"A stitch in time saves nine."

Thomas Fuller, 1732

LANDSLIDE HAZARD ZONATION AND REMEDIATIONS 8

Natural Hazard means the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area while *Zonation* refers to the division of land in homogeneous areas or domains and the ranking of these areas according to their degree of actual or potential hazard caused by mass movement (Varnes, 1984).

Slope instability processes are the product of local geomorphic, hydrologic and geologic conditions; the modification of these conditions by geodynamic processes, vegetation, landuse practices and human activities; and the frequency and intensity of precipitation and seismicity. A Landslide Hazard is commonly shown on maps that display the spatial distribution of hazard classes (or Landslide Hazard Zonation). These hazard classes expresses about the susceptibility or likelihood that a phenomenon (in this case, a landslide) will occur in an area on the basis of the local terrain conditions and the recurrence periodicity of triggering factors such as rainfall or seismicity. Prediction of landslide hazard for areas not currently subject to landsliding is based on the assumption that hazardous phenomena that have occurred in the past can provide useful information for prediction of future occurrences (Soeters and Westen, 1996).

Further, review of Previous Studies on Landslide hazard assessment helps the investigations in understanding the efficacy of adopted approach and methodology, and strengthening the gaps so as to derive the most reliable inferences that can be utilized for adopting mitigatory measures.

The Kumaun Himalayan demonstrates illustrates innumerable cases of landslides, inspite of this there exists very few studies leading to the level of hazard zonation. Anbalagan (1992), while studying Kathgodam-Nainital area has very creditably attempted landslide hazard evaluation and zonation by involving various Landslide Hazard Evaluation Factors (LHEF). Important factors viz. lithology, structural discontinuities, slope and slope morphometry, relative relief, landuse and landcover, and groundwater conditions have been assigned ratings as 2 and 1 with maximum rating of 10. Based on these factors, he put forth in all 05 hazard categories, ranging between Very High Hazard (> 7.5) and Very Low Hazard (< 3.5).

Although this adopted methodology is very similar to that of Beineawski (1979); it does not take into account precise information on joint severity characteristics, rock strength parameter and needed correction to derive Slope Mass Rating (Romana, 1993) particularly with reference to anthropogenic factors.
His subsequent works (Anbalagan and Singh, 1996) and Gupta and Anbalagan, 1997) in other parts of Kumaun and Garhwal Himalayas is on the line of similar approach.

Bali (1997, 1998a & b) has carried out landslide hazard evaluation in adjacent Dhauliganga river valley using GIS approach.

Bureau of Indian Standards [IS 14496 (Part – 2) : 1998] deliberates on the systematic approach for landslide hazard zonation at macro level. The recommended guidelines are very much similar to that suggested by Anbalagan (1992).

REMOTE SENSING AND GIS IN LANDSLIDE HAZARD ZONATION

Potentially unstable slopes and landslides are often local scale features, even though they can occur in great numbers over a wide area. This and the limited size of many damaging or socio-economically significant mass movements require the use of observational data with much greater spatial resolution with respect to those used for other natural disasters such as floods, earthquakes, volcanic eruptions (Wasowski and Singhroy, 2002). Earlier large scale, stereo aerial photographs have been extensively applied in landslide investigations for several decades. They are very useful for the recognition, characterization and geomorphic analysis of landslides. Present days, there has been a considerable increase in satellite remote sensing studies for slope stability investigations. This appears to have resulted from (i) the greater data availability of several new Earth Observation (EO) satellite systems in the last decade (e.g. European ERS-1 and ERS-2 satellites, SIR-C/X-Synthetic Aperture Radar flown onboard of NASA's Space Shuttle, Japanese JERS-1, Canadian RADARSAT, United States LANDSAT TM 5 and 7, and the French SPOT and Indian IRS satellites); (ii) the improved capabilities (high resolution, stereo and frequent revisits) of the optical and In-SAR satellites and (iii) the development of more advanced EO data processing techniques.

Landslide information extracted from remote-sensing images is mainly related to the morphology, vegetation, and drainage conditions of the slope (Soeters and Westen, 1996). The interpretation of slope movements from remote-sensing images is based on recognition or identification of elements associated with slope movements and interpretation of their significance to the slope instability process in terms of characteristics associated with these features. The interpretability of such features in an image is influenced by the contrast that exists between features with their background and the spatial resolution of remote-sensing images.

The objective procedure to quantitatively support the slope instability assessment requires evaluation of the spatially varying terrain conditions as well as the spatial representation of the landslides. Thus, a Geographical Information System (GIS) allows the storage and manipulation of information concerning the different terrain factors as distinct data layers and provides an excellent tool for slope instability hazard zonation. An idealized GIS for landslide hazard zonation combines conventional GIS procedures with image-processing capabilities and a relational database (Soeters and Westen, 1996). The advantages of GIS for assessing landslide hazard includes –

1. A much larger variety of hazard analysis techniques becomes attainable. Because of the speed of calculation, complex techniques requiring a large number of map overlays and table calculations become feasible.
2. It is possible to improve models by evaluating their results and adjusting the input variables. Users can achieve the optimum results by a process of trial and error, running the models several times, whereas it is difficult to use these models even once in the conventional manner. Therefore, more accurate results can be expected.
3. In the course of a landslide hazard assessment phase, the input maps derived from field observations can be updated rapidly when new data are collected. Also, after completion of the project, the data can be used by others in effective manner.

LANDSLIDE HAZARD ZONATION OF TAWAGHAT – JIPTI ROUTE CORRIDOR

One of the objectives of this work is to develop a methodology with the help of remote sensing that could produce a hazard zonation map over a large area with higher degree of accuracy in a GIS environment. In the past, several probabilistic methods (quantification theory, multiple regression, discriminate analysis, monte-carlo simulation, etc.) were attempted (Hayashi, 1952; Carrara, 1983; Haruyama and Kitamura, 1984; Kawakami, 1984; Yin and Yan, 1988; Jade and Sarkar, 1993; Jibson et. al. 1999, Luzi et.al. 2000) to derive landslide hazard zonation map. In this work, the information theory had been utilized to construct the map on landslide hazard zonation. It is most preferable over other methods by virtue of its accuracy and field applicability. The generated hazard maps were cross validated with field data and recent satellite data for accuracy.

METHODOLOGY

Present study utilizes data from IRS 1D and Shuttle Radar Topographic Mission (SRTM) satellites. It has a LISS III sensor, which operates in four spectral bands. Three bands are in visible and near infrared region with spectral bandwidths as 0.52-0.59 μm, 0.62-0.68 μm and 0.77-0.86 μm and spatial resolution as 23.5 m. Fourth band with spectral bandwidth of 1.55-1.75 μm falls in short wave infrared region and has a spatial resolution of 70.5 m. The Panchromatic sensor (PAN) has high spatial resolution of 5.8m.The SRTM data provides microwave data in L-band (4-6 cm). The height information (30m contours) is generated from this microwave data.

LISS-III and PAN data were merged together to give high resolution multispectral satellite image (Figure 8.1), which was then utilized to generate different thematic layers such as landuse, lineament and landslide inventory. The slope and aspect maps were generated from the Digital Elevation Model (DEM) derived from the SRTM data (Figure 8.2).

For this study a buffer zone of TWO kilometers distance on either side of the road alignment, was considered.

The adopted methodology as depicted in Figure 1.1 includes a three tier approach viz.

- Generation of digital database from the satellite and other collateral data
- Empirical modeling and prediction of probable hazard zones
- Field validation and accuracy estimation

Data Loading

All the scenes, which were entered in plan process details, were loaded in the system. Three well-defined points (tie points) whose latitude - longitude values are known were selected on all the scenes and their line and pixel numbers were noted.

Image Geo-referencing

Satellite data was geo-referenced using Survey of India toposheets (SOI) and Global positioning system (GPS) inputs using a first order polynomial equation with a RMS error of 0.5. The satellite data was rectified using *Polyconic Projection* with *Modified Mount Everest* as *datum*.

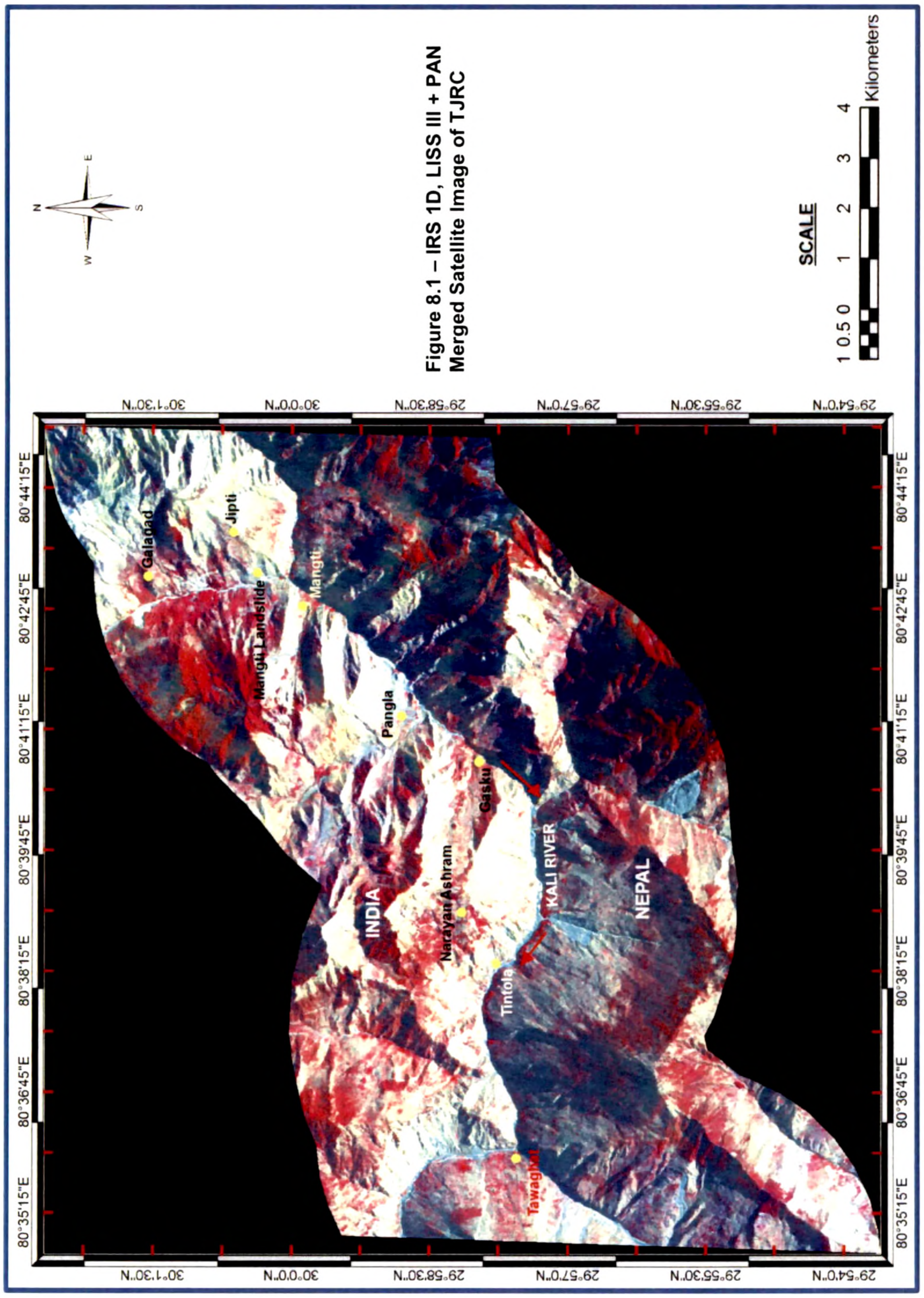


Figure 8.1 – IRS 1D, LISS III + PAN Merged Satellite Image of TJRC

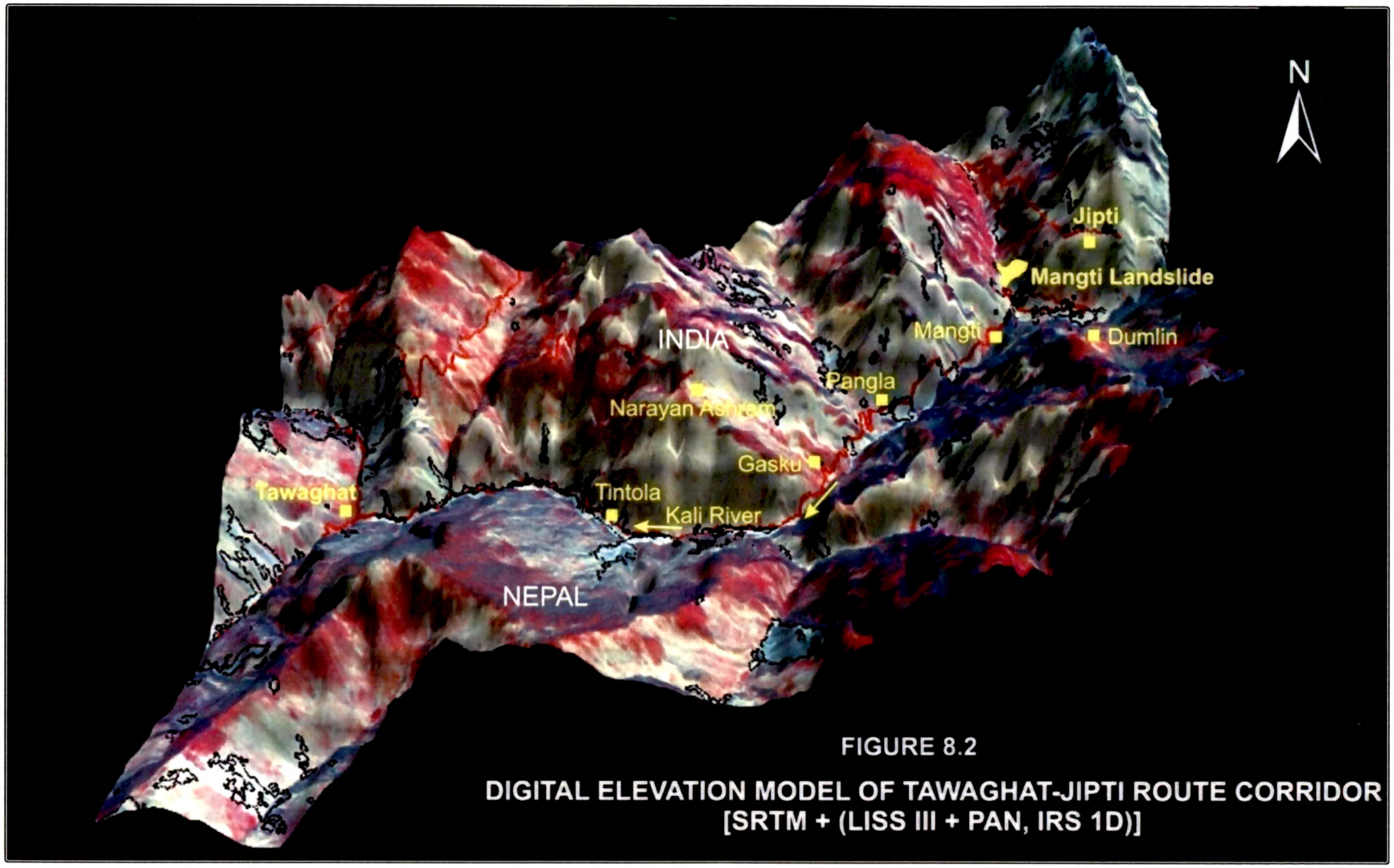


FIGURE 8.2

DIGITAL ELEVATION MODEL OF TAWAGHAT-JIPTI ROUTE CORRIDOR
[SRTM + (LISS III + PAN, IRS 1D)]

Image Enhancement

Histogram stretching enhances the LISS-III image. For resolution merge (between LISS-III and PAN), following procedure was carried out. First, the LISS-III image was transformed into Hue, Intensity and Saturation (IHS). Second, the intensity component was replaced by high resolution PAN data. Third, the IHS data was reverted to RGB domain. The edge enhancement was carried out by running high pass, Prewitt and Sobel filters.

Image Classification

Supervised classification of the image was carried out by selecting appropriate training sets using maximum likelihood classifier.

Generation of Slope and Aspect

The slope and aspect maps were generated using the SRTM derived Digital Elevation Model (DEM).

Generation of Vector Layers

The thematic vector layers were converted from the raster layers/ digitized from the collateral data and integrated in ARCINFO environment.

Data In-puts

The main data input for this study include

- ✓ Satellite data in the optical region (LISS-III+PAN, December 2002)
- ✓ Satellite data in the microwave region (SRTM)
- ✓ Collateral data on Geology, geotechnical properties, seismicity etc.
- ✓ Survey of India toposheets

Software Used

The satellite data retrieval, rectification, enhancement, classification and related image processing were carried out using the ERDAS IMAGINE software (ver.8.7). The spatial database and non-spatial data generation and analyses were carried out with ARCINFO WORKSTATION software (ver.9.0) with Visual Basic back end. The empirical modeling was performed using SPSS statistical software.

EMPIRICAL MODELING

INFORMATION THEORY

Information Theory was born in 1948 out of Claude Shannon landmark paper, *"A Mathematical Theory of Communication"*. As a scientific field it lies somewhere between Communication Theory, Statistics, and Probability Theory. This technique aim at measuring the information associated with occurrence of certain event having a probability **'p'**.

The first reduction towards this process will be to ignore any particular features of the event, and only observe whether or not it happened. In essence this means that one can think of the event as the observance of a symbol whose probability of occurring is **p**. Thus the information can be defined in terms of the probability **p**.

The information measure **I (p)** has several properties:

1. Information is a non-negative quantity: $I(p) \geq 0$.
2. If an event has probability **1**, we get no information from the occurrence of the event: $I(1) = 0$.
3. If two independent events occur (whose joint probability is the product of their individual probabilities), then the information we get from observing the events is the sum of two informations: $I(p_1 * p_2) = I(p_1) + I(p_2)$
4. The information measure is a continuous (and, in fact, monotonic) function of the Probability (slight changes in probability should result in slight changes in information).

Thus,

i) $I(p^2) = I(p * p) = I(p) + I(p) = 2 * I(p)$

ii) Further, $I(p^n) = n * I(p)$

iii) $I(p) = I\{(p^{1/m})^m\} = m * I(p^{1/m})$, so

$I(p^{1/m}) = 1/m * I(p)$ Hence, in general

$I(p^{n/m}) = n/m * I(p)$

iv) Therefore, by continuity, we get, for

$0 < p \leq 1$, and $a > 0$ a real number:

$I(p^a) = a * I(p)$

From this, we can derive

$I(p) = -\log_b(p) = \log_b(1/p)$ for some base b.

<u>Summarizing from the four properties -</u>

1. $I(p) \geq 0$

2. $I(p_1 * p_2) = I(p_1) + I(p_2)$

3. I (p) is monotonic and continuous in p

4. $I(1) = 0$

<u>We can derive that</u>

$I(p) = \log_b(1/p) = -\log_b(p)$,

For some positive constant 'b' the base 'b' determine the units.

INFORMATION THEORY AND LANDSLIDE HAZARD ZONATION

The analysis used for the landslide hazard was the Information Value method based on probability theory and is summarized as below:

Suppose there are N potential factors/variables that affect the slope instability, then the degree of potential hazard in an area can be estimated on the basis of number of fatigue factors and their severity and interactions. However, the main objective is to predict the areas of various degrees of landslide susceptibility. For this, first a given area is divided analytically into a number of polygon elements by considering the micro-watershed boundaries. As per the law of Information theory, every element **'j'** (j =1, 2..................N) can be defined stable or unstable on the basis of the information value (**I_j**) of that element. Higher the value of 'I_j' more unstable the element **'j'** is, within the slope.

The total information value in the element **'j'** can be calculated as (Equation 10):

$$I_j = \sum_{i=1}^{M} I_i X_{ji} \qquad \textbf{(10)}$$

X_{ji} = value of i^{th} variable (i =1, 2, ..,M) for the j^{th} element (j = 1, 2, ...,N);

= 1, if variable **'i'** exists in element **'j'**

= 0, if variable **'i'** does not exist in element **'j'**

M = number of variables associated with a given area

I_i = Information value supplied to landslide by variable 'i'

= **log [(S_i/N_i)/ (S/N)]** **(11)**

N = total number of elements

S = number of elements with history of landslide occurrence

S_i = number of elements with history of landslide occurrence involving variable **i**

N_i = number of elements involving variable **i**

ACCURACY OF PREDICTION

The experimental probability of prediction was evaluated using Equation 12 –

$$P = KS/ S * [1- (K-KS) / N-S]^{1/3} \quad (12)$$

N = Total no of elements

S = No. of elements containing landslides

K = No. of elements falling into High and Moderate classes

KS = No. of elements falling into High and Moderate classes containing Landslides

GENERATION OF THEMATIC LAYERS AND PROGRAMME STRUCTURE

For evaluating Information Values (**I_j**) requires identification of the total number of polygon elements associated with the given area (**N**) and terrain specific conditioning and triggering factors **(variables)**. For preparing the discrete element map, the area was divided into small blocks/elements on the basis of slope; aspect and watershed divide (Figure 8.3). In all 220 polygon elements have been identified for TJRC. This technique is helpful in better understanding the relationship between landslide events and variables. From the field investigations, the following variables (M) were identified as key conditioning and triggering factors.

GEOLOGY AND GEOTECHNICAL CHARACTERISTICS

Geology of the above region has been elaborately discussed in preceding Chapters 2 and 4. In this present study, lithological details have been based on Powar (1972), Jnawali and Jha (1997) and authors personal observations during his field visits to the study area. Thus, final geological map prepared for the study area has been adopted from (Figure 2.6). Lithology of Tawaghat-Jipti Route Corridor (TJRC) comprises fifteen major rock types and variables **X1-X15** correspond to lithology. Accordingly, if a litho-type is present in a discrete element, then **X = 1** else **0**.

The geotechnical character of the rocks belonging to TJRC has been detailed in Chapter 4 and the adopted SMR Classes for various litho-units occurring in TJRC are shown in Table 8.1. It is observed that the SMR Class of the rocks belonging to TJRC vary from Class III to V with only one incidence of Class II rock, indicating ***Normal, Bad*** and ***Very Bad*** quality rocks respectively. Accordingly these values are classified into three classes and assigned the binary values of 0 and 1 depending on their presence or absence. Thus,

.if X16 = SMR = CLASS III then 1 else 0

.if X17 = SMR = CLASS IV then 1 else 0

.if X18 = SMR = CLASS V then 1 else 0

TECTONIC FEATURES AND LINEAMENT FABRIC

The detail tectonic frame work has been discussed earlier in Chapter 2. Many faults and thrusts are active even today, which reflects in the form of frequent seismic events. Since these thrusts, faults and associated fracture system play a pivotal role in slope stability; the mapping and understanding of the region in their relationship to slope is essential. Further, the active faults also are the source of seismic shocks, which means the one of the main triggering factors for landslides. In this study, these tectonic features were mapped using high resolution IRS-LISS-III and Pan merged data products.

Prominent among the major tectonic features of this transect from south to north includes North Chiplakot Thrust (NCT), Main Central Thrust (MCT=Munsiari Trust) and Vaikrita Thrust (VT). The NCT (observed near Pangla village) forms the structural divide between the Chiplakot Crystallines and Sirdang Sedimentaries. Whereas, the MCT (observed near Mangti village) forms the structural divide between Sirdang Sedimentaries and Higher Himalayan Crystallines. The Vaikrita Thrust (= Malari Trust) within the Higher Himalayan Crystalline is evidenced north of the MCT near the Jipti village. From the satellite imagery, these structural features (Figure 8.4) were extracted by visual, semi automatic and automatic techniques.

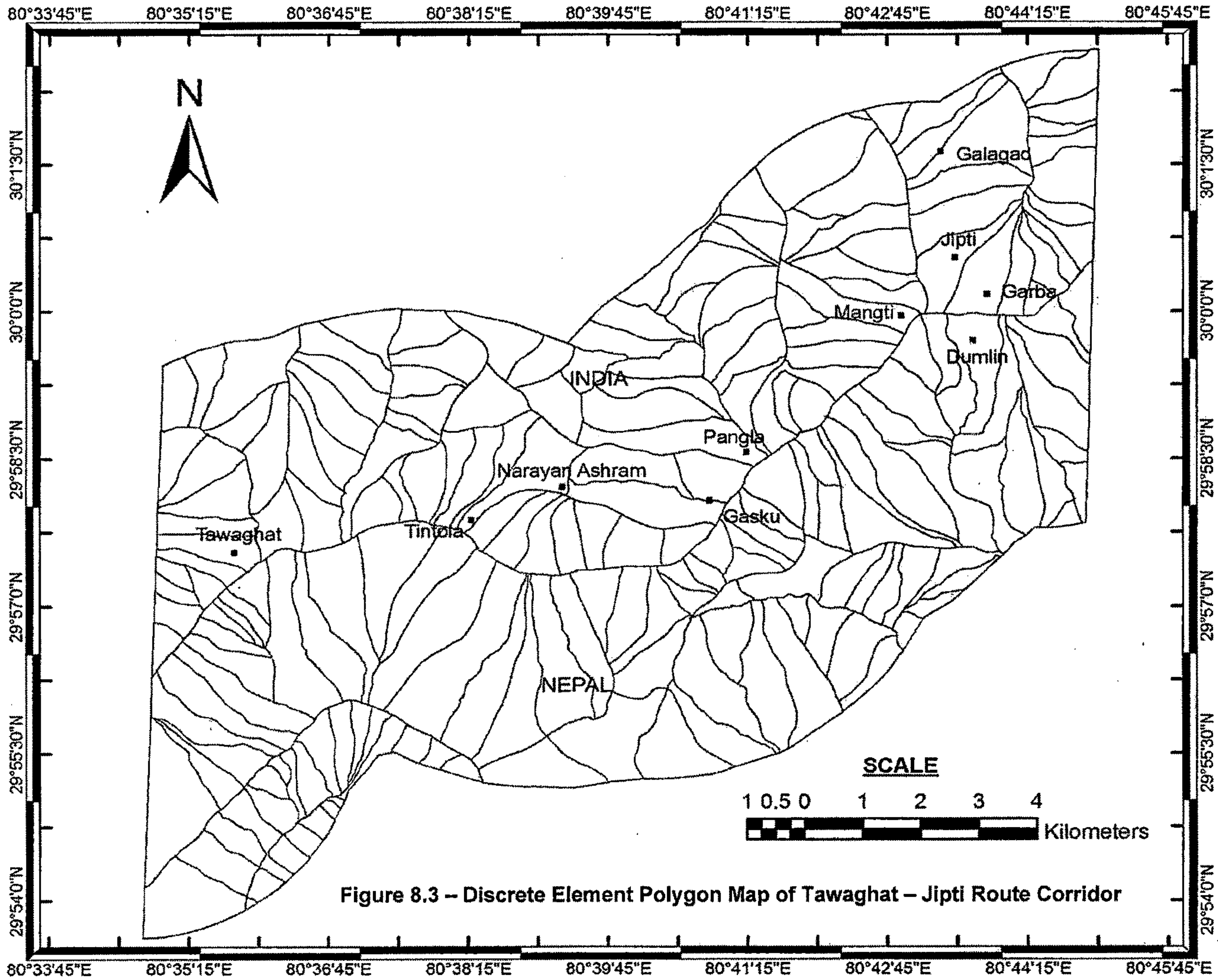


Figure 8.3 – Discrete Element Polygon Map of Tawaghat – Jipti Route Corridor

Table 8.1 – Adopted SMR Classes For Various Litho-units Along TJRC

STRETCH	SMR	SMR CLASS
Biotite Gneiss CHIPLAKOT CRYSTALLINES	37.69	IV
SIRDANG SEDIMENTARY ZONE		
Chlorite Schist	31.1	IV
Quartzite	44.35	III
Chlorite Schist	0	V
Amphibolite	53	III
Chlorite Schist	27.62	IV
Amphibolite	51.35	III
Chlorite Schist	25	IV
Quartzite	33	IV
Chlorite schist	40	IV
Carbo-phyllite	59.1	III
Quartzite	60.40	III
Calcsilicate Rock	35.60	IV
Talc-Chlorite Schist	32.23	IV
Phyllite	38	IV
Graphite Schist	38	IV
Garnetiferous Schist	33	IV
Calc-Schist	35	IV
Quartzite	51	III
Carbo phyllite	48	III
Flaggy quartzite	16	V
Calcschist	3	V
Flaggy Quartzite	28.35	IV
Calcschist	6.3	V
Chlorite schist	27.35	IV
Quartzite	45.5	III
Amphibolite	55	III
Quartzite	43.60	III
Chlorite Schist	19.60	V
Amphibolite	46.30	III
Chlorite Schist	31	IV
Quartzite	55.4	III
Amphibolite	52.7	III
Quartzite	52.4	III
Amphibolite	48	III
Quartzite	52.35	III
HIGHER HIMALAYAN CRYSTALLINES		
Biotite Gneiss	38.35	IV
Amphibolite	33	IV
Migmatised Gneiss	70	II
Amphibolite	35	IV
GM Schist	16.50	V
Amphibolite	35	IV
Biotite Gneiss	30.62	IV
Amphibolite	35	IV
Migmatised Gneiss	70	II
Biotite Gneiss	30.62	IV
GM Schist	16.50	V
Amphibolite	35	IV
Biotite Gneiss	30.62	IV
GM Schist	16.50	V

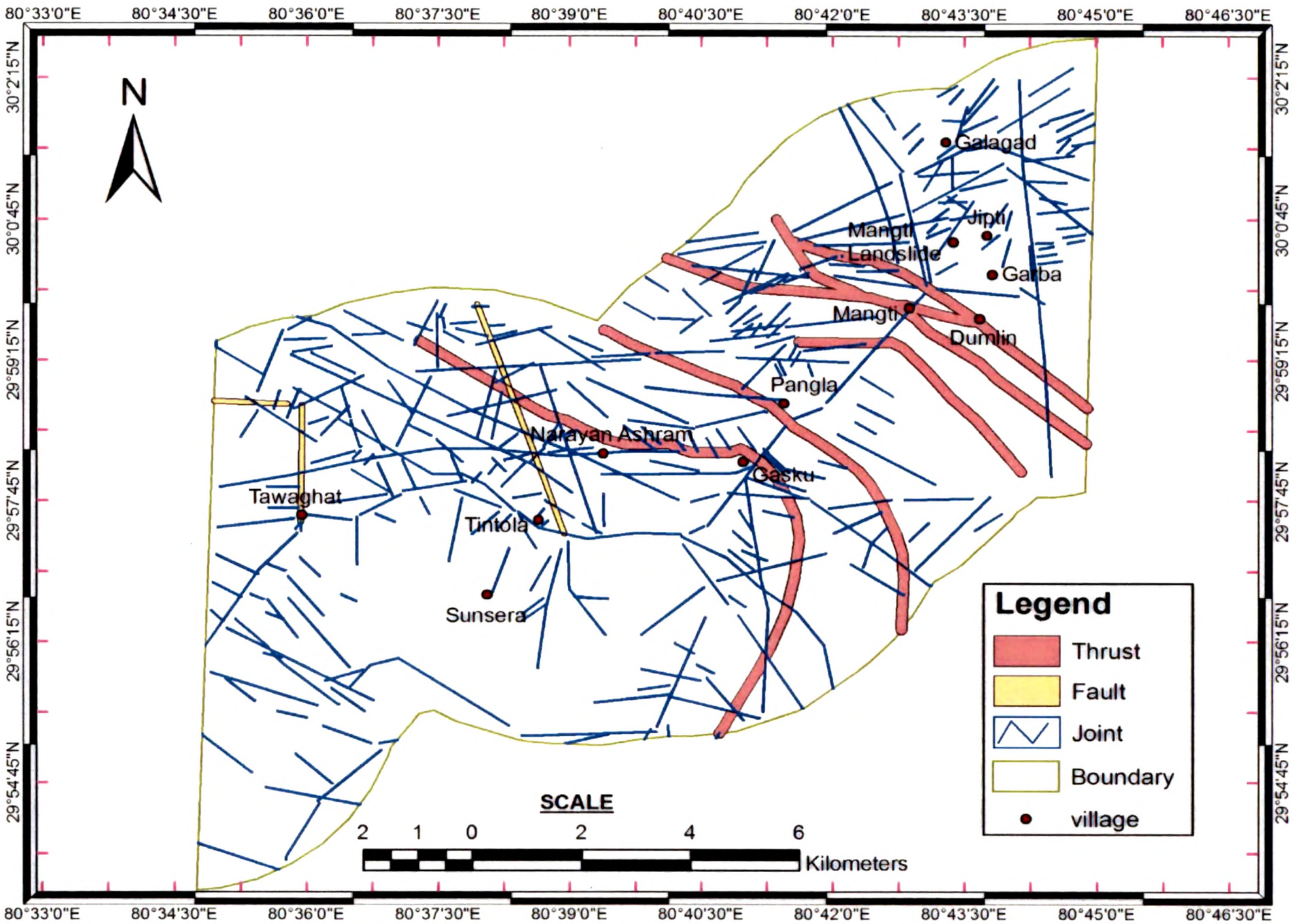


Figure 8.4 – Lineament Map of Tawaghat – Jipti Route Corridor

Major thrusts such as MCT, NCT are very clearly evident to naked eye (due to tone, texture and association changes) as major, continuous and prominent lineaments. Image enhancement techniques (edge enhancement techniques such as High Pass, Compass, Sobel and Prewitt filters) helped in identifying three additional, prominent linear features between NCT and MCT. One such lineament observed near village Maidu indicate sheared contact between quartzite and phyllite with changes in attitude of beds. These lineations run parallel to NCT and continue in Dhauliganga valley also. The Vaikrita Trust is also apparent after edge enhancement and run parallel to MCT.

Automated lineament extraction using Hough Transform (Karnielli et al., 1996) helped in extracting less prominent, discontinuous linear features. From the field observations, it is evident that these discontinuous lineaments match well with the joints / foliation plane. Thus on the basis of continuity, tonal, textural association and field observations, the lineaments are divided in to two categories viz., **Major Lineaments** (thrusts and faults) and **Minor Lineaments** (joints and bedding plane cleavages). On the basis of presence or absence of a structural element such as thrust / fault / prominent joints, two variables **(X19 & X20)** are assigned as 0 or 1.

SEISMICITY / EARTHQUAKES

The epicenters of the seismic events were digitized from the collateral data and attributed with magnitude. Since the magnitudes of the seismic events are less than 6, a buffer zone of 50 km^2 from epicenters were generated and used for this study. In the investigated area, available occurrences of seismic events are so far confined to major thrust and faults. Further, the intensity of these shocks ranges between 5 and 6 on the Richter scale. Hence, buffer zones up to 50 km^2 from the epicenter was made and uniformly assigned the variable **'X21'** as vulnerable to seismic shaking.

SLOPE AND ASPECT

The Slope (Figure 8.5) and Slope Aspect Maps (Figure 8.6) for TJRC were generated and classified from the DEM derived from SRTM data. The classification of the slope is made as per Indian Standard code of Practice IS 14496 (Part – 2) : 1998 guidelines.

Five classes are made on the basis of field observations between slope amount and incidence of landslides. Accordingly,

. if slope > 46^0 then X22 = 1 else 0

. if slope 35^0 - 45^0then X23 = 1 else 0

. if slope 25^0- 34^0 then X24 = 1 else 0

. if slope 15^0 - 24^0 then X25 = 1 else 0

. if slope < 15^0 then X26 = 1 else 0

On the basis of Slope Aspect four classes are made. Thus,

. if aspect is 0^0-90^0 then X27 = 1 else 0

. if aspect is 91^0-180^0 then X28 = 1 else 0

. if aspect is 181^0-270^0 then X29 = 1 else 0

. if aspect is 270^0-360^0 then X30 = 1 else 0

LANDSLIDE INVENTORY

The Tawaghat – Jipti Route corridor depicts some of the spectacular and massive landslides in this region. This area can be termed as a museum of landslides as it shows all possible kinds of landslide failure mechanism. To ascertain the severity of the problem inventory of stabilized and active landslides (Figure 8.7) were carried out with the aid of satellite imagery, topographic sheets and field information. The total study area within the buffer zone of 02kms on either side of Kali River Channel is **158.22 sq.km.** In all **205** landslide incidences could be mapped from the satellite imagery and out of these **203** particularly show signatures of recent mass movements and/or are **active landslides,** while **02** landslides show **stabilized signatures** with thick growth of vegetation over them and at sporadic critical places show some signs of reactivation. This can be clearly identified from the tone and colour contrast in the False Colour Composite Satellite Imagery. Since most of the study area remains inaccessible so only those landslides which can be physically visited along TJRC could be classified. The total area covered by the *active landslides* is **6.671 sq.km,** while the area covered by *stabilized landslides* is **1.676 sq.km**. The gneissic rocks support huge amount of talus / scree materials. Since these materials often slide down as debris slides / creep / flow even after a short spell of rainfall, they are also mapped and incorporated as a variable.

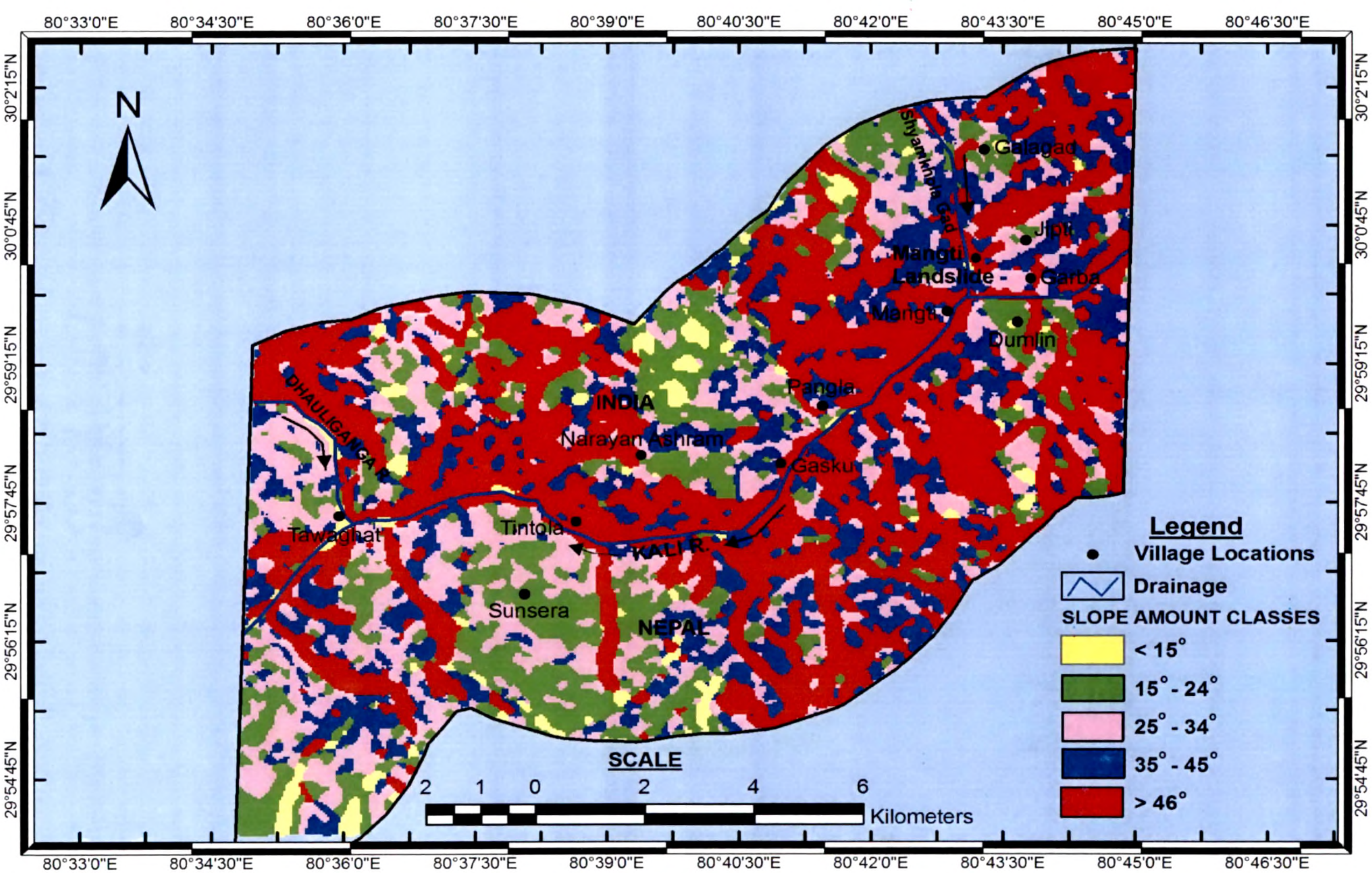


Figure 8.5 – Slope Map of Tawaghat – Jipti Route Corridor

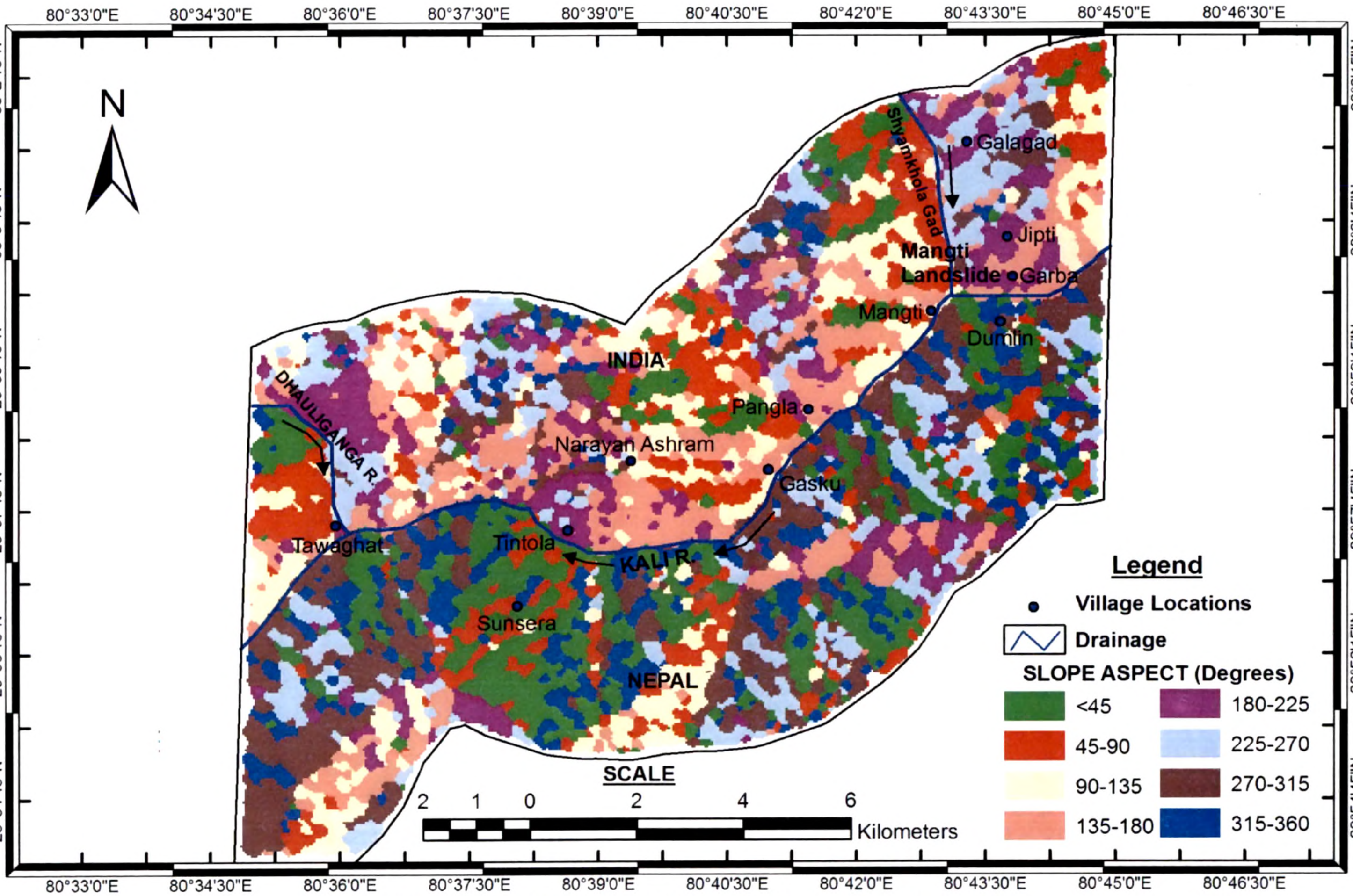


Figure 8.6 – Slope Aspect Map of Tawaghat – Jipti Route Corridor

Tawaghat – Jipti Route bears a great strategic significance as it's the only communication route to the high altitude settlements and Tibet – China international border region, while on the other side in Nepal it is observed that this part is mostly rural with sporadic settlements and It is not seen from the satellite imagery that the landslides there are causing any structural damage. The Tawaghat – Sobla Route Corridor has already been studied by Bali R, 1999. As some part of the study area coincides within their area of study hence some details have been incorporated into the present work. Thus, with a view to importance of the talus/scree to re-activation and generation of new mass movements, they are mapped only in the Indian side along TJRC. Along TJRC the talus/scree deposit constitutes a total of **13.573 sq.km**.

The spatial and temporal information on vital landslide activity monitored during prolonged field visits to the study area is tabulated in Table 8.1 and is sequentially depicted in Plate VII.1. In all **2** *rockfall incidences*, **4** *Planar Slides*, **4** *Wedge Slides*, **10** *Shallow Circular Slip Debris Slides*, **6** *Deep Seated Circular Slip Debris Slides*, **2** *Translational Slides*, **1** *Toppling Failure*, *Road Formation Washouts* at **2** places have been recorded along TJRC. The entire zone between Mangti and Jipti shows imperceptible *creep movement* along its slopes. Apart from this, minor incidences of rockfalls or dislodging of blocks from discontinuity cut surfaces have kept on occurring from time-to-time during the entire monsoon season. The order of field photographs depiction (Plate VIII.1) is synchronous with the description followed in Table 8.2. A total of 31 landslide incidences have been evaluated in detail. It has revealed that certain landslides, viz. Nos. 3, 4, 5, 10, 16, 18 and 31 have formed in natural conditions but with human interference now shows increased activity and shows mass movements with every rainfall event > 22mm. These invariably block the route every time the rainfall threshold is crossed. The stretch of this route between Mangti and Jipti Village has been recently constructed and is just 1km away from reaching the targeted Jipti Village. Since it is newly constructed the removal of confinement from the base of the slope mass has initiated fresh new landslides. This stretch was chronically affected by numerous shallow circular slip debris slides after the cloud burst that occurred in the night of 18th July 2004. A preliminary assessment of the affected area is presented in Table 8.2, however, because of stalling of work due to some untoward reasons the stretch of road below Galagad village had become completely inaccessible during the field visits in year 2005 monsoons. At most of the places there were complete formation washouts and had become inaccessible, pointing towards the severity of landslide activity that had grown in magnitudes during a span of one year, which were just a small initiations a year before. It calls for an urgent assessment of the economic loss that has to be incurred for redevelopment and maintenance activities.

Landslide incidence records maintained by BRO-GREF at their head quarters, 65 RCC, Pithoragarh, were procured and a sample data sheet is presented in **Appendix – 1**. Only data from year 2001 till 2003 were available with them. For complete analysis authors own data prepared from field visits in the study area between 2003 and 2006 have been utilized in deriving correlation of landslide activity with rainfall and seismicity activity.

Thus after carrying out an in-depth inventory of the historical aspects of landslide activity and mapping of active landslides, stabilized landslides and talus/scree deposits this aspect was designated as variable **'X31'** in information theory method evaluation.

LAND USE / LAND COVER

Forests in hilly areas are fast disappearing due to large scale tree cutting for timber, and household fuel. Also excessive grazing on the mountain slopes decreases vegetation cover and exposes the ground surface to denudational agencies. Soil erosion is a very common problem in such barren hilly terrains and becomes a cause of new landslide development. The vegetation cover binds the soil and reduces infiltration, thereby preventing soil erosion. Thus to investigate the landuse pattern in the study area and quantify various land attributes viz. Dense Forest cover, Open Forest cover, Grass/Fallow land, Scrub land cover, Agricultural Fields and Barren Rock Terrain; Landuse/Landcover map was digitally generated from IRS 1D LISS-III + PAN merged, December 2002 Satellite Image by selecting suitable training

sets and adhering to the maximum likely-hood classification technique. The resultant map was field validated and requisite corrections were incorporated (Figure 8.8).
It is observed from the imagery that about 60% of the study area along TJRC falls in Barren/Rocky exposure landuse class. Dense Forests are restricted only to isolated pockets and agriculture activities are mostly confined to terraces. Accordingly Five variables **'X32-X36'** are assigned to five major landuse classes viz. Forests, Grass/fallow land, Scrub land, Barren/Rocky Area and Agricultural land and incorporated in hazard zonation using Information Theory.

ANTHROPOGENIC ACTIVITIES

Since blasting and modification of slopes for roads forms one of the main triggers of landslides, hence roads were digitized from the satellite images (Figure 8.7) and buffered for 20m distances. It is being designated as variable **'X37'** and includes any anthropogenic interference such as road cuttings in landslide hazard zonation.

All the different input layers are intersected in ARC/INFO and the statistical analyses are done on the resultant layer in Visual Basic front end. Result from this analysis will be in tabular form. The output will comprise details pertaining to the information value of variables, information value of each element, minimum and maximum information value, element number and grades of instability associated with each element. This data can be further classified into different grades of instability based on the range of information and the number of elements in each of the instability classes. The results of the information value for the individual variable 'X_i' are tabulated in Table 8.3.

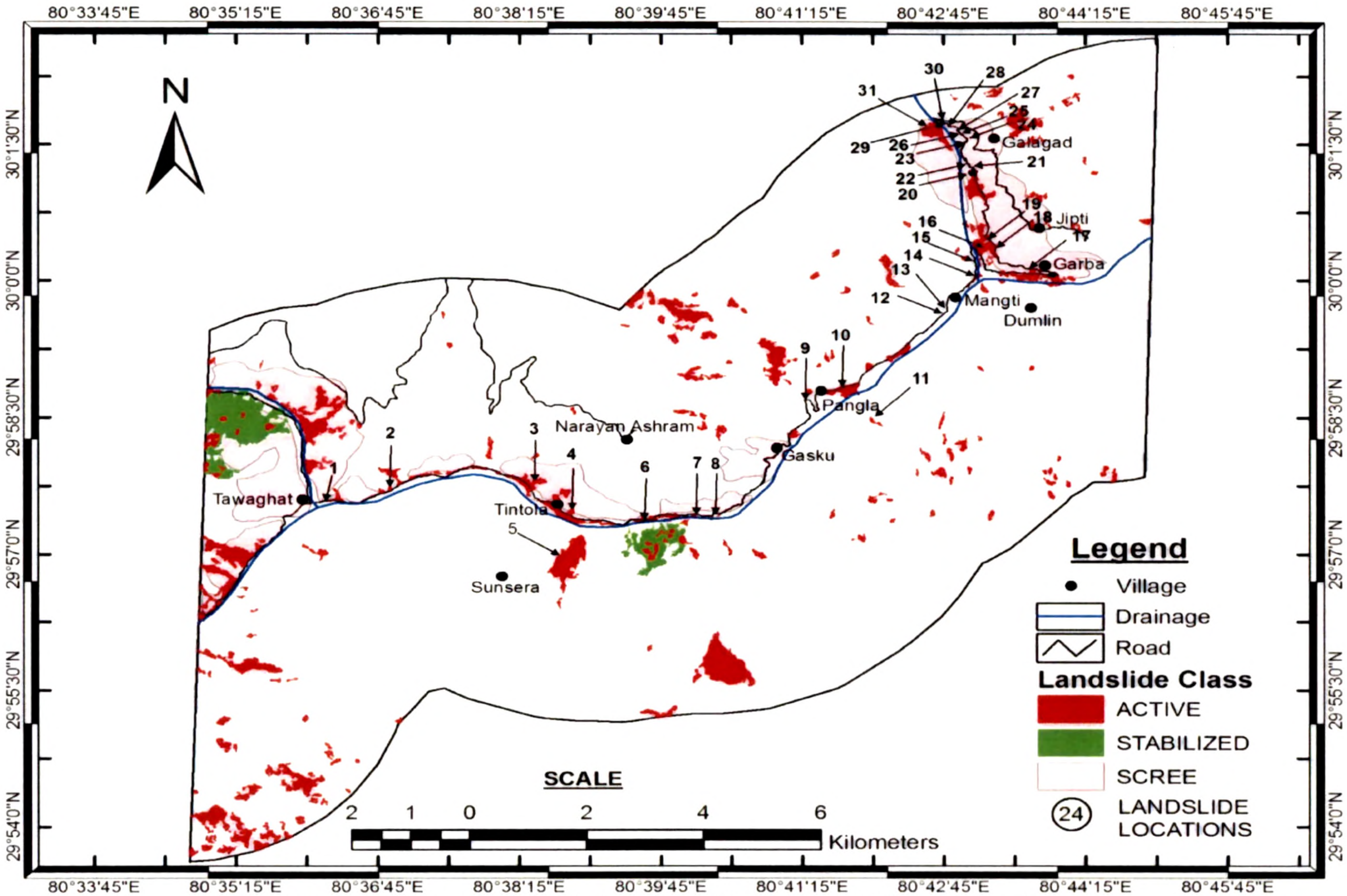


Figure 8.7 – Landslide Distribution Map of Tawaghat – Jipti Route Corridor

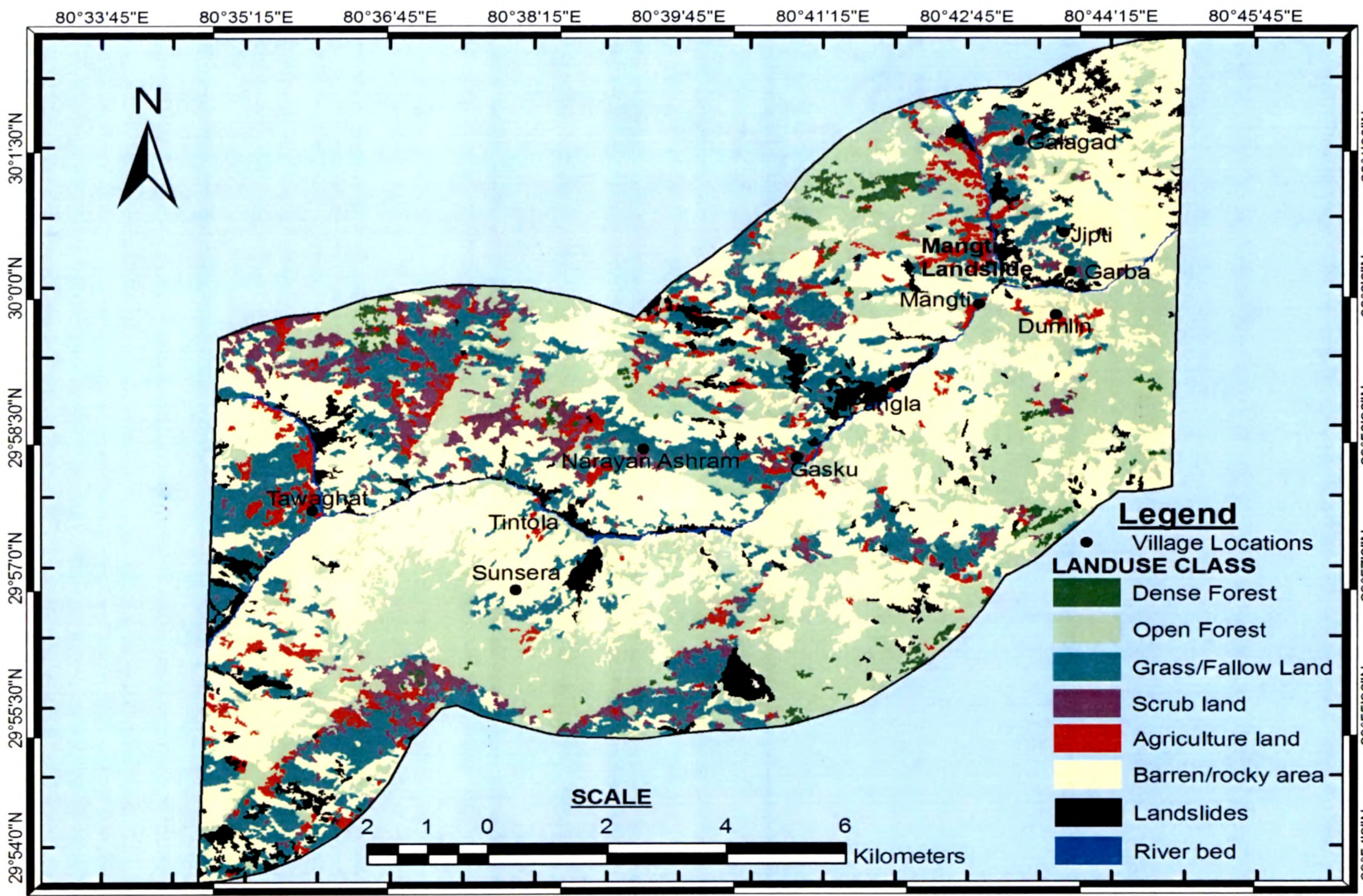


Figure 8.8 – Landuse/Landcover Map of Tawaghat – Jipti Route Corridor

Table 8.2 – Landslide Distribution in Tawaghat – Jipti Route Corridor

SLIDE NO.	LAT./LON.	GEOLOGICAL FORMATION	NATURE OF MATERIAL	TYPE OF FAILURE	APPROX AREA COVERED (Hectares)	LANDUSE	OBSERVATIONS/REMARKS
1	$29^0$57'34" N 80^{0}36'19" E	Biotite Gneiss (CCB)	Broken Rock Fragments	Rock falls	1.37	Barren Hilly Terrain	Clayey soil was observed deposited on the slope face indicating intense weathering of rocks along discontinuity surfaces and eventually under influence of intense rainfall could have instigated the rockfall.
2	$29^0$57'43"N 80^{0}36'54"E	------do-------	Sand/Silt matrix supported Boulder/Cobble Debris Mass	Shallow soil slip debris slide	0.53	Open Scrub Land	Due to high porosity and permeability coupled with low plasticity dissipates the pore water pressure fast, thus only the surface mass upto shallow depth is affected by loss of cohesion and they slip down under the influence of gravity.
3	$29^0$56'49" N 80^{0}38'57" E	------do-------	--------do----------	Deep seated debris slide showing circular failure pattern	11.42	Village Settlement/ Grass Fallow Land	A stream is seen flowing through the centre of this slide. This keeps on recharging the landslide with ground water. During monsoons when the influx of water is very high this slide gets slowly saturated and when the threshold pore water pressure is crossed the debris mass tends to flow down the slope as a viscous liquid.
4	$29^0$57'26" N 80^{0}38'46" E	------do-------	Detached Rock Blocks	Discontinuity controlled translational rock slide	16.06	Barren/ Rocky Area	Here although the foliation plane dips away from the valley face still the combination of other three sets of discontinuities has cut the rock into small blocks. The J_3 joint set dips towards the slope and it is this which facilitates the block slide.
5	$29^0$57'19" N 80^{0}38'59" E	------do-------	Sand/Silt matrix supported Boulder/Cobble Debris Mass	Discontinuity controlled massive wedge slide	34.23	Grass/Fallow land and open forest in shoulder region	Nepal side opposite to landslide no. 4; on the opposite side of the previously discussed slide there exists enormous talus and scree deposits. In addition to this the foliation plane dips towards the valley and in combination with other two intersecting sets of

Table 8.2 contd.....

							discontinuities displays a classical geometry of a plunging wedge slide.
6	$29^0$57'22" N $80^0$39'12" E	------do-------	Detached Rock Blocks	Discontinuity controlled planar rock slide	0.02	Barren rocky hill slope	Occurred on 18/7/05; rainfall – 20.828mm The rock unit consists a substantial amount of mica minerals which is very much vulnerable to different agencies of weathering. Continuous freeze and thaw cycles, removal of infilling material by seepage of ground water through the discontinuity surfaces have slowly reduced the friction between the two discontinuity surfaces, hence under the influence of gravity these blocks have slipped down the slope.
7	$29^0$57'27" N $80^0$39'56" E	------do-------	Detached Rock Blocks	Discontinuity controlled planar rock slide	0.01	Barren rocky hill slope	Occurred on 6/7/04 On close observation of the slip surface, it showed that the joints were filled in with substantial amount of clay gouge and also thick moss and algae growth. This indicates that there was a constant source for seepage, further under heavy inflow of water the clay gouge, moss and algae have reduced cohesion and friction thereby triggering the rock slide.
8	$29^0$57'28" N $80^0$40'17" E	-------do-------	Sand/Silt matrix supported Boulder/Cobble Debris Mass	Shallow circular slip debris slide	2.67	Barren rocky hill slope covered with grass	Due to high porosity and permeability coupled with low plasticity dissipates the pore water pressure fast, thus only the surface mass upto shallow depth is affected by loss of cohesion and they slip down under the influence of gravity.
9	$29^0$58'42" N $80^0$41'17" E	Quartzite-Chlorite Schist intercalation (SSZ)	Huge boulders and debris mass	Formation washout	30m road length	Perennial stream	Occurred on 18/7/04 due to cloud burst and heavy rainfall. The catchment of this stream received enormous amount of runoff in a very short span of time, carrying a lot of huge boulders and sediments destroying complete road formation built over this stream.
10	$29^0$58'48" N $80^0$41'32" E	Quartzite (SSZ)	Sand/silt matrix intermixed with quartzitic	Deep seated circular slip debris slide	9.42	Step farming	Irrigation activities keep this slide recharging with ground water periodically. The slope mass comprises of silt/clayey soil hence it facilitates slow builtup of pore

Table 8.2 contd.....

			boulder/cobbles				water pressure and on complete saturation flows as viscous liquid.
11	$29^0 58'41''$ N $80^0 41'41''$ E	Quartzite (SSZ)	Detached Rock slabs	Discontinuity controlled planar rock slide	1.5	Grass/Fallow land	Nepal side, opposite to landslide no. 10 The foliation plane is seen steeply dipping and the rock unit is cut by other two intersecting joint sets thus along the foliation plane the rocks are seen sliding down the slope.
12	$29^0 59'47''$ N $80^0 42'47''$ E	Amphibolite/Quartzite (SSZ)	Detached rock fragments and liquefied overburden soil	Discontinuity controlled translational rock slide	0.4	Grass/Fallow land	Occurred on 19/8/2004; rainfall – 22.234 mm The mountain face here shows near vertical dip, in addition to this rock unit consists a substantial amount of mica minerals which is very much vulnerable to weathering. Continuous freeze and thaw cycles, removal of infilling material by seepage of ground water through the discontinuity surfaces have slowly reduced the frictional resistance between the two discontinuity surfaces, hence under the influence of gravity these blocks have slipped down the slope.
13	$29^0 59'49''$ N $80^0 42'47''$ E	Quartzite (SSZ)	Detached rock slabs	Discontinuity controlled planar rock slide	0.01	Barren rocky terrain	Occurred on 4/8/2004; rainfall – 17.817mm The quartzites adversely dip towards the road and these quartzites show parallel arrangement of mica flakes that defines its foliation. Thus due to weathering of these minerals have led to the detachment of rock blocks and sliding along the foliation plane.
14	$30^0 00'05''$ N $80^0 43'05''$ E	Biotite Gneiss (HHC)	Detached rock fragments	Rock fall	0.01	Step farming	Occurred on 23/7/05 Intense weathering of rocks along discontinuity surfaces and intense rainfall could have instigated the rockfall.
15	$30^0 00'14''$ N $80^0 43'05''$ E	Biotite Gneiss (HHC)	Detached rock blocks	Toppling failure	0.3	Grass/Fallow land in vicinity to perennial stream	Occurred on 17/8/04; rainfall 20.074mm The biotite gneisses are dipping vertically and show profuse weathering along the joint planes. Along the foliation plane the rocks have detached and seen falling causing road blockade.

Table 8.2 contd.....

16	$30^0$00'13" N $80^0$43'10" E Mangti Landslide	Biotite Gneiss (HHC)	Sand matrix intermixed with biotite gneiss boulders	Deep seated circular slip debris slide	11.56	Grass/Fallow land	**Mangti Landslide (Lower Level);** reactivated in lower level and present activity has advanced to third phase
17	$30^0$00'08" N $80^0$43'45" E	Biotite Gneiss (HHC)	Detached rock fragments	Wedge slide	0.01	Grass/Fallow land	Three incidences have been recorded from the same site. 22/7/2004-1st initiation, 10/8/2004- Rocks sliding wedge were seen, 18/8/2004- The rock slide had further advanced headward and along the shoulder portion. Such incidences are on account of removal of confinement from the base due to road building activity.
18	$30^0$00'20" N $80^0$43'17" N	Biotite Gneiss (HHC)	Sand/silt matrix supported biotite gneiss boulders/cobbles	Deep seated circular slip surface debris slide		Grass/Fallow land	**Mangti Landslide (Upper Level);** The present third stage and headward expansion in this landslide is witnessed.
19	$30^0$00'27" N $80^0$43'14" E	Biotite Gneiss (HHC)	Sand matrix supported biotite gneiss boulders/cobbles	Shallow slip surface debris slide	0.12	Grass/Fallow land	The right shoulder region of Mangti Landslide is seen advancing with shallow slip surface debris slides. This region is already under the influence of slow creep movement and further removal of confinement from the base has enhanced shallow soil slip that has induced lateral expansion of Mangti Landslide.
20	$30^0$01'13" N $80^0$43'04" E	Porphyroblastic Gneiss (HHC)	Sand/silt matrix supported boulder/cobble debris mass	Shallow slip surface debris slide, structure foundation erosion	13.80	Open forest	Road is constructed from toe upto crown with hair pin bends, a common practice in hill road construction to gain elevation with ease & cut down distance. But without proper structural measures could cause a lot of damage.
21	$30^0$01'17" N $80^0$42'59" E	Porphyroblastic Gneiss (HHC)	Discontinuity controlled broken rock fragments and weathered soil	Discontinuity controlled wedge slide	0.06	Open forest	Initiated on 22/7/2004, rainfall 17mm; 2nd reactivation on 18/8/2004, rainfall 22.234mm Extremely weathered rocks, widely open joints filled with silt/clay gouge, removal of confinement at the base has conditioned the slope with intense rainfall acting as a trigger for slope failure.

Table 8.2 contd.....

22	$30^0$01'20" N $80^0$42'58" E	Porphyroblastic Gneiss (HHC), Talus overburden	Thick soil deposit intermixed with porphyroblastic gneiss boulders	Creep	-----	Open forest, Grass cover	Slow imperceptible movement (creep) indicated by tilting of trees
23	$30^0$01'33" N $80^0$43'00" E	Biotite gneiss (HHC), Talus overburden	Thick soil deposit intermixed with weathered gneissic boulders	Shallow circular slip debris slides	0.01	Dense forest	Occurred after the cloud burst incidence of 18th July 2004; intense rainfall had caused sudden increase in pore water pressure and loss of cohesion leading to shallow slip debris slides.
24	$30^0$01'34" N $80^0$43'00" E	Biotite gneiss (HHC), Talus overburden	Thick soil deposit intermixed with weathered gneissic boulders	Shallow circular slip debris slides	0.04	Dense forest	Occurred after the cloud burst incidence of 18th July 2004 and seen expanding during the field visit on 18th August 2004. A stream is seen flowing through the body of the landslide thus continuously charging slope with ground water. Further on saturation the slide has shown periodic mass movements and is still in process of expansion.
25	$30^0$01'37" N $80^0$42'57" E	Biotite gneiss (HHC), Talus overburden	Thick soil deposit intermixed with weathered gneissic boulders	Shallow circular slip debris slides	0.01	Dense forest	Occurred after the cloud burst incidence of 18th July 2004. This slide is the result of enormous surface runoff during heavy downpours. Decrease in vegetation cover has resulted in the erosion of slopes and such shallow slip slides.
26	$30^0$01'39" N $80^0$42'55" E	Biotite gneiss (HHC), Talus deposit	Thick soil deposit intermixed with weathered gneissic boulders	Deep seated circular slip debris slide	0.21	Dense forest	First initiation was seen after 18/7/04; subsequently it just started expanding very rapidly. A stream flowing through it had continuously charged the landslide. On 7/8/04 soil was seen flowing down the road on account of full saturation. By 18/8/04 it had shown a substantial growth in dimension. Revisit to this site on 16/7/05 showed further expansion.
27	$30^0$01'40" N $80^0$42'54" E	Weathered Biotite gneiss (HHC)	Detached weathered rock fragments and infilling Sand soil	Discontinuity controlled Wedge failure	0.1	Dense forest / Grass covered slope	Occurred after cloud burst of 18/7/04 Extremely weathered rocks, widely open joints filled with silt/clay gouge, removal of confinement at the base has conditioned the slope to fail and with intense rainfall as a trigger has led to slope failure.

Table 8.2 contd.....

28	$30^0$01'42" N 80^{0}42'49" E	Biotite gneiss (HHC), talus deposits	Sand matrix intermixed with biotite gneiss boulders	Shallow circular soil slip debris slide	0.2	Grass/Fallow land	Occurred after cloud burst of 18/7/04 This slide is the result of enormous surface runoff during heavy downpours. Decrease in vegetation cover has resulted in the erosion of slopes and such shallow slip slides.
29	$30^0$01'46" N 80^{0}42'43" E	Biotite gneiss (HHC), talus deposits	Sand matrix intermixed with biotite gneiss boulders	Shallow circular soil slip debris slide	0.16	Grass/Fallow land	------------------------------do------------------------------------
30	$30^0$01'47" N 80^{0}42'44" E	Biotite gneiss (HHC), talus deposits	Sand matrix intermixed with biotite gneiss boulders	Shallow circular soil slip debris slide	0.14	Grass/Fallow land	------------------------------do------------------------------------
31	$30^0$01'42" N 80^{0}42'40" E	Biotite gneiss (HHC), talus deposits	Sand/silt matrix supported biotite gneiss boulders/cobbles	Deep seated circular slip debris slide	10.65	Dense forest	Steep slopes with enormous quantum of talus and scree deposit, that moves down on saturation under natural conditions

1. View of Rockfall near Tawagha; dt-18/7/04

2. View of **s**hallow **c**ircular slip debris slide

3. View of a part of Tintola village landslide zone

4a. View of right flank of translational planar rock slide in biotite gneiss of CCZ;Jan-2003

4b. Field photograph of left flank of translational planar rock slide in biotite gneiss of CCZ;Jan-2003

4c. View of the same left flank in June 2004. Surficial material have washed off and huge size rock blocks are seen in critical stage of sliding

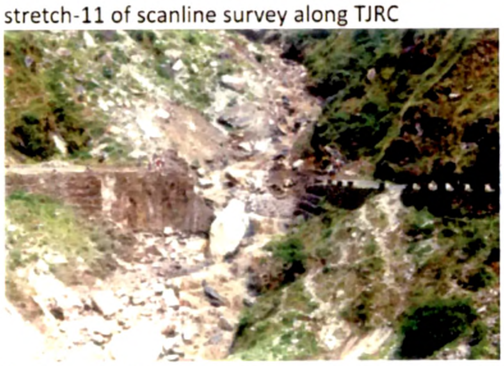
5.Field photograph of massive wedge debris slide below Sunsera village in Nepal; opposite to planar rock slide at no.4 in India.

6. View of rockslide occurred on 18/7/05 near stretch-9 of scanline survey between Tintola&Gasku

Plate VIII.1 contd.....

7. View of rockslide occurred 6/7/04 exactly at stretch-11 of scanline survey along TJRC

8. View of debris slide in biotite gneiss of CCB at stretch-12 of scanline survey.



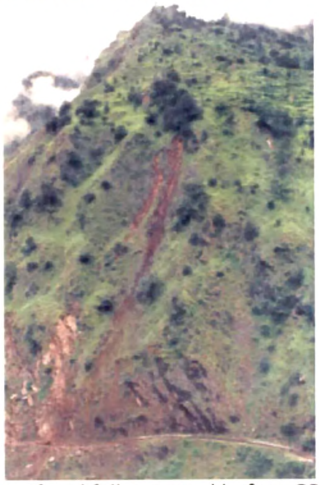
9. View of 30m formation washout occurred due to cloud burst above Pangla village; dt-18/7/2004

10. Field view of deep seated circular slip debris slide at Pangla village.

11. View of planar rock slide in steeply dipping quartzites of SSZ; opp. Pangla village in Nepal side

12. View of rockslide in quartzite-chlorite schist of SSZ, adjacent to MCT; dt-19/8/04

13. View of planar rockslide occurred in quartzites at the contact zone of MCT; dt-4/7/04



14. View of rockfall occurred before GREF camp; dt- 23/7/05 damaging the road below

Plate VIII.1 contd.....

15. View of toppling failure occurred near GREF camp;dt- 17/8/04

16. View of toe region of Mangti Landslide

17a. View of 1st initiation with a rockfall below Garba village; dt-22/7/04

17b. View of the same location where rocks are seen sliding down a wedge; dt-10/8/04

17c. View of lateral and headward expansion of the wedge slide; dt-18/8/04

18. View of debris mass at Mangti Landslide flowing down the slope over the retaining wall on saturation -dt-22/7/05

19. View of shallow soil slip debris slides seen in right shoulder region of Mangti Landslide, indicating lateral expansion of the slide zone.

20a. View of ongoing road construction activity with steeply inclined hairpin bends

Plate VIII.1 contd.....

20**b.** View of toe erosion at the foundation of retaining wall caused by sliding of debris mass

20c. View of dozer clearing the slided material along this newly constructed segment of road

20d. View of uprooted trees along the slopes on account of widespread landsliding after cloud burst of 18/7/04

21a. View of discontinuity controlled wedge slide on upper level of road below Galagad village; slide occurred on 22/7/04

21b. View of laterally expanding shallow soil slips and the expanding wedge slide due to lateral support removal by road construction;dt-18/8/04

22. Field view of unstable slope showing creep movement; all the trees are seen inclined on the upper level road before Galagad village.

23. View of shallow circular soil slip debris slides blocking the newly constructed road stretch below Galagad village after cloud burst of 18/7/04

24. View of severely affected newly constructed road stretch below Galagad village with profuse shallow soil slip debris slides; 18/7/04

Plate VIII.1 contd.....

25. View of shallow slip debris slide on the road stretch below Galagad village occurred in the night of 18/7/04

26a. View of first initiation of a debris slide, some debris mass moves down the road with the vegetation grown over it; dt- 19/7/04

26b. View of a stream flowing throught the slide is charging this debris slide and more slope material is seen flowing down and the crown is seen expanding; 22/7/04

26c. The slope mass is seen to be completely saturated and the soil is flowing down the slope like a viscous fluid. Although the traveling rate is too low, about 5cm/min; dt-29/7/04

26d. The crown portion appears to have further advanced and the dimensions of this slide has substantially increased; dt-18/8/04

26e. This slide which started as a small shallow slip has now developed into a massive deep seated circular slip debris slide; dt- 16/7/05

27. View of wedge failure seen completely damaging the road; dt-18/7/04

28. View of multiple shallow slip debris slides completely destroying the newly excavated road below Galagad village; dt-18/7/04

Plate VIII.1 contd.....

29. View of Author carrying out inventory of shallow debris slide before Galagad village; dt-19/7/04

30. View of Author marking the position of shallow slip debris slide just before Galagad village in GIS-GPS data collection system; dt-19/7/04

31. View of deep seated circular slip Shymkhola debris landslide in its natural condition

Plate VIII.1 - Sequencial Field Photographs of Landslide Distribution in TJRC

Table 8.3 – Showing Derived Information Values of the Variables

Variable	Information Value	Variable	Information Value	Variable	Information Value
X1	-0.003	X16	0.048	X31	0.0002
X2	0.001	X17	-0.006	X32	0.054
X3	0.009	X18	0.025	X33	0.057
X4	-0.003	X19	0.003	X34	0.004
X5	0.022	X20	0.019	X35	0.001
X6	0.022	X21	0.008	X36	-0.002
X7	0.062	X22	-0.001	X37	0.003
X8	0.033	X23	0.0003		
X9	0.046	X24	0.0002		
X10	0.027	X25	-0.016		
X11	0.017	X26	0.008		
X12	0.027	X27	-0.001		
X13	0.043	X28	0.013		
X14	0.027	X29	0.048		
X15	0.037	X30	-0.003		

Accordingly, the information value of the element j will be calculated using values from Table 8.2 as per the following Equation 10,

$$I_j = -0.003X_{j1}+0.001X_{j2}+0.009X_{j3}..........+0.003X_{j37} \qquad (13)$$

The information values of all the polygon elements are found using these equations and on the basis of histogram distribution, the polygon elements are classified into five hazard classes' viz. **Very Low** (Ij <= -0.02); **Low** (-0.02 < Ij < 0.103); **Moderate** (0.10 <Ij <0.23); **High** (0.23 < Ij < 0.40); and **Very High** (Ij > 0.40) landslide hazard prone zones. On the basis of this information, Probable Landslide Hazard Zonation Map of Tawaghat – Jipti Route Corridor is prepared in ARC/INFO (Figure 8.9).

From the overlay analysis of landslide incidences and hazard zones, it is apparent that the hazard maps generated correlate well with the landslide distribution map. There is high degree of conformity among the hazard zones vis-à-vis the event map in terms of both landslide incidences and magnitude of an event expressed in terms of area (Table 8.4) –

Table 8.4 – Statistics of Landslides' Area and Incidences in the Study Area

Landslide Hazards Class	Area (km^2)	% Area Covered by Each Hazard Class	Landslide Incidences
Very Low	4.16	2.63	0
Low	45.53	28.77	12
Moderate	19.57	12.37	36
High	72.95	46.11	135
Very High	16.01	10.12	22
Total	**158.22**	**100.00**	**205**

ACCURACY ESTIMATION

The accuracy of information theory in predicting the slope stability was evaluated by the experimental probability **Equation-12**. Thus, the derived accuracy of slope instability prediction for the Tawaghat-Jipti Route Corridor is **78%**.

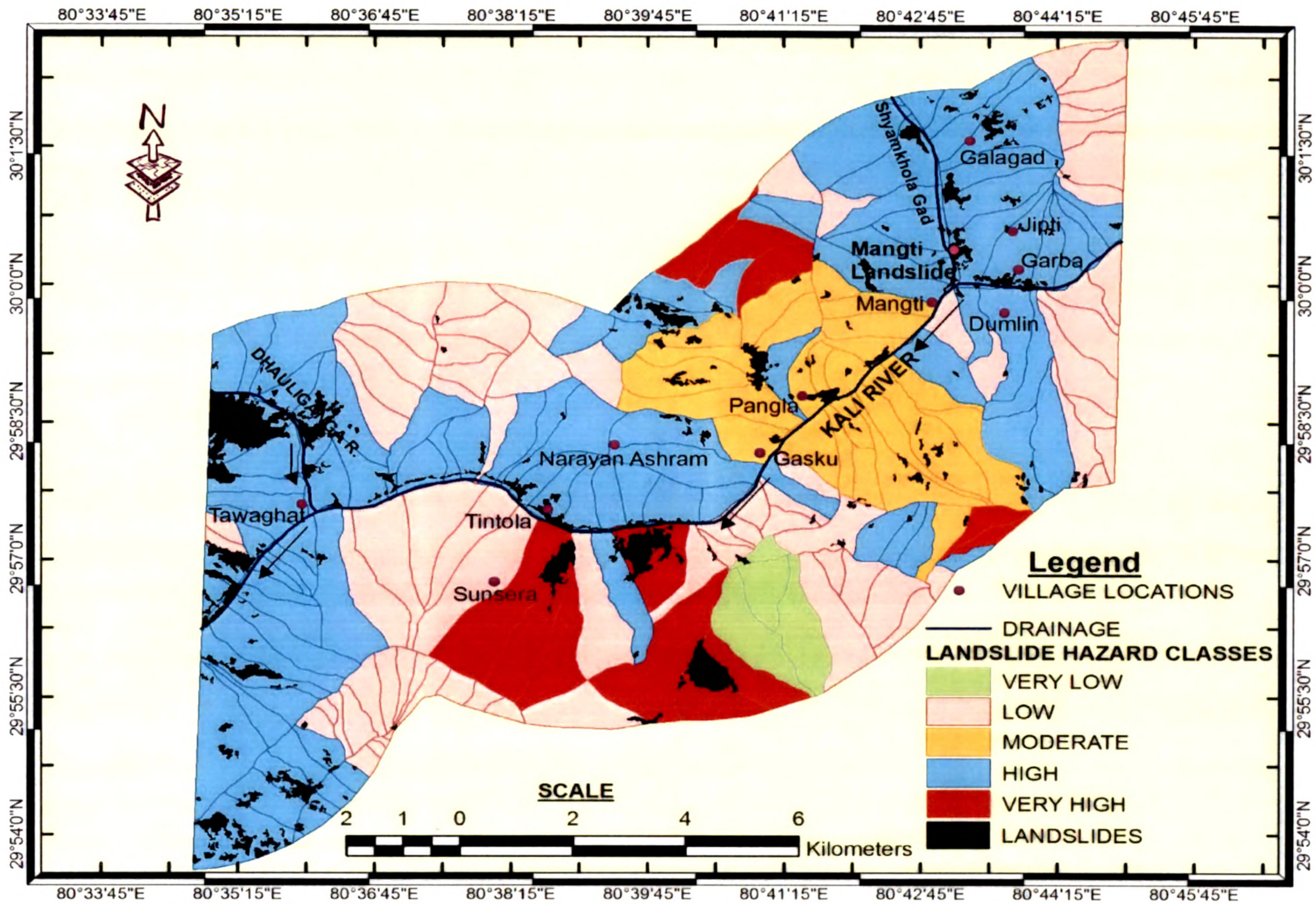


Figure 8.9 – Probabilistic Landslide Hazard Zonation Map of Tawaghat – Jipti Route Corridor

Discretization of the area into polygon elements is advantageous as they have been classified depending on the slope and aspect category and thus, assessed the instability of each element independently.

The information value of each polygon element unit has been determined using the **Equation 10** and evaluated the accuracy by using **Equation 12**. From the overlay analysis of landslide incidences and hazard zones, it is apparent that the hazard maps generated correlate well with the landslide event map. There is high degree of conformity among the hazard zones vis-à-vis the event map in terms of both landslide incidences and magnitude of an event expressed in terms of area **(Table – 8.4)**.

From the overlay of landslide distribution over derived Landslide Hazard Zonation Map it appears that the medium and high hazard classes of information theory method do not commensurate well. The discrepancy may be attributed to the following reasons,

1. Certain polygon elements with a given landslide can fall within a low to medium grades of instability; these polygon elements, however, are assigned a high grade of slope instability. This discrepancy of grades arises when factors considered in the analysis have a low weightage in that particular element.

2. The landslide in that element might have occurred due to a factor, which has not been considered in analysis because; it does not have a significant influence on the overall landslide occurrences in the area under study.

However, efficacy of Landslide Hazard Zonation (LHZ) particularly in case of High – Moderate Classes has been testified and validated through field checks and thus, authenticates the applicability of Information Theory in prediction of landslide hazards in the study area.

A comprehensive map incorporating all thematic variables including Landslide Hazard Zonation of the study area i.e. Tawaghat–Jipti Route Corridor is given as **Pocket Map – 2**

LANDSLIDE REMEDIATIONS

Basic key to design a stable slope depends much on data in-puts acquired through field investigation, laboratory tests of slope mass material, stability analysis and proper construction control on adopted remediation. As most of the details involved in design of stable slopes cannot be standardized; good engineering judgments, experience and intuition must be coupled with the best possible data gathering and analytical techniques to achieve a safe and economical solution to slope stabilization. Basic approaches to the design of stable slopes can be categorized as under

- Avoid the problem
- Reduce the forces tending to cause movement, and
- Increase the forces resisting movement (Gedney & Weber, 1978).

A summarized account on these approaches is given in Table 8.5.

REMEDIATION METHODS – Commonly used correction methods can be divided into the following 05 main groups –

1. **Geometrical Methods**, which involves the change of the geometrical conditions of a slope so as to curtail magnitude of driving forces.
2. **Hydrological Methods**, such as lowering of the groundwater table or reduction of water content of the soil or rock by way of providing surface and sub-surface drains. Collection ditches can greatly control the pore-water pressure (Figure 8.10).
3. **Chemical Methods**, such as grouting, application of epoxy on slope surface to check the permeability of the slope mass, which cause an increase of the average shear strength of the soil.
4. **Bio-Technical Methods**, such as reforestation of un-stable slopes particularly vulnerable/affected by shallow sheet and soil slides. Fast growing grasses, deciduous tress may be preferred as they dry soil close to the surface and decrease erosion due to rapid rate of evapo-transpiration. Some important biotechnical measures as suggested by Gray and Sotir, (1992) are given in Table 8.6.

5. **Mechanical Methods:** There exist large varieties of techniques that can be adopted as Stabilization Measures and Protection Measures. Mechanical methods may be divided into two groups based on requirement of stabilization externally or internally. Scheme of externally and internally stabilized systems accounting for mechanical and chemical methods, as suggested by O' Rourke and Jones (1990) is given in Table – 8.7.

Table 8.5 - Summary of Approaches to Potential Slope Stability Problems
(After, Gedney and Weber 1978)

CATEGORY	PROCEDURE	BEST APPLICATION	LIMITATIONS	REMARKS
	Relocate facility	As an alternative anywhere	Has none if studied during planning phase; has large cost if location is selected and design is complete; also has large cost if reconstruction is required	Detailed studies of proposed relocation should ensure improved conditions
Avoid Problem	Completely or partially remove unstable material	Where small volumes of excavation are involved and where poor soils are encountered at shallow depths	May be costly to control excavation; may not be best alternative for large landslides; may not be feasible because of right-of-way requirements	Analytical studies must be performed; depth of excavation must be sufficient to ensure firm support
	Install bridge	At side hill locations with shallow soil movements	May be costly and not provide adequate support capacity for lateral forces to restrain landslide mass	Analysis must be performed for anticipated loadings as well as structural capability
	Change line or grade	During preliminary design phase of project	Will affect sections of roadway adjacent to landslide area	------
Reduce Driving Forces	Drain surface	In any design scheme; must also be part of any remedial design	Will only correct surface infiltration or seepage due to surface infiltration	Slope vegetation should be considered in all cases
	Drain sub-surface	On any slope where lowering of groundwater table will increase slope	Cannot be used effectively when sliding mass is impervious	Stability analysis should include consideration of seepage forces

		stability		
	Reduce weight	At any existing or potential slide	Requires lightweight materials that may be costly or unavailable; excavation waste may create problems; requires right-of-way	Stability analysis must be performed to ensure proper placement of lightweight materials
Increase Resisting Forces				
Apply External Force	Use buttress and counter weight fills; toe berms	At an existing landslide; in combination with other methods	May not be effective on deep seated landslides; must be founded on a firm founda-tion; requires right-of-way	Consider reinforced steep slopes for limited right-of-way
	Use structural system	To prevent movement before excavation; where right-of-way is limited Where right-of-way is limited	Will not stand large deformations; must penetrate well below sliding surface	Stability and soil-structure analyses are required
	Install anchors	Where right-of-way is limited	Requires ability of foundation soils to resist shear forces by anchor tension	Study must be made of in situ soil shear strength; economics of method depends on anchor capac-ity, depth, and frequency
Increase Internal Strength	Drain sub-surface	At any landslide where water table is above shear surface	Requires experienced personnel to install and ensure effective operation	------
	Use re-inforcement backfill	On embankments and steep fill slopes; land-slide reconstruction	Requires long-term durability of reinforcement	Must consider stresses imposed on reinforcement during construction
	Install in-situ reinforcement	As temporary structures in stiff soils	Requires long-term durability of nails, anchors, and micropiles	Design methods not well established; requires thorough soils investigation and properties testing
	Use biotechnical	On soil slopes of	Climate; may require irrigation	Design is by trial

Table 8.5 – contd….

	stabilization	modest heights	in dry seasons; longevity of selected plants	and error plus local experience
	Treat chemically	Where sliding surface is well defined and soil reacts positively to treatment	May be reversible; long-term effectiveness has not been evaluated; environmental stability unknown	Laboratory study of soilchemical treatment must precede field installations; must consider environ-mental effects
	Use electro-osmosis	To relieve excess pore pressures and increase shear strength at a desir-able construction rate	Requires constant direct current power supply and maintenance	Used when nothing else works; emergency stabilization of landslides
	Treat thermally	To reduce sensitivity of clay soils to action of water	Requires expensive and carefully designed system to artificially dry or freeze sub soils	Methods are experimental and costly

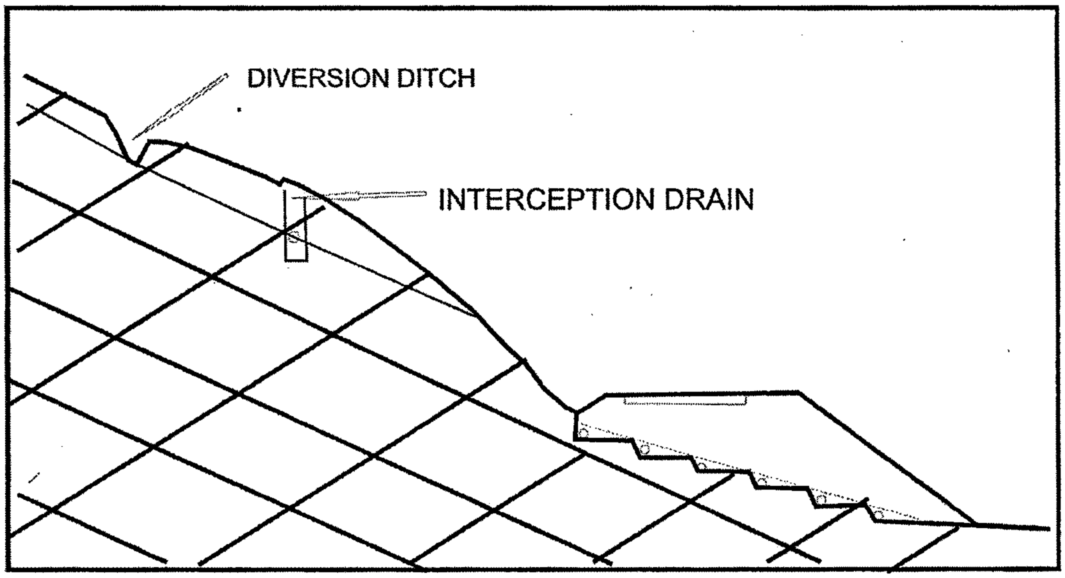


Figure 8.10 - Schematic Diagram for Surface Drainage, Diversion Ditch & Interceptor Drain as Landslide Remediation Measure.

RECOMMENDED LANDSLIDE MITIGATORY MEASURES

Engineering geological investigations of landslide hazard would remain incomplete with out an appropriate prescription/s on possible mitigation measures. Further, an in-depth geotechnical investigation of Mangti Landslide and the Micro-Zonation of Landslide Hazards for the Tawaghat – Jipti Route Corridor has clearly established that the magnitude of landslide hazards along this strategically important route is very high, imbibed with inherent geological complicacies. This has resulted into intercepting variety of landslides that are different from the point of view of material characteristics as well as mechanism of failure. Therefore, prescribing any single and or independent remediation for individual landslide or for the entire route corridor would be grossly un-realistic and practically unviable.

Recommended landslide remediations for the Mangti landslide have been specifically worked out by simulation of introducing re-enforced structures into Limit Equilibrium Analysis. Where as, for the route corridor buffer zone are broad based.

MANGTI LANDSLIDE

As it has already been elucidated, the Mangti Landslide over Biotite gneiss is a case of typical colluvial, multi-phased rotational slide. The matrix material with embedded large bouldery clasts is predominated by porous – permeable sandy and gravely fractions. Also, the toe portion of this landslide is characterized by a typical fluviatile sandy – gravels. Further, the landslide and its adjacent shoulder regions are characterized by scanty vegetation cover. Looking to this non-homogeneity in material characteristics prescribing any single remediation technique to derive a stable slope may not fulfill the desired objectives. Therefore, to design a stable slope, blends of remedial techniques are recommended.

1. **STRUCTURAL RETENTION SYSTEM**

The mechanical methods encompassing variety of externally and internally stabilized techniques (Figure 8.11) may be adopted. Some of the important one includes – Gravity Walls viz. masonry, concrete, cantilever, gabion, crib, reinforced, soil and hybrid systems comprising geo-textile. The gravity/retaining walls which represents relatively stiff structural elements are able to tolerate much movement and considered to be widely used practice and highly cost effective. Other improvised techniques like reinforced geo-synthetics have become more common for earth retaining structures. A schematic

CATEGORY		EXAMPLES
LIVE CONSTRUCTION	Conventional Plantings	• Grass seeding • Sodding • Transplants
MIXED CONSTRUCTION	Woody plants used as reinforcements and barriers to soil movement	• Live staking • Contour wattling • Brush layering • Soft gabions • Brush mattress
MIXED CONSTRUCTION	Plant/ structure associations	• Breast walls with slope face plantings • Revetments with slope face plantings • Tiered structures with bench plantings
MIXED CONSTRUCTION	Woody plants grown in the frontal openings or interstices of retaining structures	• Live cribwalls • Vegetated rock gabions • Vegetated geogrid walls • Vegetated breast walls
MIXED CONSTRUCTION	Woody plants grown in the frontal openings or interstices of porous revetments	• Joint plantings • Staked gabion matresses • Vegetated concrete block revetments • Vegetated cellular grids • "Reinforced" grass
INERT CONSTRUCTION	Conventional Structures	• Concrete gravity walls • Cylinder pile walls • Tie back walls

Table 8.6 - Categorization of Biotechnical Slope protection & Erosion Control Measures

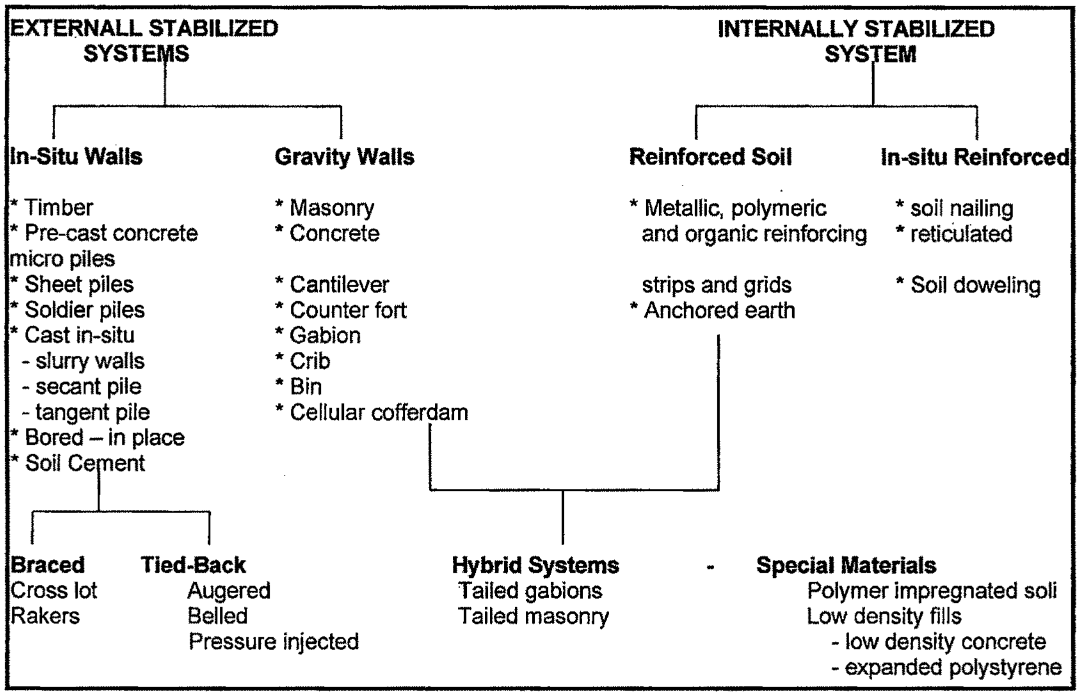


Table 8.7 - Scheme of Earth Retention Systems (After O'Rourke & Jones, 1990)

diagram comprising varied models of reinforced walls and slopes using geo-synthetic reinforcement (Mitchell & Villet, 1987) is given as Figure 8.12.

The Mangti Landslide is situated on a presently developing road to Jipti. Its field monitoring has clearly established about its pronounced response to the rainfall threshold value and causing frequent hurdles during onward road construction activities by the BRDO-GREF. The hazards posed by this landslide has necessitated to adopt and implement some measures to prevent its movement particularly its top (3rd Phase) and Toe (1st Phase) parts. Therefore, as an emergency measures construction of masonry retaining wall had been recommended. This recommended construction of retaining wall with in-built provisions of drain holes (Plate VIII.2 A-D) has improved the situation to a great extent. Hence, based on observed effectiveness of masonry retaining wall additional structural retention systems have been recommended based, which are based stability analysis and landslide modelling.

A. View of Landslide Activity Initiation after Threshold Rainfall at Upper Level Mangti Landslide

B. View of Under-construction Retaining Wall as Remediation at Upper Level Mangti Landslide

C. View of Under-construction Retaining Wall as Remediation at Upper Level Mangti Landslide

D. View of 4m high constructed Masonry Retaining wall at at Upper Level Mangti Landslide

Plate VIII.2 – Field Photographs of Masonry Brick Retaining Wall with Drains Constructed at Upper Level Mangti Landslide to Check Debris Flow

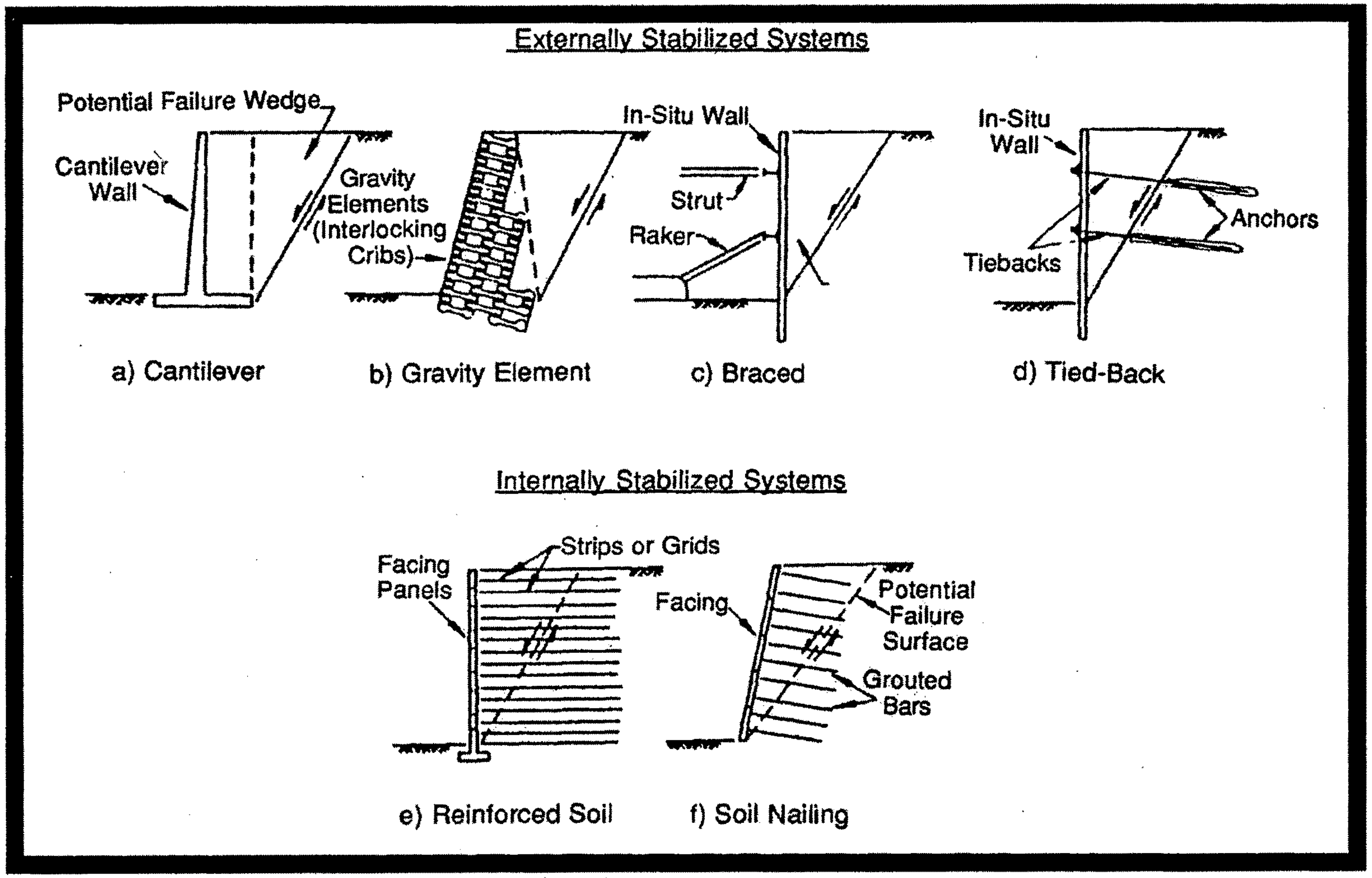


Figure 8.11 - Schematic Diagrams Suggesting Externally & Internally Stabilized Earth Retention Systems (After O'Rourke and Jones, 1990)

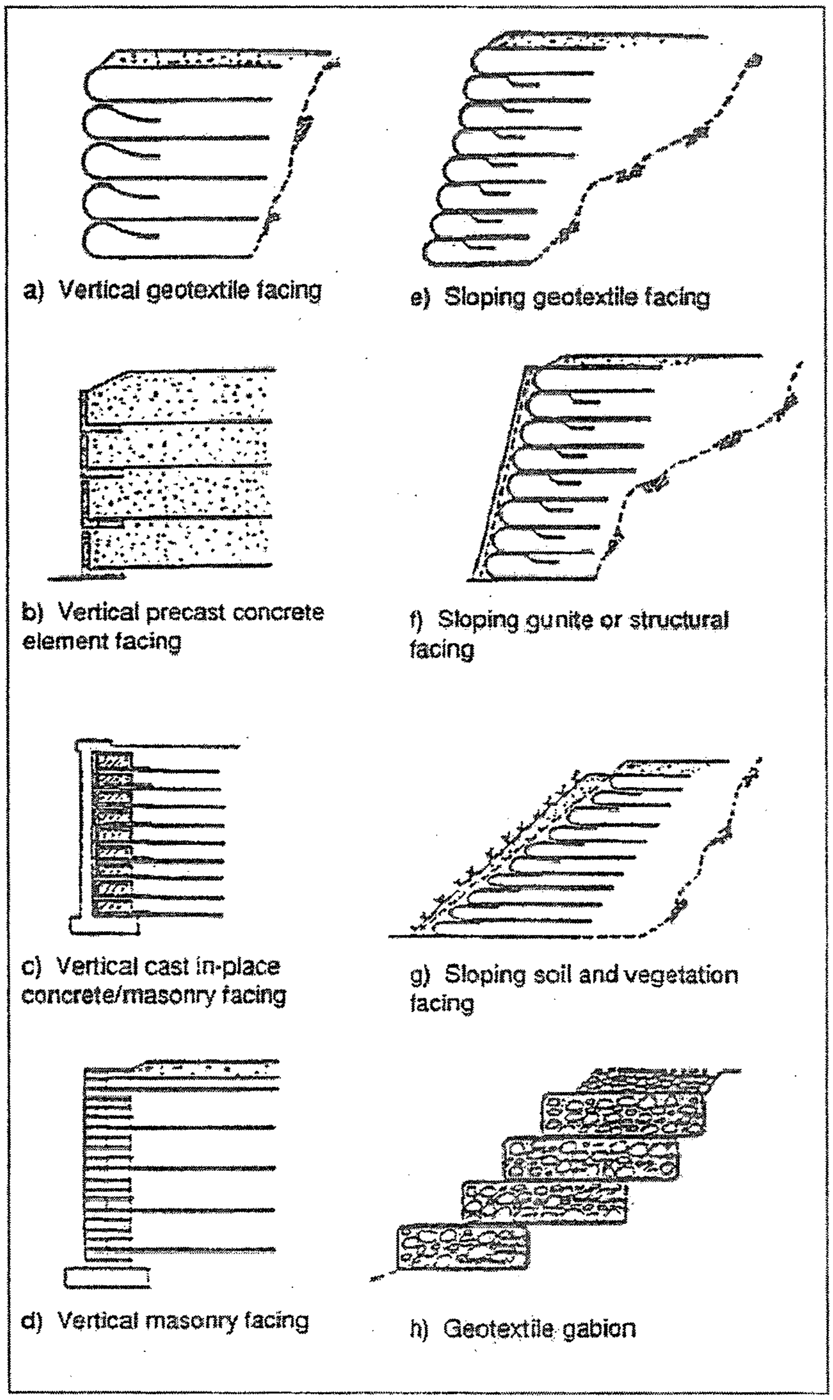


Figure 8.12- Design of Reinforced Walls and Slopes Using Geosynthetic Reinforcement

i. **Rock Gabions** - In order to counter the driving forces it is recommended to construct rock gabbion wall on the toe portion of both upper and lower level landslide up to 4m high for Upper Level and 5m high at Lower Level Landslide with a material having unit weight of up to 25 kN/m^3 (Figure 8.13).

ii. **Anchors –** Since Mangti is a deep seated landslide and to provide shear resistance to such a huge volume of unstable slope mass, anchors are considered to be the most effective measure. Therefore, it is recommended to install anchoring system in 03 rows on Upper Level Landslide. As the anchors are to be penetrated beyond slip plane i.e. with in the bed rock it has to be of variable lengths so as to achieve a factor of safety up to 1.125. Same way 05 rows of Anchoring system restricted with in the regolithic mass are proposed for the Lower Level Landslide to achieve factor of safety up to 1.115. The various recommended design parameters for the proposed anchoring system and their locations are given in Table 8.8a & b; and Figure 8.13

iii. **Soil Nails –** From the Slope Stability Analysis carried out for Mangti Landslide it is observed that at the toe region of Lower Level Landslide the critical slip surface passes through a shallow depth, so looking towards the feasibility of incorporating Soil Nails, 02 rows of these reinforcement elements are being proposed and their dimension parameters and location of installment are shown in Table 8.8b and Figure 8.13.

Table 8.8a – Dimensional Parameters for the Proposed Anchoring System to be Installed on Upper Level Mangti Landslide

Dimension Parameters	Anchor 1	Anchor 2	Anchor 3
Constant Applied Load (kN)	5000	5000	3000
Bond Length (m)	15	15	09
Bond Diameter (m)	0.318	0.318	0.318
Bond Safety Factor	1	1	1
Bond Skin Friction (F/Area)	335	335	335
Spacing	2	2	2
Bar Capacity (kN)	5000	5000	3000
Bar Safety Factor	1	1	1
Shear Capacity	0	0	0
Shear Safety Factor	1	1	1
Apply Shear	Parallel to Slip	Parallel to Slip	Parallel to Slip

Table 8.8b – Dimensional Parameters for Anchors and Soil Nails to be Installed on Lower Level Mangti Landslide

Dimension Parameters	Anchor 1	Anchor 2	Anchor 3	Anchor 4	Anchor 5	Nail 1	Nail 2
Constant Applied Load (kN)	5000	5000	5000	5000	5000	-	-
Bond Length (m)	15	15	15	15	15	-	-
Bond Diameter (m)	0.318	0.318	0.318	0.318	0.318	0.318	0.318
Bond Safety Factor	1	1	1	1	1	1	1
Bond Skin Friction (F/Area)	335	335	335	335	335	335	335
Spacing	4	4	2	2	2	2	2
Bar Capacity (kN)	5000	5000	5000	5000	5000	3000	3000
Bar Safety Factor	1	1	1	1	1	1	1
Shear Capacity	0	0	0	0	0	0	0
Shear Safety Factor	1	1	1	1	1	1	1
Apply Shear	Parallel to Slip	Parallel to Slip	Parallel to Slip	Parallel to Slip	Parallel to Slip	Parallel to Slip	Parallel to Slip

2. HYDROLOGICAL MEASURES

The effectiveness of structural retention system may be further enhanced if the precipitated water from the vulnerable slopes, particularly the left shoulder region and the landslide proper is diverted to outside regions or to natural drainage. For this purpose open water diversion ditches and interception drains are recommended (Figure 8.13).

3. BIO-TECHNICAL MEASURES

The studied landslide and its shoulder mass are devoid of vegetation and large number of cattle's move for grazing. Therefore, it is recommended to adopt Afforestation programme. As deciduous plants are capable of higher order of transpiration, which in turn helps in keeping soil dry close to the surface and decrease surface erosion therefore, preference to deciduous trees is given over the traditional conifers. Entire landslide zone should be restricted from easy access by way of providing barbed fencing. As the local inhabitants would become direct beneficiaries to this landslide remediation, it is recommended that the mitigation work be executed by taking them into confidence and be implemented on Participatory basis. A comprehensive Landslide Management Plan prepared for Mangti Landslide is given in Figure 8.13.

TAWAGHAT – JIPTI ROUTE CORRIDOR

The 33 km long Tawaghat – Jipti Route Corridor along Kali River valley is characterized by a variety of landslides. Some of the route segments are highly dangerous and chronically affected by rock falls, rock slides and block slides, particularly at Elagad, Teentola, between Pangla and Mangti. These landslides are predominantly associated with the Pre-Cambrian Crystalline mass (Chipplakot and Rungling Crystallines). Further, these landslides are manifestation of intercepting joint patterns day lighting towards the valley slopes. This has resulted into variety of failures viz. wedge, planner and toppling failures (Plate VIII.1). Therefore, its remediation seems to be a mammoth task and shall be different from the soil/debris slide remedial measures as recommended in case of Mangti Landslide.

STABILIZATION OF ROCK SLOPES

Rock Slope Stabilization Techniques may be grouped into three broad categories viz.

- Rock Reinforcement
- Rock Removal
- Protection Measures

It is a proven fact that efficacy of any stabilization techniques is site specific hence; selection of any landslide remediation measure is solely dependent of basic field data inputs. Important rock slope stabilization techniques that can be adopted, after due consideration of site specific geomechanical parameters are given in Figure 8.14.

1. Rock Reinforcement

There exists large number of reinforcement techniques that may be adopted to secure potentially vulnerable rock on the cut face of the rock. These techniques on implementation minimizes the relaxation and loosening of the rock mass that may

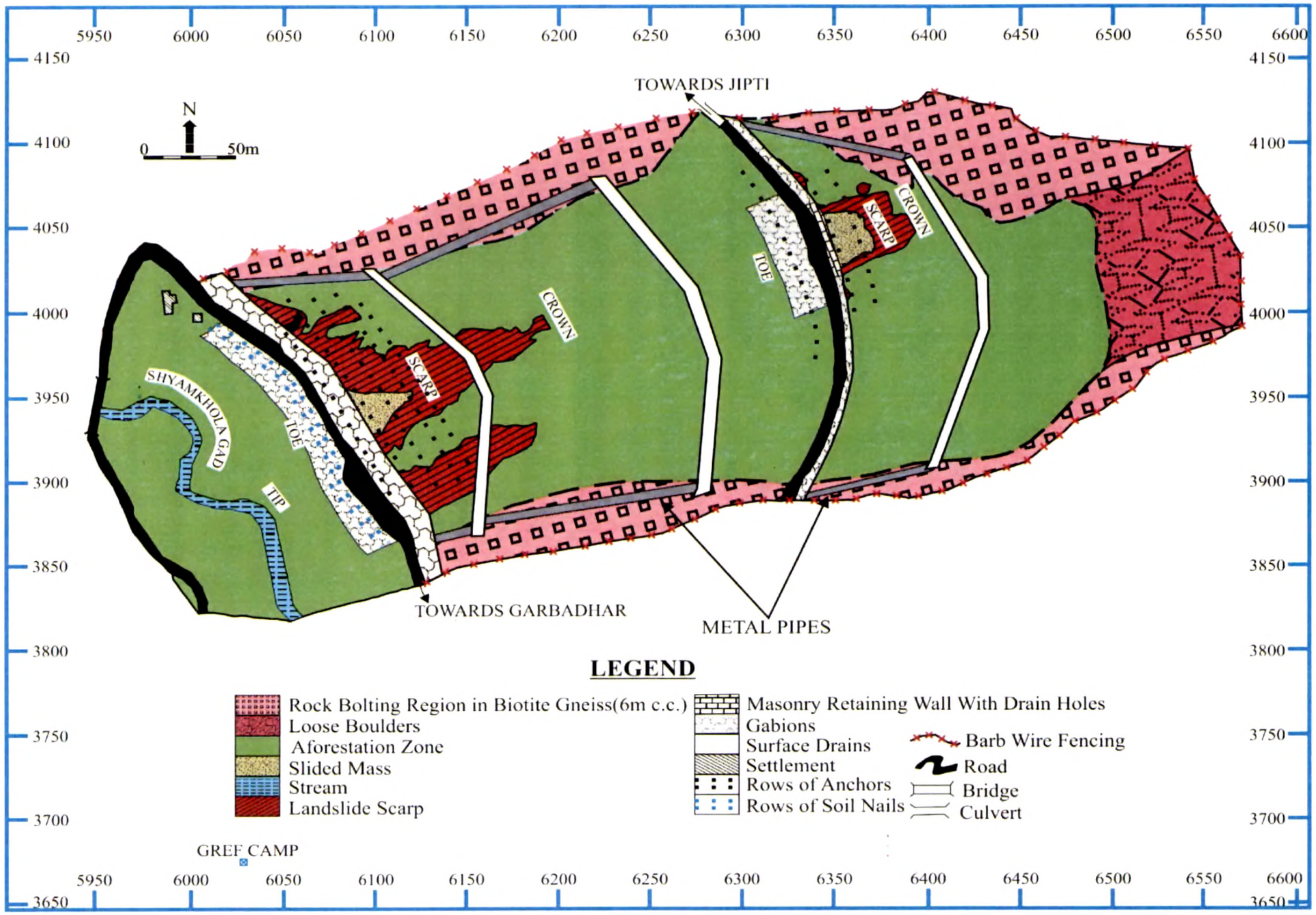


Figure 8.13 - Suggested Remediation's for Mangti Landslide

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take place as a result of excavation and unloading. Once relaxation has been allowed to take place, there is a loss of interlock between the blocks of rocks and a significant decrease in the shear strength (Hoek, 1983). A schematic section (Figure 8.15) shows numerous reinforcement techniques that may be implemented as remedial measures.

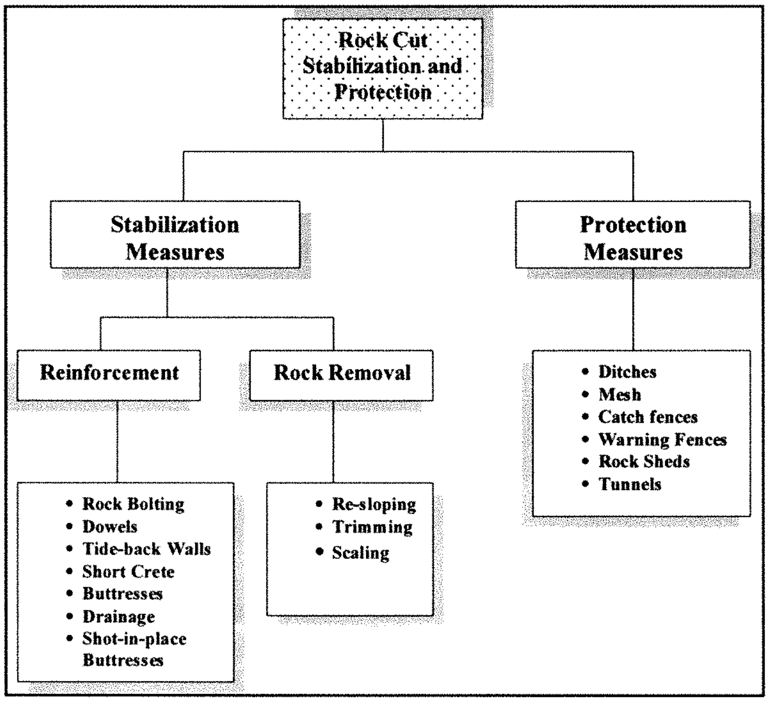


Figure 8.14 - Techniques for Rock Slope Stabilization Measures

2. Rock Removal

Rock removal is preferred method of stabilization as on implementation it eliminates the hazard without any future maintenance. Stabilization of rock slopes can be attained by the removal of potentially unstable rock mass. The method includes-

- Re-sloping zones of unstable rock mass
- Trim blasting overhangs, and
- Scaling individual rock blocks

The route segment between Teentola and Gasku is riddled with such typical case examples (Plate VIII.1) where this method can resolve the problem on permanent basis. A schematic diagram exhibiting various rock removal techniques (Figure 8.16) may be useful remediation measure for such shown cases.

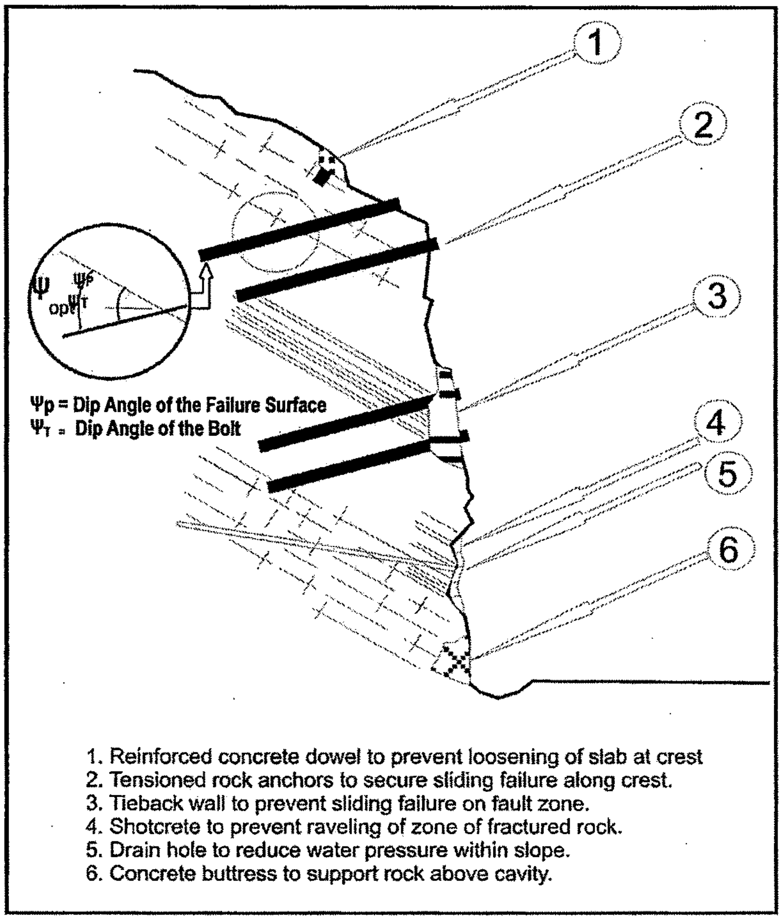


Figure 8.15 - Rock Slope Reinforcement Methods

3. Protection Measures

The prevailing protection methods viz. ditches, mesh, catch fences, rock sheds, and flex post rockfall fence are the most effective and proven techniques in minimizing the hazards of rock falls. Tawaghat – Jipti Route Corridor provides ample locations where in these protection measures can be adopted in conjunction with hydrological and bio-technical measures. It is further recommended to install versatile flex post rockfall fence (Figure 8.17) at certain locations to avoid frequent incidences of casualty, particularly between Pangla and Mangti wherein quartzite and limestone rocks (Sirdang Sediments) abnormally experiences rock falls.

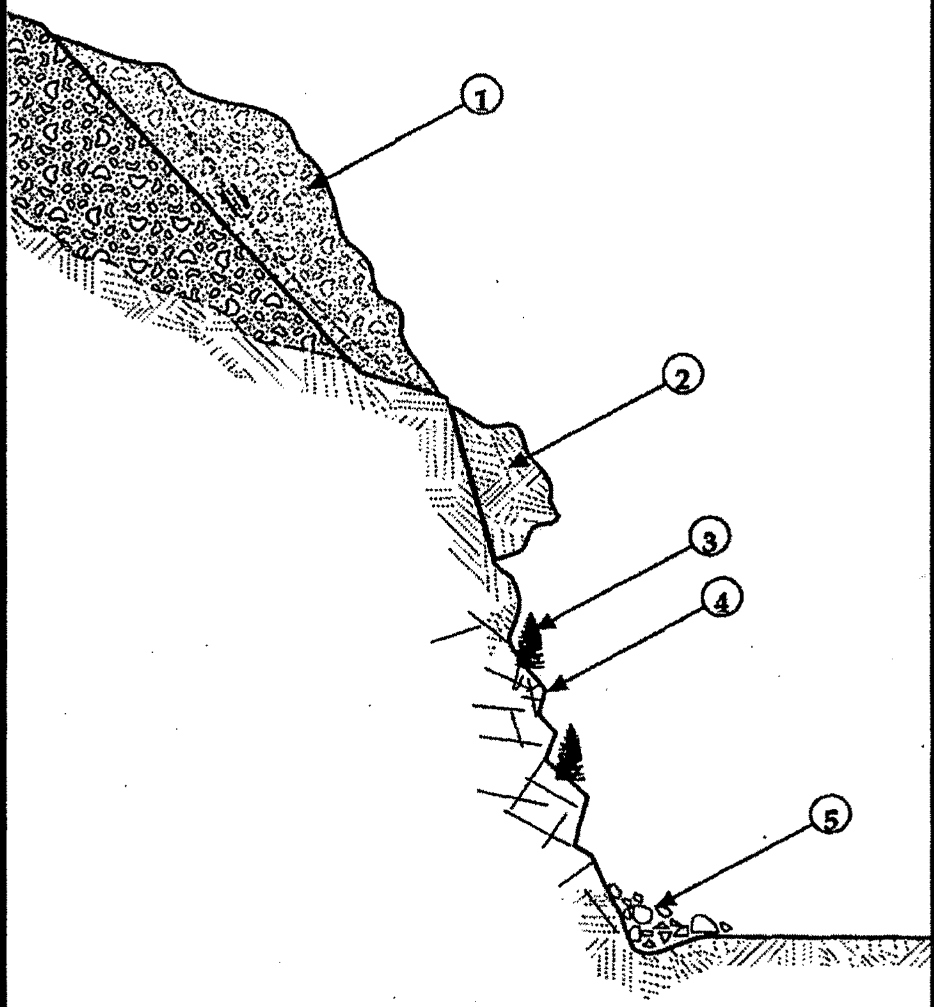
4. Shotcrete

Closely spaced fractured/jointed rocks can be protected by applying a layer of shotcrete to the rock face (Figure 8.15). This technique is extremely effective as it controls both the fall of small blocks of rock and progressive raveling that normally produces large, unstable overhangs on the slope face. As its primary function is to give only surface protection it is important that drain holes be provided through the shotcrete to prevent buildup of water pressure behind the face. The drain holes should be drilled before shotcrete is applied and should have spacing between 1 – 2m centre to centre.

To achieve optimum effectiveness it is recommended that shotcrete should be reinforced to reduce the risk of cracking and spalling. Therefore, reinforcement using welded-wire mesh (~ 3-4 mm Ø) and steel fibers be placed in between two layers of shotcrete comprising fine-aggregate mortar (< 13mm aggregate size) having 75 – 100mm thickness (ACI, 1983).

5. Tie - Back Walls

Tie-Back wall is a blend of rock bolting and reinforced wall normally placed where there is potential for sliding failure in closely fractured rock (Figure 8.15). Tensioned rock bolts are required to support this portion of slope, as the fractured rock may degrade and ravel from under the reaction plates of the bolts thus, causing loss of tension in the bolts (Turner and Schuster, 1996). Then a reinforced wall may be constructed to cover the area of fractured rock followed by rock bolting, particularly below crown scarp and middle part of landslide body.



(1) Resloping of unstable weathered material in upper part of slope
(2) Removal of rock overhang by trim blasting
(3) Removal of trees with roots growing in cracks
(4) Hand scaling of loose blocks in shattered rock
(5) Clean ditch

Figure 8.16 - Schematic Cliff Section Depicting Rock-Removal Technique for Slope Stabilization (After Duncan et al., 1996)

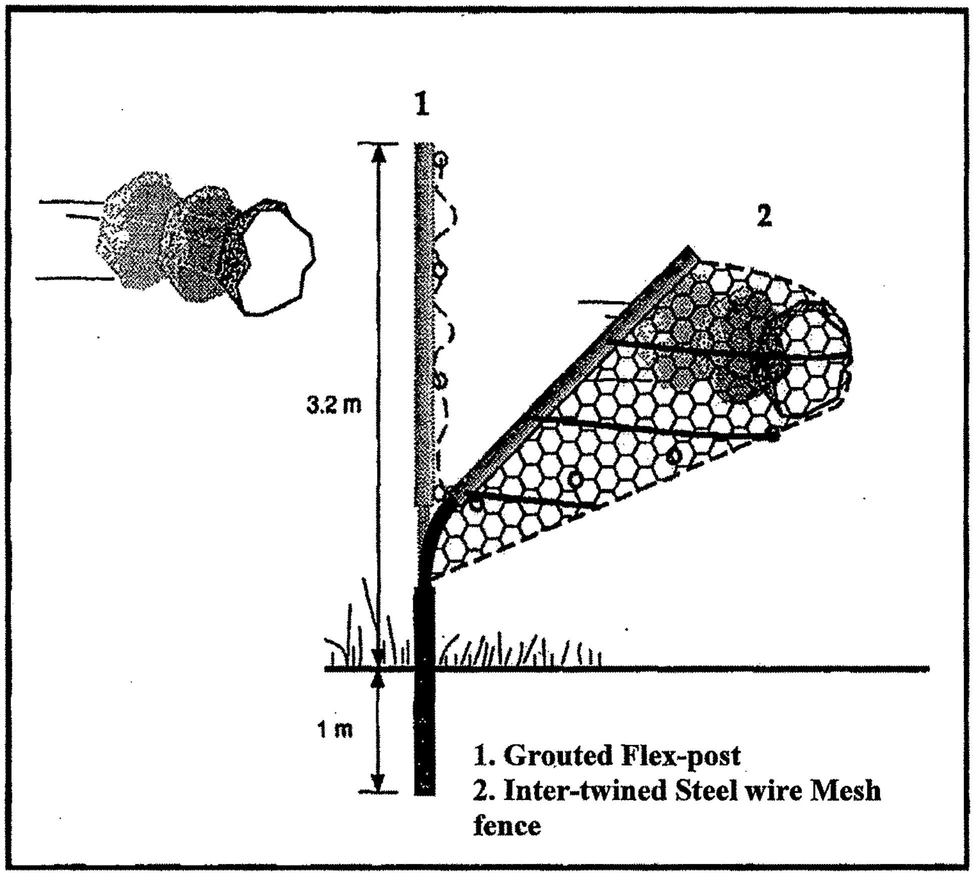


Figure 8.17 - A Schematic Sketch of Flex-post Rock-fall Fence
(After, Hearn, 1991)

6. Drainage

In order to prevent the entry of rainwater appropriate surface drains and collection ditches be developed, particularly the slopes lying above the crown portion of the landslide.

7. Rock Gabbion Wall

In order to counter the driving forces it is recommended to construct rock gabion wall on the toe portion of the landslides after giving due consideration to the landslides' attributes.