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Visualization of 3-D digital elevation model for landslide assessment and prediction in mountainous terrain: A case study of Chandmari landslide, Sikkim, eastern Himalayas

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ABSTRACT: Techniques for recognizing and mapping of landslides are complex in mountainous terrains. Most of the methods applied to landslide identification and prediction involves assignment of different contributing factors in landslide hazard zonation; however, it is difficult to observe the main causes of landslides. 3-D digital elevation modeling capabilities and Guided Visual Program (GVP) module of Datamine Software is utilized to successfully enumerate the various contributing factors for causing the landslide in Sikkim, Eastern Himalaya in the case study of Chandmari Landslide. A landslide warning system is discussed for the site-specific Chandmari landslide area.

Key words: Landslides-3D Modelling-Chandmari-Sikkim-Eastern Himalaya

1. INTRODUCTION

India has about 25% of its geographical area under mountainous terrain and being the youngest mountain chain is geologically/tectonically very unstable and seismically active. The high population density, rapid increase in the developmental activities, the loss of human life and enormous economic loss of the order of US$500 million per year due to landslides. Chandmari landslide, Sikkim with a loss of 38 lives in 1997 and the Malpa landslide, Pittoragarh district, Uttranchal with a loss of 200 lives in 1998 are the known example in the Himalaya. The Government of India has set up a National Steering committee (DST, 1999) to co-ordinate activities related to landslides and to review the known examples of landslide in the Himalaya, the methodology of the landslide zonation, geotechnical investigations, land use zoning and regulation is the focal responsibilities of Ministry of Mines, Ministry of Science and Technology and Ministry of Environment and Forest respectively.

The site-specific studies were initiated by Department of Science and Technology, Govt. of India with a maximum Landslide Hazard Evaluation Factor (LHEF) rating for zonation with contributing factors such as lithology, slope, relief (Table 1) and landslide hazard zonation on the basis of Total Estimated Hazard (TEHD) have been created (Table 2). LHEF and TEHD are closely related to their approach followed by Anbalagan (1992); Lee and Choi (2003) and DST (1994). However, such TEHD does not include the use of qualified risk analysis (QRA) such as increase in life fatalities with respective number of years for risk reduction options. The above LHEF and TEHD do not quantify the hazard in relation to factor of safety (R7815, SWK & Co. Ltd and University of Durham, 2002).

Factor of Safety (FS)=sum of restoring forces/sum of distributing forces

=1 is the limit of safety
>1 is safe; whereas
<1 is unsafe.

The risk involved is also quantified on the basis of factors of hazard and vulnerability where the hazard could be estimated by TEHD or LHEF in relation to settlements or infrastructures.

In case of shallow landslide occurrence (Burton et al., 1998) the factor of safety (FS) can be derived as;

$$FS = \frac{\text{Resistance of soil to shearing}}{\text{Down slope component of soil weight}}$$

This is significant when only geotechnical and quantitative approach is taken into consideration (Tables 1, 2).

The landslide and slope instability problems are quite common in Sikkim Himalaya (Fig. 1a). The Chandmari landslide of Eastern Himalaya falls between 27°10'-27°30' N latitude and 88°25'-88°40'E longitudes (Fig. 1b), which is one of the major landslides, occurred in the year 1997. The heavy rainfall (cloudburst) on June 9, 1997 *i.e.* 211mm in 4 hours and poor drainage system led to saturation and increase in pore pressure in highly fractured and foliated rocks of the area. Apart from these the heavy concrete structures and poor maintenance of road is also responsible

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Table 1. Maximum Landslide Hazard Evaluation Factor (LHEF) ratings (DST, 1994)

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
Ground water conditions	1.0
Total	10.0

Table 2. Landslide hazard zonation based on Total Estimated Hazard (TEHD; DST, 1994)

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

for disaster. It covered an area of 200 sq. mt. The extensive damages in Chandmari-Tathangchen area were reported debris flow, which has swept away houses and buried many people alive 38 persons were killed and more than 50 injured due to unprecedented and consequent landslides on the night of June 8/morning of June 9, in a number of places in and around Gangtok City.

2. METHODOLOGY

Chi-square test is a popular statistical procedure by which dichotomous or non-dichotomous data can be easily analyzed (Gurung and Iwao, 2001). The contour intervals on 1:5000 scale toposheet and cross slope distances were measured and the data was used to construct a frequency distribution histogram. These histograms were used to interpret whether the area is a stable one or not.

Toposheet (Survey of India sheet no. 6, 78 A/11, 1972, at 1:5,000) of the area has scanned and vectorized by using Winpro Professional and AutoCAD Map software. The

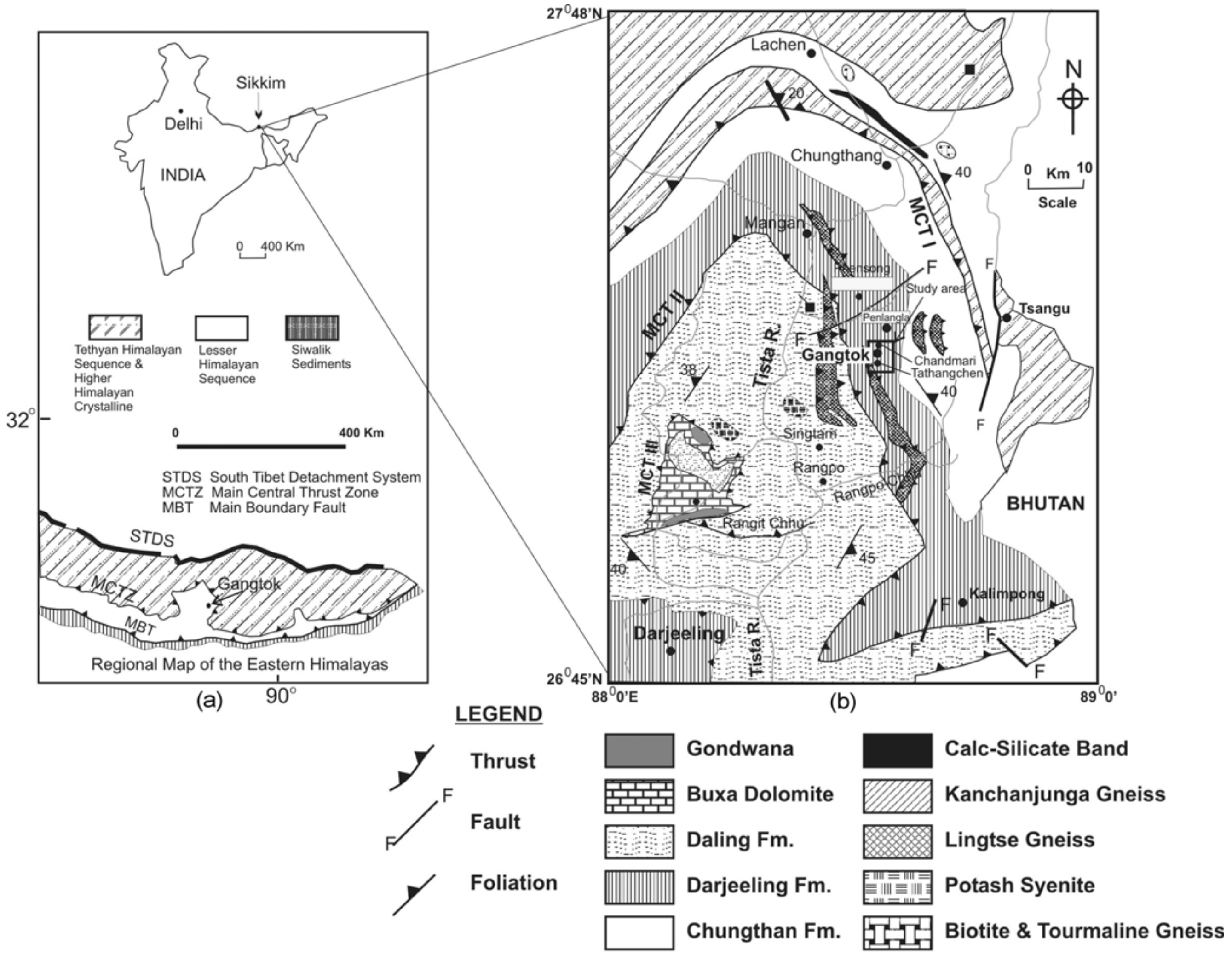

Fig. 1. Regional Geological map of Sikkim, Eastern Himalaya.

contours were created and transferred as strings to Datamine studio software for 3D geological modeling and mine planning to the scale. The software is virtual, 3-dimensional software, which provides a live demonstration of the surface and sub-surface using actual 3-dimensional coordinates. The contours were then converted into a Digital terrain model using wire frame technique. The Digital terrain model can be visualized from any side using user guided visualizer program at any angle. Profiles/sections could be generated along any two designated points.

Geological fieldwork was carried out in Chandmari-Tathangchen near Gangtok and proper attention has been given to major, minor structures, orientation of joints and their relation to drainage pattern in various litho units. The geomorphic and geological features such as drainage pattern, landslide stability map and geological contacts were also digitized and imported in Datamine software as separate strings. These layers/features are later draped to exact scale and superimposed on Digital terrain model to visualize them on the topography.

3. GENERAL GEOLOGY

Stratigraphically, the rocks around Chandmari area have been classified into a) Darjeeling Formation, b) Daling Formation, and c) Lingtse Gneiss (Acharyya, 1989). Darjeeling Formation comprises of gneiss, Kyanite-sillimanite schist, Kyanite gneiss, Kyanite staurolite schist, Staurolite-garnet schist and Garnet schist associated with bands of amphibolite. The Staurolite-garnet schist and Garnet schist form the lower members of the Darjeeling Formation.

Daling Formation consists of chloritoid schist and phyllites intercalated with quartzite belonging to green schist facies. The contact between the medium to high-grade gneisses and migmatites overlying the staurolite and garnet bearing schists at Deorali near Gangtok is a sheared one and the rocks are highly mylonitized along the contact. The gneisses are highly fractured and are covered by thick soil in Chandmari Tathangchen area. The streaky biotite gneiss (Lingtse gneiss) occurs in the form of bands, which are present within the low grade Daling and medium to high grade Darjeeling Formations. The Lingtse gneiss is characterized by sheared contacts with Darjeeling and Daling Formations (Table 3). The regional strike of all the mentioned lithological units near Gangtok is NW-SE dipping 20-65° towards NE. Local variations in the strike trend are attributed to several phases of deformation.

Table 3. Lithostratigraphic Sequence of East Sikkim (Dubey, 1993)

Lingtse formation	**Streaky biotite gneiss (Lingtse gneiss)**, sheared and mylonitized porphyroclastic, micaceous quartz feldspar gneiss.
Daling formation	**Low grade green schist facies,** chloritoid and chlorite schist, greenish sheeny carbonaceous and ferruginous phyllites associated with quartzite.
Darjeeling formation	**Medium to high-grade gneisses** Migmatitic gneisses with Kyanite-Sillimanite, staurolite, and garnet schists associated with amphibolite bands.

3.1. Chandmari Area

The rock types Chandmari area is characterized by medium to high-grade gneisses overlying staurolite and garnet bearing schist (Fig. 2). The medium to high-grade gneisses are well exposed in the east of Gangtok along Chandmari and Rongnek-Bhushuk road. It is hard and fresh near Bagcha Chu. The important rock forming minerals are quartz, feldspar (orthoclase and plagioclase), biotite, muscovite and chlorite where biotite shows mineral lineation at 35-45° towards SE (Fig. 2). The granite gneiss is foliated in the northeastern side of Gangtok, which overlie on highly altered staurolite garnet schist and retrograded garnet schist towards palace at Gangtok. Staurolite garnet schist is gradually enriched with biotite towards 400m north of Gangtok (below Sikkim high court). It is characterized by retrograded effects at 0 km stone on National highway (NH 31A) near Gangtok, 500 m East of Gangtok (base of Sikkim Palace) and 2 km South of Gangtok (near Deorali). The retrograded staurolite garnet schist is hard and compact. It consists of chlorite along with other minerals. The garnet schist is exposed near Gangtok along and in the west of Indira bypass road. It is highly altered and shows tectonic contact with Lingtse gneiss towards the west of Gangtok which is green, soft and friable consisting of quartz, muscovite, chlorite and garnet. The garnet porphyroblasts occur along S_2 along with biotite. The S_2 foliation trends vary NW-SE, E-W and N-S and dipping at 30-60° due NE, N and E. It also underlies Lingtse gneiss towards west of Gangtok. The quartz veins are co-folded and boudinaged parallel to S_2 foliations.

4. STRUCTURE

The Eastern Sikkim area is tectonically delineated by well-defined thrusts *i.e.*, The Main Central Thrust Zone (MCTZ), which brings the migmatites and gneisses over the medium to high-grade schists and gneisses. These in turn are in tectonic contact with the Lingtse gneiss and low-grade Daling phyllites. During the last stage of deformation (F_2) the rocks were affected by thrusting which acquired a domal structure due to ramping of the MCT-I, MCT-II and MCT-III. According to various workers (Dubey, 1993; Catlos et al., 2002, 2003 and Dubey et al., 2003) the presence of MCT-II is located near Gangtok (Fig. 1B) associated with east-west and north-south trending folds on minor scale. The MCTZ is considered as imbricate structures with

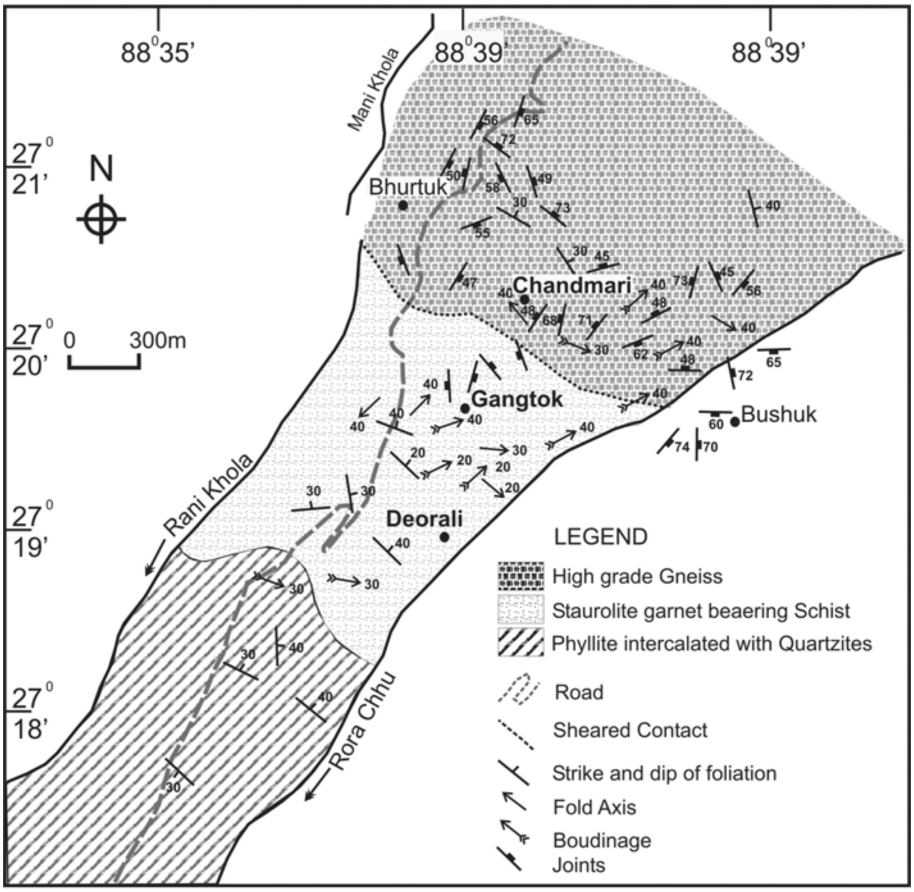

Fig. 2. Geological map of Gangtok–Chandmari area.

multiple thrust sheets. The signatures of post-metamorphic thrusting are evidenced in the field by strong retrograde metamorphic effects (chloritization), which took place after the F_3 folding movements. The P-T-t results indicate that the shear zone experienced a complicated slip history and has implications for the understanding of the mid crustal extrusion and the role of out-of-sequence thrusts in convergent plate tectonic settings (Catlos et al., 2004).

The general strike of the beds in the area is along NW-SE dipping mainly due NE (Fig. 2). On the basis of plotting of about 200 dips, foliation and cleavage planes (parallel to each other) inferred that there is an eccentric axial symmetry of fabric along SW direction (Turner and Weiss, 1963). In the present area a single maximum of S_1 foliation with irregular contours is noticed. A faulted contact between high-grade gneisses, staurolite and garnet bearing schist has been observed (Bhattacharyya et al., 1987) trending ENE–WSW.

There are three sets of joints observed in the area, which shows parting in the rocks without displacement and perpendicular to each other. The prominent set is in east west directions while other is in north south directions. The mesoscopic planner fabric data (S-surface) and linear structures (fold axis) plotted on the stereonet for structural analysis depicted variation in the orientation and geometry of the p_2 axis of F_2 folds. The girdle passing through the maximum shows p_2 axis with a plunge of 40° NE indicating a variation F_2 in the folds. In Gangtok-Ranikund area the p_2 axis plunges at low angles towards NW.

5. GEOMORPHOLOGY AND RAINFALL

Nearly two-third of Sikkim consists of very high mountains partially covered with snow from which descends glaciers like Zemu, Changsang, Lonak and Tanum. The glaciers are the sources of major rivers in Sikkim such as Teesta, which arises from Zemu glacier. The Teesta and Rangit, which originate from the Western portion of the State merge together and flow down to West Bengal. The State's climatic condition is determined almost exclusively by the difference in altitudes.

Most of the rivers and streams in this area are in the boulder stage and have not attained a permanent regime even before entering the plains. While regular meandering courses, deep well defined beds and wide flood plains are the characteristics of stable rivers in the plains, the boulder rivers are having shallow beds and shifting braided and interlaced channels. Urbanization in the road vicinity and also in the catchment areas is one of the major causes inducing unstable conditions, especially surface scour and thereby allowing water to percolate and create pore pressure conditions that

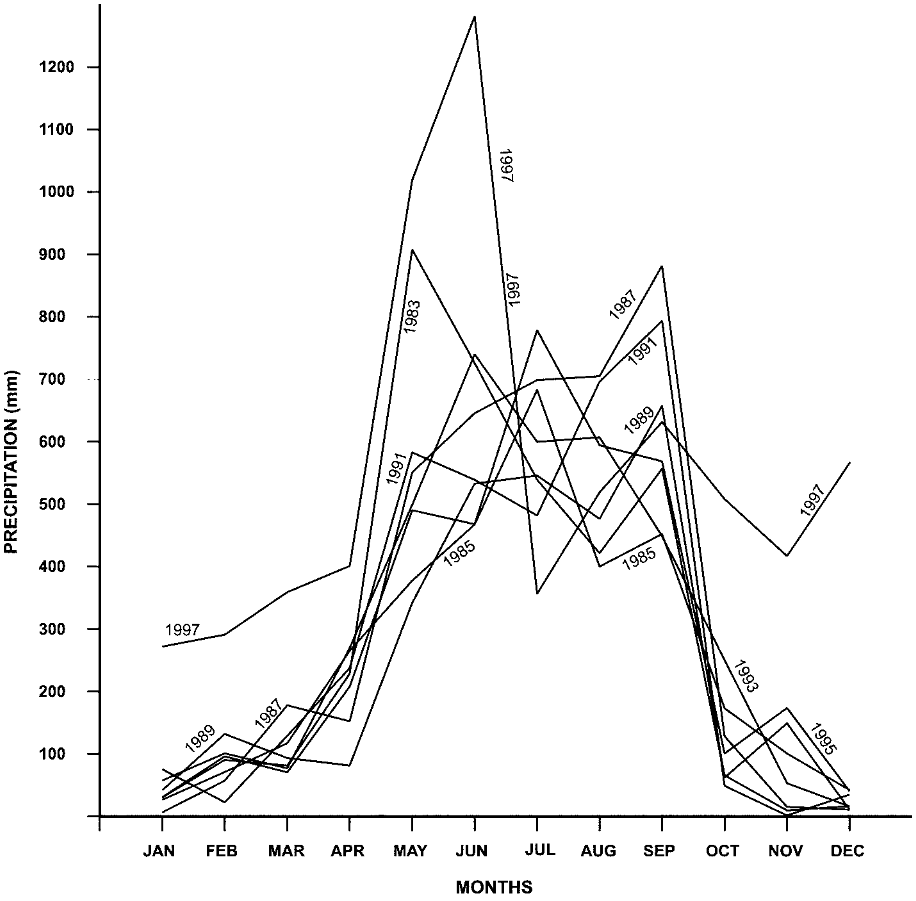

Fig. 3. Rainfall data by months.

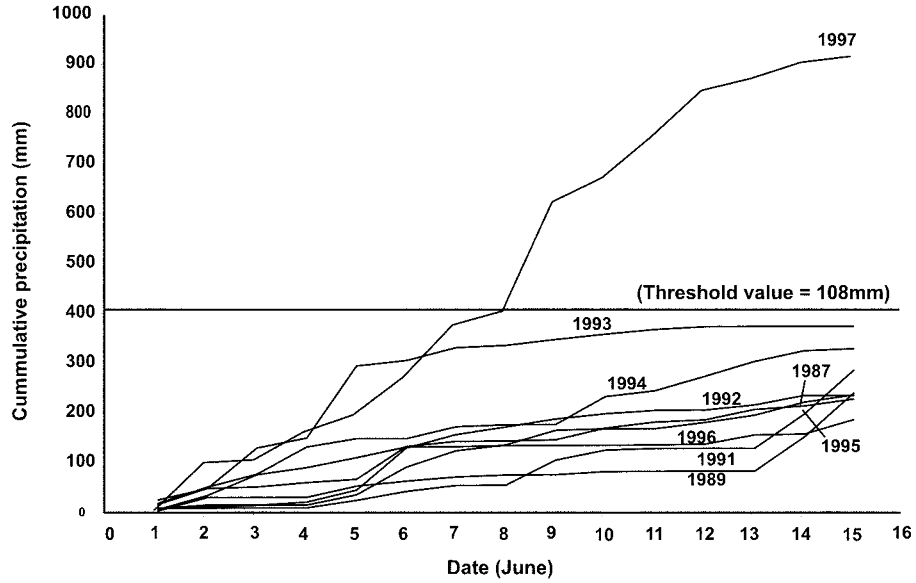

Fig. 4. Cumulative Precipitation for first fifteen days in the month of June for Chandmari landslide area.

cause movement of large scale debris creating blockage.

The drainage basin of the present area is fan-shaped and has a greater run-off rate. The chief component of vegetation of the present area is subtropical broad-leaved hill forest. While at the upper reaches above 1800 m it consists of temperate coniferous forest (Sudhakar et al., 1994). The terrain in the source area of landslide has an average slope of 30°-35°. The top soil in the area consists of mainly sandy loam to clayey type of soil followed at the down slope by mixed boulder beds and soil with clay followed by boulder beds and weak jointed rock exposures along with mainly boulder beds at the toe of the landslide. The uppermost part of the soil (about 2 m thick) is fine grained and humus rich. Boreholes carried out at the site (for the purpose of installing peizometers) have indicated that the bedrock at various places is at a depth of more than 20 m. Weathering has presumably altered and broken down the upper part of the bedrock in the region by chemical decomposition and physical disintegration (Bhasin et al., 2002).

The annual average rainfall is about 3,540 mm and the average for the month of June varies from 330 to a maximum of 1,280 mm in the year 1997 (the year of landslide) (Figs. 3 and 4). The heavy rainfall (cloudburst) on June 9, 1997 *i.e.* 211 mm in 4 hours (the limit of cloudburst is above 200 mm in day or so) and poor drainage system along with the heavy structure like concrete buildings and poor road maintenance lead to over saturation and further loading on already unstable, highly jointed and foliated rocks in this area.

6. CHI-SQUARE TEST AND PROBABILISTIC APPROACH

Evaluation of slope stability at first instance needs consideration of historic record of landslide. The use of a probabilistic framework can be significant improvement over the deterministic framework but its role may be limited to handling only some of the main uncertainties (Chowdhury and Flentje, 2003). The chi square test based on the contour intervals and cross slope distances (Gurung and Iwao, 2001) provides an uncertainty when used for the entire area while it is more certain and deterministic when applied to local areas already identified as stable or unstable in the landslide hazard zonation.

Methodology to draw graphs for Chi-Square test is simple. The inter distance between two adjoining contours are measured radially in all the directions and frequency for different intercepts is calculated. Graph is drawn between various contour intervals and their respective frequency percentages. Once the graph is generated, inference can be drawn on the basis of smoothness or ruggedness of the frequency curve. Frequency curves with multiple peaks indicate an unstable area whereas a smooth single peak suggests a relatively stable area. On the x-axis of the graph, contour interval as measured on map in mm is provided whereas the y-axis, frequency percentage of various contour intervals is provided.

The Chi-square test was applied on whole area, which gave an uncertain answer whereas when applied to Chandmari and Tathangchen areas multiple-peaks were witnessed signifying unstable areas (Fig. 5). Another area which falls under stable zone was also tested which provided single peak and hence was found stable. Therefore, it can be concluded that this test cannot be used in isolation for prediction of the stability of the area but is used as a supportive test.

7. LANDSLIDE HAZARD MAP

A landslide hazard map has been created taking into account a number of parameters (Table 1). These parameters include slope, lithology, drainage, relief, land use and land cover, hydrogeology and structure. The area has been classified in 5 zones based on the stability quotient as very low hazard zone through moderate hazard zone to very high hazard zone (Anbalagan, 1992; Fig. 6). These are broad zones only and indicate probabilities of landslide hazards. The maps are prepared on scales of 1: 5,000 and based on a combination of desk and field investigations.

8. 3-D MODELLING AND APPLICATION OF SOFTWARE

The contours drawn from existing toposheet were imported

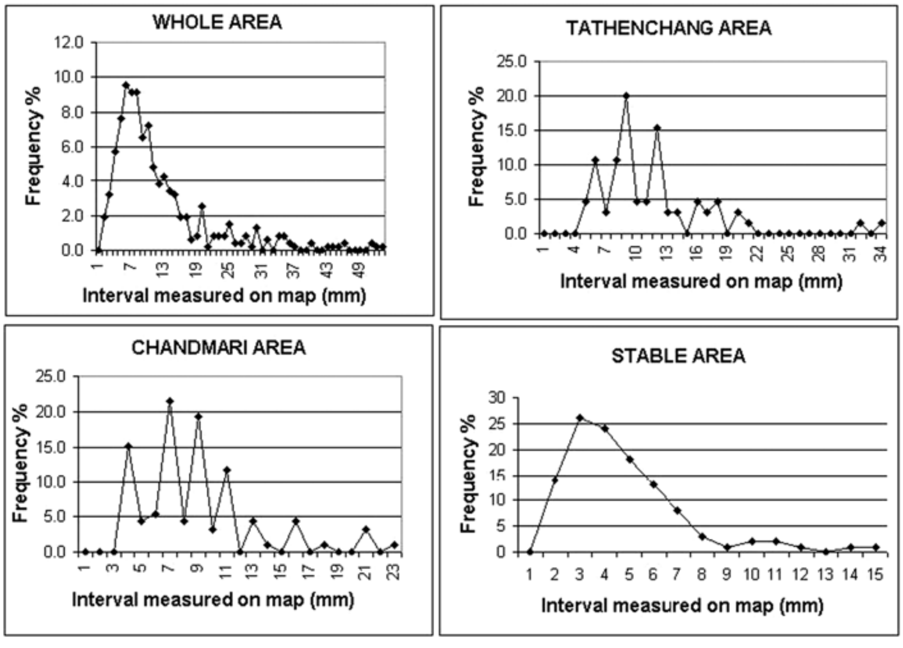

Fig. 5. Graph showing chi-square distribution.

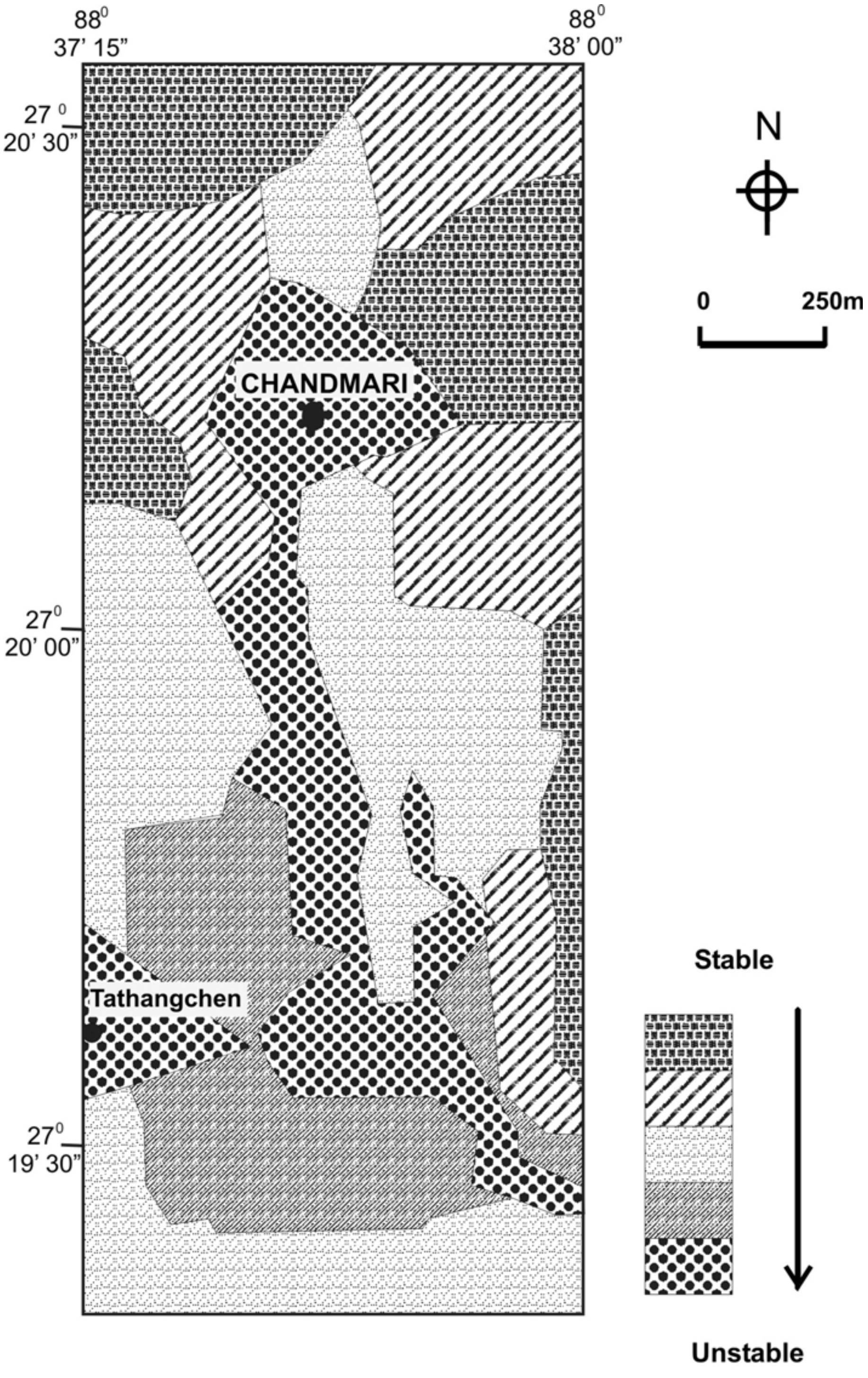

Fig. 6. Landslide stability map of Chandmari-Tathangchen area.

in Datamine software to create a Digital elevation model. Datamine is software that deals in geological applications, exploration and mine planning. It also provides a visualization facility for user to visualize and assess the stability of the area in 3-dimensions from desired angle/direction by superimposing various layers e.g. DTM, slope, lithology, structure etc. as well as to understand their inter-relationship. The geomorphic features such as drainage, landslide hazard zones and lithology were imported in the software as separate strings. These features as different layers were then draped on to Digital elevation model to see the interrelationship of these layers with the topography.

Borga et al. (1998) have discussed a model that delineates areas prone to shallow landsliding due to surface topographic effects on hydrological response based on high- resolution digital data. However, the digital recent elevation data can only show the effects of recent landsliding in the mountainous basins. The historic record of landsliding in Sikkim Himalayas and other places are scarce. The reports and research papers are lacking the precise locations and database for the previous landslides for any meaningful interpretation. Digital elevation model developed on Survey of India sheet 6 of 1972 through Datamine software significantly pointed out the vulnerable slopes specifically in the Chandmari and Tathangchen area depicting historic evidence of landsliding in the area (Fig. 7a, b). The empirical approaches for ranking potential for stability of different slopes such as Chi-square test, geotechnical parameters, and standard hazard maps could not exactly define the factors responsible for the cause of Chandmari landslide. The draping of lithological layer and drainage on Digital elevation model (Fig. 7a, b) and visualizing the above in guided visual programme of Datamine clearly indicated causal factors of Chandmari landslide being a combination of the historic vulnerable slopes and structurally controlled weak lithtectonic contact of high grade, brittle and jointed gneisses over the highly altered and retrograde sheared schists accentuated by the cloud burst and heavy rainfall. The contact acted as a conduit for the development of a small drainage basin. It was easy to create and view the 3-D profiles and make 2-D sections at any desired orientation and angle (Fig. 8). The landslide hazard map and other layers draped on Digital elevation model (Fig. 7a, b) depicted a clear picture of the location of Chandmari and Tathangchen landslides in the unstable zone in 3-D model.

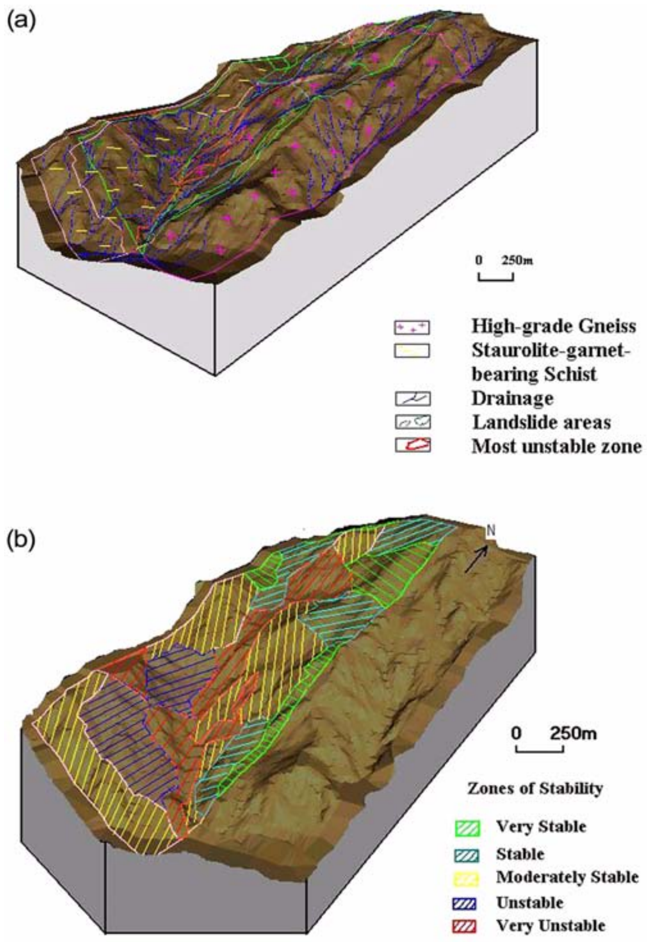

Fig. 7. (a) Digital Terrain Model with drainage, geology and major landslides, (b) Digital Terrain Model with stability zones.

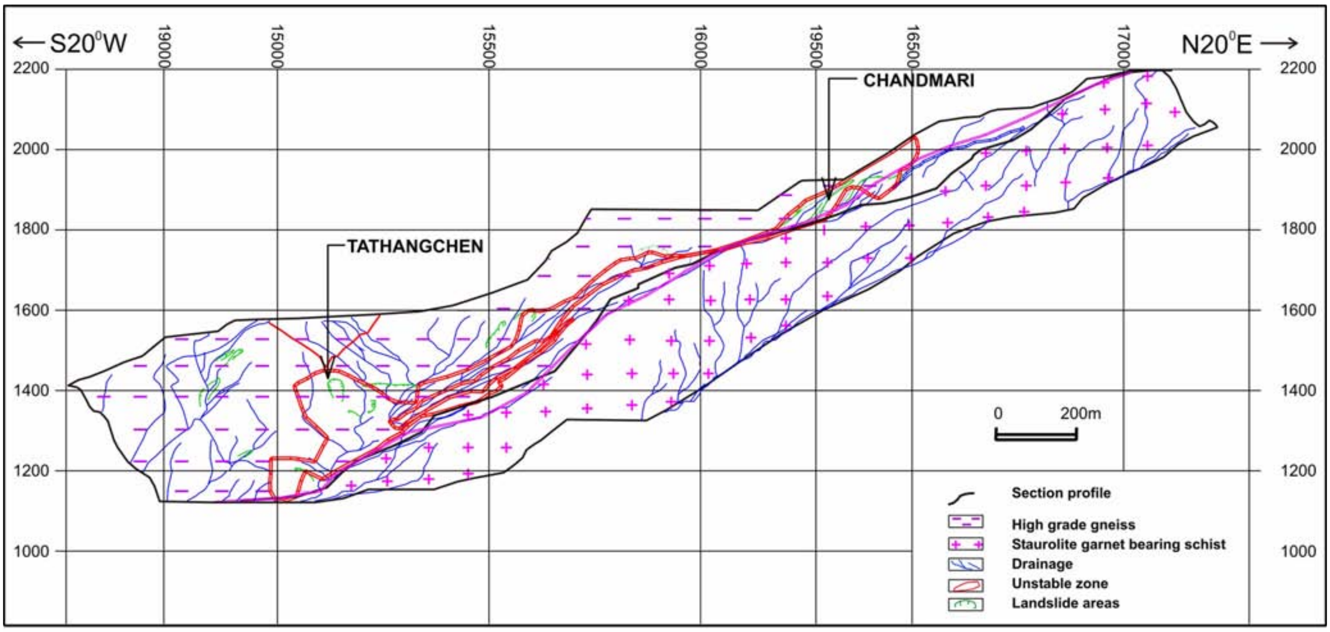

Fig. 8. Topographic profile along N20°E line through Chandmari and Tathangchen landslide areas.

9. REAL TIME LANDSLIDE WARNING SYSTEM DURING HEAVY RAINFALL

Several workers have discussed various models based on parameters responsible for landsliding and their work has been summarized in a special volume (Env. Geol., 1998).

The rainfall data is important in triggering the landslides in the mountainous terrains and could be used as a real time system for issuing warnings of landslides during heavy rainfalls. Prediction of landslides in mountainous terrain (e.g. Chandmari landslide) requires historical observations of rainfall, landslide occurrence and certain assumptions concerning slope, lithology, drainage and flow of water through hillside soils as well as historic rainfall data. Several relationships between rainfall and debris flow/rockslide have been developed from world wide historical and regional data. Keefer et al., (1987) made simplified assumptions that 1) all of the rainfall that falls infiltrates initially into a saturated zone above the potential slide plane, and, 2) total rate of drainage is proportional to the thickness of the saturated zone. Under these assumptions, the drainage rate would increase as the rain accumulates reaching a maximum when the slope fails. The equation for rainfalls with the combination of intensity and duration required to emplace the critical quantity of water to initiate landslide on a given hill slope is given by:

$$(I_r - I_0)D = Q_c$$

Where $I_r=14.82D^{-0.39}$; I_r is intensity of rainfall in mm per hour and D is in hours, I_0 is drainage by average rate and Q_c is critical volume of water retained in the saturated zone. The I_r is calculated to be 8.62 for four-hour duration (Fig. 9).

According to Keefer et al., (1987), the value of threshold parameters I_0 and Q_c depends upon the geometry of hill slopes, position of the slip surface and mechanical and hydrological properties of the slope material. In the case of Chandmari and Tathangchen landslides, the hydrological properties of the slope material are a function of the lithologies and gravity-pull of the burden of high-grade jointed gneisses over sheared schist with low shear strength and weak folia. So the relationship for abandoned debris flow can be approximated by an expression with I_0=3.7 mm (for 4 hour duration) and Q_c=19.68 cu mm by various curves and figures.

Statistically, the rainfall-triggering threshold is not constant and is variable with respect to soil moisture conditions. Terlien (1998) calculated rainfall duration and intensity for various wet and dry initial soil moisture conditions that lead to saturation of topsoil profile. He observed that when the rainfall intensity exceeds a certain level (14 mm/h), the maximum infiltration capacity of the soil is exceeded and overland flow occurs and if it is less than 5 mm/h, the maximum pore-water pressures that are reached significantly lower than zero even when rainfall duration is very long. This is because of the fact that vertical percolation rate exceeds the rainfall intensity.

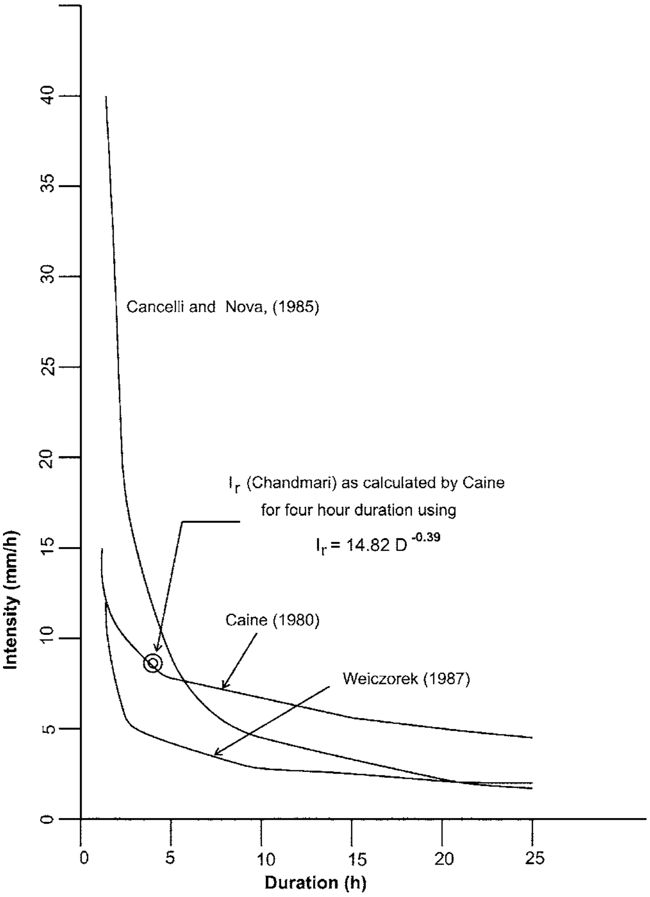

Fig. 9. Rainfall intensity/duration threshold for shallow landslides developed after Caine, 1980; Weiczorek, 1987; Cancelli and Nova, 1985).

Crosta (1998) stressed that the relationships between intensity versus rainfall duration becomes particularly important when related to soil permeability and thickness, and demonstrate the role of antecedent precipitation.

Therefore, the rainfall intensity of about 17 mm/hour has been estimated to be sufficient to trigger off a landslide in the study area based on deterministic rainfall triggering thresholds (Terlien, 1998). The threshold value of 17 mm/hour has been arrived at on adding a standard error of mean to per day mean cumulative rainfall of 15 days for nine years. The definition of cloud burst in mountainous terrains is considered to be a rainfall of more than 204 mm in 24 hours. Thus, a threshold rainfall of over 200 mm in 24 hours may trigger a landslide in this area in the present set up. Generally, in mountainous regions like Chandmari area the tribal population has a tendency to continue with their dwellings even in the worst natural disasters. A landslide warning system on the basis of rainfall predictions and pore saturation conditions above the threshold (Q_c) along with training to the tribal to evacuate and move in nearby safer temporary camps could lessen the loss on account of property and human lives.

10. CONCLUSIONS

It is not possible to predict the landslide prone areas by Chi-square test alone at the regional scale. The chi square test applied regionally to whole area depicted stable zones whereas applied locally to Chandmari and Tathangchen areas signified unstable zones. Digital elevation model developed through Datamine software significantly pointed out the vulnerable slopes in the specific Chandmari and Tathangchen area depicting historic evidences of landsliding in the area.

The draping of lithology, drainage and landslide hazard map on Digital Elevation Model and visualizing the above in Guided Visual Programme of Datamine clearly indicated causal factors of Chandmari landslide. It was easy to create and view the 3-D profiles and make 2-D profile sections at any desired orientation and angle to exact scale for studies of the Chandmari Landslide area.

It is observed that a rainfall intensity of about 17 mm/hr was sufficient to trigger off a landslide in the mountainous terrains like Chandmari in Eastern Sikkim. The threshold value of 17 mm/hr has been arrived at on adding a standard error of mean to per day mean cumulative rainfall of 15 days for nine years. A landslide warning system on the basis of rainfall predictions and pore saturation conditions above the threshold (Q_c) along with training to the tribal to evacuate and move in nearby safer temporary camps could minimize the loss of human life and properties.

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