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Analysis of Slope Stability Based on The Effect of Rainfall on the Lombok International Airport (Bil) - Mandalika Road Sta 10+375 to Sta 10+550

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ABSTRACT

BIL - Mandalika Bypass Road connects Lombok International Airport (BIL) to Mandalika Special Economic Zone (KEK). This road has a length of 17.3 KM and was completed in 2021. The construction of this section can cut the travel time from 45 minutes to 15 minutes from BIL to the Mandalika area. In early February 2023 when it was rainy season, the BIL - Mandalika Bypass Road surface at sta 10+375 s/d 10+550 experienced cracks, and temporary maintenance was carried out to keep the road functional. At the end of May 2023, the cracks became worse and there was a decrease of road surface up to 1.2 to 1.8 meters. Based on the soil test report in the field when the landslide occurred, the groundwater level is 7.5 meters from the road surface. Laboratory test results show that sandy silt is more dominant on subgrade soil. Besides that, the 2024 planning report does not include rain parameters on slope stability reinforcement's design. The purpose of this study is to determine the effect of rain and groundwater levels on landslides and subsidence of the BIL - Mandalika STA 10+375 - 10+550 road in 2023. The simulation results of SEEP/W and SLOPE/W showed that the landslide or subsidence was caused by rain, where the slope safety factor before the landslide was 1.192 and decreased to 0.986 after rainfall happened from January 2023 to February 2023.

Keywords : slope stability, rain intensity, stability factor, Mandalika, SEEP/W, SLOPE/W, pore water pressure

INTRODUCTION

BIL - Mandalika Bypass Road was built from 2020 to 2021 (inaugurated by President Joko Widodo in November 2021 and FHO in December 2022. This road has a length of 17.3 KM and connects Lombok International Airport (BIL) with the Mandalika Special Economic Zone (SEZ). SEZ is an area with certain boundaries within the jurisdiction of the Unitary State of the Republic of Indonesia which is determined to carry out functions with certain economic benefits (Law Number 39 of 2009). The main objective of SEZ development is to create economic growth, and equitable development, and increase the nation's competitiveness. Mandalika SEZ was established through Government Regulation Number 52 of 2014 to become a Tourism SEZ. The Mandalika SEZ program is expected to accelerate the development of the tourism sector in West Nusa Tenggara Province.

As a connecting route for the Mandalika SEZ area, the BIL - Mandalika Bypass has an important role as transportation infrastructure, where the construction of the section can cut travel time from 45 minutes to 15 minutes from BIL to the Mandalika area. Bypass road has 4 lanes and 2 directions with a median width of 4 meters (type 4/2 D) and a road width of 14 meters. The bypass road is also equipped with 2 bridges, 11 overpasses, and 3 pedestrian bridges (JPO) which were built to facilitate traffic flow and access for residents. The BIL - Mandalika Bypass Road section is a national road with section number 42.050 which is determined based on the Decree of the Minister of Public Works and Public Housing Number 1688 of 2022. In addition, the BIL - Mandalika Bypass Road is also a primary arterial road based on the Decree of the Minister of PUPR.

Figure 1. Landslide location, District of Pujut, Central Lombok, NTB

In early February 2023 (2 months after FHO), BIL - Mandalika Bypass Road surface at sta 10+375 s / 10+550 experienced cracks, and temporary treatment was carried out, namely by closing the cracks and leveling road surface to reduce difference in height on the road surface so that the road remained functional. At the end of May 2023, the cracks became worse and there was a decrease of up to 1.2 to 1.8 meters. Until now, the treatment carried out is to keep the road functional. From planning report on 2023, in 2024 the landslide section of the road is planned to be handled by replacing part of the embankment using foam mortar so that the embankment load becomes lighter. in the planning design report, the influence of rain infiltration is not considered even though the landslide occurred during the rainy season.

Rainwater infiltration has a significant impact on slope stability, rainwater that seeps into the slope will increase soil moisture content, the increase of pore water pressure will reduce soil effective pressure, and soil shear strength also decreases which results in decreased safety factor (Birasa, 2022). According to Birasa (2022), slope stability is determined by rain intensity, rain duration, and soil permeability. The treatment carried out in 2024 is different from the design plan made in 2023, where the slope reinforcement plan in 2023 uses foam mortar while the implementation in 2024 uses secant piles and subdrains.

LITERATURE REVIEW

Safety Factor

A slope is a land surface that slopes or forms a certain angle of inclination in a horizontal plane and is unprotected (Das, 2010). Slopes can experience collapse caused by several things, According to J.M. Duncan (2014), the cause of the occurrence of landslides on the slope is the soil shear strength (shear strength) is smaller than the soil shear pressure (shear stress), this condition occurs in two ways, namely:

1. Decrease in shear strength of the soil
2. Increased shear stress in the soil

The slope safety factor (SF) is the ratio of the restraining force to the driving force. It indicates how much the restraining force is compared to the driving force. When the Factor of Safety is close to 1, the restraining and driving forces are balanced, and failure is assumed to be imminent with only a slight reduction in the restraining force or a slight increase in the driving pressure (Darwis, 2018). There are many methods for analyzing slope stability, namely Limit Equilibrium Methods, Finite Element Methods, Finite Difference Methods, and Discrete Element Methods. According to Irwandi Arief (2016), Limit Equilibrium Methods (LEM) is the most popular method used in the stability analysis of translational and rotational sliding type slopes. It is relatively easy and simple to use and has proven its reliability in engineering practice over the years.

There are several methods in slope stability analysis with Limit Equilibrium Method (LEM), some fulfill all equilibrium conditions (Morgenstern and Price - 1965, Spencer - 1967, Sarma - 1973, and Janbu - 1968) and some do not fulfill all equilibrium conditions (Bishop's Modified - 1955). Although Bishop's Modified method does not satisfy all equilibrium conditions, the resulting Safety Factor value is as accurate as the Finite Element Method. According to Bowles (1989), slope stability is classified based on the Safety Factor (SF) value as follows:

1. SF >= 1.25: the slope is stable (safe)
2. SF = 1.07 - 1.25: Landslides have occurred (critical slope)
3. SF < 1.07: Landslides occur frequently (unstable slope)

Rainfall Intensity

Rainfall conditions and intensity are classified into 5 categories (Suyono Sosrodarsono, 2003) according to Table 1. According to Atikah (2017), the average rainfall intensity in Indonesia has duration of 5 - 7 hours, so in calculating the hourly rainfall intensity from the daily average using this range of values. The rainfall data available on the BMKG official website is only daily rainfall data, therefore for further analysis, it needs to be converted first into hourly rainfall intensity using the Mononobe method (Atikah, 2017).

$$i = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{2/3} \qquad \dots (1)$$

Where :

i = rainfall intensity (mm/hour; m/hour)

t = time/rainfall duration (hour)

R_{24} = maximum rainfall height at 24 hours (mm)

Table 1. Rainfall Classification

Rainfall Classification	**Rainfall Intensity (mm)**	
	1 hour	**24 Hours**
Very Light Rainfall	< 1	< 5
Light Rainfall	1 – 5	5 – 20
Normal Rainfall	5 – 10	20 – 50
Heavy Rainfall	10 – 20	50 – 100
Very Heavy Rainfall	> 20	> 100

Source: Suyono Sosrodarsono (2003)

Seepage Analysis

Rainfall infiltration analysis using Geostudio's SEEP/W program. SEEP/W is a finite element modeling program used to evaluate subsurface seepage on slopes and its effect on soil pore water pressure. To use SEEP/W, requires slope cross-section geometry, soil property data, groundwater table (GWT) location, rainfall data, and boundary conditions. In SEEP/W infiltration analysis there are two types of analysis, namely transient and steady state. Steady-state analysis is used to determine the initial conditions and transient analysis is to analyze the change in pore water pressure from rainfall infiltration. To run the transient type of analysis, the volumetric water content (VWC) function and hydraulic conductivity function are required. The volumetric water content (VWC) function is a function that determines the relationship between volumetric water content and matric suction (negative pore water pressure) of soil material. While the hydraulic conductivity function is a function that determines the relationship between soil permeability and matric suction.

To be able to determine the VWC function, there are many methods that can be used, namely the volumetric water content data point function, Fredlund-Xing function, or Van Genuchten function. In this study, the Fredlund-Xing function is used because this function is the most used in VWC estimation, which requires several parameters to be inputted, namely the a, n, and m parameters. In addition to these parameters, the saturated volumetric water content parameter is also required, which is the soil water content in saturated conditions (S = 1). The next step is determining the hydraulic conductivity function using the VMC function and soil permeability for each soil layer. According to Jinchun Chai (2020), the parameters a, n, and m in the Fredlund-Xing function can be estimated using soil physical property data commonly tested in the lab using the following equation:

$$m = [(-2{,}4\ x\ 10^{-4})\ x\ (FF.PI)] + 2{,}22 \text{ for plastic soil} \quad \dots (2)$$

$$m = 1{,}67\ x\ \left(\frac{FF}{D_{15}/D_0}\right)^{-0{,}119} \text{ for non plastic soil} \quad \dots (3)$$

$$n = 0{,}952\ x\ \left\{\left[log\left(D_{60}/D_{30}\right)\right]^{-1}\right\}^{1{,}185} \quad \dots (4)$$

$$a = exp^{0{,}198\left(k_s/k_1\right)^{-0{,}184}} \text{ in kPa} \quad \dots (5)$$

Where,

k_1 = 1 m/s
D_0 = 1 mm
FF = fraction that passes the 200-sieve analysis
PI = plasticity index
D_{15} = diameter of soil particle passes 15%
D_{30} = diameter of soil particle passes 30%
D_{60} = diameter of soil particle passes 60%
k_s = soil permeability coefficient (m/s)

Slope Stability Analysis

SLOPE/W is a computer program used to perform slope stability analysis. SLOPE/W is part of GEOSTUDIO and is generally used in conjunction with the SEEP/W module to analyze the effect of rainfall and subsurface water flow on the stability of embankment slopes. The data required to run a slope stability analysis with SLOPE/W are the slope cross-section geometry, soil property data for each soil layer on the slope and subgrade, and the pore water pressure output from the previously run SEEP/W. The method used in SLOPE/W slope stability analysis is the limit equilibrium method (LEM), which is a widely used method. The accuracy of LEM is not much different from the finite element method (FEM), and the most accurate LEM method and closest to the results of the FEM analysis is Bishop's Modified (discussion of subchapter 2.1). The output of SLOPE/W is the minimum factor of safety (SF) and the critical slip plane of the slope.

RESEARCH METHODE

After the data required in this study was collected, a slope geometry model was made according to the initial design before the landslide occurred in SEEP/W for rain infiltration analysis and in SLOPE/W for slope stability analysis. Then the data required for SEEP/W and SLOPE/W analysis were inputted for each soil layer. Next, the boundary condition configuration is set up in SEEP/W to determine the groundwater table and the rain infiltration on the slope. Then the SEEP/W model was validated by running a simulation using rainfall measured in the field. Then the output of the SEEP/W simulation is the soil pore water pressure which is then compared with the measurement results of negative pore water pressure changes in the field with the same rainfall. After the simulated negative pore water pressure and the measurement results in the field are declared as valid, then the SEEP/W and SLOPE/W models are used to perform slope stability analysis based on the predetermined rainfall model. There are three rainfall models used in running the simulation, namely model I without rain, model II rainfall during January 2023 - February 2023, and model III using single intensity rainfall in normal, heavy, and very heavy rainfall, model IV to VIII uses a combination of rainfall intensity (Table 2). Model II is used to perform back analysis to prove that the cause of the landslide is rain based on the safety factor value (SF<1). Furthermore, model III is used to see the stability of the slope when getting rain with a certain intensity and duration.

Table 2. Rainfall Model for Simulation

No	Rainfall Model	Description	Rainfall Intensity (mm/day)
1	I	No rainfall	0
2	II	Rainfall January – February 2023	0 – 71,2
3	III	Single Rainfall	20; 40; 80; 94,77; 114,15
3	IV	Heavy Rainfall in short duration (4 hours)	114
4	V	Rainfall 40 mm for 3 weeks, no rainfall for 10 days, rainfall 25 mm for 10 days	40, 0, 25
5	VI	Normal rainfall is 20 mm for 3 weeks, no rainfall for 10 days, rainfall 20 mm for 30 days	20, 0, 20
7	VII	Normal Rainfall is 20 mm for 20 days and heavy rainfall is 94,77 mm for 1 day	20, 94.77

Normal rainfall is the average rainfall that occurs from January 2023 to February 2023, while heavy and very heavy rainfall is taken from the 2-year and 4-year rainfall return periods (Figure 2). The continuous single-intensity rainfall model is to see the changes in slope stability (factor of safety) based on the intensity and time required to reduce the slope factor of safety. The slope stability analysis with the combination rainfall model aims to see the increase and decrease of soil pore water pressure and slope safety factor caused by rainfall with changing intensity at a predetermined duration and to see which combination of rainfall has the most effect on reducing the slope safety factor.

DATA COLLECTION

Data is collected from Balai Pelaksanaan Jalan Nasional Nusa Tenggara Barat (BPJN NTB) based on soil investigation at STA 10+475 in March 2023 for SEEP/W input as shown in Table 3 and data for SLOPE/W as shown in Table 4.

Table 3. Data Soil Parameter For SEEP/W

No	Depth (m)			Type of Soil	ϴs = n x S	Ks (m/det)	Saturated Wc (cm^3/cm^3)
1	0	-	2,4	White silty sand and gravel, dense	42,451	5,17E-03	44
2	2,4	-	4,6	White silty sand and gravel medium	23,779	5,17E-03	43
3	4,6	-	6,6	Brown sandy silt and gravel, dense	44,313	5,65E-04	48
4	6,6	-	9,4	Brown sandy and clayey silt, hard	46,963	6,70E-09	54
5	9,4	-	14,5	Gray silty clay, stiff	48,535	7,70E-08	56
6	14,5	-	18,0	Brown clayey silt, hard	44,392	3,60E-08	53
7	18,0	-	24,0	Grey Silty Sand, hard	47,620	1,70E-07	48
8	24,0	-	30,0	Gray breksi, hard	39,733	5,10E-05	54

SEEP/W needs data coefficient of permeability (Ks), saturated water content (Wc), and fitting parameter a, n, and m. a is mainly related to the air-entry value (AEV), n is related to the rate of desaturation, and m is mainly related to the residual degree of saturation on SWCC (Sr). This parameter is calculated by using equations 2 – 5 because the Fredlund-Xing method is used to estimate the volumetric water content function and hydraulic conductivity function. SLOPE/W configuration needs three main data to be included in the calculation, namely unit weight, cohesion, and angle of friction.

Other data required in this analysis is rainfall data. Rainfall data is taken from the official BMKG website and sourced from the nearest rain station to the research location, namely the Zainuddin Abdul Madjid meteorological station which is 12.32 KM from the research location. Rainfall data for 11 years (2013 - 2023) is used to determine rainfall patterns in the area around the research location and to make annual rainfall plans using the Gumbel method. This annual rainfall plan is used to determine the maximum rainfall that occurs at the local location. **Table 5** shows that the maximum rainfall in 2023 occurred in February 2023 (71.20 mm) where cracking and settlement of the road body began, while in 2022 the highest rainfall occurred in December 2022 (86.90 mm).

Table 4. Data Soil Parameter For SLOPE/W

No	Depth (m)			N-SPT	γ (kN/m3)	γ_{sat} (kN/m3)	Cohesion (kN/m^2)	Angle of Friction (^{o})
1	0	-	2,4	45	19,30	19,44	13,10	22,59
2	2,4	-	4,6	11	17,60	19,55	5,70	25,53
3	4,6	-	6,6	30	18,40	18,75	4,00	28,68
4	6,6	-	9,4	60	17,20	17,92	8,00	19,34
5	9,4	-	14,5	15	16,60	17,39	15,50	11,03
6	14,5	-	18,0	21	17,00	17,88	8,70	13,69
7	18,0	-	24,0	60	18,50	18,59	6,00	16,32
8	24,0	-	30,0	60	16,1	18,87	8,00	17,47

Table 5a. Rainfall Data 2022 – 2023 Zainuddin Abdul Madjid meteorological station

Mont	2022			2023		
	Number of Days	Average	Max	Number of Days	Average	Max
January	20	9,75	46,50	18	5,95	38,80
February	14	5,22	58,50	21	11,88	71,20
Mart	16	5,71	35,80	18	8,20	47,00

Table 5b. Rainfall Data 2022 – 2023 Zainuddin Abdul Madjid meteorological station

Mont	2022			2023		
	Number of Days	Average	Max	Number of Days	Average	Max
April	11	4,67	57,80	16	3,50	31,40
May	5	1,40	13,00	3	0,11	1,50
Jun	9	3,02	47,50	0	0,00	0,00
July	2	1,27	35,70	8	3,20	46,70
August	3	0,61	10,90	1	0,03	1,00
September	8	0,66	4,80	1	0,72	21,60
October	24	11,48	67,50	0	0,00	0,00
November	19	8,02	82,00	8	6,09	64,80
December	15	9,63	86,90	14	6,23	52,00

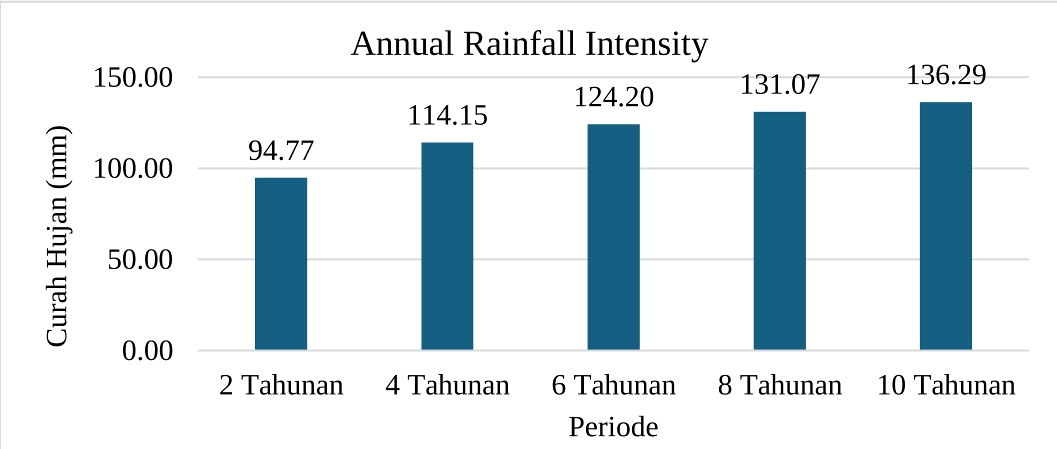

Figure 2. Annual Rainfall Intensity in District of Praya, Central Lombok, NTB

RESEARCH ANALYSIS

In the back analysis to find the cause of landslides on the BIL - Mandalika road section STA 10+375 - STA 1+550, two stages of analysis were used, namely slope stability analysis in initial conditions without considering rainwater infiltration using SLOPE/W and by considering rainwater infiltration using a combination of SEEP/W and SLOPE/W. At each stage of the analysis, three conditions were analyzed, namely:

1. Without considering the earthquake load
2. By considering the earthquake load
3. With back calculation

The results of the slope stability analysis without earthquake load show the slope safety factor is above two so that it is safe, and no landslides occur after adding vehicle loads, a groundwater level of 7.5 meters, and rain infiltration (Table 6). In the next stage of analysis, earthquake loads *kh* = 0.24 and *kv* = 0.12 were added (PuSGeN 2017) on analysis. The result showed that the slope safety factor dropped sharply from 2.208 to 0.900 (less than one), and the final safety factor after adding the vehicle load and the groundwater level is 0.894 (Table **7**). At the time of the landslide, there was no earthquake at the site, so the landslide was not caused by earthquake factors. On the other side in the condition without an earthquake, the safety factor of the slope after adding the groundwater level at a depth of 7.5 meters and vehicle load became 1.833 (Bishop) from the initial safety factor of 2.208, so the slope condition is still safe. Furthermore, back-calculation was conducted on the condition before the landslide so that new parameters were obtained.

Table 6. Slope Stability Analysis Result Without Earthquake Load

No	Stages	Safety Factor (SF)	
		Bishop	**Morgenstern - Price**
1	Initial Condition (Without GWL)	2,208	2,208
2	Add Traffic Load	2,146	2,146
3	Add Traffic Load + GWL 7,5 m	1,844	1,844

Table 7. Slope Stability Analysis Result with Earthquake Load

No	Stages	Safety Factor (SF)	
		Bishop	**Morgenstern - Price**
1	Initial Condition (Without GWL)	2,208	2,208
2	Add Earthquake Load	0,900	0,904
3	Add Earthquake Load + Traffic Load	0,904	0,908
4	Add Earthquake Load + Traffic Load + GWL 7,5 m	0,770	0,775

Table 8. Slope Stability Analysis Result of *Back-Calculation*

No	Stages	Safety Factor (SF)	
		Bishop	**Morgenstern - Price**
1	Initial Condition (Without GWL)	1,192	1,192
2	Add Traffic Load	1,158	1,159
3	Add Traffic Load + GWL 7,5 m	0,995	0,995

By using the back-calculated parameters, the slope stability analysis results are shown in Table 8, where the SF of the initial condition without the water table is 1.192. After adding traffic load, and groundwater level at 7.5 meters, the safety factor becomes 0.995.

In the results of the slope stability analysis by adding earthquake loads, it appears that there is a very significant decrease in the slope safety factor (59% of the initial condition SF value), while the decrease in the safety factor after adding a groundwater level of 7.5 meters the SF value drops by 14,8%. The earthquake had a significant effect on the slope stability due to the low cohesion value with an average value of c = 8.63 kPa. For further analysis involving rainfall infiltration and landslide conditions in February 2023 will use the data from the back-calculation analysis. The next step is analyzing the slope stability by considering rain intensity. The rainfall data used is the rainfall of January 2023 - February 2023 or model II. The rainfall intensity that has been inputted in the SEEP/W module looks like in Figure 3.

Before analyzing the effect of rainfall on slope stability, first, validate the change in negative pore water pressure (soil suction) resulting from the simulation of the SEEP/W model with negative pore water pressure obtained from field measurements using a soil tensiometer on the road median with a depth of 0.5 m (Figure 4).

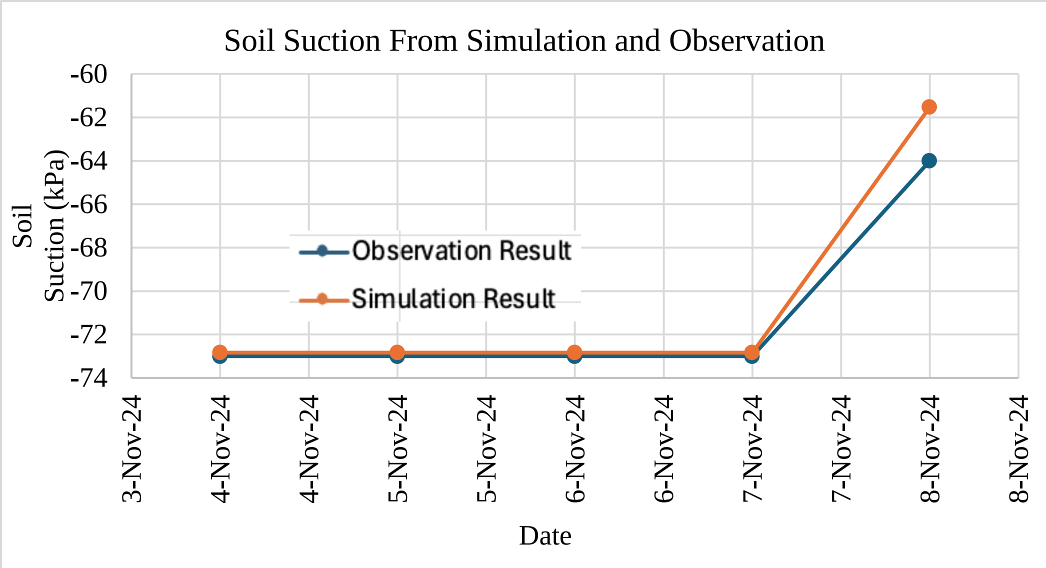

Figure 4. Comparison of Pore Water Pressure from Simulation and Observation

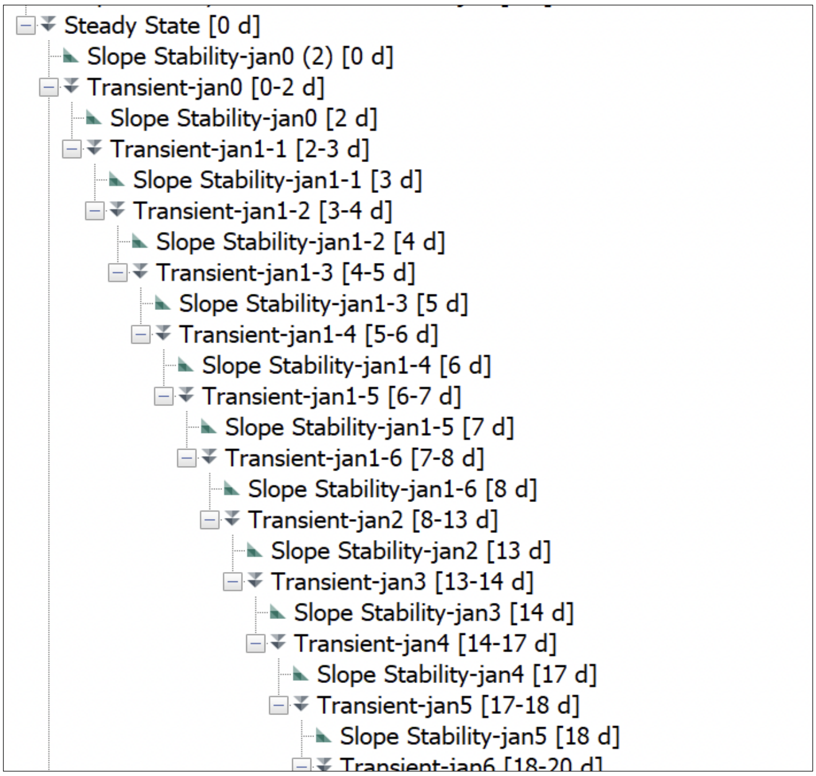

Figure 3. SEEP/W model for rainfall January 2023-February 2023

The output of the SEEP/W module is pore water pressure due to rain infiltration at each stage. This pore water pressure becomes the input for SLOPE/W to analyze slope stability. The initial groundwater level of 8,2 meters is obtained from the steady state in SEEP/W. After adding the rain variable with rainfall varying from January 1, 2023 - February 28, 2023, the slope safety number dropped to 0.986 in the bishop type analysis and 0,987 in the Morgenstern - Price type analysis.

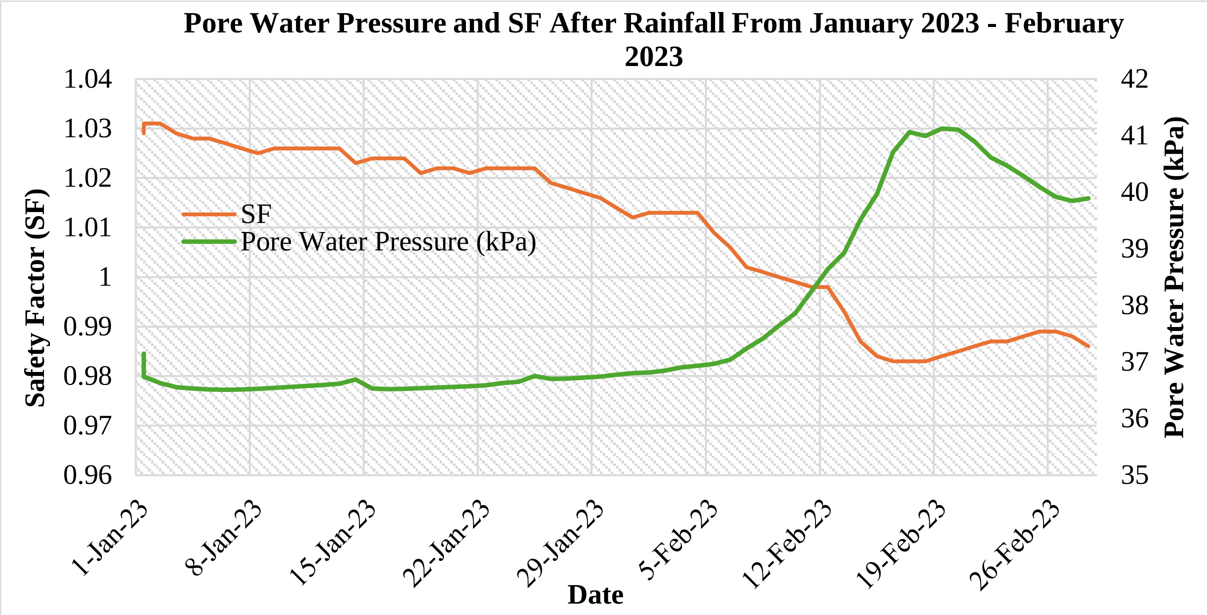

Figure 5. Graph Safety Factor and Pore Water Pressure after rainfall from January 2023 – February 2023

Table 6. Safety Factor of Simulation Rainfall Model II with Initial GWL 8,2 m

No	Stages	Safety Factor (SF)	
		Bishop	Morgenstern - Price
1	Ground Water Table + Traffic Load	1,029	1,029
2	Ground Water Level + Traffic Load + Rainfall (January 2023 - February 2023)	0,986	0,987

Rainfall intensity from January 2023 to February 2023 varied from 0 mm/day to 71.2 mm/day and occurred intermittently, with rain occurring one day or several days and then no rain for several days. The pore water pressure at a depth of 12 meters from the top of the slope changes following the rainfall intensity (Figure 4). On February 7, 2023, the pore water pressure starts to rise and peaks on February 20, 2023. The factor of safety dropped to 1.002 on February 7, 2023, and 0.984 on February 15, 2023. Based on the report from BPJN West Nusa Tenggara Province, the road settlement cracks began on February 9, 2023, on the right side of the road at a depth of 2 cm, on February 15, 2023, there was an additional settlement crack on the right side of the road of 2 cm, on February 19, 2023, the total settlement crack on the road body was 35 cm and on February 22, 2023 road surface was a drop 40 cm, the safety factor on February 15, 2023, is 0.987.

In the simulation of model III, where several rainfall intensities are used to see the changes in pore water pressure and safety factor of slope. The result of this model III simulation is shown in Figure 6. It shows that the longer the rain duration, the lower the factor of safety. In addition, the higher the rainfall intensity, the faster the factor of safety drops. Figure 8 shows the changes in soil pore water pressure when viewed from point A (12 meters from the top of the slope), the longer the rain duration, the more the pore water pressure increases, and the higher the rain intensity, the faster the increase in pore water pressure occurs.

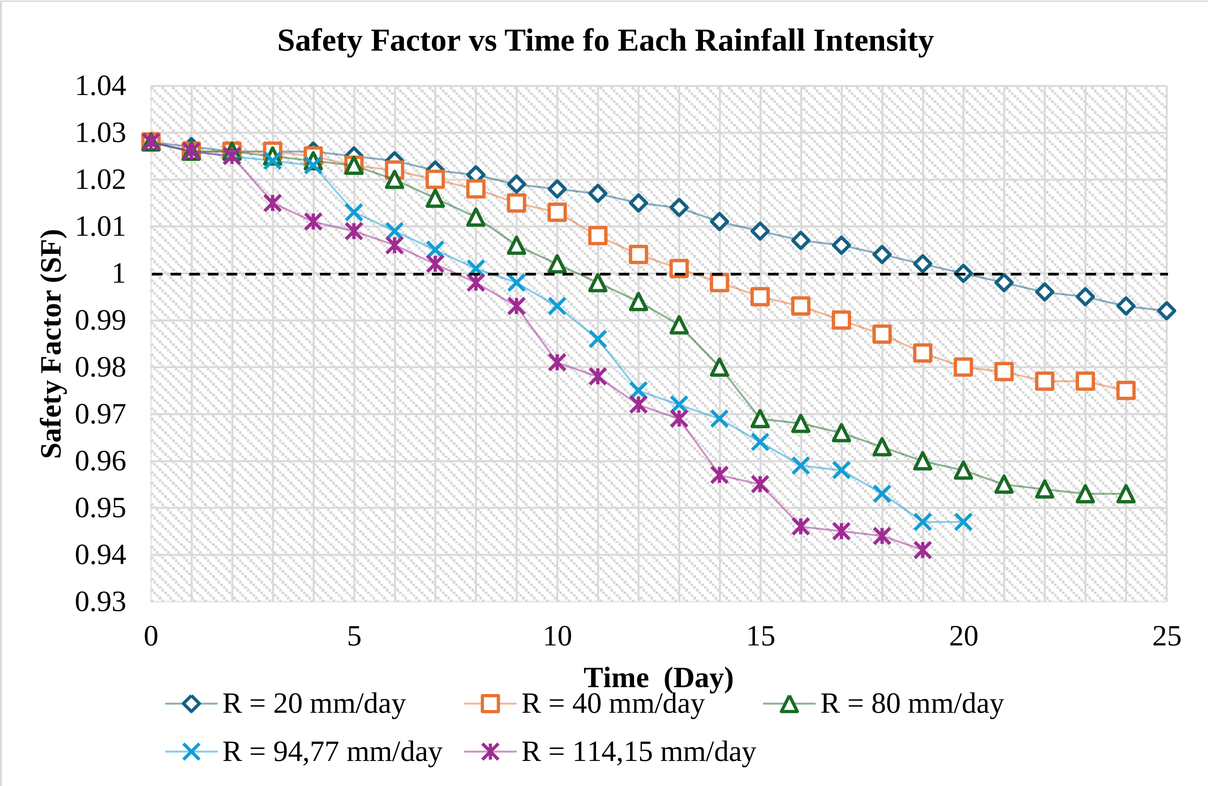

Figure 6. Safety Factor and Time Correlation on *Several Rainfall* Intensity

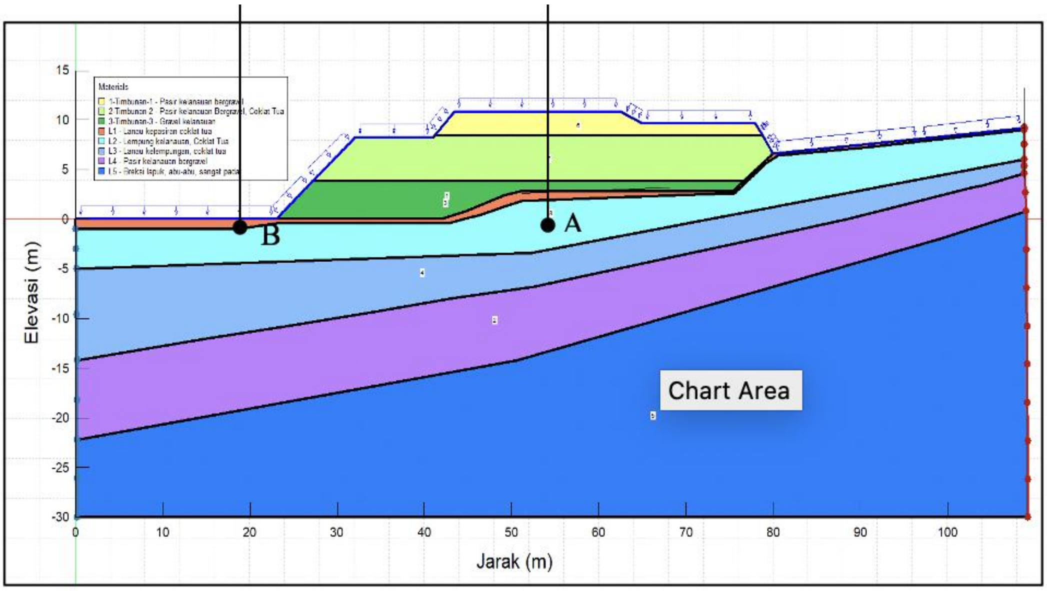

Figure 7. Slope Geometric Model with Waterflux Boundary Condition

Figure 8 shows the change of pore water pressure induced by each rainfall at a specific duration monitored at a depth of 12 meters from the road surface (point A). The higher the rainfall, the higher the pore water pressure and the faster the increase in soil pore water pressure. Figure 9 shows the change of pore water pressure (PWP) monitored at point B, 1,2 meters from the surface. PWP increases faster than the location on point A because the distance of observation location from the soil surface is shorter than on point A, this condition makes water seep faster to reach the location on point B.

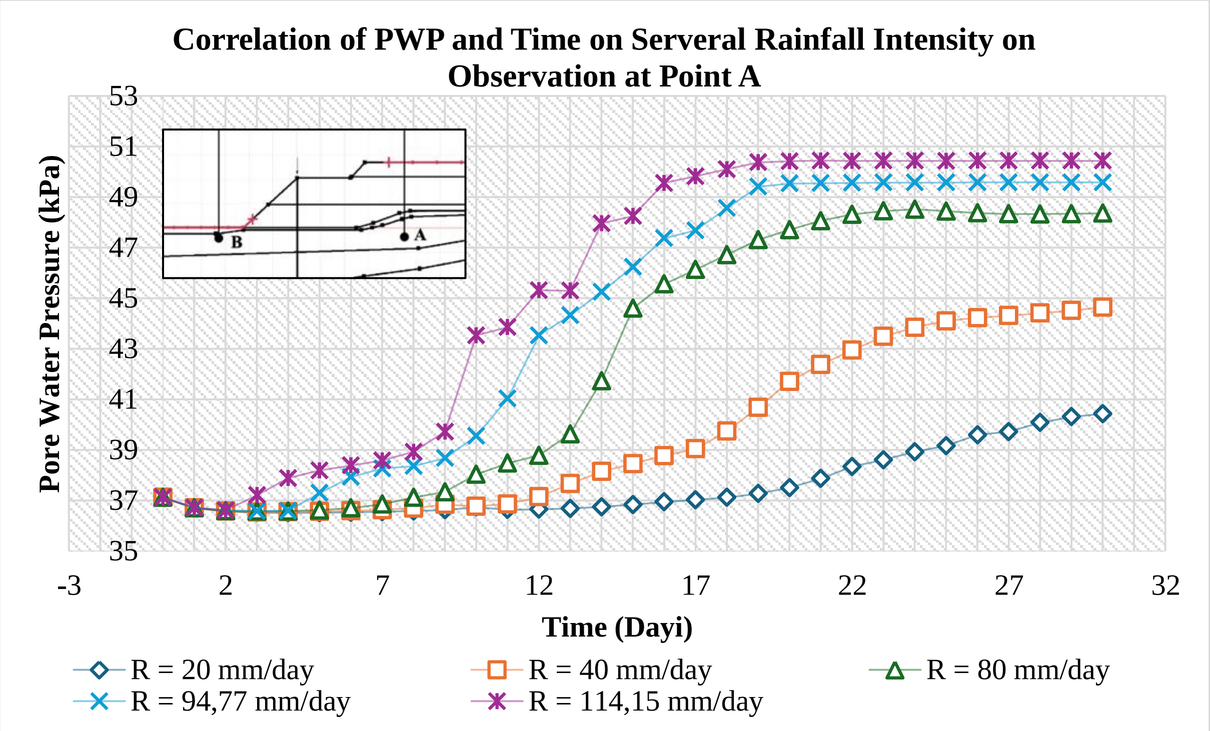

Figure 8. Pore Water Pressure Changes on Rainfall Intensity and Duration at Point A (12 m from the top of the slope)

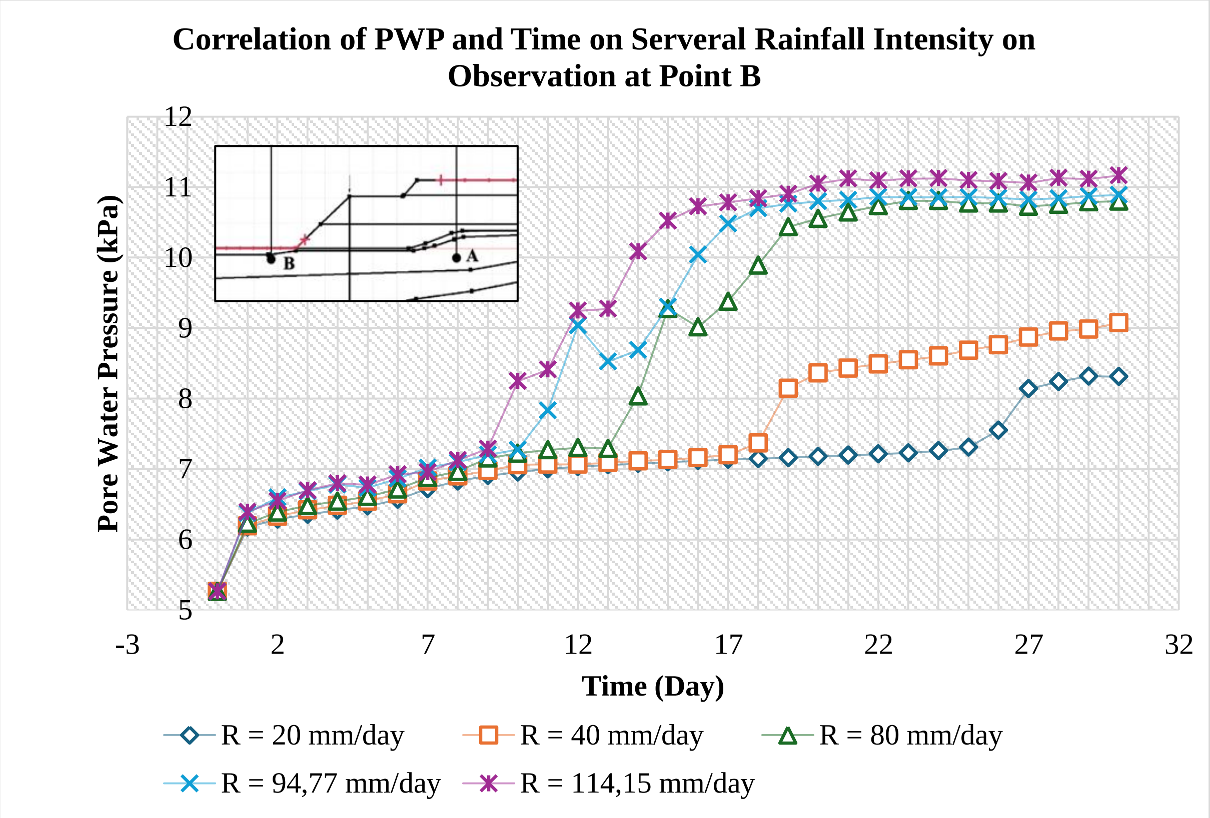

Figure 9. Pore Water Pressure Changes on Rainfall Intensity and Duration at Point B (1,2 m from foot slope)

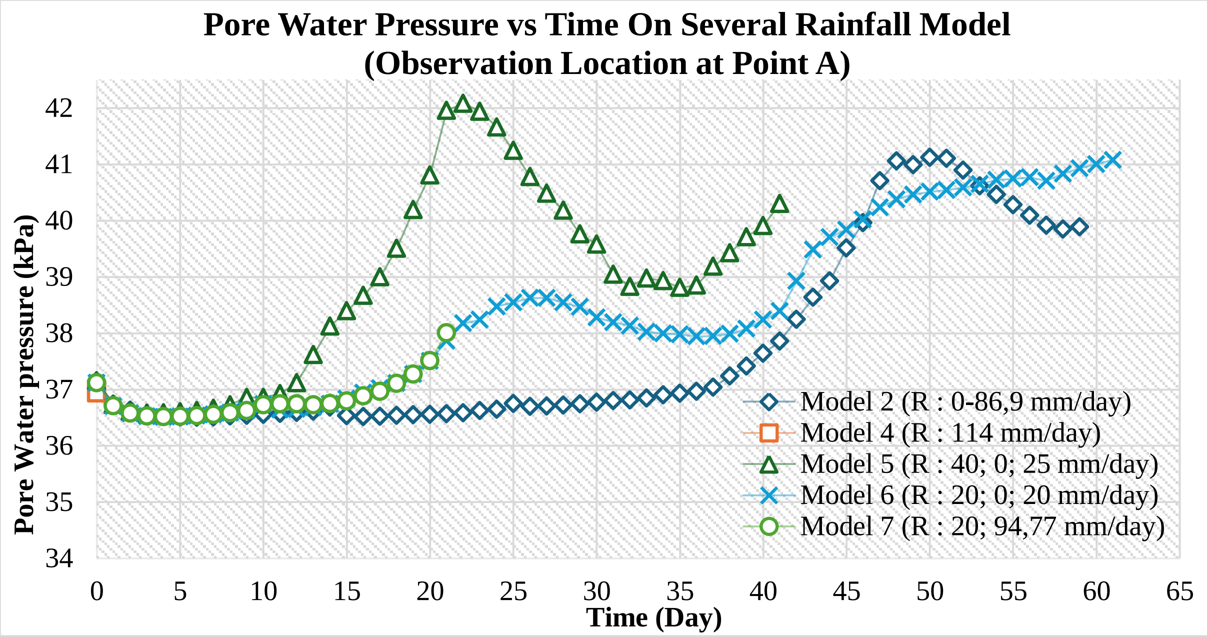

Figure 10. Pore Water Pressure Changes on Combined Rainfall Intensity and Duration at Point A

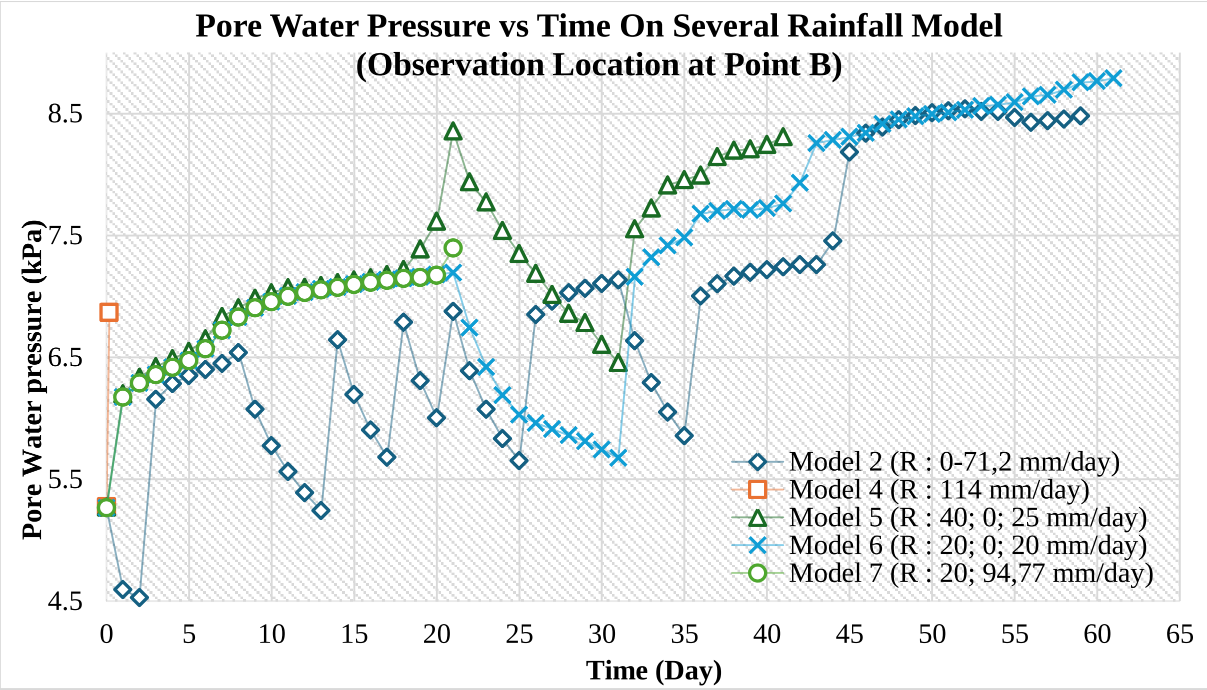

Figure 11. Pore Water Pressure Changes on Rainfall Intensity and Duration at Point B

The rainfall model in Figure 10 shows the rain at the beginning did not affect the increase in pore water pressure until the 10th day PWP started to increase. This is because rainwater that seeps into the soil takes time to reach the initial water table depth of 8.2 meters to increase pore water pressure. In addition, the increase in pore water pressure is also influenced by rainfall intensity, this can be seen in the graph of model 4, where the rainfall intensity of 40 mm/day causes a faster and higher increase in pore water pressure when compared to models with lower rainfall intensity. The pore water pressure at point B increases immediately at the beginning of the rainfall, This is because the pore water pressure at the foot of the slope is monitored at a depth of 1.2 meters, where water infiltration reaches a depth of 1.2 meters faster.

In the combined rainfall model, the order of the rainfall model that has the most effect on increasing soil pore water pressure when viewed at a depth of 12 meters from the road surface (point A) is model 5, model 2, model 6, model 7, and model 4. When viewed from a depth of 1.2 meters at the foot of the slope (point B), the order of influence of the rain model on increasing soil pore water pressure is model 5, model 6, model 2, model 8, model 7, and model 4.

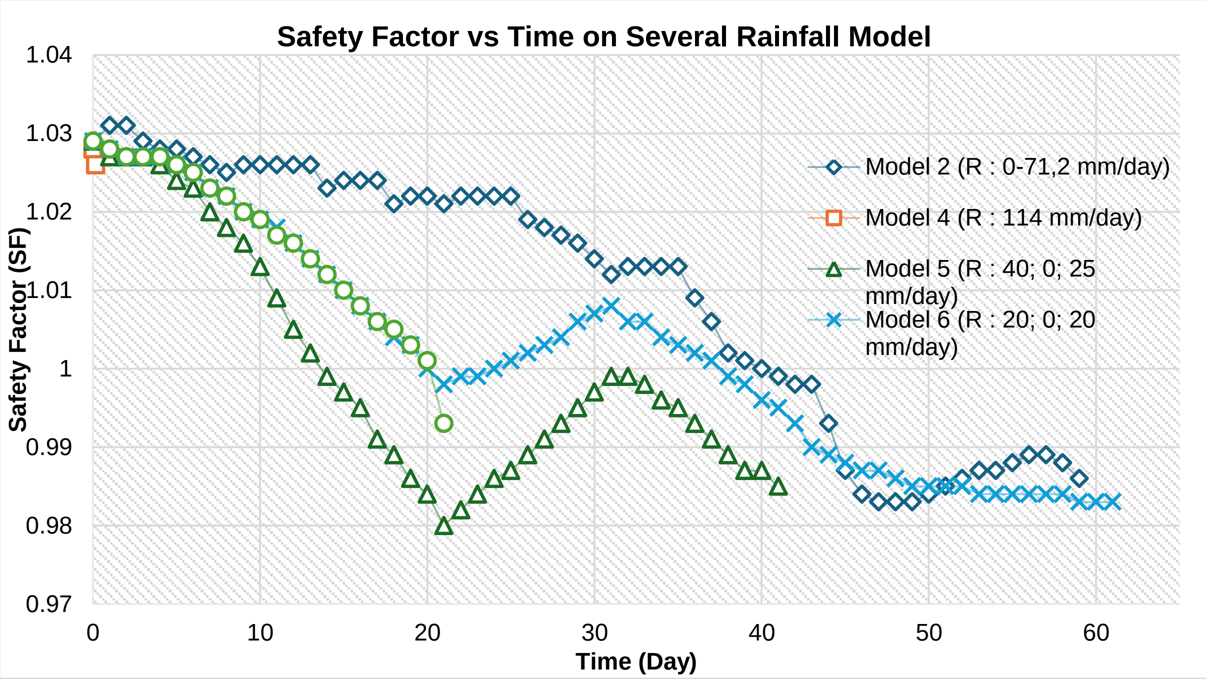

Figure 12. Pore Water Pressure Changes on Rainfall Intensity and Duration at Point B

The increase of soil pore water pressure due to rainfall directly affects the stability of the slope, which is seen in the decrease and increase in the slope safety factor following the rain intensity as shown in Figure 12. The higher the rain intensity, the lower the slope safety factor. Model 5 has a rainfall intensity of 40 mm/day (higher than the other models), showing a lower factor of safety value (0.98) and in the fastest time. Figure 12 also shows that the longer the rain duration, the lower the slope factor of safety. This can be seen in model 6, where the rain duration is the longest and results in a low factor of safety value (0.983).

CONCLUSIONS

Based on the result of slope stability analysis on Bypass BIL – Mandalika STA 10+475 using Geostudio 2018, it can be concluded that:

1. Slope stability on the BIL - Mandalika road section STA 10+375 - 10+550 is influenced by the intensity and duration of rainfall and the depth of the groundwater table. Based on the back-calculation analysis, the landslide occurred in February 2023 after receiving rainfall from January 2023 to February 2023 with the lowest safety factor value of 0.983.
2. Slope stability affected by rainfall duration and intensities, the higher rainfall intensities, safety factor of slope drop faster. The longer rainfall duration, the lower the safety factor of slope.

REFERENCES

[1] Ahmad, N., Haroon, W., & Abid, M. M. (2020). "Effect of air voids on permeability and durability of hot mix asphalt". *Journal of the National Science Foundation of Sri Lanka, 463 - 474.*

[2] Atikah, D. (2017). "Pengaruh Hujan Pada Stabilitas Lereng Di Jalan Tol Gempol – Pandaan". J*urnal Teknik Pengairan, 8(1), 79-88.*

[3] Badan Standarisasi Nasional. (2017). *SNI 8460:2017 Persyaratan Perancangan Geoteknik*. Jakarta, DKI Jakarta, Indonesia.

[4] Chai, J., & Khaimook, P. (2020). "Prediction of soil-water characteristic curves using basic soil properties". *Transportation Geotechnics 22 (2020) 100295*.

[5] Darwis. (2018). *Dasar-Dasar Mekanika Tanah.* Pena Indis. Yogyakarta.

[6] Das, B. M. (2010). *Principle Of Geothecnic Engineering Advanced Soil Mechanics, Seventh Edition.* Cengage Learning. Stamford, USA.

[7] Duncan, J., Wright, S. & Brandon, T. (2014). *Soil Strength and Slope Stability (Second Edition ed.).* John Wiley & Sons, Inc. Hoboken, New Jersey.

[8] Dwikorita, K. (1997). "Prediction of Rain-Induced Landsliding By Using Slope Hydrodinamic Numerical Model". *Forum Teknik, Jilid 20 No.1*.

[9] G. Wright, S., Duncan, J. & L. Brandon, T. (2014). *Soil Strength and Slope Stability* (Second Edition ed.). John Wiley & Sons, Inc. Hoboken, New Jersey.

[10] J.E., B. (1989). *Sifat-sifat Fisis dan Geoteknis Tanah.* Erlangga. Jakarta.

[11] Kristo, C., Rahardjo, H. & Satyanaga, A. (2017). "Effect of variations in rainfall intensity on slope stability in Singapore". *International Soil and Water Conservation Research 5, 258–264.*

[12] Malla, B. (2021). *Effect of Rainfall on Stability of Soil Slope*. *Proceedings of 10th IOE Graduate Conference Peer Reviewed ISSN: 2350-8914 (Online), 2350-8906 (Print)* (pp. 1299 - 1303). Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University. Nepal.

[13] Muntohar, A. S. & Saputro, R. I. (2014). Pengaruh Kedalaman Muka Air Awal Terhadap Analisis Stabilitas Lereng Tak Jenuh. *Inovasi Struktur dalam Menunjang Konektivitas Pulau di Indonesia* (pp. 985-990). Seminar Nasional X – 2014 Teknik Sipil ITS Surabaya. Surabaya.

[14] Murthy, V. (2002). *Geotechnical Engineering Principles and Practices of Soil Mechanics and Foundation Engineering (first ed.).* CRC Press. Florida.

[15] Nasional, B. S. (2019). *Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan nongedung.* Jakarta.

[16] Pramusandi, S. (2017). "Determination of Unsaturated Soil Properties and Slope Deformation Analysis due to the Effect of Varies Rainfall". *Poli Teknologi Vol. 10 No.1, Januari 2011*.

[17] Sosrodarsono, S. (2003). *Hidrologi untuk pengairan.* PT Pradnya Paramita. Jakarta.

[18] Subiyanti, H. (2011). "Analisis Kelongsoran Lereng Akibat Pengaruh Tekanan Air Pori di Saluran Induk Kalibawang Kulonprogo". *Jurnal Ilmiah Semesta Teknika*, *14*(1), *15-25*.

[19] Triatmodjo, B. (2008). *Hidrologi Terapan.* Beta Offset Yogyakarta. Yogyakarta.

[20] Widisaputra, R., Zakaria, Z., & Iqbal, P. (2020). "Pengaruh Beban Gempa Terhadap Kestabilan Lereng Tanah Daerah Liwa dan Sekitarnya Kabupaten Lampung Barat". *Padjadjaran Geoscience Journal, Vol. 4, No. 5:411-419.*