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## Slope Stability Analysis Using GeoStudio-Based Finite Element Method

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### ABSTRACT

Landslides frequently occur in areas with steep slopes, high rainfall intensity, and human-induced land disturbances, posing significant risks to infrastructure and communities. This study investigates the soil characteristics and slope stability conditions of a landslide-prone area in Nagari Aia Dingin, Lembah Gumanti District, Solok Regency, Indonesia. The research employed field investigations, Standard Penetration Tests (SPT), laboratory testing, and numerical analysis using the GeoStudio-based Finite Element Method (FEM). Laboratory tests included water content, specific gravity, Atterberg limits, and grain size distribution to determine the physical properties and classification of the soil. The results indicate that the soil is predominantly classified as silty sand and silt (SM and ML) according to the Unified Soil Classification System (USCS), characterized by low cohesion and a high dependence on frictional resistance. Slope stability analyses were performed for slope angles of 30°, 45°, and 60° using GeoStudio. The calculated factors of safety (FS) ranged from 1.149–1.276 at 30°, 0.447–0.737 at 45°, and 0.450–0.490 at 60°. All values were below the minimum recommended safety factor of 1.5, indicating unstable slope conditions. The results demonstrate that increasing slope inclination significantly reduces stability and increases the likelihood of failure. Combined with unfavorable soil characteristics and prolonged rainfall infiltration, the study area exhibits a high susceptibility to landslides. These findings provide valuable information for slope hazard assessment and the development of appropriate mitigation measures in vulnerable mountainous regions.

**Keywords :** slope stability, landslide, GeoStudio, finite element method, factor of safety

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### INTRODUCTION

Slope instability induced by rainfall remains a critical geotechnical and environmental challenge, particularly in regions characterized by steep terrain, heterogeneous soil profiles, and intensive land use pressures. Slope landslides triggered by high intensity rainfall have a high potential to occur in hilly areas and mountainous slopes, where rapid infiltration alters the hydro mechanical equilibrium of the soil mass and reduces shear strength parameters (Polemio and Petrucci, 2000). High intensity rainfall in a relatively short duration on continuous or infinite slopes can significantly affect slope stability by increasing pore water pressure and decreasing matric suction

in unsaturated soils, thereby reducing effective stress and factor of safety (Muntohar and Liao, 2010). Recent studies emphasize that rainfall induced slope failure is strongly governed by coupled hydro mechanical processes, including transient seepage, unsaturated soil behavior, and progressive failure mechanisms, which require advanced numerical modeling approaches for accurate prediction (Ng et al., 2019; Rahardjo et al., 2021). In addition, the natural conditions of the slope and the characteristics of the soil type are important factors that determine the potential level of slope instability. Soil properties such as permeability, cohesion, internal friction angle, and degree of saturation interact dynamically with rainfall infiltration, making slope response highly nonlinear and site specific (Zhang et al., 2020; Li et al., 2022). The thickness of the soil layer on continuous or infinite slopes is also a factor that contributes to the potential for landslides, particularly when deeper weathered profiles allow prolonged water accumulation and delayed failure (Wang et al., 2021).

In recent years, the application of numerical modeling techniques, particularly the Finite Element Method implemented in software such as GeoStudio, has significantly improved the ability to simulate slope behavior under varying environmental conditions. The Finite Element Method enables detailed analysis of stress strain relationships, seepage flow, and coupled hydro mechanical interactions, which are essential for understanding rainfall induced slope failure mechanisms (Fredlund et al., 2019; Krahn, 2020). GeoStudio, as an integrated geotechnical software suite, allows the coupling of SEEP W and SLOPE W modules to simulate infiltration processes and evaluate slope stability simultaneously, thereby providing a more realistic representation of field conditions compared to traditional limit equilibrium methods (Azam et al., 2021; Singh et al., 2022). Several recent studies have demonstrated that FEM based approaches can capture progressive failure, strain localization, and temporal variations in factor of safety more effectively than conventional methods (Chen et al., 2020; Zhao et al., 2023). Furthermore, the incorporation of unsaturated soil mechanics into FEM analysis has enhanced the accuracy of slope stability predictions, particularly in tropical regions where seasonal rainfall variations play a dominant role (Nguyen et al., 2021; Pradhan et al., 2022).

The Alahan Panjang landslide disaster, precisely in the Air Dingin area, Lembah Gumanti District, Solok Regency, represents a typical case of rainfall induced slope failure exacerbated by anthropogenic activities. The event cut off the transportation flow between Solok Regency, South Solok, and Sungai Penuh, Jambi for seven days, causing significant socio-economic disruption and highlighting the vulnerability of critical infrastructure to geohazards (Minang, 2020). Hundreds of vehicles that usually pass through this route were halted, indicating the strategic importance of this corridor for regional connectivity. The 25 meter landslide not only disrupted

transportation but also caused the destruction of residential structures, as two local houses were swept away by landslide material originating from a mining excavation area located upslope. Although no fatalities were reported, the incident underscores the potential severity of combined natural and anthropogenic triggers in slope failure events. The chronology of the disaster began with continuous high intensity rainfall over a period of one week, which likely led to progressive saturation of the soil mass and a critical reduction in shear strength. Recent literature confirms that prolonged rainfall events are more dangerous than short intense storms because they allow deeper infiltration and sustained pore pressure build up, which ultimately leads to delayed but catastrophic slope failure (Kim et al., 2021; Luo et al., 2022).

In addition to climatic factors, human activities such as mining significantly alter slope geometry, disturb natural drainage systems, and weaken soil structure, thereby increasing landslide susceptibility. Excavation at the toe or crest of slopes can reduce confining stress and trigger instability, especially when combined with unfavorable geological conditions (He et al., 2020; Zhou et al., 2023). The presence of a C excavation mine above the residential area in Alahan Panjang likely contributed to the destabilization of the slope by modifying its natural contour and increasing surface runoff concentration. Recent studies highlight that land use changes, including mining and deforestation, play a critical role in accelerating slope failure processes, particularly in tropical environments where intense rainfall is frequent (Sassa et al., 2021; Gariano and Guzzetti, 2022). Therefore, slope stability analysis must integrate both natural and anthropogenic factors to provide a comprehensive risk assessment framework.

From a methodological perspective, the use of GeoStudio based Finite Element Method provides a robust platform for analyzing such complex slope systems. By integrating seepage analysis with stability calculations, researchers can simulate rainfall infiltration patterns, evaluate transient pore water pressure distribution, and determine the temporal variation of factor of safety under different rainfall scenarios (Alvioli et al., 2020; Huang et al., 2021). Moreover, FEM allows for the incorporation of advanced constitutive models that account for soil plasticity, strain softening, and unsaturated behavior, which are essential for capturing real world slope responses (Sun et al., 2022; Li and Zhang, 2023). The ability to model progressive failure and identify critical slip surfaces enhances the predictive capability of slope stability analysis and supports the development of early warning systems and mitigation strategies. Consequently, the integration of GeoStudio based FEM with field data and rainfall records offers a scientifically rigorous approach to understanding and managing landslide hazards in vulnerable regions such as Alahan Panjang.



Figure 1. Condition of the slope after the landslide



Figure 2. Condition after the slope after the landslide

This research will determine how soil characteristics affect landslide potential at disaster sites. Slope gradients will also be varied in the testing. The expected results can inform landslide mitigation efforts, particularly at current disaster sites.

## **METHOD**

This study employed an experimental and analytical approach to evaluate slope stability using a GeoStudio-based Finite Element Method (FEM). The research was conducted systematically following sequential stages consisting of literature review, field investigation, laboratory testing, data processing, and slope stability analysis through the determination of the factor of safety.

### **1. Literature Review**

The initial stage involved a comprehensive literature review to establish the theoretical and methodological framework of the study. This included the review of recent international journal publications related to slope stability, rainfall-induced landslides, unsaturated soil mechanics, and numerical modeling using FEM. Particular emphasis was placed on understanding soil shear

strength parameters, infiltration mechanisms, and the application of GeoStudio software, especially the integration of SEEP/W and SLOPE/W modules. The literature review also guided the selection of laboratory tests and field investigation techniques relevant to the study area conditions.

## **2. Site Survey and Sampling**

A field survey was conducted in Aie Dingin, Lembah Gumanti District, Solok Regency, which is characterized by high rainfall intensity and landslide susceptibility. The purpose of this stage was to identify slope geometry, soil stratification, groundwater conditions, and evidence of previous slope failures.

Soil sampling was carried out using disturbed sampling techniques due to accessibility and field constraints. Samples were collected from representative points along the slope, particularly in zones showing signs of instability. The sampling depth was adjusted based on visible soil layers and slope morphology. All samples were properly labeled and stored to preserve their physical characteristics prior to laboratory testing.

In addition to sampling, field testing was conducted using the Standard Penetration Test (SPT) to determine in situ soil resistance. The SPT results were used to estimate relative density, consistency, and preliminary shear strength parameters of the soil layers.

## **3. Laboratory Testing**

Laboratory testing was performed to determine the physical properties of the soil, which are essential for slope stability analysis. The tests were conducted in accordance with standardized geotechnical testing procedures. The following tests were carried out:

### **a. Water Content (Moisture Content Test)**

This test was conducted to determine the natural moisture content of the soil, which significantly influences soil strength and permeability. The oven drying method was applied following standard procedures.

### **b. Unit Weight (Specific Gravity and Bulk Density)**

The unit weight and specific gravity of soil particles were determined to evaluate soil mass characteristics. These parameters are essential for calculating overburden stress and slope stability.

### **c. Atterberg Limits**

The Atterberg limits test was conducted to determine the liquid limit, plastic limit, and plasticity index of the soil. These parameters are used to classify fine-grained soils and assess their consistency and plasticity behavior.

#### **d. Grain Size Distribution (Sieve Analysis)**

Sieve analysis was performed to determine the distribution of particle sizes within the soil. This test provides insight into soil classification, permeability, and mechanical behavior.

The results of these laboratory tests were used to define soil parameters such as cohesion, internal friction angle, and unit weight for further numerical modeling.

#### **4. Field Testing (SPT)**

The Standard Penetration Test was conducted to obtain in situ soil resistance values. The SPT N-values were used to estimate soil density and consistency, as well as to correlate with engineering properties such as shear strength and stiffness. These results were integrated with laboratory findings to improve the reliability of soil parameter determination.

#### **5. Data Processing**

All data obtained from laboratory and field tests were compiled and processed to generate input parameters for numerical analysis. Soil classification was performed based on the Unified Soil Classification System. Engineering parameters such as cohesion, internal friction angle, unit weight, and permeability were derived from empirical correlations and laboratory results.

In addition, slope geometry was defined based on field survey data, including slope height, inclination angle, and layer thickness. Groundwater conditions and rainfall infiltration scenarios were also considered in the data processing stage.

#### **6. Slope Stability Analysis Using GeoStudio (FEM)**

Slope stability analysis was conducted using GeoStudio software with a Finite Element Method approach. The analysis involved the following steps:

##### **a. Model Geometry Definition**

The slope profile was modeled based on field measurements, including stratification and layer thickness.

##### **b. Material Property Assignment**

Soil parameters obtained from laboratory and field tests were assigned to each soil layer.

##### **c. Seepage Analysis (SEEP/W)**

Transient seepage analysis was conducted to simulate rainfall infiltration and pore water pressure distribution within the slope.

##### **d. Stability Analysis (SLOPE/W or SIGMA/W)**

The stability of the slope was analyzed by incorporating pore water pressure results into the stability model. The Finite Element Method was used to evaluate stress distribution and potential failure surfaces.

**e. Factor of Safety (FK) Determination**

The factor of safety was calculated to assess slope stability. A slope is considered stable if the factor of safety is greater than the minimum acceptable value, typically 1.3 for static conditions.

**7. Interpretation and Evaluation**

The results of the analysis were interpreted to identify critical slip surfaces, failure mechanisms, and the influence of rainfall and soil properties on slope stability. The findings were used to evaluate the level of slope safety and to provide recommendations for mitigation measures.

This structured methodology ensures that the analysis is scientifically rigorous, integrates both field and laboratory data, and utilizes advanced numerical modeling to accurately assess slope stability conditions. The research implementation process is presented in the form of a flowchart in Figure 3.

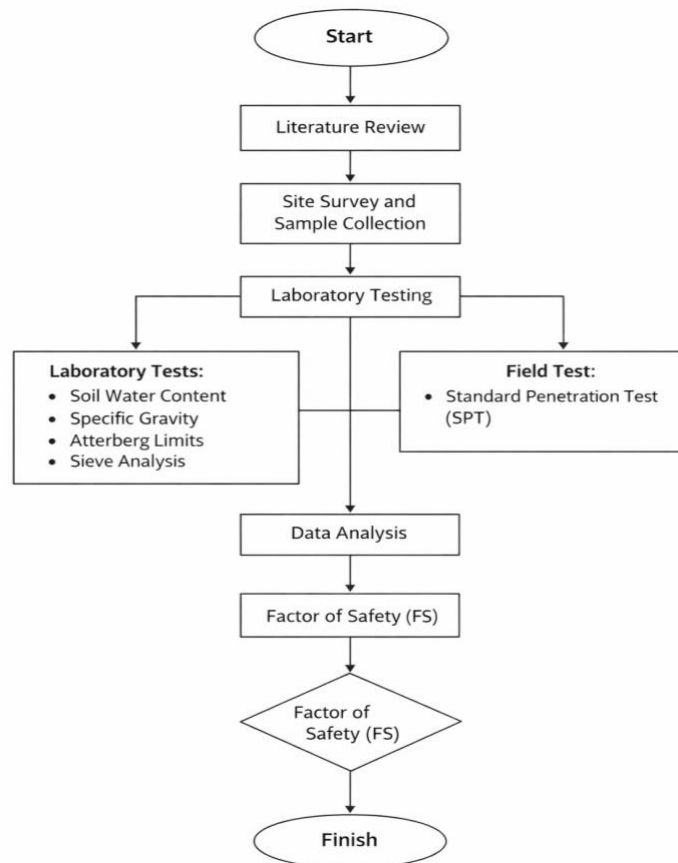


Figure 3. Research Flowchart

The soil samples utilized in this study were classified as undisturbed samples, meaning that their natural structure, particle arrangement, water content, and in situ physical properties were

preserved during the sampling process. These samples were carefully extracted to minimize disturbance, ensuring that they accurately represent field conditions without being significantly affected by excavation, compaction, or mechanical alteration. The undisturbed soil samples were obtained from boreholes at three Standard Penetration Test (SPT) locations, which were strategically selected to represent the geotechnical conditions of the study area.

Laboratory testing was conducted to determine the physical characteristics of the soil using standardized geotechnical procedures. The determination of natural water content was performed in accordance with SNI 1965:2008, employing the oven-drying method to ensure accurate measurement of moisture conditions. The specific gravity of soil particles was determined based on SNI 1964:2008 using appropriate laboratory apparatus to evaluate the relative density of the soil solids. Soil consistency limits, including liquid limit and plastic limit, were tested following SNI 1967:2008 and SNI 1966:2008, respectively, to assess the plasticity and consistency behavior of fine-grained soils. In addition, the grain size distribution analysis was carried out through sieve analysis in accordance with SNI 03-1968-1990, which provided essential information on soil gradation and classification.

**RESULTS AND DISCUSSION**

1. Results Of Soil Physical Properties Testing

Based on the results of the tests that have been carried out, the soil parameter values obtained are as presented in Table 1 and Table 2 below.

Table 1. Laboratory Test Results on BH - 1

No	Depth (m)	Percentage of Passing Items								Atterberg Limit			Water content	Specific gravity GS	Info
		Gravel		Sand						LL	PL	PI	W		
		3/8	No.4	No.10	No.20	No.40	No.100	No.200	(%)	(%)	(%)	(%)			
1	3.55 - 4.00	100.00	99.14	90.48	84.11	77.18	66.64	61.48	-	LP	-	45.09	2.6	ML	
2	7.55 - 8.00	100.00	100.00	87.59	84.67	80.20	69.41	64.87	-	LP	-	42.61	2.59	ML	
3	13.55 - 14.00	100.00	97.11	84.55	74.43	67.90	48.46	42.87	-	NP	-	-	2.6	SM	
4	21.55 - 22.00	100.00	100.00	87.14	78.54	68.09	45.11	37.81	-	NP	-	-	2.6	SM	

Table 2. Laboratory Test Results on BH - 2

No	Depth (m)	Percentage of Passing Items								Atterberg Limit			Water content	Specific gravity GS	Info
		Gravel		Sand						LL	PL	PI	W		
		3/8	No.4	No.10	No.20	No.40	No.100	No.200	(%)	(%)	(%)	(%)			
1	3.55 - 4.00	44.87	42.25	39.2	35.94	33.96	24.83	21.27	-	NP	-	-	2.65	ML	
2	11.55 - 12.00	96.46	90.83	82.73	73.75	58.05	32.78	27	-	NP	-	-	2.63	ML	
3	12.00 - 22.00	100.00	89.22	82.2	71.58	57.39	36.14	29.58	-	NP	-	-	2.64	SM	

Based on the test results, the soil sample at drill point BH-1 showed a percentage of grains passing through the No. 200 sieve of less than 50%. Based on the soil classification criteria according to the USCS, this condition indicates that the soil at that location is included in the coarse-grained soil group. The same thing was also obtained in the soil sample from drill point BH-2, where the percentage of grains passing through the No. 200 sieve was also less than 50%, so that based on the USCS classification system the soil is also categorized as coarse-grained soil.

The classification of the soil as coarse-grained (SM and ML) indicates that the material is dominated by sand-sized particles with limited fines content. From a geotechnical perspective, this type of soil typically exhibits relatively low cohesion and relies primarily on frictional resistance to maintain stability. The presence of silty fractions (ML) further reduces permeability control and may contribute to rapid changes in pore water pressure during rainfall events. This condition implies that under saturated conditions, the shear strength of the soil is significantly reduced due to the loss of matric suction, which is consistent with unsaturated soil mechanics (Fredlund et al., 2019).

## 2. Slope Stability Analysis Results

From a mechanical standpoint, the slope stability behavior observed in this study is strongly influenced by the interaction between slope geometry and soil shear strength parameters. As the slope angle increases, the driving forces acting along the potential slip surface become greater, while the resisting forces remain constant, resulting in a decrease in the factor of safety. In addition, the absence of cohesion ( $c' \approx 0$ ) in sandy soils means that stability depends primarily on the internal friction angle. Under saturated conditions, the effective stress decreases, leading to reduced shear strength.

Slope stability analysis using GeoSlope software requires a number of soil parameters as initial input data. These parameters are presented in Tables 3 and 4.

Table 1. BH Soil Data Parameters - 1

No	Depth (m)	Material	NSPT	Model	E	$\nu$	$\gamma_{unsat}$ (kN/m <sup>3</sup> )	$\gamma_{sat}$ (kN/m <sup>3</sup> )	$c'$ (kN/m <sup>2</sup> )	$\phi'$ (°)
1	0 - 11	Loose Sand	7	MC	9000	0.3	14	15	0	28
2	11 - 24	Dense Sand	36	MC	48000	0.3	18	19	0	36
3	24 - 25	Very Dense Sand	60	MC	50000	0.3	18	19	0	38

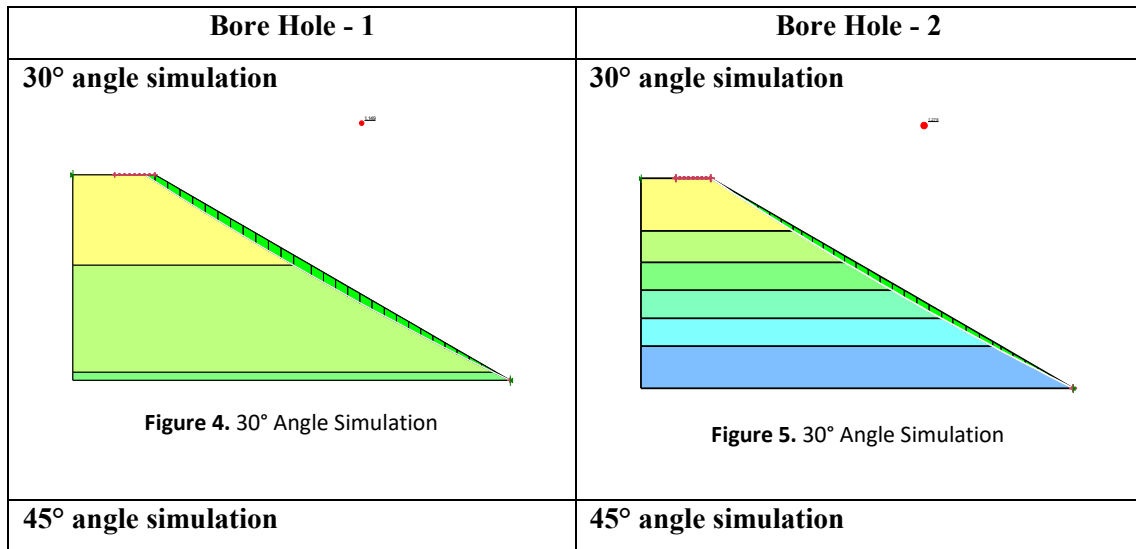
Table 2. BH Soil Data Parameters - 2

No	Depth (m)	Material	NSPT	Model	E	$\nu$	$\gamma_{unsat}$ (kN/m <sup>3</sup> )	$\gamma_{sat}$ (kN/m <sup>3</sup> )	$c'$ (kN/m <sup>2</sup> )	$\phi'$ (°)
1	0 - 7.5	Very Dense Sand	60	MC	50000	0.3	18	19	0	38

2	7.5	-	12	Medium Dense Sand	24	MC	13000	0.3	17	18	0	32
3	12	-	16	Dense Sand	53	MC	48000	0.3	18	19	0	36
4	16	-	20	Very Dense Sand	60	MC	50000	0.3	18	19	0	38
5	20	-	24	Dense Sand	35	MC	48000	0.3	18	19	0	36
6	24	-	30	Very Dense Sand	60	MC	50000	0.3	18	19	0	38

Soil parameters in the form of internal friction angle ( $\phi$ ), effective cohesion ( $C'$ ), unsaturated soil density ( $\gamma_{unsat}$ ), and saturated soil density ( $\gamma_{sat}$ ) were obtained based on the correlation of soil parameters to the Standard Penetration Test (SPT) value. The research location is in Nagari Aia Dingin, Lembah Gumanti District, which is located at an altitude of approximately 1420 m above sea level (masl). Based on the topographic conditions at the research location, the slope is  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$  and  $75^\circ$ , so the slope can be categorized as a steep slope.

Next, a slope stability analysis was performed using GeoStudio software with slope angles of  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$  in Figure 4. This simulation was conducted to determine the effect of variations in slope angle on the slope's factor of safety.



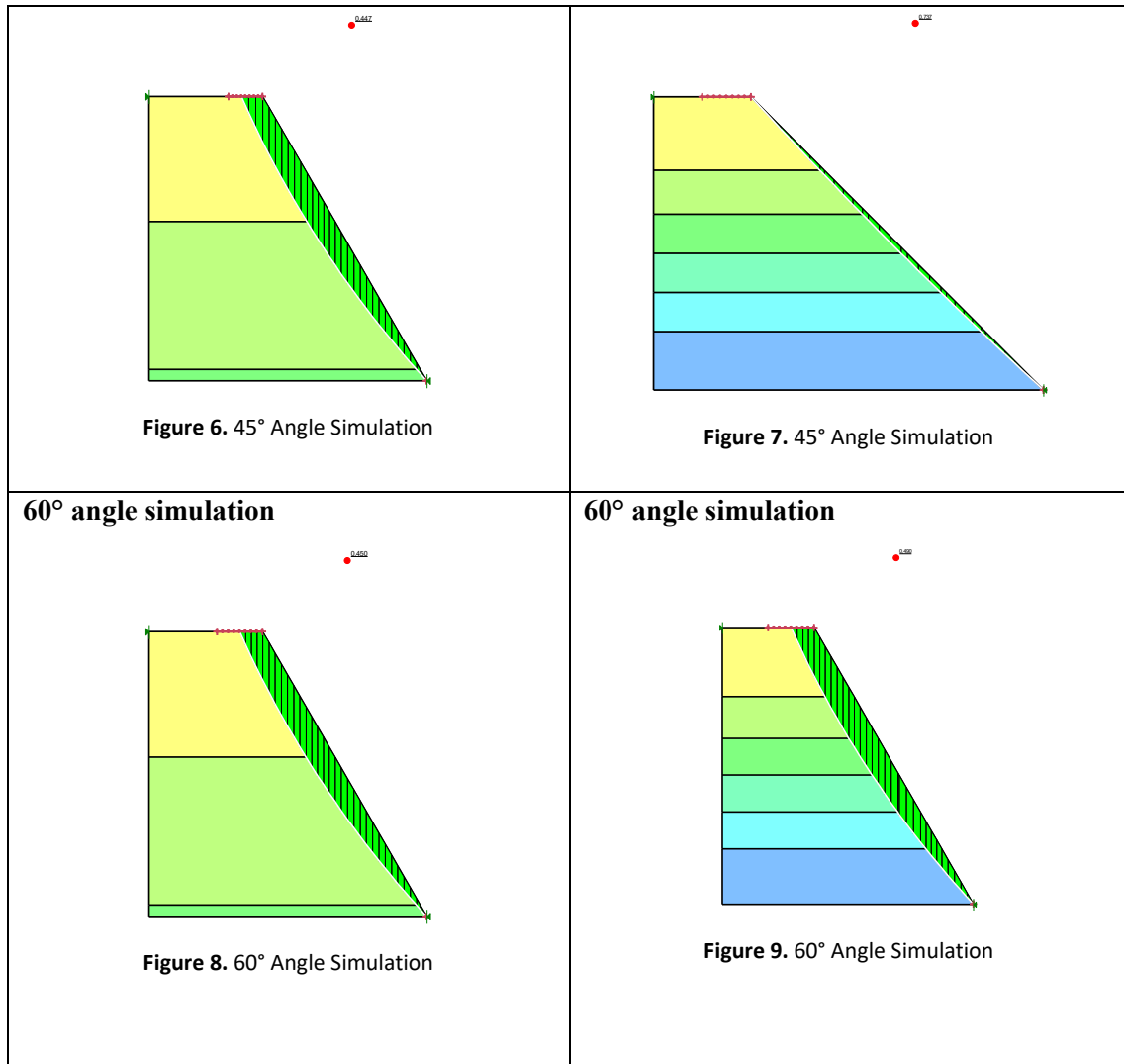


Figure 4. Slope stability analysis using GeoStudio software

The research location is in Nagari Aia Dingin, Lembah Gumanti District, at an altitude of approximately 1420 m above sea level (masl) with a slope ranging from 30° to 75°, so that the slope at this location can be categorized as a steep slope. Slope stability analysis was carried out using GeoStudio software to obtain the safety factor (FK) value at angles of 30°, 45°, and 60° slope inclination.

The simulation results show that the safety factor value decreases as the slope angle increases. At a slope of 30°, the FK value is 1.149 at BH – 01, FK 1.276 at BH – 02, at a slope of 45°, the FK value is 0.447 at BH – 01, FK 0.737 at BH – 02, at a slope of 60°, the FK value is 0.450 at BH – 01, FK 0.490 at BH – 02. Based on slope stability criteria, a slope is generally declared stable if it has a FK value  $\geq 1.5$ . Therefore, from the analysis results obtained, it can be concluded that the

slope at the research location is in an unstable condition at the analyzed slope angle because the safety factor value obtained is less than 1.5.

The obtained results are consistent with previous studies on rainfall-induced slope failure in sandy and silty soils. For instance, Rahardjo et al. (2021) reported that slopes composed of unsaturated sandy soils may experience a rapid decrease in shear strength when subjected to prolonged rainfall due to the reduction of matric suction. Similarly, Nguyen et al. (2021) demonstrated that FEM-based simulations using GeoStudio show a significant decline in factor of safety as slope inclination increases, particularly under transient seepage conditions.

However, the FK values obtained in this study are relatively lower compared to those reported by Chen et al. (2020), where slopes with similar materials still exhibited marginal stability at lower slope angles. This difference may be attributed to site-specific conditions, such as higher rainfall intensity, disturbed slope geometry due to mining activities, and variations in soil density and permeability.

Furthermore, the influence of anthropogenic activities observed in this study aligns with findings by Sassa et al. (2021) and Gariano and Guzzetti (2022), who emphasized that land-use changes such as excavation and mining significantly accelerate slope instability. In this case, the modification of slope geometry due to excavation likely reduced the resisting forces and contributed to the low FK values obtained from the analysis.

Overall, the combination of unfavorable soil characteristics, steep slope geometry, and external triggering factors such as rainfall and human activities creates a highly unstable slope system. The consistency between the numerical results and established geotechnical theories, as well as previous research findings, confirms the reliability of the analysis conducted in this study. Therefore, the results not only reflect site-specific conditions but also contribute to the broader understanding of rainfall-induced slope failure mechanisms in tropical regions.

## **CONCLUSION**

The findings of this study indicate that the soil composing the slope is predominantly classified as poorly graded silty sand, which is characterized by low cohesion, limited particle interlocking, and high susceptibility to changes in moisture conditions. Such soil characteristics inherently reduce shear strength, particularly under conditions of increased water content due to rainfall infiltration. The slope stability analysis conducted using the GeoStudio-based Finite Element Method demonstrates that the calculated Factor of Safety (FK) values for slope angles of 30°, 45°, and 60° are consistently below the minimum acceptable threshold of 1.5. This indicates that

the slope is in an unstable condition under the analyzed scenarios.

From a geotechnical perspective, the low FK values reflect a critical imbalance between resisting and driving forces, which is further exacerbated by unfavorable soil properties and slope geometry. The increase in slope angle significantly contributes to the reduction in stability, highlighting the sensitivity of the slope to geometric modifications. Consequently, the analyzed slope is categorized as highly vulnerable and poses a significant risk of failure, particularly under external triggering factors such as prolonged or high-intensity rainfall. Therefore, without appropriate mitigation measures, the slope has a high potential to experience future landslides, which may result in severe environmental and infrastructural impacts.

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