NUMERICAL ANALYSIS OF POST RAINFALL SLOPE STABILITY WITH REINFORCEMENT CASE STUDY IN PURWOSARI KULON PROGO

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Abstract
Continuous rainfall over several days caused a landslide along Jalan Penggung, Purwosari Village, Girimulyo District, Kulon Progo Regency. This study was conducted to analyse slope stability under rainfall conditions and to evaluate reinforcement alternatives including soil nailing, ground anchors, and gabions. The slope topography was obtained from DEMNAS data and processed using AutoCAD Civil 3D, while soil parameters were derived from laboratory testing. Rainfall data were obtained from the JAXA satellite and effective rainfall infiltration was calculated using the SCS-CN method. The infiltration was modelled using SEEP/W and the slope stability was subsequently analysed using SLOPE/W with and without reinforcement. The analysis of the existing slope without seismic loading produced an initial safety factor (SF) of 0.922, which decreased to 0.801 after one day of rainfall. When seismic loading was considered, the initial SF was 0.639 and further decreased to 0.550 after one day. These results indicate that the existing slope is unsafe under both static and seismic conditions, making reinforcement necessary. The SF of the slope increased by 118% with soil nailing, 128% with anchors, and 14% with gabions under static conditions. Under seismic loading, soil nailing increased the SF by 101%, anchors by 110%, and gabions by 15%. These findings demonstrate that soil nailing and anchors can improve slope stability to safe levels, whereas gabions are ineffective for the studied slope conditions.

Keywords: *Gabion, Ground Anchor, Rainfall Infiltration, Slope Stability, Soil Nailing*

INTRODUCTION

Landslides are one of the most frequent natural hazards in tropical regions such as Indonesia (Pratama et al. 2022), where high rainfall intensity and complex geological conditions often lead to slope instability. A landslide occurs when the driving forces, including gravity and pore water pressure, exceed the resisting forces of the slope materials such as shear strength and cohesion (Hidayat et al. 2023; Wang et al. 2024b; Wang et al. 2024a; Brilli et al. 2025; Lei et al. 2025). This phenomenon can be triggered by several factors such as geological conditions, vegetation cover, slope geometry, and particularly, rainfall infiltration which significantly affects the pore water pressure distribution and soil strength (Irawan et al. 2020; Naryanto et al. 2020; Wang et al. 2024a; Yang et al. 2025; Zhang et al. 2025a).

Previous studies have shown that prolonged or intense rainfall can lead to a significant reduction in the factor of safety (FoS) of slopes, increasing the risk of slope failure. For instance, research by Wang et al. (Wang et al. 2024a) and Brilli et al. (Brilli et al. 2025) demonstrated that rainfall infiltration increases pore water pressure and decreases shear strength, accelerating slope movement. Similarly, studies by Hidayat et al. (Hidayat et al. 2023) and Muchtaranda et al. (Muchtaranda et al. 2024) confirmed that longer rainfall duration correlates with a continuous decline in slope stability. Therefore, understanding the hydrological impact of rainfall on slope stability is critical for developing effective mitigation strategies.

Various reinforcement methods have been developed to enhance slope stability, including soil nailing, ground anchors, and gabions. Soil nailing provides passive resistance through steel bars embedded into the slope, while ground anchors transfer tensile forces to deeper and more stable soil or rock layers. On the other hand, gabions with rectangular wire mesh cages filled with rocks, serve as surface protection structures to prevent shallow erosion. The effectiveness of each method depends on the failure mechanism and the depth of the sliding surface. Studies by Rahayu et al. (Rahayu et al. 2024) and Li et al. (Li et al. 2025) found that deep reinforcement techniques such as soil nailing and anchors are more effective for rotational and deep-seated failures, while gabions are better suited for shallow slides.

However, most previous studies have either analysed rainfall-induced slope failures without considering reinforcement performance under both static and seismic conditions or focused on a single type of reinforcement. Limited research has integrated transient seepage analysis (SEEP/W) and slope stability analysis (SLOPE/W) to evaluate the comparative effectiveness of multiple reinforcement methods after rainfall events in real case studies.

Therefore, this study aims to fill this gap by numerically analysing post-rainfall slope stability using SEEP/W and SLOPE/W software for a real slope in Purwosari, Kulon Progo, Yogyakarta. The objectives are to evaluate the influence of rainfall infiltration on slope safety and to compare the effectiveness of three reinforcement alternatives soil nailing, ground anchors, and gabions under both static and seismic conditions. The results are expected to provide practical insights into selecting suitable reinforcement strategies for rainfall-affected slopes in tropical regions such as Indonesia.

METHODS

This research was conducted in Purwosari Village, Girimulyo District, Kulon Progo Regency, Yogyakarta. The slope under study is located along Jalan Penggung, which experienced a landslide after several days of continuous rainfall. The geographical coordinates of the study area are 7°43'54.6" S and 110°10'33.8" E.

The study utilized both primary and secondary data sources. Primary data were obtained from field investigations and laboratory tests, while secondary data were gathered from online databases.

Data Collection

1. Primary Data are soil sampling and testing: disturbed soil samples were collected for laboratory testing. The tests included water content (ASTM D-2216-8), specific gravity (ASTM D-854-83), Atterberg limits (ASTM D-423-66, ASTM D-424-74, ASTM D-427-85), grain size distribution (ASTM D-422-63), permeability (ASTM D-2434 - 68), cohesion (ASTM D3080), and friction angle (ASTM D-3080).
2. Secondary Data:
   - Rainfall Data: Daily rainfall data from 2019–2023 were obtained from the JAXA satellite (https://sharaku.eorc.jaxa.jp/GSMaP/). Frequency analysis was conducted using Normal, Log-Normal, Gumbel, and Log-Pearson Type III distributions to determine the design rainfall.
   - Topographic Data: Digital Elevation Model (DEMNAS) data from the Indonesian Geospatial Information Agency (BIG) (https://tanahair.indonesia.go.id/portal-web/) were processed using AutoCAD Civil 3D to obtain slope geometry.
   - Seismic Data: Earthquake data and Peak Ground Acceleration (PGA) were retrieved from the Ministry of Public Works and Housing portal (https://rsa. ciptakarya. pu.go.id/2021/).

Hydrological and Infiltration Analysis

Rainfall infiltration was computed using the Soil Conservation Service Curve Number (SCS-CN) method to estimate effective rainfall and infiltration depth. The Alternating Block Method (ABM) was applied to derive the rainfall hyetograph with a 30-minute time interval.

SEEP/W Analysis

The transient seepage analysis was conducted using GeoStudio SEEP/W software to simulate changes in pore water pressure and groundwater level due to rainfall infiltration. The model inputs included:

- Soil Properties: Volumetric water content, permeability, cohesion, and friction angle (Table 1).
- Boundary Conditions: No-flow boundaries along the upper surface, constant head boundaries at the base, and rainfall infiltration boundaries along the slope surface.
- Simulation Duration: 5 hours and 24 hours post-rainfall.

SLOPE/W Stability Analysis

Slope stability analysis was performed using GeoStudio SLOPE/W with the

Morgenstern-Price method and the Entry-Exit technique to locate the critical slip surface. The soil behaviour followed the Mohr-Coulomb failure criterion. Safety factor (SF) values were analysed under both static and seismic conditions. The analysis considered two scenarios:

1. Existing Slope Condition (before and after rainfall)
2. Slope with Reinforcement (soil nailing, ground anchors, gabions)

Reinforcement Modelling

Three reinforcement techniques were evaluated:

1. Soil Nailing: Nine nails, each 30 m long with a 0.05 m diameter and 1.5 m spacing using DYWIDAG catalogue.
2. Ground Anchors: Seven anchors, 30 m long with 7 m bond length and 1.5 m spacing, embedded into stable strata using DYWIDAG catalogue.
3. Gabions: Rectangular wire mesh cages (4 m × 1 m × 1 m) stacked up to 6 m in height, filled with rock fragments (γ = 20.5 kN/m³, c = 17 kPa, φ = 40°) using Maccaferri catalogue.

RESULT AND DISCUSSION

General Conditions

The study area, located in Purwosari Village, Girimulyo District, experienced a rotational landslide (Figure 1a) in May 2023 at approximately 21:00 local time following several days of continuous rainfall. Field observations revealed tension cracks of approximately 4 cm on the road surface and the occurrence of mass movement along the slope, which disrupted local traffic (Figure 1b). Laboratory testing results (Table 1) classified the soil as ML (silt with low plasticity) according to the Unified Soil Classification System (USCS) based on the criteria of the U.S. Army Corps of Engineers (USACE, 1992), as illustrated in Figure 2. The soil has a cohesion (c) of 7.55 kPa and an internal friction angle (ϕ) of 32°, indicating relatively low shear strength. These parameters were used as input data for numerical simulations.

Figure 1a. Failure Pattern

Figure 1b. Landslide Conditions

Table 1. Soil Parameter Data

Soil Parameter	Value	Unit
Water Content (*w*)	36.59	%
Specific Gravity (G_s)	2.62	-
Wet Volume Weight (γ_b)	16.76	kN/m^3
Dry Volume Weight (γ_d)	12.27	kN/m^3
Liquid Limit (LL)	45.60	%
Plastic Limit (PL)	38.66	%
Shrinkage Limit (SL)	17.35	%
Plasticity Index (PI)	6.95	%
% Silt	51.13	%
% Sand	48.87	%
% Gravel	-	%
Cohesion (*c*)	7.55	kPa
Friction Angle (φ)	32	°
Permeability (*k*)	1.11E-06	m/s

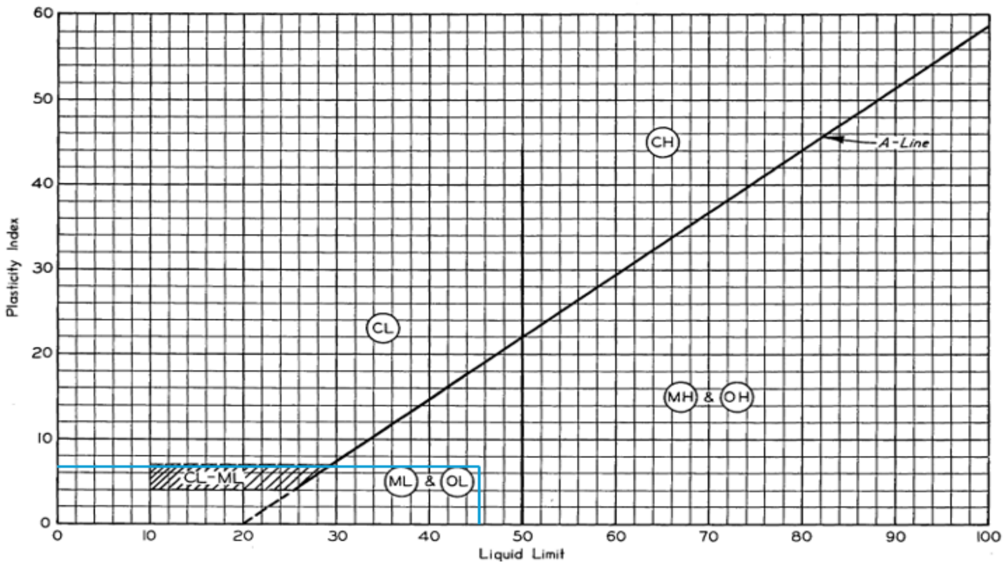


Figure 2. Soil classification based on the USCS method

Rainfall Analysis

Maximum daily rainfall data from 2019-2023 were analysed using several probability distribution methods (Table 2). The Kolmogorov–Smirnov (K–S) test was applied to evaluate the degree of agreement between the observed rainfall data and several theoretical probability distributions. This non-parametric statistical test compares the cumulative distribution function (CDF) of the observed dataset with that of a theoretical model. The K–S statistic, denoted as D, represents the maximum absolute difference between the two CDFs and is expressed as: $D = \max|F_0(x)-F_t(x)|$. Smaller D value indicates a closer correspondence between the observed and theoretical distributions. Based on this analysis, the Log-Pearson Type III distribution was identified as the best fit, yielding a design rainfall of 136.94 mm for a 10-year return period (Table 3). This return period was selected in accordance with SNI 2415:2016 (SNI; 2016) and (Chow et al. 1988) for slope and road drainage design, representing a significant yet realistic rainfall event. Although only five years of rainfall data were available, the dataset was considered sufficient for this case study due to the consistency of the rainfall pattern and its correspondence with historical regional trends. The Alternating Block Method (ABM) produced a hyetograph with a maximum rainfall intensity of 63.56 mm at 2.5 hours (Figure 3). Effective rainfall was then calculated using the SCS-CN method, resulting in an infiltration depth of 97.6 mm during a 5-hour storm event (Figure 4).

These results are consistent with previous studies, such as Hidayat et al. (Hidayat et al. 2023) and Aisah & Gofar (Aisah and Gofar 2022), which found that intense rainfall exceeding 100 mm/day can significantly reduce slope stability due to increased pore water pressure and soil saturation.

Table 2. Maximum Rainfall Each Year

No.	Year	Maximum Rainfall (mm)
1	2019	125.04
2	2020	119.37
3	2021	119.34
4	2022	131.64
5	2023	74.93

Table 3. Frequency Analysis Results

Return Period (Year)	Normal (mm)	Log-Normal (mm)	Gumbel (mm)	Log-Pearson III (mm)
2	114.06	111.93	110.38	119.88
5	132.96	135.61	130.22	133.27
10	142.84	149.91	143.36	136.94
25	153.38	166.83	159.96	138.91
50	160.18	178.77	172.27	139.43

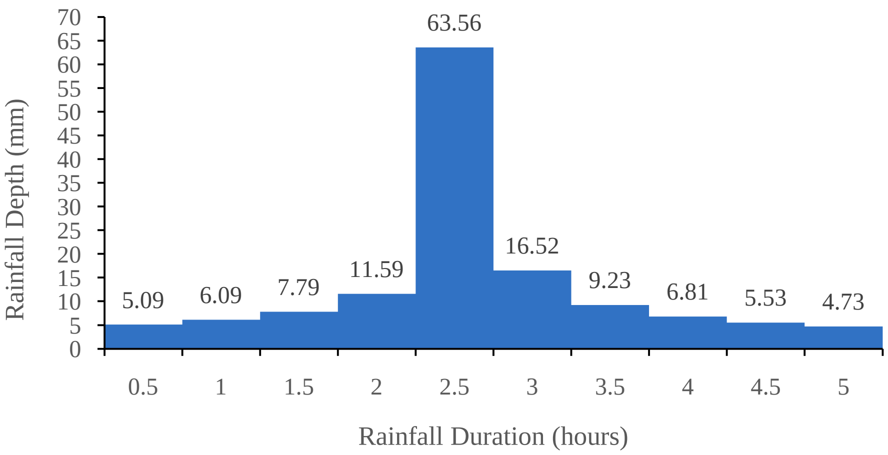


Figure 3. ABM hyetograph

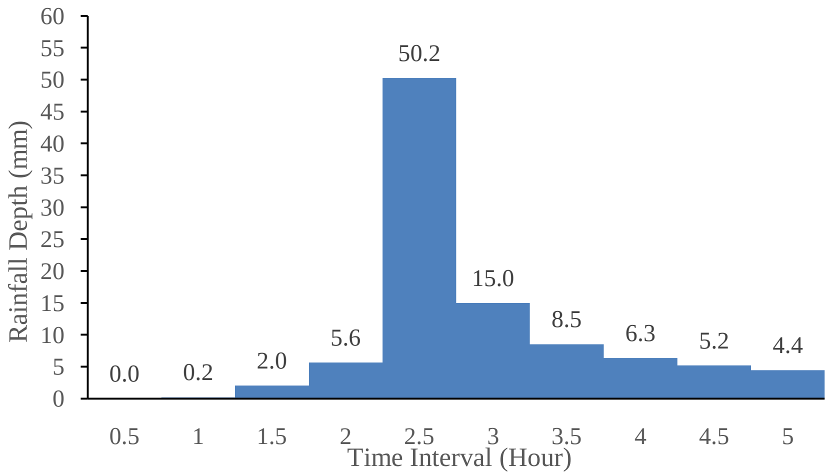


Figure 4. Rain Infiltration

Existing Slope Stability Analysis

The slope geometry analysed is shown in Figure 5. Two simulations were performed the existing slope condition, and the slope after reinforcement. Rainfall infiltration was modelled with SEEP/W, and slope stability was evaluated using SLOPE/W.

SEEP/W analysis (transient type) was used to model changes in pore water pressure and groundwater table movement due to rainfall infiltration. Input parameters included slope geometry, soil properties (Table 1), volumetric water content, and hydraulic conductivity (Table 4).

In SEEP/W, three types of boundary conditions were applied: no-flow, water head, and rainfall infiltration. The no flow boundary was defined along the ground surface above the groundwater table, represented by a water rate of 0 m^3/s, indicating that no water flow occurs across this boundary.

The water head boundary was assigned at the bottom of the slope below the groundwater table, modelled as a total waterhead with constant values according to the respective elevations, representing a stable groundwater level. Rainfall infiltration was applied as a water flux boundary along the slope surface, with a total infiltration depth of 97.6 mm over a 5-hour storm event, as calculated using the SCS-CN method (Figure 4).

This flux condition simulates the downward entry of rainwater into the soil, which increases pore water pressure and raises the groundwater. The SEEP/W analysis results, presented in Table 5, show clear temporal variations in pore water pressure and groundwater movement. These variations occur because rainfall infiltration gradually fills the soil pores with water, leading to increased pore water pressure and a rising groundwater table. As the infiltration continues, the slope becomes progressively saturated, and the magnitude of these changes increases with rainfall duration (Wang et al. 2024a).

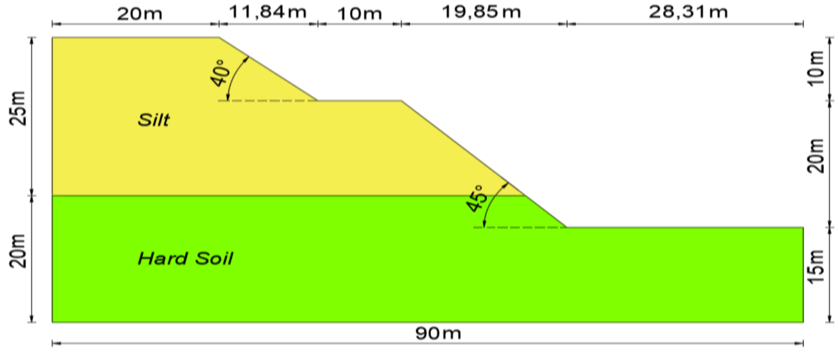
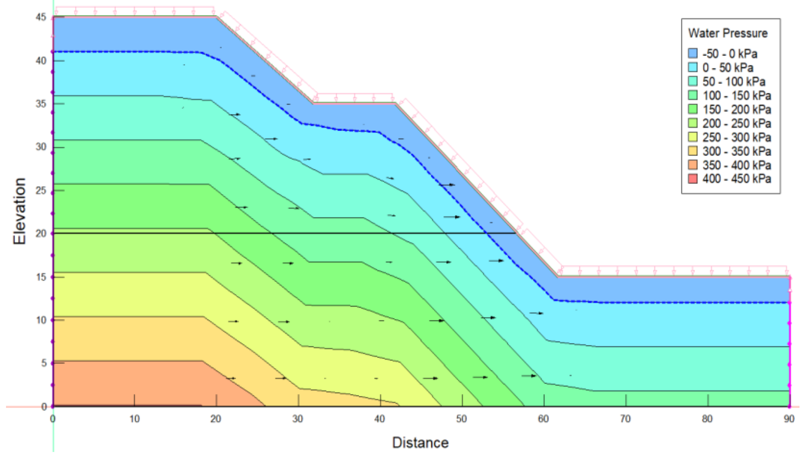
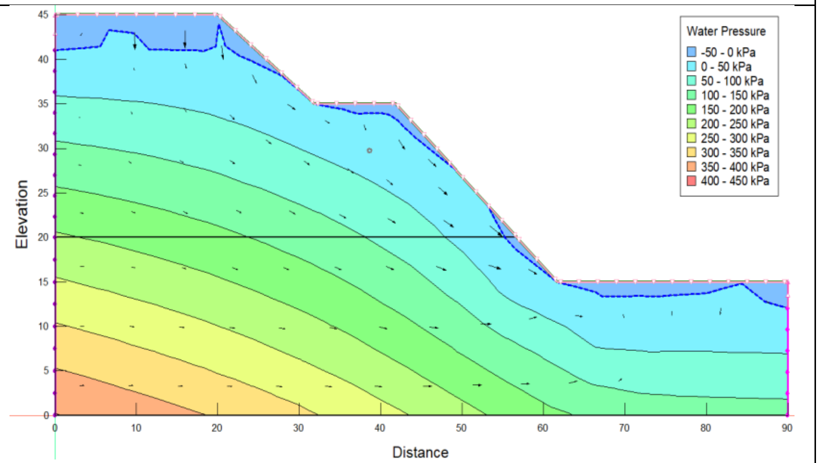


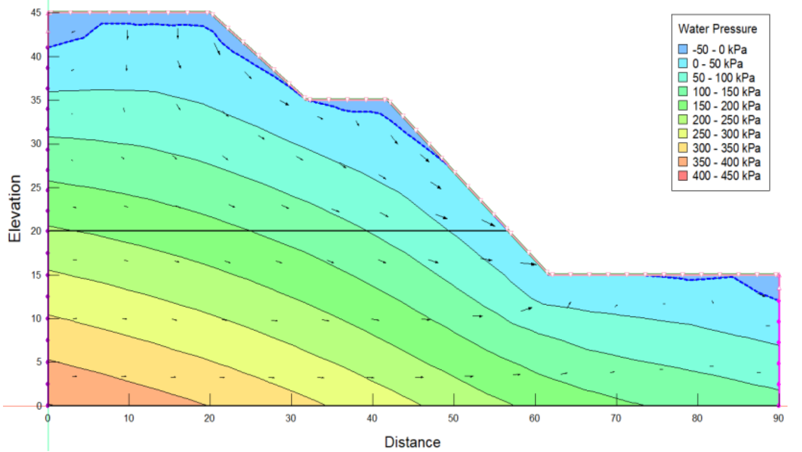
Figure 5. Slope Modelling

Table 4. SEEP/W Parameters

Parameter	Silt	Hard Soil	Unit
Volumetric Water Content (w)	0.366	0.15	-
Hydraulic Conductivity (k)	0.0000011	0.000001	m/s

Table 5. Results of Existing Slope Analysis with SEEP/W

Condition	SEEP/W Analysis
Initial	
5 hours after rain	

Condition	SEEP/W Analysis
1 day after rain	

The SLOPE/W analysis was carried out as a continuation of the SEEP/W simulation in order to calculate the safety factor (SF) of the existing slope. The Morgenstern Price method was employed with the slip surface determined using the Entry Exit technique. The soil was modelled using the Mohr Coulomb failure criterion, and the input parameters included dry unit weight (γ_d), cohesion (c), and friction angle (ϕ), as presented in Table 6.

Table 6. SLOPE/W Parameters

Parameter	*Silt*	*Hard Soil*	Unit
Dry Volume Weight (γ_d)	12.27	20	kN/m^3
Cohesion (c)	7.55	50	kPa
Friction Angle (φ)	32	15	°

Note: Silt from laboratory testing; Hard soil parameters were determined based on assumptions due to the absence of laboratory test data.

Figure 6 presents the results of the slope stability analysis for the existing condition. The initial safety factor (SF) was 0.922 without seismic loading and decreased to 0.639 when earthquake loading was applied, indicating that the slope was already unstable even before rainfall. When rainfall infiltration was introduced, the SF progressively decreased with time.

After 5 hours of rainfall, the SF dropped to 0.856 without seismic loading and 0.593 with seismic loading. Prolonged infiltration over 1 day further reduced the SF to 0.801 and 0.550 under static and seismic conditions, respectively. These results confirm that rainfall infiltration significantly accelerates the reduction in slope stability, and when combined with seismic loading, the slope becomes critically vulnerable. This analysis clearly demonstrates that rainfall infiltration is a major triggering factor for slope instability in the study area (Zhang et al. 2025b).

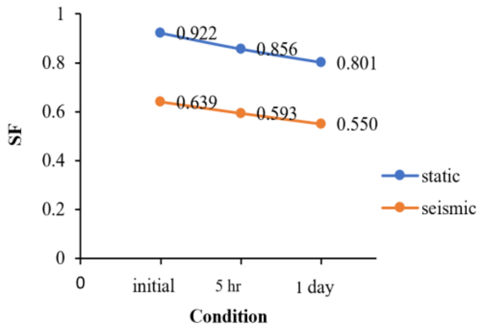


Figure 6. Comparison of SF values over time

Reinforcement Analysis

The first reinforcement alternative applied to the slope was soil nailing. A total of nine nails were installed, each 30 m long with a diameter of 0.05 m and spaced at intervals of 1.5 m. Table 7 presents the results of the slope stability analysis with soil nailing, both static and seismic conditions. The analysis shows that soil nailing increased the safety factor to 1.749 under static conditions and 1.106 under seismic loading, both of which satisfy the minimum safety factor criteria recommended by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, 1953), where a factor of safety (SF) ≥ 1.5 indicates stability under static loading and SF ≥ 1.1 under seismic conditions.

The second reinforcement alternative was ground anchors. Seven anchors were installed, each with a diameter of 0.05 m, a total length of 30 m, and a bond length of 7 m. The anchors were placed at 1.5 m intervals. The results indicate that the use of ground anchors was effective, improving the safety factor to 1.829 under static loading and 1.153 under seismic loading, also exceeding the required limits set by the same design codes.

The third reinforcement alternative was gabions. Each gabion unit measured 4 m in length and 1 m in height, stacked six layers vertically for a total height of 6 m. The input material properties for gabions are shown in Table 8. However, the results of the analysis indicate that the gabion reinforcement was not effective. The safety factor remained below the required thresholds, with values of 0.917 under static conditions and 0.632 under seismic loading.

These findings demonstrate that the effectiveness of reinforcement depends strongly on its compatibility with the slope's failure mechanism. Soil nailing and ground anchors provide deep reinforcement by mobilizing tensile resistance within the soil mass and anchoring forces into more stable layers, which significantly increases the safety factor. In contrast, gabions mainly provide surface protection and are more effective for shallow erosion or surficial failures. Since the failure mechanism in this study area is rotational and deep-seated, gabions could not adequately resist the driving forces, resulting in safety factors below the stability threshold.

In the actual field condition, local stakeholders mitigated the slope using a gravity retaining wall. This type of structure stabilizes slopes by mobilizing its self-weight to resist sliding forces. While gravity walls can be effective for shallow to medium-depth slope failures, they may not provide the same improvement in stability as deep reinforcement methods such as soil nailing or ground anchors when dealing with rotational, deep-seated failures. This highlights the importance of selecting reinforcement strategies that are consistent with the failure mechanism and site-specific geotechnical conditions.

Table 7. Slope analysis with reinforcement

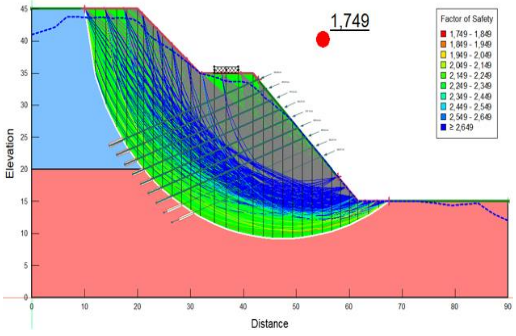
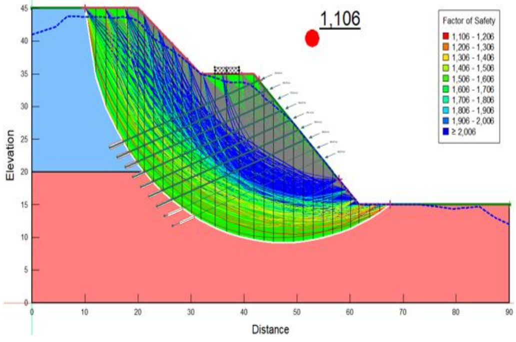
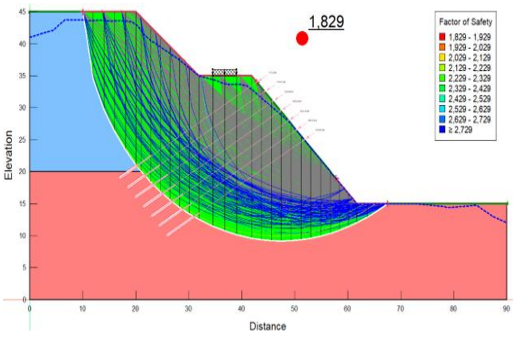
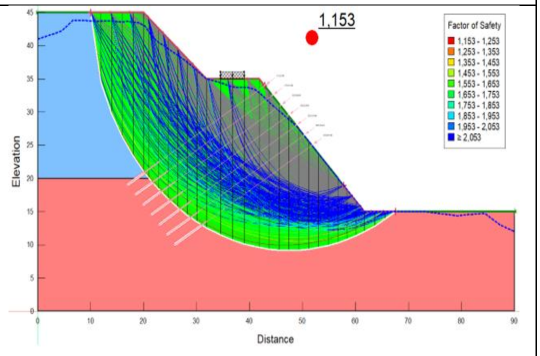
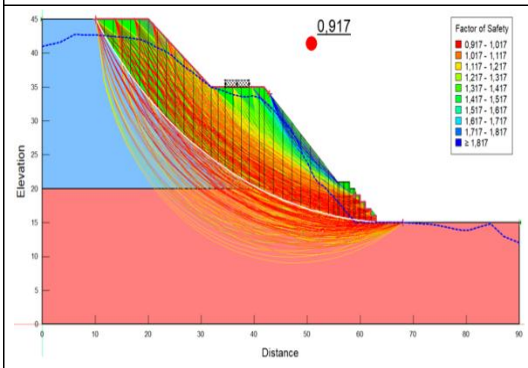
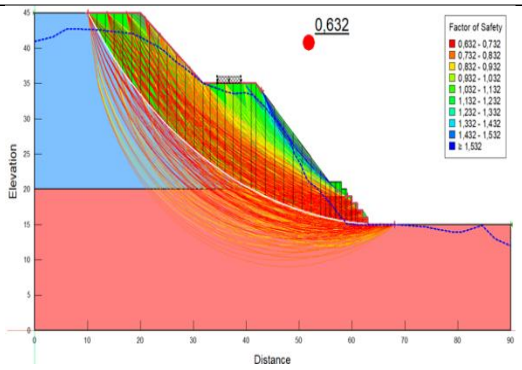
Static condition	Seismic condition
Soil Nailing	Soil Nailing
 SF = 1,749 > 1,5 (safe)	 SF = 1,106 > 1,1 (safe)
Anchor	Anchor
 SF = 1,829 > 1,5 (safe)	 SF = 1,153 > 1,1 (safe)
Gabion	Gabion
 SF = 0,917 < 1,5 (unsafe)	 SF = 0,632 < 1,1 (unsafe)

Table 8. Gabion Parameters

Parameter	Gabion	Unit
Volume Weight (γ)	20.5	kN/m^3
Cohesion (c)	17	kPa
Friction Angle (φ)	40	°

CONCLUSION

The numerical analysis using SEEP/W and SLOPE/W confirmed that the slope in Purwosari Village, Kulon Progo, is unstable under both static and seismic conditions, particularly after rainfall infiltration. Continuous rainfall significantly increased pore water pressure, reduced shear strength, and lowered the safety factor below the stability threshold, indicating a high potential for failure.

The simulation results demonstrated that reinforcement methods substantially improved the slope stability, with varying degrees of effectiveness. The existing slope, with safety factors of 0.801 under static conditions and 0.550 under seismic conditions, was categorized as unsafe. After the application of reinforcement, soil nailing and ground anchors increased the safety factor to 1.749 and 1.829 under static conditions, and 1.106 and 1.153 under seismic conditions, respectively, both meeting the stability criteria.

In contrast, the gabion reinforcement method, with safety factors of 0.917 under static conditions and 0.632 under seismic conditions, remained below the required limits and was considered ineffective. These findings indicate that soil nailing and ground anchors are the most effective methods for improving slope stability in areas with rotational and deep-seated failure mechanisms, while gabions are more suitable for shallow slope protection.

Overall, this study emphasizes the importance of selecting slope reinforcement methods based on the dominant failure mechanism, hydrological characteristics, and subsurface conditions. The results of this research provide valuable insight for the design and implementation of slope stabilization in tropical regions prone to high rainfall intensity and seismic activity.

REFERENCES

Aisah, E. and Gofar, N., 2022, Studi Pengaruh Curah Hujan Terhadap Stabilitas Lereng Menggunakan Program Perisi. *Jurnal Rekayasa Sipil (JRS-Unand)* 18(2), pp. 133–147.

Brilli, N., Masi, E.B., Rossi, G. and Tofani, V., 2025, Slope stability modelling of shallow landslides at a regional scale. *Geoenvironmental Disasters* 12(1), p. 18.

Chow, V.T., Maidment, D.R. and Mays, L.W., 1988, *Applied Hydrology, MacGraw-Hill*.

Hidayat, R., Wijaya, I.P.E.P. and Munir, M.D., 2023, Mekanisme Longsor Akibat Infiltrasi Dari Genangan Air (Studi Kasus Longsor Di Lahat, Sumatera Selatan). *Jurnal Teknik Hidraulik* 14(1), pp. 1–12.

Irawan, L.Y., Syafi'i, I.R., Rosyadi, I., Siswanto, Y., Munawaroh, A., Wardhani, A.K. and Saifanto, B.A., 2020, Analisis potensi rawan bencana tanah longsor di Kecamatan Jabung, Kabupaten Malang. *Jurnal Pendidikan Geografi: Kajian, Teori, dan Praktek dalam Bidang Pendidikan dan Ilmu Geografi* 25(2), pp. 102–113.

Lei, X., Zhang, W., He, S., Zhang, S., Yang, Z., Qin, C. and Chen, X., 2025, Numerical modelling of rainfall-induced internal erosion process within vegetated deposited slopes. *Journal of Rock Mechanics and Geotechnical Engineering* 17(8), pp. 5170–5187.

Li, X., Ishikawa, T., Kasama, K. and Zhang, T., 2025, Slope stability-soil runout integrated analysis considering surface flow during heavy rainfall. *Engineering Geology* 356, p. 108268.

Muchtaranda, I.H., Sulistyowati, T. and Muhajirah, M., 2024, Pengaruh Hujan Terhadap Stabilitas Lereng Dengan Retakan Pada Tanah Kohesif (Studi Kasus : Tanah Longsor di Desa Guntur Macan Kecamatan Gunung Sari Kabupaten Lombok Barat): The Effect of Rain on Slope Stability with Cracks in Cohesive Soil (Case Study: Landslide in Guntur Macan Village, Gunung Sari District, West Lombok Regency), Spektrum Sipil.

Naryanto, H.S., Prawiradisastra, F., Ardiyanto, R. and Hidayat, W., 2020, Analisis Pasca Bencana Tanah Longsor 1 Januari 2020 Dan Evaluasi Penataan Kawasan Di Kecamatan Sukajaya, Kabupaten Bogor. *Jurnal Geografi Gea* 20(2, October), pp. 197–213.

Pratama, A.R.I., Latipah, S.A. and Sari, B.N. 2022. Optimasi Klasifikasi Curah Hujan Menggunakan Support Vector Machine (SVM) Dan Recursive Feature Elimination (RFE). *JIPI (Jurnal Ilmiah Penelitian dan Pembelajaran Informatika)* 7(2), pp. 314–324.

Rahayu, W. et al., 2024, Effect of slope protection using concrete waste on slope stability during rainfall. *Results in Engineering* 24, p. 103244.

SNI; 2016. *SNI 2415:2016 Tata Cara Perhitungan Debit Banjir Rencana*. Badan Standar Nasional Indonesia.

U.S. Army Corps of Engineers, 1953, *The Unified Soil Classification System (Technical Memorandum No. 3-357).*

Wang, J.-H., Xu, W.-J. and Liu, X.-X., 2024a, A slope stability analysis method considering the rainfall hydrology process. *Engineering Geology* 343, p. 107775.

Wang, J.-P. et al., 2024b, Effect of vegetation on unsaturated soil hydraulic and the slope stability under rainfall. *Rhizosphere* 31, p. 100933.

Yang, Y. et al., 2025, Analysis of the Response Mechanism of Slopes With Different Inclinations Under Rainfall Infiltration. *Wiley* 7(3).

Zhang, J., Yang, B., Lu, M. and Sharma, A., 2025a, Assessing annual failure probability of soil slopes under rainfall and evaporation. *Computers and Geotechnics* 187, p. 107517.

Zhang, L., Jiang, X., Sun, R., Cui, C., Gu, H. and Qiu, Y., 2025b, A novel analytical approach for 3D stability of unsaturated soil slopes with cracks under rainfall infiltration. *Engineering Failure Analysis* 175, p. 109545.