Meso-Scale Landslide Hazard Zonation (LHZ) Mapping Technique - A Case Study of Nainital Area, Uttarakhand

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ABSTRACT

Planning and execution of development schemes in Himalayan terrain is often a challenging task because of fragile nature of this mountain ecosystem. Improperly planned constructional practices, without taking into account adverse geological features, may result in large scale hill slope instabilities. The current paper deals with detailed description of meso-scale (1:5000 – 1:10000) landslide hazard zonation (LHZ) technique which has been evolved incorporating various causative factors responsible for slope instability. This technique may prove to be helpful for town planners for choosing suitable locations for urbanization and also expansion of existing urban settlements in hilly terrains. As a case study, this technique has been applied for evaluating stability of hill slopes in and around Nainital, a famous hill station in Kumaun Himalaya, India.

Keywords: Landslide hazard zonation; Meso-scale mapping; Causative factors

1. INTRODUCTION

In recent times, a large number of development schemes have been implemented and many more are under planning in all the hilly states of India. These schemes, planned to boost tourism and other economic activities, dominantly include making road and rail links, setting up of hotels, expansion of urban settlements and other such civil constructions. Fast rate of construction practices sometimes overlook adverse geological features that are inherently present in a mountain ecosystem. Hence, it is essential to carry out landslide hazard evaluation of hill slopes during planning stage. In this context LHZ mapping on meso-scale (1:5000 - 1:10000) is one such hazard evaluation technique, which has been discussed in detail in this paper, may find application for systematic town planning and expansion of urban settlements in hilly terrains.

LHZ mapping on meso-scale is an empirical approach, which demarcates hill slopes into zones of varying degree of stability on the basis of their relative hazards. This approach takes primarily into account inherent causative factors responsible for slope instability and accordingly rates them depending on their influence in inducing the instability. Effects of external causative factors like seismicity and rainfall are also incorporated in this technique. The smallest unit of study in this technique is a slope facet (hill slope having same amount of inclination and direction with a range of ±20° for both).

Detailed landslide hazard evaluation of hill slopes within urban areas is often a difficult and expansive job. Keeping this in mind, the meso-scale LHZ maps may have effective application in the safe planning of civil constructions. The present meso-scale LHZ technique has been developed following the basic concept of LHZ on macro-scale as proposed by Anbalagan (1992), Anbalagan & Singh (1996), which is also the present Indian National Standard Code (No. IS: 14496 - Part 2, 1998) for landslide hazard zonation purpose. Suitable modifications have been incorporated for individual factors to develop the technique on meso-scale.

2. LANDSLIDE HAZARD EVALUATION FACTOR (LHEF) RATING SCHEME

The LHEF rating scheme follows an empirical approach, which takes into consideration the net effect of all inherent and external causative factors responsible for slope instability (Table 1). Inherent causative factors are those whose effect can be studied and assessed on slope facet. External factors like seismicity and rainfall may initiate slope movements and are accordingly called triggering factors. Their effect in general is felt over large areas and hence it is obvious that their effect will not vary from facet to facet for meso-zonation purpose.

Table1 - Maximum LHEF rating for different causative factors

<table>
<tr><th colspan="3">Causative Factors</th><th>Maximum LHEF rating</th></tr>
<tr><td rowspan="5">A. Inherent</td><td rowspan="2">Geology</td><td>1. Lithology</td><td>2.0</td></tr>
<tr><td>2. Structure</td><td>2.0</td></tr>
<tr><td colspan="2">3. Slope parameter
a) slope morphometry and b) relative relief</td><td>2.0</td></tr>
<tr><td colspan="2">4. Land use and land cover</td><td>2.0</td></tr>
<tr><td colspan="2">5. Hydrogeological conditions</td><td>1.0</td></tr>
<tr><td>B. External</td><td colspan="2">a) Seismicity + b) Rainfall</td><td>1.0 (=0.5 + 0.5)</td></tr>
<tr><td colspan="3">Total</td><td>10.0</td></tr>
</table>

The maximum value of ratings for individual factors is awarded on the basis of its estimated significance in causing slope instability. The factors like slope morphometry and relative relief have been clubbed together and named as slope parameter. Description of various causative factors and their corresponding LHEF rating values are explained below.

2.1 Inherent Factors

2.1.1 Lithology

a) **Rock slopes:** The lithology is an important factor in controlling the stability of hill slopes and awarded a LHEF rating of 2. The resistance to processes of weathering and erosion differs for different rock types. Accordingly, a three tier classification is suggested to account for various types of rocks. The type-I rocks mainly consist of hard crystalline igneous and metamorphic rocks along with hard calcareous rocks. These types of rocks suffer less weathering and erosion and stand out as steep slopes. The type-II rocks are mainly comprised of both well and poorly cemented terrigenous sedimentary rocks, in addition to calcareous rocks with intercalations of argillaceous rocks. The type-III category consists of soft argillaceous rocks and their low grade metamorphic equivalents along with foliated gneissic rocks. Soft rocks like claystone, siltstone, mudstone, shale, schist, phyllite and other such rocks erode much faster and are easily weathered close to surface. Moreover schist and phyllite have foliation plane along which sliding often takes place. Same is the case with gneissic rocks with thick foliated bands. In LHEF rating scheme, weathering of fresh rocks is also included as a correction factor which is to be multiplied to the rating of respective fresh rock, for type-I and II. The Type-III rocks usually have an inbuilt higher rating, for which there is as such no requirement to multiply with the correction factor. But depending on weathering condition, their rating can be suitably modified to represent the field condition. The ratings for different rock types are tabulated in Table 2 and the weathering corrections for different rock types are tabulated in Table 3.

Table 2 - LHEF Ratings for rock types

Category	Rock types	Rating
Type-I	Basalt, quartzite, massive limestone & dolomite	0.2
	Granite, gabbro and dolerite	0.3
	Massive granitic gneiss and metavolcanics	0.4
Type-II	Thickly bedded calcareous rock with intercalations of argillaceous rocks	0.8
	Well-cemented terrigenous sedimentary rocks (dominantly sandstone) with minor beds of claystone and gneissic rocks	1.0
	Poorly-cemented terrigenous sedimentary rocks (dominantly sandstone) with intercalations of clay or shale beds	1.3
Type-III	Foliated gneiss	1.0
	Fresh to moderately weathered shale & slate	1.2
	Fresh to moderately weathered argillaceous rocks like siltstone, mudstone and claystone	1.4
	Fresh to moderately weathered phyllite	1.6
	Fresh to moderately weathered schistose rocks	1.7
	Highly weathered shale and all other argillaceous rocks, phyllite and Schistose rocks	2.0

Table 3 - Correction factors for weathering in rock slopes (modified after, BIS code on macrozonation - *IS: 14496 - Part 2, 1998* and London Geol. Soc., 1995)

Weathering condition	Description	Rating	
		Rock type-I	**Rock type-II**
Completely weathered	Rock totally decomposed/ disintegrated to soil, no or minor existence of initial rock structure (*Correction factor C_1*)	C_1 = 4.0	C_1 = 1.5
Highly weathered	Rock totally discolored, discontinuity planes show weathering products, rock structure altered heavily with minor soil formation near surface (*Correction factor C_2*)	C_2 = 3.5	C_2 = 1.35
Moderately weathered	Rock prominently discolored with remnant isolated patches of fresh rock, weathering and alteration prominent along discontinuity planes, considerable alteration of rock structure (*Correction factor C_3*)	C_3 =3.0	C_3 =1.25
Slightly weathered	Rock partially discolored along discontinuity planes indicating weakening of rock mass, rock structure is slightly altered *(Correction factor C_4)*	C_4 =2.5	C_4 = 1.15
Faintly weathered	Rock slightly discolored along discontinuity planes which may be moderately tight to open in nature, intact rock structure with or without minor surface staining (*Correction factor C_5*)	C_5 =2.0	C_5 =1.0

b) **Soil slopes:** Some hill slopes may be composed of loose soils and debris material. So, in slopes comprised of loose overburden materials, genesis and relative age are considered as the main criteria while awarding ratings. Older in-situ as well as alluvial soil is generally well compacted with high shear strength and also resistant to weathering. On the other hand hill-slide debris and younger incompact residual soil are generally loose with low shear resistance and erosion resistance which make them prone to further sliding activity. LHEF rating for different types of soil types are shown in Table 4.

Table 4 - LHEF rating for soil types

Description		**Rating**
Older in-situ soil (elluvial), older well compacted fluvial fill material (alluvial)		0.8
Clayey soil with naturally formed surface (elluvial, alluvial, aeolian)		1.0
Sandy soil with naturally formed surface (alluvial)		1.4
Debris comprising mostly loose rock pieces mixed with clayey or sandy soil (colluvial)	Older, well compacted	1.2
	Younger loose material	2.0
Younger, incompact residual soil (lying as thin cover over hill slopes)		2.0

2.1.2 Structure

a) **Rock Slopes:** Stability of hill slopes consisting of in-situ rocks is largely dependent on the relationship between orientation of slope and attitude of dominant discontinuities. Structures include both primary and secondary discontinuities like bedding, foliation, schistosity, joints, shear zones and other such features. In this connection two types of failure modes – Translational and Toppling, are taken into account. Translational failure include plane and wedge failures while toppling failure takes into account block topple and wedge topple. For individual failure modes, three types of conditions exist between the slope and the most unfavorable discontinuity plane or the line of intersection of two discontinuity planes.

i) Parallelism between the slope and the discontinuity: The extent of parallelism between inclination direction of slope and the dip of discontinuity plane or the plunge of line of intersection of two such planes is considered here. In LHEF rating scheme, maximum rating given for this condition is 0·50 (Table 5). The symbols and abbreviations used in Tables 5 to 7 for structural ratings are as follows.

α_j = Dip direction of discontinuity, α_i = Direction of plunge of the line of intersection of two discontinuity surfaces, α_s = Direction of slope inclination, β_j = Dip amount of discontinuity, β_i = Amount of plunge of line of intersection of two discontinuity surfaces, β_s = Amount of slope inclination, VF = Very Favorable, F= Favorable, U = Unfavorable and VU = Very Unfavorable.

Table 5 - Ratings for relationship of parallelism between slope and discontinuity

Category	**Difference in angle of parallelism** A. Translational Failure: 1. Plane : $\lvert(\alpha_j - \alpha_s)\rvert$ 2. Wedge : $\lvert(\alpha_i - \alpha_s)\rvert$ B. Toppling Failure: 3. Block Topple: $\lvert(\alpha_j - \alpha_s) \pm 180°\rvert$ or $\lvert(\alpha_j - \alpha_s)\rvert$ 4. Wedge Topple: $\lvert(\alpha_j - \alpha_s) \pm 180°\rvert$ or $\lvert(\alpha_j - \alpha_s)\rvert$	Rating	Slope condition
I	> 30°	0.20	VF
II	21 - 30°	0.25	F
III	11 - 20°	0.30	Fair
IV	6 - 10°	0.40	U
V	≤ 5°	0.50	VU

Note: For slopes falling in category I in Table 5, the ratings for structure as given in Tables 6 and 7 will not be applicable and hence a rating of 0 may be given out of remaining 1.5 points.

ii) The relation between inclination of slope and amount of dip of discontinuity/ plunge of wedge line: The differences in dip amount of slope and discontinuity plane or plunge of line of intersection of two such planes are taken into consideration. If the slope is steeper than the discontinuity surface or the line of intersection of two planes (day lighting condition), the slopes become vulnerable to plane or wedge failure modes. For toppling failure, the dip of discontinuity or plunge of line of intersection is added to inclination amount of the slope. Most unfavorable situation for toppling failure (both block and wedge topple) appears when the added value exceeds 160°. The maximum rating for all these cases are given as 1·00 (Table 6).

iii) The amount of dip of discontinuity/plunge of wedge line: As the amount of dip of discontinuity plane or plunge of line of intersection of two such planes, increases, it may exceed the friction angle of the unfavorable joint leading to slope instability. The maximum rating for this relation, as awarded in the rating scheme, is 0·50 (Table7).

After determining the facet wise rating for each of the three conditions, they are added to get the total rating for structure.

Table 6 - Ratings for relationship between amount of dip/ plunge of discontinuity and that of slope inclination

Category	**Difference in angles** 1. Plane Failure: (β_j - β_s) 2. Wedge Failure: (β_i - β_s)	**Rating**	**Sum of angles** 3. Block Topple (β_j + β_s) 4. Wedge Topple (β_i + β_s)	**Rating**	**Slope condition**
I	> 10°	0.30	≤ 110°	0.30	VF
II	0 - 10°	0.50	111 - 130°	0.50	F
III	0°	0.70	131 - 140°	0.70	Fair
IV	0 – (-10°)	0.80	141 - 160°	0.90	U
V	> -10°	1.00	>160°	1.00	VU

Note: For slopes falling in category I in Table 6, the ratings for structure as given in Table 7 will not be applicable and hence a rating of 0 may be given out of remaining 0.5 points.

Table 7 - Ratings for amount of dip of discontinuity

Category	**Dip amount** 1. Plane (β_j) **Plunge amount** 2. Wedge (β_i)	**Rating**	**Dip amount** 3. Block Topple (β_j) **Plunge Amount** 4. Wedge Topple (β_i)	**Rating**	**Slope condition**
I	< 15°	0.20	< 50°	0.20	VF
II	16 - 25°	0.25	51 - 60°	0.30	F
III	26 - 35°	0.30	61 - 70°	0.40	Fair
IV	36 - 45°	0.40	71 - 80°	0.45	U
V	> 45°	0.50	> 80°	0.50	VU

b) **Soil slopes:** In case of slope facets comprising of overburden soil and debris material, the usual mode of failure is in the form of planar debris slide (talus failure) and rotational. The type of failure, which may occur, will primarily depend on slope angle, thickness of debris material and other parameters. When slope angle is steep

(>35°), it shows more proneness to failure (Table 8), irrespective of mode of failure. When slope angle is less than 35°, thickness of debris material should be considered to assign the rating (Table 8). This may also indicate the probable mode of failure, as the mode of failure changes with increasing depth of overburden.

Table 8 - LHEF Ratings for structure category in loose soil/ debris slope

A. Slope angle > 35°; slope angle is the criteria for awarding LHEF rating		
Slope Angle	**Probable mode of failure**	**Rating**
36 - 45º	Probability of slope instability increases with increasing slope angle, whatever be the failure mode	1.0
46 - 60º		1.5
> 60º		2.0
B. Slope angle ≤ 35°; thickness of overburden is the criteria for awarding LHEF rating		
Overburden thickness	**Probable mode of failure**	**Rating**
< 5m	Dominantly Planar Debris slide (Talus slide)	0.65
5 – 10m	Planar Debris slide and sometimes Rotational slide	0.85
11 – 15m	Rotational slide and sometimes Planar Debris slide	1.30
16 – 20m	Dominantly Rotational slide (Circular failure), though some times slip circle may be non-circular type	1.50
> 20m		2.00

2.1.3 Slope parameter

Slope parameter includes slope morphometry and relative relief of individual facets. The impact of these two factors have been considered together to assess their significance in inducing instability. In this context it is proposed to consider their combined significance in a matrix form. The maximum LHEF rating for slope parameter is 2.0.

a) **Slope morphometry:** Slope morphometry map categories facets based on inclination of slope angles. The slope morphometry maps for meso-zonation purpose are prepared after assessing the slope angle from topographic map and subsequent field observation along the direction of slope inclination. For meso-zonation purpose, the spacing pattern of contours may indicate local slope angle within a facet. If there is a significant variation (>20°) along the slope profile, it is preferable to study that part of slope, by making a separate facet or sub-facet. Finally all the slope facets may be categorized into six different classes (A to F) with certain range of slope angle values (Table 9).

Table 9 - Slope morphometry classes based on slope angle of facets

Slope type	**Slope angle**	**Probable type of failure**	**Class**
Very gentle slope	< 15°	Slides with probable creep movement	A
Gentle slope	16 - 25°		B
Moderate slope	26 - 35°	Slides	C
Steep slope	36 - 45°		D
Very steep slope	46- 65°	Slides and falls	E
Escarpment / Cliff	> 65°	Falls and topples	F

b) **Relative relief:** Relative relief represents the maximum height of a facet, from top (ridge/ spur) to bottom (valley floor) in the direction of slope inclination. Relief of a facet can simply be calculated by counting the elevation difference between the lowest and the highest elevations along the slope direction. For meso- zonation purpose, five relief classes (I to V) are considered which are presented in Table 10.

Table 10 - Classes for relative relief

Relief classes	**Relative relief (m)**	**Class**
Very low	< 50	I
Low	50 - 100	II
Medium	101 – 200	III
High	201 - 300	IV
Very high	> 300	V

The combined impact of these two factors has been considered to award LHEF rating for slope parameter. Accordingly a [5×6] matrix format has been prepared, on which relative relief classes of slope are shown row wise and slope morphometry classes are presented column wise (Table 11). A perusal of this table indicates that the slope parameter rating increases along the row from left to right with the increase in the slope angle value. However, the increment is very less down the column with the increase of value of relative relief class. This implies the fact that of the two factors, more importance is given to slope morphometry than relative relief. It is because that the former reflects the change in slope gradient which is considered to be more important for selecting a slope for locating urban structures. From Table 11, it can be inferred that slopes with steep slope angle (>35°) and more than 100m relief are usually not favorable for civil constructions. However, the slopes with gentle angle and low relief are generally favorable. Hence on the basis of the rating values, the slope parameters have been categorized into five classes (I to V) indicating the suitability of slopes for construction purpose (Table 12).

Table 11 - Rating for Slope Parameter

Slope parameter		a) Slope morphometry classes					
		A (<15º)	B (16–25°)	C (26-35°)	D (36-45°)	E (46-65°)	F (>65°)
b) Relative relief classes	I (<50m)	0.5	0.9	1.3	1.5	1.8	1.9
	II (50 -100m)	0.6	1.0	1.4	1.6	1.9	2.0
	III (101-200m)	0.7	1.1	1.5	1.7	1.95	2.0
	IV (201-300m)	0.8	1.2	1.55	1.75	2.0	2.0
	V (>300m)	0.9	1.3	1.6	1.8	2.0	2.0

Table 12 - Description for slope parameter

Rating	**Description**	**Category**
< 0.8	Very favorable	I
0.8 – 1.2	Favorable	II
1.3 – 1.5	Moderately favorable	III
1.6 – 1.8	Unfavorable	IV
> 1.8	Very unfavorable	V

2.1.4 Land use and land cover

Land use and land cover pattern is one of the important parameters governing slope stability and in LHEF scheme maximum rating of 2.0 has been awarded for this factor. Vegetation has major role to resist slope movements, particularly for failures with shallow slip/ rupture surfaces. A well spread network of root system increases the shearing resistance of the slope material due to natural anchoring of slope materials, particularly for soil slopes. Moreover, a thick vegetation or grass cover reduces the action of weathering and erosion, hence adds to stability of the slopes. On the other hand, barren or sparsely vegetated slopes are usually exposed to weathering and erosion action, thus rendering it vulnerable to failure. In hilly terrain, chances of landslide increases many times for slopes which face toe erosion/ toe cutting by first order streams or fast moving water of any other natural drainages. Agricultural activity is generally practiced on hill slopes which are very gentle to gentle. For higher slope angle, usually it is carried out by making flat terraces. These slopes, apart from receiving natural precipitation, also get recharged by additional water for agriculture purpose. Because of the fact that even after many years of such practice they remain stable, it is quite logical to consider them as safe from landslide point of view. Similarly a populated land on a very gentle slope (slope angle $\leq 15°$) under normal circumstances is least expected to suffer from slope instability. Slope instability is also induced because of anthropogenic activities, i.e. urbanization, particularly on higher slope angles ($\geq 30°$). It not only removes vegetation cover but also adds to the natural weight of the slope as surcharge due to weight of civil structures. In a hill slope with higher slope angle, buildings are usually located by making local cut slopes and flat terraces. With this concept urbanization is broadly classified into three categories. A sparsely urbanized slope is one where construction terraces are located far apart (more than 15m of horizontal spacing) providing a considerable distance between two terraces along the slope. A moderately urbanized slope is characterized by comparatively closer location of construction terraces but leaving an optimal horizontal spacing of 5-15m between individual terraces. In a heavily urbanized slope construction terraces are located very close to each other ($\leq$ 5m horizontal spacing) in such a way that successive terraces almost touch each other at places. With increasing urbanization, water due to domestic usage may be released on the slope surface wherever the drainage measure is inadequate. This water may get added up to the subsurface water and may develop pore water pressure, leading to slope instability. Similarly barren land, affected by anthropogenic activities has also been found to be most vulnerable to landslides. All these aspects have been suitably accounted while awarding the LHEF ratings (Table 13).

2.1.5 Hydrogeological conditions

The hydrogeological conditions are studied based on visual estimation of groundwater condition on slope surface using qualitative terms such as dry, damp, wet, dripping and flowing. The presence of water generally decreases shear strength of slope materials and thereby increasing the probability of failure. Since it is difficult to assess subsurface flow of groundwater quantitatively for entire facet, a visual estimation of field condition has been considered as an alternative measure to award the ratings. For better assessment of groundwater condition, it is advisable to collect field data after monsoon season. Maximum rating for this parameter is 1.0. The field hydrogeological conditions of facets along with their respective ratings have been tabulated in Table 14.

Table 13 - Ratings for land use and land cover types

<table>
<tr><th colspan="2">Land use & land cover types</th><th>Rating</th></tr>
<tr><td colspan="2">Agricultural land or populated flat land (≤ 15°)</td><td>0.65</td></tr>
<tr><td colspan="2">Thickly/ densely vegetated forest area</td><td>0.80</td></tr>
<tr><td colspan="2">Moderately vegetated forest area</td><td>1.20</td></tr>
<tr><td colspan="2">Sparsely vegetated area with thin grass cover</td><td>1.50</td></tr>
<tr><td colspan="2">Barren land – without anthropogenic activity</td><td>1.70</td></tr>
<tr><td colspan="2">Hill slopes experiencing active toe erosion/ toe cutting by rivers, streams or any other form of natural drainage</td><td>2.00</td></tr>
<tr><td colspan="2">Sparsely urbanized slope</td><td>1.20</td></tr>
<tr><td colspan="2">Moderately urbanized slope</td><td>1.50</td></tr>
<tr><td rowspan="2">Heavily urbanized slope</td><td>With proper surface and subsurface drainage measures – no dampness or wet patches on slope</td><td>1.60</td></tr>
<tr><td>Inadequate drainage measures – dampness or wet patches left on slope</td><td>1.80</td></tr>
<tr><td colspan="2">Barren land with slope excavation (cut slopes for rail and road routes, construction terraces, mining activities, etc) incurring blasting and induced vibration damage to slope</td><td>2.00</td></tr>
</table>

Table 14 - Ratings for hydrogeological conditions

Groundwater condition on slope	Rating
Dry	0.0
Damp	0.2
Wet	0.5
Dripping	0.8
Flowing	1.0

2.2 External Factors

The location of study area is important, while considering the regional seismicity and rainfall pattern, as external parameters. Seismically, India is divided into four major zones from Zone II to zone IV [Indian National Standard Code No. - IS 1893 (Part 1): 2002] on the basis of intensity of ground motion. The intensity of ground motion increases proportionately from Zone-II to Zone-V. In Zone-II, the ground motion is least for which it represents an area of minimum seismic hazard while Zone-V indicates an area of maximum intensity of ground motion, i.e. most prone to seismic hazards. So a slope which is critically stable under existing slope conditions may become unstable if it falls in higher seismic zones and may result in landslide phenomenon. Similar problems may be faced on hill slopes falling in zones of high annual precipitation. Following a heavy spell of rain there are chances of sudden build up of pore water pressure on these slopes, which may also induce slope instability. The rainfall distribution map of India (www.surveyofindia.gov.in) provides data pertaining to annual rainfall distribution pattern in various parts of India. Otherwise the annual rainfall amount can also be obtained if a rain gauge station is located in and around study area. The maximum rating for external parameter is 1.0 which is divided equally to award ratings for seismicity and rainfall (Table 15). Ratings for these two factors are given separately and finally added to other LHEF ratings pertaining to inherent parameters so as to obtain overall hazard potential of the slope.

Table 15 - LHEF Ratings for external factors

Seismic zone	**Rating**	**Average annual rainfall of the area**	**Rating**
II	0.2	≤ 50 cm	0.2
III	0.3	51 – 100cm	0.3
IV	0.4	101 – 150cm	0.4
V	0.5	> 150cm or history of cloud burst	0.5

3. TOTAL ESTIMATED HAZARD (TEHD) FROM LHEF RATINGS

Total estimated hazard (TEHD) value is calculated by adding the LHEF ratings for individual inherent and external parameters. The TEHD value indicates the overall condition of slope instability and shall be calculated facet wise. This value is determined on a 10 point scale and can be obtained by adding all the values of inherent and external parameters as indicated below.

Total Estimated Hazard (TEHD) =∑ LHEF Ratings for (inherent factors + external factors) = [LHEF ratings for (lithology + structure + slope parameter + land use and land cover + hydrogeological conditions) + LHEF ratings for (seismicity + rainfall)] .

The LHZ map on meso-scale of an area is prepared from the TEHD values of the facets. On the basis of range of TEHD values, all the slope facets in an area can be categorized into five classes of relative hazards (Table 16). A meso-scale LHZ map will show the spatial distribution of these hazard zones.

Table 16 - Landslide hazard zones based on TEHD value

Hazard zone	**Range of TEHD value**	**Description of zone**
I	TEHD < 3.5	Very Low Hazard (VLH) zone
II	3.5 ≤ TEHD < 5.0	Low Hazard (LH) zone
III	5.0 ≤ TEHD ≤ 6.5	Moderate Hazard (MH) zone
IV	6.5 < TEHD ≤ 8.0	High Hazard (HH) zone
V	TEHD > 8.0	Very High Hazard (VHH) zone

4. PROCEDURE FOR LHZ MAPPING ON MESO-SCALE

The LHZ mapping on meso-scale is an empirical approach used for systematic town planning in hilly terrains on 1:5000 – 1:10000 scale. This approach involves hazard assessment of hill slopes and is carried out in two phases – a) Desk study and b) Field study. The procedure is shown in the form of a flow chart (Fig. 1).

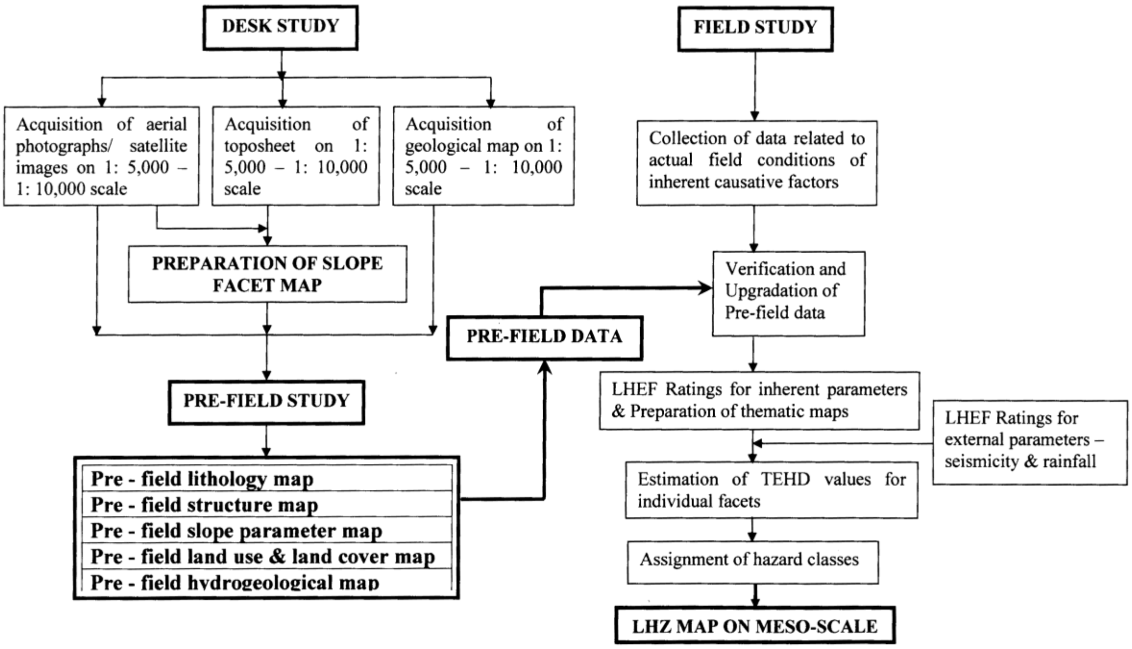

Fig. 1 - Flow chart showing methodology of meso-scale LHZ mapping technique

4.1 Desk Study

Initially the base maps and other data such as toposheet, geological map, aerial photograph and satellite imageries on 1: 5000 – 1: 10 000 scale are acquired. The meso-scale LHZ study starts with the preparation of slope facet map mainly from toposheet. Later various pre-field thematic maps are prepared from LHEF rating scheme using slope facet map as the base. Apart from topographic map, aerial photographs and satellite imageries in appropriate scale are also studied to prepare slope facet map of the study area. Pre-field slope morphometry and relative relief maps can be prepared mainly from topographic map in addition to relevant inputs from aerial photographs and satellite imageries. Taking these two maps as inputs, pre-field slope parameter map of the area can easily be prepared. Pre-field geological maps consisting of lithological and structural maps are prepared separately on the required scale of 1: 5000 – 1:10 000. If not available, regional geological maps of the area can be referred and required details can be transferred to meso-scale. Pre-field land use & land cover map and hydrogeological map can be prepared from toposheets, aerial photographs and satellite imageries. The data derived from all these maps are called pre-field data and the maps are called pre-field thematic maps. Hence, in desk study, all thematic maps shall be prepared on the slope facet map, which may be carried to the field for further verification. Information gathered from desk study will help to plan and execute field study in a systematic manner.

4.2 Field Study

During field visit all the pre-field maps are verified facet wise and necessary corrections are done. This process will upgrade the existing pre-field maps. Once the data related to all the five inherent parameters are upgraded and their ratings awarded after field study, the final thematic maps are prepared.

The value of TEHD can vary widely from one facet to another depending on the condition of stability of the respective facets. The LHZ map on meso-scale of an area is prepared from TEHD values of the facets.

4.3 Meso-Scale LHZ Map for Systematic Town Planning and Future Expansion of Existing Urban Settlements

A LHZ map on meso-scale classifies an area on varying relative hazard levels (Table 17). For town planning and construction purposes, slope facets which fall in VLH and LH zones are suitable. In comparison, slopes falling in MH class are considered relatively less safe for construction practice. They may contain local pockets of instability, which should be suitably accounted while planning for constructions on these slopes. On the other hand, slopes falling in HH and VHH classes are unfavorable and are to be avoided as far as possible. If unavoidable, suitable control measures should be taken up before excavation. These facets shall be studied in detail preferably on 1:1000 - 1:2000 scale incorporating analytical and observational techniques. Such studies may help to work out suitable remedial measures for these slopes. Hence, for effective and systematic town planning purposes, the nature of hazard classes should be taken into consideration for planning various civil structures. The choice of setting up of urban settlement with respect to hazard zones is shown in Table 17.

Table 17 - LHZ classes and their significance in planning for civil constructions

<table>
<tr><th>Description of hazard zone</th><th>Importance of hazard zones for civil constructions</th></tr>
<tr><td>Very Low Hazard (VLH) zone</td><td rowspan="2">Safe zones - favorable site for civil constructions</td></tr>
<tr><td>Low Hazard (LH) zone</td></tr>
<tr><td>Moderate Hazard (MH) zone</td><td>Fairly safe for constructions - may contain some local unstable areas– remedial measures required</td></tr>
<tr><td>High Hazard (HH) zone</td><td rowspan="2">Unsafe and unfavorable for civil constructions – may be avoided in general - if unavoidable, detailed systematic study involving analytical and observational approach shall be taken up to select suitable remedial measures</td></tr>
<tr><td>Very High Hazard (VHH) zone</td></tr>
</table>

5. MESO-SCALE LANDSLIDE HAZARD ZONATION MAPPING OF NAINITAL AREA

Nainital is a beautiful hill station of Kumaun Himalaya, famous for its lake and picturesque beauty of the surrounding Lesser Himalayan Mountains. This is located (Latitude: N 29° 22′ - N 29° 24′ and Longitude: E 79° 26′ - E 79° 28′) in Kumaun Lesser Himalaya of Uttarakhand state, India (Fig. 2). The study area is approximately 4.5 sq. km. and falls in Survey of India Toposheet No. 53 O/7 (1:50 000). Nainital lake is located within a saucer shaped depression, bounded by hills from all sides, except on the southern side, wherefrom Balia stream, the only outlet of lake emerges out and passes through Kailakhan area. Based on physiography and nature of vulnerability to slope failures, the study area was broadly divided into following segments namely Sher – ka – danda Hill (≈ 31% of study area), Naina Hill (≈ 22.38% of study area), Ayarpatha Hill (≈ 25.71% of study area) and Kailakhan (≈ 8.41% of study area). The remaining portion of study area comes under Naini lake (≈ 7.29%) and Sukha Tal (≈ 0.6%) along with roads (≈ 4.68%). The areas were calculated from slope facet map (Fig. 3.) which is again prepared from SOI topographic map of the town on 1: 5000 scale. Nainital is facing hill slope instability problems for over a long period. Earliest reported incidence of landslides dates back to 18th century. Since then, the landslide problems were being reported intermittently causing damages to civil structures (Anbalagan, 1993). In view of this, a LHZ map of Nainital has been prepared on meso-scale (1:5000) to study landslide hazard probability of town area surrounding the lake, adopting the technique discussed above.

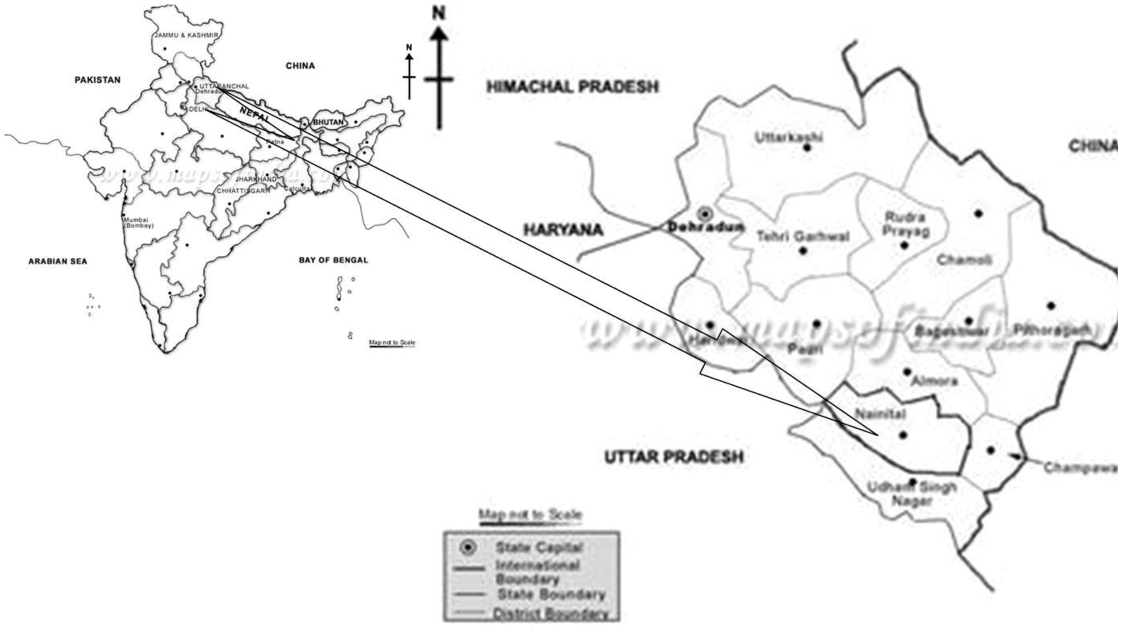

Fig. 2 - Location map of Nainital area (*Source – www. mapsofindia.com*)

5.1 Geology of Study Area

Geologically the area is represented by rocks of Infra-Krol, Krol & Tal Formations of Proterozoic age (Valdiya, 1980, 1988). In Kailakhan area, major rock type is black to reddish grey shales and slates of Infra-Krol Formation. Rock types exposed in Sher-ka-danda hill include grey slates and phyllites (Lower Krol Formation). In Naina hill, massive limestones intercalated with phyllites and slates (Middle Krol Formation), form major rock type. Ayarpatha-Deopatha hills are dominantly represented by limestone and dolomites with minor slates of Upper Krol Formation.

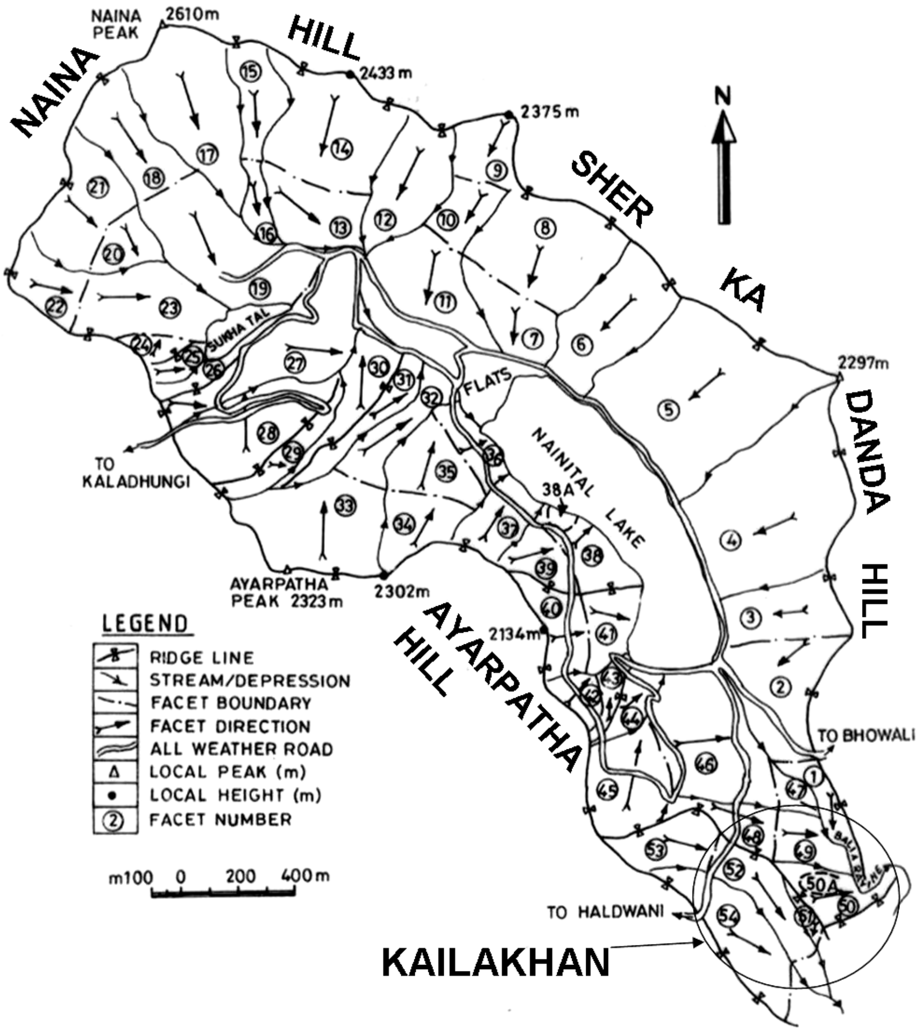

Fig. 3 - Slope facet map of study area Nainital

5.2 Preparation of Meso-scale LHZ Map of Nainital

For the purpose of preparation of LHZ map of Nainital town area on meso-scale, the slope facet map (Fig. 3) of the lake catchments was prepared as a first step from the toposheet (1:5000). Altogether 56 facets were identified in the slope facet map. Various pre-field thematic maps were prepared using toposheet, geological reports and maps of the area as well as other available information. Pre-field thematic maps were carried to field for verifying and collecting additional quantitative information related to inherent causative factors facet wise. After field verification, the final thematic maps were prepared and LHEF ratings were assigned. As the study area falls in seismic zone IV and average annual precipitation is of the order of 150 cm, ratings for external parameters were also applied and finally LHEF ratings for inherent and external factors were added to get the TEHD values for each facet. Afterwards, using TEHD values, landslide hazard classes were determined to prepare LHZ map of the study area (Fig. 4).

A perusal of meso-scale LHZ map of Nainital area (Fig. 4.) shows that major portion of Sher-ka-danda Hill falls in HH class. On the other side of the lake, the Ayarpatha Hill shows have dominance of LH and MH classes. A lone active slide zone falling in VHH class is seen close to the lake. Nearly one third potion of Naina Hill area falls under HH class and this zone includes the Naina peak, wherefrom occasional rockfall is reported. Interestingly there is no VLH and LH class in Kailakhan area and majority of slopes falls in MH class. The slopes close to Balia stream conspicuously fall in HH class with one facet falling in VHH representing an active slide zone.

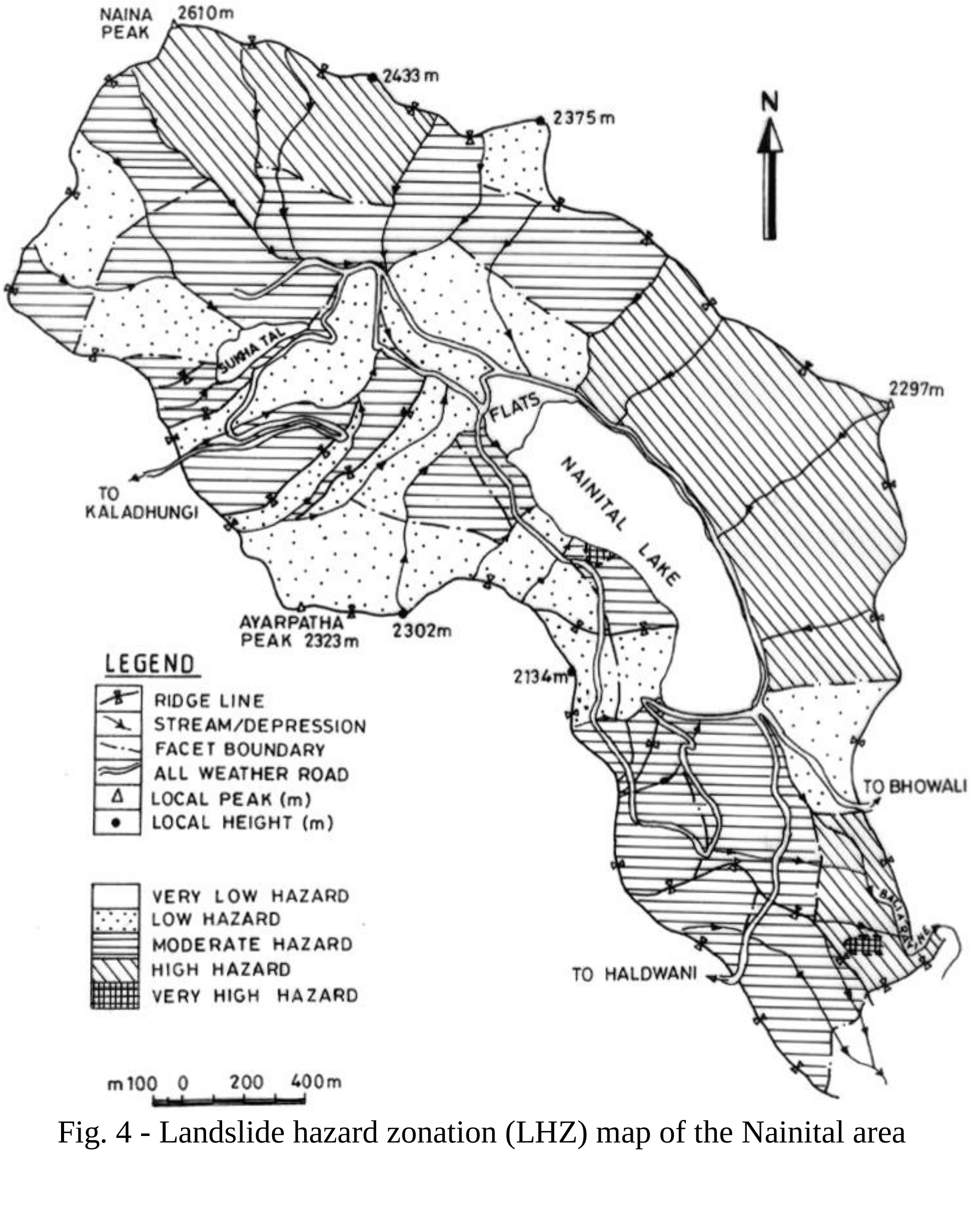

Fig. 4 - Landslide hazard zonation (LHZ) map of the Nainital area

Fig. 5 - Ground Instability Indicator map of the study area. Note: Highlighted portions show the areas where evidence of slope distressing is most prominent

5.3 Validadation of Meso-Scale LHZ Mapping Technique

From meso-scale LHZ map of Nainital, it can be inferred that HH facets are mainly present in three segments. First cluster is observed on lake facing slopes of Sher-ka-danda Hill. They are also present in Naina Hill side where rock cliff face is observed. There is another cluster observed along steep slopes of Balia Stream in Kailakhan area. There are two VHH facets, one in Kailakhan area and the other on lake facing slope of Ayarpatha Hill, both representing active landslide areas. The meso-scale LHZ mapping technique is validated by preparing a ground instability indicator map of the study area (Fig. 5.). The ground instability indicator map had been prepared by taking field traverse during pre and post monsoon period after which visible signs of slope distressing, wherever observed, had been picked up and plotted on the slope facet map. Field investigations showed signs of distressing on hill slopes in Sher-ka-danda hill in the form of ground cracks, tilting of trees, cracking of civil structures, bulging of retaining walls and subsidence of roads (Fig. 5.) and thus corroborating the presence of

HH slope facets on the hill. In case of Naina Hill, the very fact that slopes are very steep to vertical and traversed by three sets of discontinuities renders them prone to intermittent rock fall problems. However, taking into account the inaccessibility of the facets, ground instabilities could not be picked up directly on the slope facet map. Alternatively by plotting the poles of dominant discontinuities it was observed that for one major set it falls inside toppling failure envelop (Anbalagan et al 2007). Hence it may be fair to infer that intermittent rock fall problem in the area may be linked with rock topples at upper and inaccessible part of the slope and this validates assignment of HH class for those facets. In Kailakhan area, apart from steep slope composed of weak rocks, high gradient of Balia Stream coupled with sharp bends along stream course, has resulted in toe erosion on both the banks of Balia Stream. Particularly, close to stream level this is visible in the form of scarp faces formed due to occasional slumping on rock slope and tension cracks and damaged retaining walls on soil slopes. These observations justify and validate the location of HH slopes and one VHH slope in this area. The lone VHH facet in Ayarpatha Hill is characterized by very steep slope with occasional rolling down of debris material. Field visit also revealed possibilities of planar debris slide in this part of the hill slope and thus validates the hazard class as assigned.

6. CONCLUSIONS

The Himalaya represents one of the most fragile mountain ecosystems of the world, where systematic planning is a prime requisite for successful implementation of developmental schemes. In this regard, LHZ mapping on meso-scale (1:5000 – 1:10000) is one such technique which may guide the town planners to select relatively safe areas for future constructions. Meso-scale LHZ mapping is an empirical approach, which takes into account both inherent and external parameters responsible for slope instability, rates them on the basis of their relative importance to induce instability and finally classifies slopes into five relative hazard classes namely VLH, LH, MH, HH and VHH. The approach involves desk study and field study components and based on LHEF ratings for inherent and external factors, assigns the hazard class of each facet. As a case study, a meso-scale LHZ map of Nainital town was prepared. The map indicates three dominant clusters of vulnerable hill slopes around Naini lake which shall be suitably considered while planning for civil constructions in these areas. First cluster is at lake facing slope facets of Sher-ka-danda Hill, where signs of slope distressing have been observed. The other pocket is noticed in steep, right bank slopes of Balia stream in Kailakhan area. This portion also represents an active slide zone within study area. The third cluster is seen over the steep slopes of Naina Hill, where intermittent rock fall problems are often reported. There is also an isolated pocket of instability on lake facing slope of Ayarpatha Hill, where planar debris slide was identified during field study. The mesoscale LHZ map of Nainital area is finally validated through field observations, where visible signs of slope instabilities were identified to prepare a ground instability map of the area. It was further noticed that all the noticeable signs of ground instabilities fall in the HH and VHH classes, corroborating their TEHD values (hazard classes) and hence validates the mesoscale LHZ mapping technique.

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