Chapter 3

RESEARCH METHODOLOGY

3.1 GENERAL

The risk or threat to human life and property due to slope instability / landsliding is the product of several factors like the hazard posed by landsliding, exposure of elements at risk to the hazard, their vulnerability and the consequences of any event. Similarly the hazard of slope instability is product of several factors like local geomorphic, hydrologic, and geologic conditions; the modification of these conditions by geodynamic processes, vegetation, land use practices, and the human activities; and intensity of precipitation and seismicity (Soesters and Westen, 1996). Deterministic hazard analysis is usually adopted for a particular landslide location which requires exhaustive geotechnical investigations. For larger study areas having inherent geotechnical variability and in-homogeneity, coupled with high costs of investigations, the deterministic approach does not remain valid. For these large areas under investigations, the knowledge of all the causal factors, their spatial and temporal variability, and the extent of their individual and collective contribution to the slope instability process is required to assess LHP. Therefore, based on this analogy, a multi-prong methodology was adopted consisting of identification and acquisition of the requisite LHP and risk analysis data through walk-over surveys; analysis of the data using Fuzzy Logic Technique; intensive field investigations to obtain precise parameters at the selected locations. The analyzed data was first converted to LHP Maps. Using LHP and landslide risk related data, Landslide Risk Maps were prepared.

Field investigations covered the LHP and risk scoring data collection in the study area, excavation of test pits, drilling of boreholes, collection of disturbed and undisturbed samples and in-situ testing including electrical resistivity testing of the sub-surface strata. The research performed during this study is divided into following main tasks (Fig. 1.1):

- Literature Review
- Site Reconnaissance / Visits
- Field Investigations
- Laboratory Investigations
- Landslide Hazard Zonation and Mapping
- Landslide Risk Zonation and Mapping

The research methodology adopted in this study is explained in the following sections.

3.2 FIELD RECONNAISSANCE

The purpose of the site visits was to evaluate the slope instability processes and to ascertain the type (usage) and nature (construction) of building structures in the area. To gather requisite information meetings were held with the officials of Tehsil Municipal Administration, Revenue Department, and Landslide Information Centre of PHD. In addition, information regarding slope stability problems in the area was also gathered by interviewing population and construction contractors working in the area. The information acquired during the field visits helped to formulate an optimum field investigations plan.

3.3 FIELD INVESTIGATIONS

Field investigations are recognized as the central and decisive tool for the studies of landslides or landslide-prone areas. In this research, field investigations consisted of surface mapping and subsurface explorations. Surface mapping included the collection and mapping of data related to the factors contributing to the initiation / triggering of landslides scenarios. The data was collected in an inventory sheet titled ‘Landslide Hazard Potential (LHP) and Risk Data’. Subsurface explorations included test pits, boreholes, disturbed and undisturbed sampling, in-situ testing and electrical resistivity testing. Piezometers were also installed in drilled boreholes to monitor fluctuation of water levels during different seasons.

Field investigations methodology is explained in the following sections, while the results are discussed in the Chapter 4.

3.3.1 Development of Landslide Hazard Potential (LHP) Factors

Mostly engineering studies related to landslides, concentrate on individual landslides, their investigations, and site specific solutions. Such studies are local in nature and do not help determine the instability potential of a larger / entire area of concern. As explained in Chapter 2, this can be accomplished by carrying out statistical modeling of the factors contributing to the slope instability in the area. In any slope stability problem, there are always a group of factors directly affecting the stability, known as primary factors. Each primary factor has several stems of secondary factors; each one of these affects the stability process to a varying degree. The secondary factor in turn has a set of specific tertiary attributes. These primary, secondary, and tertiary factors, when combined together, with due considerations to their individual weightage to the slope stability process, furnish LHP.

In any LHP process, first step is to determine the primary and secondary level factors affecting the stability of slopes in a particular area. Each primary and secondary level factor contributes to a different level to the instability process. Second step is awarding weightage / grade to primary and secondary factors in order of their relative contribution in influencing / triggering instability to the slopes. For any particular area, the determination of weightages / grades requires:

- A detailed study of the natural and human-induced processes leading to slope instability in the area.
- The conceptual development of causal factors including both conditioning and triggering factors affecting these processes.
- The spatial and temporal variation study of these processes in the light of the conditioning and triggering factors.

These steps were achieved by carrying out in-depth study of the existing research, projects conducted in the area and the insight developed regarding slope instability problems concerning the study area through extensive field reconnaissance. Resultantly, primary and secondary level factors responsible for the initiation of landslides in the study area were identified and are tabulated in Table 3.1. Each secondary factor is further stemmed into several tertiary level attributes specific to the area. Tertiary level factors identified for the study area are tabulated in Table 3.2.

3.3.2 Collection of Landslide Hazard Potential (LHP) Data

Primary and secondary level factors developed in Section 3.3.1 were collected through walk-over surveys across the study area (Fig. 1.2). The data was collected for every 30m distance intervals of all the roads except Lower Jhika Gali Road and Jhika Gali-Kuldana Road, where RDs are marked. In addition to recording the specified factors, landslides inventory was also prepared along the study routes. Landslide inventory was based on observation and interviews with local population, the information gathered included the type and nature of landslides, intensity and frequency of occurrence, season and soil conditions in which triggering mostly occurred, and maintenance / rehabilitation history.

The data collection strategy for the factors enumerated in Tables 3.1 and 3.2 is explained in the following paragraphs. A database of the collected LHP data was prepared in Microsoft ACCESS. Typical LHP database formulated for all the routes is provided in Appendix I.

Table 3.1. Primary and Secondary Level Factors affecting Slope Stability in the Study Area

Primary Level Factors	**Secondary-Level Factors**
A. Geology	Overburden Soil Type
	Overburden Soil Thickness
	Rock Type
	Weathering Extent
	Bedding Planes
	Aperture
	Infillings
	Dip
	Strike
B. Metrology	Maximum Daily Rainfall (mm)
	Maximum Hourly Rainfall (mm)
	Maximum Snowfall (ft)
	Maximum Temperature Range
	Minimum Temperature Range
C. Vegetation	Vegetation (Type)
	Vegetation (Density), %
D. Hydrology	Presence of GWT
	Flow through Slope
	Permeability of Top Soils
	Drainage Facilities
E. Topography	Gradient (Rock)
	Gradient (Soil)
	Height (m)
	Shape (Vertical)
	Land Form
	Protection Facility

Table 3.2. Tertiary Level Attributes to the Secondary Level Factors Affecting Slope Stability in the Study Area

GEOLOGY						**REMARKS**
Overburden Soil Type	None	Gravels	Silt	Sandy Clay	Clay	
Overburden Thickness						
Rock Type	Sandstone	Limestone	Slate	Alt. Shale / Sandstone	Shale	
Weathering Extent	Fresh	Low	Medium	High	Complete	
Bedding Planes	>30cm	20-30cm	10-20cm	6-10cm	<6cm	
Infilling						
Aperture						
Dip	Not Day				Day lighting	
Strike	>6^o	3^o – 6^o		0^o – 3^o	Parallel	
TOPOGRAPHY						
Gradient (Rock)	<20	20-30	30-40	40-60	>60	
Gradient (Soil)	<15	15-25	25-35	35-45	>45	
Height (m)	25-50	50-75	75-100	>100	Infinite	
Shape (Vertical)		Concave	Straight	Convex	Complex	
Land Form		Stable		Previous Landslide	Man-made cut	
Protection Facility	Retaining Wall	Breast Wall	Toe Wall	Gabions	None	
VEGETATION						
Vegetation (Type)	----	Trees	Shrubs	Grass	No Cover	
Vegetation (Density), %	>75	50-75	25-50	10-25	<10	
HYDROLOGY						
Presence of GWT	---	No GWT	----	When Raining	Stable GWT	
Drainage Facilities	---	Two-way	One-way	One-way (H)	No Facility	
Permeability of Top Soils	---	v High	High (sand)	Medium (silt)	Low (Clay)	
Flow through Slope	---	General	---	Channelized	Subsurfac	

3.3.3 Geologic / Geotechnical Data

In addition to the effect of geologic formation on the general landslides behavior of the area, certain geologic features have been identified to be controlling the localized landslide behavior. Geologic features associated with the overburden soil layers and rocks considered to be affecting the landslides phenomena in the study area are listed below:

- Overburden soil layers
    - Type
    - Thickness(es)
    - Erosion Potential
- Rocks / Bedrock
    - Type
    - Structure
    - Weathering Extent
    - Weathering Potential

Type of overburden soil layers and type, structure, and weathering extent of the rocks were recorded using walkover surveys. The weathering extent of the rocks was observed from the existing vertical cuts and eroded strata layers. Thicknesses of soil and rock layers and their precise classification and weathering extent were determined using a combination of geophysical and borehole investigation techniques.

Based on the extent of weathering of the strata present in the area, the collected and evaluated geologic features were finally converted to several subsurface strata models bearing specific geotechnical behavior.

3.3.3.1 Geotechnical Strata Models

Several geologic formations are present in Galliat area, while only Murree formation was encountered in the study area. Based on the field observations, Murree formation is divided into following geotechnical behavior models.

- Sandstone-Shale bedded layers.
- Sandstone-Shale bedded layers with vegetated soil cover.
- Boulder Clay (Sandstone Boulders in Clay matrix).
- Boulder Clay with maximum Clay.
- Boulder Clay with abundance of Sandstone Boulders.
- Only Sandstone Boulders.

Accordingly, geotechnical strata map of the study area was prepared and is shown in Chapter 4.

3.3.3.2 Climatic Data

Climatic data of an area refers to daily, monthly, and seasonal variations of temperature, humidity, and precipitation. The climate of an area not only controls the geotechnical behavior of the strata in terms of pore pressures, but also directly affects the type and intensity of weathering and degradation of rocks in the area. Peltier (1950) developed relationship of various types and intensity of weathering of rocks with mean annual precipitation and mean annual temperature of the area. Peltier's study is still considered the best source for describing the weathering process and his graphical illustrations are still being used to explain the complex processes constantly occurring on the earth surface (Fowler and Peterson, 2004). Plots developed by Peltier (1950) are shown from Figs. 3.1 to 3.6.

The requisite climatic data for Murree Station was acquired from Pakistan Metrological Department and attached in Appendix II. Data for Murree area was acquired for the last 10 years. The climatic data was used to categorize the study area into several weathering types and intensity zones. Mean Annual Temperature and Mean Annual Rainfall was plotted on the Peltier's charts (Figs. 3.1 to 3.6) to locate the area into potential weathering type and its intensity.

3.3.3.3 Vegetation Data

Presence or absence of certain type and extent of vegetation on slopes have contributed significantly to the formulation and generation of landslides. The effect of presence or absence of vegetation is manifold: besides acting as a resistant to the erosion of the surficial material, vegetation also provides an increase in the shear strength of the soil layers through anchorage and regulation of moisture levels. Despite several advantages associated with several types of

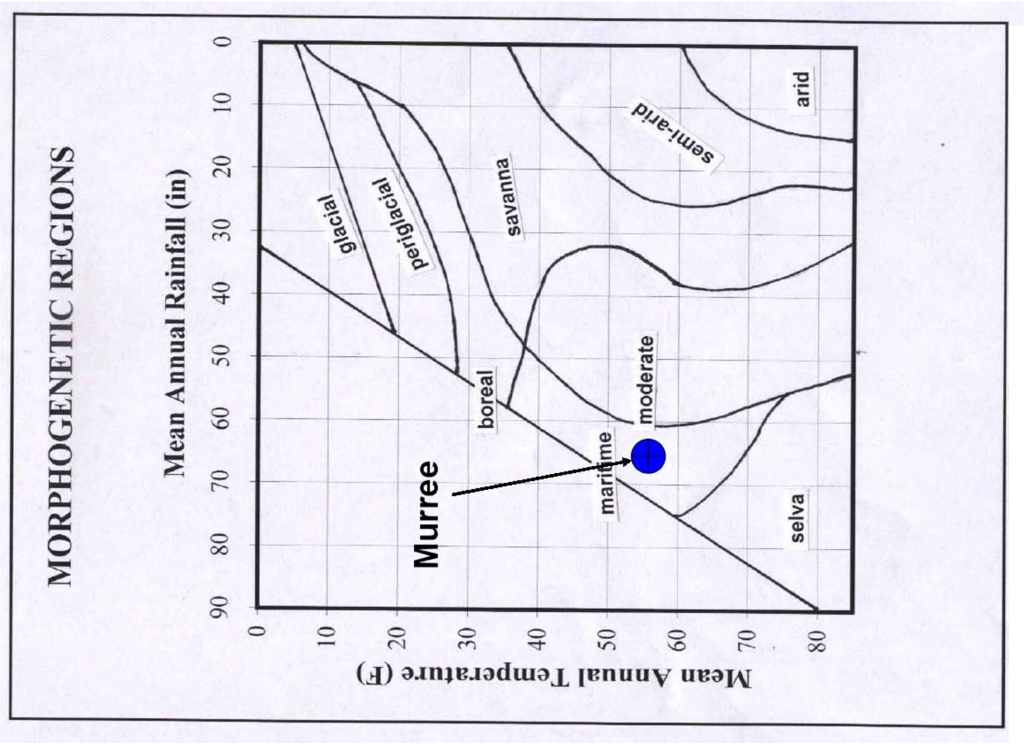

Fig. 3.1. Morphogenetic Regions (after Peltier, 1950)

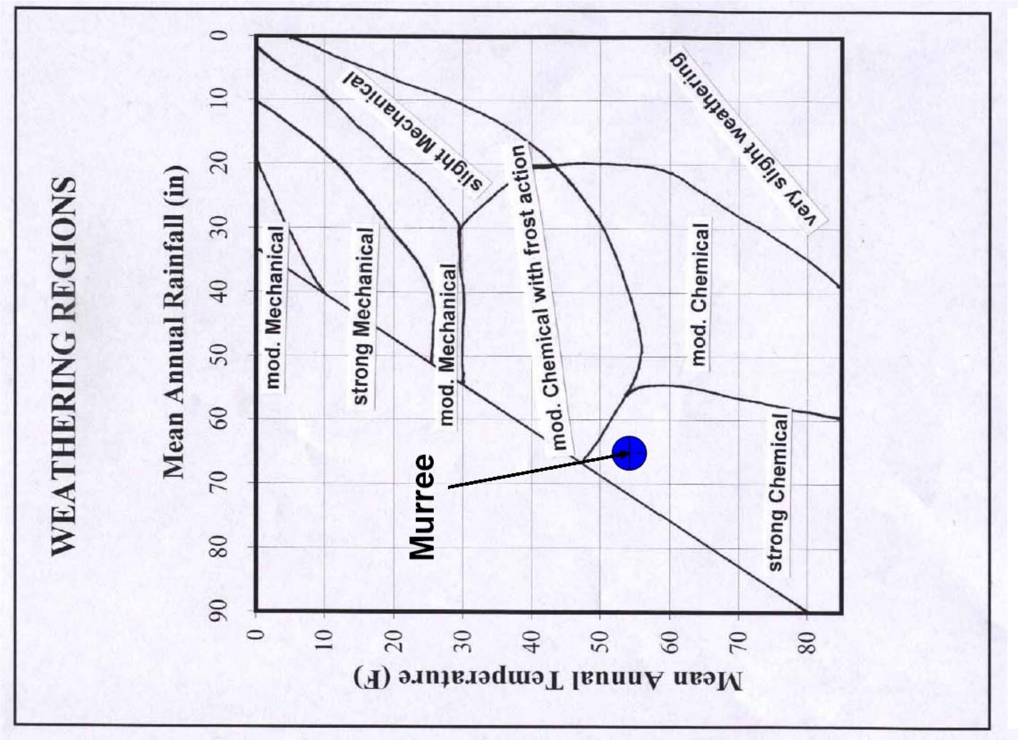

Fig. 3.2. Weathering Regions (after Peltier, 1950)

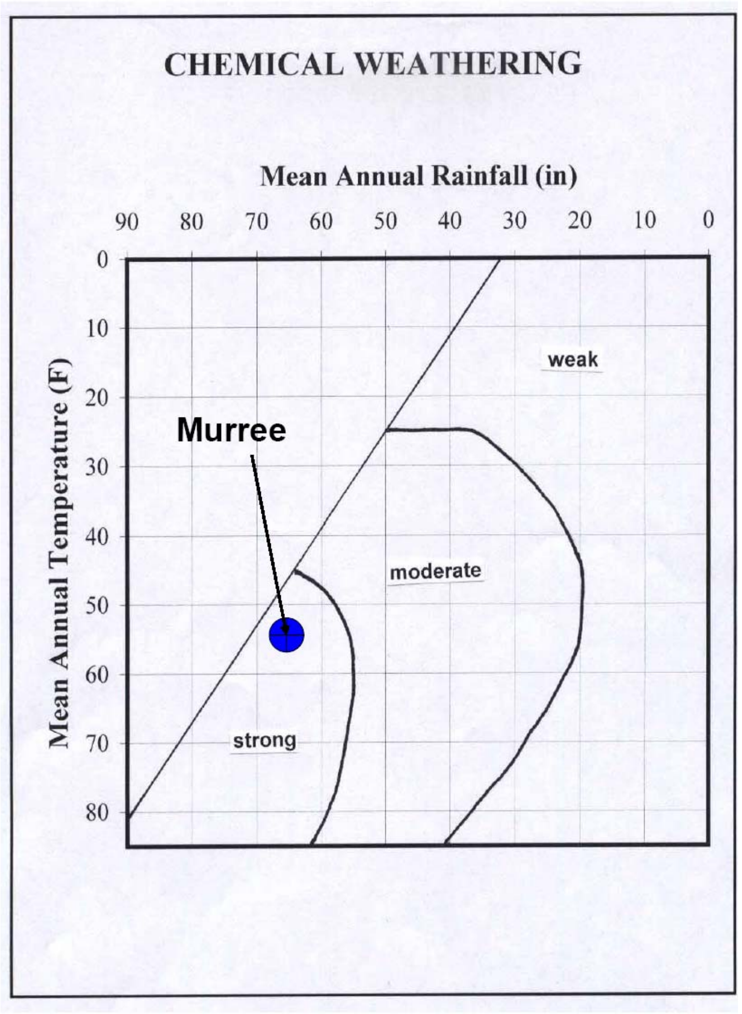

Fig. 3.3.Chemical Weathering Regions
(after Peltier, 1950)

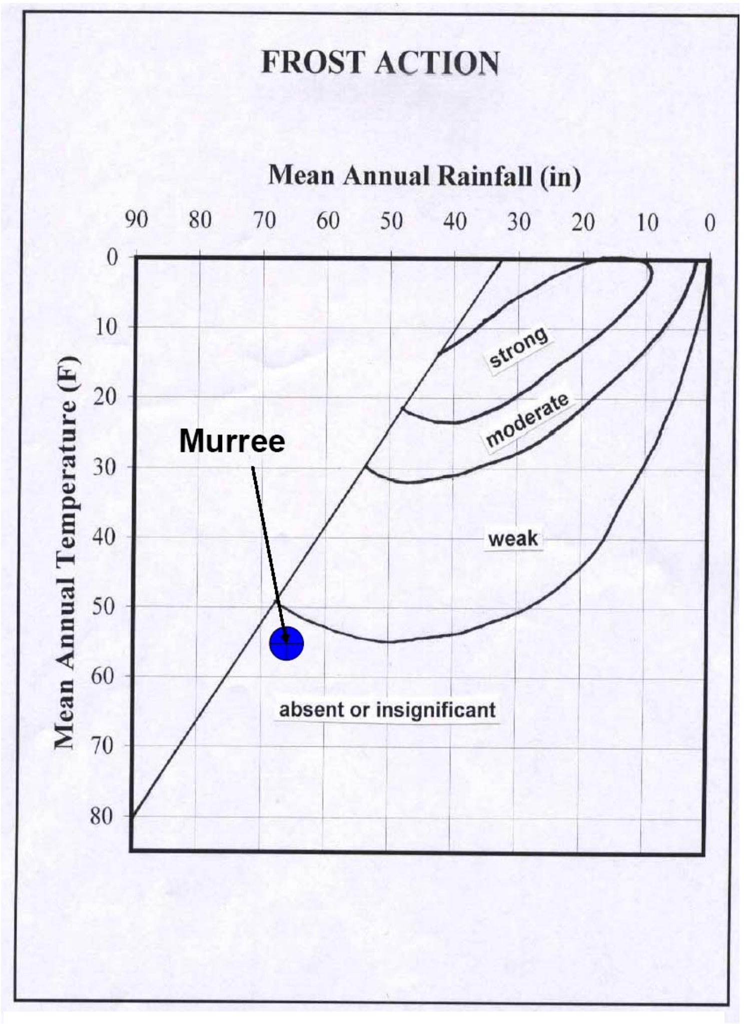

Fig. 3.4.Frost Action Regions (after Peltier, 1950)

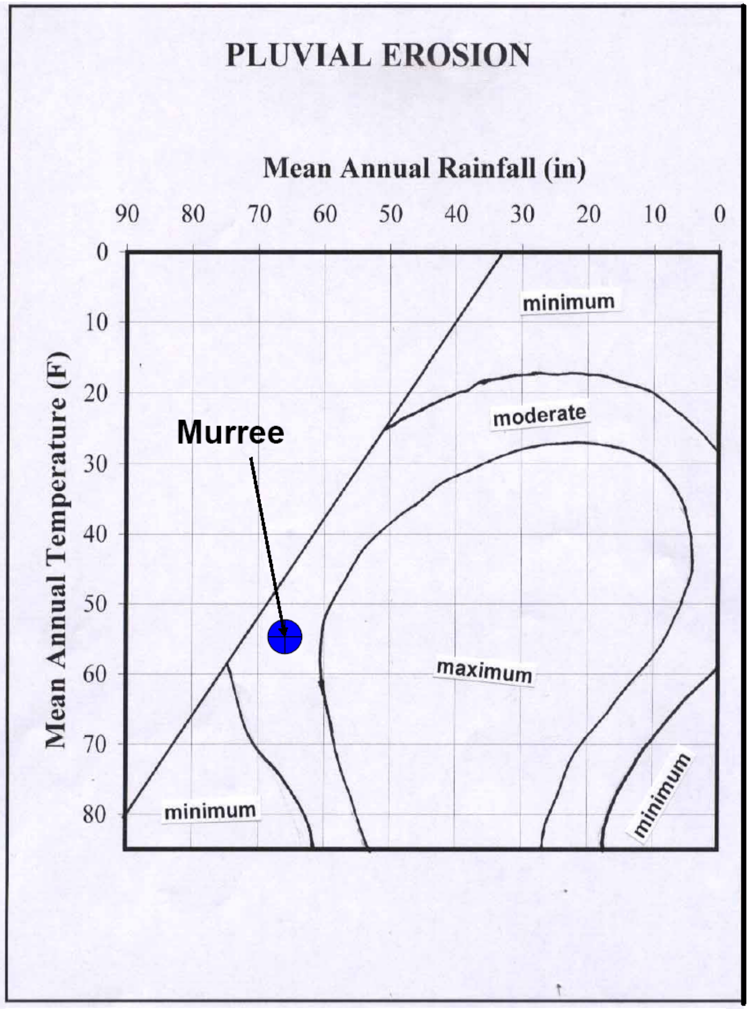

Fig. 3.5.Pluvial Erosion Regions (after Peltier, 1950)

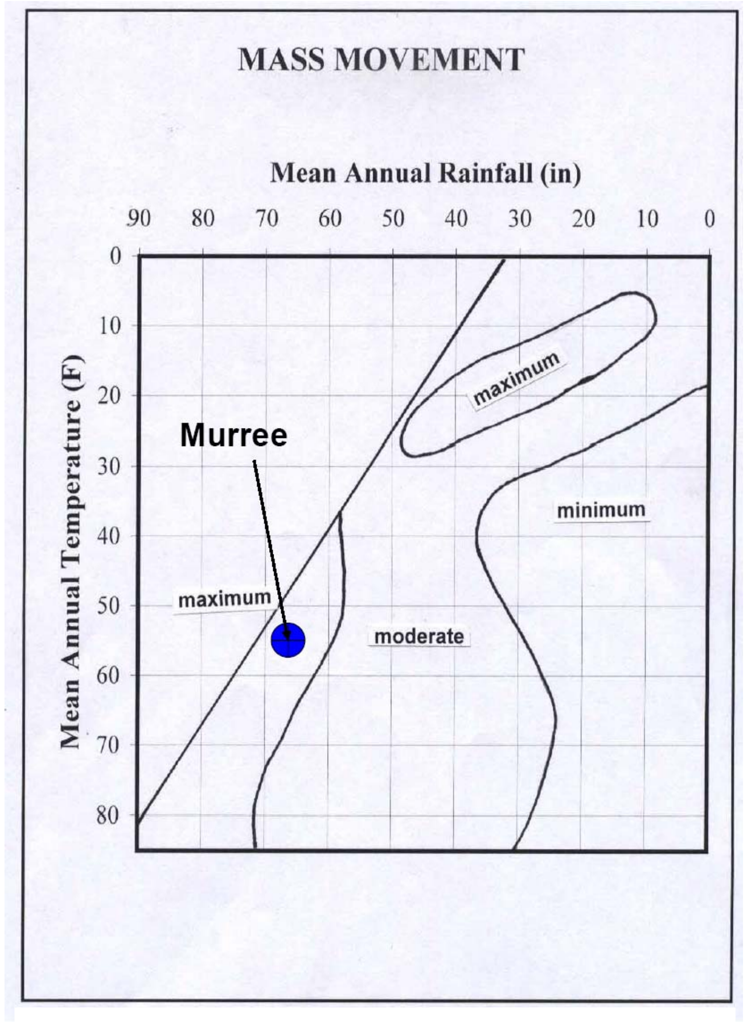

Fig. 3.6.Mass Movement Regions (after Peltier, 1950)

vegetation on slopes, roots of trees and shrubs act as weathering agents in rocky strata through root wedge action.

From slope stability point of view, the type of vegetation in the study area has been divided into three general categories: Trees, Shrubs, and Grasses. Each category was selected with due considerations, keeping in mind their contribution to the engineering behavior of slopes.

As of various types of vegetation, the density of each specific type of vegetation also affects the global stability of the slopes. Different ranges of vegetation density have been defined in order to cater the effect of this factor and are shown in Table 3.2. The vegetation type and density maps prepared as an outcome of the study are shown and discussed in Chapter 4.

3.3.3.4 Hydrologic Data

Hydrologic features of an area constitutes surface and subsurface water aquifers; their extent, seasonal fluctuations, and flow characteristics. In addition to recording and assessing these features, main consideration was given to the mechanism how these hydrologic features could affect the landslides scenario in the area. For instance, high water tables may not always be taken as threat to the slope instability; rather it would be problematic if the aquifer is ‘undrained’ during the application of engineering loadings. Moreover, a perennial spring or nullah should not be taken as instability scene if a proper drainage structure is provided throughout its flow path. Therefore, along with recording and assessing nature, extent, and variation of the surface flows, provision and efficiency of the “drainage conditions” were also noted down during the walkover surveys. For this specific study, drainage conditions refer to:

- Presence and efficiency of culverts and bridges.
- Permeability / Percolation characteristics of the surficial strata.
- Provision and efficiency of drainage facilities.

It has been observed that the provision and efficiency of the drainage facilities play a significant role in the stability of the study area. Slope instability problems were observed wherever adequate drainage facilities are not provided.

The knowledge of the subsurface aquifers was acquired through interviews with the locales and further confirmed through resistivity tests. Use of electrical resistivity tests for ascertaining the subsurface aquifers are explained in Section 3.3.4.1. In addition, standpipe piezometers were installed in the drilled boreholes to assess the depth and seasonal fluctuation of the subsurface water levels. The details of the installed piezometers are provided in Section 3.3.4.4.

3.3.3.5 Topographic / Landform Data

Geomorphology of the slopes has a great role in the instability processes. Geomorphology not only covers slope angle, height, and shape, but also changes in the shape due to slope movements and / or due to presence of slope protection facility. Different aspects of the geomorphologic attributes affecting slope stability, as defined in Table 3.2 were documented during walkover surveys.

Besides a well-known effect of slope angles and height on the slope instability phenomena, shape of the slope has a considerable effect on the landslide generation. Convex slopes have got lesser confinement as compared to the straight runs while concaves have the maximum inherent confinement. Moreover, previous landslides existing in certain areas and not treated properly, remain susecptable to further future instabilities.

3.3.4 Subsurface Explorations

LHP data collected during the walkover surveys was mainly based on the surface observations. In order to augment the surface data with subsurface information, subsurface exploration techniques were employed. The subsurface exploration was optimized using electrical resistivity tests.

The details of the subsurface explorations techniques adopted in this study are provided in this section.

3.3.4.1 Electrical Resistivity Tests

Geophysical tests fall under indirect subsurface strata investigations techniques. Electrical resistivity test was carried out for the following reasons:

- The saturation levels of the subsurface strata are targeted.

- Inclination and thickness of overburden soil layers and bedrock is required.

Since above given requirements are the key inputs in the determination of LHP, electrical resistivity test was selected as one of the core investigation tool for this study. 1-D and 2-D resistivity tests were performed during field investigations. Wenner alpha configuration with variable electrode spacing as per ASTM G 57 was adopted for this study.

Total eight electrical resistivity tests were performed in the study area, 1-D electrical resistivity tests were performed at five locations along different roads, while 2-D tests were performed at three locations. The resistivity test results are directly obtained in the form of apparent resistivities of the subsurface strata. These apparent resistivity values were then converted to absolute values through 1-D & 2-D inverse modeling technique. IPI2Win and Res2DINV Software were used for inverse modeling.

3.3.4.2 Test Pits

Test pit is a shallow subsurface exploration technique. In this technique, the subsurface stratum is directly observed at the shallow depths. In addition, undisturbed block samples can also be acquired from the test pits. Undisturbed block samples are considered the best class of undisturbed samples obtained during any geotechnical investigation of the subsurface strata.

In this study, pits were excavated manually to depths varying from 1 to 1.5m. Undisturbed driven tube and block samples were collected from the test pits. The samples obtained from the test pits were sealed, labeled, and transported to NIT Material Testing Laboratory at Risalpur for further studies. In addition, Vane Shear and Penetrometer tests were conducted in the softer overburden strata. The finalized test pit logs are presented in Appendix III.

3.3.4.3 Drilling and Sampling of Boreholes

A borehole is considered a valuable tool for field investigations. Boreholes are direct subsurface investigation technique and provide access for collection of undisturbed samples and carrying out in-situ tests in various layers of the subsurface strata.

Four locations were selected for drilling of boreholes. The borehole locations were finalized keeping the following in considerations:

- Stable Area
- Unstable Area (Landslides)
- Potential Unstable Area
- Undisturbed Sampling of Shale / Clay

The drilling of boreholes was carried out using a hydraulic rotary drilling rig. The subsurface strata were penetrated by straight rotary drilling method in which water was used as drilling aid. In the soil and weaker / softer rock layers, Standard Penetration Tests (SPTs) were performed at a depth interval of 1.5m. These tests were performed generally in accordance with ASTM D 1586 using a split spoon sampler of 35mm inner diameter and 50mm outer diameter. The samples recovered from split spoon sampler were visually inspected and classified as per ASTM D 2488. A description of soil samples recovered and the number of blows of the standard hammer used in SPTs for successive 15cms of penetration was recorded on field borehole logs.

Upon encountering harder rock strata, boring was advanced using double tube core barrel attached with tungsten carbide bit. After drilling a core run of 1.5m, the cored rock was removed from the core barrel, and Recovery and Rock Quality Designation (RQD) was recorded for each core run. Softer Shale / Siltstone strata was sampled using Shelby Tube Sampler, while harder Shale layers were sampled using Dennison Sampler. After sampling, the ends of the sampler tubes were waxed to prevent any moisture loss from the samples. All the recovered samples were carefully preserved and brought to NIT Material Testing Laboratory at Risalpur for further studies. Borehole logs were prepared in the field and were finalized after the laboratory testing. Summary of borehole locations is given in Table 3.3. The finalized borehole logs are presented in Appendix III.

Table 3.3. Summary of Borehole Locations

S. No.	**Road**	**RD**	**BH No.**	**Depth (m)**
1	Jhika Gali - Kuldana (JK)	2002	BH-JK	7.7
2	Lawrence College - Jhika Gali	155	BH-LCJG	6.5
3	Lawrence College – Station HQ (LCSHQ)	172	BH-SHQ	12.5
4	Jhika Gali – GPO (JGGPO)	16	BH-UJG	15

3.3.4.4 Installation of Standpipe Piezometers

Knowledge of variation of subsurface water levels during different seasons of the year is essential for understanding the landslide behavior in the study area. For this purpose, standpipe piezometers were installed in the drilled boreholes.

The piezometers consisted of 50mm diameter PVC pipes. The pipes were made perforated by drilling 10mm holes at a spacing of 20cm. A typical piezometer pipe section is shown in Fig. 3.7. After the completion of the borehole, the piezometer was lowered to the bottom of the borehole. The annular space in between the borehole walls and piezometer pipe was filled with graded filter material. After filling with filter material, the last 10cm was plugged with soil-cement mortar. Water levels in the piezometers were measured using a Dipmeter.

Fig. 3.7. Perforated PVC Pipe Used for Standpipe Piezometers.

3.4 LABORATORY INVESTIGATIONS

Disturbed and undisturbed samples retrieved during field investigations were transported to NIT Material Testing Laboratory at Risalpur. A laboratory investigations program was prepared to determine strength, stiffness, weatherability / durability, resistivity, and permeability characteristics of the subsurface strata. The details of the tests carried out along with the specifications are provided in the following sections while results are attached as Appendix IV.

3.4.1 Classification Tests

Grain size distribution including Sieve Analysis and Hydrometer, and Atterberg limits were performed on the samples obtained during the investigations. The results were used to classify the subsurface strata as per Unified Classification System (USCS).

3.4.2 Triaxial Strength Studies

As already discussed in the previous sections, Shale and Clay type of strata covers most of the study area. Due to the high susceptibility of such type of strata to the moisture saturation levels, it is essential to develop correlations between shear strength of such type of strata and saturation levels. In order to determine the variation of strength of such type of strata with moisture levels, Triaxial Tests were carried out on the undisturbed samples retrieved from the boreholes.

For Triaxial testing, specimens were prepared from the undisturbed samples and tested at different saturation levels. Unconsolidated-Undrained (UU) types of tests were conducted on the specimens as per ASTM D 2850.

3.4.3 Swell / Consolidation Tests

The clayey and Shaley strata present in the study area is characterized by high swell potential. In addition, at higher saturation levels, such type of strata attains very softer consistency. Under softer nature, the strata may undergo high compressions through the process of consolidation. Therefore, in order to test the swell and consolidation behavior of this type of strata, Consolidation / Swell tests were carried out on the undisturbed samples as per ASTM D 2435.

3.4.4 Slake Durability Tests

Most of the rocks present at the site are degradable in nature and get easily weathered and eroded when come in contact with flowing water. This property of rocks is known as Slakability, which determines the weathering potential of the degradable type of rocks. The concept can be used for the determination of the 'temporal stability' of the slopes composed of such rocks.

There are several laboratory tests available to determine the slake durability of such types of rocks. Slake Durability Test method as per ASTM D 4644 is used for the determination of weathering potential of degradable rocks.

3.5 LANDSLIDE HAZARD ZONATION AND MAPPING

An ideal map of slope instability hazard should provide information on the spatial probability, temporal probability, type, magnitude, velocity, run-out distance, retrogression limit of the mass movements predicted in a certain area (Hartle`n and Viberg, 1988). As already discussed, slope instability hazard modeling could be performed through the use of one or a combination of the following concepts:

- White Box Models (Pure Deterministic Models).
- Black Box Models (Pure Statistical Models).
- Grey Box Models (a combination of Deterministic and Statistical Models).

For the investigations and studies of large areas, geotechnical variability of the strata coupled with the costly and time-consuming investigation techniques make pure deterministic approach unsuitable for such areas. Pure statistical approach on the other hand requires a complete comprehension of the landslide processes in the area.

In this research, statistical analysis of the LHP data collected during the investigations was carried out using fuzzy logic technique. Fuzzy logic analysis is mainly based on bivariate and partially on multivariate statistical analysis procedures. The outcome of the fuzzy logic analysis was Landslide Hazard Potential Indices (LHPIs) for each 30m section of the investigated road slopes.

The results of the fuzzy logic analysis were transferred to GIS software. SURFER has been used for creating LHPI maps of the area routes.

3.5.1 Statistical Modeling using Fuzzy Logic Analysis

Slope instability zonation of the study area has been carried out using statistical models. For larger areas under investigation, deterministic techniques do not yield satisfactory solutions. Geotechnical variability of the data in larger areas and the high costs associated with the investigations make these techniques not feasible. For such cases, the requirement is to comprehend and collect the causal factors affecting the slope instability processes. Next is to develop a statistical equation to correlate these factors to develop slope instability models. In this study, statistical analysis of the LHP data collected during field investigations was carried out using fuzzy logic technique.

Fuzzy logic is one of the techniques classed under bivariate statistical analysis techniques, and it has been widely used worldwide for the LHP analysis. The basic process involved in a Fuzzy Logic Process is shown in Fig. 3.8. The essence of fuzzy logic analysis for the current research is the series of steps required to convert LHP data into Landslide Hazard Potential Index (LHPI). Various steps carried out for the Fuzzy Logic analysis of the Slope Stability behavior, are described below.

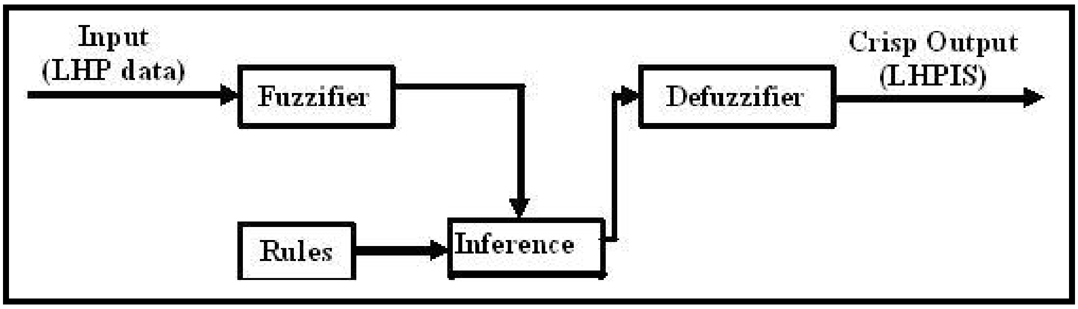

Fig. 3.8. Typical Fuzzy Logic Process Adopted in the Study

3.5.1.1 Input

Input, in fuzzy logic, means the input of primary, secondary, and tertiary level LHP data in the form of an evaluation tree (Fig. 2.9). The values of the recorded LHP factors are input in the process as fuzzy values i.e., very high, high, medium, low etc. These fuzzy attributes are then converted to crisp values by assigning numerical equivalents to all the recorded data. The numerical equivalents for each fuzzy value were decided on the basis of weightage of each individual factor to the instability process. In the current study, all the recorded LHP data was stored and analyzed in a database. The database was then fed as input to a Fuzzifier engine.

3.5.1.2 Fuzzifier

In fuzzy logic, a Fuzzifier converts the crisp data into fuzzy data. The Fuzzifier used in this study is as given below:

$$R = [\ {}_{j=1}\Pi^{n} (r_j)^{wj}\ ]^{\beta} \qquad (3.1)$$

Where:

$R =$ "combined weightage" of LHP based on all the LHP factors on a given branch of the evaluation tree,

$r_j =$ rating of failure potential according to the factor i,

$w_j =$ weight of the factor i as compared with other factors on the same branch of the evaluation tree,

$n =$ number of branches in the given branch of the evaluation tree, and

$$\beta = 1 / ({}_{j=1}\ \Pi\ w_j) \qquad (3.2)$$

Based on the extensive field and laboratory investigations, studying the landslides processes, the primary, secondary, and tertiary level factors were awarded weightage grades varying from A to E. Each grade was assigned a membership function depending on the relative contribution of each of these factors to the slope instability process for each specific area. Based on the research findings, weightage grades and their membership functions assigned to primary, secondary and tertiary level factors are shown in Table 3.4 and Table 3.5.

In the fuzzification process, Eq. 3.2 is repeatedly used to combine these grades; the repetition is performed four times at secondary level and one time at primary level. The whole process is governed by several in-built rules and inferences.

Table 3.4. Primary and Secondary Level Factors and Their Grades with Assigned Values Considered in Landslide Hazard Analysis.

Primary Level Factor	Weight	Value	Secondary-Level Factor	Weight	Vlaue
A. Geology	**A**	0.93	Overburden Soil Type	**A**	0.93
			Overburden Soil Thickness	**B**	0.78
			Rock Type	**C**	0.58
			Weathering Extent	**A**	0.93
			Weathering Potential	**A**	0.93
			Bedding Planes	**A**	0.93
			Aperture	**A**	0.93
			Infillings	**A**	0.93
			Dip / Strike	**A**	0.93
B. Metrology	**A**	0.93	Maximum Daily Rainfall (mm)	**A**	0.93
			Maximum Hourly Rainfall (mm)	**A**	0.93
			Maximum Snowfall (ft)	**B**	0.78
			Maximum Temperature Range (^{o}F)	**C**	0.58
			Minimum Temperature Range (^{o}F)	**B**	0.78
C. Vegetation	**B**	0.78	Vegetation (Type)	**B**	0.78
			Vegetation (Density), %	**B**	0.78
D. Hydrology	**A**	0.93	Presence of GWT	**A**	0.93
			Flow through Slope	**A**	0.93
			Permeability of Top Soils	**B**	0.78
			Drainage Facilities	**A**	0.93
E. Topography	**B**	0.78	Gradient (Rock)	**C**	0.58
			Gradient (Soil)	**A**	0.93
			Height (m)	**B**	0.78
			Shape (Vertical)	**A**	0.93
			Land Form	**A**	0.93
			Protection Facility	**A**	0.93

Table 3.5. Tertiary Level Attributes to Secondary Level Factors and Their Corresponding Grades with their Numerical Values Effecting Stability of Slopes in the Study Area.

Primary Level Factor	Weight	Value	Secondary-Level Factor	Weight	Value
Vegetation (Type)	**B**	0.78	No Cover (NC)	**A+**	1.00
			Grass (GR)	**A**	0.93
			Shrubs (SR)	**B**	0.78
			Trees (TR)	**D**	0.35
Vegetation (Density), %	**B**	0.78	Less than 10	**A**	0.93
			10 -25	**B**	0.78
			25 – 50	**C**	0.58
			50 – 75	**D**	0.35
			Greater than 75	**E**	0.13
Drainage Facilities	**A**	0.93	Built –up are (BA)	**A+**	1.00
			Drainage with no culvert (DNC)	**A**	0.93
			Inefficient drainage (DIE)	**B**	0.78
			Efficient drainage (DE)	**E**	0.13
Gradient (Soil)	**A**	0.93	Greater than 45	**A**	0.93
			35 – 45	**B**	0.78
			25 – 35	**C**	0.58
			15 – 25	**D**	0.35
			Less than 15	**E**	0.13
Height (m)	**B**	0.78	Greater than 25	**A+**	1.00
			15 – 25	**A**	0.93
			10 – 15	**B**	0.78
			5 – 10	**C**	0.58
			Less than 5	**E**	0.13
Shape (Vertical)	**A**	0.93	Convex (CX)	**A+**	1.00
			Complex (CM)	**A**	0.93
			Straight (ST)	**C**	0.58
			Concave (CC)	**E**	0.13
History	**A**	0.93	Major (MAJ)	**A+**	1.00
			Medium (MED)	**A**	0.93
			Minor (MIN)	**B**	0.78
			Stable (STB)	**D**	0.35
Protection Facility	**A**	0.93	Absent (AB)	**A**	0.93
			Provided in poor condition (PPC)	**B**	0.78
			Provided in good condition (PGC)	**D**	0.35

3.5.1.3 Rules and Inferences

Rules in the fuzzy logic are the set of instruction which govern the fuzzification process and results. These rules are verified during each repetition on all the branches of the evaluation tree. Based on the extensive investigations and observations carried out, several set of rules were defined for the fuzzy logic process. For example, in the process, intense rainfall has been awarded grade ‘A’, which means that it has got maximum effect on the slope stability. But, as a rule, the effect of intense rainfall will be maximum on the boulder clay / Shaley strata rather on intact rock. Therefore, a rule is in-built in the process which controls the incorporation of relative effect of intense rainfall on several types of strata.

Fuzzification process results in ‘inferences’. The inferences are qualitative expressions stating the LHPI i.e., very high, high, medium, low, and very low. The linguistic data (fuzzy data) is finally converted to crisp values through defuzzification process.

3.5.1.4 Defuzzification

Several methods are available for the conversion of inferences (LHPIs) to crisp values. In this study, the method proposed by Juang et al. (1992) was used for the defuzzification process. In this method, LHPI is defined as

$$\text{LHPI} = (A_L - A_R + 1) / 2 \qquad (3.3)$$

Where:

A_L = area enclosed by the universe and to the left of the membership function of the final fuzzy number obtained, and

A_R = area enclosed by the universe and to the right of the membership function of the final fuzzy number obtained

Final LHPI values and LHP database were transferred to a graphic software for the preparation of LHPI zoned maps of the study area.

3.5.2 LHPI Zoned Maps

Landslide Hazard Potential Indices (LHPIs) acquired through the fuzzy logic process and the LHP Database prepared in MS ACCESS were transferred to a software Surfer for the preparation of LHPI zoned maps. Finalized LHPI maps, are discussed in Chapter 4. Besides LHPI zoning, maps showing vegetation type, vegetation density and geotechnical strata of the study area are also prepared and discussed in Chapter 4.

3.6 IDENTIFICATION AND COLLECTION OF FACTORS CONTRIBUTING IN LANDSLIDE RISK OF THE STUDY AREA

As explained in Section 2.11, in most of the cases, it is intricate to assign risk in absolute terms because of the difficulties in assessing absolute values for the hazard, the assets or elements at risk and possible adverse consequences. In such circumstances, it is highly practical to assign relative risk by assessing the relative levels of the threat by the particular hazard, based on both factual data and subjective appraisal. The significance of relative risk assessment is that it can enable sites to be compared quickly and thereby allow early decisions to be made where limited financial resources should be utilized.

The risk or threat created by a hazard is function of several factors such as hazard itself, exposure of population and property to hazard, their vulnerability and the consequences. Keeping in view the different types of construction practices in the area and seasonal variations in the population, the first step was to identify the various variables that contribute to the landslide risk. The factors identified as contributors to the landslide risk were collected at each RD using walkover surveys. At each RD, the pertinent data was collected within a visual corridor of about 500m. The routes and roads of the area were mapped using hand-held GPS recorder having an accuracy of ±15 m (Lowrance Inc., USA). The collected data was later on augmented and confirmed through the available maps of the area. The risk factors, defined for the study area are explained in the following sections.

3.6.1 Population

The information obtained through literature review and the site visits reveal that the population of the study area varies throughout the year. Therefore, the most important factor considered in the evaluation of landslide associated risk is the spatial and temporal distribution of population in urban Murree area. The maximum concentration of population is in the surroundings of GPO Chowk especially during monsoon season. While it has been observed that the population thins out towards Lower Jhika Gali and Jhika Gali to Kuldana roads. During the winter season, the population drops down to its lowest estimated value of approximately 30000, the majority of these are the permanent residents of urban Murree. During winter season majority of permanent residents also migrate to the plains. Whereas, during monsoon season, the area is visited by a large number of tourists; raising the population to an estimated peak strength of 300,000. Keeping in view the account of the variation in population, the whole year has been divided into four seasons i.e., Monsoon, Winter, Spring and Summer as defined in Table 3.6. The spatial and temporal population variation maps of the study area are shown and discussed in Chapter 4.

Table 3.6. Different Seasons of Year and Corresponding Population and Saturation Levels

S. No.	Season	Month	Population Level	Saturation Level
1	Monsoon	July - September	Very High	Very High
2	Winter	October - February	Low	Medium
3	Spring	March – April	Medium	Very High
4	Summer	May – June	High	High

3.6.2 Type of Structures

In the study area, landslides and slope failures could result in ground movements sufficient to cause collapse and / or damage to the structures built on the slopes. The relative movement and the consequent collapse depend on the type of the structures. Certain structure types are more sensitive to the ground movement compared to others. Based on this analogy, various structure types in the area are divided into categories having relatively high to low sensitivity to the slope movements. Various structure types in the study area are listed below:

- Frame Structures - FR
- Wall Bearing Structures with RCC Slab - BR
- Wall Bearing Structures with Corrugated Galvanized Iron Sheet Roofs -BS
- Mud or Brick Walled and Mud Plastered Structures – MBS
- Roads and Utility Lines - RU

Generally, frame type of construction has been used for the multistorey structures with raft type foundations. Based on the relatively high flexibility of these types of structures, they are less vulnerable to collapse and / or damage as compared to wall bearing structures having isolated or strip type of footings. Different types of building structures were assigned suitable grades keeping in view their vulnerability to slope movements. Roads and utility lines were classified as least resistant to any slope failure event. It has been observed that even creep movements in the slopes have contributed towards the opening of the pipelines joints causing persistent seepage and percolation in the subsurface strata. The grades and the corresponding values assigned to various types of structures are tabulated in Table 3.7.

3.6.3 Nature of Structures

As explained in the Section 3.6.2, various types of structures exist in the study area. Each of the structure type carries a certain level of risk to human life, depending mainly on its occupancy level. Keeping this fact in view, the structures present in the study area were classed and assigned different grades according to their residential capacity. Based on the occupancy levels, different categories of structures have been identified in the study area and are listed below:

- Multistory Buildings
- Single Storey Buildings (Residential)
- Office Buildings
- Academic Centers (Schools and Colleges)

- Commercial Centers (Shops / Restaurants)
- Roads and Utility Lines (e.g., electricity poles, sewerage and water supply lines, gas pipelines etc) and
- Un-Inhabitant Land

Multistorey buildings with high occupancy including school / college buildings are graded as A+, while land without any habitation was assigned the lowest grade i.e., E. Various categories of structures and the corresponding assigned grades are shown in Table 3.7.

3.6.4 Consequence Level

The most important step in the risk analysis is to assess the adverse consequence or damage level of any event. In the study area, consequences of slope failures were assessed based on different types and nature of structures and their occupancy level. For instance, maximum loss of human life may occur in case of the collapse of a multistorey or a school building. On the other side, no adverse consequences will occur in case of even a very massive landslide in an un-inhabited land. Based on the extent of loss of life and property at a specific place and under a specific slope failure event, different levels of consequences have been defined for the study area. The defined levels of consequences alongwith the assigned grades are tabulated in Table 3.7.

3.6.5 Value of Land

The value of the elements at risk is an important aspect in risk analysis. Depending upon the locality, same type of structures, risked by a potential landslide, may have different worth. For example a single storey building near Kashmir Point has more market value than the building near bus stand area. For this purpose, the study area has been divided into five zones. Based on the relative land value, each zone was assigned a weightage grade and corresponding numerical value. The identified zones and their respective grades are tabulated in Table 3.7 and listed below:

- Zone A – Kashmir Point to GPO Chowk and Mall Road

- Zone B – Jhika Gali Chowk to GPO Chowk (Upper Jhika Gali Road)
- Zone B – Station Headquarter to GPO Chowk (CECIL Hotel Road)
- Zone C – Station Head Quarter to Sunny Bank and GPO Chowk
- Zone D – Lower Jhika Gali Road
- Zone D – Jhika Gali Chowk to Kuldana Chowk

Table 3.7. Different Factors and their Grade & Values in Risk Analysis

RISK FACTOR	CLASSES	GRADE	VALUE
Nature of Structure	Multistorey Building (MS)	A+	6
	Academic Centers (Schools and Colleges)	A+	6
	Single Storey Buildings (Residential)	A	5
	Commercial Centers (Shops / Restaurants)	B	4
	Offices (OF)	C	3
	Roads and Utility Lines	D	2
	Un-inhabitant Land (UL)	E	1
Type of Structure	Other Structure (MBS / Roads / Utility Lines etc (OR)	A+	6
	Wall Bearing Structure with RCC Roof (BR)	B	4
	Wall Bearing Structure with GI Sheet Roof (BS)	C	3
	Frame Structure (FR)	D	2
Consequences Level	Severe Damage	A+	6
	Major Damage with Loss of Life	A	5
	Major Damage with Serious Injury	B	4
	Major Damage	C	3
	Minor Damage	E	1
Value of Land	Zone A	A+	6
	Zone B	A	5
	Zone C	B	4
	Zone D	C	3
	Zone E	E	1
Season	Monsoon	A+	6
	Summer	A	5
	Spring	C	3
	Winter	D	2

3.7 LANDSLIDE RISK MODELING AND MAPPING

According to literature review, there are two approaches in risk analysis i.e., quantitative and qualitative. The approach and method adopted for the risk analysis should depend on the scope, purpose, and scale of the hazard and risk assessment. For regional studies, approaches and methods may be largely based on remote sensing including satellite imagery and aerial photographs. For more detailed studies, use should be made of local knowledge and databases concerning relevant parameters and elements at risk. The approach adopted for urban areas may be qualitative or semi-quantitative. The quantitative approach has several limitations including difficulties involved in collection of extensive and precise risk data and their spatial and temporal variability. From the literature, the qualitative risk analysis methodology is found to be a successful approach for the type and nature of the area under this research study (Robin Chowdhury et al., 2001). Therefore, qualitative risk analysis approach, based on the relative risk scoring has been adopted in this study.

3.7.1 Risk Modeling

Keeping in view the factors described in the previous sections, the risk is defined as follows:

$$\text{RISK} = f\,(\text{Hazard, Vulnerability, Consequences})$$

The above relation has been transformed into the following equation:

$$\text{RISK} = (\text{Hazard} \times \text{Vulnerability} \times \text{Consequences})$$

$$\text{RISK} = (\text{LHPI}) \times (\text{ToS} + \text{NoS}) \times (\text{EV}+\text{C}) \times (\text{S}) \qquad (3.4)$$

Where:

LHPI = Landslide Hazard Potential Index

ToS = Type of Structure (on the basis of occupancy)

NoS = Nature of Structure (on the basis of resistant to collapse)

EV =Value / Cost of Land at Risk

C = Level of Consequences Anticipated

S = Season

Table 3.6 show different levels of these factors and corresponding numerical assigned value. As a typical example, the risk analysis of a multistorey building at GPO chowk to a slope failure hazard is shown below:

Landslide Hazard Potential Index (LHPI) = 0.73

Nature of Structure (Multistory Building) = 6

Type of Structure (Frame) = 2

Element Value (Zone A) = 6

Consequences (Severe Damage) = 6

Season (Monsoon) = 6

Risk = 0.73 × (6 + 2) × (6 + 6) × 6 = 420

3.7.2 Risk Mapping

All the collected data was stored in Microsoft ACCESS database. The database was used to convert grades to risk values. The risk values were then transferred to MS Excel for further analysis. MACROS based algorithms were prepared in MS Excel for the conversion of individual risk data values to Risk Scores. The risk scores obtained for the whole area for different seasons were statistically analyzed to define various levels of risk. Normal distribution curves were plotted for the risk scores for different seasons. From these plots, cutoff lines for various risk levels were drawn at Mean +1.5 SD, Mean +0.5SD, Mean +1SD, Mean -0.5SD, Mean -1SD, Mean -1.5SD and Mean. In addition combined normal distribution curve for all four seasons was also plotted. These cutoff lines were used to define Very High, High, Moderate, Low, and Very Low risk zones respectively. For this purpose monsoon season was used as it has maximum risk score and hazard potential. The risk score greater than 1.5SD were defined as very high, scores ranging from 0.5SD to 1.5SD as high, -0.5SD to 0.5SD as moderate, -1.5SD to -0.5SD as low and scores less than -1.5SD were defined as very low. Normal distribution curve for monsoon season is shown in Figs. 3.9 while in Table 3.8 calculated and selected cutoff values are shown.

The risk scores from MS Excel algorithm, along with their corresponding coordinates were exported to the graphical software SURFER. SURFER was used to draw risk score contour maps. In the software, natural neighborhood algorithm was found most suitable and appropriate to interpolate data in between the data points. The risk maps prepared for different seasons are shown and discussed in Chapter 4.

Table 3.8. Cutoff Values for Defining Different Level of Risk in Monsoon

GRADES	**Limits**				**No. of Data Points**
	Actual	**Selected**			
Very High	357	350	and above		80
High	249	250	to	349	91
Moderate	142	150	to	249	151
Low	35	50	to	149	349
Very Low	0	0	to	49	0
Total No. of Data Points =					671

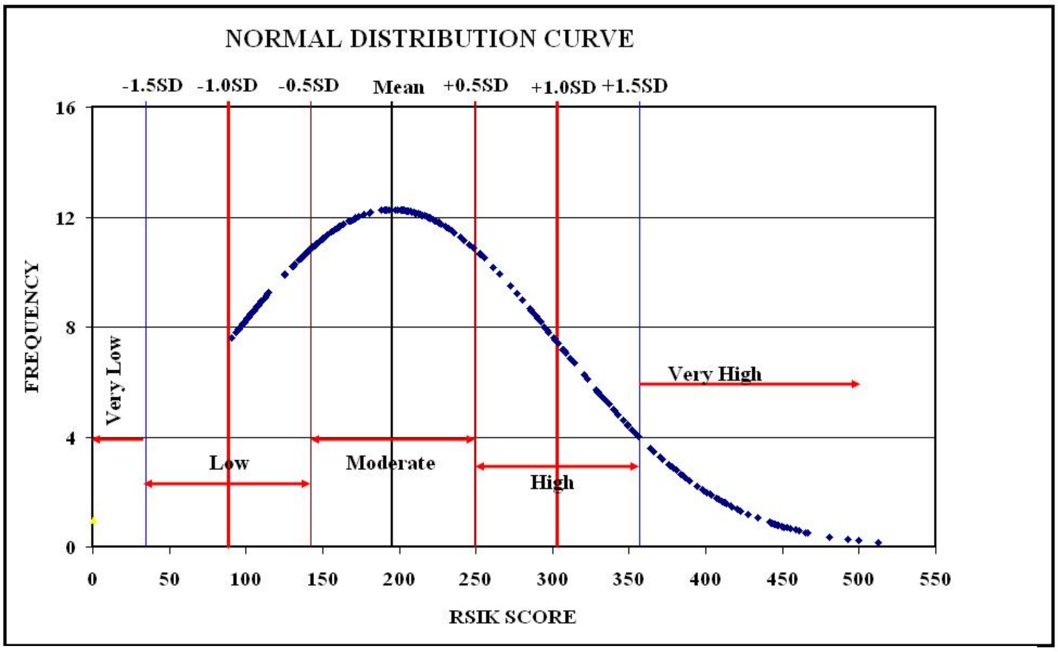

Fig. 3.9. Normal Distribution Curve for Risk Scores during Monsoon