1.5 Relative Relief Map

Relative relief map may be defined as the maximum height within a slope facet, measured in the direction of slope. Relative relief map of the area (Fig. 4.6) shows the distribution of all the three sub-categories of relative relief in the region, namely low relief (≤100 m), medium relief (101m-300m) and high relief (>300), which occupy 2.67%, 17.77% and 79.56% of the area respectively (Table 4.5).



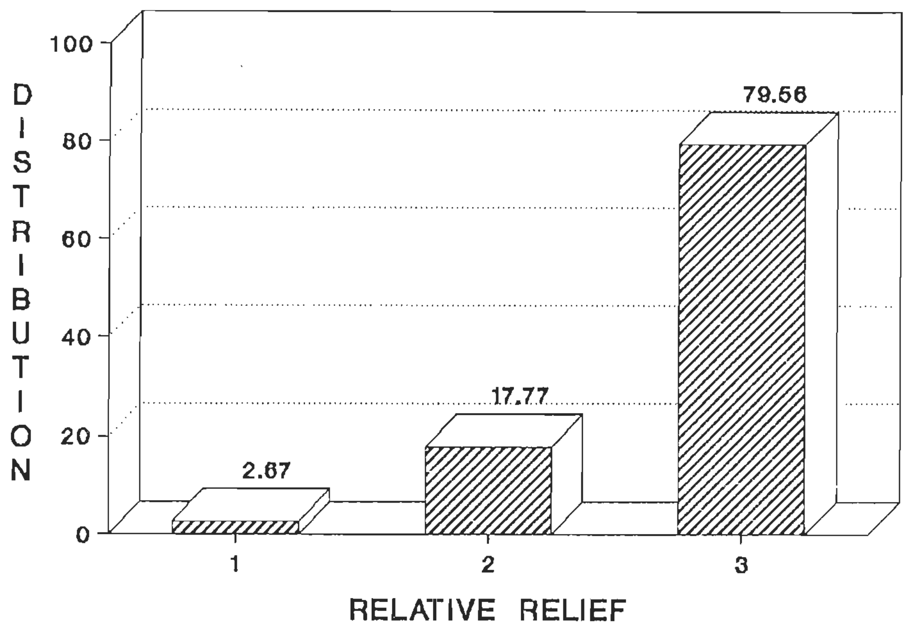
LEGEND

HIGH RELIEF (>300 M)
MEDIUM RELIEF (101-300M)
LOW RELIEF (<100M)

FIG. 4.6 RELATIVE RELIEF MAP OF THE STUDY AREA

TABLE 4.5 DISTRIBUTION SUB-CATEGORIES OF RELATIVE RELIEF IN THE STUD AREA.

SL. NO.	RELATIVE RELIEF (Subcategories)	DISTRIBUTION (Area in Percent)
1	Low Relative Relief	02.67
2	Medium Relative Relief	17.77
3	High Relative Relief	79.56



Slopes of Low relief, cover a small part of the area and these slopes are mostly found along both the banks of the Bhagirathi river. The old terraces of the Bhagirathi river fall in low relief areas. Low relief slopes are also found along the Maniyar river and in the northwestern region. Medium relief slopes are well distributed in the study area and are seen in most of the parts of the region. High relief slopes share the major part (79.56%) of the region and are well distributed throughout the area.

4.1.6 Hydrogeological Condition Map

Hydrogeological condition map (Fig. 4.7) indicates the surface water conditions in the study area. All the five sub-categories namely flowing, dripping, wet, damp and dry conditions are seen in the study area. The distribution of sub-categories of

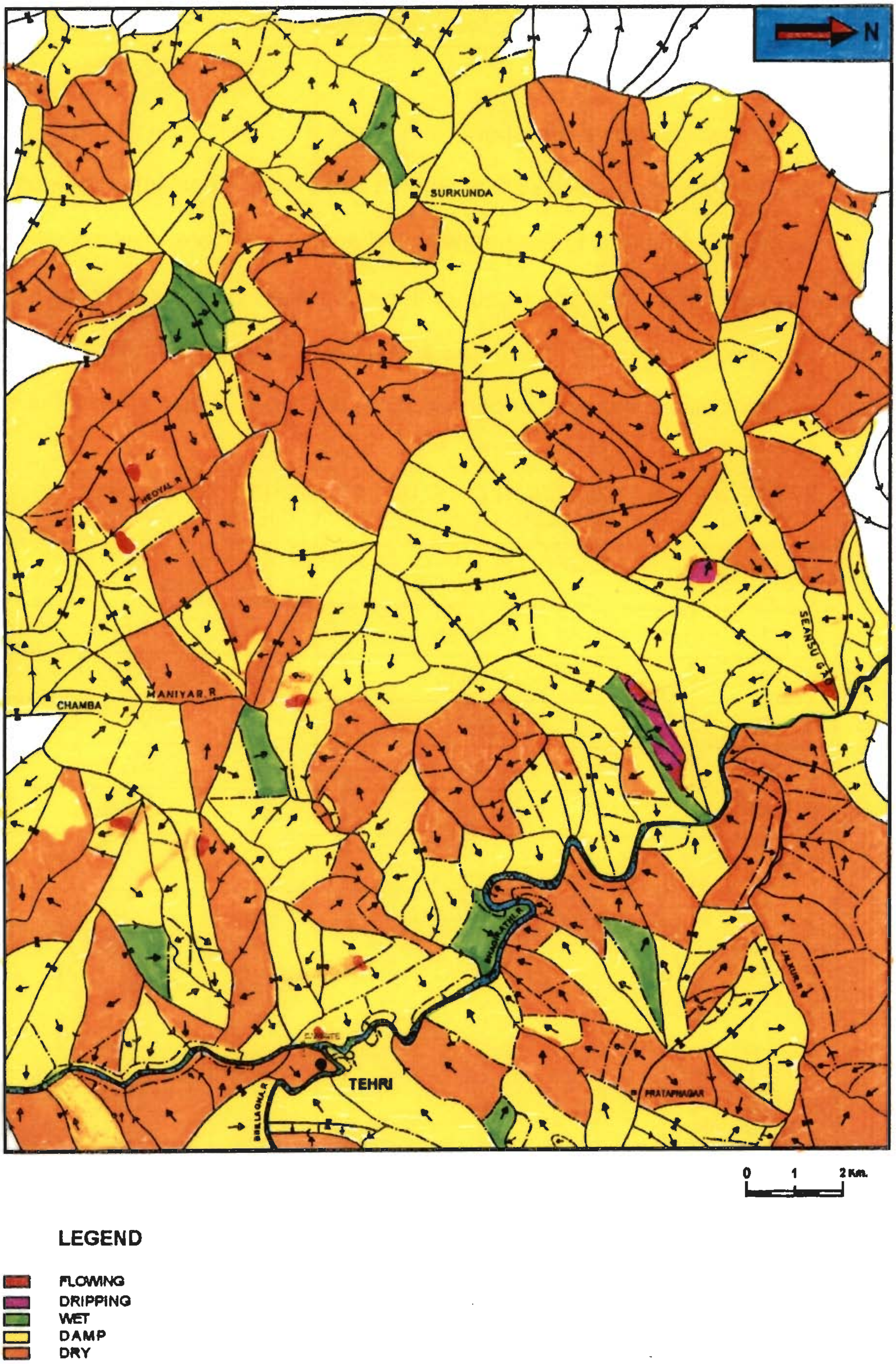


FIG. 4.7 HYDROGEOLOGICAL CONDITION MAP OF THE STUDY AREA

hydrogeological conditions are shown in Table 4.6 as well as in the form of bars. Flowing and dripping conditions are present in less than one percent of the study area and are mainly prevailing in the northern and southern regions. Wet conditions are also prevailing on a few slope facets of the study area. Damp conditions, the most dominant one, cover 57.7% of the area and are well distributed throughout the area. Dry conditions also share a major part (39.65%) and are well distributed in the region.

TABLE 4.6 DISTRIBUTION OF SUB-CATEGORIES OF HYDRO - GEOLOGICAL CONDITIONS IN THE STUDY AREA

SL. NO.	HYDROGEOLOGICAL CONDITIONS (Subcategories)	DISTRIBUTION (Area in Percent)
1	Flowing	00.11
2	Dripping	00.23
3	Wet	02.30
4	Damp	57.70
5	Dry	39.65

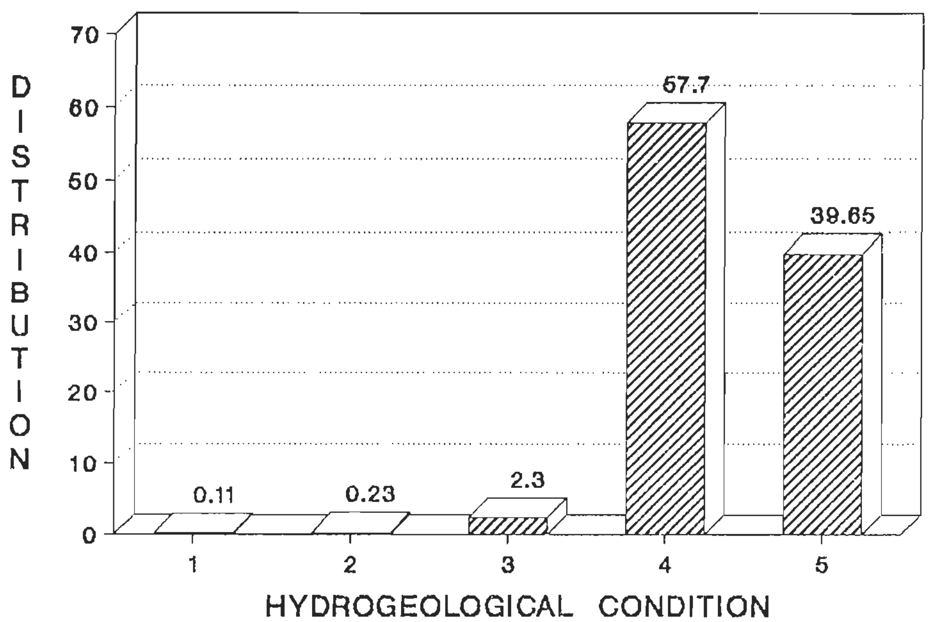


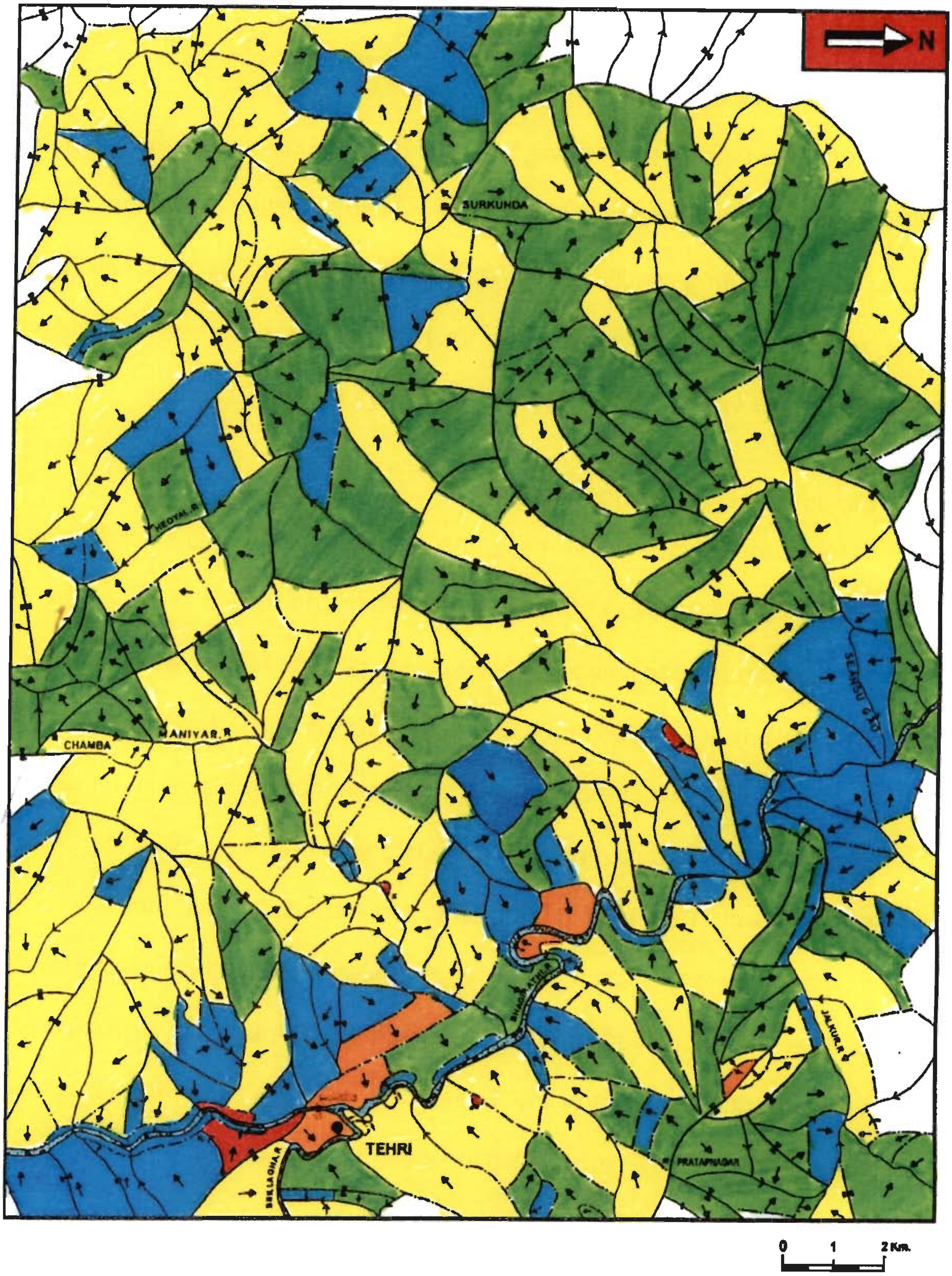
PLATE 6

Panoramic view of a hill with steep slopes and high relief between Tehri and Bhaldiyana.

In case of slope facets showing wet, damp and dry conditions, the dominant type of hydrogeological conditions have been assessed and the rating is awarded. The areas of dripping and flowing conditions are generally seen in small patches, which may fall within a small area of slope facet. The fractional ratings have been calculated and added to get the total LHEF rating for each slope facet.

4.1.7 Landslide Hazard Zonation Map

After the preparation of factorial maps, the ratings of all the causative factors have been added slope facet-wise, to get the total estimated hazard (TEHD). The TEHD values have been used to categorise the slope facets into hazard zones such as very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH), and very high hazard (VHH). The distribution of different hazard zones in the study area is shown in the landslide hazard zonation (LHZ) map (Fig. 4.8). Here, the probability of failure is shown in terms of relative time, since absolute time frame for landslide events do not have any relation. For example, the probability of failure of a moderate hazard slope is more as compared to a low hazard slope but less as compared to a high hazard slope. A perusal of the Table 4.7 shows that all the hazard categories VLH, LH, MH, HH and VHH are seen in the area. The distribution of hazard categories are; 1.12%, 32.46%, 53.56%, 12.51% and 0.35% for VLH, LH, MH, HH and VHH respectively. The present study of LHZ mapping has covered 365 slope facets, covering an area about 450 sq. km. The mapping has indicated that the number of slope facets falling in VLH, LH, MH, HH and VHH zones are 6, 118, 166, 70 and 5 respectively (Table 4.7) and the same has been shown in bars.



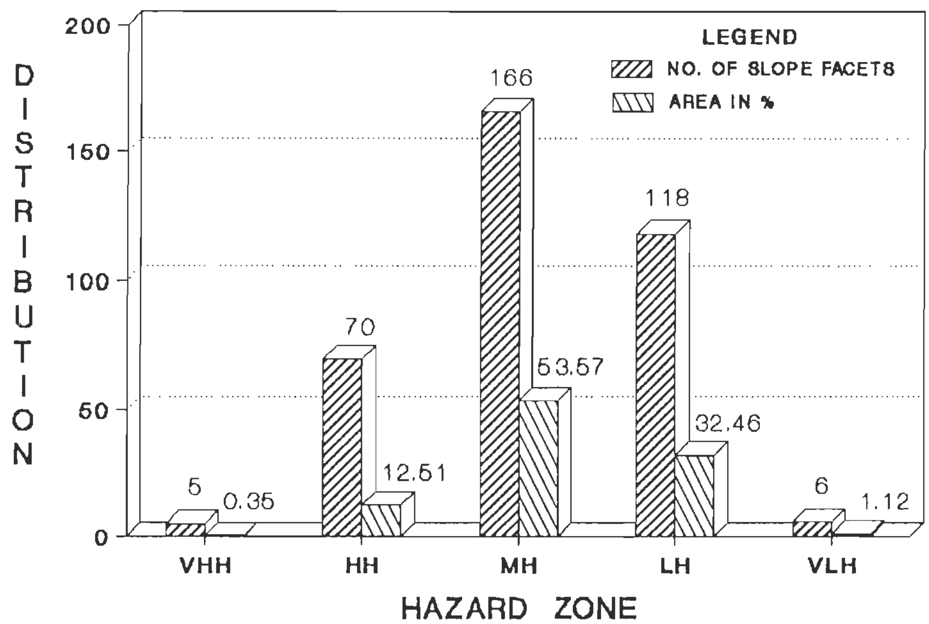
LEGEND

- VERY LOW HAZARD ZONE
- LOW HAZARD ZONE
- MODERATE HAZARD ZONE
- HIGH HAZARD ZONE
- VERY HIGH HAZARD ZONE

FIG. 4.8 LANDSLIDE HAZARD ZONATION MAP OF THE STUDY AREA

TABLE 4.7 TOTAL AREA COVERED BY VARIOUS HAZARD ZONES

SL. NO.	HAZARD ZONES	NO. OF SLOPE FACETS	AREA (In Percent)
1	VERY HIGH HAZARD (VHH)	5	00.35
2	HIGH HAZARD (HH)	70	12.51
3	MODERATE HAZARD (MH)	166	53.57
4	LOW HAZARD (LH)	118	32.46
5	VERY LOW HAZARD (VLH)	6	01.12



River terraces, which are mostly flat lands, form the most stable parts of the study area and are covered by the VLH zones. The LH slopes are found to be present in abundance and distributed well throughout the area. They are mainly seen in the northeastern and northwestern regions. The MH zones are the most dominant ones covering about 53.36% of the area and well distributed throughout the study area. The HH zones are mainly confined in those slope facets, which are close to the Bhagirathi river in the northeast region and HH slope facets are also present in southwestern region. The VHH slope facets, which covers less than half percent, are mainly seen in the isolated slope facets.

□ 4.2 DISTRIBUTION OF SUB-CATEGORIES OF CAUSATIVE FACTORS IN VARIOUS HAZARD ZONE

In order to know the influence of sub-categories of each causative factor over individual hazard zones, their percentages have been calculated and percent polygons have been plotted. Distribution of sub-categories of individual causative factors are discussed below:

4.2.1 Lithology

Distribution of various rock and soil types have been studied for different hazard zones shown in Table 4.8.

TABLE 4.8 DISTRIBUTION OF LITHOLOGY (IN PERCENT) IN VARIOUS HAZARD ZONES

LITHOLOGY	HAZARD ZONES				
	VLH	LH	MH	HH	VHH
Sl+Q Band	-	0.13	4.62	8.26	-
Ph	12.13	12.59	29.05	53.26	76.74
Q	-	38.83	18.32	9.28	-
Lst	5.15	4.95	5.38	4.23	-
SC	-	4.11	2.95	0.88	12.79
RBM	82.72	3.88	0.28	1.84	-
Sl	-	-	0.85	1.87	-
Ph +Q Band	-	6.76	12.08	8.69	10.46
M	-	0.08	0.14	-	-
Q+Ph Band	-	14.53	9.94	4.49	-
Ph+Lst, C &Q Band	-	1.46	0.99	-	-
Lst+Q & Sl Band	-	4.47	6.49	4.79	-
Q+Sl & Ph Band	-	5.29	3.32	-	-
Band of Q & Ph	-	2.91	5.59	2.39	-

Sl-Slate, Ph-Phyllite, Q-Quartzite, Lst-Limestone, SC-Soil Cover, RBM-River Borne Material, M-Metabasics, C-Conglomerate

VLH-VERY LOW HAZARD, LH-LOW HAZARD, MH-MODERATE HAZARD, HH-HIGH HAZARD AND VHH-VERY HIGH HAZARD

Rocks like phyllite and limestone, in addition to river borne material (RBM) are mainly present on VLH slopes. The rock borne material (RBM) has a major share covering an area of 62.72%, which are seen in the form of old river terraces adjoining Bhagirathi river. Low hazard (LH) zones are present in a major part (32.46%) of the study area include the various rock and soil types. Their distribution in percentage have been shown in the Table 4.8. A major part (38.83%) of the low hazard zones is occupied by quartzite rock. MH zones cover the largest part (53.26%) of the region and it's maximum part is covered by phyllites (29.05%). The percent distribution of slope forming materials in moderate hazard zones have been shown in Table 4.8. High hazard slope facets cover a considerable part (12.51) of the study area. The distribution of rock and soil types exposed in the HH zones are shown in Table 4.8. The most dominant rock in HH slope facets is phyllite (53.26%). Very high hazard (VHH) slope facets cover less than a half percent of the study area. The major part (76.74%) of VHH zones is covered by phyllites and the other lithology are soils (12.79%) and phyllite with minor bands of quartzite (10.47%).

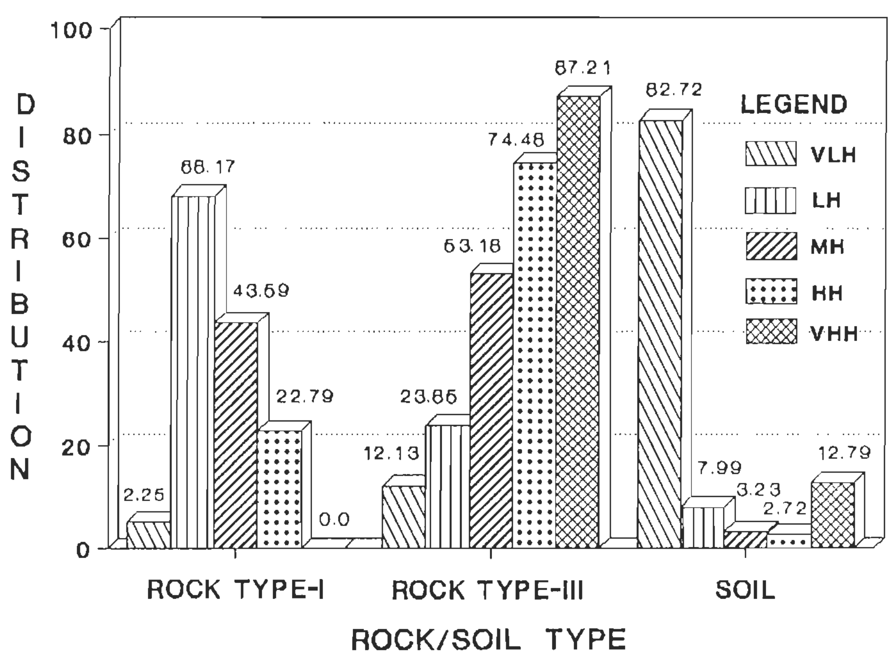
It is to be noted that percentage of hazard zones is calculated with respect to total area covered by the 365 slope facets, whereas the percentage of rock and soil types is calculated with respect to the area covered by corresponding hazard zones.

Rock and soil types which are exposed in the area fall mainly in three groups of rock and soil according to the modified LHEF rating scheme. These three groups namely, rock type-I, rock type-III and soil with their percent distribution for different hazard zones have been shown in Table 4.9 as well as in the form of bars. Rock type-I represents, relatively hard rocks like quartzite and limestone, which are resistant to erosion. Rock type-II represents, terrigenous sedimentary rocks which are absent in the study area. Rock type-III represents, relatively soft rocks like phyllite and slate, which weathers quickly and promote instability. Soil includes the older well-compacted fluvial fill material (alluvial) to younger loose material. The distribution of rock type-I & III and soil in the study area have been shown again as percent polygons for different hazard zones (Fig.4.9). The figure shows three distinct trends for the slope materials including rock type-I & III and soil.

TABLE 4.9 DISTRIBUTION OF ROCK/SOIL TYPES (IN PERCENT) IN VARIOUS HAZARD ZONES

ROCK/SOIL TYPE	HAZARD ZONES				
	VLH	LH	MH	HH	VHH
Rock Type-I	05.15	68.17	43.59	22.79	-
Rock Type-III	12.13	23.85	53.18	74.48	87.21
Soil	82.72	07.99	03.23	02.72	12.79

VLH-VERY LOW HAZARD, LH-LOW HAZARD, MH-MODERATE HAZARD, HH- HIGH HAZARD AND VHH-VERY HIGH HAZARD



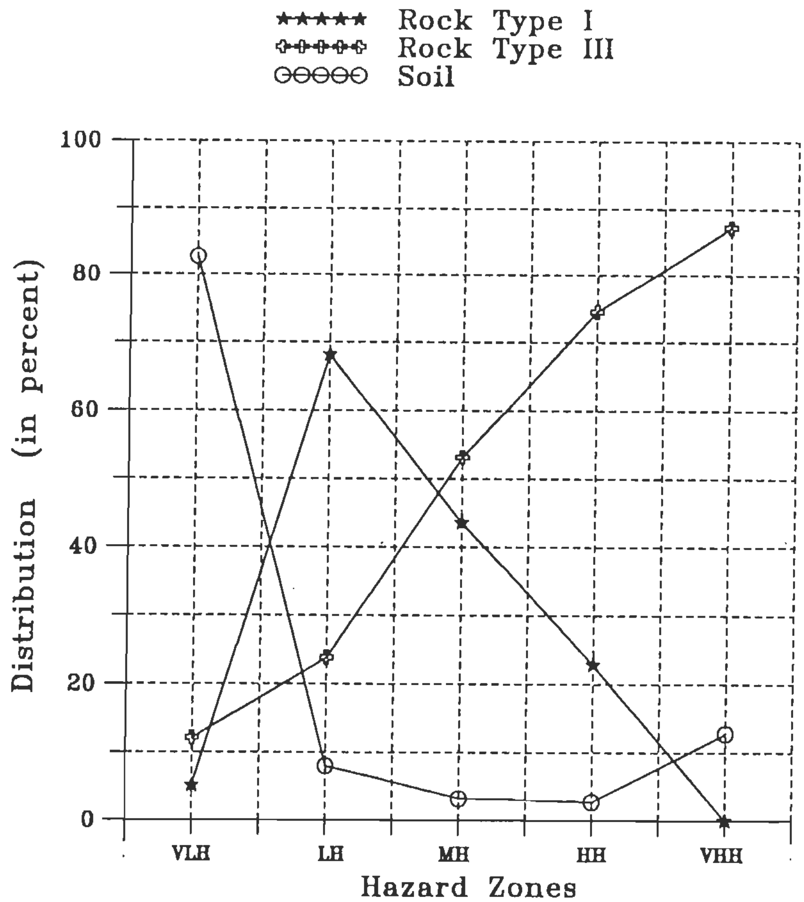


FIG. 4.9 PERCENT POLYGONS OF ROCK TYPE I & III AND SOIL IN VARIOUS HAZARD ZONES

A perusal of Fig.4.9 shows VLH slope facets mainly cover the older well compacted river borne material (RBM). For example, in case of VLH zones, soil occupies more than 80% of the area, whereas rock type-I & III cover about 20% area. On the other hand, soil is generally less than the 10% for other hazard zones.

The rock type-I, is maximum for LH zones (68.17%) and show decreasing trend towards VHH zones indicating that rocks are less prone to instability in the study area. The rock type-III, which includes phyllites and other weak rocks, consistently increases in percent form VLH (12.13%) zones to VHH (87.21%) zones. It indicates that rock type-III is more prone to instability.

Finally it is concluded from the above discussion that soil dominates the VLH zones. LH zones, which are considered stable areas, are dominated by rock type-I, which represents the strong rock and have less LHEF rating. MH zones are considered as fairly stable slopes, mainly covered by rocks of type-I and III in almost equal percentages. HH and VHH zones which are to be considered relatively unstable and most unstable zones respectively, are dominated by rock type-III. In general, in the higher hazard zones percentages of rock type-III increases as it represents the weak rocks and have more LHEF ratings. On the other hand percentage of rock type-I decreases in the higher hazard zones as it is represented by the group of relatively hard rocks.

4.2.2 Structure

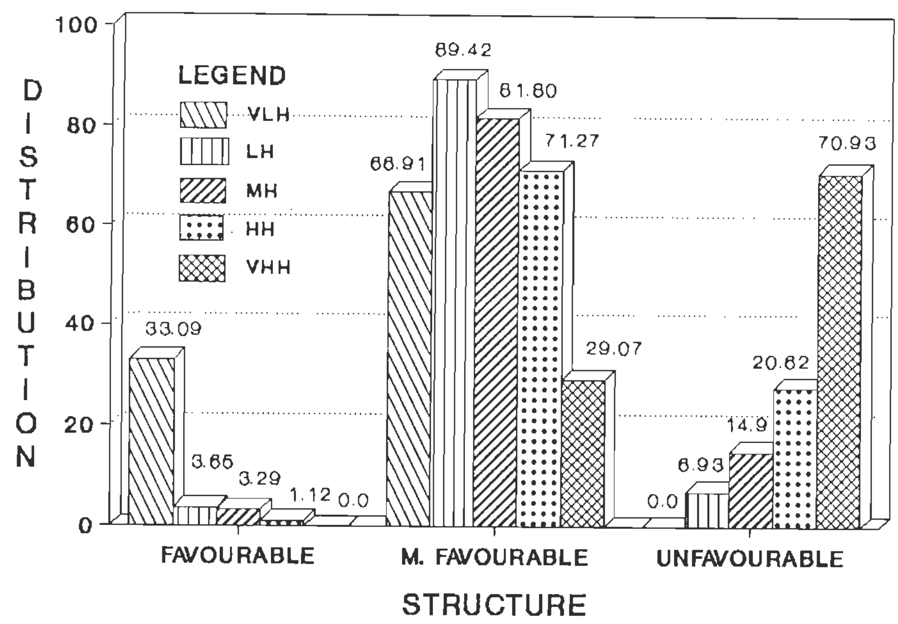
Three sub-categories of structure namely favourable, moderately favourable and unfavourable have been considered for the structure. The percent distribution of these sub-categories over various hazard zones are given in the Table 4.10. The study reveals that moderately favourable sub-category dominates all the hazard zones except very high hazard zones, where sub-category `unfavourable' persisting over (70.93%) area of VHH zones.

Percent polygons of all the sub-categories have also been plotted (Fig.4.10) over different hazard zones to assess the relative trends of the categories. A review of Fig 4.10 reveals that there are three distinct trends corresponding to the three sub-categories. The sub-category `favourable' shows a negative trend with a minimum value (0.0%) for VHH zones. Moderately favourable sub-category also shows a

TABLE 4.10 DISTRIBUTION OF SUB-CATEGORIES OF STRUCTURE IN VARIOUS HAZARD ZONES

STRUCTURE (Sub-categories)	HAZARD ZONES				
	VLH	LH	MH	HH	VHH
FAVOURABLE	33.09	3.65	3.29	1.12	0.0
MODERATELY FAVOURABLE	66.91	89.42	81.80	71.27	29.07
UNFAVOURABLE	0.0	6.93	14.90	27.62	70.93

VLH-VERY LOW HAZARD; LH-LOW HAZARD; MH-MODERATE HAZARD; HH- HIGH HAZARD AND VHH-VERY HIGH HAZARD



negative trend in general with a peak value (89.42%) for LH zones. This sub-category covers maximum percent area in most of the hazard zones except VHH zones. The sub-category `unfavourable' shows an increasing trend from VLH zones (0.0%) to VHH zones (70.93%). Finally, it is concluded that the sub-categories which have more LHEF rating are widely distributed in unstable zones and vice versa.

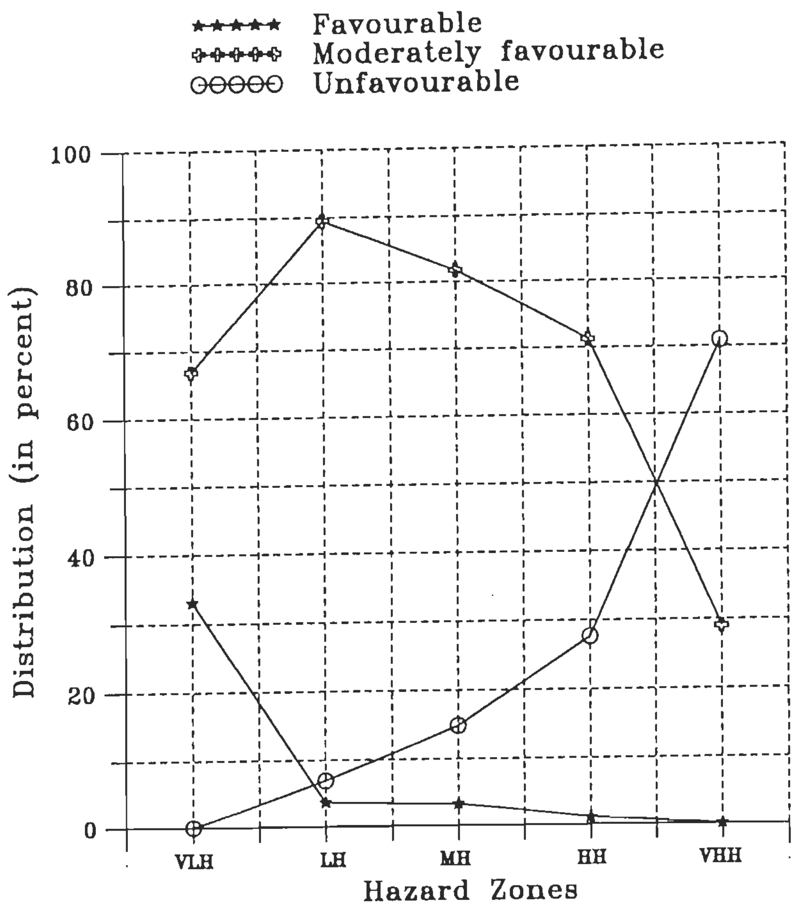


FIG 4.10 PERCENT POLYGONS OF STRUCTURE IN VARIOUS HAZARD ZONES

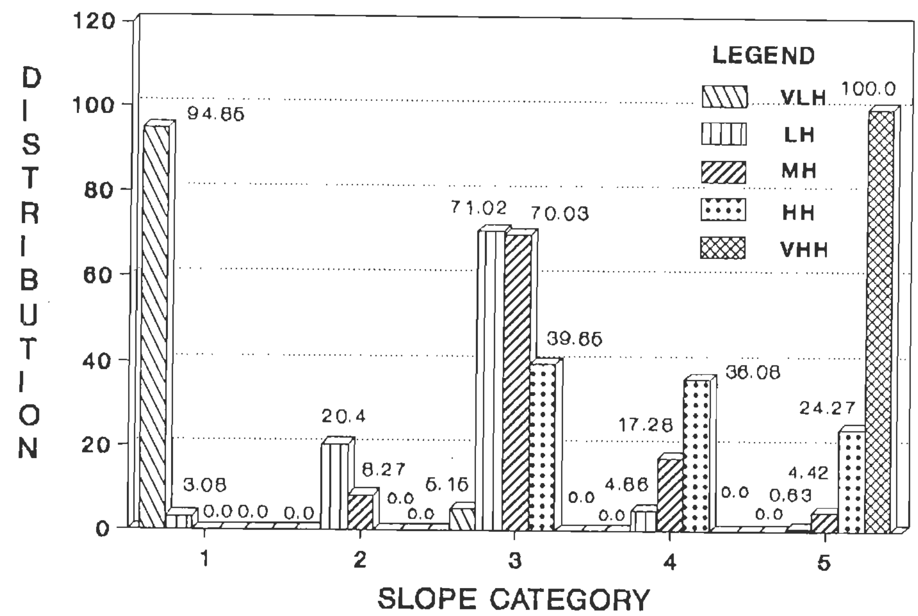
4.2.3 Slope Morphometry

The percent distribution of various sub-categories of slope morphometry over the different hazard zones have been shown in Table 4.11 as well as in bars. Very gentle slopes and moderately steep slopes have been observed on very low hazard (VLH) zones. VLH zones are mainly covered by very gentle slopes (94.85%), which give the minimum LHEF rating in case of slope morphometry. Though, low hazard (LH) zones are covered by all the five sub-categories of slope morphometry, but major areas have been covered by the moderately steep slopes (71.02%) and gentle slopes (20.4%).

TABLE 4.11 DISTRIBUTION OF SUB-CATEGORIES OF SLOPE MORPHOMETRY (IN PERCENT) IN VARIOUS HAZARD ZONES

SL. NO.	SLOPE CATEGORY	HAZARD ZONES				
		VLH	LH	MH	HH	VHH
1	Very Gentle Slope	94.85	03.08	-	-	-
2	Gentle Slope	-	20.40	08.27	-	-
3	Moderately Steep Slope	05.15	71.02	70.03	39.65	-
4	Steep Slope	-	04.86	17.28	36.08	-
5	Cliff/Escarpment	-	00.63	04.42	24.27	100

VLH-VERY LOW HAZARD, LH-LOW HAZARD, MH-MODERATE HAZARD, HH- HIGH HAZARD AND VHH-VERY HIGH HAZARD



In case of moderate hazard (MH) zones, the major areas are shared by moderately steep slopes (70.03%) and steep slopes (17.28%). Three sub-categories of slope morphometry namely moderately steep slopes, steep slopes and cliff or escarpment are distributed over the high hazard zones. The percent distribution of these sub-categories are 39.65%, 36.08% and 24.27% respectively. Very high hazard (VHH) zones covered by the escarpment/cliff only.

This distribution has also been shown as percent polygons for different hazard zones (Fig.4.11). A study of this figure shows five distinct trends of each sub-category of slope morphometry.

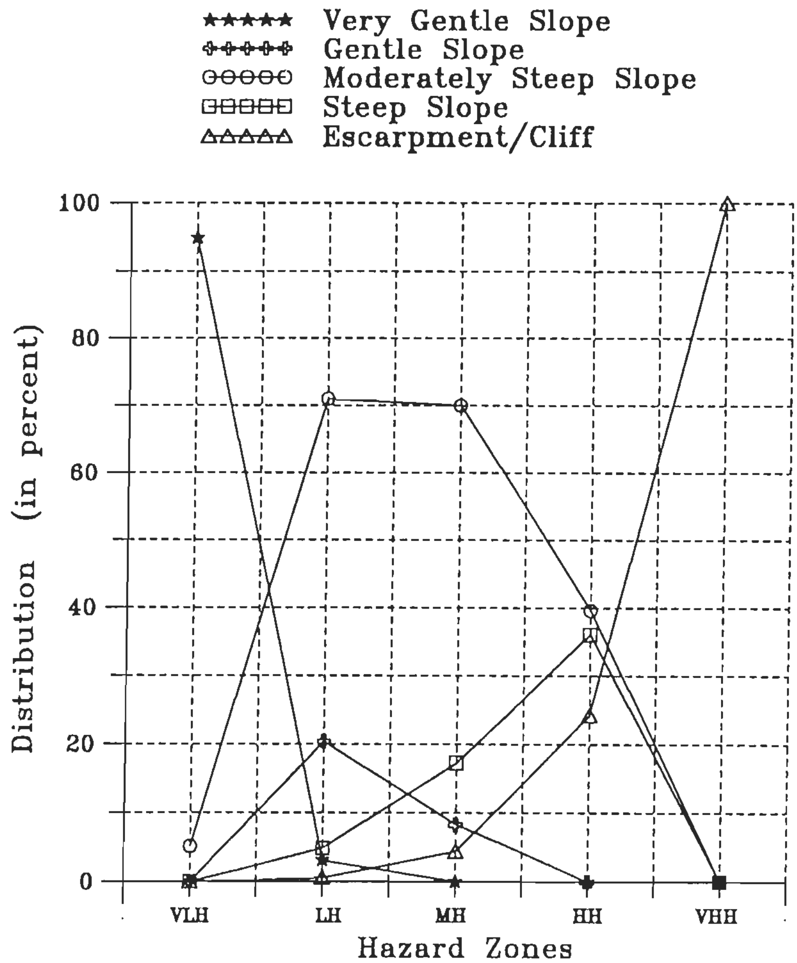


FIG 4.11 PERCENT POLYGONS OF SLOPE MORPHOMETRY IN VARIOUS HAZARD ZONES

Very gentle slopes show the negative trend. These slopes are dominantly present (94.85%) in the VLH zones, whereas in LH zones they cover 3.08% area only. Gentle slopes distributed over a small part of LH (20.4%) and MH (8.27%) zones. Moderately steep slopes, which are distributed just over 5.15% area of VLH zones, cover the maximum area (71.02%) in LH zones and afterwards show a decreasing trend with

39.65% area covered in the HH zones. Steep slope shows an increasing trend towards higher hazard zones. Steep slopes cover 4.86% of the LH zones, whereas 36.08% of the HH zones. Cliffs/Escarpments also show the increasing trend from LH zones to VHH zones. Cliffs/escarpments cover 0.63% area of the LH zones , whereas 100% area of the VHH zones.

Finally, it is concluded that sub-categories of slope morphometry, which are less prone to instability, mainly distributed in stable zones. On the other hand, sub-categories, which are more prone to instability, mainly distributed in unstable zones such as HH & VHH zones. For example, very gentle slopes (>15°) dominantly occupy the area in very low hazard zones, gentle slopes are mostly seen in low hazard zones, Moderately steep slopes mainly distributed in low hazard and moderate hazard zones. Steep slopes mainly fall in the high hazard zones. Very high hazard zones which are considered as the most unstable zones, completely (100%) covered by the cliff or escarpment.

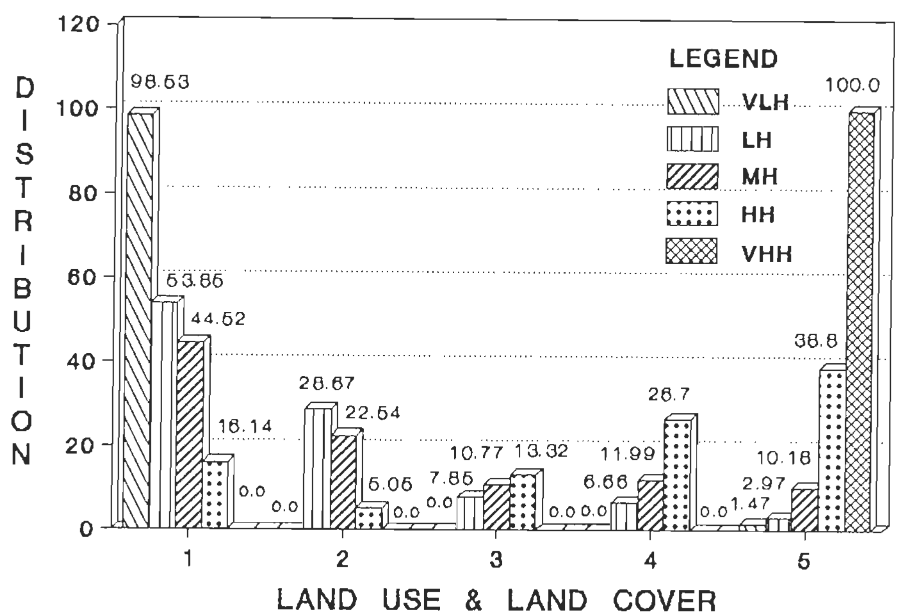
4.2.4 Land use and land cover

Distribution of various sub-categories of land use and land cover have been studied and their distribution in percent over different hazard zones are shown in Table 4.12 as well as in the form of bar diagrams. Very low hazard (VLH) slope facets are seen on the river terraces which forms the flat lands and the most fertile agricultural fields. Therefore, a major part (98.53%) of VLH zones is covered by agricultural land or populated flat land, which has minimum LHEF rating towards the instability and rest of the part is covered by barren lands. Although, all the five sub-categories of land use and land cover are seen in low hazard zones. yet, a large part of low hazard zones is covered by the agricultural land/populated flat land (53.85%) and thickly vegetated forest area (28.67%).

TABLE 4.12 DISTRIBUTION OF SUB-CATEGORIES OF LAND USE AND LAND COVER (IN PERCENT) IN VARIOUS HAZARD ZONES

Sl. No.	LAND USE AND LAND COVER (Subcategories)	HAZARD ZONES				
		VLH	LH	MH	HH	VHH
1	Agricultural Land/Populated Flat Land	98.53	53.85	44.52	16.14	-
2	Thickly Vegetated Forest Area	-	28.67	22.54	05.05	-
3	Moderately Vegetated Forest Area	-	07.85	10.77	13.32	-
4	Sparsely Vegetated Forest With Lesser Ground Cover	-	06.66	11.99	26.70	-
5	Barren Land	01.47	02.97	10.18	38.80	100

VLH-VERY LOW HAZARD, LH-LOW HAZARD, MH-MODERATE HAZARD, HH-HIGH HAZARD AND VHH-VERY HIGH HAZARD



In case of moderate hazard zones, all the five sub-categories of land use and land cover have been distributed, but still the major part of the MH is shared by agricultural land/populated flat land (44.52%) and thickly vegetated forest area (22.55%). On the other hand, moderately vegetated forest area, sparsely vegetated area with lesser ground cover and barren land also cover considerable part (about 10%) of the MH zones. It indicates that distribution of those sub-categories has increased in MH zones, which may cause more instability. All the five sub-categories are also observed in high hazard (HH) zones. But, a large part of the HH zones is shared by the barren land (38.8%) and sparsely vegetated forest with lesser ground cover (26.70%), whereas agricultural land/populated flat land and thickly vegetated forest area cover only 16.614% and 5.05% respectively. The above distribution shows that the sub-categories which play more important role in instability are widely distributed in the HH zones. Slope facets of very high hazard (VHH) zones are barren and have maximum LHEF rating.

The distribution of all the five sub-categories in the study area have also been shown as percent polygons for various hazard zones (Fig. 4.12) The figure shows the five distinct trends for the sub-categories.

Agricultural land/populated flat land shows a negative trend, which indicates that the area covered by the agricultural land/populated flat land decrease subsequently in higher order hazard zones. This may be due to the fact that the higher order hazard zones are not as suitable as VLH zones for human settlement and agriculture purposes. Since, agriculture practices are not possible on very steep slopes, agricultural lands/populated flat lands are not seen in VHH zones, which are covered by the escarpment/cliff (>45°). Thickly vegetated forest area is not found on VLH zones, mainly due to the human interference, as these zones are mainly used for agriculture practice.

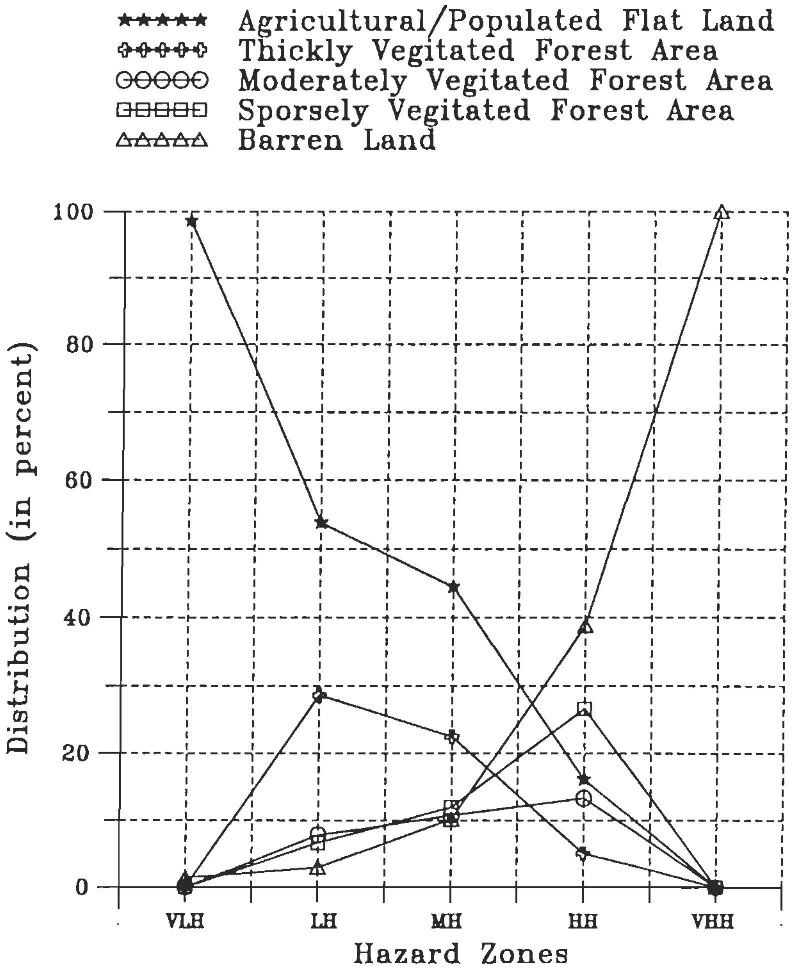


FIG 4.12 PERCENT POLYGONS OF LAND USE AND COVER IN VARIOUS HAZARD ZONES

The second major part (28.67%) of LH zones is covered by thickly vegetated forest land, commonly observed in the higher reaches. In general, percentage of thick forest cover decreases as the hazard category increases. Moderately vegetated forests have been observed in LH, MH and HH zones. Similarly, sparsely vegetated areas with lesser ground cover have also been observed in LH, MH and HH zones. Their distribution show an increasing trend from LH to HH zones. It is observed that barren lands show increasing trend toward higher hazard zones. Barren lands cover the minimum area (1.47%) of the VLH zones and 100% area of VHH zones. It indicates that barren slopes are prone to instability.

Finally, it is concluded that the sub-categories which give less LHEF ratings are mainly distributed in stable zones, such as VLH and LH. On the other hand sub-categories namely, sparsely vegetated forest with lesser ground cover and barren lands give more LHEF ratings and are mainly distributed in higher order hazard zones such as HH and VHH zones.

4.2.5 Relative Relief

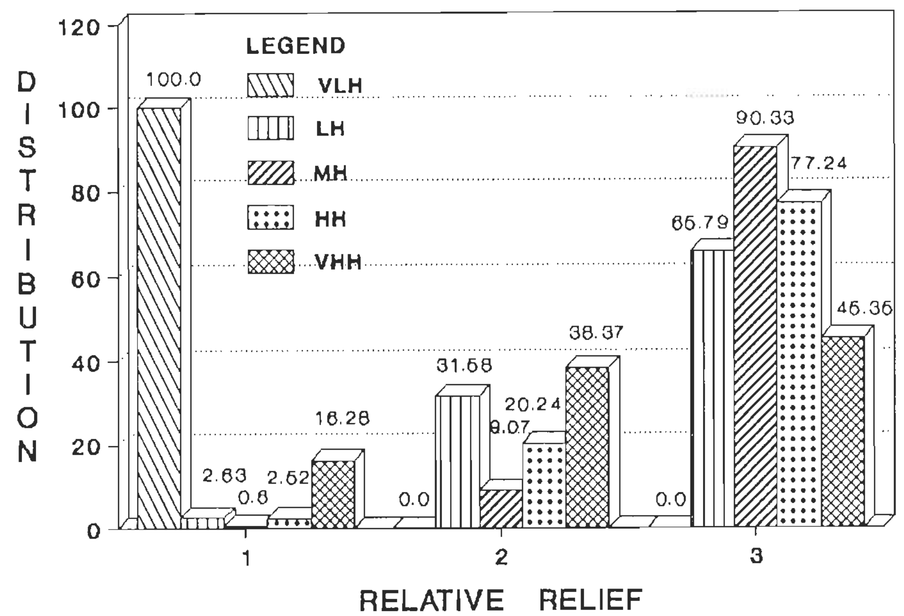
Percent distribution of all the three sub-categories namely low, medium and high relief over various hazard zones is shown in Table 4.13 as well as in the form of bars.

All the slope facets in very low hazard zones are cover by the low relief. More than 95% area of LH zones are cover by high (65.79%) and medium (31.58%) relief. High relief distributed over 90.32% area of the MH zones, whereas 9.07% has been covered by medium relief and less than a percent covered by low relief. A major part of the areas of high hazard zones is covered by high relief (77.23%) and medium relief (20.24%). In case of very high hazard zones, size of the slope facets are comparatively small. Therefore, the percent distribution of low relief has become considerable. But, still the major part (45.35%) of the VHH zones has been covered by high relief.

TABLE 4.13 DISTRIBUTION OF SUB-CATEGORIES OF RELATIVE RELIEF (IN PERCENT) IN VARIOUS HAZARD ZONES

SL. NO.	RELATIVE RELIEF (Subcategories)	HAZARD ZONES				
		VLH	LH	MH	HH	VHH
1	Low Relative Relief	100	02.63	00.60	02.52	16.28
2	Medium Relative Relief	0	31.58	09.07	20.24	38.37
3	High Relative Relief	0	65.79	90.33	77.24	45.35

VLH-VERY LOW HAZARD, LH-LOW HAZARD, MH-MODERATE HAZARD, HH-HIGH HAZARD AND VHH-VERY HIGH HAZARD



This distribution has also been shown as percent polygons for different hazard zones (Fig.4.13). Relative relief of the slope facets depend upon the size of the individual slope facet and slope facet angle, to some extent. Generally, large slope facets have high relief. Very low hazard areas are completely covered by the low relief as these zones are nearly flat. Distribution of low relative relief is small in case of low hazard (2.63%), moderate hazard (0.60%) and high hazard (2.52%) zones, as their slope facet size is comparatively large in general. Since, very high hazard (VHH) slope facets are generally very small in size, distribution of low relief in very high hazard zones is noticeable. Medium relief shows a similar trend and its distribution drops in MH zones in comparison to LH zones, as most of the zones are large in size in MH zones. Medium relief is again well distributed in HH and VHH zones as slopes of these zones are steep. High relief covered the maximum area in MH zones mainly due to the large slope facet size. High relief also covered the maximum area, comparatively in high hazard and very high hazard zones as these zones have steep slopes.

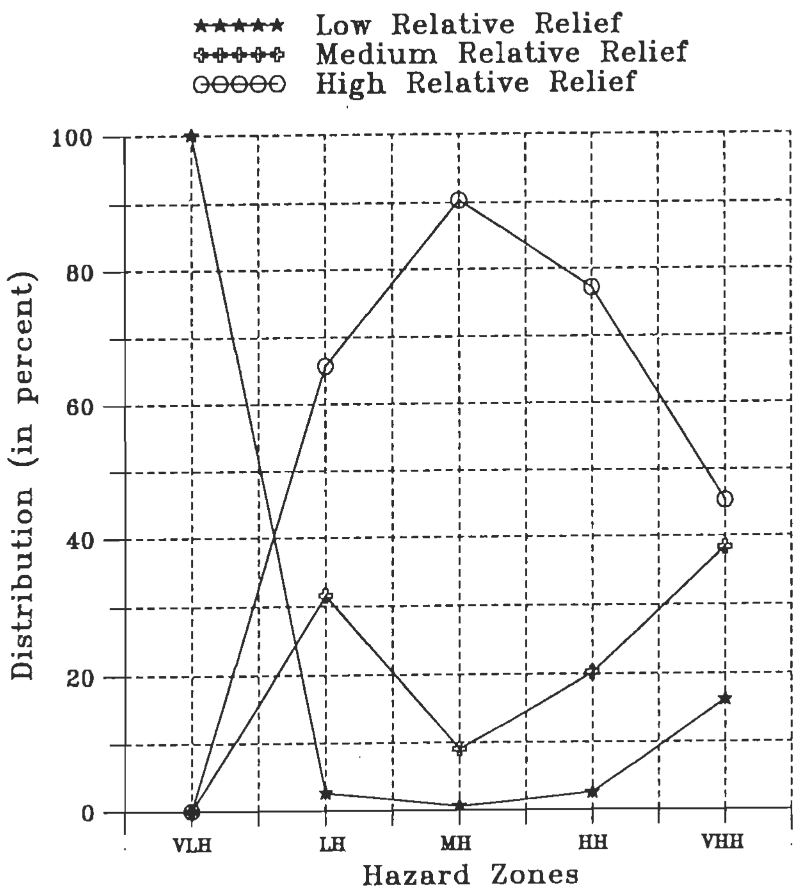


FIG 4.13 PERCENT POLYGONS OF RELATIVE RELIEF IN VARIOUS HAZARD ZONES

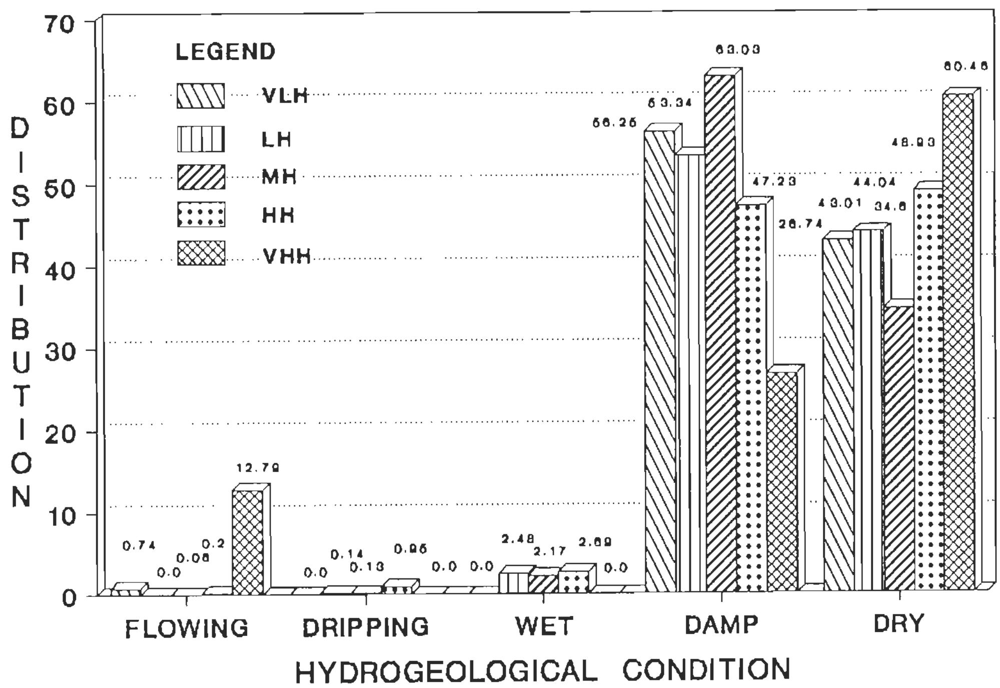
4.2.6 Hydrogeological Conditions

Hazard zone-wise distribution of all sub-categories, in percent, are given in Table 4.14 as well in the form of bars.

TABLE 4.14 DISTRIBUTION OF SUB-CATEGORIES OF HYDROGEOLOGICAL CONDITIONS (IN PERCENT) IN VARIOUS HAZARD ZONES

HYDROGEOLOGICAL CONDITIONS (Sub-categories)	HAZARD ZONES				
	VLH	LH	MH	HH	VHH
Flowing	00.74	-	00.06	00.20	12.79
Dripping	-	00.14	00.13	00.95	-
Wet	-	02.48	02.17	02.69	-
Damp	56.25	53.34	63.03	47.23	26.74
Dry	43.01	44.04	34.61	48.93	60.46

VLH-VERY LOW HAZARD, LH-LOW HAZARD, MH-MODERATE HAZARD, HH- HIGH HAZARD AND VHH-VERY HIGH HAZARD



All the five sub-categories of hydrogeological conditions are present in the study area. But, over 95% study area is shared by damp and dry hydrogeological conditions. As such, there is no distinct pattern found in the distribution of hydrogeological conditions. In most of the hazard zones, 95% of the area is always shared by damp and dry conditions. Though, in case of very high hazard zones flowing conditions are contributing 12.79% of the VHH zones. But, this does not represent the actual condition of the study area, as VHH zones itself represent less than a half present of the total hazard zones.

This distribution of all the five sub-categories of hydrogeological conditions has also been shown as percent polygons for different hazard zones (Fig 4.14). Hydrogeological conditions, which show the surface water conditions of the study area does not follow any trend. Two conditions, dry and damp are mainly persisting throughout the study area over the different hazard zones. Presence of other three conditions such as wet, dripping and flowing are negligible.

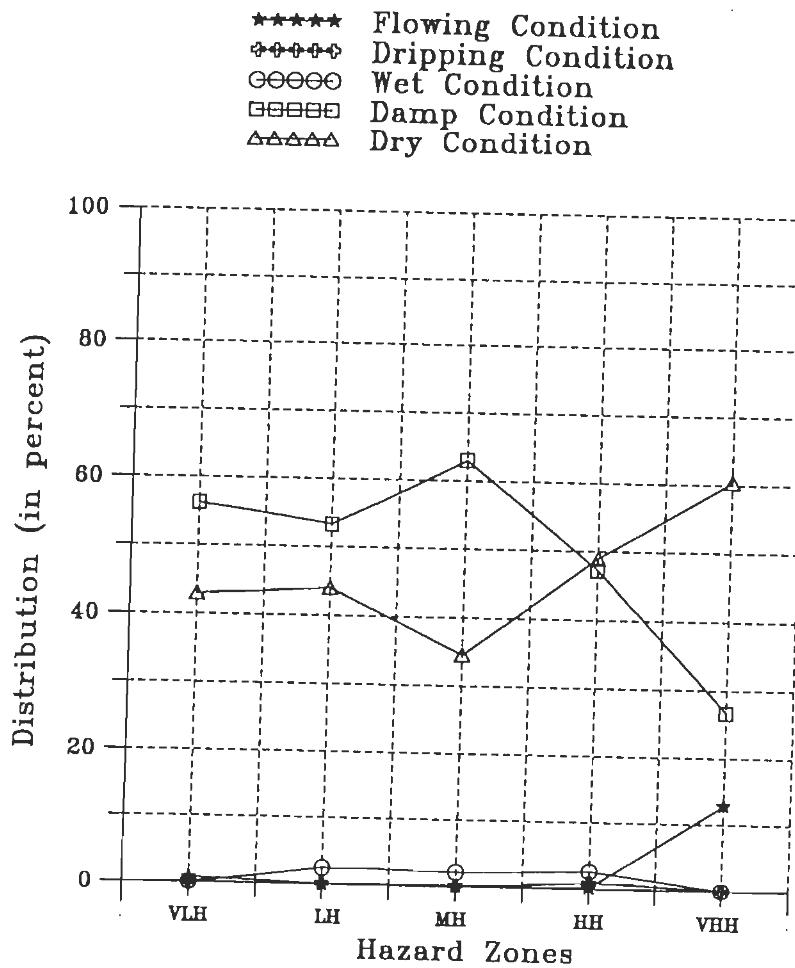


FIG 4.14 PERCENT POLYGONS OF HYDROGEOLOGICAL CONDITIONS IN VARIOUS HAZARD ZONES

□ 4.3 STATISTICAL ANALYSIS

Statistics is a body of *concepts and methods*_used to collect and interpret data concerning a particular area of investigation and to draw conclusions in situations where uncertainty and variation are present (Johnson, 1977). Statistical methods are useful to analyse and draw conclusions from the enormous quantum of data. Nonparametric is one of the model of statistics, which can be defined as the "approximate solutions to exact problems" (Conver, 1980). Required data for the statistical analysis needs a scale of measurement. According to Davis, 1973, a measurement is a numerical value assigned to an observation which reflects the magnitude or amount of some characteristics. The manner in which numerical values are assigned, determines the scale of measurement, and this is in turn determines the type of analysis that can be made on the data. There are four measurement scales. The first two are the nominal scale and the ordinal scale, in which observations are simply classified into mutually exclusive categories. The final two scales, the interval and ratio are those which involve determination of the magnitudes of an attribute.

The nominal scale is the weakest of the four measurement scales. As its name implies, the nominal scale distinguishes one object or event from another on the basis of a name e.g. 1,2,3, or blue, yellow, red or A,B,C.

Ordinal scale of measurement refers to measurements where only the comparisons `greater', `less' or `equal' between measurements are relevant. The numeric value of the measurement is used only as a means of arranging the elements being measured in order, from the smallest to the biggest. It is this need to order the elements, on the basis of the relative size of their measurements that gives the name to the ordinal scale. The difference between rankings are not necessarily equal. Mohrs' hardness scale is a classic example of a ranked or ordinal scale, in which ten minerals, Talc to Diamond have been arranged, according to their increasing hardness and ranked from 1 to 10.

The third scale, the interval of measurement, consider as pertinent information not only the relative order of the measurement as in the ordinal scale but also the size of the interval between measurements. The interval scale involves the concept of a unit distance and the distance between any two measurements may be expressed as some number of units. A good example of interval measurement is the measurement of temperature in degrees Fahrenheit or degrees Celsius. The zero point on Fahrenheit and Celsius thermometer does not indicate an absence of temperature.

Ratio scales are the highest form of measurement. These scales not only have equal increments between steps but also have a true zero point. In other words, ratio scales have the properties of the first three scales and the additional property that their ratios are meaningful. It is reasonable to speak of one quantity being "twice" another quantity. Height, weight and distance are the various examples of ratio scales.

Most nonparametric methods assume either the nominal scale or the ordinal scale to be appropriate. Of course, each scale of measurement has all of the properties of the weaker measurement scales, therefore statistical methods requiring only a weaker scale may be used with the stronger scales also.

The LHEF rating scheme (Anbalagan, 1992) used in this research work, falls in the second scale of measurement i.e. ordinal scale. Thus, for the above mentioned reasons, the nonparametric statistical methods have been used to obtain the rank correlation coefficient and the order of influence. Spearman rank correlation has been used to obtain rank correlation coefficients in the whole study area between total estimated hazard (TEHD) & six variables (causative factors) and among six variables (causative factors) themselves. In addition to that order of influence has been calculated between all the six causative factors for each hazard zone as well as for the whole area of study. Order of influence has been established by using Friedman Test and later verified by the Page's Test.

4.3.1 Rank Correlation Coefficient

The rank correlation determines the degree of association between two random variables say X & Y. It provides a numerical value for the amount of linear dependence. The association need not to be linear; only an increasing or decreasing relationship is provided. The measures of correlation should assume only values between -1 to +1. If the large values of X tend to be paired with the larger values of Y, and hence the smaller values of X & Y tend to be paired together, then the measure of correlation should be positive, and close to +1 if the tendency is strong. Then it is called as positive correlation between X & Y. If the larger values of X tend to be paired with the smaller values Y, and vice versa, then the measure of correlation should be negative, and close to -1 if the tendency is strong. Then it is called as negative correlation between X & Y. If the values of X seems to be randomly paired with the values of Y, the measure of correlation should be fairly close to zero.

This should be the case when X & Y are independent, and possibly some cases where X & Y are not independent. Then, X & Y are uncorrelated or have no correlation, or have correlation zero (Conver, 1980).

The most commonly used measure of correlation is Pearson's product moment correlation coefficient (γ). This measures of correlation may be used with any data of a numeric nature. However, it is difficult to interpret Pearson's correlation coefficient (γ) unless the measurement is at least interval. Further, γ has no value as a test statistics in nonparametric tests until and unless the distribution of (X,Y) is known.

Thus, for the reasons enumerated above, the Spearman rank-correlation coefficient (ρ) has been used to know the relationship if any between the total estimated hazard (TEHD) and six causative factors (Variables) and among causative factors, Spearman's rank-correlation coefficient (ρ) has been computed for two-tailed test at 5% level of significant. The test is called a two tailed test, if the rejection region corresponds to both `tails' of the test statistics' possible values, whereas the level of significance, or α, is the maximum probability of rejecting a true null hypothesis. Following formula has been used to calculate the Spearman's rank-correlation coefficient (ρ).

$$\rho = \frac{\sum_{i=1}^{n} R(X_i)R(Y_i) - n\left(\frac{n+1}{2}\right)^2}{\left[\sum_{i-1}^{n} R(X_i)^2 - n\left(\frac{n+1}{2}\right)^2\right]^{1/2} \left[\sum_{i=1}^{n} R(Y_i)^2 - n\left(\frac{n+1}{2}\right)^2\right]^{1/2}} \qquad \ldots (4.1)$$

where,

ρ = Spearman rank-correlation coefficient

$R(X_i)$ = Rank of X_i as compared with the other X values for i=1,2,...,n

$R(Y_i)$ = Rank of Y_i as compared with the other Y values for $i=1,2,\ldots,n$

n = number of observation.

The total estimated hazard (TEHD) is calculated from the six variables namely Lithology (Lit), Structure (Str), Slope Morphometry (SM), Land Use and Land Cover (LULC), Relative Relief (RR) and Hydrogeological Conditions (HGC).

The ratings, given to above enumerated six variables, have been arranged in order of size and assigned a rank to each value. The smallest value is assigned a rank of 1, the second smallest a rank of 2. The same procedure has been followed for the total estimated hazard (TEHD) values. In case of ties i.e. two or more observations have the same values, each tied value has been assigned the average of the ranks, given to them. Thus, after assigning the ranks to each of the six variables and TEHD value, the rank correlation coefficients have been calculated for all 21 pairs of variables from 365 slope facets and are presented in Table 4.15. These coefficients have also been tested for statistical significance (5%; 2-Tail). The critical value at this level of significance is +/-0.103.

A perusal of Table 4.15 shows that all causative factors except hydrogeological conditions shows relationship with total estimated hazard (TEHD) at 5% significant level for 2-tail test.

TABLE 4.15 CORRELATION COEFFICIENTS BETWEEN TEHD & CAUSATIVE FACTORS AND AMONG CAUSATIVE FACTORS IN THE STUDY AREA

VARIABLES	VARIABLES						
	TEHD	Lit	Str	SM	LULC	RR	HGC
	RANK CORRELATION COEFFICIENT						
TEHD	1.00						
Lit	0.47	1.00					
Str	0.27	-.13	1.00				
SM	0.58	-.05	0.10	1.00			
LULC	0.68	0.16	-.02	0.38	1.00		
RR	0.18	-.11	0.06	0.05	-.03	1.00	
HGC	0.03	0.03	-.03	-.07	-.13	-.06	1.00

TEHD - TOTAL ESTIMATED HAZARD, LIT - LITHOLOGY, STR - STRUCTURE, SM - SLOPE MORPHOMETRY, LULC - LAND USE AND LAND COVER, RR - RELATIVE RELIEF, HGC - HYDROGEOLOGICAL CONDITIONS

CRITICAL VALUE (2-TAIL, 0.05) = +/- 0.103

4.3.1.1 *Rank Correlation between TEHD and Lithology*

TEHD show the positive correlation with the lithology. It indicates as the TEHD increases i.e. landslide hazard potential increases, there is an increase in the distribution of weak lithology such as phyllite which has more LHEF rating.

4.3.1.2 *Rank Correlation of TEHD with Structure*

The rank correlation between TEHD and structure is 0.27, indicates that relation is not linear but still it is significant at 5% level. This relation of TEHD and structure indicates that as the probability of hazard (TEHD) increases, the contribution of LHEF rating for structure also increases.

4.3.1.3_*Rank Correlation of TEHD with Slope Morphometry*

The rank correlation between TEHD and slope morphometry is 0.58 at 5% level of significance, which indicates that as the steepness of slope increases, probability of hazard potential increases or vice versa.

4.3.1.4. *Rank Correlation of TEHD with Land Use and Land Cover*

Rank correlation coefficient between TEHD and land use and land cover is 0.68. It is a good correlation between them at 5% significant level. It indicates that as the slope become more barren, probability of hazard potential increases.

4.3.1.5 *Rank Correlation of TEHD with Relative Relief*

Rank correlation between TEHD and relative relief is just 0.18. Though, it is a weak positive correlation but significant at 5% level. It indicates that as the TEHD increases, height of the slope facets also increases.

4.3.1.6 *Rank Correlation of TEHD with Hydrogeological Conditions*

The correlation between TEHD and the hydrogeological conditions does not have significant correlation at 5% level of significance. It is almost zero (0.03), indicating that the hydrogeological conditions which represent the surface water moisture conditions may not have much influence on slope instability.

4.3.1.7 *Rank Correlation among causative factors*

According to rank correlation coefficient (Table 4.15) relationships among causative factors are insignificant in most of the cases. Though, few of them have significant correlation at 5% level. But these rank correlations show weak relationships among causative factors. Hence, it is concluded that causative factors may be considered independent from each other. It means influence of any causative factor does not affect others.

4.3.2 Order of Influence of Causative Factors

The usual parametric method of testing the null hypothesis of no treatment difference is called the two-way analysis of variance. The following nonparametric methods depend only on ranks of the observation within each block (slope facet) and the ranks of the block to block (slope facet to slope facet) sample ranges. Therefore it may be considered as two way analysis of variance on ranks. These tests have been applied to analyse several related samples.

The Friedman test has been used to determine the relative order of influence of six variables (Causative factors), predictors of TEHD. Relative order of influence has been determined hazard zone wise as well as for the whole area.

This test has been further checked by using Page's test with same assumptions. This test is appropriate in two-way analysis of variance hypothesis-testing situations in which an ordered alternative is meaningful.

The data required for these tests consist of b mutually independent k- variate random variables (X_{i1} ,$X_{i2,}$ ....X_{ik}) called b blocks, i=1,2,...,b. The b blocks are arranged as follows:

	Treatment			
Block	1	2	...	k
1	X_{11}	X_{12}	...	X_{1k}
2	X_{21}	X_{22}	...	X_{2k}
3	X_{31}	X_{32}	...	X_{3k}
...	...	...	...	...
b	X_{b1}	X_{b2}	...	X_{bk}

In present case, the slope facets represent the blocks while the six causative factors represent the treatments. Here, treatments are same (k=6) for all zones as well as for whole area, whereas block (b) represent number of slope facets present in different hazard zones as well as in the whole area. Let $R(X_{ij})$ be the rank, from 1 to k, assigned to X_{ij} within block i. That is, for block i the random variables $X_{i1}, X_{i2}, \ldots X_{ik}$ are compared with each others and the rank 1 is assigned to the smallest observed value, the rank of 2 to the second smallest, and so on to the rank k, which is assigned to the largest observation in block i. Ranks are assigned in all of the b blocks using average ranks in case of ties.

DATA: After obtaining ranks within block are $R(X_{ij})$, R_j is obtained by summing the ranks for each treatment.

$$R_j = \sum_{i=1}^{b} R(X_{ij}) \qquad for\ j=1,2,\ldots,k \qquad \ldots(4.2)$$

4.3.2.1 *Friedman Test*

This test appeared to be more powerful when number of treatments are five or more. It may be preferred when comparisons among the different blocks are not possible.

ASSUMPTIONS:

1. The bk - variate random variables are mutually independent
2. The variable of interest is continuous.
3. There is no inter-relation between blocks and treatments
4. Within each block the observations may be ranked in order of magnitude.
5. No comparisons between different blocks need to be made.

HYPOTHESIS:

H_0: Each ranking of the random variables within a block is equally likely, that is variables have identical effects.

H_1: At least one of the variables tends to yield large observed values than at least one other treatment.

TEST STATISTICS : Firstly, the term A_2 is calculated by

$$A_2 = \sum_{i=1}^{b} \sum_{j=1}^{k} [R(x_{ij})]^2 \qquad \ldots (4.3)$$

Then the term B_2 is calculated as

$$B_2 = \frac{1}{b} \sum_{j=1}^{k} R_j^2 \qquad \ldots (4.4)$$

where R_j is given by equation (4.2). Now the test statistic is

$$T_2 = \frac{(b-1)[B_2 - bk(k+1)^2/4]}{A_2 - B_2} \quad , A_2 \neq B_2 \qquad \ldots (4.5)$$

where b is number of blocks (slope facets) and k is number of treatments (causative factors) and A_2 & B_2 are given in equations (4.3) and (4.4) respectively. If $A_2 = B_2$, the point is considered to be in critical region and critical level is given as

$\alpha\text{^} = (1/k!)^{b-1}$.

DECISION RULE: The null hypothesis i.e. the variables have identical effect, can only be rejected at the level of significance α=.05, if and only if T_2 exceeds the 1-α quantile of F distribution with degree of freedom k_1 = k-1 and K_2 = (b-1)(k-1).

MULTIPLE COMPARISONS:

The Friedman test for comparing individual treatments may be used only if the test results in rejection of the null hypothesis. Treatments i and j are considered different if the following inequality is satisfied.

$$|R_j - R_i| > t_{1-\alpha/2}\left[\frac{2b(A_2 - B_2)}{(b-1)(k-1)}\right]^{1/2} \qquad \ldots(4.6)$$

Where,

$t_{1-\alpha/2}$ is the $1-\alpha/2 = .975$ quantile of the t distribution with (b-1)(k-1) degree of freedom.

In present case, the null hypothesis is rejected in all five hazard zones as well as for whole area also, at a significant level of 5%. Therefore, it is concluded that there is a tendency for few variables to be preferred over others. Thus, treatments (causative factors) are compared for order of influence by their R_j (sum of ranks) in the inequality (4.6). Two or more causative factors may acquire same order if their on of ranks in inequality (4.6) is not significant at 5%. The order of influence of six causative factors in all five hazard zones and for whole area are given in Table 4.16. Influence of six causative factors in all the five hazard zones and in whole area of study has been tabulated in descending order starting from 1 to 6. If, two or more causative factors possing almost same R_j at 5% level of significance, have been placed together under the same order, writing them in the descending order of their R_j. Computer program for Friedman Test has been prepared in FORTRAN and run on TATA ELXI 3020.

TABLE 4.16 ORDER OF INFLUENCE OF CAUSATIVE FACTORS

HAZARD ZONES	FRIEDMAN TEST ORDER OF INFLUENCE					
	1	2	3	4	5	6
Very Low Hazard	Str	Lit & LULC	SM	RR	HGC	-
Low Hazard	SM & Str	LULC, RR & Lit	HGC	-	-	-
Moderate Hazard	SM	Str	LULC	Lit & RR	HGC	-
High Hazard	SM & LULC	Str & Lit	RR	HGC	-	-
Very High Hazard	LULC & SM	Lit & Str	RR & HGC	-	-	-
Whole Area	SM	Str	LULC	Lit	RR	HGC
Level of significance (α) = .05						
Lit-Lithology, Str-Structure, LULC-Land Use and Land Cover, SM-Slope Morphometry, RR-Relative Relief and HGC-Hydrogeological Conditions						

4.3.2.2 *Page's Test*

This procedure is appropriate when the alternative hypothesis is ordered.

ASSUMPTION: The assumptions are the same as those for the Friedman test.

HYPOTHESIS: Let T_j designate the effect of the jth treatment

H_0: The random variable within a block are identical.

H_1: The treatment effects T_1, T_2,..,T_k are ordered in the following way: $T_1 \leq T_2 \leq .. \leq T_k$

TEST STATISTIC : The test statistic is

$$L = \sum_{j=1}^{k} jR_j = R_1 + 2R_2 + \ldots + kR_k \qquad \ldots (4.7)$$

where,

R_1,.... ,R_k are the treatments (causative factors) rank sum as given in equation (4.1).

If the treatment effects are ordered as specified in hypothesis H_1, then R_j tends to be larger than $R_{j'}$ for j'<j. Since the treatment rank sums are weighted by the index of their position in the ordering specified by H_1, L tends to be larger when H_1 is true

DECISION RULE

Reject H_0 at the α=.o5 level of significance if the computed value of L is greater than or equal to the critical value of L for k, b and α.

LARGE SAMPLE APPROXIMATION: For large samples, the statistic

$$Z = \frac{L-[bk(k+1)^2/4]}{\sqrt{b(k^3-k)^2/144(k-1)}} \qquad \ldots(4.8)$$

is distributed approximately as the standard normal. H_0 is rejected at the α=.05 level of significance if the computed Z is greater than or equal to Z value which has α area to its right.

In present work, there are six causative factors, therefore hypothesis H_1 can be written in 6! (720) ways. The statistic (4.8) have been tested for same results as obtained in Friedman test, by preparing computer program in FORTRAN run on TATA ELXI 3020. The analysis for those order of influence in different hazard zones as well as for the whole area, which is given in Friedman test, illustrated below. It is shown by the following exercise that Page's Test confirms the Friedman test. Hence, it is concluded that all the causative factors are independent and there is always treatment which is preferred over other in all hazard zones as well as in the whole study area.

1. Very high hazard (VHH):

HYPOTHESIS:

H_0 : The ratings of six causative factors within a slope facet are identical.

H_1 The causative factors ordered as

$HGC \leq RR \leq Str \leq Lit \leq SM \leq LULC$

TEST STATISTICS:

L = 7 + 2x8 + 3x17.5 + 4x19.5 + 5x25.5 + 6x25.5 = 434

DECISION RULE (for small sample approximation):

Critical value of L for k=6, b=5 and α=.05 is 397. Therefore, H_0 is rejected as computed value of L is greater than critical value of L.

Hence, H_1 is the order of influence.

2. High Hazard (HH):

HYPOTHESIS:

H_0 : The ratings of six causative factors within a slope facet are identical.

H_1 : The causative factors ordered as

$HGC \leq RR \leq Lit \leq Str \leq LULC \leq SM$

TEST STATISTICS:

L = 70.5 + 2x160 + 3x253 + 4x270 + 5x356 + 6x359 = 6163.5

DECISION RULE (for large sample approximation):

Z= 3.11

H_0 at α=.05 level of significance with k=6 and b=70 rejected as computed Z= 3.11 is greater than the Z value i.e. 0.1256 which has α area to its right.

Hence, H_1 is the order of influence.

3. Moderate hazard (MH):

HYPOTHESIS:

H_0 : The ratings of six causative factors within a slope facet are identical.

H_1 : The causative factors ordered as

HGC $\leq$ RR $\leq$ Lit $\leq$ LULC $\leq$ Str $\leq$ SM

TEST STATISTICS:

L = 165 + 2x528 + 3x543 + 4x615 + 5x783 + 6x847 = 14307.

DECISION RULE (for large sample approximation):

Z= 4.18

H_0 at α=.05 level of significance with k=6 and b=166 rejected as computed Z= 4.18 is greater than the Z value i.e. 0.1256 which has α area to its right.

Hence, H_1 is the order of influence.

4. Low Hazard (LH):

HYPOTHESIS:

H_0 : The ratings of six causative factors within a slope facet are identical.

H_1 : The causative factors ordered as

HGC $\leq$ Lit $\leq$ RR $\leq$ LULC $\leq$ Str $\leq$ SM

TEST STATISTICS:

L = 121 + 2x364 + 3x389 + 4x394 + 5x596 + 6x613 = 10250.

DECISION RULE (for large sample approximation):

Z= 3.71

H_0 at α=.05 level of significance with k=6 and b=118 rejected as computed Z= 3.71 is greater than the Z value i.e. 0.1256 which has α area to its right.

Hence, H_1 is the order of influence.

5. Very Low Hazard (VLH):

HYPOTHESIS:

H_0 : The ratings of six causative factors within a slope facet are identical.

H_1 : The causative factors ordered as

$HGC \leq RR \leq SM \leq LULC \leq Lit \leq Str$

TEST STATISTICS:

L = 6 + 2x12 + 3x20 + 4x25 + 5x28 + 6x35 = 540

DECISION RULE (for small sample approximation):

Critical value of L for k=6, b=6 and α=.05 is 474. Therefore, H_0 is rejected as computed value of L is greater than critical value of L.

Hence, H_1 is the order of influence.

6. Total area:

HYPOTHESIS:

H_0 : The ratings of six causative factors within a slope facet are identical.

H_1 : The causative factors ordered as

$HGC \leq RR \leq Lit \leq LULC \leq Str \leq SM$

TEST STATISTICS:

L = 369 + 2x1098 + 3x1207 + 4x1417 + 5x1702 + 6x1866 = 31560.

DECISION RULE (for large sample approximation):

Z= 6.33

H_0 at α=.05 level of significance with k=6 and b=365 rejected as computed Z= 6.33 is greater than the Z value i.e. 0.1256 which has α area to its right.

Hence, H_1 is the order of influence.

4.3.3 Interpretation of Order of Influence of Causative Factors

The order of influence of the six causative factors in all the five hazard zones as well as in the whole area of study has been brought out by using Friedman Test and later verified by Page's Test. A perusal of results shows that slope morphometry and structure are the two most important causative factors in most of the hazard zones as well as in the whole area of the study in inducing instability. In the present study moderate hazard (MH), High hazard (HH) and very high hazard (VHH) zones and the whole area of study are the important ones from the view point of landslides.

Order of influence of various causative factors in MH zones is more or less same, as in the whole area of study. MH zones cover the largest part (53.56 %) of the study area and may have the properties of lower as well as higher hazard zones. Slope morphometry is the one, which influences most, the stability of slope facets . Structure and land use and land cover are the second and third most influencing causative factors in the stability of MH slope facets, whereas hydrogeological conditions shows a minimum influence on the slope stability. The order of influence of all the six causative factors are more or less same in HH and VHH zones. Slope morphometry and land use and land cover are the ones which play the most important role to influence the stability of hill slopes, whereas, structure and lithology are the second most important causative factors which influence stability of slope facets of HH and VHH zones.

Detailed Investigations

Regional landslide hazard zonation is the first step to identify potentially unstable zones. The landslide hazard zonation (LHZ) map divides the area into zones of different hazard categories such as very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH). Out of these, two potentially hazardous categories, namely HH and VHH zones, are to be studied in detail for stability analysis.

The detailed investigations of potentially unstable slope facets have been done on 1:2000 scale. For this purpose the shear strength and other properties of the slope material have been determined. The detailed studies include an assessment of status of stability in terms of factor of safety (FOS), taking into consideration the total shear stresses acting on the potential planes of failure and the shear strength of the discontinuities. If a slope indicates a FOS of less than unity, it is in an unstable condition and it may require remedial measures. The detailed studies include the followings:

i) Nature of slope materials

ii) Attitude of geological discontinuities with reference to the slope, in case of rock slopes.

iii) The strength properties of the slope materials such as cohesion `C' and angle of internal friction `ϕ'.

iv) Strength along the planes of discontinuities

v) Section and height of the slope

vi) Possible seepage water pressures.

The VHH slope facets represent landslide potential of highest order. These slope facets generally contain partially or completely failed slope with a factor of safety (FOS) less than one. However, the HH slope facets, which also indicate a high landslide potential, may not show the signs of failure. Therefore, the detailed studies have been done on the high hazard (HH) slope facets to assess the nature of instabilities. In this context, the first step is to identify the kinematically unstable slopes in the HH slope facets and the possible mode of failure. This can be done with the help of Markland test.

□ 5.1 MARKLAND TEST

The principle of the Markland test is that a potentially unstable plane should dip less than the inclination of slope and more than that of angle of internal friction (ϕ). The conditions of the Markland test are as follows:

$\alpha_s > \alpha_p > \phi$ - For plane failure

$\alpha_s > \alpha_i > \phi$ - For wedge failure

where,

α_s - Slope face inclinations

α_p - Failure plane inclination

α_i - Plunge of a line, formed by intersection of two planar discontinuities

ϕ - Angle of internal friction

All the high hazard slope facets have been initially studied to identify whether they satisfy the Markland test. For that purpose, the data pertaining to lithology, structural discontinuities as well as direction and inclination of slope facets have been collected from all HH slope facets. The collected discontinuity data have been plotted on stereonet separately for each slope facet to get the preferred orientation of structural discontinuities and the same have been used for Markland test. The angle of internal friction has been obtained from RMR classification.

□ 5.2 GEOMECHANICAL CLASSIFICATION

Geomechanical classification or Rock Mass Rating (RMR) system proposed by Bieniaski (1973) and modified by Bureau of Indian Standard (BIS: 13365, part II) has been used to determine the shear strength parameters of rock mass. The basic parameters required for RMR are as follows;

i) Uniaxial compressive strength of intact rock,

ii) Rock quality designation (RQD),

iii) Spacing of discontinuities,

iv) Condition of discontinuities and

v) Ground water conditions.

5.2.1 Uniaxial Compressive Strength

In order to obtain the uniaxial compressive strength of intact rock, cores of NX (5.4 cm diameter) size have been made from the fresh intact rock samples of different lithological units. These cores have been tested in laboratory, following the standard procedures. Uniaxial Compressive strength for different rocks have been calculated using the following formula

$$q_c = \frac{P}{A} \; kg/cm^2 \qquad \ldots (5.1)$$

where,

q_c = Uniaxial compressive strength

p = Load at failure in kg

A = Cross sectional area in cm^2

The calculated average value of uniaxial compressive strength for different rock types is shown in Table 5.1.

5.2.2 Rock Quality Designation (RQD)

The rock quality designation (RQD) has been obtained using the Palmstörm, 1981 relation as follows

$RQD = 115 - 3.3\ J_v$

where,

J_v is the total number of joints present in $1m^3$ of rock mass.

TABLE 5.1 UNIAXIAL COMPRESSIVE STRENGTH AND ROCK DENSITY OF VARIOUS ROCKS EXPOSED IN HIGH HAZARD SLOPE FACETS

ROCK TYPE	UNIAXIAL COMPRESSIVE STRENGTH (kg/cm^2)	ROCK DENSITY (gm/cm^3)
Phyllite Phyllite	615 645.5	2.45 2.55
Quartzite Quartzite	1940 2010	2.85
Limestone Limestone	1050 1100	2.6
Slate Slate	670 728	2.53

5.2.3 Spacing of Discontinuities

The term discontinuity includes bedding, joint, foliation, shear zone, minor fault and other weak structural features. The linear and shortest distance between two adjacent discontinuities of the same set have been measured for all sets of discontinuities in field.

5.2.4 Conditions of Discontinuities

This parameter includes roughness of discontinuity surfaces, their separation, lateral continuity, weathering of the discontinuity surface and in-filling material. These conditions have been visually estimated in field for different high hazard slope facets.

5.2.5 Ground water Conditions

In this case, the general conditions such as dry, damp, wet, dripping and flowing have been considered and visually estimated in field for their corresponding discontinuities.

The ratings awarded for various parameters as indicated above, have been added up to get the final RMR values.

5.2.6 Determination of Angle of Internal Friction (ϕ) from RMR Value

The shear strength parameters, namely angle of internal friction (ϕ) and cohesion (C) corresponding to their rock mass ratings of various high hazard slope facets have been calculated (Table 5.2). The value of angle of internal friction (ϕ) would be more or less same for both the rock mass and structural discontinuities, where the discontinuities are free from clay fillings and are not slickensided. Therefore, the lower value of angle of internal friction, as obtained by RMR has been used for identifying the kinematically unstable slope facets by using Markland test.

TABLE 5.2 ROCK MASS RATING AND SHEAR STRENGTH PARAMETERS IN RESERVOIR AREA

SLOPE FACET NO.	PARAMETER							
	ROCK MASS RATING							
	UCS	RQD	SP.	COD	GWC	RMR	ϕ	C
57	7	12	10	12	10	51	25-35	2-3
60	11	14	12	20	15	72	35-45	3-4
65	6	12	10	12	10	50	25-35	2-3
69	12	16	14	25	10	77	35-45	3-4
74	7	12	12	15	10	56	25-35	2-3
84	7	15	9	15	10	56	25-35	2-3
106	7	15	11	12	10	56	25-35	2-3
122	12	11	12	20	15	70	35-45	3-4
126	7	14	11	15	10	57	25-35	2-3
132	12	15	12	15	15	69	35-45	3-4
133	12	15	14	15	10	66	35-45	3-4
143	6	10	8	10	10	44	25-35	2-3
145	6	12	8	12	10	48	25-35	2-3
146	6	15	10	15	10	56	25-35	2-3
147	6	15	10	12	10	53	25-35	2-3
148	6	15	8	15	15	54	25-35	2-3

Cont.

153	6	13	9	14	15	57	25-35	2-3
154	6	14	10	14	10	54	25-35	2-3
156	6	12	7	12	10	47	25-35	2-3
157	6	12	7	12	10	47	25-35	2-3
166	6	14	10	14	15	59	25-35	2-3
173	6	13	10	14	13	56	25-35	2-3
175	6	14	9	15	13	57	25-35	2-3
176	6	14	9	15	14	58	25-35	2-3
187	6	13	8	14	13	54	25-35	2-3
191	7	15	10	12	10	54	25-35	2-3
194	7	14	10	10	15	56	25-35	2-3
195	7	13	8	12	10	50	25-35	2-3
196	7	12	12	18	10	59	25-35	2-3
197	7	14	10	15	12	58	25-35	2-3
198	7	12	10	12	15	56	25-35	2-3
200	7	12	12	15	10	56	25-35	2-3
202	7	12	9	12	15	55	25-35	2-3
204	7	15	11	15	10	58	25-35	2-3
205	7	14	11	14	10	56	25-35	2-3
206	7	12	10	15	10	54	25-35	2-3
209	7	15	10	14	10	56	25-35	2-3
210	7	12	8	12	10	49	25-35	2-3
212	7	15	12	15	10	60	25-35	2-3
216	7	15	12	15	15	65	25-35	3-4
217	7	13	10	18	10	59	25-35	2-3
218	7	13	10	15	10	56	25-35	2-3
241	7	12	11	12	10	52	25-35	2-3
251	7	12	9	12	10	50	25-35	2-3
258	7	12	11	14	15	59	25-35	2-3
264	8	14	11	12	15	60	25-35	2-3
270	7	12	10	15	10	54	25-35	2-3
282	7	12	8	15	10	52	25-35	2-3
286	8	13	11	12	15	59	25-35	2-3
290A	6	10	8	14	13	51	25-35	2-3

Cont.

290B	8	13	12	15	13	61	35-45	3-4
293	6	14	12	12	10	54	25-35	2-3
295	6	12	12	14	15	59	25-35	2-3
308	12	14	12	20	10	68	35-45	3-4
313	6	12	12	12	10	52	25-35	2-3
316	6	13	12	12	10	53	25-35	2-3
317	6	12	10	15	12	50	25-35	2-3
318	6	12	8	15	15	56	25-35	2-3
319	6	15	8	14	15	58	25-35	2-3
322	12	14	14	25	10	75	35-45	3-4
328	12	16	14	20	10	72	35-45	3-4
339	7	15	12	14	10	58	25-35	2-3
343	7	15	12	15	10	59	25-35	2-3
344	7	13	10	12	15	57	25-35	2-3
347	6	15	14	12	10	57	25-35	2-3
348	6	14	12	15	10	57	25-35	2-3
361	6	15	12	15	10	58	25-35	2-3

UCS = Uniaxial Compressive Strength
RQD = Rock Quality Designation
SP = Spacing Between Discontinuities
COD = Condition of Discontinuities
GWC = Ground Water Condition
RMR = Rock Mass Rating (Basic)
C = Cohesion (Kg/cm^2)
ϕ = Angle of Internal Friction(Degrees)

□ 5.3 SLOPE STABILITY ANALYSIS

The stability analysis of the high hazard slope facets, satisfying the Markland test, has been carried out to calculate the factor of safety (FOS). The `Factor of safety' may be defined as the ratio of the total force available to resist sliding to the total force tending to induce sliding (Hoek and Bray, 1981). Out of a total of 10 critical slope facets, which are identified for the detailed analysis, one accounted for plane mode of failure, seven accounted for wedge mode of failure and two accounted for both plane and wedge mode of failures (Table 5.3).

TABLE 5.3 CRITICAL SLOPE FACETS IDENTIFIED BY MARKLAND TEST FOR WEDGE AND PLANE FAILURES

SLOPE FACET NO.	MODE OF FAILURE					
	WEDGE			PLANE		
	1	2	3	1	2	3
143	●	●				
145	●		●			
156		●	●			
157		●	●			●
195				●		
202		●	●			
206		●	●			
210		●	●			
251		●	●		●	
308		●	●			

Discontinuities 1 = Bedding/joint/Foliation plane
Discontinuities 2 = Joint set J_1
Discontinuities 3 = Joint set J_2

The cross sections and attitudes of discontinuities in nine critical slope facets have been shown in Fig. 5.1. The attitude of discontinuities of these nine critical slope facets have been listed in Table 5.4. In addition to these rock slope failures, a rotational mode of failure has been observed on one slope facet no. 177. The location of these eleven slope facets , for which plane, wedge and circular failure analysis has been carried out, is shown in Fig. 5.2. The analysis has been carried out for dry, wet as well as for dynamic conditions. In the stability analysis, earthquake loading effect has been incorporated by assuming that the acceleration induced by the earthquake can be replaced by an equivalent static force of α.W (Hoek and Bray, 1981)
where,

α is the horizontal acceleration of earthquake

W is the weight of the sliding block.

PLATE 7

Landslide in phyllites along dam road south of Tehri.

A rock block, fall from the adjoining slope, damaged a bridge between Tehri and Bhaldiyana.

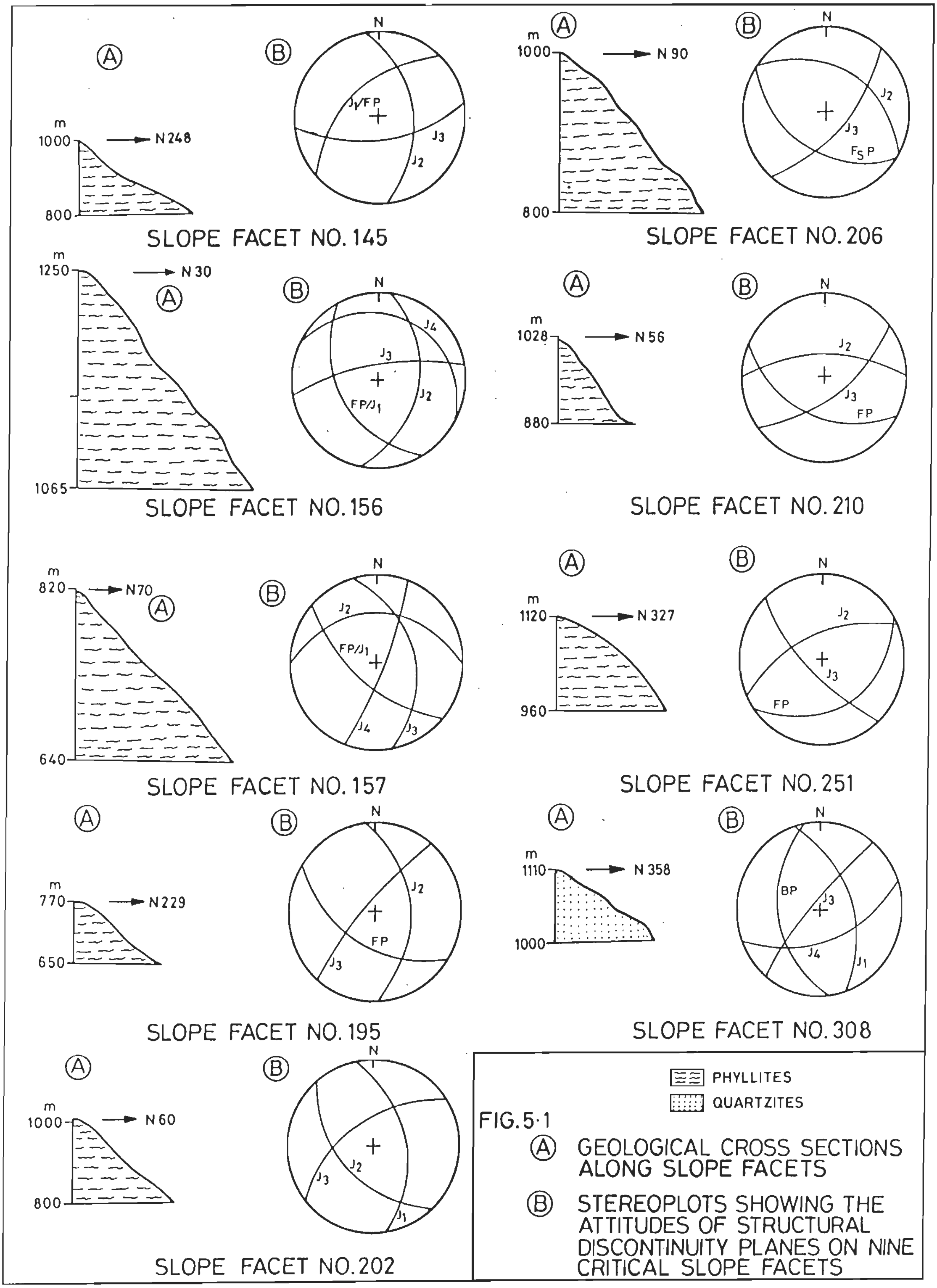
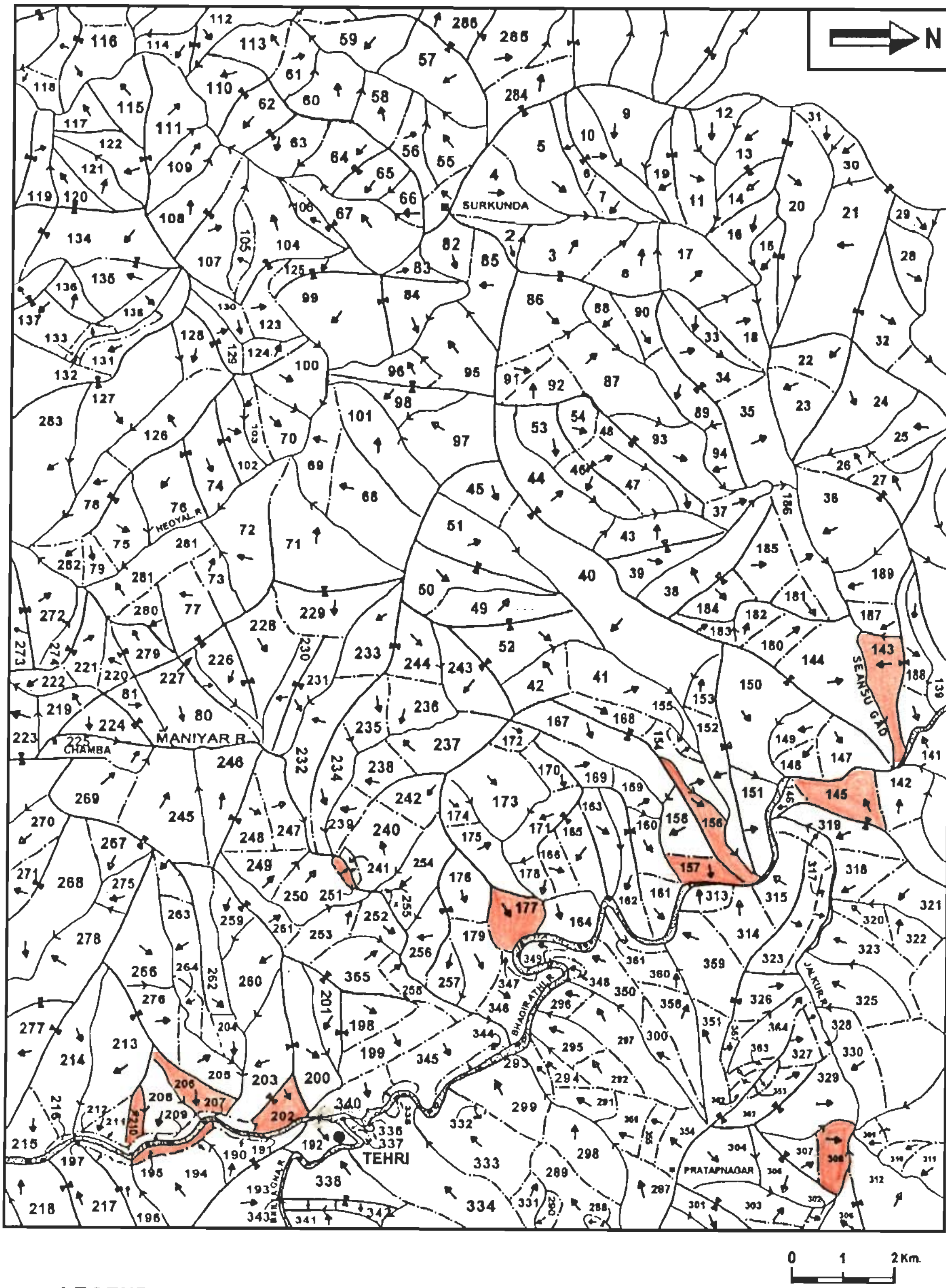


FIG. 5·1

Ⓐ GEOLOGICAL CROSS SECTIONS ALONG SLOPE FACETS

Ⓑ STEREOPLOTS SHOWING THE ATTITUDES OF STRUCTURAL DISCONTINUITY PLANES ON NINE CRITICAL SLOPE FACETS



LEGEND

- RIDGE LINE
- STREAM COURSE
- FACET BOUNDARY
- SLOPE DIRECTION
- LOCATION OF CRITICAL SLOPE FACET

FIG. 5. 2. LOCATION OF ELEVEN CRITICAL SLOPE FACETS

TABLE 5.4 ATTITUDE OF STRUCTURAL DISCONTINUITIES OF NINE POTENTIALLY UNSTABLE SLOPE FACETS

SLOPE FACET NO.	STRUCTURAL INTERPRETATION							
	BP/FP/J_1		J_2		J_3		J_4	
	DIP AM.	DIP DR.	DIP AM	DIP DR.	DIP AM	DIP DR.	DIP AM	DIP DR.
145	50	N315	45	N82	60	N179	-	-
156	40	N240	40	N98	70	N350	16	N25
157	60	N220	38	N5	42	N76	80	N110
195	48	N211	45	N84	78	N310	-	-
202	46	N224	47	N80	52	N322	-	-
206	39	N208	36	N30	63	N130	-	-
210	40	N204	60	N358	61	N144	-	-
251	30	N147	56	N334	70	N225	-	-
308	38	N260	48	N70	80	N310	50	N160

BP - Bedding plane
FP - Foliation plane
J_1, J_2, J_3, J_4 - Joint planes
DIP AM. - Dip Amount
DIP DR. - Dip Direction

In the present analysis, the horizontal acceleration ($\alpha \approx 0.25g$) has been calculated by using the following relation given by Trifunac & Brady (1975) for seismic zone IV.

$$\text{Log } \alpha_H = 0.014 + 0.30 I_{mm} \qquad \text{...(5.2)}$$

where,

I_{mm} = 8 for zone IV.

I_{mm} stands for "modified Mercalli" scale of intensity.

$\text{Log } \alpha_H = 0.014 + 0.30 \text{x} 8$

or $\alpha_H \approx 0.25g$

The above relation has been used to compute α_H from given intensity in modified Mercalli scale (IS code 1893-1984). The code has classified the area of country into number of different zones in which one may reasonably expect earthquake shocks of more or less of same intensity. The modified Mercalli intensity such as V or less, VI, VII, VIII, IX and above are broadly associated with various seismic zones 1,2,3,4 and 5 respectively. The area under study falls in zone IV and therefore, intensity 8 is considered in the equation 5.2.

5.3.1 Determination of Shear Strength Parameters

The Cohesion (C) and the angle of internal friction (ϕ) of the discontinuities are important parameters required for the slope stability analysis. These two shear strength parameters (C & ϕ) can be determined in laboratory tests. Shear strength parameters (C & ϕ) can also be determined by the back analysis of the failed slopes. Since the reliability of the first method to apply in field conditions is doubtful, the second method is preferred. Therefore, back analysis of existing failed slopes have been carried out for determination of shear strength parameters (C & ϕ) of the discontinuities. However, only one of the shear strength parameters out of the two, can be obtained by the back analysis. Out of these two parameters, it is safer to obtain the value of angle of internal friction (ϕ) from RMR classification. For this purpose, lowest values of angle of internal friction (ϕ) have been used in back analysis and later in the analysis of plane and wedge modes of failure. The values of angle of internal friction (ϕ) would be more or less same for the rock mass and discontinuities as discussed in section 5.2.6. Hence, the angle of internal friction (ϕ), obtained from RMR values, is used in calculating the corresponding value of cohesion (C) of the discontinuities by Back analysis.

The value of cohesion `C' of discontinuities involved in the failed slopes have been calculated by back analysis. The same cohesion (C) values have been used for those structural discontinuities which are also involved in the kinematically unstable slopes. The geometry of four failed slopes having plane mode of failure and the calculated cohesion values of discontinuities along which the slopes have been failed, is shown in Table 5.5

TABLE 5.5 GEOMETRY AND SHEAR STRENGTH PARAMETERS OF FOUR FAILED SLOPES

SLOPE FACET NO.	GEOMETRICAL PARAMETERS					γ T/m³	ϕ Deg	C T/m²
	Ψ_f Deg	Ψ_p Deg	H m	Z m	Z_w m			
157	80	45	23	13.34	3.3	2.45	25	10.1
195	79	40	16	9.6	2.4	2.55	25	6.24
206	74	42	18	8.86	2.22	2.55	25	6.14
308	80	44	25	14.75	3.69	2.85	35	9.6
Factor of Safety = 1 Unit Weight of Water = 1 T/m³ Release Joint is vertical								
Ψ_f = Slope Inclination Ψ_p = Failure Plane Inclination H = Height of Slope γ = Unit Weight of Rock					Z = Depth of Release Joint Z_w = Depth of water in Release Joint ϕ = Angle of Internal Friction C = Cohesion			

Out of these three slope facets showing plane mode of failure, the value of cohesion (C) obtained by Back analysis has been used in two slope facets (157 & 195). In case of third slope facet (251), where the Back analysis is not possible, the lowest value of cohesion (C) as obtained from the RMR, has been used.

The cohesion (C) values determined by the back analysis have been used in the wedge failure analysis if, the same discontinuity is involved in both failed slopes as well as in kinematically unstable slope facets having wedge mode of failure. The wedge failure analysis has been carried out in nine slope facets. Out of these, value of cohesion (C) obtained from back analysis has been used in four slope facets (156, 157, 210 & 308) to obtain the factor of safety. For remaining slope facets where back analysis has not been possible, the value of cohesion (C) has been obtained directly from RMR values, wherever rocks are massive yielding high RMR value. In such cases the lowest value of range of cohesion (C) has been used. Under this category, wedge analysis has been carried out for three slope facets (145, 202, & 251). In case of slope facet no. 206 value of cohesion (C) has been obtained from back analysis for one discontinuity only and value for the other discontinuity obtained from RMR value. In case of slope facet no. 143, minor tension cracks have been observed in certain parts of the upper reaches and one of the discontinuities involved in possible wedge mode of failure is foliation plane which is first order discontinuity. In view of this, the value of cohesion (C) has been reduced to half (10 T/m^2) the value of cohesion obtained from RMR value.

□ 5.4 FACTOR OF SAFETY

5.4.1 Plane Failure

The factor of safety (FOS) in three high hazard slope facets of plane mode of failure in static dry and wet conditions as well as in dynamic dry and wet conditions is determined by the method of Hoek & Bray (1981). The values of factor of safety have also been determined for various conditions of release joint such as quarter-filled, half-filled and fully-filled with water.

The geological cross sections across the potentially unstable high hazard slope facets for plane mode of failure have been prepared (Fig.5.1).

The following equations of Hoek & Bray (1981) have been used to calculate factor of safety for dry and wet conditions under static as well as dynamic conditions.

$$F=\frac{C\,A + (w.\cos\psi_p - U - V.\sin\psi_p)\tan\phi}{w.\sin\psi_p + V.\cos\psi_p} \quad \ldots(5.3)$$

$$F=\frac{C\,A + [w(\cos\psi_p - \alpha\sin\psi_p) - U - V.\sin\psi_p]\tan\phi}{w(\sin\psi_p + \alpha\cos\psi_p) + V.\cos\psi_p} \quad \ldots(5.4)$$

where,

F = Factor of safety

C = Cohesion

A = Area of the sliding block

w = Weight of the sliding block

ψ_p = Inclination of the failure plane

U = Uplift force due to water pressure on the sliding surface

V = Force due to water pressure in the tension crack

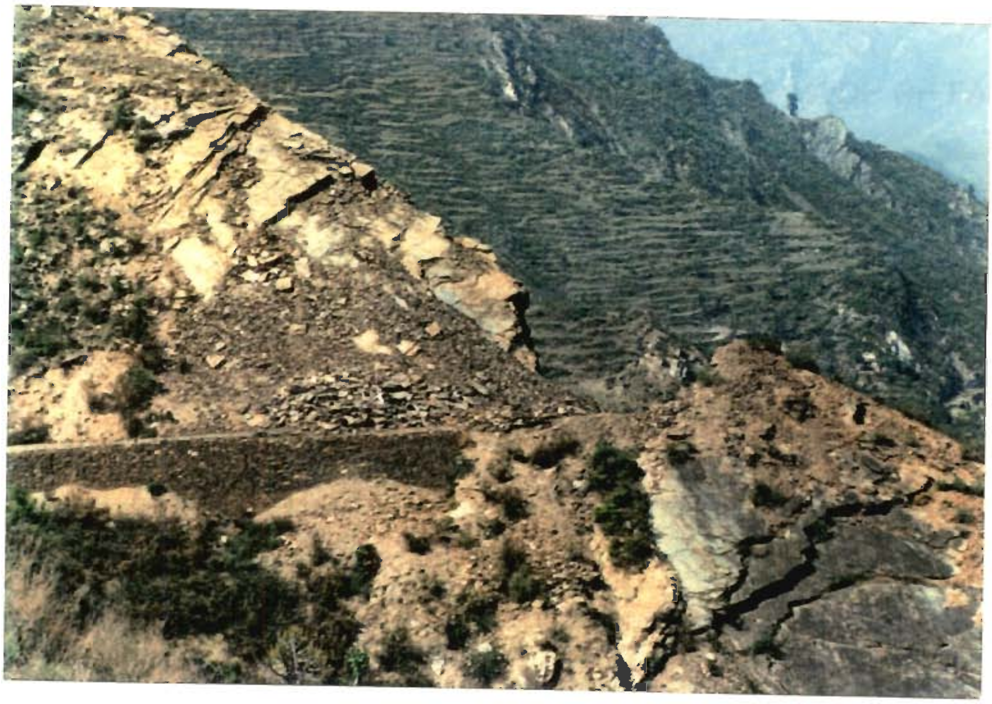
ϕ = Angle of internal friction and

α = Horizontal acceleration of earthquake (0.25)

The values of U,V and α will be zero for static dry conditions. The input data of three slope facets having plane mode of failure are given in Table 5.6

The calculated values of factor of safety (FOS) of the slope facets having plane mode of failure are shown in Table 5.7. These results are also shown in Fig.5.3 for a visual comparison of factor of safety calculated for slope facets at different conditions.

PLATE 8



Plane failure in phyllites along Chamba - Bhaldiyana road (under construction).

Plane failure in quartzites of Berinag Formation near Surkunda.

TABLE 5.6 INPUT DATA OF SLOPES HAVING PLANE MODE OF FAILURE IN HIGH HAZARD SLOPE FACETS

SLOPE FACET NO.	GEOMETRICAL PARAMETERS								
	Ψ_f Deg	Ψ_{fd} Deg	Ψ_p Deg	Ψ_{pd} Deg	H m	ϕ Deg	C T/m^2	γ T/m^3	α
157	47	N70	42	N76	180	25	10.1	2.45	0.25
195	51	N229	48	N211	120	25	6.24	2.55	0.25
251	58	N327	56	N334	160	25	20.0	2.45	0.25

Ψ_f = Slope Inclination
Ψ_{fd} = Direction of Slope
Ψ_p = Failure Plane Inclination
Ψ_{pd} = Direction of Failure Plane
H = Height of Slope

ϕ = Angle of Internal Friction
C = Cohesion
γ = Unit Weight of Rock
α = Earthquake Horizontal Acceleration

TABLE 5.7 FACTOR OF SAFETY OF SLOPES HAVING PLANE MODE OF FAILURE IN HIGH HAZARD SLOPE FACETS

SLOPE FACET NO.	FACTOR OF SAFETY							
	STATIC				DYNAMIC			
	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
157	1.09	0.99	0.88	0.63	0.76	0.68	0.6	0.41
195	1.27	1.17	1.12	1.01	0.9	0.86	0.82	0.73
251	3.25	3.2	3.14	3.01	2.68	2.64	2.58	2.48

F_1 = Dry Release Joint
F_3 = Release Joint filled half with Water
F_5 = Dry Release Joint + Earthquake Loading
F_7 = Release Joint filled half with Water + Earthquake Loading

F_2 = Release Joint filled quarter with Water
F_4 = Release Joint fully filled with Water
F_6 = Release Joint filled quarter with Water + Earthquake Loading
F_8 = Release Joint filled full with Water + Earthquake Loading

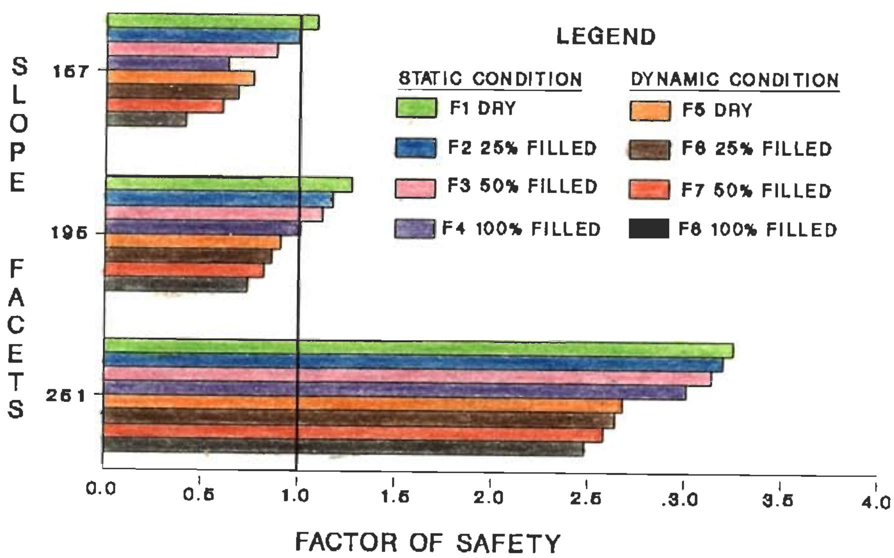


FIG. 5.3 FACTOR OF SAFETY OF SLOPE FACETS HAVING PLANE MODE OF FAILURE IN THE FORM OF BARS

DISCUSSION OF RESULTS:

A careful study of results obtained, indicate the followings:

The Factor of Safety (FOS) of slope facet number 157 is slightly more than unity (1.09) in static dry condition, indicating that slope facet is just stable. In other conditions, namely static wet (quarter, half and fully-filled with water) the values of factor of safety are less than the unity (0.99, 0.88 & 0.63) respectively. Further under dynamic dry and wet conditions values of factor of safety get reduced considerably below unity. Hence, it may be considered that slope facet is unstable.

The slope facet number 195 is stable in static dry as well as in wet conditions. Though the factor of safety is close to unity (1.01) in static wet (fully-filled with water) condition. On the other hand, the values of factor of safety (FOS) reduces to less than unity in dynamic dry as well as in wet conditions making the slope unstable.

The results of plane failure analysis of slope facet number 251 indicates that values of factor of safety are quite high in all the cases of static dry and wet conditions. Therefore the slope facet is stable even in the most adverse conditions i.e. release joint fully-filled with water and earthquake loading.

According to Sharma (1995), the difference between slope angle and the angle of discontinuity plane along which failure may occur, plays an important role. He has shown statistically that the difference is inversely proportional to the factor of safety i.e. as the difference increases the factor of safety reduces. In case of slope facet no. 251, since the difference between slope angle and the angle of discontinuity plane is just 2°, the obtained factor of safety is high, though the slope facet satisfies the conditions for plane failure.

5.4.2 Wedge Failure

In order to calculate factor of safety of wedge failure, the program `RWEDGE' has been used which is based on the comprehensive solution (Hoke and Bray, 1981). A brief out line of the program `RWEDGE' is given in Annexure -1.

The factor of safety has been calculated for wedge failure under static `dry & wet' and dynamic `dry & wet' conditions. The factor of safety is determined in wet conditions when the releasing joints are quarter-filled with water and half-filled with water. The geological cross sections across the potentially unstable, high hazard slope facets for wedge mode of failure are shown in Fig.5 1.

Since, minor tension cracks have been developed on a part of the slope facet No. 143, the affected part of this slope facet has been mapped on 1:2000 scale by electronic Theodolite and Distomate (Fig.5.4)

The required input data to obtain factor of safety for wedge failures is given in Table 5.8, whereas the results are shown in Table 5.9. For a visual comparison of calculated factor of safety at different conditions for all slope facets having wedge mode of failures are shown in Fig. 5.5.

DISCUSSION OF RESULTS:

The following conclusions can be drawn after a careful study of result of slope stability analysis of slope facets having wedge mode of failure:

The results of wedge failure analysis of slope facet 145 indicate that the values of factor of safety (FOS) are sufficiently higher than unity for different conditions.

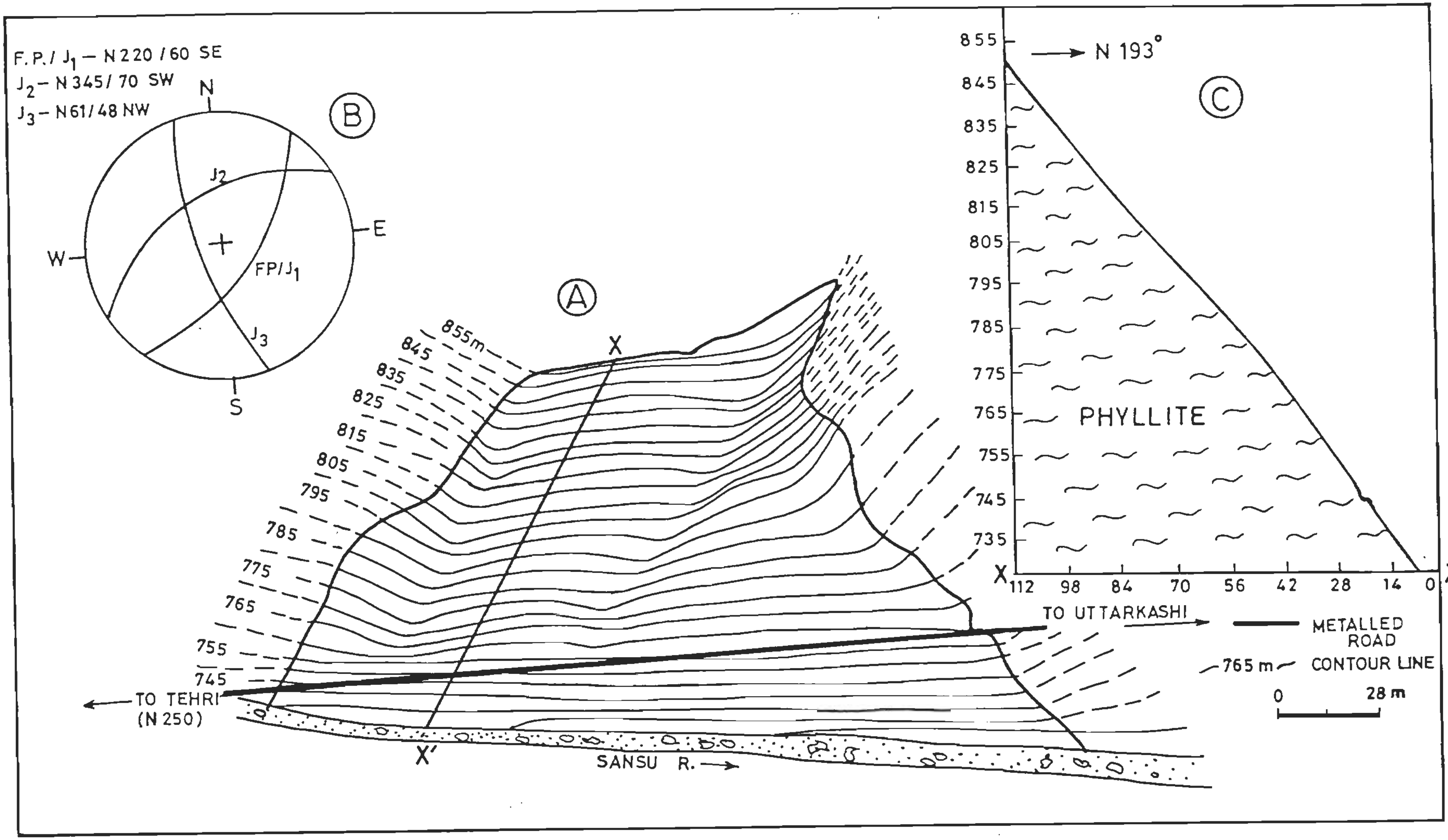


Fig. 5.4.A – PLAN OF THE SLOPE FACET NO. 143
B – STEREOPLOT SHOWING THE ATTITUDE OF STRUCTURAL DISCONTINUITY PLANES
C – SECTION DRAWN ALONG XX' LINE

Therefore, slope facet number 145 is stable even in dynamic wet (half filled with water) condition. The slope facet numbers 202, 210 and 308 are stable in all the conditions except dynamic wet (half-filled water) condition, where the factor of safety is less than unity (0.41, 0.79 and 0.61) in the respective slope facets.

TABLE 5.8 INPUT DATA FOR CALCULATING FACTOR OF SAFETY OF CRITICAL WEDGES IN HIGH HAZARD SLOPE FACETS

PARAMETERS	SECTIONS/SLOPE FACET NUMBERS								
	143	145	156	157	202	206	210	251	308
α_1	60	50	40	38	47	36	60	56	48
β_1	N130	N315	N98	N5	N80	N30	N358	N334	N70
α_2	70	60	70	42	52	63	61	70	80
β_2	N225	N179	N350	N76	N322	N130	N144	N225	N310
α_3	8	10	0	0	18	5	16	22	20
β_3	N165	N248	N30	N70	N60	N90	N56	N327	N358
α_4	53	38	53	47	44	52	48	58	59
β_4	N165	N248	N30	N70	N60	N90	N56	N327	N358
C_1	10.0	20.0	10.1	10.1	20.0	20.0	6.14	20.0	9.6
C_2	10.0	20.0	10.1	10.1	20.0	6.14	6.14	20.0	9.6
ϕ_1	25	25	25	25	25	25	25	25	35
ϕ_2	25	25	25	25	25	25	25	25	35
γ	2.45	2.45	2.45	2.45	2.45	2.55	2.55	2.45	2.85
H	122	200	185	180	200	200	148	160	110

α_1 = Dip of plane 1 (Deg.)
α_2 = Dip of plane 2 (Deg)
α_3 = Dip of upper slope surface (Deg)
α_4 = Dip of slope face (Deg.)
C_1 = Cohesion of plane 1 (T/m^2)
C_2 = Cohesion of plane 1 (T/m^2)
γ = Unit Weight of rock (T/m^3)

H = Height of the slope (m)
β_1 = Dip direction of plane 1 (Deg)
β_2 = Dip direction of plane 2 (Deg)
β_3 = Dip direction of upper slope surface (Deg)
β_4 = Dip direction of slope face (Deg.)
ϕ_1 = Angle of internal friction of plane 1(Deg)
ϕ_2 = Angle of internal friction of plane 2 (Deg)

TABLE 5.9 RESULTS OF ANALYSIS OF CRITICAL WEDGES IN HIGH HAZARD SLOPE FACETS

SLOPE FACET NO.	DRY Condition		WET CONDITION			
			25%		50%	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
143	2.30	1.66	1.93	1.37	0.63	0.45
145	2.76	1.77	2.44	1.55	2.12	1.32
156	1.43	0.94	1.22	0.78	1.00	0.45
157	1.46	0.97	1.21	0.79	0.35	0.18
202	2.50	1.66	2.16	1.42	1.82	0.41
206	1.41	0.91	1.24	0.79	1.07	0.59
210	2.04	1.23	1.73	1.01	1.42	0.79
251	3.00	2.23	2.61	0.29	0.34	0.23
308	2.07	1.39	1.72	1.11	1.37	0.61

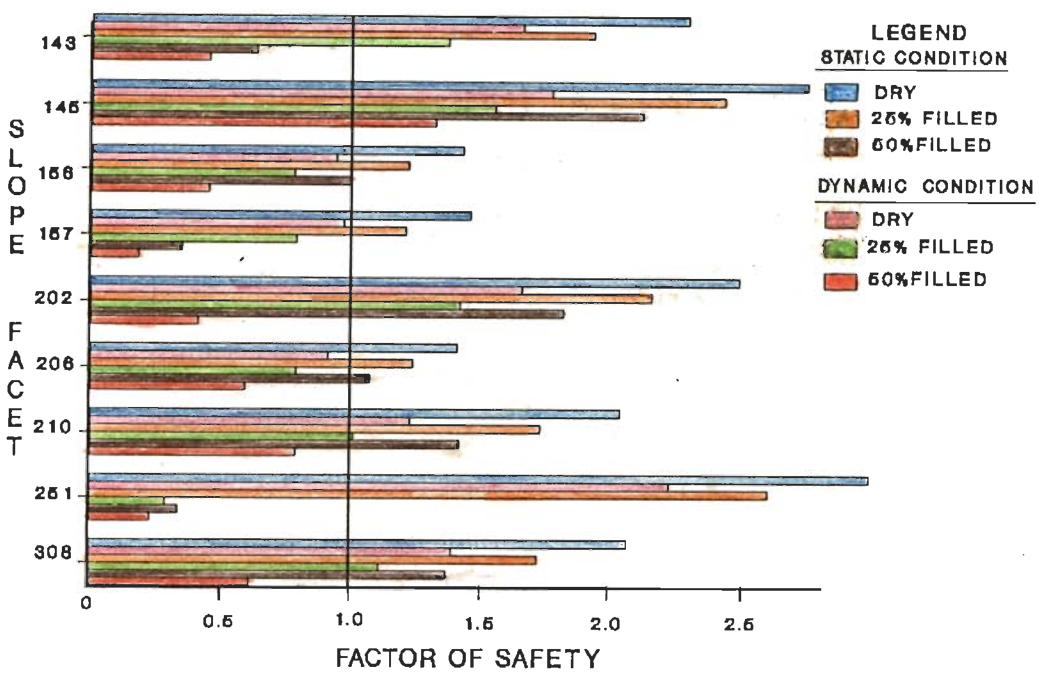


FIG. 5.5 FACTOR OF SAFETY OF SLOPE FACETS HAVING WEDGE MODE OF FAILURE IN THE FORM OF BARS

The values of factor of safety of slope facet numbers 156 and 206 show that they are stable in static dry as well as in static wet conditions, although the slope facet number 156 shows a unit factor of safety in static wet (half-filled with water) condition. On the other hand, these slope facets are unstable in dynamic dry as well as in dynamic wet conditions.

The values of factor of safety of slope facet number 143 suggest that it is stable in static dry and wet (quarter-filled with water) and dynamic dry & wet (quarter-filled with water). On the other hand the values of factor of safety reduces below unity (0.63 and 0.45) for static wet (half-filled with water) and dynamic wet (half-filled with water) conditions, indicating that the slope is unstable in such conditions.

The values of factor of safety indicates that slope facet number 157 is stable in static dry and wet (quarter-filled with water) conditions as it is sufficiently higher than unity. The slope facet is critically stable in dynamic dry (FOS = 0.97) and it is unstable in all other static and dynamic conditions.

The slope facet number 257 is stable in static dry, dynamic dry and static wet (quarter-filled with water) conditions. On the other hand, it is unstable in dynamic wet (quarter and half-filled with water) and in static wet (half-filled with water) conditions as the values of factor of safety are less than unity.

From the above discussion, it is evident that all the slope facets are stable in static dry and static wet (quarter-filled with water) conditions. Moreover, out of nine, six slope facets (143, 145, 202, 210, 251 and 308) are stable in dynamic dry condition. In dynamic wet (quarter-filled with water) condition, few slope facets such as 143, 145, 202 and 308 are stable. In static wet (half-filled with water) condition the slope facet numbers 145, 202, 210 and 308 are stable, whereas, slope facet numbers 156 and 206 are critically stable. A single slope facet number 145 is stable even in dynamic wet (half-filled with water) condition as the factor of safety (1.32) is sufficiently higher than unity.

5.4.3 Circular Failure

Circular failure or rotational failure are usually found in soil or highly weathered or crushed rocks. In such cases, failure usually occurs along a nearly circular surface, the axis of which is nearly parallel to the slope facet.

Circular failure conditions have been identified on the slope facet number 177. The rock exposed on this slope facet is phyllite which is highly weathered in nature . Further the surface run-off water has resulted in the formation of rills on the slope facet. In addition, the Bhagirathi river takes a sharp rectangular turn roughly from north to east direction, resulting in toe erosion which might have initiated the sliding.

In order to carry out the stability analysis of the slope facet for circular mode of failure, the entire affected area has been mapped on 1 : 2000 scale using the electronic Theodolite. A contour map and a cross section have also been prepared along section line X-Y (Fig. 5.6).

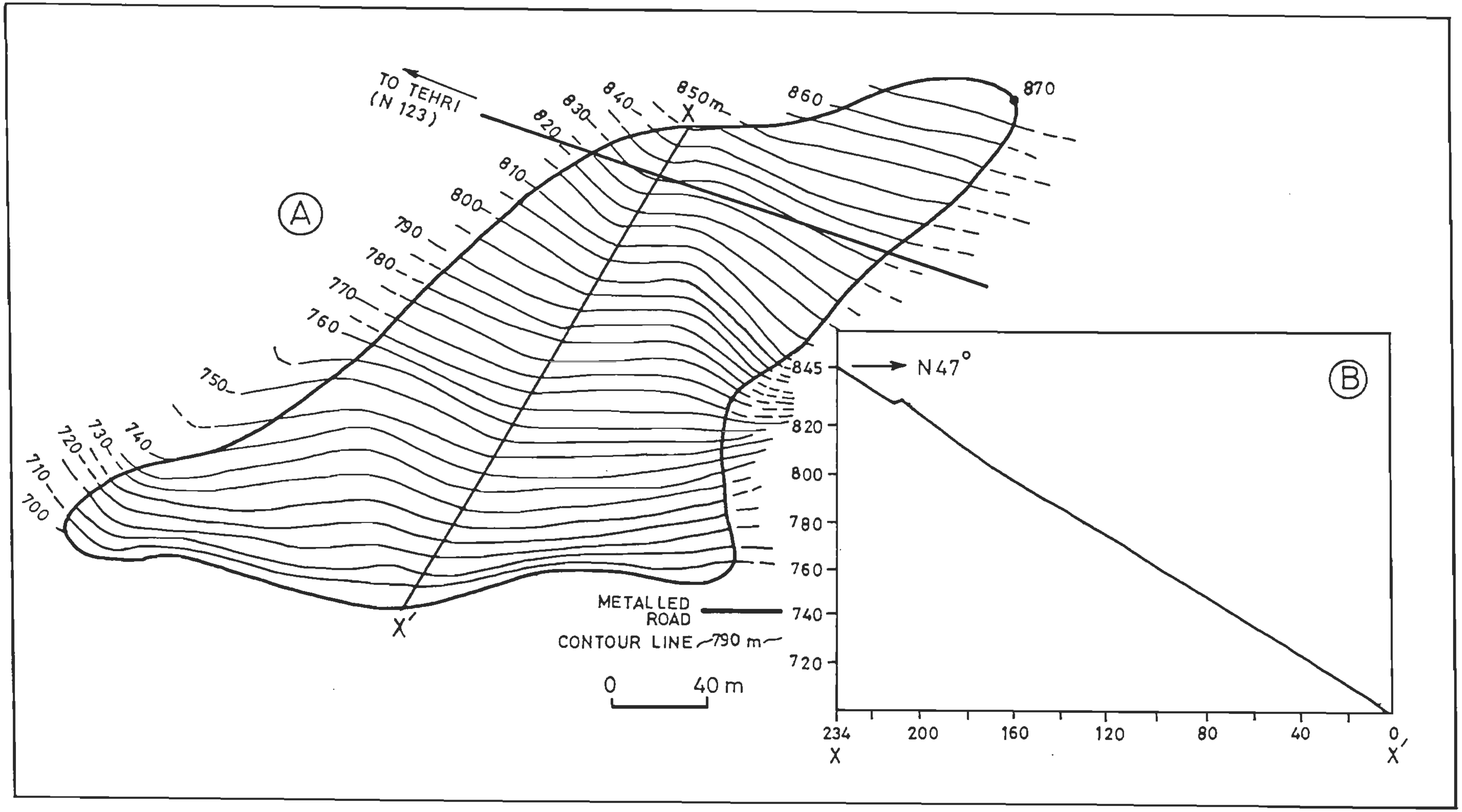


Fig. 5.6. A – PLAN OF THE SLOPE FACET NO. 177
B – SECTION DRAWN ALONG XX'

The computer program BASC has been used to obtain the shear strength parameters of the slope facet material. Bishop's (1955) method of slices has been used in this program and the same is modified for the dynamic analysis taking into account earthquake forces. A brief outline of the program is given in Annexure-1. The computer program BASC can analyse any surface profile and calculates the representative shear strength parameters, cohesion (C) and angle of internal friction (ϕ). In order to obtain cohesion (C) value, judicially chosen values of angle of internal friction (ϕ) are taken as input to obtain corresponding value of cohesion (C). The input data required by the program `BASC' to determine the cohesion (C) value is shown in Table 5.10.

The output result of BASC is shown in the Table 5.11, which shows the calculated cohesion values corresponding to their values of angle of internal friction. The values of cohesion (C) corresponding to the value of ϕ (35° and 40°) are negative and therefore these values have been neglected. The value of cohesion (7 T/m^2) from the rest of the three values and the corresponding value of angle of internal friction (25°) have been chosen for the stability analysis, keeping in view the general condition of slope materials.

In order to carry out the stability analysis of the slope facet having rotational mode of failure, the computer program SARC has been used. The required input data for the stability analysis of the slope facet is given in the Table 5.12.

TABLE 5.10 BACK ANALYSIS FOR SHEAR STRENGTH PARAMETERS OF SLOPE FACET NUMBER 177

PARAMETER	VALUE	INPUT DATA SHEET	
NPHI	5	GAMA (T/m^3) = 2.45 BBAR = 0.1 ZWR = 0.0 AH = 0.0 NFS = 1.0 NX = 5.0 DELX = 2.0 ENTX = 0.0	GAMAW (T/m^3) = 1.0 ZC (m) = 0.0 RWL (m) = 0.0 AV = 0.0 FS = 1.0 NY = 5.0 DELY = 2.0 ENTY = 0.0
PHI (I) I = 1 to NPHI	20,25, 30,35,40		
ROCK (m)	-20.0		
XCUT (m)	118		
XHILL (m)	234		
CX,CY (m)	-11, 247		

NPHI = Number of Phi Values
PHI = Angle of Internal Friction
ROCK = Elevation of Hard Strata w.r.t Origin
XCUT = X-coordinate of a point before which 10 slices should be there for proper accuracy
XHILL = X-coordinate of top of the slope
GAMA = Unit weight of rock/soil
GAMAW = Unit weight of water
BBAR = Pore water pressure/gama * Av.hight of slices
ZC = Depth of tension crack
ZWR = Depth of water in tension crack/ZC

RWL = Reduced level of reservoir w.r.t origin
AH = Horizontal component or earthquake acceleration
AV = Vertical component of earthquake acceleration
NFS = No. of sets of factor of safety
FS = Factor of safety
NX = No of centre points in NY X and Y direction (in array)
DELX = Increment in centre in X and Y
DELY direction
CX,CY = Coordinates of centre of slip circle
ENTX, = X and Y coordinate of entry point
ENTY of the circle

TABLE 5.11 RESULT OF 'BASC' PROGRAM

RESULTS FOR CRITICAL SLIP CIRCLE	
Angle of Internal Friction, ϕ (Deg)	Cohesion, C (T/m^2)
20	11.9
25	7.0
30	2.1
35	-2.9
40	-8.5

The program SARC identifies the probable slip surfaces along which rotational failure may take place. Besides this, the program also calculates the radius and centre of the slip circles for which the factor of safety is minimum. Program SARC uses the Bishop's (1954) equation while calculating the factor of safety.

TABLE 5.12 INPUT DATA SHEET FOR STABILITY ANALYSIS OF HIGH HAZARD SLOPE FACET NUMBER 177 FOR CIRCULAR FAILURE

ROCK= -20 RWL=0 ZC=0 ZWR=0 BBAR=0.1 & 0.2		GAMA(T/m^3)=2.45 GAMA(T/m^3)=1 AH=0.12 AVR=0.5
PARAMETERS	SLOPE FACET NO. 177	N = Number of profile coordinate NENP = Number of entry points XEXIT (I) = X-Coordinate of exit point of circle XEL = X-Coordinate of first exit point of circle XEL = X-Coordinate of last exit point of circle NEP = Number of exit point XS = X-Coordinate Surcharge Point WI = Surcharge Intensity C = Cohesion PHI = Angle of internal friction
N	35	
NENP	1	
XEXIT (I) XEXIT (L)	62 234	
NEP	0	
XS	0	
WI (T m^{-2})	0	
C (T m^{-2})	7	
PHI (Deg.)	25	

The results of slope stability analysis of slope facet number 177 are shown in Table 5.13 and the same have been shown in Fig. 5.7 for comparison of factor of safety at different conditions.

TABLE 5.13 RESULTS OF STABILITY ANALYSIS OF HIGH HAZARD SLOPE FACET NO.177

Exit point (X,Y)	DRY CONDITION		WET CONDITIONS			
			Bbar=0.1		Bbar=0.2	
	S	D	S	D	S	D
232.00,143.50	1.1	0.7	0.98	0.62	0.87	0.54

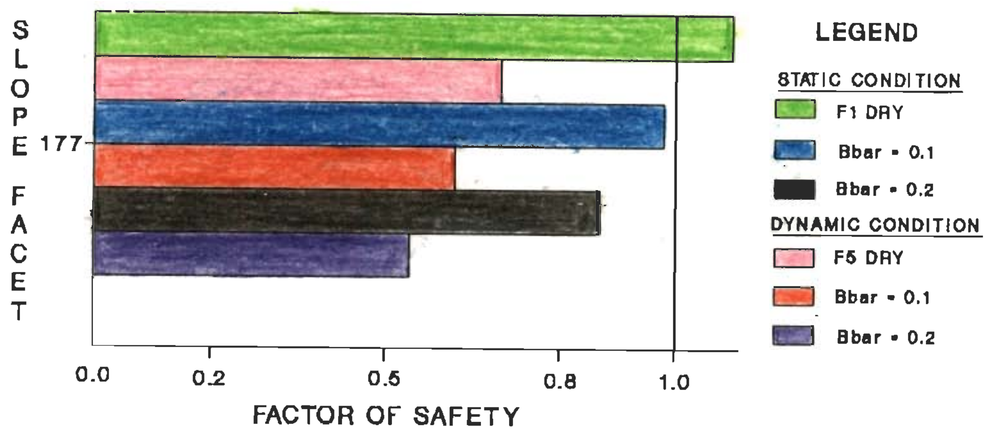


Fig. 5.7 FACTOR OF SAFETY OF SLOPE FACET HAVING CIRCULAR MODE OF FAILURE IN THE FORM OF BARS

The results of stability analysis show that the values of factor of safety of the slope facet in static dry condition is just above unity (1.1). It reveals that the slope is just stable. The values of factor of safety go down below unity in static wet conditions. This shows that the slope is unstable. In dynamic dry and dynamic wet conditions, the factor of safety decreases considerably below unity indicating unstable conditions.

CHAPTER VI

Conclusions and Remedial Measures

To meet the ever increasing demand of the growing population, scores of engineering projects such as multistoryed buildings, transportation routes in the form of roads, rope ways and railway lines and huge hydro-energy projects have come up in the recent times. The environmental impacts of these development activities leading to landslide problems of the region, urgently require a proper and in-depth evaluation in order to keep them to a minimum. The landslide hazard zonation (LHZ) mapping is the first step for achieving sustainable development of the area.

A landslide hazard zonation map depicts a division of land surface into zones of varying degrees of stability based on an estimated significance of causative factors in inducing instability. The LHZ maps, having an important role in planning and development of mountainous area, are useful for the following purposes.

i) Identification and delineation of hazardous area in the mountainous region to avoid the highly unstable zones for development projects.

ii) Ecologically sound mitigation measures can be adopted, depending on the nature of the hazard zones, to check further environmental degradation of the area.

iii) These maps provide input data for carrying out risk analysis, which is helpful in landslide hazard management .

Landslide hazard zonation mapping of Tehri and its vicinity falling between latitudes 30^0 20'-30' and longitudes 78^0 15'-30' in the Bhagirathi valley has been carried out, considering the geoenvironmental conditions.

The rocks exposed in the study area lie in the Inner as well as Outer Lesser Himalaya. The rocks of Inner Lesser Himalaya belong to Rautgara Formation of Dhamtha Group, Deoban Formation of Tejam Group and Berinag Formation of Jaunsar Group. The rocks exposed in the Outer Lesser Himalaya belong to the Chandpur and Nagthat Formations of Jaunsar Group and Blaini, Krol and Tal Formations of Mussoorie Group. A number of major as well as minor structures have been observed in the area of study. The major structures includes the North Almora Thrust (NAT) and the Berinag Thrust and minor structures include the beddings foliations, joints, small scale folds and faults.

An empirical method, namely Landslide Hazard Evaluation Factor (LHEF) rating scheme (Anbalagan, 1992) has been modified and used to prepare LHZ map of the area. A LHZ map of an area delineates the entire area of study into five different hazard zones namely Very High Hazard (VHH), High Hazard (HH), Moderate Hazard (MH), Low Hazard (LH) and Very Low Hazard (VLH) .

A total of three hundred and sixty five slope facets spanning over approximately 400 sq km area has been covered during the study. The study shows that the area can be divided into five slope facets of VHH, seventy slope facets of HH, one hundred sixty six slope facts of MH, one hundred and eighteen slope facets of LH and remaining six slopes facets of VLH zones. The area covered by VHH, HH, MH, LH and VLH hazard zones are 0.35%, 12.51%, 53.56%, 32.46% and 1.12% respectively.

The slope facets falling under VLH and LH zones are considered stable. Though MH slope facets are considered stable in general, they may contain some local pockets of unstable zones, which need to be investigated during project implementation. On the other hand, HH and VHH slope facets represent potentially unstable slopes which need to be studied in detail involving calculation of factor of safety (FOS).

In order to know the distribution of sub-categories of various causative factors in the area of study and within all the five types of hazard zones, the percent area of sub-categories have been calculated separately. Further, percent polygons of sub-categories of each causative factor have been plotted separately. Percent polygons of sub-categories provide the relative trends of percent distribution over different hazard zones.

Following conclusions are drawn from the percent polygons of sub-categories of various causative factors:

i) Percent polygons of rock/soil types show that percentage of rock type-I increases and rock type-III decreases in higher order hazard zones and vice versa whereas soils dominate the very low hazard zones.

ii) Percent polygons of sub-categories of structure show that distribution of unfavourable condition increases and distribution of favourable conditions decreases in higher order hazard zones.

iii) It is inferred from the percent polygons that sub-categories of slope morphometry which are less prone to instability, mainly distributed in stable zones. On the other hand, sub-categories which are more prone to instability, mainly distributed in unstable zones such as HH and VHH zones. For example, very gentle slopes (>15°) dominantly occupy the area in very low hazard zones, gentle slopes are mostly seen in low hazard zones, Moderately steep slopes mainly distributed in low hazard and moderate hazard zones. Steep slopes mainly fall in the high hazard zones. Very high hazard zones which are considered as the most unstable zones, completely (100%) covered by the cliff or escarpment.

iv) Percent polygons of sub-categories of land use and land cover indicate that sub-categories which give less landslide hazard evaluation factor (LHEF) ratings are mainly distributed in stable zones, such as VLH and LH. On the other hand sub-categories namely, sparsely vegetated forest with lesser ground cover and barren lands give more LHEF ratings and are distributed in higher order hazard zones such as HH and VHH.

v) Relative relief of the slope facet depend upon the size of the individual slope facet and to some extend on slope facet angle. Low relief covers the entire VLH zones as these zones have very gentle slopes whereas higher relief dominates the other four hazard zones.

vi) Particularly, there is no distinct pattern found in the distribution of hydrogeological conditions. It is due to the fact, that in most of the hazard zones, a major part of over 95% is always shared by the damp and dry conditions.

Statistical analysis has been carried to find the correlation and order of influence. Rank correlation coefficient has been calculated between total estimated hazard (TEHD) & causative factors and among causative factors by using Spearman Rank Correlation Coefficient method. All the causative factors except Hydrogeological conditions show a positive correlation with TEHD at 5% level of significance. This suggests that, as the LHEF ratings of these causative factors except hydrogeological conditions increase, landslide hazard potential also increases correspondingly.

Relationships among causative factors are insignificant in most of the cases, though, few of them (structure-lithology, land use and land cover-lithology, land use and land cover-slope morphometry, relative relief-lithology and hydrogeological condition-land use and land cover) show weak relationships with rank correlation coefficients -0.15, 0.16, 0.38, -0.11 and -0.13 respectively. This indicates that the influence of one causative factor does not affect others, appreciably.

Order of influence of all the causative factors have been established for the whole area as well as for each hazard zone using Friedman Test and later verified and strengthened by Page's Test. Regarding the order of influence of causative factors based on Friedman Test and Page's Test the following inferences have been drawn.

The order of influence of causative factors which induce instability are LULC & SM and Lit & Str in VHH zones; SM & LULC and Lit & Str in HH zones: SM & Str in MH zones: SM & Str and LULC, RR & Lit in LH zones and Str and Lit & LULC in VLH zones for the first two places (Table 4.16). In general, it is found that SM , Str and LULC plays most important role in inducing instability (Table 4.16). The influence of causative factors in the whole area has been found to be in the following decreasing order; SM, LULC, Lit, RR and HGC. Hydrogeological conditions have least influence in inducing hazard in each zone, since damp and dry conditions mostly persist.

Detailed studies have been carried out for high hazard slope facets involving calculation of factor of safety (FOS). It is found that 10 critical HH slope facets satisfy the Markland Test. Out of these one slope facet accounts for plane mode of failure, seven account for wedge mode of failure and two account for both plane and wedge mode of failures. The values of factor of safety have been calculated for these slope facets in static (dry and wet) conditions as well as in dynamic (dry and wet) conditions.

The plane failure analysis suggests the following conclusions:
The slope facet number 157 is critically stable in static dry condition and is found to be unstable in other conditions while slope facet number 195 is stable in the static and unstable in the dynamic conditions, whereas slope facet number 251 is stable in both the static and the dynamic conditions.

The wedge failure analysis suggests the following conclusions:

All the slope facets are stable in static dry and static wet (quarter-filled with water) conditions. Moreover, out of nine, six slope facets (143, 145, 202, 210, 251 and 308) are stable in dynamic dry condition. In dynamic wet (quarter-filled with water) condition, few slope facets such as 143, 145, 202 and 308 are stable. In static wet (half-filled with water) condition the slope facet numbers 145, 202, 210 and 308 are stable, whereas, slope facet numbers 156 and 206 are critically stable. A single slope facet number 145 is stable even in dynamic wet (half-filled with water) condition as the factor of safety (1.32) is sufficiently higher than unity.

In addition to these rock slop failures, rotational mode of failure has also been observed on one slope facet and the factor of safety has been calculated for this slope facet. Results reveal that slope is just stable in static dry condition as the factor of safety attains a value just above the unity (1.1) and it is unstable in dynamic dry, static wet and dynamic wet conditions.

A set of general remedial measures have been suggested below for the stabilization of potentially unstable slope facets. The potentially unstable slopes falls mainly in three categories plane, wedge and rotational failures.

Plane and Wedge mode of failures: Out of a total of 10 critical slope facets, which are identified for the detailed analysis, one accounted for plane mode of failure, seven accounted for wedge mode of failure and two accounted for both plane and wedge mode of failures. These plane and wedge mode of failures occur mainly due to the road excavations, following remedial measures have been suggested for these slopes.

i) Anchoring on potentially unstable slopes using grouted or pre-tensioned anchors driven as far as possible perpendicular to the major structural discontinuities.

ii) Shotcreting on chain-link fabric leaving 25% area for drainage.

iii) A suitable breast wall or retaining wall along the road on the hill side.

The rotational mode of failure observed on slope facet number 177. The rotational failure extends roughly over 290 m distance at the base and reaches at a height of 170 m from the river. The Tehri-Uttarkashi road section is located at 830 m elevation in the slide area. The river Bhagirathi takes an acute turn at the base of slide area. The slope materials mainly consists of slide debris. The following remedial measures are suggested for this site.

i) A wire crated toe wall of 3 to 5 m height adjoining the river course in steps of 1.5 m each.

ii) A series of 2 to 3 m high check dams made out of wire crated walls may be constructed at 20 m intervals on the stream bed in the side area and further above.

iii) The entire area may be afforested with suitable plant species.

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ANNEXURE I

A BRIEF OUTLINE OF COMPUTER PROGRAMS

The Computer Programs, namely RWEDGE, BASC and SARC are developed in the Department of Civil Engineering, University of Roorkee, Roorkee and same has been used in the present study.

A number of workers including Geologists, Civil Engineers and Mining Engineers have used these programs over the last 15 years for stability studies of assessment of dam abutment and dam reservoir slopes, design of rail and road side cut slopes, site development for building complexes, landslide control and planning of eco-development in seismic hilly areas.

USE OF COMPUTER PROGRAMS (RWEDGE, BASC AND SARC)

The programs (X) are written in Fortran 77. The user's manual is also included as IX. NEW for preparation of input data files. Further, typical input data files are also given as IX.DAT beginning with I. The corresponding output files OX.DAT are added, beginning with O.

The typical computer commands are

NE IX.DAT	-	To open Input File
NE OX.DAT	-	To open output File
X	-	Name of Computer Program
IX.DAT	-	Input File Name
OX.DAT	-	Output File Name
2	-	For Execution
1	-	For Help menu
NE OX.DAT	-	For seeing output file OX.DAT

The capability of each program, used in this research work, is described below:

RWEDGE

This program is used for the computation of factor of safety of tetrahedral wedge formed by the intersection of two discontinuities, the slope face and the upper surface. The program automatically chooses a pair of discontinuities from the given set of data and it checks whether such planes form surface along which the rock wedge could slide. The influence of tension crack is included in the program. The program also allows for different strength parameters on the two planes of weakness and different water conditions on the slope face i.e. no crack and dry condition, wet slope with no crack, presence of crack with water and presence of crack with no water.

The special feature of this program is to compute the factor of safety under earthquake loading. Moreover, the program also calculates the dynamic displacement of slope by utilising the correlation developed by Lavania et al. (1987).

BASC

Computer program BASC facilitates the back analysis of slopes to determine the strength parameters cohesion (C) and angle of internal friction (ϕ) of a rock/soil slope with probable circular mode of failure. As already discussed in Chapter V, only one of the two shear strength parameters can be determined by the back analysis. Hence, for judicially chosen values of angle of internal friction, the values of cohesion is calculated by the program BASC.

This program analyses any general surface profile and considers the effect of pore water pressure, tension crack at the top of the slope and earthquake loading to determine the shear strength parameters.

SARC

This program facilitates to compute the factor of safety with circular failure surface emerging at the toe. It analyses any general profile of the slope surface and for various forces i.e. pore water pressure, depth of tension crack at the top of the slope, depth of water in tension crack and earthquake force. In the first step, it draws the various slip surfaces along which failure can take place. Then it calculates the radius and centre of each slip surface.

In the next step, the factor of safety is computed using Bishop's equation for various slip surfaces until a minimum factor of safety is obtained. The analysis evaluates critical acceleration for slopes with factor of safety less than unity and computes dynamic displacement utilising correlation developed by Lavania et al., 1987.