HILL SLOPE STABILITY STUDIES OF A PART OF TEHRI RESERVOIR, HIMALAYA, INDIA

A THESIS

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **HILL SLOPE STABILITY STUDIES OF A PART OF TEHRI RESERVOIR, HIMALAYA, INDIA** in fulfillment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the DEPARTMENT OF EARTH SCINECES, University of Roorkee, Roorkee, U.P., India, is an authentic record of my own work carried out during a period from April 1995 to October 2000 under the supervision of Dr. A.K. AWASTHI and 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.

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ABSTRACT

A rock-fill dam planned to a height of 260.5 m, is under construction across the Bhagirathi river - 1.5 km. downstream of its confluence with the river Bhilangna near Tehri township (Uttar Pradesh, India). On its completion the reservoir is estimated to be of 35.5 * 10^8 m^3 storage capacity at target of maximum reservoir level of 840 m. The reservoir when full, will extend upstream from the Dam to 44 km along the river Bhagirathi and 25 km along the river Bhilangna . The stability of hill slopes flanking the reservoir, therefore, forms a very important aspect with regard to this dam. The present study is an endeavour to evaluate the stability of the reservoir bounding hill slopes of the Lesser Himalaya falling in the Survey of India Toposheet Number 53 J/7 and 53 J/11, with the following major objectives:

(i) Identification of hazard prone slopes.

(ii) Impact of landslide induced water waves in the reservoir on the proposed dam.

(iii) Suggest remedial measures for improving stability of hazard prone slopes.

The rocks exposed in Tehri reservoir area are the Chandpur phyllites and quartzites of the Garhwal Group. In the Bhilangna valley, towards north and east of dam site, Chandpur phyllites come in contact with quartzite of Garhwal Group and are separated by the Srinagar thrust. The rocks are foliated with average dip of about 57^0 towards $N224^0$. The rocks are invariably jointed. The joint orientations in decreasing order of prominence are $N247^0/52^0$, $N101^0/47^0$, $N103^0/27^0$ and $N121^0/26^0$.

Initially, a slope facet map of the area of study has been prepared which served as a base map to evaluate the hill slope stability around reservoir. Of the total 156 facets studied, 93 belong to the Bhagirathi and 63 to the Bhilangna river valley slopes. In Bhagirathi river valley, out of 93, 57 facets are on right bank and 36 facets on left bank. Similarly, out of 63

facets in Bhilangna river valley, 32 facets are on right bank and 31 facets on left bank. Cross sections across all these 156 slope facets have been investigated for their stability aspects in Bhagirathi and Bhilangna valley. The conventional approach, by using Markland test indicates that the slopes, in general, are stable except four potential failure slopes at different locations. However, when Hoek and Bray's approach of calculating Factor of Safety (F.O.S.) was used, only one slope facet on left bank of Bhagirathi valley appears to be unstable in both dry and wet of dynamic conditions, considering earthquake acceleration 0.16. No slope on right bank of Bhagirthi valley appears to be unstable. Likewise, similar slope analysis was done in the Bhilangna river valley, one of the three potential failure slopes appears to be unstable under 'dynamic and wet' condition. The other two slopes are just critically stable under 'dynamic and wet' condition. No slope facet on left bank of Bhilangna valley is potentially unstable.

The conventional approach based on average slope of the facets does not take into account the variation of the slope within a facet. Hence realizing this limitation a more pragmatic approach has been adopted. In this approach, smallest possible unit between two closely spaced successive contours has been considered for slope stability investigation. It involves back analysis, which takes into account the following steps :

1. Identification of locally steep slopes (potential failure slopes), of the facet, based on Markland test.
2. Determination of Factor of Safety (F.O.S.) for the potentially unstable slopes for various conditions i.e. 'static and dry', 'static and wet', 'dynamic and dry' and 'dynamic and wet'.
3. Based on Factor of Safety the slopes are classified into three different categories (i) stable (F.O.S.>1.5) (ii) critically stable (1<F.O.S.<1.5) and (iii) unstable (F.O.S. < 1).

Based on this new approach, a total of 72 potential failure slopes have been identified as against one by conventional approach in Bhagirathi valley. Out of these 72 slopes, 20 are potential wedge failure and 52 are potential plane failure slopes. Results obtained by calculation of Factor of Safety of all the potential failure slopes show that all potential wedge failures are stable even under worst possible condition (dynamic and wet). Out of 52 potential plane failures, 43 are unstable (i.e. 23 possible slides on right bank and 20 on left bank). Field observations confirm the results obtained by new approach. In Bhagirathi valley most of the slides (unstable slopes) are located near Bhaldgaon, Raolakot and Bhaldiyana villages.

In Bhilangna valley there are 65 potential failure slopes as per the new approach as against three by conventional approach. Out of these 65 potential failure slopes, 25 are wedge failures and 40 are plane failures. All the 25 potential wedge failures have FOS > 1.5 and therefore are stable under four different conditions. Out of 40 potential plane failures, 11 are unstable (FOS < 1), and located on right bank. There is no slide on left bank of Bhilangna valley. In Bhilangna valley, most of the slides are close to Myunda and Dewal villages.

As the geological and environmental conditions are same throughout the area of study, the stability measures have been suggested keeping in view of the results obtained by stability analysis. They include modification of slopes, installation of rock anchors , shotcreting on steel chain linked wire mesh and afforestation. For afforestation locally available plant species can be used namely Chir pine (*Pinus roxburghii*), Buras (Rhododendron *arboreum*), Oak (Quercus *incana*), Kilmore (Berberis *spp.*), Dhaula (Woodfordia *fruiticosa*), Hinselu (Rubus *ellipticus*), Deodar (Cedrus *Deodara*), Pipal (Fias *religrose*), Neem (Azardirachta *indica*), Barh (Ficus *benghalensis*) and other similar plant species.

Sudden failure of slopes around the reservoir would generate water waves in the reservoir. The distance, to which these waves would travel depends mainly upon kinetic energy involved in it. A sufficiently massive slide from the rim slopes could cause overtopping of the dam, either by wave action or simply by raising the water surface faster than the spillway could discharge. In the present analysis, an attempt has been made to calculate the wave height generated by the possible slides in the reservoir area. In Bhagirathi valley, total 43 slides have been considered for this purpose (23 on right bank and 20 on left bank). Wave height due to possible slides for the reservoir rim slope, pertaining to left bank of Bhagirathi valley, varies from $0.101*10^{-6}$ m to $0.4493*10^{-5}$ m. For right bank, wave height varies from $0.165*10^{-6}$ m to $0.2*10^{-3}$ m. In Bhilangna valley, variation is from $0.116*10^{-6}$ m to $0.1*10^{-5}$ m. As the dam has 5 m free board such waves are not likely to affect it adversely. The present study indicates that even in adverse condition of slope failure the wave generated have a maximum amplitude to $0.2*10^{-3}$ m which is much less than 5 m. Therefore, it can be concluded that due to possible slides in the reservoir area, stability of the dam structure will not be endangered.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Among the mountain hazards, the landslides have often resulted in adverse impacts 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 get sometimes breached. 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 results in flash flood over a wide area in the downstream side.

The mountainous terrains such as Himalaya, though look to be mighty and strong, have inherent weak geological features such as thrusts, faults, shear zones, joints and 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.

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. Wide spread 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 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)

A 260.5 m high rock-fill dam is under construction across Bhagirathi river downstream of the confluence of the river Bhilangna near Tehri township (Fig. 1.1, Appendix 1, Plate 1.1 and Plate 1.2). The gross storage at El 840 m which would create a long reservoir in both Bhagirathi and Bhilangna and it is estimated to be $35.5*10^8$ m^3. The Tehri lake will extend upto 44 Km along river Bhagirathi and 25 Km along river Bhilangna and it is flanked by high hills all along both the sides. This reservoir area basically constitute study area. The water level in the lake will vary by 90 m between the normal maximum reservoir level and the dead storage level from October to June every year. According to Mazari, 1983, because of saturation of rocks, the shear parameters may be adversely affected and the slopes along the reservoir rim may slide causing large scale movements due to fluctuation in the lake. He felt that large scale hill slides in the reservoir may pose serious threats to the dam by formation of 'seiches (huge water waves)' . Small scale slides can cause siltation and deforestation. Fears have been expressed regarding large scale hill slides in Tehri reservoir area (Indian Express, 1978).

This aspect has been analysed further and it has been opined that there are some isolated patches in Bhagirathi Valley along the reservoir rim which are prone to slope movements; but they are essentialy shallow, surficial movements, which are unlikely to pose major stability problems (Singh et al, 1983).

Landslide hazard map of different parts of Kumaun and Garhwal Himalaya has been prepared by Anbalagan, 1992; Chaubey and Litoria, 1990; Gupta, 1996; Gupta and Anbalagan, 1995 and Shantanu, 1996.

Awasthi et al., 1995 and Tabatabaei, 1992 have emphasized the role of terrain attributes and drainage texture for landslide study in a part of Garhwal Himalaya. Detailed slope stability investigation for Vyasi dam reservoir area, Garhwal Himalaya has been carried out by Jain,

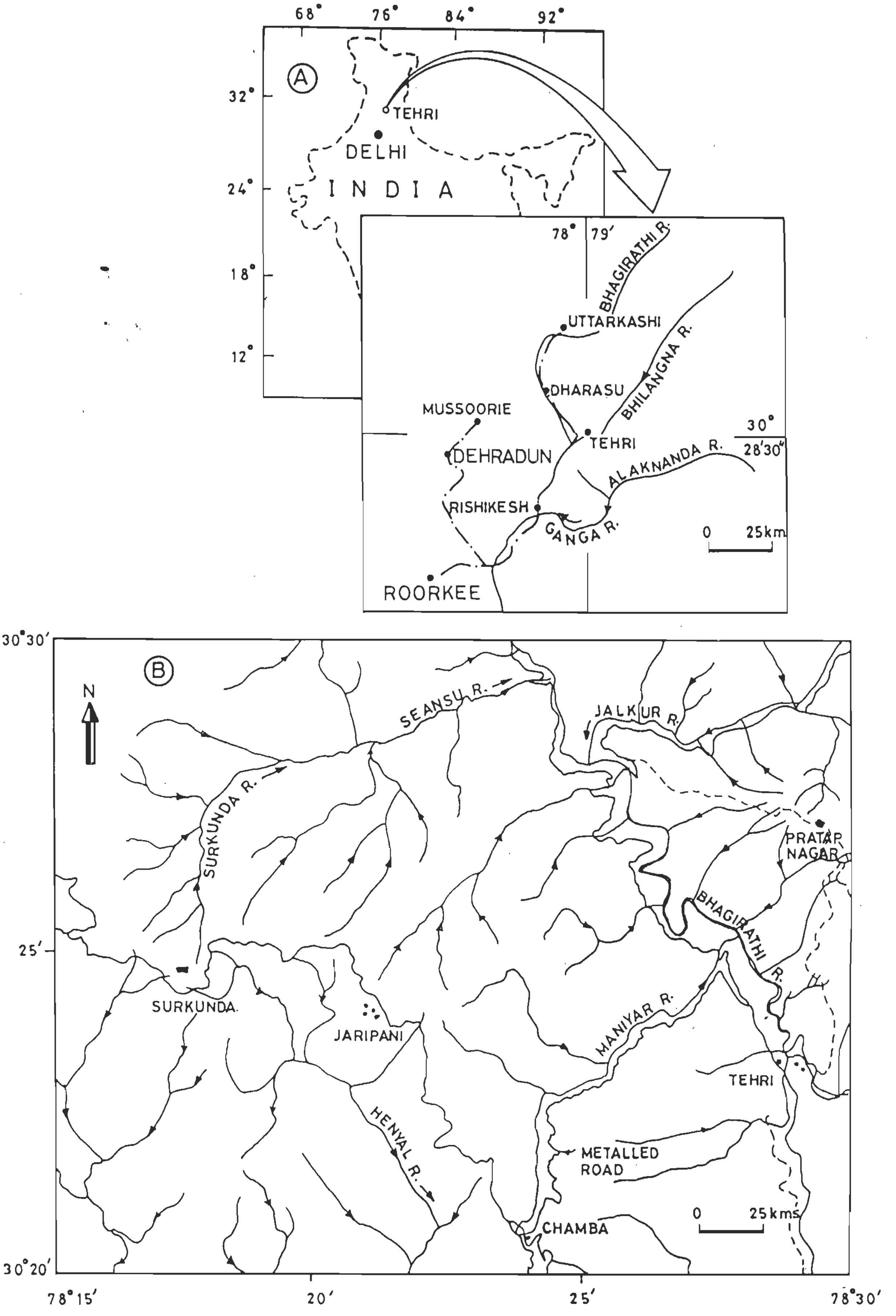


Fig. 1.1 Location of Study area

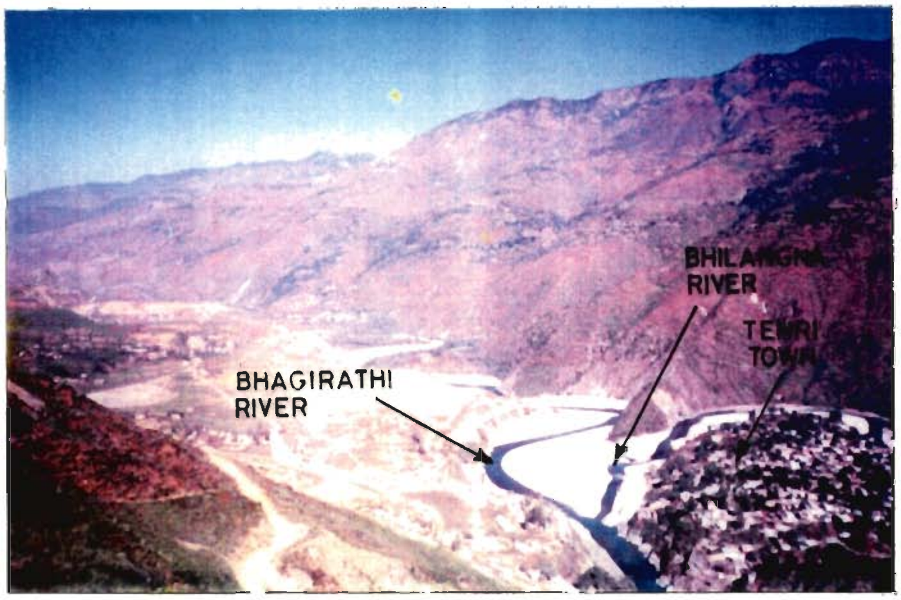


Plate 1.1 Panoramic View of the Area of Study

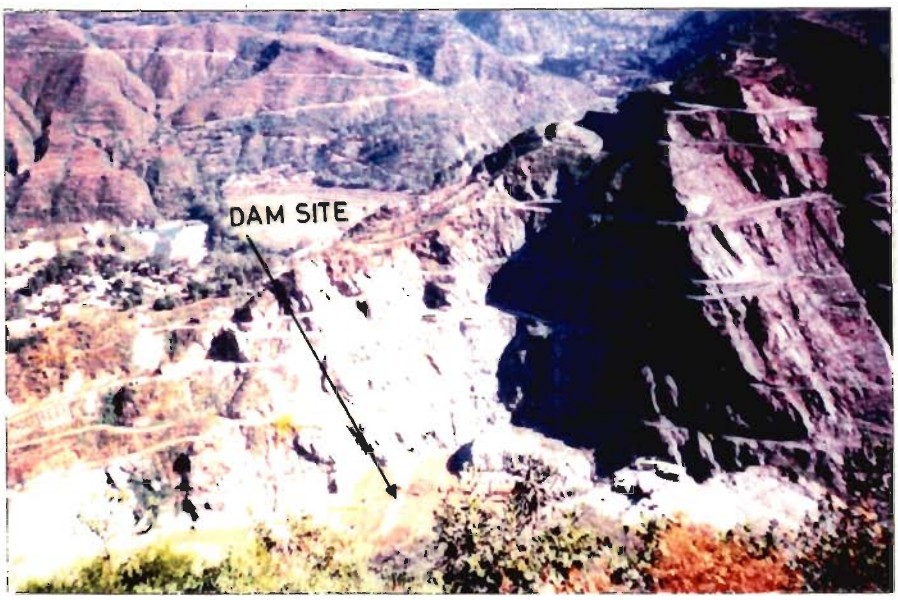


Plate 1.2 Location of the Dam Site

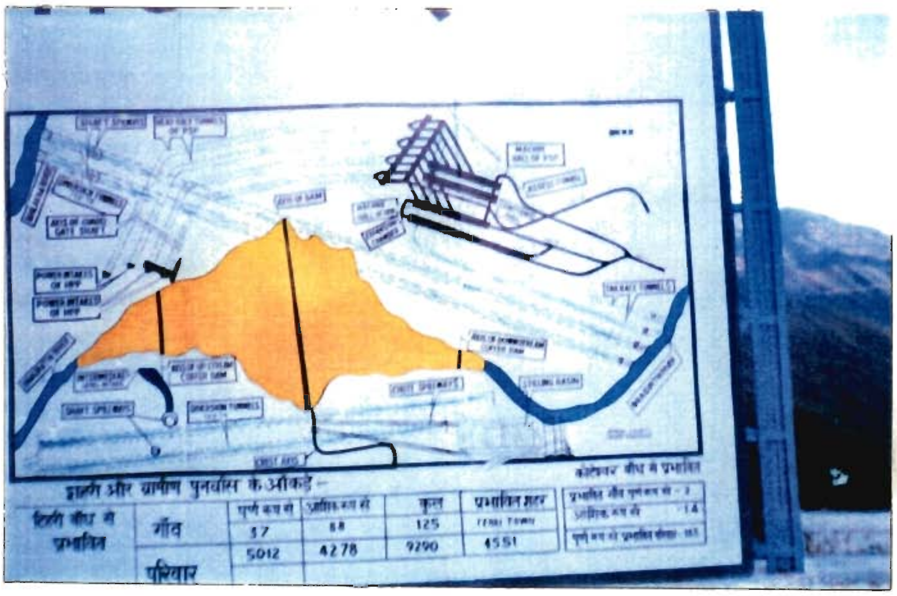


Plate 1.3 Details of the Tehri Dam Project

1995, while the same for Kishau dam project, Garhwal Himalaya has been carried out by Kumar, 1993 and Raghuvanshi, 1996. Singh, 1993 has analysed the geotechnical aspects of Lakhwar dam reservoir, Garhwal Himalaya. Some potential failure slopes in Ladhiya Valley, Kumaun Himalaya has been studied by Srivastava, 1994. Stability study of coastal cliffs of Cox's bazar area, Bangladesh has been done by Rahman, 1995. Probabilistic approach for landslide studies has been discussed by Chowdhury and Zhang, 1993 and Gokceoglu et al., 2000. Gupta et al., 2000 have applied Geostatistical approach for Landslide hazard evaluation in Garhwal Himalaya. Okura et al., 2000 determined the physical properties affecting the distance traveled by landslides with dry particles and elucidating the mechanism of the properties affecting landslide fluidization. Malik and Farooq, 1996 have provided details of Landslide hazard management and stability measures in Pakistan. Details of Landslide studies and management in Nepal have been discussed by Upreti and Dhital, 1996. Application of GIS in Landslide Hazard Zonation has been suggested by Van Westen, 1993. Methods for stabilization of unstable slopes have been discussed by Anbalangan, 1993; Ramaswamy, 1993; Joshi, 1993 and Singh and Goel, 1999.

1.2 LOCATION AND ACCESSIBILITY OF AREA

Present work envisages to carry out stability analysis of slopes of a part of Tehri Dam Reservoir, which extends over 44 Km upstream along Bhagirathi Valley and 25 Km upstream along Bhilangna Valley, from dam site. The study area is situated in Lesser Himalaya of Garhwal hills and is located within the administrative limits of Tehri district of Uttar Pradesh. The area of study (16 km from damsite in Bhagirathi river valley and 12 km in Bhilangna river valley) falls in the Survey of India Toposheet Number 53 J/7 and 53 J/11. The State Highway-

54, off-taking from Rishikesh passes through Chamba Tehri, Dharasu and further extends upto Uttarkashi. The Tehri-Dharasu road and Tehri- Ghansyali road traverses through the reservoir of Bhagirathi and Bhilangna valleys.

1.3 OBJECTIVES

The following are the objectives of the study :

(i) Identification of unstable slopes using Markland test and calculation of Factor of Safety(F.O.S.).

(ii) Study of limitation of conventional approach of slope stability investigation.

(iii) Modification of existing approach to identify locally unstable slopes.

(iv) General stability measures for improving stability of hazard prone slopes.

(v) Study of impact of hillslide induced water waves on stability of dam.

1.4 PHYSIOGRAPHY AND DRAINAGE PATTERN

Physiographically, the study area, falling in Lesser Himalaya is highly rugged due to high mountains, steep slopes and deep valleys. The river Bhagirathi flows roughly in a southerly direction and the East flowing, Bhilangna river joins the Bhagirathi river at Tehri. The region is well drained by numerous streams, which are mostly of first and second order in nature. Dendritic and sub-dendritic drainage patterns are commonly seen in a major part of the region. A number of springs are also present in the region.

1.5 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 (IS : 1893-1975). 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 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 earthquakes have also occurred in this region. Seismic Hazard Map of India and adjacent area has been prepared by Khattri et al., 1984.

1.6 VEGEGATION

The study area has a good forest cover at some places. The natural vegetation follows climatic zonation in mountainous region, because of temperature variations. The development processes such as, urbanisation, excessive road construction, hydroelectric projects have put tremendous pressure on the vegetation, wild life and pastoral lands. In this context, Garhwal Himalayan region has been 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 goat, rabbit, monkey, langour and several types of birds.

1.7 ENVIRONMENTAL ASPECT OF TEHRI DAM PROJECT

1.7.1 Seismic Impact of Reservoir Filling

The Tehri dam project is located in middle Himalayas. The mountains are of recent origin and the rocks in the area have been subjected to intense tectonic activities. Some micro seismic activity is still being observed and the area is shown in zone IV of Indian standard 1893-1975 (Agrawal et al, 1985). The rock formation at the dam site are phyllites of Chandpur series.

Ever since the famous Koyna earthquake of 1966, reservoir induced seismicity has become an important environmental issue for every dam project, especially for a high dam like Tehri.

Out of about 425 large dams in the world, only 15 dams have shown on increase in seismicity after reservoir filling.

Continuous diving of the oceanic apron of the Indian plate beneath Tibet plateau, led to the formation of the Himalaya. The relative displacements in the Himalaya are of the order of 2 to 3 cm/year across the whole of lesser and greater Himalayas. This continuous dipping of the Indian continental plate towards the Asian plate indicated that the region has a tendency to move upward while water load of the reservoir will be downwards and impounding of reservoir would have the effect of delaying any probable fracture (Agrawal et al, 1985). It has been shown theoretically that the development of pore pressure due to reservoir worsens the stress - state in the case of Normal faults, driving it towards failure state whereas in case of Thrust fault it improves the stress - state. Thus in case of Tehri dam or for that matter all dams in Himalayas, there are chances that filling of the reservoir may actually lead to reduction in seismic activity, as in the Himalayas thrust fault environment prevails. (Singh & Raj, 1992).

1.7.2 Rationale for the Tehri Dam Project

On the river Ganges, a number of run-off-the-river schemes for irrigation and a few also for power generation have come up, but no storage reservoir has been constructed so far. With high degree of skewness in annual precipitation need for construction of a few storage schemes is quite apparent for optimal exploitation of any river basin. Tehri Dam is the first and the only storage scheme proposed and at the moment under construction on river Bhagirathi at the most suitable site for a high dam for conservation of its waters.

Besides, there is an acute shortage of power in the Northern Grid which further accentuates at the time of peak demand. Hydro Power is the most suitable and cheapest source of energy for meeting the peak loads. The present proportion of hydro to thermal power generation at 28:72 is far from the ideal mix of 40:60. The Tehri Hydro Power Complex, will reduce the peak deficit by 2400 MW and also improve the hydro thermal mix. Details of Tehri dam project are shown in Appendix 1 and Plate 1.3.

1.7.3 Impact of Submergence on Forests

Forty four km long lake formed by such a high dam submerges only 5,200 hectares of land as the flooding is confined within the narrow valley through which the river flows. The area submerged comprises of 1600 hectares of cultivated land, 200 hectares of uncultivated land and 1600 hectares of degraded forest land with only 10 to 15 trees of less than 10.cms girth per hectare.

The present status of the forest highlights the dysfunctional aspects of not building the dam. Increasing population has put pressure on agricultural land. The absence of any alternate means of livelyhood and modern sources of energy has forced people to clearing the forests for cultivation and to felling the trees for firewood. On the otherhand, Tehri Project has taken on itself the burden of treating the catchment. A scheme has been under operation for treating 36,000 hectares of land taking into account the existing land use, the extent of degradation suffered and the requirement of local people for food and fodder. Under this scheme, 15,333 hectares of land have already been afforested. In addition, compensatory afforestation to the tune of 4,500 hectares is being carried out in arid region of the State of Uttar Pradesh to compensate for submergence and small amount of forest land acquired for the purposes of rehabilitating people. Thus the Tehri dam, instead of destroying the forest, as is usually alleged, is actually helping in improving the environment.

1.7.4 Impact of Submergence on Flora and Fauna

The project authorities commissioned Botanical Survey of India (BSI) and Zoological Survey of India (ZSI) to carry out surveys of the submergence area to find the impact of submergence on flora and fauna.

The vegetation in the submergence area is rather scanty and mostly dominated by dry subtropical to temperate shrubby components. As a result of random clearing and exposing the land for cultivation and habitation, the herbaceous elements are rather poor in the area. The surrounding mountains overlooking the large reservoir are mostly devoid of any natural forest vegetation and much disturbed due to constant biotic interference.

The survey listed 462 plants under 99 families in the area. About 64 species of economic and medicinal importance are located in the submersible area. But these have wide distribution in the Himalayas and no special conservation measures are required. However, the survey indicates about twelve threatened and rare plants belonging to the three families namely Orchidaceae, Liliaceae and Poaceae which require protection.

The project authorities have proposed setting up five botanical-cum-genetic gardens in the Bhagirathi river valley in different biomes. The proposed garden cluster will function as plant resource centres for each biome. Thus this proposal will lead to conservation of various botanic species that not only belong to submergence area but also those present in the various biomes of the entire river catchment. The project has no adverse impact on the fauna.

1.7.5 Submergence and Rehabilitation

India is a highly populous country and therefore, every dam project faces a serious rehabilitation problem and Tehri dam is no exception. Tehri Dam submerges Tehri town and 25 villages fully and 68 villages partially . In terms of families, 10,406 rural and 4,693 urban families will be affected from Tehri reservoir. Studies were made to save the town from submergence by shifting the dam upstream of Tehri but it was found that while the cost of the dam increased, the benefits decreased thereby jeopardising the benefit cost ratio of the project.

Tehri Hydro Development Corporation has been conscious that shifting people from their moorings is a big social and human problem and has tried to handle it very sensitively. Rehabilitation package being made available aims at providing better living conditions to the people as compared to their existing status.

One important aspect of rehabilitation policy is that people should be able to get jobs in professions to which they are used in their new environs. Since main occupation of the people in Tehri area is agriculture, the basic tenet for rehabilitation policy adopted has been to provide land unless cash compensation is specifically requested by an individual. Main features of rehabilitation policy for rural population are as under :

- 2 acres of fully developed agricultural land to each family even when their land holdings are less and also to landless labourers. This way, project will be distributing much more land than actual agricultural land being submerged by the dam.

- Cash compensation to those who request for it at rates assessed according to Land Acquisition Act plus ex-gratia payments assessed according to class of land.

- Compensation for house at the prevailing market rates plus ex-gratia payment equal to amount of depreciation.

- A cash grant for seed and fertilizers for starting agriculture.

- A cash grant for shifting house-hold effects to the site of rehabilitation.

Existing villages have very poor irrigation, & drinking water facilites, ladies being required to fetch water from long distances. Educational facilites are also far & wide. Community facilities such as approach roads, irrigation and drinking water, electricity, medical, post office, school and Panchayatghar (Community Hall) etc. at each rehabilitation site at the project cost are being provided.

1.8 PLAN OF STUDY

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

Chapter 1 : INTRODUCTION, The chapter begins with a brief discussion on the major landslide dams in the Himalaya. This chapter includes the profile of the study area embodying location and accessibility, physiography, drainage pattern, seismicity, vegetation and climate. The objectives of the study and environmental aspect of Tehri dam project is also outlined.

Chapter 2 : GEOLOGICAL SETTING, covers mainly regional geology and geology of the study area.

Chapter 3 : METHODOLOGY, covers description of stability investigation of the study area and adoption of a new comprehensive approach for detailed stability analysis.

Chapter 4 : SLOPE STABILITY STUDIES OF STUDY AREA. This chapter includes stability evaluation using cross sections across various facets. It also deals with stability investigation using a new comprehensive approach.

Chapter 5 : IMPACT OF HILL SLIDES ON STABILITY OF DAM DUE TO WAVE GENERATION AND STABILITY MEASURES. This chapter covers wave height generated by possible slope failure in reservoir area and stability measures for possible hazard prone slopes.

Chapter 6 : SUMMARY AND CONCLUSION, covers mainly the conclusions obtained by stability analysis in Chapter 4 and Chapter 5 to provide a comprehensive output of the research programme.

1.9 SUMMARY

Landslides cause adverse impact on mountain environment. They also threaten the vary existence of dam project. Fears have been expressed regarding largescale hill slides in Tehri reservoir area. Objectives of the study are to identify unstable slopes using Markland test and calculation of Factor of Safety, limitation of technique of slope stability studies, modification of existing technique, general stability measures and impact of hillslides on stability of dam due to wave generation. The area of study falls in Lesser Himalaya and highly rugged. It lies within zone IV of the seismic zoning map of India. Some parts of the study area have forest cover. Tehri reservoir will submerge 5,200 hectares of land. The vegetation in the submergence area is sparse. 10,406 rural and 4,693 urban families will be affected from Tehri reservoir.

CHAPTER 2

GEOLOGICAL SETTING

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 from south towards north. 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) on the south and Main Central Thrust (MCT) on the north. 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 comprising of high grade metamorphics to soaring heights of the 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).

The Garhwal Himalaya falls in four well-defined tectonic geomorphic zones, each being a distinct geologic unit - (i) Siwalik or Outer Himalaya (ii) Lesser Himalaya (iii) Great Himalaya and (iv) Tibetan Himalaya (Fig. 2.1).

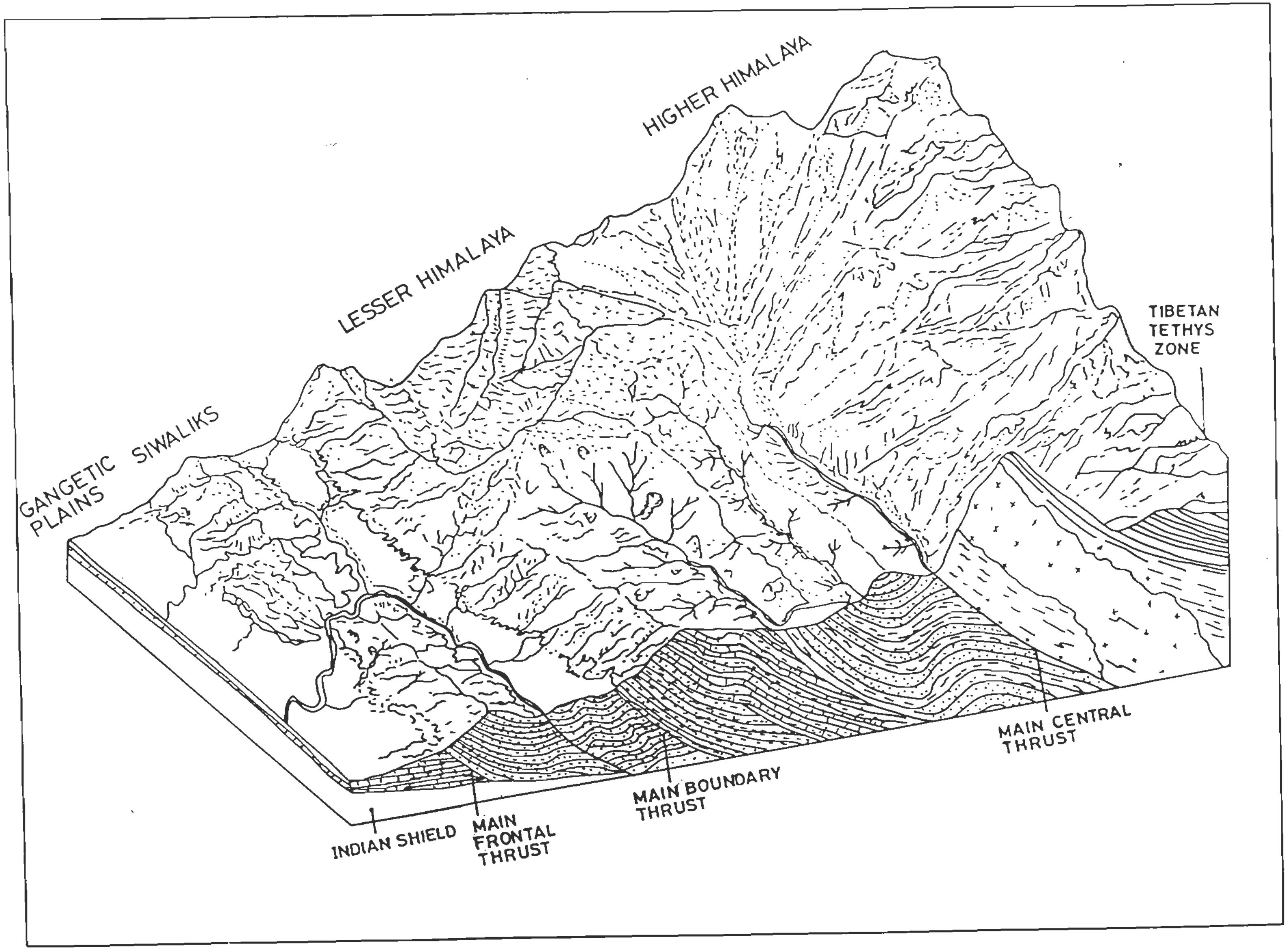


Fig. 2.1 Block Diagram of the Himalaya (Deoja et al., 1991)

2.1 OUTER HIMALAYA

The outer Himalayan belt is composed of early Cenozoic Subathu-Dagshai-Kasauli sediments which are thrust over the late Cenozoic Siwalik Group along the Main Boundary Thrust (MBT). The northern margin of this Tertiary belt is invariably a thrust contact, the Krol thrust.

2.2 LESSER HIMALAYA

The Lesser Himalayan zone, 2000-3000m high, composed of the late Precambrian-Eocene rock between the Krol Thrust and the Main Central Thrust (MCT), is characterised by very complex structure comprising superimposed thrust sheets. A series of thrust faulting has brought about a general reversal in the stratigraphic succession. Thus, the younger Tertiary succession is overlain tectonically by the older late Precambrian rocks which in turn, are tectonically overlain by Precambrian rocks.

2.3 HIGHER HIMALAYA

This forms the zone of the greatest vertical uplift. Main Central Thrust (MCT) marks the southern boundary between the Lesser and the Higher Himalaya. This part is characterised by low to high grade metamorophic rocks like schist, gneiss, granite and complex sequences of para-ortho-metamorphites with igneous rocks of Precambrian to Tertiary age.

2.4 TIBETAN HIMALAYA

To the north of Higher Himalaya lies the vast expanse of Tethys or Tibetan Himalaya, forming normal sequence of forssiliferous sedimentary rocks. The rocks of this part range in age from Palaeozoic to Mesozoic.

2.5 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). The 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.

2.6 REGIONAL GEOLOGY

Four major lithotectonic units, each characterised by distinct lithological composition, stratigraphic succession, structural pattern and magmatic history have been recognised in Lesser Himalaya (Table 2.1 & Fig. 2.2) by Valdiya, 1980, which is being discussed below :

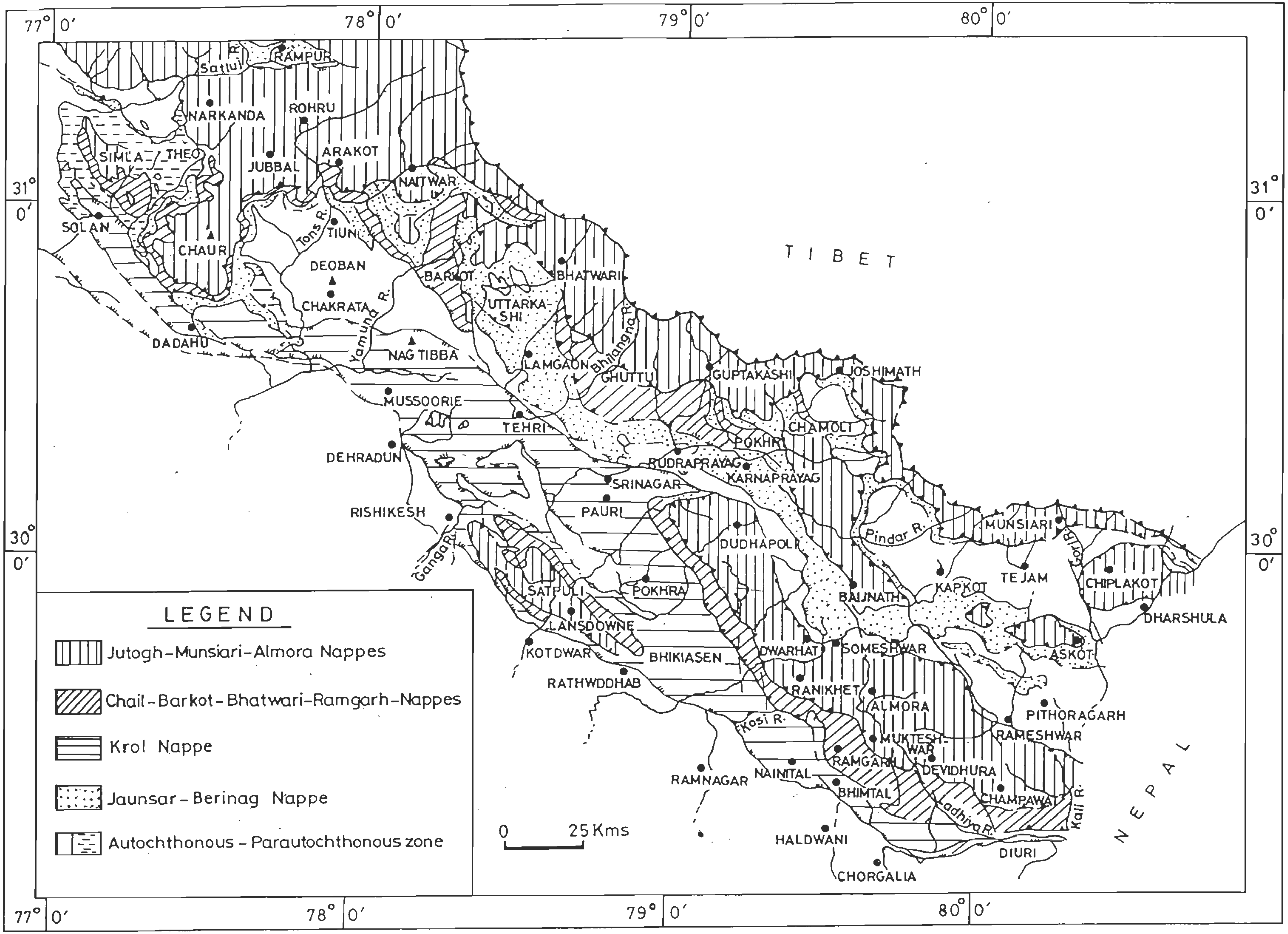


Fig. 2.2 Geological Map of Kumaun Lesser Himalaya (Valdiya, 1980)

TABLE 2.1 STRATIGRAPHIC SUCCESSION OF THE KUMAUN LESSER HIMALAYA

GROUP	INNER LESSER HIMALAYA	OUTER LESSER HIMALYA
	FORMATIONS	
Almora	Munsiari	Gumalikhet
		Champawat Granodiorite
		Saryu
	----Munsiari Thrust ------	----Almora Thrust------
Ramgarh	Barkot and Bhatwari	Debguru Pophyroid
		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

The major stratigrphic units 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 autochtonous Precambrian sedimentary Groups. The Lower Damtha Group at its base consists of the Chakrata Formation of trubidite 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 predominantly by dolomites with prolifically developed branching stromatolites. This Formation grades upwards into the pyritous-carbonaceous slated, marl and interbedded calcite, marbles of the Mandhali Formation (Valdiya, 1980).

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 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; 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. The 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 vast and thick suite 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, 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.

2.7 GEOLOGY OF THE STUDY AREA

A number of workers carried out geological studies in the study area and its vicinity. 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 Bhilangana 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 Formation of Jaunsar Group and Blaini, Krol and Tal Formations of Mussoorie Group.

The stratigraphic succession of the study area is shown in the Table 2.2 and the distribution of different Formation belonging to the various Groups is shown in Fig 2.2.

TABLE : 2.2 STRATIGRAPHIC SUCCESSION OF THE STUDY AREA

GROUP	INNER LESSER HIMALAYA	OUTER LESSER HIMALAYA	AGE
	FORMATION		
Mussoorie		Tal	Ordovician(?)Devonian (500-350my)
		Krol	Cambrian (570-500my)
		Blaini	Precambrian 650-570my)
Jaunsar	Berinag	Nagthat	-
		Chandpur	-
Tejam	Deoban		Middle Riphean
Damtha	Rautgara		>1300my

2.7.1 Rautgara Formation

The Rautgara formation is exposed at two places towards the north of the study area (Fig. 2.3). 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 Chandpur Formation. The Rautgara 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).

2.7.2 Deoban Formation

The Deoban Formation is also exposed towards the northeast of the study area (Fig. 2.3). This is sandwitched between the Rautgara and the Blaini Formation 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.

2.7.3 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. 2.3). 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 wackes. The Chandpur Formation occupies the valley all along the Bhagirathi river.

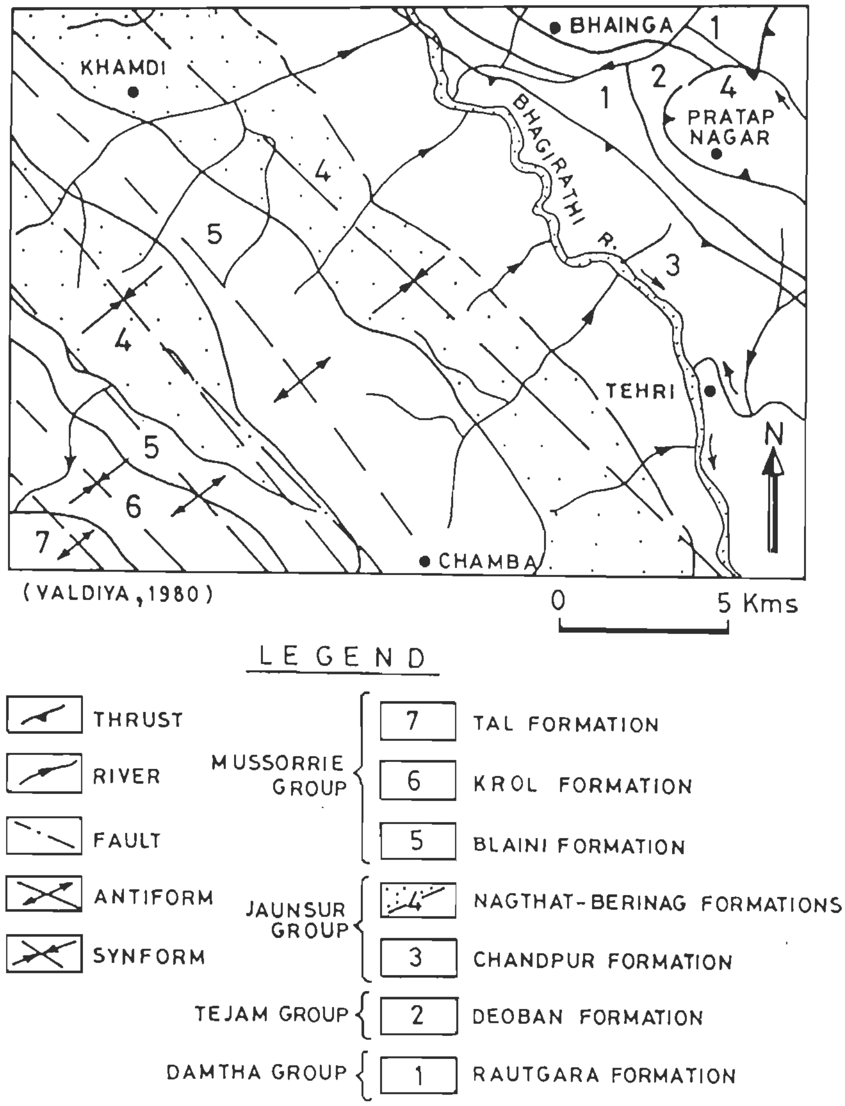


Fig. 2.3 Geological Map of the Study Area (Valdiya, 1980)

2.7.4 Nagthat Formation

The Nagthat Formation is exposed roughly at the western region of the study area (Fig. 2.3). The northern end of this formation is restricted by the Chandpur Formation. As a result of folding, it 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 on the south. 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.

2.7.5 Berinag Formation

The rocks of the Bering Formation are exposed towards northeast of the study area (Fig. 2.3). The Berinag Formation is separated by the Berinag Thrust at it's base. The Berinag Formation consists of white, purple and green coloured quartzites.

2.7.6 Blaini Formation

The rocks of the Blaini Formation are also exposed towards west and southwest of the study area (Fig. 2.3). The formation consists of quartzites, limestones, slates, phyllites and conglomerates with sub-rounded to well rounded clasts (cobble to pebble size).

2.7.7 Krol Formation

Rocks of the Krol Formation are exposed towards southwest of the study area with Blaini Formation at its base and the Tal Formation at the top (Fig. 2.3). Krol Formation comprises sequence of limestone with intercalations of grey and greenish grey slates and siltstone.

2.7.8 Tal Formation

Rocks of the Tal Formation are exposed towards southwest of the study area (Fig. 2.3). This formation mainly comprises white and grey coloured limestone with intercalations of pale quartzites and grey slates.

2.8 STRUCTURE

Major as well as minor structures have been observed in and around 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, one 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.

The Srinagar thrust is a regional feature (Fig. 2.4), having a strike continuation of 100 Km and lies about 6 Km towards north of Tehri dam site (Nawani et al., 1990). This tectonic plane merges with the North Almora thrust in its eastern extension (Narula and Shome, 1989).

2.9 SUMMARY

The present area of study lies in the Lesser Himalya of Uttar Pradesh (U.P.). Lesser Himalyan domain is demarcated by thrusts such as Main Boundary Thrust (MBT) on the south

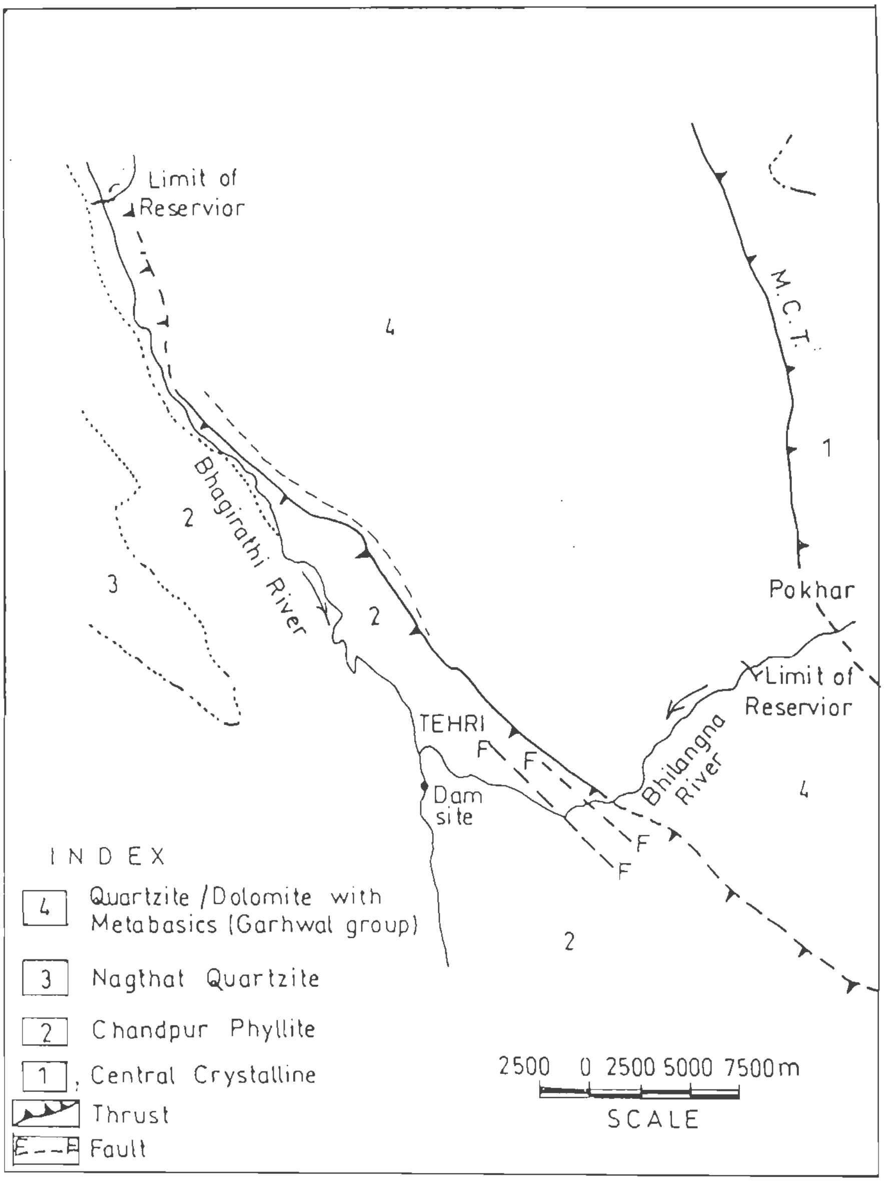


Fig. 2.4 Geological Map of the Area around Tehri Dam Project (Nawani et al., 1990)

and Main Central Thrust (MCT) on the north. The rocks exposed in the study area belong to Chandpur Formation of Jaunsar Group. The Chandpur Formation is delimited towards north by a well defined thrust called North Almora Thrust (NAT) trending roughly northwest-southeast and dipping southwest. 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 wackes. The Chandpur Formation occupies the valley all along the Bhagirathi river.

CHAPTER 3

METHODOLOGY OF SLOPE STABILITY ANALYSIS

Present work is concerned with the stability studies of rock slopes, including methods for assessing their stability and techniques for improving the stability of potentially dangerous slopes. Assessment of rock slope failures or the remedial measures, required to prevent them, are necessary for developmental schemes like Tehri Hydel project.

3.1 PLANNING STABILITY INVESTIGATIONS

It is a fact that certain combinations of geological discontinuities, slope geometry and hydrological conditions result in slopes in which risk of failure is high. If these combinations can be recognised during slope stability studies, steps can be taken to deal with the slope problem which are likely to arise in the study area. Slopes in which these combinations do not occur, require no further investigation.

Systematic approach to the planning of hill slope stability studies in an area is outlined in the chart presented in Table 3.1 and it will be seen that two distinct stages are proposed : (i) field study and (ii) desk study.

Field study consists of collection of geological data and preparation of geological map.

The dominant role of geological discontinuities in rock slope behaviour has been emphasised already in stability calculations and are based upon an adequate collection of geological data.

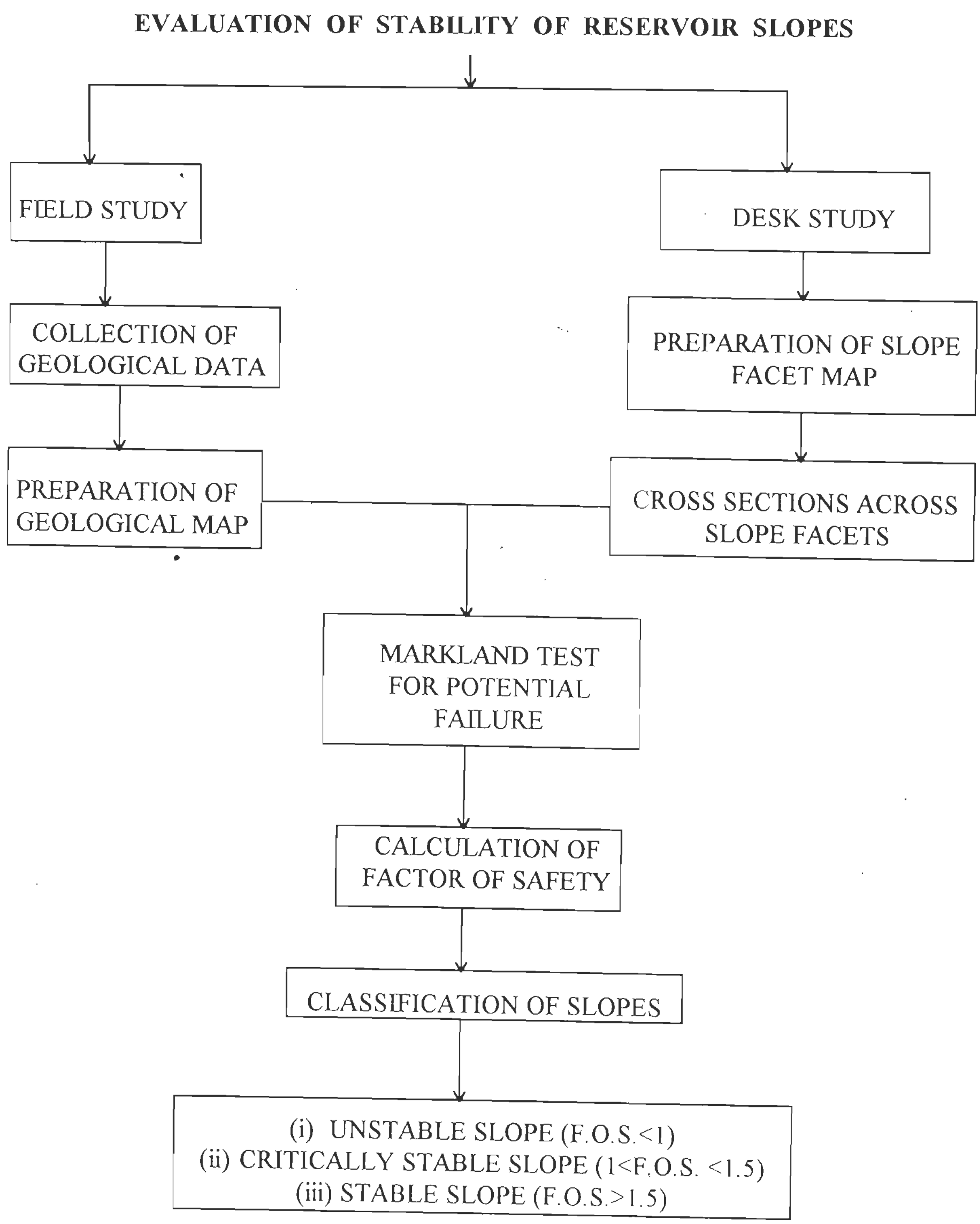


Table 3.1 Evaluation of stability of reservoir slopes

Potential failure slopes can only be defined if necessary information is available for their stability to be evaluated. Collection of geological data involves an examination of existing regional geological maps, detail examination of geological features of the area of study and detailed mapping.

An important aspect of the geological investigations is the systematic collection and presentation of the data in a form which can be understood and incorporated into stability analysis (Hoek and Bray, 1977). Spherical projections provide a convenient means for the presentation of geological data. The projection which is used exclusively in this work is the 'equal area projection', Lambert projection or the Schmid net.

The collection of structural data is time consuming and expensive and it is important that the amount of data collected should be the adequate to define the geometrical characteristics of the rock mass. Collection and interpretation of structural data for the purpose of slope stability analysis cannot be treated as a routine statistical exercise. There are many factors, in addition to the density of pole concentration, which have to be taken into account in assessing the most likely failure mechanism on any given slope (Hoek and Bray, 1977). An appreciation of the role of other factors, which include the shear strength parameters of the rock mass and the hydrological conditions of the slope, assist to understand slope failure mechanism.

3.1.1 Analysis of Data

Desk study consists of various activities. Data pertaining to structural discontinuities are plotted and pole concentrations have been used in order to get preferred orientation of discontinuity planes. For this purpose, an equal area stereonet was used and contouring was done by Mellis Circle Method.

3.1.2 Evaluation of Potential Slope Problems

Plotting of structural data results in a number of significant pole concentration. It is important to identify those which represent potential failure planes and to eliminate those which are unlikely to be involved in slope failures.

Markland's test is designed to establish the possibility of a wedge failure in which sliding takes place along the line of intersection of two planar discontinuities. Plane failure is also covered by this test, since it is a special case of wedge failure. If condition is maintained on both planes, sliding can only occur along the line of intersection which must be less than the dip of the slope face, measured in the direction of the line of intersection (Fig. 3.1). In case of plane failure, direction of sliding is along the dip direction of plane (Fig. 3.2).

3.1.3 General Conditions for Plane Failure

If the sliding should occur on a single plane, the following geometrical conditions must be satisfied :

(a) The plane on which sliding occurs must strike parallel or nearly parallel (within approximately ±20) to the slope face.

(b) The failure plane must 'daylight' in the slope face. This means that its dip must be smaller than the dip of the slope face (i.e. $\psi_f > \psi_p$).

(c) The dip of the failure plane must be greater than the angle of friction of this plane (i.e. $\psi_p > \phi$).

3.1.4 General Conditions for Wedge Failure

Condition of sliding is defined by $\psi_f > \psi_i > \phi$. In case of wedge failure line of intersection must 'daylight' in the slope face. Data required for wedge stability analysis is shown in stereoplot (Fig. 3.2A).

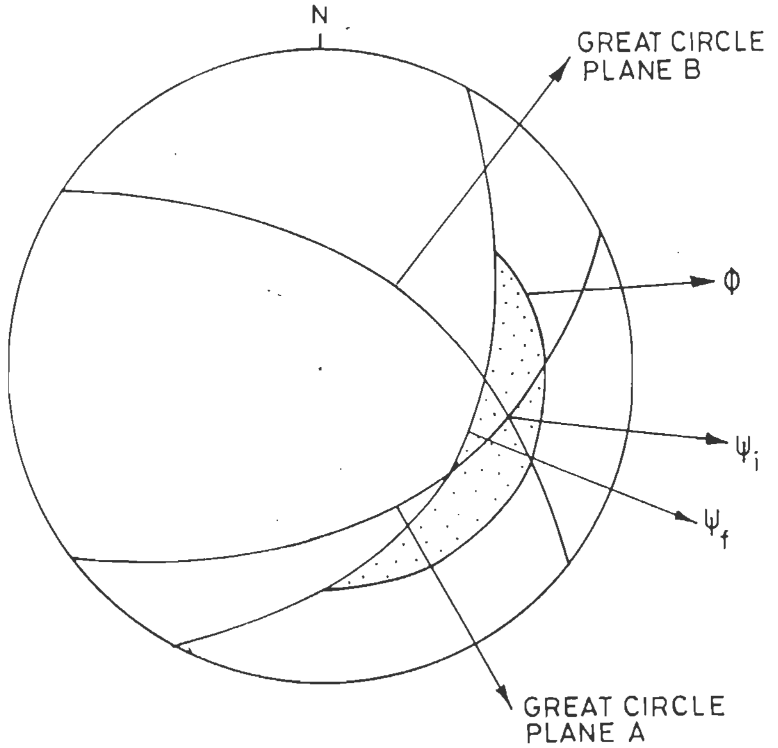


Fig. 3.1 Markland Test for Wedge Failure (Hoek and Bray, 1977)

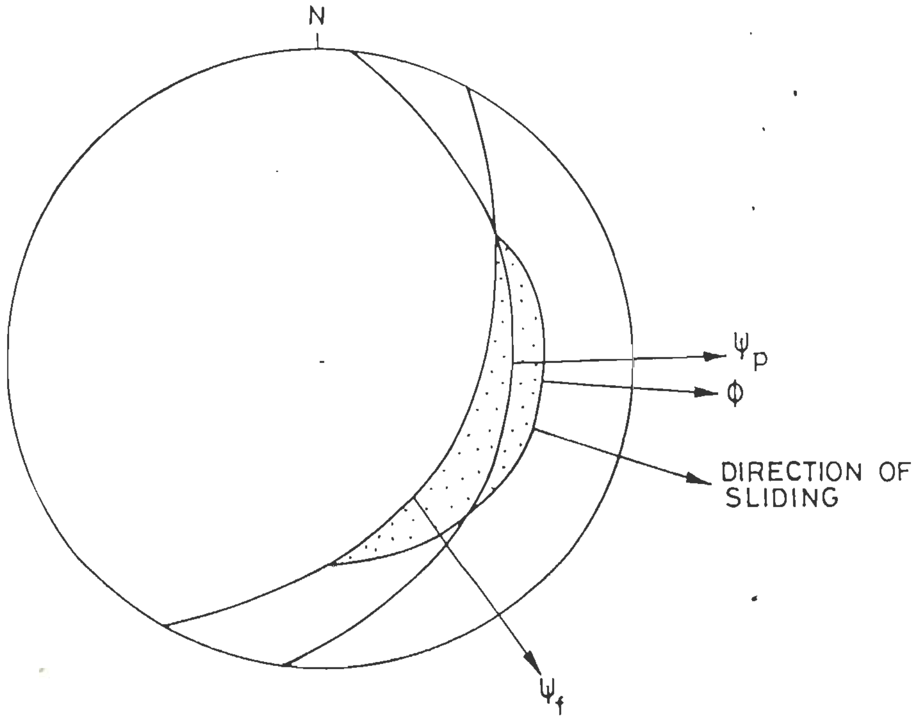


Fig. 3.2 Markland Test for Plane Failure (Hoek and Bray, 1977)

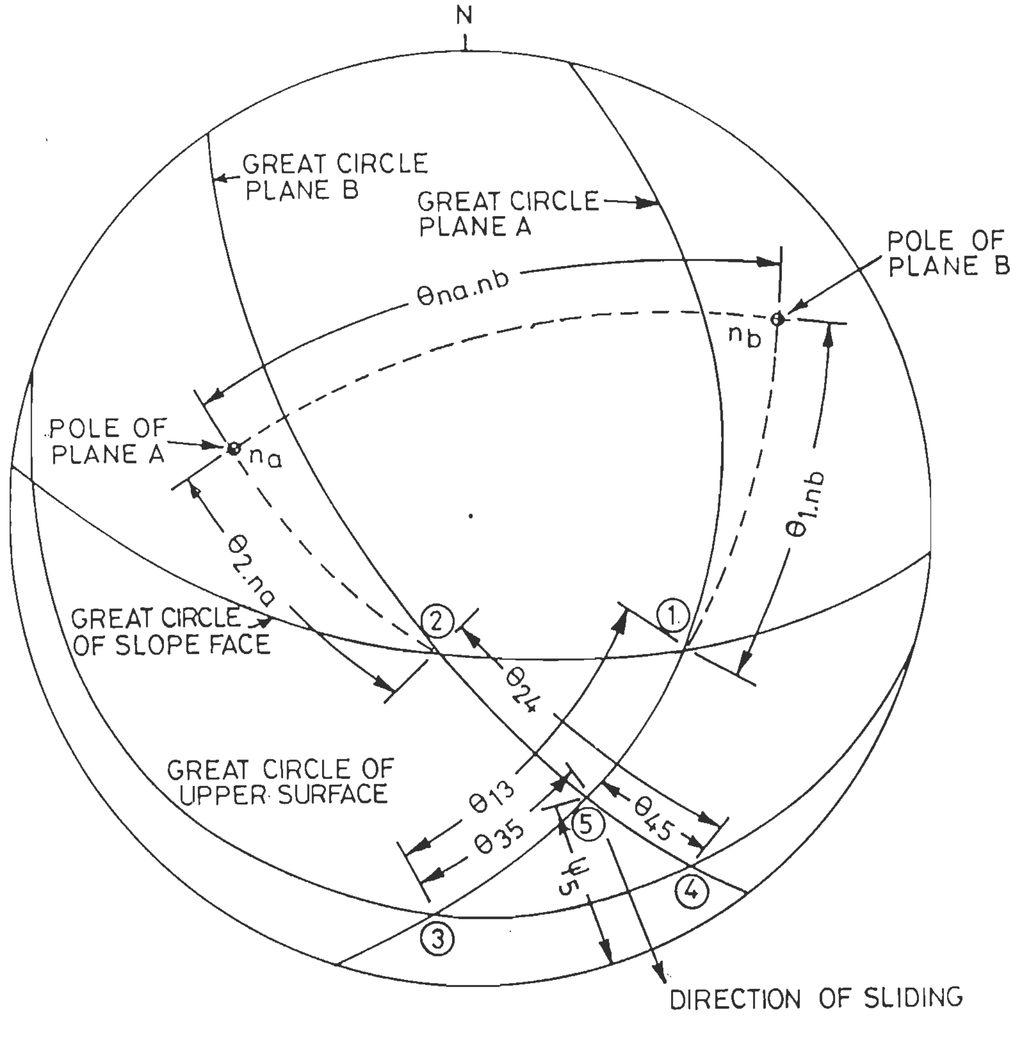


Fig. 3.2A Stereoplot of Data required for wedge stability analysis (Hoek and Bray,1977)

3.1.5 Slope Facet Map

Initially, a slope facet map of the area of study has been prepared which serves as a base map in order to evaluate the stability of reservoir. 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. 3.3 and Fig. 3.4). The general slope direction of a slope facet is shown by an arrow. Initially the topography of the study area is studied carefully on topographical map. 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 based on significant change in the attitude of slope. Slope facet may vary in shape and size depending upon the uniformity and nature of the slope.

3.1.6 Preparation of Cross Sections

Cross sections across various facets have been taken in such a way that dip direction of cross section and facet remains the same. Cross section represent the maximum length across the facet. These cross sections have been used for stability analysis.

3.1.7 Application of Markland Test

In order to identify the possible mode of failure on hillslopes, the Markland test has been applied. In Markland test stereographic projections are used to identify the possible mode of failures. For that purpose the structural discontinuity planes and the great circle representing the slope face are plotted over the stereonet. Also, a friction circle corresponding to angle of internal friction is plotted over it. According to Markland test the following conditions should be satisfied for the failure to occur :

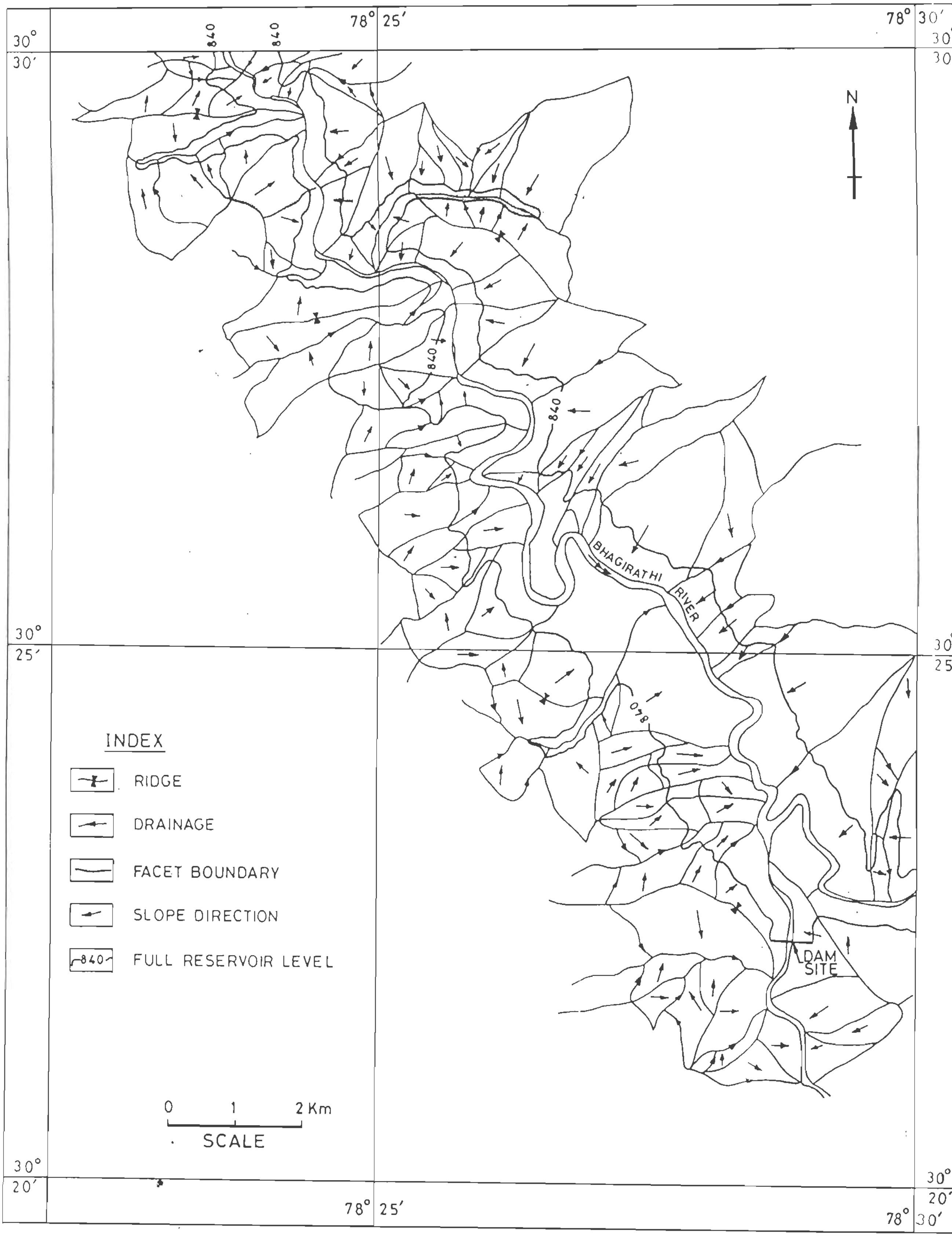


Fig. 3.3 Facet Map of Study Area (Bhagirathi Valley)

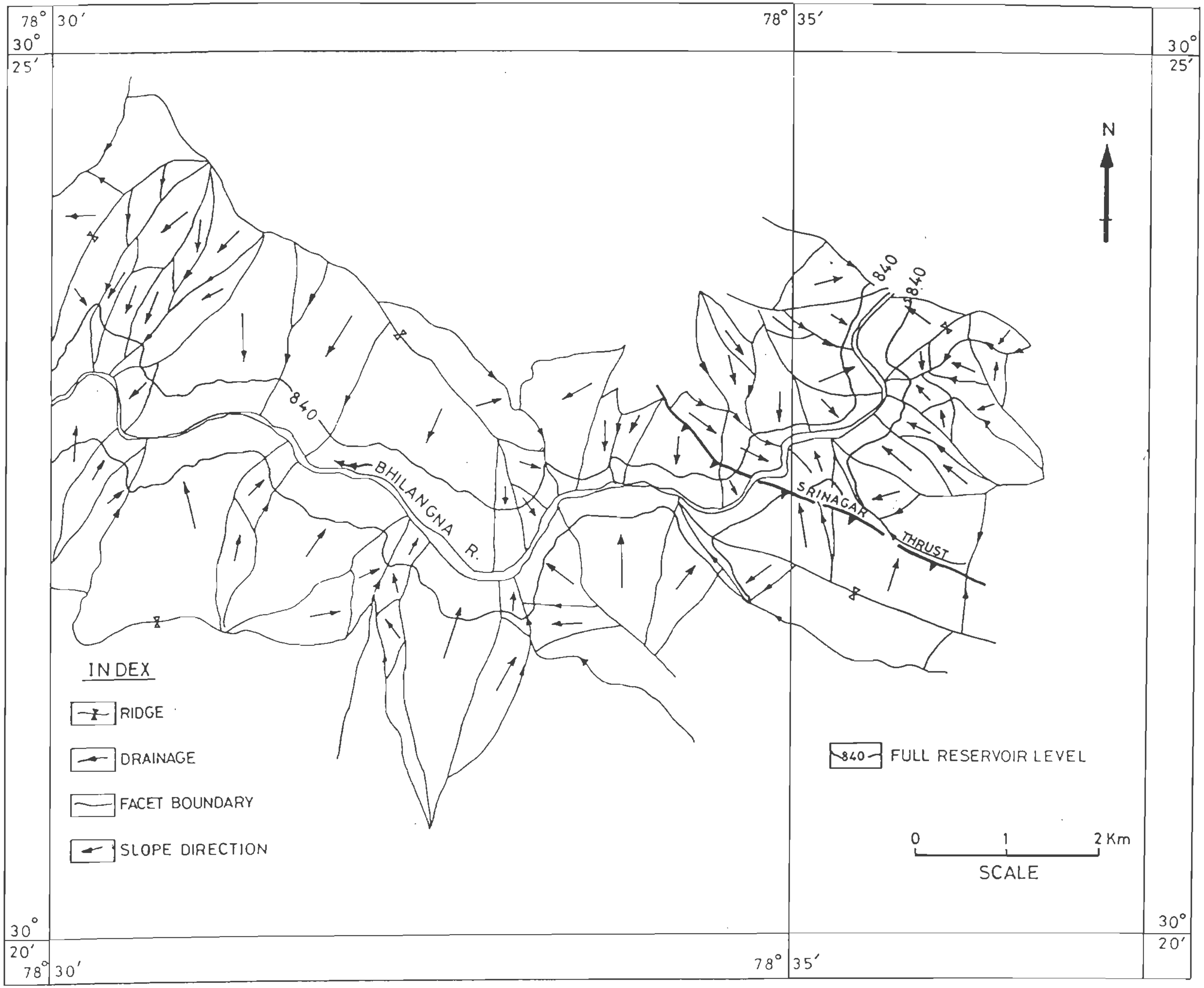


Fig. 3.4 Facet Map of Study Area (Bhilangna Valley)

Markland Test Condition	
For Plane failure $\psi_f > \psi_p > \phi$ For Wedge failure $\psi_f > \psi_i > \phi$	Where ψ_f = Slope face inclination ψ_p = Failure plane inclination ψ_i = Plunge of line of intersection ϕ = Angle of internal friction

Markland test has been applied to determine the conditions of potential failures in terms of slope direction and slope angle. All cross sections have been checked to identify those cross sections which satisfy the conditions obtained by Markland test. These cross sections serve as the case of potential failures for further analysis.

3.1.8 Determination of Shear Strength Parameters

In analysing the stability of a rock slope, the most important factor to be considered is the geometry of the rock mass behind the slope face. The next most important factor is the shear strength of the potential failure surface, which may consist of a single discontinuity plane or a complex path following several discontinuities and involving some fracture of the intact rock material. Geomechanical classification or Engineering classification was proposed by Barton, 1974 and Bieniawski, 1979 to determine shear strength parameters of rock mass. Application of rock mass classification for Civil Engineering projects has been discussed by Singh and Goel, 1999. Choice of appropriate shear strength values depends upon a sound understanding of the basic mechanics of shear failure and of the influence of various factors, which can alter the shear strength characteristics of a rock mass (Hoek and Bray, 1977). The strength parameters are chosen judiciously based on the experience of evaluating the stability of slopes in the lower Himalayas. The chosen values of strength parameters are checked using an Indirect method, Back Analysis (Singh and Ramaswamy, 1980). It is assumed that the steepest slopes existing at the site may be on the range of failure and therefore, if these slopes are analysed using the chosen values of strength parameters, the factor of safety values should be close to 1.0. Accordingly, from the contour map of the reservoir area, steepest slopes occurring in each type of material are identified. These slopes are analysed assuming dry condition and no earthquake forces using the assumed values of strength parameters. These values are as follows:

S.No.	Description	Unit Weight (kg/m^3)	ϕ (Degree)	C (kg/m^2)
1.	Phyllite	2.5	30°	1.5
2.	Quartzite	2.7	36°	3.0

3.1.9 Earthquake Coefficient

During an earthquake, due to oscillatory nature of the ground motion, it introduces repetitive stresses, which changes in direction and magnitude. During an earthquake, the inertial forces corresponding to particular acceleration pulse may result in reduction of factor of safety to a value below unity and incipient failure condition would develop which would cause outward movement of the rock wedge. The acceleration level below which no deformation could occur, will not lead to any movement. The yield acceleration has to be evaluated to estimate the movement of the sliding rock wedge. The threshold value of the ground acceleration which gives a factor of safety of unity of the sliding mass gives the yield acceleration. The acceleration pulse having amplitude greater than yield acceleration will induce movement and displacement can be computed by integrating twice the area of the pulses of the ground acceleration time history, above the yield acceleration level. The computed net displacement provide a measure of deformation and damage of slope during an earthquake. The Tehri Dam Project lies in seismic zone IV. However, it has been conservatively assumed for carrying out slope stability analysis to be located in seismic zone V as per seismic zoning map of India incorporated in Indian

Standard criteria for Earthquake Resistant Design of structures (IS:1893-1984). Accordingly the horizontal components of base earthquake acceleration (α_o) is 0.08. The code further recommends that the design acceleration should be multiplied by a factor of 2 for important slopes whose instability will endanger the life and property of the nation. Hence the adopted coefficient of horizontal earthquake acceleration is 0.16.

3.1.10 Calculation of 'Factor of Safety'

Factor of Safety (F.O.S.) can be defined as the ratio of total force available to resist the sliding to the total force tending to induce sliding or shear strength to shear stress. When the slope is stable, the resisting forces are greater than the disturbing forces and the value of factor of safety will be greater than unity. Similarly, when slope is unstable then the value of factor of safety will be less than unity. If value of factor of safety falls within 1-1.5 range, slope will be considered as critically stable. When the slope is on the point of failure, a condition of limiting equilibrium exists in which the resisting and disturbing forces are equal, and the factor of safety F = 1.

As per the value of factor of safety, slopes of the area of study can be classified into three categories :

1. Stable slopes (Factor of Safety > 1.5)
2. Critically stable slopes (1 < Factor of Safety < 1.5)
3. Unstable Slopes (Factor of Safety < 1)

Factor of safety has been calculated using technique of Hoek and Bray (1977) for various conditions e.g. 'static and dry', 'static and wet', 'dynamic and dry' and 'dynamic and wet' conditions. Calculations have been done using program made in FORTRAN (Appendix 2 and Appendix 3). Factor of safety has been calculated for all cross sections showing cases of potential failures, as indicated by Markland test. For dry condition the value of unit weight of water (γ_w) is 0 kg/m^3 and for wet condition it is 1001.19 kg/m^3. Value of earthquake acceleration for static condition is 0 m/s^2 and for dynamic condition, it is 0.16*9.8 = 1.5 m/s^2. Once the value of Factor of Safety has been established, slopes are classified into three categories.

3.1.11 Preparation of Hazard Map

After finishing stability analysis, a hazard map is prepared based on the result obtained by calculation of Factor of Safety. To explain the outcome in lucid manner, maps showing potential failure slopes for different conditions have been also prepared. Hazard map has been prepared for area of study pertaining to Bhagirathi valley as well as to Bhilangna valley.

3.2 ADOPTION OF A COMPREHENSIVE APPROACH

After assessing the limitations of stability evaluation, a new approach has been adopted. This approach takes care of limitations of previous approach. This approach also consists of two distinct stages (i) field study (ii) desk study. Field study is same as in previous approach.

There is a distinct variation in desk study. Once the set of conditions for potential failure have been established, with reference to slope direction and slope angle, by applying Markland test, a search has been made throughout the area of study to identify those slopes which satisfied the above conditions (Table 3.2). Smallest possible unit which can be considered for this analysis lies between two closely spaced successive contours. Such slopes are identified for different possible wedge failure caused by intersection of different planes and for various plane failures along some discontinuity planes. Number of such small slopes are identified on both banks of Bhagirathi river and on right bank of Bhilangna river.

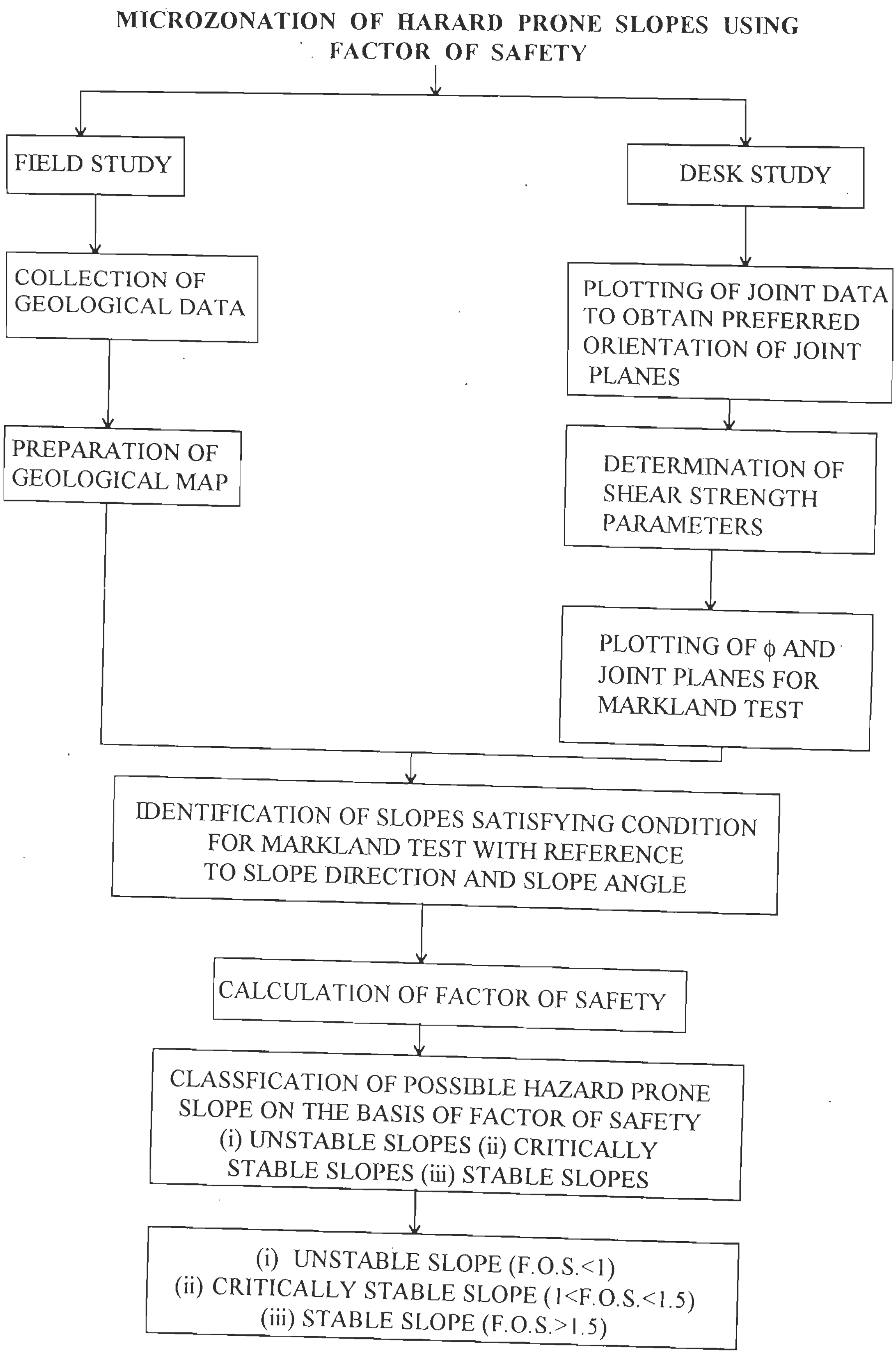


Table 3.2 Microzonation of Hazard Prone Slopes using Factor of Safety

After identifying potential failure slopes, Factor of Safety is calculated for various conditions i.e. 'static and dry', 'static and wet', 'dynamic and dry' and 'dynamic and wet'. Then again slopes are classified into three categories as per the value of 'Factor of Safety'. Result are shown in the form of various maps depicting stability of slopes for various conditions as stated above.

3.2.1 Preparation of Hazard Map After Adoption of Comprehensive Approach

After calculating the value of 'Factor of Safety', a final map is prepared showing location of various hazard prone slopes under worst possible condition. This final map is prepared for Bhagirathi valley as well as for Bhilangna valley.

3.2.2 Preparation of Final Hazard Map Consisting of Outcome of Both Approaches

A final hazard map was prepared, which depicts the results obtained by both approaches. This map gives the comprehensive information regarding stability environment under worst possible condition (dynamic and wet).

3.3 HEIGHT OF WAVE GENERATED IN RESERVOIR DUE TO POSSIBLE LANDSLIDES

Sudden failure of slopes around the reservoir would generate water waves in the reservoir. The distance, upon which these waves would travel depends mainly upon kinetic energy involved in it. A sufficiently massive slide from the rim slopes could cause overtopping of a dam, either by wave action or simply by raising the water surface faster than the spillway could discharge. In the reservoir area hazard prone slopes will fail under the anticipated adverse condition after the reservoir impoundment. In the present analysis, an attempt has been made to calculate the wave height generated by the possible slides in the reservoir area. Besides, the kinetic energy involved in a possible slide has also been computed. For this purpose, computer program 'WAVE', prepared by Misra, 1988 (Appendix 4), has been used. An attempt has been made to find out the quantum of weight (W) required to generate waves having amplitude more than 5 m (provided as free board in dam design). This analysis has been carried out for right bank of Bhagirathi valley, left bank of Bhagirathi valley and right bank of Bhilangna valley.

3.4 SUMMARY

Systematic approach of hill slope stability studies in an area consists of two distinct stages (i) field study and (ii) desk study. Systematic collection and presentation of the geological data is done using 'equal area projection'. Preferred orientation of discontinuity planes are obtained by contouring using Mellis Circle method. A facet map of the study area and cross sections across various facets have been prepared. After that Markland test has been applied to identify the possible mode of failure. As per the value of factor of safety, slopes are classifieds into three categories (i) Stable slope (ii) Critically stable slopes (iii) Unstable slope. A new comprehensive approach has been followed to take care of limitations of previous approach. After identifying the potential failure slopes, using this new approach Factor of Safety has been calculated and landslides hazard map of the area of study is prepared. Height of wave generated in reservoir due to possible landslides has been calculated. Quantum of material required to generate the waves having amplitude greater than 5m (free board in dam design) has also been calculated.

CHAPTER 4

SLOPE STABILITY STUDIES OF AREA OF STUDY

For hill slope stability evaluation, various steps have been followed. These steps have been shown in previous chapter (Table 3.1 and Table 3.2). Application of Markland test and calculation of Factor of Safety using Technique of Hoek and Bray (1977) form important part of Hill slope stability investigation.

4.1 SLOPE FACET MAP

Initially a slope facet map of the study area, covering Bhagirathi and Bhilangna valley has been prepared on 1:50000 scale. This map serves as a base map for further analysis. There are total 57 facets on right bank of Bhagirathi valley and 36 facets on left bank. Similarly there are total 32 facets on right bank of Bhilangna and 31 facets on left bank. (Fig. 3.3 and Fig. 3.4). Therefore, in total 156 facets located around reservoir rim have been considered for stability investigation.

4.2 BHAGIRATHI VALLEY

4.2.1 Preparation of Cross Section

The location of cross sections across various facets of area of study is shown in Fig.4.1 and Fig. 4.2. Cross sections of slopes for left and right bank of the river are shown in Fig.4.3A, Fig. 4.3B, Fig. 4.3C, Fig. 4.3D, Fig. 4.4A, Fig. 4.4B and Fig. 4.4C. These cross section have been used for applying Markland test.

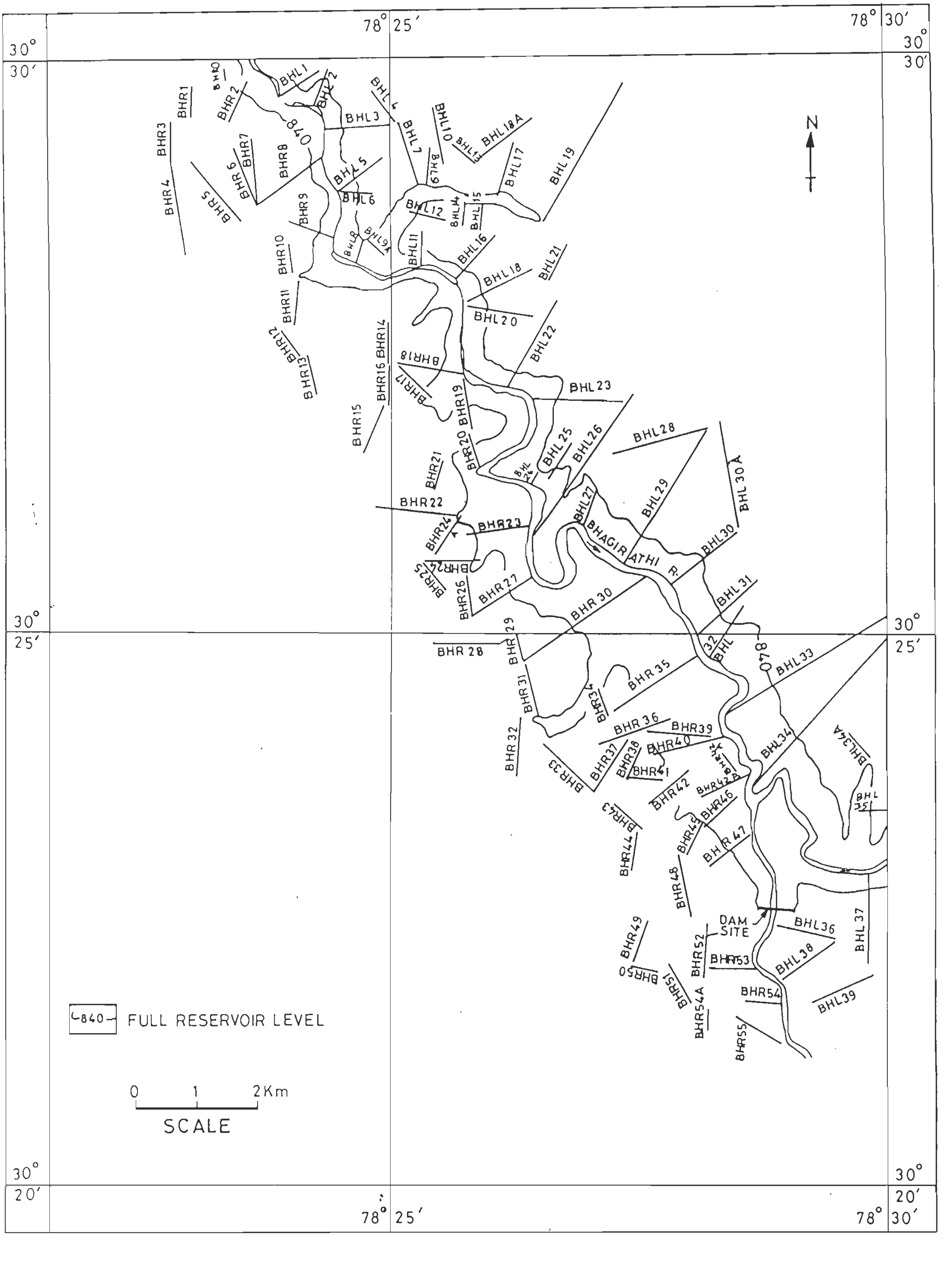


Fig. 4.1 Location of Cross Sections Across Various Facets of Area of Study (Bhagirathi Valley)

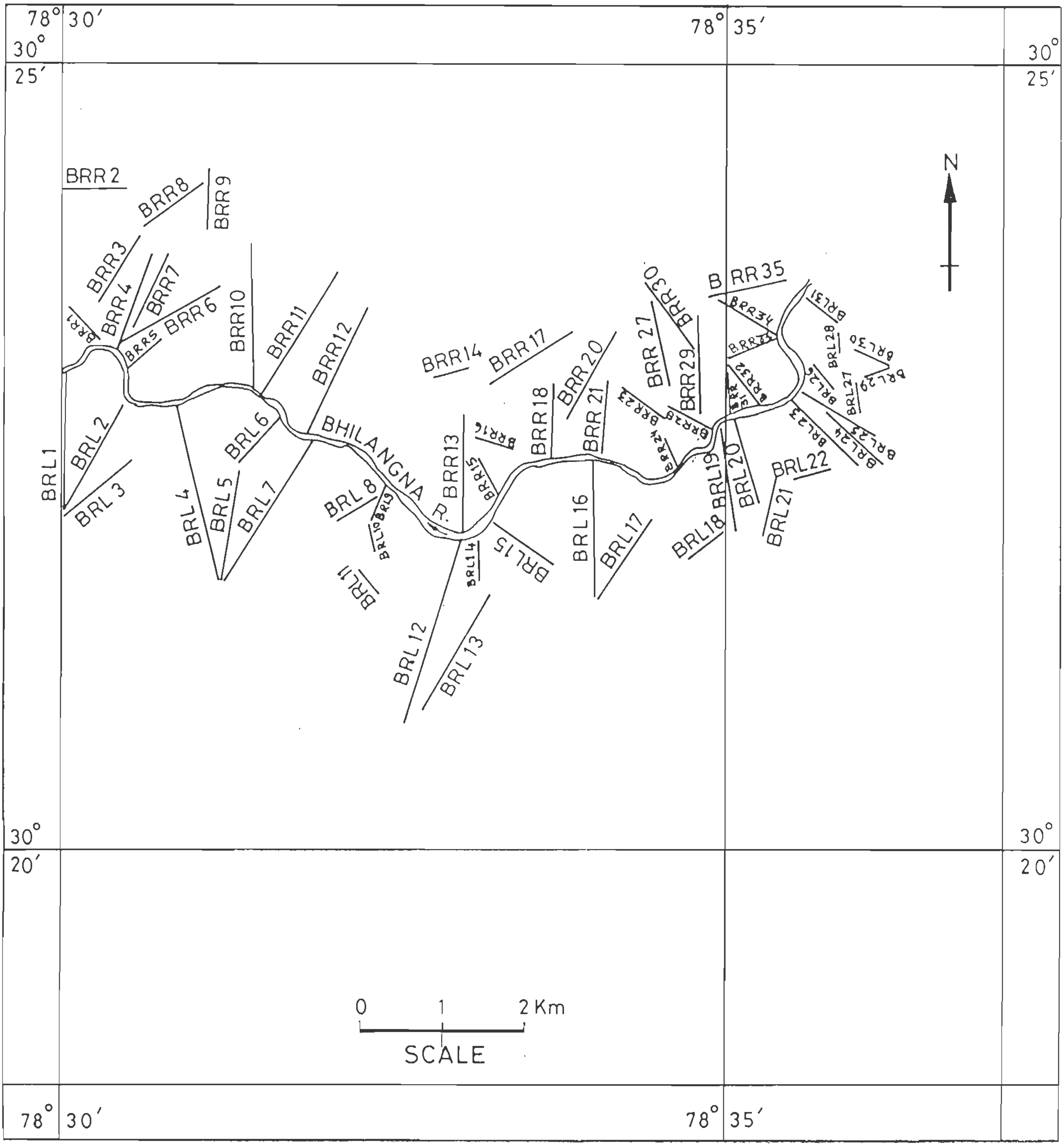


Fig. 4.2 Location of Cross sections across various facets of area of Study (Bhilangna Valley)

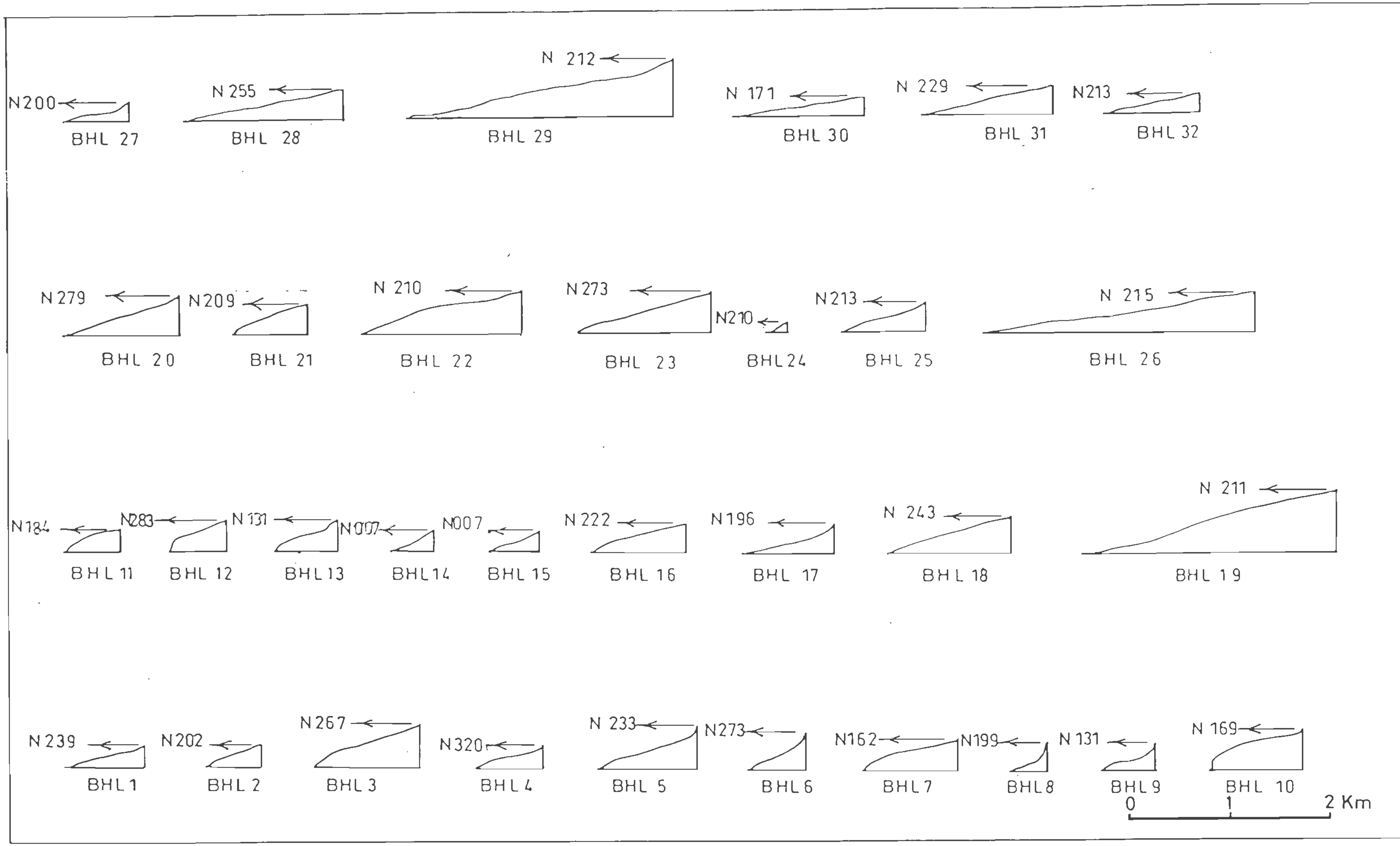


Fig. 4.3A Cross sections of slopes across various facets of area of Study (Bhagirathi Valley, Left bank)

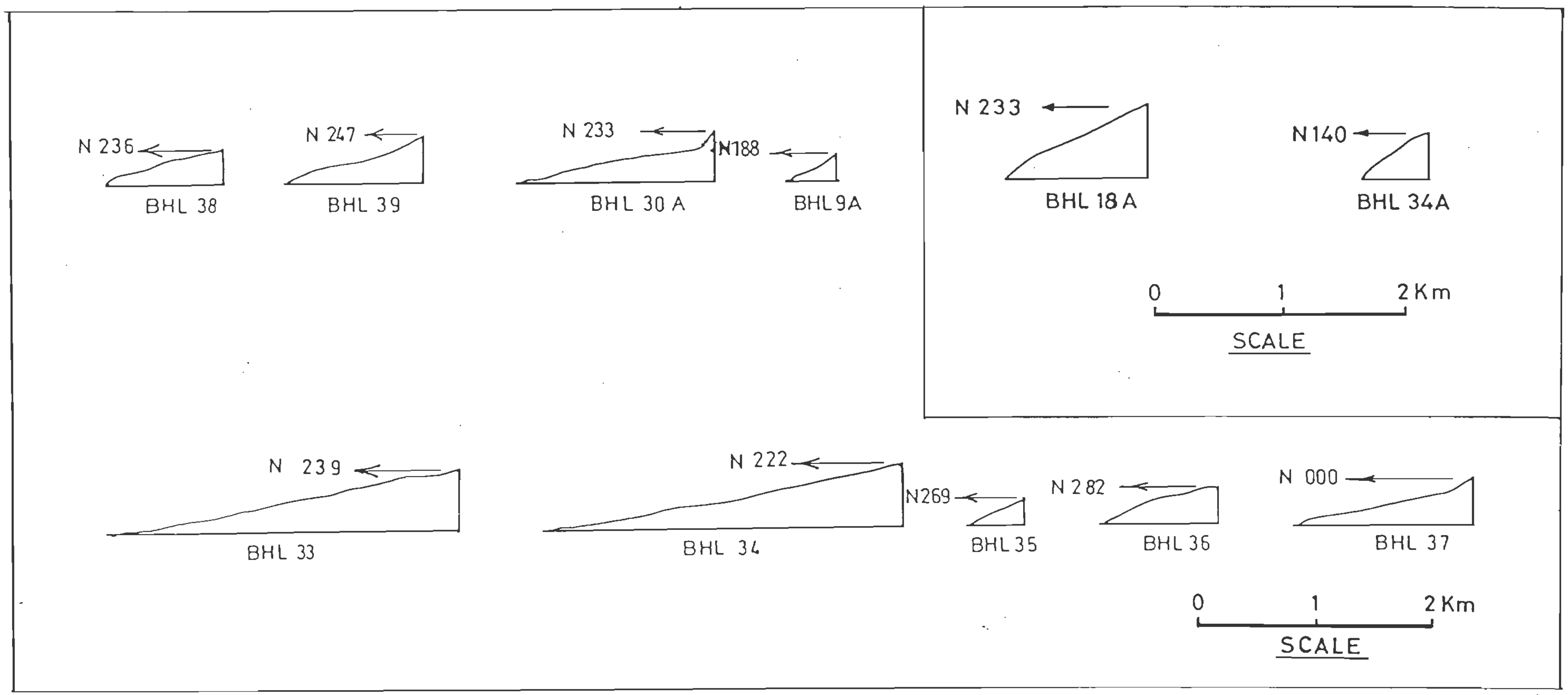


Fig. 4.3B Cross sections of slopes across various facets of area of Study (Bhagirathi Valley, Left bank)

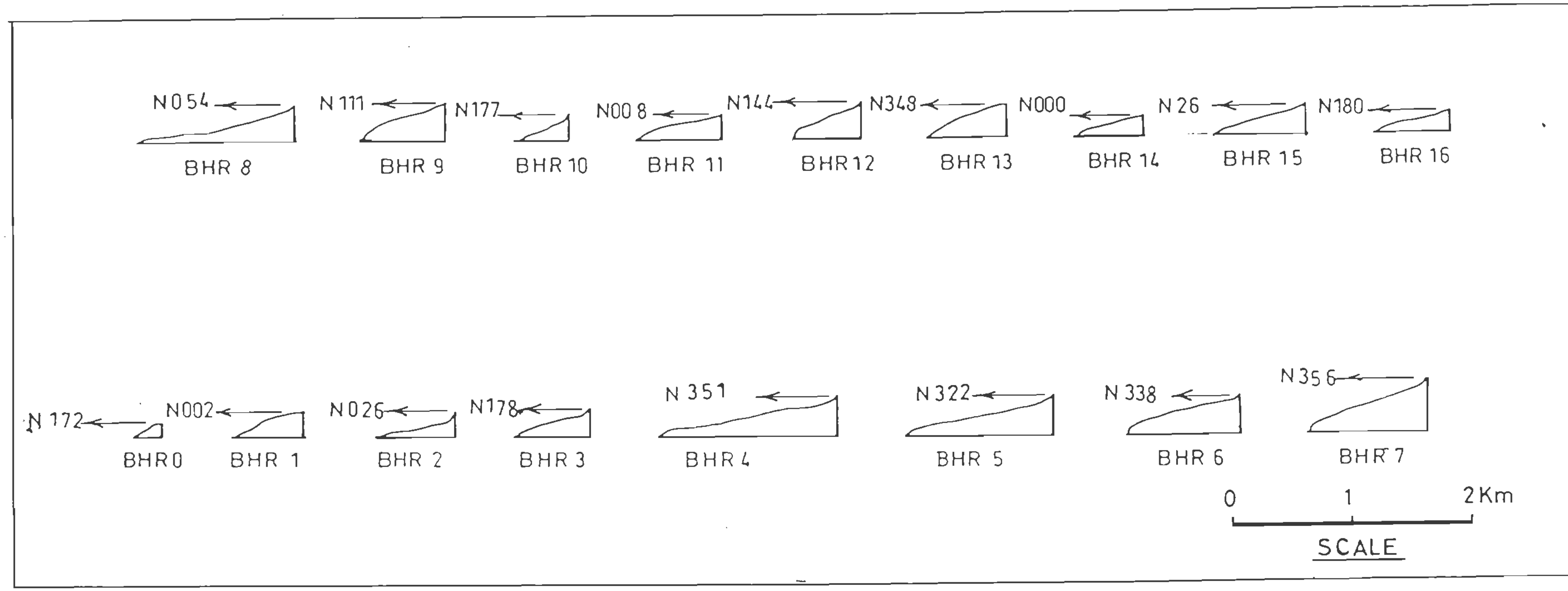


Fig. 4.3C Cross sections of slopes across various facets of area of Study (Bhagirathi Valley, Right bank)

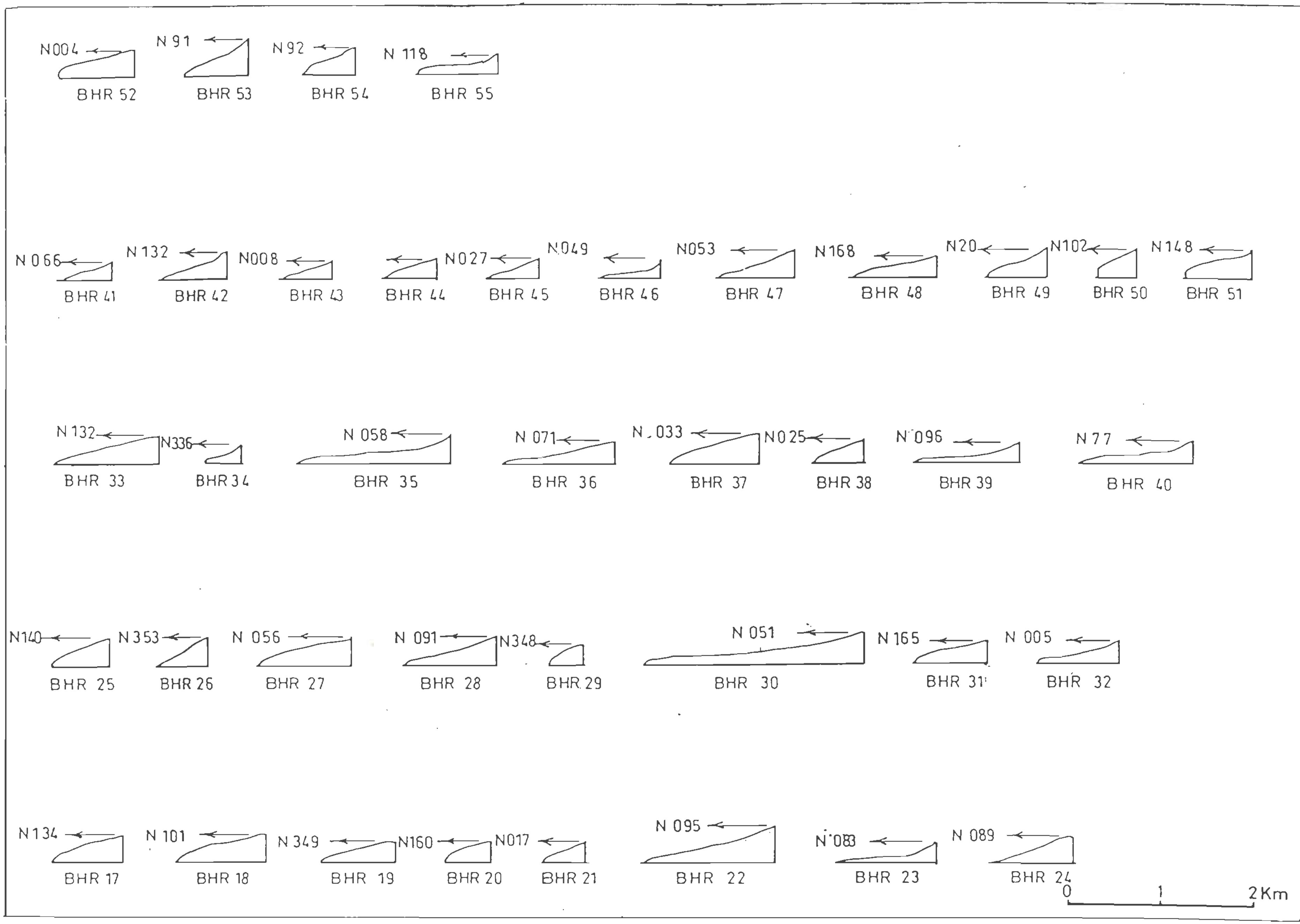


Fig. 4.3D Cross sections of slopes across various facets of area of Study (Bhagirathi Valley, Right bank)

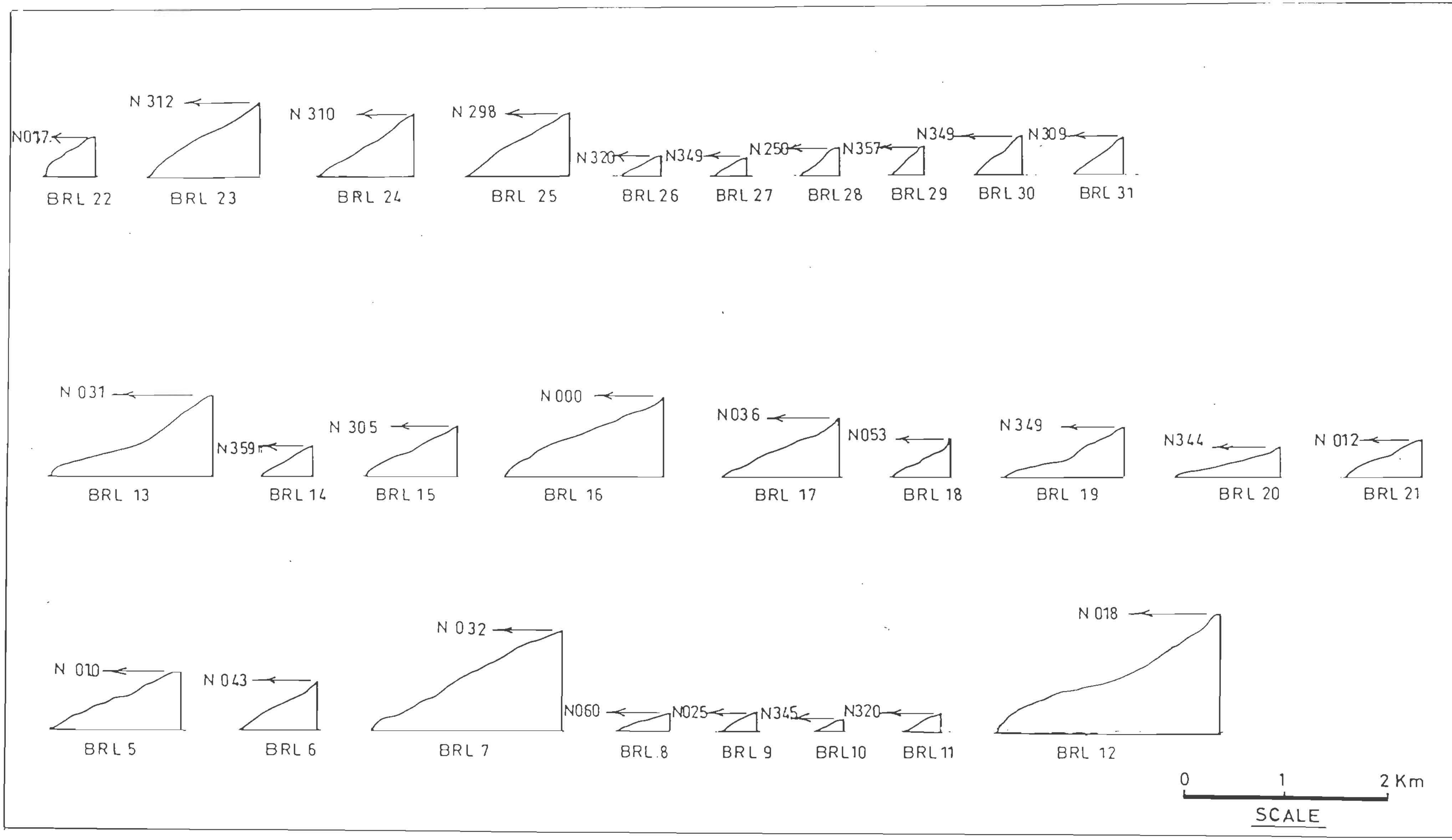


Fig. 4.4A Cross sections of slopes across various facets of area of Study (Bhilangna Valley, Left bank)

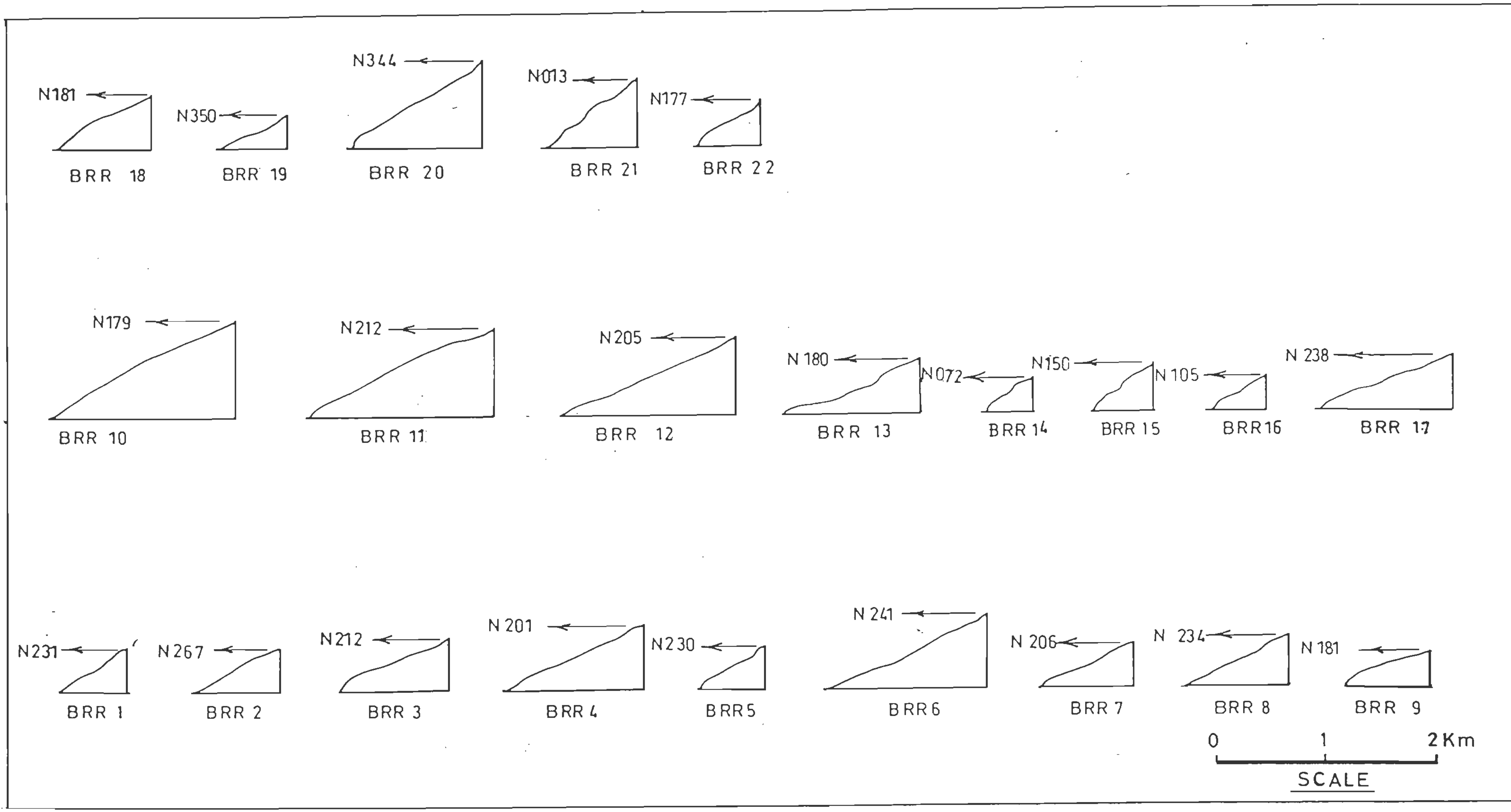


Fig. 4.4B Cross sections of slopes across various facets of area of Study (Bhilangna Valley, Right bank)

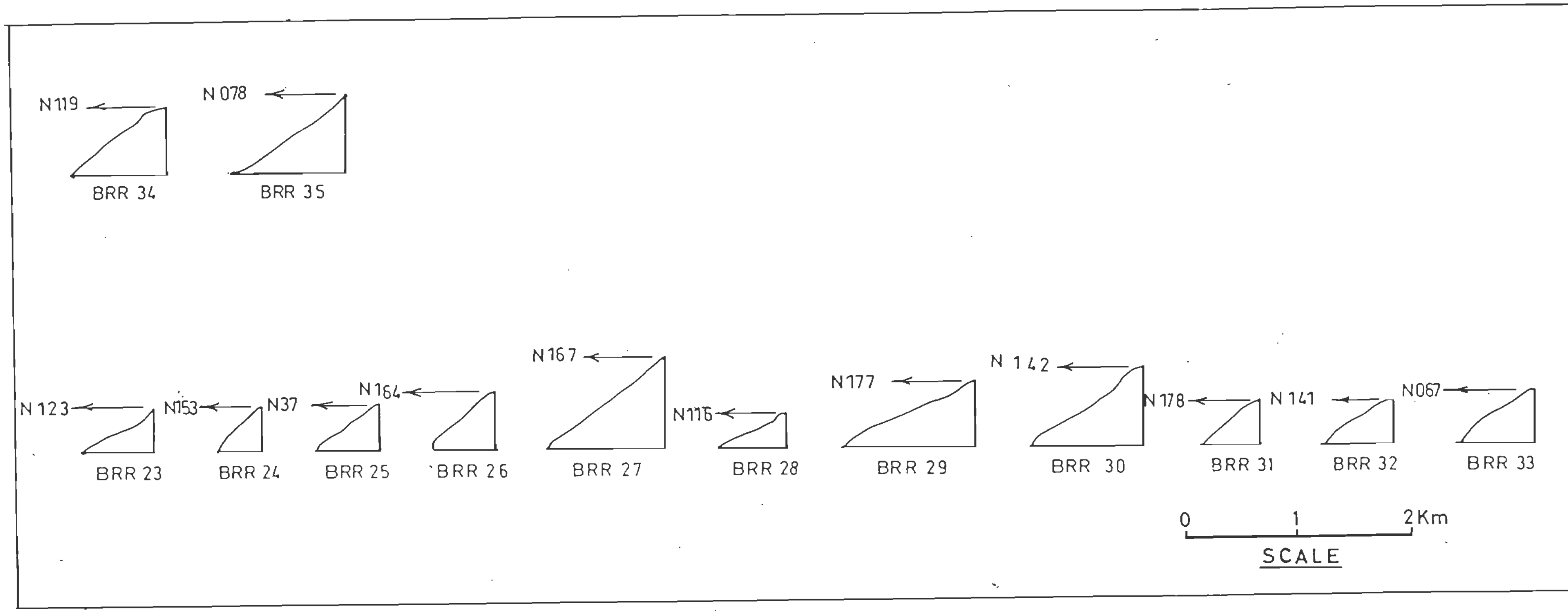


Fig. 4.4C Cross sections of slopes across various facets of area of Study (Bhilangna Valley, Right bank)

4.2.2 Analysis of Joint Data

The observed joint data have been plotted on the equatorial equal area stereonet as π poles and contoured by Mellis circle method. The great circles corresponding to maximas of pole concentration of structural discontinuities (Fig. 4.5) of the study area are as follows.

	DISCONTINUITY	ORIENTATION	
		Dip Direction (In Degree)	Dip Amount (In Degree)
1.	Foliation	N224	57
2.	Joint Set J_1	N247	52
3.	Joint Set J_2	N101	47
4.	Joint Set J_3	N103	27
5.	Joint Set J_4	N121	26

4.2.3 Frequency Distribution of Joint Data

Frequency Distribution of joint data has been shown in form of histogram (Fig. 4.6). Dip direction of slopes at 20° class interval shown on X-axis, while Y-axis represents frequency. A careful glance at this plot shows that structural discontinuities pertaining to class intervals, 220-240, 240-260, 100-120 and 120-140 are relatively more in number as compared to other class intervals.

4.2.4 Application of Markland Test

Structural discontinuities and friction circle corresponding to angle of internal friction have been plotted on equal area stereonet (Schimd Net, Fig. 4.5A). For identification of potential plane failure following structural discontinuities have been considered :

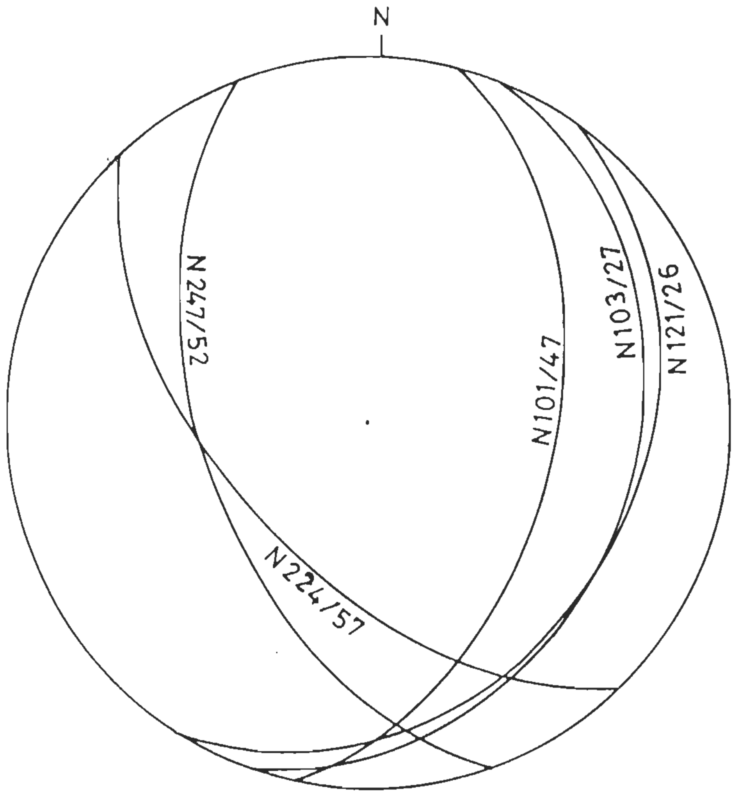


Fig. 4.5 General pattern of discontinuities in area of study (Bhagirathi Valley)

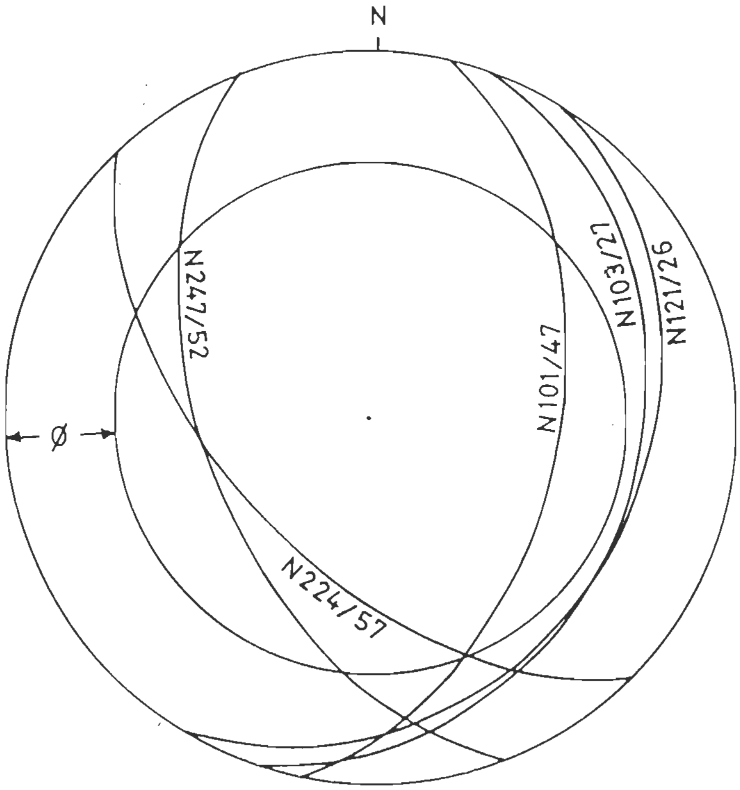


Fig. 4.5A Application of Markland Test (Bhagirathi Valley)

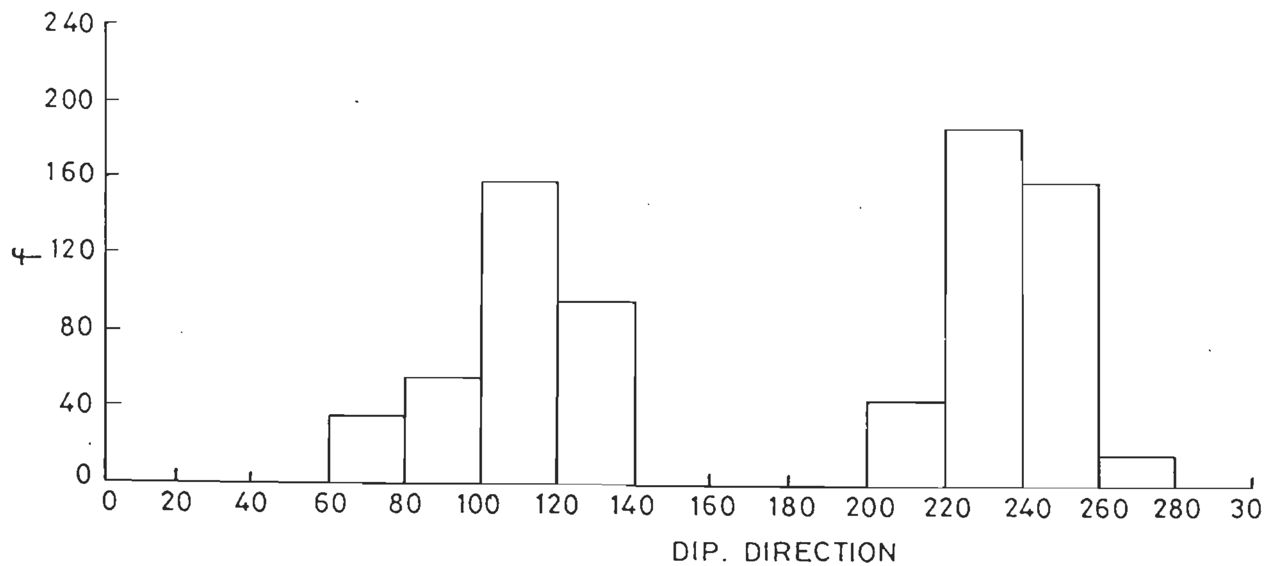


Fig. 4.6 Frequency distribution of joint data

(i) $N224^0/57^0$

(ii) $N247^0/52^0$

(iii) $N101^0/47^0$

For identification of potential wedge failure following pairs of joint planes have been considered :

(i) $N224^0/57^0$ and $247^0/52^0$

(ii) $N224^0/57^0$ and $N101^0/47^0$

4.2.5 Plane Failure Analysis

(a) For joint plane $N224^0/57^0$ following set of conditions were established by applying Markland test :

(i) Slope direction should be between $N204^0$ to $N244^0$

(ii) Slope angle should be greater than 57^0

Direction of sliding is N224° and angle of sliding is 57°. No cross section in area of study in Bhagirathi valley satisfy above set of conditions. Hence, there is no case of potential failure with reference to plane $N224^0/57^0$. Hence, no further stability analysis needs to be carried out.

(b) For joint plane $N247^0/52^0$ following set of conditions are considered :

(i) Slope direction should be between N227° to N267°

(ii) Slope angle should be greater than 52^0

Direction of sliding is N 247° and angle of sliding is 52°. Here also no cross section in area of study pertaining to Bhagirathi valley satisfy above set of condition. So, no further analysis has been taken up.

(c) For joint plane N101°/47° following set of conditions have been determined by applying Markland test :

(i) Slope direction should be between N81° to N121°

(ii) Slope angle should be greater than 47°

Direction of sliding is N101° and angle of sliding is 47°. Results are same as in previous two cases . Hence, it can be established that no cross section can be considered for potential plane failure.

4.2.6 Wedge Failure Analysis

(a) There is a formation of wedge by intersection of joint planes N224°/57° and N247°/52°. Following set of conditions have been established by applying Markland test :

(i) Slope direction should be between N240° to N280°

(ii) Slope angle should be greater than 51°

Direction of sliding is N260° and angle of sliding is 51°. No cross section in area of study, pertaining to Bhagirathi valley satisfy above set of conditions. So, there is no case of potential wedge failure with reference to wedge formed by joint planes N224°/57° and N247°/52°. Hence, further stability analysis for wedge failure has not been carried out.

(b) Another wedge is found by intersection of joint planes N101°/47° and N224°/57°. Following set of conditions have been determined by applying Markland test :

(i) Slope direction should be between N137° to N177°.

(ii) Slope angle should be greater than 32°.

Direction of sliding is N157° and angle of sliding is 32°. Only one cross section BHL 34A (Table 4.1) satisfies the above set of conditions. So, stability analysis for wedge failure has been carried out for cross section BHL 34A.

Stereoplot of wedge failure analysis (Fig. 4.7) has been used to derive input data for calculation of Factory of Safety (Table 4.2). Factor of Safety was calculated for various conditions such as 'static and dry', 'static and wet', 'dynamic and dry', and 'dynamic and wet'.

Results obtained by calculation of Factor of Safety indicate that the slope is stable under 'static and dry', and 'dynamic and dry' conditions. Slope is unstable under 'static and wet' and 'dynamic and wet' conditions (Fig. 4.8).

4.2.7 Preparation of Hazard Map (Bhagirathi Valley)

After finishing stability analysis, a landslide hazard map of the area has been prepared (Fig. 4.9). It shows that only one slope facet BHL34A is unstable under the most adverse possible condition (dynamic and wet conditions).

4.2.8 Limitation of Slope Stability Evaluation Using Cross Sections Across the Slope Facets

When a cross section across the slope facet is considered for stability analysis it represents a general slope. Here, there is an assumption that slope is homogeneous with reference to dip direction and dip amount of slope. But there may be locally steep slopes, which may cause instability of slope. The microchanges in attitude of slope may have important consequences locally, which may sometime affect stability of slope. As local slope variations are not accounted in stability analysis using cross sections across the slope facets, it is felt that there is a necessity to suitably modify the existing approach by more object oriented approach.

Table 4.1: Application of Markland Test for wedge formed by joint planes N 101°/47° and N 224°/57° (Bhagirathi valley)

M.O.F.	WEDGE				
JOINT PLANES	N 101°/47° & N 224°/57°				
CONDITIONS FOR MARKLAND TEST	Slope direction should be between N 137°-N 177°& Slope angle should be >32°				
SERIAL NUMBER	CROSS SECTIONS	IF CONDITIONS FOR MARKLAND TEST SATISFIES	SERIAL NUMBER	CROSS SECTIONS	IF CONDITIONS FOR MARKLAND TEST SATISFIES
1.	BHL1	NO	20.	BHL20	NO
2.	BHL2	NO	21.	BHL21	NO
3.	BHL3	NO	22.	BHL22	NO
4.	BHL4	NO	23.	BHL23	NO
5.	BHL5	NO	24.	BHL24	NO
6.	BHL6	NO	25.	BHL25	NO
7.	BHL7	NO	26.	BHL26	NO
8.	BHL8	NO	27.	BHL27	NO
	BHL9A	NO	28.	BHL28	NO
9.	BHL9	NO	29.	BHL29	NO
10.	BHL10	NO	30.	BHL30	NO
11.	BHL11	NO	31.	BHL31	NO
12.	BHL12	NO	32.	BHL32	NO
13.	BHL13	NO	33.	BHL33	NO
14.	BHL14	NO	34.	BHL34	NO
15.	BHL15	NO	35.	BHL34A	YES
16.	BHL16	NO	36.	BHL35	NO
17.	BHL17	NO	37.	BHL36	NO
18.	BHL18	NO	38.	BHL37	NO
	BHL18A	NO	39.	BHL38	NO
19.	BHL19	NO	40.	BHL39	NO

M.O.F. : Mode of Failure

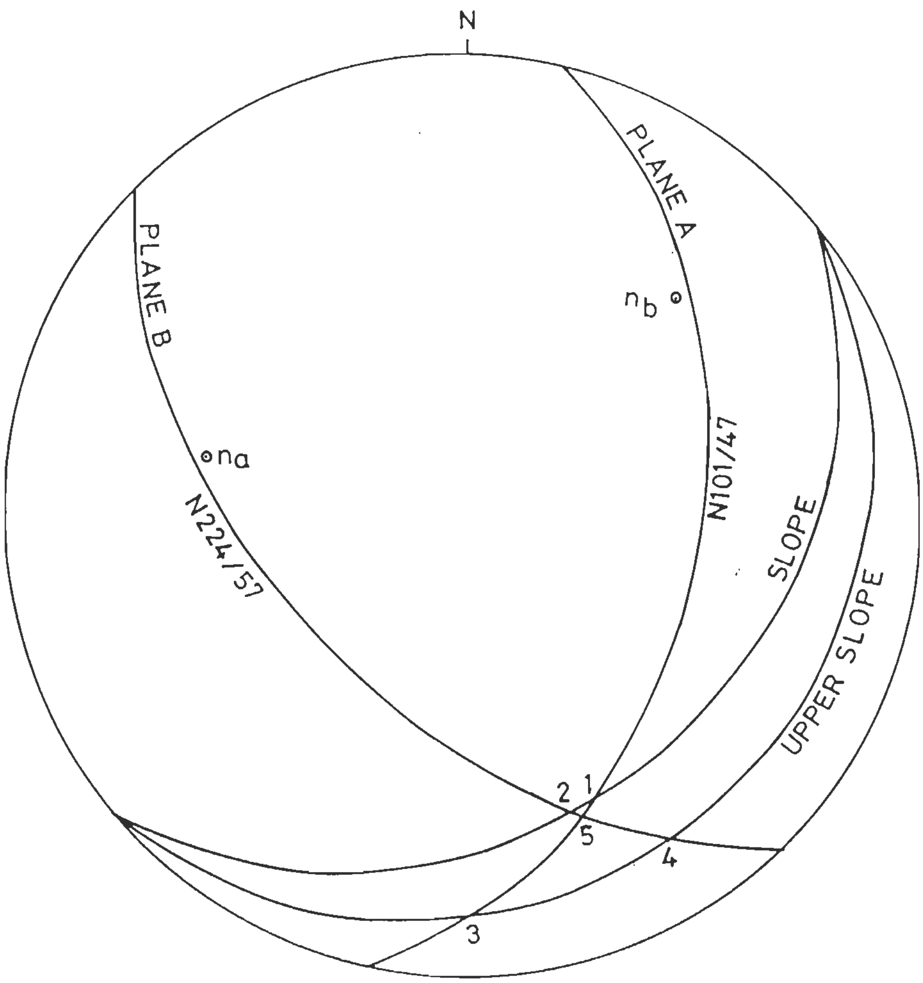


Fig. 4.7 Stereoplot of Wedge failure analysis for cross section BHL34A (Bhagirathi Valley)

Table 4.2 Factor of Safety for various conditions

MOF			WEDGE	WEDGE	WEDGE	WEDGE
LCNS			BLN, BRR18	BLN(QTZ), BRR30	BHAGIRATHI BHL 34A	BLN, BRR24
JOINT PLANES			N110/79 & N216/38	N71/78 & N212/66	N101/47 & N224/57	N71/78 & N212/66
SLOPE			N181/37	N142/57	N140/34	N153/48
Upper Slope			N181/22	N142/31	N140/19	N153/12
ψ_a			38	66	47	66
ψ_b			79	78	57	78
ψ_5			35	45	32	45
$\theta_{na.nb}$			92	129	88	129
$\theta_{2.4}$			18	28	20	38
$\theta_{4.5}$			16	16	17	35
$\theta_{2.na}$			89	80	88	88
$\theta_{1.3}$			44	30	29	44
$\theta_{3.5}$			40	17	25	40
$\theta_{1.nb}$			88	80	86	88
ϕ			30	36	30	36
g			2500	2700	2500	2700
C			15000	30000	15000	30000
h			150	150	425	200
FOS	SC	DRY	12.0	6.0	3.3	11.7
		WET	1.4	3.4	-2.2	3.6
	DC	DRY	10.9	3.9	2.0	9.6
		WET	0.3	1.3	-3.5	1.5

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B; BLN - Bhilangna; QTZ - Quartzite

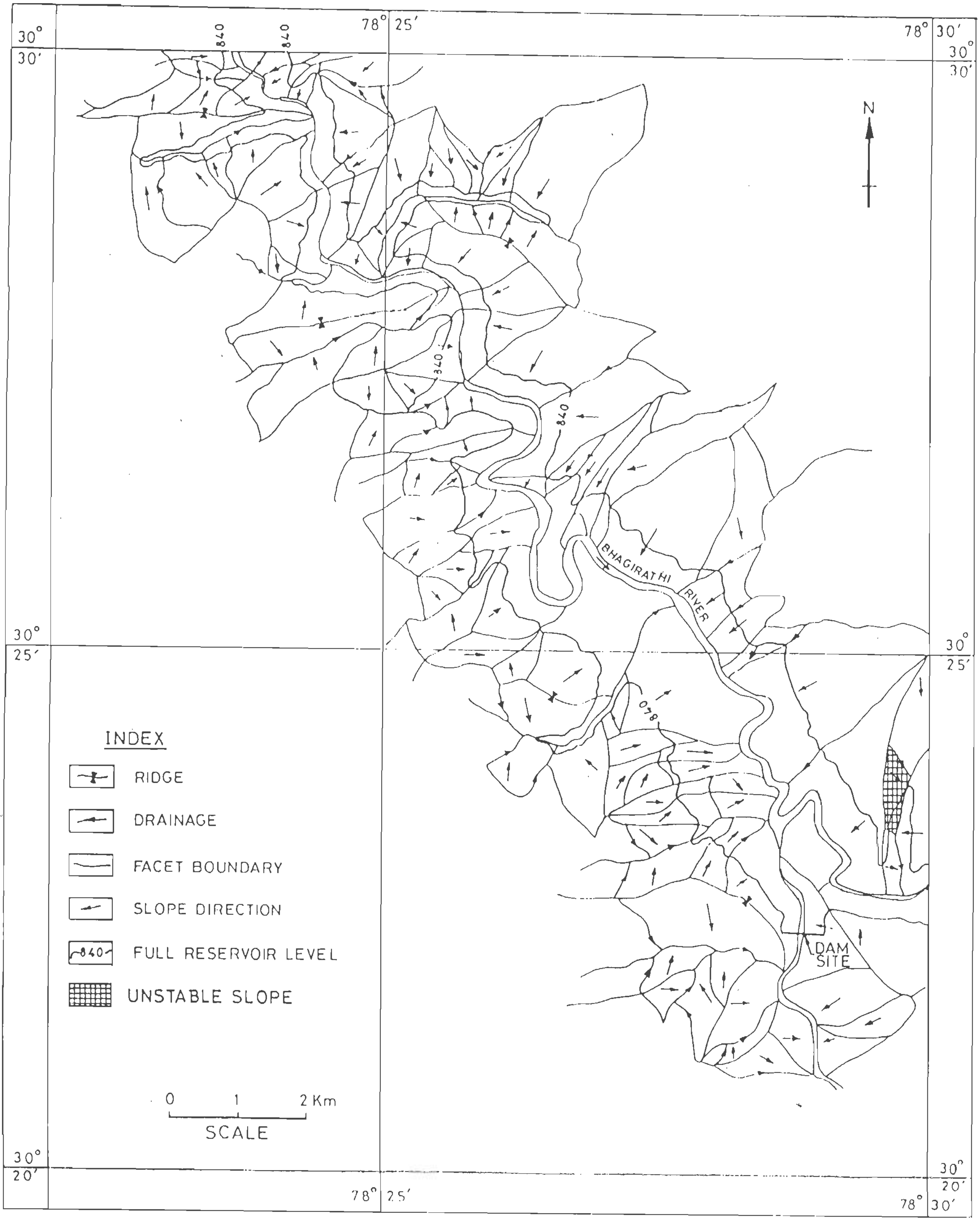


Fig. 4.8 Stablility of slope under 'static and wet' and 'dynamic and wet' condition (BHL34A)

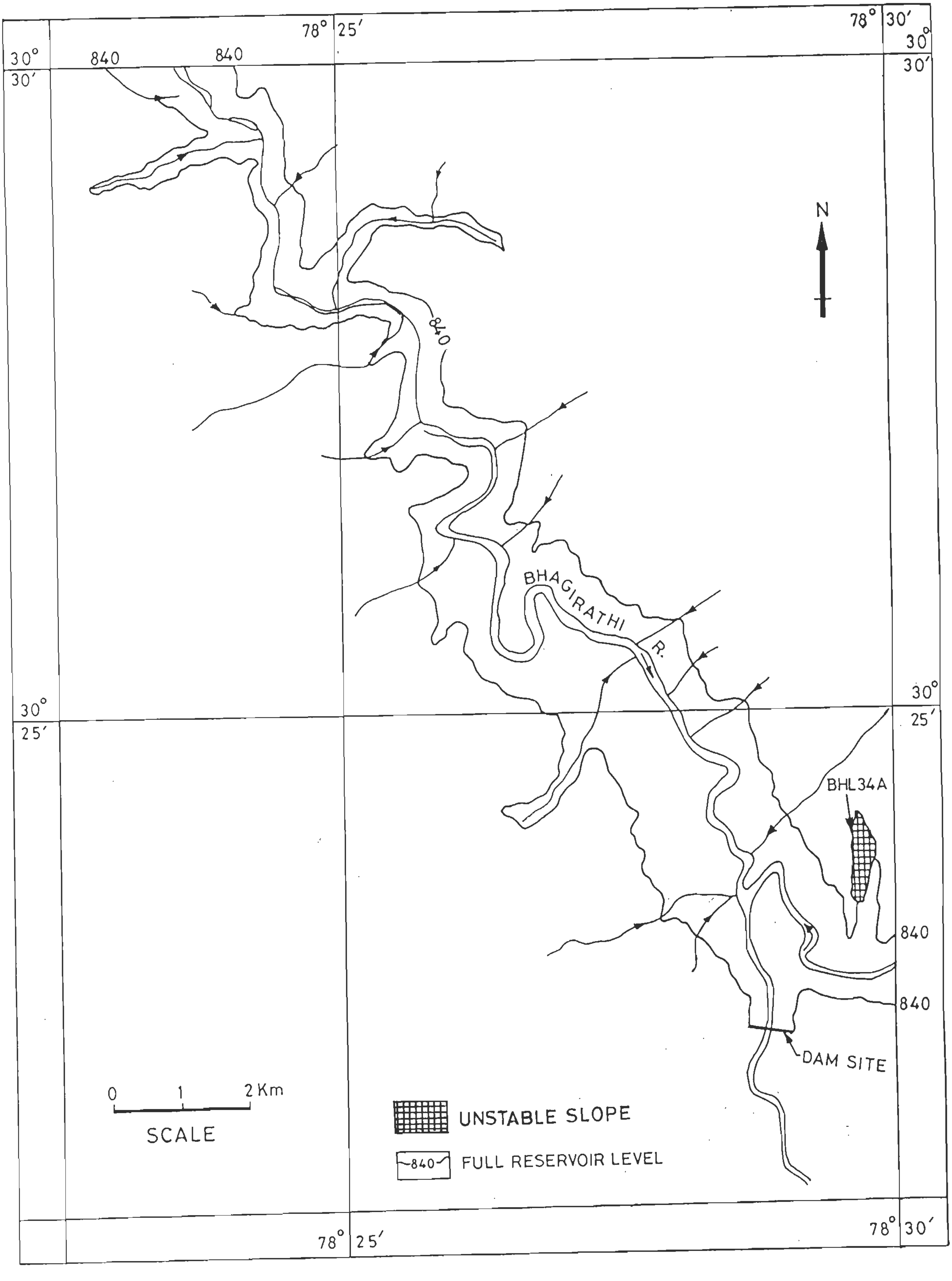


Fig. 4.9 Hazard Map (Bhagirathi Valley)

4.2.9 Stability Analysis by Using a New Comprehensive Approach

In order to take care of limitations of previous approach, a new comprehensive approach has been adopted. In this approach, set of conditions favourable for potential failure (which are established in course of previous approach for the study of plane and wedge failure by applying Markland test) have been incorporated.

4.2.10 Wedge Failure Analysis

(a) For wedge formed by intersection of N224^0/57^0 and N247^0/52^0, set of conditions, for potential failure as obtained by Markland test are shown in Fig. 4.10.

Direction of sliding is N260° and angle of sliding is 51°. There are total 12 slopes satisfying the above conditions. Stability analysis for these slopes have been carried out (Fig. 4.11A & Fig. 4.11B). Results obtained by calculation of Factor of Safety show that all slopes are stable under 'Static and dry', 'Static and wet', 'dynamic and dry' and 'dynamic and wet' conditions (Table 4.3A and Table 4.3B). These results are also shown in the form of a map (Fig. 4.12).

(b) For another wedge formed by intersection of joint planes N101/47^0 and N224/57^0, set of conditions for potential failure as determined by Markland test are shown in Fig. 4.10.

Direction of sliding is N 157°/32° and angle of sliding is 32° . There are total 8 slopes satisfying the above conditions. Stability analysis for all these slopes are carried out (Fig. 4.13). Here, as in previous case slopes are stable under various adverse conditions (Table 4.4 and Table 4.4A). These results are shown in the form of a map (Fig 4.14).

4.2.11 Plane Failure Analysis

(a) For joint plane N247°/52^0 conditions for potential failure are shown in Fig. 4.10. Direction of sliding is N 247° and angle of sliding is 52°. There are total 17 slopes satisfying the above conditions. All these 17 slopes are stable under 'static and dry' conditions, while

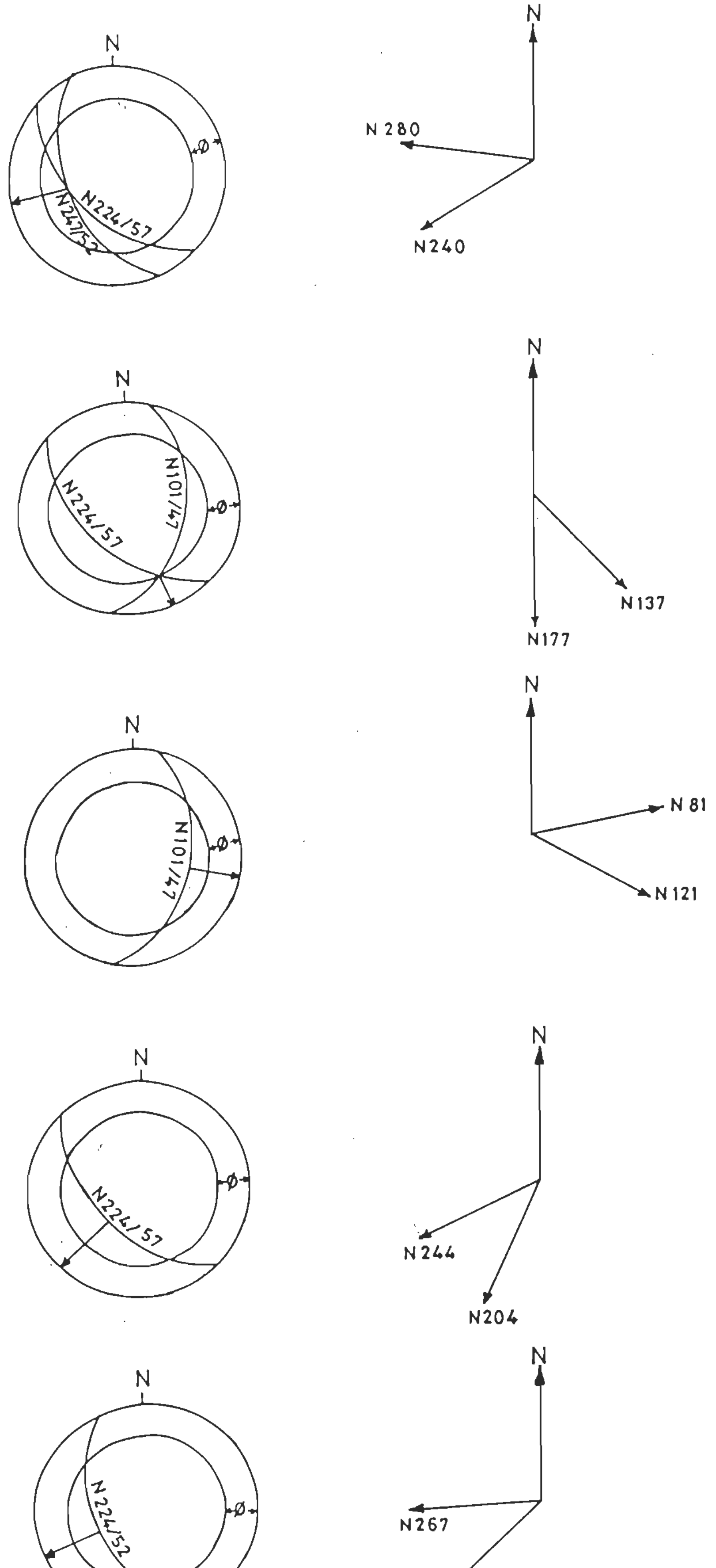


Fig. 4.10 Set of conditions for potential failure obtained by Markland test (Bhagirathi Valley)

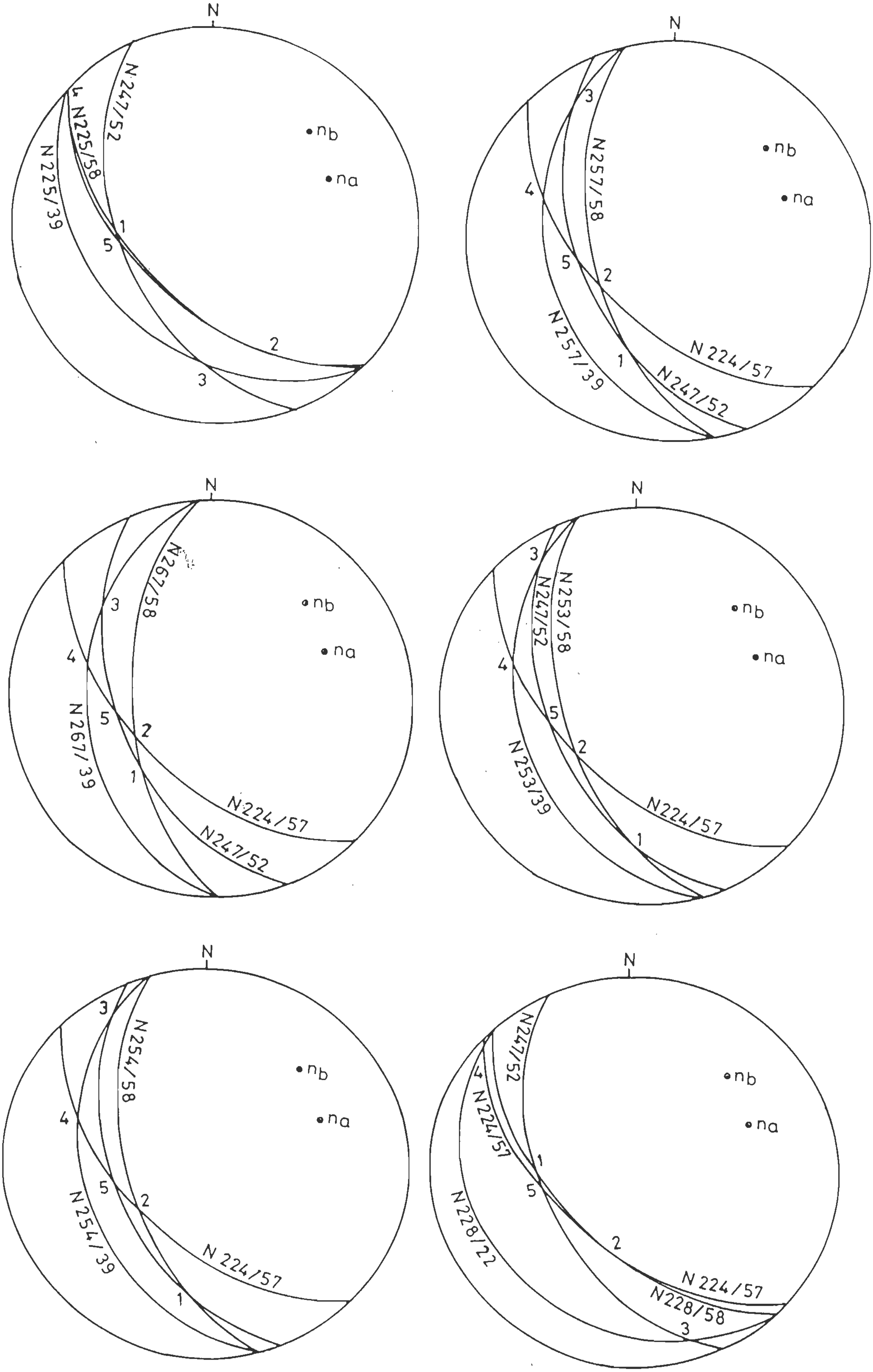


Fig. 4.11A Stereoplots for Stablility analysis of slopes (For Wedge formed by intersection of joint planes N224/57° and N247/52°, Bhagirathi Valley)

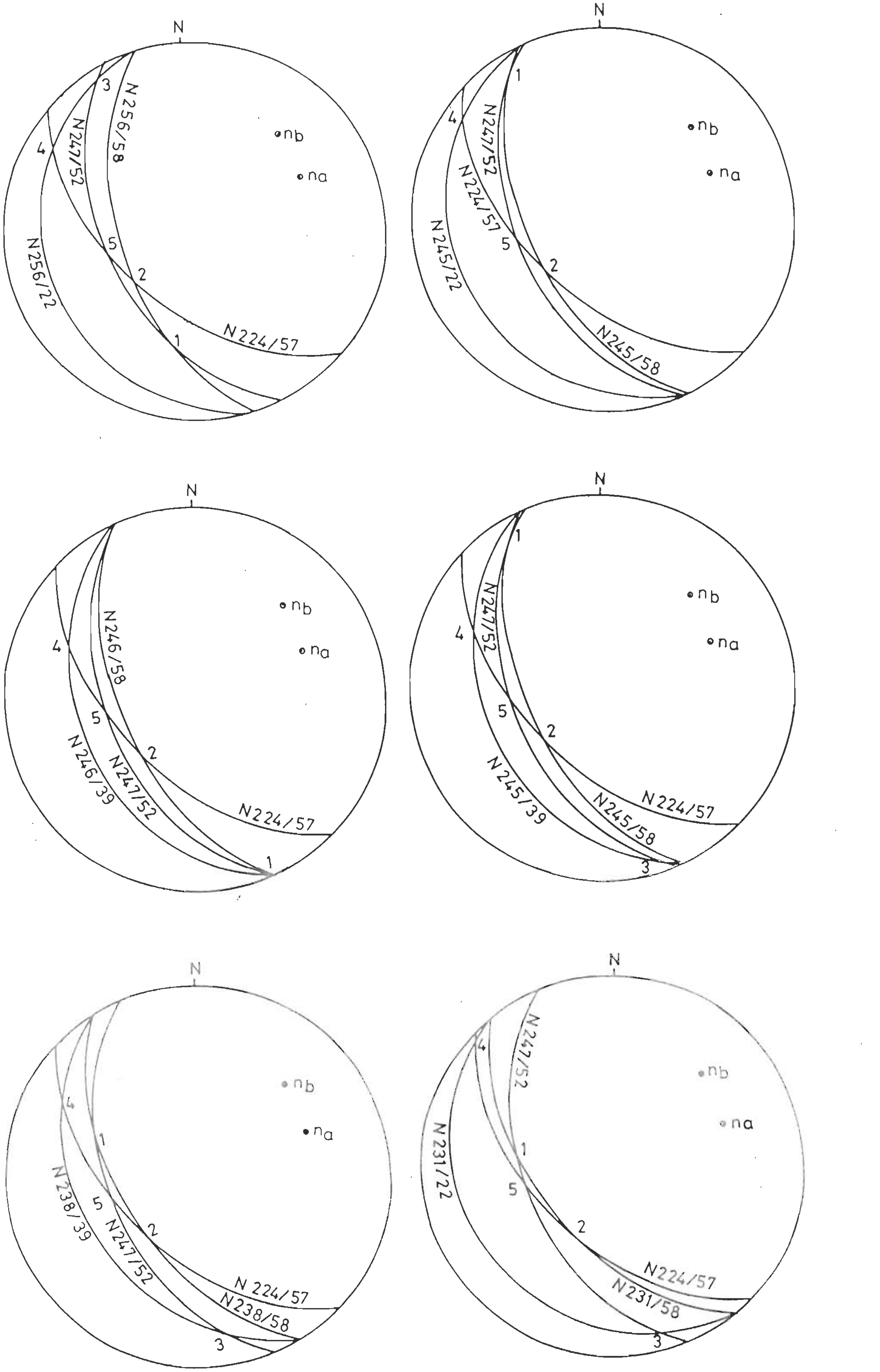


Fig. 4.11B Stereoplots for Stablility analysis of slopes (For Wedge formed by intersection of joint planes N224/57° and N247/52°, Bhagirathi Valley)

Table 4.3A Factor of Safety for various conditions (for wedge formed by intersection of joint planes N224^{0}/57^{o} and N247^{o}/52^{o}, Bhagirathi valley)

MOF			Wedge	Wedge	Wedge	Wedge	Wedge	Wedge	Wedge
LCNS			1	2	2A	3	4	7	8
JOINT PLANES			N247/52 & N224/57	N247/52 & N224/57	N247/52 & N224/57	N247/52 & N224/57	N247/52 & N224/57	N247/52 & N224/57	N247/52 & N224/57
SLOPE			N225/58	N257/58	N267/58	N253/58	N254/58	N228/58	N256/58
Upper Slope			N225/39	N257/39	N267/39	N253/39	N254/39	N228/22	N256/22
Ψ_a			52	52	52	52	52	52	52
Ψ_b			57	57	57	57	57	57	57
Ψ_5			51	51	51	51	51	51	51
$\theta_{na.nb}$			20	20	20	20	20	20	20
$\theta_{2.4}$			140	42	34	44	44	103	66
$\theta_{4.5}$			68	26	22	28	28	65	50
$\theta_{2.na}$			72	86	87	86	86	78	86
$\theta_{1.3}$			60	104	64	120	124	94	118
$\theta_{3.5}$			58	60	42	66	68	8	74
$\theta_{1.nb}$			90	104	97	106	108	88	103
ϕ			30	30	30	30	30	30	30
g			2500	2500	2500	2500	2500	2500	2500
C			15000	15000	15000	15000	15000	15000	15000
h			55	55	55	55	55	45	45
FOS	**SC**	**DRY**	420.9	6.0	6.0	6.2	6.4	83.0	5.6
		WET	272.5	4.0	4.0	4.2	4.3	52.1	4.0
	DC	**DRY**	420.3	5.4	5.4	5.5	5.7	82.3	5.0
		WET	271.9	3.5	3.5	3.6	3.7	58.5	3.5

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

Table 4.3B Factor of Safety for various conditions (for wedge formed by intersection of joint planes N224°/57° and N247°/52°, Bhagirathi valley)

MOF			Wedge	Wedge	Wedge	Wedge	Wedge
LCNS			9	10	11	12	13
JOINT PLANES			N 247/52 & N 224/57	N 247/52 & N 224/57	N 247/52 & N 224/57	N 247/52 & N 224/57	N 247/52 & N 224/57
SLOPE			N 245/58	N 246/58	N 245/58	N 238/58	N 231/58
Upper Slope			N 245/22	N 246/39	N 245/39	N 238/39	N 231/22
Ψ_a			52	52	52	52	52
Ψb			57	57	57	57	57
Ψ_5			51	51	51	51	51
$\theta_{na.nb}$			20	20	20	20	20
$\theta_{2.4}$			73	54	55	66	95
$\theta_{4.5}$			56	33	20	44	65
$\theta_{2.na}$			84	84	101	84	82
$\theta_{1.3}$			164	4	158	102	99
$\theta_{3.5}$			97	99	91	76	86
$\theta_{1.nb}$			72	110	72	82	86
ϕ			30	30	30	30	30
g			2500	2500	2500	2500	2500
C			15000	15000	15000	15000	15000
h			45	55	55	55	45
FOS	SC	DRY	5.1	4.9	-3.2	6.8	9.2
		WET	3.8	3.3	-1.9	4.6	6.6
	DC	DRY	4.5	4.4	-3.8	6.2	8.6
		WET	3.2	2.7	-2.5	4.0	6.0

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

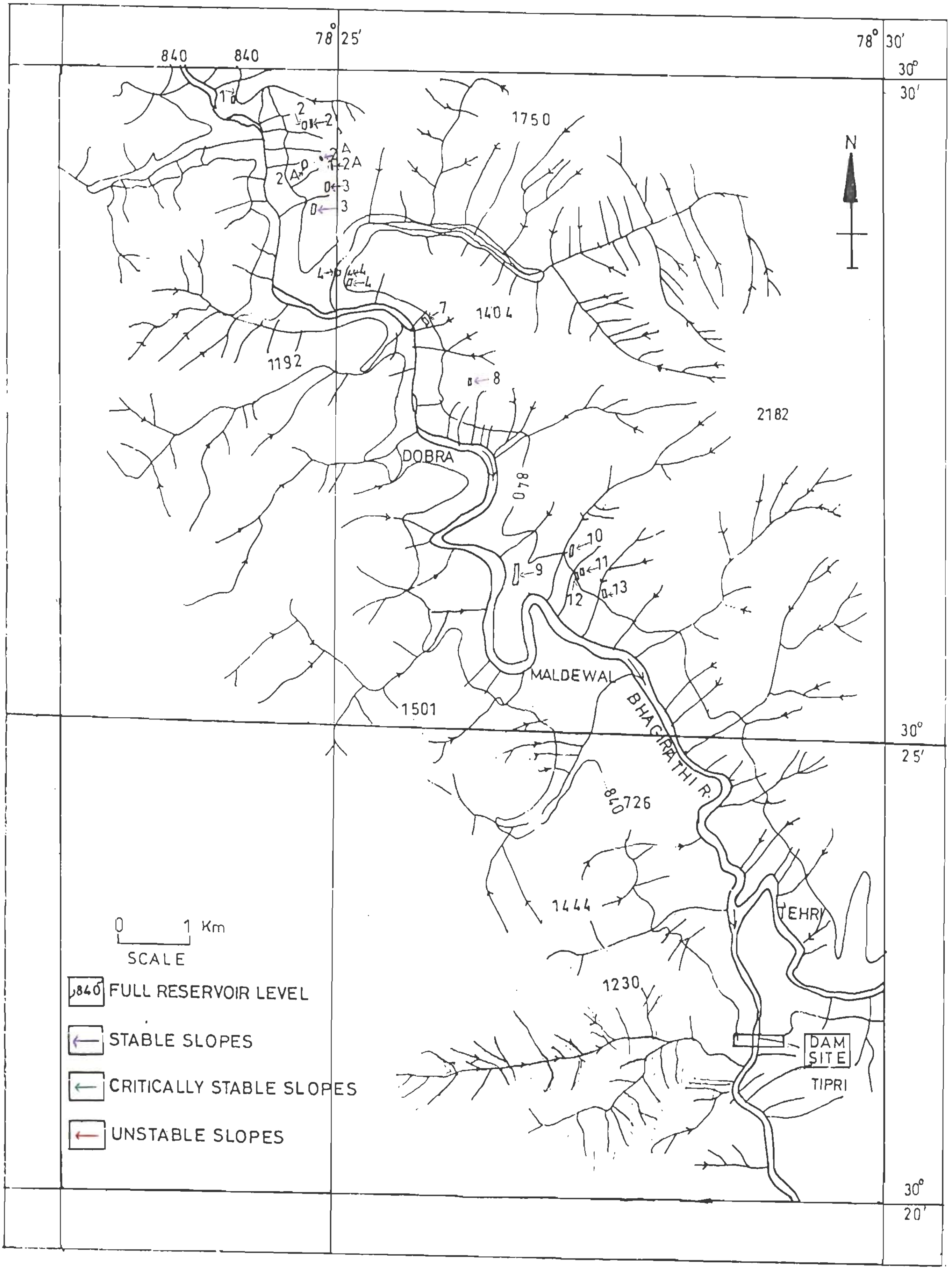


Fig. 4.12 Stability of Slopes Under Various Conditions (For Wedge Formed by Intersection of Joint Planes N224°/57° and N247°/52°, Bhagirathi Valley)

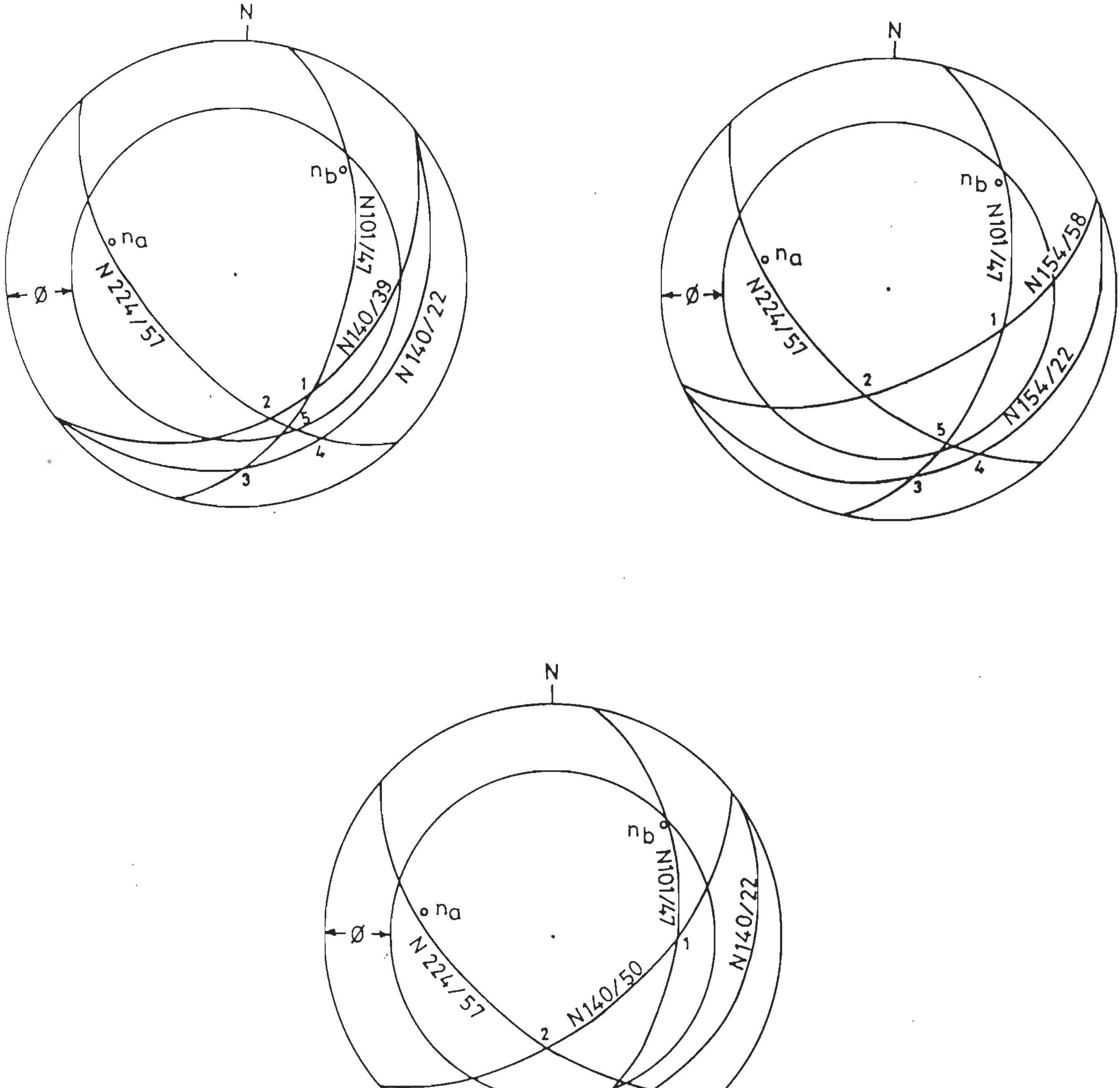


Fig. 4.13 Stereoplots for Stability Analysis of Slopes
(For Wedge Formed by Intersection of Joint Planes
N101°/47° and N224°/57°, Bhagirathi Valley)

Table 4.4 Factor of Safety for various conditions (for wedge formed by intersection of joint planes $N101^0/47^0$ and $N224^0/57^0$, Bhagirathi valley)

MOF			Wedge	Wedge	Wedge	Wedge	Wedge	Wedge	Wedge
LCNS			1A Bhagriathi	1B Bhagriathi	2 Bhagriathi	3 Bhagriathi	4 Bhagriathi	5 Bhagriathi	6 Bhagriathi
JOINT PLANES			N 101/47 & N 224/57	N 101/47 & N 224/57	N 101/47 & N 224/57	N 101/47 & N 224/57	N 101/47 & N 224/57	N 101/47 & N 224/57	N 101/47 & N 224/57
SLOPE			N 140/58	N 140/58	N 151/58	N 154/58	N 164/58	N 171/58	N 139/58
Upper Slope			N 140/22	N 140/39	N 151/39	N 154/22	N 164/39	N 171/39	N 139/39
Ψa			47	47	47	47	47	47	47
Ψb			57	57	57	57	57	57	57
$\Psi 5$			32	32	32	32	32	32	32
$\theta na.nb$			89	89	89	89	89	89	89
$\theta 2.4$			39	19	22	44	25	29	19
$\theta 4.5$			13	7	10	12	10	10	8
$\theta 2.na$			64	64	59	59	57	53	64
$\theta 1.3$			74	38	30	58	24	23	39
$\theta 3.5$			22	14	14	16	12	10	16
$\theta 1.nb$			38	38	46	48	56	57	35
ϕ			30	30	30	30	30	30	30
g			2500	2500	2500	2500	2500	2500	2500
C			15000	15000	15000	15000	15000	15000	15000
h			45	55	55	45	55	55	55
F O S	S C	DRY	5.1	4.3	3.6	5.7	3.9	4.1	3.9
		WET	4.0	3.2	2.8	4.4	2.9	3.1	3.0
	D C	DRY	3.8	3.0	2.3	4.4	2.6	2.8	2.6
		WET	2.7	1.9	1.5	3.1	1.6	1.8	1.7

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

Table 4.4A Factor of Safety for various conditions (for wedge formed by intersection of joint planes N101^0/47^0 and N224^0/57^0, Bhagirathi valley)

MOF			wedge
LCNS			7(7)
JOINT PLANES			N 101/47 & N 224/57
SLOPE			N 140/39
Upper Slope			N 140/22
Ψ_a			47
Ψb			57
Ψ_5			32
$\theta_{na.nb}$			89
$\theta_{2.4}$			20
$\theta_{4.5}$			13
$\theta_{2.na}$			84
$\theta_{1.3}$			34
$\theta_{3.5}$			20
$\theta_{1.nb}$			89
ϕ			30
g			2500
C			15000
h			57
FOS	SC	DRY	34.9
		WET	22.9
	DC	DRY	32.8
		WET	20.8

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5 - Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

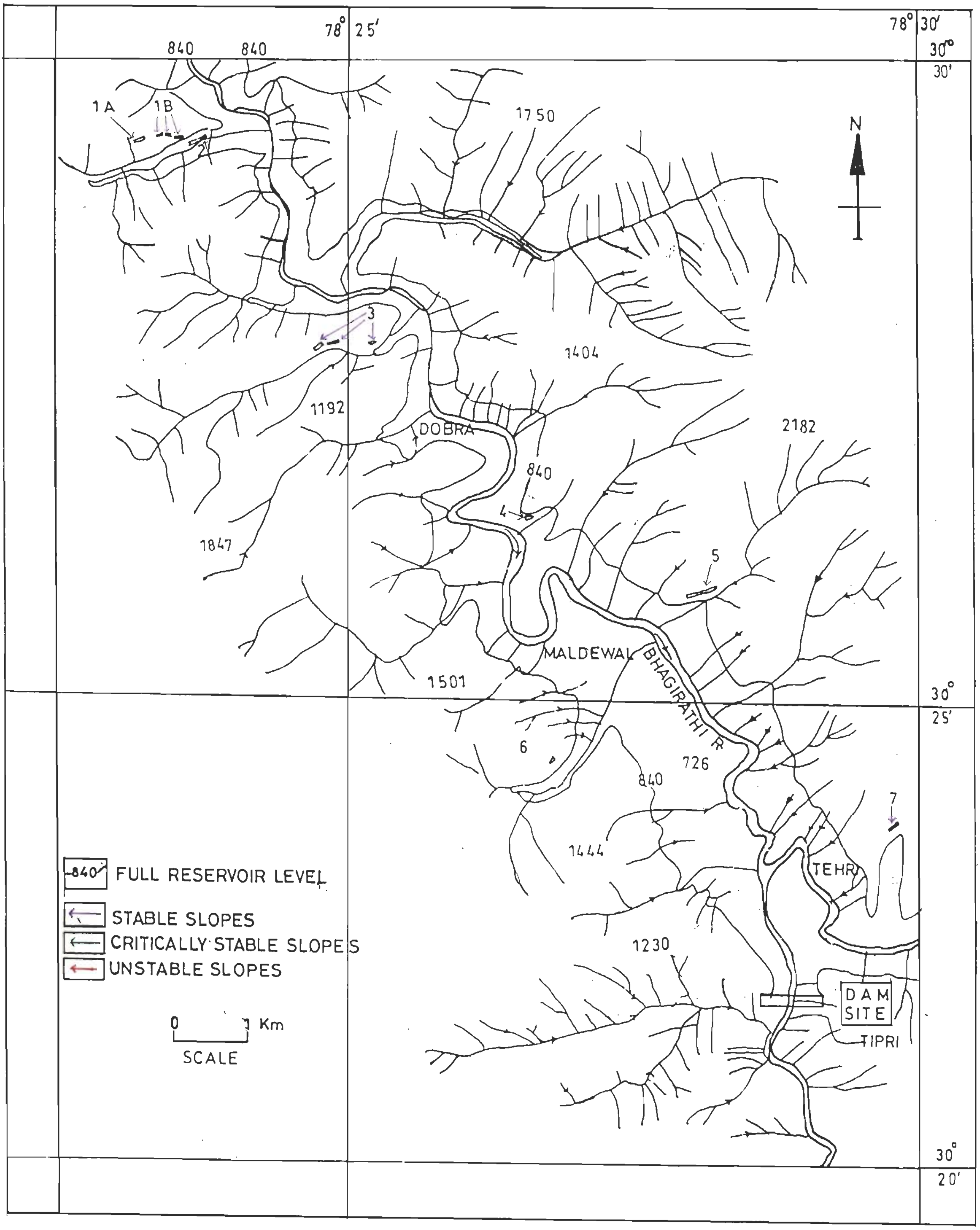


Fig. 4.14 Stability of Slopes Under Various Conditions (For Wedge Formed by Intersection of Joint Planes N101°/47° and N224°/57°, Bhagirathi Valley)

unstable under 'dynamic and wet' condition (Table 4.5). Out of 17 slopes, 13 slopes are stable under ' static and wet' conditions, while rest of 4 slopes are critically stable. Same slopes which are stable under 'static and wet' condition become critically stable under 'dynamic and dry' condition while other slopes which are critically stable under 'static and wet' condition, become unstable under 'dynamic and dry' condition (Fig. 4.15, Fig 4.16 and Fig. 4.16A).

(b) For joint plane N101^0/47^0, set of potential failure conditions are shown in Fig. 4.10 . Direction of sliding is N 101° and angle of sliding is 47°. There are total 25 slopes satisfying the above conditions. All these slopes are stable under 'static and dry' condition but unstable under 'dynamic and dry' and 'dynamic and wet' conditions. Out of total 25 slopes, 13 slopes are stable and remaining 12 slopes are critically stable, under static and wet condition (Table 4.5, Fig. 4.17 and Fig.4.18).

(c) For joint plane N224°/57^0, set of conditions, as determined by Markland test, are shown in Fig. 4.10. Direction of sliding is N 224° and angle of sliding is 57°. There are total 10 slopes satisfying the above conditions. Out of these 10 slopes, 5 slopes are stable under all hazard prone conditions, while rest of 5 slopes, are stable under 'static and dry' condition, critically stable under 'static and wet' condition and unstable under 'dynamic and dry' an well as 'dynamic and wet' condition (Table 4.5, Fig 4.19 & Fig. 4.20).

4.2.12 Preparation of Landslide Hazard Map (Bhagirathi Valley)

On a perusal of the results obtained for various potentially failure slopes, the slopes having F.O.S. (Factor of Safety) less than 1 under any of the possible Hazard prone condition, have been chosen (Fig. 4.21). It shows that locations of possible slide are present on right as well as on left bank. Based on this new approach, a total of 72 potential failure slopes

Table 4.5 Factor of Safety for various conditions (for plane failure, Bhagirathi valley)

MOF			Plane	Plane	Plane	Plane	Plane	Plane
LCNS			Bhagirathi Valley	Bhagirathi Valley	Bhagirathi Valley	Bhagirathi Valley	Bhagirathi Valley	Bhagirathi Valley
JOINT PLANES			N101/47	N247/52	N224/57	N224/57	N247/52	N101/47
ψ_f			58	58	58	68	68	68
ψ_p			47	52	57	57	52	47
ϕ			30	30	30	30	30	30
H			40	40	40	40	40	40
γ			2500	2500	2500	2500	2500	2500
C			15000	15000	15000	15000	15000	15000
FOS	SC	DRY	2.3	3.5	17.7	2.1	1.7	1.6
		WET	1.6	2.3	11.0	1.4	1.2	1.2
	DC	DRY	0.5	1.1	8.3	0.6	0.3	0.2
		WET	0.3	0.6	5.0	0.2	0.1	0.1

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); H - Height of slope (in m); C - Cohesion (in kg/m^2); γ - Unit Weight of Rock (in kg/m^3); ψ_f - Slope face inclination (in degree); ψ_p - Failure plane inclination (in degree)

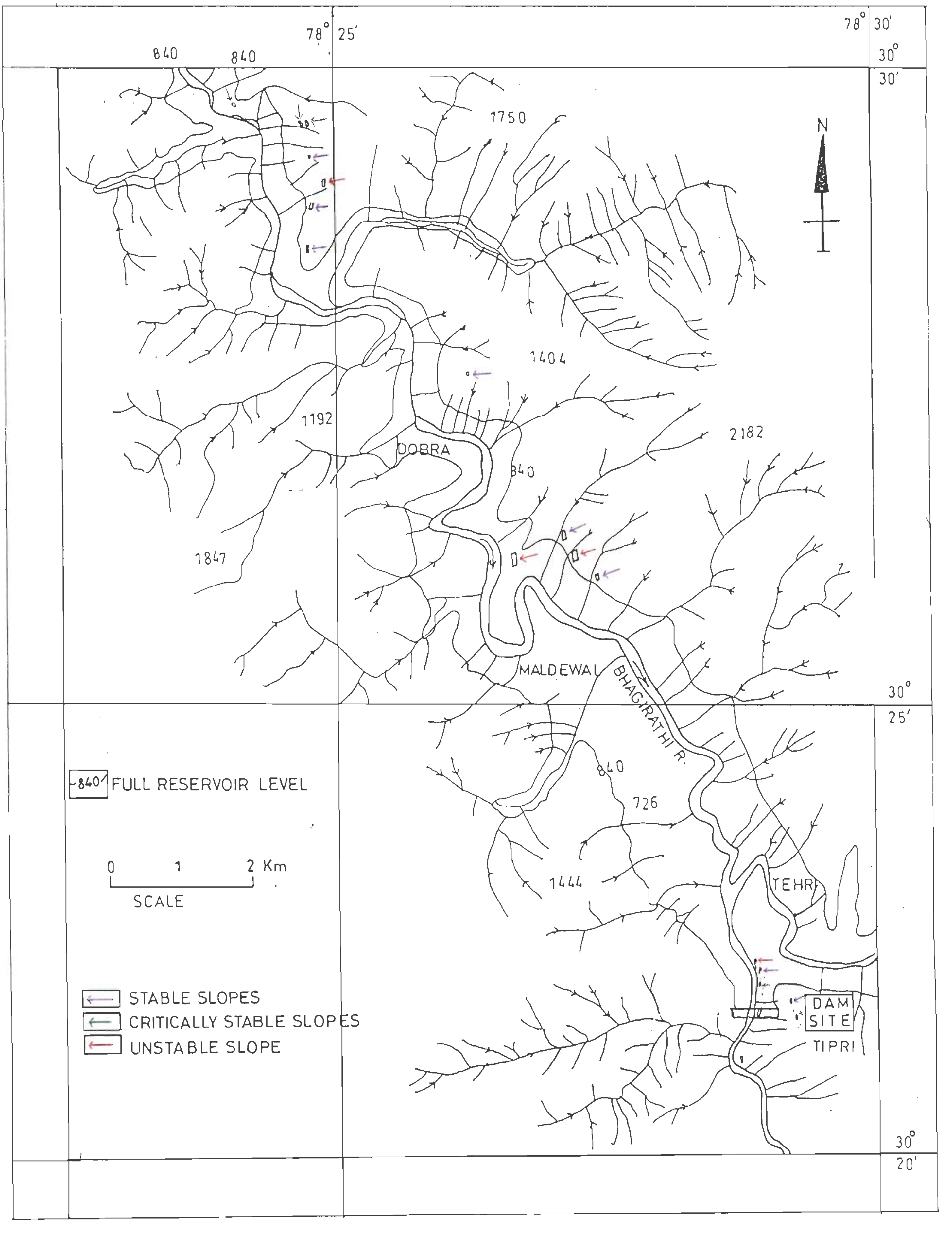


Fig. 4.15 Stability of Slopes Under 'Dynamic and Dry' Condition (For Plane Failure along Joint Plane N247°/52°, Bhagirathi Valley)

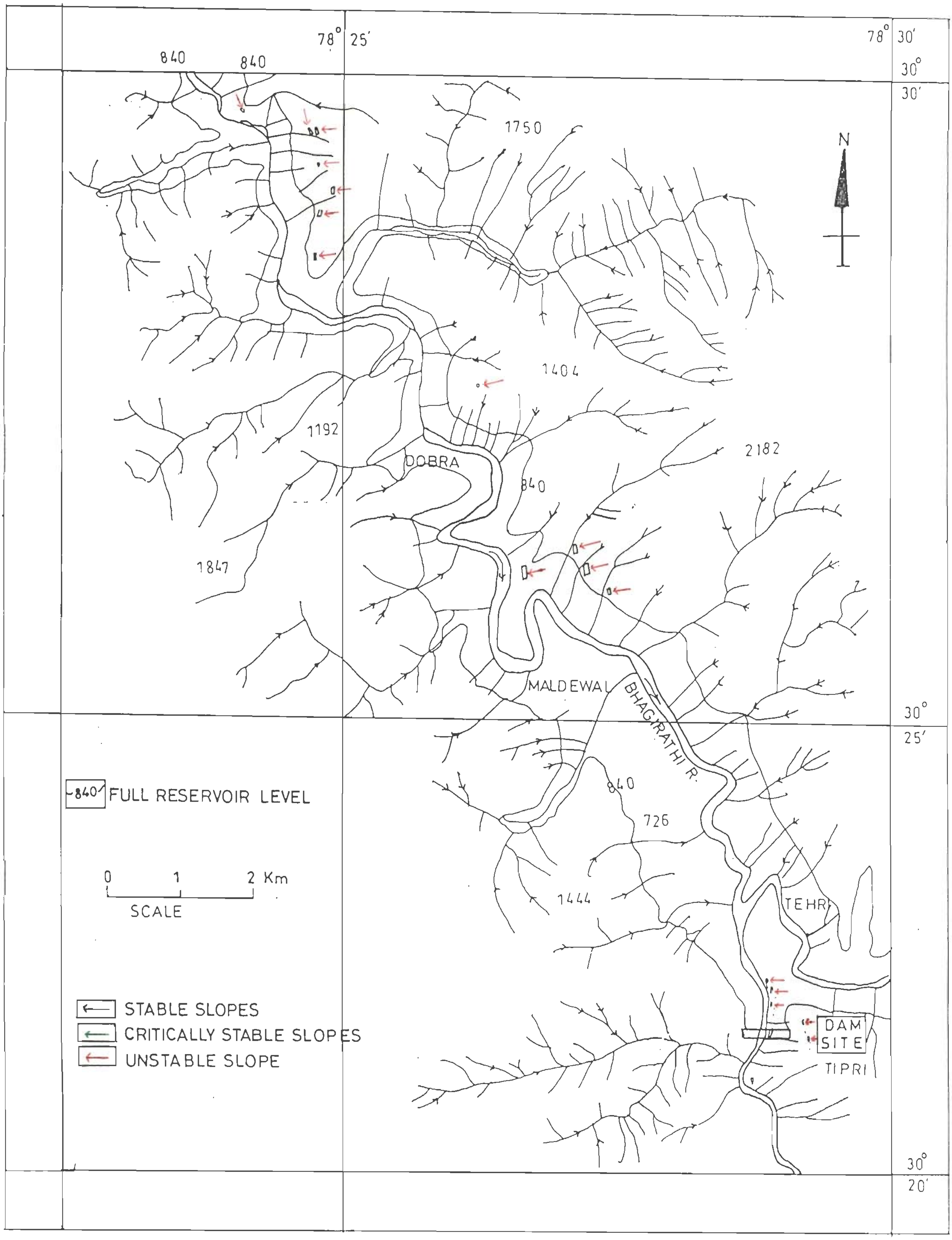


Fig. 4.16 Stability of Slopes Under 'Dynamic and Wet' Condition (For Plane Failure along Joint Plane N247°/52°, Bhagirathi Valley)

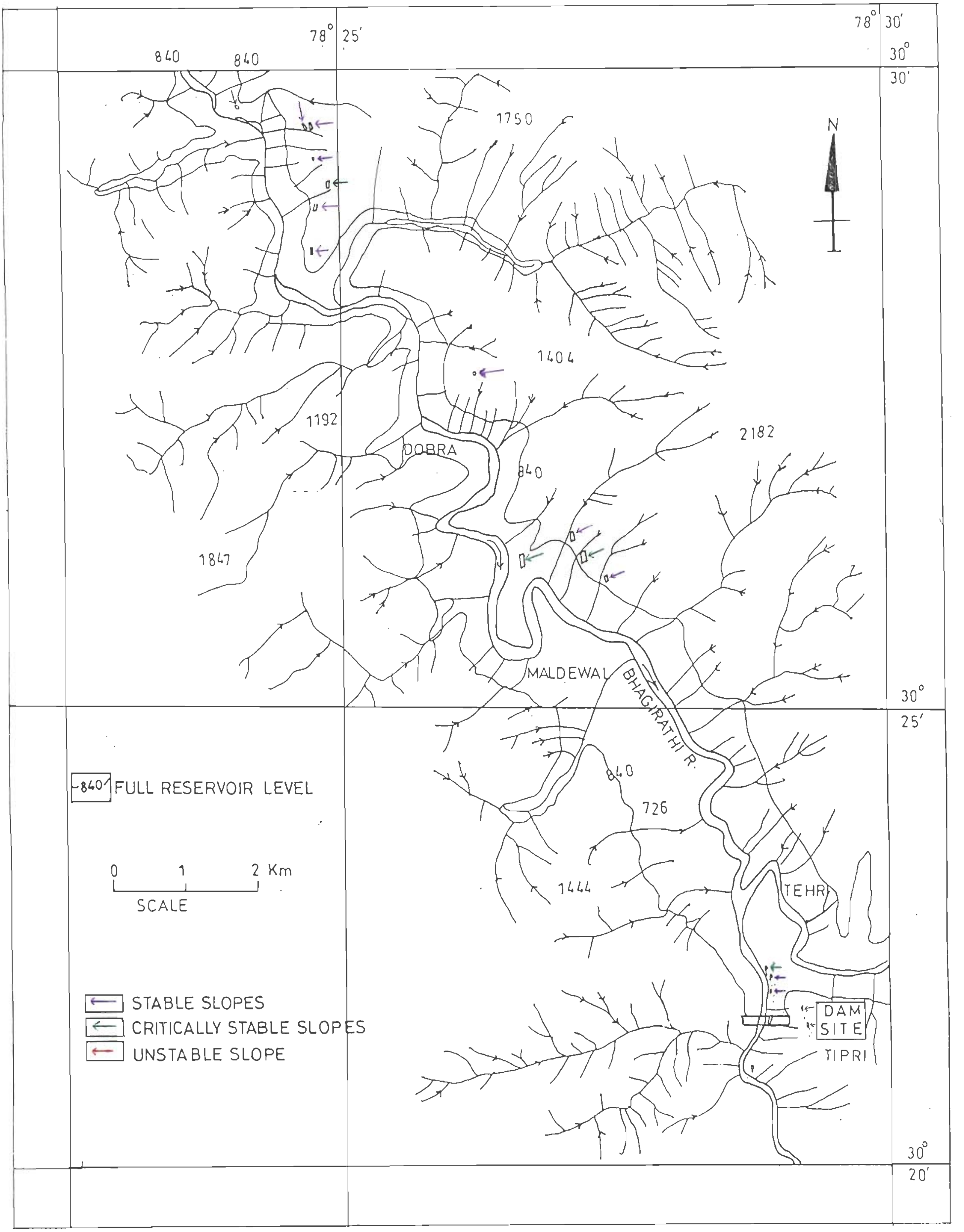


Fig. 4.16A Stability of Slopes Under 'Static and Wet' Condition (For Plane Failure along Joint Plane N247°/52°, Bhagirathi Valley)

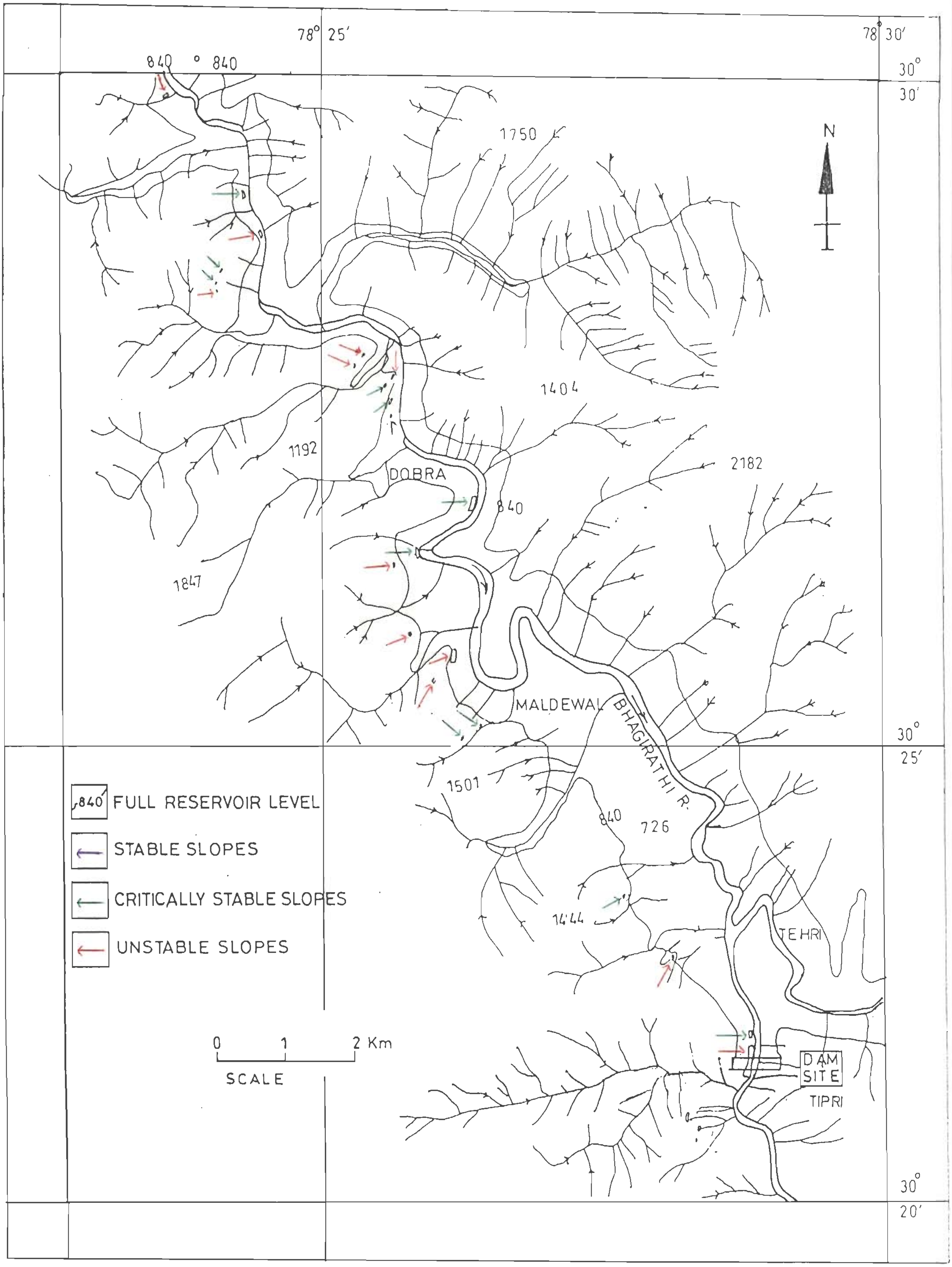


Fig. 4.17 Stability of Slopes Under 'Static and Wet' Condition (For Plane Failure along Joint Plane N101°/47°, Bhagirathi Valley)

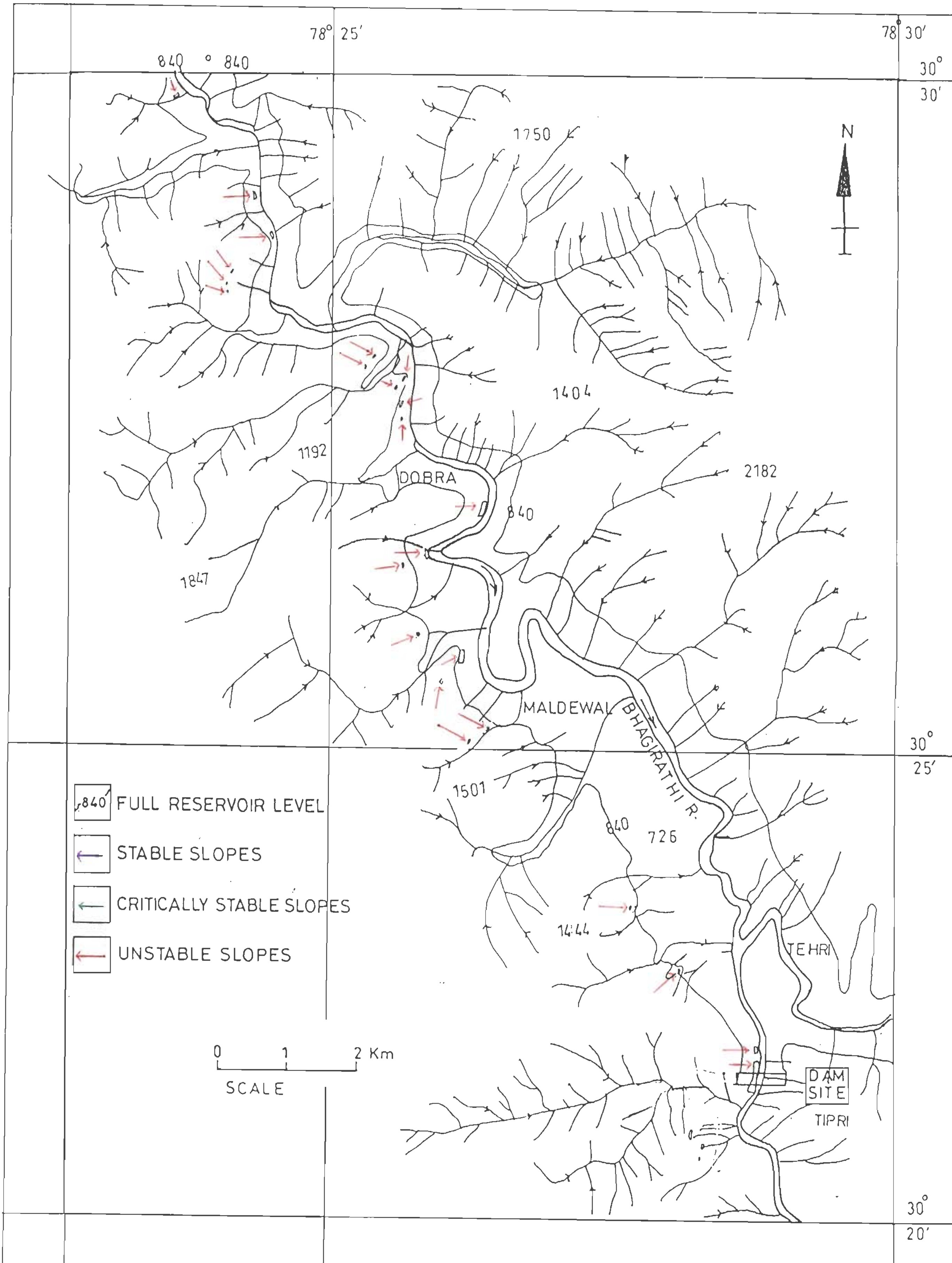


Fig. 4.18 Stability of Slopes Under 'Dynamic and Wet' Condition (For Plane Failure along Joint Plane N101°/47°, Bhagirathi Valley)

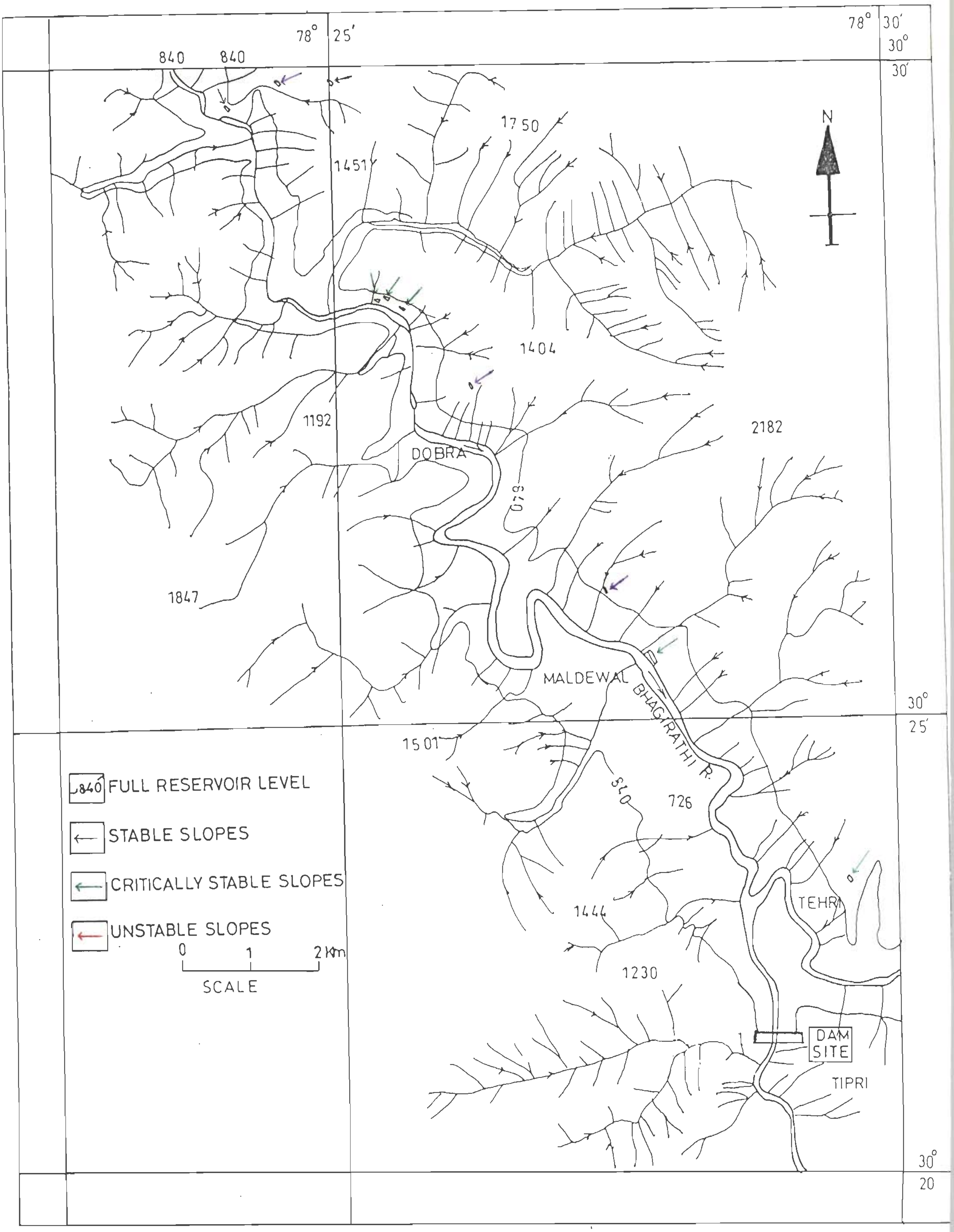


Fig. 4.19 Stability of Slopes Under 'Static and Wet' Condition (For Plane Failure along Joint Plane N224°/57°, Bhagirathi Valley)

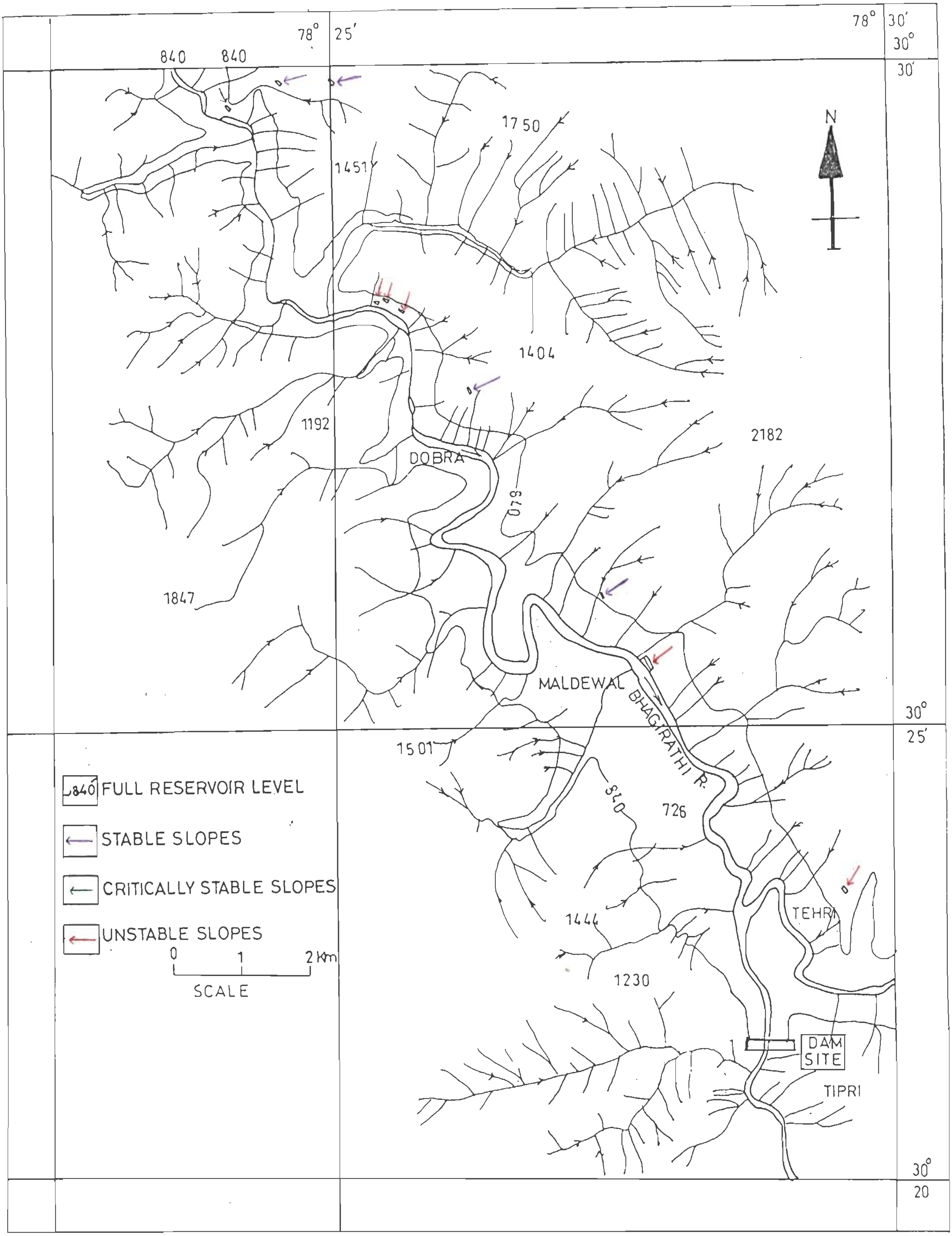


Fig. 4.20 Stability of Slopes Under 'Dynamic and Wet' Condition (For Plane Failure along Joint Plane N224°/57°, Bhagirathi Valley)

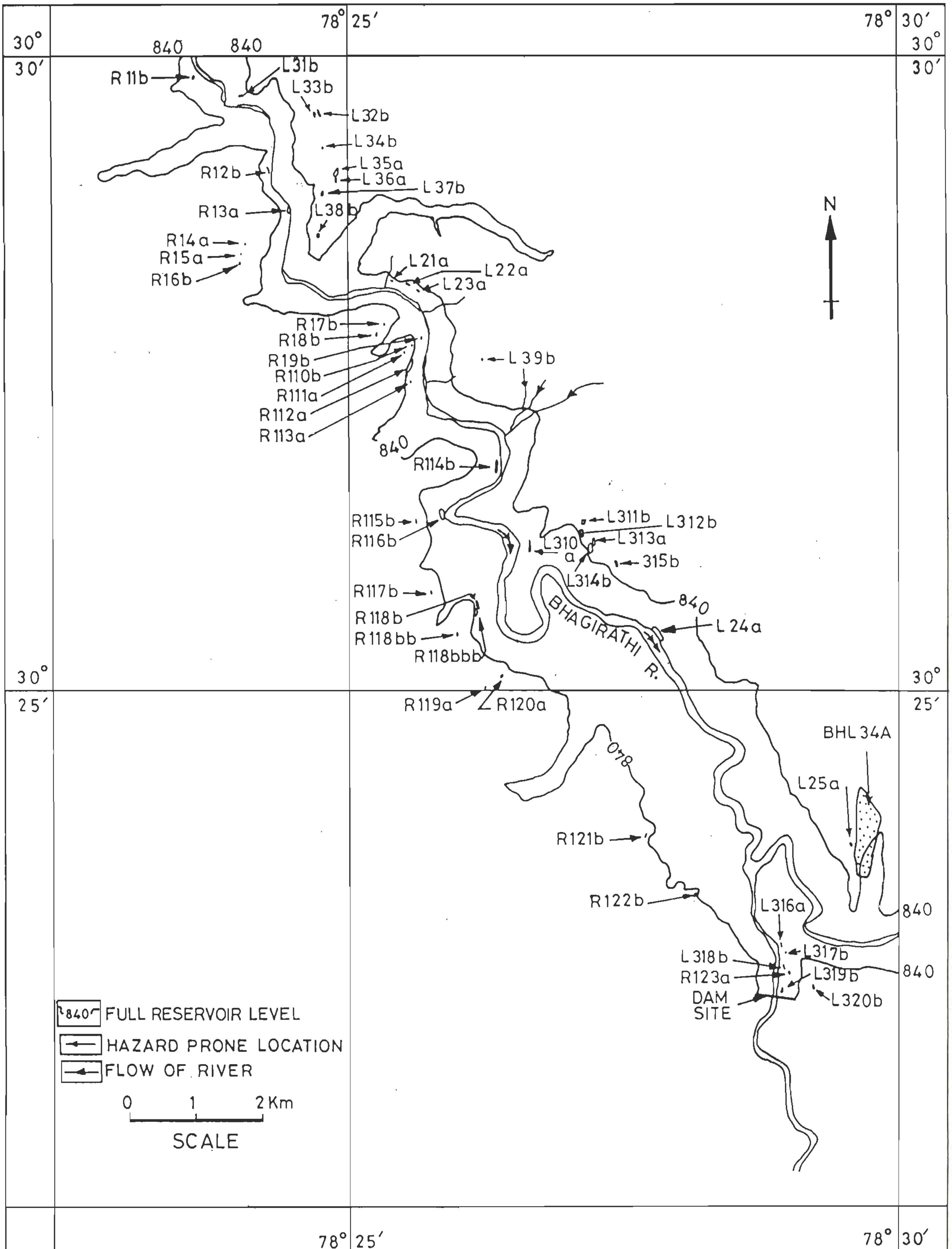


Fig. 4.21 Landslide Hazard Prone Location Map of the Area (Bhagirathi Valley)

have been identified as against one by conventional approach in Bhagirathi valley. Out of these 72 slopes, 20 are potential wedge failure and 52 are potential plane failure slopes. Results obtained by calculation of Factor of Safety of all the potential failure slopes show that all potential wedge failures are stable even under worst possible condition (dynamic and wet). Out of 52 potential plane failures, 43 are unstable (i.e. 23 possible slides on right bank and 20 on left bank). All these slide are plane failures except the slope BHL 34 A. Field observations confirm the results obtained by new approach. In Bhagirathi valley most of the slides (unstable slopes) are located near Bhaldgaon, Raolakot and Bhaldiyana villages.

4.3 BHILANGNA VALLEY

4.3.1 Bhilangna Valley (Between Tipri and Dewal Village)

The general trend of structural discontinuities (Fig. 4.22) for area of study pertaining to Bhilangna valley (between Tipri and Dewal village) is as follows :

	DISCONTINUITY	ORIENTATION	
		Dip Direction (In Degree)	Dip Amount (In Degree)
1.	Foliation	N216	38
2.	Joint Set J_1	N199	46
3.	Joint Set J_2	N110	79

4.3.2 Application of Markland Test

Structural discontinuities and friction circle corresponding to angle of internal friction has been plotted on equal area stereonet (Fig. 4.23). For identification of potential plane failure following joint planes have been considered :

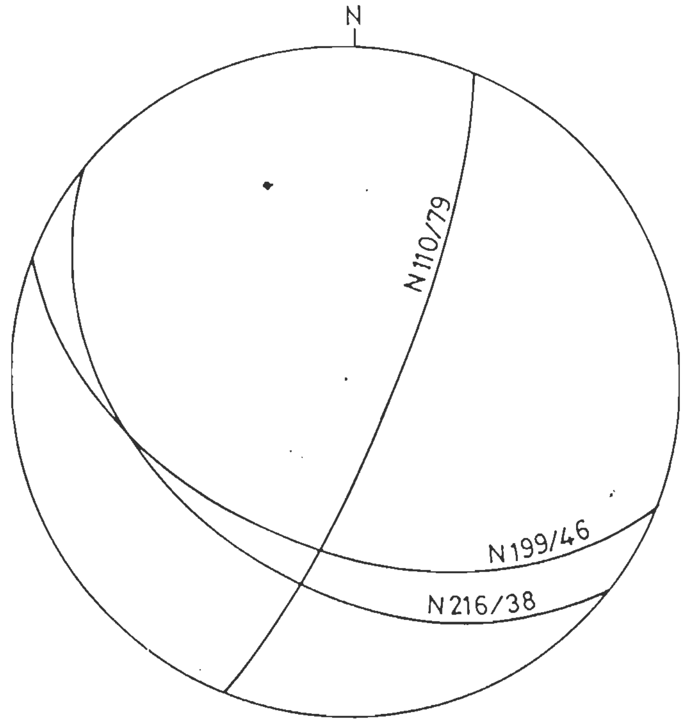


Fig. 4.22 General pattern of discontinuities in area of study (Bhilangna Valley, between Tipri and Dewal)

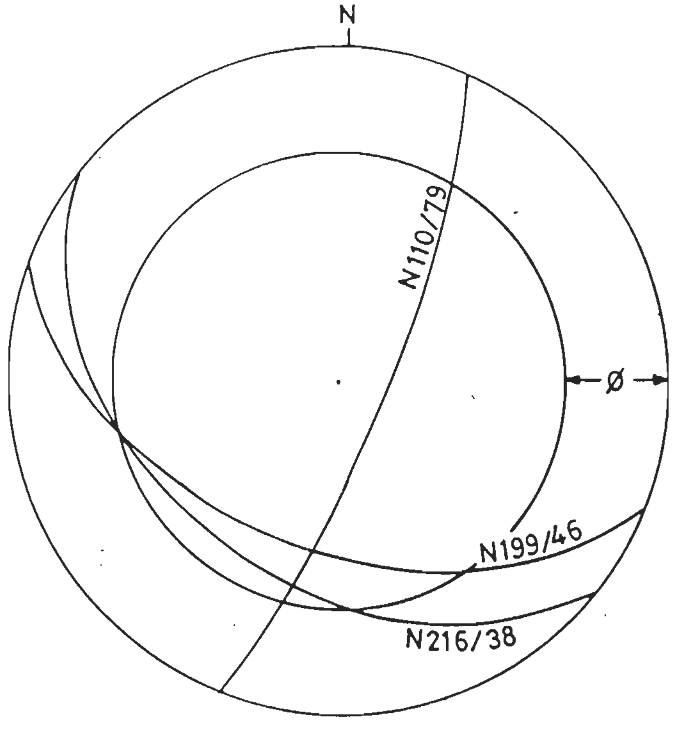


Fig. 4.23 Application of Markland Test
(Bhilangna Valley, Between Tipri and Dewal)

(i) N110^0/79^0

(ii) N216^0/38^0

(iii) N199^0/46^0

For identification of potential wedge failure following pair of joint planes have been considered :

(i) N110^0/79^0 and 216^0/38^0

(ii) N199^0/46^0 and N110^0/79^0

4.3.3 Plane Failure Analysis

(a) For joint plane N216^0/38^0 following sets of conditions have been established by applying Markland test :

(i) Slope direction should be between N196^0 to N236^0

(ii) Slope angle should be greater than 38^0

Direction of sliding is N 216° and angle of sliding is 38°. No cross section in area of study satisfies above set of conditions. So, there is no case of potential failure with reference to plane N216°/38^0. Hence, no further stability analysis needs to be carried out.

(b) For joint plane N199°/46^0 following set of conditions are there :

(i) Slope direction should be between N179° to N219°

(ii) Slope angle should be greater than 46^0

Direction of sliding is N 199° and angle of sliding is 46°. In this case also no cross section in area of study satisfies above set of condition. So, no further analysis has been taken up.

(c) For joint plane N110°/79^0 following set of conditions have been determined by applying Markland test :

(i) Slope direction should be between N90° to N130°

(ii) Slope angle should be greater than 79°

Direction of sliding is N 199° and angle of sliding is 46°. Results are same as in previous two cases . Hence, it can be established that no cross section can be considered for potential plane failure.

4.3.4 Wedge Failure Analysis

(a) Here is the formation of wedge by intersection of joint planes N199°/46° and N110°/79°.

Following set of conditions were established by applying Markland test :

(i) Slope direction should be between N168° to N208°.

(ii) Slope angle should be greater than 45°.

Direction of sliding is N118° and angle of sliding is 45°. No cross section in the study area satisfies above set of conditions. So, there is no case of potential wedge failure with reference to wedge formed by joint planes N199°/46° and N110°/79°. So, further stability analysis for wedge failure has not been carried out.

(b) There is a formation of another wedge by intersection of joint planes N110°/79° and N216°/38°. Following sets of conditions have been determined by applying Markland test :

(i) Slope direction should be between N171 ° to N211 °.

(ii) Slope angle should be greater than 35°.

Direction of sliding is N191° and angle of sliding is 35°. Only cross section BRR18 (Table 4.6) satisfies the above set of conditions. So, stability analysis for wedge failure has been carried out for cross section BRR18.

Table 4.6: Application of Markland Test for wedge formed by joint planes N 110°/79°and N 216°/38° (Bhilangna valley)

M.O.F.	WEDGE				
JOINT PLANES	N 110°/79° & N 216°/38°				
CONDITIONS FOR MARKLAND TEST	Slope direction should be between N 171° - N 211° & Slope angle should be >35°				
SERIAL NUMBER	CROSS SECTIONS	IF CONDITIONS FOR MARKLAND TEST SATISFIES	SERIAL NUMBER	CROSS SECTIONS	IF CONDITIONS FOR MARKLAND TEST SATISFIES
1.	BRR1	NO	19.	BRR19	NO
2.	BRR2	NO	20.	BRR19	NO
3.	BRR3	NO	21.	BRR21	NO
4.	BRR4	NO	22.	BRR22	NO
5.	BRR5	NO	23.	BRR23	NO
6.	BRR6	NO	24.	BRR24	NO
7.	BRR7	NO	25.	BRR25	NO
8.	BRR8	NO	26.	BRR26	NO
9.	BRR9	NO	27.	BRR27	NO
10.	BRR10	NO	28.	BRR28	NO
11.	BRR11	NO	29.	BRR29	NO
12.	BRR12	NO	30.	BRR30	NO
13.	BRR13	NO	31.	BRR31	NO
14.	BRR14	NO	32.	BRR32	NO
15.	BRR15	NO	33.	BRR33	NO
16.	BRR16	NO	34.	BRR34	NO
17.	BRR17	NO	35.	BRR35	NO
18.	BRR18	YES			

M.O.F. : Mode of Failure

Stereoplot of wedge failure analysis (Fig. 4.24) has been used to derive input data for calculation of Factory of Safety (Table 4.2). Factor of Safety has been calculated for various conditions such as 'static and dry', 'static and wet', 'dynamic and dry', and 'dynamic and wet'.

Results obtained by calculation of Factor of Safety indicate that slope is stable under 'static and dry' and 'dynamic and dry'. Slope is critically stable under 'static and wet' but unstable under 'dynamic and wet' condition.

4.3.5 Bhilangna Valley (Between Dewal and Ghonti Village)

The general trend of structural discontinuities for area of study pertaining to Bhilangna valley (between Dewal village and Ghonti Village) is as follows :

	DISCONTINUITY	ORIENTATION	
		Dip Direction (In Degree)	Dip Amount (In Degree)
1.	Bedding Joint	N161	75
2.	Joint Set J_1	N71	78
3.	Joint Set J_2	N212	66

The general trend of joint sets for the area of study pertaining to Bhilangna valley (between Dewal and Ghonti village) is shown in Fig. 4.25.

4.3.6 Application of Markland Test

Joint planes and friction circle corresponding to angle of internal friction has been plotted on equal area stereonet (Fig. 4.25A). For identification of potential plane failure following joint planes have been considered :

(i) $N71^0/78^0$

(ii) $N212^0/66^0$

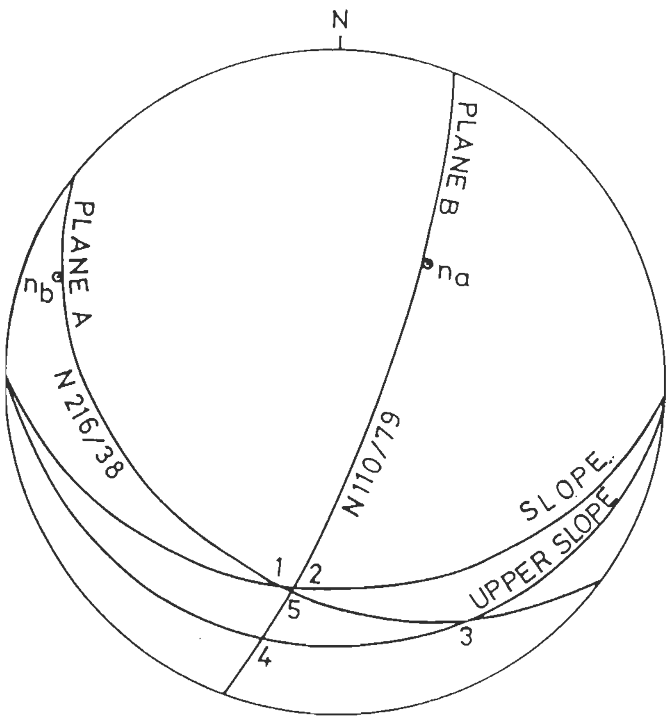


Fig. 4.24 Stereoplot of Wedge Failure Analysis for Cross Section BRR18 (Bhilangna Valley)

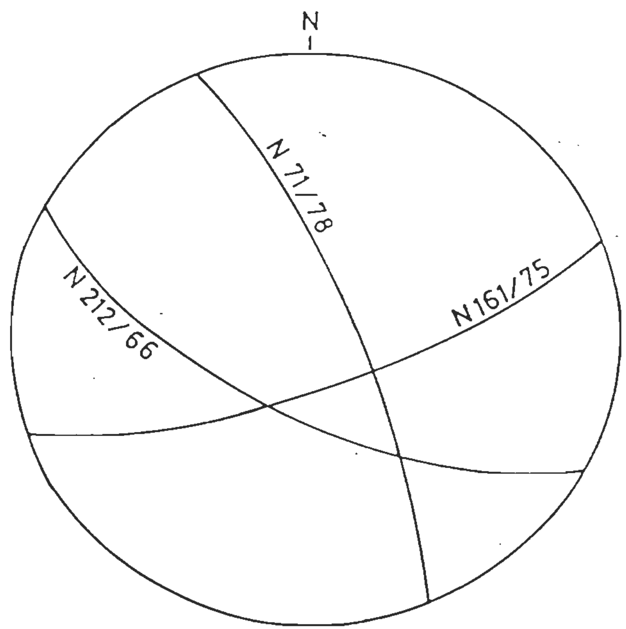


Fig. 4.25 General Pattern of Discontinuities in Area of Study (Bhilangna Valley, Between Dewal and Ghonti)

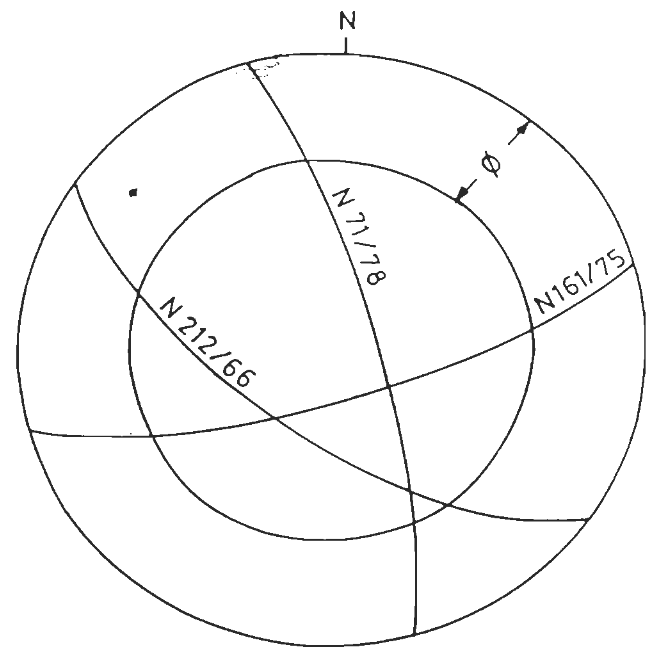


Fig. 4.25A Application of Markland Test (Bhilangna Valley, Between Dewal and Ghonti)

(iii) $N161^0/75^0$

4.3.7 Wedge Failure

For identification of potential wedge failure following pairs of joint planes have been considered :

(i) $N71^0/78^0$ and $212/66^0$

For joint plane $N71^0/78^0$ following set of condition were established by applying Markland test :

(i) Slope direction should be between $N51^0$ to $N91^0$

(ii) Slope angle should be greater than 78^0

Direction of sliding is $N71^0$ and angle of sliding is 78^0. No cross section in area of study satisfies above set of conditions. So, there is no case of potential failure with reference to plane $N71^0/78^0$. Hence, no further stability analysis needs to be carried out.

4.3.8 Plane Failure

(a) For joint plane $N212^0/66^0$ following set of conditions are there :

(i) Slope direction should be between $N192^0$ to $N232^0$

(ii) Slope angle should be greater than 66^0

Direction of sliding is $N212^0$ and angle of sliding is 66^0. Here also no cross section in area of study satisfies above set of condition. So, no further analysis has been taken up.

(b) For joint plane $N161^0/75^0$ following set of conditions have been determined by applying Markland test :

(i) Slope direction should be between $N141^0$ to $N181^0$

(ii) Slope angle should be greater than 75^0

Direction of sliding is N161^0 and angle of sliding is 75^0. Results are same as in previous two cases. Hence it can be established that no cross section can be considered for potential plane failure.

4.3.9 Wedge Failure Analysis

(a) There is a formation of wedge by intersection of joint planes N71^0/78^0 and N212^0/66^0. Following set of conditions have been established by applying Markland test.

(i) Slope direction should be between N125^0 to N165^0.

(ii) Slope angle should be greater than 47°.

Direction of sliding is N145^0 and angle of sliding is 47^0. Two cross sections in area of study satisfy above set of conditions (Table 4.7). So, there are two case of potential wedge failures with reference to wedge formed by joint planes N71^0/78° and N212^0/66°.

Therefore, stability analysis for wedge failure has been carried out for cross sections BRR24 and BRR30.

Stereoplot of wedge failure analysis (Fig. 4.26 & Fig 4.27) has been used to derive input data for calculation of Factory of Safety (Table 4.2). Factor of Safety has been calculated for various conditions such as 'static and dry', 'static and wet', 'dynamic and dry', and 'dynamic and wet'.

Results obtained by calculation of Factor of Safety indicate that slope BRR30 is stable under 'static and dry', 'static and wet' and 'dynamic and dry'. Slope is critically stable under 'dynamic and wet' condition while slope BRR24 is stable under 'static and dry', 'static and wet' and 'dynamic and dry' conditions. This slope is critically stable under 'dynamic and wet' condition.

Table 4.7: Application of Markland Test for wedge formed by joint planes N 71°/78° and N 212°/66° (Bhilangna valley)

M.O.F.	WEDGE				
JOINT PLANES	N 71°/78° & N 212°/66°				
CONDITIONS FOR MARKLAND TEST	Slope direction should be between N 125°-N 165° & Slope angle should be >47°				
SERIAL NUMBER	CROSS SECTIONS	IF CONDITIONS FOR MARKLAND TEST SATISFIES	SERIAL NUMBER	CROSS SECTIONS	IF CONDITIONS FOR MARKLAND TEST SATISFIES
1.	BRR1	NO	19.	BRR19	NO
2.	BRR2	NO	20.	BRR19	NO
3.	BRR3	NO	21.	BRR21	NO
4.	BRR4	NO	22.	BRR22	NO
5.	BRR5	NO	23.	BRR23	NO
6.	BRR6	NO	24.	BRR24	YES
7.	BRR7	NO	25.	BRR25	NO
8.	BRR8	NO	26.	BRR26	NO
9.	BRR9	NO	27.	BRR27	NO
10.	BRR10	NO	28.	BRR28	NO
11.	BRR11	NO	29.	BRR29	NO
12.	BRR12	NO	30.	BRR30	YES
13.	BRR13	NO	31.	BRR31	NO
14.	BRR14	NO	32.	BRR32	NO
15.	BRR15	NO	33.	BRR33	NO
16.	BRR16	NO	34.	BRR34	NO
17.	BRR17	NO	35.	BRR35	NO
18.	BRR18	NO			

M.O.F. : Mode of Failure

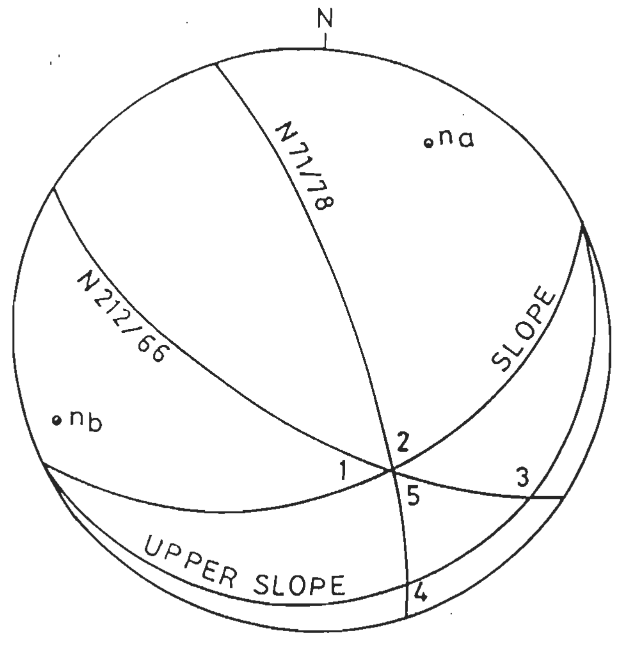


Fig. 4.26 Stereoplot of Wedge Failure Analysis for Cross Section BRR24 (Bhilaugna Valley)

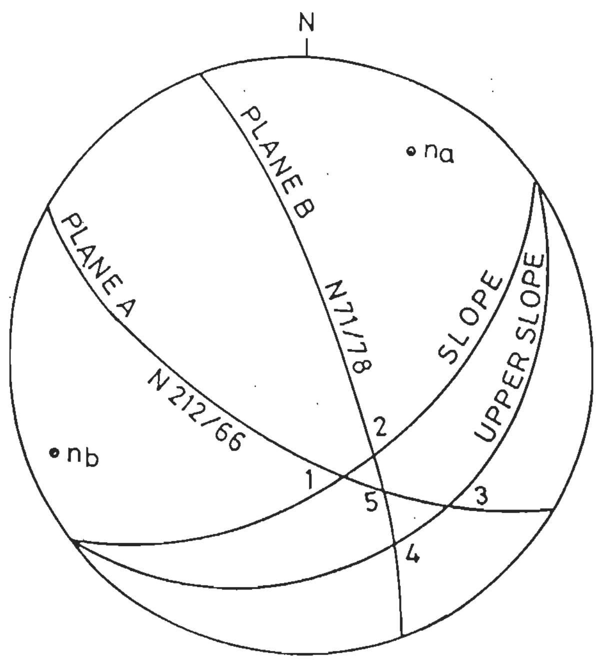


Fig. 4.27 Stereoplot of Wedge Failure Analysis for Cross Section BRR30 (Bhilaugna Valley)

(b) Two more wedges have been formed by intersection of following joint planes :

(i) N212°/66° and N161°/75°

(ii) N71°/78° and N161°/75°

Since line of intersection in the case of these wedges is very steep and no such steep slope exists in study area, conditions of Markland test are not satisfied here. Therefore, stability analysis for these two wedges need not to be carried out. Hazard map of the area shows one unstable slope BRR18 (Fig 4.27A).

4.3.10 Application of Comprehensive Approach

4.3.11 Bhilangna Valley (Between Tipri and Dewal Village)

4.3.12 Wedge Failure Analysis

(a) For wedge the formed by intersection of N199^0/46^0 and N216^0/38^0, set of conditions, for potential failure as obtained by Markland test are shown in Fig. 4.28 .

Direction of sliding is N 251^0 and angle of sliding is 32^0. There are total 5 slopes satisfying the above conditions. Stability analysis for all these slopes has been carried out (Fig. 4.29). Results obtained by calculation of Factor of Safety show that all slopes are stable under 'Static and dry', 'Static and wet', 'dynamic and dry' and 'dynamic and wet' conditions (Table 4.8). These results are shown in the form of a map (Fig. 4.30).

(b) For another wedge, formed by intersection of joint planes N216^0/38^0 and N110^0/79^0, set of conditions for potential failure as determined by Markland test are shown in Fig. 4.28.

Direction of sliding is N191^0 and angle of sliding is 35^0. There are total 6 slopes satisfying the above conditions. Stability analysis for all these slope has been carried out (Fig. 4.31). Here, as in previous case slopes are stable under various adverse conditions (Table 4.9A, Table 4.9B and Table 4.9C). These results are shown in the form of a map (Fig.4.32).

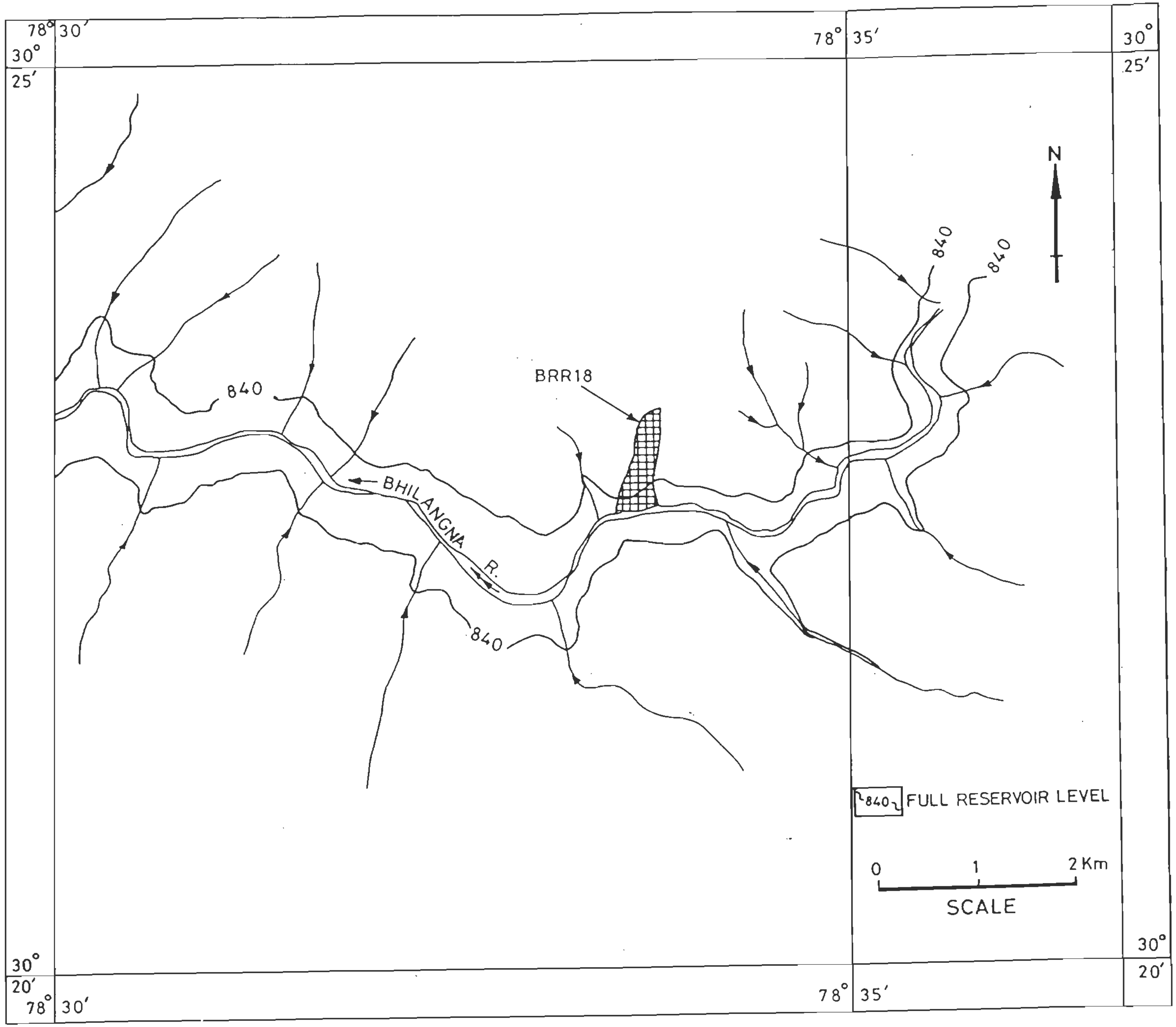


Fig. 4.27A Hazard Map (Bhilangna Valley)

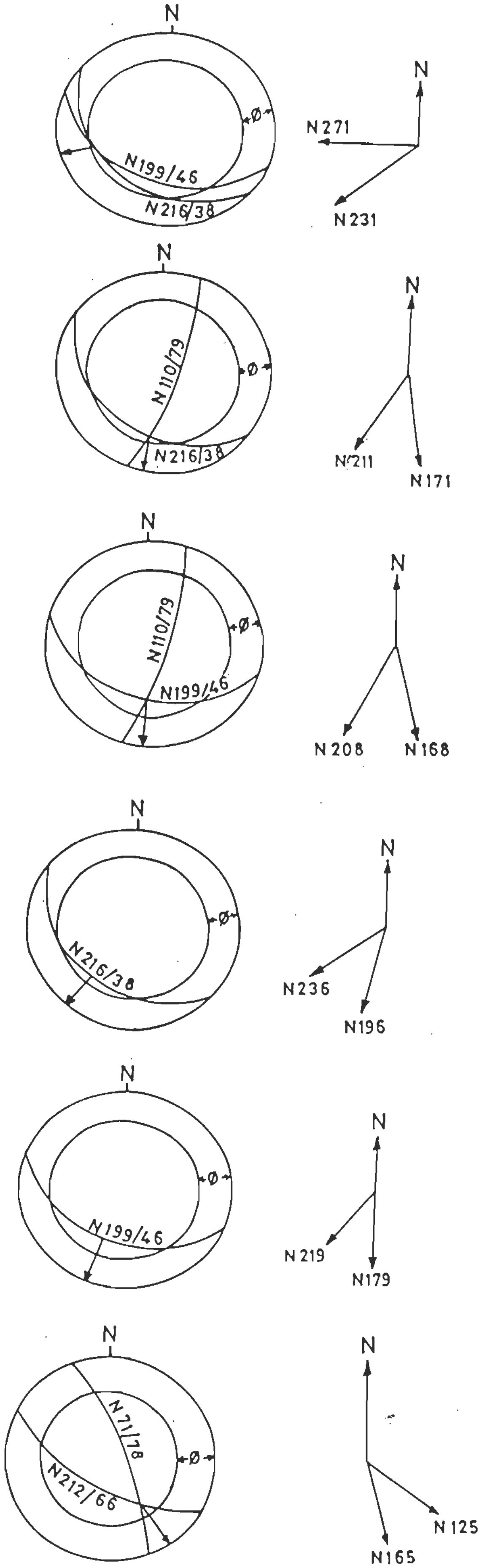


Fig. 4.28 Set of conditions for potential failure obtained by Markland test (Bhilangna Valley)

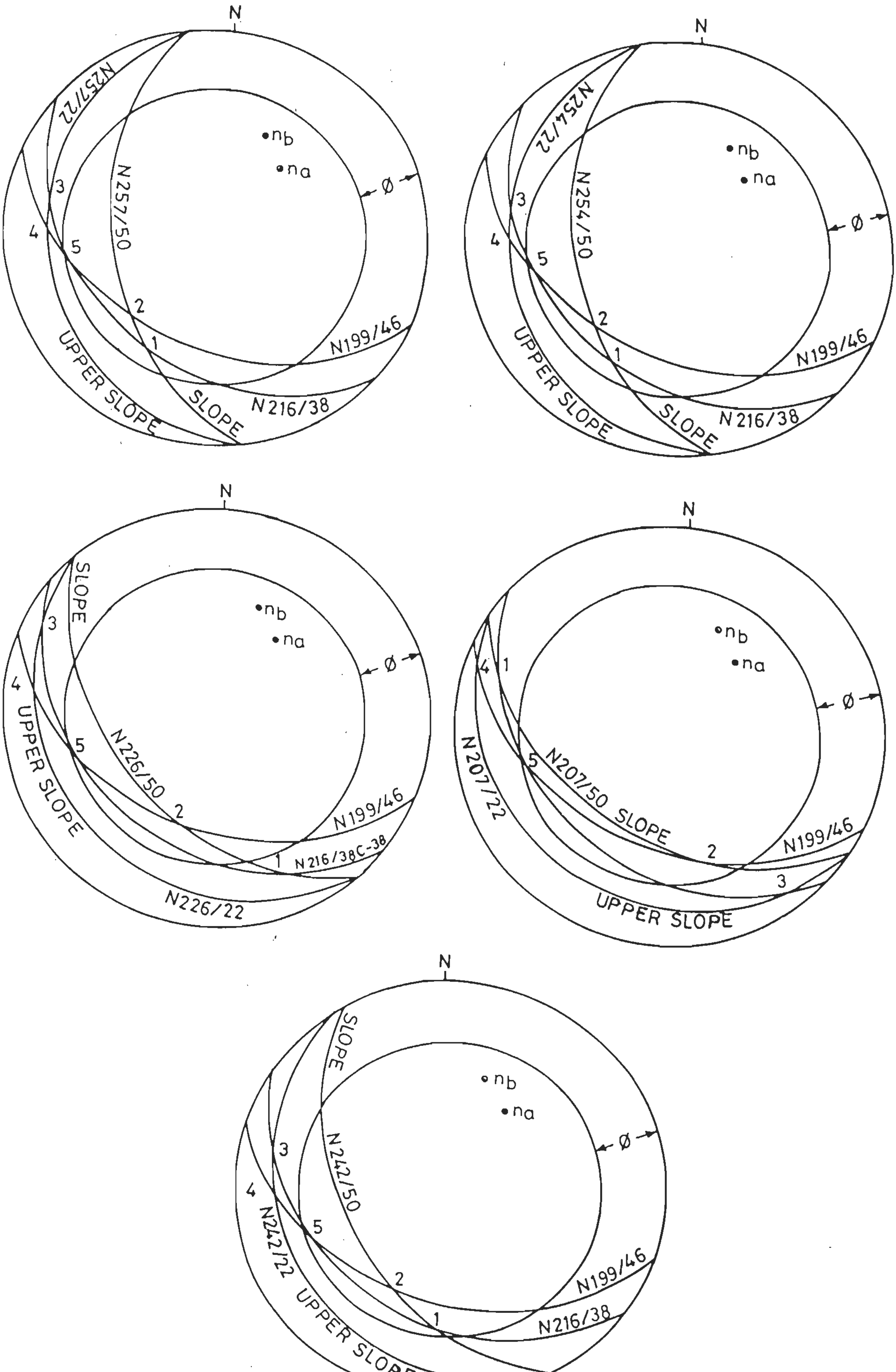


Fig. 4.29 Stereoplots for Stability Analysis of Slopes (For Wedge Formed by Intersection of Joint Planes N199°/46° and N216°/38°, Bhilangna Valley)

Table 4.8 Factor of Safety for various conditions (for wedge formed by intersection of joint planes $N199^0/46^0$ and $N216^0/38^0$, Bhilangna valley)

MOF			Wedge	Wedge	Wedge	Wedge	Wedge
LCNS			Bhilangana Valley	Bhilangana Valley	Bhilangana Valley	Bhilangana Valley	Bhilangana Valley
JOINT PLANES			N199/46 & N216/38 (Case 5)	N199/46 & N216/38 Case 2	N199/46 & N216/38 Case 3	N199/46 & N216/38 Case 4	N199/46 & N216/38 Case 1
SLOPE			N 242/50	N 254/50	N/226/50	N 207/50	N 257/50
Upper Slope			N 242/22	N 254/22	N 226/22	N 207/22	N 257/22
Ψ_a			38	38	38	38	38
Ψb			46	46	46	46	46
Ψ_5			32	32	32	32	32
$\theta_{na.nb}$			14	14	14	14	14
$\theta_{2.4}$			54	46	73	118	45
$\theta_{4.5}$			20	16	25	41	17
$\theta_{2.na}$			84	85	81	77	85
$\theta_{1.3}$			86	67	132	138	62
$\theta_{3.5}$			32	27	45	108	24
$\theta_{1.nb}$			102	100	104	83	100
ϕ			30	30	30	30	30
g			2500	2500	2500	2500	2500
C			15000	15000	15000	15000	15000
h			38	38	38	38	38
FOS	SC	DRY	7.1	9.3	5.5	6.3	7.9
		WET	5.6	7.2	4.4	5.0	6.1
	DC	DRY	6.3	8.5	4.7	5.5	7.0
		WET	4.7	6.4	3.6	4.2	5.3

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

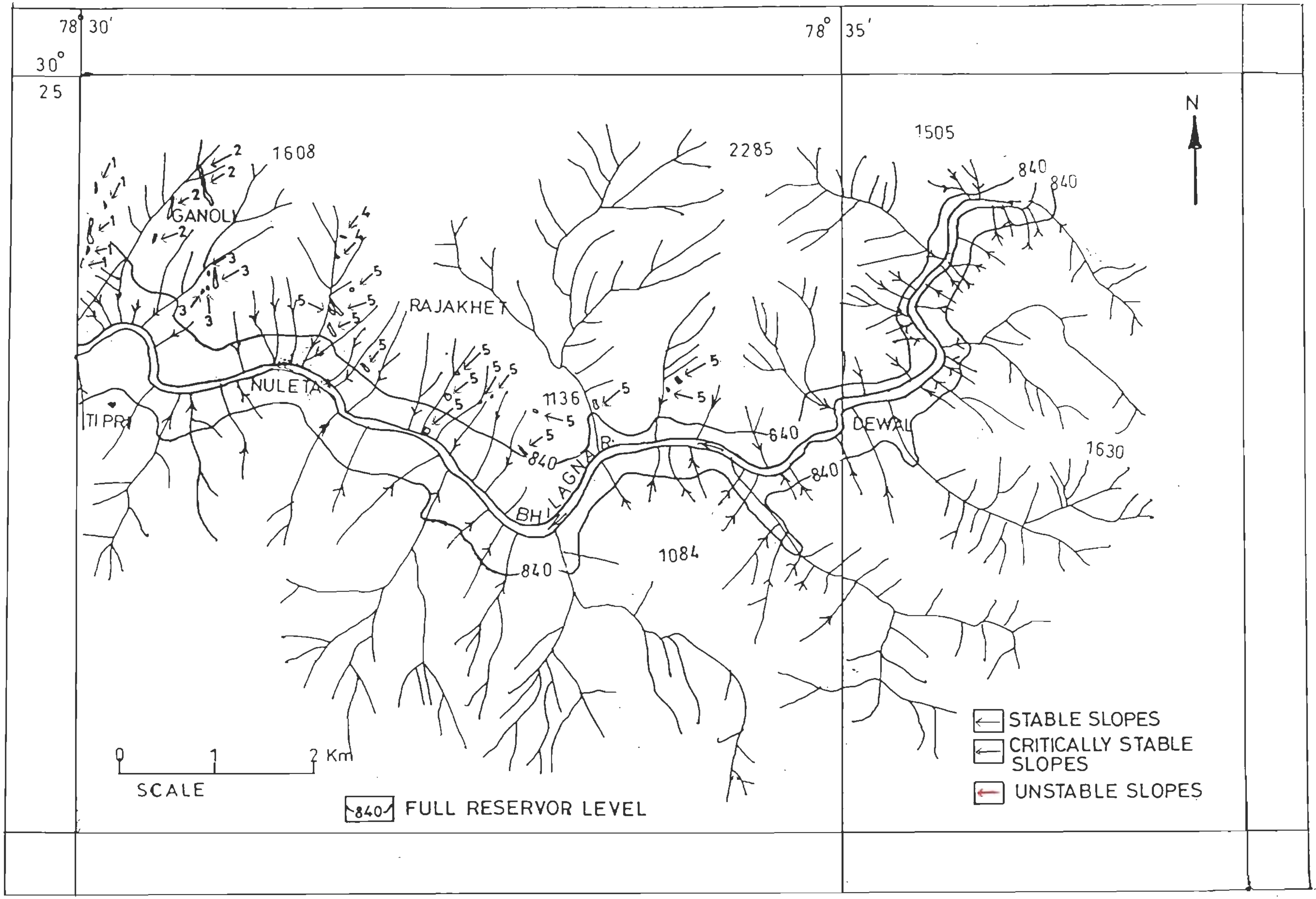


Fig. 4.30 Stability of Slopes Under 'Dynamic and Wet' Condition (For Wedge Formed by Intersection of Joint Planes N199°/46° and N216°/38°, Bhilangna Valley)

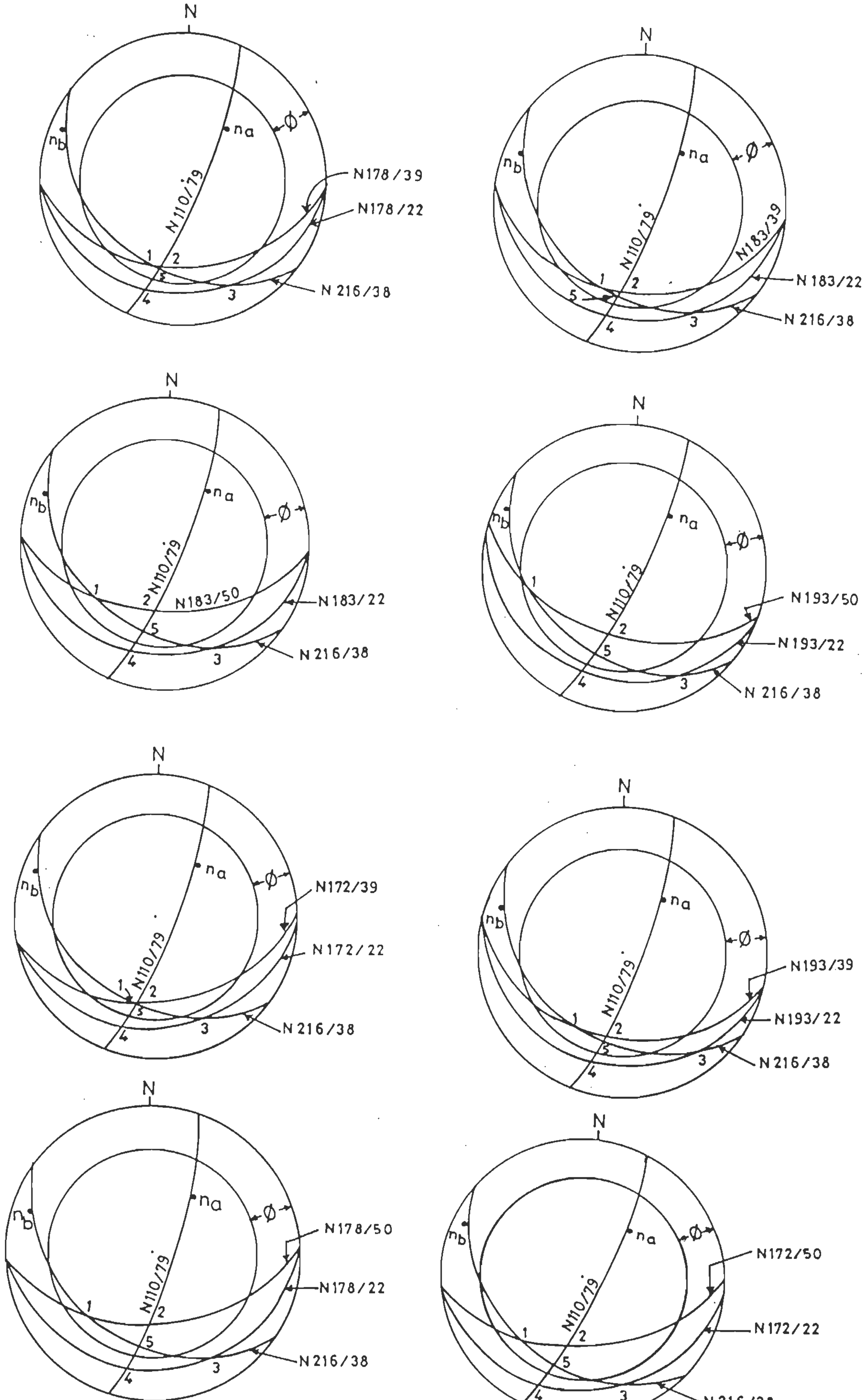


Fig. 4.31 Stereoplots for Stablility analysis of slopes (For Wedge formed by intersection of joint planes N216/38° and N110/79°, Bhilangna Valley)

Table 4.9A Factor of Safety for various conditions (for wedge formed by intersection of joint planes 'N216^0/38^0 and N110^0/79^0' and 'N110^0/79^0 and N199^0/46^0', Bhilangna valley)

MOF			wedge	wedge	wedge	wedge	wedge	wedge
LCNS			1, BLN	4, BLN	2A, BLN	2, BLN	1, BLN	1, BLN
JOINT PLANES			N 216/38 & N 110/79	N 216/38 & N 110/79	N 110/79 & N 199/46	N 110/79 & N 199/46	N 110/79 & N 199/46	N 110/79 & N 199/46
SLOPE			N 178/39	N 172/50	N 193/50	N 183/50	N 178/50	N 178/50
Upper Slope			N 178/22	N 172/22	N 193/39	N 183/22	N 178/22	N 178/39
Ψ_a			38	38	46	46	46	46
Ψb			79	79	79	79	79	79
Ψ_5			35	35	45	45	45	45
$\theta_{na.nb}$			92	92	82	82	82	82
$\theta_{2.4}$			18	18	11	21	31	12
$\theta_{4.5}$			16	16	6	16	26	7
$\theta_{2.na}$			88	88	86	86	86	87
$\theta_{1.3}$			45	38	106	88	81	42
$\theta_{3.5}$			38	35	58	68	67	28
$\theta_{1.nb}$			84	88	43	72	76	77
ϕ			30	30	30	30	30	30
g			2500	2500	2500	2500	2500	2500
C			15000	15000	15000	15000	15000	15000
h			24.5	24.5	37.5	22	22	37.5
FOS	SC	DRY	32.1	46.2	13.8	18.5	17.8	19.0
		WET	27.2	39.1	10.6	16.0	15.4	14.6
	DC	DRY	31.0	45.1	13.0	17.7	17.1	18.3
		WET	26.1	38.0	9.8	15.2	14.6	13.8

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

Table 4.9B Factor of Safety for various conditions (for wedge formed by intersection of joint planes N216^0/38^0 and N110^0/79^0, Bhilangna valley)

MOF			wedge	wedge	wedge
LCNS			2, BLN	3, BLN	3, BLN
JOINT PLANES			N 216/38 & N 110/79	N 216/38 & N 110/79	N 216/38 & N 110/79
SLOPE			N 183/50	N 193/50	N 193/39
Upper Slope			N 183/22	N 193/22	N 193/22
Ψ_a			38	38	38
Ψ_b			79	79	79
Ψ_5			35	35	35
$\theta_{na.nb}$			92	92	92
$\theta_{2.4}$			30	29	18
$\theta_{4.5}$			15	14	14
$\theta_{2.na}$			76	77	87
$\theta_{1.3}$			76	98	62
$\theta_{3.5}$			41	47	47
$\theta_{1.nb}$			56	41	76
ϕ			30	30	30
g			2500	2500	2500
C			15000	15000	15000
h			31.5	31.5	24.5
FOS	SC	DRY	7.0	7.1	22.3
		WET	5.8	5.8	18.9
	DC	DRY	6.0	6.0	21.2
		WET	4.7	4.8	17.9

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and Plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

Table 4.9C Factor of Safety for various conditions (for wedge formed by intersection of joint planes N216^0/38^{0}and N110^0/79^0, Bhilangna valley)

MOF			wedge
LCNS			4A, BLN
JOINT PLANES			N 216/38 & N 110/79
SLOPE			N 172/50
Upper Slope			N 172/22
Ψ_a			38
Ψ_b			79
Ψ_5			35
$\theta_{na.nb}$			92
$\theta_{2.4}$			30
$\theta_{4.5}$			15
$\theta_{2.na}$			77
$\theta_{1.3}$			60
$\theta_{3.5}$			36
$\theta_{1.nb}$			67
ϕ			30
g			2500
C			15000
h			31.5
FOS	SC	DRY	8.0
		WET	6.6
	DC	DRY	7.0
		WET	5.5

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree) ; $\theta_{na.nb}$ - Angle between poles of plane A and plane B

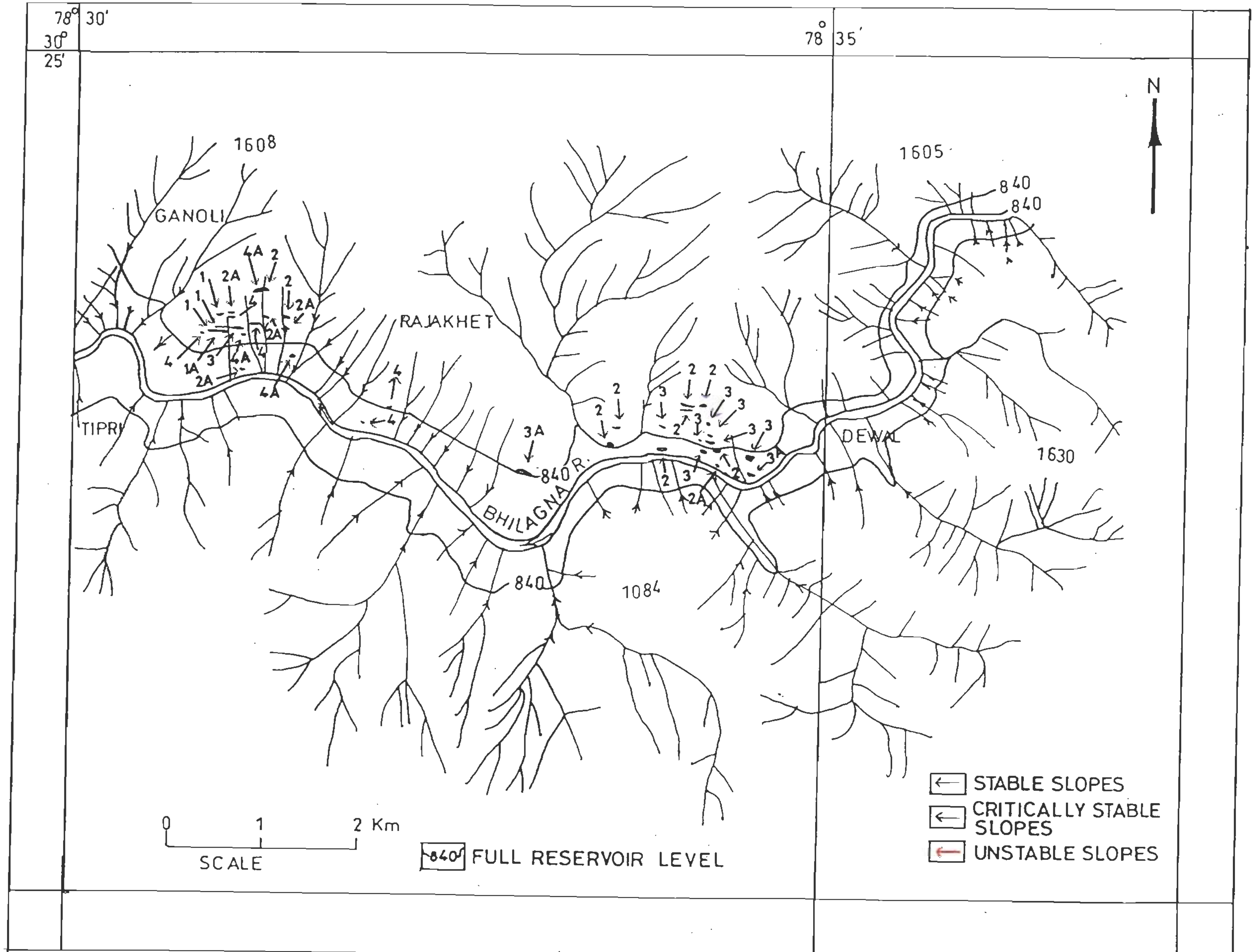


Fig. 4.32 Stability of Slopes Under 'Dynamic and Wet' Condition (For Wedge Formed by Intersection of Joint Planes N216°/38° and N110°/79°, Bhilangna Valley)

(c) For the wedge formed by intersection of joint planes N110^0/79^0 and N199^0/46^0, set of conditions for potential failure as determined by Markland test are shown in Fig. 4.28. Direction of sliding is N118^0 and angle of sliding is 45^0. There are total 7 slopes satisfying the above conditions. Stability analysis for all these slopes has been carried out (Fig. 4.33A and Fig. 4.33B). Here, as in previous case, slopes are stable under various adverse conditions (Table 4.10 and Table 4.9A). Results are shown in the form of a map (Fig. 4.34).

4.3.13 Plane Failure Analysis

(a) For joint plane N216^0/38^0, conditions for potential failure are shown in Fig. 4.28. Direction of sliding is N216^0 and angle of sliding is 38^0. There are total 26 slopes satisfying the above conditions. All these slopes are stable under 'static and dry' and 'static and wet' conditions, while unstable under 'dynamic and wet' condition (Table 4.11). Out of these 26 slopes, 11 slopes are critically stable and 15 slopes are stable under 'dynamic and dry' condition (Fig. 4.35 and Fig. 4.36).

(b) For joint plane N199^0/46^0, set of potential failure conditions are shown in Fig.4.28. Direction of sliding is N199^0 and angle of sliding is 46^0. There are total 14 slopes satisfying the above conditions. All these slopes are stable under various hazard prone conditions (Fig. 4.37).

4.3.14 Bhilangna Valley (Between Dewal and Ghonti Village)

For the wedge formed by intersection of N71^0/78^0 and N212^0/66^0, set of conditions, for potential failure as obtained by Markland test are shown in Fig. 4.28

Direction of sliding is N145^0 and angle of sliding is 47^0. There are total 7 slopes satisfying the above conditions. Stability analysis for all these slopes has been carried out (Fig. 4.38A and Fig. 4.38B). Results obtained by calculation of Factor of Safety show that all slopes

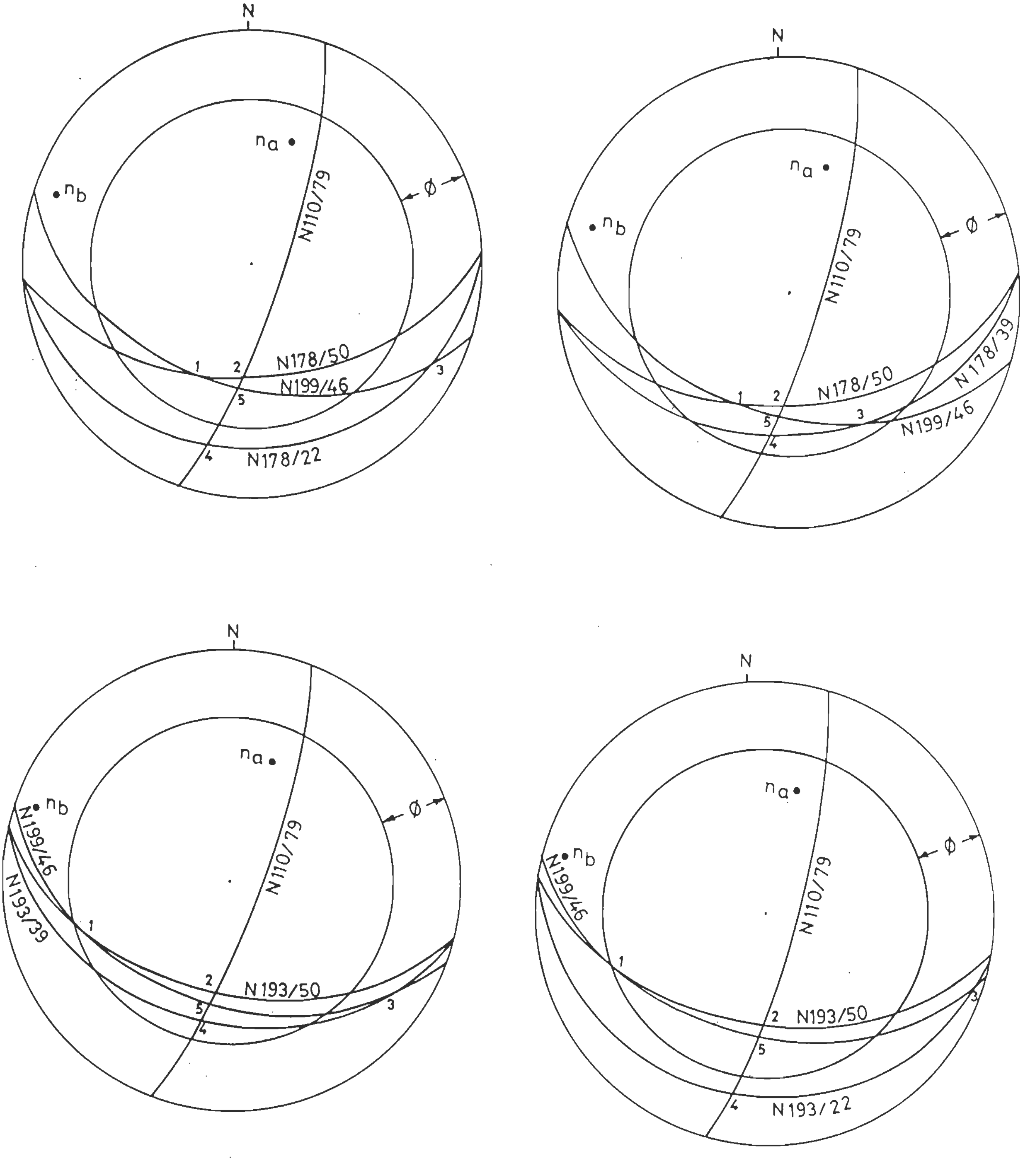


Fig. 4.33A Stereoplots for Stability Analysis of Slopes
(For Wedge Formed by Intersection of Joint Planes
N110°/79° and N199°/46°, Bhilangna Valley)

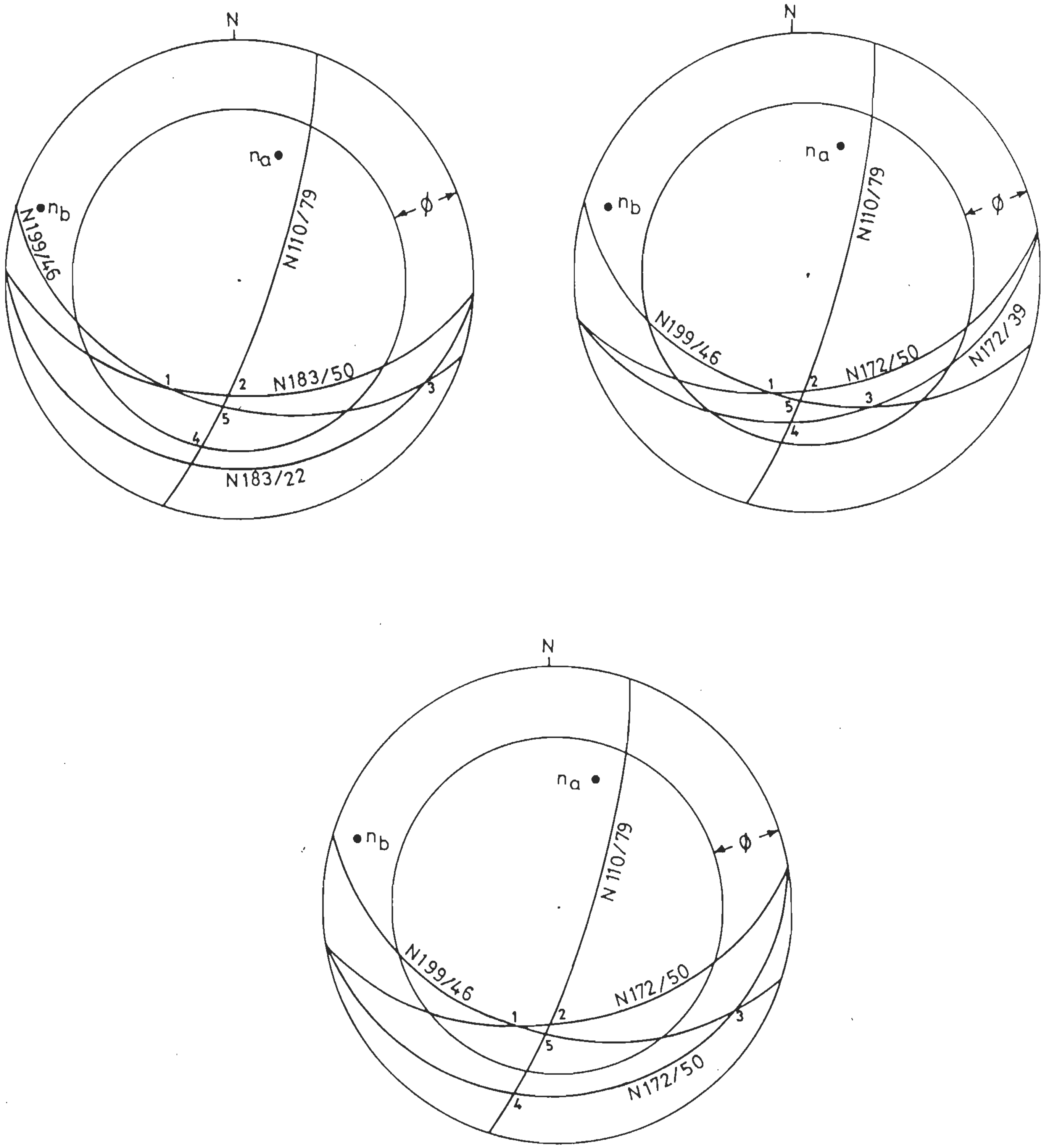


Fig. 4.33B Stereoplots for Stability Analysis of Slopes (For Wedge Formed by Intersection of Joint Planes N110°/79° and N199°/46°, Bhilangna Valley)

Table 4.10 Factor of Safety for various conditions (for wedge formed by intersection of joint planes N110^0/79^0 and N199^0/46^0, Bhilangna valley)

			wedge	wedge	wedge
MOF			wedge	wedge	wedge
LCNS			3, BLN	2B BLN	3A BLN
JOINT PLANES			N110/79 & N199/46	N110/79 & N199/46	N110/79 & N199/46
SLOPE			N 172/50	N 193/50	N 172/50
Upper Slope			N 172/22	N 193/22	N 172/39
Ψ_a			46	46	46
Ψ_b			79	79	79
Ψ_5			45	45	45
$\theta_{na.nb}$			82	82	82
$\theta_{2.4}$			30	29	13
$\theta_{4.5}$			26	24	8
$\theta_{2.na}$			88	86	87
$\theta_{1.3}$			74	128	14
$\theta_{3.5}$			64	76	25
$\theta_{1.nb}$			80	40	82
ϕ			30	30	30
g			2500	2500	2500
C			15000	15000	15000
h			22	22	37.5
FOS	SC	DRY	31.8	15.3	17.2
		WET	27.4	13.2	13.2
	DC	DRY	31.0	14.5	16.4
		WET	26.6	12.4	12.4

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m^2); g - Unit Weight of Rock (in kg/m^3); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B; BLN - Bhilangna

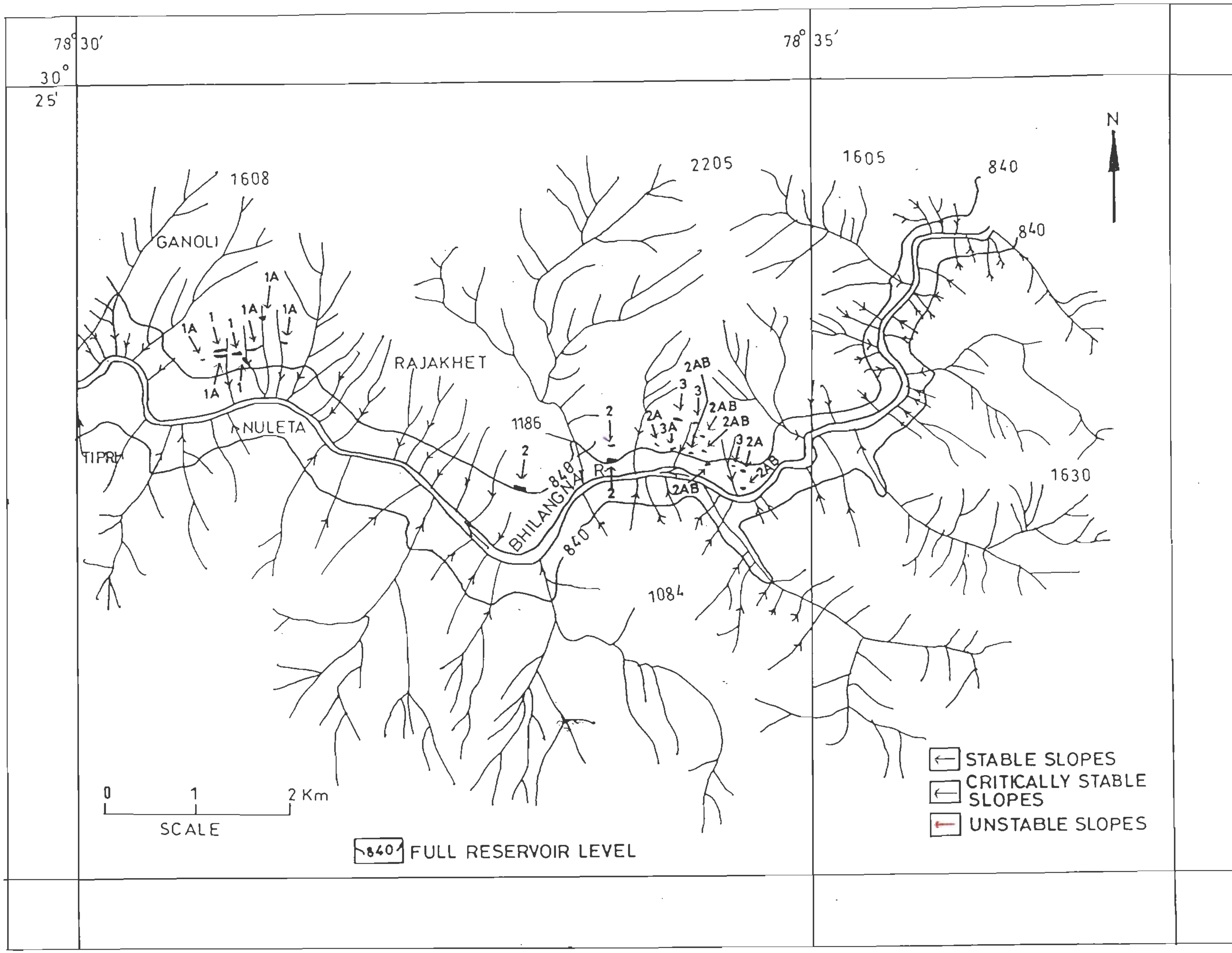


Fig. 4.34 Stability of Slopes Under 'Dynamic and Wet' Condition (For Wedge Formed by Intersection of Joint Planes N110°/79° and N199°/46°, Bhilangna Valley)

Table 4.11 Factor of Safety for various conditions (for plane failure, Bhilangna valley)

MOF			Plane	Plane	Plane	Plane
LCNS			BLN	BLN	BLN	BLN
JOINT PLANES			N216/38	N216/38	N199/46	N216/38
ψ_f			50	39	50	50
ψ_p			38	38	46	38
ϕ			30	30	30	30
H			20	20	20	20
γ			2500	2500	2500	2500
C			15000	15000	1500	15000
FOS	SC	DRY	4.3	35.8	9.7	4.3
		WET	3.6	29.1	7.9	3.6
	DC	DRY	1.1	11.6	3.5	1.1
		WET	0.9	9.3	2.8	0.9

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); H - Height of slope (in m); C - Cohesion (in kg/m^2); γ - Unit Weight of Rock (in kg/m^3); BLN - Bhilangna; ψ_f - Slope face inclination (in degree); ψ_p - Failure plane inclination (in degree)

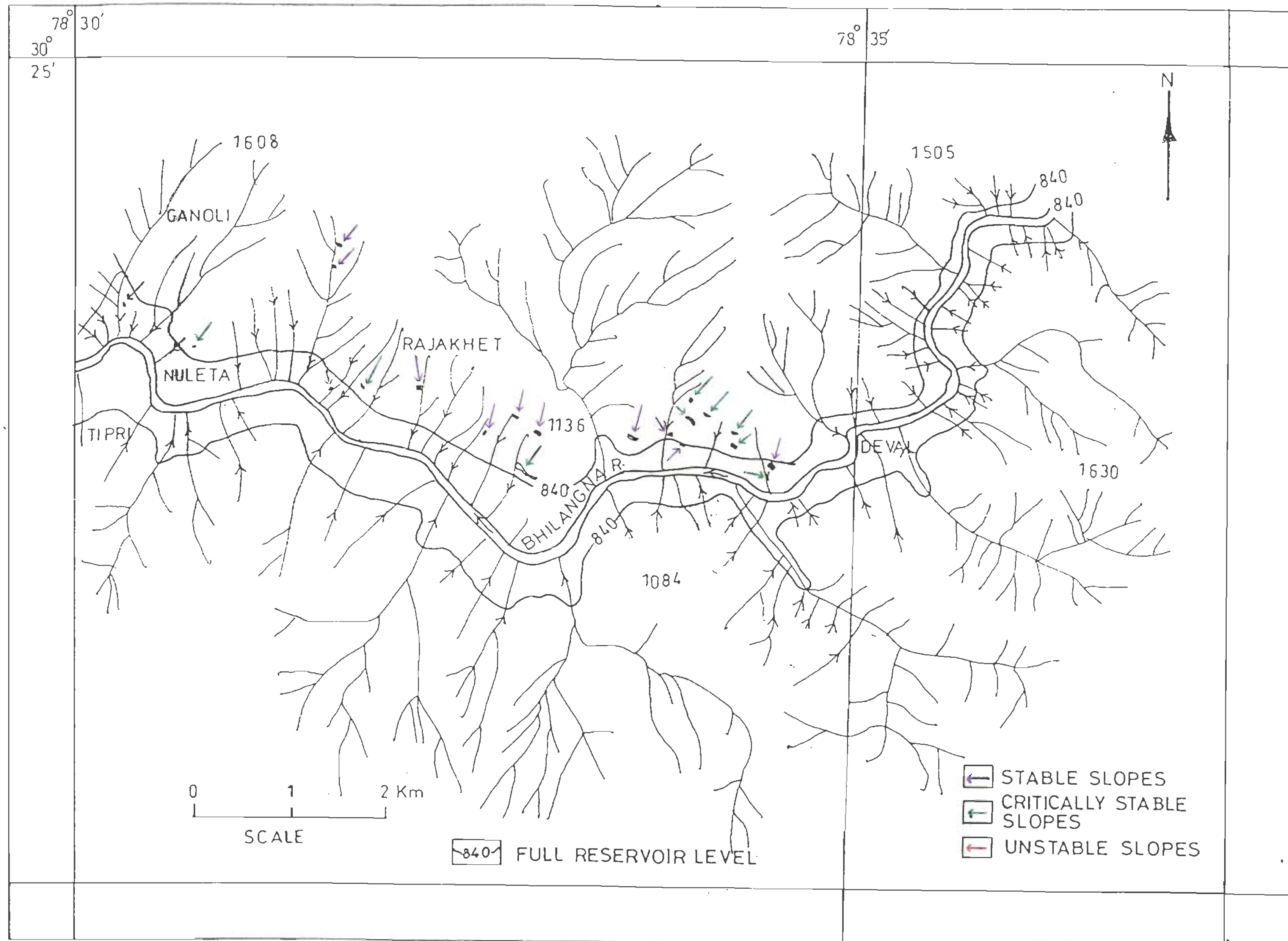


Fig. 4.35 Stability of Slopes Under 'Dynamic and Dry' Condition (For Plane Failure along Joint Plane N216°/38°, Bhilangna Valley)

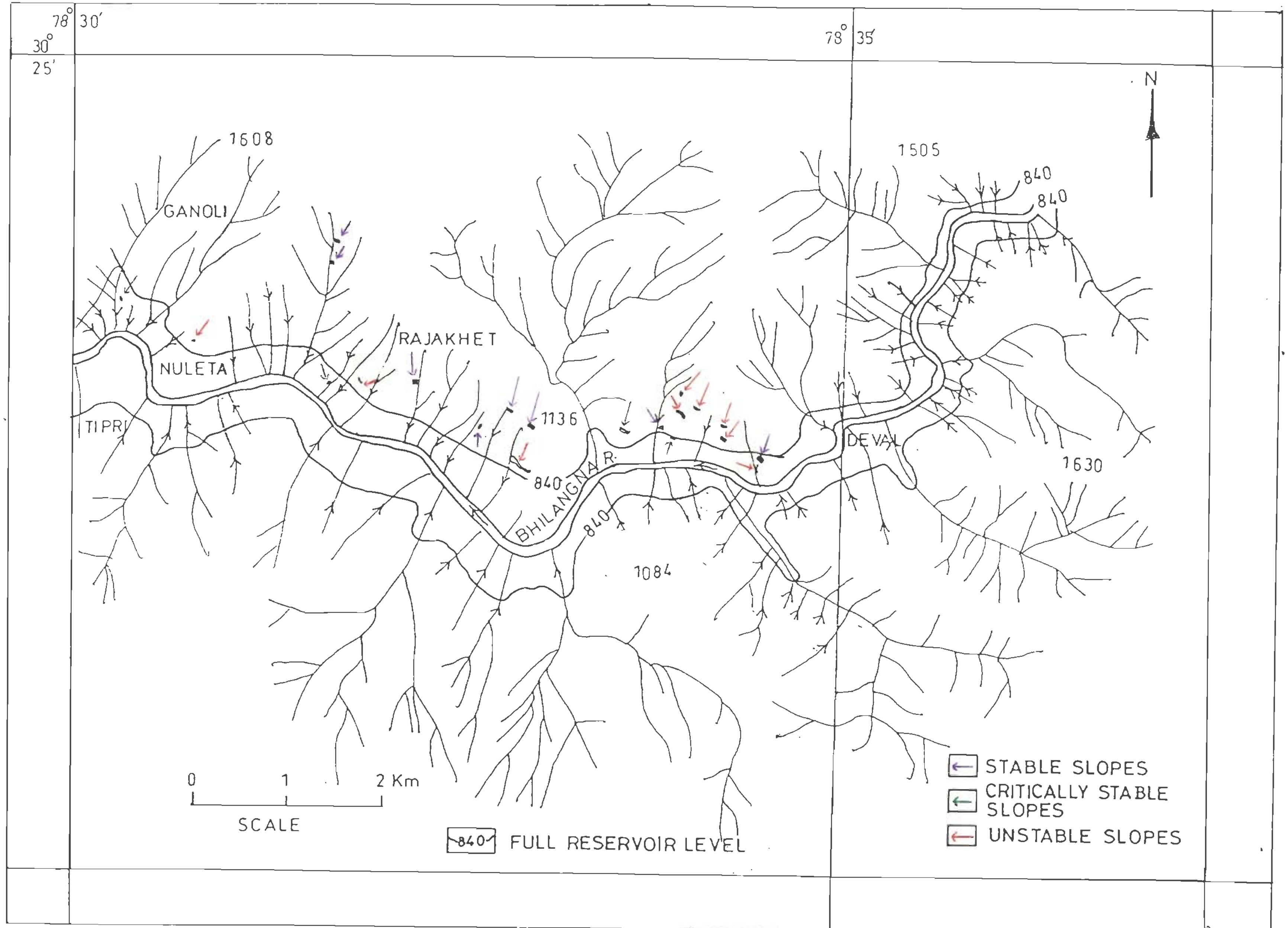


Fig. 4.36 Stability of Slopes Under 'Dynamic and Wet' Condition
(For Plane Failure along Joint Plane N216°/38°, Bhilangna Valley)

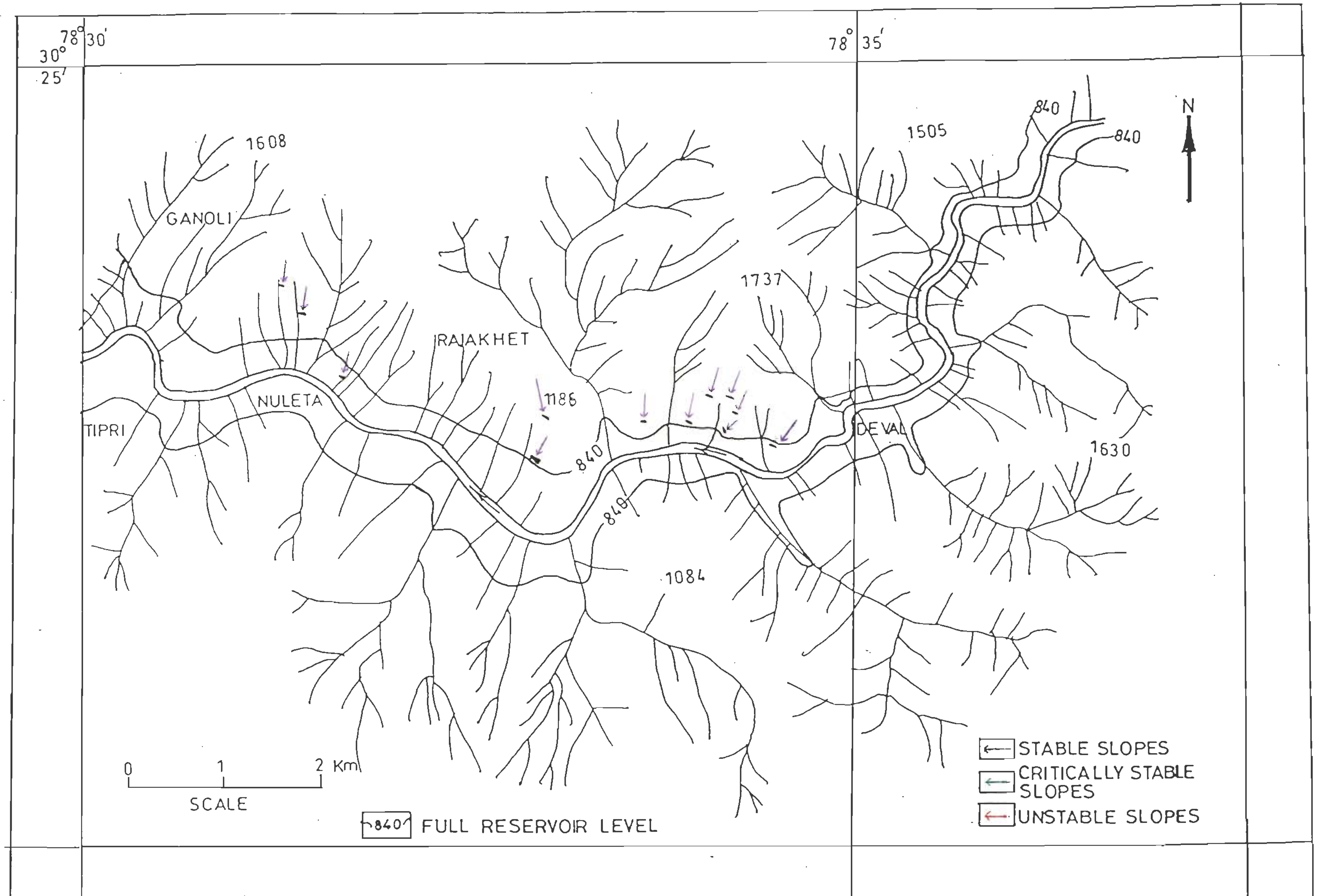


Fig. 4.37 Stability of Slopes Under 'Dynamic and Wet' Condition
(For Plane Failure along Joint Plane N199°/46°, Bhilangna Valley)

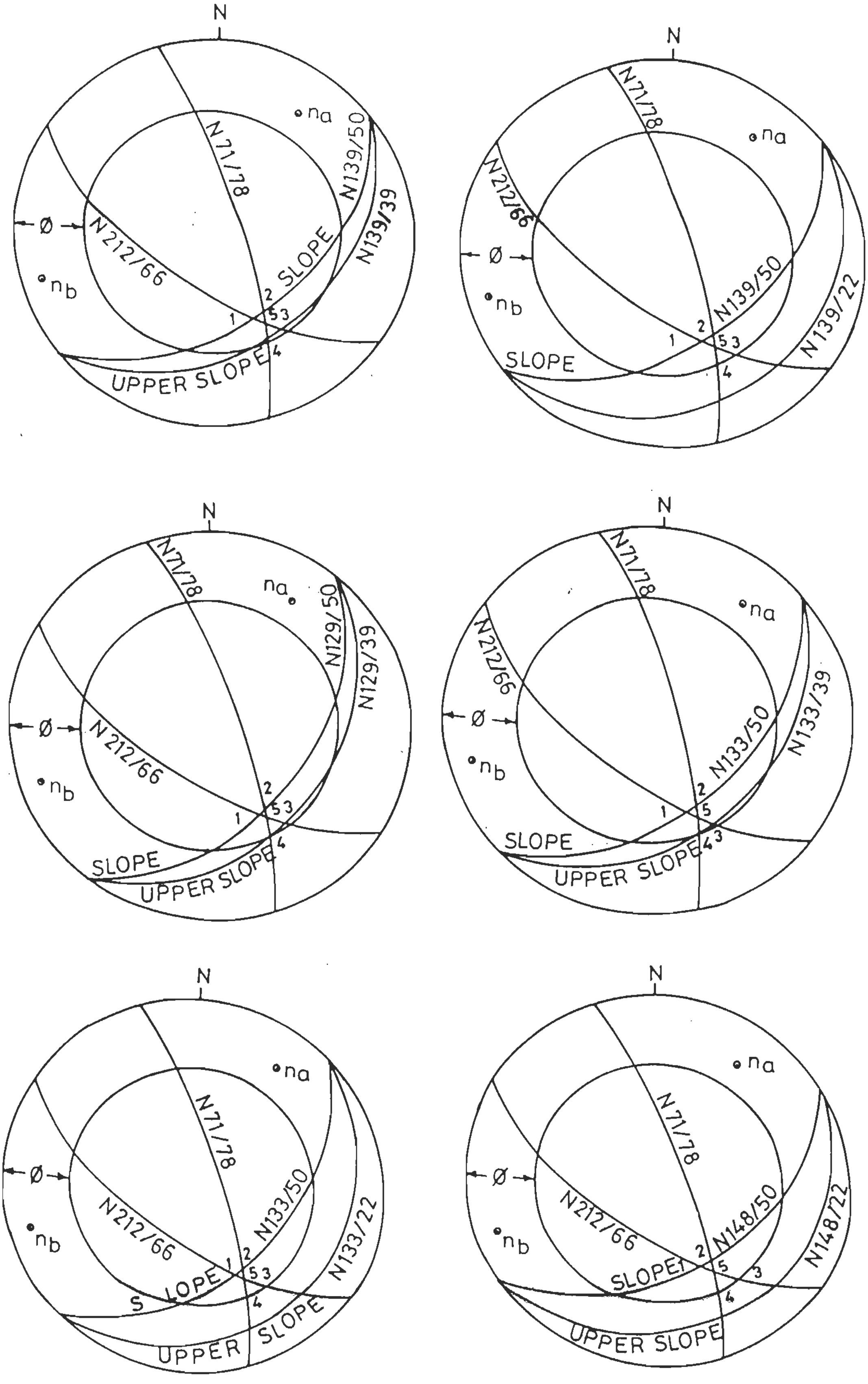


Fig. 4.38A Stereoplots for Stability Analysis of Slopes (For Wedge Formed by Intersection along Joint Planes of N71°/78° and N212°/66°, Bhilangna Valley)

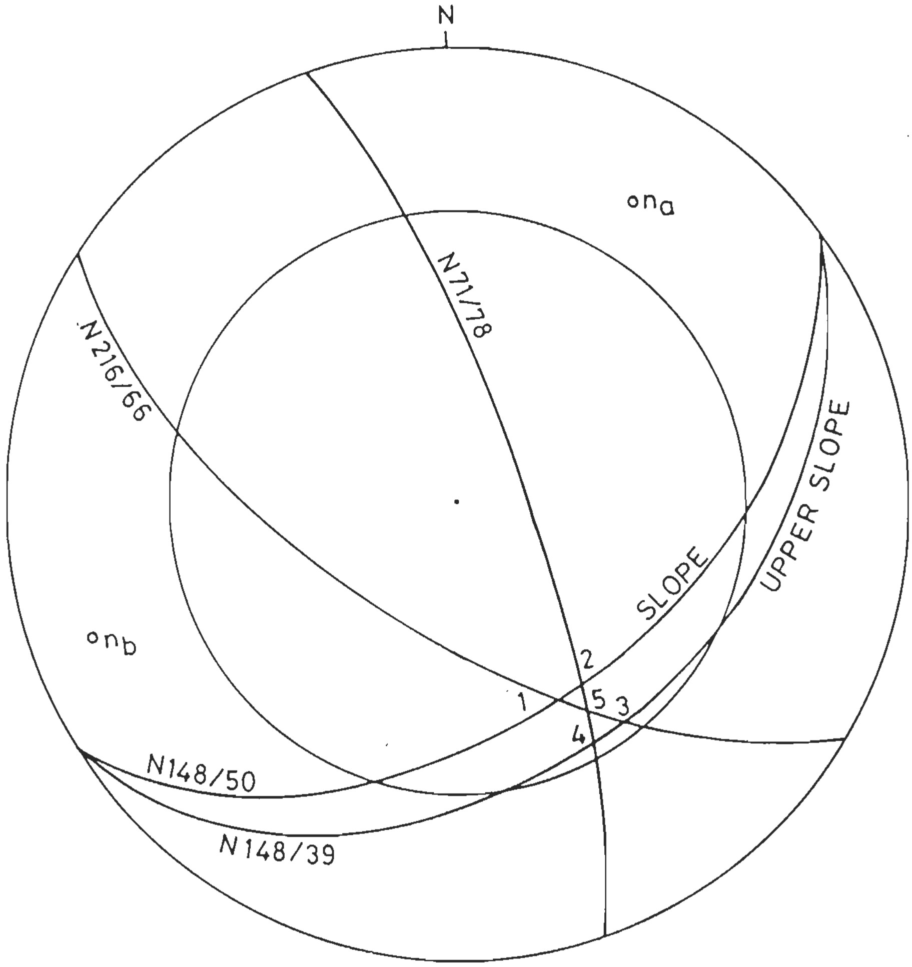


Fig. 4.38B Stereoplot for Stability Analysis of Slopes
(For Wedge Formed by Intersection along Joint Planes
of N71°/78° and N212°/66°, Bhilangna Valley)

are stable under 'Static and dry', 'Static and wet', 'dynamic and dry' and 'dynamic and wet' conditions (Table 4.12). These results are shown in the form of a map (Fig. 4.39).

4.3.15 Landslide Hazard Map (Bhilangna Valley)

For the preparation of Landslide Hazard map (Bhilangna Valley), potential failure slopes having F.O.S. less than 1, have been chosen. In Bhilangna valley there are 65 potential failure slopes as per the new approach (as against three by conventional approach). Of these 65 potential failure slopes, 25 are wedge failures and 40 plane failures. All potential wedge failures have FOS > 1.5 and therefore, under all conditions are stable. Out of 40 potential plane failures, 11 are unstable (FOS < 1). All of them are located on right bank (Fig. 4.40). There is no slide on left bank of Bhilangna valley. Field observations confirm the results obtained by new approach.

4.4 APPLICATION OF GIS

Digital Elevation Model (DEM) prepared by using GIS package ILWIS, shows that area of study consists of number of steep slopes. Vector map of the study area has been prepared by digitization of contours (Plate 4.1). After digitization followed by rasterization and interpolation, DEM has been prepared (Plate 4.5). Landuse and land cover maps indicate that a large part of the study area consists of sparse vegetation (Plate 4.3 and Plate 4.4). Drainage map of the study area shows dendritic drainage pattern (Plate 4.2).

4.5 SUMMARY

There are 57 facets on right bank and 36 facets on left bank of Bhagirathi valley. Similarly, there are 32 facets on right bank and 31 facets on left bank of Bhilangna valley. Cross

Table 4.12 Factor of Safety for various conditions (for wedge formed by intersection of joint planes N71°/78° and N212°/66°, Bhilangna valley)

MOF			Wedge	Wedge	Wedge	Wedge	Wedge	Wedge	Wedge
LCNS			3, BLN	2A, BLN	2A, BLN	1, BLN	1, BLN	2, BLN	3A, BLN
JOINT PLANES			N71/78 & N212/66	N71/78 & N212/66	N71/78 & N212/66	N71/78 & N212/66	N71/78 & N212/66	N71/78 & N212/66	N71/78 & N212/66
SLOPE			N148/50	N133/50	N133/50	N139/50	N139/50	N129/50	N148/50
Upper Slope			N148/39	N133/22	N133/39	N139/39	N139/22	N129/39	N148/22
Ψ_a			66	66	66	66	66	66	66
Ψb			78	78	78	78	78	78	78
Ψ_5			45	45	45	45	45	45	45
$\theta_{na.nb}$			129	129	129	129	129	129	129
$\theta_{2.4}$			12	30	12	12	30	13	30
$\theta_{4.5}$			6	26	8	7	25	9	24
$\theta_{2.na}$			86	87	87	88	88	88	86
$\theta_{1.3}$			14	31	11	13	33	12	34
$\theta_{3.5}$			8	27	7	7	27	8	28
$\theta_{1.nb}$			86	88	88	88	88	88	86
ϕ			36	36	36	36	36	36	36
g			2700	2700	2700	2700	2700	2700	2700
C			30000	30000	30000	30000	30000	30000	30000
h			37.5	22	37.5	37.5	37.5	37.5	22
FOS	SC	DRY	48.6	82.4	65.7	90.1	61.0	74.7	53.7
		WET	41.5	75.2	56.0	76.7	52.0	63.6	49.0
	DC	DRY	46.6	80.3	63.6	88.1	58.9	72.6	51.6
		WET	39.4	73.1	53.9	74.7	49.9	61.6	47.1

MOF - Mode of Failure; LCNS - Slope Locations; FOS - Factor of Safety; SC - Static Condition; DC - Dynamic condition; ϕ - Angle of internal friction (in degree); h - Height of slope (in m); C - Cohesion (in kg/m²); g - Unit Weight of Rock (in kg/m³); θ - Angle between two points on stereonet; ψ_a - Dip of the plane A; ψ_b- Dip of the plane B; ψ_5- Angle of line of intersection of plane A and plane B (in degree); $\theta_{na.nb}$ - Angle between poles of plane A and plane B

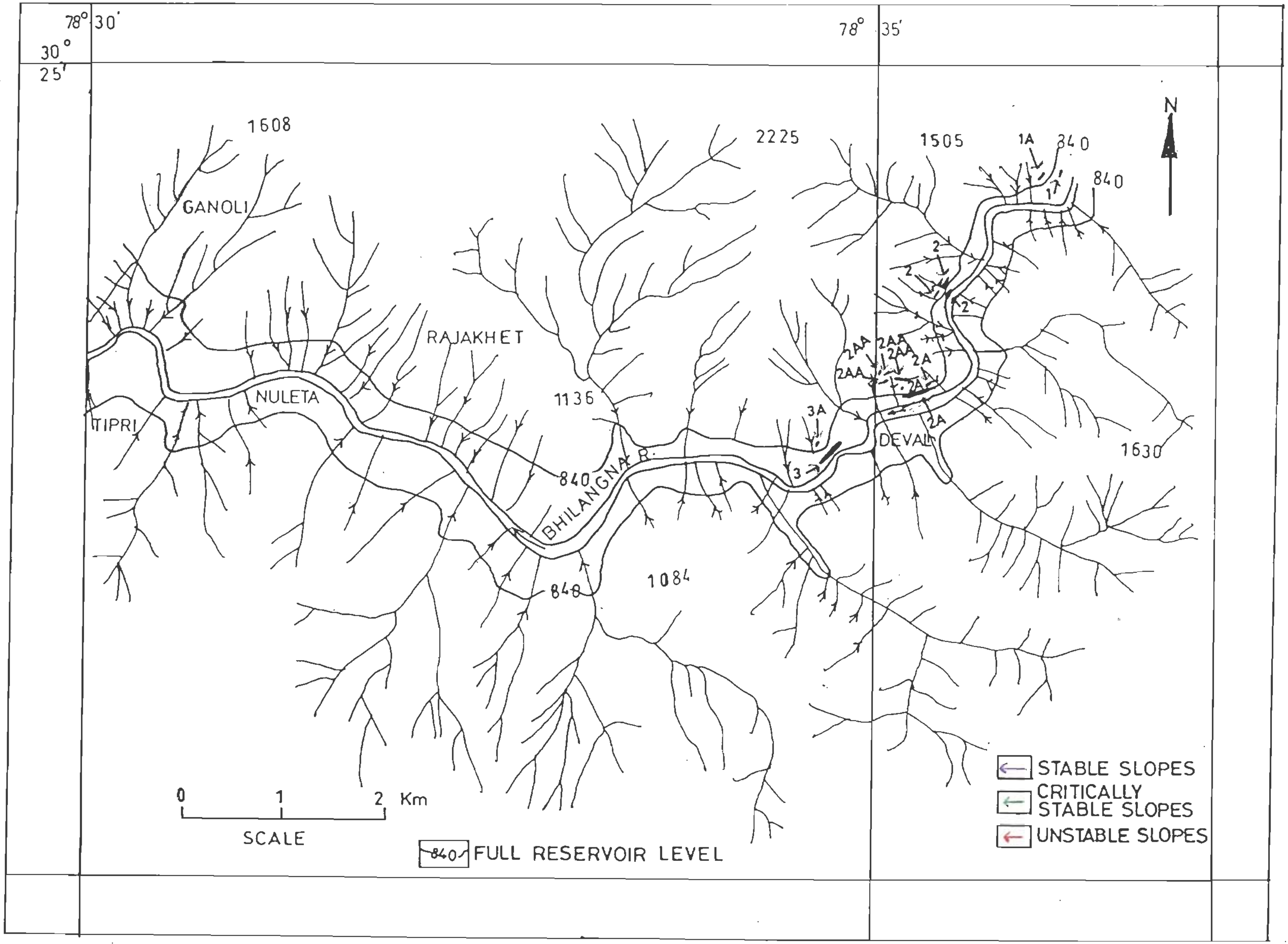


Fig. 4.39 Stability of Slopes Under 'Dynamic and Wet' Condition (For Wedge Formed by Intersection of Joint Planes N71°/78° and N212°/66°, Bhilangna Valley)

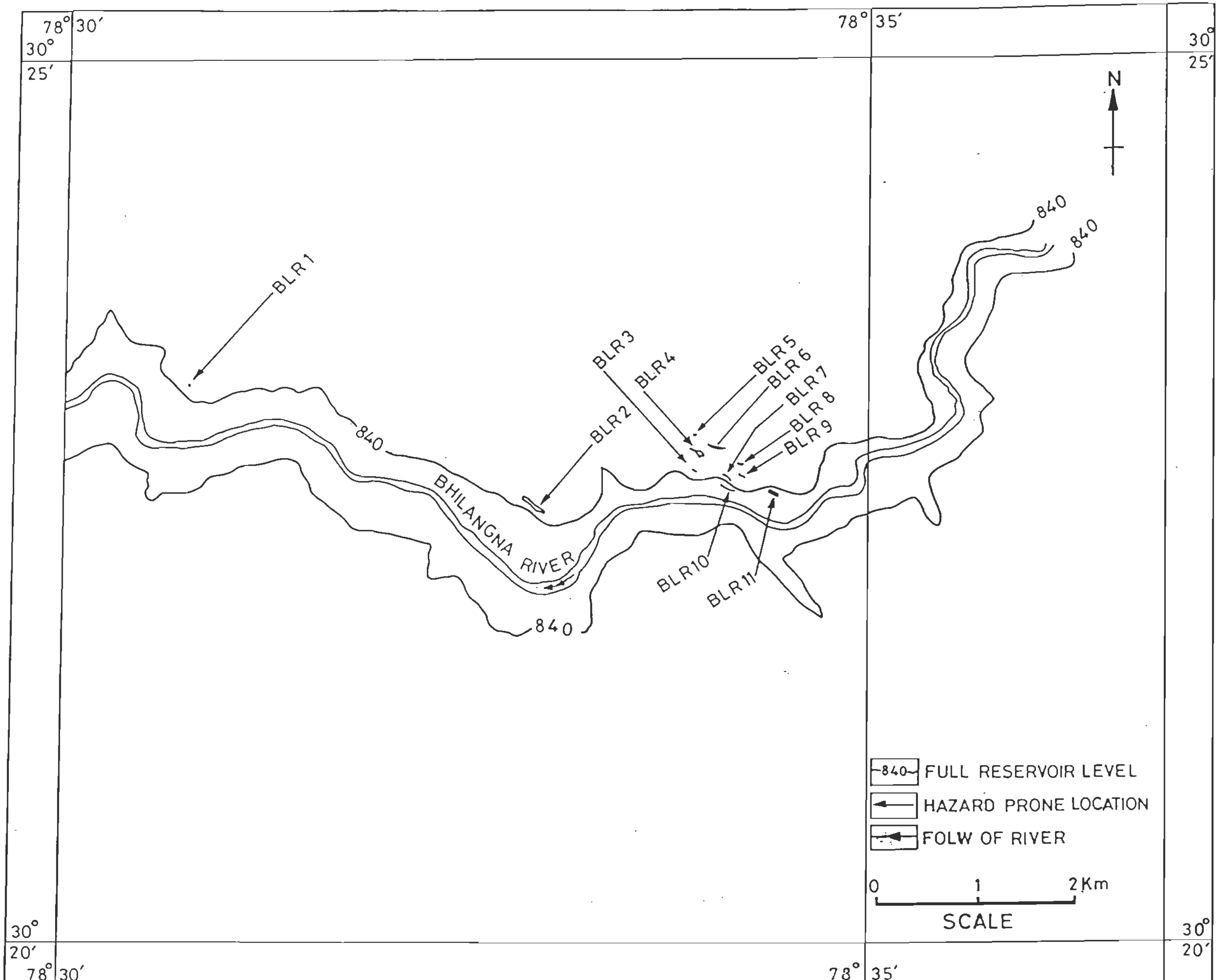


Fig. 4.40 Landslide Hazard Prone Location Map of the Area (Bhilangna Valley)

sections across various facets of the area of study are prepared. Slope stability investigation shows that in Bhagirathi valley, one slope facet BHL34A is unstable under the most adverse possible condition. While in Bhilangna valley, BRR18 is unstable. As per new comprehensive approach, there are 23 possible slides on right bank and 20 possible slides on left bank in Bhagirathi valley. In Bhilangna valley, there are 11 possible slides on right bank.

DEM (Digital Elevation Model), drainage map and 'landuse and landcover map' of the area of study have been prepared using GIS package ILWIS.

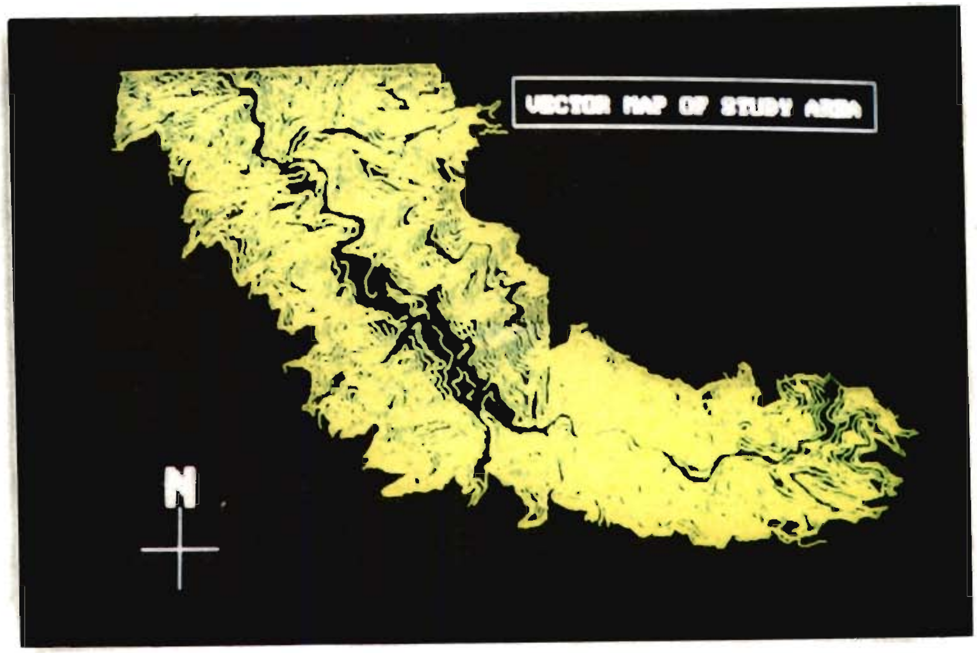


Plate 4.1 Vector Map of the Study Area

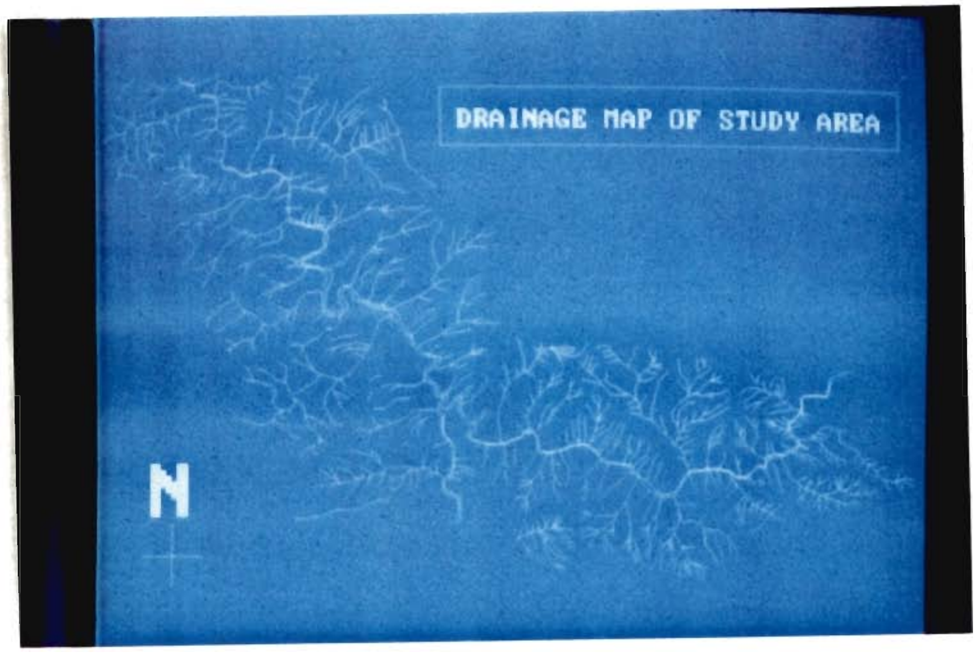


Plate 4.2 Drainage Map of the Study Area

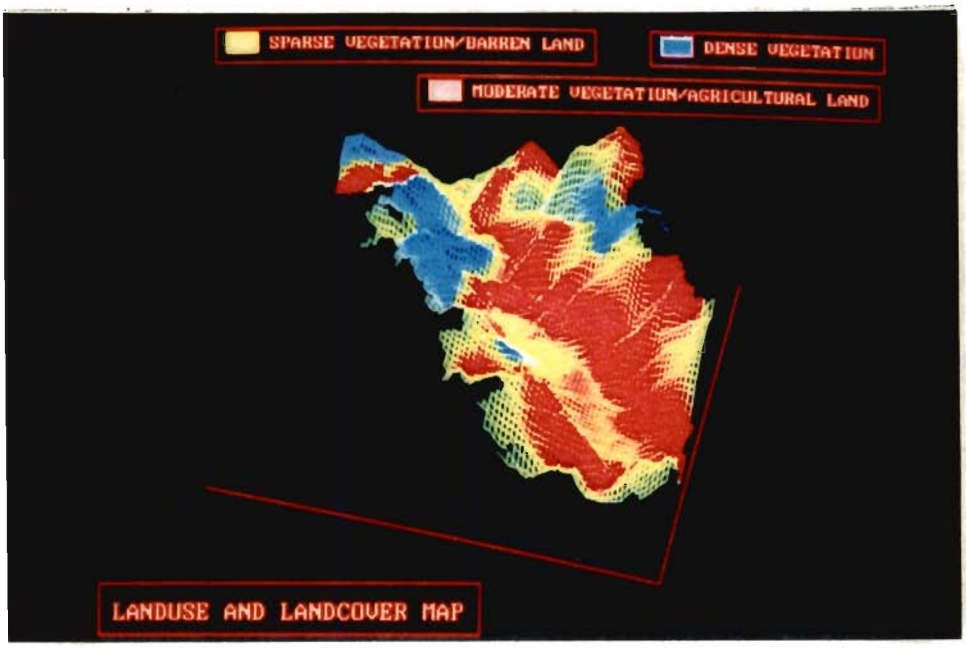


Plate 4.3 Landuse and Land Cover Map (Bhagirathi Valley)

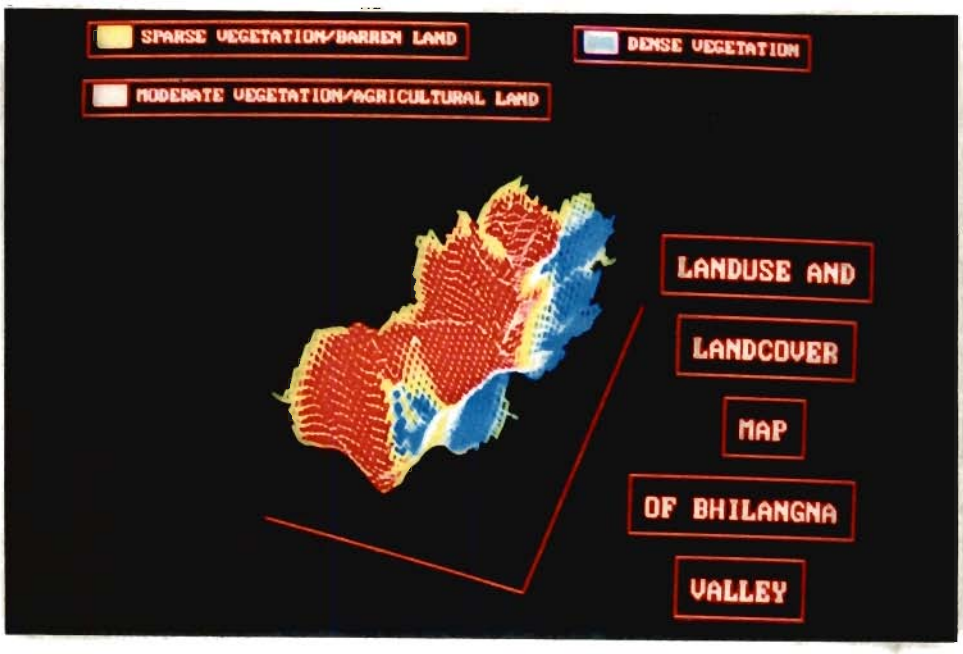
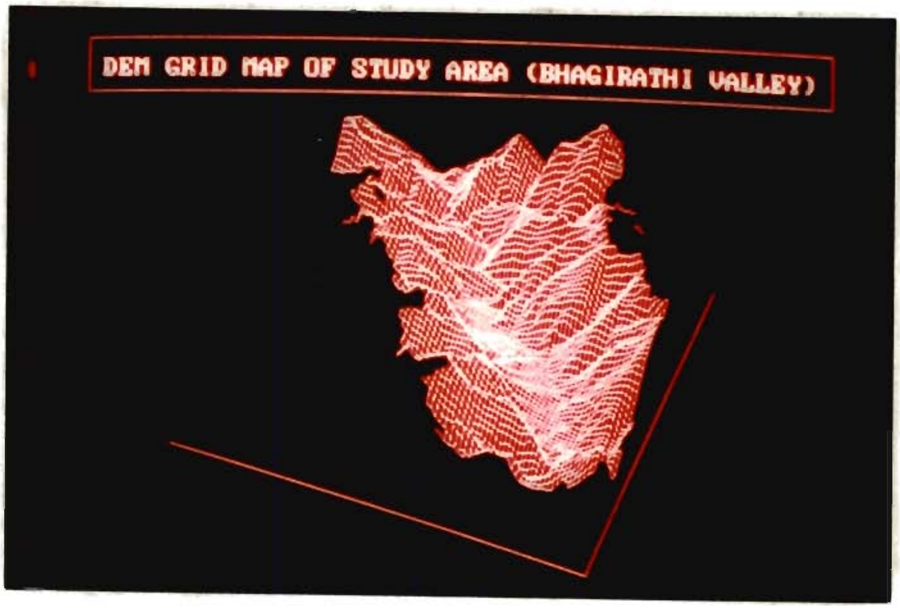
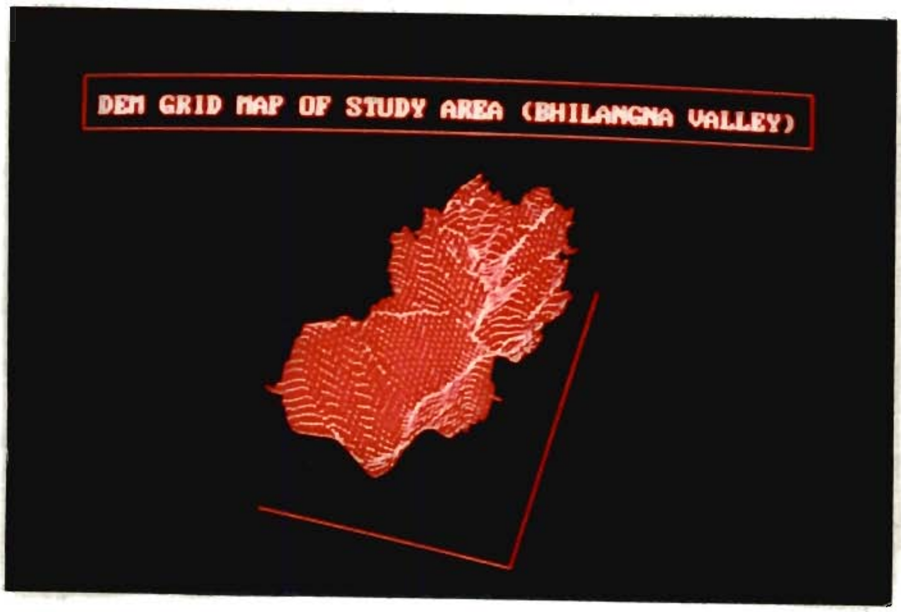


Plate 4.4 Landuse and Land Cover Map (Bhilangna Valley)





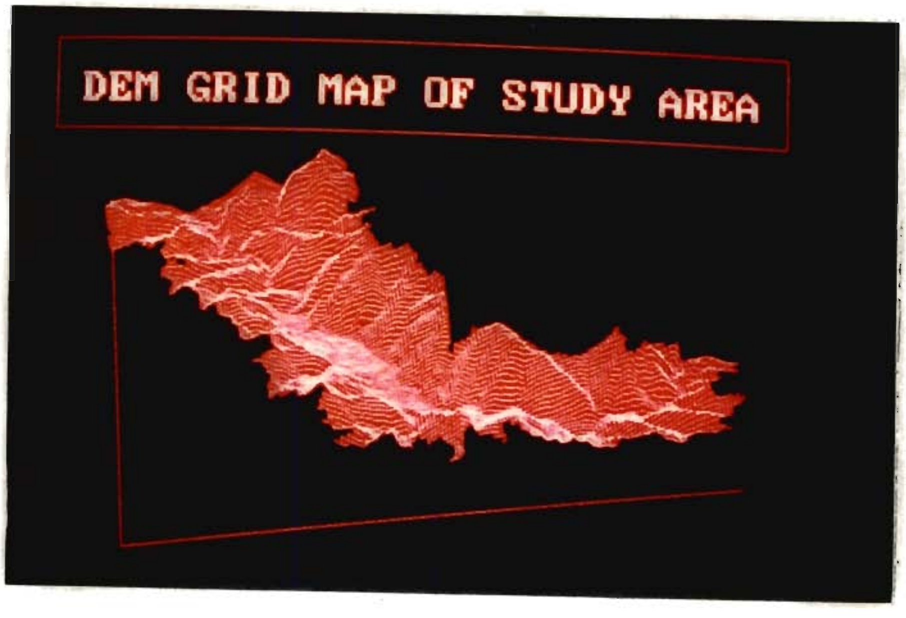


Plate 4.5 DEM Grid Maps of the Study Area

CHAPTER 5

IMPACT OF HILL SLIDES ON STABILITY OF DAM DUE TO WAVE GENERATION AND STABILITY MEASURES

Hillslides in reservoir area, generate water waves of such magnitude, which can over top the main body of dam. This may cause erosion of dam. Apart from threatening the stability of dam structure and reservoir, by forming the 'seiches' (huge water waves), hillslides in reservoir area can affect the environment adversely by causing siltation and deforestation. One of the greatest tragedies occured due to hillslide, on September 9, 1963 on the site of the 168 m high Vaiont Dam in the Italian Alps when more than 224 million/m^3 (4 mt) of rockmass slided down the mountain slope at a rate of 25-30 m/s within a short duration of 30-60 seconds, filling the reservoir almost completely and generating a 7 minute catastrohic flood that killed 2600 people within a 2 km downstream stretch (Valdiya, 1987).

5.1 HEIGHT OF WAVE GENERATED IN RESERVOIR DUE TO POSSIBLE LANDLISDES

Wave program is based on the model given by Slingerland and Voight, 1979. This program has been prepared by Misra,1988. The input data required to calculate the wave height, generated by the possible slides in the reservoir rim area is shown in Table 5.1. Height of wave generated in reservoir due to possible slope failure under anticipated adverse conditions, has been calculated for all slopes shown in final hazard map (Fig. 4.21 and 4.40).

In Bhagirathi valley, total 43 slides have been considered for this purpose, 23 on right bank and 20 on left bank. Wave height due to possible slides for the reservoir rim slopes, pertaining to left bank of Bhagirathi valley, varies from $0.101*10^{-6}$ m to $0.4493 *10^{-5}$ m

Table 5.1 Height of wave due to possible landslide (BHL34A and BRR18)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_{ω}	RD	Wave Height
BRR18	0.0	15°	601160	150	35°	0.0	60	9.8	1	9400	2×10^{-4}m
BHL 34A	0.0	15°	16073437.5	425	32°	0.0	40	9.8	1	3200	67×10^{-4}m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s²); GAMAW (γ_{ω}) = Unit weight of water (in kg/m³)
H = Height of slope (in m); ϕ = Angle of sliding friction (= $\phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

(Table 5.2A, Table 5.2B and Table 5.2C). For right bank, wave height varies from $0.165*10^{-6}$ m to $0.2*10^{-3}$ m (Table 5.3A and Table 5.3B). In Bhilangna valley, variation is from $0.116*10^{-6}$ m to $0.1*10^{-5}$ m for right bank (Table 5.4). As no slide exist on left bank, wave height has not been calculated. As there is a provision of free board of 5 m in dam design, there will not be any significant impact on stability of dam. Therefore, it can be concluded that due to possible slides in the reservoir area, stability of dam structure will not be endangered. Wave height for slope BHL34A in Bhagirathi valley is $67*10^{-4}$m. Similarly, wave height for slope BRR18 in Bhilangna valley is $2*10^{-4}$ m (Table 5.1).

An attempt has been made to find out the quantum of weight (W) required to generate waves having amplitude more than 5 m (provided as free board in dam design). This analysis has been carried out for right bank of Bhagirathi valley, left bank of Bhagirathi valley and right bank of Bhilangna valley.

For left bank of Bhagirathi valley, an average of various parameters pertaining to slides L35a, L36a, L37b and L38b has been taken. It can be observed from the perusal of Table 5.5 that 10^9 W (W = 0.39 tonne) is required to generate the waves having amplitude more than 5 m. For right bank, an average of various parameters pertaining to slides R112a, R17bm R18b, R110b, and R111a (WBLR13, Table 5.6). Total weight required in this case is 10^{10} W (W = 0.6403 tonne). For Bhilangna valley slides BLR3, BLE4, BLR5, BLR6, BLR7, BLR8, BLR9, BLR10 and BLR11 have been considered. Total weight required is 10^9 W(W = 0.1701 tonne, Table 5.7). For slope BHL34A, in Bhagirathi valley total weight required is 10^4W (W = 16073437.5 tonne, Table 5.8) and for slope BRR18 it is 10^7 W (W = 601160 tonne, Table 5.9).

Table 5.2A Height of wave due to possible landslide (Left bank of Bhagirathi Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_{ω}	RD	Wave Height
L21a	0.2	15°	0.03825t	40	57°	0.0	120	9.8	1	12500	0.280×10^{-6}m
L22a	0.2	15°	0.057375t	40	57°	0.0	160	9.8	1	12450	0.295×10^{-6}m
L23a	0.2	15°	0.03825t	40	57°	0.0	160	9.8	1	12400	0.222×10^{-6}m
L24a	0.2	15°	0.19125t	40	57°	0.0	40	9.8	1	6150	0.4493×10^{-5}m
L25a	0.2	15°	0.03825t	40	57°	90	240	9.8	1	2400	0.1701×10^{-5}m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_{ω}) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction (= $\phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.2B Height of wave due to possible landslide (Left bank of Bhagirathi Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
L35a	0.1	15°	0.11475t	40	57°	290	160	9.8	1	14200	$0.2199 x 10^{-5}$m
L36a	0.1	15°	0.0765t	40	57°	250	160	9.8	1	14100	$0.1495 x 10^{-5}$m
L310a	0.1	15°	0.153t	40	57°	0.0	90	9.8	1	8400	$0.1545 x 10^{-5}$m
L313a	0.1	15°	0.0765t	40	57°	170	240	9.8	1	8050	$0.14169 x 10^{-5}$m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_ω) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction (= $\phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.2C Height of wave due to possible landslide (Left bank of Bhagirathi Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
L31b	0.3	15°	0.014125t	40	52°	0.0	120	9.8	1	15500	0.101×10^{-6}m
L32b	0.3	15°	0.02825t	40	52°	190	160	9.8	1	15050	0.455×10^{-6}m
L33b	0.3	15°	0.02119t	40	52°	150	160	9.8	1	150150	0.313×10^{-6}m
L34b	0.3	15°	0.014125t	40	52°	250	160	9.8	1	14600	0.348×10^{-6}m
L37b	0.3	15°	0.02825t	40	52°	90	200	9.8	1	14000	0.238×10^{-6}m
L38b	0.3	15°	0.02119t	40	52°	90	160	9.8	1	13350	0.248×10^{-6}m
L39b	0.3	15°	0.014125t	40	52°	290	200	9.8	1	11400	0.411×10^{-6}m
L311b	0.3	15°	0.02825t	40	52°	90	160	9.8	1	8500	0.474×10^{-6}m
L312b	0.3	15°	0.02825t	40	52°	20	240	9.8	1	8400	0.117×10^{-6}m
L315b	0.3	15°	0.0219t	40	52°	90	170	9.8	1	7600	0.420×10^{-6}m
L314b	0.3	15°	0.042375t	40	52°	130	240	9.8	1	8000	0.620×10^{-6}m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_ω) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction (= $\phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.3A Height of wave due to possible landslide (Right bank of Bhagirathi Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
R13a	0.1	15°	0.02025t	40	47°	0.0	20	9.8	1	13700	0.409x10^{-5}m
R14a	0.1	15°	0.050625t	40	47°	290	160	9.8	1	13300	0.119x10^{-5}m
R15a	0.1	15°	0.050625t	40	47°	280	160	9.8	1	13150	0.118x10^{-5}m
R111a	0.1	15°	0.050625t	40	47°	80	300	9.8	1	11500	0.326x10^{-6}m
R112a	0.1	15°	0.253125t	40	47°	0.0	120	9.8	1	11400	0.1278x10^{-5}m
R113a	0.1	15°	0.050625t	40	47°	0.0	80	9.8	1	10700	0.610x10^{-6}m
R119a	0.1	15°	0.050625t	40	47°	130	280	9.8	1	6300	0.890x10^{-6}m
R120a	0.1	15°	0.050625t	40	47°	50	160	9.8	1	6300	0.722x10^{-6}m
R123a	0.1	15°	0.10125t	40	47°	0.0	40	9.8	1	400	0.478x10^{-4}m
R124a	0.1	15°	0.30375t	40	47°	0.0	40	9.8	1	200	0.208x10^{-3}m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_ω) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction ($= \phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.3B Height of wave due to possible landslide (Right bank of Bhagirathi Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
R11b	0.2	15°	0.03075t	40	47°	0.0	80	9.8	1	15750	0.268×10^{-6}m
R12b	0.2	15°	0.0615t	40	47°	0.0	140	9.8	1	14300	0.301×10^{-6}m
R17b	0.2	15°	0.3075t	40	47°	90	220	9.8	1	12000	0.284×10^{-6}m
R18b	0.2	15°	0.046125t	40	47°	80	240	9.8	1	11800	0.330×10^{-6}m
R19b	0.2	15°	0.03075t	40	47°	0.0	60	9.8	1	11700	0.459×10^{-6}m
R110b	0.2	15°	0.03075t	40	47°	40	220	9.8	1	11650	0.165×10^{-6}m
R114b	0.2	15°	0.123t	40	47°	0.0	50	9.8	1	11500	0.1456×10^{-5}m
R115b	0.2	15°	0.046125t	40	47°	160	120	9.8	1	9200	0.1238×10^{-5}m
R116b	0.2	15°	0.123t	40	47°	0.0	20	9.8	1	9200	0.393×10^{-5}m
R117b	0.2	15°	0.03075t	40	47°	40	200	9.8	1	8300	0.250×10^{-6}m
R118b	0.2	15°	0.0615t	40	47°	0.0	130	9.8	1	7800	0.588×10^{-6}m
R118bbb	0.2	15°	0.09225t	40	47°	0.0	130	9.8	1	7700	0.795×10^{-6}m
R118bb	0.2	15°	0.03075t	40	47°	130	200	9.8	1	7300	0.657×10^{-6}m
R121b	0.2	15°	0.03075t	40	47°	50	160	9.8	1	3200	0.918×10^{-6}m
R122b	0.2	15°	0.046125t	40	47°	30	240	9.8	1	1800	0.1077×10^{-5}m
R16b	0.2	15°	0.03075t	40	47°	280	160	9.8	1	13100	0.762×10^{-6}m

AI = Dip of plane or intersection of joint planes (in degree)

FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$); G = Acceleration due to gravity (in m/s^2)

GAMAW (γ_ω) = Unit weight of water (in kg/m^3); H = Height of slope (in m); ϕ = Angle of sliding friction ($= \phi_r/2$)

RWL = Mean depth of reservoir (in m); RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)

W = Weight of sliding material (in tonne)

Table 5.4 Height of wave due to possible landslide (Right bank of Bhilangna Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
BLR1	0.13	15°	0.0103125t	20	38°	50	140	9.8	1	4000	0.351×10^{-6}m
BLR2	0.13	15°	0.056719t	20	38°	70	120	9.8	1	7900	0.972×10^{-6}m
BLR3	0.13	15°	0.0103125t	20	38°	70	100	9.8	1	9800	0.244×10^{-6}m
BLR4	0.13	15°	0.04125t	20	38°	160	120	9.8	1	9850	0.1003×10^{-5}m
BLR5	0.13	15°	0.0103125t	20	38°	200	120	9.8	1	9800	0.442×10^{-6}m
BLR6	0.13	15°	0.03094t	20	38°	250	160	9.8	1	9900	0.878×10^{-6}m
BLR7	0.13	15°	0.020625t	20	38°	40	120	9.8	1	10050	0.225×10^{-6}m
BLR8	0.13	15°	0.0103125t	20	38°	170	100	9.8	1	10150	0.443×10^{-6}m
BLR9	0.13	15°	0.0155t	20	38°	130	100	9.8	1	10200	0.486×10^{-6}m
BLR10	0.13	15°	0.030938t	20	38°	0.0	80	9.8	1	9900	0.278×10^{-6}m
BLR11	0.13	15°	0.020625t	20	38°	0.0	150	9.8	1	10500	0.116×10^{-6}m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_ω) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction (= $\phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.5 **Quantum of weight required to generate waves having amplitude more than 5 m (Left bank of Bhagirathi Valley)**

No. (L35a+L36a+ L37b+L38b)	FS	ϕ	W	H	AI	S	RWL	G	γ_{ω}	RD	Wave Height
W137ab	0.0	15°	0.39	80	57°	180	170	9.8	1	13912.5	0.000 m
W137ab	0.0	15°	39	80	57°	180	170	9.8	1	13912.5	0.0001 m
W137ab	0.0	15°	390	80	57°	180	170	9.8	1	13912.5	0.0005 m
W137ab	0.0	15°	3900	80	57°	180	170	9.8	1	13912.5	0.0024 m
W137ab	0.0	15°	39000	80	57°	180	170	9.8	1	13912.5	0.0121 m
W137ab	0.0	15°	390000	80	57°	180	170	9.8	1	13912.5	0.0621 m
W137ab	0.0	15°	3900000	80	57°	180	170	9.8	1	13912.5	0.318 m
W137ab	0.0	15°	39000000	80	57°	180	170	9.8	1	13912.5	1.63 m
W137ab	0.0	15°	390000000	80	57°	180	170	9.8	1	13912.5	8.37 m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_{ω}) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction ($= \phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.6 Quantum of weight required to generate waves having amplitude more than 5 m (Right bank of Bhagirathi Valley)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_{ω}	RD	Wave Height
WBLR13	0.00	15°	0.6403	100	47°	58	220	9.8	1	11670	0.000002 m
WBLR13	0.00	15°	6.403	100	47°	58	220	9.8	1	11670	0.000009 m
WBLR13	0.00	15°	64.03	100	47°	58	220	9.8	1	11670	0.000046 m
WBLR13	0.00	15°	640.3	100	47°	58	220	9.8	1	11670	0.000238 m
WBLR13	0.00	15°	6400	100	47°	58	220	9.8	1	11670	0.001222 m
WBLR13	0.00	15°	64000	100	47°	58	220	9.8	1	11670	0.006261 m
WBLR13	0.00	15°	640000	100	47°	58	220	9.8	1	11670	0.032111 m
WBLR13	0.00	15°	6400000	100	47°	58	220	9.8	1	11670	0.164685 m
WBLR13	0.00	15°	64000000	100	47°	58	220	9.8	1	11670	0.84 m
WBLR13	0.00	15°	640000000	100	47°	58	220	9.8	1	11670	4.33 m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_{ω}) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction ($= \phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.7 Quantum of weight required to generate waves having amplitude more than 5 m (Right bank of Bhilangna Valley)

No. (BLR3+4+5+6+7+8+9+10+11)	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
BLR12	0.13	15°	0.1701	20	38°	113.33	116.67	9.8	1	10016.67	0.000002 m
BLR12	0.13	15°	1.701	20	38°	113.33	116.67	9.8	1	10016.67	0.000011 m
BLR12	0.13	15°	17.01	20	38°	113.33	116.67	9.8	1	10016.67	0.000057 m
BLR12	0.13	15°	170.1	20	38°	113.33	116.67	9.8	1	10016.67	0.000292 m
BLR12	0.13	15°	1701	20	38°	113.33	116.67	9.8	1	10016.67	0.001496 m
BLR12	0.13	15°	17010	20	38°	113.33	116.67	9.8	1	10016.67	0.007673 m
BLR12	0.13	15°	170100	20	38°	113.33	116.67	9.8	1	10016.67	0.03935 m
BLR12	0.13	15°	1701000	20	38°	113.33	116.67	9.8	1	10016.67	0.20 m
BLR12	0.13	15°	17010000	20	38°	113.33	116.67	9.8	1	10016.67	1.03 m
BLR12	0.13	15°	170100000	20	38°	113.33	116.67	9.8	1	10016.67	5.3084 m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_ω) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction ($= \phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.8 Quantum of weight required to generate waves having amplitude more than 5 m (BHL34A)

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
BHL34A	0.00	15°	16073437.5	425	32°	0.0	40	9.8	1	3200	0.0067 m
BHL34A	0.00	15°	160734375	425	32°	0.0	40	9.8	1	3200	0.034596 m
BHL34A	0.00	15°	1607343750	425	32°	0.0	40	9.8	1	3200	0.177427 m
BHL34A	0.00	15°	16073437500	425	32°	0.0	40	9.8	1	3200	0.90 m
BHL34A	0.00	15°	160734375000	425	32°	0.0	40	9.8	1	3200	4.66 m
BHL34A	0.00	15°	1607343750000	425	32°	0.0	40	9.8	1	3200	23.9343 m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & ϕ = ϕ_r/2)
G = Acceleration due to gravity (in m/s²); GAMAW (γ_ω) = Unit weight of water (in kg/m³)
H = Height of slope (in m); ϕ = Angle of sliding friction (= ϕ_r/2); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

Table 5.9 **Quantum of weight required to generate waves having amplitude more than 5 m (BRR18)**

No.	FS	ϕ	W	H	AI	S	RWL	G	γ_ω	RD	Wave Height
BRR18	0.00	15°	601160	150	35°	0.01	60	9.8	1	9400	0.0002 m
BRR18	0.00	15°	6011600	150	35°	0.01	60	9.8	1	9400	0.00091 m
BRR18	0.00	15°	60116000	150	35°	0.01	60	9.8	1	9400	0.024 m
BRR18	0.00	15°	601160000	150	35°	0.01	60	9.8	1	9400	0.123 m
BRR18	0.00	15°	6011600000	150	35°	0.01	60	9.8	1	9400	0.63 m
BRR18	0.00	15°	60116000000	150	35°	0.01	60	9.8	1	9400	3.223 m
BRR18	0.00	15°	601160000000	150	35°	0.01	60	9.8	1	9400	16.5285 m
BRR18	0.00	15°	6011600000000	150	35°	0.01	60	9.8	1	9400	84.77 m

AI = Dip of plane or intersection of joint planes (in degree)
FS = Static residual factor of safety of the slope during landslide (C = 0.0 & $\phi = \phi_r/2$)
G = Acceleration due to gravity (in m/s^2); GAMAW (γ_ω) = Unit weight of water (in kg/m^3)
H = Height of slope (in m); ϕ = Angle of sliding friction (= $\phi_r/2$); RWL = Mean depth of reservoir (in m)
RD = Distance of land slide from dam (in m); S = Distance of movement of land slide (in m)
W = Weight of sliding material (in tonne)

5.2 STABILITY MEASURES

Some of the potentially unstable slopes, identified using Markland test tend to become unstable under dynamic and wet condition.

Most of the potentially unstable slopes are smaller in nature except on one slope in Bhagirathi and another in Bhilangna valley. As the geological and environmental conditions are same throughout the area of study, the stability measures have been suggested keeping in view of the results obtained by stability analysis.

Since all the landslides occur on rock slopes, in order to improve the stability environment, the following measures can be undertaken :

(i) Trimming of over hangs and modification of slopes.

(ii) Installation of rock anchors approximately ranging from 5 m to 15 m. These anchors should be aligned more or less perpendicular to the local slopes.

(iii) On the slope and towards the end of the anchors steel wire mesh can be spread. Anchor plates of 0.5 m*0.5 m size may be used to secure the wire mesh to the slope.

(iv) Shotcreting of slopes, leaving 20% surface area for the drainage shall be carried out.

(v) Afforestation measure will help to reduce the ingress of surface water in addition to binding the top slope material.

5.3 SUMMARY

Water waves generated by hillslides in reservoir area, can erode the main body of dam by overtopping it. Height of the wave generated in reservoir due to possible slope failure under anticipated adverse condition, has been calculated for all slopes, shown in hazard map. Wave height due to possible slides for the reservoir rim slopes pertaining to left bank of Bhagirathi valley, varies from $0.101*10^{-6}$ m to $0.4493*10^{-5}$ m.

Wave height due to possible slides for the reservoir rim slope, pertaining to left bank of Bhagirathi valley, varies from $0.101*10^{-6}$ m to $0.4493*10^{-5}$ m. For right bank, wave height varies from $0.165*10^{-6}$ m to $0.2*10^{-3}$ m. In Bhilangna valley, variation is from $0.116*10^{-6}$ m to $0.1*10^{-5}$ m for right bank.

For left bank of Bhagirathi valley, the quantum of weight (W) required to generated waves having amplitude more than 5 m (provided as free board in dam design) is 10^9 W (W = 0.39 tonne), for right bank it is 10^{10} W (W = 0.6403 tonne) and in case of Bhilangna valley total weight required is 10^9 W (W = 0.1701 tonne).

CHAPTER 6

SUMMARY AND CONCLUSION

A 260.5 m high rock-fill dam is under construction across Bhagirathi river downstream of the confluence of the river Bhilangana near Tehri township. The gross storage at El 840 m which would create a long reservoir in both Bhagirathi and Bhilangana, and it is estimated to be $35.5 * 10^8$ m^3. The Tehri lake will extend up to 44 Km along river Bhagirathi and 25 Km along river Bhilangana and it is flanked by high hills all along both the sides.

Area of study pertaining to Tehri dam reservoir consists of rugged topography and dendritic drainage pattern. Hill slope stability of a part of Tehri dam reservoir has been investigated by considering cross sections across various slope facets. There are total 57 facets on right bank of Bhagirathi valley and 36 facets on left bank. Similarly there are total 32 facets on right bank of Bhilangna and 31 facets on left bank. Results show that there is one slope facet BHL34A in Bhagirathi valley and anther slope facet BRR18 in Bhilangna valley, which is hazard prone. Great circles of structural discontinuities, obtained by contouring, have been used in stability analysis. Slope facets BRR24 and BRR30 are stable under 'static and dry', 'static and wet', and 'dynamic and dry' conditions, but critically stable under 'dynamic and wet' condition. Direction of sliding for slope facet BHL34A is N157° and angle of sliding is 32°. For slope facet BRR18 direction of sliding is N191° and angle of sliding is 35°. Similarly for slope facets BRR24 and BRR30, direction of sliding is N145° and angle of sliding is 47°. In course of investigation, it has been felt that there may be microchanges in slope attitude, which may have significance regarding stability condition. In order to accommodate local slope variation in stability analysis, a more object oriented comprehensive approach has been adopted. Smallest possible unit between two closely spaced successive contours has been considered for slope stability investigation. Some of the potentially unstable slopes, identified using Markland test tend to become unstable under dynamic and wet condition. Comprehensive landslide hazard map, prepared by considering the slopes having Factor of Safety < 1 under any of the possible hazard prone conditions, shows that there are 54 possible slides in study area.

Based on this new approach, a total of 72 potential failure slopes have been identified as against one by conventional approach in Bhagirathi valley. Out of these 72 slopes, 20 are potential wedge failure and 52 are potential plane failure slopes. Results obtained by calculation of Factor of Safety of all the potential failure slopes show that all potential wedge failures are stable even under worst possible condition (dynamic and wet). Out of 52 potential plane failures, 43 are unstable (i.e. 23 possible slides on right bank and 20 on left bank). Field observations confirm the results obtained by new approach. In Bhagirathi valley most of the slides (unstable slopes) are located near Bhaldgaon, Raolakot and Bhaldiyana villages.

In Bhilangna valley there are 65 potential failure slopes as per the new approach as against three by conventional approach. Out of these 65 potential failure slopes, 25 are wedge failures and 40 are plane failures. All these potential wedge failures have FOS > 1.5 and therefore are stable under four different conditions. Out of 40 potential plane failures, 11 are unstable (FOS < 1), and located on right bank. There is no slide on left bank of Bhilangna valley. In Bhilangna valley, most of the slides are close to Myunda and Dewal villages.

Distance of hill slides from Tehri dam varies from 0.2 km to 15.75 km in Bhagirathi valley and from 4 km to 10.2 km in Bhilangna valley. Most of the hillslides are located on slopes having sparse vegetation (i.e. left bank of Bhagirathi river and right bank of Bhilangna river).

Height of wave generated in reservoir due to possible slope failure under anticipated adverse condition, has been calculated for all slopes shown in final hazard map.

In Bhagirathi valley, total 43 slides have been considered for this purpose, 23 on right bank and 20 on left bank. Wave height due to possible slides for the reservoir rim slope, pertaining to left bank of Bhagirathi valley, varies from 0.101 x 10^{-6} m to 0.4493 x 10^{-5} m. For right bank, wave height varies from 0.165 x 10^{-6} m to 0.2 x 10^{-3} m. In Bhilangna valley, variation is from 0.116 x 10^{-6} m to 0.1 x 10^{-5} m for right bank. As no slide exist on left bank, wave height has not been calculated. As there is a provision of free board of 5m in dam design, there will not be any significant impact on stability of dam. Therefore it can be concluded that due to possible slides in the reservoir area, stability of dam structure will not be endangered. An attempt has been made to find out the quantum of weight (W) required to generate waves having amplitude more than 5 m (provided as free board in dam design). This analysis has been carried out for right bank of Bhagirathi valley, left bank of Bhagirathi valley and right bank of Bhilangna valley.

For left bank of Bhagirathi valley, an average of various parameters pertaining to slides L35a, L36a, L37b and L38b has been taken. It can be observed from the perusal of Table 5.5 that 10^9 W (W = 0.39 tonne) is required to generate the waves having amplitude more than 5 m. Similarly, for right bank, an average of various parameters pertaining to slides R112a, R17bm R18b, R110b, and R111a (WBLR13, Table 5.6) has also been considered. Total weight required in this case is 10^{10} W (W = 0.6403 tonne). For Bhilangna valley slides BLR3, BLE4, BLR5, BLR6, BLR7, BLR8, BLR9, BLR10 and BLR11 have been considered. Total weight required is 10^9 W(W = 0.1701 tonne, Table 5.7). For slope BHL34A, in Bhagirathi valley total weight required is 10^4W(W = 16073437.5 tonne, Table 5.8) and for slope BRR18 it is 10^7 W (W = 601160 tonne, Table 5.9).

Digital Elevation Model (DEM) prepared by using GIS package ILWIS, shows that area of study consists of number of steep slopes. It depicts area of study in three dimension. Similarly, landuse and land cover map indicates that a large part of area of study consists of sparse vegetation.

As the geological and environmental conditions are same throughout the study area, stability measures were suggested keeping in view of the results obtained by stability analysis. This include modification of slopes, installation of rock anchor and anchor plates, spreading of steel wire mesh, shotcreting and afforestation. For afforestation locally available plant species can be used i.e. 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*) and other similar plant species.

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APPENDIX 1

SALIENT FEATURES OF TEHRI DAM PROJECT

(Singh et al., 1983)

1. **Location** : On river Bhagirathi in District Tehri, Uttar Pradesh, 1.5 km downstream of the confluence of Bhagirathi and Bhillangana river at Tehri Town.

2. **Hydrology :**

(a) Catchment area

(i) Total catchment area	7,511 sq. km.
(ii) Catchment area excluding snow bound area.	5,183 sq. km.

(b) Maximum recorded flood discharge	3,800 cumecs
(c) Maximum probable flood	
(i) Dam with frequency 1 in 10,000 years.	19,460 cumecs
(ii) Spillway (frequency 1 in 2,500 years in flow 17,000 cumecs)	11,000 cumecs
(iii) Tunnel (frequency 1 in 1,000 years in flow 15,040 cumec)	9,000 cumecs
(e) Average annual rainfall	1016-1778 mm
(f) Maximum Annual run-off	1.27×10^{10} m^3
(g) Minimum Annual run-off	0.57×10^{10} m^3
(h) Average annual run-off	0.903×10^{10} m^3

	(i)	Run-off on 90% yearly availability	0.70×10^{10} m^3
	(j)	Run-off 70% yearly availability	0.842×10^{10} m^3
3.	**Reservoir**		
	(a)	Normal maximum reservoir level	830 m
	(b)	Maximum level during design flood	840 m
	(c)	Dead storage level	740 m
	(d)	Dead storage at Rl. 740 m	9.15×10^8 m^3
	(e)	Live storage	26.153×10^8 m^3
4.	**Dam**		
	(a)	Type	Rockfill with impervious core
	(b)	Elevation of top of dam	839.5 m.
	(c)	River bed level	594.0 m
	(d)	Expected deepest foundation level	579.0 m.
	(e)	Maximum height above deepest foundation level	260.5 m
	(f)	Thickness at top of dam	20.0 m
	(g)	Thickness at river bed level	1124.75 m
	(h)	Height of Ist stage dam (coffer dam)	115 m.
5.	Spillway		
	(a)	Type	Chute spillway with ski-jump bucket.
	(b)	Type and number of gates	Tainter gates, 5 of 16.0 x 14.2m

	(c)	Design capacity	11,700 cumecs
6.	**Diversion**		4 (two tunnels on each bank of 11 m diameter)
7.	**Power Generation**		
	(a)	Maximum head	231.3 m
	(b)	Minimum head	141.3 m
	(c)	Design head	217.5 m.
	(d)	Power Units	4 Nos. each of 250 mw (in first phase) 4 Nos. each of 250 mw (in II phase)
	(e)	Intake structure	Open type terminating in two high pressure tunnels each 850 m long and 12.5 m dia.
	(f)	Surge tanks	One on each HRT of 32 m dia.
	(g)	Penstocks	
		(i) Main Penstocks	8.1 m dia (bifurcated into 2)
		(ii) Unit penstocks	5.73 dia.

(h)	Location of power house	Underground on left bank (width of cavity 22.5 m)
(i)	Type of turbines	Francis type vertical shaft turbines.
(j)	Normal speed	214.3 r.p.m.
(k)	Transformer location	Single phase transformers underground (width of cavity 17.5 m)
(l)	Switchyard	Outdoor on left bank.

APPENDIX 2

PROGRAM FOR PLANE FAILURE

```
c      FOS FOR PLANE FAILURE   NCN·PhD-97
c        --------   ---------------------------
c       DIMENSION sif(100),sip(100),dphi(100)
c      IMENSION P(100,9),U(100),W(100),Z(100),A(100)
c        DIMENSION psif(100),psip(100),phi(100)
c        DIMENSION h(100),g(100),gw(100),c(100),alfa(100),U(100),W(100)
c        DIMENSION A(100),FN1(100),FD(100),FOSP(100)
          OPEN(1,FILE='d1.dat',STATUS='OLD')
          OPEN(2,FILE='d2.out',STATUS='NEW')
          WRITE(2,*)'LOCATION:
          READ(1,*)sif,sip,dphi,h,g,gw,c,dalfa
c       ------------------------------
          WRITE(2,61)sif,sip,dphi
61      FORMAT(' SIF  =  ',F16.6/'  SIP =  ',F16.6/' DPHI = ',F16.6/)
C       ==============================================
          WRITE(2,62)h,g,gw
62      FORMAT(' h = ',F16.6/' g = ',F16.6/' gw = ',F16.6/)
C       ------------------------------------------
          WRITE(2,63)c,dalfa
63      FORMAT(' c = ',F16.6/' alfa = ',F16.6/)
          psif=(sif)*(3.14/180.0)
          psip=(sip)*(3.14/180.0)
          phi =(dphi)*(3.14/180.0)
c      READ(1,*)((P(I,J),J=1,9),I=1,N)
C       WRITE(*,*)((P(I,J),J=1,9),I=1,N)
C       =================================
c      AMAX=1
c      AMIN=10000a
c      DO 77 I=1,N
c      IF(P(I,4).GT.AMAX)AMAX=P(I,4)
c      IF(P(I,4).LT.AMIN)AMIN=P(I,4)
c77     CONTINUE
C      DO 88 I=1,N
C      P(I,4)=P(I,4)*AMIN/AMAX
C88     CONTINUE
C      ==================================
c      DO 5 I=1,N
c      iDO 10 J=1,3
c      P(I,J)=P(I,J)*3.14/180.0
c5      CONTINUE
C      ==================================
c      DO 15 I=1,N
C      -------------------------------------
         U=(0.25*gw*(h**2))/(SIN (psip))
         WRITE(2,12)U
12     FORMAT('U = ',1X,F16.5/)
```

```
C     WRITE(*,*)U(I)
C     z(I)=P(I,4)*(1-SQRT(TAN(P(I,2))/TAN(P(I,1))))
        W=((0.5*g)*(h**2))*((1.0/(TAN (psip)))-(1.0/(TAN (psif))))
c     /TANpsip(P(I,2))-1.0/TANpsif(ifP(I,1)))
        WRITE(2,13)W
13    FORMAT('W =',F16.5/)
        A=(h)/(SIN (psip))
        WRITE(2,14)A
14    FORMAT('A= ',F16.5/)
        V  = (COS(PSIP)) - (dalfa * (SIN( PSIP)))
        D  = (SIN(PSIP)) + (dalfa * (COS( PSIP)))
        WRITE (2,41)V,D
41      FORMAT (' V =  ' ,F16.5 / 'D = ', F16.5/)
        FN1 = (c*A) + (((W*V) - (U)) *(TAN (phi)))
        FD  = W*D
C     ------------------------------
C      FN1=(c*A)+(((W*(COS (psip)))-(dalfa*(SIN (psip))-U))*(TAN (phi)))
c       --------------------
        WRITE(2,15)FN1
15    FORMAT(' FN1  =  ', F16.5/)
c     FN2(I)=P(I,8)*A(I)+(W(I)*(COS(P(I,2))-P(I,9)
c    1 *SIN(P(I,2))))*TAN(P(I,3))
C      FD=(W*(SIN (psip)))+(dalfa*(COS (psip)))
        FOSP=(FN1)/(FD)
c     FOSPD(I)=FN2(I)/FD(I)
C     ==================================================
        WRITE(2,33)FD,FOSP
33    FORMAT ('FD   = ',F16.5/'FOSP  = ',F16.5/)
cC
c     -------------------------------------
c15    CONTINUE
c     WRITE(*,*)W(1),A(1)
        STOP
        END
```

APPENDIX 3

PROGRAM FOR WEDGE FAILURE

```
c          PROGRAM FOR WEDGE FAILURE
           open (1,file= 'ct.dat',status='old')
           open (2,file= 'ct.out',status='new')
           read(1,*)psia,psib,psi5,thnanb,th24,th45,th2na
           read(1,*)th13,th35,th1nb,phi,g,gw,c,h,palh
           write(2,*)'--------------------------------------'
           write(2,*)'LOCATION:                          '
           WRITE(2,11)psia,psib,psi5
11          format('PSI A = ',f16.6/'PSI B = ',f16.6/'PSI 5 =',F16.6/)
           write(2,12)thnanb,th24
12          format('THETA na.nb =',f16.6/'THETA 2.4 =',F16.6/)
           write(2,13)th45,th2na
13          format('THETA 4.5 =',F16.6/'THETA 2.na =',f16.6/)
           write(2,14)th13,th35
14          format('THETA 1.3 =',F16.6/'THETA 3.5 =',f16.6/)
           write(2,15)th1nb,phi
15          format('THETA 1.nb =',f16.6/'PHI =',f16.6/)
           write(2,16)g,gw
16          format('GAMMA =',f16.6/'GAMMA W =',f16.6/)
           write(2,17)c,h
17          format(' C =',F16.6/'H =',f16.6/)
           sia = (psia)*(3.14/180.0)
           sib = (psib)*(3.14/180.0)
           si5 = (psi5)*(3.14/180.0)
           tnanb = (thnanb)*(3.14/180.0)
           t24  = (th24)*(3.14/180.0)
           t45  = (th45)*(3.14/180.0)
           t2na = (th2na)*(3.14/180.0)
           t13  = (th13)*(3.14/180.0)
           t35  = (th35)*(3.14/180.0)
           t1nb = (th1nb)*(3.14/180.0)
           si   = (phi)* (3.14/180.0)

           write(2,171)palh
171         format('alpha =  ',f16.6/)

      A=(cos(sia)-(cos(sib)*cos(tnanb)))/(sin(si5)*(sin(tnanb)**2))
           write(2,18)A
18          format('A  = ',f16.6/)
      B=(cos(sib)-(cos(sia)*cos(tnanb)))/(sin(si5)*(sin(tnanb)**2))
           write(2,19)B
19          format('B =',f16.6/)
           X=(sin(t24))/((sin(t45))*(cos(t2na)))
           write(2,20)X
20          format('X =',f16.6/)
           Y=(sin(t13))/(sin(t35)*cos(t1nb))
           write(2,21)Y
```

```
21          format('Y =',f16.6/)
           P=(((3*c)/(g*h))*(X+Y))
           D=(palh)*(sin(si5))
                   write(2,91)D
91          format(' d = ',f16.6/)
           dm=(cos(si5))-((palh)*(sin(si5)))
                   dN=(sin(si5))+((palh)*(cos(si5)))
                   write(2,212)dm,dN
212          format(' M = ',f16.6/ 'N = ',f16.6/)
c           Q=(A-((gw/(2*g))*X))*(tan(si))
            Q=(((A+B)*dm)*((tan(si))))/(dN)
                    write(2,213)Q
213           format(' Q = ',f16.6/)
            dT=((gw*(X+Y))*(tan(si)))/(2*(g))

            write(2,214)P,dT
214           format(' P = ',f16.6/' T = ',f16.6/)
c            T=(B-((gw/(2*g))*Y))*(tan(si))
           F= (P+Q)-(dT)
           write(2,22)F
22           format('F = ',f16.6/)
           write(2,*)'-------------------------------------------'
            stop
           end
```

APPENDIX 4

PROGRAM FOR CALCULATION OF HEIGHT OF WAVE GENERATED IN A RESERVOIR DUE TO LANDSLIDE

(Misra, 1988)

```
*****************************************************************************
THIS PROGRAM CALCULATES THE
HEIGHT OF WAVE GENERATED IN A RESERVOIR DUE TO LANDSLIDE
*****************************************************************************
GIVE DATA IN THE FOLLOWING SEQUENCE :

NCASE ( = NUMBER OF PROBLEMS)
TITLE OF PROBLEM IN ONE LINE (<80 CHARACTERS)
FS,PHI,W,H,AI,S,RWL,G,GAMAW,RD
THE ABOVE TWO LINES ARE REPEATED NCASE TIMES.
*****************************************************************************
ENTER 0 FOR TERMINATION
   1 fOR FURTHER HELP
   2 FOR EXECUTION
*****************************************************************************
AV     = COEFFICIENT OF VERTICAL EARTHQUAKE ACCELERATION
AH     = COEFFICIENT OF HORIZONTAL EARTHQUAKE ACCELERATION
AI     = DIP OF PLANE OR INTERSECTION OF JOINT PLANES
       = AVERAGE DIP OF CIRCULAR WEDGE
FS     = STATIC RESIDUAL FACTOR OF SAFETY OF THE SLOPE
         DURING LAND SLIDE. ( C = 0.0 & PHI = PHIR/2)
G      = ACCELERATION DUE TO GRAVITY
GAMAW  = UNIT WEIGHT OF WATER
H      = HEIGHT OF SLOPE
PHI    = ANGLE OF SLIDING FRICTION (= PHIR / 2 )
RWL    = MEAN DEPTH OF RESERVOIR
RD     = DISTANCE OF LAND SLIDE FROM DAM
S      = DISTANCE OF MOVEMENT OF LAND SLIDE
*****************************************************************************
ENTER 0 FOR TERMINATION
   2 fOR EXECUTION
```

```
C2345678
      DIMENSION TITLE(20)
      REAL KE
C     ***********************************************************
C     THIS PROGRAM CALCULATES MAXIMUM HEIGHT OF WAVE GENERATED BY
C        LAND SLIDE AND WAVE HEIGHT AT ANY DISTANCE (1993)
C     ***********************************************************
C     W    =WEIGHT OF WEDGE DURING LAND SLIDE
C          =WEIGHT PER UNIT RIM LENGTH OF RESERVOIR * WIDTH OF
C           LAND SLIDE FOR PLANE WEDGE /CIRCULAR WEDGE
C     KE   =KINETIC ENERGY OF LAND SLIDE(DIMENSIONLESS)
C     PHI  =RESIDUAL ANGLE OF FRICTION(6 TO 22)
C     WAV  =HEIGHT OF WAVE AT ANY RD
C     WAVM =MAXIMUM HEIGHT OF WAVE GENERATED BY LAND SLIDE
C     S    =DISTANCE OF MOVEMENT OF LAND SLIDE
C          =(HEIGHT OF SLOPE)*COSEC(AI)*.67 IF S=0.0
C          =TAN(PHI)/TAN(AI) (ASSUMED IF FS=0.0)
C     V    =MAXIMUM VELOCITY OF LAND SLIDE AFTER MOVEMENT BY DISTANCE 'S'
C     ACCN =ACCELERATION OF LAND SLIDE
C     AI   =AVERAGE DIP OF CIRCULAR WEDGE
C     ****************************************************************
      CHARACTER*20 INPT,OUTPT
      WRITE(*,32)
32    FORMAT(' Please Type Input File Name ->')
      READ(*,34)INPT
34    FORMAT(A20)
      WRITE(*,36)
36    FORMAT(' Please Type Output File Name ->')
      READ(*,34)OUTPT
      OPEN ( UNIT=1, FILE= INPT)
      OPEN ( UNIT=2, FILE= OUTPT)
      WRITE(*,42)
42    FORMAT(5X,'DO YOU WANT HELP REGARDING INPUT DATA'/
     * 5X,'ENTER 1 FOR HELP'/11X,'2 FOR EXECUTION'/)
      READ(*,*)NHELP
      IF(NHELP.EQ.1)CALL HELP(NHELP)
      IF(NHELP.EQ.0)GO TO 100
      NO=1
      READ(1,*)NCASE
2     READ(1,38) (TITLE(I),I=1,20)
38    FORMAT(20A4)
      WRITE(2,9) (TITLE(I),I=1,20)
9     FORMAT(5X,20A4,//)
      WRITE(2,7)
7     FORMAT(/4X,74(1H*)/
     * 5X,'UNITS USED          -> TONNE - METER - DEGREE')
      WRITE(2,41)INPT,OUTPT
41    FORMAT(5X,'INPUT FILE NAME     ->',A20/
     * 5X,'OUTPUT FILE NAME    ->' ,A20)
      READ(1,*) FS,PHI,W,H,AI,S,RWL,G,GAMAW,RD
      C1=3.1415927/180.
      AII=AI*C1
      PHII=PHI*C1
      IF(FS.EQ.0.0)FS=TAN(PHII)/TAN(AII)
      ACCN=G*SIN(AII)*(1.0-FS)
```

```
      IF(S.EQ.0.0)S=0.67*H/SIN(AI1)
      WRITE(2,10)NO,FS,PHI,W,H,AI,S,RWL,G,GAMAW
10    FORMAT(/4X,74(1H*)/5X,'CASE =',I2//
     1 5X,'RESIDUAL FACTOR OF SAFTY              =',F10.4/
     2 5X,'RESIDUAL ANGLE OF FRICTION            =',F10.4/
     3 5X,'WEIGHT OF WEDGE (TOTAL)               =',E10.3/
     4 5X,'HEIGHT OF SLOPE                       =',F10.4/
     5 5X,'DIP OF LAND SLIDE                     =',F10.4/
     6 5X,'DISTANCE OF SLOPE MOVEMENT            =',F10.4/
     7 5X,'HEIGHT OF WATER ABOVE TOE             =',F10.4/
     8 5X,'ACCELERATION DUE TO GRAVITY           =',F10.4/
     9 5X,'UNIT WEIGHT OF WATER                  =',F10.4)
      IF(FS.GT.1.0)GO TO 100
C     CALCULATE MAXIMUM SLIDE VELOCITY(V)
      V2=2.*ACCN*S
      V=SQRT(V2)
C     CALCULATE THE KINETIC ENERGY OF LAND SLIDE (DIMENSIONLESS)
      KE=0.5*W*V2/(GAMAW*G*RWL**4)
C     ESTIMATE MAXIMUM HEIGHT OF WAVE
      WAVM=.0562341*(KE**.71)*RWL
C     CALCULATE WAVE HEIGHT AT DISTANCE RD FO LAND SLIDE
C     (ASSUME PEAK WAVE AT RD=4*RWL)
      WAV=4.*RWL*WAVM/RD
      IF(WAV.GT.WAVM)WAV=WAVM
      WRITE(2,20) WAVM,WAV,RD,V,KE
20    FORMAT(5X,'MAXIMUM WAVE HEIGHT DUE TO LAND SLIDE=',F10.4/
     1 5X,'HEIGHT OF WAVE                  =',F10.4/
     2 5X,'AT DISTANCE FROM LAND SLIDE     =',F10.4/
     3 5X,'MAXIMUM VELOCITY OF LAND SLIDE  =',F10.4/
     4 5X,'KINETIC ENERGY OF LAND SLIDE    =',F10.4//4X,74(1H*))
      NO=NO+1
      IF(NO-NCASE)2,2,100
100   STOP
      END
C ************************************************************************
      SUBROUTINE HELP(NHELP)
      WRITE(*,10)
      WRITE(2,10)
10    FORMAT(5X,74(1H*)/5X,'THIS PROGRAM CALCULATES THE '/
     *5X,'HEIGHT OF WAVE GENERATED IN A RESERVOIR DUE TO LANDSLIDE'/
     *5X,74(1H*)/
     *5X,'GIVE DATA IN THE FOLLOWING SEQUENCE :'//
     *5X,'NCASE ( = NUMBER OF PROBLEMS)'/
     *5X,'TITLE OF PROBLEM IN ONE LINE (<80 CHARACTERS)'/
     *5X,'FS,PHI,W,H,AI,S,RWL,G,GAMAW,RD'/
     *5X,'THE ABOVE TWO LINES ARE REPEATED NCASE TIMES.'/5X,74(1H*)/
     *5X,'ENTER 0 FOR TERMINATION'/11X,'1 fOR FURTHER HELP'/
     *11X,'2 FOR EXECUTION')
      READ(*,*) NHELP
      IF(NHELP.NE.1) GO TO 30
      WRITE(*,20)
      WRITE(2,20)
20    FORMAT(5X,74(1H*)/
     *5X,'AV    = COEFFICIENT OF VERTICAL EARTHQUAKE ACCELERATION'/
     *5X,'AH    = COEFFICIENT OF HORIZONTAL EARTHQUAKE ACCELERATION'/
```

```
      *5X,'AI     = DIP OF PLANE OR INTERSECTION OF JOINT PLANES'/
      *5X,'       = AVERAGE DIP OF CIRCULAR WEDGE'/
      *5X,'FS     = STATIC RESIDUAL FACTOR OF SAFETY OF THE SLOPE'/
      *5X,'         DURING LAND SLIDE. ( C = 0.0 & PHI = PHIR/2)'/
      *5X,'G      = ACCELERATION DUE TO GRAVITY'/
      *5X,'GAMAW  = UNIT WEIGHT OF WATER'/
      *5X,'H      = HEIGHT OF SLOPE'/
      *5X,'PHI    = ANGLE OF SLIDING FRICTION (= PHIR / 2 ) '/
      *5X,'RWL    = MEAN DEPTH OF RESERVOIR'/
      *5X,'RD     = DISTANCE OF LAND SLIDE FROM DAM'/
      *5X,'S      = DISTANCE OF MOVEMENT OF LAND SLIDE'/5X,74(1H*)/
      *5X,'ENTER 0 FOR TERMINATION'/11X,'2 fOR EXECUTION')
       READ(*,*) NHELP
 30    RETURN
       END
```
□