

# Assessments of Geotechnical Conditions and Slope Stability Analysis: Case Study in Gedo town, Ethiopia

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**Abstract** – Slope stability analysis is a vital task to Geotechnical Engineers as slope failures can have devastating social and economic impacts. This paper focuses on the assessments of geotechnical conditions and slope stability analysis of Gedo town, which is located in central Ethiopia, where landslide incidence is active. The study involves a collection of both disturbed and undisturbed soil samples for laboratory tests, such as natural moisture content, unit weight, specific gravity, Atterberg limits, grain size analysis, and shear strength tests were conducted as per ASTM standard. The characteristics of the terrain, soil, groundwater table, and depth and geometry of the failures, were studied in this work. For the slope stability analysis, the safety factor is computed based on the general limit equilibrium method that encompasses various methods inside using slope/w in Geo Studio 2012 software packages. According to the results, the slope in the study area is unstable. The main types of landslide are slides and fall for the soil in the study area, and groundwater, rainfall, soil type, land use, shape, and angle of slopes are the major landslide factors. According to this research finding, the rainfall has an outstanding contribution to slope failure in the study area.

**Keywords** – slope stability, geotechnical conditions, limit equilibrium, land slide.

## I. INTRODUCTION

### 1. Background

Construction and infrastructure projects have increased over the years, and therefore the requirements for excavation, footing, and road design are increasing. Thus, all Geotechnical engineers must take into account all geotechnical aspects such as the properties of soil materials, the stability of slopes, and natural disasters that affect their design and cause social, political, and economic disruption. The natural slope, which has been stable for many years, may occur due to changes in slope geometry, loss of slope material shear strength, and an external factor like excavation [1].

Owing to the combined effects of heavy rainfall, steep topography, and soil conditions, the natural slope may also fall [2]. An internal triggering factor causes failure due to internal changes, such as increasing pore water pressure and or imbalanced forces due to external load [3]. Such landslides are common problems in the mountainous regions, particularly along the hill-cut slope of the Gedo town.

### 2. Statements of the problem

The slope stability analysis is vital, particularly in a construction project near the slope area. This analysis is carried out to determine the safe design of artificial or natural slopes and the equilibrium conditions. Incorrect slope analysis design can cause a slope failure, which is one of the most common disasters causing excellent properties and life losses. Thus, the initial soil must be appropriately investigated to achieve the actual soil condition for a specific place where the construction will commence. Landslide incidence is growing worldwide, resulting in loss of life, loss of livestock, disruption or destruction of residential and industrial developments, villages or even entire towns, degradation of agricultural and forest land, and adverse effects on water quality in rivers and streams [4].

According to the previous case studies [5], slope failures in Ethiopia are mainly controlled by the presence of soft and low permeability materials or shales. Landslides are very common in developing countries, and economic losses are sometimes equal or exceed their gross national products [11]. Naturally, Gedo town is located on the mountainous type of terrain and is known to be prone to landslide, as shown in Figure 1.



Figure 1: Photograph of the landslide in the Gedo area

### 3. Objectives of the study

#### • General objective

The main aim of the study is to characterize the Geotechnical conditions of the site and analyze the stability of the landslide in Gedo town.

#### • Specific Objectives

1. To evaluate the Geotechnical properties of soil in the landslide affected area in Gedo town.
2. To investigate the main causes and triggering factors for the occurrence of landslides in Gedo town.
3. To analyze slope stability and determine the factor of safety of the slopes of Gedo town using Geo Studio Software.
4. To recommend possible remedial measures to minimize risks from a landslide in the study area

## II. MATERIALS AND METHODS

### 1. Study Area

The Ethiopian highlands are the results of the past geological and erosional processes and marked by variable topography with landform of the steep hill slope, the plateau, and the deeply incised gorge/valley [9]. This study was conducted in Gedo town, located in Central Ethiopia, in the Oromia regional state. Figure 2 shows a map of the study area. The city is an administrative center of the Chelia Woreda zone. It is about 173 km from Addis Ababa, through Ambo Town. The South-western part of the town has always been affected by the landslide phenomena, as shown in Figure 1. The area characterized by a significant rainfall lasting from May to the end of September.

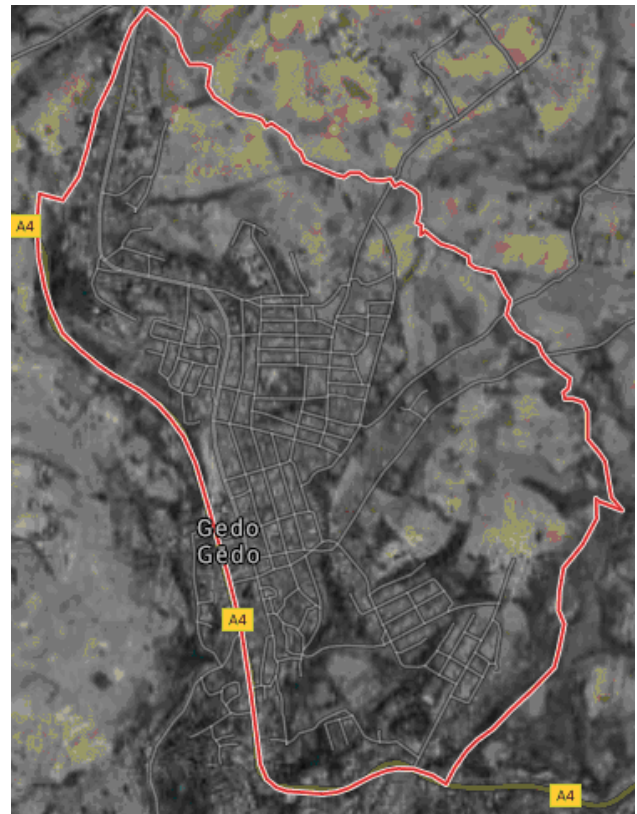


Fig.2. Map of the study area (Source: Google Map 2020).

### 2. The topography of the Study Area

The study site is characterized by highly variable topographic features, where the region is dominated by steep hill slope and deep-cut valley. Since the hill slopes are steep enough, external factors such as rainfall and road cut could trigger the angle to failure. Figure 3 shows the topography of the study area.



Fig.3. Photograph of the topography of the study area.

### 3. Methodology

The research was conducted using both experimental and analytical methods and was also designed to gather essential and accurate information to investigate the properties of soil from laboratory tests at the study area to analyze the slope stability of the affected prone area. Modern limit equilibrium software Geo-studio (Slope/W) was used for computation of factor of safety of slope. The conventional Limit Equilibrium method was employed to analyze the high embankment slope stability. The Geo-Studio (SLOPE/W) is formulated in terms of moment and

force equilibrium factor of safety equations and supports a full list of limit equilibrium methods, including Morgenstern-Price, Spencer, Bishop, Janbu, and the Ordinary method. The analysis provides a factor of safety, defined as the ratio of the shear strength of soil to the shear stress required for equilibrium [7]. Due to its simplicity and precision, the limit equilibrium method is one of the oldest and best-known numerical methods to be used regularly in geotechnical engineering work [10].

### III. RESULT AND DISCUSSION

#### 3.1 Laboratory Test Result

- **Soil Moisture:** the moisture content test was performed for an undisturbed soil sample of the slope section for nine samples at various depth intervals. The average moisture content of the selected slope section ranges from 33.4% to 36.6%.
- **Unit Weight of Soil:** the unit weight of the sample Was determined based on the laboratory test result of the undisturbed sample. This test was performed for three soil samples of each section, taken at different depth intervals. The result of the tests shows that the unit weight of the soil in the study area is in the range of 16.3 KN/m<sup>3</sup>-17.9 KN/m<sup>3</sup>.
- **Specific Gravity of Soil:** the specific gravity of the Soil in the selected slope section was determined using a pycnometer with a specified temperature of distilled water. The specific gravity of selected samples was measured following the ASTM D 854-98 (Standard Test Method for Specific Gravity of Soils). The results of the tests show that the specific gravity of the soil at the study area ranges between 2.68- 2.78.
- **Atterberg's Limits:** Laboratory tests performed to determine the Plastic Limit (PL) and Liquid Limit (LL) of the soil samples. The experiment was conducted with ASTM D4318 -98 (Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils). The test result shows that the liquid limit ranges between 57.8 % to 63.7 %, while plastic limit of the study area ranges between 33.6 % to 37.8 %.
- **Grain size analysis:** three slope profiles were selected along the landslide area, and a total of nine samples were collected with three samples from each slope profile. For each of the nine samples, a grain size analysis was performed according to ASTM D6913-04 to determine the grain size distribution and the percentage of soil passing sieve No. 200 (P200) for the soil in the study area ranges from 62.02% to 66, 62%.

- **Shear strength parameter determination:** in this study, the shear strength parameters such as cohesion and the internal friction angle in the selected failed slope sections were determined from the direct shear strength test. The cohesion and friction angle of the soil at the study area is in the range of 2.3KN/m<sup>3</sup> – 6.1KN/m<sup>3</sup> and 18.1-21.3, respectively, as indicated in table 1.

Table -I: Summary of Laboratory test results

Section	Depth at	Moisture Content (%)	Unit weight (KN/m <sup>3</sup> )	Specific Gravity	Atterberg Limits			P 200(%)	Cohesion (kN/m <sup>2</sup> )	Angle of friction (°)
					LL (%)	PL (%)	PI (%)			
S <sub>1</sub>	Layer 1	33.4%	16.3	2.70	57.8	33.6	24.2	62.02	5.4	17.9
	Layer 2	34.2%	16.7	2.72	59.3	34.6	24.7	64.43	5.7	18.1
	Layer 3	35.3%	17.1	2.75	62.4	35.5	26.9	66.62	6.1	18.3
S <sub>2</sub>	Layer 1	34.3%	16.3	2.68	59.4	32.3	27.1	63.12	2.3	19.4
	Layer 2	34.8%	16.5	2.71	62.5	33.6	28.9	64.41	2.5	19.6
	Layer 3	34.2%	17.0	2.73	63.7	34.2	29.5	66.34	3.3	20.0
S <sub>3</sub>	Layer 1	33.6%	17.1	2.76	61.5	36.9	24.6	61.18	3.1	20.3
	Layer 2	35.9%	17.3	2.78	62.3	37.4	24.9	63.38	3.5	20.7
	Layer 3	36.6%	17.9	2.75	62.9	37.8	25.1	65.44	3.8	21.3

#### 3.2 Slope Stability Analysis

##### 1. Input Variables for Software's

The first task for calculating the safety factor using the slope / w software is to determine input parameters followed by the definition of geometry, area/material, pore water pressure, and slip surface test.

These can be described in the following sections. The slope stability analysis in the selected slope section was performed based on the input data (cohesion, internal friction angle, unit weight on the bottom, and groundwater condition). Table 2 shows the input variable such as cohesion, internal friction, and unit weight of the selected section that is obtained from laboratory results and used as an input for GeoStudio SLOPE/W software to determine the factor of safety

Table 2: Input parameters for Slope stability analysis  
 SampleDepth (m) Unit weight (KN/m<sup>2</sup>) Cohesion (KN/m<sup>2</sup>) Angle friction (o)

Sample	Depth (m)	Unit weight (KN/m <sup>2</sup> )	Cohesion (KN/m <sup>2</sup> )	Angle friction (°)
S <sub>1</sub>	Layer 1	16.3	5.4	17.9
	Layer 2	16.7	5.7	18.1
	Layer 3	17.1	6.1	18.3
S <sub>2</sub>	Layer 1	16.3	2.3	19.4
	Layer 2	16.5	2.5	19.6
	Layer 3	17.0	3.3	20.0
S <sub>3</sub>	Layer 1	17.1	3.1	20.3
	Layer 2	17.3	3.5	20.7
	Layer 3	17.9	3.8	21.3

##### 2. Geometry

Defining a work area with appropriate geometry, scale, and unit are the essential activities to be carried out in the analysis of slope stability. It is the process of defining the physically admissible ideal slope geometry of the study area. The geometry of an ideal slope was determined based on a scale of 1 to 2 using points and polygons.

Accordingly, the average slope height of 15 - 20 m and a width of 35 - 40 m were used for the three-section.

### 3. Material

The material statement is one of the critical elements in slope/w analysis. There are different ways to define the material in the slope stability analysis, such as Mohr-Coulomb, undrained strength, and bedrock (impermeable material), which depends on the data available for the analysis. In this work, Mohr-Coulomb was used. The unit weight of soil mass, cohesion, and the internal friction angle are also included in this study. Based on the field observation and information of the laboratory test results, the soil in the study area was more or less homogeneous. Therefore, the material of the region was assumed to be homogeneous.

### 4. The Pore Water Pressure

Defining the pore water pressure is one of the critical elements in any slope stability analysis. Most of the time, the slope instability is typical due to the presence of pore water pressure in a given slope soil. Therefore, a proper definition of a pore water pressure regime is an essential component of slope stability analysis.

### 5. Critical Slip Surface

When analyzing the stability of a slope, the definition of the critical potential slip surface is an essential step to obtain a minimum safety factor in the selected slope section using a slope/w software. This can be performed by applying various searching options like entering and exiting, grid, and radius, and the search options specified by block [6]. However, in current slope modeling, a critical slipping surface is defined using enter and exit search options. Because it is suitable and can be controlled by the user to adjust the slip surface search until the most critical slip surface is found. Figure 4 shows the critical slip surface of Section 1 using the ordinary analysis method having the geometry of height 18m and width 40m.

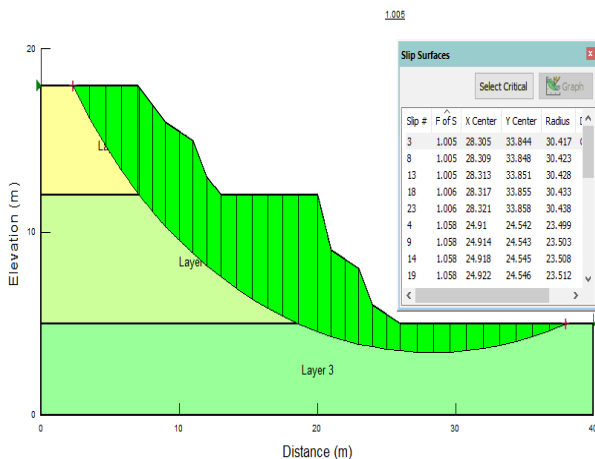


Fig.4. Ideal geometry, critical surface and a minimum factor of safety in Section 1.

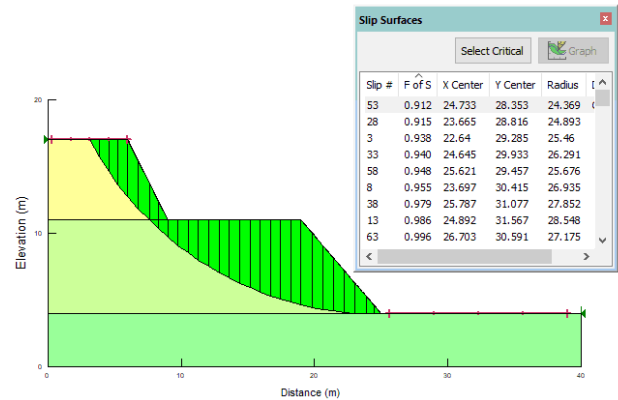


Fig.5. Ideal geometry, critical surface and a minimum factor of safety in Section 2.

Figure 5 shows the critical slip surface of Section 2 using the ordinary analysis method having the geometry of height 17m and width 35m. Figure 6 shows the critical slip surface of section 3 using the ordinary analysis method having the geometry of height 16m and width 35m.

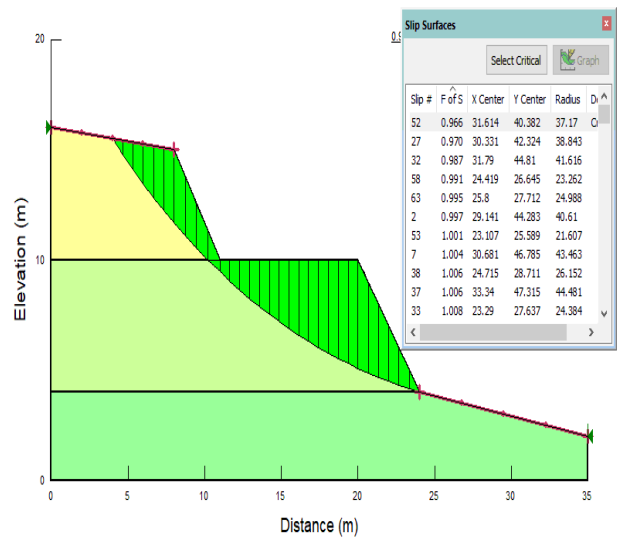


Fig.6. Ideal geometry, critical surface and a minimum factor of safety in section 2.

### 6. The factor of safety Computation

#### • Factors of Safety Computation Using Ordinary Method (OM)

This method was applied to calculate the factor of safety for selected failed slope sections under various groundwater conditions but does not take into account the normal, and shear interslice forces and does not satisfy force in equilibrium. Thus, it does not provide a factor of safety vs. lambda graph because lambda is not defined. The ordinary method only satisfies the equation of moment in equilibrium. The force polygon closure is not possible, as shown in Figure 7.

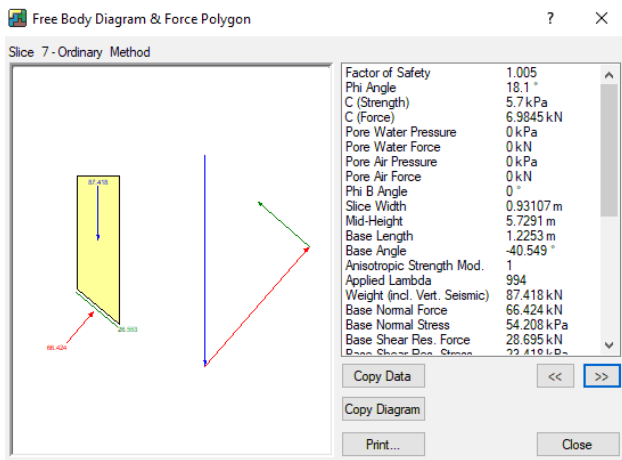


Fig.7. Free body diagram and Force Polygon closure in for Section 1.

- Factors of Safety Computation Using Bishop Method (BM)

This method satisfies the overall moment equilibrium but not the horizontal force equilibrium. It has inter-slice normal force but not inter-slice shear force. The force polygon closure was examined under similar slice numbers, which is an excellent contrast to the ordinary one, as shown in Figure 8 below. The sliding masses are almost in horizontal force equilibrium. In the case of a factor of safety vs. lambda graph, unlike the ordinary-simplified method, Bishop's simplified method factor of safety falls in the moment equilibrium curve when lambda is zero, as shown in Figure 12.

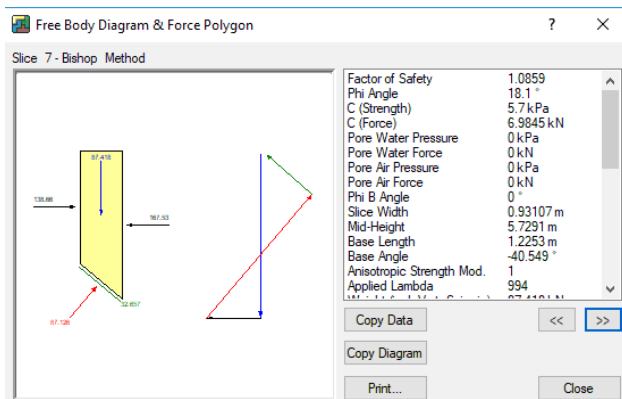


Fig.8. Free body diagram and Force Polygon closure in for Section 1 using Bishop.

- Factors of Safety Computation Using Janbu Simplified Method (JM)

Janbu's simplified method is the third limit equilibrium method that is satisfied only with the overall horizontal force in equilibrium. This method considers inter-slice normal force like Bishop, but it ignored the inter-slice shear force. As shown in Figure 9, the force polygon closure in this method is better than the Bishop's simplified method. Thus, the slice of the slide mass is in

horizontal force equilibrium. The factor of safety of Janbu is lower than the Bishop's simplified method because the force in equilibrium in the Janbu method is sensitive to inter-slice shear force. Its ignorance of the inter-slice shear force is the reason for the reduction of a factor of safety in the Janbu simplified method. However, Bishop's simplified method satisfied the overall moment in equilibrium, and as a result, it is not sensitive to inter-slice shear force in a circular slipping surface.

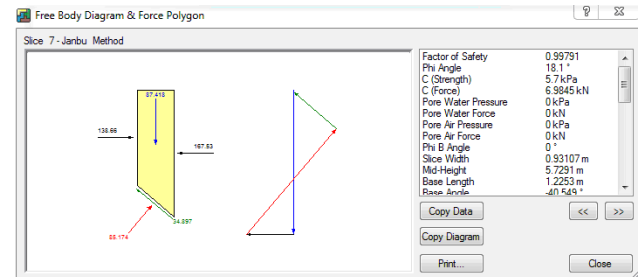


Fig. 9. Free body diagram and Force Polygon closure in for Section 1 using JM.

- Factors of Safety Computation Using Spencer Method (SM)

This method satisfies both the moment and the force in balance. At the same time, this method takes inter-slice forces into account and assumed the constant relationship between the inter-slice shear force and normal force. It has quite good force polygon closure, as shown in Figure 10. Consequently, all slices are in force equilibrium. Unlike Bishop and Janbu, the value of lambda is greater than zero, as shown in Figure 12. This method has both inter-slice shear and normal force because lambda is the ratio of interslice shear to the inter-slice normal force. This method is used to calculate two factors of safety, like the factor of safety concerning moment and force equilibrium.

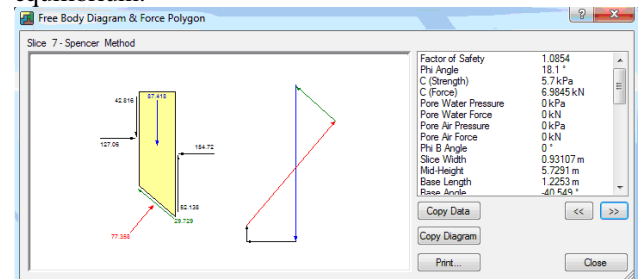


Fig.10. Free body diagram and Force Polygon closure in for Section 1 using SM.

- Factors of Safety Computation Using Morgenstern Price Method (MPM)

This method satisfied the overall moment and force equilibrium. It took into account the two inter-slice forces and had an excellent force polygon closure, as shown in Figure 11. It is so important to calculate all possible factors of safety and to plot the factor of safety versus the lambda graph. Unlike Spencer, this method is allowed for

various inter-slice force functions. Therefore, this method is the best of all the other limit equilibrium methods. This method satisfies all equations of statics and used to plot the factor of safety vs. lambda graph that is so important to compare the factor of safety in each method.

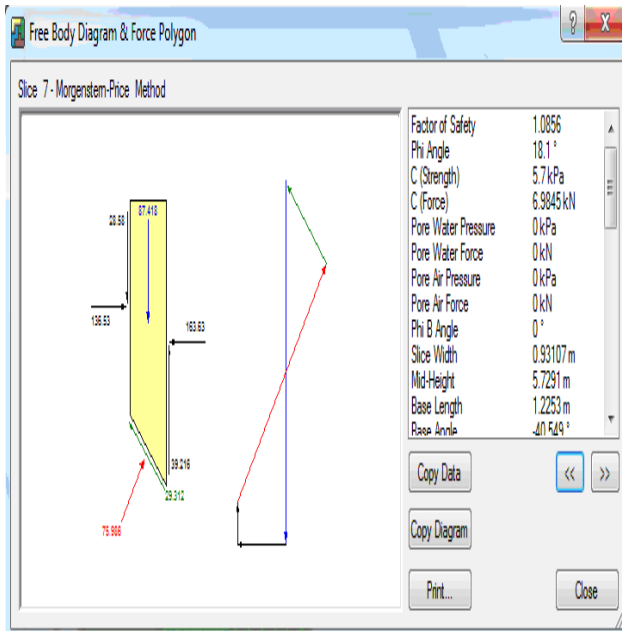


Fig. 11. Free body diagram and Force Polygon closure in for Section 1 using MPM.

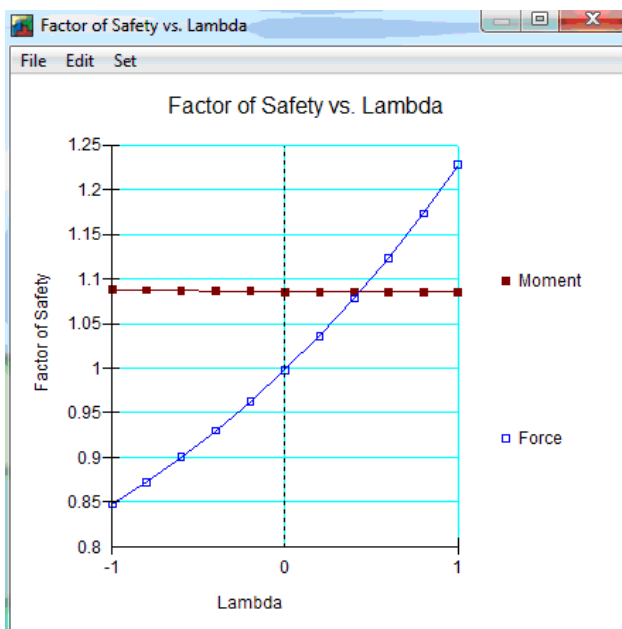


Fig.12 . Factor of safety Vs Lambda graph.

- The slope stability analysis results of three selected slope sections

The minimum factor of safety and critical slip surface of the three selected slope sections are calculated and searched for different limit equilibrium methods by considering various groundwater conditions using various

methods have been summarized in Table 3. All slopes at each section are unstable in both dry and wet conditions.

Table 3: Summary of Minimum Factor of safety for each slope section

Slope Section	Methods	Factor of safety		Slope Status
		Groundwater condition		
		Dry Condition	Wet Condition	
Section 1 (S1)	OM	1.005	0.56759	Unstable
	BM	1.0859	0.54606	Unstable
	JM	0.99791	0.47971	Unstable
	SM	1.0854	0.55747	Unstable
	MPM	1.0856	0.55703	Unstable
Section 2 (S2)	OM	0.91159	0.44757	Unstable
	BM	0.97526	0.38106	Unstable
	JM	0.89285	0.33347	Unstable
	SM	0.97111	0.39679	Unstable
	MPM	0.97123	0.39578	Unstable
Section 3 (S3)	OM	0.96572	0.52072	Unstable
	BM	0.98588	0.42795	Unstable
	JM	0.95889	0.40334	Unstable
	SM	0.98492	0.43298	Unstable
	MPM	0.98488	0.43269	Unstable

### 3.3 Possible landslide factors

From field observations, laboratory results, and interviews with local people, the main factors of the landslide identified were rainfall, land use, groundwater, slope, slope modification, and loss resent sediments.

#### 1. Rainfall

Slope failure has occurred in the middle, end of July, August, and September with intense and prolonged rainfall in the study area. As indicated in the bar graph of Figure13, the rainfall intensity varies from month to month. For instance, the rainfall intensity in July, August, and September are so high. The information that has gathered from local people interview, natural soil moisture test result, liquidity index, and Google Earth image interpretation indicates landslides in the study area have occurred related to heavy and prolonged rainfall. Thus, rainfall is one of the most important triggering factors for slope failure in the study area. As designated in Table 1, the natural soil moisture content of the soil increases with depth for the selected failed slope section. It implies the fluctuation of soil moisture due to the effects of rainfall. This result shows, during the rainy season, the humidity of soil increases and causes the unsaturated reduction zone of the soil profile. It also causes a reduction of shear strength but the increasing weight on the slope and driving force. These all trigger the slope instability in the area. However, the presence of heavy and prolonged rainfall in a given region may not cause landslide unless other conditioning factors are available. In the study area, in particular, cool zones that

have high rainfall but have not subjected to landslide incidence due to flat topography and the absence of slope modification. Therefore, rain by itself does not trigger landslide without the contribution of other factors like geology, soil depth, slope gradient, slope modification, vegetation cover, and vegetation type.

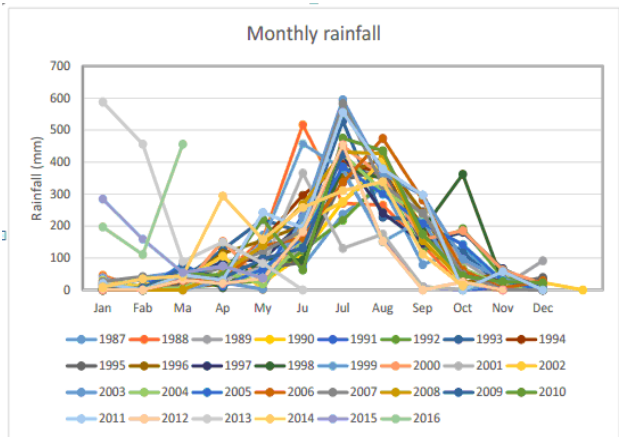


Fig. 13. Monthly based rainfall of Gedo town from 1987-2016.

## 2. Groundwater

Ethiopia has a lot of perineal and in perineal rivers that sourced from the mountain peak and diversified lakes as well as springs in the rift, plateau, and the hillside of the peaked mountain. The basic hydro stratigraphy units include resending unconsolidated sediments, Cenozoic volcanic rocks, Mesozoic sedimentary rocks, and locally important basement rocks [8].

The groundwater aquifer zone of the area ranges from very shallow to intense zones, and its main recharge source is rainfall that recharged through fast, selective recharge from heavy rainfall and direct, diffuse recharge through soil and root zones. The groundwater depth varies from 0 - 65m with static water level ranges from 5 - 41 m. This indicates that groundwater in the study area is close to the surface, which has susceptible to volume fluctuation within various seasons. The fluctuation of the water level might affect the moisture content of the soil. This may be an aggravated slope stability condition problem. Groundwater surface features such as wet and flowing springs have been observed in the field. A landslide in the study area occurred near the springs. The presence of surface sources indicates that the area contains shallow groundwater. The volume of most springs fluctuates during the summer and winter seasons. During the rainy season, their volume will increase. This can cause a reduction in the thickness of the unsaturation zone. The reduction of a thickness of the unsaturated zone can also heighten slope instability. However, during the dry season, their volume decreases and causes the soil mas to shrink its volume, which develops cracks that also cause a reduction to the shear strength of soil material in the slope. The factor of safety results at various groundwater levels is different, which implies

groundwater fluctuation has a fundamental effect on slope stability problems. Therefore, groundwater in the study area has a great role in slope stability.

## 3. Land use/cover

Landslides in the study area have occurred in lands severely eroded by the river or stream due to the removal of vegetation along the coast for agricultural purposes. Even though agricultural activity in the study area practices on a flat slope, it has a great effect on landslide occurrence because of the presence of gully and stream bank erosion. Settlement and deforestation are typical on a steep slope of the study area. This increased the removal of soil by erosion and caused slope movement down a slope. The area, which has bare or scatters vegetation cover, is susceptible to the landslide. However, the moderately vegetated area is less susceptible to a landslide because it reduced the power of rainfall in leaves intercept and infiltration due to evapotranspiration. In the study area, landslides have occurred in overgrazing land, bare to scatters vegetation cover and along stream/river bank. This confirms that land use/cover has a great role in slope instability.

## 4. Slope and modification

The slope gradient of the study area has changed into the steep slope from the natural slope through excavation for road construction. Thus, the landslide has occurred in gentle to very gentle slope gradient. Therefore, landslides can occur at any slope gradient when required conditions fulfill. The steeper slope gradient of the study area also caused the occurrence of rockfall, debris, and earthflow in all section villages. Besides, the slope gradient, the orientation, and the shape of the slope also have a great effect on slope stability problems in the study area. In the study area, landslides are common in concave and convex slope shape. This is because of the hydraulic and gravity effect of the open and convex shape of the slope. The concave upward slopes enhanced rainwater ponding and infiltration into the soil mass. This further enhances the reduction of shear strength of soil mass in a slope.

## IV. CONCLUSION

Based on the laboratory test results, the soils in the three selected failed slope sections have similar properties, which were more or less homogeneous. Thus, the soil mass in each slope section has worse engineering behavior based on their Atterberg limit test results. Due to the higher value of liquid limit, plasticity index, liquidity index, and compression index, the soil mass in the failing slope section has higher swelling and shrinkage potential. As a higher value of Atterberg and driving the limit result, we can conclude that the soil mass in the selected failed slope section has poor hydraulic properties. This can cause to increase the volume of soil when it interacts with water and can develop pore water pressure. These all lead

to increasing the driving force but decreases resisting force. This further increases the slope failure in the area. From the rainfall analysis, natural moisture content, local people interview, and Google Earth image time series interpretation, the present work finds out that the rainfall is one of the essential landslides triggering factors in addition to other factors. The slope angle, slope shape, and slope geometry modification have a great role in landslide occurrence, especially in all three sections. As usual, the steeper the slope, the higher will be landslide susceptibility; however, it might not always be true. A landslide can occur in a gentle slope due to slope geometry modification through natural and anthropogenic activity. This is true in the present study area; most landslides have occurred in gentle slope due to excavation and stream/riverbank erosion. Slope shape is another critical element of the slope stability problem in the study area.

The factor of safety in the study area is less than or almost equal to one and decreases as the groundwater level rises. This ensured that groundwater has a great role in the slope stability problem, and the soil mass in the selected failed slope section was inherently worse. Using the limit equilibrium method, the slope stability analysis was performed. The selected slope is unstable at a present condition in which the factor of safety is less than nearly equal to one. The factor of safety of OM and JM is less than that of other methods, but BM provides a factor of safety close to SPM and MPM. Indeed, although BM is not satisfied with all the static equations, it is not sensitive to intersection shear in a circular sliding surface. While SM and MPM provided a similar safety factor, MPM allowed users to select a variety of inter-slice force functions, unlike SPM, which only used a constant inter-slice strength function. Therefore, the MPM is the preferable method in slope stability analysis because it satisfies all equations of statics. It considers inter-slice shear normal force assumption, which used to plot factor of safety vs. lambda graph, and allows users to select a variety of inter-slice force functions. The study would have the advantage of understanding the conditions of slope stability and the various causes of slope collapse in the city of Gedo. In addition, this work is useful for all engineers and executive contractors who plan to carry out certain construction activities in Gedo Town and take appropriate corrective action to reduce the impact of a landslide on vulnerable areas. Landslide susceptibility analysis without any preventive and mitigation measure is senseless in the scientific world. Landslides are known to result from the combination of two or more landslide conditioning factors. Appropriate preventive and remedial action can be recommended based on landslide factors. Hence, there is a landslide in the study area due to the presence of various conditioning and triggering factors like groundwater, rainfall, soil type, land use, shape, and angle of slopes. Based on the implication of such factors, the most important preventive and mitigation methods were proposed in this study. These are Retaining/masonry

wall construction, land use management, vegetation cover, slope water management, and soil erosion management.

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