Effect of Rainfall Characteristics on The Stability of Tropical Residual Soil Slopes

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Abstract* — This study investigates a slope composed of tropical residual soil using the SEEP/W and SLOPE/W modules within the GeoStudio finite element analysis software. The research examines changes in slope stability under various rainfall patterns and soil parameters. Curves showing the variation of the slope's factor of safety over rainfall duration were generated. The results indicate that the advance rainfall pattern has the most significant impact on slope stability compared to the delayed, uniform, and peak patterns. Under all rainfall patterns, continuous rain consistently leads to a gradual decrease in slope stability. Increased rainfall causes a rise in pore water pressure and a corresponding reduction in the factor of safety. Steeper slopes experience a more pronounced decrease in the factor of safety. The advance rainfall pattern produces a rapid increase in pore water pressure and a sharp drop in the factor of safety within a short period.
Keywords: slope stability; rainfall pattern; pore water pressure; factor of safety; tropical residual soil.

I. INTRODUCTION

Slope failure caused by rainfall is one of the most common hazards worldwide. Slope failure can be caused by various factors, such as slope soil material, soil strength parameters, slope geometry, rainfall, and construction methods(Wang et al., 2020). Slope failures often occur during the rainy season. Rainfall is one of the main triggering factors. Studying the effects of rainfall on soil slope stability is important for geotechnical engineering. There is still little information available on the effects of rainfall intensity and duration on the stability of residual soil slopes. Rainwater that is absorbed into slopes will cause an increase in pore water pressure, which reduces the shear strength of the soil. Thus, when it rains, slopes experience seepage and failure. Rainfall can affect stability in several ways, including an increase in soil density, a decrease in matrix suction, a reduction in strength, and a rise in the groundwater table. Landslides are closely related to rainfall intensity, soil mechanical properties, groundwater table, boundary conditions, and initial slope conditions (Wang et al., 2020).

The effects of rainfall (duration, infiltration, rainfall patterns) are considered to be the main factors contributing to slope failure, but in reality, trapped water has a more significant effect when present on slopes. A pattern with heavy rainfall at the beginning of the event duration is considered one of the worst-case scenarios for slope stability, as the soil experiences intense and sustained water infiltration over a shorter period. The influence of slope gradient is also considered. According to (Chen et al., 2017), rainfall is one of the main external factors contributing to slope failure. Increased pore water pressure and groundwater table, along with enhanced suction and shear strength of the soil matrix, can influence soil instability (Liu & Li, 2015).

II. LITERATURE REVIEW

Rainfall is the main external factor affecting slope stability. Rainfall patterns are classified into four types: advantage, delayed, peak, and uniform. Each pattern has a different effect on the development of pore water pressure and slope safety factors. High intensity rainfall at the beginning of the period (advance) tends to be the most dangerous because it accelerates infiltration and increases pore water pressure.

In addition to patterns, two important characteristics are rainfall duration describes the length of rainfall event; the longer the duration, the greater the volume of water that enters the soil, although other factors such as topography and wind also have an effect (Muallif, 2023; Sofia & Nursila, 2019)Rainfall intensity indicates the amount of rainfall in a given period of time. In Indonesia, landslides are often triggered by short-term high-intensity rainfall or prolonged peak rainfall (Gómez-Escalonilla et al., 2024).

Infiltration plays an important role in slope instability processes. Infiltration is the movement of water from the surface into the ground through pores or cracks, which is greatly influenced by soil permeability, saturation level, vegetation, and topography(Geotechnical Manual for Slope Geotechnical Engineering Office Civil Engineering and Development Department The Government of the Hong Kong Special Administrative Region, 2011). Rainfall infiltration increases pore water pressure and decreases soil shear strength, thereby reducing the safety factor of the slopes.

In the context of slope stability, safe conditions are achieved if SF > 1.25, critical conditions if SF < 1.07 (Bowles, 1989). The presence of rainwater increases tension and decreases the shear strength of the soil, thus becoming the dominant cause of slope collapse (Karnawati D, 2005; Suryolelono, 2001). With a certain type of slope, differences in rainfall patterns will be directly reflected in the response of pore water pressure; an advance pattern reduces stability more quickly, while the uniform and delayed patterns are more gradual.

III. METHOD

This study uses a quantitative descriptive research method. Quantitative descriptive research in this case is intended to explain events and facts in the field related to the effect of rainfall on slopes modelled using finite element method software.

1. Research Place
   The location of this research is the Upper Cisokan Pumped Storage project, specifically at STA 22+300 on the PLN Cisokan – Saguling access road, West Java.
2. Data
   Data was obtained from secondary data on the Upper Cisokan Pumped Storage project in bandung. The data obtained consisted of slope geometry data, borehole log data, laboratory test results, and monitoring data using geotechnical instruments.
3. Data Analysis Techniques
   1. Rain Data Processing
      Rainfall data was obtained from the BBWS Citarum hydrology unit website at the Rongga Station. The data is only available from September 9, 2024. Rainfall patterns were determined by observing trends and then selecting several dates that showed advanced, delayed, uniform, and peak trends.

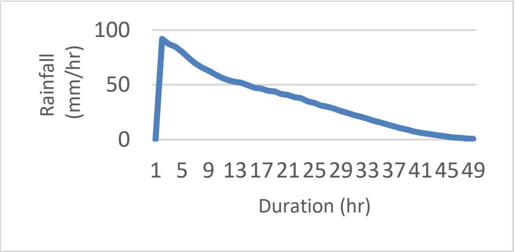

Figure 1. Advance pattern

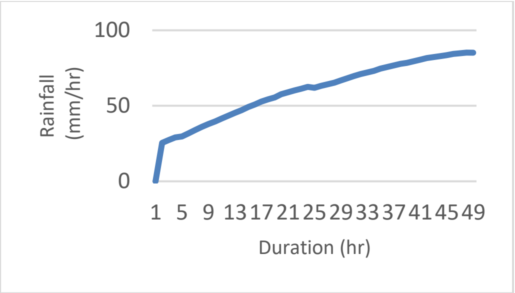

Figure 2. Delayed pattern

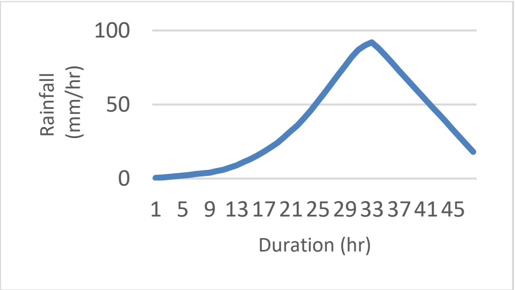

Figure 3. Peak pattern

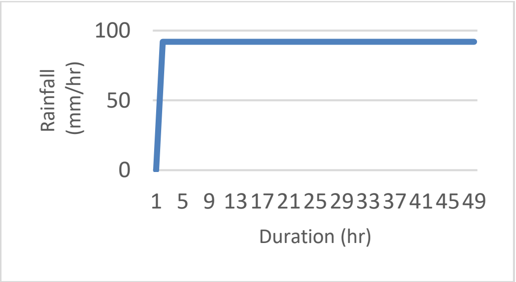

Figure 4. Uniform pattern

   2. Soil Data Processing
      The data available is soil data after the landslide, so the results from the Geostudio software show a safety factor value of less than 1. The cohesion value was then changed to

obtain an estimate of the safety factor before rainfall. The estimated cohesion values:

Table 1. Estimation cohesion values

Slope Gradient	Cohesion (kPa)
55º	22

3. Formulation and numerical modeling processes using Geostudio Seep/W and Slope/W software
   The stages can be traced as follows:
   a. Input
      - Define project
      - For the water option, select the initial head/PWP condition from the water table
      - Enter the duration to be analyzed
   b. Draw slope geometry
   c. Draw initial water table
   d. Boundary condition
      - No flow – water rate, potential seepage review checked to automatically divide the water that will run off
      - Water head – height of the right and left slopes
      - Flux – water flux for rainfall infiltration in units $m^3/sec/m^2$
   e. Assign boundary condition
      - No flow on the right and left sides of the slope above the water table
      - water head on the right and left sides of the slope below the water table
      - flux is drawn on the upper side of the slope as rainfall infiltration
   f. Define material
      - Volumetric water content
      - Permeability function
   g. Assign material
   h. Running
4. Calculating the Safety Factor
   a. Define project add slope/w limit equilibrium
      - Change the time from last to all
   b. Assign material
      - C’
      - ϕ’ (°)
      - γsat
      - γn
      - advance choose calculate from the material Vol.WC
   c. Create slip surface
   d. Start analysis

IV. RESULTS AND DISCUSSION

Borehole soil investigations were carried out at two points with a depth of up to 20 m, several undisturbed soil samples were taken for use as soil laboratory investigation data. Soil stratification was then carried out based on the empirical correlation value of soil consistency. Based on this stratification, it was found that the subsoil at the location was soft to a depth of 2 m. below a depth 2 m, the soil became hard.

Table 2. Soil parameter

Layer	Depth	Thickness	Soil Type	Description	NSPT
1	0 – 2	2	*Clay*	-	-
2	2 – 8	6	Clay	Hard	60
3	8 – 20	12	Batu Lempung	-	-

Soil permeability values are very important in this study. Since soil permeability data are not available, the author used corellations. Permeability values are related to the ability of soil to release water from soil pores, thereby affecting the rate at which soil compacts. Permeability values for each soil layer:

Table 3. Soil Permeability Parameter

Layer	Soil Type	Description	NSPT	K (m/s)
1	*Clay*	-	-	9.57.E-07
2	*Clay*	Hard	60	2.72.E-06
3	Batulempung	-	-	1.E-03

The advance rainfall pattern causes a very rapid response in pore water pressure and a sharper decline in the safety factor in a short period of time. Steep slopes with this rainfall pattern are at high risk of failure in a short period of time. The peak rainfall pattern shows rapid and stable increase in pore water pressure from the outset, but the decline in the safety factor tends to be slower than in the advance pattern. This indicates a cumulative effect, whereby stability degradation continues even after the peak rainfall intensity as decreased. The delayed rainfall pattern shows that the increase in pore water pressure occurs rapidly, but a significant decrease in the safety factor only occurs after the slope has been exposed to high pore water pressure for a sufficiently long period time.

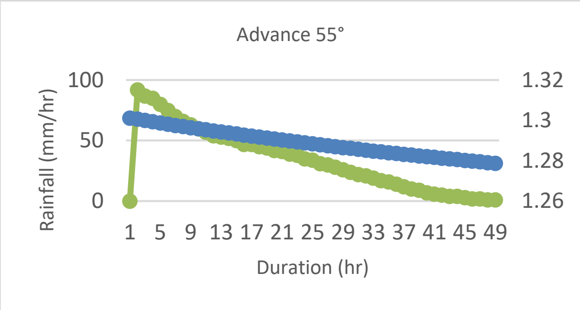

Figure 5. Factor of safety advance pattern

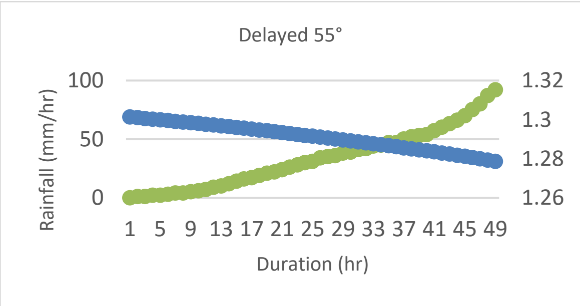

Figure 6. Factor of safety delayed pattern

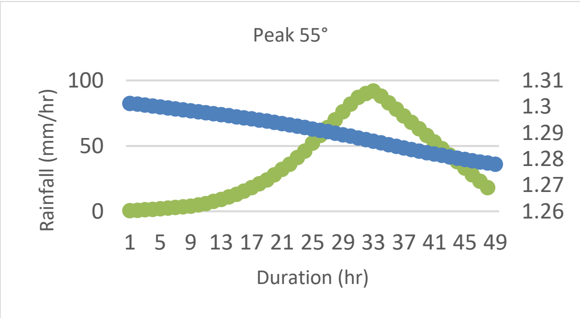

Figure 7. Factor of safety peak pattern

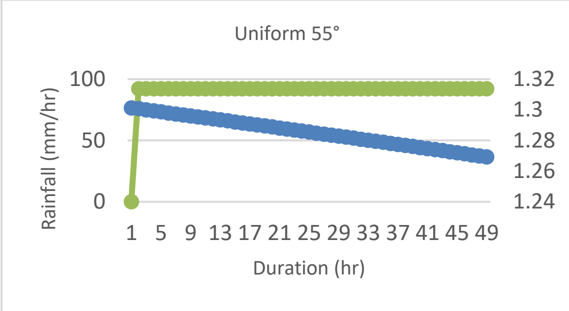

Figure 8. Factor of safety uniform pattern

High intensity rainfall patterns cause rapid saturation and a sharp, immediate increase in pore water pressure. This triggers a rapid decline in the safety factor. This response is dominant on the steep slopes, where the slope does not have time to adapt, and failure can occur within the first few hours. Conversely, rainfall patterns with lower intensity but longer duration cause an instant increase in pore water pressure, but the impact on the safety factor delayed. A significant decrease in the safety factor only occurs after the slope has been exposed to high pore water pressure for a sufficiently long period of time. The failure mechanism in the advantage patterns begins with a rapid increase in the pore water pressure, which directly reduces the effective stress on the soil material. This reduction in effective stress, which is a component of soil shear strength, causes a significant decrease in the safety factor.

V. CONCLUSION

Based on the analysis results, it can be concluded that the advance rainfall pattern causes a very rapid increase in pore water pressure and the most significant decrease in the factor of safety. The most critical condition occurs when the advance rainfall pattern is combined with a 55° slope. The steeper the slope, the more sensitive it becomes to increases in pore water pressure.

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