Evaluation of Slope Stability Due to Rain Infiltration (Case Study: National Road Connecting Enrekang and Toraja Regency)

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ABSTRACT

Landslides are one of the natural disaster phenomena that cause the most casualties, infrastructure damage, and economic losses. One example is the landslide case that occurred on the national road connecting Enrekang Regency and Tana Toraja Regency. This road section is the main access for people who want to pass from Makassar to Tana Toraja Regency. The landslide that occurred resulted in a long traffic jam from both directions, disrupting the economic activities of the community, to traffic accidents. According to local residents, the landslide phenomenon on this road section occurs almost every year, especially when the intensity of rainfall is high. Landslides can be triggered by several factors such as geological structure, morphology, regional climate, and geotechnical properties of surface rocks. The purpose of this paper is to know and understand the factors that trigger landslides at the research location and the appropriate handling. The information used in the research is in the form of soil data from drilling at 2 points, geophysical surveys on 3 tracks, and laboratory testing of several soil samples taken from the research site. The landslide at this location occurred gradually, starting from the subsidence of the slope soil at the edge of the road body and the collapse of the road body surface. Within a period of 4 - 5 months, three landslides can occur, namely in December 2022, March 2023 and May 2023. The analysis shows that the clay soil material, which is the type of soil at the research site, is the controlling factor for landslides triggered by high rainfall intensity. Infiltration of rainwater through soil fractures resulted in a significant increase in water content, the load on the slope soil increased, triggering landslides. In this research, an analysis will be conducted using the Limit Equilibrium Method to determine the condition of slope stability due to factors that trigger landslides.

Keywords:
Slope stability, infiltration, landslide, soft soil, geophysical survey

1. INTRODUCTION

Indonesia is a country that has a high potential and risk of disasters in the world. This is due to Indonesia's geographical location on three active plates, causing the geomorphological conditions in Indonesia to vary greatly in each region and impacting on the high potential for landslides [1]. Landslides that occur especially in mountainous areas are major erosion processes that cause landscape dynamics and cause significant damage and losses, including damage to infrastructure and the environment [2]. Temporal slope movements on natural slopes are usually caused by controlling factors such as slope geometry, properties, structure and property indices of the soil composing the slope where any event or action that causes changes in these controlling factors will be a trigger factor for landslides [3][4]. The existence of factors that affect the occurrence of landslides such as topography, geology, hydrology and land cover causes landslides that occur in various regions to be different from one another [5]. Landslides are triggered by external factors such as earthquakes, volcanic eruptions, heavy rainfall and human activities that can cause the possibility of landslides occurring in different periods of time [6].

In general, landslides are triggered by two main factors, namely seismic activity such as earthquakes and rainfall intensity [7][8]. Rainfall that infiltrates into the slope surface will cause an increase in pore water pressure and a decrease in soil shear strength so that the materials that make up the slope become unstable. High rainfall intensity can cause an increase in groundwater levels, soil saturation limits, and the formation of surface water puddles. Soil saturation limit is a condition where the soil water content due to the infiltration process can no longer be accommodated by soil pores, allowing water to flow through other pathways such as cracking and triggering landslides [9]. The occurrence of shallow landslides triggered by the decrease of matric suction in water infiltrated soil during heavy rainfall (unsaturated) is one of the main mechanisms of slope instability in various tropical and subtropical regions [10]. Rainfall processes and mechanisms that trigger shallow landslides are closely related to rainfall intensity, slope conditions, and the type of soil that makes up the slope [11]. In this study, the landslide case chosen as the research location is a landslide on the national road, precisely in Kulinjang Hamlet, Enrekang Subdistrict, Enrekang Regency, South Sulawesi Province, as shown in Figure 1.

The research location is the main access from Makassar City to Tana Toraja Regency, so the landslide at that location has caused many losses both in the form of material and social, such as infrastructure damage, casualties and disconnection of road access. Landslide disrupted traffic activities on the national road connecting Enrekang Regency and Tana Toraja Regency, causing a long traffic jam from both directions. This had a huge impact on the mobility of the local community, especially in economic activities, considering that Enrekang and Tana Toraja districts are one of the tourism sectors in South Sulawesi Province. Road damage due to landslides will certainly be an obstacle for tourists who will visit the region. It was also noted that traffic accidents along this road section increased due to landslides.

Based on information from local residents, landslides on national roads in the Enrekang Regency area occur almost every year in the wet month or during the rainy season, the landslide event takes place gradually until there are two landslides in a period of 4 - 6 months. In addition to the rainfall factor, the high traffic load is also one of the triggering factors for landslides because the static load of heavily loaded vehicles such as large trucks and buses passing by will cause changes in the pressure balance on the slope, resulting in a force that will push the soil on the lower slope. Therefore, research on landslide cases at this location is very important to identify factors that trigger landslides in order to obtain appropriate mitigation.

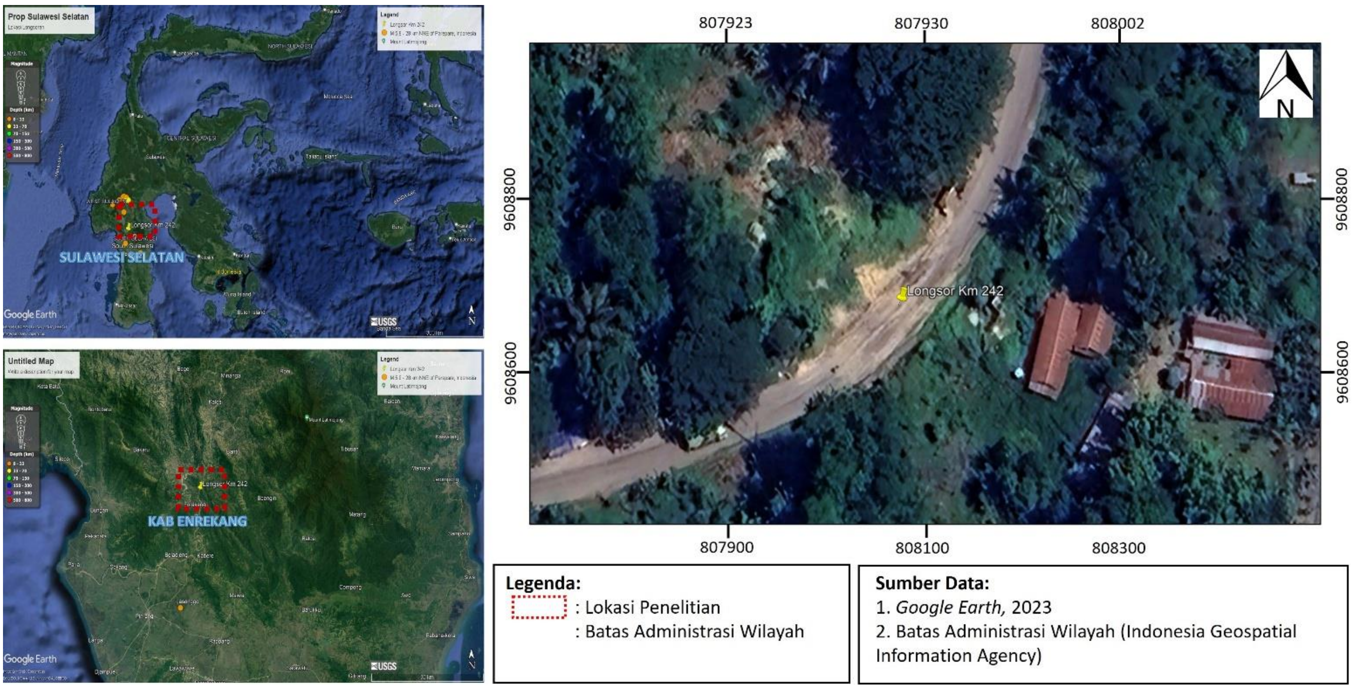
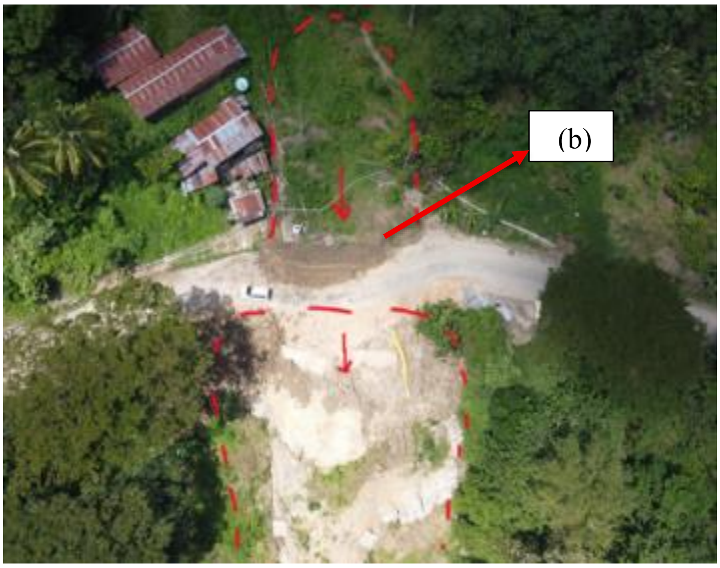


Figure 1. Research Location

2. RESEARCH METHODOLOGY

2.1 Landslide Location

Natural phenomena such as landslides triggered by rain infiltration are annual events in Indonesia, especially in mountainous or hilly areas. The first landslide on the national road connecting Enrekang Regency - Tana Toraja Regency at Km 232 was reported in December 2022 where the road body began to collapse due to waterlogging. The second landslide occurred in March 2023, the third landslide in May 2023 and gave the most significant impact, the landslide expanded as shown in Figure 2. The presence of standing water on the road surface caused the road body to collapse for 50 meters and the landslide material slid down the lower slope. This landslide occurred during the rainy season and is classified as a type of shallow slope collapse triggered by heavy rainfall.



(a)

(b)

Figure 2. (a) Appearance of the landslide location (aerial imagery)
(b) Roads and slope edges after temporary treatment.

Enrekang Regency has a high potential for land movement and is included in the high landslide hazard area in South Province with high rainfall intensity throughout the year [12]. Annual rainfall in this region ranges from 2,300-2,900 mm per year with the number of rainy days ranging from 160 to 220 rainy days per year. Based on the report of BPBD Enrekang Regency, 2022 - 2024, that every rainy season there are always landslides. The number of landslides in Enrekang Regency triggered by high rainfall shows the urgency of analyzing the approach of rain infiltration in its influence on slope stability. Through numerical approach, several boundary conditions will be applied, namely saturated and unsaturated soil conditions.

2.2 Geotechnical Setting

Soil investigation at the research location uses the SPT (Standard Penetration Test) method at two drilling points to determine the nature and strength of the soil, geoelectric testing on three line to obtain soil or rock resistivity and predict the depth of slip areas, taking surface soil samples for testing in the laboratory, as shown in Figure 3.

Figure 3. Bor hole point and geoelectrical line map [12]

The consistency of cohesive soil types in each layer can be determined based on the correlation of N-SPT values as proposed by Terzaghi and Peck (1967) [13]. N-SPT testing was carried out by drilling to a depth of 20 meters. The consistency of the clay soil in each layer based on N-SPT data obtained from both drilling points can be seen in Table 1. The geoelectric survey was carried out on three tracks across the road body with a track length of ±110 m. The results of both types of tests show that the soil layer at the research location is a type of clay with a soft to hard soil.

Table 1. Clay soil consistency based on N-SPT

BH	Depth (m)	N-SPT	Description
01	0 – 3	2	Soft
	4 – 10	16	Stiff
	10 – 20	> 30	Hard
02	0 – 3	4	Soft
	4 – 10	29	Stiff
	10 – 20	> 30	Hard

Soil stratigraphy was carried out across the road, through both drilling points, and interpreted based on geoelectric trajectories to approximate the condition of the soil/rock below the surface, as in Figure 4. The stratigraphy shows that the clay soil layer at the research location consists of three types of layers, namely 1st of soft clay, 2nd layer of stiff clay, 3rd layer of hard clay. The results of geoelectric survey data processing will show the resistivity values for each layer of soil and rock below the surface. In general, geoelectric survey results can be used to support N-SPT data.

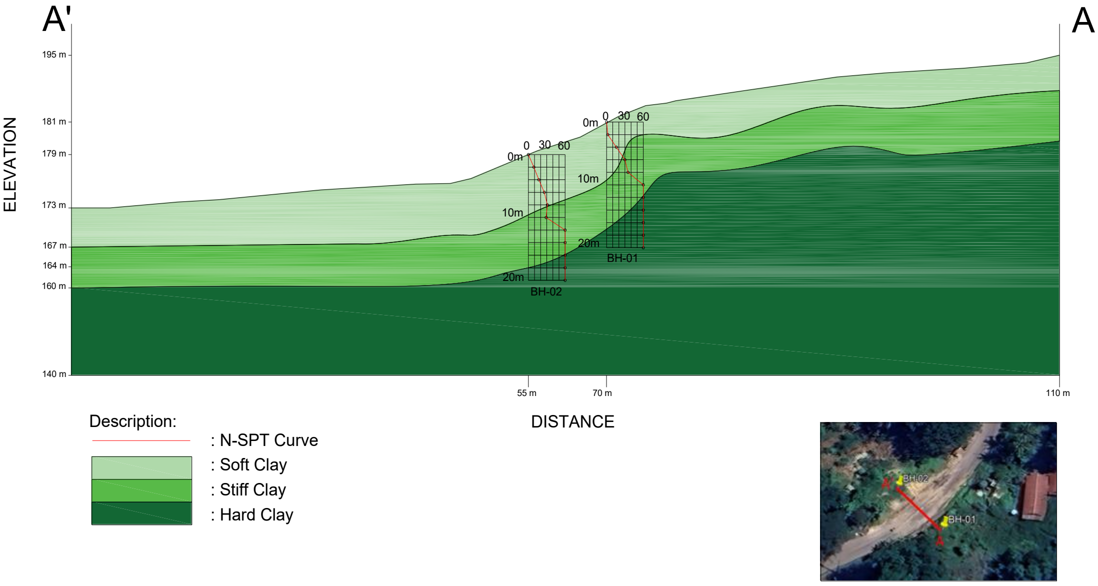


Figure 4. Soil Stratigraphy

The interpretation results of the geoelectric mapping survey show that the research area is at an altitude of 160 - 195 meters with a geoelectric measurement path length of 120 meters, as in Figure 5. The results of the geoelectric survey modeling show that the landslide is in the form of top soil with a resistivity value range of 2 - 10 Ohm meters at a depth 1 – 5 meters. This is in accordance with the theory of resistivity in soil and rock layers, that landslide zones will occur in layers that have low resistivity values.

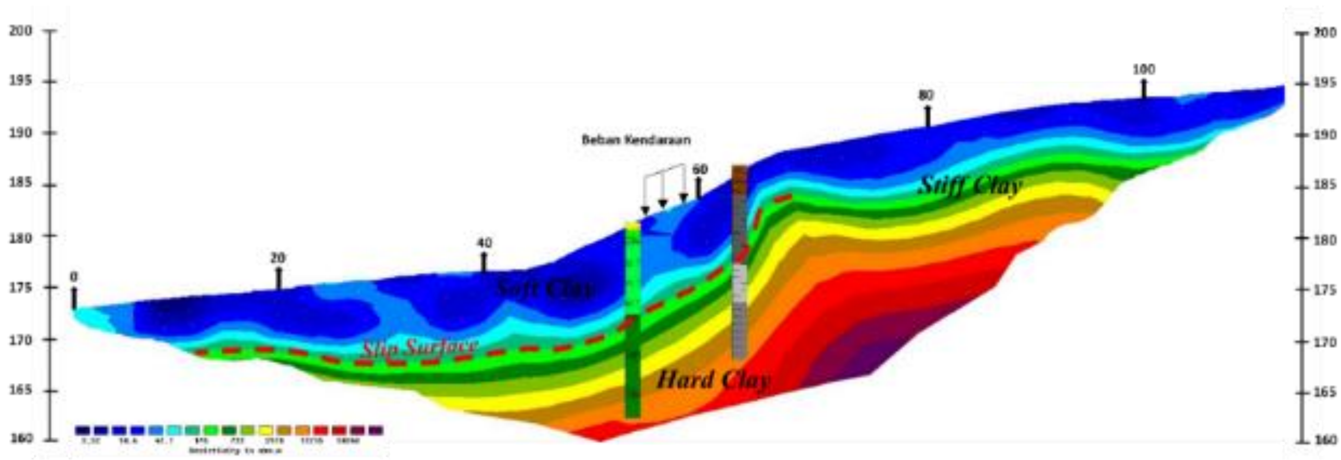


Figure 5. Geoelectric survey results on line 2 [20]

Based on N-SPT test data, the top soil as a landslide zone is dominated by soft clay soil. The soil classification of each layer based on the geoelectric resistivity value shows suitability when correlated with the soil classification based on N-SPT data, so that it can be concluded that the geoelectric test data can support the interpretation of drill hole test data (N-SPT). In this landslide it can be seen that the dominant landslide zone is on the lower slope at a depth of ± 9 m from the ground surface. This is due to the flow of water between the soil layers which is shown in light blue. The water flow is thought to flow from the upper slope to the lower slope, forming a slip surface and making the soil above it unstable. The slip surface is the contact area between soft clay soil as a weak zone, while the stiff and hard clay layer beneath it, allowing the soft soil to move. Slip areas are located at the contact between soil materials that have different characteristics or at the boundary of soil and rock, especially on steep slopes. The depth of the landslide zone ranges from 1 – 5 meters with the length of the landslide generally being greater than its depth. Resistivity imaging from geoelectric test results can be interpreted geologically using standard resistivity values for rock, mineral and sediment types based on available literature and local geological knowledge in the research area. *Reynolds, J.M* (1997) and *R.E Hunt* (2007) provide a range of resistivity values for several types of soil materials, which can be seen in Tables 2 and 3.

Table 2. Resistivity of rock material [14]

Rock Material	Resistivity (Ohm-meter)
Top soil	50 – 100
Alluvium	25 – 1500
Syenite	100 – 100,000
Gnesis	200 – 34,000
Granite	300 – 20,000
Basalt	200 – 20,000
Marble	100 – 200,000
Quartzite	10 – 200,000
Gabbio	15,000
Schist	50 – 100,000
Biorite	50,000
Shale	80 – 20,000
Sandstone	30 – 500,000
Clay-shale	0.00004 – 900
Limestone	30 – 500,000
Clay	1 – 100
Fresh groundwater	10 – 100
Loams	10 – 450
Sand	100 – 500,000
Marl	50 – 90
Oil sands	60 – 900

Table 3. Resistivity of geology material [15]

Geology Material	Resistivity (Ohm-meter)
Clayey soils: wet to moist	1.5 – 3
Silty clay and silty soils: wet to moist	3 – 15
Silty and sandy soils: moist to dry	15 – 150
Bedrock: well fractured to slightly fractured with moist soil-filled cracks	150 – 300
Sand and gravel with silt	± 300
Sand and gravel with silt layes	300 – 2,400
Bedrock: slightly fractured with dry soil-filled cracks	300 – 2,400
Sand and gravels deposits: coarse and dry	> 2,400
Bedrock: massive and hard	> 2,400
Freshwater	20 – 60
Seawater	0.18 – 0.24

Based on geoelectric interpretation which is correlated with the regional geology of the research area, the rock layers in the research area consist of clay, andesite, sandstone, siltstone and mudstone flakes. Based on the results of geological interpretation of geoelectrical survey data, clay shale is interpreted to have a resistivity value between 2.14 – 8.73 Ohm meters (dark blue), sandy tuff with fresh water content with a low resistivity value range of between 35 – 40 Ohm meters (light blue), rock andesite in the range of values 145 – 589 Ohm meters (green), basalt tuff in the range of values 2396 Ohm meters (yellow – brown), and clay tuff in the range of values 9753 – 39072 Ohm meters (orange – red). Based on the results of testing surface soil samples at the FT UGM Soil Mechanics Laboratory, the results showed that the soil at the research location had an average specific gravity value of between 2.587 – 2.617. Soil classification using the Unified System (USCS) shows that the soil at the research location is a type of "fat" clay with high plasticity (fat clay, CH). Laboratory test results for the two soil samples can be seen in Table 4.

Table 4. Laboratory test results

Parameter	DS-1	DS-2	Units
Soil type	CH	CH	-
Water content	32.161	24.876	%
Dry soil weight (γ_d)	1.181	1.184	gr/cm^3
Saturated soil weight (γ_{sat})	1.697	1.694	gr/cm^3
Specific gravity (G_s)	2.617	2.587	-
Void ratio (e)	1.217	1.184	-
Porosity (n)	54.890	54.214	%
Degree of saturation (S_r)	70.5	55.40	%
Plasticity Index (PI)	33.84	28.12	%
Liquid Limit (LL)	66	53	%
Fraction passing through the sieve No 200	71.2	50.7	%
Permeability (k)	4.12938E-09	4.53448E-09	m/s
Cohession (c)	13.37	12.43	kPa
Internal friction angle (φ)	10.35	9.31	degree

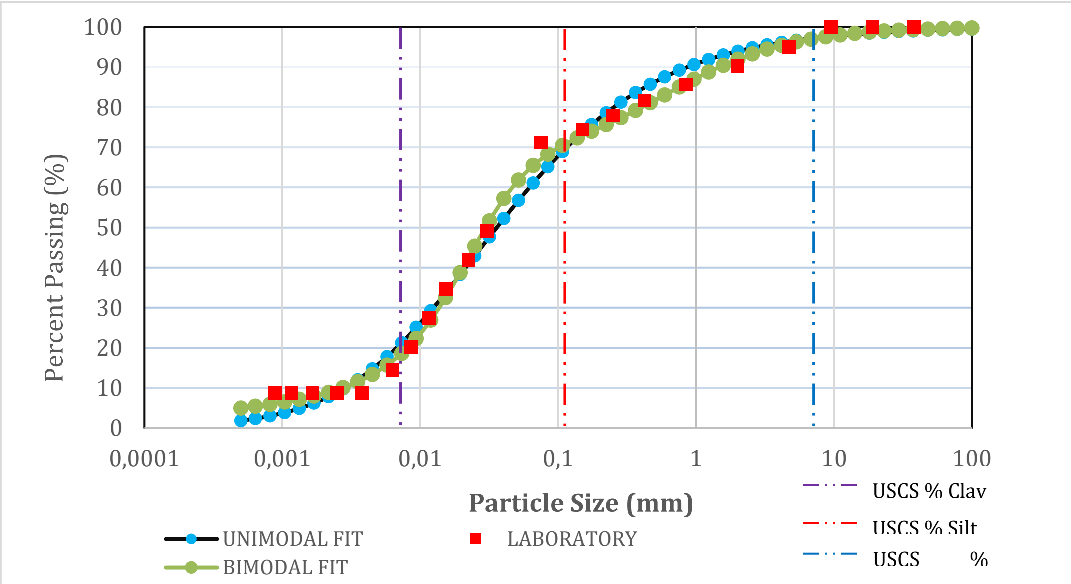
2.3 Soil Water Characteristic Curve (SWCC)

Soil Water Characteristic Curve is used to determine and predict soil properties regarding changes in suction. SWCC can also be used to obtain unsaturated soil parameters that will be used to estimate modeling limits. To obtain SWCC, the first step that must be taken is fitting the soil grain size distribution. Fitting the size distribution is done with the help of a database in *the SoilVision Database software*. Fitting the grain size distribution using two equations: bimodal and unimodal.

The fitting results of the grain size distribution for the two soil samples DS-1 and DS-2, a bimodal equation was obtained that is closest to the laboratory test results with a coefficient of determination value, R2 ≈ 1, which can be seen in Figures 6a and 6b. A comparison of the coefficient of determination obtained from the two equations for the two soil samples can be seen in Table 5.

Table 5. Comparison of R^2 value

Equation	Coefficient of Determination (R^2)	
	DS-1	DS-2
Unimodal	0.9912	0.9960
Bimodal	0.9973	0.9934



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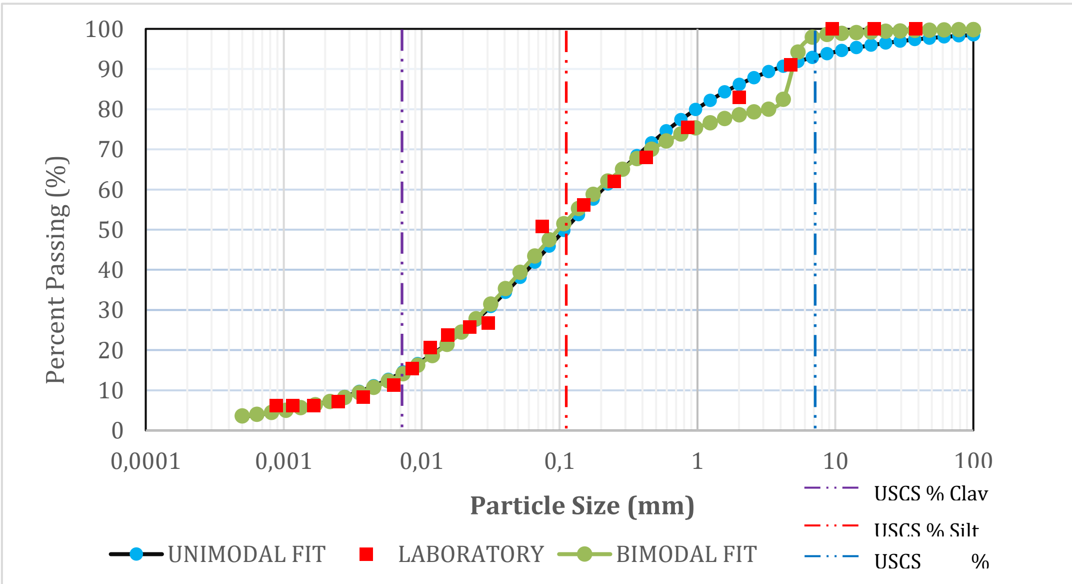
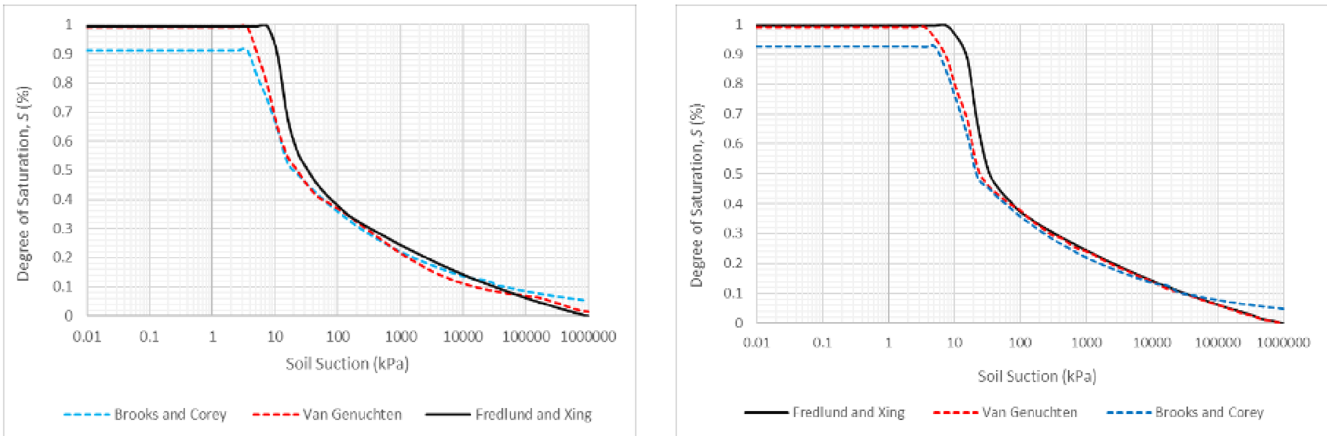


(b)

Figure 6. Graph for the fitting grain size distribution results (a) DS-1 (b) DS-2.

Each soil sample has a fitting result of grain size distribution that is close to the grain size distribution curve from laboratory tests, with a coefficient of determination (R^2) value reaching 0.99 for all soil samples. Hence, the grain size distribution curve can be used to determine the SWCC value through three equations - the Fredlund and Xing equation, the Van Genuchten equation and the Brooks and Corey equation, as in Figure 7.



(a) (b)

Figure 7. SWCC for sample soil (a) DS-1 (b) DS-2

Based on the SWCC graph in Figure 7, a relationship between the degree of saturation and soil suction is obtained. If the degree of saturation of the soil increases, the suction value will decrease, otherwise if the degree of saturation of the soil decreases, the suction value will increase. High soil suction values occur when the soil is dry because in this condition the soil will absorb water so that the soil pores containing air will be filled with water. When the soil is saturated, the soil pores will be filled with water, so the soil suction value will decrease, which means the soil's ability to absorb water is also reduced. From the three equations used, the Fredlund – Xing equation was chosen to determine the soil suction value. This equation was chosen to estimate the suction value because it has a higher coefficient of determination ($R^2 \approx 1$) compared to the Van Genuchten and Brooks – Corey methods. A comparison of the coefficient of determination value for each of these equations can be seen in Table 6.

Table 6. Comparison of R^2 value

Equation	Coefficient of Determination (R^2)	
	DS-1	DS-2
Fredlung and Xing	0.9999	0.9999
Van Genutchen	0.9899	0.9930
Brooks and Corey	0.9694	0.9651

The hydraulic conductivity of soil is determined by the degree of saturation and suction of the soil. Based on the results of hydraulic conductivity calculation using SWCC analysis, a graph of the relationship between matric suction and soil hydraulic conductivity can be drawn as shown in Figure 8.

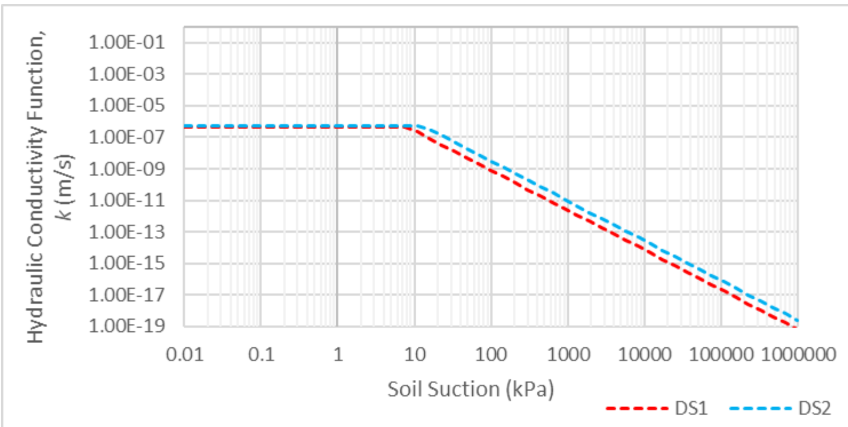


Figure 8. Hidraulic Conductivity Graph

3. LANDSLIDE POTENTIAL

3.1 Regional Geological and Geotechnical Factors

Morphology in the Enrekang Regency area is generally a hilly or mountainous area that has a slightly steep to steep slope. The research area is at an altitude ranging from 160 – 190 meters above sea level. The crown of the landslide was at a height of ± 190 meters above sea level with a height difference of ± 20 m from the surface of the road. Slope inclination is generally stated in (%) which is the tangent and degree of slope. The more sloping of the slope, it will be easier the material to down the slope due to gravitational force and loads acting on the slope such as construction loads, vegetation and water. Slope with inclinations more than 15º require attention to the possibility of landslides by considering other factors. The slope at the research location ranges from 15° - 25°, as in Figure 9.

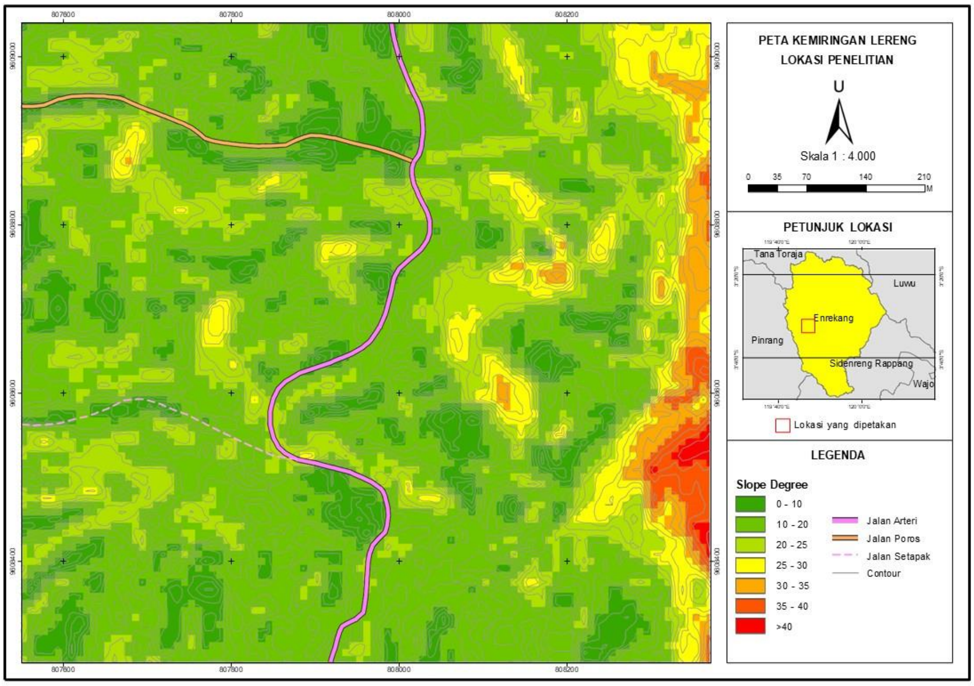


Figure 9. Slope Map

It is very important to know the condition and inclination of the slope because the gravitational force on the sliding surface can be the beginning of a landslide or soil movement. Slopes with inclination of 20º (40%) or more gently, generally material movement in the form of creeping, these slopes are located at the bottom or foothills of the hill [16]. At this research location, the upper slope experienced downward movement, resulting in the road body at the foot of the slope experiencing movement until it collapsed along 50 m and the soil material moved creeping down the slope.

Based on lithology, rock formations in the Enrekang Regency area are generally composed of surface deposits, sedimentary rocks and volcanic rocks. Based on the 1997 Enrekang – Sulawesi Geological Map Sheet [17], The research location is in the Enrekang Regency area, as shown in Figure 10a, is right on two adjoining formations, namely the Tpw formation and the Tmlv formation., which can be seen in Figure 10b. The Tpw formation, called the Walanae formation, is formed from sedimentary rocks, and the Tmlv formation, called the Loka formation, is formed from volcanic clastic rocks. The similarities between these two formations are composed of sandstone, siltstone and mudstone. This is accordance with the soil investigations results that have been described previously, that type of material at the research location is dominated by clay material with consistency soft to hard. The physical properties of soil that greatly influence soil stability and are closely related to landslide events are the permeability and plasticity index of the soil [18].

Slopes composed of clay material are susceptible to landslides, especially during the rainy season because clay soil has low permeability, resulting in rainwater infiltrating into the slope soil being difficult to get out, being stuck on the slope and increasing the load on the slope, as a result the mass of soil/rock that makes up the slope becomes unstable [19]. On the contrary, when conditions are dry, clay material with high plasticity will easily shrink and crack, resulting in cracks forming which can later become a path for water to flow down the slope. Water will cause the soil to lose shear strength, creating weak zones along the cracks. Changes in the volume of clay material due to changes in water content are the swelling and shrinkage properties of clay soil. Clay soil with high swelling and shrinkage properties is a type of problematic clay soil.

Based on the Atlas of the distribution of problematic mudstones in Indonesia on the South Sulawesi Province sheet, the material in the Enrekang Regency area is dominated by problematic mudstone types [20]. Georeferencing results using QGIS 3.4 software show that the research location is in the problematic mudstone distribution zone, which can be seen in Figure 10c. These georeferencing results also show conformity with N-SPT data and geoelectric resistivity, that the material at the research location is dominated by clay material. The swelling and shrinkage properties of fine-grained soils are a very important technical problem. Local cracks or fissures will form in the soil due to capillary pressure that exceeds the shear strength or tensile strength of the soil. These cracks are part of the clay macrostructure and also become weak zones which will significantly reduce the strength of the soil mass as a whole. Changes in the volume of clay material due to the swelling and shrinkage process due to changes in water content often damage buildings and road pavements built on them [21].

The past and present are keys to the future (Varnes, 1984), it means that landslide events in the past and present can explain landslide events that may occur in the future. An area that is considered stable or has a low threat because land movement has never occurred or occurred in small amounts, does not mean that it will never experience slope instability in the future. In addition to the type of slope material, the existence of adverse human activities such as slope cutting, the potential for natural disasters such as earthquakes, the dynamics of climate change such as wet seasons and prolonged dry seasons are factors that can trigger the instability of slope material. From the results of tracing the ground movement vulnerability zone through the ESDM disaster portal website, it is known that the research location is in the yellow zone, which means medium ground movement vulnerability [22], which can be seen in Figure 10d.

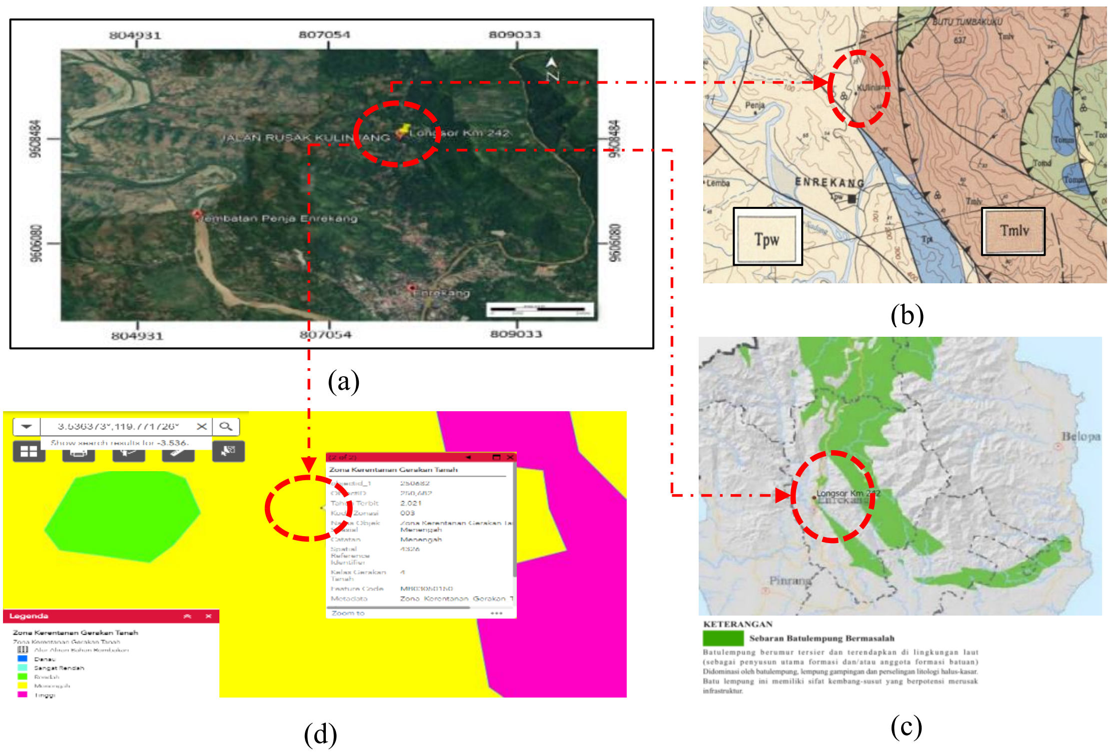


Figure 10. Landslide location (a) Aerial imagery from *Google Earth* (b) Geological map of Enrekang sheet (c) *Georeferencing* with *software QGIS 3.28* (d) Vulnerability zone of soil movement, *website ESDM.*

3.2 Hydrological Factors

The geological condition of Enrekang Regency, which consists of hills with a rock composition consisting of sedimentary rocks and volcanic clastics, accompanied by high rainfall, makes this area susceptible to landslides. The landslide that occurred at the research location was a progressive landslide. According to the properties of clay soil at the research location as previously described, when conditions are dry it will experience shrinkage marked by the formation of cracks, then when rainfall is high, the clay soil will expand as it is filled with water that enters through the cracks. The low permeability of clay soil causes water to be retained and the clay soil becomes full of water, the soil becomes unstable so it experiences movement down the slope. The increasingly widespread movement of land due to water causes the road body and slope edges to collapse. The swelling and shrinking properties of fine-grained soil are a very important technical issue. Local cracks or fissures will form in the soil due to capillary pressure exceeding the shear strength or tensile strength of the soil. These cracks are part of the macrostructure of clay and also become weak zones that significantly reduce the overall strength of the soil mass, as shown in Figure 11. Changes in the volume of clay material due to swelling and shrinkage caused by changes in water content often damage buildings and paved roads built on top of them.

(a) (b)

Figure 11. Cracking conditions on the ground at the research site (a) upper slope (b) lower slope.

Landslide can be triggered by many factors, one of which is rainfall. In this case, rainfall is considered to be the main trigger factor for landslides. The landslide that occurred at the research site was a progressive landslide. High rainfall intensity with low soil permeability accompanied by a lack of drainage systems will cause the process of rainwater infiltration into the soil to be slow, resulting in surface water flow (runoff) and the formation of puddles. If this continues for a long time, it will cause a weakening of the soil's shear strength, resulting in a landslide, as can be seen in Figure 12.

Figure 12. Puddles on the side of the road.

Based on Enrekang Regency BPBD data, most of the landslides in this area were reported to occur in the wet months, namely months with high rainfall intensity. The counted rainfall as a trigger for landslides is not only high-intensity rain that occurred immediately before the landslide but also the cumulative rain that occurred several days or several months before the landslide.

Observation of rain data obtained from JAXA Global Rainfall Watch (GsMap) for the last 20 years, from 2004 to 2023, the highest rainfall occurred in October to Desember 2022 and March to May 2023, with maximum daily rainfall intensity reaching 23.63 – 237.54 mm/day. Distribution of rainfall intensity observed for 8 months can be seen in Figure 13. Based on the rain distribution graph, the rain that occurred from October to early December caused the soil to become saturated after experiencing a dry period in the previous month. During this period, cracks were formed which allowed rainwater to slowly enter and accumulate in the slope. This condition causes additional load acting on the slope (vertical pressure) and will be the driving force that pushes the material to move down the slope (horizontal pressure). Therefore, cracks formed in the soil can be the beginning of a landslide.

The dominant rainfall that occurred during this period was light - normal rainfall and very heavy rainfall. Rainfall that lasts for 1 - 15 days can be counted as rainfall that triggers shallow landslides, while rainfall that lasts for 1 - 3 months can be counted as rainfall that triggers deep landslides [23].

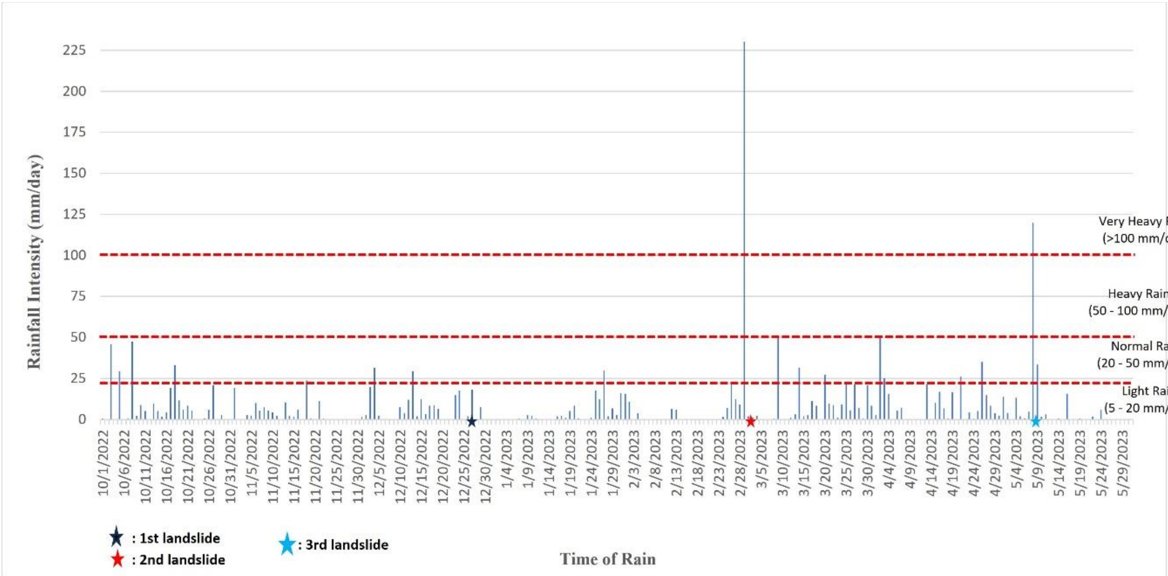


Figure 13. Daily Rainfall Data from October 2022 to May 2023.

The low permeability of clay soil causes water to be retained and the clay soil to become saturated, making the soil unstable and causing it to move downhill. The movement of soil, which is exacerbated by water flow, will cause the road surface and the edge of the slope to collapse. An illustration of the road surface subsidence at the research site can be seen in Figure 14.

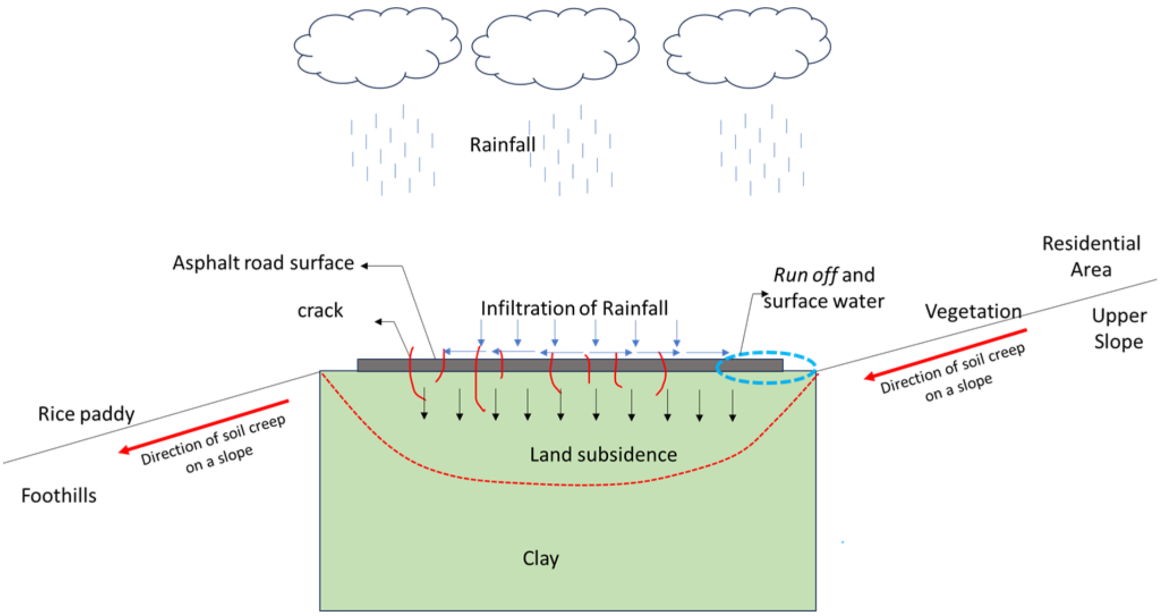


Figure 14. Illustration of road subsidence at the research site

Based on the results of rainfall distribution analysis using the WindRose diagram, the dominant duration of rain at the research location for rain with light, normal and very heavy intensity is different. Rain with normal intensity occurs for a longer duration than other rain intensities. To determine the characteristics of the depth of rain for each intensity at a certain return period, an analysis was carried out using maximum rainfall data for each year as an input parameter.

Table 7. Duration and depth of maximum rainfall

Intensity	WindRose	Rain depth for probability
	Duration (Day)	mm/day
Light	2	18.59
Normal	3	42.85
Very Heavy	1	143.91

The amount of rainfall at the 2 year return period was used as the planned rainfall because it was considered to represent the intensity of rainfall events that usually occur at the research location. In this study, the dominant rainfall duration and rainfall depth for each intensity at the 2 year return period are presented in Table 7, while the rainfall distribution diagram for each intensity can be seen in Figure 15.

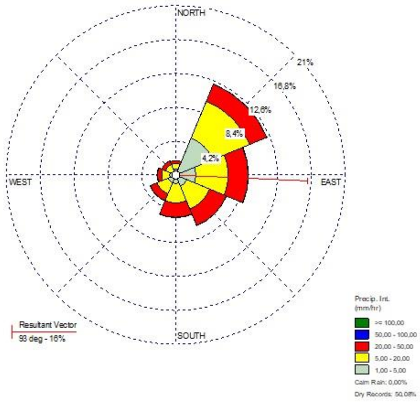


Figure 15. WindRose diagram

4. RAINFALL INFILTRATION ANALYSIS

Soil moisture and pore water pressure in the field generally indicate partial or complete loss of matric suction at shallow depths associated with rainwater infiltration during light, normal or heavy rainfall events of long duration. Subsequently, puddles of water on the ground surface or transient positive pore water pressures are formed. It is observed that in low slope areas, there can be a significant increase in transient positive pressure. However, the mechanism of pore water pressure formation is specific to each location depending on hydrological conditions, rainfall patterns, topography, and soil properties [24].

Infiltration is an important component in the triggering factor of rainfall-induced ground motion. The infiltration of rainwater will result in changes in pore water pressure, affecting the shear strength of the soil slope in the landslide plane. A series of rainfall events will cause significant changes in the soil surface from unsaturated water to saturated water due to the infiltration process of rainwater. Rainwater infiltrating into the soil will move slowly downward in the direction of gravity and pass through the soil pores. When the soil pores are filled with water or full of water, where the soil is saturated, the infiltration rate will decrease. Under these conditions, the pore water pressure in the slope increases and causes slope instability.

Therefore, infiltration analysis will be analyzed based on rainfall conditions. The slope infiltration capacity analysis will be conducted using the Green Ampt method for the three types of rainfall models, namely light rain, normal rain and very heavy rain. In the infiltration analysis, variations in the degree of soil saturation and the degree of slope must also be taken into account because each modeling will provide different values of infiltration rate and capacity.

Based on the Regulation of the Minister of Forestry of the Republic of Indonesia Number: P.12/Menhut-Ii/2012 concerning Procedures for Preparing Technical Plans for Forest and Land Rehabilitation of Watersheds (Rtkrhl-Das) [25], the classification of infiltration rates for landslide and erosion studies according to Kohnke (1968) in Cho and Lee (2002) can be seen in Table 8.

Table 8. Infiltration Rate Classification

Classification	Infiltration Rate	
	(mm/hour)	(mm/day)
Very slow	< 1	< 24
Slow	1 – 5	24 – 120
Medium slow	5 – 20	120 – 480
Medium	20 – 65	480 – 1,560
Medium fast	65 – 125	1,560 – 3,000
Fast	125 – 250	3,000 – 6,000
Very fast	> 250	> 6,000

When the rain first falls, all rainwater will seep into the soil until it reaches the inundation time. However, after reaching the inundation time, the infiltration rate tends to decrease until the rain stops. This can happen because the soil is dry when the rain starts falling, so the soil still has a high capacity to absorb water. As the rain falls, soil saturation increases and the ability of the soil to absorb water decreases, so the infiltration rate decreases. The cumulative infiltration value will continue to increase as the rain continues until the rain stops. At the research site, as an example of normal rain modeling with an intensity of 42,852 mm/day for 3 days on a slope with a slope of 20°, the infiltration rate results for a degree of saturation of 70% is 1.9732 mm/day or 0.0822 mm/hour, while for a degree of saturation of 98% is 0.6938 mm/day or 0.0289 mm/hour, can be seen in Table 9.

Table 9. Infiltration Rate based on Saturation Degree

Sr Saturation Degree, (%)	*F* Cummulative Infiltration (mm)	*f* Infiltration Rate (mm/hari)
70	11.1458	1.9732
80	9.2288	1.6546
90	6.7326	1.2404
94	5.3764	1.0160
96	4.5229	0.8753
97	4.0152	0.7919
98	3.4161	0.6938

Based on Table 8 and Table 9, it can be seen that the infiltration rate at the research site is included in the very slow class. The process of soil saturation due to rain infiltration causes the negative pore water pressure in the soil to change into positive pore water pressure so that the effective stress of the soil decreases and slope stability decreases. The infiltration capacity value obtained is the basis for calculating the depth of the landslide plane and the slope safety factor, because this calculation takes into account the rainfall event and the infiltration of rainwater into the soil. This will give the length of rainfall that can cause slope instability in the field and show that rainwater does affect slope stability triggering landslides.

The increase in pore water pressure due to seepage during rainy conditions may result from the decreased shear resistance of the soil due to tensile cracking at the crown of the slope and rainfall conditions that reduce the shear strength of the soil. In the wet month period with continuous and heavy rainfall intensity, the increase in pore water pressure increases significantly compared to the dry month period, causing a decrease in the safety factor of the slope. The increase in rainfall on the slope causes a decrease in suction and increases the mass displacement of the slope simultaneously [26]. The slope safety factor is analyzed using infinite slope stability analysis where the forces acting on both vertical planes are considered equal taking into account the infiltration that occurs during rainfall. The slip plane depth (z_w) and safety factor (SF) of the slope at the study site for each rainfall modeling can be seen in Table 10.

Table 10. Depth of slip plane and slope safety factor for each rainfall modelling

Rainfall modelling	Slope gradient, β (°)	Rainy day to-	Depth of slip plane, z_w (mm)	Safety Factor (SF)
Light	15	220	8060.3443	1.0826
	20	103	4216.8409	1.0818
	25	65	2839.7411	1.0887
Normal	15	220	8060.3940	1.0826
	20	103	4216.8946	1.0818
	25	65	2839.7977	1.0887
Very heavy	15	220	8060.4042	1.093
	20	103	4216.9048	1.147
	25	65	2839.8095	1.093

The safety factor obtained based on the day of the rainfall event shows that the slope is in a critical condition and is prone to movement until landslide. This is in accordance with Bowles (1984), which states that the safe factor value for critical slopes is in the range of 1.07 - 1.25. Based on the data in Table 10, it is known that the depth of the sliding plane (z_w) is inversely proportional to the degree of slope of the slope, the more gentle a slope, the deeper the sliding plane. However, when compared based on rainfall modeling, the results of the depth of the sliding plane (z_w) on the slope have a similar magnitude. In addition, there is a variance in the time required for the slope to reach an unstable condition based on the degree of slope, the more gentle the slope, the longer it takes to reach an unstable condition. The results of the analysis and observations at the research site show that the predicted time to reach slope instability is close to the actual time in the field.

Infiltration and slope stability analysis can also be done by numerical methods in 2D using Seep/W and Slope/W software which aims to compare the results of slope stability analysis due to the influence of rain infiltration in 1D. The slope geometry with a slope of 20° and soil parameters from the DS-1 sample will be used as input data in the modeling because it is considered the closest to the conditions in the field. In the numerical modeling, the initial groundwater level will be taken into account when no rain has occurred, this condition is referred to as the initial condition of the slope. Rainfall events will cause an increase in groundwater level so that pore water pressure also increases. From the results of numerical analysis, it can be seen the direction of seepage flow due to rain infiltration, a gradual increase in pore water pressure to the movement of slopes due to water flow characterized by the value of the slope safety factor that decreases gradually. The results of the 1D and 2D analyses have significant differences in the time required for the slope to reach instability and the resulting safety factor values. This is because the 2D analysis takes into account the slope geometry and the initial water table while the 1D analysis only takes into account the degree of slope, soil parameters in one layer, and rainfall intensity.

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