The effect of rainfall on the slope stability with numerical simulation on Tawaeli-Toboli road, Central Sulawesi

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Abstract. Tawaeli-Toboli is an arterial road that often experiences landslides due to rainfall, which increases pore water pressure and thus, decreases the soil's shear strength. This research analyzes the effect of rainfall on Tawaeli-Toboli road with numeric simulation to determine the characteristics such as changes in pore pressure and slope stability. Frequency analysis with HAVARA software was used to determine the maximum rainfall, while the dominant rain duration was analyzed using WindRose. Furthermore, the SoilVision software was used to fit grain size distribution, and the results are used to estimate the soil-water characteristic curve (SWCC). Analysis of pore water pressure changes was carried out using the SEEP/W program. The results were used as input data to determine the slope stability analysis using the SLOPE/W program. The frequency analysis result showed that the maximum amount of rainfall on Tawaeli-Toboli road is 205.698 mm after 11 days. During normal rainfall (20 mm/day), the Western slope remains stable with a safety factor value of 1.50. Simultaneously, in heavy rains, it decreases significantly to 1.350 after 11 days of rain. The eastern slope is quite stable because it has a safety factor value of 1.721 during heavy rain conditions.

1. Introduction

The Tawaeli-Toboli road stretches over a mountainous topography, with a significant amount passing through relatively steep hillsides in slope angles ranging from $35^\circ$ to $70^\circ$. All vehicles from Manado, Gorontalo in northern Sulawesi, Makassar, and Kendari and other districts in Central and Southern Sulawesi pass through the Tawaeli-Toboli axis when entering Palu, and vice versa. Some of the slopes on the Tawaeli-Toboli have been converted into plantations for cloves, coffee, cocoa, and vegetables by the local community. Until now, slope landslides were found on the road due to cutting and their original condition during the rainy season. The effect of rainfall on slope stability occurs in four stages as follow: 1) heavy rain, 2) the process of infiltration of rainwater into the slopes, 3) an increase in the water level in the slope, which automatically increases the pore water pressure in the soil, thereby leading to a decrease in the shear strength of the soil on the slope, 4) the movement of soil mass in slopes [1-3]. Infiltration is the process by which water on the ground surface enters the soil at a certain capacity. This process is influenced by rainfall intensity through several stages, including infiltration, water flow, and storage [4,5]. The slope and seepage analysis's stability using computer software is an easy task for geotechnical engineers when the slope information and material properties are known. Many computer software has come into general use, and any hard computations and simulation can be carried out through them by giving them appropriate inputs and data. This results in less error frequency and more detailed analysis when compared with field observations. The numerical modeling computer program i.e. SEEP/W and SLOPE/W of Geo-Slope Company can be employed to simulate seepage,
phreatic surface, slope stability, and drawdown conditions for different scenarios [6]. Hence, this study was carried out by making numerical simulation modeling using software from Geostudio, with SEEP/W and SLOPE/W, used to analyze changes in pore water pressure and slope stability. The research aims to determine the most influential rain's characteristics and its effect on pore water pressure and slope stability.

2. Methods

2.1 Research Sites
This research was carried out on the slope of the Tawaeli-Toboli road section 25-35 Km, North of Palu that shown in Figure 1 [7]. The road is located between two districts, namely Donggala and Parigi Moutong districts, Central Sulawesi.

![Figure 1. Tawaeli-Toboli Road](image)

2.2 Method Of Analysis
The analysis was carried out in several stages, as follows:

a. Fitting Soil Water Characteristic Curve (SWCC). SWCC is the relationship between groundwater potential, gravimetric/volumetric water content, or saturation level. The Soil Water Characteristics Curve (SWCC) is the main parameter used for modeling groundwater flow [8]. SWCC is a curve that describes the relationship between the amounts of water in the soil that affects changes in its suction [9-12]. The amount of water is defined as volumetric water content ($\theta$), gravimetric water content ($\omega$), or degree of saturation ($Sr$). SWCC is also often known as retention or volumetric water content curve that describes soil's ability to store and release water.

SWCC fitting to the size distribution data of threads and analyzing hydraulic conductivity values using SoilVision and SEEP/W software.

b. In determining the maximum rainfall, a frequency analysis was performed with HAVARA software's help, while the duration of the dominant rain was analyzed using WindRose.

c. Changes in pore pressure were analyzed using the SEEP/W program, the results were then integrated to analyze slope stability using the SLOPE/W program.

d. The stability of the slope is determined based on the Bowles safety factor classification [13] that shown in Table 1.
Table 1. Bowles safety factor classification [13]

| Safety Factor (SF) | Slope Condition |
|--------------------|-----------------|
| SF ≥ 1.25          | Stable          |
| 1.07 ≤ SF ≤ 1.25   | Critical        |
| SF < 1.07          | Unstable        |

3. Result And Discussion

3.1 Slope Conditions

The seismic survey results [14] show that the low-velocity layer (fault zone) was detected between km 27+900m - km 27+950m with a width of 20 m, as shown in Figure 2(b). From the drilling results, it is known that the thickness of the first layer/colluvial deposit is 5 m. While the second layer has a thickness of 5 - 20 m and deeply weathered schist with a value of N > 50 (hard soil). Furthermore, the third layer is a very harsh weathered schist. During the drilling survey, no groundwater levels were found at each point, and there were also no muddy water leaks flowing into the borehole.

Based on the results of laboratory testing, it was found that the soil in the research location was generally in the form of silty sand (SM) based on the Unified classification standard [15]. The detailed laboratory test results are shown in Table 2.

Table 2. Results of laboratory testing

| Laboratory testing       | Units | Sample I (S1) | Sample II (S2) | Sample III (S3) |
|--------------------------|-------|---------------|----------------|-----------------|
| Type of soil             | SM    | SM            | SM             | SM              |
| Friction Angle           | (°)   | 26.370        | 31.500         | 30.240          |
| Cohesion                 | kPa   | 16.672        | 7.846          | 18.633          |
| Unit Weight              | kN/m³ | 18.241        | 18.928         | 17.555          |
| Water content            | %     | 26.800        | 20.400         | 25.490          |
| Porosity                 |       | 45.090        | 41.610         | 47.020          |
| Hidraulik Conductivity   | m/sec | 1.00E-06      | 1.00E-07       | 5.50E-07        |
| Specific gravity         | -     | 2.670         | 2.750          | 2.690           |
| Volume of water content  | %     | 40.11         | 33.33          | 36.99           |
| Degree of Saturation     | %     | 87.28         | 78.57          | 77.18           |
3.2 SWCC Fitting and Hydraulic Conductivity Analysis

Size distribution fitting on the road is performed using the help of basic data in SoilVision software, while the grain size distribution fitting uses the bimodal and unimodal equations. The results obtained that the unimodal equation closest to the laboratory test and coefficient of fitting results for all locations is $R^2 = 0.99$. This result means that the grain size distribution curve can be used to calculate the SWCC value, with the resulting data used as input to estimate the suction matric value of the SEEP/W program. The results of the fitting for the grain size distribution in each location used the unimodal equation, with the estimation results of the suction matrices shown in Figures 3-6.

The matric suction data estimated by the SEEP/W program were used to determine the SWCC fitting data using the SoilVision Database program. Furthermore, the Fredlund and Xing, as well as Van Genuchten equations were used to obtain the SWCC curve. The result of the fitting is based on the Fredlund and Xing equations because the coefficient of determination is higher ($R^2 \approx 1$) compared to the Van Genuchten method. Table 3 compares the coefficient of determination between the variables.

Table 3. Comparison of the coefficient of determination ($R^2$)

| Sample | Fredlund and Xing Equation | Van Genuchten Equation |
|--------|----------------------------|------------------------|
| S1     | 0.960                      | 0.916                  |
| S2     | 0.994                      | 0.963                  |
| S3     | 0.946                      | 0.886                  |

Soil hydraulic conductivity analysis was carried out based on the Brooks and Corey equations using parameters derived from the SWCC fitting results. Figure 7 shows the graph of the relationship between matric suction with hydraulic conductivity.

![Figure 3. Grain size distribution fitting with SoilVision for Sample I (S1)](image1)

![Figure 4. Grain size distribution fitting with SoilVision for Sample II (S2)](image2)

![Figure 5. Grain size distribution fitting with SoilVision for Sample III (S3)](image3)

![Figure 6. Matric suction curve](image4)
3.3 Earthquake
The data from the Meteorology, Climatology and Geophysics Agency, Class 1 Geophysics Station, Palu, showed that the magnitude of the earthquake of more than 4 is less than 20% of the total earthquake. The impact of these earthquakes was very small, and the majority did not cause disturbance to the environment.

3.4 Rain Analys and Modeling
The rain data used were obtained from the station closest to the research location, the Stasiun Meteorologi Pertanian Khusus (SMPK) Dolago, in the form of rainfall data from 2000-2013 [16], as shown in Figure 8.

3.4.1. Duration Of Rain
Daily rainfall data were used as input in the WindRose software. The result shows that the dominant rain intensity occurred above 194 mm, with a rain duration of 11 days, as shown in Figure 9.
3.4.2. Maximum Rainfall Frequency Analysis

The calculations results using the chi-square and smirnov-kolmogorov test method with HAVARA software, shows that the best result is obtained using the Pearson Type III distribution method. In this study, a 1.1 year return period of the Pearson Type III distribution was used to determine the maximum amount of rainfall, which is 205.698 mm.

3.4.3. Design Rain Model

The design rain model used in the numerical simulation is obtained from the previous analyses combined results, as shown in Table 4.

| Slope         | Rain intensity $(q = \text{mm/days})$ | Rain model   |
|---------------|--------------------------------------|--------------|
| west slope / east slope | 20                                    | normal       |
|               | 50                                    | heavy        |
|               | 100                                   | very heavy   |
|               | 205.698                               | maximum      |

3.5 Numerical Analysis Results

The initial conditions were run from a transient analysis file with a defined groundwater level in the research. Meanwhile, the effect of rain is modeled by transient analysis based on a review of the intensity of the variation modeled with the unit flux $(q)$ value, with the potential seepage used to determine seepage's effect on the slope. The first layer is silty sand soil, while the second is igneous rock, which is depicted in the modeling as bedrock. The boundary conditions used are as follows:

1. The western slope consists of 10364 nodes and 10261 elements, while the eastern slope consists of 9195 nodes and 9084 elements. Furthermore, the mesh patterns used were quads and triangles with an element size of 0.5 m, as shown in Figure 10.
2. The initial condition's groundwater level is between the first and second layer boundaries, also known as bedrock.
3. The lower and downstream limits of rock layers (bedrock), as well as the upstream limits of the slopes are given the no-flow boundary conditions of Total flux $Q = 0$ (△).
4. The downstream limit of the first soil layer is given a boundary condition with the Total flux \((Q = 0)\) activated to determine the slope’s potential seepage flow (△).

5. For the transient analysis, the effect of rain is modeled by the unit flux \((q)\) by activating the potential seepage review (▽▽).

![Diagram](image)

**Figure 10.** The pore water review location

Changes were observed in pore pressure at the top (line A), middle (line B), and foot of the slope (line C), as shown in Figure 11.
Changes in pore water pressure are influenced by the level of soil saturation and groundwater level. The result showed that the pore water pressure is positive, neutral, and negative for the soil below, between, and above the groundwater level, respectively. The change in pore water pressure from the numerical simulation results with the SEEP/W program in Figure 11 shows the pore pressure contours due to the infiltration of rainwater into the slope. Zero pore water pressure indicates standing water on the soil.

3.5.2 Changes In Pore Water Pressure On The West Side Slopes
The change in pore water pressure is relatively linear without rainfall. In this condition, the pore water pressure is positive at depth below the groundwater level, and the value decreases until it reaches negative at the depth above the groundwater level. However, when it rains, the top (line A), middle (line B), and foot of the slope (line C) experience a significant change in pore pressure. For example, in Figure 11.
12, the pore water pressure, initially at -93 kPa, increased to 0 kPa in the middle of the slope (line B) after raining for one day. In general, the pore water pressure on the slope changes at a depth of 5-9 m.

Furthermore, the laboratory test results show that the first layer of the west slope's hydraulic conductivity value is 0.0864 m/day. However, when the rainfall is less than the value of hydraulic conductivity, the infiltrated water becomes more than the overflow. It causes the slope to experience a saturated and critical condition with an increase in mass due to rainwater infiltration and suction loss.

3.5.3 Changes In Pore Water Pressure On The Eastern Slopes
When it rains, the top (line A), middle (line B), and the foot of the slope (line C) experience a significant change in pore water pressure. For example, when it rains for a day, the initial pore water pressure of -25 kPa, in the middle of the slope (line B), increases to 0 kPa. The pore water pressure on the slopes changes at a depth of 3-5 m. Therefore, in general, pore water pressure changes tend to be the same from day 1 to day 11. The middle of the slope (line B) is the most affected by rain, as shown in pore pressure changes. Figure 13 shows that pore pressure changes in the middle of the slope (line B) are due to 100 mm/day rain pressure.

![Figure 12](image1.png)

**Figure 12.** Changes in pore water pressure on the west slope during heavy rain conditions (100 mm/day): (a) line A, (b) line B, (c) line C.

![Figure 13](image2.png)

**Figure 13.** Changes in pore water pressure on the eastern slope during heavy rain conditions (100 mm/day): (a) line A, (b) line B, (c) line C.

3.5.4 Changes In Pore Water Pressure On Slope Stability
a) West Slope Stability
The change in pore pressure obtained from the previous analysis is used to analyze slope stability with the SLOPE/W program. Meanwhile, the west slope stability simulation results show that in normal rainy conditions (20 mm/day), the safety factor ranges from 1.50 to 1.60 for 11 rainy days. It shows that the slope conditions are still stable despite normal rainfall for 11 days. Heavy rain for 11 days, especially at 100 mm/day, continuously affects the west slope stability with a continuous decrease from its original value of 1.578 to 1.350 on the 11th day. Figure 14 shows the slip surfaces while the stability analysis results of the west slope for each rain condition with a safety factor is shown in Figure 15.

**Figure 14.** Location of slip surfaces on the west slope for normal rainy conditions (100 mm/day) on the 11th day.

**Figure 15.** Distribution of safety numbers on the west slope

b) *East Slope Stability*

The stability simulation results show that the eastern slope is stable with a safety number of more than 1.7 for all rainy conditions, as shown from the slight decrease in the safety number. For heavy rain conditions (50 mm/day), the safety figure decreased significantly compared to others, where the value
of the safety factor initially at 1.726 decreased to 1.721 after 2 rainy days. The slip surface location for the smallest safe number after 11 days of heavy rain (50 mm / day) is shown in Figure 16, while others can be seen in the attachment section. In general, the stability analysis result of the west slope for each rain condition has a safe factor value of more than 1.70, which indicates that the eastern slope is stable during rainfall, as shown in Figure 17.

![Figure 16. Location of slip surfaces on the eastern slope in heavy rain conditions (50 mm/day) for 2 days](image_url)

![Figure 17. Distribution of safety numbers on the east slope](image_url)

4. **Conclusion**

Based on the results of research and data analysis, the following conclusions were obtained:

1. The soil type in the research location is classified as SM (silty sand) in accordance with the Unified Classification Standard.
2. The maximum rainfall frequency using HAVARA software with a return period of 1.1 years of Pearson Type III distribution is 205.698 mm/day.
3. The duration and intensity of rain influence the changes in pore water pressure.
4. The western slope is the most significant reduction in safety, especially during rainfall, because the soil's hydraulic conductivity value is large enough to increase the infiltration speed. Therefore, the
slopes are faster and easier to be saturated when it rains as well as in stable condition for normal rainfall (20 mm/day) for 11 days. This is indicated by the value of the safety factor, which ranges from 1.50 to 1.60. Meanwhile, for heavy rains with frequencies of 50 mm/day, 100 mm/day, and 205.698 mm/day, the safety factor decreases, especially at 100 mm/day, where the safety factor decreases significantly. In the initial conditions before the rain, the safety factor’s value was 1.578, and to 1.350 after 11 days.

5. The eastern slope is stable because it has a large safety factor value above 1.7 and against the effect of rain. The smallest safe factor is 1.721 during heavy rain conditions at 50 mm/day.

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