Geotechnical Evaluation of Landslide in Nanggerang Village

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ABSTRACT

Landslides are significant geological events that can cause extensive damage to infrastructure, disrupt communities, and pose serious safety hazards. Understanding the mechanisms behind slope failures is crucial for effective risk mitigation and the development of engineering solutions to improve slope stability. According to data from the National Disaster Management Agency (BNPB), Indonesia experienced 83 landslide events from January to February 2024. A notable landslide occurred in Nanggerang Village, Sukasari Sub-district, Sumedang Regency, West Java Province, on February 3, 2024. This landslide happened in a terraced rice field area following heavy rainfall earlier in the day. This study focuses on evaluating the failed slope to understand its condition just before failure and the material properties that influence the landslide event. The research methodology includes field data collection, soil testing, and slope stability analysis using the Limit Equilibrium Method (LEM) with a probabilistic approach via Slide 2 software. The analysis revealed that the failed slope had an average safety factor (FS) of 0.968 and a landslide probability of 58.897%. Sensitivity analysis showed that the cohesion parameter in the soil layer (CWZ) significantly impacts the safety factor of the slope. The study concludes that the reduction in soil cohesion and internal friction angle due to excessive moisture was the primary cause of the landslide, and the cohesion parameter of the soil layer is the most sensitive factor affecting slope stability.

Keyword: Landslide, Nanggerang, Slope Stability Analysis, Limit Equilibrium Method, Sensitivity Analysis

INTRODUCTION

A landslide is the movement of material, such as rocks, soil, or a combination of both, down a slope due to the collapse along a weak plane of the slope (Cruden, 1991). Landslides are significant geological events that can cause substantial damage to infrastructure, disrupt communities, and pose severe safety hazards. Understanding the mechanisms behind slope failures is crucial for effective risk mitigation and the development of engineering solutions to enhance slope stability.

According to data from the National Disaster Management Agency (BNPB), Indonesia experienced 83 landslide events from January to February 2024. Among the affected areas, Nanggerang Village in Sukasari Sub-district, Sumedang Regency, West Java Province, experienced a notable landslide on February 3, 2024. This landslide occurred in a terraced rice field area following heavy rainfall earlier in the day. Terracing, while beneficial for agriculture, can present unique challenges for slope stability, especially when subjected to intense precipitation. The increased water infiltration and added weight from the rain can reduce soil cohesion and increase the likelihood of slope failure.

In geotechnical engineering, evaluating slope stability involves analyzing the properties and behaviors of soil and rock layers that compose the slope. Factors such as soil cohesion, internal friction angle, and unit weight are critical in determining the stability of a slope (Duncan et al., 2014). Detailed geotechnical evaluations help identify potential failure zones and the conditions under which a slope may become unstable.

This study focuses on evaluating the failed slope to understand its condition just before the failure and the material properties that influence the landslide event. The stability of the slope is analysed using the Limit Equilibrium Method (LEM). Currently, the slope safety factor value is widely determined using the Limit Equilibrium Method (LEM) (Tantri et al., 2015), which states that the forces acting on the slope must reach equilibrium to achieve a non-collapsing slope condition.

Slope stability calculation uses probabilistic methods to address the uncertainty of variable data produced from laboratory testing. The sampling technique used is Monte-carlo, Prediction using Monte-carlo requires repeated testing of the same data with different random numbers that have uniformity so that information can be generated more efficiently (Gentle, 2005).

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Due to the detailed and time-consuming nature of this analysis, it is conducted using specialized computer software. The software used for this analysis is Slide 2. The results of the analysis can later be compared with the recommended safety factor values from Pd T-09-2005-B regarding the engineering measures for slope failure in residual soil and rock (PUPR, 2005) to determine whether the slope is classified as stable.

RESEARCH METHOD

The research method for the geotechnical evaluation of slope failure involves several key steps, utilizing both field data collection and advanced analytical techniques. The primary objective is to determine the conditions leading to the slope failure and to assess the stability of the slope using the Limit Equilibrium Method (LEM) with a probabilistic approach. The steps are outlined as follows:

1. Data Collections: Conduct thorough field surveys to gather data on the physical and geological conditions of the slope. This includes soil and rock sampling, mapping the landslide area, slope geometry measurement, and documenting any visible signs of instability.
2. Soil Testing: Perform laboratory tests on soil and rock samples to determine key geotechnical properties such as cohesion, internal friction angle, and uniaxial compressive strength. These tests help to define the soil's strength parameters, crucial for stability analysis.

Soil mechanical properties, such as the internal friction angle and cohesion, are obtained from direct shear tests, while rock mechanical properties are obtained from Schmidt hammer testing.

The comparison between the driving force and the resisting force can be indicated by the safety factor (SF). If the SF value is greater than the driving force, a slope is considered safe (Arif, 2016). It is calculated using the following formula:

$$\text{FoS} = \frac{\Sigma \text{ Resisting Forces}}{\Sigma \text{ Driving Forces}} \quad \text{.................................(1)}$$

$$\text{FoS} = \frac{\Sigma\{cl + \tan(\varphi)(W \text{ cso } \alpha - ul)\}}{\Sigma W \sin\alpha} \quad \text{........................(2)}$$

Where:
c : Cohesion
l : Length of the slip surface
Φ : Internal friction angle
W : Weight of the soil mass
α : Angle of the slope
u : Pore water pressure

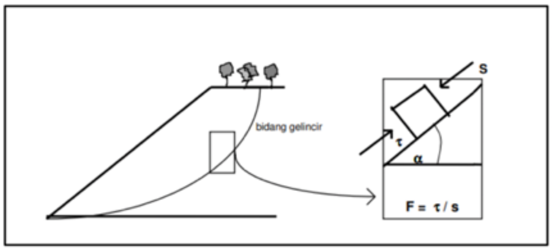

Figure 1. The Scheme of Forces Acting on a Slope (Zakaria, 2011)

Limit Equilibrium Methods (LEM) are a set of methods used in slope stability analysis based on the principle of force equilibrium. These methods are used to estimate the stability of a slope by assuming the occurrence of a failure surface. In LEM, the failure surface can be assumed to be either circular or non-circular. The method assumes that a slope will fail or slide if the driving forces exceed the slope's resisting capacity.

Based on the limit equilibrium principle by Morgenstern and Price in 1965, this method can be used for all types of failure surfaces and satisfies all equilibrium conditions. The Morgenstern-Price method uses the same assumptions as the general limit equilibrium method, namely that there is a relationship between the shear forces between slices and the normal forces between slices (Setyananda et al., 2024).

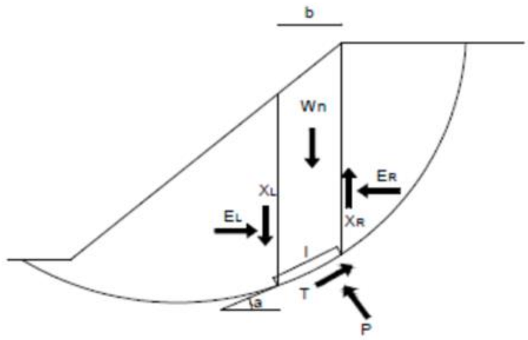

Figure 2. Forces Acting on the Sliding Plane Intersection (Morgenstern & Price, 1965)

The equation based on the forces acting on a slice is as follows:

$$P = \frac{[Wn - (XR - XL) - \frac{1}{F}(c'(\sin\alpha - ul \tan\phi' \sin\alpha)}{\cos a \, (I + \tan\alpha \frac{\tan\phi'}{E})} \quad \text{................(3)}$$

Where:
P : Normal force
c′ : Cohesion (use cu for undrained conditions and effective cohesion for drained conditions)
Wn : Force due to the n-th soil load

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A : Angle between the midpoint of the slice and the center of the arc of the failure surface
φ' : Soil shear angle (use 0 for undrained conditions)
u : Pore water pressure
XL, XR : Friction forces acting on the edges of the slice

RESULT AND DISCUSSION

Lithological Conditions of the Research Area

The geological condition of the research location was determined through direct field observations and sample collection for further description. The observations and sample descriptions revealed the presence of tuff and andesite rocks. The tuff is believed to be the sliding surface from a previous landslide event.

The tuff outcrop forms the body of the landslide with an exposure height of 12.3 meters and a width of 24 meters. This rock has a fresh colour of yellowish-gray and a weathered colour of blackish-brown. The tuff grains are fine, rounded, with good sorting, poor grading, and a closed packing. It is soft, strongly weathered, and exhibits a layering structure with a strike and dip of N 122° E/36°. The dip of the tuff rock has the same direction as the slope inclination. If the rock layers have lower shear strength or weaknesses along the layers, this can facilitate the formation of shear planes aligned with the slope. Additionally, if there is water accumulation along the layers aligned with the slope, it can reduce the cohesion between rock particles and decrease the shear strength of the layer.

The andesite rock has a fresh yellowish-gray colour and a weathered brownish-yellow colour. It has a mesocratic colour index (30%-60%) and an aphanitic hypocrystalline texture. It shows uniform equigranular crystal sizes with a predominance of hypidiomorphic granular texture and a sheeting joint structure.

Figure 3. Distant and Close View of the Tuff Outcrop

Figure 4. Close-Up View of the Andesite Outcrop

Soil Conditions at the Research Area

The soil conditions were determined through direct field observations and laboratory physical property testing. The soil type classification used the USCS system with parameters including colour, strength level, degree of weathering, layering structure, and moisture content. The surface soil found at the research location is High Plasticity Silt (MH).

High Plasticity Silt (MH) forms the upper layer on the slope and surrounding areas. This soil is estimated to originate from the weathering of tuff. It has a reddish-brown to blackish-brown colour, with silt-sized particles and high plasticity. The soil has very high moisture content and high cohesive properties. According to the soil strength classification ISRM (1978), this soil ranges from S1 (very soft clay) to S3 (firm clay), characterized by the soil being compressible by a few inches with the thumb under slight pressure. The degree of weathering of this soil falls within the completely weathered zone (CWZ) up to the topsoil.

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Figure 5. Distant and Close Views of the Silt (top soil) Outcrop in the Research Area

Figure 6. Distant and Close Views of the Silt (CWZ) Outcrop in the Research Area

Slope Condition

The slope is composed of highly plastic silt (MH), which ranges in colour from reddish-brown to dark brown and has high plasticity silt particle size. The slope consists of two soil profiles: a topsoil layer with a thickness of 0.8 meters and a layer classified as completely weathered (CWZ), which has a thickness of about 5 meters. Beneath this soil layer lies a tuff rock layer with a fresh yellowish-gray colour and weathered blackish-brown, characterized by fine tuff particles, a medium weathering degree (MWZ), and a thickness of 12.3 meters.

Before the landslide, the slope had a geometry consisting of 18 terraces with an average width of 2.45 meters, an average height of 1.52 meters, and an overall slope inclination of 32°. After the landslide, the slide scar formed has dimensions of 12 meters in length, 21 meters in width, and 16 meters in height, with an overall slope inclination of 34°.

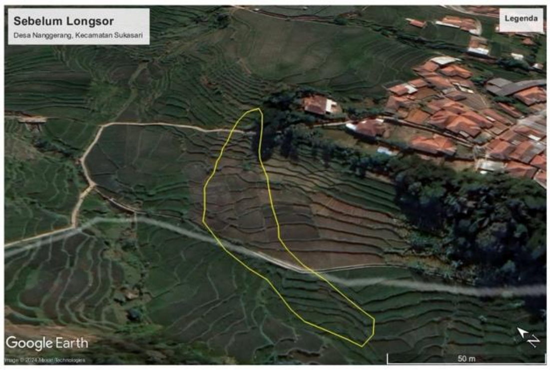

Figure 7. Satellite Imagery of the Research Area Before Landslide

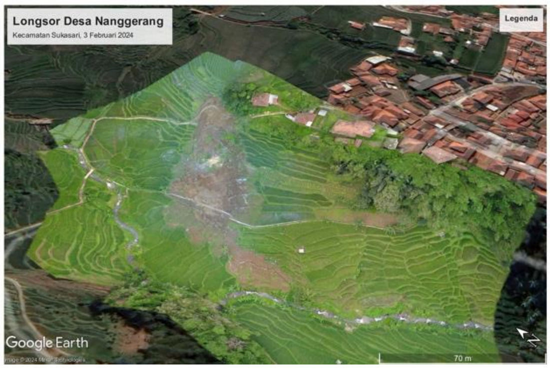

Figure 8. Satellite Imagery of the Research Area After Landslide

Types of Landslides

Based on direct observations at the research location, the type of landslide occurring in Nanggerang Village in Sukasari Sub-district, Sumedang Regency, West Java Province, is a translational landslide with a sliding movement. This is followed by a earth flow-landslide, specifically an earth flow. The translational landslide is validated by the presence of a sliding surface that is planar and gently undulating, the dip of rock layers aligned with the slope inclination can also contribute to translational landslides. while the earth flow is identified by the accumulation of debris from the landslide, which includes a significant number of fine materials such as clay, silt, and a small amount of sand.

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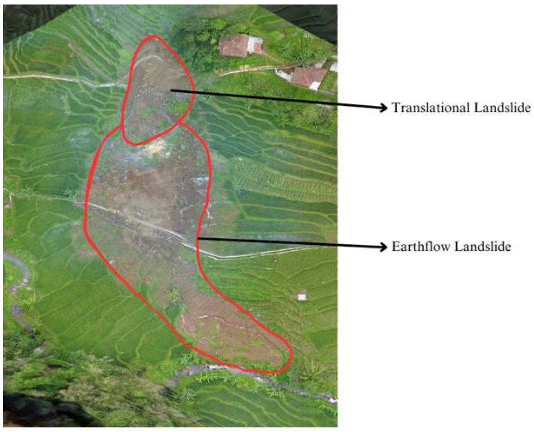

Figure 9. Types of Landslides in the Research Area

Results of Soil Mechanical Property Testing

Testing the mechanical properties of the soil is conducted using the direct shear test. This test is performed to obtain the values of the internal friction angle and soil cohesion, which are then used as input parameters for slope stability calculations. The testing is conducted on 5 samples from the topsoil layer and 7 samples from the (CWZ) soil layer with undisturbed sample conditions. Each sample is tested 3 times with different normal loads.

Based on Table 1, the topsoil layer has an average internal friction angle of 9.59° and an average cohesion value of 8.62 kPa, while the (CWZ) soil layer has an average internal shear angle of 17.69° and an average cohesion value of 35.18 kPa. With these values, it is concluded that the soil samples from the study area do not represent data under natural conditions. This is supported by the very high moisture content in the samples, which reduces the values of the mechanical property parameters.

Tabel 1. The values of mechanical properties form laboratory test

Sample code	Profile	Internal friction angle (°)	Cohesion (kPa)	Unit weight (kN/m^3)
TS-2	Topsoil	9,848	9,53	21,418
TS-7	Topsoil	6,526	7,335	18,465
TS-8	Topsoil	4,904	5,609	20,734
TS-9	Topsoil	6,526	7,335	19,816
LGT-TOP	Topsoil	20,19	13,28	16,370
TNH-2	CWZ	10,42	6,69	21.153
TNH-4	CWZ	10,85	6,296	20.327
TNH-6	CWZ	17,464	6,884	20.773
LGT-BOT	CWZ	27,61	15,03	16,04
UDS-10	CWZ	24,3	13,54	14,19
LR-1	CWZ	17,49	109,39	12,61
LR-2	CWZ	15,68	88,45	14,96

Soil Swelling Potential

This study used the Free Swell Index test. This test was conducted on one undisturbed soil sample from each soil layer. The results of the test provide the Swelling Index value and soil expansion classification based on Indian Standard 2720 Part 40 (1977). The Free Swell Index test showed that the soil expansion level for samples TS-2 and TNH-2 is 7.692%. According to the soil expansion potential classification by Holtz & Gibbs (1956), this value is categorized as low expansive. Therefore, it is concluded that the area around the landslide is dominated by soil with low expansion potential, and the landslide event in the study area was not caused by soil volume expansion or expansive soils.

Results of Soil Mechanical Property Testing

Testing the mechanical properties of the rock was conducted using a Schmidt hammer. The result of this test is the UCS (uniaxial compressive strength) value, which has been

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calibrated from the Schmidt hammer rebound value according to the calibration number of the Schmidt hammer used. The test was performed on tuff rock with 30 test points. The tuff rock has an average UCS value of 12.71 MPa, which categorizes it as R2 (weak rock). However, field identification revealed that the tuff rock crumbled during the Schmidt hammer test and could be scraped with a knife. This identification suggests that the tuff rock is more accurately categorized as R1 (very weak rock) with a UCS value ranging from 1-5 MPa, indicating a limitation of the Schmidt hammer with a minimum reading of 10 MPa.

Several simulation trials on the tuff rock layer using UCS values of 12.71 MPa, 5 MPa, and 1 MPa were conducted to determine whether the formed slip surface was in the tuff rock layer consistent with the actual conditions at the research area. The simulation with a UCS value of 5 MPa showed that the slip surface remained within the tuff rock layer, while the simulation with a UCS value of 1 MPa showed the slip surface slightly cutting through the tuff rock layer. Therefore, it can be concluded that the UCS value of the slope at the research site is 5 MPa.

Rock Mass Condition

The rock mass conditions in the study area are determined through macroscopic observation in the field and assessed using the Geological Strength Index (GSI). The structural observation of the tuff rock is categorized as blocky with the rock surface condition categorized as fair. Based on the Geological Strength Index table (wyllie & Mah, 2004), the obtained GSI value is 40.

Slope Stability Analysis Before Landslide Occurrence

This analysis focuses on the stability of slope cross-section A-A" before the occurrence of a landslide. The groundwater table condition on this slope is fully saturated because the entire slope is used as agricultural land. Data from the BMKG also shows that in February 2024, the research area had rainfall exceeding 500 mm (BMKG, 2024), categorized as very high rainfall. The slope geometry used is derived from direct measurements of the slope adjacent to a previous landslide. Each terrace has a slope of 90° because the terraces were created by farmers as planting media. The calculation uses the Morgenstern-Price limit equilibrium method with 1000 iterations to ensure accuracy and reliability.

The analysis was conducted with the groundwater table at a level parallel to the surface (fully saturated) without incorporating a seismic factor. The exclusion of seismic factors is due to the absence of earthquake events at the time of the landslide. The calculation results show a deterministic factor of safety (FK) value of 0.891, an average FK value of 0.968, and a probability of landslide (PK) of 58.897%. According to the recommendations for slope safety factor values from PUPR (2005)regarding slope failure handling engineering in residual soil and rock, the slope in cross-section A-A" is declared unstable. This conclusion is validated by the occurrence of an actual landslide, confirming the accuracy and reliability of the analysis.

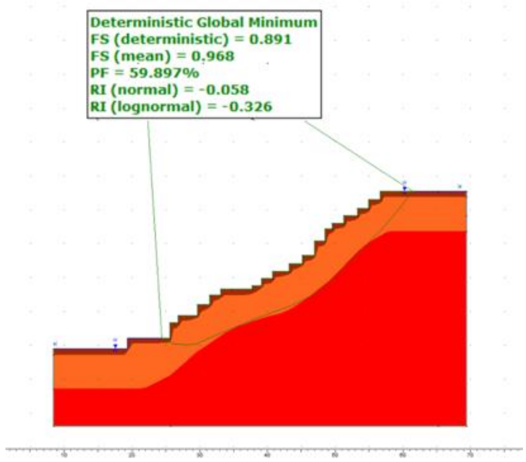

Figure 10. Simulation results of slope stability for cross-section A-A

Sensitivity Analysis

Sensitivity analysis is a feature of the Slide 2 software. This feature provides information about which material properties most significantly affect slope stability calculations and the probability of failure. The analysis is conducted by plotting the material properties to obtain the equations for each variable. Variables with high sensitivity will show distinct graphs compared to others. The material properties used in the sensitivity analysis include the internal friction angle (φ), cohesion (c), and the unit weight of the topsoil layer, soil layer (CWZ), and tuff rock. The results of the sensitivity analysis for each layer are shown in Figure 9. From the sensitivity analysis plotting, it is observed that the cohesion parameter of the soil layer (CWZ) has a much steeper graph compared to other parameters, indicating that changes in soil cohesion have a significant impact on the factor of safety for a slope. Therefore, it is concluded that the cohesion parameter of the soil layer (CWZ) is more sensitive compared to other parameters.

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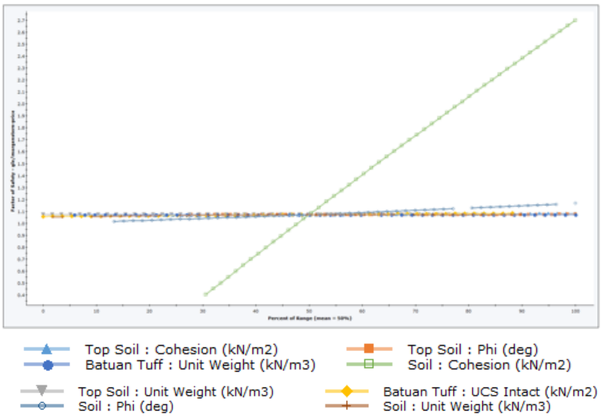

Figure 11. Sensitivity Plot Graph of Material Properties for Each Slope Material

CONCLUSION

Based on the above research, the conclusions are as follows:

- The study area consists of two lithologies, such high-plasticity silt (MH) and tuff rock. The soil is divided into two layers: the topsoil and the completely weathered zone (CWZ), while the tuff rock has a moderately weathered zone (MWZ) profile.
- The results of the landslide identification in the study area show that the type of landslides occurring are translational landslides with a sliding movement type, and flow-type landslides consisting of earth flow.
- The slope stability calculations show a deterministic safety factor (FK) of 0.891, an average safety factor (FK) of 0.968, and a probability of landslide (PK) of 59.89%. Based on the PUPR (2005), the slope in the study area is declared unstable.
- Slope stability analysis results show that landslides occurred in the soil layer (CWZ) with an average cohesion value of 35.18 kPa and an average internal friction angle of 17.69°. Landslides were caused by a reduction in the internal friction angle and cohesion of the soil due to excessive moisture content.
- Sensitivity analysis results for each slope layer show that the cohesion parameter in the soil layer (CWZ) is the most sensitive parameter compared to others, so changes in cohesion values will result in significant changes in the factor of safety.

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