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RESEARCH ARTICLE

Slope Stability Analysis Throughout Road Around Bukit Barisan Selatan National Park (BBSNP) using Fellenius Method

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Abstract

Bukit Barisan Selatan National Park (BBSNP) is a nature conservation area in Indonesia. The slope stability of the interprovincial roads in BBSNP needs to be assessed for slope stability. This study assesses slope stability using the Fellenius method for the factor of safety calculation. The data utilized consists of geological and structure regional conditions, soil descriptions, soil physical and mechanical properties, water content, liquid limit, plastic limit, plasticity index, specific gravity, soil strength, slope dimensions, and slope weight. The sampling process is conducted un-disturb, followed by laboratory testing. The laboratory tests conducted include soil elasticity and plasticity, soil cohesion, and internal friction angle. The critical slopes at LT-L01 and LT-L23 are compromised due to the low cohesion values, making both slopes susceptible to landslides. The stable slope at LT-R04, LT-L15, LT-L19, and LT-R30 exhibit variability properties across the slopes. The lithology for slope LT-R04 consists of inorganic clay with high plasticity, slopes LT-L15 and LT-R30 have same lithology of silty clay with medium plasticity, while slope LT-L19 has lithology of silty clay with low plasticity. The safety factor values indicate stability due to moderate - high cohesion, contributing to slope stability. Material compaction is required to enhance cohesion values on the slopes. Additionally, need to mitigate water saturation conditions in the slope materials.

Keywords: *Slope Stability, Fellenius, Soil, Safety Factor, Landslide Model*

1. Introduction

Bukit Barisan Selatan National Park (BBSNP) is a nature conservation area which has a lot of potential, flora, fauna, and natural attractions that have a high value of naturalness (Meizannur and Wulandari, 2015). There exists an interprovincial thoroughfare traversing the region. The general populace consistently avails itself of the utilization of interprovincial thoroughfares in the vicinity of BBSNP. Ensuring road infrastructure safety, particularly slope stability along cross-province road BBSNP, is imperative. Slopes are part of the topography of the land formed due to differences in elevation from the two soil surfaces (Arya et al., 2020).

Several slopes alongside the cross-province road of BBSNP have experienced landslides, disrupting the movement of vehicles and pedestrians along the road (Fig 1). Moreover, these landslides pose a safety hazard to residents in the area surrounding the cross-province road of BBSNP. Efforts are underway to reinforce these slopes to enhance road safety. The road reinforcement initiatives have been preceded by field mapping and engineering geological studies conducted by local and central governments. Our research aims to complement these field mapping and engineering geological studies, thereby providing valuable support to local authorities and disaster management agencies (BNPB) regarding landslide data.

The natural slopes surrounding the interprovincial roads of BBSNP consist of various types of soil, rocks, and their mixtures. There are several methods to analize the stability slope with rock and/or soil materials, such as Slope Mass Rating (SMR), QSlope, Fellenius, Bishop, etc. The study on the slope stability values of rock materials has been discussed in Alviyanda et al. (2021) research. Different material from Alviyanda et al. (2021) research, the study focuses on slope stability with soil materials. Specific gravity is commonly used in soil mechanics and geotechnical engineering to characterize and classify soils based on their particle sizes and composition. It can provide insights into the compactness and composition of soil, helping engineers understand its behavior in various construction and geotechnical applications.

The slope stability analysis of the interprovincial road in BBSNP has been conducted for slopes containing rock materials using the rock mass rating (RMR) and slope mass rating (SMR) method. RMR calculation on three slopes with rock material is around 38-43, rock class 3-4 with fair–poor rock type, and then kinematics analysis showed dominant type of landslides are direct toppling with SMR calculations on three slopes are around 42-50, slope class 3 with normal slope type (Alviyanda et al., 2021).

The slope stability analysis of interprovincial roads in BNSSP for slopes containing soil material also needs to be assessed using the Fellenius method for the factor of safety (FS) calculation. This research examines the slope stability analysis with soil material, considering several parameters of soil's physical and mechanical properties.

Fig 1. Several landslide alongside the cross-province road of BBSNP

2. Data and Methods

Radityo et al. (2022) said field mapping and engineering geological study are necessary to provide reinforcement recommendations for the area. The research used field mapping and engineering geological study especially on soil slope safety employs the Fellenius method, with several field-collected data parameters. Investigations and field studies concerning the soil materials and dimensions of slopes are imperative to ascertain the inherent characteristics of the slope.

2.1. Data

In this study, the data utilized consists of geological and structure regional conditions, soil descriptions, soil physical and mechanical properties, water content, liquid limit, plastic limit, plasticity index, specific gravity, soil strength, slope dimensions, and slope weight (Fig 2). BBSNP is a protected natural conservation area, which restricts sample collection. The sample selection procedure involves using pre-defined disaster-prone red zones. Sampling is conducted using undisturbed methods, where samples are retrieved by driving a tube into the soil. Undisturbed samples are crucial for maintaining the rock conditions as found in their original location. The distance for retrieving undisturbed samples is significant, due to compliance with disaster-prone red zones and restrictions imposed by BBSNP regulations, which designate it as a protected conservation area. Beside that, several slope with rock material already researched with Alviyanda et al. (2021) research team.

The sampling process is conducted undisturb, followed by laboratory testing. Undisturbed samples are obtained using a percussion hand drill. Undisturbed samples contained with natural soil are subsequently sealed with wax or paraffin, and several stoppers such as paper, plastic, etc. This is carried out to preserve the soil content same with its natural condition. The laboratory tests conducted include soil elasticity and plasticity, soil cohesion, and internal friction angle. Cohesion is adhesion between soil particles (Fitriansyah et al., 2019). In coarse-grained soils (non-cohesive), shear strength is primarily a result of the friction between soil particles, often referred to as the internal friction angle (Fitriansyah et al., 2019). The cohesion value and soil shear angle can also be utilized to analyze whether a cliff or slope is in a naturally stable condition before any slope reinforcement and stabilization measures are undertaken (Haris et al., 2018).

2.2. Methods

The stability of slopes is influenced by several factors, both internal and external conditions. The primary factors are resisting force and driving force. A slope is considered stable when the resisting force is greater than the driving force. Even though a slope may have been stable for a long period, it can become unstable due to several factors such as: Type and condition of the soil/rock layers forming the slope, geometric shape of the slope cross-section (e.g., slope height and steepness), addition of water content to the soil (e.g., seepage or rainfall infiltration), weight and distribution of loads, and vibrations or earthquakes (Pangemanan et al., 2014)

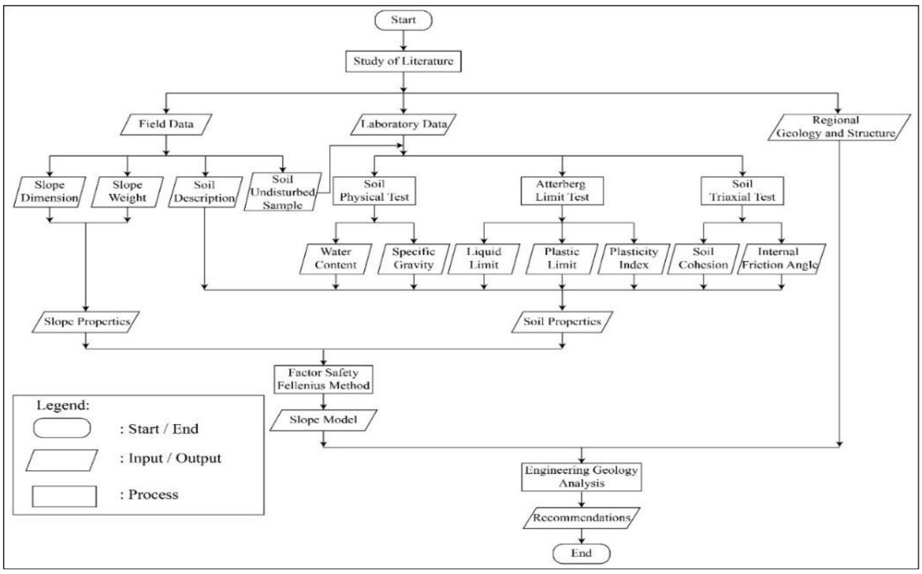

Fig 2. Research flowchart

The Fellenius method is one of the techniques to assess slope stability by considering various parameters such as soil properties and slope characteristics. Fellenius presented his methodology by stating the assumption that collapse occurs through the rotational movement of a soil block on a circular (circular) slip surface, with point O as the center of rotation. This method also posits that the normal force P operates at the midpoint of the slice (Fellenius, 1927). According to Zakaria (2011), the Fellenius method for calculating Slope Safety Factors involves analyzing the strength of each segment of the slope through slope cross-section. The calculation of slope stabilization using the Fellenius slice method influenced by the groundwater table can be elucidated as follows:

$$F = \frac{c\,L + \tan\phi \sum(Wi + \cos\alpha i - \mu i * li)}{\sum(Wi \sin\alpha i)} \qquad (1)$$

Soil properties necessitate laboratory testing data encompassing parameters such as water content, specific gravity, liquid limit, plastic limit, plasticity index, soil cohesion, and internal friction angle from the undisturbed sample. Furthermore, soil properties also necessitate field data in the form of soil description. The laboratory examinations conducted encompass soil physical testing, Atterberg limit testing, and soil triaxial testing. Slope properties necessitate field-measured dimensional data of the slopes.

The stability analysis of slopes using the Fellinius formula will yield a Factor of Safety (FS) value. If the FS value is greater than 1.25, the slope is considered stable. If the FS value falls within the range of 1.07 to 1.25, the slope is categorized as critical. If the FS value is below 1.07, the slope is considered unstable (Table 1) (Bowles, 1984).

Table 1. Bowles safety factor classification

Safety Factor	Slope Condition
SF ≥ 1.25	Stable
1.07 ≤ SF ≤ 1.25	Critical
SF ≤ 1.07	Unstable

If the slope is stable, then the slope is considered safe, but it is essential to consider external conditions, especially natural factors, which can influence the stability of the slope. The natural factors that can influence slope stability include rainfall, geological structure, slope loading, and earthquakes. If the rainfall intensity is high and increases the water saturation of the slope, the slope will become saturated with water. When a slope becomes saturated, the cohesion and internal friction angle will decrease. Geological structure can also affect the stability of slopes because geological structures can create weak zones that can compromise the condition of the slope. Loading on the slope can weaken it by adding additional weight. Earthquakes can trigger natural slope failures. Earthquakes can shake the stability of a slope, leading to a degradation of soil properties, which can result in landslides. These factors can make the slope heavier and increase the driving force on the slope. The slope becomes unstable, and landslides can occur. Landslides happen when the driving force exceeds the resisting force. Recommendations for strengthening and supporting slopes are necessary for maintaining stability under external conditions, particularly natural factors.

The stability of slopes not covered by undisturbed sample collection will be mapped for disaster vulnerability using data obtained from both slopes with rock material and soil material. These data will be integrated to produce a disaster vulnerability map to be provided to BNPB, which will contribute to future research endeavors.

2.3. Location

The road is an infrastructure frequently utilized by humans. A road serves as a passage for the movement of people (van Westen et al., 2008). Road safety is crucial for the well-being of individuals as they traverse it. This research focuses on examining the stability of the surrounding slopes near the road, considering geological conditions, lithology, slope stability, and previous landslides. The main road is in the southeast of Bukit Barisan Selatan National Park. This road is part of the West Sumatra Crossroad, connecting Semaka District to Bengkunat District. The length of the road being studied is 30 km (Fig 3).

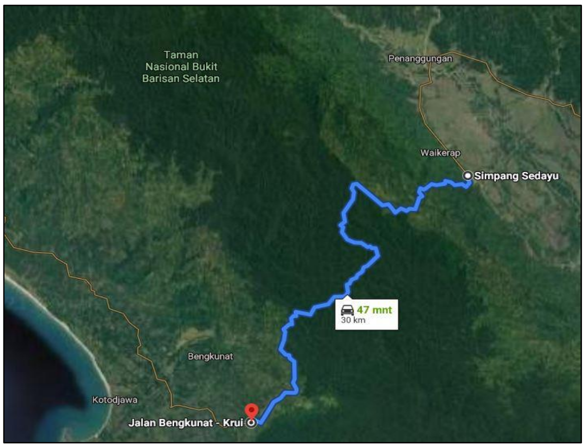

Fig 3. Research field data collection in BBSNP road

The topographical conditions of the road vary, dominated by hilly terrain, with some areas comprising valleys, highlands, and lowlands. The slope conditions around the road are prone to landslides, with some areas already experiencing landslides. This is estimated to occur due to the presence of clay-rich rock materials composing the slope, a tight geological structure, the direction of rock strata inclination toward the road, high rainfall intensity, and a lack of reinforcement on the slopes around the road. The region experiences high fault activity due to its location along the Semangko Fault Line. It is essential to provide recommended reinforcement measures to secure the stability of the slopes around the road.

2.4. Regional Geology and Structure

The regional geology of the research area along the road can be observed on the Geological Map of the Kota Agung Sheet, the Research Area (Amin et al., 1993) (Fig 4). Along this road, several formations are encountered, such as the Seblat Formation, Hulusimpang Formation, Bal Formation, and intrusive rocks.

The Seblat Formation (Toms) consists of interbedded mudstone, sandstone, tuffaceous sandstone, shale, limestone, marl, generally chalky, and thin-bedded or nodular limestone layers (Amin et al., 1993).

The Hulusimpang Formation (Tomh) comprises volcanic breccia, lava, andesitic-basaltic tuff, altered rocks, quartz veins, and sulfide minerals (Amin et al., 1993).

The Bal Formation (Tmba) consists of dacitic volcanic breccia, dacitic tuff, and sandstone intercalations (Amin et al., 1993). The intrusive rock (Tmgr) is in the form of granite (Amin et al., 1993).

The Semangko Fault is part of the larger tectonic context in the region. It is associated with the subduction of the Indian Plate beneath the Eurasian Plate, resulting in intense tectonic activity in Sumatra. This fault is a strike-slip fault, where two blocks of the Earth's crust slide horizontally past each other.

The Sumatra Fault or Semangko Fault is an active fault on the island of Sumatra, with a predominantly lateral (dextral) relative movement, spanning a length of up to 1900 km and divided into 19 fault segments, each with lengths ranging from 60 to 200 km ((Bellier and Sebrier, 1994), (Lelgemann et al., 2000), (Natawidjaja and Triyoso, 2007), and (Saaty. 2008)).

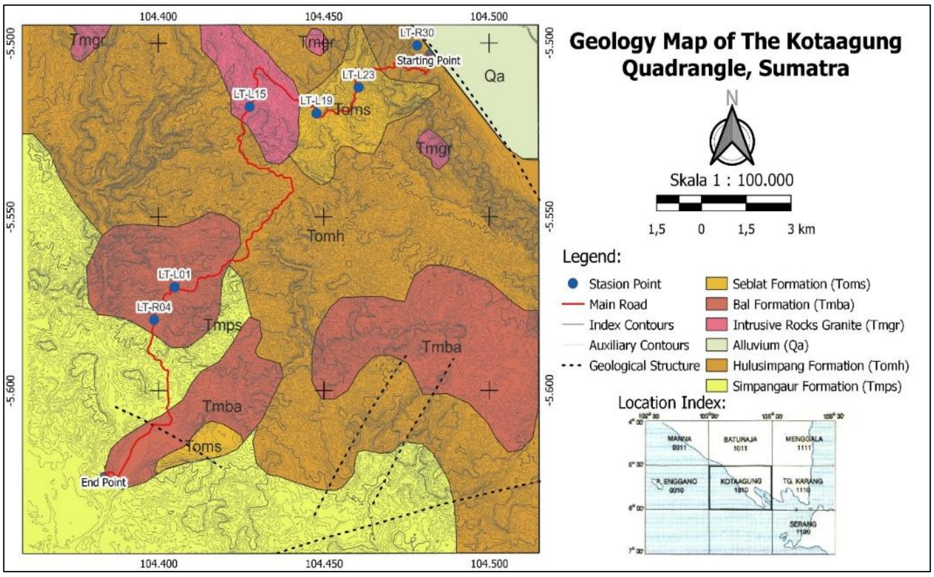

Fig 4. Geology of the Kotaagung Quadrangle, Sumatera

3. Result and Discussion

The research has generated by substantial amount of data from various field parameters, laboratory experiments, and slope safety factor modeling. Below are the explanation of the field and laboratory data that have been previously obtained. Subsequently, the results are analyzed and saveral slope safety factor model is developed.

The general depiction of slopes along the main road sides shows predominantly relative stability. There are several slopes already failure and become landslides, typically located at intersections with rivers.

3.1. Result

There are a total of six research stations with soil material slopes. The sampling method employed was the undisturbed sample type. Subsequently, soil samples were subjected to laboratory testing to obtain soil properties data. The following soil properties data were obtained: specific gravity, water content, liquid limit, plastic limit, plasticity index, cohesion value, internal friction angle, USCS classification, safety factor value, and landslide classification (Table 2).

Table 2. Soil properties slope data

Station Point	Specific Gravity (Gs)	Water Content (%)	LL (%)	PL (%)	PI (%)	Cohesion (kPa)	Internal Friction Angel (°)	USCS Classification	Safety Factor	Slope Classification
LT-L01	1,85	68,32	62,5	27,06	35,44	15,17	30,68	Inorganic Clay of High Plasticity	1,23	Critical
LT-R04	2,19	72,42	65,5	32,66	32,84	21,3	22,42	Inorganic Clay of High Plasticity	1,34	Stable
LT-L15	1,84	78,37	63,4	29,12	34,36	71,64	39,81	Inorganic Clay of High Plasticity	3,77	Stable
LT-L19	1,88	67,19	81,46	72,29	9,17	42,59	49,42	Silty Clay of Low Plasticity	3,12	Stable
LT-L23	1,93	76,98	60,7	24,35	36,35	11,45	36,96	Inorganic Clay of High Plasticity	1,2	Critical
LT-R30	2,47	69,69	65,5	50,16	15,34	27,77	41,6	Silty Clay of Medium Plasticity	2,97	Stable

Several parameters from laboratory tests and safety factor calculations are shown in the data table. Diverse conditions of slopes in the research area are indicated by the data. Several slopes with different materials were examined in this research. Different specific gravities for each slope are shown by the data. The smallest specific gravity, 1.84 Gs, was found in LT-L15. All materials were denser than water because the samples were collected during rainy conditions. The mean specific gravity is 2.02 Gs.

The slope conditions are predominantly saturated with water, as indicated by the sufficiently high-water content above 67%. The potential for landslides is present in the slope conditions with saturated water. The saturated condition of water within slope materials can impose a load on the slope and enhance the driving force value. The mean water content in this research is 72.16%. Table 3 presents descriptive statistics for each station point and its parameters. Figure 5 shows a scatter plot between specific gravity and water content.

Table 3. Statistic descriptive soil properties data

Descriptive Statistic	Specific Gravity (Gs)	Water Content (%)	LL (%)	PL (%)	PI (%)	Cohesion (kPa)	Internal Friction Angel (°)	Safety Factor
count	6	6	6	6	6	6	6	6
mean	2,02	72,16	66,51	39,27	27,25	31,65	36,81	2,27
std	0,25	4,63	7,55	18,58	11,83	22,45	9,33	1,14
min	1,84	67,19	60,7	24,35	9,17	11,45	22,42	1,2
Q1 25 %	1,85	68,66	62,72	27,57	19,71	16,70	32,25	1,25
Q2 50 %	1,90	71,05	64,45	30,89	33,6	24,53	38,38	2,15
Q3 75 %	2,12	75,84	65,5	45,78	35,17	38,88	41,15	3,08
max	2,47	78,37	81,46	72,29	36,35	71,64	49,42	3,77

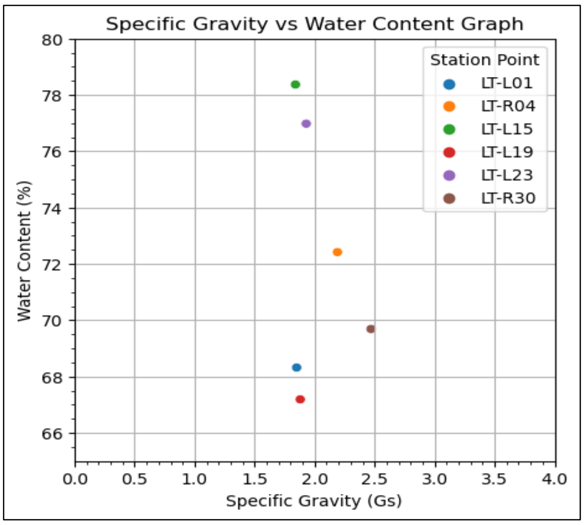

Fig 5. Specific gravity vs water content graph

Furthermore, in relation to the water content in the soil material on the slope, variations in the values of Plastic Limit (PL), Liquid Limit (LL), and Plasticity Index (PI) are shown by the data. The Plastic Limit, which is the moisture content at which soil transitions from a plastic, moldable state to a semi-solid state, is shown to be more than 24% for each slope, indicating medium to high plasticity. The highest plastic limit value, 72.29%, was found in slope LT-L19. The mean plastic limit in this research is 39.27%.

The Liquid Limit, which is the moisture content at which soil changes from a plastic state to a liquid state and begins to flow under its own weight along a groove of standard dimension, is shown to be more than 60% for each slope, indicating that the soil material on the slope is relatively wet and saturated with water. The highest liquid limit value, 81.46%, was found in slope LT-L19. The mean liquid limit in this research is 66.51%.

The Plasticity Index, which is the numerical difference between the Liquid Limit (LL) and the Plastic Limit (PL) and measures the range of moisture content over which the soil exhibits plastic behavior, is shown to be less than 37% for each slope, indicating medium to high plasticity. The lowest plasticity index value, 9.17%, was found in slope LT-L19. The mean plasticity index in this research is 27.25%. The basic properties of slope LT-L19 material differ significantly from others, with high water saturation, low cohesive strength, and low plasticity conditions, indicating a potential risk of landslides in the future. Figure 6 shows a scatter plot between the liquid limit and the plasticity index.

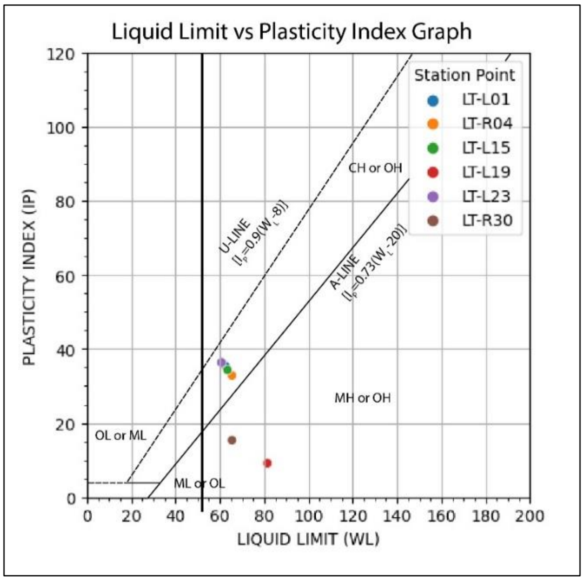

Fig 6. Liquid limit vs plasticity index graph

Cohesion, defined as the internal molecular attraction that holds the particles of a soil together, represents the soil's inherent strength due to cohesive forces between particles. In practical terms, it is the shear strength of a soil when it is not subjected to external forces. The data indicates highly varied cohesion, ranging from very soft with a value of 11.45 kPa to firm with a value of 71.64 kPa, with a mean value of 31.65 kPa. The diversity of this data indicates variations in the strength of each soil material on the slope, leading to diverse slope safety factor values as well.

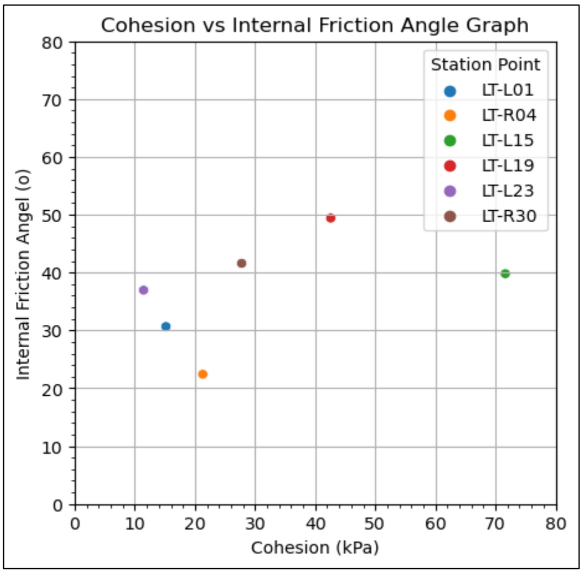

Fig 7. Cohesion vs internal friction angle graph

The internal friction angle, which measures the resistance of a soil to deformation or failure along a potential failure plane, is the angle between the horizontal and the inclined plane along which soil failure occurs. The data indicates a moderately varied internal friction angle, ranging from a low angle with a value of 22.42° to a high angle with a value of 49.42°, with a mean value of 36.81°. The internal friction angle influences the angle formed when a material becomes prone to failure and deforms. Subsequently, these effects impact the resultant forces on the internal properties of the soil material. Figure 7 shows a scatter plot between cohesion and internal friction angle.

The safety factor is considered a key criterion for slope design and analysis. A safety factor greater than 1 indicates that the resisting forces are greater than the driving forces, suggesting slope stability. Conversely, a safety factor less than 1 implies that the driving forces exceed the resisting forces, indicating a potential risk of slope failure. If the FS value is greater than 1.25, the slope is considered stable, whereas if the FS value falls within the range of 1.07 to 1.25, the slope is categorized as critical.

According to the data table, station point slopes can be classified into two categories: critical slope and stable slope. Critical slopes (LT-L01 and LT-L23) are situated in relatively tight contours, while stable slopes (the remaining slopes) tend to be in flat terrain or relatively open contours. The slope safety factor model for each station point is generated based on laboratory data (Fig. 8).

The critical slopes at LT-L01 and LT-L23 (Fig. 8a and 8e) exhibit nearly uniform soil properties, such as specific gravity below 2 Gs, water content saturated with water, and low cohesion classified as very soft, with an internal friction angle ranging from 30° to 40°. The plasticity properties are only slightly different from each other. Their lithology consists of inorganic clay of high plasticity. The critical safety factor is compromised due to the low cohesion values, making both slopes susceptible to landslides. There is a need for support and reinforcement, such as material compaction, to enhance cohesion values on the slopes. Additionally, there is a need to mitigate water saturation conditions in the slope materials.

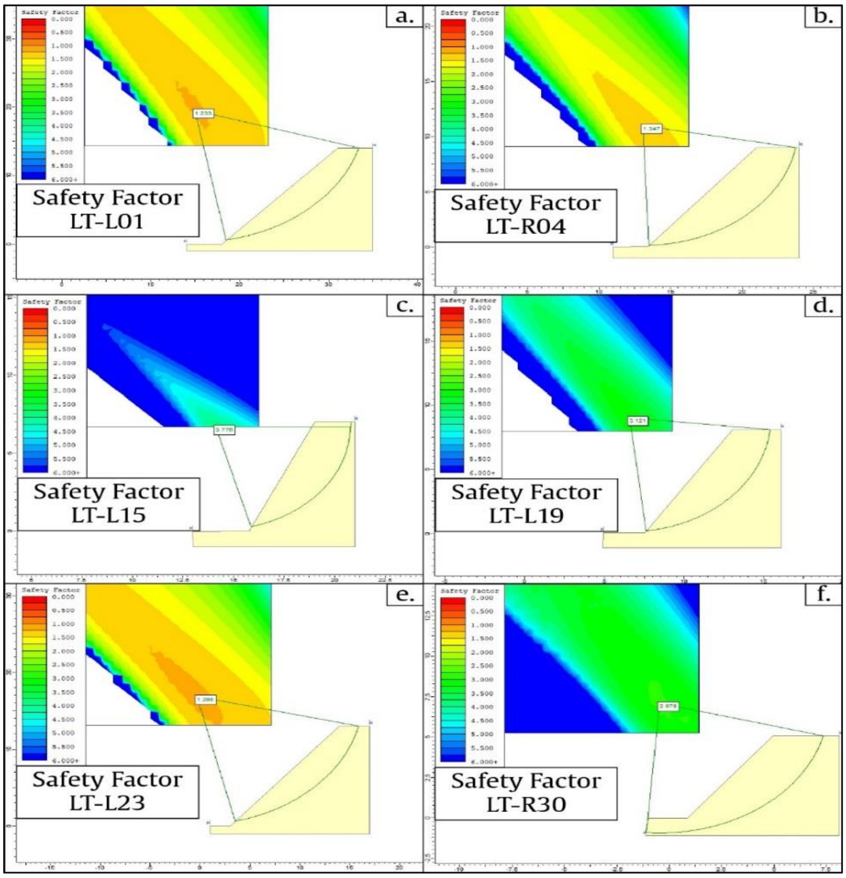

Fig 8. The slope safety factor model for each station points. a. Safety Factor LT-L01, b. Safety Factor LT-R04, c. Safety Factor LT-L15, d. Safety Factor LT-L19, e. Safety Factor LT-L23, f. Safety Factor LT-R30,

The stable slopes (Fig. 8b, c, d, and f) exhibit variability across the slopes. Specific gravity values are below 2 Gs for slopes LT-L15 and LT-L19, while they are above 2 Gs for slopes LT-R04 and LT-R30. The water content, saturated with water, shows no significant difference among the slopes. Cohesion values for the slopes range from moderate to high, falling into the firm category. Internal friction angle values range from approximately 20° to 50°. Plasticity properties vary significantly from one slope to another. The lithology for slope LT-R04 consists of inorganic clay of high plasticity, slopes LT-L15 and LT-R30 share the lithology of silty clay of medium plasticity, while slope LT-L19 has lithology in the form of silty clay of low plasticity. The safety factor values indicate stability due to moderate to high cohesion, contributing to slope stability. Material compaction on the stable slopes is necessary to enhance cohesion values. Additionally, dewatering measures are required to reduce saturated conditions in the slope materials.

Slope LT-L19 exhibits several properties that significantly differ from other slopes, such as high values of liquid limit, plastic limit, cohesion, and internal friction angle, along with a low plasticity index. This data indicates that the material on this slope is highly saturated with water, has low plasticity but strong interparticle bonding, and a high internal friction angle. The calculated safety factor falls into the stable category; however, caution is warranted due to the extremely high-water saturation and low plasticity of the material. Specifically for slope LT-L19, dewatering measures are mandatory to reduce the water content within the slope material.

3.2. Discussion

The research resulted in slope classification ranging from critical to stable, with safety factor intervals of 1.2 to 3.77. This condition necessitates slope reinforcement to enhance stability and longevity. Similar observations were also made by previous researchers. Arbenta (2016) stated that from calculations using the Fellenius method, a safety factor of < 1.5 was obtained, indicating that the slope is susceptible to landslides, necessitating planning to mitigate this hazard.

Another previous researcher stated that slope stability analysis of the interprovincial road in BBSNP has been conducted for slopes containing rock materials using RMR calculations. The rock material in three slopes ranges from 38 to 43, categorized as rock class 3-4 with fair to poor rock type. Kinematic analysis revealed that the dominant type of landslide is direct toppling, with SMR calculations showing values around 42-50 for three slopes categorized as slope class 3 with normal slope type (Alviyanda et al., 2021).

Researcher Alviyanda et al. (2023) stated that earthquakes, landslides, and liquefaction in the BBSNP and surrounding areas are triggered by the Sumatra Fault. There are three regions that are potentially affected by geological hazards. The first region has a high fracture density in the western part of the Sumatra Fault. The second and third regions have a low fracture density based on USGS earthquake history. The condition of the regional geological structure causes slopes in the research area to become weaker and susceptible to landslides.

Further studies are needed to discuss recommendations for strengthening slopes in the research area and creating a disaster susceptibility map. The disaster susceptibility map will be provided to BNPB to assist local communities in better understanding the conditions of landslide-prone slopes around them.

4. Conclusion

Slopes can be classified into two categories of slope classification: critical slope and stable slope. The critical slope at LT-L01 and LT-L23 exhibits nearly uniform soil properties with lithology consisting of inorganic clay of high plasticity. The critical safety factor is compromised due to the low cohesion values, making both slopes susceptible to landslides.

The stable slope at LT-R04, LT-L15, LT-L19, and LT-R30 exhibit variability properties across the slopes. The lithology for slope LT-R04 consists of inorganic clay of high plasticity, slopes LT-L15 and LT-R30 share the lithology of silty clay of medium plasticity, while slope LT-L19 has lithology in the form of silty clay of low plasticity. The safety factor values indicate stability due to moderate to high cohesion, contributing to slope stability.

There is a need for support and reinforcement like material compaction is required to enhance cohesion values on the slopes. Additionally, there is a need to mitigate water saturation conditions in the slope materials.

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5. Recommendations for Future Research

The main research is divided into several studies with different themes such as structural geology studies, slope stability analysis with rock materials, slope stability analysis with soil materials, and the creation of landslide susceptibility maps. For the continuity of the research, it is recommended that the data be combined into a single map in the form of a landslide susceptibility map, which will be published subsequently.

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