



**Slope Stability Analysis on a Selected Slope Section
along the Road Gohatsion – Dejen**

A Thesis

Submitted to

The School of Graduate Studies

Addis Ababa University

**In Partial Fulfillment of the Requirements for the Degree of
Masters in Earth Sciences (Engineering Geology)**



Samuel Molla



June 2011



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School of Graduate Studies
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DECLARATION

I, the undersigned, declare that this thesis is my original work and has been carried out by me under the supervision of Dr. Tarun K. Raghuvanshi. I further declare that this work has not been submitted to any other university or institute for a degree on any other university.

All sources of materials used for the thesis work have been duly acknowledged.

Samuel Molla

Signature: _____

Date: June, 2011

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Abstract

Rainfall triggered landslides is a common problem in many areas; along road cuts, hilly and mountainous regions of the highlands of Ethiopia. In the Blue Nile gorge, landslide is a common problem for last many years, especially during the rainy seasons. Slope instability problems in the form of rock fall, landslide and complex disturbances are the common events in the area on the sides of the main road from Gohatsion to Dejen. Detailed slope stability studies along this road will give opportunity to deal with the different mode of failure separately and to provide the best remedial measures for the different slope sections independently to protect failure of structures and loss of life because of the slope instability problems.

For the present study a detailed slope stability analysis was carried out for a critical slope section which falls 15 km short of Dejen town about 215km from Addis Ababa. For the study, both primary and secondary data were used. The primary data was collected from the field work measurements and the observations. The secondary data used for the present slope stability analysis were collected from the GSE and JiCA teams working on the landslide problem along the road from Gohatsion to Dejen. Sensitivity analysis was also performed to estimate the shear strength parameters (cohesion and internal friction angle) for the detail slope stability analysis.

The deterministic slope stability analysis approach was followed to perform the detailed slope stability analysis of the selected slope section in the present study. In the present study factor of safety for the selected slope section was determined for the different conditions using SARC software. In addition, SLOPE/W software was also used to determine the factor of safety for the present condition under static state.

The results of the slope stability analysis clearly indicate that the slope section is stable only for the dry condition under static state with a FOS of 1.28. For the other conditions, both under static and dynamic state, the slope section will be unstable with a FOS less than 1.0. The factor of safety for the dynamic state for worst condition is even less than 0.5. Thus, finally based on the slope stability analysis findings for existing and anticipated worst conditions suitable remedial measures were worked out.

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Chapter I

Introduction

1.1 Preamble

Most natural hazards are inherited in mountainous regions. From the natural hazards landslide is significant hazard in many parts of the world. Destructions caused by catastrophic landslides are a worldwide phenomenon, and the rapid increase of population and developmental works have augmented the problem (Varnes, 1981; as cited in Shimelies Ahmed, 2009).

Landslides are rock, earth, or debris flows on slopes due to gravity. Landslides can occur on any terrain with the given right conditions of soil, moisture, and the angle of slope. Integral to the natural process of the earth's surface geology, landslides serve to redistribute soil and sediments in a process that can be in abrupt collapses or in slow gradual slides. Also known as mud flows, debris flows, earth failures, slope failures, etc., they can be triggered by rains, floods, earthquakes, and other natural causes as well as human-made causes, such as; grading, terrain cutting and filling, excessive development, etc. Because the factors affecting landslides can be natural or human-made, they can occur in developed areas, undeveloped areas, or any area where the terrain was altered for roads, houses, utilities, buildings, and even for lawns in one's backyard. Destructions caused by catastrophic landslide are a worldwide phenomenon, and the rapid increase of population during this century has augmented the problem. During the period from 1971-1974 an average of nearly 600 people per year, worldwide, were killed by landslides (Varnes, 1981; as cited in Shimelies Ahmed, 2009).

In Ethiopia, rainfall triggered landslide is a common problem in many areas; along road cuts, hilly and mountainous regions of the highlands of Ethiopia. Lulseged Ayalew (1999), Temesgen et al. (2001), Nyssen et al. (2002), Lulseged Ayalew and Yamagishi (2004), Tenalam Ayenew and Barbieri (2004). indicated that landslides in these terrains have been affecting human lives, infrastructures, agricultural lands and the natural environment. Landslide generated problems have claimed about 300 lives, damaged over 100 km of asphalt road demolished more than 200 dwelling houses and devastated in excess of 500 ha of land in Ethiopia in the years 1991-1998 (Fig.1) (Lulseged Ayalew, 1999).

Although it could be said that the occurrence or non-occurrence of landslides depends mainly on natural causes and factors, such as; geological and geo-hydrological characteristics of any locality, exogenous factors such as; intense precipitation over a short interval of time and earthquakes also triggers and accelerate landslides. Similarly, growing human and animal populations in mountainous regions create other imbalances such as; deforestation and encroachment on steep slopes. Construction activities have also a positive contribution to slope instabilities (Shimelies Ahmed, 2009). Hence, the complexity of these causes increases due to natural and human factors. In addition to these, the human and economic consequences of such incidents are becoming more damaging, adding to the miseries of people who are already in the grip of poverty.



Fig. 1.2 Spatial distribution of zones of recent landslides in the Ethiopian Highlands
(Source : after Lulseged Ayalew, 1999).

Generally, the causes and mechanisms of the different slope failures are not clearly understood so far; this will make the damage to be much more and the remedial measures not to be more effective. Only minor works are done to reduce the damage on properties

and to protect the loss of life due to the landslides that are occurring in every part of Ethiopia (Shimelies Ahmed, 2009).

1.2 Problem Justification

Slope instability along road cuts is a common problem in many areas. This can cause damage to human beings as well as properties. Such areas has to be clearly identified including the different processes that cause the failure, mechanism of failure and the possible remedial measures for that landslide problem.

In the Abay Gorge, slope movement in the form of landslides, rock falls and complex disturbances were evident along the Gohatsion - Dejen road, adjacent to the main tributaries and around small villages. Examination of historical records of slope failures in the northern section of the basin indicated that in 1960, a bigger landslide had destroyed the Gembechi village, and 45 people were reported dead in the tragedy (Lulseged Ayalew, 1999).

There are many active landslides along this road. Recently there was a landslide event near to the Gohatsion town. According to different reports, there is circular, planar, wedge as well as toppling mode of failure along the road section (Lulseged Ayalew, 1999).

From remote sensing data some landslide areas are clearly visible along the road cut. Most of the slope instability problems in this area occur during rainy seasons (OJEC, 2008).

One of the possible causes for slope failures along the road sides is due to presence of perennial springs on the exposed rock faces. In addition, the road construction also caused the area to be disturbed and make the slope unstable due to inappropriate design of the slope. Water acts as a lubricant along the discontinuity surfaces, besides it may also exert uplift force along the discontinuity surfaces. Thus, reducing the normal stress and increasing the potential for instability of the slope sections (Shimelies Ahmed, 2009).

Identification of the different slope instability areas, the causes of failure, stability study for the present and worst conditions on individual slopes will lead to the establishment of appropriate remedial measures that can withstand the slope for a long period of time.

Different slope failures may be triggered by different mechanisms. Therefore, detailed investigation on individual slopes is appropriate.

1.3 Significance of the study

The primary significance of the study was to identify the causes and mode of the slope failure and to calculate the factor of safety for the present and the possible worst conditions. Later, possible remedial measures have been suggested by taking the possible feasibility into consideration.

Countries like Ethiopia, which is economically not strong, should have to use their resources wisely. Developmental works like road constructions causes several unstable slopes. For such slopes detailed studies should be conducted to recommend the exact possible remedial measures, taking the economy into consideration, for the long life of the road.

Besides, such research work may initiate other researchers to work on a detailed slope stability analysis in other parts of the country to reduce the possible damage that may be caused by the landslide hazards in the country. In addition, the experience gained from this research may allow the application of the method for other projects by other researcher and it may also enable the identification and hence the modification of the limitations of this approach, by comparing it with the approach to be followed.

1.4 Objective of the study

1.4.1 General Objective

The general objective of the present study is to investigate the causes and mechanism of the selected slope failure using different methods supported by different geotechnical data like: borehole data, surface extensometer data and shear strength parameters of the geotechnical material present in the area. In addition the factor of safety is calculated for the present and the possible worst conditions. Moreover, possible remedial measures have been recommended in by considering its feasibility and simplicity to implement to minimize the risk due to the landslide that could happen in future.

1.4.2 Specific objectives

- Determination of the geotechnical properties the slope mass

- Determining the possible cause/s for the failure of the slope section
- Determination of the groundwater condition for the different seasons in the slope section
- Detailed characterization of the slope section for the evaluation of the stability analysis using existing and secondary surface and subsurface data
- Determination of the stability condition based on appropriate method for the existing and possible worst conditions for the slope section
- To provide possible remedial measure for stabilization of the given slope

1.5 Approach and Methodology

To accomplish the above objectives effectively and systematically, the following methodology has been followed;

- Literature review of the study area on geological, geomorphological, hydrogeological, engineering geological and Structural outline of the area
- Collection of relevant material and secondary data that include any available published or unpublished works. Such data includes geological, engineering geological, hydrogeological maps, groundwater condition, topographic maps, geophysical and borehole data, geotechnical properties of different material, satellite imageries, aerial photos, etc.
- Collection of primary data in the field and marking different scarp faces and tension cracks on the map
- Collection of primary data for the selected slope section along the road which mainly include the different engineering geological and geotechnical properties
- Processing of the data by following graphical, analytical, experimental and empirical approach
- Determination/ estimation of the shear strength parameters of different geotechnical units
- Analysis of data which were collected during the field works and from the secondary sources

- Detailed deterministic slope stability analysis of the slope section using different slope stability analysis software
- Based on the above analysis and interpretations appropriate remedial measures were worked out

1.6 Analytical tools and materials used

Different analytical tools and materials were used in order to achieve the objectives of the present research, these were;

- Topographical map (1:50,000 scale) was used so as to delineate and prepare the base map for the present study.
- Topographical map (1:3000 scale) for the selected slope section was also used.
- To locate and to map the springs, the scarps and tension cracks, Garmin GPS was used.
- Different software were used to map the area and to carry out analysis. These software are; ArcMAP 9.3, AutoCad MAP 2007, Global MAPPER 11, ArcMAP 9.3, 3 DEM. PhotoScape 3.5 was used to prepare other graphical figures. For slope stability analysis SLOPE/W 2005 and SARC software were used.

1.7 Outcome of the study

The present research work may contribute towards the general understanding of the slope instability problem in the area. The findings from the results may be important for decision makers to solve the problem before causing a great economical loss and damage to the infrastructures and to the human life in the area. This study will also help researchers intending to work on critical slope sections in other parts of the country. Moreover, through the present study recommendations are also forwarded on proper remedial measures to be adopted in similar critical slope sections along the road alignments.

Chapter 2

Literature Review

2.1 Preamble

The landslides represent a serious problem almost in all parts of the world, because they cause economic or social losses on private and public properties. They can occur on any terrain given the right conditions of soil, moisture, and the angle of slope (Dai et al., 2002; Kanungo et al., 2006; Pan et al., 2008).

The term landslide denotes “the movement of a mass of rocks, earth or debris down a slope” (Cruden, 1991). Landslide is either a natural process or it occurs as a result of human activities which disturb the slope stability. These phenomena differ according to their shape, size of the displaced mass, moving mechanisms, velocity and other characteristics. Some features might be noticed before major landslides: springs, seeps, or saturated ground in areas that have not typically been wet before, new cracks or unusual bulges in the ground, street pavements or sidewalks, soil moving away from foundations, ancillary structures such as; decks and patios tilting and/or moving relative to the main house, tilting or cracking of concrete floors and foundations, broken water lines and other underground utilities, leaning telephone poles, trees, retaining walls or fences, offset fence lines, sunken or down-dropped road beds, sudden decrease in creek water levels when rain is still falling or just recently stopped, sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb (Ercanoglu, 2008 as cited in Shimelies Ahmed, 2009).

2.2 Types of Slope failure

The most common types of landslides are described below. These definitions are based mainly on the works of Varnes (1978) and USGS (www.pubs.usgs.gov/fs/2004/3072/pdf/fs2004-3072.pdf).

2.2.1 Fall

Falls are abrupt movements of masses of geological materials that become detached from steep slopes or cliffs. Movement occurs by free-fall, bouncing, and rolling (Fig.2.1). Depending on the type of earth materials involved, the result is rock fall, soil fall, debris fall, earth fall, boulder fall, and so on. All types of falls are promoted by undercutting, differential weathering, excavation, or stream erosion.

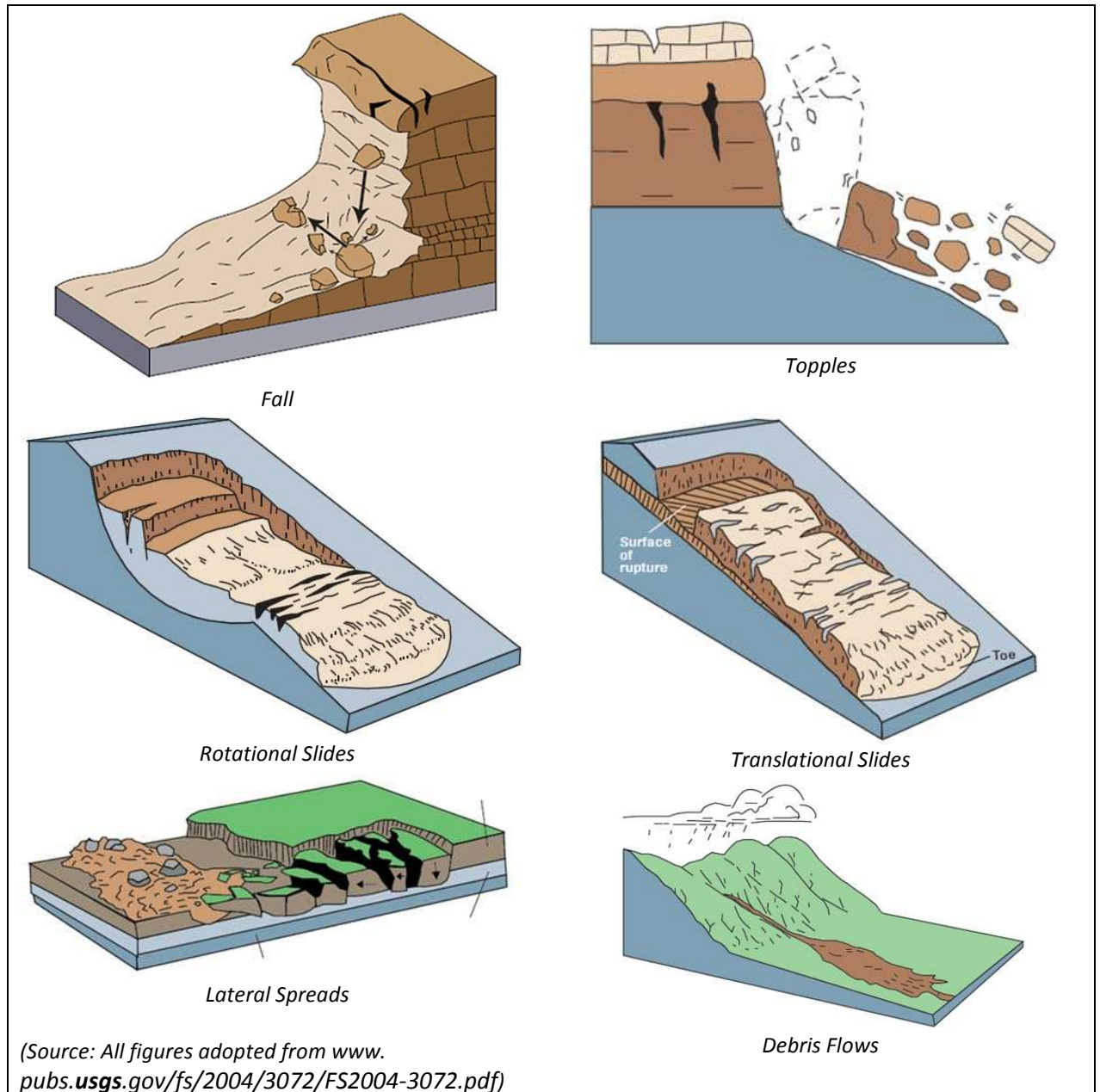


Fig. 2.1 Types of Slope failure

2.2.2 Topple

A topple is a block of rock that tilts or rotates forward on a pivot or hinge point and then separates from the main mass, falling to slope below, and subsequently bouncing or rolling down the slope (Fig.2.1).

2.2.3 Slide

A slide is a down slope movement of a soil or rock mass occurring on surfaces of rupture or on relatively thin zones of intense shear strain. Movement does not initially occur simultaneously over the whole of what eventually becomes the surface of rupture; the volume of displacing material enlarges from an area of local failure.

2.2.3.1 Rotational Landslide

A landslide on which the surface of rupture is curved upward (spoon-shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope (Fig.2.1). The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump.

2.2.3.2 Translational Landslide

The mass in a translational landslide moves out or down, outwards along a relatively planar surface with little rotational movement or backward tilting (Fig.2.1). This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil. In freezing environments the slide may also move along the permafrost layer.

2.2.4 Lateral spread

Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer (Fig.2.1). Such failures commonly are accompanied by some general subsidence into the weaker underlying unit.

2.2.5 Flows

A form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows in down slope direction. They have been informally and inappropriately called “mudslides” due to the large quantity of fine material that may be present in the flow. Occasionally, as a rotational or translational slide gains velocity and the internal mass loses cohesion or gains water, it may evolve into a debris flow (Fig.2.1). Dry flows can sometimes occur in cohesionless sand (sand flows). Debris flows can be deadly as they can be extremely rapid and may occur without any warning.

2.2.6 Complex

These are landslides that feature components of two or more of the basic types of landslides and can occur either simultaneously or at different times during the onset of slope failure.

2.3 Factors influencing slope stability

The varied topographic features of the earth’s surface are possible only because the shear strength of the soil exceeds shearing stresses imposed by gravity or other loadings. Slope failure not only can occur in the steepest slope but sometimes occur in relatively flat slopes. Factors leading to instability can generally be classified based on the effect they have on slopes (Varnes, 1984; Yokota and Iwamatsu, 1999; Chigira, 2002).

2.3.1 Gravity

The main force responsible for mass wasting is gravity. Gravity is the force that acts everywhere on the Earth's surface, pulling everything in a direction toward the center of the earth. On a slope, the force of gravity can be resolved into two components: a component acting perpendicular to the slope and component acting tangential to the slope. On a steeper slope, the shear stress or tangential component of gravity increases and the perpendicular component of gravity decreases. Therefore, the down-slope movement of a material is favored by steep slope angles which increase the shear stress, and anything that reduces the shear strength, such as; lowering the cohesion among the particles or lowering the frictional resistance (www.tulane.edu/~sanelson/geol204/slopestability.htm).

2.3.2 The role of water

Although water is not always directly involved as the transporting medium in mass-wasting processes, it does play an important role. Water becomes important for several reasons. Nelson (2010) has described the role of water in slope stability which is described in the following Paragraphs (www.tulane.edu/~sanelson/geol204/slopestability.htm):

Addition of water from rainfall adds weight to the slope. Water can seep into the soil or rock and replace the air in the pore spaces or fractures. Weight is force, and force is stress divided by area, so the stress increases and this can lead to slope instability.

Water has the ability to change the angle of repose. If the sand is somewhat wet, however, one can build a vertical wall. If the sand is too wet, then it flows like a fluid and cannot remain in position as a wall.

- Dry unconsolidated grains will form a pile with a slope angle determined by the ***angle of repose***. The angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable, and is controlled by the frictional contact between the grains. In general, for dry materials the angle of repose increases with increasing grain size, but usually lies between about 30° and 37° .
- Slightly wet unconsolidated material exhibits a very high angle of repose because surface tension between the water and the solid grains tends to hold the grains in place.
- When the material becomes saturated with water, the angle of repose is reduced to very small values and the material tends to flow like a fluid. This is because the water gets between the grains and eliminates grain to grain frictional contacts.

Water can be absorbed by minerals in the soil. Absorption causes the electronically polar water molecule to attach itself to the surface of the minerals. Adsorption causes the minerals to take the water molecules into their structure. By adding water in this fashion, the weight of the soil or rock is increased. Furthermore, if adsorption occurs then the surface frictional contact between mineral grains could be lost resulting in a loss of

cohesion, thus reducing the strength of the soil. In general, wet clays have lower strength than dry clays, and thus adsorption of water leads to reduced strength of clay-rich soils.

Water can dissolve the mineral cements that hold grains together. If the cement is made of calcite, gypsum, or halite, all of which are very soluble in water, water entering the soil can dissolve this cement and thus reduces the cohesion in between the mineral grains.

Liquefaction occurs when loose sediment becomes oversaturated with water and individual grains loose grain to grain contact with one another as water gets in between them. This can occur as a result of ground shaking.

Groundwater exists nearly everywhere beneath the surface of the earth. It is water that fills the pore spaces between grains in rock or soil or fills fractures in the rock. Changes in the level of the water table occur due to changes in rainfall. The water table tends to rise during wet seasons when more water infiltrates into the system, and falls during dry seasons when less water infiltrates. Such changes in the level of the water table can have effects on the factors discussed above.

Another aspect of water that affects slope stability is fluid pressure. As soil and rock get buried deeper in the earth, the grains can rearrange themselves to form a more compact structure, but the pore water is constrained to occupy the same space. Which inturn increase the fluid pressure to a point where the water ends up supporting the weight of the overlying rock mass. When this occurs, friction is reduced, and thus the shear strength holding the material on the slope is also reduced, resulting in slope failure.

2.3.3 Geological factors

Translational/rotational slides generally occur in relatively cohesive, homogeneous soils and rocks. Landslide events are strongly controlled by the nature of the regolith material (Yokota and Iwamatsu, 1999; Wakatsuki et al., 2005).

Failure commonly occurs along bedrock bedding planes that are deep-seated and dip into the same direction as the slope surface. In saturated conditions, incompetent material may fail under overburden weight and high pore pressures, resulting in a deep-seated rotational-type failure. Translational slides commonly are controlled structurally by surfaces of

weakness such as; faults, joints, bedding planes, and contacts between bedrock and overlying deposits (Sidle and Ochiai, 2006).

Slope stability generally influenced by the following geological factors:

- Type and engineering-geological properties of soils/rocks, their distribution, and the effect of groundwater on these properties
- Geological structures such as; cleavage, joints, faults and folds
- Stresses in geological history

Engineering-geological properties

Lithological units, such as; basalts, shales, sandstones and limestones have different shear strength characteristics because of the varying conditions under which they are formed. They also have different mineral constituents and fabrics. Therefore, they undergo different changes in strength on remolding i.e. sensitivity (Malik, 1996).

Geological structures

Geological structures, such as; bedding, joints, foliation, cleavage, schistosity, and faults are potentially weak planes in a slope. Their strength is generally less than the surrounding intact rock. It is therefore imperative to know their orientation in relation to slope angle, direction, and strength along such potential weak planes (Sidle and Ochiai, 2006).

Stresses in geological history

In addition to the geological structures and lithology, weathering plays an important role. Mechanical and chemical weathering changes the strength parameters of the rock and soil considerably. In many landslide events, chemical alterations, such as; hydration and ion exchange in clay, are thought to have contributed to the landslide triggering (Zaruba and Mencl, 1982).

Geological history is also an important factor in determining the response of materials to excavation or landslides. In over consolidated materials, stresses stored may not have been completely released at the time of slope formation and this result into an outward movement at the base of the slopes (Malik, 1996).

2.3.4 Soil Properties

Both the hydraulic properties and the shear strength behaviors of soils can affect the stability of a slope with or without a rainstorm. Another attributed effect is the presence of soils that contain a high proportion of a type of clay mineral called smectites or montmorillinites. Such clay minerals expand when they become wet as water enters the crystal structure and increases the volume of the mineral. When such clays dry out, the loss of water causes the volume to decrease and the clays to shrink or compact. Failure is attributed with pore water pressure built up within such soils (Shimelies Ahmed, 2009).

2.3.5 Effect of vegetation

It is well understood that vegetation influences the slope stability in two ways: through hydrological effects and mechanical effects. Hydrological effects involve the removal of soil water by evapotranspiration through vegetation, which lead to an increase in soil suction or a reduction in pore-water pressure, hence, an increase in the soil shear strength. The shear strength of the soil is also increased through the mechanical effects of the plant root matrix system (Greenway, 1987).

2.3.6 Causes of Landslide

There are two primary categories of causes of landslides: natural and human-caused. Sometimes, landslides are caused, or made worse, by a combination of the two factors. These triggering factors are described below (pubs.usgs.gov/circ/1325/pdf/Sections/-Front.pdf):

2.3.6.1 Natural Occurrences

This category has three major triggering mechanisms that can occur either singly or in combination; (i) water, (ii) seismic activity, and (iii) volcanic activity. Effects of all of these causes vary widely and depend on factors such as; steepness of slope, morphology or shape of terrain, soil type, underlying geology, and whether there are people or structures in the affected areas.

2.3.6.2 Human Activities

Population expansion onto new land and creating neighborhoods, towns, and cities is the primary means by which humans contribute to the occurrence of landslides. Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides. Other examples include over steepening of slopes by undercutting the bottom and loading the top of a slope to exceed the bearing strength of the soil or other component material. However, landslides may also occur in once-stable areas due to other human activities such as; irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes. New construction on landslide-prone land can be improved through proper engineering (for example, grading, excavating) by first identifying the site's susceptibility to slope failures and by creating appropriate landslide zoning.

A mass-wasting event can occur any time a slope becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is always unstable and the process is continuous. On the other hand, triggering events can happen that cause a sudden instability. The triggering mechanisms could be shocks and earthquakes (Keefer, 2002), slope modification, undercutting or changes in hydraulic characteristics (De. Vleeschauwer and De Smedt, 2002).

2.4 Landslide Analysis Techniques

The approaches taken to analyze landslide hazard depend greatly on the scope of the problem and the physical and social context. A regional assessment, for example, is likely to differ markedly from the assessment of a high value or potentially high-risk site. The nature of information used to assess hazard may also differ depending on whether the site involves a natural slope, artificially cut slope or constructed earthworks. The presence of existing landslides also allows the application of a different set of methodologies compared to those employed in areas where no landslides exist and the hazard from first-time landslides is being assessed.

Four types of approaches for landslide susceptibility mapping are applied; landslide inventory analysis, heuristic methods, statistical analysis, and process-based or deterministic modeling. In each approach, several methods are applied, i.e. index-based and analytical

hierarchical process in the heuristic approach, statistical index, certainty factor, conditional analysis, weight of evidence modeling, landslide susceptibility analysis, probability, multiple linear regression and logistic regression method in the statistical analysis approach, and slope safety factor modeling based on static or dynamic hydrological condition in the deterministic approach (LESSLOSS, 2006).

2.4.1 Landslide Inventory Analysis

A landslide inventory map images shows the locations and outlines of landslides. A landslide inventory is a data set that may present a single event, a regional event, or multiple events. Small-scale maps may show only landslide locations whereas large-scale maps may distinguish landslide sources from deposits and classify different kinds of landslides and show other pertinent data.

Landslide inventory maps show locations and characteristics of landslides that have moved in the past but generally do not indicate the mechanism(s) that triggered them. The geologic, terrain and climatic conditions that has led to the past slope failures often provide clues to the locations and conditions of future slope failures. Therefore, inventory maps provide useful information about the potential for future landsliding. In addition, recognizing the type of landsliding can also facilitate the scope and design of site-specific geotechnical investigations and guide slope remediation strategies. Inventory maps are prepared primarily by geomorphic analysis of aerial photographs and secondarily by field reconnaissance, interpretation of topographic map contours and review of previous mapping (www.consrv.ca.gov/cgs/information/publications/Pages/LSIM_index.aspx).

2.4.2 Heuristic Analysis

Heuristic methods are also called qualitative methods and depend on expert opinion. They can be classified into two groups; geomorphological mapping (direct mapping) and index-based mapping (indirect mapping), (Soeters and Van Westen, 1996).

Geomorphological mapping, where hazard is determined by the geomorphologist in the field, is called direct mapping. The mapping is subjective and relies on the experience of the field geomorphologists. The assessment is carried out by subjective expertise, which can be

seen as advantage or disadvantage. The reason for disadvantage is the subjectivity of the assessment being strongly dependent on the originator (Van Westen, 1996).

The index based mapping considers the instability factors that play role in landsliding in the considered area. The instability factors are ranked and weighted according to their relative importance in landslide activity (Soeters and Van Westen, 1996). For this reason, the index-based mapping is called indirect mapping. The final hazard map depends on how much the expert understands the landsliding process.

In principle, a heuristic assessment model has the following steps;

- Coverage of the causal factor for slope instability as data layer (GIS – Layer)
- Normalization using internal weighting of the causal factors by assigning each attributes a weight representing the relative contribution to slope instability.
- Generation of weighted normalized data layers by reclassification or multiplication of the attribute values with the corresponding weights.
- External weighting of each criteria-data layer for the assessment of the relative significance of each causal factor for slope stability.
- Generation of a hazard index, e.g. by linear weighted addition of the criteria data layer.
- Classification of the area to zones of different degrees of exposure.

Heuristic methods assume that landslides arise under complex interaction of different casual factors which contribute to slope instability to a varying degree. In case those causal factors are recorded, it is possible to evaluate the hazard of the area by weighting and combination of those.

The basic advantages of heuristic analysis are that, there are no established rules for hazard mapping and hence there may be several hazard maps for the same area by different experts (Soeters and Van Westen, 1996).

2.4.3 Statistical Analysis

In statistical methods, sets of factors which have influence on landslide occurrence are determined. A relation between the landslide occurrence and the factors is then formed in order to predict future landslides in the area of interest. There are basically two different

approaches in statistical landslide hazard zonation; bivariate and multivariate methods (LESSLOSS, 2006).

In principle, a statistical assessment model has the following general steps;

- Selection/collection of the causal factors for slope instability and the known landslides that have occurred in the past as GIS layers.
- Calculation of the statistical parameters (depending on the selected method) for each causal to determine the significant factors that are causing landslides.
- Determining the weights for attribute (class) for each causal factor on the basis of the calculated statistics. The weights represent the relative importance of the attributes for slope instability.
- Combination of all causal factors (depending on the selected method) in the statistical model.
- Classification of the area in zones of different hazard levels.

They are based on the assumption that landslides occur in the future under equal or similar conditions as in the past. Consequently the knowledge about historical mass movements is required (Carrara et al., 1992).

2.4.4 Bivariate Methods

Each factor map (e.g. slope, geology, land- use, etc.) is combined with landslide distribution map. Then weighting values based on landslide densities evaluated for each parameter class such as; slope class, Land-use type, etc. are assigned. Among the several methods for computing the weights, the following are the most widely used ones;

- Landslide susceptibility method (Van Westen, 1993)
- Information value method (Kobashi and Suzuki, 1988)
- Weight of evidence modeling method (Van Westen et al., 2003)

2.4.5 Multivariate Methods

The methods were developed mainly in Italy by Carrara (1983) and his colleagues (Carrara et al., 1992). In these methods, all relevant factors are sampled either on a grid-cell basis or morphometric units. For each sampling unit, presence and absence of landslides are determined. The resulting matrix analyzed is based on logistic regression or discriminate

analysis. Logistic regression relates predictor variables (topographic factors, land-use, geology, etc.) to the presence and absence of landslide and uses the established relationship to produce a map of probability of future landslides (Chung et al., 1995). Good results can be obtained by these methods if the homogenous zones or only a few types of landslide processes exist in the area. Artificial neural network (ANN) classifiers are another type of multivariate method, where ANN is trained by the use of a set of associated input and output values.

Drawbacks of statistical analysis

The following are the drawbacks of statistical analysis (LESSLOSS, 2006);

- There is a tendency to simplify the factors that condition landslides, by taking only those that can be relatively easily mapped in an area or derived from a digital elevation model.
- The use of past and present observation/data can be the keys to the future assumption introduces too much generalization
- The fact that each landslide may have its own set of causal factors is not taken into account.
- The statistical analyses ignore the temporal aspects of landslides and are not able to predict impact of changes in landslide controlling conditions (e.g. fluctuations in water table, changes in land-use, rate of erosion, etc).

2.4.6 Deterministic Analysis

Deterministic analyses are quantitative and apply to small to medium size areas at large to medium scale mapping. They also require a large amount of detailed input data such as; laboratory tests, field measurements etc. for shallow rainfall induced landslide, several authors developed GIS model coupled with a dynamic hydrological model which simulate the pore water pressure over time. Deterministic landslide hazard maps normally provide the most detailed results, expressing the hazard in absolute values in the form of safety factors, or the probability of failure given a set of boundary conditions for groundwater levels and seismic acceleration. However, deterministic models require the availability of detailed geotechnical and groundwater data, and they may lead to oversimplification if such data are only partially available (LESSLOSS, 2006).

Major drawbacks of these methods include (LESSLOSS, 2006);

- As the input data normally have a high degree of uncertainty, the values that result from the computations should not be considered as absolute values of landslide occurrence.
- A considerable effort should be spent for sensitivity analysis which requires high degree of parameterization.
- The methods are not suitable for complex landslides especially the landslides with complex hydrological systems.

From the above mentioned landslide analysis techniques, for the present detail slope stability analysis, deterministic approach was followed.

2.5 Previous works

2.5.1 Previous works on landslides in Ethiopia

The magnitude of landslide occurrences and its resulting damage have been increasing from time to time in the northern, western and southern highlands of Ethiopia (Shiferaw Ayele , 2009). In the past, many researchers have tried to identify the nature, causes and intensity of these landslides in the different parts of the country.

Lulseged Ayalew (1999) discussed the relation between the mechanism of landslide and rainfall in the highlands of Ethiopia. Lulseged Ayalew (1999) has 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.

As cited in Shiferaw Ayele (2009), Getachew et al (2000) had made mass movement hazard assessment in Betto, Goffa district, North Omo Zone, Southern Ethiopia. Accordingly, they identified the existence of old landslides on steep slopes that was covered by deeply weathered, closely jointed or sheared basaltic rocks this has controlled and initiated the slope instability of the area.

Berhanu et al. (2001) conducted a research by using GIS and Remote sensing methods for natural hazard assessment of the landslide in the Wondo-Genet area. In their work they evaluated the occurrences of landslides and their relationships with various event controlling parameters using GIS and Remote Sensing techniques.

The land slide hazard zonation mapping of Dessie town was done by Kefeyalew (2001). He classified the landslide hazard zone of the Dessie town in to high, moderate, low and very low risk. In addition, Tenalem and Barbieri (2004) have conducted an inventory landslides and susceptibility mapping in the Dessie area. As cited in Sheferaw (2009), Gebretsidik Eshete (1982) has also identified and located 9 landslide areas in Dessie town.

In recent years, Kifle Woldearegay (2008) carried out geological, geotechnical and geohydrological investigations to understand the causes and triggering mechanisms of the large-scale landslide in Tarmaber area, central highlands of Ethiopia.

Shimelies Ahmed (2009) has conducted his research work in Dogua's Tembien district, Tigray regional state on Slope Stability Analysis Using GIS and Numerical Modeling Techniques. His main focus was to assess the stability of slopes from geomorphological, geological and geotechnical point of views.

2.5.2 Previous works on landslides in the Study Area

The problem of landslide hazard in the Blue-Nile basin is significant. There are still active landslides in this area. Specially, along the road from Gohatsion to Degen on the sides of the road many landslides have been identified previously. The area has been of particular interest to many researchers. As cited in Henok Woldegiorgis (2008) the Ethiopian Road Authority (ERA, 1967), identified the condition between the village Filiklik and Washa Mikael church. The main aim was to study the stability condition of the slope sections that passes along the road. According to the ERA investigation, weathered basaltic rock and the colluvial moving materials under the pier foundations were responsible for the failure of the viaduct.

The Ethiopian Institute of Geological Survey (EIGS) has explained the material characteristics of a selected section of the proposed new route using different Geophysical methods. The study was conducted to determine the depth to the hard rock material and the quality of the rock defined; to locate any linear features like faults, fractures, contacts and lineaments; and also to produce engineering geological map of the area (Mesfin Wubeshet et al., 1994).

Following this investigation, a detail investigation was done by the EIGS staff members. In this study the main objectives were to prepare geological and engineering geological maps along the road from Gohatsion to Degen; to carry out integrated geophysical surveys, drilling and pitting along the proposed route (Almaz and Tadesse Dessie, 1994).

Almaz and Tadesse Dessie (1994) identified four Engineering Geological problems in Abay Gorge and its tributaries related to landslides. The problems are; continuously moving granular deposits from the slopes of basalt escarpments, rotational failure of colluvial soil, rock fall and toppling and gully erosion. Further, Almaze Gezahegn and Tadesse Dessie (1994) identified some of the possible causes for the slope instability in the area. These causes are; (i) the huge columnarly jointed basalt, (ii) uncontrolled surface runoff, (iii) jointing of rocks and (iv) the presence of marl and shale within hard rocks.

Transport Construction Design Share Company (TCDS Co.) in collaboration with Oriental and Japan Engineering consultants (OJEC) has done geotechnical investigation for the Gohatsion-Dejen-Debre Markos road project in December 2003. By drilling and test pitting it was attempted to evaluate the engineering behavior of the subsurface material. According to their report, it was described that thick unconsolidated colluvial soil mass was the cause for the distortion of the northern parts of the road.

Lulseged Ayalew and Yamagishi (2003) have investigated a slope failure on the portion of the Blue Nile basin that stretches from Gohatsion to Yet Nora, a small village about 8-km north of Dejen. The purpose of the study was to examine mainly the contribution of landslides and rock falls to the development of deep gorges and hence to indicate landscape evolution. The entire work was supported by data from aerial photo interpretations, field surveys, and 25-m digital elevation model (DEM) analyses in GIS. They developed nine landforms on the basis of combinations of lateral and vertical slope failures. Through this study they described, the nine landforms in particular can control the occurrence, type, and distribution of landslides and rock falls. It is also discussed that the contribution of slope failures leads to the formation of the landforms by themselves. It is also highlighted that the causes and the effect relationship between slope failures and topography is prominent throughout the landscape evolution. According to Lulseged Ayalew and Yamagishi (2003), DEM-based statistical analyses showed that biconvex and biconcave topographic surfaces are the most common forms of landscapes in the study area and landforms with convex lateral profiles are the most stable, failure if it occurs, involves quite a big area, and the resulting landscape is often biconcave.

Jemal Saed (2005) worked on the slope stability analysis on the sides of the road from Gohatsion to Degen. He has identified 17 critical slope sections, among these 9 were taken for detail analysis. According to Jemal Saed (2005) 4 were having planar mode of failure, 2 wedge mode of failure and remaining 3 were soil sections having a circular mode of failures.

OJEC (2008) have conducted a research for immediate counter measure against landslide. Different monitoring instruments like subsurface tube strain gauge, borehole extensometers and also automatic ground water level recorder were installed. This work was, relatively, detailed than the previous works in the area. According to the report, a total of 5 boreholes were drilled to obtain samples of subsurface material to recognize the formation of stratum and to install underground monitoring equipments. After making analysis different counter measures were proposed for the different slope failures.

Henok Woldegiorgis (2008) conducted a regional research work on the Blue Nile basin. The main purpose of his research work was the Zonation of areas that are susceptible to high and very high hazard landslide occurrences and also for the mitigation of the slope sections that mainly fall in the high and very high hazard zones. He classified the area into different hazard zones and he tried to calculate factor of safety for the different critical slope sections.

The most recent work was conducted by Shiferaw Ayele (2009). The main objective of his research work was to generate landslide hazard map of the Abay (Blue Nile) Gorge using integrated Remote Sensing (RS) and GIS techniques.

Generally, many research works on landslides have been conducted by different researchers in the Abay Gorge. Almost all of them are on a regional scale, no work has been conducted in a detailed scale except the one conducted by OJEC.

The present research study mainly concentrates on a single large landslide area where attempts were made to investigate the various factors responsible for instability of the slope. Later a detailed stability analysis was carried out by limit equilibrium method for existing and anticipated adverse conditions.

Analyzing individual slope section in a detailed scale is advantageous, because different slope sections have different materials forming the slope section with different geotechnical

properties and with different mode of failure. Some of the slope sections have rock materials and others may be of colluvial materials; some may have rotational mode of failure and others may have wedge mode of failure. Since there are different types of failure, they have to be treated independently. This will give opportunity to determine exactly what the cause of that individual slope failure is and to come up with, more or less, appropriate solution for the remedial measures.

Chapter 3

Methodology

3.2 Methodology

3.2.1 Pre- field activities

Before field work different works have been done to have detailed information about the area and to be well prepared for the field work. Since there are several studies carried out in past by many researchers in the area, therefore as a part of literature review exhaustive review of previous studies was undertaken.

3.2.1.1 Literature Review and Previous studies

The review of previous studies was done systematically to have detailed knowledge about the subject matter and to be well informed about the study area. This was done in two stages:

- The first one was to assess what works on landslide were carried out in Ethiopia and
- The second one was to review the works done in the study area.

In the literature review chapter a detailed description about the geology, geomorphology, structures and the engineering properties of geotechnical materials present in the study area has been presented. Besides, during the literature review, it was attempted to understand the subject matter and to have a detailed knowledge about “landslide”; types of slope failure, mechanism of failure, triggering factors for slope instability and some techniques to the slope stability analysis.

3.2.1.2 Collection of Secondary data

Collection of secondary data relevant for the present study was the second pre field activity. During secondary data collection, it was attempted to collect information which were relevant and important for the present study.

Secondary data were collected from published and unpublished sources. The data, thus collected for the present study includes;

- Geological map
- Engineering geological maps

- Groundwater condition
- Topographic map
- Borehole log data
- Borehole inclinometer data
- Surface extensometer data
- Geotechnical properties of different material
- Satellite images, DEM, etc.

From the DEM data a contour map was produced. The resolution of the DEM is 30m. From this data a 1:3,000 scale contour map was extracted, which was later used for the base map preparation. This was done by utilizing ArcGIS 9.3 and Global Mapper 11 software.

3.2.2 Activities during Field Work

Field work is relevant and necessary for any landslide study. It is essential to observe the clear indications and field manifestations pertaining to slope instability and to collect data on various causative factors responsible for inducing instability to the slope.

- During the field work, efforts were made to determine and to identify the different instability manifestation features present on the slope and to identify and collect data for the probable causative factors for the slope instability. Besides, information was gathered by informally interviewing the local people.

In addition to these, it was attempted to identify the damages caused by the landslide on infrastructure.



Damage on the road



Tension Crack on the road



Newly developed slide



Spring water



Colluvial material



Scarp face

Fig. 3.1 Different instability manifestation features and causative factors present in the study area

During the field work following data was collected:

- Identification of the type and the distribution of various geotechnical materials forming the slope and the field manifestations of slope distress and movement.
- Major and minor scarp faces, distribution and dimensions of cracks and other damages caused to the infrastructures were observed and recorded.
- The tension cracks, the spring waters that can affect the stability of the slope were also mapped.
- Damages that occurred on the road, agricultural lands, church and houses because of the landslide process were also recorded.
- Indications or traces for probable future landslide activity were observed and recorded.
- Data about the landslide process by informal interviewing of the local people were also made.

GPS was used to locate different points and to map the different features on the map throughout the field work.

3.2.3 Post field activities

After the field work, different tasks were performed using different software. Data were organized in such a way, so that it can be accessed and used easily when needed. The tasks performed include:

- Digitization of the Scarps and Tension cracks and map preparation using different GIS software like ArcGIS 9.3, Global Mapper 11, ERDAS 9.1
- Editing the photographs taken from field by PhotoScape 3.5.
- Locating the data collected from different secondary sources and field investigation on the map.

The data collected from secondary sources include:

- Borehole inclinometer data

The method of borehole inclinometer is to measure the inclination of the guide pipe that is installed in the borehole and the purpose of main slip surface survey is to determine the position of the slip surface.

- Borehole extensometer data

Borehole extensometer is installed to measure movement of slip surface in the ground.

- Surface extensometer data

The extensometers are installed along the direction of landslide movement to measure the amount of expansion and contraction in cracks and subsidence, if any.

- Meteorological data

Meteorological data is collected to know about the history of the meteorological condition, rainfall history, of the area and to know what was the maximum and minimum rainfall and then to determine the worst condition.

- Borehole log data

The borehole log data are used in the preparation of the cross section of the area and later utilized for the model preparation for stability analysis.

➤ Data about groundwater condition

Data about the groundwater condition was collected to determine the piezometric surface in the area and to use it later in the slope stability analysis.

Secondary data, as mentioned above, was analyzed and processed to get the required information and input for further detailed stability analysis. To know the geometry of the slope, cross section was prepared by utilizing DEM data. Further, geological cross section was prepared by utilizing the geological map and the borehole log data. To anticipate the actual groundwater conditions during the time of slope movement piezometric data was analyzed and correlated with the rainfall data.

One of the important input for any slope stability analysis is the shear strength parameters; Cohesion and angle of shearing resistance. Since the present slope is mainly composed of colluvial material no experimental data was available. Thus, attempts were made to make estimations on shear strength parameters by conducting sensitivity analysis. Sensitivity analysis is an interactive process adopted to more realistically simulate the slope instability conditions and to determine the influence of the different parameters in the Factor of Safety. It indicates which input parameters may be critical to the assessment of slope stability, and which input parameters are less important. Computations were performed using the SARC program and were based on the shear strength parameters on the determination of the Factor of Safety in order to identify the critical situations on the slope stability.

Detailed slope stability analysis was performed using a deterministic approach of slope stability analysis. The softwares used for the stability analysis are SARC and SLOPE/W.

SARC

SARC facilitates to analyze rotational mode of failure. It provides deterministic analysis of a slope to compute the factor of safety. It requires different parameters like cohesion (C),

internal friction angle (ϕ), unit weight and BBAR. A detailed description on SARC is presented in Annexure II.

SLOPE/W

SLOPE/W, developed by GEO-SLOPE International Canada, is used for slope stability analysis. SLOPE/ W provide deterministic analysis and uses limit equilibrium theory to compute the factor of safety of earth and rock slopes. The comprehensive formulation of SLOPE/W makes it possible to easily analyze both simple and complex slope stability problems using a variety of methods to calculate the factor of safety. SLOPE/W has application in the analysis and design for geotechnical, civil, and mining engineering projects. Thus, SLOPE/W was utilized to perform slope stability analysis during the present study.

Finally, based on the slope stability analysis results for existing and anticipated adverse conditions interpretations were made and systematic remedial measures were worked out.

Chapter 4 General Site Description and Geology

4.1 The Study Area

4.1.1 Location

The study area is located in the Amhara Regional state near to the town Degen within the Degen sub sheet. It is found on the sides of the main road from Gohatsion to Degen. It lies within the Abay basin. Geographically the area is bounded between UTM coordinates 407500m and 408500m Easting and 111700m and 111800m Northing. The present study area in total covers an area of about 10,000sq.m.

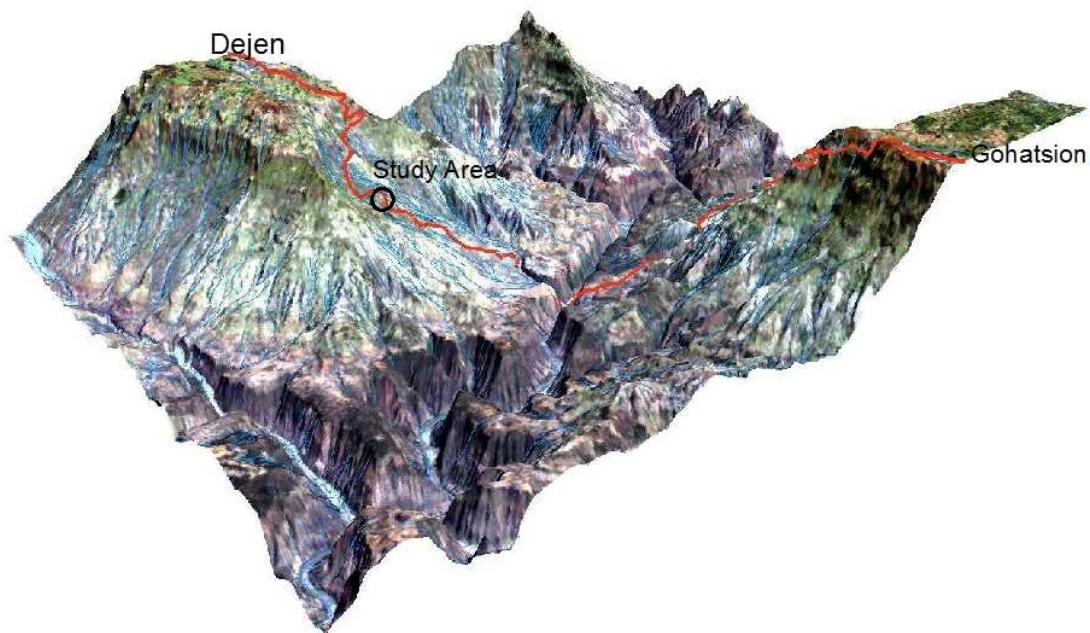


Fig.4.1 3D view of the study area (Source: Yoseph, 2010)

4.1.2 Accessibility

The study area can be reached using a four wheel drive from Addis Ababa through Gohatsion to Dejen. The study area is about 215km from Addis Ababa and about 15km before Dejen. The road is asphalt and comfortable to drive in all seasons.

4.1.3 Geomorphology of the area

The study area is a part of the central Ethiopian high lands and it is characterized by 1400 – 1500m deep gorge regionally, which is made up of stratified sedimentary rocks capped by basaltic plateau (Almaz et.al, 1994).

The study area is characterized by rugged topography having a maximum elevation of around 1900m a.s.l and a minimum elevation value of around 1700m a.s.l. The present regional 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 deep canyon, erosional leveling, weathering and mass wasting have played a major role in creating the present landform (Almaz et.al,1994).

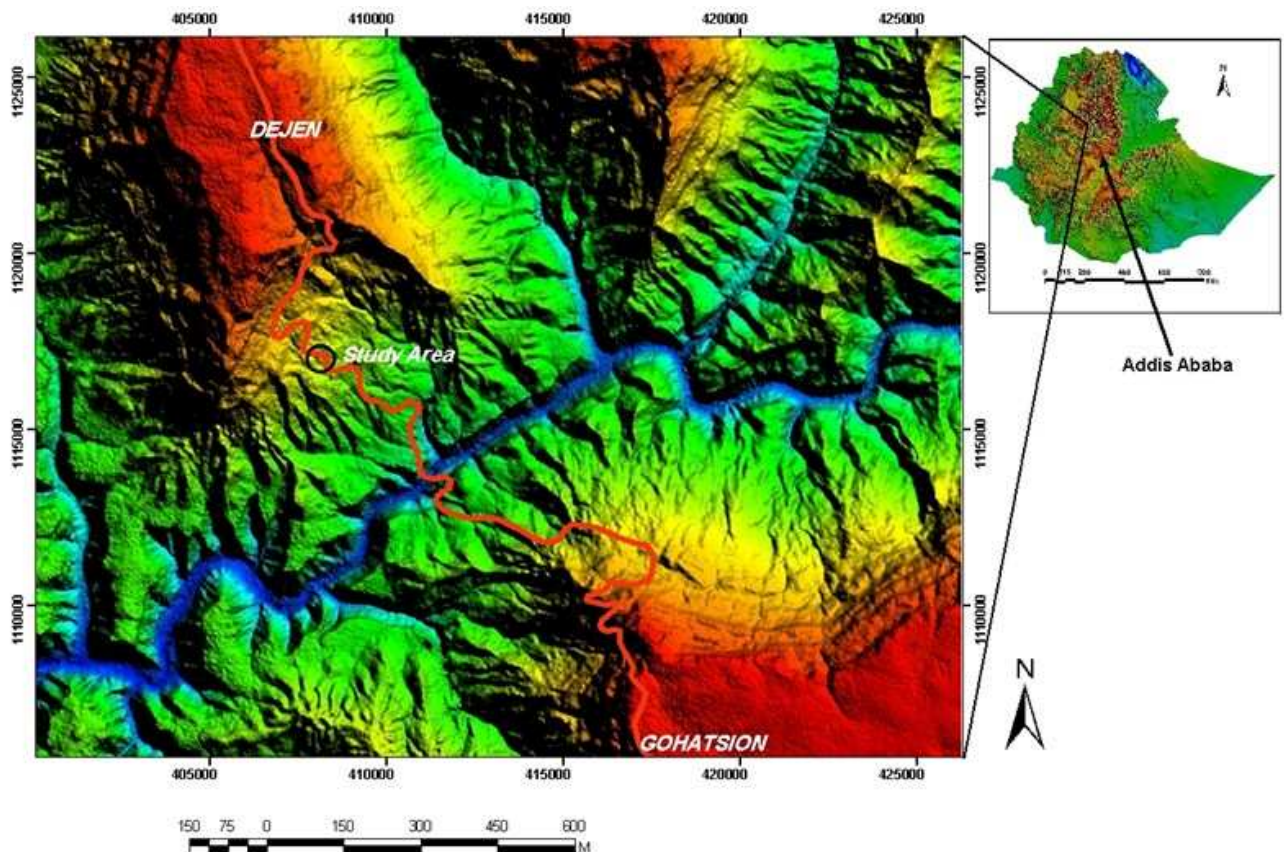


Fig.4. 2 Location map of the study area

4.1.4 Climatic condition of the study area

The climate falls under warm subtropical climate condition. The area receives rainfall twice in a year; heavy precipitation from June to September and light to moderate precipitation from mid-February to mid-March. The rainfall peaks in July or August at about 300 to 400 mm per month; about 50% of annual precipitation is within July and August. Existing rainfall observation records in the Abay Gorge area are of 49 years data for Dejen and 34 years data for Filiklik. The annual average rainfall for Dejen area is about 1,394 mm/year and that of Filiklik is 1,195mm/year. In March 2006, there was an unusually high rainfall of over 100 mm in Gohatsion (OJEC, 2007). According to the Meteorological map of Ethiopia, 1979, the study

area receives annual rainfall in the range of 1400 – 2000 mm with moisture index >1 which is humid and mild effective temperature varying between 14°C and 20°C which is most of the time comfortable.

To workout the climatic conditions in the study area, data from Dejen metrological station, which is about 10 km away from the study area, have been utilized.

4.1.5 Seismicity of the study area

As cited in Jemal Saed (2005), the Seismic zone of Ethiopia have been delineated by Gouin (1979) and later updated by Laike Mariam Asefaw (1986). According to Laike Mariam Asefaw Asfaw (1986), the 'Seismic Risk Map' produced for a hundred year return period and 0.99 probability shows that the study area falls within 7 M.M scale.

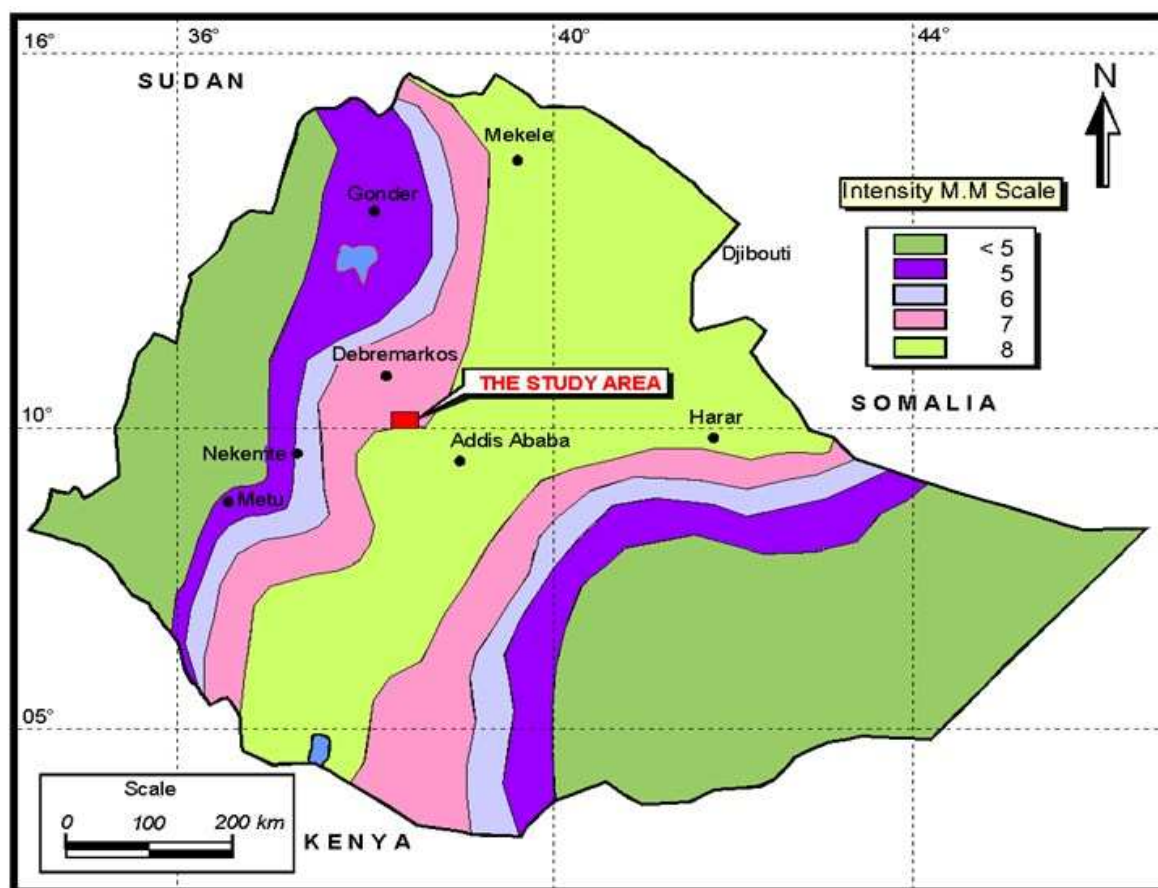


Fig. 4.3 Seismic risk map of Ethiopia 100 year return period, 0.99 probability
(After Laike Mariam Asefaw Asfaw, 1986)

Based on the MM scale intensity, the estimated horizontal earthquake acceleration is found to be $0.08g$, as determined from the MM intensity graph (Johnson et al, 1988). For the present research, this value was utilized in the stability analysis.

4.1.6 Vegetation cover

The study area is dominantly covered with agricultural crops, except sparsely dispersed thorny *acacia* trees. The most dominant agricultural crop products are sorghum, teff and small scale production of vegetables like, cabbage and fruits such as; bananas, orange, lemon, and papayas near Kurar village.

4.2 Regional Geology

The Precambrian metamorphic rocks with syn-tectonic and post-tectonic intrusives are the basement for Late Palaeozoic and Mesozoic sediments, and the Tertiary to Quaternary volcanic rocks in Abay basin, at northwestern part of Ethiopia (Getaneh Assefa, 1991).

The sedimentary history of the Mesozoic succession is related to the formation of basins around the borders of the mega continent, especially along the eastern Africa margin. These basins are the results of the break-up of Gondwanaland during Paleozoic-Jurassic times. The basins, largely fault-controlled and with limited marine access, are filled with a thick succession of Karoo sediments (known also as the Gumburo Formation in Ethiopia) (Russo et. al., 1994).

During the starting of the regression phase is marked by the deposition of sediments under continental conditions in the Abay Basin (Getaneh Assefa, 1991). The subsequent deposition was characterized by restricted marine evaporite sediments in Somalia and Southern Ethiopia, and by lagoonal, sabkha sediments and continental sandstones in Abay River and Northern Ethiopia (Russo et. al., 1994).

There are five formations that are established for the Mesozoic sediments of the Blue Nile Basin (Getaneh Assefa 1979, 1991). From the bottom to top, these formations are:

- The Adigrat Sandstone
- The Gohatsion Formation of Getaneh Assefa, 1980
- The Antalo Limestone or The Lagajima Limestone
- The Mugher Mudstone and
- The Debre Libanos Sandstone

The Lower Sandstone Unit is mostly sandstone intercalated with layers of siltstone, mudstone, occasional beds of conglomerates and shales. It is as much as 700 m thick and deposited in a fluvial and deltaic environments.

The Shale and Gypsum Unit, 300 m thick, consists of interbedded sandstone, siltstone, mudstone and shale in the lower part and alternations of gypsum, dolomite, limestone and shale in its upper part. The terrigenous clastics are deposited in deltaic while the gypsum, limestone, dolomite and associated shales are deposited in shallow lagoonal and supratidal environments (Getaneh, 1991). The Abay Formation previously named as Abay beds and the lower unit of Antalo Group (Kazmin, 1972) consists of 196 m of sandy limestone and calcareous sandstone, 257 m thick unit of gypsum, as well as 138 m thick upper unit of alternating shale and limestone (Mengesha et al., 1996). The Abay Formation is middle Jurassic in age.

The Limestone Unit consists of approximately 600 m of thick fossiliferous carbonate interbedded with marl, shale and mudstone which has been deposited in open marine to shallow shelf environment. It is equivalent to the Antalo Limestone (Getaneh Assefa, 1991). In the Abay River canyon, the Antalo Formation is found in between Abay Formation and Tertiary volcanics and is considered to be Middle to Late Jurassic in age (Mengesha et al., 1996).

The Shaly Sandstone Unit (Mugher Mudstone), 320 m thick is composed largely of alternating fine grained sandstone and mudstone with beds of siltstone and shales and is equivalent to the Agula shale of Tigray region. The environment of deposition is supratidal, grading in to meandering river system (Getaneh Assefa, 1991).

The upper Sandstone Unit (Debre Libanos Sandstone) unconformably overlain by Tertiary basalt, is composed of sandstone with thin beds of conglomerate, mudstone and shale. It is equivalent to the Amba Aradam Sandstone and being deposited in a braided river system (Getaneh Assefa, 1991).

The Ashange Formation consists of basalt flows of several hundreds of meters to a kilometer thick of strongly weathered, crushed, tilted basalt which lie below the major pre Oligocene unconformity. It consists of predominantly mildly alkaline basalts with interbedded

pyroclastics and rare rhyolites. It was believed that these early flood basalts are restricted to the northwestern plateau until a group of early flood basalts were found in southwestern Ethiopia with K/Ar age between 49 to 36 Ma. This formation is Eocene to Oligocene in age (Mengesha et al., 1996 and the references there in).

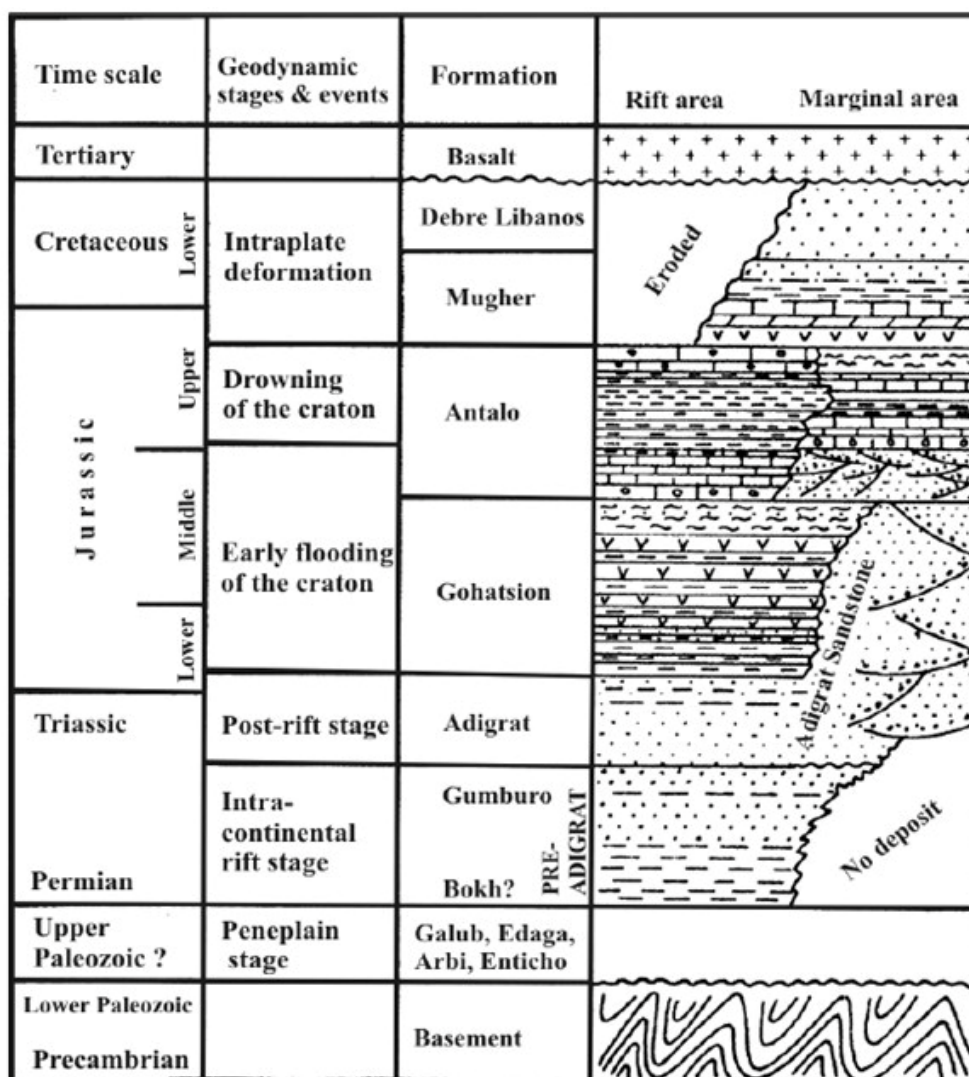


Fig. 4.4 Chronostratigraphy, major geodynamic events and lithostratigraphy of the Abay (Blue Nile) basin (Source: Russo et al 1994)

4.3 Local Geology

The description of the local geology is based on the geology from Gohatsion to Dejen. The geology is compiled mainly from previous works done by Almaz and Tadesse Dessie (1994).

Sandstone

In the Abay gorge, the river bank and terrace is made of highly consolidated sandstone, which is well cemented fine to medium grained that belongs to the Adigrat formation. It is intercalated with mudstone, siltstone and shale. It is about 270 meters thick. It is red in color; in some places due to chemical weathering, it varies to brownish grey, pinkish and greenish grey. This units, in this locality, underlain by channel filling upper Paleozoic sediments and have gradational contact with the overlying silt stone. It is, generally, horizontally bedded and also show cross bedding, graded bedding. The unit has three well developed joint sets. It forms vertical cliff resulting rock fall due to the intersection of the three joint sets.

Siltstone

The silt stone unit is composed of silt/clay particles cemented together. It is found intercalated with shale, mudstone and sandstone with calcite and/or gypsum veins in places which indicates a change of the depositional environment. It is mostly yellowish green to brownish in color. It is highly consolidated and partly alternating, which is thickly laminated and cross-bedded. It is characterized by weak and friable layers. It is horizontally bedded with closely spaced minor vertical joints.

Clay Stone

The shale unit, which is found in between the underlying silt stone and the overlying gypsum unit, is often called “the lower clay stone unit” and the one which is found between the gypsum and limestone is “the upper clay stone unit”. The thickness of this unit is about 150 meters. It varies in color from place to place to grey, black, red, green and purple. The clay stone unit consists of kaolinite, monmorillonite and illite. Minerals like quartz and mica are also observed. In some parts of the area the continuity of the lower shale disappeared from its original place of deposition due to its susceptibility to weathering and erosion.

Gypsum

This unit has about 150 – 250 m thickness. It is sandwiched between two shale units. Generally, it is white in color but varies in to grey, bluish grey and black in some places. The variation in color is due to some ferruginous minerals and organic impurities (Almaz and Tadesse Dessie, 1994). It forms flat-lying, moderate slope and steep slope topography with variable thickness and laminated and/or bedded. The gypsum is intercalated with thinly bedded shale. This unit is comprised with

three well developed joint sets. The intersection of the three joint sets result into wedge mode failure and makes it easily exploitable.

Limestone

This unit is directly underlies the basaltic unit, and it is on top of the shale unit. It comprises thin bedded to massive beds of limestone. It is also called Antalo limestone. It is about 400 meters thick and, generally, horizontally bedded intercalated with shale, carbonaceous clay and marl and it is highly fossiliferous. The upper most part of the limestone is thickly bedded (0.5 – 2m) where as the lower most part is thinly bedded (5cm – 30cm). It is generally white in color, in some places it varies to yellowish grey and brownish grey (Almaz and Tadesse Dessie, 1994). It consists of well developed three joint sets. The interaction of the three joint sets combined with weathering results rock falls composed of huge blocks. According to Almaz and Tadesse Dessie (1994), rock fall in limestone is so sever due to the intercalation of soft layers of shale and marl which act as sliding surfaces.

Basalt

This rock unit covers the top flat highlands on both sides of the valley. It is found in huge stocks at the beginning of the gorge both on Dejen and Gohatsion sides. This flood basalt is unconformably overlies on top of limestone. It is dark in color, fine grained, composed of ferro-magnesium minerals, oxidation reaction at the surface of the basalt resulted in reddish brown color (Almaz and Tadesse Dessie, 1994). It is characterized by the presence of well developed columnar joints which makes it susceptible to detachment and falling apart in to blocks and boulders. Rock falls from this unit are found as far as 1 km down slope towards the valley bottom (Yoseph, 2010).

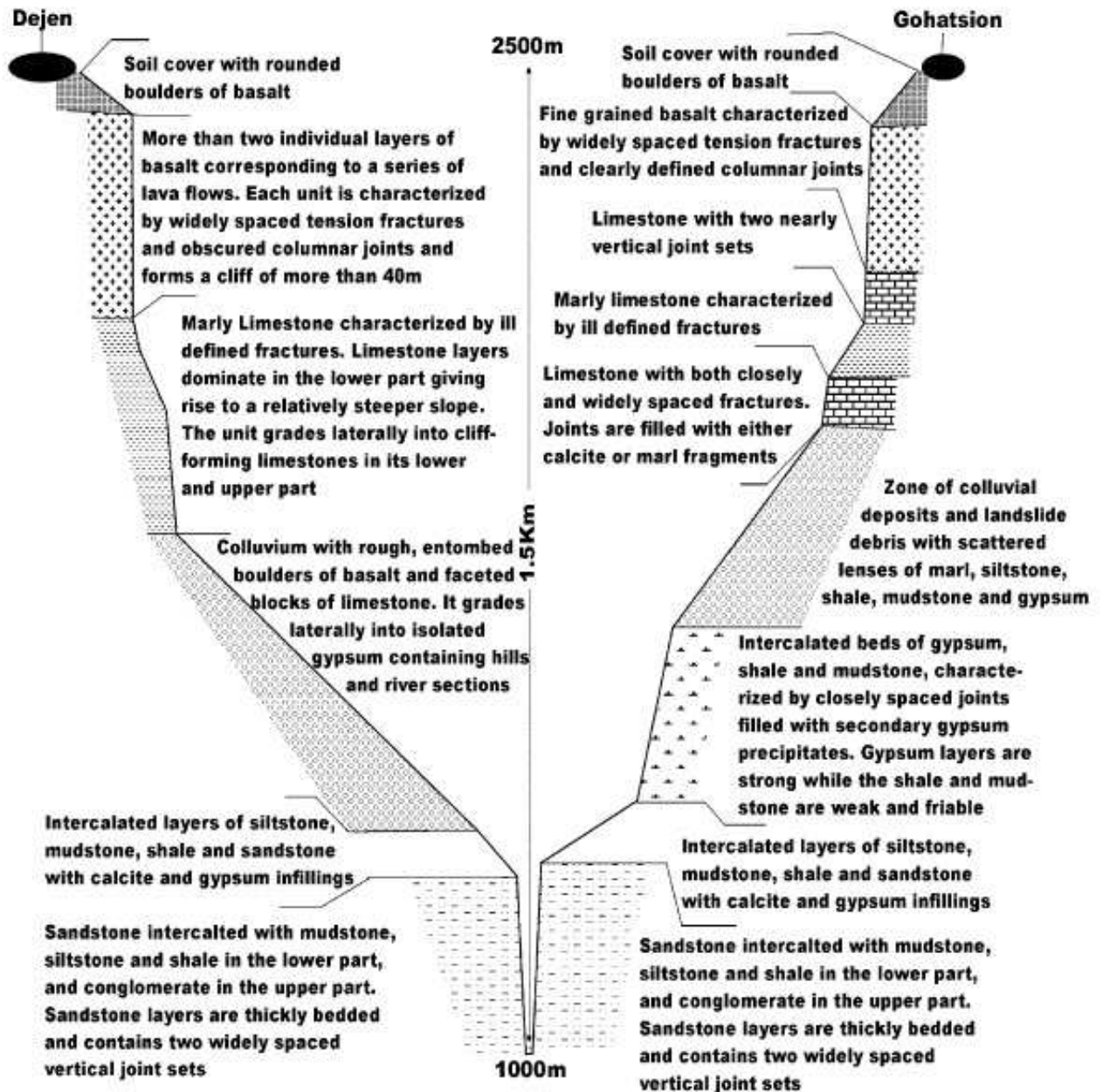


Fig. 4.5 Geological cross section along the north south section of the Abay River gorge
(After Lulseged Ayalew A., 2003)

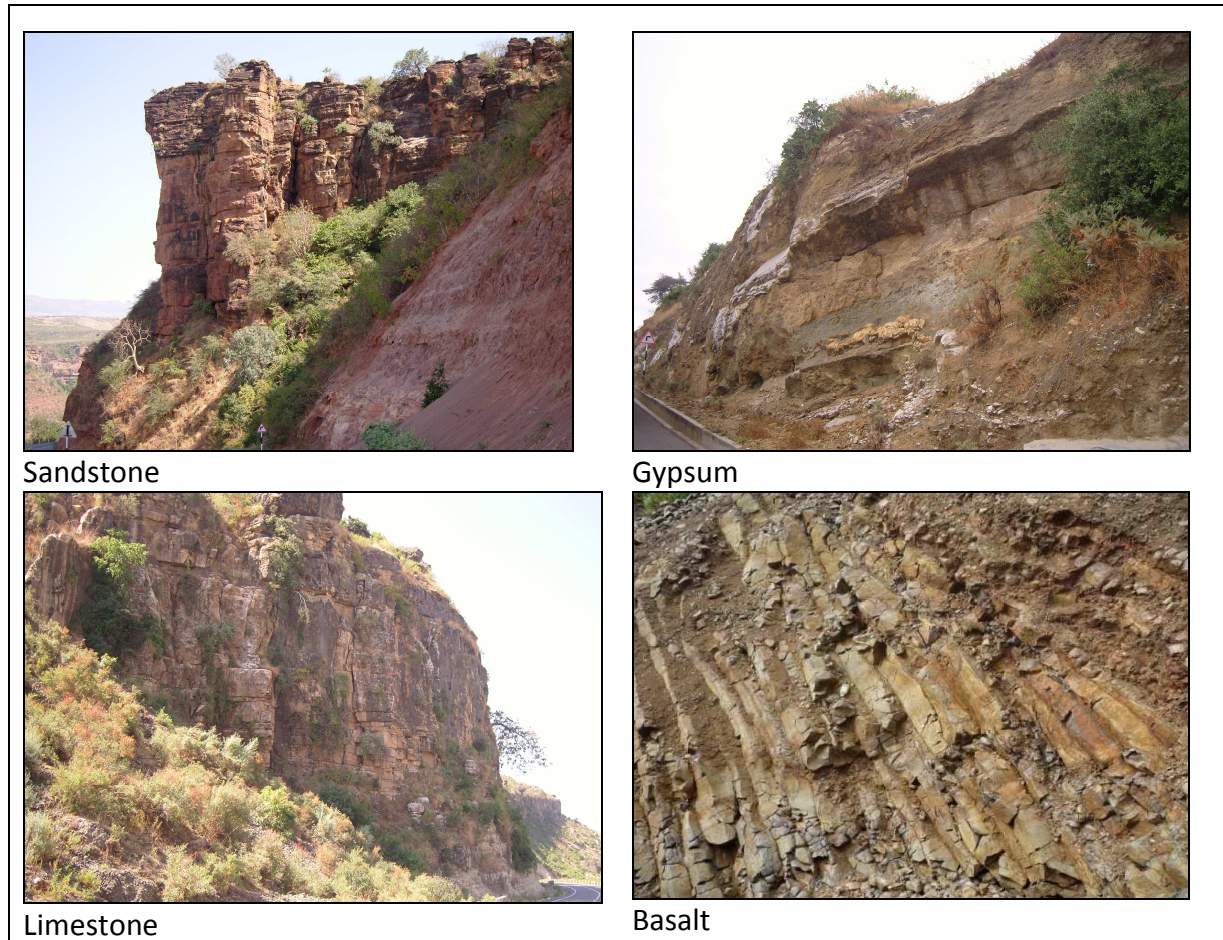


Fig. 4.6 Different lithological units in the area

4.4 Geology of the Site

At the site the area is covered dominantly by colluvial material with variable grain sizes. The grain size of the colluvial material ranges from silty size to very big boulders. The clay soils in the study area are of two types. The difference in the type of the clay soils in the area is due to the difference in the nature and type of the source rocks.

Colluvial Soil

The colluvial soils are deposited or built up at the bottom of a low-grade slope or against a barrier on that slope, transported by gravity. The processes that deposit colluviums are avalanches, mudslides, and landslides (www.oregon.gov/ODOT/HWY/REGION1/Sunrise_FEIS/5I_SunriseFEIS_Ch3_GeologySoils_Dec2010.pdf).

The colluvial deposits in the study area are collected at the foot of a steep slope or cliff and made the slope to be gentler than the opposite Gohatsion side. It is mainly composed of

gravel, cobble and boulder sizes of basalts and limestone within silty clay matrix. It is generally poorly sorted resulting in the occurrence of voids and hence the colluviums could be categorized as very loose, weak, heterogeneous and permeable unit. Most of the springs emanate from the colluvial soil indicates high permeability nature of the colluvial material.

At the present site the colluvial material sources are mainly limestone and basalt; their composition and engineering properties as well depend on their origin. In the areas where the dominant material is basaltic source, there is a black clay soil, weathering product of the transported basaltic material. The color of this clay is dark and shows cracks on the dried parts of the soil. This soil is known by its expansive and shrinkage behavior and is problematic soil in engineering works. In areas where limestone is dominant, the clay is yellowish in color.

4. 5 Regional Structural Geology

Many researchers have conducted their research work in the Blue Nile gorge. It is still attracting many researchers. Gani et al., (2008) have conducted their research work in the Blue Nile basin. The following regional geology is compiled from the works of Gani et al. (2008).

The Blue Nile Basin has evolved through three main phases, including (i) pre-sedimentation phase involving the peneplanation of Neoproterozoic basement rocks, (ii) sedimentation phase including deposition of thick Mesozoic strata represented by repetitive marine transgression and regression, and (iii) post-sedimentation phase involving emplacement of extensive Early–Late Oligocene and Quaternary volcanic rocks.

The early stage in the evolution of the Blue Nile Basin was dominated by Jurassic–Cretaceous NE–SW extension producing NNE-trending normal faults in the Neoproterozoic basement rocks and NW-trending faults which provided the depocentres for the deposition of the Mesozoic sedimentary rocks in marine and continental environments.



Colluvial material from basaltic source



Basaltic and Limestone source



Clay soil from basaltic source



Clay soil from limestone source

Fig. 4.7 Colluvial material and soils in the study area

The Afar Mantle Plume resulted in extrusion of Early–Late Oligocene volcanic rocks that covered much of the Mesozoic sedimentary section. This volcanic event was followed by NW–SE-directed extension resulting in the opening of the NE-trending Main Ethiopian Rift and superimposition of NE-trending faults on rocks within the Blue Nile Basin.

The Quaternary Era in the region is characterized by the extrusion of _300m thick volcanic rocks, and varying directions of tensile stresses (E–W, NNE–SSW and NE–SW) related to tectonic events within the Main Ethiopian Rift and Afar Depression. These resulted in superimposition of Quaternary N-, ESE- and NW-trending extensional structures on the Blue Nile Basin.

4.5 Landslide Problems in the Present Study area

The landslide problem in the present study area is very active. It covers an area more than 300,000 sq. m. The type of landslide in the area is rotational slide and the material involved is colluvial. The colluvial material in this area is from two different sources, basalt and limestone. The size of the colluvial material ranges from silt to big boulders. Beside the major sliding mass, small circular failures were also observed. According to the local people, historically, the landslide problem in this locality is very recent. It started within the past five years. Just before five years, spring waters started to emanate at different places; tension cracks were developed at different places before the large landslide problem occurred. Then the massive landslide occurred after a few months later.

This landslide causes several problems during and after that time:

- Some people displaced from their home
- Disturbance on agricultural lands – causing damage on the crops as well
- Damage on the road
- The St. Gabriel Church was completely damaged
- Cracks on some houses appeared
- Damage on the gabion wall before a year life time occurred
- Fortunately, there was no injury or life loses due to this landslide problem.

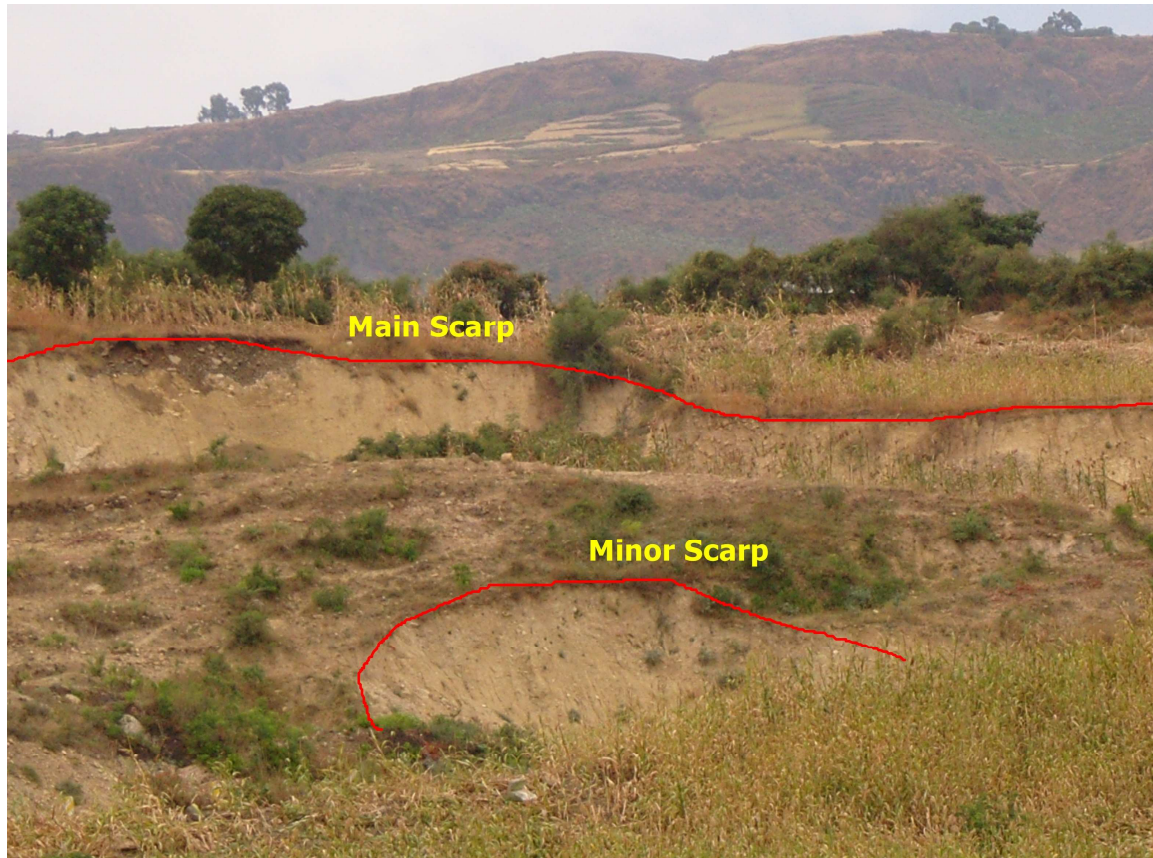


Fig. 4.8 Photo showing the main and minor scarps of the landslide

The landslide is active and still causing problems in the area. It damages the new church which is under construction; the road is under a risk. There are many tension cracks which are developed in the area, and these tension cracks are indications for probable some more slides to occur in the near future.

According to the local people, after the large landslide, there are always landslides after the end of the rainy seasons, many times, at the beginning of September. Even if the local people could not recognize the exact year, the big landslide took place in the month of September just after the end of the rainy season; the church is even damaged in the beginning of the month of September which is the end of the rainy season. From this we can understand that rainfall is the main cause for the landslide.



Fig.4.9 Photo showing tension crack on the road

Mode of failure

Along the road section, from Gohatsion to Dejen, there are different modes of failures, like plane mode of failures, wedge mode of failures and circular mode of failures. In the study area, for the present slope section, the mode of failure is rotational. There are minor failures observed with rotational mode within the main sliding mass of the slope section.

Currently the Ethiopian Geological Survey (EGS) and JiCA are working together on a project for developing countermeasures against landslide in the Abay River Gorge. The project is active and they are working on the slope along the road section from Gohatsion to Dejen. They have drilled more than 20 boreholes along the road section.

Besides, they have installed different monitoring instruments like surface extensometer, borehole extensometer and borehole inclinometer. No remedial measures are followed yet, except the gabion wall constructed at the base of the church.



Damage on the old church



Damage on the church under construction



Tension crack on soil mass



Damage on Gabion wall



Massive slide on the road



Tension crack cutting the road

Fig 4.10 Hazards caused by the landslide

Chapter 5

Field Observations and Data Preparation

5.1 Preamble

Field observation and data preparation forms the important part of any scientific research, especially in earth sciences stream. This stage is the best opportunity to collect the exact data needed for further analysis of the research work. Field observation helps in understanding the site condition and to have a clear knowledge about the geology, geomorphology, etc. of the study area. Geologic information and information regarding in-situ engineering properties of soil and rock material need to be collected during field observation. Accordingly for the present study a systematic field program was executed and all necessary field observations were undertaken, besides all relevant primary data on various parameters were also collected which later formed the basis for analysis as per the scope of the present study. A detailed description on field observations, data collection and its preparation is organized in the present chapter.

5.2 Field Observations

The field work was conducted for 10 successive working days from November 12 to November 21, 2010. During the field work all relevant information and data pertaining to the stability condition of the area were collected. Information was collected by informal interviews of the local people and through visual observation in field work. Furthermore, all the scarp faces and the tension cracks located in the area were mapped. Data about seasonal and perennial spring waters were also collected and located on the maps.

5.2.1 Informal Interviewing

Interviewing is one of the methods for data collection about the past events. During the field work, informal interviewing of the local people was conducted to know and understand about the past events of the landslide. In the informal interviewing different questions were asked from the randomly selected respondents. The questions include:

- When the first landslide was occurred?
- What was the season when the sliding occurred?

- What were the damages on infrastructures, agricultural lands, individual houses, etc.?
- When was the church structure damaged?
- Is there any loss of life because of the landslide activity?
- Is there any recent landslide activity?

During the field work it was attempted to get answers for such questions. According to the respondents, historically, the landslide problem in this locality is very recent. It started within the past five years. Just before five years, spring waters started to emanate at different places; tension cracks were developed at different places before the large landslide occurred. The massive landslide occurred after a few months later. According to the respondents, after the large landslide, there were always landslides after the end of every rainy season, many times, at the beginning of September; even the big landslide has occurred at the end of the rainy season.

According to the information from the local people, the rain could be one of the factors that trigger the landslide events at different times. This information from the local people helped to put emphasis on the ground water level fluctuation in comparison to rainfall records to understand the impact of the rain on the slope instability, as it could be surface water infiltration one of the major causative factors for the landslide problem encountered.

The field observation and respondents indicated that damages on infrastructures, agricultural lands and individual houses have occurred at different time after and during the massive landslide. The damages caused during and after the massive slide include:

- displacement of Some people from their home
- Disturbance on agricultural lands – causing damage on the crops as well
- Damage on the road
- The church was completely damaged
- Cracks on some houses
- Damage on the gabion wall before a year life time
- Fortunately, there was no life lose due to this landslide problem.

5.2.2 Observations and measurements

Landslide and its extent

The potential for landslide exists across the entire gorge, from Gohatsion to Dejen. Regionally, the area is highly affected by sliding problem with a variety of modes of failure containing different materials forming the slope (Henok Woldegiorgis, 2008). Specifically, the study area has a high potential for landslide hazard; the sliding mass is composed of colluvial material ranging in size from clay to very big boulders. It is characterized by rotational mode of failure and covers a wide area of about more than 100,000 square meters. Different surface manifestations that show previous landslides and indications for probable future slide like tension cracks and scarps were observed and mapped.

Past movement and Potential for failure

During the field work, different features that shows the past movement and potential for future failure were observed. These features include the main scarps as well as minor scarps which indicate the past movement and tension cracks that indicate the potential for future failures. These features are described below.

Scarps

Scarps are steep exposures of the upper edge of slip surfaces marked by a sudden increase in slope angle, sometimes nearing vertical (Cruden and Varnes, 1996). They generally first appear as tension cracks parallel to the slope contours and then develop into a scarp, concave down slope in map view. The head scarp is the upper edge of the main slip surface and is the uppermost scarp. Minor scarps are generally located within the moving mass and usually mark the beginning or end of a down dropped block or bench. These minor scarps appear morphologically similar to head/main scarps but are always located within the landslide and below the head scarp (Cruden and Varnes, 1996). Scarps are common within the extending portion of the landslide mass.

Among the features found in the study area resembling scarps, many of them associated with active landslides displayed continuous, steep face with a concave down slope shape. Other scarp-like features only displayed the steep, concave down slope escarpment, which remained vegetated with plants like water-loving vegetation and displaced trees. At the

extreme, some scarp-like features only displayed a moderately steep escarpment that may or may not be continuous. The measured vertical offset of scarps ranged from 0.5 to 20 meters throughout the study area (Fig. 5.1).

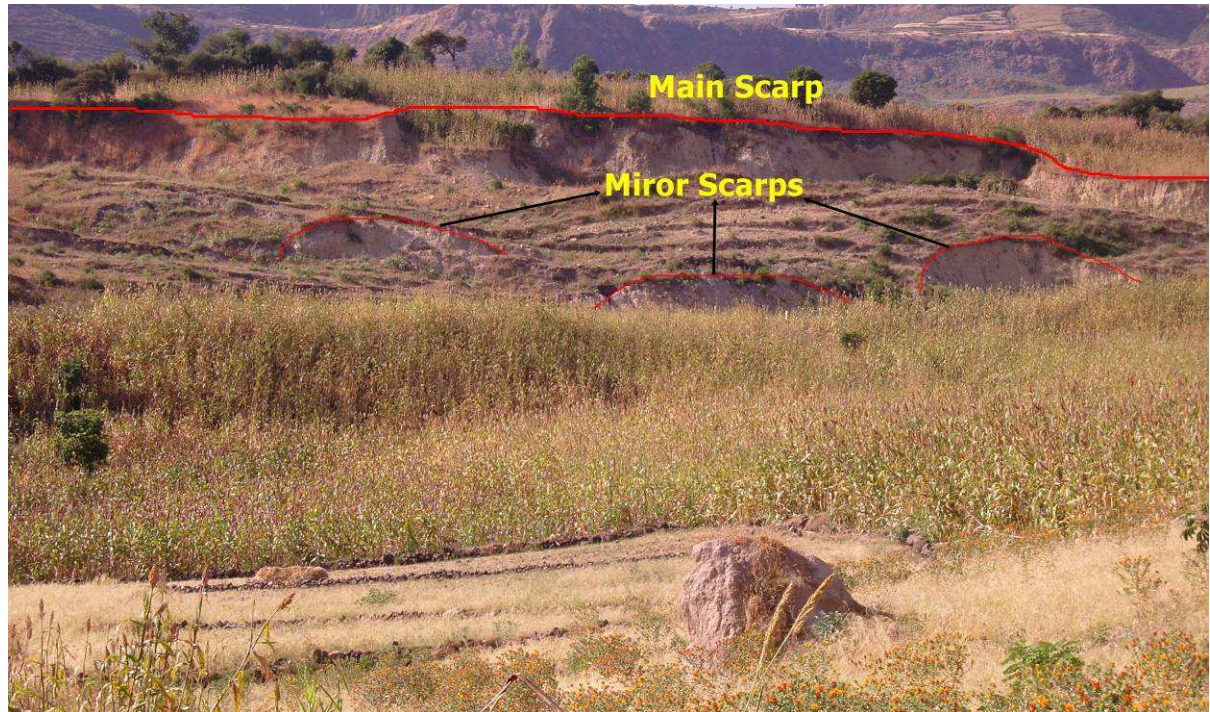


Fig. 5.1 Photograph showing main and minor scarps

Tension Cracks

Tension cracks are open fractures in the ground that have rough and irregular surfaces (Fleming and Johnson, 1989). Movement is initially normal to the fracture, but lateral movement can occur later. These features are generally found above the head scarp and can be the first signs of movement (Richards, 1982). Tension cracks can also be found along the flanks, outside the main landslide zone. Traverse cracks are located within the moving mass at the toe of the main slip surface (Cruden and Varnes, 1996).

In the area many tension cracks being developed on the agricultural lands as well as on the main roads were observed and mapped (Fig. 5.2). Some of the Tension cracks extend for more than 50 - 70 meters. Some have wide openings about 5 – 10 cm. In some areas along such tension cracks traces of sliding movement can also be observed. During rainy season, water infiltrates into the ground and the water loosens the colluvial material to reduce the cohesion (www.isprs.org/proceedings/XXIX/congress/part7/754_XXIX-part7.pdf).



a. Tension crack on agricultural land



b. Tension crack developed on the road

Fig. 5.2 Photograph showing tension cracks

Damages occurred

Many landslides caused damages on human life as well as on properties and infrastructure all over the world. According to Varnes (1981) during the period from 1971-1974 an average of nearly 600 people per year, worldwide, were killed by landslides.

As reported, in the study area, fortunately, there is no loss to life. The damage in the study area is on infrastructure, agricultural lands, individual houses and the church. On the road differential settlement and tension cracks were observed. The church is completely damaged; even the new church which is under construction was damaged. According to the local people and the observations made during the field work Individual houses are cracked along the walls and the floors; agricultural lands are cracked and suffered a slide every time after rainy seasons. Tilted trees were also observed in different parts of the study area, which are indication for the landslide and its direction of movement (Fig. 5.3).

Groundwater

One of the factors that control the slope instability is groundwater fluctuation and its movement through the underground. Most landslides are preceded by saturation of the slope. This is commonly caused by heavy rainfall events, periods of extended precipitation that saturate the upper part of the slope or raise groundwater levels (www.pubs.usgs.gov/fs/2004/3072/pdf/fs2004-3072.pdf).



a. Damage on the main road



b. Tilted trees

Fig. 5.3 Photograph showing damage on the road and tilted trees

Subsurface water buildup can cause landslides in several possible ways. The water may increase the weight of materials on a slope above their point of gravitational equilibrium. It may increase pore pressures within a zone of weakness in the materials underlying a slope. It may decrease the coefficient of friction on a potential sliding surface. It can cause clays to hydrate and expand increasing slope instability. It can decrease the overall strength of the materials making up the slope. It can dissolve minerals that are binding the particles of material that make up the slope. (www.wgwa.org/articles/landslidesandgroundwater.pdf).

In the study area groundwater fluctuation is recorded from every borehole. In some of the boreholes, the groundwater level is measured by automatic water level meter and in some of them it was measured manually. The water level recorded from the different boreholes was used for the slope stability analysis. The main source of the groundwater in the area is rainfall. The water that comes from rainfall will infiltrate into the ground through the tension cracks present in the area.

Besides the tension cracks, land plough for agricultural processes makes it easy for the water infiltration into the ground. In the study area spring waters were also observed and their effect is described below.

Spring water

Spring water in the study area is located at several places (Fig. 5.4). According to Darcy's law, groundwater flow from higher head to lower head. Because of the high permeability of the colluvial material, water can travel underground and appears on the surface of the earth whenever favorable conditions exist. In the study area some of the springs are perennial and at some other places they have formed a pond.

The movement of the water in underground can cause piping effect by washing out the finer materials. In the rainy season, water will occupy the void space within the colluvial material and increases the pore water pressure; when the rainy season is over, the water will leave the void space. This process may cause differential settlement in the area and which could probably be the cause for the development of cracks. Besides, Ponds are commonly formed in different places of the study area.



a. Developed spring water



b. Pond

Fig. 5.4 Photograph showing spring water and pond in the study area

5.3 Data preparation

From secondary sources and during the field work various data that are important for the slope stability analysis were collected. These data include borehole data, surface and borehole extensor meter data, ground water level and regarding the geotechnical materials type in the study area.

5.3.1 Borehole data

In the study area 10 boreholes were drilled by EGS and JICA. All the 10 boreholes were logged and a cross section was produced. The minimum borehole depth is 25 meters and the maximum depth is 45 meters. Samples from the boreholes were taken by the GSE and JICA for the bulk density laboratory analysis.

Borehole extensometer and borehole inclinometer data were collected from the boreholes. Besides, three automatic groundwater meters were installed by the GSE and JICA in three of the boreholes and measurements were taken to estimate the piezometric level for different time.

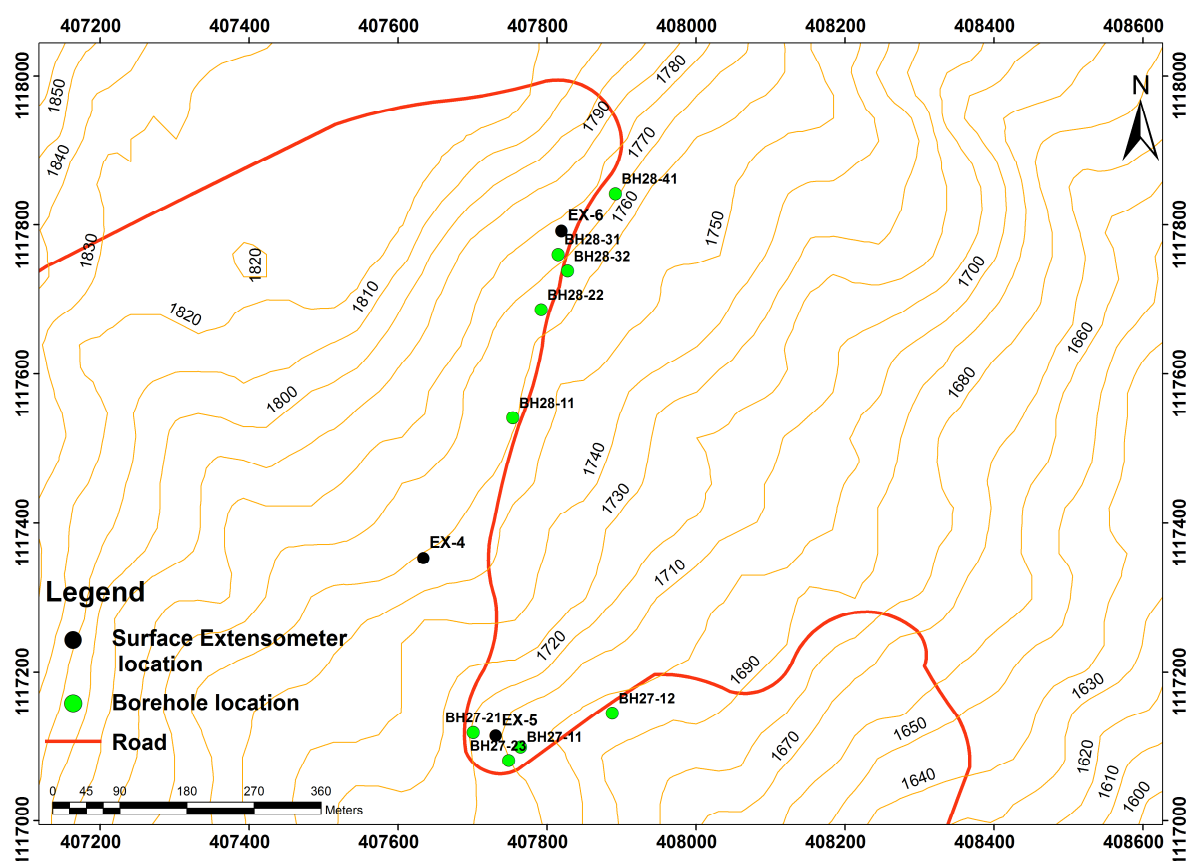


Fig. 5.5 Map showing the locations for borehole and surface extensometer data

Borehole inclinometer

The method of borehole inclinometer is to measure the inclination of the guide pipe that is installed in the borehole and the purpose of main slip surface survey is to determine the position of the slip surface. The borehole extensometer is to measure the movement of a slip surface in the ground.

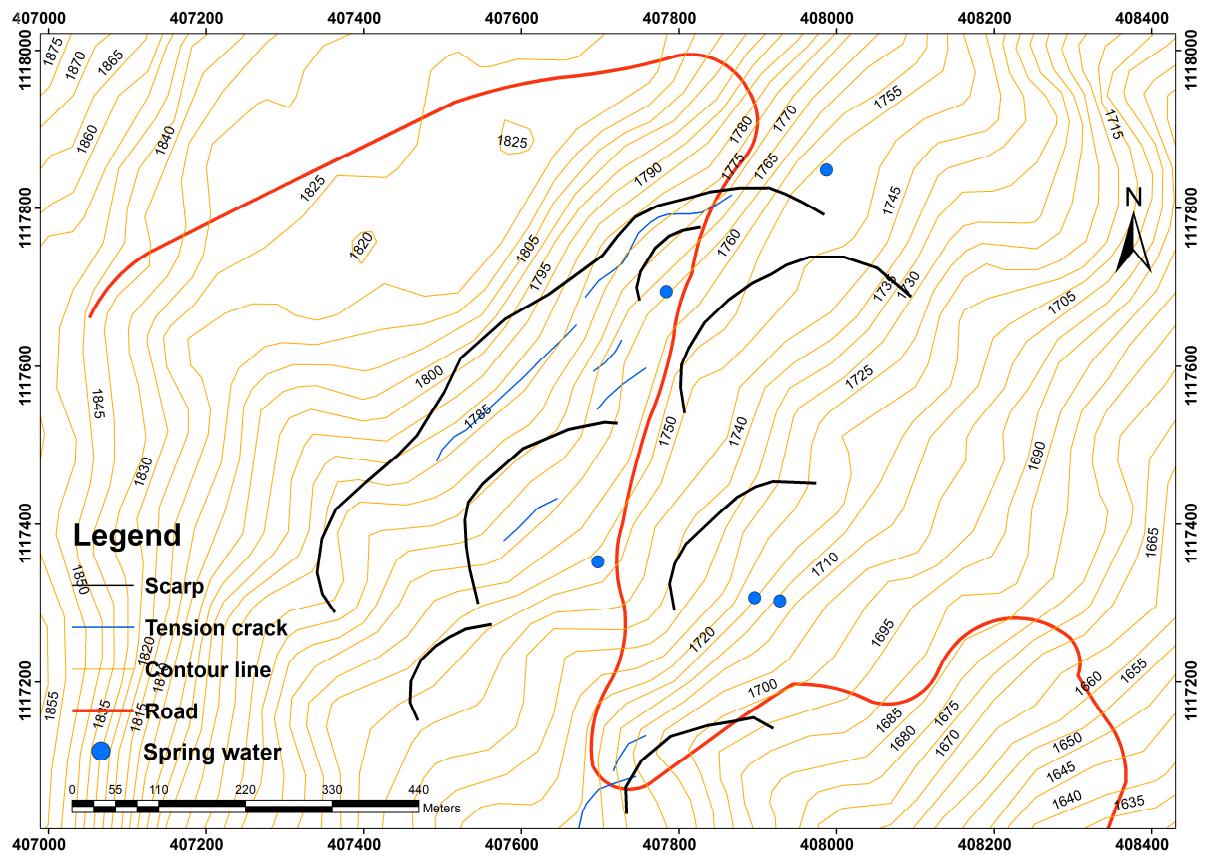


Fig.5.6 Map showing the different features in the study area (Scarps, Tension cracks and spring water locations)

Borehole inclinometer data were collected from 5 boreholes (BH 27-11, BH 27-22, BH 28-11, BH 28-31 and BH 28-32) in the study area and a graph displacement versus depth was produced by GSE and JiCA team members (Fig. 5.7 and **Fig 5.8**).

The graphs (Fig. 5.7 and Fig. 5.8) are the results of the borehole inclinometer; at the bottom, the rain fall data is plotted against the date and at the top, (vertical plot) the borehole depth and the horizontal displacement is plotted. The graphs depict the direction of displacement obtained from the borehole inclinometer record. Each line on the graph is a result of measurements obtained at different time.

The reading of the borehole inclinometer was taken by the GSE and JiCA. Measurements were taken in two directions; one was in the expected direction of the slide and the second one was in the direction perpendicular to the first one. On the graphs, at the right side is the one which is on the expected direction of the slide and the right one which is perpendicular to the expected slide direction.

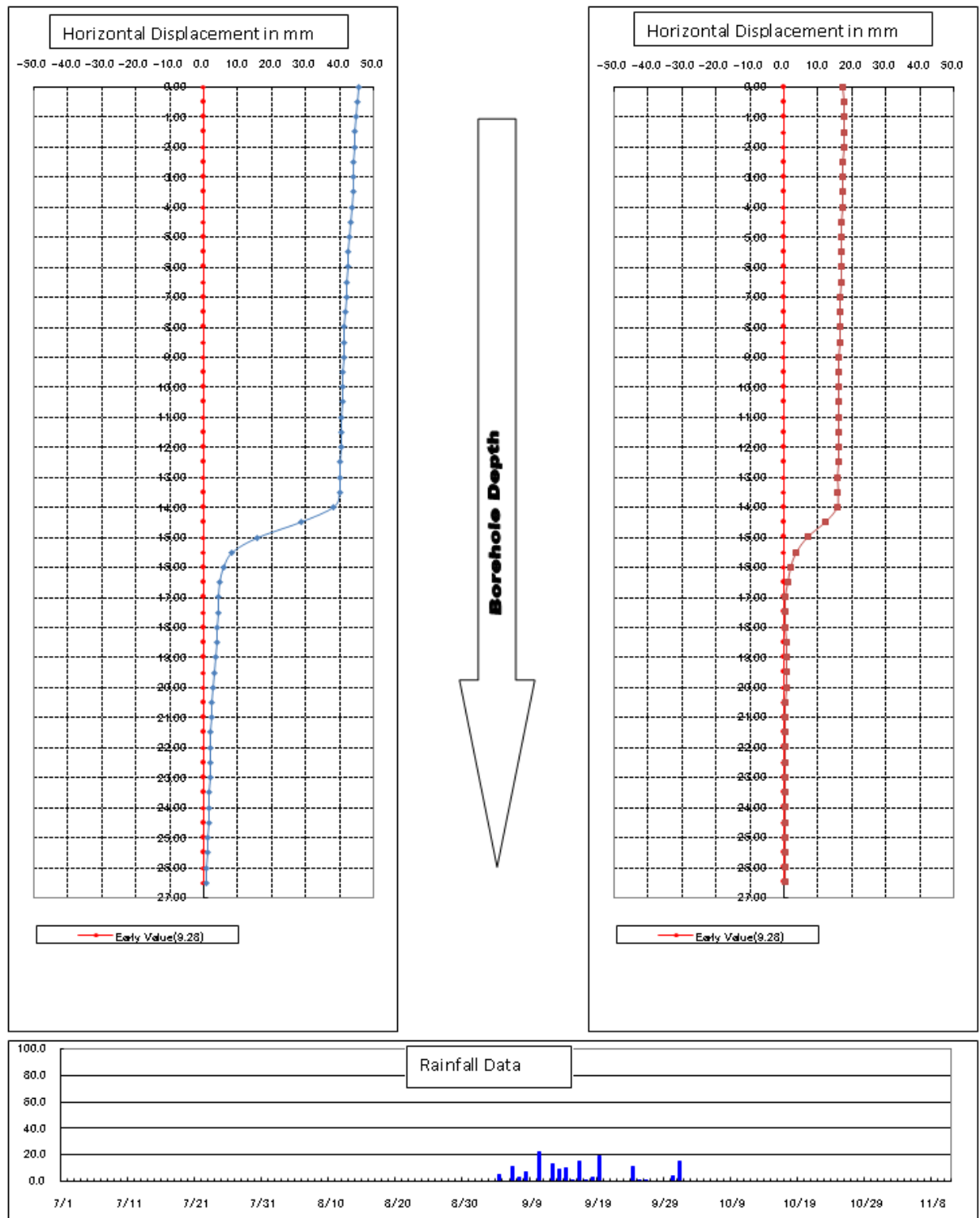


Fig. 5.7 Graph produced from a borehole inclinometer data from BH 27-22 together with the rainfall data at the site (Source: GSE and JICA)

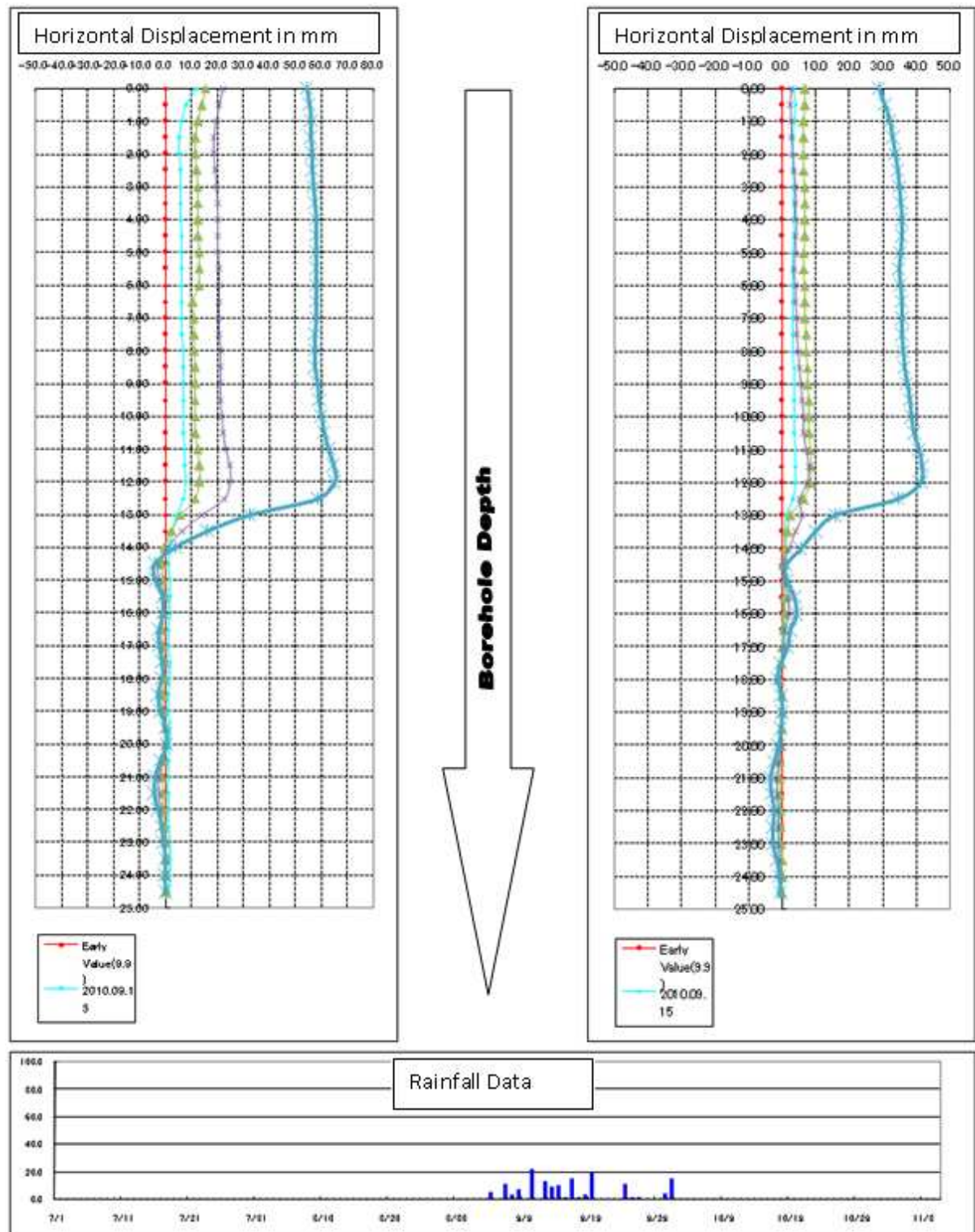


Fig. 5.8 Graph showing the borehole inclinometer data result from BH 28-31 (Source: GSE and JiCA)

At some of the boreholes, before taking the second record, portion of the borehole was closed by a sliding mass and records have been interrupted. Because of the failure, measurement in many of the boreholes was impossible. At some boreholes the measurement from the borehole inclinometer was found to be more than 400mm.

During the present study the data from borehole inclinometers was utilized to understand the possible mode of failure and direction of mass movement which helped in modeling of the slope section for the slope stability analysis. This information later guided to adopt a representative cross section to be used for slope stability analysis model.

Groundwater level in boreholes

Ground water level fluctuation was measured continuously, and the correlation between ground water level and precipitation was investigated. The measurement was done by the EGS and jiCA staffs who are working on the landslide project work in the Abay Gorge. Ground water level was measured using both manual and automatic groundwater level meter.

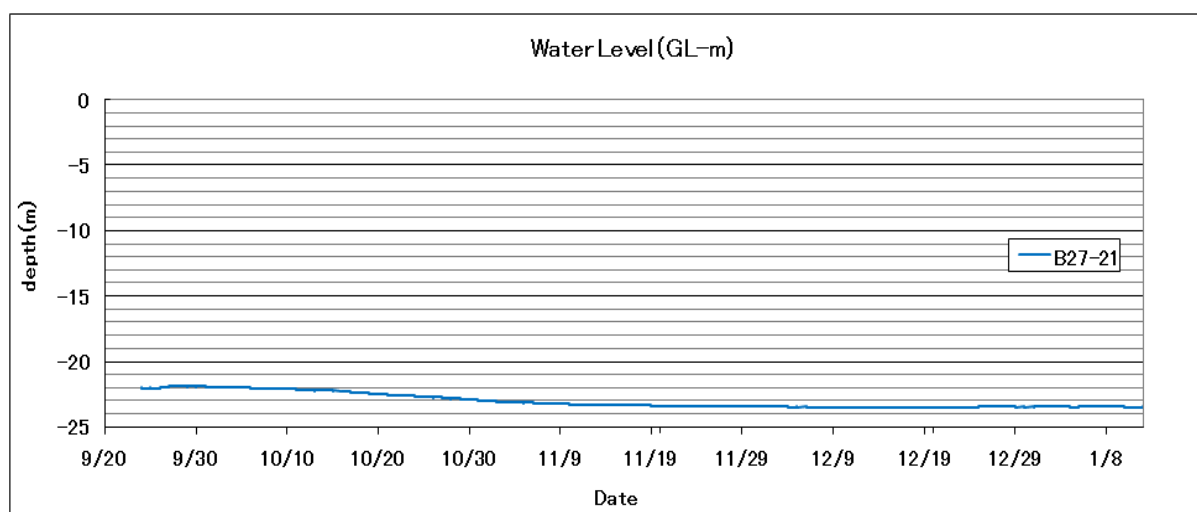


Fig. 5.9 Graph showing groundwater level at B27-21 (Source: GSE and JiCA)

The measurement of the groundwater level was started in September (2010) and still continued till date. Graphs (Fig.5.9 and 5.10) show the groundwater level below the surface at three boreholes at which measurements were taken using automatic groundwater meter. Accordingly in most of the boreholes, the average depth to groundwater is 20 meters and more from the surface. Based on the ground water level records presented supported with, logical interpolation extrapolation were made. Thus, the average peizometric level for the groundwater (25m) was utilized for the slope stability analysis in the present condition.

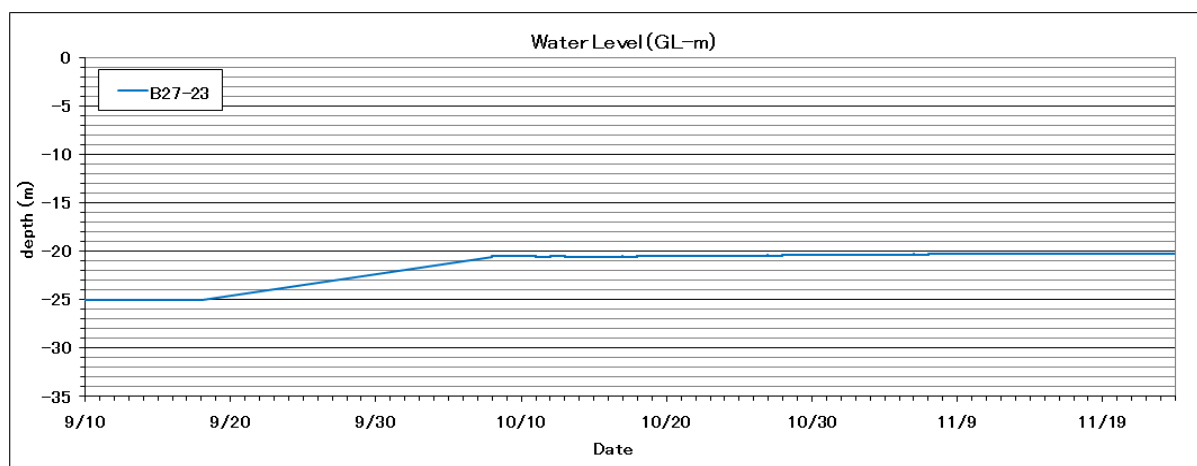


Fig. 5.10 Graph showing groundwater level at B27-23 (Source: GSE and JiCA)

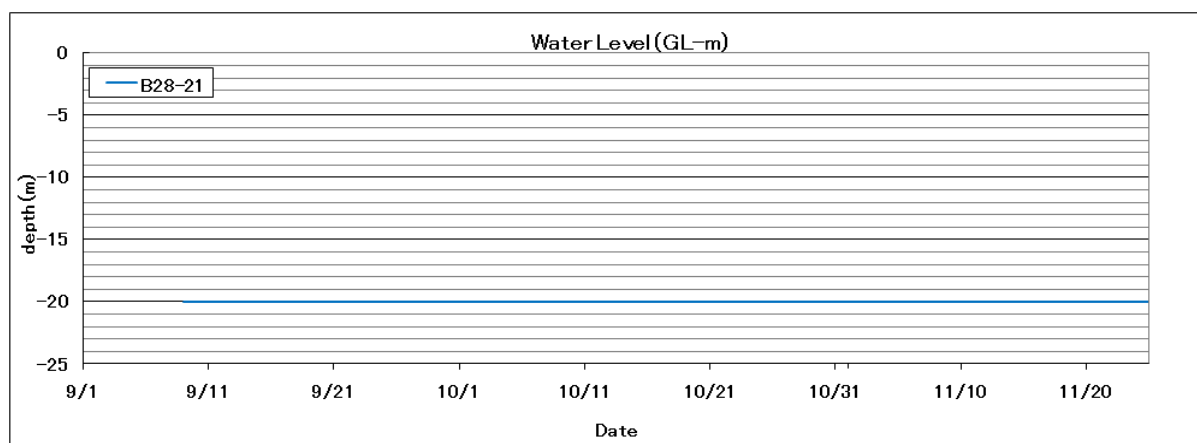


Fig. 5.11 Graph showing groundwater level at B28-21 (Source: GSE and JiCA)

Borehole Cross Section

In the study area 10 boreholes were drilled and logged by the project team working on the counter measure for landslide containing GSE and JiCA staff members. From borehole data it was tried to produce cross sectional map shown below. Six borehole data were used to produce the cross-section (BH 28-41, BH 28-31, BH 28-32, BH 28-22, BH 28-11, BH 27-21).

The cross section data will help in understanding the general geology of the area and the distribution of the colluvial material from the different sources within the slope section. The line at which the cross-section is produced is shown on Fig. 5.18.

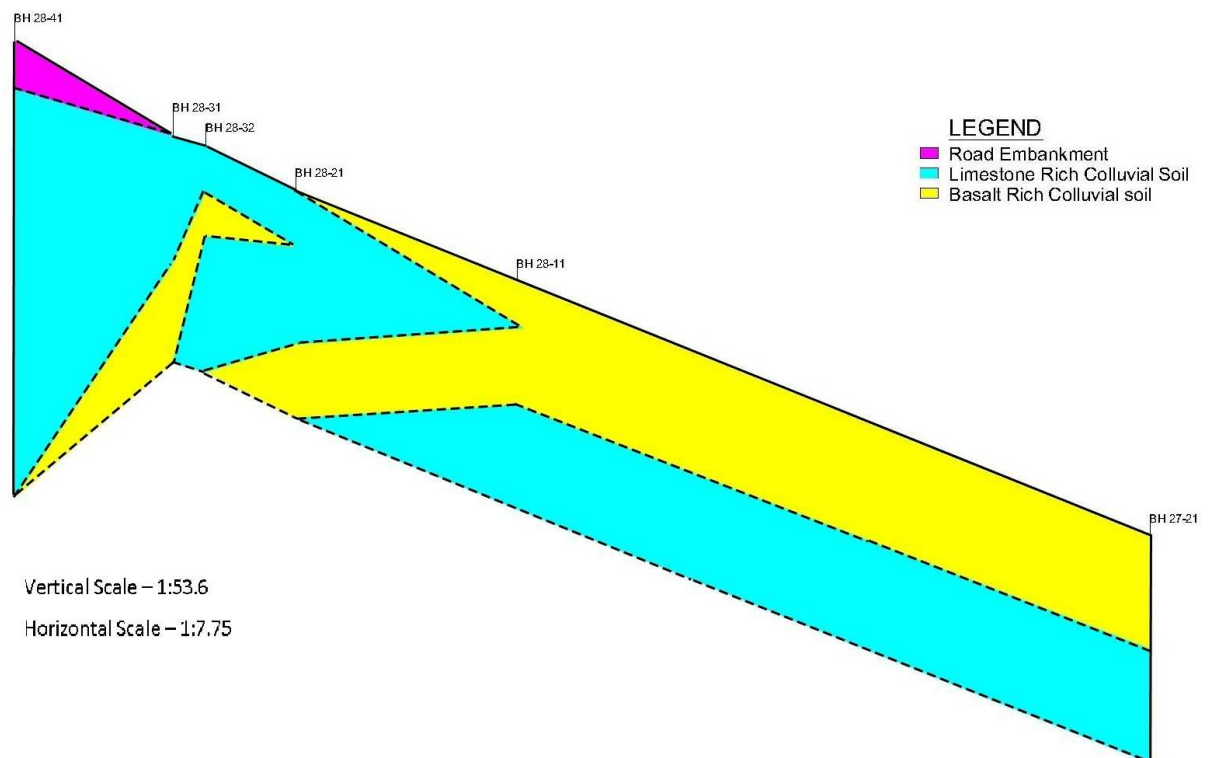


Fig. 5.12 Figure showing the cross section of the study area

5.3.2. Surface extensometer data

The extensometers are installed along the direction of landslide movement to measure the amount of expansion and contraction in cracks and subsidence, if any. There are three extensometers installed in the study area. The surface extensometer number 4 is installed between the church and the borehole B28-1, the surface extensometer 5 is installed near to the church and the last extensometer, number 6 is installed near to borehole B28-31, around the main scarp. The extensometer data is also collected from the EGS and JICA project work.

The record of extensometer can be obtained in real time to compare with inducing factors such as precipitation and ground water level. The data collected from the surface extensometer was graphed; the graph is displacement versus date to show the movement with respect to the days and different rainfall period (Fig. 5.13).

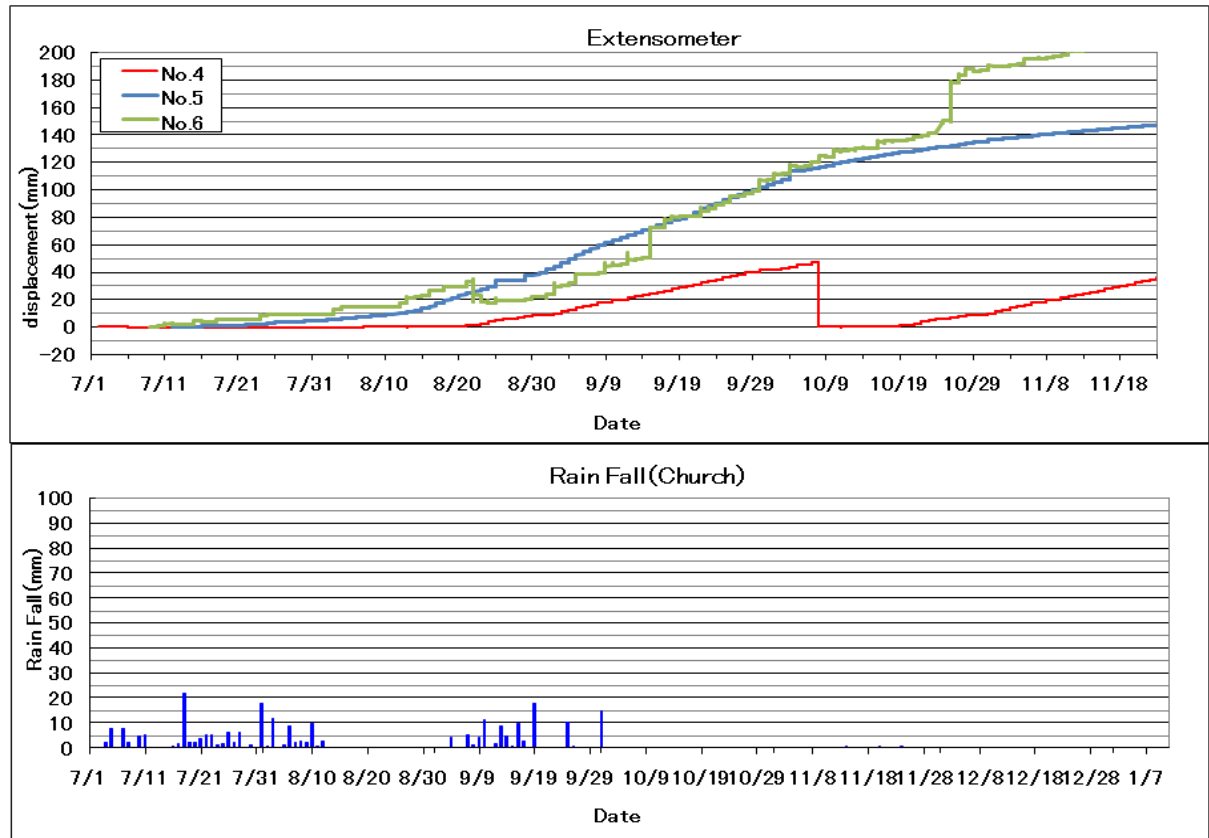


Fig. 5.13 Graph showing the extensometer data result (Source: GSE and JiCA)

From the extensometer graph, it is clearly observed that the displacement starts to increase during the rainy season; it reaches about 200mm at the middle of November (2010) from the number 5 extensometer record and 150mm from number 6 surface extensometer record. In the same month the extensometer number 6 shows only about 50mm displacement per day. Thus, based on this data anticipated adverse conditions were defined and accordingly stability analysis was carried out. Besides, the effect of rainfall on the present landslide problem was also discussed with the help of this data.

5.3.3 Material type and Characterization for engineering parameters

One of the factors that control the slope instability is the type of geotechnical material composing a slope. The study area is covered by colluvial material of basalt and limestone origin. Colluvium is a general term used to describe soil and rock material that has been transported and deposited by gravitational forces. It is typified by poorly sorted mixtures of soil and rock particles ranging in size from clay to large boulders (Almaz and Tadesse Dessie,

1994). Moreover the deposit in the study area doesn't have uniformity in proportions and layering.



Fig. 5.14 Photograph showing the big boulders in the colluvial soil



Fig. 5.15 Photograph showing fine clay to gravel size materials

On consequence the required representative engineering properties of colluvial soils are extremely difficult to determine in the laboratory or in situ. In this research the heterogeneity of the deposit was taken into account and maximum efforts were made to obtain representative values for parameters of engineering interest (shear strength parameters and unit weight).

Determination of the unit weight

The unit weight used in analysis was obtained by taking the average of nine number of bulk density values obtained from laboratory tests conducted on representative samples.

Table 5.1 Table showing laboratory bulk density results (Source: GSE and JiCA)

Borehole no.	Average Bulk Density (g/cm³)
B27-11	2.11
B27-21	2.16
B27-22	2.18
B27-12	2.20
B28-11	2.80
B28-21	2.37
B28-31	2.72
B28-32	2.3
B28-41	2.4
Average Bulk density	2.36

From the average bulk density result, the unit weight is determined using the formula:

$$\text{Unitweight} = \text{Bulkdensity} * g$$

Where; g is acceleration due to gravity, which is 9.8m/s^2 .

Therefore, after calculation, the unit weight is determined as 23.52KN/m^3 .

Estimation of Shear Strength Parameters

Engineering properties of colluvial material are extremely difficult to determine in the laboratory as well as in situ because of the large variability of the grain size of the material, forming the colluvial deposit. A useful method for determining shear strength properties in both colluvium and talus is to analyze an existing slope failure (WSDOT Geotechnical Design Manual, 2010).

The shear strength parameter values for the current slope stability analysis were adopted from literatures and previous studies conducted on the same soil type done in the nearby area, Gohatsion side and a sensitivity analysis conducted to estimate the representative values for the shear strength parameters.

The sensitivity analysis was carried out for the different values of cohesion, angle of internal friction and BBAR by keeping one of these values constant at a time. Below, the results from the sensitivity analysis are shown and representative values for the current stability analysis process is adopted based on this result and some information from previous studies on the same soil type.

Table 5.2 Table showing sensitivity analysis keeping cohesion (C = 0.3) and BBAR (BBAR =0.0) constant

BBAR	Cohesion	PHI	FS
0.0	0.3	10	1.1621
		11	1.2780
		12	1.3929
		13	1.5095
		14	1.6279

Table 5.3 Table showing sensitivity analysis keeping cohesion (c = 0.5) and BBAR (BBAR =0.0) constant

BBAR	Cohesion	PHI	FS
0.0	0.5	10	1.1849
		11	1.3021
		12	1.4171
		13	1.5342
		14	1.6537

Table 5.4 Table showing sensitivity analysis keeping cohesion (c = 0.5) and BBAR (BBAR =0.3) constant

BBAR	Cohesion	PHI	FS
0.3	0.5	10	0.8362
		11	0.9167
		12	0.9994
		13	1.0794
		14	1.1616

Table 5.5 Table showing sensitivity analysis keeping cohesion (c = 0.3) and BBAR (BBAR =0.3) constant

BBAR	Cohesion	PHI	FS
0.3	0.3	10	0.8156
		11	0.8957
		12	0.9770
		13	1.0572
		14	1.1388

Accordingly for the slope stability analysis, the angle of internal friction was adopted to be 11° and that of cohesion (C) was 3 KN/m^3 for the present (existing) condition. For the worst anticipated condition, adjustment was made on the cohesion, since cohesion of the colluvial soil materials could be reduced by the impact of the water, i.e. when it become fully saturated; the value of cohesion adopted for the worst anticipated condition is 0.1 and the value of angle of internal friction will be the same.

Table 5.6 Table showing sensitivity analysis keeping internal friction angle (PHI = 11) and BBAR (BBAR =0.0) constant

BBAR	PHI	Cohesion	FS
0.0	11	0.0	1.2276
		0.1	1.2481
		0.2	1.2637
		0.3	1.2780
		0.4	1.2903
		0.5	1.3021

5.3.4 Slope Geometry

The general slope geometry of the study area is shown in the figure (Fig. 5.17). It has a length of about 800m and a height of about 100m. The general failure direction is SE (Fig. 5.18). The angle of the slope profile is about 12° in the SE direction. As it is clearly observed on the slope geometry, it is somehow rigged topography showing undulation.

From Pos: 408113.657, 1117250.6 To Pos: 407477.044, 1117759.696

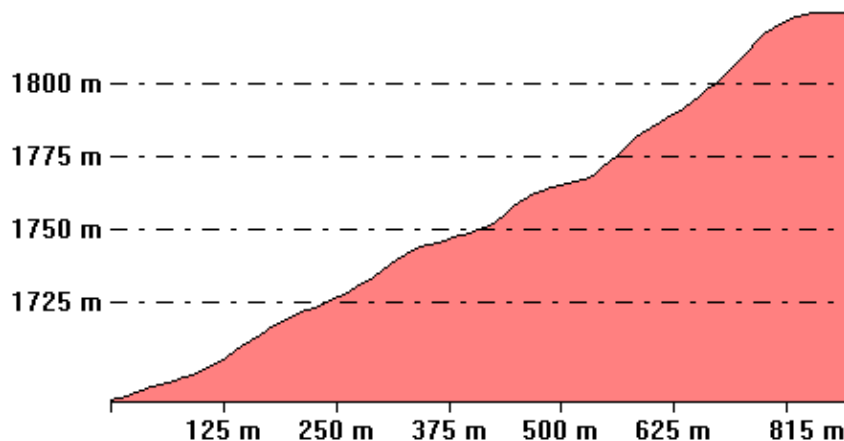


Fig. 5.16 Figure showing the general slope geometry along the failure direction

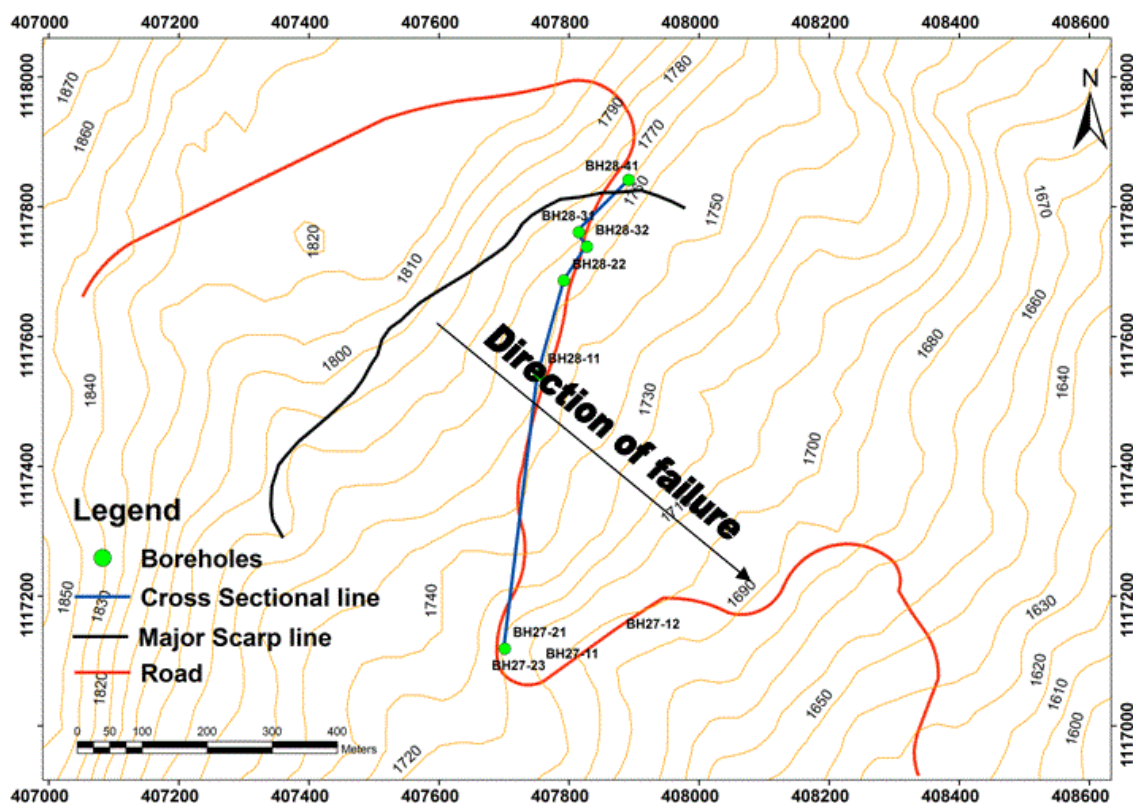


Fig. 5.17 Figure showing the possible direction of the slope failure and the cross-sectional line

Thus the data presented in this chapter formed the input for slope stability analysis. A detailed description on systematic compilation of input data for slope stability analysis is given in Chapter 6.

Chapter 6 Stability Analysis and Measures

6.1 Preamble

The slope stability analyses is performed to assess the safe and economic design of a human-made or natural slopes (e.g. embankments, road cuts, open-pit mining, excavations, landfills etc.) and the equilibrium conditions. The term slope stability may be defined as the resistance of inclined surface to failure by sliding or collapsing.

The main objectives of slope stability analysis are:

- Finding endangered areas
- Investigation of potential failure mechanisms
- Determination of the slope sensitivity to different triggering mechanisms
- Designing of optimal slopes with regard to safety, reliability and economics
- Designing possible remedial measures, e.g. barriers and stabilization.

Successful design of the slope requires geological information and site characteristics, e.g. properties of soil/rock mass, slope geometry, groundwater conditions, alternation of materials by faulting, joint or discontinuity systems, movements and tension in joints, earthquake activity, etc.

Analyses must be based upon a model that accurately represents the site subsurface conditions, ground behavior, and applied loads. Judgments regarding acceptable risk or safety factors must be made to assess the results of analyses.

Generally, slope stability analysis of the current selected slope section is conducted based on secondary data available from different sources and the data collected during the present field works.

6.2 Uncertainties in slope stability analysis

In slope stability analysis, there are uncertainties that come from different sources and conditions. According to Alonso (1976) (as cited in Shien, 2005), uncertainties in soil properties, environmental conditions, and theoretical models are the most important source for a lack of confidence in deterministic analysis.

Morgenstern (1995) divided geotechnical uncertainty into three distinctive categories:

- parameter uncertainty,
- model uncertainty and
- human uncertainty

Parameter uncertainty is the uncertainty in the inputs of analysis; model uncertainty is due to the limitation of the theories and models used in performance prediction; it is the gap between the theory adopted in prediction models and reality while human uncertainty is due to human errors and mistakes, this results when incorrect mechanism is modeled or failure occurs due to mistake in correctly determining the chosen model or it may be due to carelessness and ignorance, misleading information, poor construction, inappropriate contractual relationships and lack of communication between parties involved in the project. Model uncertainty is probably the major source of uncertainty in geotechnical engineering (Morgenstern, 1995).

6.3 Factors responsible for the current slope instability

Rainfall and Landslide

Rainfall is the source of the water. Rainwater easily penetrates into the ground through cracks and the voids present in the colluvial soil. The high permeability of the colluvial soil facilitates the movement of the rainwater into the underground. The infiltrated rainwater occupies the void space present in the underground and produces the pore water pressure inside the soil mass. Besides increasing the pore water pressure, the rainwater causes the reduction in the soil cohesion to reduce the shear strength of the soil mass and leads to the failure of the slope section. At areas where the soil is black clay, because of the expansive nature of such soils, the soil mass starts to swell during the rainy season and exerts pressure on the adjacent soil masses and lead to the failure of the slope in a favorable direction.

The results of the surface extensometer data shows that, the movement of mass becomes increasing after the end of the rainy season (as shown in Fig. 5.15, in Chapter 5). This is just after the soil mass becomes highly saturated by the rain and it loses its cohesion because of the rainwater. After the end of October, the surface extensometer result shows more than 180mm displacement as measured by the surface extensometer number 6; that of number

5 shows about 160mm displacement and that of the number 4 extensometer shows a maximum of 50mm displacement, movement is maximum after the end of the rainy season. From the results of the surface extensometer data, it can be clearly observed that the movement is, generally, occurred after the end of the rainy season.

The water that comes from the rain is the only sources of water that fluctuate the groundwater level in the study area. During rainy season, water moves into the underground and springs emanate at different places. This movement of the water in the underground also causes piping effect and this may leads to differential settlement in different parts of the area and clearly observed on the road. Therefore, it can be concluded that, the water that comes from rain is one of the major cause for the instability of the slope in the area.

Geology/colluvial soil and Landslide

The colluvial deposit in the study area is deposited at the foot of a steep slope or cliff which forms the slope gentler than the opposite slopes towards Gohatsion side. It is mainly composed of gravel, cobble and boulder of basalts and limestone within silty clay matrix. It is generally poorly sorted resulting in the occurrence of voids and hence the colluviums could be categorized as very loose, weak, heterogeneous and permeable unit. Most of the springs emanate from the colluvial soil indicates high permeability nature of the colluvial material.

At the present site the colluvial material sources are mainly limestone and basalt; their composition and engineering properties as well depend on their origin. In the areas where the dominant material is basaltic source, there is a black clay soil, weathering product of the transported basaltic material. The color of this clay is dark and shows cracks on the dried parts of the soil. This soil is known by its expansive and shrinkage behavior and is problematic soil in engineering works. The presence of this black clay in the area causes problems in some parts of the slope section. When the soil is saturated, its volume increased and exerts pressure on the adjacent soil materials. This pressure pushes the adjacent materials in the direction favored for the slope instability. Besides, when the soil unit is dried out it will be cracked; this will allow water to infiltrate into the ground easily.

Construction of the road and Landslide

The disturbance during the construction of the road has played a great role. During the construction of the road there was excavation; the excavation has disturbed the slopes in the area and make it unstable. Beside the excavation work, during the construction work, natural streams were blocked and were diverted to some other way. When it is diverted, the natural flow direction of the water has been changed and the amount of water traveling together becomes more and the water finds some other courses. During such time, due to the high permeability of the soil material present in the area, the water gets into the ground and travels through the underground. This has caused an increase in the pore water pressure and at the same time, the finer particles probably washed out; this might have caused a piping effect when the water leaves the pore spaces. Due to the underground erosion/piping, at many places, differential settlement has also occurred, which was observed at places during the field investigation.

Agricultural process and Landslide

Human activity like land plough for agriculture produces disturbance on the surrounding soil material. This activity also facilitates the infiltration of water into the ground to join the subsurface water and to produce the impacts mentioned above.

6.4 Limit equilibrium Analysis

Limit equilibrium types of analyses for assessing the stability of earth slopes have been in use in geotechnical engineering for many decades. The idea of discretizing a potential sliding mass into vertical slices was introduced early in the 20th century and is consequently the oldest numerical analysis technique in geotechnical engineering.

Methods of limit equilibrium are largely used in the stability evaluation of natural slopes. There are several such methods which determine stability condition of slope in terms of Factor of safety. Those methods assume that soil at failure obeys the perfectly plastic Mohr Coulomb criterion (Fellenius (1926) and Terzaghi (1943)). However, over the last 30 years the analysis of slopes using the limit-equilibrium method has been significantly refined by using various methods of vertical slices (Bishop (1955), Janbu (1954) and Spencer (1967)).

Through the use of these methods in the design, the magnitude of a safety factor is obtained. By definition, when the slope is on the verge of failure its factor of safety is unity, and the analysis along the failure surface or part of failure surface if the shearing resistance is assumed to be known along the remainder.

Stability analysis for the Slope Section is performed by one of the limit equilibrium analysis techniques, Bishop Method. This method is based on two dimensional slope profile sections. The concept behind this method is the estimation of the minimum factor of safety from the possible slip surfaces. For this purpose Geotechnical software; SARC and SLOPE/W were utilized during the present research study. Bishop's simplified method, utilizing a circular arc slip surface, is probably the most popular limit equilibrium method.

6.4.1 Stability Analysis

During the present study stability analysis was conducted using, two software; SARC and SLOPE/W. SLOPE/W is commercial software and in this study the student version was utilized. The student version has some application limitations over dynamic stability analysis. The static slope stability analysis was conducted using both software and the dynamic slope stability analysis was performed by using SARC.

Assumptions and General Conditions for Present Slope Stability Analysis

As described in the previous chapter, the sensitivity analysis was conducted using SARC for different shear strength parameters and values for cohesion and internal friction angle was determined. The result of the sensitivity analysis is given in tables (Table 5.2 – Table 5.6). Based on the sensitivity analysis the shear strength parameters values adopted for cohesion and internal friction angle were 0.3 KN/m^2 and 11° , respectively for the slope stability analysis for the present condition; and a unit weight was taken from the laboratory results, where average bulk density was considered.

For the stability analysis and modeling, it was considered that the material is homogeneous because of the complexity of the cross section. The complexity of the cross section arises from the different sources for the colluvial material present in the study area; it will be difficult in modeling the slope section for the stability analysis without considering it as a homogeneous material. Besides, it was considered that the slope failure is deep seated and

a slope stability analysis was conducted for the deep and large slope failure, not the shallow failures observed within the large landslide.

6.4.2 Computer programs and data used for Stability Analysis SARC

SARC software was developed by Prof. Bhawani Singh and is written in FORTRAN programming language. It works in a DOS operating system. SARC is developed to analyze a slope with rotational mode of failure. For the present study sensitivity analysis for shear strength parameters was also conducted using this software.

This software calculates the centre and the radius of the possible slip surface, weight of the wedge and the minimum factor of safety for the slope section. Some of the Input parameters for this software are coordinates of the slope profile, unit weight of the layers, and exit and entry points for the possible failure surface. The software calculates FOS for all possible slip surfaces and provides results for the slip surface, for which FOS is minimum.

SLOPE/W

SLOPE/W is in use since 1977. The initial code was developed by Professor D.G. Fredlund at the University of Saskatchewan. Like any other geotechnical software for slope stability analysis, it requires to have the shear strength parameter of the soil, the slope geometry and the different soil layer thickness, the groundwater level, etc. Besides the slope stability analysis, SLOPE/W has been designed and developed to be a general software tool for the stability analysis of earth structures.

Data

For SARC some of the data that are required are: coordinate points from the profile line of the slope section, shear strength parameters, horizontal and vertical earthquake accelerations. For the SLOPE/W the shear strength parameters, the slip surface grid and radius are the main input data for the static stability analysis.

For the present study the coordinates for the profile section of the slope were determined from the profile section produced by Global Mapper¹¹ and the shear strength parameters used were determined from the sensitivity analysis from the SARC software and with the help of previous studies on the same soil type in the nearby area, Gohatsion side. For the

SLOPE/W, the slip surface grid and the slip surface radius were determined from the results of the SARC software since it gives the coordinates of centre of the radius of the slip surface and the length of the radius of the slip surface. The data that were used for the detail slope stability analysis are listed in the Table 6.1.

In addition to the data discussed above, the effect of earth quake was also considered in the dynamic slope stability analysis. As discussed in chapter 1 the area is found in the zone 7 with a value of the earthquake magnitude in Richter scale as 7.0. Horizontal and vertical earthquake acceleration values used as input data in the SARC software are 0.08g and 0.4g, respectively for the dynamic slope stability analysis.

Table 6.1 Shear strength parameters adopted for the stability analysis

Condition	Unit Weight (Ton/m ³)	Cohesion (Ton/m ²)	Internal Friction
Static Dry	2.36	0.3	11 ⁰
Static Present	2.36	0.2	11 ⁰
Static worst	2.36	0.1	11 ⁰
Dynamic dry	2.36	0.3	11 ⁰
Dynamic present	2.36	0.2	11 ⁰
Dynamic worst	2.36	0.1	11 ⁰

The Different Conditions

Dry condition: Dry condition is the condition by considering that the slope section is completely dry; stability analysis for this condition is performed under both static and dynamic state. This condition defines that the water within slope, if any, will not contribute any kind of destructive water forces within the slope and may not contribute towards the instability of the slope.

Moderately Saturated/Present Condition: Moderately saturated condition is the condition which represents the current situation of the groundwater condition. Under this situation the water forces within the slope will be moderate and the slope material will be partially saturated. Such situation may occur during moderate rainfall. For this condition stability analysis is performed under both static and dynamic state.

Worst anticipated condition: The worst anticipated condition is the condition which represents the worst condition when the slope is fully saturated with water, i.e. when the groundwater level is almost at the surface. This situation may occur during very heavy sustained raining in the area. The groundwater will be fully recharged and the slope material

will be fully saturated. Under such situation the water forces developed within the slope material will be destructive and induce instability in the slope. For this condition stability analysis is performed under both static and dynamic state.

6.4.2.1 Static Stability Analysis using SARC

Static stability analysis was performed by making both horizontal and vertical acceleration as zero, i.e. by neglecting the effect of earthquake. Static stability analysis is conducted for three different cases; for dry condition, for the present condition and for the anticipated worst condition.

Stability Analysis for the Dry condition

For the slope stability analysis in the Dry condition the groundwater level is considered to be much below the influence zone in the cross section i.e the groundwater level is believed to be below the possible failure surface. Thus, the slope section is considered to be dry and there will not be any effect of the groundwater in inducing instability to the slope. From the stability analysis, it was found that the factor of safety under dry condition will be 1.28 and the possible radius of slip surface will be 1333.43m and the coordinates for the center of slip surface will be at (126.95, 3018.61) (Table 6.2).

Stability Analysis for the present condition

For the slope stability analysis, under the present condition, the groundwater table was determined from the three borehole measurement records. The average groundwater level as deduced is 20m below the surface; almost $\frac{3}{4}$ of the slope section is saturated with water. From this analysis, the factor of safety for the slope under the current condition is calculated and the center of the radius of the slip circle is identified. For the present condition a factor of safety of 0.89 was obtained.

Stability Analysis for the anticipated worst condition

For the anticipated worst condition, the slope stability analysis was conducted by assuming that the whole slope section is saturated. This will be useful to estimate the factor of safety for the worst condition. Here, the cohesion is assumed to be 0.1 since entire slope mass is saturated and BBAR to be 0.4. Under the static state, a factor of safety of 0.74 is obtained.

Table 6.2 Stability analysis for Static Condition

Static Dry Condition				
Input Data	ROCK = 0.000	RWL = 0.000	XS = 0.000	WI = 0.000
	ZC = 0.000	ZWR= 0.000	C = 0.3	PHI = 11.00
	GAMA = 2.36	GAMAW= 1.000	BBAR= 0.0	AH = 0.000
	AVR = 0.000	EQM = 0.000		
Output Data	F.S	WEIGHT OF WEDGE(T)	COORDINATE OF CENTER	RADIUS (M)
	1.28	0.39E+05	(126.95, 3018.61)	1333.43
Present Condition (Static)				
Input Data	ROCK = 0.000	RWL = 0.000	XS = 0.000	WI = 0.000
	ZC = 0.000	ZWR= 0.000	C = 0.200	PHI = 11.00
	GAMA = 2.36	GAMAW= 1.000	BBAR = 0.3	AH = 0.000
	AVR = 0.000	EQM = 0.000		
Output Data	F.S	WEIGHT OF WEDGE(T)	COORDINATE OF CENTER	RADIUS (M)
	0.88	0.34E+05	(102.22, 3169.74)	1482.03
Worst anticipated condition (static)				
Input Data	ROCK = 0.000	RWL = 0.000	XS = 0.000	WI = 0.000
	ZC = 0.000	ZWR= 0.000	C = 0.1	PHI = 11.00
	GAMA = 2.36	GAMAW= 1.000	BBAR = 0.4	AH = 0.000
	AVR = 0.000	EQM = 0.000		
Output Data	F.S	WEIGHT OF WEDGE(T)	COORDINATE OF CENTER	RADIUS (M)
	0.74	0.29E+05	(70.62, 3362.84)	1673.09
ROCK = Reduced level of hard strata with respect to origin RWL = Reduced level of groundwater/reservoir water with respect to origin XS = X-Coordinate of point from where surcharge starts WI = Uniform surcharge intensity ZC = Depth of tension crack ZWR = Depth of water in tension crack / ZC C = Cohesion of soil/rock PHI = Angle of internal friction (Degree) of soil/rock GAMA = Unit weight of soil/rock GAMAW = Unit weight of pore water BBAR = Pore water pressure/(GAMA * Average height of slices) AH = Horizontal component of EQ. acceleration near crest of slope AVR = Vertical component of EQ. acceleration / AH EQM = Corresponding EQ. magnitude on Richter Scale				

6.4.2.2 Dynamic Stability Analysis

For the dynamic stability analysis, the input parameters are the same except some of the additional parameters are used. In the dynamic stability analysis the effect of earthquake was considered and both vertical and horizontal earthquake accelerations were used.

As discussed in the first chapter the area is found in the zone 7 with value of the earthquake magnitude in Richter scale as 7.0 and this value was used for the slope stability analysis for the dynamic condition. Besides, values of 0.08g and 0.4g for horizontal and vertical earthquake accelerations have been adopted.

Under the dynamic stability analysis, slope stability analysis for the different conditions, i.e. for dry condition, present condition and for the worst anticipated conditions, was performed. Here the slope stability analysis input and output data will be presented for the present dynamic condition and for the rest will be summarized in the next section since the input data is almost similar with the static slope stability analysis except that of the inclusion of earthquake effect.

Dynamic Stability Analysis for the present condition

For the slope stability analysis of the present condition under the dynamic state, the effect of earthquake is considered and the horizontal and vertical components of the earthquake acceleration were included in the stability analysis. Under this condition, a factor of safety of 0.58 is obtained.

6.4.3 Static Stability Analysis using SLOPE/W

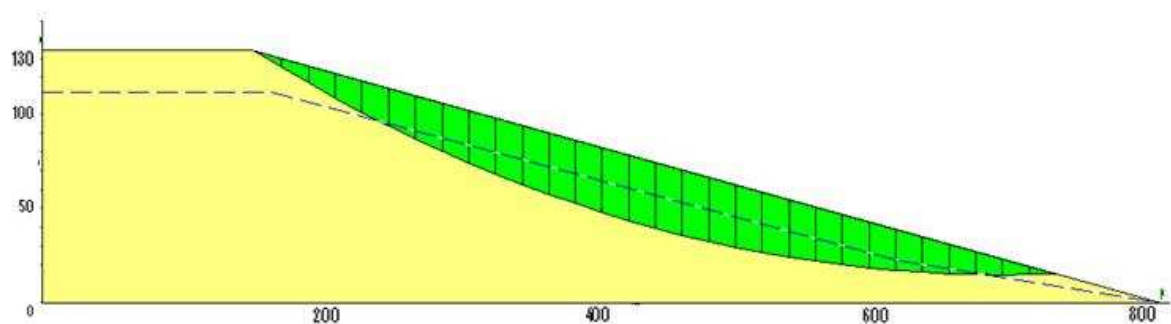
Static stability analysis was also performed using the SLOPE/W student version. SLOPE/W allows using different limit equilibrium analysis techniques like Bishop, Janbu, Spencer and Morgenstern-Price methods. In this study only Bishop, Ordinary and Janbu methods were used for the slope stability analysis. For the slope stability analysis, the grid and radius of the slip surface were determined from the results of the SARC stability analysis and the piezometric surface is determined from the borehole data as discussed in the previous chapter. The slope stability analysis using SLOPE/W was performed for the present static condition only; this is because of the limitation in the functions of the SLOPE/W software under the student license which makes it impossible to work for the dynamic condition.

Table 6.3 Input and output data for the dynamic slope stability analysis for the present condition

Input Data			
ROCK = 0.000	RWL = 0.000	XS = 0.000	WI = 0.000
ZC = 0.000	ZWR= 0.000	C = 0.2	PHI = 11.00
GAMA = 2.36	GAMAW= 1.000	BBAR = 0.3	AH = 0.08
AVR = 0.40	EQM = 7.000		
Output Data			
F.S	WEIGHT OF WEDGE(T)	COORDINATE OF CENTER	RADIUS (M)
0.58	0.36E+05	(112.8, 3105.09)	1418.34
Note: Description on notations and abbreviation is already given in Table 6.2			

The slope stability analysis for the present condition is modeled as below (Fig. 6.1); the model is generated based on the slope section profile. During the slope stability analysis 36 slip surfaces were analyzed; the slip surfaces were taken based on the combination of the slip surface grid and slip surface radius. Among those 36 slip surfaces 16 slip surfaces result in a factor of safety less than 1 and the 16 slip surfaces resulted factor of safety greater than 1. Among the 36 slip surfaces 4 of them could not be analyzed since they were located above the surface of the slope during the combination of the slip surface grid and the slip surface radius.

The results for the factor of safety for the different slip circles are shown in Fig. 6.2. The minimum factor of safety is determined by the Bishop and it comes out to be 0.83. The 36 slips surfaces were selected by the combination of the given slip surface grid and the slip surface radius.

**Fig. 6.1 Result of the slope stability analysis with a slip surface with a minimum factor of safety**

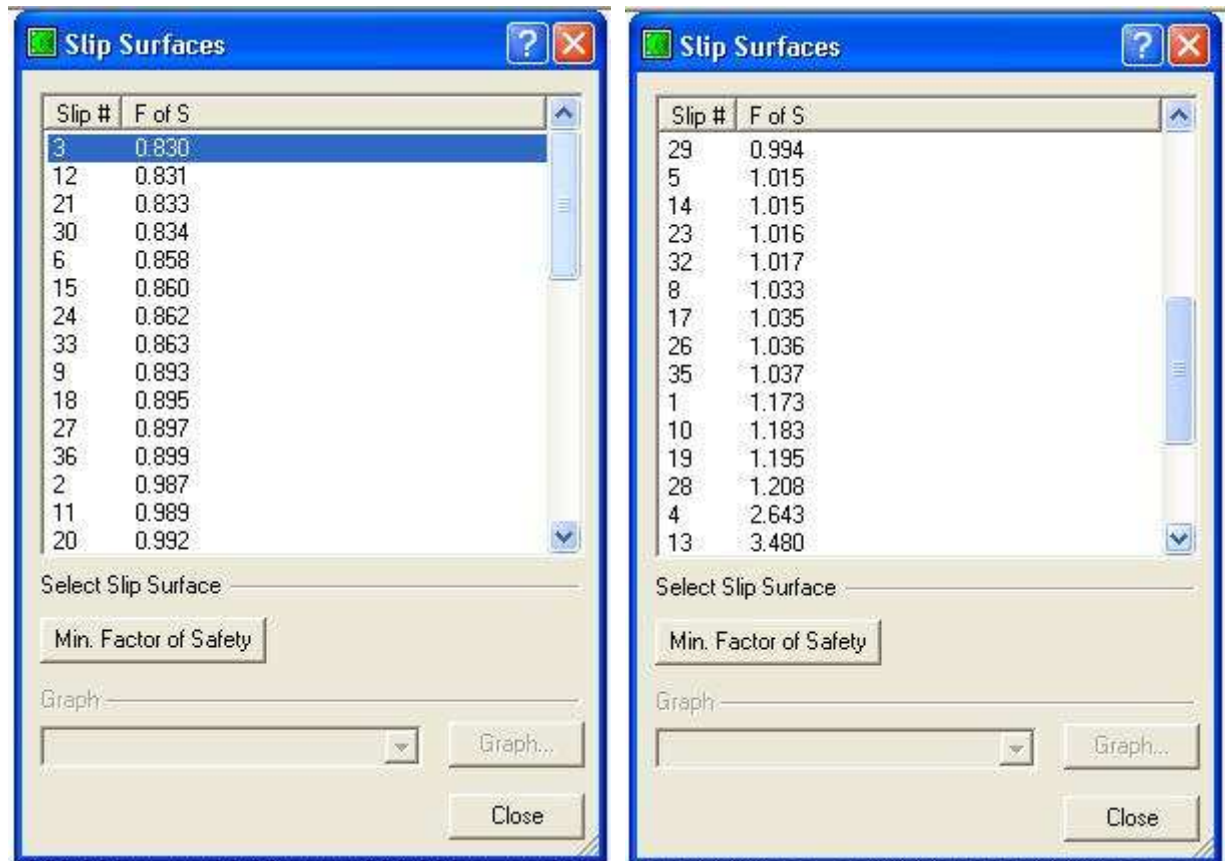


Fig. 6.2 Results of the factor of safety for the different slip surfaces

6.5 Results and discussion

Slope stability analysis was conducted for the different conditions (dry, present and worst anticipated conditions) under both static and dynamic states based deterministic approach using SARC and for the present static condition using both SARC and SLOPE/W. The analysis was carried out for the entire slope section even if there were minor slope failures within the main slope section. In the slope stability analysis process, maximum efforts were made to consider the heterogeneity of the soil in the slope section.

Slope stability analysis was done by using the shear strength parameters that were adopted from the sensitivity analysis and the slope profile coordinate points determined from the slope profile by Global Mapper¹¹ software; the unit weight is derived from the laboratory bulk density result. The factor of safety for the different conditions, which were obtained from SARC, is summarized in the table below (table 6.4).

The table 6.4 shows the results from the SARC software. The minimum factor of safety for the critical slip surface resulted from SARC static stability analysis is 1.28 for dry condition, 0.89 for the case with water table for the present condition and 0.74 for the static anticipated worst condition. The results from SARC were also summarized in graphical form (Fig. 6.3), which gives a clear comparison between the different conditions under both static and dynamic states.

Table 6.4 Factor of safety for different conditions resulted from SARC

Conditions	FOS	Weight (Ton)	Center Point Coordinates	Radius of Slip Circle (m)
Static Dry	1.28	0.39E+05	(126.95, 3018.61)	1333.43
Static moderately saturated	0.88	0.34E+05	(102.22, 3169.74)	1482.03
Static anticipated worst	0.74	0.29E+05	(70.62, 3362.84)	1673.09
Dynamic Dry	0.85	0. 36E+05	(112.80, 3105.09)	1418.34
Dynamic moderately saturated	0.58	0.36E+05	(112.80, 3105.09)	1418.34
Dynamic Worst	0.49	0.30E+05	(74.12, 3341.43)	1651.86

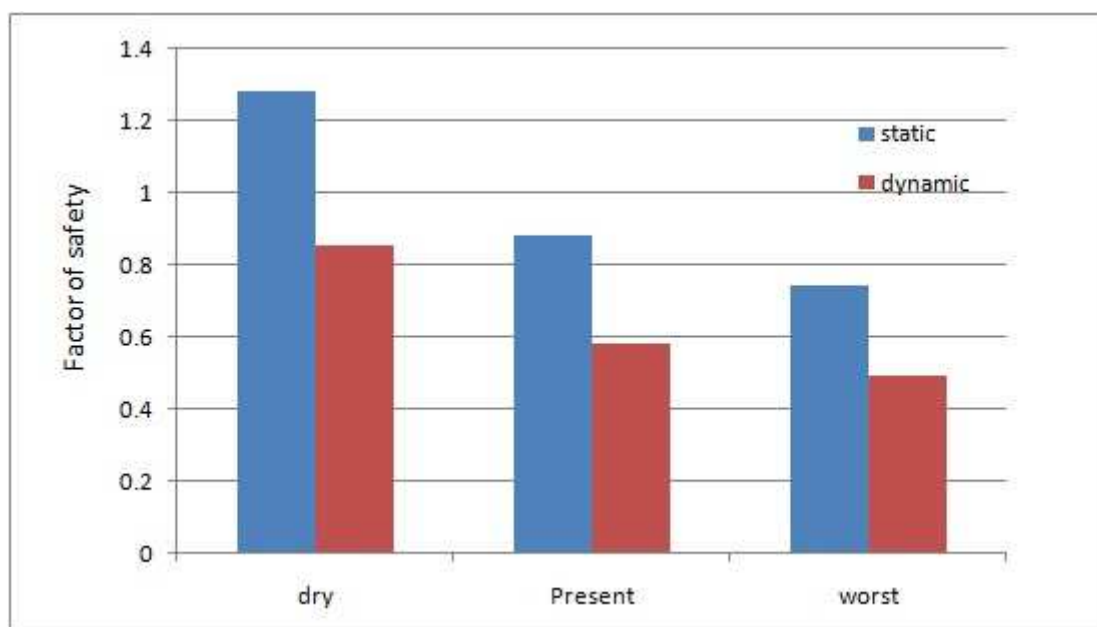


Fig. 6.3 Graphical presentation of results from SARC indicating stability under varied condition

Beside the SARC software, the factor of safety for the present static condition was determined by SLOPE/W. For the SLOPE/W software, to determine the slip surface grid and

the slip surface radius, some inputs have been taken from the results of the SARC. Based on the given slip surface grid and slip surface radius, 36 possible slip surfaces were analyzed and a minimum factor of safety 0.83 was obtained which is only 0.05 less than the results obtained from SARC with the same condition.

Visually in the field, it was clearly observed that there are recent movements in the area, and show that the area is under unstable condition. The gabion wall constructed near to the St. Gabriel church was damaged without giving service even for one year (Fig. 6.1). At the base of the church it was clearly observed that big slope mass is moving down. Based on the information collected during the field work, this sliding mass is damaging the road and maintenance is going on frequently. Besides, the displacements along the road section show that the slope section is unstable and it needs attention and follow up to maintain the road before any significant damage would occur on the road.

Based on the results obtained from the stability analysis, it is clearly observed that the slope section is stable only under the dry static condition. At the dry static stage, the factor of safety of the slope section is 1.28. For the rest of the cases under static and dynamic conditions the slope is unstable, the factor of safety is below 1. Under the dynamic slope stability analysis, the factor of safety obtained for the worst condition is even under 0.5.

In addition to the results of the stability analysis, result of the surface extensometer data also shows that there is a movement still going on. From the graph of the surface extensometer data (in previous chapter) it can be clearly observed that the movement is active and it reaches about 200mm within three months in one of the extensometers data; the other extensometer records also show recent movements which is directly related with the rainy season. The borehole inclinometers record also show active movements in the study area.

From these results, one can understand that the slope is unstable even in the current condition, i.e. under moderately saturated condition; that is why the factor of safety is below 1. Generally, the field observation and the surface extensometer and borehole inclinometer records show that the area is actively sliding; this may validate the results obtained from the present slope stability analysis for the different conditions.



Fig. 6.4 Damage on the Gabion wall

6.7 Remedial Measures

Stability of soil slopes highly depends on the shear strength parameters (cohesion and angle of shearing resistance) of the soil present in the study area and the degree of different natural and human effects on the slope section.

From the slope stability analysis it is clearly observed that the slope is unstable for the current condition and all the other conditions except for the static dry condition. For almost all the cases, except for the static dry condition, the factor of safety is less than 1 and for the dynamic worst conditions, it is less than 0.5. Therefore, before fatal landslide problem occurs in the area it is necessary to adopt suitable remedial measures.

As already discussed, the area is characterized by a big mass movement with circular/rotational mode of failure. In the stability analysis, it was clearly described that the effect of rainfall significantly contributes towards the instability of the slope; and the behavior of the land and engineering material/colluvial soil present in the slope section also

plays a great role. Such conditions with other human impacts can cause a disastrous problem if measures will not be taken as soon as possible. Since the material of the slope section is colluvial soil, the remedial measures to be taken are different from those of the rock slopes. The best remedial measures to be taken are mentioned below by taking the different causative factors into account.

Proper drainage management

Water infiltration in the overburden during heavy rains and consequent increase in pore pressure within the overburden reduces the strength of the material and causes sliding of the landmass. This can be minimized by reducing infiltration by providing adequate drainage network. In this regard, a strategy must be adopted such as reducing flow of water into the vulnerable slope material by constructing interceptor drain, trench drain, diverting side drains and by channelization of all drains.

The drainage to be constructed should be designed after a detail field visit; most probably, their position should be before the scarps and tension cracks in the upward side. This will protect the infiltration of water through the tension cracks. Most important, all drainage systems need regular maintenance and surveillance for detecting any changes in the flow pattern or pore water pressure.

Bio-engineering

It is a well-understood fact that plant cover largely increases the stability of the underlying ground by increasing root strength, intercepting direct effect of precipitation and reducing pore water pressure by evapotranspiration. Therefore, bio-engineering methods including that of large scale afforestation and protection of existing vegetation cover needs to be adopted in the critical slope section and the landslide prone area around the slope section. The selection of suitable plant species should be such that can withstand the existing hydrological conditions of the terrain.

On the bases of the economy and the time to cover the area vetiver grass is recommended as a remedial measure. Since the slope is gentle and the main causative factors for the landslide problem are rainfall and the type geotechnical material the slope section, vetiver grass will be the best choice to protect the slope from sliding further and destroying the

infrastructures and agricultural lands in the surrounding area. Below, some of the important points about the vetiver grass are discussed.

Roots: Vetiver has a highly developed, dense and net-like adventitious root system derived from the underground parts of Vetiver stems and tillers that can penetrate into very deep parts of the soil profile. Generally roots go 2-3m deep but can reach 5m in some cases with a record of 5.2m documented in Thailand. The root diameter can range from 0.6mm to 23.2mm with 33.3% found in the 0.6mm - 0.8mm range, 33.2% in the 0.8mm - 1.2mm range, and 24.9% in the 1.2mm - 2.2mm range (Cheng and Zhang, 2002). Although white colored in their early tender stage, Vetiver roots gradually turn pale-yellow to yellow-brown over time. Roots, fresh or dry, emit a special fragrance from the constituent vetiverol which is extracted for use in the perfume industry.

Temperature: Being a tropical grass, Vetiver is capable of enduring not only a high temperature of 55°C, but also a low temperature of -15.9°C. With colder temperatures the above ground parts will perish, but the underground part will survive. It begins growth slowly when the mean daily temperature reaches 8°C, then quickens as the temperature increases. Vetiver attains its maximum growth rate when the mean daily temperature reaches 20°C - 30°C. During its peak growth period, it will grow at a rate of 2-3cm/day. Nonetheless, with temperatures over 30°C, its growth rate decreases (Cheng and Zhang, 2002).

Soils: Vetiver has been found growing in very wide range of soil conditions including clayey red earth, shifting sands, sandy soils without clay, strongly acid soils with a pH of 3, extremely alkaline soils with a pH of 11, saline soils, gravel soils with little loam on sloped land and infertile soils containing few N, P, or K nutrients. Vetiver grass has even become established on a residual plinthite layer with a severely eroded red earth profile after the A and B horizons have been totally washed away and where only small amounts of N and P were applied (Lu et al., 1994).

The vetiver soil can grow in many environments. The environmental condition of the study area is found in condition which is favorable for the vetiver grass to grow. Generally, vetiver grass can grow in the study area, but further study and experiments has to be conducted on

the chemistry of the soil to decide whether it is favorable or not for the vetiver grass to grow.

Generally the results of the detail slope stability analysis show that the slope section is in active movement; In addition to the result of this analysis, the different secondary data (Surface extensometer and Borehole inclinometer) show that the slope is in active movement. Therefore, the results of the secondary data show the validity of the slope stability analysis result.

Chapter 7 Conclusion and Recommendation

7.1 Conclusion

Landslides in Blue Nile gorge, particularly along the Gohatsion – Dejen road has been a common problem, especially during the rainy seasons. These Landslides have caused damages to the infrastructures and agricultural lands of the area. Hence, detailed investigation of the type of landslides and the materials involved in the slope instability and identification of the causes of the slope instability are necessary for the developmental works in the area. A detailed slope stability analysis will give the opportunity to analyze slopes individually, and to understand the causes for independent slope sections. This will also be helpful to find a better remedial measure, because different slope sections may have different mode of failure, and may involve different engineering materials.

For the present study a detailed slope stability analysis was carried out for a critical slope section which falls 15 km short of Dejen town about 214km from Addis Ababa. The geotechnical material present at the slope section is colluvial soil from two different sources; basalt and limestone. Because of the variation in its origin, the engineering property of the colluvial soil varies from place to place; the grain size of this colluvial soil ranges from clay sized particles to a very big boulders. During the slope stability analysis, a maximum effort was attempted to consider the heterogeneity of the soil in the slope section. At some places a black clay soil with expansive nature was also observed. In the present study, the shear strength parameters of the colluvial soil has been determined from sensitivity analysis, and it has been in line with other research works on the same soil near to the Gohatsion side of the road. Moreover, the unit weight has been determined from the laboratory bulk density results.

In the present study, detail slope stability analysis on a selected slope section along the road of Gohatsion – Dejen was conducted using deterministic approach; for this, SARC and SLOPE/W software have been used. Besides, Geoslope 11 has been used to produce the profile section and to visualize the DEM, and ArcGIS 9.3, to produce different maps. Beside the slope stability analysis, sensitivity analysis has also been conducted to determine the shear strength parameters using the SARC.

The data used for the slope stability analysis were obtained from primary field investigation, and secondary data source from the GSE and JiCA working along the road Gohatsion -Dejen. The secondary data used were surface extensometer, borehole inclinometer, groundwater data and borehole log data.

The major causative factors for the slope stability problems identified in the area are rainfall and the geotechnical property of the colluviim soil present in the study area; excavation during the road construction and agricultural process also played a great role in the slope stability problem.

Stability analysis was conducted under the static and dynamic states for varied water saturation conditions. Stability analysis for the static moderately saturate/present condition was conducted using both SARC and SLOPE/W software, whereas, for the dynamic conditions, stability analysis was conducted using only the SARC - due to the license problem of the SLOPE/W software. The main importance of the slope stability analysis is to determine the factor of safety of the selected slope section for different conditions under static and dynamic states, and then to recommend the best and economic remedial measures of slope stabilization.

The factor of safety from SARC for the static dry condition is 1.28; for the other static conditions - moderately saturated and worst anticipated conditions - are 0.88 and 0.74, respectively. For all conditions under the dynamic state, the factor of safety is less than 1 (for dry 0.85, for moderately saturated condition 0.58, and for worst anticipated condition 0.49). The minimum factor of safety for the static moderately saturated/current condition obtained from SLOPE/W is 0.83. The results obtained from the SARC and SLOPE/W software for the static moderately saturated condition, are almost similar.

From the results of the surface extensometers data, the movement in one of the extensometers was recorded as about 200mm within three months (from middle of August – middle of November, 2010), and it is recorded right after the end of the rainy season. The other two extensometers have recorded 150mm and about 50mm in the same period of time. From the results of the surface extensometer, it can be clearly observed that the movement is still active, and it can be said that slope stability analysis result validates with the actual instrumental observational data.

7.2 Recommendation

- (i) Since there are many landslide problems that exist along the road Gohatsion – Dejen, similar detailed slope stability analysis works are recommended in other parts the road, in order to identify and describe clearly the different types of slope failures. This will help to calculate and predict the factor of safety for the current and worst anticipated conditions for the different slope sections separately. Besides, it helps to recommend the remedial measures that are to be taken in order to reduce the damages expected to be caused by individual slope failures.
- (ii) Except the static dry condition, the study area is highly unstable; but for all the other conditions, the factor of safety is less than 1. Thus, attention should be given to protect the infrastructures and human life from damage, so that, effective remedial measures that are discussed in the previous chapter should be adopted.
- (iii) The study area consists of agricultural lands and individual houses. In some cases, it may be essential to resettle the local people to other places, in order to adopt the remedial measures. Therefore, awareness should be created among the local people to cooperate for any of the remedial measures to be implemented.
- (iv) As the slope section is covered by agricultural lands, the agricultural activities may also play a great part in the instability of the slope section. Therefore, the agricultural lands on the slope sections should be replaced by other stable lands; or any appropriate compensation should be given for the land owners. So that, trees and vetiver grass may be planted on the unstable lands, and thus loss of crops due to landslide problem will be protected.

Finally, in the present study maximum efforts were made to conduct the detailed slope stability analysis on the selected slope section in a systematic manner well supported by actual scientific data and realistic field observations. Such works require enough financial support, time and resources (availability of different licensed software); this research work was conducted under such constraints. All these constraints might have affected the quality of the results. Therefore, some additional works are strongly recommended in order to determine the shear strength parameters using different techniques, and to validate the

results obtained from sensitivity analysis. Besides, it will be reasonable to use other software for the detail slope stability analysis to validate the results obtained from the present study.

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Annexure

Annexure I: Borehole log data

Borehole name	BH27-11		Location	Around 1km from Goha Tsion, Abay Gorge area, National road 3			Latitude	10.06.234	
Organization	Geological Survey of Ethiopia, JICA Study Team			Duration	作業日報確認		Longitude	38.09.325	
Surveyer	Shoji Tsuchiyama			Core appraiser	Shoji Tsuchiyama		Drilling operators	作業日報確認	
Elevation (m)	1722.0m		Depth (m)	25.0		Drilling rig, Engine, Pump		作業日報確認	
Angle	Vertical	Direction		Gradient		Remarks		Installation of borehole inclinometer	

Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs	Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test
1.0					colluvial deposit	black grey	relatively-low	soft			0.00-8.90m: colluvial deposit in black grey in color. It is dominantly composed of basaltic gravel.		60				
2.0													80				
3.0											In the surface layer, some tuffaceous gravels is found. The gravels are around 20-60mm in diameter in size, hard in hardness and sub-angular - angular in shape. (possibility of natural ground)		90				
4.0													70				
5.0						yellow brown - black grey	high	hard			The sandy gravels mixed with clayey soil. The gravels in geological property are dominantly basalt, and silty - clayey soil partly found. It is dominantly composed of sub-angular - angular gravels and around 20-50mm in size. The gravels in hardness is hard.		100				
6.0													100				
7.0													100				
8.0													100				
9.0	###	8.9	8.9										100				
10.0			9.4		sliding soil mass (mainly silt and shale)	greenish grey		slightly high	slightly weathering	15 - 19 cm	8.90-9.40m: weathered silt(tuffaceous)		100	19	19		
11.0		###									9.40-11.00m: slightly weathered silt(tuffaceous). It is composed of rock fragment - short columnar core. It sounds fozy when hammered blow to core.		100	15	26		
12.0						brownish grey					11.00-22.65m: It is dominantly composed of rock fragment core. The porous cracks by force of weathering are distinguished. The color around cracks partly become brown grey. It can check rock structure remaining. It is fractured when hammered lightly-blow to core. The hardness extent of CL class.		100				
13.0													100				
14.0			14			greenish grey					14.10-15.35m: moderate whethereed shale in greenish grey in color.		100				
15.0			15			brownish grey					15.35-17.15m: moderate whethereed silt(tuffaceous) in reddish grey in color.		100				
16.0													100				
17.0			17			greenish grey					17.15-18.50m: moderate whethereed shale in greenish grey in color.		100	10	10		
18.0			###										100	10	10		
19.0											18.50-25.00m: moderate whethereed silt in reddish grey in color.		100				
20.0													100				
21.0											20.80-21.45m: shale in greenish grey - white grey in color.		100				
22.0											22.65-25.00m: silt in brown grey in color. It is composed of rock fragment - short columnar core. The hardness extent of C _L -C _M class. The cracks in a horizontal direction are dominantly distinguished. At 24.60-25.00m in depth, the cracks in a vertical direction is distinguished.		100	10	10		
23.0													100	15	26		
24.0													100	21	21		
25.0	###	###	###										100				

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																				
Borehole name		BH28-21		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.426						
Organization		Geological Survey of Ethiopia, JICA Study Team				Duration		作業日報確認						Longitude		38.09.335				
Surveyer		Shoji TSUCHIYAMA				Core appraiser		Shoji TSUCHIYAMA				Drilling operators		作業日報確認						
Elevation (m)		1772.0m		Depth (m)		25.0		Drilling rig, Engine, Pump				作業日報確認								
Angle		Vertical	Direction			Gradient						Remarks		Installation of Automatic water level meter (depth 24.7m)						
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs	Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test		
	1771.5	0.5	0.5		Top soil						Top soil (replaced by cement for drilling)									
1.0					colluvial deposit	Slightly greyish white - grey brown	slightly low	slightly soft	moderately		0.00-6.20m: mainly composed by Limestone gravels. Slightly greyish white - grey brown. The rock in core is hard, the hardness extent of CL-CM class. It is composed of rock fragment - short columnar core in entire. In particular, 4.95-5.06m: Some andesitic gravel are partly found.		100							
2.0													100							
3.0													100							
4.0													90							
5.0													90							
6.0			6.2										80							
7.0													80							
8.0													90							
9.0													90							
10.0													90							
11.0													100							
12.0													100							
13.0													100							
14.0													100							
15.0			14.85			100											15.25			
16.0			15.65			white brown	slightly low	slightly hard	slightly-weathered	ng	14.85-15.65m: slightly weathered limestone in white brown in color. The hardness extent of C ₄ class. It sounds poor fozy when hammered lightly-blow to core.	100						labo 1 15.40		
17.0	1755.0	16.50	17.00			yellow greyish brown	very low	very soft	high-weathered	s	15.65-16.30m: high weathered shale in yellow greyish brown in color. The core columnar shape condition is sandy - sandy gravel by force of high weathering. It is very soft. The hardness extent of D ₄ class.	100								
18.0					sliding soil mass (mainly basalt and sometime contain limestone)	blackish grey	high	hard	moderately	12 - 22 cm	16.90-25.00m: sliding soil mass which moderate-weathered basalt and limestone in black gray in color. Rock fragment - short columnar core is entirely found. The hardness extent of C ₁ -C ₄ class. It sounds poor fozy when hammered lightly-blow to core. In particular, 19.75-20.20m and 20.85-22.40m depth: moderate weathering tuff. It is hard. The hardness extent of C ₁ -C ₄ class. 23.45-24.80m depth: Some tuffaceous rock fragments are partly found.		100							
19.0													90							
20.0													90							
21.0													90							
22.0													100					22.00		
23.0													100					labo 2 22.15		
24.0													100							
25.0	1747.0	8.0	25.0										24.77m 8.Sep	100				Automatic water level meter		

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																			
Borehole name		BH28-31		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.450					
Organization		Geological Survey of Ethiopia, JICA Study Team						Duration		作業日報確認				Longitude		38.09.343			
Surveyer		Shoji TSUCHIYAMA						Core appraiser		Shoji TSUCHIYAMA				Drilling operators		作業日報確認			
Elevation (m)		1778.0m		Depth (m)		25.0		Drilling rig, Engine, Pump				作業日報確認							
Angle		Vertical	Direction			Gradient		Remarks				Installation of borehole inclinometer							
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs	Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test	
1.0	1777	0.7	0.7		Top soil						Top soil (replaced by cement for drilling)		80						
2.0					colluvial deposit	slightly yellow brown - slightly white brown	very low	very soft	high-weathering	15 - 16 cm	0.70-14.00m: colluvial deposit contains high weathered limestone, siltstone and shale in slightly yellowish brown - slightly white brown in color. The matrix core become in sandy sedimentation, partly argillation by force of high weathering. 0.70-1.80m: high-weathering in core is distinguished, it can see rock structure remained. 1.50-2.00m: Some andesitic gravels in core are found, and hard in hardness. 4.55-4.80m: Some andesitic gravels in core are found, and hard in hardness. 4.80-4.90m: Some tufficious gravels in core are found, and hard in hardness. 5.70-5.80m: Some tufficious gravels in core are found, and hard in hardness. 8.25-8.35m: Some andesitic gravels in core are found, and hard in hardness. 7.00-7.40m: Some tufficious gravels in core are found, and hard in hardness. 8.80-12.75m: It is entirely composed of hard rock-fragment core. Partly, 10.10-10.35m, 10.55-10.70m and 11.15-11.30m: sandy gravels in core are composed.		80						
3.0													80						
4.0													80						
5.0													80						
6.0													80						
7.0													90						
8.0													90						
9.0													100						
10.0													100						
11.0													90						
12.0													100						
13.0													90					13.20	
14.0	1764.0	13.3	14.0										100					labo 3 13.50	
15.0					sliding soil mass (basaltic tuff-breccia)	black grey	relatively high	relatively hard	no weathering (fresh) - slightly weathering	13 - 32 cm	14.00-23.60m: sliding soil mass which composed by basaltic tuff-breccia in black grey in color. 14.00-14.60m: It is composed of long columnar core. It indicates the hardness extent of C ₄ class. It sounds clearly-metallic when hammered blow to core. 14.60-16.20m: It is composed of rock-fragment - short columnar core. The hardness extent of C ₄ class. In particular, 14.60-15.00m: sandy sediment - sandy gravels among gravels in core are found. 16.20-20.70m: It is dominantly composed of sandy sediment - sandy gravels. It can partly see argillation to core, and hard andesitic gravels in core are found. The hardness extent of D ₄ -D ₅ class. It is relatively soft. 20.70-23.60m: slightly weathered andesite in black grey in color. It is composed of rock-fragment - short columnar core. The hardness extent of C ₄ class. Rock fragments in hardness are hard. It sounds lightly-fozy when hammered blow to core.		100						
16.0													100						
17.0													100						
18.0													100						
19.0													100						
20.0													100						
21.0													100					21.00	
22.0													100					labo 1 21.15	
23.0													23.0m	100					
24.0	1754.4	9.6	23.6										8.Sep	100				24.85	
25.0	1753.0	1.4	25.0		limestone	greyish white	slightly low	slightly soft	slightly fresh	12 cm	23.60-25.00m: little weathered limestone in slightly white grey - greyish white in color. It is composed of rock fragment - short columnar core. The hardness extent of C ₄ class. It sounds poorly fozy when hammered light-blow to core. At 23.75-23.90m depth, the core is lightly weathered, and sandy pediment is composed.		100	12	12	Anchor of Borehole Inclinometer labo 2 25.00			

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																					
Borehole name		BH28-32		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.443							
Organization		Geological Survey of Ethiopia, JICA Study Team				Duration		作業日報確認						Longitude		38.09.345					
Surveyer		Shoji TSUCHIYAMA				Core appraiser		Shoji TSUCHIYAMA				Drilling operators		作業日報確認							
Elevation (m)		1777.0m		Depth (m)		40.0		Drilling rig, Engine, Pump				作業日報確認									
Angle		Vertical	Direction		Gradient					Remarks				Installation of borehole inclinometer							
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs				Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test
1.0	1776.3	0.7	0.7		top soil						0.00-0.70m: topsoil or cultivation impact, which is in/ slightly blackish brown. Some plant roots or organic matter are mixed. The topsoil and blackish or darkish soils are dominantly around 20-40mm in diameter. Moisture content is variable.					90					
2.0																90					
3.0																90					
4.0											0.70-11.80m: colluvial deposit					90					
5.0											0.70-2.45m: It is dominantly composed of basaltic gravels, which are around 20-40mm in diameter in size. The gravels in shape are dominantly sub-rounded - rounded. The gravels in hardness are hard. Blackish grey in color.					80					
6.0											2.45-5.15m: It is dominantly composed of limestone gravels in greyish white in color. Silty - clayey soil in the matrix core is mixed. Sub-angular - angular Gravels in hardness are hard, and in size are around 30-60mm in diameter.					90					
7.0											5.15-11.80m: It is dominantly composed of hard basalt. The gravels in size are around 30-60mm in diameter. sub-angular - angular gravels in shape. The core in color is blackish grey.					100					
8.0																90					
9.0																90					
10.0																80					
11.0																100					
12.0	1765.2	11.1	11.8													100					
13.0																100					
14.0											11.80-24.65m: It is composed of hard and fresh massive limestone.					80	18	18			
15.0																80					
16.0																90					
17.0																90					
18.0										10-22 cm	The gravels in size are around 10 -60 mm in diameter, in shape are sub-angular - angular, and in color are greyish white.					80					
19.0																80	10	10			
20.0																100	15	28			
21.0																90	18	18			
22.0																100	10	10			
23.0																100	22	53			
24.0	1752.4	12.85	24.65													100	19	29			
25.0											24.65-40.00m: siltstone and limestone altanation in greenish grey - brownish grey in color.					100	15	38			
26.0																100	22	33			
27.0											Thereamong, 24.65-32.05m: relatively weathered tuff in greenish grey - brownish grey in color. The dominant cracks by force of weathering are distinguished. Sandy sediment - rock fragment condition in core is found. It is relatively soft. The hardness extent of DH-CL class. Rock structure remaining is found. It is slightly soft. In paticular, 24.65-30.35m: greenish grey in color. And 30.35-32.05m: brownish grey in color.					100	20	20			
28.0																100					
29.0																100					
30.0																100					
31.0																100					
32.0																100					
33.0										15- 30 cm	32.05-40.00m: relatively fresh massive tuff in greenish grey - partly brownish grey in color. It is composed of rock fragment - short columnar core. Core in hardness is relatively hard, the hardness extent of C _u -C _u class. The cracks in angle and elevation are dominantly around horizontal (0 degree) - 30 degree, however, at 35.50-36.70m depth, the cracks of about 60 degree is distinguished. Core in hardness is hard. It sounds poorly fozy when hammered blow to core.					100					33.60
34.0																100	30	78			labo 1
35.0																100	15	25			33.75
36.0																100	16	16			
37.0																100					
38.0																100	20	38			
39.0																100					
40.0	1737.0	27.2	40.0													100				Anchor of borehole inclinometer	

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDESIN THE ABAY RIVER GORGE																										
Borehole name		BH28-41		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.477												
Organization		Geological Survey of Ethiopia, JICA Study Team						Duration		作業日報確認						Longitude		38.09.365								
Surveyer		Shoji TSUCHIYAMA						Core appraiser		Shoji TSUCHIYAMA						Drilling operators		作業日報確認								
Elevation (m)		1788.5m				Depth (m)		45.0				Drilling rig, Engine, Pump				作業日報確認										
Angle		Vertical		Direction				Gradient				Remarks				Installation of borehole extensometer										
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs				Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-situ test	Laboratory test					
1.0					embankment	blackish-brown	low	soft			0.00-5.30m: embankment. The matrix core is sandy clay in black-brown in color, which is mixed with some gravels. The gravels are dominantly composed of no weathered basalt and limestone in sub-angular and angular shape. The size of gravels is around 30-60 mm in diameter. The hardness of them is hard. The water content is entirely moderate.					40										
2.0												60														
3.0												60														
4.0												80														
5.0	1783.2	5.3	5.3									80														
6.0				8.8		yellow-brown	low	soft			5.30-8.80m: sliding soil mass (and/or colluvial deposit). Sandy gravels in brownish-red and yellowish brown in color, which is mixed with clay. The gravels are sub-angular and angular and around 30-60mm in diameter in size, and geological composition is dominantly limestone, siltstone and sandstone. The hardness of them is hard. The water content of clay is low. The agglomeration degree is high.					100										
7.0												100														
8.0												100														
9.0												100														
10.0												100														
11.0												100														
12.0												100														
13.0												100														
14.0												100														
15.0												100														
16.0												100														
17.0												100														
18.0												100														
19.0					sliding soil mass (limestone, siltstone and mudstone)	white-brown	low	soft			8.80-25.50m: sliding soil mass. Sandy gravels in whitish brown in color. The gravels are dominantly composed of limestone, siltstone and sand, and indicates around 30-60 mm in diameter in size. The hardness is very hard. Sand among gravels in core is sparsely found and filled up.					100										
20.0												100														
21.0												100														
22.0												100														
23.0												100														
24.0												100														
25.0												100														
26.0												100														
27.0												100														
28.0												100														
29.0												100														
30.0												100														
31.0												100	13	13												
32.0												100	34	46												
33.0												100	12	12												
34.0												100	14	14												
35.0												100	12	12												
36.0	1753.0	30.2	35.6		siltstone	yellow-grey	relatively-high	relatively-hard	slightly-weathering	26-39 cm	35.50-38.55m:sliding siltstone in slightly yellow grey in color. The hardness in core is hard. The hardness extent of Cu class: In particular, 35.50-36.50m, 36.70-38.80m, 37.00-37.80m, 37.60-37.80m, and 38.20-38.35m in depth, clayey property by force of high weathering are found. It is dominantly composed of rock fragment - short columnar core in brown and yellowish brown in color.					100	20	30								
37.0												100	16	26												
38.0	1750.0	3.05	38.55									100	20	39												
39.0	1749.2	0.75	39.3									limestone	relatively-high	relatively-high	relatively-hard	slightly-weathering	23 cm	38.55-39.30m: limestone is slightly greenish white. Short - middle columnar core. The hardness extent of Cu/Cu class indicator: In particular, at 38.55-39.00m in depth, rock fragment - clayey property by force of high weathering is distinguished.					100	23	75	
40.0					100	27	67																			
41.0				shale	dark greenish grey	relatively-soft	relatively-soft	moderately	12-40 cm	39.30-45.00m:moderately-weathered shale in dark greenish grey in color, (and it may be originally pyroclastic materials). 39.30-39.40m and 40.30-40.65m in depth: the core rock indicator rock fragment - angular property by force of high weathering. Clay in the matrix grounds in core is sparsely found. The hardness extent of Cu class is entire. 40.00-41.35m: Highly weathered basalt around cracks becomes brown in color. 41.70-42.60m: The scattered pores and cracks in core are found. The cores are dominantly composed of rock fragment. 42.60-43.50m: Fresh massive limestone with cracks and calcite vein. The cores around calcite veins are dominantly weathered. 42.60-43.50m: The cores by force of thrust alteration indicates reddish-brown in color.The rock in core is hard. The hardness extent of CM class.									100	12	12					
42.0																		100	13	47						
43.0																		100	24	61			42.8			
44.0																		100	33	66			43.0			
45.0	1743.5	5.7	45.0								100	40	81		Anchor of Borehole extensometer											

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																																							
Borehole name		BH28-11		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.379																									
Organization		Geological Survey of Ethiopia, JICA Study Team				Duration		作業日報確認				Longitude		38.09.322																									
Surveyer		Shoji TSUCHIYAMA				Core appraiser		Shoji TSUCHIYAMA				Drilling operators		作業日報確認																									
Elevation (m)		1762.0m		Depth (m)		25.0		Drilling rig, Engine, Pump				作業日報確認																											
Angle		Vertical		Direction		Gradient		Remarks				Installation of borehole inclinometer																											
Scale (m)		Elevation (m)		Thickness (m)		Depth (m)		Column		Geology/ Soil		Colour		Relative density		Hardness		Weathering		Size		Geological logs				Groundwater level (m)		Core recovery (%)		Maximum length (cm)		Rock Quality Designation		SPT N value		In-site test		Laboratory test	
		1761.6		0.4		0.4		X		top soil												Top soil (replaced by cement for drilling)																	
1.0										colluvial deposit		black grey - dark grey		low		soft						0.40-4.70m:colluvial deposit in black grey - dark grey in color. 0.00-1.25m: It is dominantly composed of sandy gravels mixed with coarse sand. The sub-angular gravels are around 2-10mm in diameter. The gravels in geology are andesite. 1.25-2.50m: It is dominantly composed of andesite, tuff and limestone gravels of around 10-30mm in diameter. Coarse sand among gravels is mixed. 2.50-4.70m: It is dominantly composed of basalt, tuff and limestone gravels of around 10-40mm (max 100 mm) in diameter. sub-angular sandy gravels mixed with clay. Coarse sand and a bit of clay among gravels is mixed.				50													
2.0																				50																			
3.0																				40																			
4.0																				50																			
5.0																				100																			
6.0												white grey		high		hard				4.70-5.80m: slightly weathered limestone in white grey in color. It is composed of rock fragment - short columnar core. The hardness extent of C ₁ -C ₂ class (hard core)				100												6.20			
7.0																		5.80-13.60m: relatively weathered andsite in black grey in color.				70												labo 1 6.35					
8.0												black grey		slightly high		slightly hard		5.80-6.40m: It is composed of short columnar core.The hardness extent of C ₂ class.It is hard. 6.40-7.35m: It is composed of rock fragment - angular-shaped core. The hardness extent of C ₁ class. slightly hard. 7.35-7.90m: It is composed of short columnar core. The hardness extent of CM class.It is hard. 7.90-9.00m: It is dominantly composed of rock fragment core and a bit of coarse sand. The hardness extent of C ₁ class. 9.00-9.70m: It is dominantly composed of rock fragment - short columnar core. The rock in core hardness is the extent of C ₂ class. 9.70-11.05m: sandy gravels mixed with clay, greyish black - dark grey in color. The matrix core is dominantly andesitic sub-angular - angular gravel. Sand and clay among rock fragments are found. The hardness extent of C ₁ class in entire.It is slightly hard.				90																	
9.0																		100																					
10.0																		100																					
11.0																		100																					
12.0																		100																					
13.0		1748.1		13.55		13.95												100																					
14.0												white grey - greenish grey		slightly high		slightly hard		moderately		24 cm				100															
15.0				1.05		15.00						white grey - reddish brown grey		very low		very soft		high weathering		20 -22 cm				100		24		34											
16.0																		13.95-25.00m: moderately and highly weathered sliding soil mass (mainly silt and shale) in greenish grey - reddish brown grey in color. 13.95-15.00m: moderately weathered shale in white grey - greenish grey in color. The hardness extent of CL class (the upper part D class: like loose surface soil) 15.10-18.00m: high weathered siltstone (to sand) in greenish grey - reddish brown grey in color. The hardness extent of DM-DH class. It is very soft. It can check rock structure slightly-remained, argillation by force of high weathering is partly found. Rock fragment-shaped core is partly found.				100		20		20													
17.0																		100																					
18.0				2.6		17.6												100														18.50							
19.0																		17.60-25.00m: moderately weathered siltstone in mainly reddish grey in color. It indicates the hardness extent of C ₁ class. It can entirely check rock structure remained. In particular, 21.25-21.95m, 22.30-22.70m, and 23.20-24.35m depth: the matrix core become brown in color by force of high weathering, and argillation of the cores is found. At 24.35-25.00m depth, the porous cracks with weathering is distinguished. It indicates the hardness extent of C ₁ class.				100		22		57						18.65							
20.0																		100																					
21.0																		100				26		46															
22.0																		100																					
23.0																		100																					
24.0																		100																					
25.0		1737.0		7.4		25.0												100														Anchor of Borehole inclinometer							

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																						
Borehole name		BH27-12		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.249								
Organization		Geological Survey of Ethiopia, JICA Study Team				Duration		作業日報確認				Longitude		38.09.364								
Surveyer		Shoji Tsuchiyama				Core appraiser		Shoji Tsuchiyama				Drilling operators		作業日報確認								
Elevation (m)		1709.0m		Depth (m)		25.0		Drilling rig, Engine, Pump				作業日報確認										
Angle		Vertical	Direction		Gradient						Remarks				Installation of borehole extensometer							
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs				Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test	
1.0	1708.1	0.9	0.9		Top soil						Top soil (replaced by cement for drilling)					40						
2.0																60						
3.0																80						
4.0			3.95								0.90-13.40m: colluvial deposit. the core characterized by basaltic boulder in black grey - brown grey in color.					90						
5.0											0.90-3.95m: It is dominantly composed of basaltic gravel. The gravels in size are around 20-60mm in diameter. It is composed of sub-rounded - sub-angular gravels. The hardness of gravels are hard.					90						
6.0																100						
7.0											3.95-7.60m: sandy basaltic gravels, which is mixed with clay. blackish brown - brownish grey. The gravels are around 20-60 mm in diameter. Clay among gravels is partly found. It is dominantly composed of sub-rounded - sub-angular gravels.					100						
8.0			7.6													100						
9.0																100						
10.0											7.60-13.40m: hard basaltic gravels in blackish grey in color. The gravels are around 30-60 mm in diameter. Some basaltic gravels among tuffaceous ones is partly found. It is dominantly composed of sub-rounded - sub-angular gravels.					100						
11.0																100						
12.0																100						
13.0	1723.4	12.5	13.4													100						
14.0						greyish white		very low	slightly-soft	high-weathering	13 cm	13.40-15.70m: high weathered silt(tuffaceous) in greyish white in color. It is composed of sandy - rock fragment by force of high weathering. The hardness extent of D _h -D _u class in entire. It is possible to break up the rock fragments by finger. It is very soft, however, can check rock structure slightly remaining.					100					
15.0						greyish white		slightly high	hard	relatively-fresh	10-13 cm	15.70-17.30m: relatively fresh massive siltstone in greyish white in color. It is composed of rock fragment - short columnar core. The rocks in core are hard. The hardness extent of C ₁ -C ₄ class. It sounds poor fozy when hammered lightly-blow to core.					100	13	23			
16.0			15.7			brownish gray		slightly low	slightly-soft	high-weathering	10 cm	17.30-18.70m: high weathered silt and shale in slightly brownish gray - brownish gray in color. It is composed of sandy - rock fragment by force of high weathering. The hardness extent of DM-DH class. It is slightly soft.					100					
17.0			17.3														100	10	20			
18.0			18.7														100					
19.0																	100	10	10			
20.0						reddish brown - brownish yellow - greenish grey		slightly low	slightly soft	moderate - high weathering	10-12 cm	18.70-21.10m: moderate weathered tuff in brownish yellow - greenish grey(reseda) in color. It is composed of rock fragment - short columnar core by force of high weathering. The rock hardness condition is slightly soft. It can check rock structure remaining. It's fractured when hammered blow to core.					100					20.4
21.0																	100	12	12			20.5
22.0												21.10-25.00m: moderate-weathered silt and shale in brown-grey - greenish grey(reseda) in color. It is composed of sandy - rock fragment core in entire. It indicates the hardness extent of C ₁ class. It is slightly soft. It checks rock structure remaining.					100	10	10			
23.0												In particular, 22.40-22.85m: reddish brown in color by weathering.					100					
24.0												23.90-24.70m: high weathered siltstone. It is composed of sandy - angular gravel core. It break up in relatively fracture when hammered poorly-blow to core.					100					
25.0	1735.0	11.6	25.0														100			Anchor of borehole extensometer		

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																		
Borehole name		BH27-21		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.241				
Organization		Geological Survey of Ethiopia, JICA Study Team				Duration		作業日報確認				Longitude		38.09.303				
Surveyer		Shoji Tsuchiyama				Core appraiser		Shoji Tsuchiyama				Drilling operators		作業日報確認				
Elevation (m)		1734.0m		Depth (m)		25.0		Drilling rig, Engine, Pump				作業日報確認						
Angle		Vertical	Direction		Gradient				Remarks				Installation of Automatic water level meter (depth ○m)					
State (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs	Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test
	1733.7	0.3	0.3		top soil						Top soil (replaced by cement for drilling)							
1.0					colluvial deposit	blackish brown	low	soft			0.30-4.50m: colluvial deposit is mainly clay in blackish brown in color. In particular, 0.30-0.50m: Some plant roots as organic matter are found. The gravels are dominantly composed of basalt. A few of limestone are partly found. The gravels in size are around 30-50mm in diameter.		80					
2.0													80					
3.0													80					
4.0			4.5										100					
5.0													80					
6.0						blackish grey	low	soft			4.50-12.40m: It is dominantly composed of basaltic gravels. The gravels are hard in hardness and around 30-60mm in diameter in size. Sand among gravels is found.		90					
7.0												100						
8.0												100						
9.0												100						
10.0												100						
11.0											70							
12.0	1721.6	12.1	12.4									60						
13.0					sliding soil mass (mainly silt and shale)	brownish grey	very low	relatively soft	high weathering	17 cm	12.40-14.05m: highly weathered siltstone (to sand) in brownish grey in color. The matrix core become brownish grey in color by force of high weathering. The gravels are like sandy sediment, and it is possible to break them up by finger.		100					
14.0		1.85	14.05										100	17	39			
15.0						greenish grey	very low	relatively soft	high weathering	13 - 18 cm	14.05-17.60m: highly weathered tuffaceous silt(to shale) in greenish grey in color. It can check rock fragment structure remaining in core. Rock fragment is found in core. The hardness extent of D _u -C _u class, namely, it is relatively soft. Core in a high weathering partly become sandy sedimental.		100	13	24			15.0
16.0													100	18	29			15.2
17.0													100					
18.0		3.55	17.6			white grey	slightly-low	slightly-soft	slightly	10 - 17 cm	17.60-18.40m: limestone in white grey in color. The hardness extent of C _u -C _u class. It is composed of rock fragment - short columnar core in entire. 17.60-17.90m: short columnar core. And 17.90-18.40m: rock fragment getting.		100	17	27			
19.0		0.8	18.4										100	10	10			
20.0			19.5			brownish grey	relatively-low	relatively-soft	moderately-weathering	10 - 20 cm	18.40-25.00m: moderately weathered siltstone and shale (tuffaceous) in greenish grey - brownish grey in color. 18.40-19.50m: It is composed of rock fragment - short columnar core. The hardness extent of C _u -C _u class. It is relatively hard. 19.50-20.50m: Rock fragment getting. The hardness extent of D _u -C _u class. 20.50-21.25m: rock fragment - short columnar condition in core. The hardness extent of C _u class. 21.25-21.90m: gravel - rock fragment condition in core. The core become moderately weathered. The core is brownish grey in color. 21.90-25.00m: slightly weathered tuff in brownish grey - greenish grey in color. It is composed of rock fragment - short columnar core in entire. The hardness extent of CL class. At 21.90-23.30m depth, core is brownish grey in color. At 23.30-25.00m: core is greenish grey in color.		100					
21.0			20.5										100					
22.0			21.9									21.75m	100				Automatic water level meter	
23.0		4.9	23.3									24.Sep	100					
24.0						greenish grey	relatively-high	relatively-hard	slightly weathering					100	20	44		
25.0	1709.0	1.7	25.0										100	18	28			

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																					
Borehole name			BH27-22		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10.06.238						
Organization			Geological Survey of Ethiopia, JICA Study Team					Duration		作業日報確認					Longitude		38.09.315				
Surveyer			Shoji Tsuchiyama					Core appraiser		Shoji Tsuchiyama					Drilling operators		作業日報確認				
Elevation (m)			1733.0m			Depth (m)		27.0		Drilling rig, Engine, Pump					作業日報確認						
Angle		Vertical	Direction		Gradient		Remarks					Installation of borehole inclinometer									
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs		Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test		
1.0					top soil	black brownish grey					0.00-1.70m: sandy soil in black grey - brown grey in color , which is mixed with some gravels			80							
2.0					colluvial deposit	black grey	low	soft			1.70-15.40m: colluvial deposit in black grey in color. Basaltic gravels are dominantly found and around 20-50mm (max 300mm) in diameter in size. It is partly mixed with sand among basaltic gravels. The hardness of gravels is hard. (It has a possibility of natural ground)			100							
3.0													80								
4.0													40								
5.0													50								
6.0													70								
7.0													90								
8.0													90								
9.0													100								
10.0													100								
11.0													100								
12.0													100								
13.0													100								
14.0													90								
15.0													100								
16.0					sliding soil mass (mainly silt and shale)	greenish gray	slightly low	slightly soft	slightly weathering	12 cm	15.40-19.35m: slightly weathered siltstone to shale in greenish grey in color. It is composed of gravel - rock fragment (- short columnar(partly)) core. The hardness extent of C ₁ class.			100							
17.0														100							
18.0														100	12	12				19.6	
19.0			19.35											100						labo 1	19.8
20.0						greenish white	slightly low	slightly soft	slightly weathering	14 - 15 cm	19.35-21.00m: slightly weathered siltstone (to sandstone) in greenish white in color. The hardness extent of C ₁ -C ₄ class.			100	14	34					
21.0			21				100	15	15												
22.0						reddish gray	very low	very soft	high-weathering		21.00-23.40m: highly weathered shale in reddish brown in color. It is composed of gravel - rock fragment (- short columnar(partly)) core. The hardness extent of DH-CL class. It can check in fractured rock hardness when hammered light-blow to core.			100							
23.0			23.4											100							
24.0					greenish gray - reddish brown gray	slightly high	slightly hard	relatively fresh	10 - 28 cm	23.40-27.00m: It is composed of rock fragment - short columnar core. Thereamong, 23.40-24.60m: It is composed of gravel - rock fragment core by force of slightly weathering. 24.60-25.50m: slightly weathered tuff in reddish brown grey in color by force of (poor) weathering. The hardness of rock fragment is hard. It indicates the hardness extent of C ₁ -C ₄ class. 25.50-27.00m: It is composed of middle columnar core. The hardness extent of C ₁ -C ₄ class.			100								
25.0													100	10	10						
26.0													100	28	59						
27.0	1759.0	27.0	27.0										100	22	32		Anchor of Borehole inclinometer				

Slope Stability Analysis for a selected slope section along the road Gohatsion-Dejen

Name of Study : THE PROJECT FOR DEVELOPING COUNTERMEASURES AGAINST LANDSLIDES IN THE ABAY RIVER GORGE																										
Borehole name		BH27-23		Location		Around 1km from Goha Tsion, Abay Gorge area, National road 3						Latitude		10/06/22.9												
Organization		Geological Survey of Ethiopia, JICA Study Team				Duration		作業日報確認				Longitude		38/09/32.0												
Surveyer		Shoji Tsuchiyama				Core appraiser		Makito Noda				Drilling operators		作業日報確認												
Elevation (m)		1723.9m		Depth (m)		25.0		Drilling rig, Engine, Pump				作業日報確認														
Angle		Vertical	Direction			Gradient						Remarks		Installation of borehole inclinometer												
Scale (m)	Elevation (m)	Thickness (m)	Depth (m)	Column	Geology/ Soil	Colour	Relative density	Hardness	Weathering	Size	Geological logs	Groundwater level (m)	Core recovery (%)	Maximum length (cm)	Rock Quality Designation	SPT N value	In-site test	Laboratory test								
1.0					colluvial deposit	black grey	relatively-low	soft			0.00-6.10m: colluvial deposit in black grey in color. It is dominantly composed of basaltic gravel. In the surface layer, some tuffaceous gravels is found. The gravels are around 20-60mm in diameter in size , hard in hardness and sub-angular - angular in shape. (possibility of natural ground)		60													
2.0																		80								
3.0																			80							
4.0																				90						
5.0																					90					
6.0																					40					
7.0			6.1			yellowish grey					6.10-9.00m: colluvial deposit in yellowish grey in color. The sandy gravels mixed with clayey soil. The gravels in geological property are dominantly basalt, and silty - clayey soil partly found. It is dominantly composed of sub-angular - angular, dominantly basalt, and silty - clayey soil partly found. It is		60													
8.0																	80									
9.0	1714.3	3.0	3.0															40								
10.0					sliding soil mass (mainly silt and shale)	greenish grey	low	soft	high weathering	sand size -12 cm	9.00-12.50m: weathered silt(tuffaceous). It is composed of rock fragment - short columnar core. The hardness extent of CL class. It's fractured when hammered.		85													
11.0																			80	12	12			10.10		
12.0			12.5																65					10.20		
13.0																			90							
14.0																			90							
15.0																			90							
16.0																			90							
17.0																			90							
18.0																	90									
19.0			18.45														90	10	10							
20.0																	90									
21.0														10 -13 cm	18.50-25.00m: moderate weathered silt in reddish grey in color.		75									
22.0							reddish grey	relatively-high	slightly-hard	moderately weathering		18.45-18.75m, 19.90-20.35m: boulder of sandstone which white in color. 22.00-25.00m: silt in reddish grey in color. It is composed of rock fragment - short columnar core. The hardness extent of CL-C _u class. The cracks in a horizontal direction are dominantly distinguished.		85	11	11			22.10							
23.0														100	12	23			22.20							
24.0														100	13	25										
25.0	1636.3	16.0	25.0											100												

Annexure II: Geological map of Abay gorge (Source: Henok Woldegiorgis, 2008)

