



ADDIS ABABA UNIVERSITY

School of Graduate Studies

Faculty of Science

**Evaluation of Factors Responsible For Landslides
In Haro Village And It's Surrounding, North Shoa of Oromia,
Central Ethiopia**

**A Thesis
Submitted to**

**The School of Graduate Studies
of Addis Ababa University**

***In Partial Fullfillment of the requirements for the Degree of
Masters in Geo-Hazards and Disaster Management***



Beto Dimma

July 2007



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DEPARTMENT OF EARTH
SCIENCES
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**EVALUATION OF FACTORS RESPONSIBLE FOR LANDSLIDE IN HARO
VILLAGE AND ITS SURROUNDING, NORTH SHOA, CENTRAL
ETHIOPIA**

**BY
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Declaration

This Thesis is my original work and has not been presented for a degree in any other university and that all sources of material used for the thesis have been accordingly acknowledged.

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This thesis has been submitted for examination with my approval as a university advisor.

Dr. Tarun K. Raghuvanshi (advisor)

Signature _____ date _____

Date and place of submission: July 10/ 2007, Addis Ababa

ACKNOWLEDGMENTS

First of all, Thank God, my effort was nothing without his blessing. Next, I would like to express my sincere appreciation and thanks to my principal advisor Dr. Tarun Kumar Raghuvanshi, Assistant professor, Department of Earth Science, Addis Ababa University, for modifying the research topic and suggesting the methods for analyzing the problem, his guidance, encouragement, comments and constant support throughout my research work.

I greatly wish to acknowledge my brother Mr. Tesema Gadissa who motivated me to join and continue my postgraduate programme and helped me in providing moral support to face all my personal problems during the last two years. I am grateful to Mr. Merga Diyessa for his voluntary guidance in using different GIS software for my research work. I am very grateful to all Earth Science Department instructors and staffs who directly or indirectly helped me for the progress of my research work. I am also grateful to all my friends from whom I have been able to get their help during my research work. I am indebted to the officials of North Shoa Zone Disaster Prevention and Preparedness office for providing important information and problem of the area which helped me to start the present research. My acknowledgement also goes to the officials of Hidabu Abote administrative and agricultural offices for uninterrupted facilitation of transport during the whole field works.

Last but certainly not the least; I would like to express my special gratitude towards my wife Woinshet Lamecha, my father Dimma Jote and my mother Sidise Wogari for their outstanding love, encouragement and support.

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Abstract

As a consequence of frequent occurrences of landslides in Haro village and its surrounding, an investigation was undertaken to determine the factors responsible for the landslide in order to produce a landslide hazard Zonation map using the "Landslide Hazard Evaluation Factors (LHEF)" rating scheme as the main methodological tool. The geology of the area is mainly dominated by weathered and weak contact structural discontinuities of basalts, Limestone, Sandstone, gypsum and loose unconsolidated colluvial soils which are responsible for the instability of the slopes in the area.

Six major inherent causative factors; Lithology, Structure, Slope morphometry, Relative relief, Land use land cover and Ground water conditions have been recognized for the purpose of generating a landslide hazard classification. For this purpose Landslide Hazard Evaluation Factor (LHEF) approach was employed. By applying the LHEF approach, these factors were analyzed facet wise based on the chosen categories. Each category is then given a corresponding rating based on the amount the factors contribute to the landslide activity. The ratings for each facet are summed up to give the Total Estimated Landslide Hazard Rating (TELHR). Finally, the landslide hazard map, from 54 facets, has been generated and five hazard zones have been identified as; very low (18%), low (15%), moderate (15%), high (41%) and very high (11%).

From the very high and high hazard zones, the potential unstable slopes were identified and the Engineering properties of rocks and soils have been determined for classification purpose. As the slope instability poses danger to the villages are due to the geological structures, weak contact of rock beddings, poor drainages, less vegetation cover and loose unconsolidated colluvial soils, slope stability analyses and some possible methods of slope stabilization or remedial measures are necessary and have been described and suggested, and which should include; avoidance, surface and subsurface drainages improvements, constructing simple retaining structures and planting suitable trees.

CHAPTER I

INTRODUCTION

1.1 General

Landslides are caused when the force of gravity pulls rock, debris or soil down a slope. These are one of the forms of erosion called mass wasting, which is broadly defined as erosion involving gravity as the agent causing movement. As the gravity constantly acts on a slope, landslides occur when the stress produced by the force of the gravity exceeds the resistance of the material. Landslide movement is noticeable and may take the form of falls, topples, slides, spreads or flows.

Landslides are among the serious geological hazards common in many parts of the world. They constitute a major hazard to population, property and infrastructure in many hilly and mountainous areas. They cause billions of dollars worth damage to the properties and thousands of deaths and injuries each year worldwide. Academicians argue over such hazard as the most frightening and awesome. However, the most important is the necessity to evaluate them in terms of their suddenness, severity, aerial extent, potential economic losses, degree of warning and the level of possible mitigatory measures.

In Ethiopia, the magnitude of landslide occurrence and its resulting damage has been increasing in recent times. Even though its impact is local, it is a catastrophic event and claiming a vast number of human lives and destroying a great deal of property. Many researchers tried to assess the situations of these occurrences and consequences in different parts of the country, especially, in the highlands, because about 60% of the populations in Ethiopia live in the highlands with an altitude more than 1750m, where landslide activities are prevalent (Ayalew, 1999). However, when the researches conducted are compared to the occurrences and the damages the landslide is causing to human life and property, the attention given to study the problem is not proportional. However, some basic studies have been conducted that has to be appreciated.

Although some basic informative works have been done, there are also known damaging and threatening landslide areas that are not studied by the researchers. Haro village and its surrounding is one of such untouched area which belongs to the highlands with average altitude of 2500m and known with a variety of landslide occurrences and hazards in the recent past. For this reason, the present study was intended to carry out the landslide problems in the study area by identifying the research problem as “Evaluation of Factors Responsible for the Landslide in Haro Village and its surrounding.

1.2 Definition of some key Hazard terms

Hazard (H) The word 'hazard' is derived from the Arabic word for 'a die' and is often related to 'chance or probability'. In general, Hazard means the probability of occurrence within a specified period and within a given area of a potentially damaging phenomenon.

Hazard factors: are those conditions from the past (e.g. geology), present (e.g. slope angle) and future (e.g. forecast rainfall) which determine either individually or in combination with other factors as the potential for a landslide event to occur.

Hazard Zonation: the term zonation applies in a general sense to divide the land surface into areas and the ranking of these areas according to degrees of actual or potential hazard from landslides or other mass movements on slopes.

Landslide susceptibility maps: depict areas that have the potential for landsliding. These areas are determined by correlating some of the principal factors that contribute to landsliding, such as steep slopes, weak geologic units that lose strength when saturated, and poorly drained rock or soil, with the past distribution of landslides.

Landslide hazard maps: hazard maps show the aerial extent of threatening processes where landslide processes have occurred in the past, where they are occurring now, and the likelihood in various areas that a landslide will occur in the future.

1.3 Location and Accessibility of the study area

The present study area is located in Northern central Ethiopia, North Shoa Zone of Oromia administrative Region, Hidabu Abote District. It is found within the

Geographical location of 9°55'00" to 9°59'4"N and 38°22'8" to 38°27'6"E and falls in the Gebre-Guracha top sheet N₀ 0938A₂, edited in 1982. The study area forms a part of the Abay basin from the northwest, Jema River valley from the North and Selale highlands from east and south with the total area of about 50km² (Figure 1.4).

The present study area is about 171kms from Addis Ababa to the north. It is accessed by vehicle 135km on main asphalt road from Addis Ababa to Genda-Shano and 16km on gravel road from Genda-Shano to Ejere town. About 20km from Ejere to the study area is accessed on foot that needs more than four hours. Accessing to many localities within the study area is difficult because of the undulating and rugged topography.

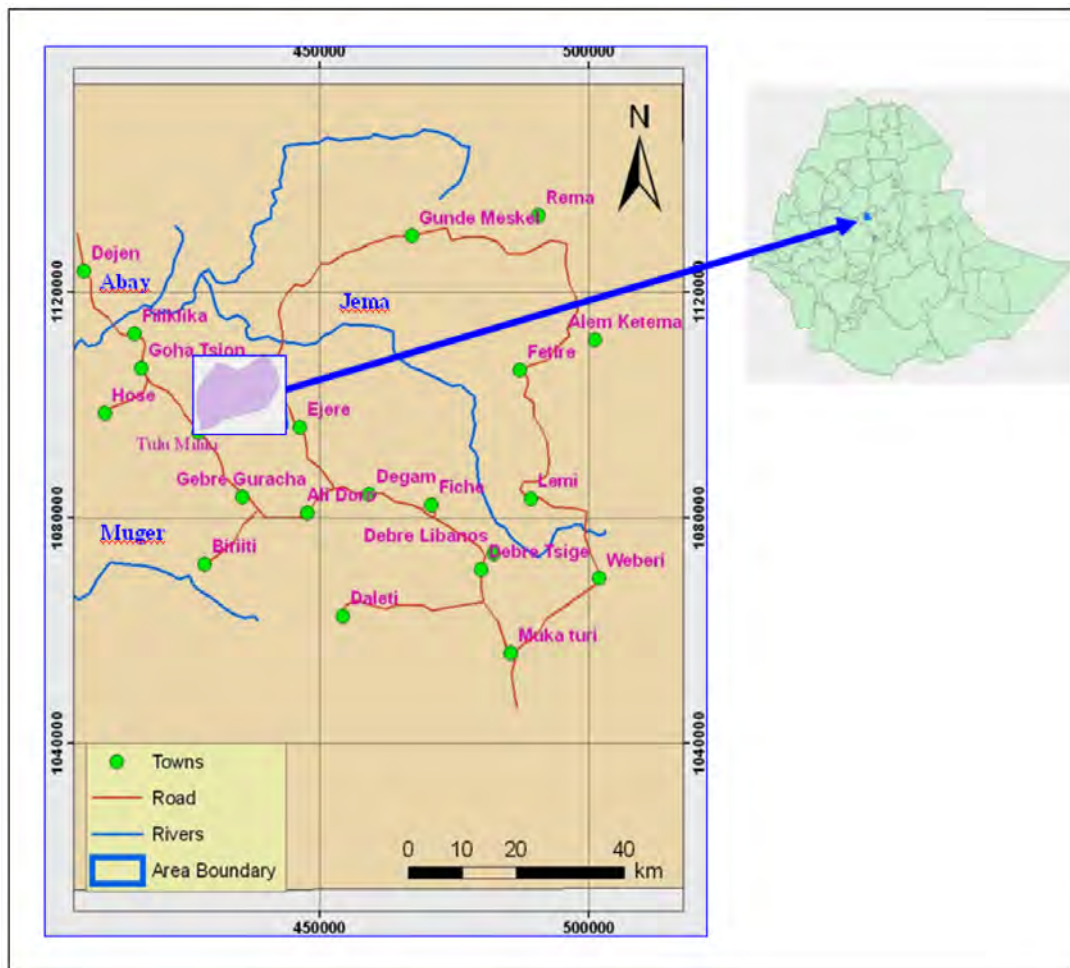


Fig. 1.1 Location map of the study area

1.4 Factors responsible for Landslides in the study area

Geologic, Topographic, Climatic conditions and human activities are some of the most important factors that have caused the landslides in the study area. The following paragraphs discuss and summarize the landslide forms by categorizing them into different types.

Most of the landslides in the area are characterized by shallow and deep seated process with different characteristics of slope materials. The slope materials include weathered, heterogeneous rocks and soil sediments. These landslides are defined as being of four types: falls, topples, slides and recent flows. Continuously moving rock fragment deposits comprise basalts on upper slopes; limestone & sandstone on the middle and lower slopes with different sizes and with angular, semi-angular and rounded in shapes.

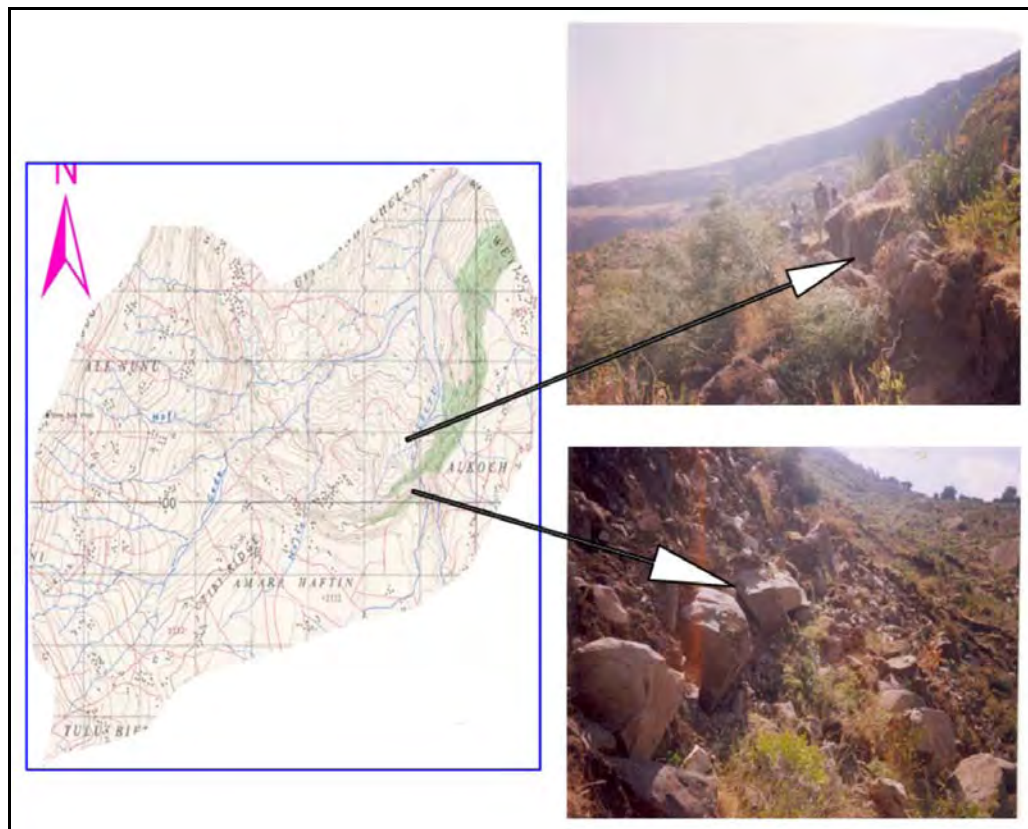


Fig. 1.2 Most of the study area shows such kind of instabilities

Rock toppling and falling: Shallow topples and falls consisting of individual rock blocks become detached from a steep slope and descending by falling or rolling and coming to rest on gentler slopes in the village. Where these occur frequently, the

bedrock is usually moderately to highly fracture with parallel and intersecting discontinuities with slopes. Toppling and falling of rocks vary in size mostly as a single block, by fracturing and often occur rapidly without warning.

Rock block slides: These are generally associated with rock types of different strengths that fail along pre-existing surfaces. They are observed on slopes where competent and relatively less competent rocks are in contact, which vary in size from very small (millimeters) to large blocks, involving one or several blocks of rocks.

Debris slides: debris slides in the area are the recent phenomena and common on steep slopes especially during the periods of intense rainfall. They tend to be deep failures and occur along planes of weakness between looser, overlying colluvial soils and highly weathered rocks. Recently, these have started to move rapidly on steep slopes and slowly on gentle slopes then become developing into debris flows very near to the villages.



Fig. 1.3 Sample view of rock toppling and falling in the study area

Debris flows: debris flows are also newly occurring phenomena on open slopes and in pre-existing falls and slides, which are predominantly loose, heterogeneous and initiated by tension cracks at the start of the failure. As these are newly creating

and moving slowly from the initiation zone, debris flows are not common until now. However, their future occurrence may become hazardous to the village.

It can be summarized that the main causes aggravating these types of instability problem in the area are; the presence of columnar jointed basalts, Jointing of rocks, the highly barren and exposed materials on steep slopes, the presence of marl and shale within the limestone and gypsum. In addition, the prolonged rainfall during rainy season accompanied with a high gravitational component, up to 80° slope angle, accelerates the movement of the loose materials.



Fig. 1.4 Recent debris slides and flows in the study area

1.5 Landslide History, problems and impacts in the study area

The pre-existence of landslides is often considered to be a good predictor of future instability. This section traces some of the past conditions of the landslide events and its impacts in the study area that brings observation up to the present-day.

The study area is part of the Abay and Jema river Basins having a long time history of slope instability problems in the form of almost all types of landslide movements. From the Geological instabilities prevail over large sections of the study area, it is easily observed that new landslides have been occurring on slopes that had previously failed with about 60% of the slopes being above 35° . For these processes, the Geologic conditions and structures greatly influence the landforms and active landslide processes on the study area. Therefore, it has been assessed from the field survey that inherent factors related to bedrock and rock discontinuities

provide a basis for understanding landslides and also in the formulation of long and short-term pro-active responses to natural hazards from these slope instabilities.

An extensive landslide activity of hill slopes is evident in the landscape of the study area. These evidence include: (1) a majority of steep hill slopes and fault scarps are decorated with old landslide scars; (2) eye-catching landslide landforms are preserved; (3) there are disturbed natural vegetations; (4) colluvium covered slopes are common; and (5) gravel-boulder fans along and at the mouth of Rivers represent deposits of long run-out landslides.

These features are a record of active landslide events and have developed over a long period of time that includes both pre-1982 events as well as those that have occurred since the last 25 years.

Landslides have been occurring frequently throughout the area and resulted in a number of effects. However, the cumulative direct and indirect economic losses and social impacts couldn't be quantified due to the lack of event-by-event records and undocumented damages. Even though the detailed data were absent, an estimated data gathered and listed in table 1.1 over the period of more than 25 years (1982 to 2006) suggests a measure of some economic losses and hardships of landslide disasters in the study area which caused deaths, injuries, and considerable damages to property. Most of the lands are affected by landslide phenomena, which were previously used for living, farmland, settlements, grazing and irrigation purposes. A common evident of landslide occurrences in the area were provided by the widespread occurrences of toppling, falling, sliding of rocks and presently by deep seated sliding and flowing of debris that were triggered by intense rainfall. For example, the impressive landslide in these years that claimed 7 peoples' and more than 120 livestock's, injured 6 persons, destroyed 9 houses and 6000 estimated quintals of different kinds of crop yields, abandoned 965.5 hectares of lands and that evacuated 2974 residents from the area illustrates the serious impacts of the landslides on the area (*Zonal Disaster Prevention and Preparedness Office, 1999 and 2002*). Since then life loss, injuries and property damage are continuing every time. Figure 1.1 is showing the damage of the house at the base of the slope by the rolling of rocks in 2002.

Table 1.1: Some past and recent Disastrous Landslides in the study area

Year of occurrences	Damages and/or Consequences
July, 2006	About 85 hectares of agricultural land were covered by rock slides
August, 2004	2 persons injured and 36 rendered homeless
August, 2002	4 people and more than 100 live stocks killed, 2265 estimated quintals of different kinds of crops destroyed, 1285 residents evacuated and 368 hectares of agricultural lands were damaged, 3 houses destroyed
August, 1998	307 hectares of crop lands covered by landslides, 3458 quintals of crop yields destroyed and 1194 residents displaced
August, 1996	206.5 hectares of crop lands covered by landslides, 221.5 quintals of crop yields destroyed and 912 house holds displaced
August, 1995	22 cattle and 3 persons were killed and 5 injured, houses damaged, and crop lands abandoned.
August, 1993	2 persons injured and over 6 houses destroyed
August, 1992	Occurred but unnoticed
July, 1993	Living conditions disrupted due to evacuation
June, 1992	Streams used for irrigation were buried
1991	Widespread landslide caused damage to life and property
1989	Farmlands abandoned, crop yields destroyed
1985	Occurred in two areas but has no consequences
1982	Occurred but unnoticed

Though the Landslide in the area occurred several times and resulted in such consequences and still threatening, the only response to this problem is to rehabilitate the villagers to other places. However, this reaction shouldn't be the sustainable solution for its prevention or mitigation. This is because the occurrences of the landslides in the area are more increasing but the villagers are not volunteers to leave this hazardous area and returned to the place even from far after they have been rehabilitated and they become vulnerable to the events again and again.



Fig. 1.5 A house damaged by the rolling of rocks in 2002

Generally, the present landslide situation in the area is such a threatening that it may become again a devastating event. In addition, although the occurrences of the landslides are such a damaging event, no individual or institution tried to conduct a research study for the area. Therefore, from these practical concerns and unstudied reasons, the present research problem is identified and a considerable emphasis is given to investigate and identify the major causative factors responsible for the occurrences of such landslides in order to produce a relative hazard zonation mapping.

1.6 The Climate of the Area

Monitoring the variability of climate that is responsible for the coming effect on an area needs the knowledge of the climatology of that area. This means knowing the long-term mean values of climatic parameters such as temperature, rainfall, etc. and their degree of variability or deviation from the mean is very important.

The climate of Ethiopia is generally characterized by different seasons. However, those that attributed to the study area and its surrounding is characterized by three climatic zones located at the altitude of 1350-2500 meters above sea level and locally known as;

Beda (Temperate): 2200 to 2500m a.s.l. with mean annual temperature of 6⁰c to 10⁰C

Beda-Dare (Sub-tropical): 1600 to 2200m a.s.l. with mean annual temperature of 10⁰c to 15⁰C

Gamoji (Tropical): 1350 to 1600m a.s.l. with a hot mean annual temperature up to 25⁰C.

For the interpretation of the climatic condition in the study area, data from National Meteorological Service Agency of Ethiopia, at Fitcha Station, was referenced for twenty years (1985-2004).

Temperature: The analysis of this data reveals that the daily average temperature varies between 7.0⁰C to 25.0⁰C and the annual average temperature ranges between 6.0⁰C to 23.0⁰C with a maximum daily temperature variation recorded during the low rainy season from December to May.

Rainfall: Rainfall is one of the most important factors in triggering landslide conditions. The consideration of this factor was based on the assumption that wet conditions are more likely to occur at areas of higher mean areal rainfall. The rainfall of the study area is characterized mostly by one long rainy season that last from June to September.

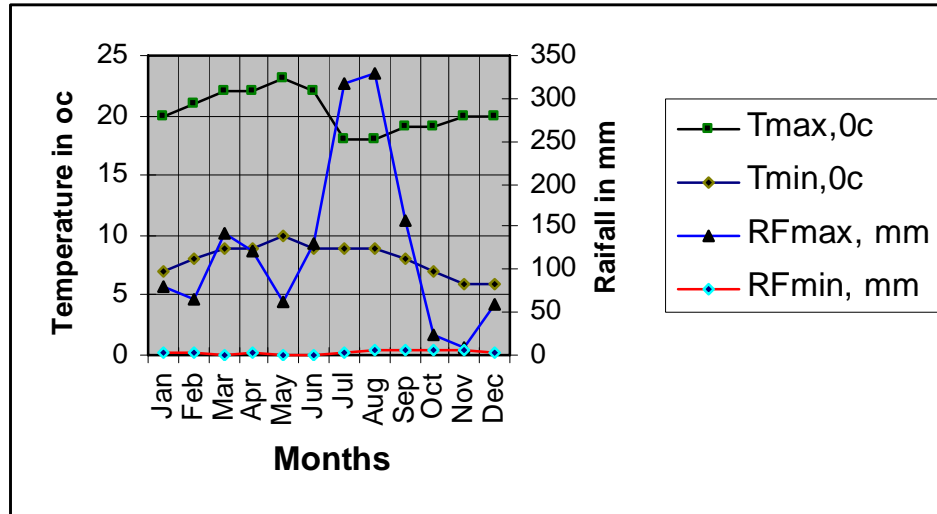


Fig. 1.6 Graph showing the mean monthly maximum and minimum Rainfall and Temperature of the study area

The Fitch rain guage station, approximately measured indicates that the average annual rainfall in a period of 20 years varies between 980 and 1530mm with maximum in 1996. The highest average monthly rainfall value of 330mm is mostly in August and the average minimum monthly rainfall of even less than 6mm was recorded in the month of November over the 20 years (table 1.2). The average annual number of rainy days varies from 93 to 126 days per year. In this period, heavy intermittent rains, lasting from few minutes to several hours even the whole day is common.

The average monthly rainfall (RF, mm), the average monthly maximum rainfall (RF_{max} , mm), the average monthly minimum rainfall (RF_{min} , mm), the mean monthly maximum temperature (T_{max} , 0c), the mean minimum monthly temperature (T_{min} , 0c) and the average monthly number of rainy days (RF_{days}) for the 20 years are indicated in table 1.2 and Fig. 1.6

Table 1.2: Mean monthly Meteorological data (1985-2004)

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T _{max} , °C	20	21	22	22	23	22	18	18	19	19	20	20
T _{min} , °C	7	8	9	9	10	9	9	9	8	7	6	6
RF, mm	23	34	68	74	47	85	193	178	113	14	10	14
RF _{max} , mm	80	66	143	123	61	131	316	330	156	23	10	58
RF _{min} , mm	4	2	1	2	1	1	2	7	6	7	6	4
RF _{days} , mm	3	3	9	11	6	14	23	25	15	2	1	1

1.7 Earthquake Activity (Siesmicity) of the area

Earthquake is a natural hazard resulting from seismic waves that may damage natural and man made structures around the epicenter. For this reason, the areas of interest are usually tried to identify such natural hazard.

In earthquake-prone area, information will undoubtedly exist on past earthquakes and associated seismic hazards. This can be supplemented with existing geologic, geophysical information and field observation. Depending on geologic conditions, some combination of ground shaking, surface faulting, landslides, liquefaction subsidence, flooding, etc. may be the most serious potential earthquake-related in the area. Therefore, maps should be prepared showing zones of these hazards according to their relative severity. This is because these maps provide the planner with data on such consideration as the spatial application of protection methods.

The seismic zone of Ethiopia have been delineated by Gouin (1979) and later updated by Laike Mariam Asfaw (1986). The seismic risk map has been produced for the probable return period destructive earthquake.

The present study area is within the influence area of the SER earthquake source (based on the attenuation relation). Hence, the effect of dynamic loading on the stability of the site has been considered in this study. The “Seismic risk map” produced for a hundred year return period and 0.99 probability shows that the study area falls within 5 MM scale. Thus the same value has been utilized for the stability analysis of the slopes in the study area. The map showing the seismic Risk zones of Ethiopia and the location of the project area is presented in fig. 1.7.

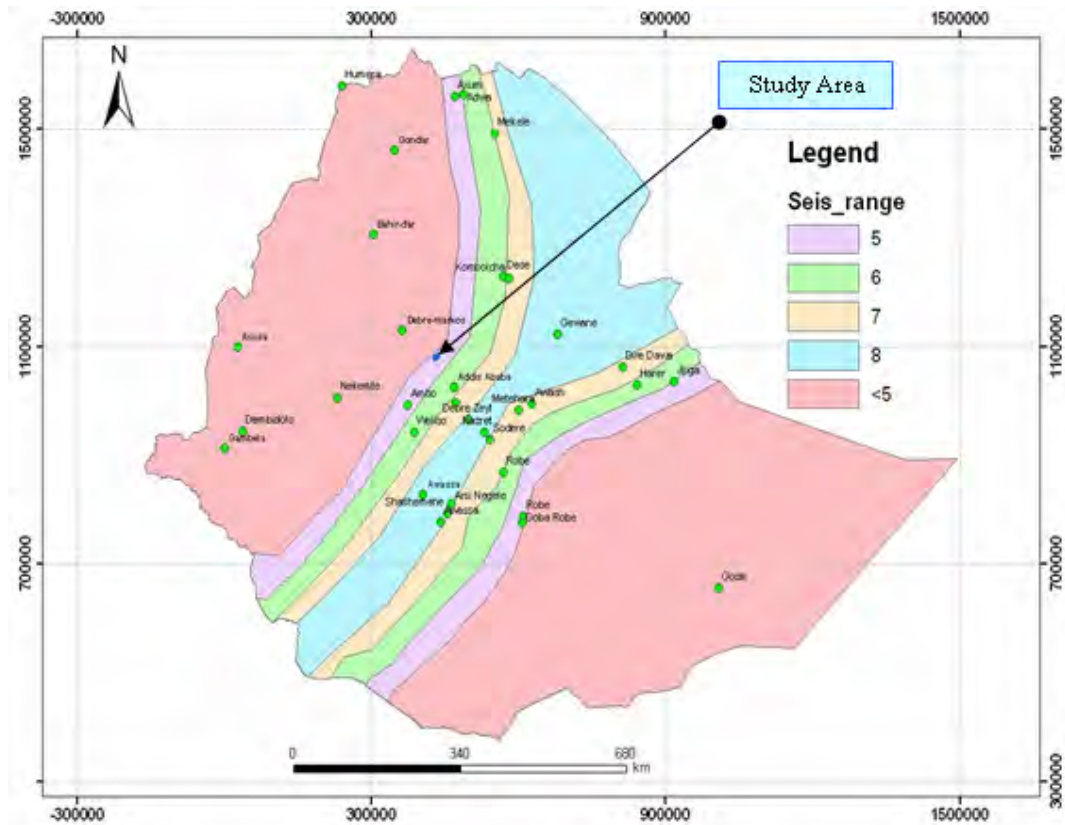


Fig. 1.7 Seismic Map of Ethiopia 100 year return period, 0.99 probability (After Laike Mariam Asfaw, 1986)

1.8 The Objectives of the study

1.8.1 General objective

The general objective of the present study is to evaluate the major factors for the cause of the landslide in the study area and to produce the landslide Hazard Zonation map by applying the Landslide Hazard Evaluation Factors (LHEF) rating scheme.

1.8.2 Specific objectives

The present study was aimed to achieve the following specific objectives.

- To evaluate and identify the major causative factors responsible for the landslide in the area by using the LHEF rating scheme facet wise.
- To rate and produce maps for the major causative factors.
- To produce landslide Hazard Zonation map based on major causative factors analyzed from the total estimated hazard ratings.

- To carry out Engineering Geological properties of rocks and soils for the study area and to provide a base line data for detail slope stability analysis
- To suggest some slope stabilization methods and remedial measures for the area.

1.9 Methodology

The following materials and methods have been employed to achieve the objectives of the present study.

- Preliminary reconnaissance of the area to have information on the topographic features, availability of information, accessibility and workability in the area.

Main data and data sources

- Regional and Zonal Disaster & Preparedness Offices, from which basic information data has been obtained for the initiation of the study.
- Ethiopian Geological Survey, from where the regional Geological map and geological description was acquired and processed.
- Ethiopian mapping Agency to procure the topographic map of the study area.
- Ethiopian Meteorological Service Agency-the source of meteorological data.
- Satellite images, the source of information on slope angle, elevation data and land use land cover of the study area.
- Books, Journals, reports, published & unpublished Theses, Internet resources and Interviews
- In-situ tests, measurements and representative samples

Methods

- Review of the literature pertaining to the objectives of the study
- Materials and data mentioned above were collected and reviewed for interpretation
- Interviews and discussions have been made with the villagers and concerned officials to have a background information of the area and landslide problems of the areas
- In-situ tests and measurements have been conducted for the proposed parameters facet wise

- Representative rock and soil samples were collected from the slopes that are identified as potentially unstables
- Delineation and creation base maps of the study area from topographic and Geological maps to carryout field mapping
- After the background work as desk study has completed, additional actual data were collected and mapped from the field to fill the gap between the available existing data on the map and the present data in study area using GPS onto the base maps, including taking photographs
- Evaluation and determination the ratings of the main causative factors on each facet from the field data collections and maps by using the LHEF rating scheme
- Generation of the main contributive factor maps for the area with the use GIS techniques
- preparing a Landslide Hazard Map which comprises the information of the relative susceptibility of the area to landslides
- Evaluations of some general Engineering Geological properties of the representative rock and soil samples and interpretations were made from unstable slopes in the laboratory for future slope stability analyses
- Suggesting the detail slope stability studies and some slope stabilization and/or remedial measures
- Based on the results, conclusion and recommendations have bee drawn

1.10 Importance and justification of the study

The study area is highly rugged and unstable where the landslides are frequently occurring and the population density in the area is relatively high. As discussed in the previous sections, the landslide phenomena have resulted in a number of live loss, property damage and repetitive rehabilitation of people. In addition to these effects and as will be pointed out in chapter four, the landslide activity in the area will be a future threatening for living and the existing land use and also become advancing to the road that connects Addis Ababa - Fitcha - Ejere - Gundomeskel.

Having the above facts in mind, the present study was planned to provide information on the relative landslide hazard zones of the area and to pave a base line for further study such as on slope stability analysis and possible remedial

measures. Because Landslide hazard maps can be used to identify different levels of risks due to landslides, which in turn facilitates implementation of appropriate loss reduction strategies for both existing and future development.

Although prediction of absolute landslide hazard is difficult, citizens, planners, engineers and developers can use the landslide hazard Zonation maps as a tool to reduce losses from existing and future landslides through prevention, mitigation and/or avoidance. The map can also be used to identify areas where detailed geologic-geotechnical investigations are desirable prior to the developmental activities. Therefore, if the area is studied and the relative landslide hazard zones will be identified, it may be helpful for the above mentioned uses.

1.11 Limitations of the Study

The present study has been attempted with all possible efforts in acquiring required inputs in the form of secondary and actual field data collection, analysis and technical interpretations. However, the study has encountered certain limitations, which are highlighted in the following paragraphs.

Shortage and absence of related literatures

As pointed out earlier, the occurrences and the effects of the landslides in the present study area have a long time history, but there is no written documentation except some information compiled as notes and there are only rudimentary reports by local officials during the time of the events. Moreover, no individual or institution tried to conduct a research study in the area. For this reason, an insufficient information and lack of documents was a major limitation for successful study in the study.

Limitations from Use of existing data

These limitations may be addressed as to the possible non-correspondence between the Geological and geomorphic maps available and the actual material properties and physical processes responsible for landslide at present. That is what is present on the existing topographic maps couldn't be coincide with the present situation in the area. For example, there are no recent toposheets and satellite images available for the present study. Therefore, to include additional information

on the maps was a problem, which is time-consuming, expensive and needs more experience.

Remoteness and problem of access

Access is a good learning experience. In geology, it is not enough to simply come up with a good idea and desire to study the problem. If access is not possible whether due to no roads, impassable roads, or remoteness, the study may not be a success. Some of the accessibility and/or workability problems in the study area were;

- The study area is about 20kms far from motorable road, which takes more than four hours to reach on foot. So traveling such long distance on foot carrying all the required samples and equipment was a difficult task.
- It was necessary that the study need samples from steep, elevated scarp slopes. But, it was difficult to hike and collect samples from each of such areas.

1.12 Proposed Outcome of the Study

The outcome of this present study may contribute to the understanding of the Landslide conditions of the area. The Landslide Hazard Zonation map prepared for the area will help to conduct further study on the detailed slope stability analyses on the slope that area identified as moderate, high and very high hazard zones. It will also help in adopting proper remedial measures in these zones.

In addition;

- The responsible local, regional and national governments have not yet given much attention to the event. Thus, it may be beneficial to them in order to take appropriate care in using the land based on the information obtained from the study.
- It may change believes and assumptions of the community that culturally and theoretically said about the landslide events in the area by providing them awareness instead to tackle against the event.

- It may also helps for similar studies in the adjacent areas and other regions, which possess the same geological setting and causative factors.

CHAPTER II

LANDSLIDE HAZARD EVALUATIONS

2.1 Preamble

While the process and the exact mechanism of landslide initiation are difficult to be well understood due to mutual interaction of various factors, previous studies combining field observations, statistical analysis and GIS techniques have shown that several factors were found to have significant influence on slope stability (Lee & Min 2001).

The most widely used classification scheme divides landslides into different types according to the material being moved and type of movement (Varnes, 1978). Recognizing these landslide fundamentals in an area helps explain how and where factors have contributed to natural slope instability in the past.

Factors inducing these slope terrain instabilities can be divided into two sets, permanent and variable (Sharpe, 1938). *Permanent factors* are characteristics of the landscape, which remain unchanged or vary little from a human perspective. The steepness of a slope or the type of rock, for example, presents changes only with the passage of long periods of time. These can be recognized and identified for specific landslides long after their occurrence. By examining existing landslides in an area, it is possible to recognize how permanent factors contributed to these slope failures. Identifying conditions and processes promoting past instability makes it possible to use these factors to estimate present and future landslides.

Variable factors are landscape characteristics that change quickly as a result of some triggering events. Ground vibration due to earthquakes, a rapid rise in groundwater levels, and increased soil moisture due to intense precipitation are examples of variable factors. They often assessed at the time of landslide occurrence or shortly thereafter. Due to the lack of long-term historic records relating landslide activity of these initiating factors, only permanent factors are usually used to estimate landslide hazard. In general, identifying landslide areas is not as such an accurate science but depicting hazard-prone areas is based on estimation.

Moreover, landslide and landslide susceptible areas can be identified along with expected triggering events.

Without considering these factors and their impacts, it is difficult to plan to use a given area for development or for other purposes. Assessing it for its future stability is of crucial importance for which the objectives of the study are intended. Therefore, for the achievement of these objectives, first understanding the geological setup of the area, second evaluating each of the individual factors for the cause of the landslide, third classifying the terrain and preparing hazard maps by rating the combination of each of the factors, fourth, studying the engineering geological properties, and finally, analyzing the stability conditions, based on the degree of the susceptibility for possible remedial measures, should be conducted.

2.2 Previous works on landslides in Ethiopia

Many researchers tried to assess Landslide occurrences and consequences in different parts of the country, especially, in the highlands with an altitude of more than 1750m and where landslides frequently occurring (Ayalew L., 1999).

Ayalew has conducted a study on the effect of seasonal rainfall on landslides in the highlands of Ethiopia. In his study, he tried to elaborate the relation between the mechanism of landslide and rainfall and suggested an empirical relationship that could help in assessing the problems of instability. He has also studied the causes and mechanisms of slope instability in Dessie town. In this work, he examined the relationship between slope instability and seasonal rainfall in the area. By taking the variation in moisture content of soil, the rate of daily precipitation, the amount of cumulative precipitation and mean annual rainfall as variable, he derived a simple equation that is useful to determine the likelihood of landslide activity in the area.

There are also a few landslide studies that have been conducted in the southern part of the country where the study area belongs. Berhanu Temesgen, et al, (1999 and 2001) worked on different landslide dynamics using remote sensing and GIS techniques in Dabicho ridge and around Wondo-genet area.

A systematic regional geological study and mapping has been undertaken in Northern central Ethiopia, especially around the Abay Gorge by Ethiopian

Geological survey (EGS) in 1986 and 1993 that has investigated the landslide problem occurred along the newly constructed road after the damaging of the viaduct. The EGS crew also investigated the susceptible and problematic area through Geophysical studies, Serawit Amene and Tamirat Mojo (1996).

A group of geologists from EGS in 1993 has investigated this area through drilling and test pit. Accordingly, five bore holes were drilled and about nine test pits excavated to identify the overburden material thickness, the depth to the bedrock at different locations and to formulate the geotechnical description of the subsurface geology. The borehole logging revealed that, on average, the top 20 meters thick overburden is described to be a mixture of gravel to cobble size basaltic rock fragments and fine materials such as sand, silt and clay including black cotton soils. Moreover, the test pit loggings indicated that at most locations black cotton rich soil is present.

Concerning the landslide study in the present study area, the intermittent occurrences of the landslides and the constant land mass movements were observed and reported by the residents and local government. However, systematic and well-recorded data for the landslide and geological hazards in the area was not available. The report mentioned only a rudimentary data that have been compiled by the committee regarding the overview of geological information and the impacts that the landslides address, but not the core causes of the instabilities.

2.3 Landslide Hazard Evaluations

There are several different methods/approaches that have been proposed for evaluating landslide hazards for mapping susceptibility to landslide activity, which have their own strengths and drawbacks. For example, some of the methods developed and practiced are:

- Heuristic method: Anbalagan, 1992; Pachauri & Pant, 1992
- Statistical method: Gupta et al, 2000; Siddle et al, 1991
- LHEF rating scheme: Anbalagan, 1992
- Geographical resources analysis support system (GRASS): Neteler and Mitasova, 2002).

Heuristic approaches involve 'if-then' rules to estimate landslide potential from data on intrinsic properties (independent variables) only. One does not require data on landslides since it is assumed that the relations between susceptibility to landslide activity and the independent variables are known and are specified in the model. However, the problem with this approach is that since the model used to combine different factors is derived from experience, the choice of coefficients may be seen as somewhat arbitrary. This is the reason why most researchers have adopted other approaches.

A statistical approach replaced with the presence or absence of landslides and a set of independent variables may be constructed based on sample data. Simple statistical techniques have been used widely in indirect mapping of susceptibility to landslide activity. However, few researchers have used fully multivariate statistical approaches. However, this method requires an advanced experience and specialties, (Siddle et al, 1991).

Studying the landslides using GRASS has been undertaken by using deterministic technique to evaluate the landslide susceptibility. It was concluded that GRASS GIS environment is an ideal tool, not only for its "price performance ratio" but also for its capability that is on equivalence with other commercial software. However, this study did not mention anything on the status of the user-friendliness of the software, (Neteler M. and Mitasova H., 2002)

Although all these approaches use different GIS computer software, the advantage of using the LHEF rating scheme is that the data collection process is less intensive, user-friendly and can be understood by a non-specialist without more intensive application of computer, even though, in some cases, it has lower accuracy compared to the others. Moreover, considering the above limitations for stability studies, LHEF scheme is selected for this study because of its advantage to handle different causative factors for evaluation of landslide hazard, easily and quickly. LHEF scheme can also cover large area of study by considering the most important geological factors and rating them based on those factors according to the influences they have on the landslide occurrences.

2.4 Landslide Hazard Evaluation factors (LHEF) Rating Schemes

The Landside Hazard Evaluation factors (LHEF) rating scheme is a numerical system which is based on major inherent causative factors of slope instability such as geology, slope morphology, relative relief, soil cover depth, land use and land cover, ground water, conditions, fault distance and others (Anbalagan, 1992). The LHEF rating scheme is based on empirical approach, which combine as past experience gained from the study of causative factors and their impact on the occurrence of the landside that anticipated in the study area. But the triggering factors or the external stimuli that initiate the movement of a landslide such as rainfall, change in ground water levels, earthquake, volcanic activities, stream erosion, snowmelt etc are not included for the purpose of landside hazard Evaluation (Lee & Min 2001).

Different researchers apply different schemes based on different causative factors, both natural and man-made. In this case, the hazard or failure zones identification schemes have been developing for over several years since Ritter, 1879 who attempted to formalize and used empirical approach to tunnel design. Different classification schemes due to engineering geological problems place different emphases on the various parameters. Most of the multi-parameters classification schemes were developed from civil engineering case histories in which all of the components of the engineering geological character of rock mass were included. Summaries of some important classification systems are presented as follows.

Terzaghi, 1946: the earliest reference to the use of rock mass classification for the design of tunnel support on the basis of a descriptive classification; *Deere et al, 1967*: introduced Rock Quality Designation index (RQD); *Wickham et al, 1972*: Rock Structure Rating (RSR); *Bieniawski, 1976*: produced a rock mass classification system called the Geo-mechanics classification or the Rock Mass Rating (RMR) system and modified this classification system in 1989; *Barton et al, 1974*: Rock Tunneling Quality Index (Q), on the basis of an evaluation of a large number of case histories of underground excavations; *Romana, 1985*: introduced slope Mass Rating (SMR) applying Beniaowski's, 1989 Rock mass Rating (RMR). The Romana's SMR technique was later modified by Anbalagan et al., 1991.

The two most widely used rock mass classifications are Bieniawski's RMR (1976, 1989) and Barton et al's Q (1974). Both methods incorporate geological, geometric and Design/ engineering parameters in arriving at a quantitative value of their rock mass quality. RMR uses compressive strength directly while Q only considers strength as it relates to in situ stress in competent rock. Both schemes deal with the geology and geometry of the rock mass, but in slightly different ways. Both consider groundwater and both include some component of rock material strength, (Engdawork Mulatu, 2005).

2.5 Methodology for LHEF Rating Scheme

The landslide hazard Zonation (LHZ) mapping is a macro Zonation approach showing the probability of landslide hazards. The LHZ mapping comprises mainly two components; desk study and field investigation. The desk study consists of preparation of profiled maps showing the status of causative factors in the study area with the help of satellite imageries, topographic maps, geological maps, etc. During the present research study, the profile maps such as Geological, slope morphometry, relative relief, and land use land cover maps were first prepared. Then the information collected from this desk study helps to plan and execute the field investigation systematically.

The field studies were carried out to collect the required actual data, preferably facet-wise, to estimate the total hazards on each facet. A facet is a part of hill slope, which has more or less similar characteristics of slope showing consistent slope direction and inclination. The facet boundaries are ridges, spurs, streams and rivers. The facet map is the base map for the LHEF scheme. During the field study, more detailed lithological, structural, slope morphometry, relative relief, rock outcrop, soil cover and land use land cover data were investigated and mapped on the base maps. Further, the desk study was verified in the field and modified wherever, felt necessary.

Thus, for the present study, using the data collected, the facet map was prepared. From each facet, the identified major causative factors were evaluated and rated by LHEF scheme. After rating the factors and generating their factor maps, the total estimated hazard rating was utilized for hazard Zonation mapping.

2.6 Landslide Hazard Zonation mapping

Assessing landslide hazard is the objective of the method to produce a relative landslide hazard map that used to provides one with a practical and cost-effective way to make further studies and various engineering constructions for the mitigation of the landslide occurrences in the future.

The term Landslide Hazard Zonation applies, in a general sense, to divide the land surface into discrete zones and rank them according to the degrees of actual or potential hazard from a landslide or slope instability based on an estimated significance of causative factors in inducing that instability, (Varnes 1984). According to him, all landslide hazard Zonation studies carried out relies on three fundamental assumptions. (a) The slope failures in future will most likely be in similar terrain conditions that have led to past and present failures. (b) The main conditions that cause landslide activity should be evaluated and identified. (c) A summary of the degree of potential hazard in area can be built up, depending on the factors present in inducing the landslides, their severity and their interaction. However, the overall accuracy of Landslide Hazard Zonation mapping for discrete areas still remains unevaluated and it is only rarely possible to predict the exact location and time of a probable landslide.

Engineers, earth scientists, and planners are interested in assessment of landslide susceptibility and/or hazard because of two purposes (Siddle et. Al. 1991): (1) the landslide hazard maps identify and delineate unstable hazard-prone areas, so that environmental regeneration programs can be initiated adopting suitable mitigation measures. (2) These maps help planners to choose favorable locations for siting development schemes such as building and road construction. Even if the hazardous areas cannot be avoided altogether, their recognition in the initial stages of planning may help to adopt suitable precautionary measures.

CHAPTER III

PHYSIOGRAPHY AND GEOLOGICAL SETTING

3.1 General

Sedimentary rocks, unconformably overlying the Precambrian basement, are exposed in the Central Ethiopia, including the Abay River valley and its surrounding tributaries. According to Kazmin's Geological map of Ethiopia (1972), these sediments are roughly exposed between latitude 9⁰10' to 10⁰30'N and Longitude 37⁰00' to 39⁰00'E covering about 40,000km² within which the present study area is found. These sedimentary rocks comprise the upper Paleozoic channel filling sandstone, siltstone and shale unconformably overlain by upper Triassic sandstone followed by Jurassic to Lower Cretaceous Clay, Gypsum, Limestone and Sandstone about more than 200m thick. It has been also assessed by Kazmin that Flood Basalts of Tertiary age unconformably overlie these sediments.

In these areas, a geological study was carried out and the upper Triassic to lower Cretaceous sediments were encountered and described for the first time in 1886. As quoted by Serawit Amene and Tamirat Mojo, (1996) from Geological Survey of Ethiopia, a pioneer French geologist, Aubry (1886), described the stratigraphy from Ejere-to-Jema-to-Gundomeskel. He classified the areal sediments into three groups: 500m of basal sandstone, followed by 200m limestone & gypsum and 500m of argillaceous limestone overlain by 300m of volcanic pile.

However, Kazmin (1972), in his compilation work on the Geological Map of Ethiopian, classified this regional sediment into five-channel filling Paleozoic sediments: Goha-Tsion Formation, Adigrat sandstone, Abay bed/strata, Antalo limestone and Amba Aradom sandstone.

Getaneh Asseffa, 1980 has extensively studied the Mesozoic sediments in the Abay River and its tributaries and he called it Goha-Tsion formation. The previous researchers considered this formation as a bed or strata. However, from the modern stratigraphical nomenclature point of view and its lithologic association (gypsum, shale and limestone with intercalation of dolomite), Getaneh's naming is more logical (Serawit Amene and Tamirat Mojo, 1996).

However, elaborate references were tried for this wide regional area to find a detail geological studies still the detail study couldn't be found. Therefore, it needs some more detailed studies at particular selected sites, as in the case of the present study area.

3.2 Physiography of the area

The present physiographical setting of the study area is a result of various processes. Besides, the uplifting which is believed to be responsible for the formation of the landscape, erosional leveling, weathering and mass wasting have played a major role in creating the present landform. The topographic surface of the area is irregular, with many cliffs, crests and spurs alternating with steep and gentle slopes.

The study area is made up of stratified sedimentary rocks overlain by basaltic plateau and characterized by a relatively deep valley and low elevation when compared to the Selale highlands. The area is bounded with a continuous mountain chain surrounding the Haro village in all directions. The common landforms that characterize the area are steep cliffs, gently slope, ridges, escarpments, erosion cut, seasonal rivers, intermittent streams, valleys etc. The total relief is 1140m, and the greatest local relief 500m, occurs along Aleltu and Horte rivers. The main rivers: Aleltu, which drained to the study area from south-east; Horte, drained into the study from south; and Gede & Hofi from south-west are those which responsible for a relatively deep and wide valleys. Generally, the following physiographic features are prevailed in the area.

3.2.1 Landforms

All controlling factors like slope, relative relief, thickness of overburden etc. varies with the landform and its stage of development in the area. Depending on their origin, the following main landforms can easily be identified, even though the area is largely rugged and undulating.

Plateau zone: this unit lies in two places; the first one is located at about elevation of 2100-2500m in the East, South and East-west of the study area. The unit is identified by almost flat terrain formed by mostly residual black cotton soils with

vesicular basalts over the Mesozoic sediments. The flatness of the surface of this plateau is related to the original horizontal setting of the residual soil used for agricultural land.

The second one is a small unit in the center of the study area bounded by small mountain chain and steep cliffs where Haro village is located at an elevation of 1800m. About 95% of this area was used for living and agricultural purposes. However, recently this unit is becoming functionless due to the long-term mass movements from the nearby slopes and is covered by the transported volcanic and sedimentary deposits.

Escarp Zone: this unit is characterized by very steep like morphology i.e., ridges and cliffs alternating with gently sloping lands. It is formed by successive layers of vesicular basaltic materials at the top part and sedimentary strata at the middle and the bottom part. Rock boulders and fragments detached from this and accumulated on the lower flat terrain in the village. Such landform is prominent from Alkoch ridge towards the northwest from the east of the study area along Aleltu River and from Tibi ridge towards the north along Horte and Hofi rivers. Most of the landslide problems are associated with this unit.

It was recognized from field verification that most of the study area has generally very low vegetation cover. Moreover, denudated lands and the scarp zones are without vegetation cover except very small-dispersed bushes. Therefore, the rocks and soils covering the slope face are highly exposed to weathering conditions, which make the slope susceptible to the landslide occurrences. Only around the Haro village and the slope face along Aleltu River are known with a relatively dense forests and grasses.

3.2.2 Vegetation cover

In the study area, very limited sections are suitable for farming. Gentle slopes, even flat terrain at the base of the slopes, are not recommended for farming due to the instabilities of the upper slopes. The dominant crops produced in the area during rainy season are sorghum, wheat, maize, teff. Vegetables and fruits produced by irrigation with small scale throughout the village are sugarcane, cabbage, bananas,

oranges, lemons, and papayas; although they have been destroyed by landslide activity.

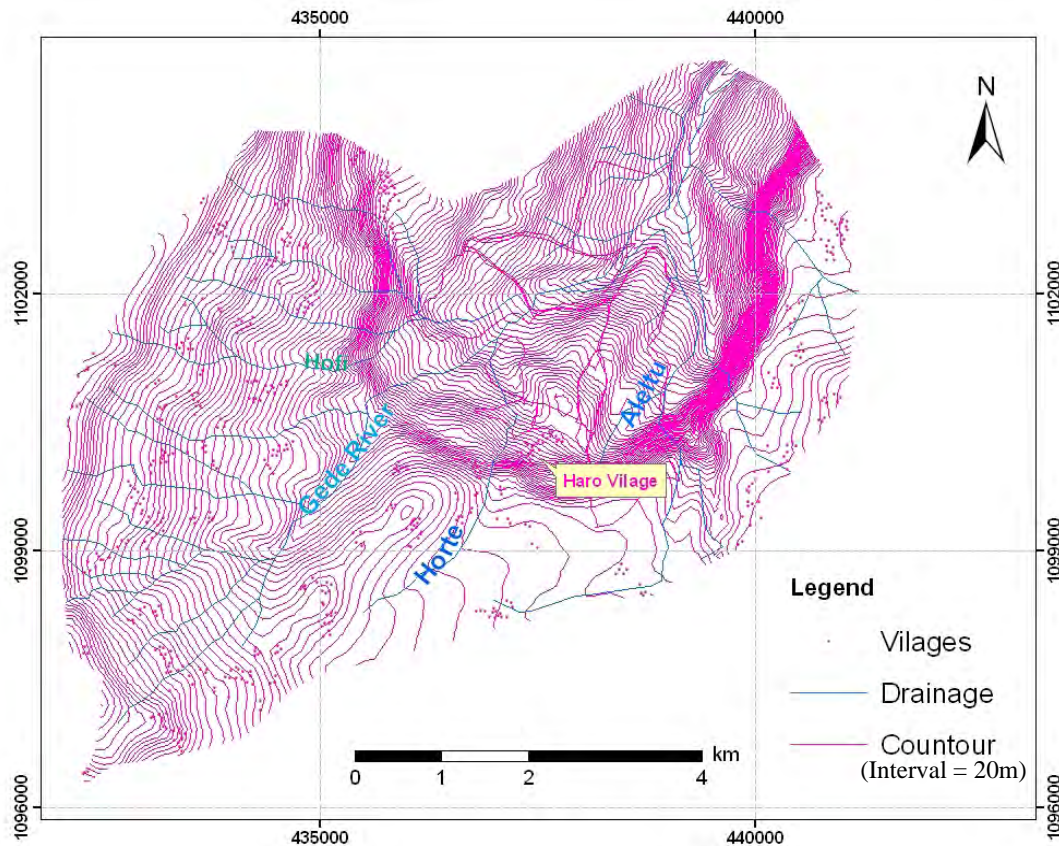


Fig. 3.1: Topographic map of the study area

3.2.3 Surface drainages

Drainage characterization is an important factor, which reflects the slope evolution of an area and an indicator of the mass wasting and related erosional aspects. Although there are many rivers and springs during rainy seasons in the study area, there is a big spring with high potential discharge and a number of small low yielding springs common at the base of the slopes throughout the year. The springs form an artificial dendritic drainage system in the village because the settlers use all the springs for irrigation purposes. As observed during the field work, this drainage system is highly responsible for cracking of the ground in cropland and under houses because the ground surfaces of the flat areas are known with weak overlying limestone. However, most of the hill faces are alternating with dry, damp and wet ground drainage conditions. The slope terrains are mostly influenced by

intermittent springs, rivers and high precipitation during rainy season. Four Rivers; Aleltu, Horte, Gede and Hofi rivers are common in study area which merge at the northern part and is one of the main tributaries of Jema River.

3.2.4 Habitation

Generally, the study area has low population density. However, the upper lands, around Amara Aftin, in the East & South and around Haro areas in the center, are relatively the populated areas. Corresponding to the west and northern side of the area, there are scattered settlements. Most other places where there are steep and unstable slopes remain relatively unoccupied. The residents in the entire area use subsistence farming being the main mode of existence. Sheep, goats and cattle are common but livestock's raring around the slope terrains, by now, is threatening because of its instability.

3.3 Regional Geological Setting

3.3.1 Geological History

There are no such drilled or sufficient geophysical studies in the mapped area, which enable to establish the history of sedimentation. In establishing the geological history of the mapped area, two studied areas were taken regionally, between which the present study area is found. One is Goha-tSION to Dejen (including Abay Gorge) in the Northwest and the other is Ejere-to-Jemma-to-Gundomeskel in the Northeast of the study area. Rabben et al.,(1980) and Beicip, (1985) in these area elaborately discussed the stratigraphic history & sedimentation of Abay River basin and its surrounding areas which are assumed to comprise a crystalline basement, paleozoic sediments, Adigrat sandstone, Goha-Tsion formation, Antalo Limestone, Amba Aradom Sandstone and Tertiary volcanic.

The deposition of these sediments is related to the transgression and regression of sea mainly consisted of limestone, gypsum, shale and sandstone (Elwerath, 1960 and Beicip, 1985). While the sea was shallower during the Middle Jurassic times, a shale-gypsum sequence of the Goha-Tsion formation with interbeds of limestone was deposited. As the sea relatively deepens, during upper Jurassic, the Antalo Limestone was deposited over a large portion of the area. The Adigrat and Amba

Aradom sandstone are mainly related to fluvial environment, which are deposited during early transgression and regression of the sea respectively.

Faulting was accompanied by widespread volcanic activity with outpouring of vast quantities of Basaltic lava, accompanied and alternating with the eruption of large amounts of Tuff and coarser fragmental material forming the trap series during tertiary times. The contact between the sedimentary and volcanic rocks is therefore unconformable, (Jemal Saed, 2005).

3.3.2 The Regional Stratigraphy

The regional Stratigraphy consists of two types of rocks: sedimentary and volcanic which ranges in age from Jurassic to Tertiary as shown in Figure 3.3. According to Rabben et al, 1980 and Beicip (1985) codes of stratigraphic nomenclature, the detailed description of Geology of the rock units outcropping from Ejere to Jema River, within which the present study area is found, are classified into five groups.

3.3.2.1 Adigrat Sandstone

In the lower Jema Valley (near Ejere), the top part of Adigrat sandstone is cropping out at the riverbed exhibiting distinct vertical lithologic variations. This type of sandstone has an exposed thickness of about 150 meters maximum and disappears under the Goha-tzion Formation (Rabben et al, 1980).

The contact between Adigrat sandstone and Goha-Tsion Formation is graded as sandstone, siltstones, shale and rare limestone alternating before the gypsum bed appears. Since, the Goha-Tsion Formation is deposited in a lagoonal environment, the gypsum bed could be a good indicator for this environment. At the riverbed of Jema, Adigrat sandstone is coarse-grained with rare intercalation of conglomerate. It is purple, becoming white to dull-white upward the section. Generally, it is fining upward the sequence with intercalation of shale, (Beciep, 1985).

3.3.2.2 Goha-Tsion Formation

This group is a complex of terrigenous and evaporitic rocks (Gypsum, mudstone, sandstone, shale and siltstone), mainly deposited in a lagoonal environment overlying the Adigrat sandstone. The Goha-Tsion Formation disappears under

Antalo Limestones and may be subdivided in to three units as; lower, middle and upper units, (Beciep, 1985).

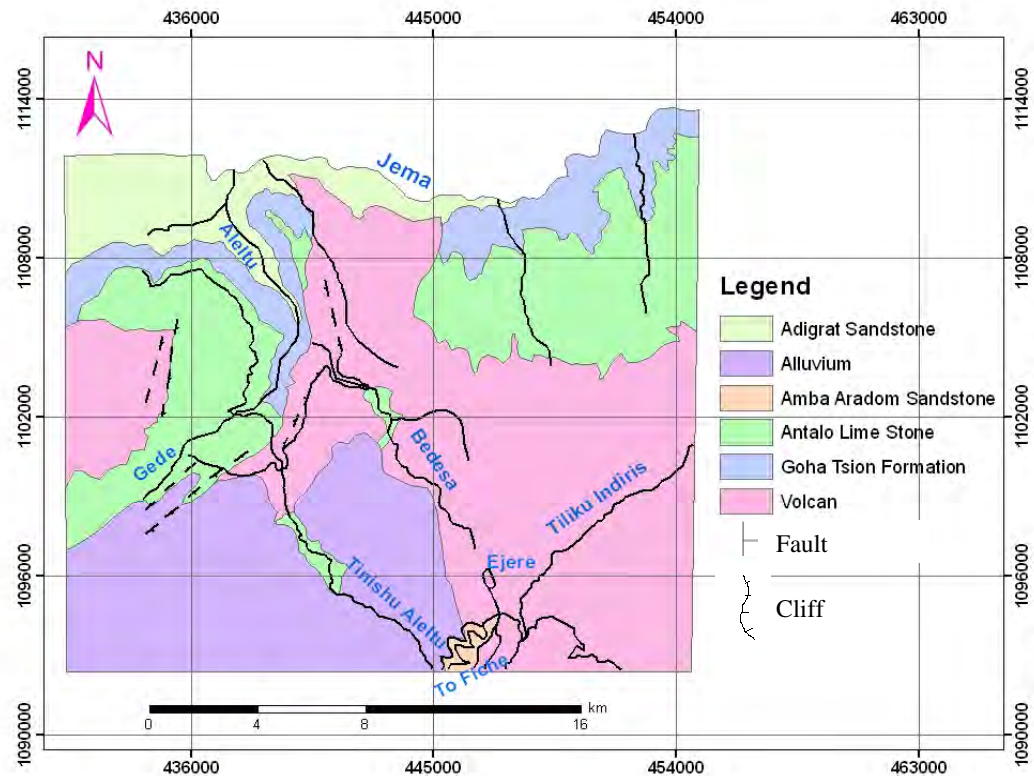


Fig. 3.2 Geological Map of Ejere Area

The Lower Unit: This unit is composed of mudstone, fine-grained sandstone and rare limestone passing up ward into alteration of limestone, dolomite, shale and gypsum. It seems from lithological association that this unit is a transitional zone from continental (fluvial) to lagoonal environment.

The Middle unit: This unit is dominated by gypsum beds. Here, Gypsum is clean, thick to thinly bedded, rarely inter bedded with mudstone and very rarely with dolomite and limestone.

The upper unit: The upper unit is mainly shale, siltstone and limestone alterations with rare thin interbeds of gypsum at the lower part indicating the area has communication with the open sea and was progressively invading the area that leads to marine environment towards its top.

3.3.2.3 Antalo Limestone

The group is believed to be upper Jurassic in age. The limestone is exposed in Ejere and the present study areas as thick as 550 meters (Beciep, 1985). It is intensely affected by volcanic activities with numerous dykes and sills. The middle part is highly fractured vertically and horizontally. Lithologically, Antalo limestone could be also divided in to three units.

The Lower Unit: This is exposed at the lower part of Jema river valley conformably overlying the Goha-Tsion formation having a thickness of about 230 meters (Rabben et al, 1980).

The middle unit: This unit is mainly crystalline, interbedded with other type of limestones near its top in Ejere and the present study area. This unit is intensely affected by volcanic activities, which either inter-bedded with and/or criss-cross the limestone beds.

The upper unit: The upper unit is argillaceous, fine-grained, yellowish, dull-white, alternating with gypsum beds in the Jema River near the sand contact. It is thickening toward Ejere area and some sand beds are inter-bedded near its top part.

3.3.2.4 Amba Aradom sandstone

This group of sandstone is deposited unconformably over Antalo Limestone. It forms an angular unconformity with the underlying Antalo and is believed to be Lower cretaceous in age. This sandstone is up to 450 meters in thickness and thinning out towards Ejere. The bottom of Amba Aradom sandstone is marked by red clay as in Jema River valley (Serawit and Tarmirat, 1995) overlain by calcareous sandstone. The Amba Aradom sandstone is mainly coarse-grained, conglomeratic, cross-bedded, massive, sometimes friable and white to pale yellow, mostly looks reddish brown due to weathering.

3.3.2.5 Tertiary Volcanic

The tertiary volcanic is about 350 meters thick and unconformably overlies the cretaceous sandstone. It is highly fractured and jointed all over the studied areas.

Lithologically basalt is dominant, however, tuffs, agglomerates are inter-bedded in the Gundomeskel and in the study area including lava flows, (Jemal Saed, 2005).

The rocks are fine to medium grained, sometimes coarse grained in the sills, black to dark and highly weathered. Vertical & horizontal, and sometimes columnar jointing is quite common. The intruded volcanic bodies are mainly medium-grained, black and highly fractured. The dykes are trending dominantly to the northeast, possibly following weak zones that have the same trend.

3.4 Geology of the study area

The regional geological setting and Stratigraphy mentioned above include and has almost the same characteristics with that of the present study area in many perspectives. This is because the extensions of the studied regional areas are chained by the same landscape and geological formation, specifically the Gohatision Formation, Antalo Limestone, Amba Aradom Sandstone and Tertiary volcanic are part of the geological setting of the study area. The sedimentary and volcanic rocks in the area are formed with the Mesozoic and Cenozoic time respectively. The Cenozoic volcanic rocks unconformably overlie the stratigraphical Mesozoic Sedimentary rocks. Relatively, the outcrops of Mesozoic formation in many areas are observed with highly dissected topography.

3.4.1 Volcanic unit

The volcanic rocks are well exposed in different Zones of the area as ridge, stream cut, cliffs, etc., and appearing as dark to gray in color, and medium to fine-grained in the upper slopes. The volcanic rocks are mostly vesicular Basalts. However, Trachylites, Rhyolites and Tuff are also common in some parts. The basalt is found outcropping in the continuous cliff, forming escarpments in many very steep slopes. Between the escarpments, on the gentle slopes, there are huge boulders and gravel few meters to millimeter sized basalts that indicate the result of weathering as well as the mass movement conditions. Different secondary structures like fractures, cracks, joints, fault lines characterize the basalt. Most of the major joints are almost parallel with slopes and the minor ones have varied orientations. The unit is columnarly jointed and massive resulting in huge blocks. Rock falls and topples are associated with these columnar joint and massive basalts.

ERA	PERIOD	FORMATION	LITHO.	THICK, m	DESCRIPTION
CENOZOIC	TERTIARY	Ajba Basalt		200	Dark, in places olive, fine-grained and jointed basalt. Locally highly affected by spheroidal weathering.
MESOZOIC	CRETACE	Amba-Arادم Sandstone		0-100	White, yellowish, sub-rounded, moderately sorted, friable massive, coarse-grained and conglomeratic sandstone.
	JURASSIC	Antalo-Limestone		525	Widely stratified. White to light yellow, fine to medium grained, bedded, locally with fragments and shells of mainly brachiopods and mollusks, occasionally oolitic and fossiliferous, rarely dolomitized limestone. Upper part argillaceous and highly weathered with some fine grained sandstone beds. Volcanic bodies intruded within the fractured limestone.
		Goha-Tsion Formation		290	White and gray, clean, bedded gypsum, with rare interbeds of shale. Shale is very dominant at the top and bottom part, and limestone alternate with shale in the upper part.
	TRIASSIC	Adigrat sandstone		0-150	Dull-white to white, bottom part purple, fine to coarse-grained, dense, well sorted, occasionally cross bedded sandstone. Rarely with inclusions of pebbles. Fining up ward with intercalations of shale.

Fig. 3.3 Generalized Stratigraphy of Ejere Area

3.4.2 Limestone unit

This unit is regionally called the Antalo Limestone which is believed to be upper Jurassic in age. It is intensely fractured vertically and horizontally and criss-cross the volcanic units with numerous dykes and sills. This unit includes calcite and shale inter-bedded, white to dull-white, at place pinkish and gray with shale and in most places it is highly weathered. Some sand beds are also inter-bedded.

The middle part of this unit is common in the area which, is thickly bedded. This type of limestone consists of joint sets such as bedding plane (horizontally) and trending NW and NE. The intersection of these sets of joints combined with weathering

resulting in the rock falling and toppling composed of huge blocks. These types of movements are so severe due to the intercalation of soft layers of shale and marl that act as sliding surfaces.

3.4.3 Goha-Tsion Formation group

This type of Geology, in large extent, is found in the northern part of the present study area. This group is a complex of terrigenous, because it is composed mainly of shale, gypsum and siltstone and in minor mudstone and limestone alternations. Therefore, in most cases, it is difficult to identify them separately.

The Gypsum unit: gypsum is the middle part of the Goha-tsion formation and is clean thick to thinly bedded, white but varies in color to gray and black where weathering advances. It is rarely interbedded with mudstone and very rarely with dolomite and limestone.

It has gradational contact with the underlying shale unit. Generally, gypsum is susceptible to weathering and erosion which result in change of color on the surface and along the joint planes.

The Shale unit: this unit is bedded in the upper Goha-tsion formation and is gray, sometimes pale yellow and dull-white. In some parts of the mapped area, the continuity of the lower shale disappears from its original place of deposition due to its susceptibility to weathering and erosion. The presence of soft, weak and decomposed shale underlying relatively dense limestone and gypsum creates instability of slopes because the shale is very thin and it cannot accommodate the overlying load exerted by both limestone and gypsum.

The Siltstone unit: this unit is found in the lower bedding of the Goha-tsion formation consisting of cemented silt particles. It is mostly yellowish green to brownish gray in color. The siltstone at place is found intercalated with shale indicating a change of depositional environment from continental to marine and vice-versa. It is horizontally bedded resting on sandstones with closely spaced minor vertical joint, (Serawit Amene and Tamirat Mojo, 1996).

3.4.4 Sandstone unit

This is widely found in the north-east of the study area marked by grayish red clay

overlain by calcareous sandstone. It is mainly coarse-grained, conglomeratic, cross bedded, massive, sometimes looks reddish-brown due to weathering inter-bedded with shale and calcareous sandstone in the lower part. Generally, this unit is coarsening upward.

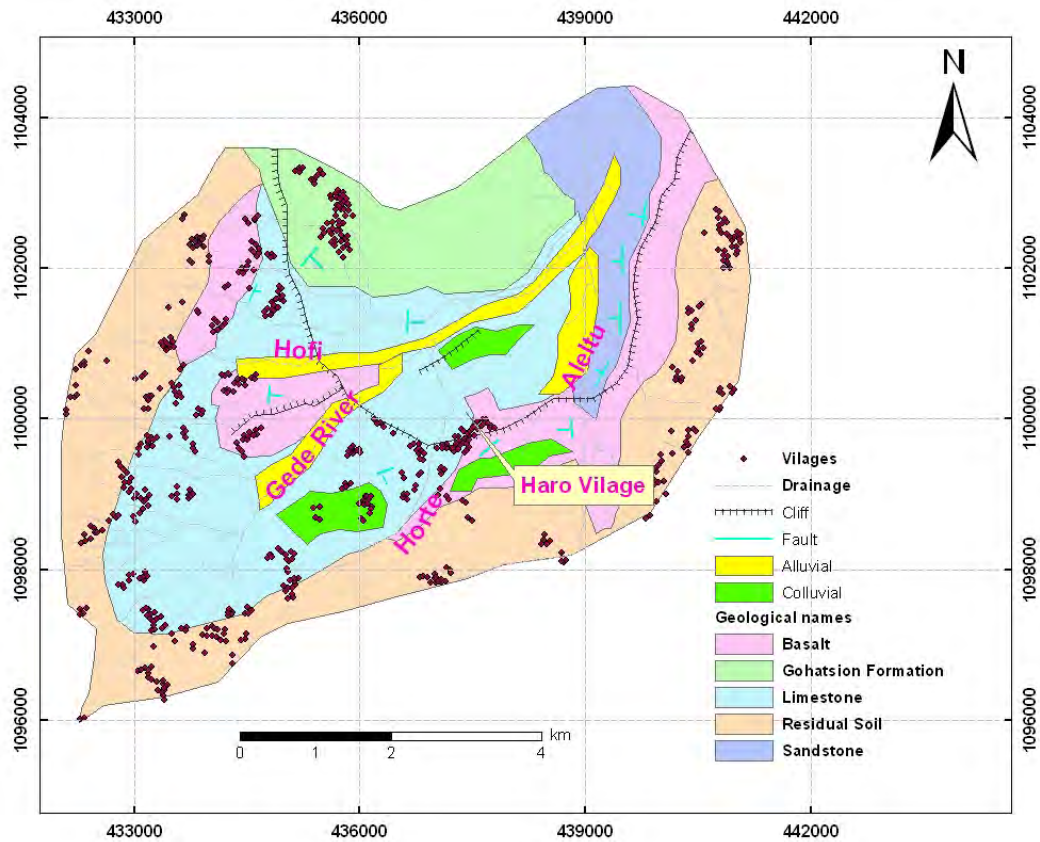


Fig. 3.4 Geological Map of the Study Area

3.4.5 Residual unit

The residual soil landscape in the area is mostly dominated by sites where deep soils have formed from in situ weathering of parent materials. The residual soils typically have level to undulating elevated landforms. They cover most of the plateau formed by basalt on almost flat lands. The residual soils developed from the basalt plateau are black in color due to weathering whereas, down to Jema they change their color to gray as the rock unit changes into limestone and shale.

CHAPTER IV

Landslide Hazard Evaluations and Zonation of the study area

4.1 General

Studying the landslide in a given area is important to get a clear understanding of the causes of slope failure because this understanding can then be applied to similar slopes that may pose a greater threat to life, infrastructure and general geological hazard of that area. To do this, the topographic map processing and field investigation, with proper methodology, is therefore, aimed to evaluate the potential landslide hazard for certain slopes within that area.

There has been no research done and no published evidence on the present study area with regard to landslides. An attempt has been made for the present study to systematically analyze and to work out landslide hazard Zonation. For this purpose “landslide hazard evaluation Factors (LHEF) rating scheme”, developed by Anbalagan (1992) has been adopted to apply for the landslide hazard mapping of the present study area. The Landslide Hazard Evaluation Factors (LHEF) rating scheme is a numerical rating system that is based on some of the major inherent causative factors for slope instability; such as bedrock geology (lithology, structure, degree of weathering), geomorphology (slope gradient, slope aspect, slope curvature, relative relief), soil (depth, structure, permeability, porosity), land use land cover, and hydrologic conditions (Anbalagan, 1992). Numerical ratings suggested by LHEF scheme were classified and rated according to the experiences gained from the study of the factors and their impact on the occurrence of the landslides anticipated in the area of study.

The main objective of this chapter is therefore, aimed to generate the hazard map of a landslide-prone area in Haro village and its surrounding by utilizing LHEF approach. For this purpose, the study included the following main steps:

- Identifying and evaluating the most contributory factors, facet wise, responsible for the landslide in the area.

- Generating individual causative factor maps by detail field studies and computer GIS aid processing.
- Grouping the factors into certain categories, giving the corresponding weighted rating and adding them to get the total estimated hazards from each facet.
- Finally, producing the hazard map.

According to LHEF technique there are number of factors, which influence the stability of the slope. For the present study, however, six major inherent causative factors have been recognized and extracted for the purpose landslide hazard classification namely; Geology (lithology and structure), slope morphometry, relative relief, land use land cover and ground water conditions. For the present work, the major rating for the landslide hazard Evaluation Factors (Anbalagan, 1992, 1996) is shown in Table 4.1 and the detail breakup values of the ratings for different factors are given in Annexure I.

Table 4.1 Proposed Maximum LHEF rating of the major contributory Factors for Landslide Hazard Zonation

Major Causative Factors	Maximum LHEF Rating values
Lithology	2.0
Relationship of structural discontinuity with slope	2.0
Slope morphometry	2.0
Relative relief	1.0
Land use and land cover	2.0
Hydrological conditions	1.0
Total	10.0

Each of causative factors used in LHEF scheme are given a maximum value, based on their perceived influence on a landslide occurrence in the area. These values can then be added to give an overall rating out of ten. This is the total estimated hazard rating (TEHDR). Based on the TEHDR values, the area is then classified into relative hazard zones.

4.2 Landslide Hazard Evaluation Factors (LHEF) Rating Scheme

In order to evaluate the landslide hazard in the area, all intrinsic properties suspected to cause the landslide in the area have been identified by preliminary reconnaissance. Out of these properties, six are taken as major causative factors and base maps were prepared during desk study from Topographic and geologic

maps, satellite imageries for field verifications and evaluations. These major causative factors selected for evaluation in the area are lithology, structure, slope morphometry, relative relief, land use land cover and ground water conditions.

Later, the field study was carried out to collect the required data on these factors for estimating the total hazards of each of the mapped facet in the area. A facet, in this context, is a part of hill slope, which has more or less similar characteristics of slope showing consistent slope direction and inclination. From each facet, data was collected and analyzed based on the chosen categories for the LHEF rating. Each category is then given a corresponding rating based on the amount the factors contribute to the landslide activity. Further, the ratings for each facet have been summed up to derive the Total Estimated Landslide Hazard Rating (TELHR). Finally, the hazard map highlighting the different relative hazard zones on the slope has been produced.

4.2.1 Geology

Geology is one of the most important factors in controlling landslides. Several researchers such as Koukis & Ziourkas (1991), emphasized the role of geology due to its major influence on the stability of slopes. A simplified geologic map of the study area has been prepared based on the information obtained from “Geological map of Ejere area” from Ethiopian Geological Survey in 1974, and field investigation during the present study (Fig. 3.4). This Geological map provides information on the lithological and structural setting of the area. For the present study, the lithology and the structure were evaluated and rated separately for better representation.

As discussed in section 3.4 of chapter 3, these geologic formations in this mapped area have been grouped into five lithologic groups with further sub units; basalt, limestone, sandstone, the Gohatsion formation and residual soils. The basalt coverage is mostly common with different primary and secondary structures; Limestone which is intensely fractured and affected by the volcanic units. It is mostly intercalated with soft layers of shale and marl; sandstone unit is conglomeratic, cross bedded, massive, interbedded with shale; a complex of terrigenous group of Gohatsion Formation is composed of shale, gypsum, mudstone, siltstone and limestone alternations which are affected with different weathering grades.

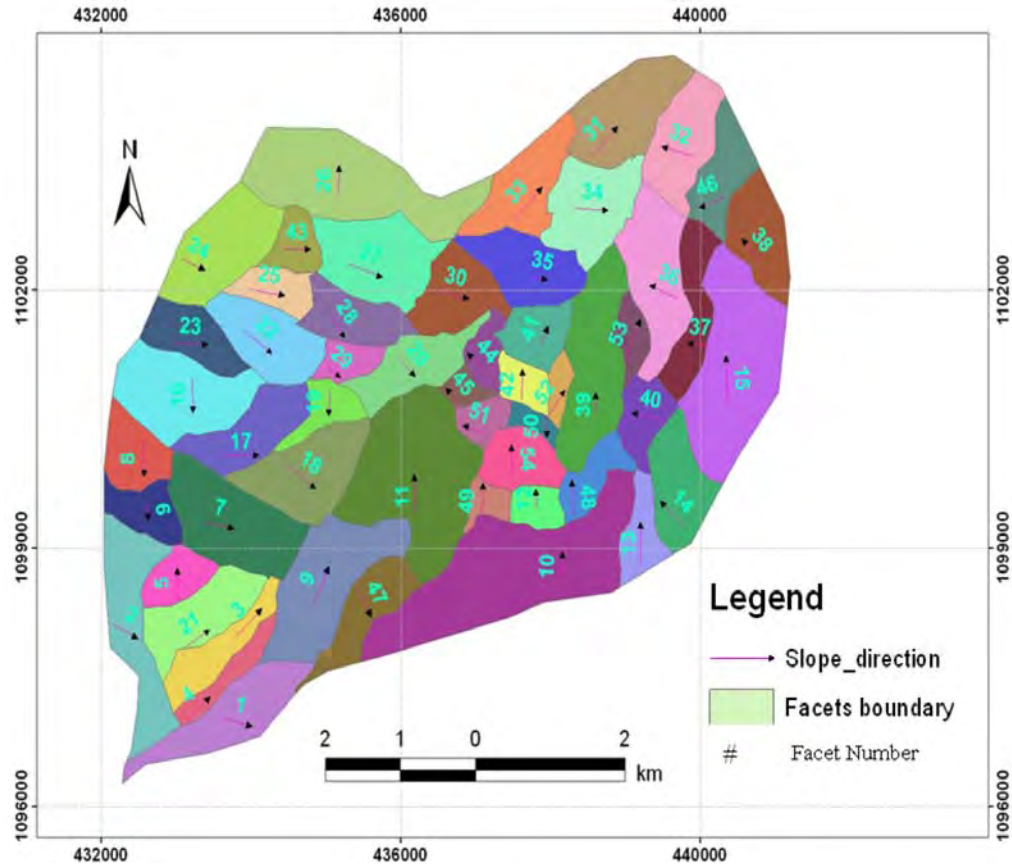


Fig. 4.1 Facet Map of the Study Area

4.2.1.1 Lithology

The lithologies of the study area have different properties and rate of weathering. Therefore, these has to be properly identified, evaluated and rated for the individual facet. Highly weathered and fractured volcanic rocks, poorly cemented terrigenous sedimentary rocks such as, limestone and sandstone with minor clay; highly weathered shale with interbedded clayey and non-clay rocks are mostly exposed in the study area (Table 4.2). For these different properties and types of Lithology, a correction factor concerning the status of weathering of rocks has also been incorporated in the analysis.

In the case of soil, unconsolidated debris comprising mostly rock pieces mixed with clayey on the slopes (colluvials) is the main considerations in awarding the ratings.

Table 4.2: Main Lithologic Groups of the study area

Lithologic group (Formation)	Main Units	Description
Tertiary Volcanic	Basalt	huge boulders and gravel resulting from high weathering and fractured with parallel discontinuities along slopes
Antalo Limestone	Calcite, Shale	Intensely affected by volcanic rocks with numerous dykes and sills, highly weathered and characterized by the intercalation of soft layers of shale and marl
Goha-Tsion Formation	Gypsum, Shale, Siltstone	Gypsum: interbedded with mudstone underling shale, susceptible to weathering and erosion Shale: susceptible to weathering and erosion due to the presence of soft, weak and decomposed shale underlying relatively dense limestone and gypsum Siltstone: consists cemented silt particles, found intercalated with shale and horizontally bedded resting on sandstones with closely spaced minor vertical joint
Amba Aradom Sandstone	Conglomerate	Overlain by calcareous sandstone, mainly coarse-grained, conglomeratic, cross bedded, massive, white to reddish-brown due to weathering
Soil	Colluvial	Debris comprising mostly rock pieces mixed with clayey/sandy soil (colluvial)

4.2.1.2 Structure

The strength of a rock mass depends on the type of rock and the presence and nature of the discontinuities; primary discontinuities such as bedding, secondary discontinuities such as joints, foliations and faults or other fractures. The more the discontinuities present in bedrock, the greater the likelihood of rock instability. The nature of such structural discontinuities in relation to slope inclination and direction has also a great influence on the stability condition of the slope. According to Anbalagan (1992), in this respect, the following three types of discontinuity-slope relationships are considered to be important:

- (i) The extent of parallelism between the direction of the discontinuities, or the line of intersection of two discontinuities and the slope. This relationship implies that the more the discontinuity or the line of intersection of two discontinuities tends to be parallel to the slope, the greater the risk of failure.
- (ii) The difference in the dip of the discontinuity or the plunge of the line of intersection of the two discontinuities to the inclination of the slope. Until the dips of the discontinuity or plunge of the line of intersection of two discontinuities do not exceed the inclination of the slope, the failure potential remains high.

(iii) The steepness of the dip of the discontinuity, or the plunge of the line of intersection of two discontinuities, the more the steepness of the dip of the discontinuity or the plunge of the line of intersection of two discontinuities, the higher the probability of the slope instability.

Accordingly, the LHEF ratings have been assigned for various stability conditions, broadly on the basis of the approach indicated by Romana, 1985. Based on the orientation of these strata-slope relationships, the data were collected and the corresponding rating was given for each facet.

4.2.2 Slope Morphometry

Slope Morphometry was considered as an important causative factor to consider in an area for landslide occurrence. The influence of slope steepness on landslide occurrence is the easiest factor to understand. Generally, steeper slopes have a greater chance of landslide. However, failures may occur on gentler slopes, as well. Other factors may make a gentle slope sensitive to failure and thus this is why various factors are combined in determining and having a relatively high hazard potential. Slope morphometry maps define slope categories on the basis of its steepness in terms of slope angle.

The slope morphometry map of the area has been prepared, first by inferring the satellite images of the area and later verified by field investigations. Accordingly, the slope angles in the study are found to be varying from 0° to 85° and grouped into five categories as; slopes of escarpment/cliff ($>45^{\circ}$), steep slope (45° - 35°), moderately steep slope (35° - 25°), gentle slope (25° - 15°) and very gentle slope including flat areas ($<15^{\circ}$) (Annexure I). It is determined from facet evaluation that the slopes of the area fall 24% in scarp zone, 17% in steep, 20% in moderately steep, 17% in gentle and 22% in very gentle slope categories. Most of the slopes in the study area fall into moderate, steep slopes and escarpment categories. Such slopes are concentrated around Aleltu, Horte, Gede and Hofi Rivers which are very near to the villages. However, gentle slopes are extensively found in the Eastern, Southern and southwestern parts of the study area (Figure 4.2).

Among the slope categories mapped in the area, past landslide activity has been

observed in the slope category greater than 45° followed by 45° to 35° . This indicates that slopes above 35° , in general, demonstrate a potential for instability. In addition, as observed during the study and though their ratings are not included as the major causative factor for the analysis; slope orientation (aspect), slope curvature (concave and convex), slope length have also a contributive influence on the slope instabilities.

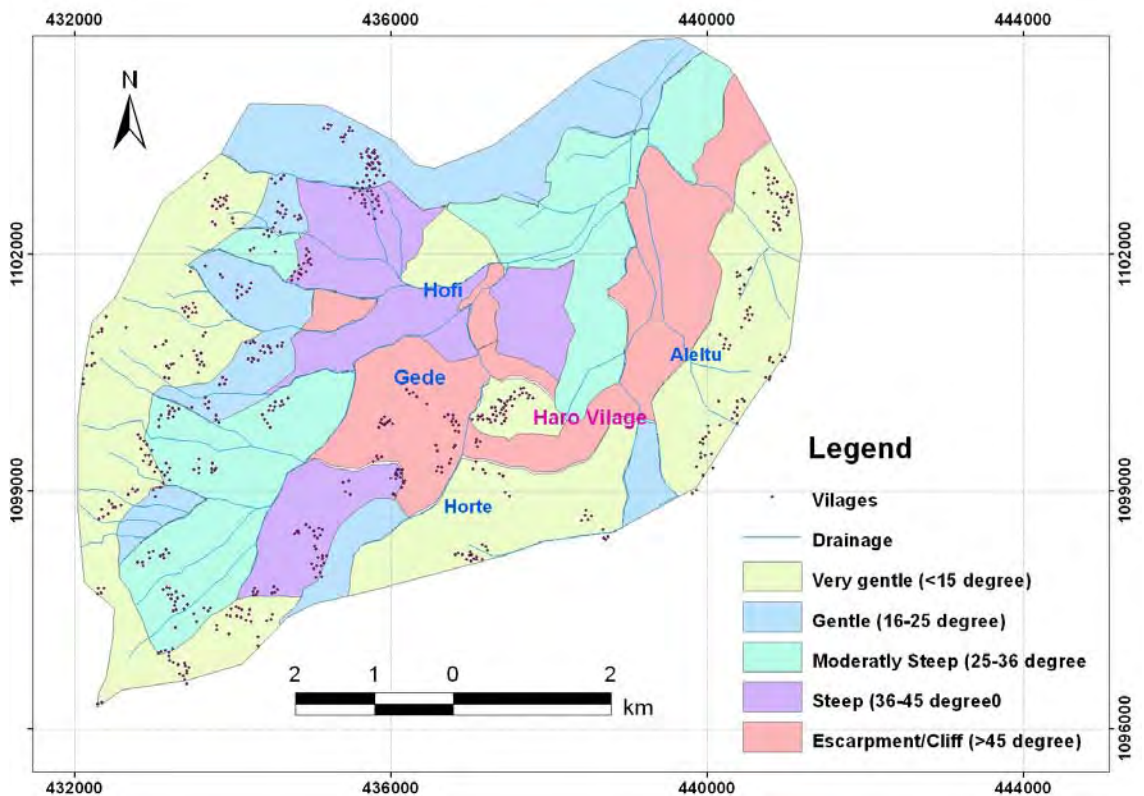


Fig. 4.2: Slope Morphometry of the Study Area

4.2.3 Relative Relief

In general, the relative relief portrays the absolute maximum difference in elevation at a specific point. In specific terms the relative relief map represents the local relief of maximum height between the ridge top and the valley floor within an individual facet. This shows the major breaks in the slopes of a given area. Gravity sliding and incidence of landslide is greatest in the areas of high relief, (Pachauri A. K. and Pant M., 1992).

For relative relief evaluation in the area, elevation data (contour map) was obtained from Satellite images and overlain on the facet map and the values are determined.

In the present study area, the total relief is 1140m and the local relief is determined facet wise. From this determination, three categories of relative relief have been identified for hazard evaluation purposes as; low relief (<100m), medium relief (101-300m) and high relief (>300m) (Anbalagan, 1992). The relative relief distribution pattern in the present study area shows 19% has high relief, 74% has medium relative relief and 7% has low relief. Therefore, from the evaluation of each facet concerning the relative relief, the chances of slope instability is quite high on the slope with high relative relief.

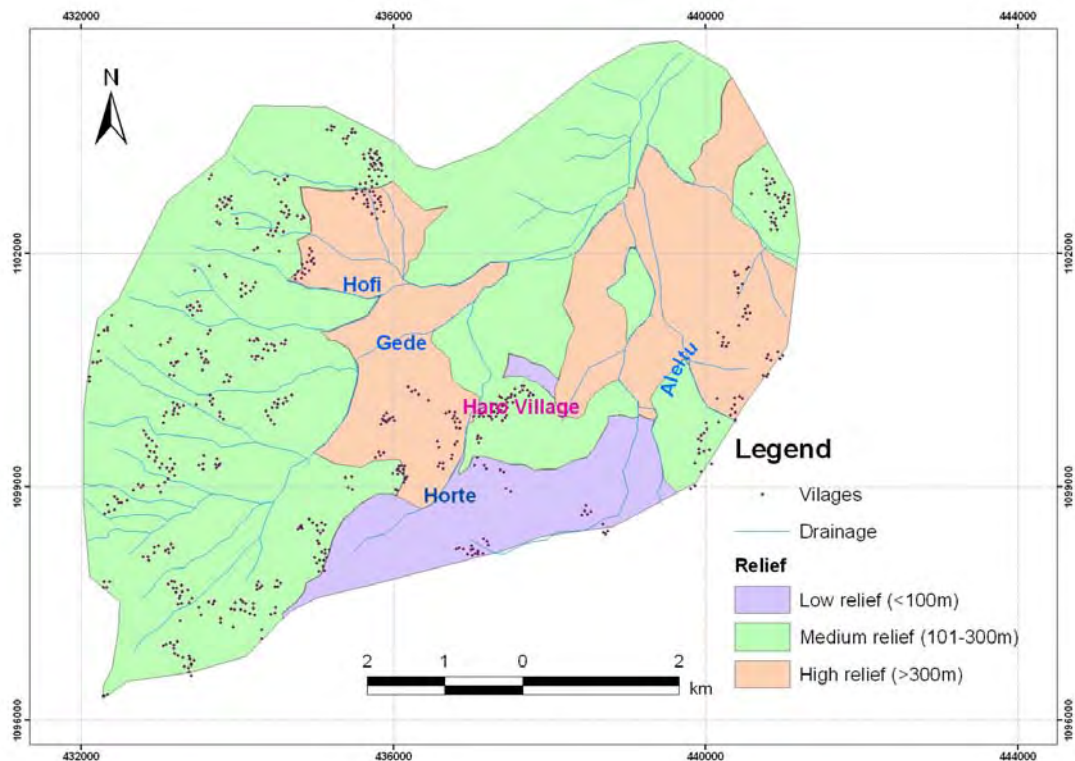


Fig. 4.3: Relative Relief Map of the Study Area

4.2.4 Land use and Land cover

Any human activity and use which carried on land is defined as land use, whereas land cover refers to natural vegetation, water bodies, rock, soil, artificial cover and other resulted due to land transformation (Yesilnacar E. and Suzen M. L., 2006). Land use land cover in an area can easily be characterized by general observations of the vegetation.

Barren and sparsely vegetated (bush) areas show faster erosion and greater instability as compared to reserve or protected forests which are thickly vegetated

and generally less prone to mass wasting processes. Forest cover, in general, reduces the action of climatic agents on the slopes and protects them from the effects of weathering and erosion, (Anbalagan, 1992).

Land use land cover categories in the area has been interpreted from detail field observation during the study and has been identified as: Agricultural and populated flat lands, dense vegetated forest lands, moderately vegetated areas, sparsely vegetated areas with lesser ground cover (bushes) lands. Most of the very steep, moderately steep, even gentle steep lands in the area are not used for agriculture due to its instability and most of it is covered with bushes. There are only relatively very few dense forest covers around Haro village and Aleltu River. Therefore, an overall assessment of the area in terms of vegetation cover suggests that 57% of the area is covered by bushes, 31% by Agriculture and populated lands, 8% by moderately vegetated area and 4% by dense forests. Generally, most of the study area shows incidence of landslides mainly due to improper land management practices and deforestation for agriculture.

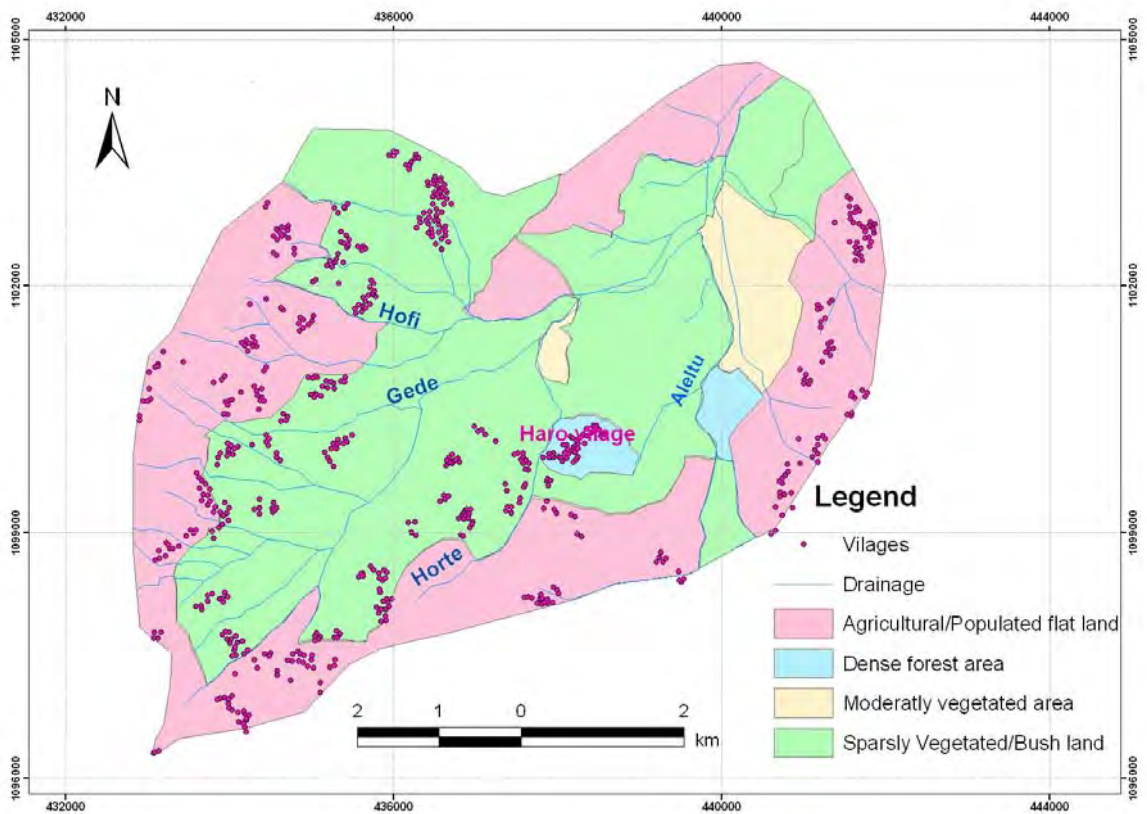


Fig. 4.4: Land use land cover Map of the Study Area

4.2.5 Ground water Condition

Water is recognized as an important factor in slope stability almost as important as gravity. The detail information on ground water condition is rarely available and therefore, an indirect measures are used which can be mapped to show the influence of the area's hydrology, such as vegetation, slope orientation (aspect), or precipitation zones (Popescu M.E, 2001).

In general, groundwater in hilly terrain can be channeled along structural discontinuities of rocks and may not be estimated directly. Therefore, in order to make a quick appraisal, direct field observations of the nature of surface indications of the behavior of groundwater will provide valuable information on the stability of hill slopes for hazard mapping purposes (Anbalagan, 1992).

Surface indications of water such as dry, damp, wet, dripping and flowing are used for rating purposes. During the present study, the observations and data collections were made before and after rainy seasons to compare and provide the possible ground water conditions.

When observed before rainy season, the surface water conditions were almost dry through out the study area, except at very few places like the major Aleltu River and in the Haro village at the base of the slope where high potential discharging spring is observed. However, after rainy season, in September, there were indications that most of the area was observed as wet and dripping, even flowing, of water during which maximum landslides occurred in the study area. The ratings are then taken as where each facet is assumed to be longer with the categorized ground water conditions.

4.3 Landslide Hazard Evaluations in the study area

In order to prepare the landslide hazard map using the LHEF rating scheme for the present area, six major causative factors were combined. Each of the factors was then grouped into classes, given a weighting depending on its degree of affiliation to the landslide hazard and added to give the total estimated landslide hazard rating for the relative hazard classification. The logical assumption made for this purpose is, that the risk of occurrence of landslide is a direct consequence of these parameters.

However, the process and exact mechanisms involved in landslide hazard evaluation is difficult and makes prediction quite uncertain. Due to this reason, there can be a substantial degree of uncertainty involved in any hazard evaluation process (Gupta et al., 2001).

Table 4.3 Facet wise TEHD ratings for the study area

Facet No	Lithology	Structure	Slope Morphometry	Relative relief	Land use land cover	G-water condition	Summation	TEHD
1	0.8	0.7	0.5	0.6	0.65	0	3.25	VLH
2	0.8	0.7	0.5	0.6	0.65	0	3.25	VLH
3	1.2	0.7	1.2	0.6	1.5	0	5.2	MH
4	1.6	0.7	1.2	0.6	0.65	0	4.75	MH
5	1.2	1.2	1.2	0.6	1.5	0	5.7	MH
6	0.3	0.3	0.5	0.6	0.65	0	2.35	VLH
7	1.2	1.5	1.2	0.6	1.5	0.2	6.2	HH
8	0.4	0.3	0.5	0.6	0.65	0	2.45	VLH
9	0.9	1.7	2	0.6	1.5	0.2	6.9	HH
10	0.8	0.7	0.5	0.3	0.65	0	2.95	VLH
11	1.6	1.7	2	1	1.5	0	7.8	VHH
12	1.2	1.5	2	0.6	1.5	0.8	7.6	VHH
13	1.2	0.9	0.8	0.3	1.5	0.5	5.2	MH
14	0.9	0.3	0.5	0.6	0.65	0	2.95	VLH
15	0.8	0.3	0.5	1	0.65	0	3.25	VLH
16	1.2	0.7	0.5	0.6	0.65	0	3.65	LH
17	1.6	1.4	0.8	0.6	1.5	0.2	6.1	HH
18	0.9	1.7	1.2	0.6	1.5	0	5.9	MH
19	1.2	0.7	1.7	0.6	1.5	0.5	6.2	HH
20	1.2	0.7	1.7	1	1.5	0	6.1	HH
21	1.2	0.7	1.2	0.6	1.5	0	5.2	MH
22	0.9	0.7	0.8	0.6	0.65	0.2	3.85	LH
23	0.9	0.7	0.5	0.6	0.65	0.2	3.55	LH
24	0.8	0.7	0.5	0.6	0.65	0.2	3.45	VLH
25	0.9	0.7	0.5	0.6	1.5	0	4.2	LH
26	0.4	0.7	0.8	0.6	0.65	0	3.15	VLH
27	0.9	0.7	1.7	1	1.5	0	5.8	MH
28	1.2	0.7	1.7	1	1.5	0	6.1	HH
29	1.2	1.4	2	0.6	1.5	0.2	6.9	HH
30	1.6	1.7	0.8	0.6	1.5	0.2	6.4	HH
31	2	0.7	0.8	0.6	0.65	0	4.75	LH
32	1.6	1.2	1.2	0.6	1.5	0	6.1	HH
33	0.9	0.3	1.2	0.6	0.65	0	3.65	LH
34	2	1.2	0.8	0.6	1.5	0.2	6.3	HH
35	1.2	1.5	1.2	0.6	1.5	0.2	6.2	HH
36	0.9	1.5	2	1	1.2	0.2	6.8	HH
37	0.6	1.5	2	1	1.2	0.5	6.8	HH
38	0.8	0.7	0.5	0.6	0.65	0	3.25	VLH
39	1.6	1.7	0.8	1	1.5	0.2	6.8	HH
40	0.6	1.7	2	1	0.8	0.5	6.6	HH
41	2	1.2	1.2	0.6	1.5	0.5	7	HH
42	2	1.5	1.7	0.6	1.5	0.5	7.8	VHH
43	0.6	0.7	0.8	0.6	1.5	0	4.2	LH
44	1.6	1.7	2	0.6	1.2	0	7.1	HH
45	1.6	1.3	1.7	0.6	1.2	0	6.4	HH
46	0.9	0.7	2	1	1.5	0	6.1	HH
47	1.6	1.5	0.8	0.3	0.65	0.2	5.05	MH
48	1.2	1.5	2	0.6	1.5	0.8	7.6	VHH
49	1.6	2	2	0.6	1.5	0.5	7.7	VHH
50	1.2	1.2	2	0.3	1.5	0	6.2	HH
51	1.6	0.7	2	0.6	1.5	0.2	6.6	HH
52	2	1.6	1.7	0.6	1.5	0.2	7.6	VHH
53	1.2	1.8	2	0.6	1.5	0.2	7.3	HH
54	0.6	1.4	0.5	0.6	0.8	1	4.9	LH

The total estimated hazard (TEHD) calculated facet-wise for the area indicates the net probability of instability, because adjoining facets may have entirely different stability conditions (Anbalagan, 1995). The TEHD of an individual facet is obtained by adding the ratings of individual causative factors for each facet obtained from the LHEF rating scheme (Table 4.3) as;

$$\begin{aligned} \text{Total estimated hazard (TEHD)} &= \sum (\text{Ratings of causative factors}) \\ &= \sum (\text{Ratings of lithology} + \text{Structure} + \text{slope} \\ &\quad \text{morphometry} + \text{relative relief} + \text{land use/land cover} \\ &\quad + \text{groundwater conditions}) \end{aligned}$$

On the basis of TEHD, five categories of landslide hazard zones have been identified in the present study, namely; very low hazard zone (VLH), low hazard zone (LH), moderate hazard zone (MH), high hazard zone (HH) and very high hazard zone (VHH) (tables 4.3 and figure 4.5).

4.4 Landslide Hazard Zonation mapping of the study area

After the determination of ratings of the six effective factors for the mapped 54 facets, each of the factor maps was generated. Later, the values of each rating were summed up to obtain the Total Estimated Hazard rating (TEHD) for the classification of the relative hazard zones. Finally, the generalized landslide hazard Zonation map of the area was produced to indicate the probable areas where the future landslide activity may take place. The earned Zonation map was classified into five hazard zones of varying degree of hazard based on the estimated significance of causative factors which influence the stability of the area.

4.4.1 Very Low Hazard Areas

Based on Anbalagan's landslide hazard classification of 1992, very low hazard zone has a TEHD value less than 3.5. Out of the total 54 facets in the study area, 10 facets fall within the very low hazard zone. These areas are relatively associated with flat lands and low relief areas located in the narrow boundary in the eastern, southern and south-western parts of the study area around Amara Haftin. In terms of percent, this zone covers 18% of the total area and comprises mainly of non-slope forming, black cotton residual soils used for agriculture. This zone is safe from

potential instability where no restrictions are warranted as reasonable human activities or natural consequences.

4.4.2 Low Hazard Areas

This low hazard zone has a TEHD value between 3.5 and 5.0. Total 8 facets falls into this category in the study area. This zone mostly falls into gentle to moderate steep slopes and medium relief areas covered with bush lands. This zone covers 15% of the total area and comprises slightly to highly weathered geologic units that found in the study area. This zone is relatively stable in the present condition but future land use activity is to be properly applied and reforestation to be practiced so as to maintain its present stable status. In addition, the poor natural drainage may trigger off the landslide activity in this zone.

4.4.3 Moderate Hazard Areas

Moderately hazard zone has a TEHD value falling between 5.1 and 6.0 (Anbalagan, 1992). Total 8 facets fall within this hazard zone and covers 15% of the total study area. In many localities of these areas, there are some indications of previous mass movements observed by virtue of its present geological formation and set up. However, many slopes falling within this zone could be destabilized by uncontrolled erosion due to weathering, poor drainages and improper land use practices.

4.4.4 High Hazard

In High Hazard zone, TEHD value falls between 6.1 and 7.5 (Anbalagan, 1992). As a result of the geo-morphological setting of the study area, most of the facets are in this zone. Out of the total 54 facets, 22 facets fall within this high hazard zone, which comprises 41% of the total area. Highly weathered and jointed rock types, unconsolidated debris of slope forming colluvial geologic units are found in this zone. From the indication of the past consequences and the TEHD values obtained in this study, this zone is potentially unstable and the landslide activity may be more likely to occur.

4.4.5 Very High Hazard

In Very High Hazard zone, TEHD value falls greater than 7.5 (Anbalagan, 1992). Only a few numbers of the facets are in this zone but found with populated villages.

Out of total 54 facets, 6 facets fall within this very high hazard zone, which comprises 11% of the total study area. Highly weathered and joined, unconsolidated debris of slope forming colluvial geologic units are also found in this zone. From the past observational inventories and the TEHD values, this zone is very unstable where landslides are most likely to occur in view of the prominent causative factors present in the area.

The area is almost affected to such a state that it is very difficult to evolve economically and socially acceptable remedial measures to prevent the recurrence of the hazard. The area has to be avoided for settlement or other developmental purposes and preferably left out for regeneration of natural vegetation.

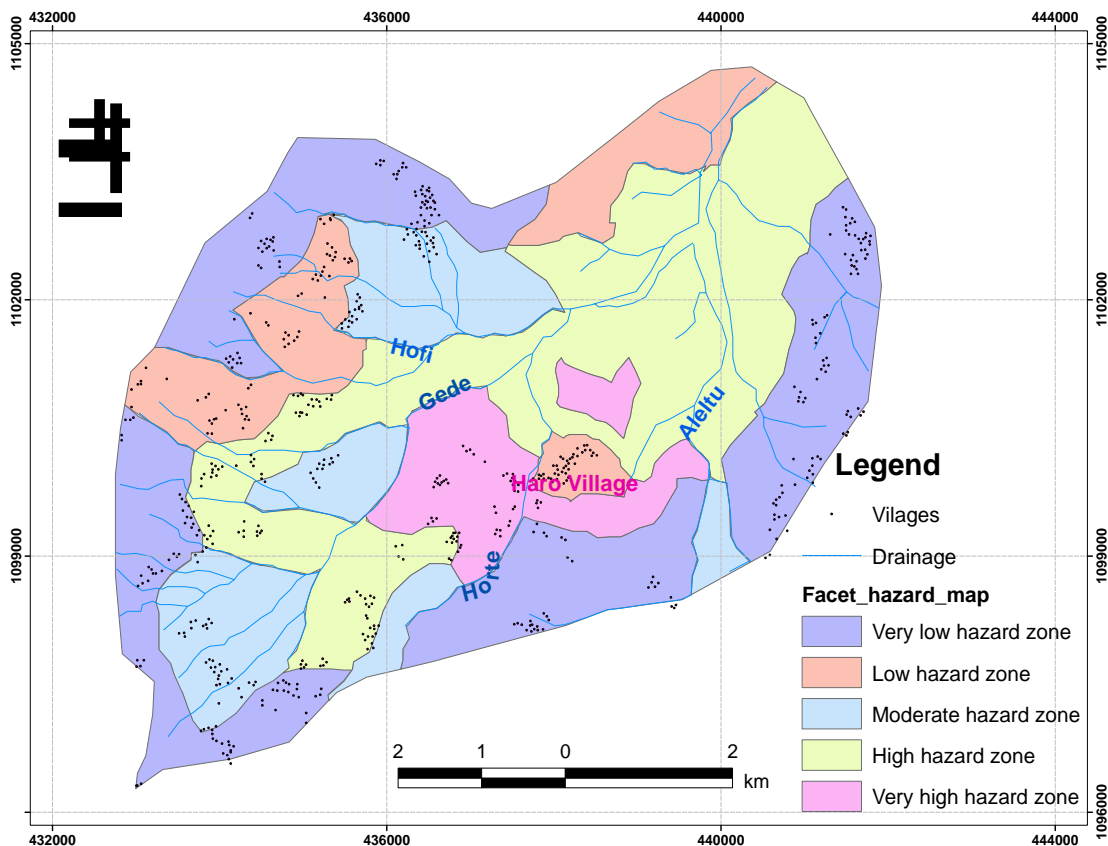


Fig. 4.5: The Landslide Hazard Zones of the Study Area

In general, perusal of figure 4.5 clearly indicates that most of the area in the study area falls into very high, high and Moderately Hazard zones, which implies that

chances of slope failures is high. Thus, the Landslide hazard zonation map prepared during the present study may be utilized to;

- Recognize geographic areas where landsliding has already occurred and future landsliding is most likely to occur
- Prepare for, modify and/or mitigate the disastrous effects of landslides on communities and infrastructures by means of appropriate engineering practices.
- Educate the community of the area what to do or not do on these identified hazard zones.

Table 4.4: Classification of landslide hazard zones on the basis of LHEF rating scheme

Zone	TEHD values	Zone description	Percent (%)
I	<3.5	Very low hazard	18
II	3.5-5.0	Low hazard	15
III	5.0-6.0	Moderate hazard	15
IV	6.0-7.5	High hazard	41
V	>7.5	Very high hazard	11

CHAPTER V

SLOPE STABILITY EVALUATION

5.1 Preamble

The total estimated hazard (TEHD) values for the present study area indicated that 11% of the slopes falls in very High Hazard, 41% in high hazard, 15% in Moderate Hazard, 15% in Low Hazard and 18% falls in very low hazard. From these results it can be concluded that 67% of the study area is in very high, high and moderate potential landslide hazard zone.

However, with only the evidence of the area being in high hazard zone, it may not be concluded that the slope will actually fail. Further, a slope may only fail when the driving forces exceed the resisting forces. Slope may also fail when the slope material is loose, homogeneous soils or when the slope material comprises of highly weathered and fractured rock mass. Moreover, even if a slope is potentially unstable, it also requires some triggering factor such as heavy water saturation, earthquake activities, etc. that facilitate the slope failure processes. This is why most landslides occurred during rainy season. Considering all these conditions, attempts have to be made to carefully identify such potential unstable slopes, addressing the Engineering properties of rocks and soils and carrying out the stability evaluation, for which some form of possible remedial measures may be worked out.

For the present study, efforts were made to evaluate the properties of the slope materials based on the hazard evaluation and practical field observations supported with some experimental data tests and empirical estimations. However, for the detail stability evaluations, the work needs elaborate tests and analyses, which in turn requires sufficient time, experience, adequate resource and financial support. Thus, all these factors made these elaborate tests beyond the reach of the present study and suggestions have been forwarded for future studies.

5.2 Identification of Potential Unstable Slopes

The presence of various signs and/or the preconditioning factors for the landslide occurrence in the area was indicated by ground conditions that was mapped and manifested by a thorough field reconnaissance and Hazard Zonation mapping. From these manifestations most areas that fall in the relative high hazard zones have experienced landslides and identified as susceptible to failure. The following features were found to be indicative of potential failure in the study area.

- Presence of discontinuities and their orientation
- Presence of recent failure scars and debris
- Evidences of presence of slope distress, such as, development of tension cracks, bulging of slope face
- Evidence of the presence of pathways for subsurface drainage networks or water bodies during rainy seasons
- Presence of cracking related to drying
- Evidence of the concentration of runoff and drainage networks, etc.

Based on these manifestations of instabilities, a general assessment of Engineering Geological characterization of rocks and soils has been conducted for which slope stability analysis, remedial measures and recommendations are suggested for the improvement of the stability of these slopes.

5.3 Engineering properties of rocks

Because of a vast range in properties of rocks due to different structures, it is difficult to determine the exact properties of the rock mass, quantitatively. Therefore, certain properties that are relatively easy to measure are used to classify the rock mass, (Catrin Elalbro, 2004). In order to classify the rock for the Potential failure in the area, data pertaining to geometrical, geological and structural information were observed, measured and recorded as UTM using GPS and the corresponding ratings were assigned for Rock mass rating.

5.3.1 Discontinuity description

Discontinuities are structural weakness planes along which movement can take place. The presence or absence of discontinuities has a very important influence

upon the stability of rock slopes and the detection of these geological features is most critical part of the stability investigation (Jemal Saed, 2006). Discontinuities are of paramount importance for rock slope stability studies because they control the possibility of unstable conditions or excessive deformation. When the rock mass contains discontinuity surfaces dipping toward the slope face, simple sliding can occur and the stability of the slope is significantly lower than those in which only horizontal and vertical discontinuities are present, (Hoek E. and John Bray, 1977). The important discontinuity properties or characteristics, upon which the Strength of rock mass greatly depends, are orientation, spacing, continuity, surface characteristics, the separation of discontinuity surface and the thickness and nature of the infilling material. Detail analysis of discontinuity joint conditions is very important for the evaluation of the stability of the slopes in the area.

5.3.2 Rock mass classification

Rock mass classification is the arrangement and combination of different features of a rock mass into different groups or classes following a specific system or principles (Catrin Edelbro, 2004). Rock mass classification systems can be of considerable use in the initial stage of a project when little or no detailed information is available. The classification system takes into consideration factors, which are believed to affect the stability of the rock mass. Classification of rock mass is an indirect method and does not measure the mechanical properties like deformation modulus directly. However, there are several empirical relations available to estimate the modulus of deformation and the rock mass strength. The value obtained is therefore, used to estimate or calculate the rock mass strength. In general, Rock Mass Classification is a rapid and very effective method to determine the overall quality of the rock mass.

5.3.2.1 Rock Mass Rating (RMR)

Though there are several rating schemes available to classify the rock mass, the Geomechanics Classification or the Rock Mass Rating (RMR) System developed by Bieniawski, 1989 has been used to workout the rock mass classification for the present study. Rock Mass rating Systems are useful in assessing the shear strength and deformability of the rock mass.

Bieniawski's five basic and one-adjustment parameters are used for the determination of the RMR. These are;

- (i) Uniaxial compressive strength of rock (UCS)
- (ii) Rock Quality Designation (RQD)
- (iii) Spacing of discontinuities
- (iv) Condition of discontinuities
- (v) Ground water condition
- (vi) Orientation of discontinuities

For these parameters, data pertaining to them were collected from the potential unstable slopes and the corresponding ratings were assigned from the standard RMR table and are added to get the total RMR value. In every measurement of each parameter, more than three values were measured and the average was taken for each rock units.

The uniaxial compressive strength (UCS) of the existing rock in the area has been determined by measuring the rebound number of Schmidt hammer values in the field and then it is calculated using the empirical relation given by Barton and Choubey, 1977 as;

$$\log_{10}(\delta_c) = 0.00088\gamma R + 1.01 \quad \dots\dots\text{eq., 5.1}$$

Where; δ_c is the Uniaxial compressive strength in Mpa, γ is the dry rock density in KN/m^3 and SHV (R) is Rebound number of Schmidt hammer.

Table 5.1: Collected data from various localities of unstable slopes and the determination of the uniaxial compressive strength of the rock mass units for the study area

Rock type	Location	Average Values		
		SHV(R)	γ , KN/m^3	δ_c , Mpa
Basalt	437758E, 1100557N	35	28	74
Limestone	436727E, 1099792N	34	25	57
Sandstone	439082E, 1103055N	32	25	52
Gypsum	435883E, 1107767N	33	20	39

In terms of the rock mass strength, the results obtained in the above table classified the rocks in the area as basalts of high strength, Limestone and sandstone as median strength and Gypsum as low strength.

Rock Quality Designation (RQD): The Rock Quality Designation index was developed by Deere (Deere et al 1967) to provide a quantitative estimate of rock mass quality from drill core logs. RQD is defined as the percentage of intact core pieces longer than 10cm in the total length of core run (Catrin Edelbro, 2004).

The Rock Quality Designation (RQD) for the present study area has been determined from volumetric count method that has been suggested by Plamstorm, (1982) when no core is available but discontinuity traces are visible in surface exposures. Thus the *RQD* can be estimated from the number of discontinuities per unit volume. The suggested relationship for clay-free rock masses is:

$$RQD = 115 - 3.3J_v \quad \dots\dots eq. 5.2$$

Where; RQD is the Rock Quality Designation (%) and J_v is the sum of the number of joints per unit length for all joint (discontinuity sets) known as the volumetric joint count.

In terms of the rock mass quality, the results obtained in Table 5.2 classified the rocks in the area as; Limestone good quality and basalts, sandstone and Gypsum as of fair quality.

Table 5.2: Collected data from various localities of unstable slopes and the determination of the Rock Quality Designation of the rock mass units for the study area

Rock type	Location	Average Values	
		J_v	RQD, %
Basalt	437758E, 1100557N	16	62
Limestone	436727E, 1099792N	11	79
Sandstone	439082E, 1103055N	13	72
Gypsum	435883E, 1107767N	14	69

For the remaining four parameters such as; Spacing of discontinuities, Condition of discontinuities, Ground water conditions and orientation of discontinuities; visual observations in the field and measurements has been made and accordingly, the ratings were assigned from the standard RMR table (Annexure II) (Table 5.3).

Table 5.3 Parameters and their ratings for the rock mass units in the study area and the determination of RMR

Rock Types	Parameters and Ratings (Average Values)						RMR	Rock Mass Classes
	UCS	RQD	Sp.	Con.	GWC	Ori.		
Basalt	7	13	10	20	10	-5	55	Fair
Limestone	7	17	8	10	15	-5	52	Fair
Sandstone	7	13	9	10	15	-5	49	Fair
Gypsum	4	13	8	10	15	-5	45	Fair

UCS-Uniaxial compressive strength, RQD-Rock Quality Designation, Sp.-spacing of discontinuities, Cod.-condition of discontinuities, GWC-Ground water condition, Ori-Orientation of discontinuities, RMR-Rock Mass Rating.

5.3.3 Shear strength of the Rock Mass

Determination of the stability of rock mass shear strength parameters, namely cohesion and angle of friction are very important as they provide the resistance to the rock mass to the sliding under the influence of gravity. In order to get the cohesion and angle of friction for a specific value of RMR, Bieniawski, 1989 has proposed the following relations. The shear strength parameters at unstable slopes have been determined from RMR as summarized in Table 5.4.

$$C = 0.05RMR \quad \text{.....eq. 5.3}$$

$$\Phi = 0.5RMR + 5 \quad \text{.....eq. 5.4}$$

Table 5.4: Shear strength determination of rock mass units for the study area

Rock Types	Average RMR	Shear strength parameters	
		Cohesion 'C' (Mpa)	Angle of Friction 'Φ' (°)
Basalt	55	2.75	32.5
Limestone	52	2.60	31.0
Sandstone	49	2.45	29.5
Gypsum	45	2.25	27.5

5.3.4 Modulus of Deformation(E_d) of Rock Mass

Rocks deform when they are subjected to stresses. Deformability means the capacity of rock to strain under applied loads or in response to unloads. RMR values are related to the deformation parameters of the rock. Thus, RMR results are used to determine the modulus of deformation using the relations developed by Serafim and Periera, 1983 and Agarwal et al, 1991. However, the equation developed by the Agarwal et al (eq. 5.5) is believed to be the best close value to the actual value and thus used to calculate the modulus of deformation of the rock mass, (Raghuvanshi T.K., 1995). Thus from these relation, an attempt has been made to empirically find

out the modulus of deformation 'E_d' of the rock mass for the area by using the determined RMR values.

$$E_d = 10 \frac{(RMR-30)}{50} \dots\dots eq. 5.5$$

Table 5.5: Modulus of deformation 'Ed' of the rock mass units in the study area

Rock Types	RMR	E_d (Mpa)
Basalt	55	3.20
Limestone	52	2.75
Sandstone	49	2.40
Gypsum	45	2.00

5.4 Engineering Properties of Soils

Engineers consider soil to be a “relatively loose agglomerate of mineral and organic materials and sediments found above bedrock” (Holtz and Kovacs, 1981). This definition includes geologic soils, unconsolidated sediments, and produced by the disintegration of rocks by the processes of weathering. The engineer's and geologist's definition of soil is therefore, commonly used in studying and describing landslides (Varnes, 1978).

5.4.1 Types of soils in the study area

Three soil types have been identified in the study area and the representative samples at specified location and depth were collected and tested were conducted for their properties and classifications in relation to the landslide conditions. These are colluvial, alluvial & Residual soils.

(i) Residual Soils

The residual soils in the study area are mostly dominated by sites where deep soils have formed from in situ weathering of basalt parent materials on very gentle and flat areas and is non-slope forming materials. These are black in color whereas, down to Jema it changes its color to gray and dull white as the rock units changes in to limestone and shale. They are used for flat agricultural lands.

(ii) Colluvial soil

Colluvial soils in the area are deposits that displaced from their original location of formation by gravity forces. From the visual observations and field tests in the study area, they can generally be categorized as very loose, unconsolidated, heterogeneous and permeable unit. These characteristics provide a good matrix for the rock fragments of variable shapes and sizes and forms voids within the soil mass, allows water to percolate and make the soil migrate and can thus resulted in the sliding process. Therefore, it can be concluded that the colluvial soils in the present study area are the most susceptible soils for the sliding process.

(iii) Alluvial soils

This is a quaternary deposit transported and deposited by the river water and found mainly following Aleltu, Gede, Horte and Hofi Rivers. From visual observations in the field, they are mostly deep, sorted and often stratified, comprising of gray silt, sand and gravel grain sizes.

For the present study soil samples were collected and tested in the laboratory only from the colluvial soil as, the other two types residual and alluvial soils do not account for the landslide activity in the area.

5.4.2 Classification of soils of the study area

Most of the study area classified as high hazard zones is covered with colluvial soils, where most landslides are frequently occurring and found to be potentially unstable. From these unstable slopes, soil samples were collected to carry out laboratory tests for classification and characterization with reference to the landslide occurrences. Thus, from the classification, it is possible to estimate the shear strengths of the soil in the area.

For soil classification many standards are available however, for the present study the 'Unified Soil Classification' (USCS) has been adopted. To determine the Index properties of the soil in the area, the particle size distribution of the samples was determined from a gradation test (sieve and sedimentation analyses) and the liquid limit, plastic limit and plasticity index from Atterberg's limit test, (tables 5.6 and 5.7).

Table 5.6: Grain size distribution of soil sample in the study area

Sieve opening	Weight retained	Percentage retained	Cumulative percentage retained	Percentage finer
>2	11.14	5.57	5.57	94.43
2-1.18	1.07	0.54	6.11	93.89
1.18-0.6	2.11	1.05	7.16	92.82
0.6-0.5	1.08	0.54	7.7	92.3
0.5-0.25	6.32	3.16	10.86	89.14
0.25-0.15	6.95	3.48	14.34	85.66
0.15-0.063	10.56	5.28	19.62	80.38
0.063-0.04	17.52	8.76	28.38	71.62
0.04-0.016	49.84	24.92	53.3	46.7
0.016-0.0063	34.73	17.36	70.66	29.34
0.0063-0.002	12.06	6.03	76.69	23.31
0.002-0.00063	26.37	13.19	89.88	10.12
<0.00063	20.25	10.12	100	-

For the classification of the analyzed soil sample following observations are being made;

- (I) The given soil sample is coarse grained as more than 50% is retained on No. 200 sieve.
- (II) The given soil sample is sands as more than 50% of coarse fraction passing No. 4 sieve.
- (III) Plasticity index is greater than 7 (for given sample, the PI is 39.24%).
- (IV) More than 12% passes No. 200 sieve.
- (V) The uniformity coefficient, $C_u = D_{60} / D_{10} = 0.0095/0.0011 = 8.36$ which is greater than 6, thus the soil is well graded.

Therefore, from the above observations according to USCS, the soil may be classified as well graded clayey sands (SC).

Table 5.7: Index properties as determined from the soil samples collected from unstable slopes

Location	Soil depth (cm)	Origin	LL, %	PL, %	PI, %	Natural water content, %
437371E, 109971N	50	Colluvial	88.34	49.10	39.24	10.75

LL-Liquid Limit, LP-Plastic Limit, PI-Plasticity Index

The natural water content of soil unit is 10.75%. The sample comprises of 29.34% clay and 70.66% silts and sand fractions. The presence of clay in the soil is a background factor that supports the triggering factors in aggravating the mass

movement in the area. From Fig. 5.1, it is indicated that the soils present in the area are classified as well graded soils as per the Unified Soil Classification System.

Further, concerning the determination of the shear strength of the soil in the laboratory, time, resource and experience were the main limitations, as these tests are very sensitive and it needs proper sampling and testing methods. Therefore, it was not possible to conduct the tests to determine the cohesion and angle of shearing resistance of the soil.

However, the values for cohesion and angle of shearing resistance have been taken from USBR, 1982 standard table based on the index properties of soil (Bowles, 1996). According to this, the cohesion, angle of friction and the dry unit weight of the soils for the area are found to be 5.0lb/in², 33.9⁰ and 115.6lb/ft³, respectively that used in stability analysis for the unstable slopes.

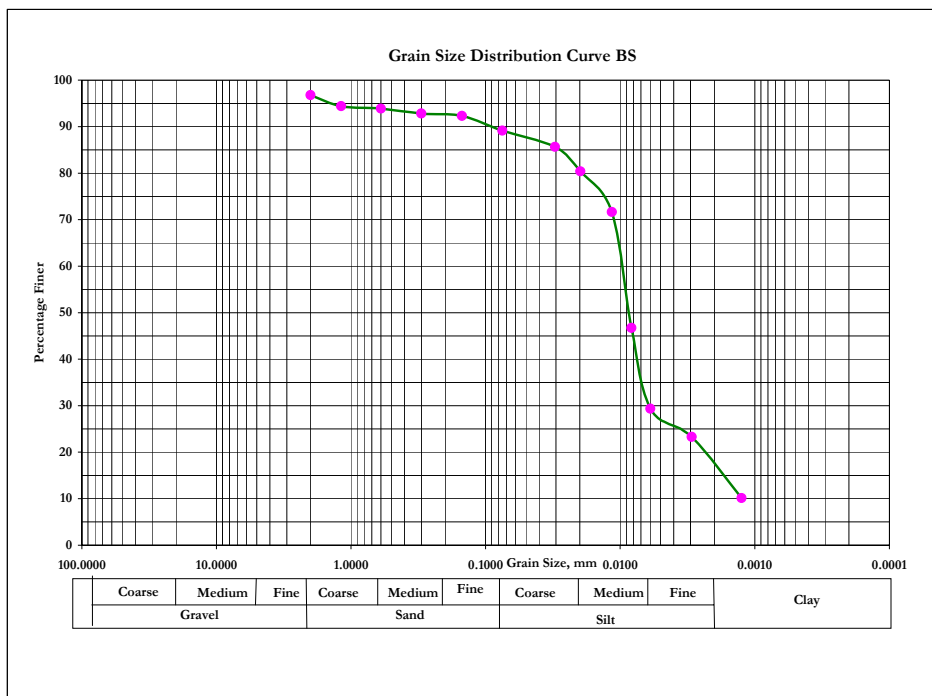


Fig. 5.1: Gradation curve of the soils present in the study area

5.5 General overview of slope stability Evaluation

In order to develop models for slope instability applicable to a given area, there is a need to analyze the causative factors controlling the occurrence of landslides to propose effective remedial measures (Varnes, 1978). This means that the primary

importance is the recognition of the conditions, which caused the slope to become unstable and the processes, which triggered that movement.

Slope analysis involves assessing forces promoting failure and comparing them analytically with forces resisting failure and arriving at a resultant Factor of safety. The factor of safety is defined as the ratio of the total forces available to resist sliding to the total forces available to induce sliding. Both of these types of forces and their components are numerous, complicated and needs a great care and personal experience to incorporate in the factor of safety analysis.

The stability of slope is generally viewed in relative terms. A slope would not remain unchanged forever. However, a slope is said to be stable if the factor of safety is greater than unity. That is the total forces available to resist sliding must be greater than the total forces available to induce sliding. And again this may not be the final conclusion to say that the slope is completely stable forever. This is because the stability of slopes can also be influenced by other triggering factors that are not included in the safety factor determination either as forces that induce sliding or forces that provide resistance to sliding. Therefore, in the analysis of the stability of the slope a careful attention should be given in considering all the anticipated factors for inducing sliding.

The important factors that influence the factor of safety of the slopes are;

- (i) Geometry of the slope: slope height, slope angle and upper slope angle
- (ii) Structural discontinuities: their preferred orientation
- (iii) Shear strength properties of discontinuities: cohesion(c) and angle of internal friction (ϕ)
- (iv) Water saturation conditions.

The Factor of safety for slope stability analysis is calculated according to the mode of failures such as; plane, wedges, Circular, etc. Thus, an understanding of these possible modes of failure is also crucial to the successful application of a method of slope analysis.

Slope stability is very important for the safe functioning of any development on unstable slopes. Identification of instability of the slopes in the initial stages may help in evolving proper remedial measures. Therefore, it is essential to carry out the

stability analysis on the unstable slopes in the initial stages of investigation and planning.

For the detailed stability analysis on the unstable slopes, the discontinuity analysis (Dip-Direction and amount of dip), the geology and the geometry of slope sections in terms of slope direction and inclination, upper slope direction, inclination and the height of the slope, the Kinematic Check for possible modes of failures should be presented.

Through the present study, an attempt is made to identify the zones which have a potential for instability. For this, a detailed landslide zonation has been carried out and the zones which have a very high and high potential for instability has been delineated, (Chapter 4). For all these very high and high potential unstable zones, a detailed stability analysis have to be carried out which may require an experience in exhaustive field data collection, sampling and systematic mathematical computations. With the limitations on time, resources and financial support such elaborate study is beyond the scope of the present study. Thus through this study, it is strongly recommended to conduct more systematic and elaborate study in future to come up with more logical and feasible recommendations for stabilization of these critical zones.

CHAPTER VI

REMEDIAL MEASURES AND RECOMMENDATIONS FOR SLOPE STABILIZATION IN THE STUDY AREA

6.1 Preamble

The purpose of this study is to inform and recommend both the public and the concerned representative bodies about the factors that cause landslides and some possible preventive and/or remedial measures that could be taken for the area.

As previously pointed out from the evaluation of landslide hazard and Zonation mapping including the field observations in the area, it was concluded that most of the slopes are potentially unstable and needs remedial measures for stabilization.

Many general reviews of the methods of landslide remediation (stabilization of existing slopes) have been made but the suitability and cost effectiveness of any particular method depends upon several factors such as, type and behavior of the slope materials, types of the landslides, nature of the topography, slope dimension and configuration, etc. (Popescu M. E., 2001). In other case, the selections of appropriate remedial measures depend on: Engineering feasibility, Economic feasibility, and environmental acceptability. Taking all these factors into consideration, the effective remedial measures to be taken for the area is found to be very difficult. However, through this study an attempt is made to suggest some form of feasible remedial measures for the critical slopes.

6.2 Remedial Measures

Irrespective of the limitations mentioned above, some remedial methods for achieving suitable stability for the area have been suggested which may include;

- (i) Avoiding the landslide prone areas for settlement, agricultural and any other activities, especially that has been identified as very high hazard zones
- (ii) Improving stability by reducing the forces that cause movement
- (iii) Improving stability by increasing the forces that resist movement, or by using their combination (i and ii).

6.2.1 Avoiding the landslide prone areas for settlement, agricultural and any other activities

Shallow and deep-seated landslides comprising colluvial soils are present on most of the slopes in the area, which are already identified as very high and high hazard zones (Chapter 4), for example facet numbers 11, 12, 48, 49 and 54. These areas are susceptible to rapid saturation from infiltration of surface runoff and direct infiltration of precipitation (especially during rainy seasons) as a result of loose unconsolidated soils and the weathered and fractured rocks. As a result, these areas may pose a danger for Haro and other villages in near future. Moreover, due to the nature of the topography and the dimensions of the slopes on which the landslides are occurring, any form of remedial measures will not be economically and/or geotechnically feasible to reduce the likelihood of the landslide by engineering mitigation measures. Therefore, avoiding the area for settlement, agricultural and any other activities on such critical slope sections become mandatory. Avoiding for settlement should be an immediate alternative method by relocating the residents to an alternate site.

Although stabilization of the unstable slopes in the present study area are found to be very difficult because of the dimensions of the slopes, some remedial measures such as the following may still be considered;

6.2.2 Reduction of the actuating forces

The slopes in the area are at a state of equilibrium and require only some actuating forces to fail and thus reducing all such forces is very important. The actuating forces can be reduced and hence the factor of safety increased by improving drainage and/or by reducing the weight of the material that potentially involved in landslide activity. The following methods are suggested for the study area in reducing the actuating forces.

6.2.2.1 Drainage improvements

Drainage improvement is one of the most widely used methods for improving slope stability. It is often a crucial remedial measure due to the important role played by pore-water pressure in reducing shear strength. Because of its high stabilization

efficiency in relation to cost, drainage of surface water and groundwater is the most widely used and generally the most successful stabilization method (Hutchinson, 1977). Drainage improvement methods can be either surface or sub/ground water surface.

Surface drainage improvements: Surface water runoff can contribute to landslide activity by causing surficial erosion and/or rapid saturation of the ground. The surficial water runoff in the study area is one of the most landslide inducing factors on colluvial slopes during rainy seasons, especially on slopes such as; steeply inclined slopes towards the populated Haro village. Surface water improvement is generally the cost effective measure that can be implemented to reduce landslide potential or mitigate existing instability. These improvements is effective where storm water runoff flows onto or near steep slopes and potential landslide areas. Surface water improvement can be done by capturing the storm water runoff and redirecting it away from sensitive slope areas. Storm water can be captured in appropriately located ditches, catch basins, etc. Once collected, the runoff should be conveyed in a tightlines to a suitable discharge location.

The prevention and/or control of the surface can also be done by closing the ground fissures at the head of landslides and by grading the slopes to minimize the direct entry of surface water into the landslide mass.

Although the techniques for the control of surface water are various, the most preferable and cost effective methods have bee described in the works of Zaruba and Mencl (1969), which can be used for further references to work on the detail remedial measurement for the area.

Subsurface water improvements: In areas where the primary driving force is groundwater seepage, suitable remedial measures usually include drainage to lower the groundwater level and to control seepage at the slope face. Although the methods are relatively costly than for surface water methods, the application of an interceptor trench sub-drains, springhead drains and drilled drains can improve stability by lowering the groundwater level in a landslide or potentially unstable slope, thereby reducing the driving forces and increasing the soil strength.

The springhead drain is used to collect water that emerges from the slope in a concentrated area, thereby reducing the actuating forces and improving stability. *Trench sub-drains* generally are applicable to slopes where the contact with the underlying low permeability material is relatively shallow. *An interceptor trench* sub-drain is installed across the slope to intercept the groundwater before it reaches the slope face.

Drilled drains are typically used to improve stability of slopes and landslides where the groundwater cannot be intercepted with trench sub-drains, or where it is not practical to excavate trench sub-drains. Drilled drains are commonly used to improve the stability of large deep-seated landslides. There are two alternatives for drilled drains: horizontal drains and directionally drilled drains. Horizontal drains are drilled from the slope face, which limits their application to sites that have suitable access near the toe of the landslide mass. Directionally drilled drains usually are installed from the top of the slope and can be aimed to intercept a specific zone where the drainage is needed.

6.2.3 Increasing the resisting Forces

Restraining structures: the forces resisting slope movement can be increased by constructing restraining structures and/or increasing the internal strength of the soil. The ultimate choice of restraining structure must be based on the site conditions and available finance. The various selected methods for restraining structures have been listed and described in the work of Hutchinson J. N. (1977). All of these methods may not be applicable for the area due to different factors. Therefore, the most effective and alternative methods can be used.

Remedial measures for rock slopes are necessary for susceptible landslide areas. As mentioned in introductory part of this paper, the present study area exhibits a very steep rock falling, toppling and sliding slopes. The number, spacing and orientation of fractures, in relationship with the slope height affect the mechanical behavior of the rock mass and that is why remedial measures are recommended. Stabilizations that reduce the likelihood of rock from moving can be improved by incorporating benches in the slope, which can prevent or limit rock falling down the

slope with rock fall netting. Benches can also be combined with ditches to prevent water infiltration.

6.2.4 Vegetation planting

In the present study area the land cover change indicated that there was a dense vegetation cover in the area before the last few years. But due to the increasing need for agriculture and settlements, the area, by now, is highly degraded. Therefore, reforestation of the area with suitable trees is mandatory.

Vegetation cover can contribute to the stability of steep slopes by reducing erosion, reducing direct infiltration from rainfall, and increasing the strength of the near-surface soil. Dense vegetation intercepts direct rainfall before raindrops impact the soil surface, thereby reducing or eliminating rain splash erosion. With dense vegetative cover and thick forest, the likelihood of overland flow can also be reduced by reducing its flow velocity. Certain types of vegetation can have an adverse effect on slope stability. Therefore, trees that pose a safety hazard should be planted in the area at the top of the slopes. Slopes vegetated with dense, low-lying, deeply-rooted plants or shrubberies provide better protection from erosion and shallow landsliding than shallow-rooted vegetation. Generally, native vegetation is desirable because it can be maintained without irrigation during the dry season.

6.3 Recommendations

6.3.1 Stability analysis study

The landslide damage in the present study area reveals the severity of the problem. For this area, landslide hazard evaluations and Zonation mapping have been addressed. However, this study may not provide the exact evidence for the relative stability in the area. Thus, a detail engineering geologic investigations and interpretations of the relative slope stability should be carried out. This investigation should, in turn, be followed by a geotechnical study and detail slope stability analysis for successful construction of possible remedial measures.

Since different types of slope failure are associated with different geological structures, there should be different modes of failures that could be identified for slope stability analysis. Therefore, the kinematic check for possible modes of

failures should be analyzed for the areas that categorized as very high, high and moderate landslide hazard zones. Further, these areas have to be further analyzed for their Factor of Safety for existing and anticipated adverse conditions.

6.3.2 Avoidance for settlement

Total avoidance for settlement in the very high hazard area, especially facet numbers 11, 12, 48, 49 and 54 around the Haro village should be made mandatory by relocating the residents to an alternate site. This is because the areas will not be economically and geotechnically feasible to reduce the likelihood of a landslide by engineering mitigation measures.

6.3.3 Drainage improvements

Most of the areas that have been affected by sliding are generally uneven and traversed by different fissures and become fully saturated, especially during rainy seasons due to the flows of surface runoff where water accumulates and wet ground develops. For this problem, different types of surface drainages should be employed. These drainage improvement methods can involve the following activities.

- (i) All surface runoff and springs flowing into the unstable slopes must be contained and diverted away from the slides.
- (ii) Excavation of open ditches with adequate dimensions is necessary for discharging of rain water runoff. Ditches must be paved with natural hard stones.
- (iii) Peripheral ditches in the upper slopes can be excavated so as to divert the surface water flowing down into the potentially unstable slopes.
- (iv) Other stabilization measures can also be practiced to reduce the progressive deterioration incorporating benches, terracing/bunding to prevent water infiltration

In areas where the primary driving force is groundwater seepage, suitable drainage improvements can be done to lower the groundwater level and to control seepage at the slope face. Although the methods are relatively costly, the application of an interceptor trench sub-drain, springhead drain and drilled drains can improve

stability by lowering the groundwater level in a landslide or potentially unstable slope.

6.3.4 Retaining structures

As most of the slopes in the area are naturally very steep and very unstable, the slope must be provided with possible retaining structure. Because constructing restraining structures can be used to increase the forces resisting slope movement and/or increase the internal strength of rock and soil masses. Although the ultimate choice of restraining structure based on the site conditions and available finance, some applicable methods of simple retaining structure such as; in-situ retaining walls, Gabion walls, Rock anchors, Buttress counterforts, Rock fall stopping systems (rock trap ditches, benches, fences) etc. can be constructed.

6.3.5 Tree planting

Trees of suitable species and those have no adverse effects on the slopes, those that have the maximum consumption of water and the highest transpiration rates have to be planted. Generally, native vegetation with dense, low-lying, deeply-rooted plants or shrubberies is desirable and provides better protection from erosion and landslide activity.

In general, most of the study area is highly prone to landslide activity. Unless immediate action plans are implemented, this zone will soon deteriorate to the critical category. Therefore, the area needs urgent attention in the form of avoidance and mitigatory measures like those mentioned in the previous paragraphs.

CHAPTER VII

CONCLUSIONS

Among the highlands and dense population areas, Haro village and its surrounding, in the Central Ethiopia, is one of the unstudied but known for catastrophic landslide occurrences and hazards. The Geologic conditions, topographic ruggedness and instability and the nature of structures greatly influence the landforms and active processes in the present study area. For this reason, living in the area and using the land has become difficult and hazardous to local inhabitants.

Geologic, Topographic, Climatic conditions and human activities are some of the factors that have contributed to the instability of the slopes in the study area. The slopes in general are characterized by shallow and deep seated landslide processes in the form of falls, topples, slides and recently flown debris deposits comprising rock fragments of varied shapes and sizes.

Mesozoic Sedimentary and the unconformably overlying Tertiary volcanic rocks form the geological formation of the present study area. Five geologic units mainly cover the area; Volcanic rocks, Goha-tSION Formation, Limestone, Sandstone, and residual soils which are characterized by different structural discontinuities and weathering grades.

In general, the slope instabilities that pose danger to the villages are more apparent and concentrated in the areas of such geological structures and types, weak contact of rock beddings, poor drainages, less vegetation cover and loose unconsolidated colluvial soils.

Even though the detailed data were absent, an estimated data gathered indicated that the landslide consequences in the past few years found to claimed 7 person's and more than 120 livestock's lives, injured 6 persons, destroyed 9 houses and 6000 estimated quintals of different kinds of crop yields, abandoned 965.5 hectares of lands and evacuated 2974 residents from the area. This shows the destructive potential of landslides, which should be considered as a serious and recurrent natural hazard in the study area.

Though the Landslides in the area occurred several times, resulted in such consequences and still threatening, the only responses to this problem was to rehabilitate the villagers to other places year after year. However, this couldn't be the sustainable solution for its prevention or mitigation.

Therefore, from these practical concerns and unstudied of the area, the present research problem was proposed to evaluate and identify the major causative factors responsible for the occurrences of such landslides in order to produce a relative landslide hazard mapping using the LHEF rating scheme to recommend slope stability analysis for some possible remedial measures. A landslide hazard zonation map is an important tool for designer, engineers and geologists that used to classify the land surface into zones of varying degree of hazard, based on the estimated significance of causative factors which influence stability.

For the present study, Anbalagan's approach (1992) of the "landslide hazard evaluation Factors (LHEF)" rating scheme has been used as the main methodological tool. Applying the LHEF scheme is selected for this study because the data collection process is less intensive, user-friendly and can be understood by a non-specialist without more intensive application of computer.

Six major inherent causative factors influential to slope failure have been recognized and extracted for the purpose of generating a simple landslide hazard classification namely; Geology (lithology and structure), slope morphometry, relative relief, land use land cover and ground water conditions. These factors are evaluated from desk study and field works, facet wise. For each facet, the data are collected and analyzed based on the selected categories for the LHEF rating. Later, the ratings for each facet were summed up to give the Total Estimated Landslide Hazard Rating (TELHR).

From the overall Landslide Hazard Evaluation of the area, the final landslide hazard map has been generated from 54 facets and five categories of landslide hazard zones have been identified as;

- (i) very low hazard zone comprising 18%
- (ii) low hazard zone with 15%

- (iii) moderate hazard zone which shares 15%
- (iv) high hazard zone which shares 41%
- (v) very high hazard zone which shares 11% of the total area

Therefore, as most of the study area is found to be in high landslide hazard zone and potentially unstable, there should be a need to carry out stability evaluations to recommend appropriate remedial measures for these slopes.

Through this study, the potentially unstable slopes (critical slope sections) have been identified and the Engineering properties rocks and soils have been evaluated based on the hazard zonation mapping and practical field observations supported with some experimental data tests and empirical estimations. However, for the detailed slope stability analyses, the work needs elaborate field data collection, sampling and systematic mathematical computations, which in turn requires sufficient time, experience, adequate resource and financial support. All these factors made these elaborate works beyond the reach of the present study. Thus, it is strongly recommended to conduct a systematic and elaborate study in future to come up with more logical and feasible recommendations for stabilization of these critical zones.

Although the slope stability analyses were not addressed in this study, some economic methods of slope stabilization methods or remedial measures have been suggested and should be recommended against the practice. These are:

- (i) Avoiding the landslide prone areas for settlement, agricultural and any other activities on the critical slope sections, especially that has been identified as very high hazard zones
- (ii) Improving the stability by appropriate surface and subsurface drainages systems
- (iii) Improving the stability by constructing simple restraining structures and
- (iv) Planting suitable trees

ANNEXURES

Annexure I: Landslide Hazard Evaluation Factors (LHEF) Rating Scheme, (Anbalagan, 1992)

Description Factors	Category	Rating	Remarks	
<p style="text-align: center;">LITHOLOGY</p> <p>Rock types</p> <p>Soil Type</p>	<p>Type - I Quartzite and limestone Granite and Gabbro Gnesis</p> <p>Type - II Well cemented terrigenous Sedimentary rocks, dominately sandstone with minor clay shale beds Poorly cemented terrigenous Sedimentary rocks, dominantly sandstone with minor clay shale beds</p> <p>Type - III Slate and Phyllite Schist Shale with interbedded clayey and non-clayey rocks Highly weathered shale, phyllite and Schist</p> <p>Older well-compacted fluvial fill material (alluvial) Clayey soil with naturally formed surface (eluvial) Sandy soil with naturally formed surface (alluvial) Debris comprising mostly rock pieces mixed with clayey/sandy soil (colluvial) Older well compacted younger loose material</p>	<p>0.2 0.3 0.4</p> <p>1.0 1.3</p> <p>1.2 1.3 1.8 2.0</p> <p>0.8 1.0 1.4 1.2 2.0</p>	<p><u>Correction factor for weathering</u></p> <p>a) Highly weathered: rock discoloured, joints open with weathering products, rock fabric altered to a large extent: correction factor C_1</p> <p>b) Moderately weathered: rock discoloured with fresh rock patches, weathering more around joint planes, but rock intact in nature: correction factor C_2</p> <p>c) Slightly weathered: rock slightly discoloured along joint planes, which may be moderately tight to open, intact rock; correction factor C_3</p> <p>The correction factor for weathering should be multiplied with the fresh rock rating to get the correct rating.</p> <p>For rock type I; $C_1 = 4, C_2 = 3, C_3 = 2$</p> <p>For rock type II; $C_1 = 1.5, C_2 = 1.25, C_3 = 1.0$</p>	
	<p style="text-align: center;">STRUCTURE</p> <p>Relationship of structural discontinuity with slope</p> <p>Relationship of parallelism between the slope and the Discontinuity*</p> <p>Planar ($\alpha_j - \alpha_s$) Wedge ($\alpha_i - \alpha_s$)</p> <p>Relationship of dip of discontinuity* and inclination of slope</p> <p>Planar ($\beta_j - \beta_s$) Wedge ($\beta_i - \beta_s$)</p> <p>Dip of discontinuity*</p> <p>Planar - β_j Wedge - β_i</p>	<p>I $>30^\circ$ II $21^\circ-30^\circ$ III $11^\circ-20^\circ$ IV $6^\circ-10^\circ$ V $<5^\circ$</p> <p>I $>10^\circ$ II $0^\circ-10^\circ$ III 0° IV $0^\circ - (-10^\circ)$ V $< (-10^\circ)$</p> <p>I $<15^\circ$ II $16^\circ-25^\circ$ III $26^\circ-35^\circ$ IV $36^\circ-45^\circ$ V $>45^\circ$</p>	<p>0.20 0.25 0.30 0.40 0.50</p> <p>0.3 0.5 0.7 0.8 1.0</p> <p>0.20 0.25 0.30 0.40 0.50</p>	<p>α_j = dip direction of joints α_i = direction of line of intersection of two discontinuities α_s = direction of slope inclination β_j = dip of joint β_i = plunge of line of intersection of two discontinuities β_s = inclination of slope</p> <p>* Discontinuity refers to the planar discontinuity or the line of intersection of two planar discontinuities, whichever, is important concerning instability</p> <p>Categories I = very favourable II = favourable III = faire IV = unfavourable V = very unfavourable</p>

Description Factors	Category	Rating	Remarks
DEPTH OF SOIL COVER <5m 6-10m 11-15m 16-20m >20m		0.65 0.85 1.30 2.0 1.20	
SLOPE MORPHOMETRY Escarpment/cliff Steep slope Moderately steep slope Gentle slope Very gentle slope	>45° 36°-45° 26°-35° 16°-25° <15°	2.0 1.7 1.2 0.8 0.5	Number of contour lines over one cm length (1:50,000) Slope angle >25 >45° 19-25 36° - 45° 13-18 26-35° 8-12 16°-25° <7 <15°
RELATIF RELIEF Low Medium High	<100m 101-300m >300m	0.3 0.6 1.0	
LAND USE/LAND COVER Agricultural (populated flat) land Thickly vegetated forest area Moderately vegetated area Sparsely vegetated area with lesser ground cover Barren land		0.65 0.80 1.2 1.5 2.0	
GROUND WATER CONDITON Flowing Dripping Wet Damp Dry		1.0 0.8 0.5 0.2 0.0	

Annexure II: Rock Mass Rating System (After Bieniawski 1989)

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS									
Parameter		Range of values							
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
		Rating	15	12	7	4	2	1	0
2	Drill core Quality <i>RQD</i>		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
			Rating	20	17	13	8	5	
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm		
			Rating	20	15	10	8	5	
4	Condition of discontinuities (See E)		Very rough surfaces, Not continuous, No separation unweathered wall rock	Slightly rough surfaces Separation <1 mm, Slightly weathered walls	Slightly rough Surfaces, Separation <1mm, Highly weathered walls	Slicksided surfaces or Gouge <5mm thick, or, Separation 1-5 mm, Continuous	Soft gouge >5 mm thick, or Separation >5mm Continuous		
			Rating	30	25	20	10	0	
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	<10	10-25	25-125	>125		
		(Joint water press/ (Major principal (δ))	0	< 0.1	0.1, - 0.2	0.2 - 0.5	> 0.5		
		General Conditions	Completely dry	Damp	Wet	Dripping	Flowing		
			Rating	15	10	7	4	0	
B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)									
		Strike and dip orientations	Very favorable	Favorable	Fair	Unfavorable	Very Unfavorable		
Ratings	Tunnels & mines		0	-2	-5	-10	-12		
	Foundations		0	-2	-7	-15	-25		
	Slopes		0	-5	-25	-50			
C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS									
		Rating	100-81	80-61	60-41	40-21	< 21		
		Class number	I	II	III	IV	V		
		Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock		
D. MEANING OF ROCK CLASSES									
		Class number	I	II	III	IV	V		
		Average stand-up time	20 yrs for 15m span	1 year for 10m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span		
		Cohesion of rock mass (KPa)	> 400	300 - 400	200 - 300	100 - 200	< 100		
		Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15		
E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions									
		Discontinuity length (persistence)	< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m		
		Rating	6	4	2	1	0		
		Separation (aperture)	None	< 0.1 mm	0.1 - 1.0 mm	1 - 5 mm	> 5 mm		
		Rating	6	5	4	1	0		
		Roughness	Very rough	Rough	Slightly rough	Smooth	Slicksided		
		Rating	6	5	3	1	0		
		Infilling (gouge)	None	Hard filling < 5mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5 mm		
		Rating	6	4	2	2	0		
		Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed		
		Ratings	6	5	3	1	0		
F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**									
Strike perpendicular to tunnel axis				Strike parallel to tunnel axis					
Drive with dip - Dip 45 – 90°		Drive with dip - Dip 20 – 45°		Dip 45 – 90°		Dip 20 – 45°			
Very favourable		Favourable		Very unfavourable		Fair			
Drive against dip - Dip 45-90°		Drive against dip - Dip 20-45°		Dip 0-20° - Irrespective of strike					
Fair		Unfavourable		Fair					

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly.

** Modified after Wickham et al (1972).

Annexure III: Weathering grade for rock mass b Irfan and Dearman, 1978

Term	Description	Weathering Grade
Fresh	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces	I
Slightly weathered	Discoloration indicates weathering of the rock material and discontinuity surfaces	II
Moderately weathered	Less than 35% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework as core stone	III
Highly weathered	More than 35% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework as core stone	IV
Extremely weathered	All the rock material is decomposed and/or disintegrated to a soil. The original mass structure is still largely intact	V
Residual soil	All the rock material is converted to soils, the mass structure and material fabrics are destroyed	VI

Annexure IV: Field Estimates of Uniaxial Compressive Strength of Rock Mass

Grade*	Term	Uniaxial Compressive Strength (MPa)	Point Load Index (MPa)	Field Estimates of Strength	Examples
R ₆	Extremely Strong	>250	>10	Rock material can only be chipped under repeated hammer blows	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R ₅	Very Strong	100-250	4-10	Specimen requires many blows of a geological hammer to break intact rock specimen	Amphibole, sandstone, basalt, grandiorite, peridotite, rhyolite, tuff
R ₄	Strong	50-100	2-4	Specimen requires more than one blow of a geological hammer to fracture the intact rock specimen	Limestone, marble, sandstone, schist
R ₃	Medium Strong	25-50	1-2	Can not be scarped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Concrete, phyllite, schist, siltstone
R ₂	Weak	5-25	**	Can be peeled with a pocket knife, specimen can be fractured with difficulty, shallow indentation made by firm blow with point a geological hammer	Chalk, claystone, potash, marl, siltstone, shale, rocksalt
R ₁	Very weak	1-5	**	Rock material crumbles under firm blows of geological pick, can be scarped by a pocket knife	Highly weathered or altered rock, shale
R ₀	Extremely weak	0.25	**	Indented by thumb nail	Stiff fault gouge

* Grade according to Brown (1981)

** Point load tests with a Uniaxial Compressive Strength below 25MPa are likely to yield highly ambiguous results.

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