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ANALYSIS OF THE EFFECT OF RAINFALL ON SLOPE SAFETY FACTORS

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ABSTRACT

At the end of 2015, a landslide hit a portion the city boundary road of Tanah Grogot - Lolo Kuaro with a total length reaching 50 m (nearly the entire bend) with a height ranging from 2.5 m to 9.6 m during the time when the region experienced frequent rainfall in the last month and intense rainfall of 322 mm/13 days in the past two months. Based on previous studies on the effect of rainfall on slope movement, a temporary conjecture was obtained that the landslide that hit KM.6 of the road was induced by rainfall making an initially unstable slope to be even more unstable.
In this study, the pressure-void ratio value was obtained using the finite element method. The pressure-void ratio value used for analysis was in failure envelope. Then, the Fellenius method was used for safety factor value analysis.
The study obtained a safety factor of slope before precipitation of 1,288, which was then down to 0,928 when the rainfall return period reached 100 years (65,37 mm/hour). Then for the results of varying rainfall, safety factor values of 1.28 (20 mm/hour), 1.21 (40 mm/hour), 1.13 (60 mm/hour), 1.05 (80 mm/hour), and 0.97 (100 mm/hour) were obtained. The last analysis of varying rainfall durations obtained safety factor values of 0.99 (60 mm/hour for 20 hours), 0.97 (80 mm/hour for 10 hours), and 0.97 (100 mm/hour for 6 hours).

Keywords: *Slope Movements; Rainfall; Rainfall Duration: Slope Safety Factor.*

I. INTRODUCTION

Roads are the only connector between Tanah Grogot Sub-District and Lolo Kuaro Village. Moreover, the road also serves as the sole access road to the capital of the province of East Kalimantan. For this reason, the road plays a rather significant role for the people as a transportation infrastructure due to the fact that various kinds of vehicles, such as private vehicles and transport vehicles, pass this road.

At the end of 2015, a landslide hit KM.6 of the city boundary road of Tanah Grogot - Lolo Kuaro. it occurred after the region experienced frequent rainfall in the last month and intense rainfall of 322 mm/13 days in the past two months. The affected road is exactly on the horizontal geometry of a bend with the width of the road prior the landslide of 11 m and shoulder width of 1.5 m each. This road is situated on a natural slope with a gradient of 1:1.5 on both sides. The landslide ate up half of the road with total length reaching 50 m or nearly the entire bend and a height ranging from 2.5 m to 9.6 m. It disrupted community activities since only one half of the road is functional.

According to Subyianti (2011), normal rainfall for an extended period of time causes groundwater to rise and when it happens, soil shear strength will diminish and if the soil is saturated, the soil shear strength will disappear. Moreover, according to Setiawan, cohesion and internal friction angle values of dry soil are higher than saturated soil. Parameters of shear strength and cohesion are aspects that affect slope stability. Changes in those parameters will directly affect slope stability. Soil cracks in a slope is one of factors causing landslides during the rainy season (Hutagamissufardal, 2018). Soil cracks will expand as the rainfall intensifies, where cracked soil will lead to reduced soil cohesion (Hutagamissufardal, 2018). Based on previous studies on the effect of rainfall on slope movement, a temporary conjecture was obtained that the landslide that hit KM.6 of the road was induced by rainfall making an initially unstable slope to be even more unstable. To prove this conjecture, the study on the effect of rainfall intensity and duration on slope safety factors was conducted.

The purpose of this study is to analyze pore water pressure that occurs in some conditions and the effect of rainfall on slope safety factors. The case study of this research was the City boundary road of Tanah Grogot – Lolo Kuaro of the province of East Kalimantan.

II. LITERATURE REVIEW

In order to obtain rainfall per hour, the maximum rainfall per year will be analyzed using the distribution of hourly effective rainfall (Mononabe). To transform design rainfall into design discharge, hourly rainfall is needed. in general, rainfall data available in the meteorology station is the daily one. However, if automatic rainfall data (automatic rainfall recorder) is available, the distribution pattern of hourly rainfall can be created using the mass curve method for every heavy rainfall episode by ignoring the time of the episode. For this study, Mononobe method will be used with the following formula:

$$Rt = (\frac{R_{24}}{t})x(\frac{t}{T})^{2/3} \quad \text{.........................(1)}$$

where:
R_t = Mean rainfall intensity in T hour (mm/hour)
R_{24} = Effective rainfall in one day (mm)
t = Rain starting time
T = Time of concentration
To calculate the distribution of hourly rainfall, the following formula can be used:

$$R_t = (t \cdot R_T) - \{(t-1) \cdot (R_{T-1})\} \quad \text{........(2)}$$

Safety factors are the ratio of resistive force to moving force (Hardiyatmo, 2010):

$$F = \frac{\tau}{\tau_d} \text{..(3)}$$

where:
τ_d = shear stress generated from gravity of the soil that is about to slide
τ = maximum shear resistance that can be exerted by soil
F = safety factor

Mohr's theory of strength stated that failure in soil mass will happen not on the plane with maximum shear stress but on the plane on which there is a critical combination of normal stress and shear stress determined using envelope strength. Soil shear strength is resistance applied by soil particles on pushing or pulling force. Based on this theory, the shear resistance that can be exerted by soil along the landslide plane is as follows:

$$\tau = c + \sigma\, tg\, \varphi \text{...............................(4)}$$

where:
c = cohesion
σ = normal stress
φ = internal friction angle

Cohesion and internal friction angle are parameters of soil shear strength along the landslide plane.
In the same way, a shear stress equation that occurs due to soil loads and other loads in the landslide plane is obtained, which is:

$$\tau_d = c_d + \sigma\, tg\, \varphi_d \text{.........................(5)}$$

In general, stability safety factor of slope is taken greater than or equals to 1.2 (Hardiyatmo, 2010).
In the presence of water effect, the formula of soil shear strength becomes:

$$\tau = c + (\sigma - u)\, tg\, \varphi \text{......................(6)}$$

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where:
σ = normal stress (kN/m^2)
u = pore water pressure (kN/m^2)
(Hardiyatmo, 2010)
In 1856, Darcy introduced a simple equation used to calculate water flow velocity within saturated soil, stated as follows:
$v = ki$…………………………………………..(7)

where:
V = flow velocity, which is the amount of water flowing in a unit of time through a unit of cross-sectional area perpendicular to the flow direction
K = seepage coefficient

Table 1 Seepage Coefficient Values in General

Soil Type	k
Clean gravel	1,0 - 100
Coarse sand	1,0 - 0,01
Fine sand	0,01 - 0,001
Silt	0,001 - 0,00001
Clay	>0,000001

(Hardiyatmo, 2010)

III. RESEARCH METHOD

Steps of this research method included:
1. Data collection, including laboratory data, precipitation data, topography data, and field data. Laboratory data were the results of the attached soil test results, and precipitation data were obtained from the Central Bureau Statistics of East Kalimantan. Topography data and field data were obtained during field visit in the form of documentation results that were presented in this report.
2. Next was the analysis of rainfall data that could be done simultaneously by varying the duration of rainfall and rainfall intensity. Precipitation data analysis began with feasibility test of data used for analysis. For variations in rain duration with three different rainfalls according to the previous analysis of rainfall intensity variations, which were 60 mm/hour that was analyzed with the duration from 1 hour to 20 hours, 80 mm/hour that was analyzed with the duration from 1 hour to 10 hours, and 100 mm/hour that was analyzed with the duration from 1 hour to 6 hours. Rainfall intensity variations were taken based on the results of hourly rainfall analysis with return period of 1-100 years and also based on rainfall intensity that made the slope unstable that was obtained after an analysis.
3. Next step was simulation using the finite element method and simulation result analysis. The finite element method used in this study was GeoStudio Seep/W. The design method and analysis of simulation results would be discussed in detail in subsequent sub-chapters.
4. Next was safety factor analysis before rain using GeoStudio Slope/W and the Fellenius method was used for after rain since the finite element method yielded low accuracy.
5. Lastly, a thorough discussion of the results of the analysis.

IV. DISCUSSIONS

Research Data

Based on soil analysis, the following soil data were obtained:
Soil data of base layer 1 : c = 25.5 kPa, φ = 10.09 °; γ = 17.9 kN/m³
Soil data of base layer 2 : c = 179.95 kPa, φ = 30 °, γ = 18.5 kN/m³
Soil data of base layer 3 : c = 480.04 kPa, φ = 35 °, γ =19 kN/m³

Rainfall data used for the calculation of design discharge were precipitation data of Tanah Grogot Station obtained from Central Bureau of Statistics of East Kalimantan. The precipitation data used were from the recording period of 2002 to 2017. The following was the design discharge obtained after the calculation testing using the Mononobe method was performed:

Table 2 Hourly Design Rainfall

n (Tahun)	R (mm)	V (Km/jam)	T (jam)	R (mm/jam)
1	278.31	1.577	6.000	29.22
2	403.85	1.577	6.000	42.40
5	482.97	1.577	6.000	50.71
10	524.34	1.577	6.000	55.05
20	558.49	1.577	6.000	58.64
25	568.44	1.577	6.000	59.68
50	596.94	1.577	6.000	62.67
100	622.57	1.577	6.000	65.37
1000	694.39	1.577	6.000	72.91

Rainfall intensity variations were taken based on the results of hourly rainfall analysis with return period of 1-100 years and also based on rainfall intensity that made the slope unstable that was obtained after an analysis. Rainfall intensity variations were tested where slope safety factors were still above 1.25, above 1, and below 1, which were 20 mm/hour, 40 mm/hour, 60 mm/hour, 80 mm/hour, and 100 mm/hour. Every rainfall intensity was simulated with the precipitation duration of 6 hours, in accordance with BMKG data on mean precipitation duration in Indonesia which ranged from 6 to 8 hours.

Rainfall intensity variations were tested with three different rainfalls according to the previous analysis of rainfall intensity variations, which were 60 mm/hour with analysis duration from 1 hour to 20 hours, 80 mm/hour with analysis duration from 1 hour to 10 hours, and 100 mm/hour with analysis duration from 1 hour to 6 hours. Different rainfall durations in every rainfall intensity were observed because at the end of the hour the slope had experienced instability. Data used to obtain pore water pressure value on soil layer were as follows:
Saturated Water Content = 30.34%, Residual Water Content was taken from 10% of saturated water content (Atikah, 2017), Residual Water Content = 3.03%, Conductivity Coefficient = 0.0005, Permeability Coefficient $k = 1.007x10^{-5}$ m/det, and hourly rainfall distribution data.

Research Results

After the analysis on the slope using the element method was performed, slope safety factor of 1.288 was obtained.

1. Local Rainfall

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Figure 1. Graphic of Relationship of Gauge Height Increase Due to Seepage and Return Period Rainfall

Based on the graphic in Figure 1, it could be concluded that the greater the rainfall return period was, which also meant stronger rainfall, the higher the gauge height increase due to rain seepage into the soil of the slope would be.

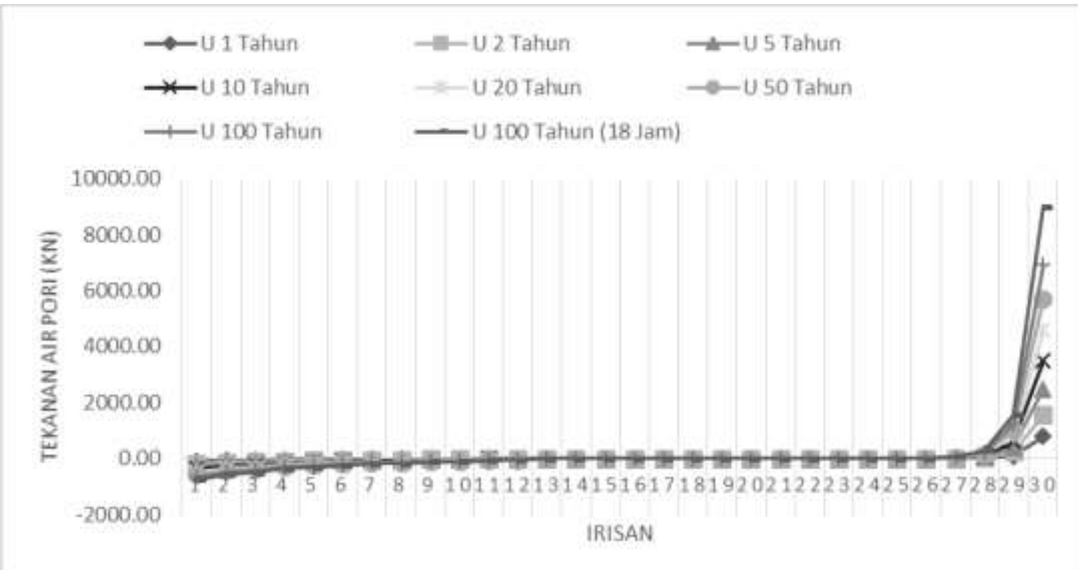

Figure 2. Graphic of Pore Water Pressure with Return Period Rainfall

The greater the intersection value was, the closer the position of intersection from the foot slope would be. Based on the graphic in Figure 2, it was known that the lower the slope height was from the foot hill, the greater the pore water pressure would be due to small particle sizes and permeability coefficient value of the soil. This caused the water from the rain to flow first to a low surface before it seeped into the soil and caused pore water pressure around the foot slope to increase. Moreover, it could also be concluded that the greater the rainfall return period was, which also meant stronger rainfall, the higher the pore pressure value would be.

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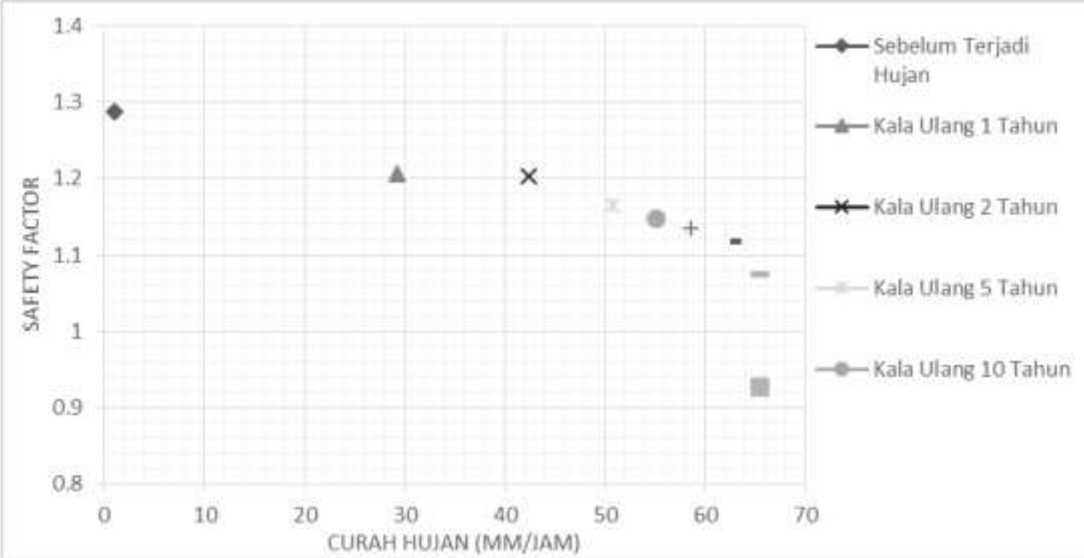

Figure 3. Graphic of Relationship of Safety Factor and Local Rainfall

Based on the graphic in Figure 3, it was known that the landslide hitting the road of Tanah Grogot – Lolo Kuaro, Tanah Paser District, was caused by 18-hour precipitation with a rainfall of 65.37 mm/hour that happened during 100-year return period rainfall. In December 2015 when the landslide occurred, the recorded rainfall reached 366 mm which was the second highest rainfall over the past 15 years. Thus, it could be concluded that the slope on the road moved downward due to the rain, where the water seeped into the soil and caused the slope to become unstable.

2. Rainfall intensity variations

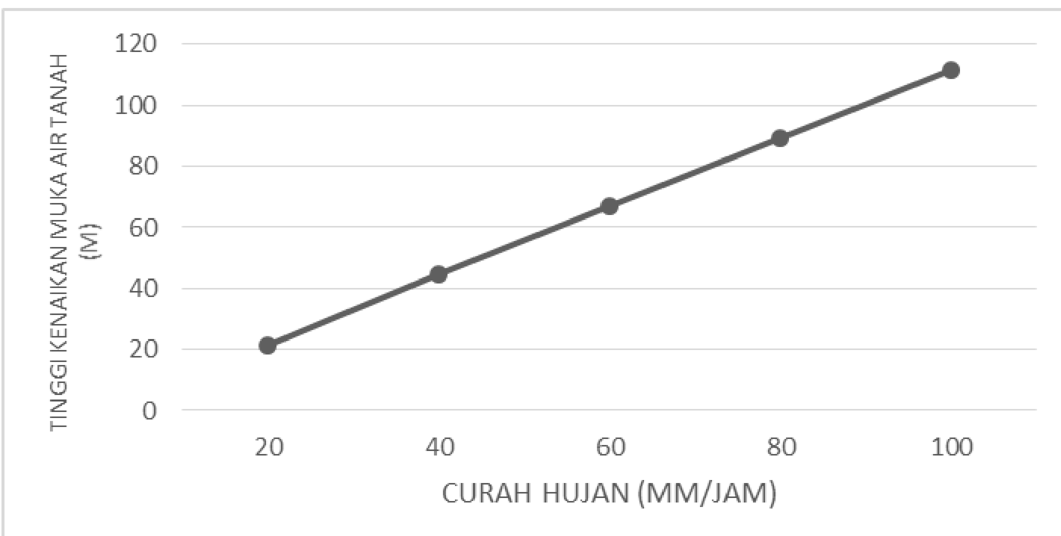

Figure 4. Graphic of Relationship of Gauge Height Increase Due to Seepage and Rainfall Variations

Based on the graphic in Figure 4, it could be concluded that the stronger the rainfall was, the higher the gauge height increase due to seepage of water into the soil of the slope would be.

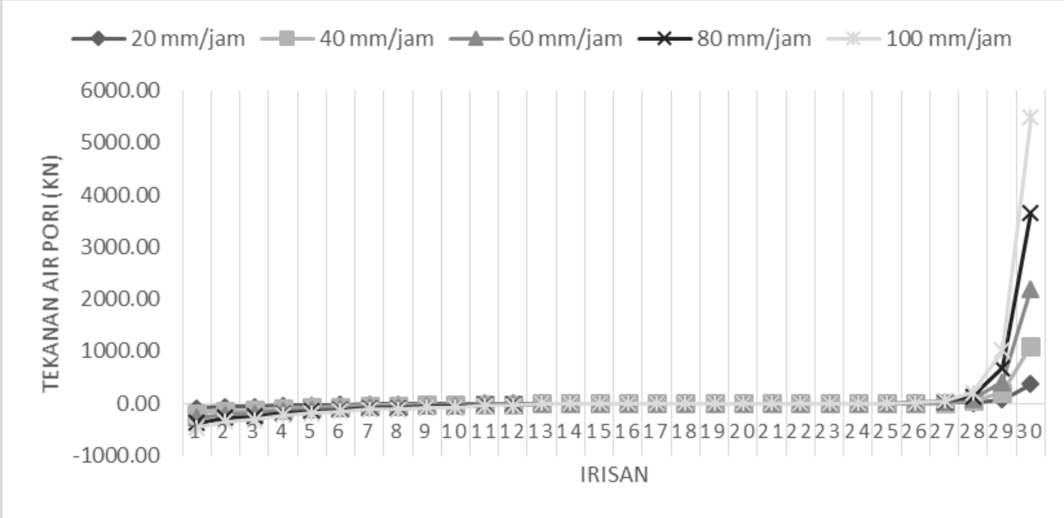

Figure 5. Graphic of Pore Water Pressure and Rainfall Return Period

The greater the intersection value was, the closer the position of intersection from the foot slope would be. Based on the graphic in Figure 5, it was known that the lower the slope height was from the foot hill, the greater the pore water pressure would be due to small particle sizes and permeability coefficient value of the soil. This caused the water from the rain to flow first to a low surface before it seeped into the soil and caused pore water pressure around the foot slope to increase. Moreover, it could also be concluded that the greater the rainfall return period was, which also meant stronger rainfall, the higher the pore pressure value would be.

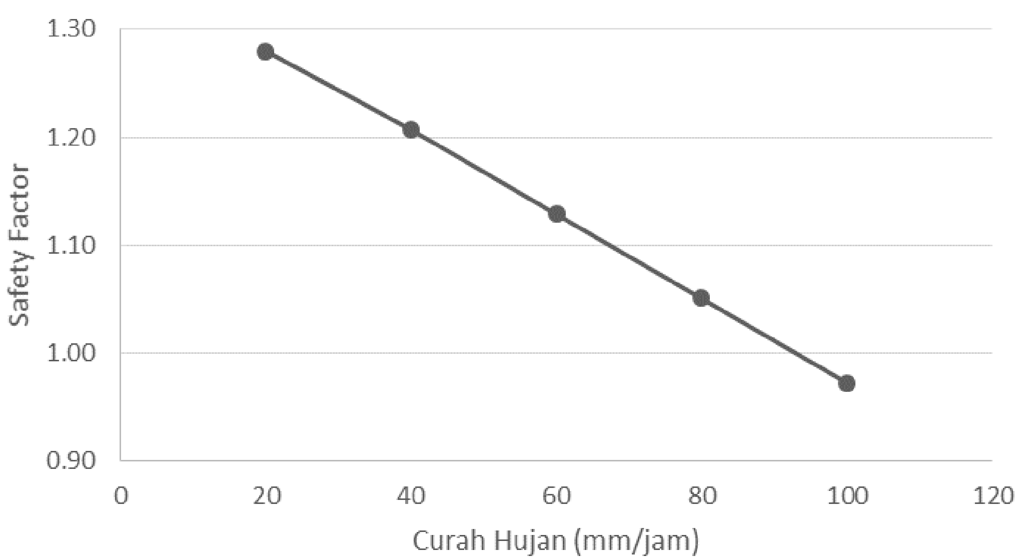

Figure 6. Graphic of Relationship of Safety Factors and Rainfall and Rainfall Variations

Based on the graphic in Figure 6, it could be concluded that the slope on the road of Tanah Grogot – Lolo Kuaro would stay stable if the rainfall was less or equals to 80 mm/hour. However, if the rainfall reached 100 mm/hour, the slope would be too unstable and a landslide might occur. If the rainfall is approaching maximum threshold, it may cause the slope to be unstable and this would necessitate preventive measures to keep it from happening.

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3. Rain Duration Variations

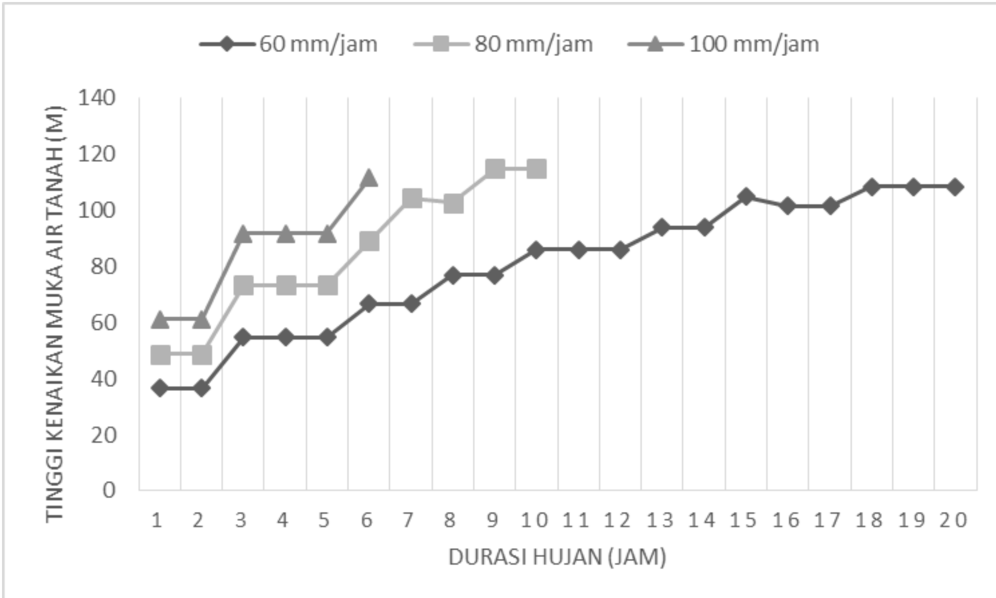

Figure 7. Graphic of Relationship of Gauge Height Increase Due to Seepage and Return Period Rainfall

Based on the graphic in Figure 7, it could be concluded that the greater the rainfall and the longer the rain duration were, the higher the gauge height increase would be due to water seepage into the soil of the slope.

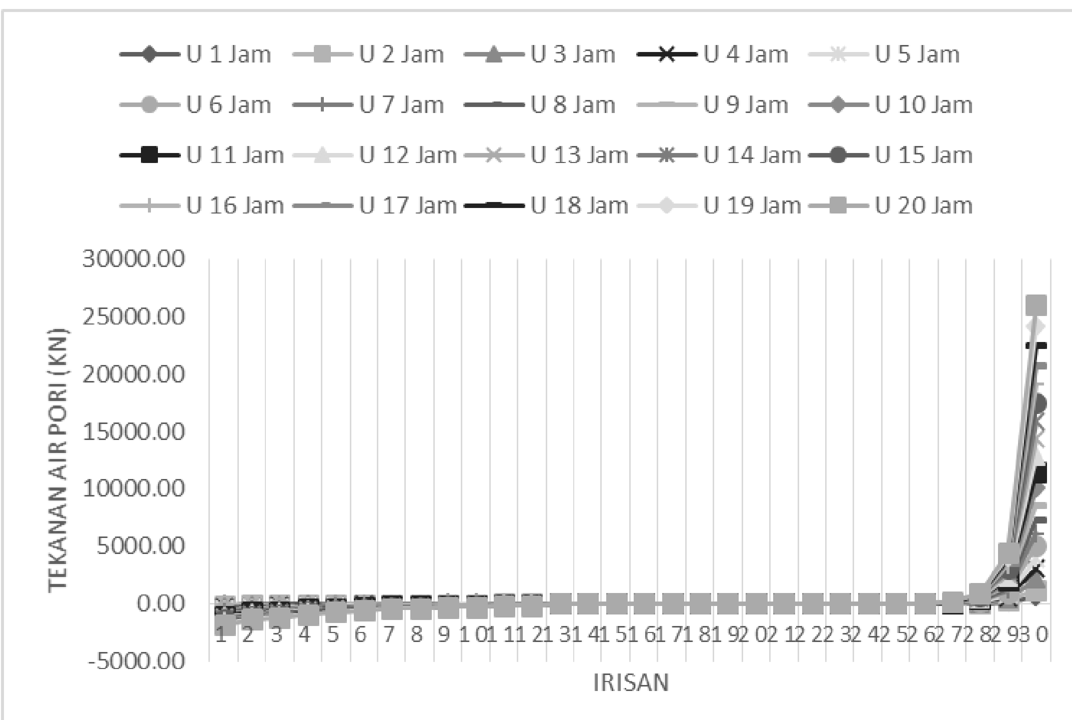

Figure 8. Graphic of Pore Water Pressure and Rain Durations with Rainfall of 60 mm/hour

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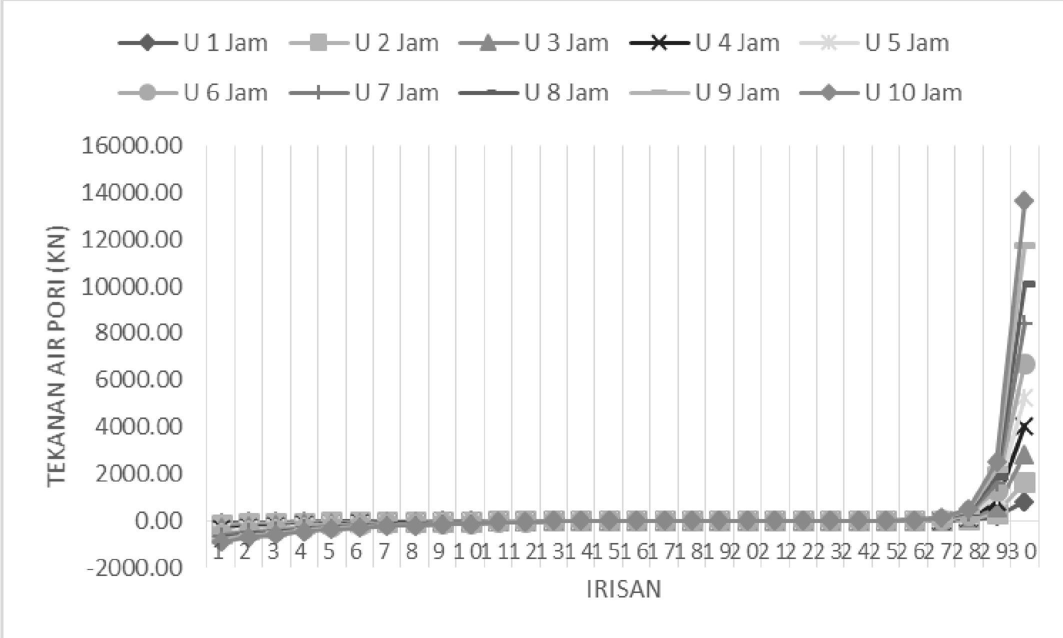

Figure 9. Graphic of Pore Water Pressure and Rain Durations with Rainfall of 80 mm/hour

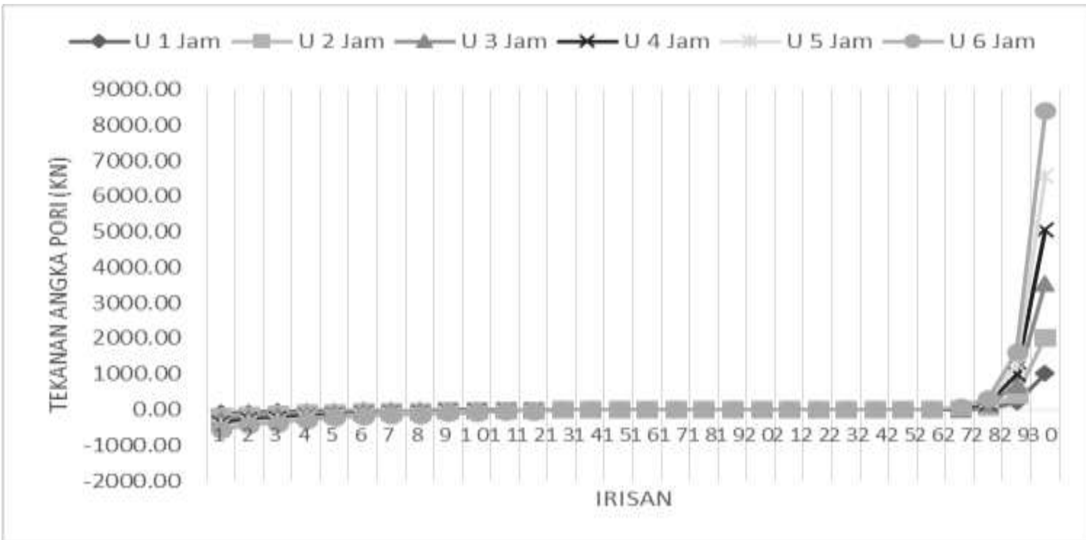

Figure 10. Graphic of Pore Water Pressure and Rain Durations with Rainfall of 100 mm/hour

The greater the intersection value was, the closer the position of intersection from the foot slope would be. Based on the graphics in Figure 8 to 10, it was known that the lower the slope height was from the foot hill, the greater the pore water pressure would be due to small particle sizes and permeability coefficient value of the soil. This caused the water from the rain to flow first to a low surface before it seeped into the soil and caused pore water pressure around the foot slope to increase. It could be concluded that the greater the rainfall and the longer the rain duration were, the higher the pore water pressure value would be.

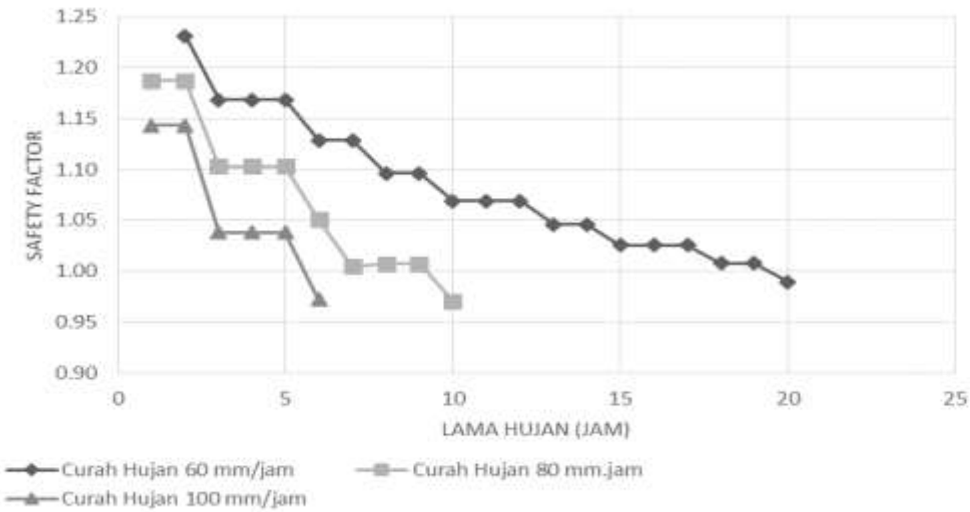

Figure 11. Graphic of Rain Duration Variations

Based on the graphic in Figure 11, it could be concluded that the slope on the road of Tanah Grogot – Lolo Kuaro would stay stable, indicated by safety factor greater than 1, if the rainfall duration was 17 hours with rainfall of 60 mm/hour, the rainfall duration was 9 hours with rainfall of 80 mm/hour, and the rainfall duration was 5 hours with rainfall of 100 mm/hour. However, if those rainfall durations exceeded those numbers, the slope would be too unstable and a landslide might occur. If the rainfall is approaching maximum threshold, it may cause the slope to be unstable and this would necessitate preventive measures to keep it from happening.

4. Soil Volume Weight

Before precipitation, the soil was unsaturated, however, when rain fell, the soil became saturated and underwent changes in soil volume weight, and ultimately affecting the slope stability. Based on the result of the finite element method by observing one section from the landslide area, we found that volume weight had increased by 0.32% and safety factor had decreased by 0.13% after rain.

V. CONCLUSIONS

1. The resulting pore water pressure value shows that the greater the rainfall return period is, which also meant stronger rainfall, the greater the pore water pressure increase on the soil will be and it affects the safety factor of the slope. Based on the analysis, the safety factor of the slope before precipitation is 1.288, then the slope collapses at safety factor of 0.928 with rainfall intensity of 65.37 mm/hour during 100-year rainfall return period.
2. The resulting pore water pressure value shows that the greater the rainfall is, the greater the pore water pressure increase on the soil will be and it affects the safety factor of the slope. Based on the analysis by varying rainfall intensities, a safety factor of 1.28 is obtained at rainfall intensity of 20 mm/hour; a safety factor of 1.21 is obtained at rainfall intensity of 40 mm/hour; a safety factor of 1.12 is obtained at rainfall intensity of 60 mm/hour; and a safety factor of 1.05 is obtained at rainfall intensity of 80 mm/hour. The slope collapses at safety factor of 0.97 with rainfall intensity of 100 mm/hour.
3. The resulting pore water pressure value shows that the greater the return period rainfall and the longer the rain duration are, the greater the pore water pressure increase on the soil will be it affects the safety factor of the slope. Based on the analysis by fixed varying rainfall intensities, at rainfall of 60 mm/hour the slope collapses at safety factor of 0.99 with rainfall duration of 20 hours and at rainfall of 80 mm/hour the slope collapses at safety factor

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of 0.97 with rainfall duration of 10 hours, and lastly, at rainfall of 100 mm/hour the slope collapses at safety factor of 0.97 with rainfall duration of 6 hours.

4. Rainfall can decrease safety factor of the slope due to a decrease in soil strength that might lead to landslide-inducing magnitude of water pore pressure on the slope.

Suggestions

Future studies are suggested to:

1. Analyze safety factor using the finite element method.
2. Take into account cracks that occur on a slope, because in previous studies, cracks on a slope affect slope safety factor and moreover, seepage resulting from rainfall causes cracks on a slope to expand in number and size.