Water Ponding Duration and It's Impact on Slope Stability-A Case Study of Gunung Batin Toll Road Access

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Abstract

Landslides are the third most frequent disaster in Indonesia. One of the main causes of landslides in Indonesia is heavy rainfall. Rainfall leads to slope saturation, increases pore water pressure, and reduces soil strength. Rainfall can also create ponding, which worsens soil conditions on slopes. Ponding varies in height and duration depending on the location. One landslide caused by ponding occurred at the Terpeka Toll Road, Gunung Batin Access, STA. 1+300. The purpose of this study is to investigate the landslide mechanism influenced by ponding duration on slope stability and to determine appropriate slope protection measures. The research method was carried out through numerical modeling using Geostudio software. Results indicate that under existing conditions, the slope at STA. 1+300 was stable, demonstrated by a safety factor (FK) >1.25 in all analysis methods. The occurrence of ponding increased soil saturation and significantly raised pore water pressure at the initial stage. The increase in pore water pressure reduced soil strength. The longer the ponding duration, the higher the pore water pressure became. At the early stage of ponding (first hour), the slope soil reached its highest saturation, which was assumed to be the initiation of failure at STA. 1+300. At the time of failure, soil strength decreased by 31%, reducing the slope safety factor to 0.976. The recommended slope protection measure is covering the slope with impermeable materials such as HDPE geomembrane. This study concludes that prolonged ponding reduces slope soil strength and increases the likelihood of landslides.

Keywords: Pore Water Pressure, Slope Stability, Water Ponding Duration

I. INTRODUCTION

Indonesia's hilly topography and complex geology make it highly vulnerable to landslides. According to the Indonesian Disaster Information Data (DIBI), from 2015 to 2024 there were 7,093 recorded landslide events across the country. Landslides are the third most frequent disaster in Indonesia, after floods and extreme weather. They disrupt human activities and affect essential functions such as transportation, electricity generation, water supply, and other public services [1]. Moreover, landslides cause economic losses through infrastructure damage and can result in fatalities [2, 3]. In general, landslides are influenced by two main factors: predisposing factors and triggering factors [4]. Predisposing factors are related to material conditions, including slope geometry, soil properties, and groundwater dynamics, while triggering factors include forces that initiate movement such as gravity or external loads [5]. Both can be driven by natural processes, such as heavy rainfall, earthquakes, and steep slopes, or by human activities like deforestation and slope cutting [6].

High rainfall is considered one of the primary causes of landslides in tropical countries such as Indonesia [7]. Rainfall-induced landslides occur almost every year [6], particularly in mountainous areas with residual and colluvial soils [8]. He et al. [9] demonstrated that rainwater infiltration increases pore water pressure, especially on slopes without proper drainage [10]. Rising pore pressure reduces effective stress, which decreases soil shear strength and directly lowers the safety factor [11]. Both rainfall intensity and duration strongly influence slope stability [12, 13]. For example, Awang Ismail et al. [14] reported a significant reduction in slope safety factor after 110 days of continuous rainfall infiltration.

During intense and prolonged rainfall, water not only infiltrates but also generates surface runoff [15]. Runoff, in turn, can worsen slope instability [16]. In some cases, runoff accumulates and creates ponding, particularly on slopes located near rivers. Increased river discharge may cause flooding and ponding on adjacent slopes [17]. Such ponding raises soil saturation, increases pore pressure, soil weight, and seepage forces, while simultaneously reducing mechanical strength—factors that can trigger slope failure [18].

Rainfall- and ponding-induced landslides are common in Indonesia. A notable case occurred along the Terbanggi Besar–Pematang Panggang–Kayu Agung Toll Road (Terpeka Toll Road) at the Gunung Batin access in Lampung. Here, ponding lasted for 19 hours (water level from +16.60 down to +14.50) and caused slope failure at STA. 1+300, as illustrated in Figure 1. This incident highlights the importance of slope stability assessment in areas prone to ponding, especially for infrastructure such as toll roads. Landslides not only endanger road users but also result in major economic losses due to transport disruptions. Ponding has site-specific characteristics, including water depth and duration. Hidayat et al. [18] emphasized that ponding depth affects slope stability, but did not analyze the role of duration. In contrast, Johnston et al. [19] argued that both ponding depth and duration must be considered in slope failure assessments. For this reason, the present study investigates the effect of ponding duration on slope stability and proposes appropriate slope protection measures for STA. 1+300 of the Terpeka Toll Road, Gunung Batin Access.

Fig. 1. Landslide on the Terpeka Toll Road Access to Gunung Batin Sta. 1+300

II. METHOD

The method employed in this study is numerical modeling using GeoStudio 2022. Rainfall and ponding were simulated with the SEEP/W program over the observation period to evaluate their influence on subsurface water flow. The analysis was further extended using the SLOPE/W program to assess slope stability through the factor of safety (FoS) at STA. 1+300, considering the effects of traffic loads, pavement loads, and additional loads in accordance with SNI 8460-2017 on geotechnical design requirements. The landslide mechanism observed at STA. 1+300 served as the basis for determining the appropriate slope protection measures.

A. Research Data

This study employed secondary data, which were obtained from CV. Geotrust and served as the primary reference for the analysis. The collected data include: (1) Soil investigation data, consisting of borehole logs with Standard Penetration Test (SPT) results, Cone Penetration Test with pore pressure measurement (CPTu), and laboratory testing results. These data were used to determine soil stratification and geotechnical parameters applied in the analysis; (2) Site-plan data, providing cross-sectional profiles of the slope at the study location, specifically at STA. 1+300 of the Terpeka Toll Road, Gunung Batin Access; and (3) Hydrological data, which were utilized to assess hydrological conditions affecting the study area, including rainfall intensity, water ponding levels, and ponding duration.

B. Research Procedures

In general, the research process in this study can be outlined as follows:

a) Literature Review, involving the collection of references related to the research topic;
b) Data Collection and Analysis, serving as input for Geostudio 2022;
c) Slope Geometry Modeling using Geostudio 2022;
d) Existing Condition Analysis, to evaluate slope stability under normal conditions;
e) Rainfall Impact Analysis, to assess slope conditions prior to the occurrence of ponding;
f) Ponding Duration Impact Analysis, to evaluate slope conditions under the influence of water ponding.

III. RESULT AND DISCUSSION

A. Data Analysis

1) Slope Cross-Section at STA. 1+300

Based on the site plan data, the cross-sectional profile of the slope at STA. 1+300 was obtained, as illustrated in Figure 2. The slope has an approximate height of ±8.8 m and a width of ±63.2 m.

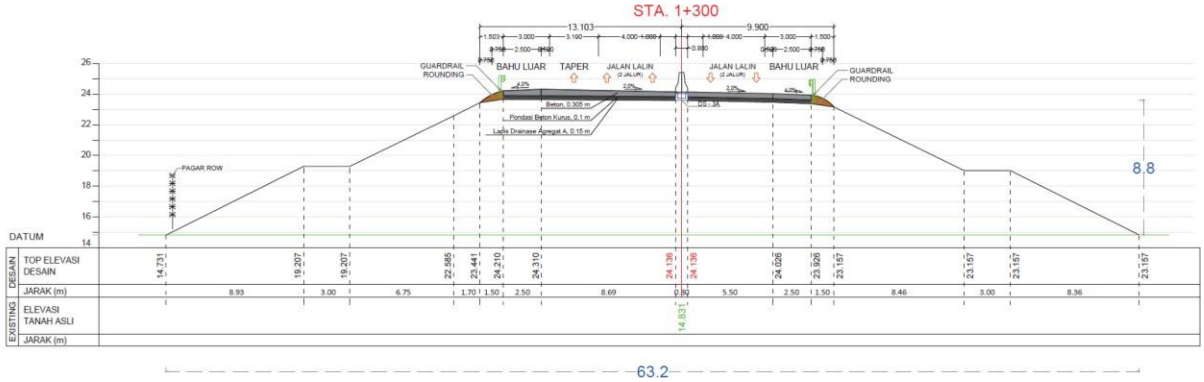


Fig. 2. Cross-Sectional Profile of the Slope at STA. 1+300

2) Soil Stratification and Parameters

Based on the soil data, the stratigraphy of the slope at STA. 1+300 up to a depth of 30 m consists of six layers. The first layer is silty clay with stiff consistency. The second, fourth, and sixth layers are sand with very dense consistency. The third and fifth layers are clay with hard consistency. The groundwater table (GWT) is located at a depth of 6 m below the borehole surface. After identifying the soil layers, an analysis was conducted to determine the soil parameters. At BH-04, an undisturbed sample (UDS) was taken at a depth of 7.5–8 m. The laboratory test results were then used as the reference in determining soil parameter values. For soil layers without laboratory test data, the parameters were determined using correlations with typical values. The results of soil stratification and parameter determination are presented in Table 1.

TABLE I. SOIL STRATIFICATION AND PARAMETERS OF THE SLOPE AT STA. 1+300

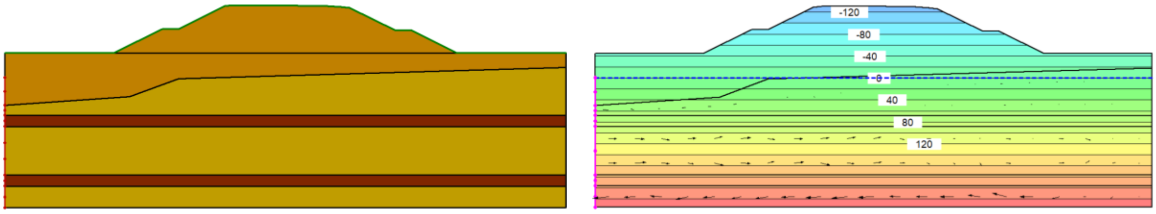
Layer	Depth (m)			Type Soil	k (cm/s)	θ	γsat (kN/m^3)	cu (kPa)	ϕu (°)	c’ (kPa)	ϕ’ (°)
1	0	-	9.5	Clay	2.75E-07	0.49	21	36.4	-	3.64	25
2	9.5	-	13	Sand	1.00E-02	0.35	20.9	-	45	-	45
3	13	-	15	Clay	1.00E-08	0.49	22	200	-	20	35
4	15	-	24	Sand	1.00E-02	0.35	20.9	-	45	-	45
5	24	-	26	Clay	1.00E-08	0.49	22	200	-	20	35
6	26	-	30	Sand	1.00E-02	0.35	20.9	-	45	-	45

3) Slope Loading

The slope loading for an embankment is determined based on SNI 8460:2017 concerning geotechnical requirements and design. Accordingly, the loads acting on the embankment slope of the Terpeka Toll Road, Gunung Batin Access, consist of traffic loads, pavement loads, and additional loads. The road at the study location is classified as Class I (arterial road), resulting in a traffic load of 15 kPa. The pavement at the site is rigid pavement, which, according to MDPI (2021), consists of three layers: a concrete layer, a base layer, and a drainage layer. Therefore, the pavement load is determined to be 12.22 kPa. An additional load of 10 kPa must also be considered in the analysis. Thus, the total load acting on the slope of the Terpeka Toll Road, Gunung Batin Access, amounts to 37.22 kPa.

B. Existing Condition Analysis

The existing condition analysis was carried out using the SEEP/W program in steady-state mode to examine the distribution of pore water pressure in the soil based on the groundwater table (GWT) elevation. The boundary condition (BC) was defined as total water head, with the input set at a groundwater table depth of 6 m below the borehole testing surface. The application of the boundary condition and the simulation results are presented in Fig. 3.

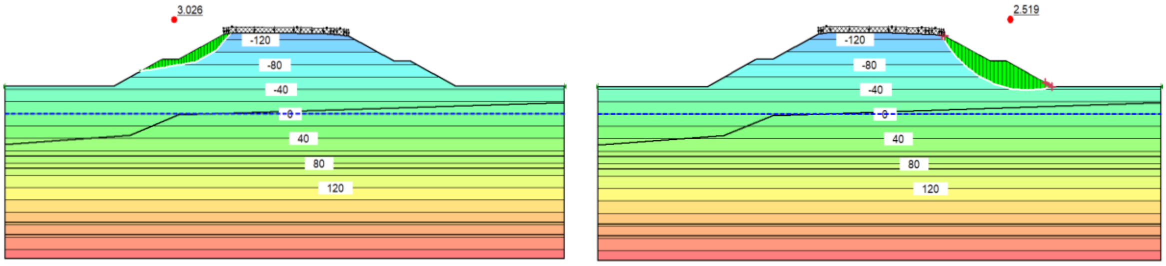


(a) (b)

Fig. 3. SEEP/W Analysis of Existing Conditions: (a) Boundary Condition Analysis; (b) Simulation Results

Based on the analysis results, the pore water pressure values at the STA. 1+300 slope under existing conditions were obtained. The zone above the groundwater table represents a negative pore water pressure zone, with a minimum value of –130.63 kPa. Conversely, the zone below the groundwater table exhibits positive pore water pressure, with a maximum value of 235.37 kPa. The deeper the soil layer, the higher the pore water pressure value [20]. The analysis was then continued using the SLOPE/W program to evaluate slope stability through the factor of safety (FoS). The analysis was performed on both the left and right sides of the slope using the Morgenstern-Price, Bishop, Janbu, and Ordinary methods. The potential slip surface was modeled using the fully specified method for the left side of the slope and the entry-exit method for the right side. A uniform surcharge load of 37.22 kPa was applied to the slope surface in the stability analysis. The analyses were conducted under both total (undrained) and effective (drained) conditions.

As an example, the results of the SLOPE/W analysis using the Morgenstern-Price method under effective conditions are presented in Fig. 4. Based on the analysis, the FoS value for the left side of the STA. 1+300 slope was 3.025. A similar analysis conducted on the right side of the slope yielded an FoS value of 2.519. A complete summary of all existing condition analyses for the STA. 1+300 slope is presented in Table 2.



(a) (b)

Fig. 4. Slope Stability Analysis under Existing Effective Conditions using the Morgenstern-Price Method: (a) Left Slope; (b) Right Slope

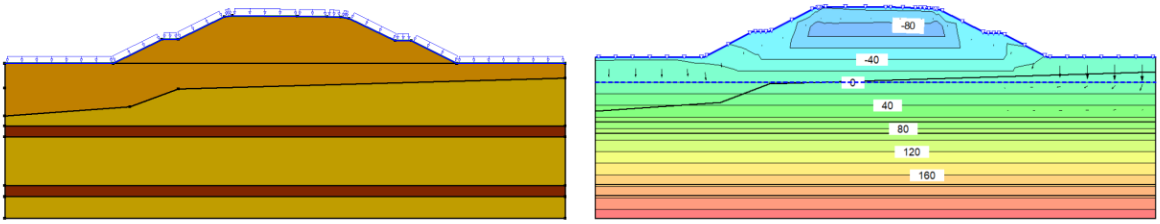
TABLE II. FACTOR OF SAFETY OF THE SLOPE UNDER EXISTING CONDITIONS

Conditions	**Analysis Method**	**Slope STA. 1+300**	
		Left	**Right**
Undrained	Morgenstern-Price	4.038	2.523
	Bishop	4.83	2.523
	Janbu	3.733	2.423
	Ordinary	3.887	2.523
Drained	Morgenstern-Price	3.026	2.519
	Bishop	3.586	2.525
	Janbu	2.81	2.33
	Ordinary	2.816	2.406

Based on the results of the slope stability analysis under existing conditions, it can be observed that the slope at STA. 1+300 is more critical under effective stress conditions. This indicates that the long-term stability of the slope decreases as pore water pressure dissipates over time. Therefore, the effective stress condition was used as the basis for further analysis in this study. Table 2 shows that the lowest factor of safety (FoS) values under effective conditions were obtained using the Janbu method, with FoS values of 2.81 on the left slope and 2.33 on the right slope. Referring to the Bowles classification (21), both FoS values fall into the safe category as they are greater than 1.25. Based on these findings, the Janbu method was selected for subsequent slope stability analyses in this study.

C. Rainfall Impact Analysis

Water ponding was assumed to occur immediately after rainfall; therefore, an analysis of rainfall influence was conducted first. This analysis employed the Seep/w – Transient program to evaluate the distribution of pore water pressure during a 9-hour rainfall event. The boundary condition (BC) applied in this analysis was a water flux function with input derived from rainfall intensity values. The rainfall intensity was determined based on hydrological data and historical rainfall records in the study area. The application of BC and the results of the rainfall impact analysis are presented in Fig. 5.



(a) (b)

Fig. 5. Seep/w Analysis of Rainfall Influence over 9 Hours: (a) Boundary Condition; (b) Simulation Results

Based on the analysis results, it can be observed that the pore water pressure within the slope increased. This increase was triggered by the infiltration effect of rainfall. Rainfall lasting for 9 hours raised the minimum pore water pressure of the slope to –96.205 kPa, representing an increase of 34.425 kPa compared to the existing condition. The slope material at STA. 1+300 consists of clay soil, which is characterized as impermeable and has low permeability, making water flow through it difficult. Consequently, the analysis shows that significant changes in pore water pressure occurred primarily at the surface of the slope. To provide a clearer representation of the pore water pressure distribution, several observation points were established on both the left and right sides of the slope. These observation points were placed at the crest, the mid-slope, and the toe of the slope. The placement of these observation points is illustrated in Fig. 6.

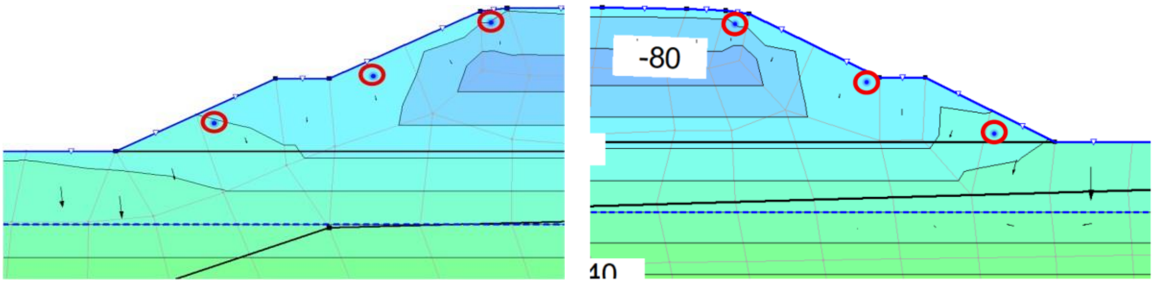
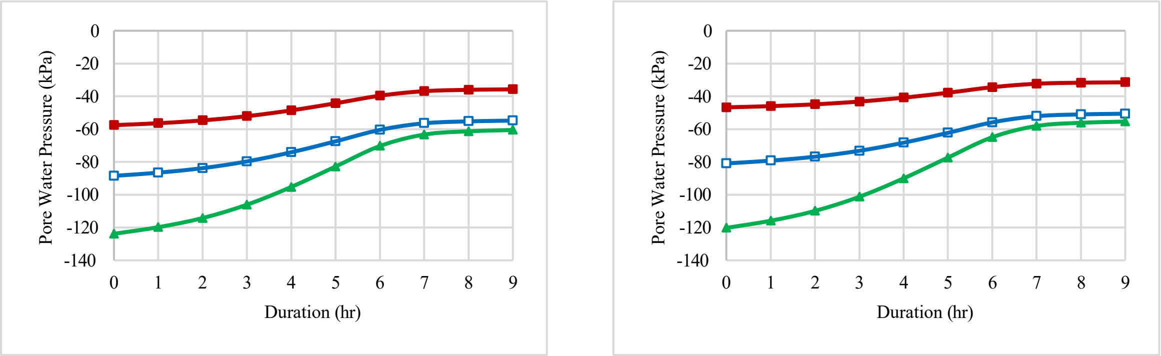


Fig. 6. Observation Points on the Slope at STA. 1+300

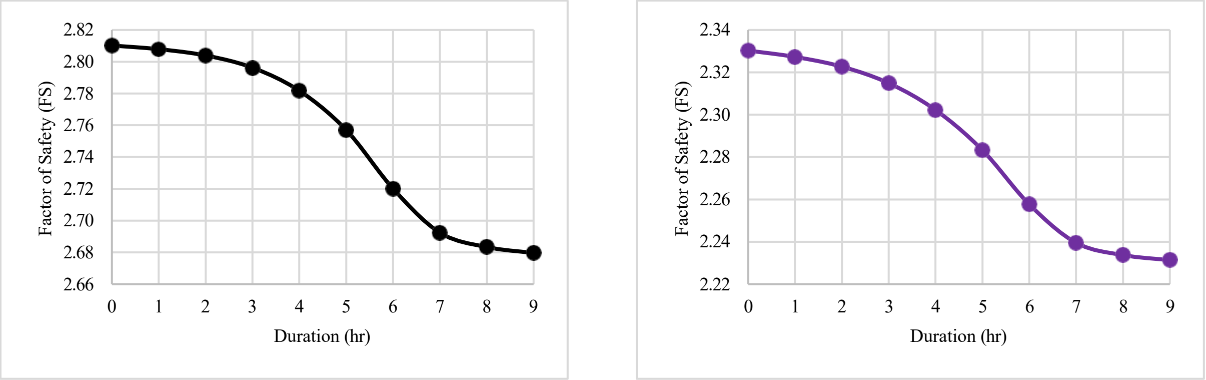
The analysis results indicate that both the left and right sides of the slope at STA. 1+300 experienced an increase in pore water pressure. This increase became more significant with the rising intensity and duration of rainfall. The distribution of pore water pressure values on both the left and right sides of the slope is presented in Fig. 7.



(a) (b)

Fig. 7. Distribution of Pore Water Pressure (u) on the Slope Surface Due to Rainfall: (a) Left Slope; (b) Right Slope

The analysis was then continued using the Slope/W program to evaluate the slope stability under the influence of rainfall. The stability analysis was carried out using the Janbu method, with the slip surfaces defined in the same manner as in the existing condition analysis. The results are presented in graphical form, as shown in Fig. 8. Based on the analysis, it was found that the factor of safety (FS) decreased as the pore water pressure increased in both the left and right slopes at STA. 1+300. However, the FS values under rainfall conditions remained relatively high, with FS > 2. Therefore, referring to the same criteria applied in the previous analysis, the slope at STA. 1+300 is still considered stable and safe.



(a) (b)

Fig. 8. Factor of Safety Analysis Under 9-Hour Rainfall: (a) Left Slope; (b) Right Slope

D. Water Ponding Duration Impact Analysis

The analysis of ponding duration effects was carried out using the Seep/W – Transient program. Several simulations were conducted with different ponding durations, namely 6 hours (red line), 19 hours (blue line), and 4 days (purple line). These variations were applied to evaluate slope conditions under rapid to prolonged ponding scenarios. In this study, ponded water was assumed to recede linearly over time. The boundary condition applied in this analysis was a water total head function, with input values based on the distribution of ponding height over the duration of occurrence. The analysis results for the left slope are presented in the graph shown in Fig. 9, while those for the right slope are illustrated in Fig. 10.

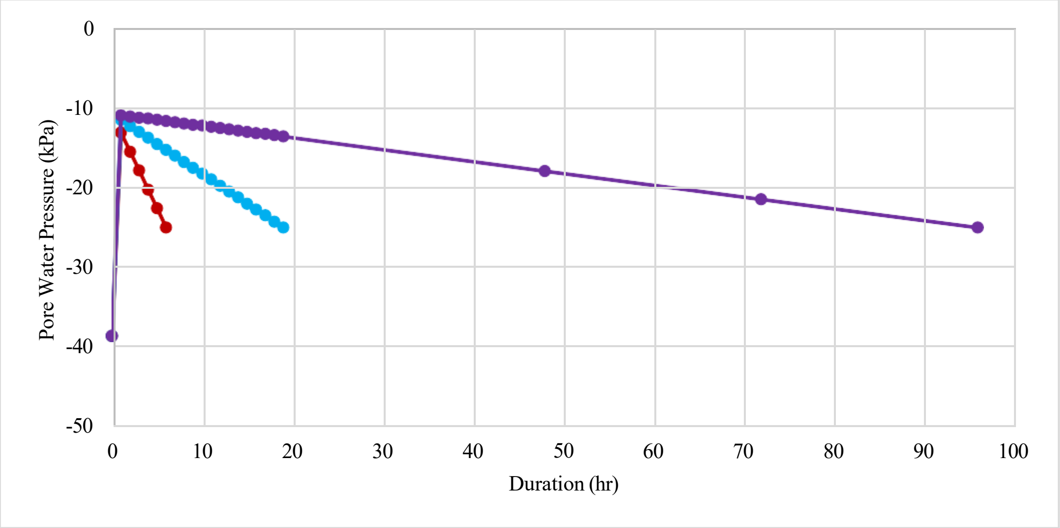


Fig. 9. Results of Seep/W Analysis of the Effect of Ponding Duration Variations on the Left Slope

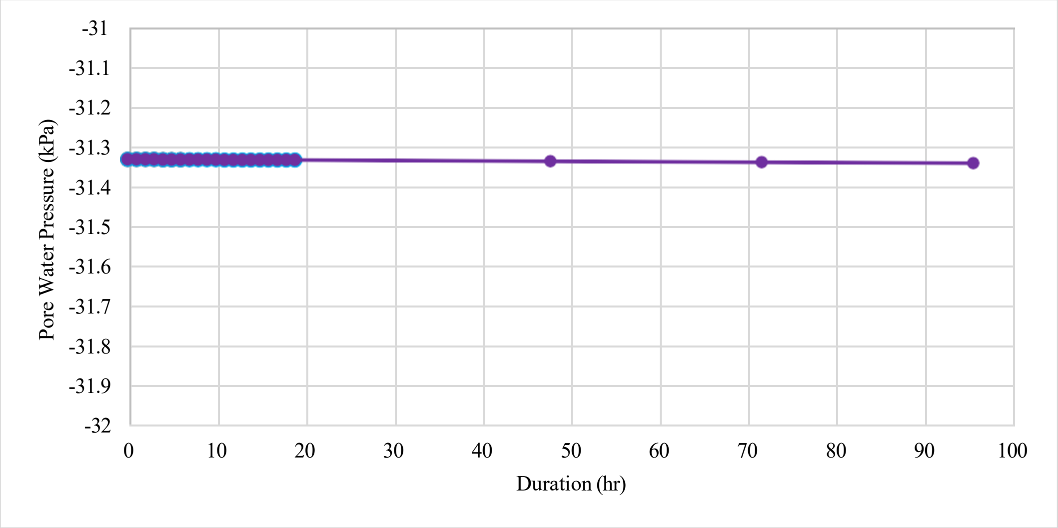


Fig. 10. Results of Seep/W Analysis of the Effect of Ponding Duration Variations on the Right Slope

Based on the analysis results for the left slope, as shown in the graph, it can be observed that the duration of ponding significantly affects the pore water pressure values. For comparison, the Seep/W analysis results at the 6th hour show that the pore water pressure values for ponding durations of 6 hours, 19 hours, and 4 days were –25.064 kPa, –15.323 kPa, and –11.7 kPa, respectively. These results indicate a considerable difference among the three conditions. The greatest increase in pore water pressure occurred in the 4-day ponding analysis, while the smallest increase was observed in the 6-hour ponding analysis. Therefore, it can be concluded that the longer the ponding duration, the higher the pore water pressure on the slope at STA. 1+300.

On the other hand, the analysis of the right slope shows no significant changes in pore water pressure values due to ponding on the left slope. Even ponding lasting up to 4 days did not affect the right slope. This condition is attributed to the clay soil characteristics of the slope, which make water infiltration and flow extremely difficult. Consequently, the right slope remained unaffected.

The analysis was then continued using the Slope/W program to evaluate slope stability under ponding conditions, both on the left and right slopes. The results are presented in Fig. 11 for the left slope and Fig. 12 for the right slope. The findings show that, at the 6th hour of ponding, the factor of safety (FoS) on the left slope varied depending on the ponding duration. The FoS values for ponding durations of 6 hours, 19 hours, and 4 days were 2.644, 2.595, and 2.57, respectively. It is evident that the 4-day ponding duration resulted in the lowest FoS, while the 6-hour duration yielded the highest. This trend is inversely proportional to the pore water pressure values obtained from the ponding duration variations. Meanwhile, the FoS on the right slope remained unchanged throughout all ponding durations, even up to 4 days.

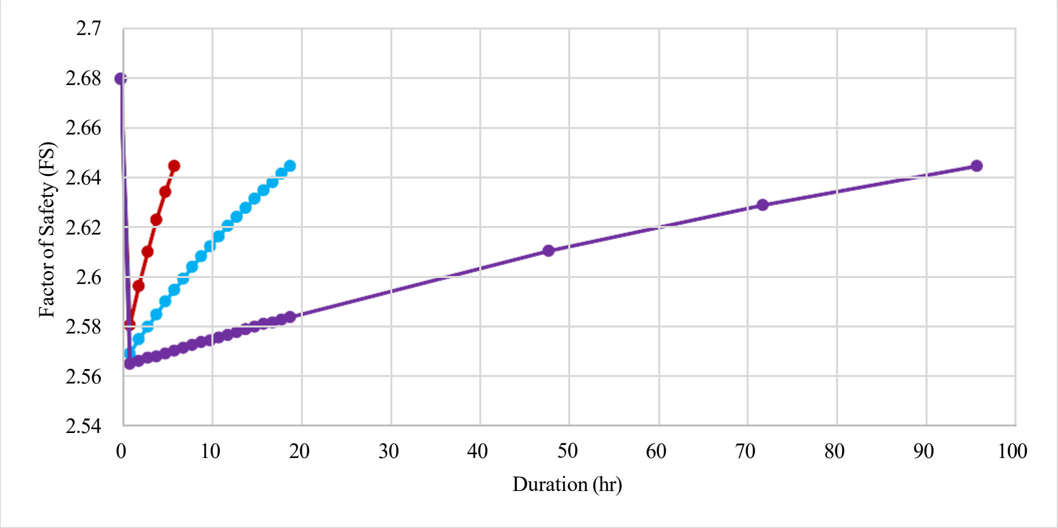


Fig. 11. Slope/W Analysis Results of the Effect of Ponding Duration Variations on the Left Slope

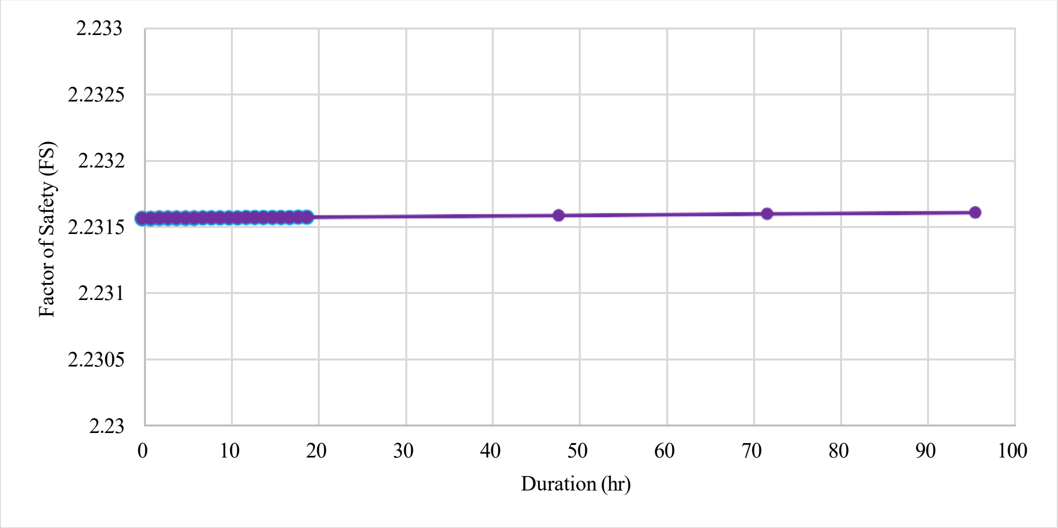


Fig. 12. Slope/W Analysis Results of the Effect of Ponding Duration Variations on the Right Slope

E. Impact of Rainfall and Ponding on Slope

The condition of the slope at STA. 1+300 under normal circumstances, based on the existing condition analysis, shows a stable and safe factor of safety (FoS) with values greater than 1.25. Infiltration caused by rainfall on the slope at STA. 1+300 leads to soil saturation. The higher the rainfall intensity and duration, the more saturated the slope soil becomes. The embankment slope at STA. 1+300 consists of silty clay soil, which, due to its low permeability, hinders water flow. Consequently, rainfall infiltration on the slope surface is unable to percolate deeply into the slope body. Rainfall infiltration therefore significantly affects the slope surface, which explains why many rainfall-induced landslides often occur in the near-surface zone. As a result of rainfall, the slope becomes more saturated, indicated by the increase in pore water pressure. Saturated soils also possess greater unit weight compared to soils in the existing condition. Moreover, the increase in pore water pressure directly reduces the effective stress in the soil, which decreases progressively as pore water pressure increases. This reduction in effective stress leads to a corresponding decrease in the soil's shear strength to resist the increasing load from saturation. In addition, based on the principles of unsaturated soil mechanics, soils possess additional strength due to suction. However, as the soil approaches saturation, suction decreases, thereby eliminating the additional strength and further reducing slope stability.

Following the rainfall event, a hydrological study on the Gunung Batin Access Road landslide reported ponding with a duration of 19 hours and a return period of 100 years. The analysis of ponding with a 19-hour duration indicates that the slope experienced further saturation, particularly at the left toe of the slope. An increase in pore water pressure occurred within the first hour of ponding. The presence of ponding exacerbates slope instability. Infiltration due to ponding increases the soil weight, raises pore water pressure, and induces seepage forces, all of which collectively weaken the soil's mechanical strength [18]. Fundamentally, landslides occur due to a decrease in resisting forces and/or an increase in driving forces. Ponding contributes to both mechanisms, namely by reducing resisting forces through the weakening of interparticle bonds, and by increasing driving forces due to the added weight of saturated soil. Based on the slope/w analysis of the 19-hour ponding event, the factor of safety (FoS) was found to decrease significantly within the first hour of ponding. Prior to ponding, the FoS was 2.679, whereas after one hour of ponding, it decreased to 2.569. However, when referring to Bowles' classification [21], the slope stability at STA. 1+300 remains within the stable and safe category. Therefore, further analysis is required to model the actual landslide event.

F. Back-analysis of Landslide at Slope STA. 1+300

Based on the analysis of the effect of ponding duration, it can be concluded that the slope at Terpeka Toll Road, Gunung Batin Access, STA. 1+300 has not yet indicated the occurrence of slope failure due to rainfall and ponding. This may be attributed to the inaccuracy of the input shear strength parameters, namely the cohesion (c') and internal friction angle (ϕ') values used in the analysis. Therefore, in order to obtain results that better represent the actual landslide event at Terpeka Toll Road, Gunung Batin Access, STA. 1+300, a back-analysis was performed to determine the values of c' and ϕ' at the time of failure. In this study, the back-analysis was carried out by modifying the soil parameters c' and ϕ' through a trial-and-error approach until the factor of safety (FoS) dropped below 1.

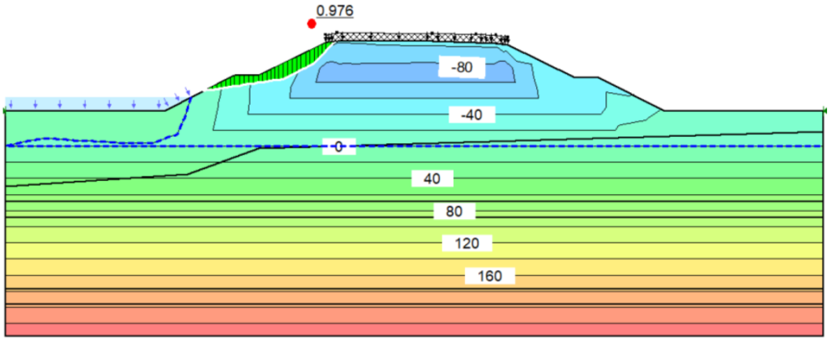


Fig. 13. Landslide Analysis Results on the Slope at STA. 1+300

The results of the analysis are considered to represent the landslide condition at STA. 1+300. Based on the previous analysis, it was found that the soil reached its highest level of saturation during the first hour of ponding. Therefore, at this duration, the slope at STA. 1+300 is assumed to have experienced failure. Figure 13 shows that the slope safety factor (SF) was 0.976 at the time of failure. This value was obtained through a reduction of the soil shear strength parameters (c′ and ϕ′) by 31% from the initial estimated values, resulting in c′ = 2.51 kPa and ϕ′ = 17° during the landslide event.

G. Slope Protection Measures

According to Purba et al. [22], slope protection methods must be implemented based on the mechanism of landslide occurrence. On a slope, two primary forces act simultaneously, namely the driving force and the resisting force. The driving force is the tangential force generated by the weight of the soil/rock mass, while the resisting force is the shear resistance of the soil/rock. Slope failure occurs when the driving force exceeds the resisting force. Therefore, the principle of slope failure mitigation is to reduce the driving force and/or increase the resisting force. The landslide at the Terpeka Toll Road, Gunung Batin Access STA. 1+300, is assumed to have occurred due to ponding at the toe of the left slope. This ponding was caused by the overflow of the Way Terusan River, which obstructed water flow at the box culvert and resulted in backwater. The ponding condition increased pore water pressure and, due to the direct contact between ponded water and the slope soil, led to a reduction in soil strength. As the soil strength decreased, the slope lost its resisting capacity, thereby triggering slope failure along this section of the road. Consequently, the most appropriate slope protection method is to cover the slope surface with impermeable materials to prevent water infiltration into the slope body, thereby stabilizing pore water pressure and maintaining soil strength. One effective method is the application of geosynthetic materials, particularly geomembranes. Various types of geomembranes are available, such as High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), and Polyvinyl Chloride (PVC). In Indonesia, HDPE geomembranes are most commonly used because of their resistance to corrosion, ultraviolet radiation, and chemical exposure.

IV. CONCLUSIONS

Based on the results of the analysis of the effect of ponding duration on slope stability at the Terpeka Toll Road, Gunung Batin Access STA. 1+300, the following conclusions can be drawn:

- The existing condition of the slope at the Terpeka Toll Road, Gunung Batin Access STA. 1+300, is classified as stable for both the left and right slopes. The effective condition analysis produced more critical safety factor (FK) values compared to the total condition analysis. The safety factor values obtained from all methods, influenced by traffic load, pavement, and additional loads, yielded FK > 1.25.
- Ponding duration significantly affects slope stability. The analysis of different ponding durations showed that the 4-day ponding duration resulted in the highest increase in pore water pressure. Conversely, the 6-hour ponding duration produced the lowest pore water pressure. The longer the ponding duration, the higher the pore water pressure within the slope. The increase in pore water pressure leads to a reduction in effective stress, thereby reducing the soil shear strength. The reduction in shear strength consequently decreases the safety factor (FK) of the slope.
- The landslide at STA. 1+300 of the Terpeka Toll Road, Gunung Batin Access, occurred due to ponding. The ponding condition caused soil saturation, increased pore water pressure, and direct contact between ponded water and slope soil, which reduced soil strength (decreasing c’ and ϕ’ values). The landslide is assumed to have occurred under the most saturated soil condition, specifically during the first hour of ponding. Based on the back-analysis, at this stage a shear strength reduction of 31% from the initial estimated values occurred. This reduction resulted in a safety factor (FK) of 0.976, with c’ = 2.51 kPa and ϕ’ = 17°.
- The landslide at STA. 1+300 of the Terpeka Toll Road, Gunung Batin Access, was triggered by ponding at the toe of the left slope. This ponding was caused by the overflow of the Way Terusan River, which

obstructed water flow at the box culvert, leading to backwater. Therefore, slope protection efforts are required to prevent an increase in pore water pressure due to ponding. One recommended method is the application of impermeable surface layers, such as HDPE geomembrane material.

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