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Landslide Hazard and Risk Mapping in the Himalaya

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The building of new infrastructure in the Hindu-Kush Himalaya has greatly increased in recent times. Due to the lack of systematic investigations, these schemes are often faced with landslide problems. Sustainable development planning should guide the design and implementation of construction projects in the hills. This paper presents methods of assessing landslide hazards and risks in the Himalaya.

Introduction

Landslides are the most common natural hazards in the Hindu Kush-Himalaya region. The Himalaya is a geologically and ecologically fragile mountain ecosystem that has been the target of intense development activities over the past few decades. The planning, design and execution of development schemes, such as road and building construction are often carried out in an unplanned way due to financial, time and other constraints. As a result, many projects pay insufficient attention to the necessary geological and geo-technical situation. The resulting unstable slopes and the increased incidence of landslides results in rapid environmental degradation.

Sustainable development in a mountainous region refers in part to the implementation of development schemes taking into consideration the existing instabilities of the terrain so that the resultant geo-environmental hazards are minimised. Sustainable development has to be integral in the planning and implementation of projects in hilly areas. Systematic investigations need to be carried out that move from the regional to the local perspective. Initially areas should be studied on a regional scale (1:25,000 to 50,000) and a landslide hazard zonation (LHZ) map prepared to indicate the distribution of hazard prone slopes. While planning infrastructure projects, different site and alignment options should be considered and the one with the minimum hazard should be chosen for implementation. Where hazard prone slopes are unavoidable for construction, their recognition early on will help engineers to adopt suitable preventive measures.

Once the landslide hazard potential of an area has been assessed by the appropriate specialists, the next step is to formulate a risk assessment. The risk depends on both the hazard probability and the damage potential. Landslide management should be based on risk assessment; priority areas should be identified by estimating where most damage to human structures will occur. For example, an active landslide in a remote area will have a lower priority for intervention than a moderate hazard slope adjoining a densely populated area.

Methods of Landslide Investigations

The investigation of landslides has undergone significant developments in the past few decades. Several new techniques have been developed which have contributed to understanding the behaviour of landslides. Recently developed techniques for investigations on a regional scale have contributed significantly to the systematic planning of infrastructure development in hilly areas.

These methods further the understanding of landslides and help in designing control measures. The choice of any method is dependent on the objectives of the investigations in terms of the required accuracy and other details. The methods of analysis can be classified as empirical, detailed, and observational (Figure 11.1).

Empirical methods

The empirical approach relates experiences gained from previous field investigations of landslides to the existing slope conditions. On the basis of field experience, causative factors are identified and their influence in bringing about instabilities is studied. The qualitative nature of field conditions is quantified on the basis of a relative rating scheme.

The empirical approach is the most recent approach and has become the usual way of assessing rock slopes. Landslide hazard zonation (LHZ) mapping and landslide risk assessment (LRA) mapping fall into this category. These methods are economical as large areas can be covered in relatively short periods. Landslide hazard zonation (LHZ) is a macro-zonation approach that categorises an area into very stable, stable, moderately stable, unstable, and very unstable zones. It is useful for the preliminary planning stages of infrastructure schemes to steer them away from unstable areas. LRA mapping is particularly useful for landslide hazard management. Although many methods are available for LHZ mapping, there is a need to rationalise all these approaches. The mapping techniques based on the basic causative factors provide the more realistic results, since these factors are global and maps made in this way can be used effectively in different terrains. Empirical studies are usually done between scales of 1:25,000 and 50,000 to provide rapid assessments covering larger areas.

Detailed methods

Detailed methods include detailed studies of unstable slopes on scales of 1:1,000 to 1:5,000. They require knowledge of soil and rock properties, which can be obtained by a carefully planned and executed field and laboratory investigation. They can also be estimated by 'back analysis' whereby a known slope is analysed by assigning a suitable factor of safety, which gives various combinations of strength parameters from which realistic values are chosen. Detailed studies are also used to analyse different slope segments using the following parameters:

- nature of slope materials;
- attitude of geological discontinuities with reference to the slope;
- strength properties of the slope materials such as c (the cohesion) and ϕ (the friction angle);
- strength along the planes of discontinuities;
- section and height of the slope; and
- possible seepage water pressures.

These studies calculate the status of stability of slopes in terms of the factor of safety (FOS) by taking into consideration the total shear stresses acting on the planes of failure and the shear strength of the discontinuities. If a slope indicates a FOS of less than 1, then it is unstable and may require remedial measures. The nature of the remedial measures required for stabilisation can be identified on the basis of the FOS. This is also called a micro-zonation approach. It also includes the computer modelling of landslides by the discrete element method (DEM). Several computer programs have been developed to study failed or high hazard slopes.

Observational methods

Observational methods refer to instrumental monitoring of slopes. The surface monitoring of movements through pegs located on the slope is one popular technique. Extensometers or incli-

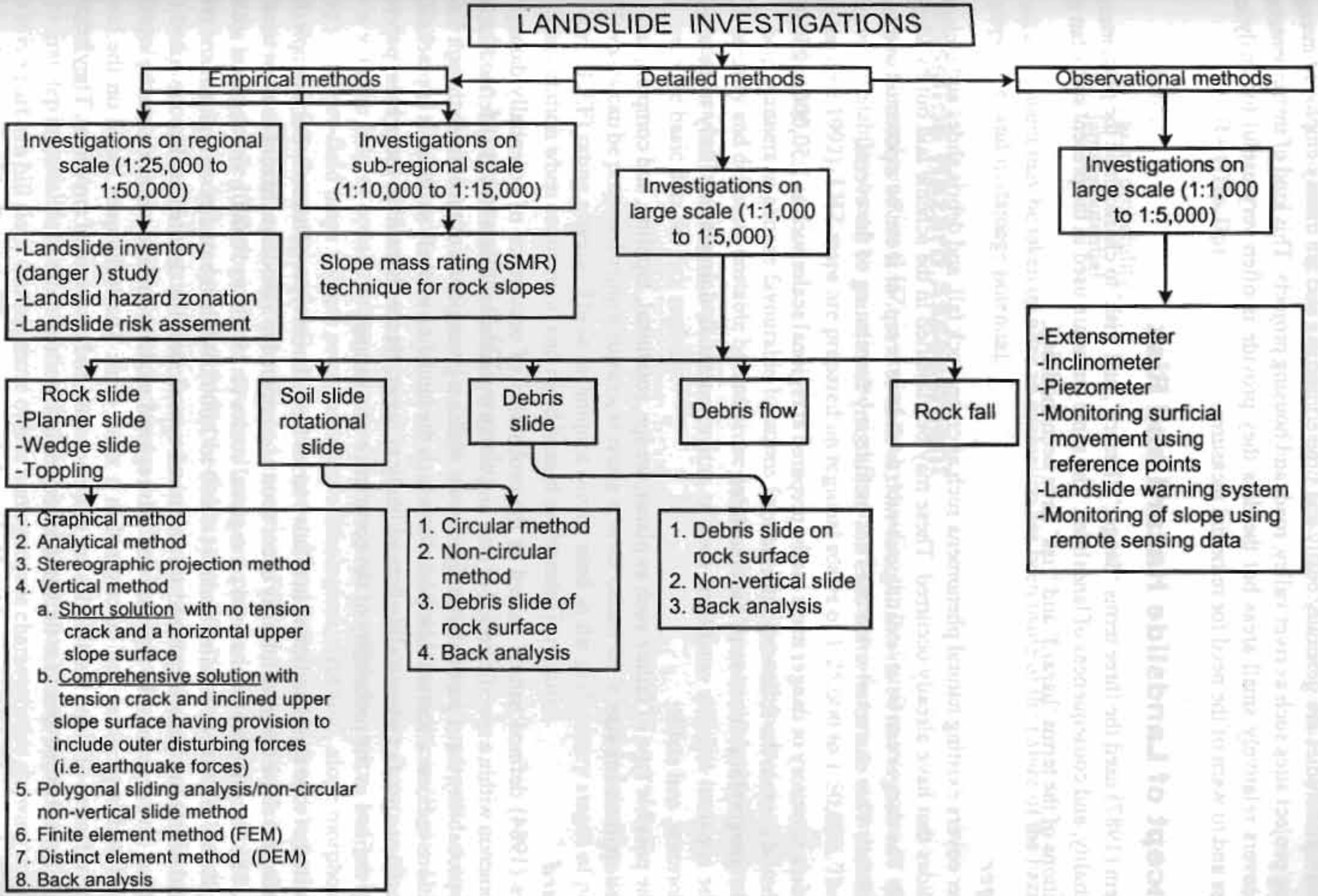


Figure 11.1: General methods of landslide investigations

nometers together with piezometers are also used to study and monitor deeper movements within unstable slopes. In these cases, the nature of movements over time is studied. However, these observational studies are generally costly and time consuming and are mainly employed in engineering project sites such as river valley, road, and housing projects. This kind of instrumentation only covers relatively small areas but the data they provide is often very useful for analytical studies and to warn of the need for remedial measures.

Concept of Landslide Hazard and Risk

Einstein (1987) used the three terms 'danger', 'hazard', and 'risk' to characterise the phenomena, potentiality, and consequences of landslides. The same terms are used in the present study but the definitions of the terms 'hazard' and 'risk' have been modified.

Danger

Danger covers existing natural phenomena such as creep, rock fall, and debris slides and includes landslides that have already occurred. These may be classified in the scheme laid out by Varnes (1978). The danger can be an existing one such as slide or creep, or it can be a potential one such as rock fall. This characterisation does not include any forecasting of the events.

Landslide inventory or danger maps can be prepared at regional scales such as 1:50,000 to 250,000 and should contain the following information:

- the geographical location of the landslides;
- the apparent stability conditions such as active, potential, dormant but likely to be active, dormant, and stable;
- the possible type of failure such as planar, wedge, rotational, toppling, and complex; and
- the approximate size.

Hazard

Varnes (1984) defined natural hazard as the probability of occurrence of potentially damaging phenomenon within a specific period of time and within a given area. Einstein (1987) defined hazard as the probability that a particular danger occurs within a given period of time. Even though these definitions indicate a limited time period in which the landslide is likely to occur, it is practically impossible to predict when a slide is most likely to occur. Hence 'hazard' in the present paper is simply defined as the probability of the occurrence of a danger.

The period of time can be indicated in relative terms for different types of hazards. For example, for a high hazard slope the landslide may occur soon as compared to a moderate hazard or a low hazard slope. The hazards may be analysed on regional scales (1:25,000 to 50,000), sub-regional scales (1:10,000 to 15,000), or detailed scales (1:1,000 to 2,000). While the studies on regional and sub-regional scales are generally based on empirical approaches, the detailed studies are based on analytical investigations. In regional and sub-regional studies, landslide hazards can be rapidly assessed and large areas can be covered in a short time. The techniques based on the basic causative factors of slope instabilities are more accurate and can be used anywhere. They help to identify hazard prone areas for further detailed studies.

Risk

The 'risk' of any slope refers to the probable extent of damage if a failure occurs. The damage may be in the form of loss or damage to life and property. The extent of damage will depend on the land use pattern of the area likely to be affected and the spread of population. A major landslide in a remote area will cause less damage than a smaller landslide in a densely populated area. Einstein (1987) defined risk as the product of hazard and the potential worth of loss. Since loss will vary with space and time, it is more logical to define risk as a function of hazard probability and the damage potential.

$$\mathbf{R = f(Hp, Dp)}$$

where,
Hp = hazard probability
Dp = damage potential

Risk assessment may be taken up after an evaluation has been made of the nature of the hazard of a slope facet and its damage potential.

Landslide Hazard Assessment

Landslide hazard zonation (LHZ) is carried out by dividing the land surface into zones of varying degrees of stability based on an estimated significance of causative factors to induce instability (Anbalagan 1992). LHZ maps are prepared on regional scales of 1:25,000 to 1:50,000. They are useful as they

- help planners to choose favourable locations for new building and roads;
- identify and delineate unstable hazard prone areas so that proper environmental regeneration measures can be initiated; and
- provide basic data for risk analysis.

LHZ maps can be prepared using a numerical rating scheme called the landslide hazard evaluation factor (LHEF) rating scheme. These techniques can be used in the preliminary stages of project implementation when economical and rapid hazard assessment is required.

Landslide hazard zonation (LHZ) mapping

LHZ maps indicate the probabilities of landslide hazards. They are generally prepared on scales of 1:25,000 to 1:50,000 and based on a combination of desk and field investigations (Figure 11.2). In the desk study, pre-field maps are prepared to show the status of causative factors in the study area with the help of aerial photographs, satellite imageries, topographic maps, and geological maps. The pre-field maps that are prepared include lithological, structural, slope morphometry, relative relief, rock outcrop and soil cover, land use and land cover, and hydrogeological maps. This information helps systematic planning and execution of field investigations. During the field study, more detailed lithological and structural maps are prepared. The details of other maps prepared during the desk study are verified in the field and modified if necessary. Field studies are carried out to collect the required data facet wise to estimate the total hazards of the facets. The general procedure of the LHZ mapping technique is outlined in Figure 11.2.

Procedure

The first step in landslide hazard zonation mapping is the preparation of a **slope facet** map. A slope facet is a part of a hill slope that has more or less homogeneous characteristics showing consistent slope direction and inclination. These are mostly bounded by ridges, spurs, gullies, or rivers. Local variations of slope inclination within a facet may be indicated as sub-facets. A slope facet forms the smallest unit of mapping. This kind of map is prepared from the topographical map of the study area.

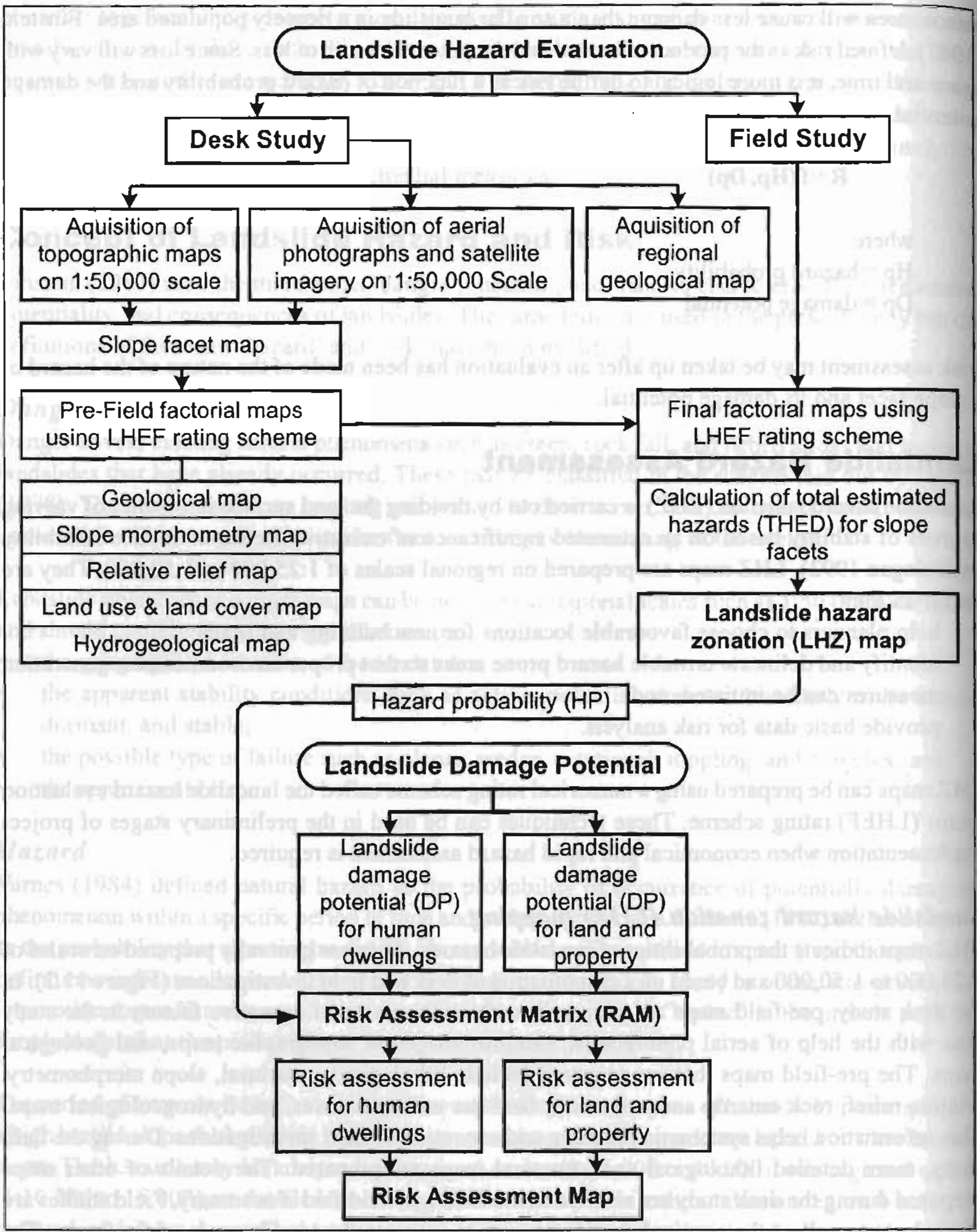


Figure 11.2: Procedure for landslide hazard mapping

The **landslide hazard evaluation factor** (LHEF) rating scheme is based on an empirical approach that combines the background knowledge of the causative factors of landslides with a study of those prevailing. The qualitative nature of field conditions can be quantified by relative rating schemes. Similar approaches have been adopted in the well-known rock mass classifications such as the rock mass rating (RMR) and Q systems (Barton et al. 1974; Bieniawski 1979).

The LHEF rating scheme is a numerical system based on the major inherent causative factors of slope instability such as geology, slope morphometry, relative relief, land use and land cover, and hydrogeological conditions. External factors such as rainfall and seismicity are not included in LHZ mapping as they are not part of the slope character and cannot be evaluated for assessing the landslide hazard of a slope facet. Such external factors are erratic and regional in nature and act over large areas. However when heavy rain or earthquakes occur, a high hazard facet is more likely to be triggered off than a low hazard one (Gupta and Anbalagan 1995). The maximum LHEF ratings for different categories are determined on the basis of their estimated significance in causing instability (Table 11.1). The maximum LHEF ratings value for the total estimated hazard (TEHD) is 10. A score of 10 describes a slope that is most likely to slide. Table 11.1 shows a detailed LHEF rating scheme with the maximum ratings related to individual causative factors.

Table 11.1: Maximum landslide hazard evaluation factor (LHEF) ratings

Contributory factor	Maximum LHEF ratings
Lithology	2.0
Relationship of structural discontinuities with slope	2.0
Slope morphometry	2.0
Relative relief	1.0
Land use and land cover	2.0
Groundwater conditions	1.0
Total	**10.0**

Geological maps provide information on the lithology and structure of the area. Lithological and structural maps are prepared separately where better representation is needed.

The erodibility, or the response of rocks to the processes of weathering and erosion, is the main criterion for judging the **lithology** of a slope and designating LHEF ratings. For example, quartzite, limestone, and igneous rocks are generally hard, massive, and resistant to erosion, and form steep slopes. In comparison, terrigenous sedimentary rocks are much more vulnerable to erosion and hence are more susceptible to landslides. Similarly, phyllites and schists are characterised by flaky minerals, which weather quickly and promote instability. A correction factor to allow for the extent of weathering of the rocks has been incorporated in the rating system. In the case of soil, genesis and age are the main consideration in awarding the ratings. Older alluvium is generally well compacted and has a high shear resistance. Recent materials such as slide debris are loose and have a low shearing resistance.

Structure includes primary and secondary discontinuities in the rocks such as bedding, joints, foliations, faults, and thrusts. The attitude of structural discontinuities in relation to slope inclination and direction has a great influence on the stability of slopes (see also Singh in this volume). Three types of relationships are considered important (Romana 1985):

- the extent of parallelism between the directions of the discontinuity, or the line of intersection of two discontinuities and the slope;
- the steepness of the dip of the discontinuity, or the plunge (dip) of the line of intersection of two discontinuities; and
- the difference in the dip of the discontinuity, or the plunge of the line of intersection of the two discontinuities to the inclination of the slope

The more discontinuities tend to be parallel to a slope, the greater is the risk of slope failure. When the dip of the discontinuity or plunge of the line of intersection of two discontinuities increases, the probability of failure also increases, because this angle may exceed the angle of friction for the discontinuity surfaces. The failure potential remains high, until the point where the dip of the discontinuity plane or the plunge of the line of intersection of the two discontinuities does not exceed the inclination of the slope. LHEF ratings have been assigned accordingly for various stability conditions (Table 11.2). If the problem is one of potential movement of soil rather than rock, the inferred depth of the soil cover is used as a basis for the ratings.

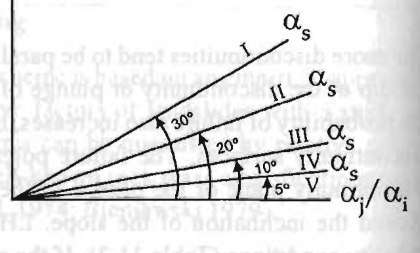
Table 11.2: Landslide hazard evaluation (LHEF) rating scheme			
Contributory Factor	Category	LHEF rating	Remarks
Lithology			
Rock Type	Type-I		*Correction factors for weathering*
	Quartzite and limestone	0.2	Correction factor C_1: Highly weathered - rock discoloured joints open with weathering products, rock fabric altered to a large extent
	Granite and gabbro	0.3	
	Gneiss	0.4	
	Type-II		Correction factor C_2: Moderately weathered - rock discoloured with fresh rock patches, weathering more around joint planes, but rock intact
	Well-cemented terrigenous sedimentary rocks, dominantly sandstone with minor beds of claystone	1.0	Correction factor C_3: Slightly weathered - rock slightly discoloured along joint planes, which may be moderately tight to open, intact rock
	Poorly cemented terrigenous sedimentary rocks, dominantly sandstone with minor clay shale beds	1.3	The correction factor for the observed degree of weathering should be multiplied by the fresh rock rating to get the corrected rating
	Type-III		For rock type I
	Slate and phyllite	1.2	$C_1 = 4$, $C_2 = 3$, $C_3 = 2$
	Schist	1.3	For rock type II
	Shale with inter-bedded clayey and non-clayey rocks	1.8	$C_1 = 1.5$, $C_2 = 1.25$, $C_3 = 1.0$
	Highly weathered shale, phyllite & schist	2.0	
Soil Type	Older well-compacted fluvial fill material (alluvial)	0.8	
	Clayey soil with naturally formed surface (eluvial)	1.0	
	Sandy soil with naturally formed surface (alluvial)	1.4	
	Debris comprising mostly rock pieces mixed with clayey/sandy soil (colluvial)		
	I. Older well compacted	1.2	
	II. Younger loose material	2.0	
Structure			
Relationship of structural discontinuity with slope			
Relationship of parallelism between the slope and the discontinuity*	I < 30°	0.20	
	II 21° - 30°	0.25	
	III 11° - 20°	0.30	
	IV 6° - 10°	0.40	
	V ≤ 5°	0.50	
Planar (α_j. α_s)			
Wedge (α_i. α_s)			Parallelism between the slope and the discontinuity (α_j /α_i. α_s)

Table 11.2 (cont'd)

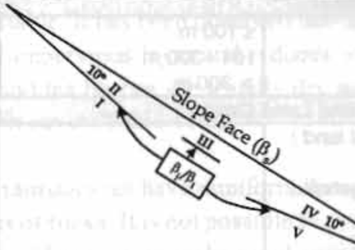
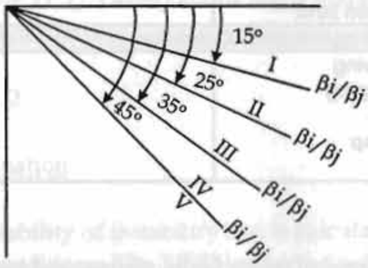
Contributory Factor	Category	LHEF rating	Remarks
Relationship of dip of discontinuity* and inclination Planar - $(\beta_j - \beta_s)$ Wedge - $(\beta_i - \beta_s)$	I > 15° II 0° - 10° III 0° IV 0° -(-10°) V -10°	0.65 0.85 1.30 2.00 1.20	 Relationship of dip of discontinuity and the inclination (dip) of slope $(\beta_j - \beta_r - \beta_s)$
Dip of discontinuity* Planar - β_j Wedge - β_i	I ≤ 15° II 16° - 25° III 26° - 35° IV 36° - 45° V > 45°	0.65 0.85 0.30 0.40 0.50	 Dip of discontinuity $(\beta_r - \beta_j)$ α_j = dip direction of joint α_i = direction of line of intersection of two discontinuities α_s = direction of slope inclination β_j = dip of joint β_i = plunge of line of intersection β_s = inclination of slope Category I = Very favourable II = Favourable III = Fair IV = Unfavourable V = Very unfavourable *Discontinuity refers to the planar discontinuity in the case of planar failure or the line of intersection of two planar discontinuities in the case of wedge failure, or whichever more is important
Depth of soil cover			
	≤5 m 6-10 m 11-15 m 16-20 m >20 m	0.65 0.85 1.30 2.00 1.20	
Slope morphometry			
Escarpment/cliff	45°	2.00	
Steep slope	36°-45°	1.70	
Moderately steep slope	26°-35°	1.20	
Gentle slope	16°-25°	0.80	
Very gentle slope	≤15°	0.50	

Table 11.2 (cont'd)

Contributory Factor	Category	LHEF rating	Remarks
Relative Relief			
Low	≤ 100 m	0.3	
Medium	101 - 300 m	0.6	
High	> 300 m	1.0	
Land Use and Land Cover			
Agricultural land / flat land		0.65	
Thickly vegetated area		0.85	
Moderately Vegetated area		1.20	
Sparsely vegetated area with lesser ground cover		1.50	
Barren land		2.00	
Hydrogeological Condition			
Flowing		1.00	
Dripping		0.80	
Wet		0.50	
Damp		0.20	
Dry		0.00	

In areas of major faults, thrusts, and intra-thrust zones, an extra rating of 0.5 may be awarded to take into account the higher susceptibility depending upon the intensity of fracturing.

Slope morphometry refers to the general slope angle with the horizontal. Slope morphometry maps define slope categories on the basis of the frequency of occurrence of different slope angles. The distribution of slope categories in any area is a result of the geomorphological history of an area. The angle of slope of each unit is a reflection of a series of micro-morphological processes and controls imposed on that facet. Slope morphometry maps are prepared by dividing the larger topographical map into smaller units defined by the slope facets. Five slope categories are used for slope morphometry study; different LHEF ratings are assigned for each (Table 11.2): escarpment/ cliff (>45^0); steep slope (35^0-45^0); moderately steep slope (25^0-35^0); gentle slope (15^0-25^0); very gentle slope (< 15^0).

On a topographical map of known scale, the number of contour lines per km of horizontal distance can be calculated for each category of slope morphometry. Thus the slope morphometry can be determined from a topographical map by counting the number of contour lines per unit distance for the slope.

Relative relief maps show the local relief, that is the maximum height between ridge tops and the valley floor within an individual facet. Thus they show the major breaks in the slopes of the study area. Three slope categories of relative relief have been chosen for hazard evaluation purposes and assigned different LHEF ratings: low (<100m), medium (101-300m) and high (>300m).

The type of **land cover** that a slope has is an indirect indicator of the stability of that slope. Barren and sparsely vegetated areas have faster rates of erosion and greater instability than areas that are thickly vegetated (as often found in reserves or protected forests). Forest cover, in general, hinders the negative action of climatic agents on slopes and protects them from the effects of weathering and erosion. A well-spread root system increases the shearing resistance of slope material. Agriculture (the **land use**) is generally practised on gentle to very gentle slopes; though moderately steep slopes are also cultivated where land is in short supply. The water levels of irrigated agricultural land are frequently recharged which makes them more stable. It has been observed that the humus produced by grass on slope surfaces provides a natural impervious layer and reduces seepage of run-off water into the slope. Slopes turfed with grass and tea bushes are usually dry and stable. Ratings are awarded based on the intensity of vegetation cover (Table 11.2).

Hydrogeological conditions — Groundwater in hilly terrain does not have a uniform flow pattern as it is generally channelled along structural discontinuities of rocks. It is not possible to evaluate the behaviour of groundwater on hill slopes over large areas. However, to make rapid appraisals, the nature of surface indications of the behaviour of groundwater will provide valuable information on the stability of hill slopes for hazard mapping. The presence of surface water such as damp, wet, dripping, or flowing areas are used for rating purposes (Table 11.2). Observations taken immediately after the monsoon will show the worst groundwater conditions.

The **LHEF ratings** for all these factors are given in Table 11.2.

Calculation of total estimated hazard (TEHD) and hazard zonation

The **total estimated hazard** (TEHD) indicates the net probability of instability and is calculated facet-wise, as adjoining facets may have different stability conditions. The TEHD of an individual slope facet is obtained by adding the ratings of the individual causative factors obtained from the LHEF rating scheme.

TEHD value = ratings of lithology + structure + slope morphometry + relative relief + land use and land cover + hydrogeological conditions

The TEHD scores allow slopes to be assigned to one of five categories of landslide hazard: very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH), (Table 11.3).

Table 11.3: **Landslide hazard zonation on the basis of total estimated hazard (TEHD)**

Zone	TEHD value	Description of zone
I	<3.5	very low hazard (VLH) zone
II	3.5 - 5.0	low hazard (LH) zone
III	5.1 - 6.0	moderate hazard (MH) zone
IV	6.1 - 7.5	high hazard (HH) zone
V	>7.5	very high hazard (VHH) zone

Case study of landslide hazard zonation from the Kumaun Himalaya, India

A landslide hazard zonation map was made for the Tanakpur-Sukhidhang area in the south-eastern part of the Kumaun Himalaya in Uttar Pradesh, India. This area covers about 70 sq.km and includes two well-defined physiographic regions: the Siwalik hill range (Outer Himalaya) in the south, which extends to Balkholi, and the Lesser Himalaya region further north (Figures 11.3 and 11.5). The Tanakpur-Ghat-Pithoragarh road, a strategically important road, passes through the centre of the area. A slope facet map (Figure 11.4) was prepared for the purposes of LHZ mapping,. Using this as a base map, other thematic maps were prepared including a lithological map (Figure 11.5), structural map (Figure 11.6), slope morphometry map (Figure 11.7), relative relief map (Figure 11.8), land use and land cover map (Figure 11.9), and hydrogeological map (Figure 11.10). From these maps, the total estimated hazard (TEHD) was calculated facet-wise and presented as a landslide hazard zonation (LHZ) map (Figure 11.11).

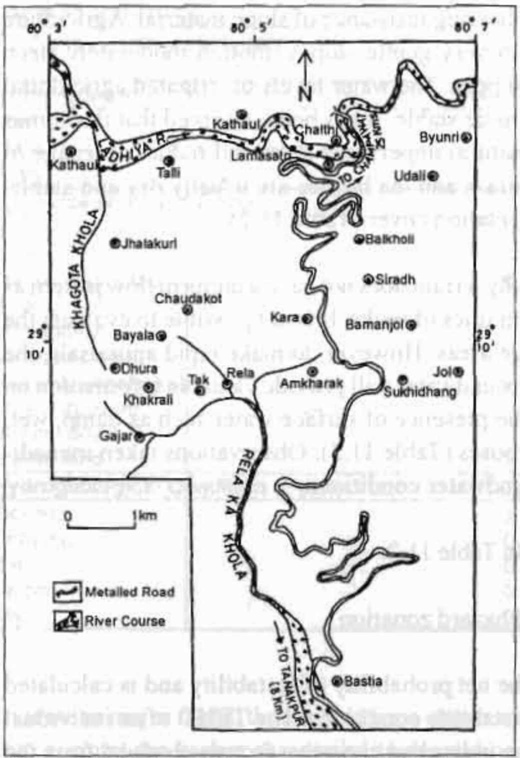


Figure 11.3: Location map of Sukhidhang area

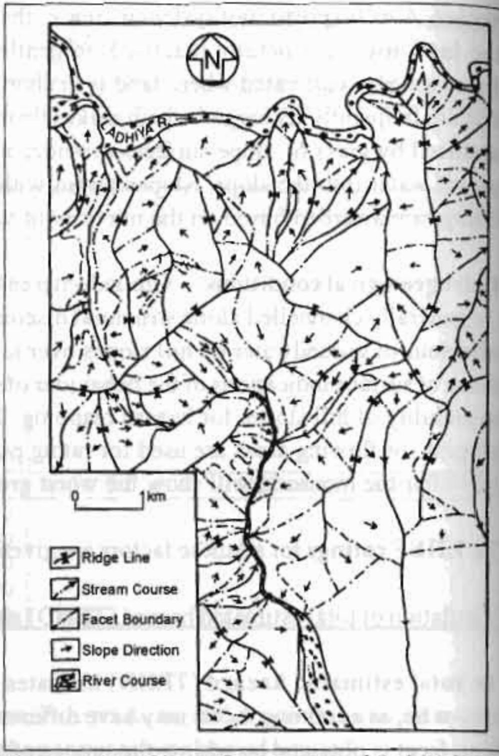


Figure 11.4: Slope facet map of Sukhidang area

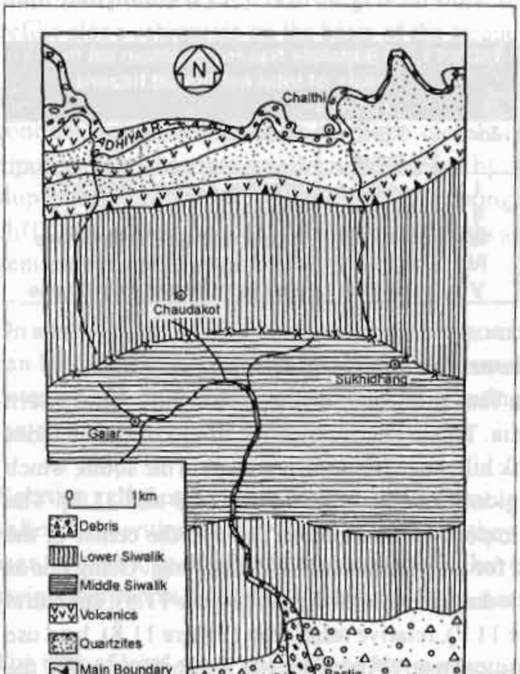


Figure 11.5: Lithological map of Sukhidang area

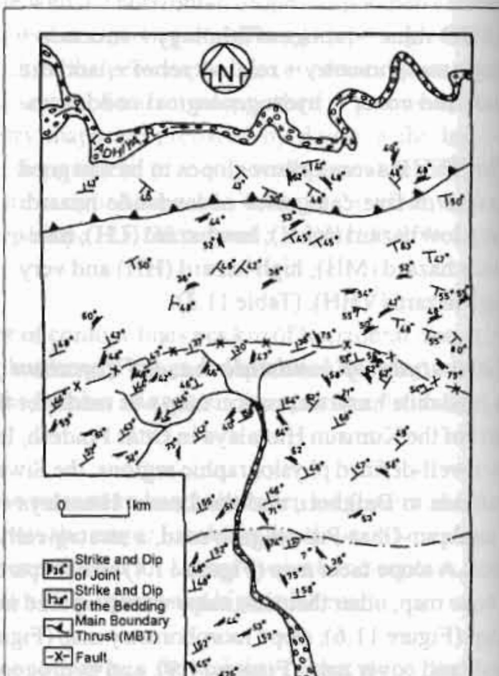


Figure 11.6: Structural map of Sukhidang area

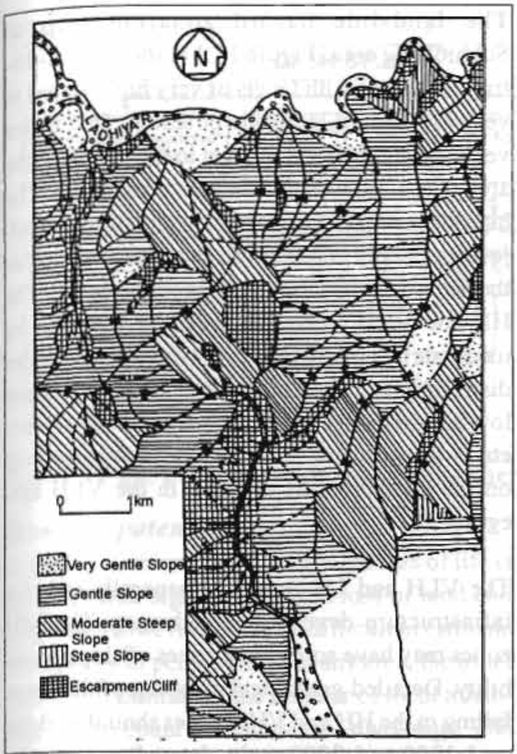


Figure 11.7: **Slope morphometry map of Sukhidang area**

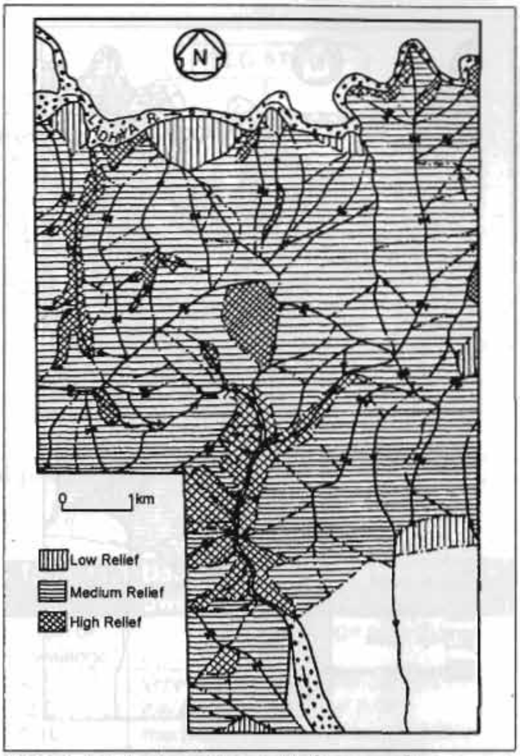


Figure 11.8: **Relative relief map of Sukhidang area**

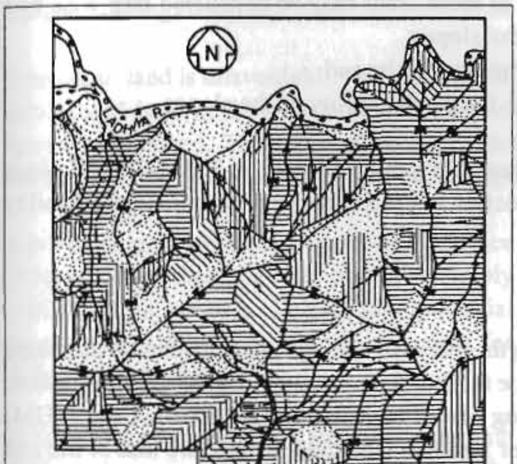


Figure 11.9: **Land use and land cover map of Sukhidang area**

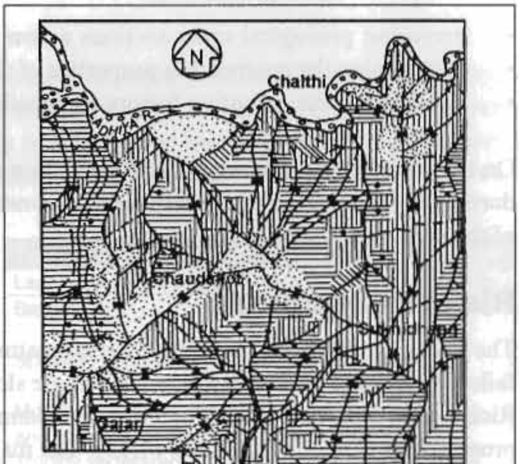


Figure 11.10: **Hydrogeological map of Sukhidang area**

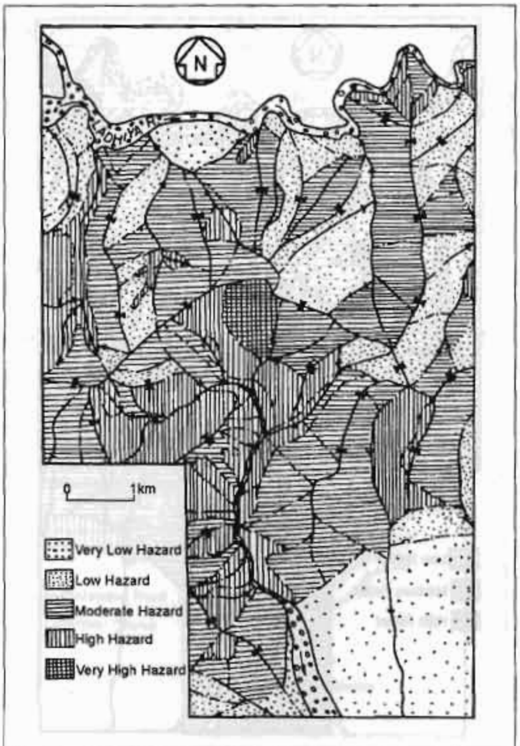


Figure 11.11: **Landslide hazard zonation map of Sukhidang area**

The landslide hazard zonation map of Sukhidhang area (Figure 11.11) shows well-distributed zones with facets of very high hazard to very low hazard landslide potential. One major very high hazard (VHH) facet in the middle of the area near Chaudakot is an active landslide. The high hazard (HH) facets are generally seen adjoining deeply dissected stream courses such as the Rela-Ka Khola and Khagota streams. The HH and VHH facets are generally bounded by moderate hazard (MH) facets, which have a wider distribution in the study area. There are many low hazard (LH) and very low hazard (VLH) facets in the northern part. The loose fan deposits on the southern part also fall in the VLH category.

The VLH and LH zones are generally safe for infrastructure development schemes. The MH zones may have some local zones of slope instability. Detailed geological mapping of the areas falling in the HH and VHH zones should be done on 1:1000 to 1:2000 scale, depending upon the total area of the facet. The factor of safety (FOS) of these areas may be calculated step-wise by

- preparing geological cross-sections across the slopes;
- determining the engineering properties of slope materials; and
- determining the causative factors responsible for the instability of the slopes.

On the basis of this, preventive and mitigation measures can be adopted in HH and VHH zones during implementation of any engineering construction to protect the geo-environmental stability of the area.

Risk Assessment

The risk assessment of a slope involves estimating the extent of damage likely to result if that slope fails. The damage may be restricted to a single slope facet or it may extend into the adjoining facets. Risk assessment (RA) maps are useful for planning proper landslide hazard management (LHM) programmes (Figures 11.12 and 11.13). The major forms of landslide damage are loss of life and injuries, and loss of land and property. The former may be significant, particularly when a landslide occurs suddenly – usually under adverse conditions of cloudbursts and/or earthquakes. In general, damage to land and property is unavoidable. These two types of damage have to be evaluated separately for the purposes of risk assessment. [Editor's note. The approach outlined here does not include an assessment of economic impact on areas beyond the actual area of damage, for example the economic impact resulting from disruption of goods transport when a road is impassable. This cost can be considerable, however, particularly in mountain areas served by a single road link, and should also be included in the assessment if possible.] The procedure for RA mapping is outlined as a flow chart in Figure 11.12.

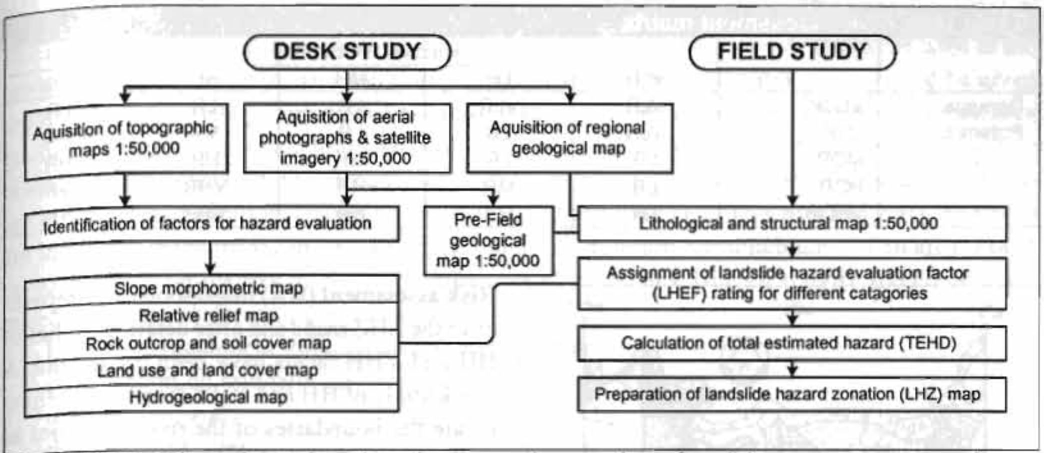


Figure 11.12: **Flow chart showing the general procedure for risk assessment mapping**

Damage potential

In risk assessment, the potential for loss of life is given greater significance than loss of land and property. However, it may be difficult to estimate the number of people living in any area; the usual method of estimating the number of local inhabitants is to count the number of dwellings. The history of damage may also be assessed on the basis of experience. The damage potential to human dwellings is rated as shown in Table 11.4.

Table 11.4: **Damage potential for human dwellings**

No. of dwellings	Status of damage potential
<2	very low damage potential (VLDP)
2-5	low damage potential (LDP)
5-10	moderate damage potential (MDP)
10-50	high damage potential (HDP)
>50	very high damage potential (VHDP)

Damage to land is unavoidable when a landslide occurs. Affected areas may include barren land, agricultural land, and forest land. Forested land may be thickly, moderately, sparsely, or very sparsely vegetated. The types of property likely to be affected by landslides include houses, roads, mines, offices, factories, schools, playgrounds, parks, and other (engineering) structures.

Since properties are located on the land surface likely to be affected, they can be shown simply with different symbols. The damage potential status scheme shown in Table 11.5 is used for different land types.

In Table 11.5 agricultural land has been joined with moderately vegetated land because they have the same moderate damage potential characteristics. Agricultural land is often indicated by some additional symbol on the risk map (Figure 11.13).

Table 11.5: **Damage potential for land types**

Land category	Status of damage potential
Barren	very low damage potential (VLDP)
Sparsely vegetated	low damage potential (LDP)
Moderately vegetated and agricultural land	moderate damage potential (MDP)
Thickly vegetated	high damage potential (HDP)
Very thickly vegetated	very high damage potential (VHDP)

Assessment of risk

The total estimated hazard (TEHD) of slope facets as drawn on landslide hazard zonation (LHZ) maps is the hazard probability (Hp) of slope facets. HH and VHH slopes obviously pose the highest risks. The damage potential will vary depending on the hazard potential of a slope facet; the relationship is indicated in a risk assessment matrix (RAM) (Table 11.6). The calculations are performed twice, once for risk to human dwellings and once for risk to land and property.

Table 11.6: Risk assessment matrix

		Hazard Probability →				
		VLH	LH	MH	HH	VHH
Damage Potential ↓	VLDP	VLR	VLR	LR	LR	LR
	LDP	VLR	LR	LR	MR	MR
	MDP	LR	LR	MR	HR	HR
	HDP	LR	MR	HR	VHR	VHR
	VHDP	LR	MR	HR	VHR	VHR

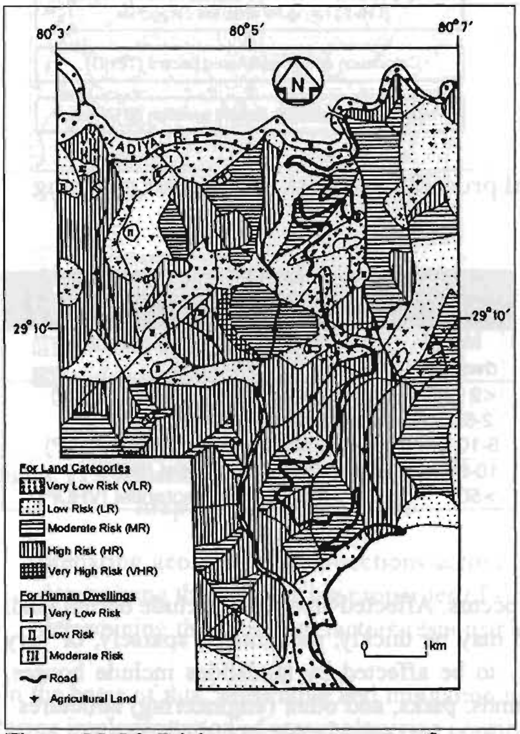


Figure 11.13: **Risk assessment map of Sukhidang area**

Risk assessment (RA) maps should be prepared after the LHZ maps and after detailed studies of HH and VHH facets have been carried out. A quick study of HH and VHH facets will help to locate the boundaries of the risk categories as well as to understand the nature of causative factors and the likely types of failure. Moreover the land use and land cover map prepared during the LHZ mapping and data on the distribution of human dwellings and other structures will help inform the risk assessment.

The boundaries of the risk categories may lie within the same slope facets as the hazard, entirely outside the facet, or partly within and partly outside. For example, if a human settlement is located on a stable slope adjoining a steep cliff, the risk from the unstable cliff face may lie entirely outside the facet containing the cliff. Hence, risk assessment maps may have different zone boundaries to LHZ maps.

The following factors are considered, when deciding on the boundaries of the risk categories.

- **Topography of the area** – Both the slope facet in which the hazard exists and the adjoining facets are important. If the hazard containing slopes are steeper, the risk may encroach onto adjoining slope facets, particularly at lower levels. Tension cracks likely to be caused by a landslide may affect adjoining slopes at higher levels.
- **Nature of failure** - Debris flow along gullies can penetrating far into adjoining slopes at lower levels. Rock falls may be only occasionally active, but are more likely to affect slopes further down. Planar, wedge, and rotational failures may affect the peripheral regions of adjoining facets. Before the actual failure, the effects of distressing may be seen on the slopes.
- **Geological factors** – For rock slides, the type of rock, the extent of fractionation, the attitude of critical discontinuities, and the nature of weathering are important in deciding how far the risk from a particular slope failing will spread.

The boundaries of the zones of risk to human dwellings are usually shown with specific symbols. The risk to other engineering structures and properties may also be indicated by different symbols. The risk assessment map for Sukhidang area is shown in Figure 11.13.

Landslide hazard management and the use of risk assessment (RA) maps

The risk assessment map indicating the threats to people, land, and property should be used as the basis for planning a risk management programme. High and very high risk areas should be given top priority for initiating remedial and control measures. Immediate short-term measures include grading of slopes, improving drainage, and building retaining walls. Long-term measures include biotechnical stabilisation, maintenance of existing drainage, and provision of sub-surface drainage, anchors, and additional catch water drains. Afforestation and other precautionary measures are important in the management of high-risk areas. In addition, the inhabitants of an area should be educated about the risk, and the consequences of landslides. Human activity should be minimised in risk prone areas by preventing

- human encroachment into the natural water courses;
- urbanisation on critically stable slopes;
- overgrazing; and
- the cutting of trees.

Since the damage potential is a variable parameter, risk assessments may need to be modified over time. In the case of progressive failures, the risk zone boundaries will expand unless long-term stabilisation measures are implemented.

Specific risks due to landslide hazards in the Hindu-Kush Himalaya

The fragile mountain ecosystems of the Hindu-Kush Himalaya are characterised by complicated geology, steep slopes, and extreme climatic conditions. They are very susceptible to landslides, and catastrophic slides often occur. Some particularly important hazards in the Himalayan region are described below.

Landslide dams

Major deep-seated landslides in the Himalaya may result in the transportation of huge amounts of debris along long steep gullies to form dams behind which reservoirs of water can build up. Such dams are usually unstable and will often burst within a few hours or days or after longer times. The resultant surging floodwater can destroy riverbanks, constructed dams, roads, buildings, and bridges. Major examples of this phenomenon include the Gohna landslide dam along the Alaknanda River, the Kanauldhia Gad landslide dam on the Bhagirathi River, and the Diexi landslide dam in China.

Debris flow

Long, steep gullies often witness sudden flows of debris (mixtures of rock, earth, and other inorganic material) from upper levels that can engulf everything in their path. During continuous periods of rain (>one week), groundwater levels may rise steeply to above the effectively impervious bedrock. At places where the debris cover is thin (<5m), water levels may rise to close to the surface. The high water pressure and resultant loss of grain-to-grain contact may induce a landslide which then becomes a debris flow. The resultant fast flowing viscous liquid charged with debris may cause large-scale toe erosion leading to more landslides further down.

Rock jumping

The steep rocky slopes of the Himalayan terrain are traversed by joints and may often release loose rock blocks as a result of loosening caused by freezing and thawing action along the joints or during earthquakes. The random unpredictable release of rock blocks may cause devastation in the areas below. The steep Naina peak of Nainital, Kumaun is a classic example of rock jumping problems, which have continued for more than a century. During major earthquakes (>6 magnitude), the rock-jumping problem is serious and causes severe damage.

Surface erosion

The Himalayan mountain range is the youngest in the world and is highly erosion prone. The rocks are weak and erodible with steep slopes. There is a wide range of estimates of denudation rates of the mountains (0.5 to 20 mm/year), but the overall average rate of about 7 mm/year indicates a high rate of erosion (Ives and Messerli 1987).

Forest fires

Forest fires often occur in the Himalaya during periods of hot weather and can contribute to the development of landslides. These fires burn away the vegetation cover exposing the soil to atmospheric hazards, in particular accelerated erosion and excessive infiltration of water into the slope during times of heavy rain. This can trigger a landslide.

A case study of risk assessment in the Sukhidang area

A risk assessment map was prepared as described above to show the landslide hazard and damage potential in the Sukhidang area. First a landslide hazard zonation (LHZ) map was prepared from six factorial maps using the LHEF rating scheme (Figures 11.5 to 11.10). The total estimated hazard (TEHD) was calculated facet-wise for the landslide hazard zonation map (Figure 11.11).

The damage potentials were evaluated using the ratings shown in Tables 11.4 and 11.5. The damage potential and landslide hazard were combined to give a risk assessment map for land categories and human dwellings (Figure 11.13). The main role of these maps is to help field engineers and engineering geologists to identify the highest risk zones so that they can prioritise remedial measures.

The risk assessment map of the Sukhidang area (Figure 11.13) shows that the high and very high risk slopes are mostly located along the sides of the south-flowing Rola-ka Khola stream and the north-flowing Khagota stream, both of which lie in steep valleys, apart from a few isolated high-risk slopes in the north-eastern and eastern parts of the area. Low to moderate risk slopes are found throughout the area. Human dwellings and agricultural lands are mostly located on the low risk slopes with some on the medium risk slopes. The highest risks to human dwellings are found on the medium risk slopes. The Tanakpur-Sukhidang-Champawat road runs mostly along low to moderate risk slopes, except in a few locations where the road passes high-risk slopes. At such points the road has been built close to the ridge tops to avoid major stability problems. A detailed risk map was prepared for the road using the damage potential indicators and the modified slope mass rating (SMR) technique of Anbalagan et al. (1992) on a 1:10,000 scale to evaluate the hazard. The method is described below.

Risk assessment of slopes for roads

Hazard assessment

Romana (1985) developed a Slope Mass Rating (SMR) technique as a special application of Bieniawski's (1979) rock mass rating (RMR) classification, which was developed to measure the stability of rock slopes. The SMR is a useful tool for the preliminary assessment of cut slopes in rocks. It helps engineers to assess the relative hazard of rock slopes without actually calculating the factor of safety. It follows some simple rules about instability modes and the required support measures.

The SMR technique uses the rock mass rating (RMR) classification to evaluate the rock mass quality. The relative hazards of instability are indicated on the basis of studies and experience with attitudes of discontinuity and slope, failure mode, and slope excavation methods.

The following parameters are measured to give the Rock Mass Rating (RMR).

- uniaxial compressive strength of rock material
- rock quality designation (RQD)
- spacing of discontinuities
- condition of discontinuities
- ground water condition

These are all measured either in the field or from boreholes. These five parameters are classified into various sub-categories that have been assigned different relative values (Table 11.8). The sum of the weighted ratings of individual parameters indicates the overall rock mass quality.

Bieniawski (1979) defines the RMR_{basic} as the basic parameter of rock mass quality. Romana (1985) calculates the SMR from the following formula.

$$SMR = RMR_{basic} + (F1 * F2 * F3) + F4$$

Table 11.8: Rock mass rating calculation matrix (Bieniawski 1979)

Parameter	Range of values						
1. Strength of intact rock material							
Point load strength index (MPa)	>10	4-10	2-4	1-2	For these low ranges the uniaxial compressive test is preferred		
Uniaxial compressive strength (MPa)	>250	100-250	50-100	25-50	5-25	1-5	<1
Rating	*15*	*12*	*7*	*4*	*2*	*1*	*0*
2. Drill Core Quality RQD%							
	90-100		75-90	50-75	25-50	<25	
Rating	*20*		*17*	*13*	*8*	*3*	
3. Spacing of discontinuities							
	>2 m	0.6-2 m	200-600 mm		60-200 mm		<60 mm
Rating	*20*	*15*	*10*		*8*		*5*
4.Condition of discontinuities							
	Very rough surfaces, not continuous; no separation; unweathered wall rock		Slightly rough surface; separation <1 mm; Slightly weathered walls	Slightly rough surface; separation <1 mm; highly weathered walls	Slickensided surfaces; gouge <5 mm; separation 1-5 mm; continuous	Soft gouge >5 mm; separation >5 mm; continuous	
Rating	*30*		*25*	*20*	*10*	*0*	
5. Groundwater in joints							
	Completely Dry		Damp	Wet	Dripping	Flowing	
Rating	*15*		*10*	*7*	*4*	*0*	
(high value is favourable, low is unfavourable)							

The parameters F1, F2, F3 are empirically established adjustment values for joints and F4 an adjustment factor for the method of excavation.

- F1 is a measure of the relative parallelism between a discontinuity and the slope face. It ranges from 1.00, when both sides are nearly parallel, to 0.15 when the angle between them is more than 30° and the failure probability is very low.
- F2 is a measure of the dip of discontinuity. It ranges from 1 for joints dipping more than 45°, to 0.15 for joints dipping less than 20°. In the toppling mode of failure, F2 remains 1.00.
- F3 is a measure of the relationship between the dip of discontinuity and the inclination of the slope. The conditions are fair when the slope face and the discontinuity are parallel. Unfavourable conditions occur when the slope dips 10° more than the discontinuity.
- F4 is an empirical adjustment factor for the method of excavation.

Here, the term discontinuity refers to the planar discontinuity in the case of potential plane failure or the line of intersection of two planar discontinuities in the case of potential wedge failure, whichever is more important. The values for F1 to F3 are given in Table 11.9, those for F4 in Table 11.10.

Table 11.9: Adjustment rating for joints (Romana 1985)

Case		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
P	$\alpha_j - \alpha_s$	>30°	30°-20°	20°-10°	10°-5°	<5°
T	$\alpha_j - \alpha_s - 180°$					
P/T	F1	0.15	0.40	0.70	0.85	1.00
P	β_j	<20°	20°-30°	30°-35°	35°-45°	>45°
P	F2	0.15	0.40	0.70	0.85	1.00
T	F2	1	1	1	1	1
P	$\beta_j - \beta_s$	>10°	10°-0°	0°	0°- (-10°)	<-10°
T	$\beta_j + \beta_s$	<110°	110°-120°	>120°	-------	--------
P/T	F3	0	-6	-25	-50	-60

P plane failure; α_s slope dip direction; β_s slope dip
T toppling failure; α_j joint dip direction; β_j joint dip

Table 11.10: Adjustment rating for methods of excavation (Romana 1985)

Method	F4
Natural slope	+15
Pre-splitting	+10
Smooth blasting	+8
Mechanical blasting	0
Deficient blasting	-8

Romana (1985) used plane and toppling failure modes for his analysis. The wedge failures were considered as special cases of plane failures and were analysed in terms of individual planes. The minimum value of SMR was taken to assess the rock slopes. However, this analysis is limited because where a wedge is unstable the instability results from the combined effect of the intersection of two joints. This can be shown by looking at a typical example (Figure 11.14). Supposing, there are two joint sets with dips of 45° and 35° towards the dip directions of N66°E and N35°W respectively. The inclination of the slope is 55° towards N10°E. The plunge and trend of the line of intersection of these wedge-forming joints are 28° and N4°E respectively. According to the SMR approach suggested by Romana (1985), the SMR value for the above two joints should be worked out separately and the critical value of SMR should be used for the classification. The adjustment factor (F1*F2*F3) calculated from Table 9 is -6.4 for the first joint and -6.3 for the second joint; but it is -20.4 for the plunge and the trend of the line of intersection of the joints. Thus it is better to estimate wedge failure on the basis of the plunge and trend of the line of intersection.

Anbalagan et al. (1992) recommended a modified SMR technique in which plane and wedge failures are treated as different cases. The method of Romana (1985) is followed to estimate SMR in cases of potential plane failure, but the plunge and direction of the line of intersection are used for potential wedge failure. This technique has been accepted as an Indian Standard by the Bureau of Indian Standards (BIS).

The SMR values are used to classify the slopes into stability classes (Table 11).

The critical slope facets need to be identified and the RMR_{basic} assessed in the field. In rock masses, movement leading to slope failure will occur along the surfaces formed by one or more sets of the geological discontinuities. The likely failure mode is determined by stereographic analysis of the geological discontinuities as they present on the slope face. Depending upon the size and structural complexity of the slope, 10 to 100 readings of the geological discontinuities will need to be made. These observations are plotted in an equal area stereo-net and contoured to show the maxima of pole concentrations. The most likely mode of failure can be identified from the pattern of maxima of pole concentrations.

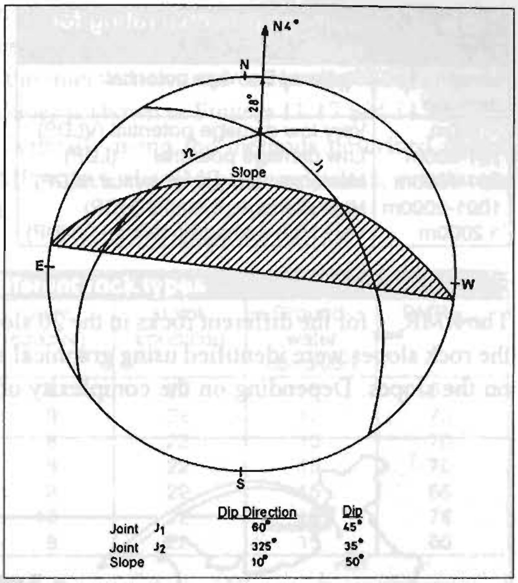


Figure 11.14: **Stereo-plot for wedge analysis**

Table 11.11: Slope mass rating (SMR) classes and hazard probability (modified from Romana 1985)

Class no.	I	II	III	IV	V
SMR	81-100	61-80	41-60	21-40	0 - 20
Description	Very good	Good	Normal	Bad	Very bad
Stability	Completely stable	Stable	Partially stable	Unstable	Completely unstable
Failures	None	Some blocks	Some joints, or many wedges	Planar, big wedges	Big planar, or soil like
Support	None	Occasional	Systematic	Important, corrective	Re-excavation
Hazard Probability	VLH	LH	MH	HH	VHH

Remedial measures to stabilise hazard-prone slopes can be recommended based on the SMR ratings. Very unstable slopes may require re-excavation and modification of their geometry. Unstable slopes may need extensive corrective measures including partial slope modification, rock anchors, and shotcreting in addition to drainage measures. Partially stable slopes may have to be supported with systematic supports such as rock bolts and rock anchors. The safe cut for slopes of less than 20m height can be determined from Table 9 by varying the slope angle ($ß_s$) until the SMR of the cut slope comes to more than 60 or any other determined value.

Risk assessment

Risk is the product of hazard probability (Hp) and damage potential (Dp). For a road, the hazard probability is obtained using the modified SMR approach (Table 11.11) and the damage potential is determined from Table 11.12. The risk assessment is then made from these using the risk assessment matrix (Table 11.7). An example is given below.

Table 11.12: Damage potential rating for roads	
Length of damage	Status of Damage potential
<100m	Very low damage potential (VLDP)
101-500m	Low damage potential (LDP)
501-1000m	Moderate damage potential (MDP)
1001-2000m	High damage potential (HDP)
>2000m	Very high damage potential (VHDP)

Case study of stability analysis for a road

The Lakshmanjhula-Shivpuri road lies in the Garhwal Himalaya (Figure 11.15). It passes through the Lesser Himalaya along slopes of varying stability. Twenty excavated hill slopes with different rock types, were selected for stability analysis using the modified SMR approach. The geology of the area is shown in Figure 11.16.

The RMR_{basic} for the different rocks in the 20 slopes are given in Table 11.13. The failure modes in the rock slopes were identified using graphical analysis of the geological discontinuities observed on the slopes. Depending on the complexity of a slope, 50-100 readings were taken of the geo-

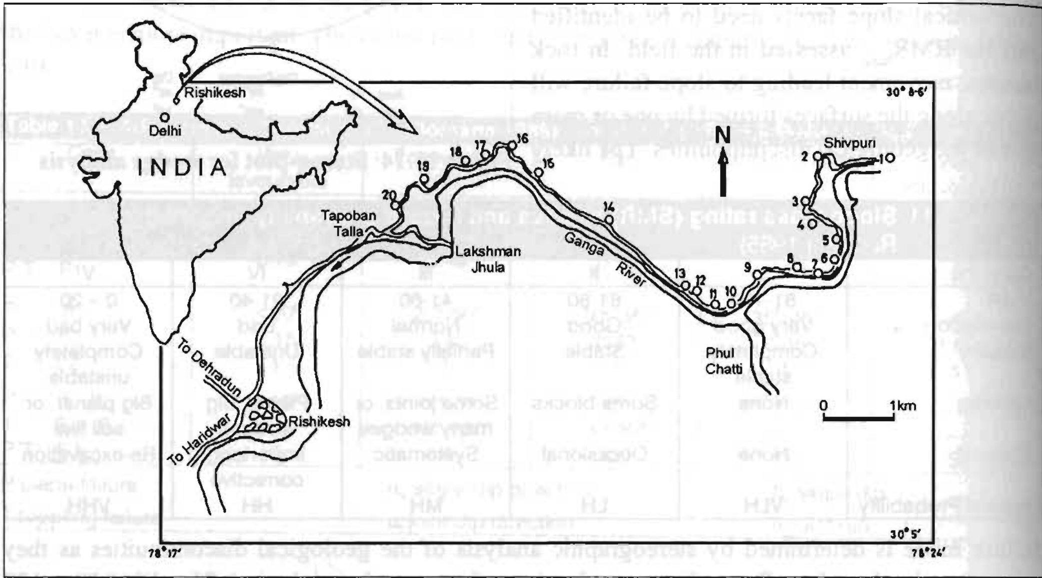


Figure 11.15: Location map of the Lakshmanjhula-Shivpuri road study area

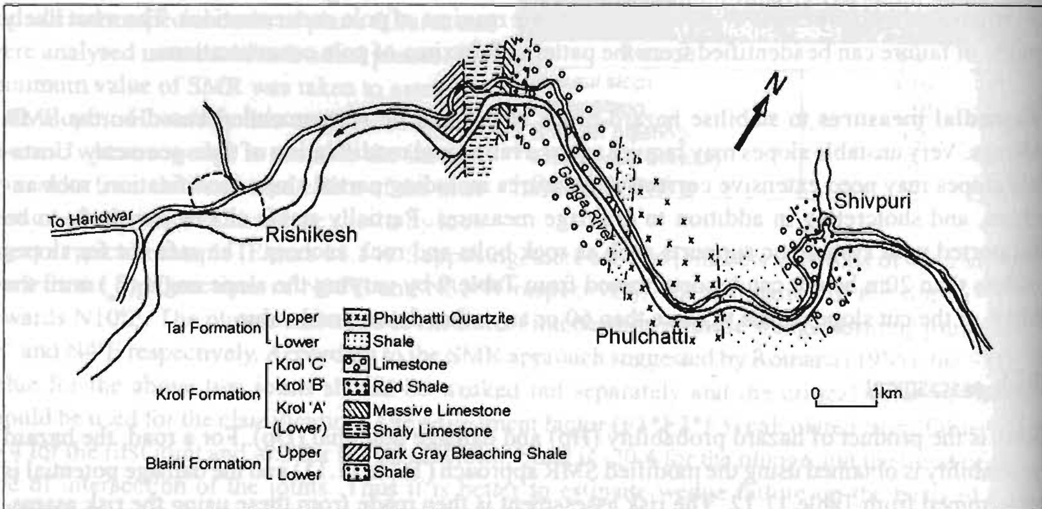


Figure 11.16: Geological map of the Rishikesh-Shivpuri area

logical discontinuities and the poles plotted on an equal area stereo-net which was contoured to show the maxima of pole concentrations. The most likely modes of failure were determined by studying the orientation of the various joints and the intersections and comparing them with the slope. The stereographical analysis of individual slopes is shown in Figures 11.17 and 11.18. The SMR classes were calculated for each slope individually using the methods described above (Tables 11.9, 11.10, and 11.11). The calculated SMR values, the SMR (hazard) class, and the required support measures are shown in Table 11.14.

Table 11.13: Rock mass rating (RMR) for the different rock types

Rock Type	Uniaxial compressive strength	RQD	Joint spacing	Joint condition	Groundwater condition	RMR_{basic}
Infra Krol Shale	7	13	8	22	15	65
Krol 'A' Shali Limestone	12	13	8	22	15	70
Krol 'B' Shale	12	13	8	22	15	70
Krol 'C' Limestone	12	13	8	22	15	70
Lower Tal Shale	7	13	8	22	15	65
Upper Tal Quartzite	12	17	10	22	15	76
Blaini Shale	7	13	8	22	15	65

Table 11.14: Slope Mass Rating (SMR) classes of 20 sample sites on the Lakshmanjhula-Shivpuri road

Location No	SMR value	Class No.	Slope description	Stability	Failures	Support
1	44.2	III	Normal	Partially stable	Wedge failure	Systematic
2	47.8	III	Normal	Partially stable	Wedge failure	Systematic
3	36.25	IV	Bad	Unstable	Planar failure	Important/ corrective
4	32.4	IV	Bad	Unstable	Planar failure	Important/ corrective
5	18	V	Very bad	Completely unstable	Big wedge failure	Re-excavation
6	24	IV	Bad	Unstable	Planar or big wedge failure	Important/ corrective
7	26	IV	Bad	Unstable	Wedge failure	Important/ corrective
8	40	III	Normal	Partially stable	Planar failure	Systematic
9	56.8	III	Normal	Partially stable	Planar failure	Systematic
10	30	IV	Bad	Unstable	Planar failure	Important/ corrective
11	69.6	II	Good	Stable	Block failure	Occasional
12	55.2	III	Normal	Partially stable	Planar failure	Systematic
13	51.6	III	Normal	Partially stable	Planar failure	Systematic
14	36.6	IV	Bad	Unstable	Wedge failure	Important/ corrective
15	60.9	II	Good	Stable	Block failure	Occasional
16	24	IV	Bad	Unstable	Planar failure	Important/ corrective
17	61.8	II	Good	Stable	Block failure	Occasional
18	57	III	Normal	Partially stable	Wedge failure	Systematic
19	22.65	IV	Bad	Unstable	Planar failure	Important
20	18.5	V	Very bad	Completely unstable	Big planar failure	Re-excavation

Conclusions

Infrastructure development programmes are being widely implemented across the Himalayas. If these programmes fail to take into account the inherent instabilities in the landscape, the new constructions could be severely damaged or even destroyed. Equally, sustainable development planning in hill areas must try and minimise damage to the environment and reduce the threats to people and property from natural hazards.

The first step is to prepare regional landslide hazard zonation maps. The VLH and LH zones are generally safe for development schemes. The MH zones may have some local zones of instability

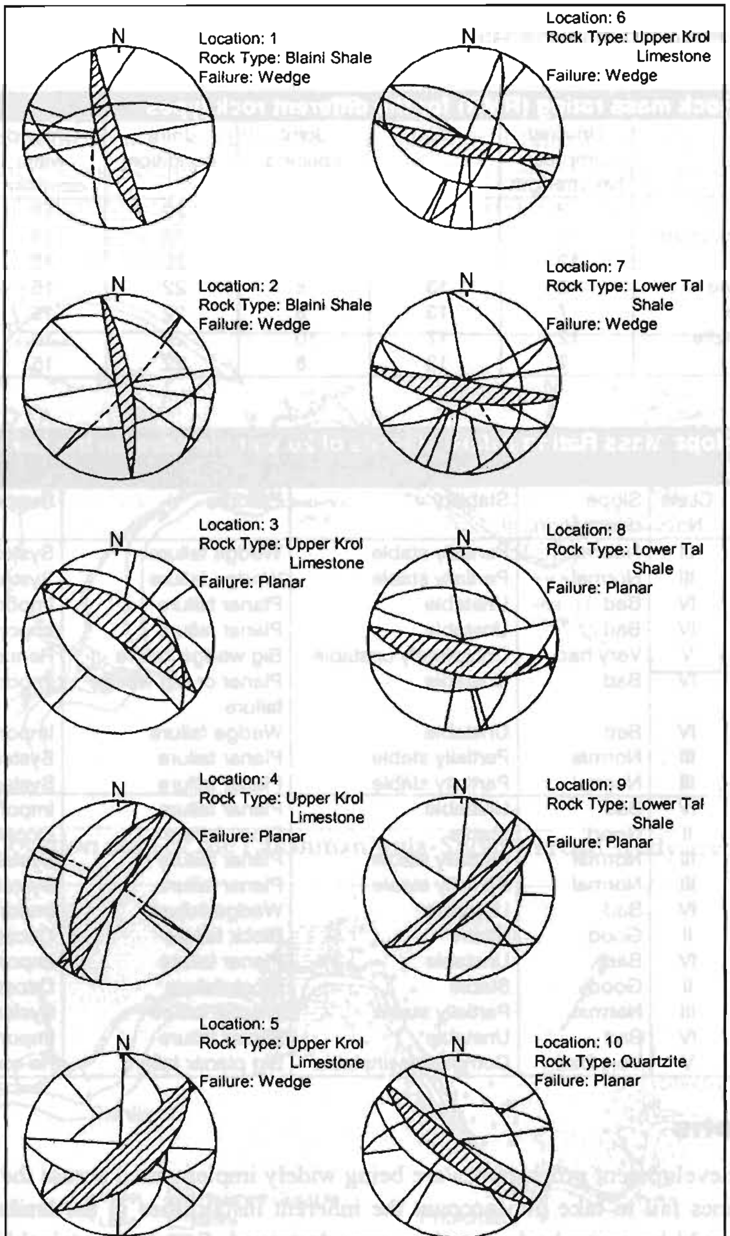


Figure 11.17: **Stereo-plots of stability analysis for locations 1-10** (Anbalagan et al. 1992) **on the Lakshmanjhula-Shivpuri road**

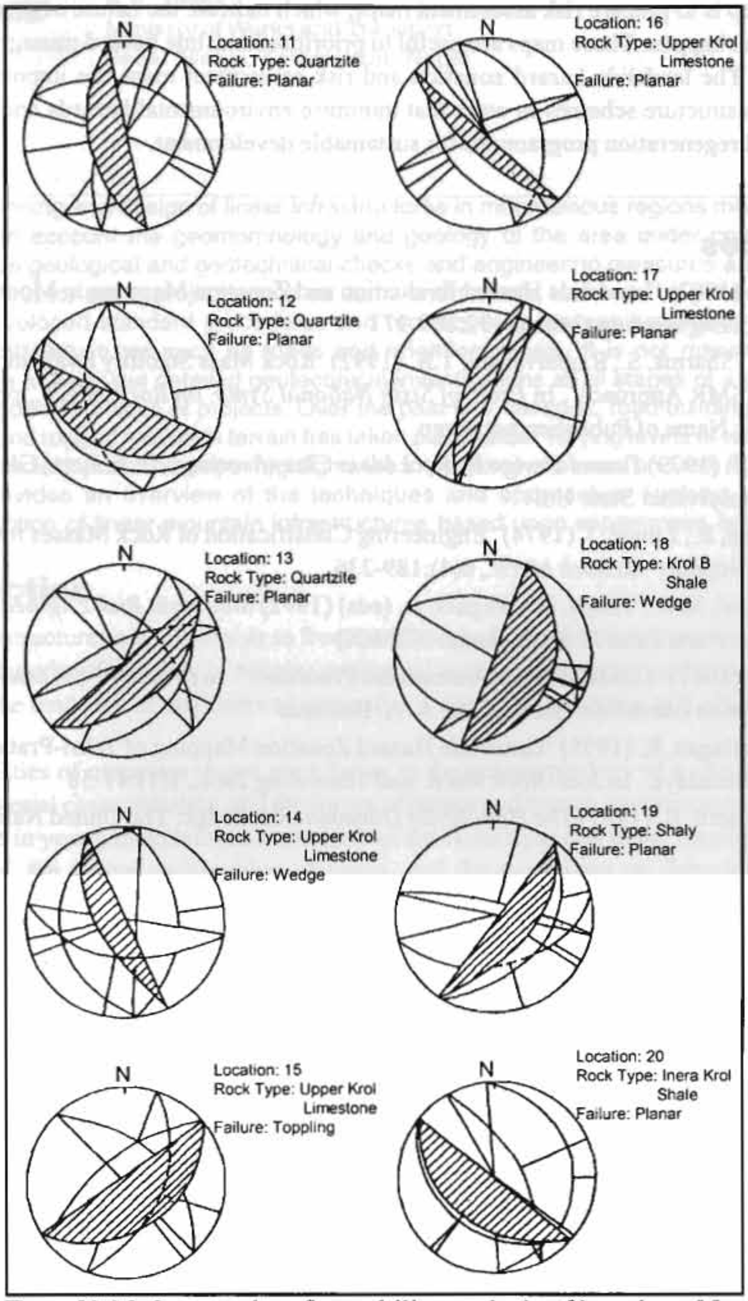


Figure 11.18: **Stereo-plots for stability analysis of locations 11-20** (Anbalagan et al. 1992)

that can be avoided. The HH and VHH zones should be avoided as far as possible. If it is not possible to avoid these areas, their initial recognition will help planners to adopt suitable preventive measures.

The second step is to prepare **risk assessment** maps, which indicate the nature of damage likely to occur if failures happen. These maps are useful to prioritise landslide hazard management (LHM) interventions. The landslide hazard zonation and risk assessment maps are important tools for designing infrastructure schemes in ways that minimise environmental hazards and for planning environmental regeneration programmes for sustainable development.

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