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RECONSTRUCTION OF NATURAL SLOPE STABILITY BY LIMIT EQUILIBRIUM METHODS AND FINITE ELEMENT METHODS

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Abstract

Slope stability analysis is particularly important for natural slopes that are relatively undesigned to be technically safe. Natural slopes are prone to collapse depending on the condition of the slope material and rainfall. A comprehensive stability analysis using numerical methods to calculate the factor of safety and probability of collapse can be used as a reference to assess the safety of a slope. This study discusses boundary equilibrium and finite element in the analysis of slope safety factor and landslide probability by reconstructing the slope with landslide history. The reconstruction of the slope is based on the actual slope condition with saturated material due to rain that has a safety factor of 0.5 using mathematical methods which are then analyzed numerically in this study. The results of the factor of safety on the saturated condition slope have a value that is not much different from the actual condition with a 100% probability of landslide. The results of low shear strength values in each slice of the limit equilibrium analysis for saturated conditions also indicate that the slope is in an unsafe condition which is supported by the development of shear and tensile strains in the finite element method analysis in the slope slide plane area which causes the stress distribution in the actual landslide area to be unstable.

***Keywords**: Failures Factors, Landslides, Rainfall Slope, Stability*

1. INTRODUCTION

Landslides on slopes are one of the disasters that often appear in everyday life, the impact of which can cause economic losses and loss of life. Landslides often occur on naturally formed slopes, in contrast to artificial slopes which are relatively safer because safe designs are taken into account in their manufacture. Landslides usually occur due to the large load being held by a slope so to achieve a stable condition with a large load, the slope will naturally release the load by causing a landslide. This happens on a slope to reach its stable point.

Many factors can cause landslides on slopes, starting from slope geometry factors, namely slope height and angle (Shiferaw, 2021), natural factors, and human factors. One of the natural factors is climate, which causes the slope shear strength to decrease to a critical limit, causing landslides. Climate and weather factors have an important impact on the process of landslides because they can change slope stability conditions through increasing pore water pressure and the degree of saturation of the slope materials (Juliantina *et al.*, 2018). This increase in pore water pressure is also often caused by intense rainwater on slopes so that slopes with high permeability in the soil cause infiltration on the slope and additional load, namely pore water, so that the shear strength of the slope will decrease and disrupt stability (Mukhlisin and Naam, 2015; De Leon and Garduño, 2020; Wu *et al.*, 2021). The shear strength parameters, cohesion (C) and internal friction angle (φ) influence the shear strength of the slope material, especially changes in cohesion (Harabinová and Panulinová, 2020).

This study conducts a safety factor reconstruction for natural slopes on a hill, utilizing a case study conducted by (Shah *et al.*, 2021). The research focuses on a slope in Malingaon Village, India, where a landslide occurred along a 512 m stretch from the crest to the toe. The slope's coordinates are 19°9'46.78" N and 73°41'7.94" E, illustrated in Figure 1 below.

Figure 1. Location of topographic features of study location (Mod. Shah et al., 2021)

Figure 1 above is a photo of the location taken using Google Earth aerial photos with updated photos for 2022 where in general the landslide area is still visible. The initial landslide in the study (Shah *et al.*, 2021) occurred in 2014 and was then analyzed using a cross-section in the landslide area which produced the appearance of the layers making up the slope as in Figure 2 below.

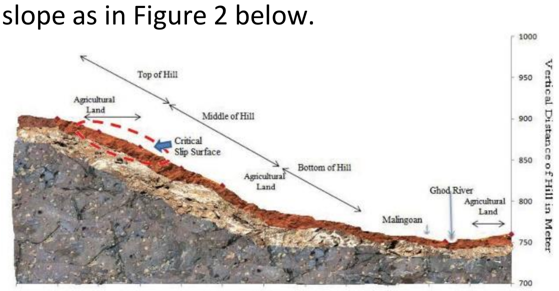

Figure 2. Cross-section study area (Shah *et al.*, 2021)

Figure 2 shows that there were three sampling zones after the landslide occurred, namely the top of Sandy-Clay, the middle of Silty Clay and the bottom of Clayey Loam. From the cross-section above, a slope stability analysis was carried out using the safety factor value for infinite slopes manually and the safety factor value was 0.5. In previous studies, it was explained that landslides occurred due to high rainfall at the research location, causing the condition of the slope material to be saturated with water, so it was necessary to analyze the saturated conditions in determining slope stability.

This study addresses the limitations of prior empirical equations in assessing slope stability, especially under saturated conditions. We employ the Limit Equilibrium Method (LEM) and Finite Element Method (FEM) to comprehensively evaluate safety factor results, comparing empirical and numerical calculations for slope stability. The Finite Element Method (FEM) is a precise and versatile approach that eliminates the need for assumptions regarding the type of slope failure ((Sungkar *et al.*, 2020). In this study, FEM is employed to assess both the magnitude and direction of soil displacement caused by landslides, validating the obtained safety factor.

Then in the analysis, the Probability of Failure Method (PoF) is used, where this method can analyze a problem, especially slope stability, to consider all conditions quickly in overcoming landslide disasters. (Salvatici *et al.*, 2018).

Specific probability of collapse was used in the advanced analysis in this study because it is widely used in slope stability to minimize the uncertainty of variable data on material properties (Huvaj and Oguz, 2018), or in other words, the safety factor on natural slopes is very difficult to use for natural slopes where the slope constituent materials such as soil and rock are heterogeneous (Kanjanakul and Chub-Uppakarn, 2018) Without considering the probability of slope failures and the obtained analysis results reliably (Kar and Roy, 2022; Yang *et al.*, 2022).

2. METHODOLOGY

This study employed secondary data derived from geotechnical laboratory tests and slope geometry in prior research conducted by (Shah *et al.*, 2021). Slope reconstruction involved digitizing the geometry depicted in Figure 2 using AutoCAD 2021 software, with a focus on delineating the previously mentioned three zones. Subsequently, the digitized slope geometry underwent analysis using the Limit Equilibrium Method (LEM) and Finite Element Method (FEM) to derive safety factor results. These methods assume that the soil properties conform to the Mohr-Coulomb criterion, specifically as a perfectly plastic material. (Sengani and Allopi, 2022). The results of digitizing slope geometry can be seen in Figure 3 below.

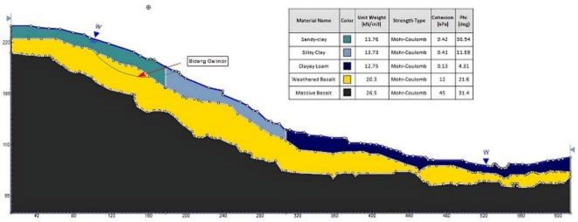

Figure 3. Slope geometry after digitized
(Source: This Study)

The figure 3 above shows three area or zone conditions by the previous case study which in this case was developed into three large zones, but the focus of the slopes analyzed is only at the top of the slope according to the critical slip surface which will provide the most critical safety factor (Rotaru, Bejan and Almohamad, 2022).

Based on the clustering of landslide zones, sampling in the analysis was also carried out to determine the mechanical characteristics of the soil that makes up the slope as shown in the following graph.

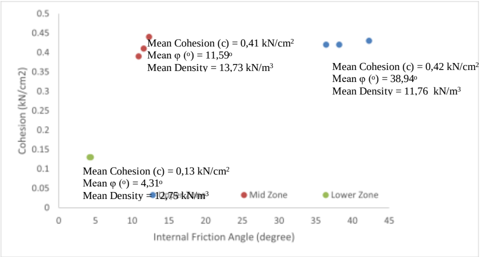

Figure 4. Clustering graph soil properties of slope (Mod. Shah et al., 2021)

The graph above is based on sampling in each zone from the top of the hill (upper zone) to the bottom of the hill (lower zone) after the landslide occurred. Representative samples taken for each zone were three samples with clustering as in Figure 4. From the graph, it can be concluded that there has been a decrease in the soil shear strength properties according to Mohr-Column criteria, namely the cohesion (c) and internal friction angle (φ). This shows that landslides occur due to factors that reduce the shear strength of the soil so that the soil reaches its critical point until a landslide occurs. The most likely factor causing the landslide is high rainfall in the study area so that the soil is saturated with water as explained in the research (Shah *et al.*, 2021).

The geological conditions of the study area are dominated by 81% basalt rock formations with susceptibility to weathering so water greatly influences the stability of the study location (Pande *et al.*, 2022). The general description of the stratigraphy or lithology of the materials making up the study location refers to research (Rane and Jayaraj, 2021) using drill data for pumping tests to obtain results like the following image.

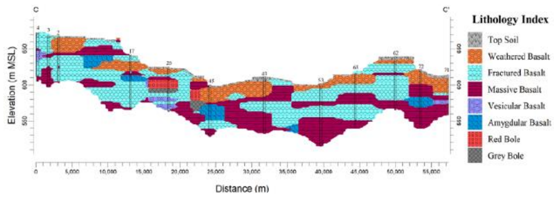

Figure 5. General stratigraphic on study area (Rane and Jayaraj, 2021)

Figure 5 above shows the layers that make up the study location, especially for the Maharashtra District in India, where the study location is in the same geological formation so that stratigraphy is used as a reference for the building blocks in slope modeling and minimizes data limitations. The layers used in modeling are the top layer from Figure 1 in the form of covered soil and the weathered basalt and massive basalt layers as in Figure 5, so that three layers are obtained according to the constituent layers used at the study location.

Modeling with the Spencer Criteria LEM using SLIDE 6 software from Rocscience. The Spencer method is used to calculate the factor of safety with the principle of moment equilibrium and force equilibrium, so this method is more complex in its analysis (Wubalem, 2022). Analyze the value of the safety factor or Strength Reduction Factor (SRF) using FEM in Phase2 software from Rocscience.

The input data in the slope analysis used secondary data from several previous studies with coverage areas according to the study location. There are five material properties used in the analysis as shown in Table 1 below.

Table 1. Material properties using slope analysis

No	Material	Density (kN/m^3)	C (kPa)	Φ (°)
1.	**Sandy-Clay**	11.8	0.42	40
2.	**Silty Clay**	13.7	0.41	11.5
3.	**Clayey Loam**	12.8	0.13	4.3
4.	**Weathered Basalt**	20.3	12	21.6
5	**Massive Basalt**	26.5	45	31.4

Source data : (1-3 from Shah et al., 2021*; 4 – 5 from* Kainthola, Singh and Singh, 2015

Analysis of slope safety factors and failure probability based on input data in Table 1 was only carried out on the slip surface of the study location (Figure 1) using Mohr-Coulomb shear strength criteria. In the analysis, saturated conditions are calculated to approach the actual conditions according to research where high rainfall occurs at the study location so that the slope is saturated, or in other words the slope surface is assumed to be all slopes below the ground water level.

The Probability of Failures Method used is the Latin Hypercube Method with a data sample size of up to 1000 data. This method has better performance than other methods such as the Monte Carlo Method which requires a lot of data and the Latin Hypercube Method is relatively short in its analysis (Wang, 2022).

3. RESULT AND DISCUSSION

The data processing in this study comprises two stages. Firstly, SLIDE 6 software was employed for the analysis to determine the factor of safety and landslide probability under two conditions. This approach was adopted to assess the impact of slope material saturation levels on both the factor of safety and slope probability. Subsequently, modeling of the sliding plane was conducted at the hill's summit, aligning with the identified sliding plane location to ensure results closely resemble actual conditions.

The factor of safety and probability of collapse were then re-analyzed using FEM on the same slide plane to validate the LEM analysis values. The statistical parameter input values for the PoF analysis are shown in Table 2 below.

Table 2. Input data for probability analysis

Parameter	Material	Mean	Rel. Min	Rel. Max
Cohesion (kPa)	Sandy-Clay	0.42	0	0.01
	Silty-Clay	0.41	0.02	0.03
Φ (°)	Sandy-Clay	38.9	2.54	3.31
	Silty-Clay	11.6	0.71	0.71

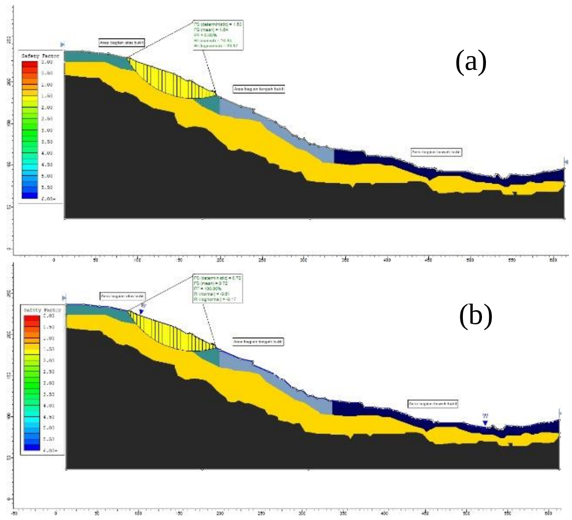

Figure 6. Slope modelling result and anlysis using LEM (Source: Study analysis)

The results, shown in Figure 6 using LEM, highlight a significant difference between dry (a) and saturated (b) slope conditions. In dry conditions, the safety factor (FK) is 1.63 with a 0% probability of failure (PF). In saturated conditions (with groundwater), the safety factor (FK) is 0.72, and the probability of failure (PF) is 100%.

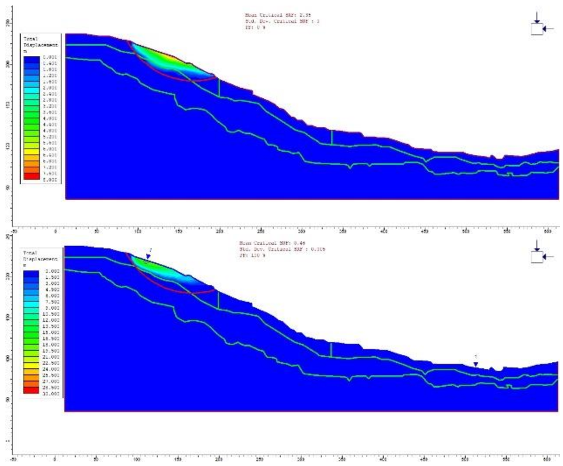

Figure 7. Slope modelling result and anlysis using FEM (Source: Study analysis)

The same results were shown by the FEM analysis where the factor of safety (SRF) for the dry slope was 2.35 with 0% PF, and the SRF for the dry slope was 0.46 with 100% PF.

These conditions indicate that under dry circumstances, the slope is secure (safety factor > 1, PoF 0%), eliminating the possibility of a landslide. Conversely, in saturated conditions (representing the actual study location), the slope is deemed unsafe (safety factor < 1) with a Probability of Failure at 100%. This underscores the high likelihood of a landslide, as substantiated by the historical landslide occurrences at the study site as reported in prior research. A comparison of the safety factor values of research by (Shah *et al.*, 2021) with the development of analysis in this study is shown in Table 3 below.

Table 3. Factor safety of slope in this study

No	Slope Condition	FoS	PoF (%)	Source
1	**Infinite Slope**	0.5	-	Shah *et al.*, 2021)
2	**Dry Slope LEM**	1.63	0	This Study
3	**Saturated Slope LEM**	0.72	100	This Study
4	**Dry Slope FEM**	2.35	0	This Study
5	**Saturated Slope FEM**	0.46	100	This Study

LEM and FEM analyses reveal that the safety factor is higher in dry slopes compared to saturated conditions, aligning with research by (Wen *et al.*, 2023) During rainfall, stability conditions can rapidly decrease, leading to landslides due to potential slip plane development. Supplementary parameters, including the material shear strength factor in the LEM analysis, yield consistent results, as illustrated in Figure 8 below.

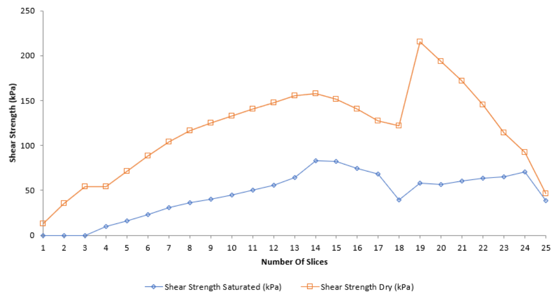

Figure 8. Shear strength dry and saturated condition (Source: Study analysis)

The results depicted in Figure 8 illustrate shear strength values under both dry and saturated conditions. The shear strength graph for each slope slice reveals higher values in dry conditions compared to saturated conditions. This indicates that the presence of water in saturated conditions, caused by rainfall, reduces the shear strength of the material. Essentially, water introduces pore water pressure, leading to the loosening of soil grains and a subsequent reduction in shear strength.

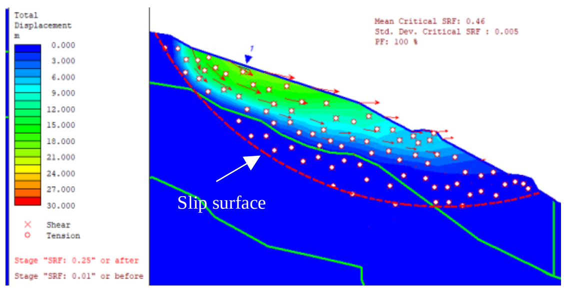

Figure 9. Displacement vectors FEM analysis (Source: Study analysis)

Through FEM analysis of the slip sirface, Figure 9 above illustrates the direction of slope displacement under saturated conditions. The material displacement tends to form a circular contour, moving towards the front of the slope, where tensile and shear strains develop. This response reflects the stresses acting on the slope when the material is saturated at the study site. The displacement vector, represented by the red arrow, validates the accuracy of the modeling, aligning logically with the landslide direction.

4. CONCLUSION

Based on some of the data analysis results, it can be concluded that the reconstruction of the slope safety factor determination in the previous study can be validated by analysis using LEM and FEM. The difference in safety factor results shows that the slope condition is not safe and the addition of the probability of collapse analysis also shows the same thing where the probability of collapse is up to 100%. The shear strength values in the saturated condition are also low for each slice in the LEM analysis so that the slope tends to be displaced, this is supported by the development of tensile and shear strains in the sliding plane area which causes the area in the plane to experience changes in stress distribution.

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