CHAPTER SIX

LANDSLIDE RISK ASSESSMENT AND IDENTIFICATION OF LANDSLIDE CAUSATIVE FACTORS

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Landslide risk assessment and Identification of Landslide causative factors

6.1 Introduction

Slope failure is a major geological hazard in North Konkan region of Maharashtra State and causes risk to both lives and property and associated socio-economic consequences. Landslide Risk Assessment is an important step in Landslide Hazard Assessment. Varnes (1984) defines landslide risk as ‘the expected number of lives lost, persons injured, property damage and disruptions to economic activities due to landslides in a given area and given period.

Landslide Risk (R) is the product of hazard (H) and vulnerability (V) and can be expressed as R = H*V. Identification of landslide risk zones provide basis for prioritization of landslide mitigation measures and also for developing disaster management policy. However, assessment of both direct (lives lost, property damage, repairing cost, no. of persons injured, loss of agricultural products, etc.) and indirect risk (disruption in traffic flow, fuel loss, delay, disruption in communication between the settlements along the communication routes, loss of energy, etc.) is a very difficult task. van Westen et al. (2006) discussed some of the important limitations in carrying out quantitative landslide risk assessment including lack of complete landslide database, insufficient damage details and difficulty in determining runout distances for different types of slope failures.

Landslide Risk mapping involves identification, quantification of elements at risk and integration of hazard and vulnerability layers to determine landslide risk prone areas with varying magnitudes. To quantify landslide risk, hazard classes are multiplied with the vulnerability to different types of elements at risk.

There are three major approaches to assess landslide risk viz. qualitative, semi-quantitative and quantitative landslide risk assessment. Keeping in mind the limitations in quantifying elements at risk in the data scarce environment, qualitative landslide risk assessment in combination with heuristic landslide hazard zonation method can be used effectively (van Westen et al. 2006). For the present work, landslide risk prone areas in North Konkan region are identified using qualitative method.
6.2 Data Sources and Methodology

The present section aims at determining landslide risk prone areas in North Konkan region of Maharashtra State. Qualitative landslide risk assessment has been carried out using three elements at risk viz. population, built up areas and road traffic density. These thematic data layers have been extracted from Google Earth images, District Road Development Plan (2001 – 2020) and Census of India, 2011. All thematic data layers of elements at risk have been reclassified using numerical weights. Reclassified thematic layers are then multiplied with landslide hazards and are integrated to produce Landslide Risk Map. The calculation of total landslide Risk is expressed as under (Westen et al. 2006).

\[ R_t = \sum (R_{\text{pop}} * LH + R_{\text{built}} * LH + R_{\text{roads}} * LH) \]

Where,

\( R_t = \) total landslide risk

\( R_{\text{pop}} = \) vulnerability to population

\( R_{\text{built}} = \) vulnerability to built up areas

\( R_{\text{roads}} = \) vulnerability to road traffic

The details of methodology adopted for landslide risk assessment in North Konkan is illustrated in Fig. 6.1.
6.3 Elements at risk

To delineate landslide risk prone areas in North Konkan region, three elements at risk viz. population, built up areas and traffic density along the roads have been considered.

6.3.1 Population

Risk to human lives caused by slope failure events is important consideration in landslide risk assessment. To delineate the areas with population concentration, the village wise population data (Census of India, 2011) have been obtained and population density (arithmetic population density) has been calculated (Popdensity = total population / total geographical area). Four population density classes viz. < 1000, 1000 – 10000, 10000 – 20000 and >20000 per Km. sq. area. have been determined. Figure 6.2 illustrates spatial patterns of population density in the study area. The highest concentration of densely populated areas is associated with urban clusters in the coastal parts of the entire study area particularly in Palghar and Thane Districts. Some isolated areas with population density of 10000 - 20000 are observed at the tehsil headquarter locations. The settlements away from coastlines, central uplands and dissected Jawhar plateau and foot slopes of Western Ghat escarpment of the study area are moderately populated whereas population density is very low in the hilly tracks of Western Ghat and isolated hillocks in the study area.

Although population density can be used as input parameter for landslide risk assessment, it gives generalized picture of population concentration because the entire geographical area of a village or a city is considered for calculating population density. Practically, the population is not distributed over the area but population concentration is observed in the actual built up areas (settlements). It is therefore, consideration of built up areas along with population density layer can be more useful in landslide risk assessment.

6.3.2 Built up areas

Slope failure in the inhabited areas also cause damage to the manmade structures like houses, buildings, roads, railway tracks, bridges etc. Therefore, consideration of spatial patterns of built up areas is important in landslide risk assessment. The thematic layer of built up areas has been extracted from Google Earth image. The distribution of built up areas in the study area is presented in Fig. 6.3. It is concentrated in the highly populated areas in the coastal plains particularly in Palghar
and Thane Districts. Few of these urban settlements located along the foot hill slopes such as Parsik hill area, Matheran area and coastal hill range near Palghar are vulnerable to slope failure. Many slope failure events have been reported in Parsik Hill areas, particularly in Mumbra – Kalwa city where large number of slums are affected by slope failure. Besides, several small settlements are located in the interior parts of the study area.

6.3.3 Roads

Slope failure in North Konkan is mainly associated with the road cut slopes along the road corridors passing across the Western Ghat escarpment. During peak monsoon period these roads are frequently affected by slope failures resulting in disruption to traffic flow, delay in traffic and sometimes damage to road structures and moving vehicles. Therefore, it was felt important to consider roads as input parameter for landslide risk mapping. For this, major roads have been digitized using Google earth images, topographical maps and District road development plan (2001-2020). All the roads have been categorized into four classes’ viz. Expressway, National Highways (NH), State Highways (SH) and District Roads (DR) (Fig. 6.4). Different types of roads have varying degree of traffic density (Fig. 6.4). National Highways (NH) and Expressway experience exceptionally high traffic flow followed by State Highways and District Roads. Kasara Ghat (NH-3), Malshej Ghat (NH-222), Mumbai – Pune expressway, Mumabi - Pune - Bangaluru National Highway (NH-4) along Bhor ghat section, and Mumbai – Goa National Hghway (NH – 17) along Kashedi ghat section are major road corridors with high traffic flow density affected by slope failures during the rainy season. The thematic data layer of roads has been reclassified on the basis of traffic density.
Fig. 6. 2 Village / Town wise Population Density map of the study area

Source: Census of India, 2011
Fig. 6. 3 Distribution of built up areas
Fig. 6. 4 Road types for risk assessment

(Description: - Eway - Expressway, NH - National Highway, SH - State Highway, MDR – Main District Road)
6.4 Landslide Vulnerability Assessment

After extraction of thematic data layers, it is important to assess vulnerability to each of the elements at risk caused by slope failures. For this, each thematic data layer is compared with LH zones and reclassified using numerical weights (Table 6.1).

Table 6.1 Rating scheme used for landslide risk mapping

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thematic Data layer</th>
<th>Classes</th>
<th>Weights used for risk mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Population Density</td>
<td>&gt; 20000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10000 – 20000</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>1000 – 10000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 1000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Built up areas</td>
<td>Built up areas</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Non-built up areas</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Roads</td>
<td>Expressway</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>National Highways</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>State Highways</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>District Roads</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Landslide Hazard Zones</td>
<td>Very High</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Moderate</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Very Low</td>
<td>1</td>
</tr>
</tbody>
</table>

(Source: based on the thematic data layers used for Risk Assessment)

6.4.1. Vulnerability to Population

Although historical records show comparatively less number of fatalities caused by slope failures as compared to other natural disasters, it is important to identify the areas prone to slope failures which may cause harm to the people. Even minor slope failure in densely populated areas may cause severe risk to human lives. To determine the zones vulnerable to human lives, the thematic data layer of population density is compared with Landslide Hazard Zones. Figure no. 6.5 depicts population density areas prone to slope failure of different magnitudes. The results clearly indicate that the densely populated settlements located in the foothill slopes of the Western Ghats escarpment and isolated hills in the study area are vulnerable to slope instability and thereby risk to the lives of people. Few fatal landslides have been reported in Sainik Nagar, Gholainagar (Kalwa), Sainiknagar (Mumbra) and Shantinagar Mumbra) areas. Besides, the foot slopes of Matheran hills, Palghar and Vada area show high vulnerability to the lives of people. Although landslide
susceptibility in the North Eastern corner of the study area is categorized as high to very high hazards, the risk to lives of people is less mainly due to low population density. The concentration of landslide vulnerability to people is limited to the highly populated areas in the western coastal belt of the study area and also the major settlements located near the foothill slopes of the isolated hills and western slopes of Western Ghat escarpment. On the basis of the population density classes, the thematic data layer of population density is reclassified using numerical weights as 4 for population density of >20000, 3 for population density of 10000-20000, 2 for population density of 1000-10000 and 1 for population density of less than 1000 persons per km² (Fig. 6.6).

6.4.2. Vulnerability to Built up areas
Slope failures in the inhabited areas often cause damage to the manmade structures. The estimation of specific risk to the built up areas caused by slope failures is an important step in landslide hazard mitigation planning. Manmade structures like houses and other infrastructure in the built up areas located on the natural slopes susceptible to slope failures. The distribution of built up areas in the North Konkan region (Fig. 6.7) clearly indicate that the highest concentration of built up areas is located in the coastal belt of the study area particularly in Palghar, Vasai, Ulhasnagar, Kalyan, Thane, Panvel and Uran tehsils. The population growth in these urban centres leads to the expansion of settlements even on the hill slopes of the surrounding areas. Mumbra Kalwa area near Parsik hills, parts of Thane city, Western slopes of coastal hill range in Palghar tehsil, hill slope settlements in Matheran area, Khalapur, hilly tracks in south Raigad District and foot slopes of Western Ghat escarpment in the entire study area show high vulnerability to built up areas. To estimate the specific risk to built up areas in North Konkan, the thematic data layer of built up areas has been reclassified using numerical weights as – 5 for built up areas and 1 for non – built up areas (Fig. 6.8).
Fig. 6.6 Vulnerability to human lives ('0' indicate no loss and '1' indicate total loss).

Fig. 6.5 Reclassified layer of population density.
Fig. 6.8 Vulnerability to built up areas ('0' indicate no loss and '1' indicate total damage to built up structure)

Fig. 6.7 Reclassified layer of built up structures
6.4.3. Vulnerability to Road traffic flow

Slope failure along roads results in major losses in terms of actual damage to road structure, delayed traffic flow, disruption in flow of goods and passengers, loss of fuel due to diversion of traffic, mental stress / fatigue, emergency situation like medical help and loss of energy. All the slope failures in North Konkan region are associated with the slope cutting for roads. Besides geo-environmental conditions, the anthropogenic activities such as road widening, removal of upslope vegetation and blasting along the cut slope also trigger slope failure in the study area. Figure 6.9 illustrates the location of roads in relation to their susceptibility to slope failure.

The distribution of vulnerable road sections in the study area shows that major roads passing across the Western Ghat escarpment of the study area are most vulnerable to slope failures. Several slope failure events are reported in Kasara Ghat (NH-3), Malshej Ghat (NH – 222), Bhor Ghat (NH-4), Mumbai – Pune Expressway, Varandh Ghat (MSH – 70), Ambenali Ghat (SH – 72) and Kashedi Ghat (NH -17) sections. The roads are classified into four categories viz. Expressway, National Highways, State Highways and District Roads on the basis of their status, importance and road traffic density. Using these classes, the thematic layer of roads has been reclassified using numerical weights as Expressway (5), National Highways (3), State Highways (2) and District Roads (1). The reclassified road classes are presented in Fig. 6.10.
6.5 Landslide Risk Zones

Reclassified thematic data layers of population density, built up areas and road types are integrated to derive total landslide risk. Figure 6.11 gives details of distribution of landslide risk classes in the North Konkan region. After integrating all the data layers using natural breaks method in GIS environment and the final output is classified into four risk classes namely, High risk, Moderate risk, Low risk and No risk. The spatial patterns of landslide risk areas are shown in table 6.2 and discussed below.

Table 6.2 Landslide Risk Zones in North Konkan

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Risk Class</th>
<th>Weights (range)</th>
<th>Area (km²)</th>
<th>Percentage Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High Risk</td>
<td>&gt; 21</td>
<td>240.25</td>
<td>1.47</td>
</tr>
<tr>
<td>2</td>
<td>Moderate Risk</td>
<td>12 – 21</td>
<td>2090.34</td>
<td>12.79</td>
</tr>
<tr>
<td>3</td>
<td>Low Risk</td>
<td>7 – 12</td>
<td>8907.23</td>
<td>54.5</td>
</tr>
<tr>
<td>4</td>
<td>No Risk</td>
<td>&lt; 7</td>
<td>5105.73</td>
<td>31.24</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>16343.55</td>
<td>100</td>
</tr>
</tbody>
</table>

(Source: based on numerical weights used for population, built up areas and roads)

6.5.1 High Risk Zone

High landslide risk zones in the study area are concentrated in the South West corner of the Thane District particularly around Mumbra Kalwa slum area, isolated hill slopes near Kalyan, Panvel and Ambarnath. The hill slopes of Matheran area also fall in high risk zone. Besides, several other settlements located along the slopes isolated hills in rugged South Raigad District show high landslide risk. Few isolated concentrations of high risk zone are observed along the foot slopes of small hills around Mahad town. The hill slopes around the Kasara railway station also fall in high risk zone. It has been observed that major communication roads passing across the Western Ghat escarpment in the study area fall in high risk zone particularly along the ghat sections. Moreover, the settlements located at the foot slopes of Western Ghat escarpment of this region are also in the high risk zone.

6.5.2 Moderate to Low Risk Zones

Moderate landslide risk prone zone is a major zone in the study area where landslide mitigation measures are to be taken on priority basis. 12.79% of the total geographical area of North Konkan falls under Moderate Landslide Risk zone. The spatial pattern of moderate risk zone is uneven. However, the settlements and communication roads in the dissected topography of Raigad District are vulnerable to
slope failures. It includes isolated hills near Karnala fort, Matheran area and hilly tracks around Mangaon and Mahad. The inhabited areas along the foot slopes of Western Ghat escarpment of Raigad District also fall in this zone.

More than half of the total geographical area of (54.5%) falls under low landslide risk zone. It covers major part of the Palghar and Raigad Districts followed by Thane District. It covers slopes of small isolated hills in the coastal low lands, North eastern dissected plateau areas, North East and coastal low lands of Raigad District. Although, plateau margins of Jawhar plateau fall in high LH zone, it falls under low risk zone probably due to low road traffic density and sparsely populated areas. The spatial distribution of low risk zone reveals that the landslide mitigation measures in these areas can be prioritized on the basis of local conditions and location of settlements in relation to the run out distances of possible slope failures in this zone.

6.5.3. No Risk Zone

31.24% of the total geographical area of North Konkan falls in No Risk zone. The distribution of safe areas with respect to landslide hazards are associated with the coastal low lands of the study area, particularly in Palghar and Thane Districts characterized by extensive valley flats with the elevation below 30 m. Besides, the coastal plains in Uran, Panvel and Alibag tehsils also fall in this zone. The plateau top of Jawhar plateau also falls in no risk zone.

The qualitative assessment of landslide risk in the North Konkan region of Maharashtra State reveals that High landslide risk prone areas are associated with the urbanised hilly section in the coastal plains whereas moderate risk prone areas are located in the dissected topography in the south eastern parts of the study area. All the road corridors passing across the steep sloping Western Ghats are also observed to be under moderate to high risk zone. The extensive coastal plains in the Northern part of the study area and plateau tops in the North East corner of the study area show no risk associated with the slope failures. The risk zones identified using qualitative method for North Konkan region can be used for prioritizing the landslide mitigation measures and for further infrastructural development planning.

6.5.4 Landslide Risk Prone Settlements

It is imperative to identify the priority areas where landslide mitigation measures need to be taken. Settlements located in the landslide prone areas are the
areas where mitigation planning should be prioritized. To identify the risk prone settlements, the thematic layer of settlements is combined with the landslide risk map and number of settlements in each of the risk zone is recorded from attribute table. The details of landslide risk prone settlements are given in Fig. 6.12 and table no. 6.3.

Table 6.3 Landslide risk prone settlements

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Risk Zone</th>
<th>Number of settlements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High risk</td>
<td>434</td>
</tr>
<tr>
<td>2</td>
<td>Moderate risk</td>
<td>815</td>
</tr>
<tr>
<td>3</td>
<td>Low risk</td>
<td>1094</td>
</tr>
<tr>
<td>4</td>
<td>No risk</td>
<td>2138</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4481</td>
</tr>
</tbody>
</table>

(Source: Based on risk map and Google Earth Pro)

The distribution of settlements prone to landslide hazards shows high concentration in the inhabited hills slopes along the foot hill slopes of isolated hills in the coastal plains. The hill slopes near urban areas like Mumbra - Kalwa are observed as high risk prone areas due to the increasing encroachment of slums along the foot slopes of Parsik hill area. Besides, few tiny hamlets located in the Western Ghat region of the study area also fall in moderate to high risk prone zones.
Fig. 6.11 Landslide risk zones
Fig. 6. 12 Landslide risk prone villages/towns in the study area
6.6 Identification of Landslide Causative Factors
Slope failures are caused by several geo-environmental factors such as slope, aspect, lithology, structural discontinuities, land use and land cover, drainage, rainfall, seismicity, etc. However, the effects of these causative and triggering parameters in the initiation of the slope instability process greatly vary both spatially and temporally. It is therefore important to establish relationship between each landslide causative and triggering factor with the actual distribution of slope failure sites in the area under investigation to determine major factors associated with slope instability. This section describes the identification of landslide causative and triggering factors responsible for slope instability process in North Konkan region of Maharashtra.

6.6.1. Data Sources and Methodology
In order to determine relative importance of landslide causative factors in the slope instability, the field observations recorded at 187 slope failure sites have been used. The parameters including elevation, slope angle, aspect, distance from major drainage, distance from road, land use type, lithology type and mean annual rainfall for each slope failure site have been used. The observations recorded during the field survey include parameters such as elevation, slope angle, aspect, distance from major drainage, land use type, distance from road, run out distance and landslide scar geometry using Laser Distance meter, measuring tape and handheld GPS. Besides, rainfall data have been obtained from India Meteorological Department and geological features in the study area have been extracted from Geological Quadrangles.

The information of the characteristics of landslide causative factors has been compared with the spatial distribution of actual slope failure sites recorded during the field. Simple descriptive statistics have been used to determine the role of each of these parameters in slope instability process in the study area.

6.6.2. Identification of Geo-Environmental Factors Causing Slope Failures
Out of ten causative considered for assessing role of each causative factor in slope instability process and distribution of slope failures is also taken into consideration.

a) Slope angle
b) Aspect
c) Elevation
d) Lithology

e) Land use and land cover

f) Rainfall

The relationship of each of the landslide causative and triggering parameters with the actual distribution of slope failures is established and is discussed below.

a) Slope angle

The slope angle is considered to be the most important parameter in the slope instability. Steeper slopes are more susceptible to slope failures than gentler ones. In the North Konkan region, 65.76% of the total slope failure events fall in the slope class between 15° to 35° whereas only 12% slope failures are observed on the slopes greater than 35° (Fig. 6.13).

![Graph showing frequency of slope failures by slope class](source: Field Survey)

Fig. 6.13 Relationship between slope angle and frequency of slope failures

However, the spatial distribution of slope failure sites with reference to slope angle is uneven (Fig. 6.14). The slope failure events in Malshej Ghat, Mumbai - Pune Expressway and Poladpur - Mahabaleshwar road falls in the slope category of slope more than 35°. On the other hand those situated along the slopes of isolated hills in the coastal plain areas are associated with slopes from 15° – 25°. Surprisingly, few slope failure sites around Mahad town show that few slope failures have initiated at the slopes below 15°.
Field landslide ID

(Source: SRTM DEM, Field Survey)

Fig. 6. 14 Relationship between slope angle and slope failures

(Description of the landslide codes used during field survey: - KSR - Kasara, VIKJW - Vikramgad Jawhar road, BEHPD - Behedpada, SAIVVR - Sai Vavar road, WKH - Wada - Khodala area, SKRST - Sakharshet landslide, KHDMK - Khodala Mokhada area, JWHMK - Jawhar Mokhada road, PRLUJN - Parali Ujjaini road, MLSHJ - Malshej ghat area, WJWH - Wada Jawhar area, NM - Neral Matheran area, MM - Mangaon Mhasla road, KONDVT - Kondvite landslide, DAS - Dasgaon landslide, TMN - Tamhini ghat, KSHD - Kashedi ghat area, SAV - Sav landslide, SH72 - Ambenali ghat area, EWAY - Mumbai Pune Expressway, SD - Shrivardhan area)

b) Aspect

Nagarajan et al. (2000) claimed that the direction of slope (aspect) is an important landslide preparatory factor in Western Ghat and Konkan region of Maharashtra. West, South and South West aspect in Western Ghat and Konkan region leads to slope failure during monsoon rains.

(Source: Field survey and DEM)

Fig. 6. 15 Aspect and frequency of slope failures
The relationship between aspect and distribution of actual slope failure sites in North Konkan depicts that above 54.53% of the slope failures are observed on West, South West, South and South East facing slope (Fig. 6.15). Over 33% of the slope failures are observed on North East and North West aspect. The distribution of slope failures in relation to the direction of slope reveals that West, South West and South are preferred slope directions for slope instability to which direct attack of South West monsoon winds makes the slopes more susceptible to fail.

c) Elevation

Relief is another major factor contributing to slope instability. Higher slopes are more susceptible to slope failures than plains. Many studies in Konkan region (Nagarajan et al., 2000; Karlekar, 2012; Thigale and Umarikar, 2007) claimed that relief greater than 300 meters is more prone to slope failures than low lands. Figure 6.16 clearly shows that about 59% of the total slope failures have occurred above 300 m. MSL.

![Graph showing relationships between elevation and frequency of slope failures](Image)

(Source: Field survey and DEM)

Fig. 6. 16 Relationships between elevation and frequency of slope failures

However, the spatial patterns of distribution of slope failures show significant variation in elevation. The relationship between elevation and occurrence of slope failure sites is presented graphically in Figure 6.17.
The distribution of slope failure events in relation to elevation clearly shows that slope failures are more frequent above 300 m. elevation in the Western Ghat section of the study area. In fact, many of the slope failures in Malshej Ghat and Poaladpur Mahabaleshwar road are situated at the elevation of about 600 m. However, few slope failure sites located in the central uplands of South Raigad District unexpectedly show elevation below 300 m. It reveals that slope failures in North Konkan are associated with three major physiographic divisions of the study area namely, Western slopes near Western Ghat crest, foot slopes of Western Ghat escarpment and slopes of isolated denudational hills in the coastal lowlands.

d) Lithology

Lithological characteristics of an area determine its susceptibility to slope failures. Entire North Konkan region of Maharashtra is a part of Deccan Volcanic Province (DVP) and is characterised by series of lava flows classified under Sahyadri group. To determine the role of lithology in the slope instability process, the information about lithology is extracted from Geological Quadrangles and is compared with distribution of actual slope failures in the study area.
Figure 6.18 presents frequency of slope failures with respect to different basaltic lava formations. The maximum frequencies of slope failures are situated in the areas dominated by Ratangarh formations followed by Diveghat formation, Purandhar formation and Karla formations. The western slopes of Western Ghat region of the study area dominated by Megacryst flows (M1, M2, M3) are most susceptible to slope failures. Undulated topography dominated by Karla formation is also affected by major landslide episode in July, 2005 (Thiagale and Umarikar, 2007). On the other hand few minor slope failures are observed in the dissected plateau areas in the North East part of the study area covered with lava flows of Salher (oldest) formation.

e) Land use and land cover

Land use pattern represents anthropogenic interventions on the surface of the earth and sometimes results in hazards induced by anthropogenic activities. Therefore, land use and land cover are considered as an important input parameter for both landslide hazard zonation and landslide risk assessment.
The relationship between land use type and frequency of slope failures is presented in figure 6.19. According to Bureau of Indian Standards (1998), barren land and rock outcrop areas are more susceptible to slope failures than any other land use. However, the distribution of slope failures in North Konkan indicates that only 36.4% of the slope failures identified in the field are located in barren and rocky surfaces whereas 38.5% and 20.3% of slope failures are observed in the categories of cultivated land and vegetated areas respectively. The complexity in the relationship between land use classes and frequency of slope failures reveals that there is a need to study more details of other anthropogenic intervention besides land use such as slope cutting for road widening, blasting and removal of vegetation.

f) Rainfall

There is no doubt that all the slope failures in Western Ghats and Konkan region are induced by intense and prolonged monsoon rainfall. To assess the role of rainfall on slope instability, the mean annual rainfall has been compared with the frequency of slope failures. Figure 6.20 illustrates the relationship between rainfall and slope failures in the study area.
The relationship between rainfall and frequency of slope failures in North Konkan clearly demonstrates the role of rainfall in inducing the slope failures. More than 65% of the total slope failures are observed in the areas with annual rainfall exceeding 3000 mm. However, the spatial patterns of slope failures and rainfall greatly vary within the study area. The amount of rainfall progressively increases from North to South except the North East part of the study area where rainfall is higher than 3000 mm. Surprisingly, the landslide prone areas in Malshej Ghat show concentration of slope failures even rainfall is less than 2500 mm. Most of the slope failure sites in Raigad District receive annual rainfall above 3250 mm.

6.6.3. Identification of LS Causative Factors

The relationships between major landslide causative factors with the actual distribution of slope failures indicate that slope instability in North Konkan is a complex phenomenon as it is influenced by several geo-environmental parameters.

The parameters including distance from road, proximity to lineaments and proximity to major drainage have not been considered for establishing their relationship with actual slope failures. Since, only major drainage lines have been extracted for the present study and only seven slope failure events are found within the buffer of 100 m. distance from drainage lines. The distance from roads could not be considered for establishing its relationship with slope failure because all the slope failure events recorded during field survey are confined to roads. No major slope failure has been observed with proximity to lineaments. This may be due to the coarse
resolution of the data used (SRTM DEM, Google Earthpro and Geological Quadrangles) for extraction of the lineaments.

On the basis of the relationships between landslide causative factors and distribution of actual slope failures, it can be inferred that slope gradient, aspect, rainfall, lithology, land use and land cover are important geo-environmental factors in the initiation of slope failures in North Konkan. Since, rainfall is a main landslide triggering factor in the study area the consideration of landslide magnitude at the time of slope failure will be more useful rather than mean annual rainfall. One of the major limitations in calculating rainfall intensity is non-availability of details about exact date and time of slope failure. Therefore, generating complete landslide database with accurate date and time of slope failure can be more effective in determining the role of rainfall in slope instability.

6.7. Conclusion

The qualitative landslide risk assessment in North Konkan region is carried out in this section. The spatial patterns of population density, road traffic and built up areas in combination with LHZ map have been considered for determining Landslide Risk prone areas in the study area. The concentration of both built up areas and population density are observed in three main pockets namely, slopes of Parsik hill near Mumbra-Kalwa town, Western slopes of coastal hill range near Palghar town and some major settlements in the coastal lowlands which are highly vulnerable areas to slope failures.

The Landslide Risk Zones identified using qualitative approach indicate that 14.26% of the total geographical area in North Konkan falls in Moderate to High risk prone areas where are more than half of the North Konkan (54.5%) are identified as Low risk areas. Densely populated and habited areas in proximity to hill slopes near Kalwa – Mumbra area, Palghar area show high risk to people and human structures. Besides, small settlements and road sections situated in the Western Ghat region are also depicted as moderate to high risk prone areas. On the other hand uninhabited areas in the foot slopes of Western Ghats escarpment, coastal lowlands and dissected plateau areas indicate low risk to both people and property. The risk prone areas identified using qualitative method may be useful in prioritizing the landslide mitigation measures and also in policy making for new infrastructure development.
Determination of relative importance of each landslide causative and triggering factor is a critical stage in landslide hazard assessment because such geo-environmental parameters influence the results of landslide hazard zonation and risk assessment. The relationship of characteristics of each causative factor with the actual distribution of slope failure indicate that the sub categories of causative factors can be assigned weights on the basis of frequency of slope failures so as to improve accuracy of LHZ maps. The results also reveal that slope angle, elevation, lithology and rainfall play significant roles in the process of slope instability.