Civil Engineering Dimension, Vol. 25, No. 2, September 2023, 135–142
ISSN 1410-9530 print / ISSN 1979-570X online
DOI: https://doi.org/10.9744/CED.25.2.135-142

Hydromechanics – Slope Monitoring in Rainy Season

Muntohar, A.S.[1]*, Hairani, A.[1], Permana, M.F.[2], and Bahti, F.N.[2]

Abstract: Rainfall and soil response are necessary to be monitored to have slope characteristics in detecting landslide occurrence. Even though much research has been carried out worldwide for rainfall monitoring, less research has been conducted in Indonesia for slope monitoring. Therefore, this research was conducted to observe the suction, soil moisture content, and rainfall in a silty sand slope. An automatic rain gauge was set on the ground to measure precipitation. Tensiometer and soil moisture content sensors were installed at depths of 0.5 m; 1 m; and 1.5 m from the slope surface. The monitoring was conducted during the peak rainy season from December 2022 to January 2023. The rainfall amount is about 436.6 mm, and the 6 hours of rainfall events contribute a relatively sizeable rainfall amount (about 31%) to the total. The safety factor of the slope is estimated to decrease by 39%-40% due to the rainfall.

Keywords: Suction; soil moisture content; rainfall; infiltration; slope monitoring.

Introduction

A natural disaster is a phenomenon causing both human and economic losses. Human activities contribute to climate change, which is indicated by the increasing global temperature and rainfall intensity. The phenomenon triggers many natural disasters in the decade [1]. Cruden [2] identifies frequent natural disasters in the form of rock movement, soil, or debris flowing downward to a cliff or slope. Many methods have been developed to determine the possibility of a landslide disaster; one of the methods used to determine the hazard is to use landslide data records [3]. In predicting landslides, research should address two fundamental questions "where" and 'when" the landslides will occur. The question "where" requires evaluation of spatially varying rainfall conditions and intrinsic natural slope factors, such as topographical, geological and geotechnical properties. However, to predict "when" landslides will occur, it is necessary to understand how slope properties vary over time. Therefore, changes in slope response with elapsed time during the rainfall infiltration are required to be monitored. The monitoring will have a coherent understanding of a critical state leading to the actual occurrence of the landslide. For this purpose, further analysis of fixed and intrinsic factors should be carried out through real-time monitoring [4,5].

[1] Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya Tamantirto, Bantul, D.I. Yogyakarta 55183, INDONESIA

[2] Landslide Research Center, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya Tamantirto, Bantul, D.I. Yogyakarta 55183, INDONESIA

*Corresponding author; Email: muntohar@umy.ac.id

Note: Discussion is expected before November, 1st 2023, and will be published in the "Civil Engineering Dimension", volume 26, number 1, March 2024.

Received 18 August 2023; revised 05 September 2023; accepted 08 September 2023.

Observing slope response due to rainfall and change in soil characteristics is necessary to detect landslides. Based on the observation, changes in rainfall and soil conditions on the slope can be analyzed for developing an early warning system. Field monitoring at a prone area is one of the most critical elements of landslide early warning technology for slopes. The monitoring relates to the combined measurement of various geological, geotechnical, meteorological, and hydromechanical factors associated with landslides. Therefore it is still necessary to research the integrated measurement of rainfall, soil pore water pressure, and soil moisture response on the slopes [6,7]. A few studies have focused on real-time monitoring slopes in Indonesia, e.g., Muntohar et al. [8] and Tohari [9]. The monitoring results have been majorly used to establish a general model for rainfall-triggered landslides [10] and early warning systems [11,12].

Muntohar and Soebowo [13] state that landslides in Indonesia frequently occur in the wet season, from December to February. There was continuous heavy rain with very high rainfall intensities during this period. The rainy season in Yogyakarta commenced from October to March in the last three decades. However, the rainy season is predicted to advance 1-2 months in most of the seasonal areas in 2022-2023, and the peak rainy season is predicted to occur from December 2022 to January 2023 [14]. This paper presents the results of slope monitoring, including rainfall, suction, and volumetric moisture content. This research aims to monitor the rainfall and the change in suction and volumetric moisture content. The objective of this research is to investigate the rainfall characteristics and the effects on the slope response, including suction and volumetric moisture content. The hydromechanics response to rainfall is beneficial for establishing a landslide early warning system incorporating physical-based modeling [11, 12, 15-18]. Muntohar et al. [8] proposed an empirical equation to evaluate the slope stability due to rainfall infiltration for typical slope as written in Equation 1.

$$FS_n = 0.9844 + 0.3971e^{-0.0296R} \quad (1)$$

where FS_n is normalized factor of safety, and R is percent of cumulative rainfall.

Research Method

Site Characteristics

Figure 1a shows the slope condition and the installed instrumentation. The slope height was about 2.6 m, and the inclination angle was 18° [6]. The five-story building rested on piles of foundations at the top of the slope. The slope was mainly sand soil deposit, which was classified as silty sand (SM). The specific gravity of the soil range from 2.66 to 2.9. These values is a common range for soil [19]. The soil was typical of the Merapi volcano quaternary volcanic residual sand deposit. The soil properties are presented in Table 1. Undisturbed soil samples were collected to determine the shear strength parameters (c and ϕ) and soil–water characteristics. A triaxial test was conducted in an unconsolidated–undrained state. The soil at -0.5 m deep has a greater cohesion than the soil at a depth of -1.0 m. It was possible due to the presence of grass roots up to the depth of -0.5 m (see Table 1). The permeability was estimated from the double-ring infiltrometer test at the field. The permeability coefficient was about 4.9×10^{-5} m/s, calculated by Philip's infiltration equation.

Slope Instrumentation

Muntohar et al. [6] have successfully developed instrumentation and monitoring for field suction on the slope. However, the monitoring was terminated because of the endurance issues of the sensors. These monitoring instruments comprised soil moisture, a tensiometer, and a rain gauge. Figure 1b shows a scheme of the slope and instruments arrangement. The tensiometers (T1 – T3) and soil moisture sensors (M1 – M3) were installed at 0.5 m, 1.0 m, and 1.5 m deep. The soil moisture sensor used the ThetaProbe ML-3 model (Figure 1c) to measure volumetric soil moisture (θ_w). The measurement range of the sensors is 0 to 0.5 $m^3.m^{-3}$ with an accuracy of ± 0.01 $m^3.m^{-3}$

Table 1. Soil Properties of the Monitored Slope

Properties	Depth		
	-0.5 m	-1.0 m	-1.5 m
Specific gravity, G_s	2.9	2.66	2.85
Unit weight, γ_t (kN/m^3)	18.3	17.5	20.9
Natural moisture content w_N (%)	12	15.2	19.7
Void ratio, e	0.74	0.98	1.56
Shear strength parameter at failure:			
Cohesion, c (kPa)	32	3.6	-
Internal friction angle, ϕ (°)	33	35	-
Saturated coefficient of permeability, k_s (m/s)	4.9×10^{-4}		
Sorptivity	4×10^{-3}		

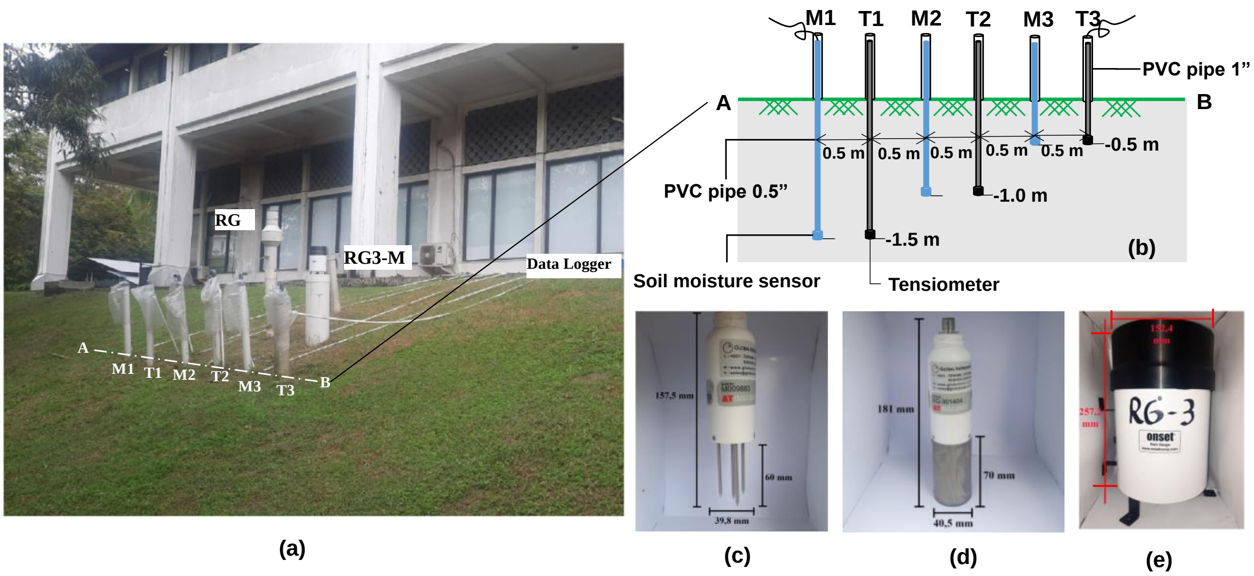


Figure 1. The Location of Monitored Slope (a) Slope Condition and Instruments Layout, (b) Details of the Sensors Arrangement, (c) The Soil Moisture Sensor, (d) The Tensiometer Sensor, and (e) The Rain Gauge.

(1%). The tensiometer used EQ-3 model of Delta T-Device (see Figure 1d). The tensiometer could measure matric suction ($u_a - u_w$) between 0 to – 1000 kPa with an accuracy of ±10 kPa. In this observation, negative pore water pressure was designated as suction (ψ). The rain gauge HOBO RG3-M model (Figure 1e) was used in this study, which could measure rainwater automatically and record it in a data logger. The monitoring was conducted during the peak rainy season from December 2022 to January 2023. The rainfall, soil moisture, and suction were recorded hourly.

Results and Discussion

Rainfall Characteristics

Figure 2 shows the daily rainfall hyetograph from the rain gauge measurement. Rainfall intensity and total rainfall duration are significant factors for evaluating precipitation properties [20, 21]. The other properties, such as rainfall amount, intensity, duration, frequency [22], and the number of rain day, was introduced by The World Meteorological Organization [23]. The WMO defines the number of rain days as the number of days with at least 1 mm of rain [23]. Table 2 presents the rainfall duration characteristics in December 2022 and January 2023. The number of rainy days in December 2022 is longer than that in January 2023. Consequently, the rainfall amount in December 2022 is higher than that in January 2023 (see Tables 3 and 4). Figure 2 also shows the number of continual rainfall events, which is indicated by R1 to R5 indicates. The peak rainfall intensity for each event is notified with I_{m1} to I_{m5}. Critical rainfall for landslide early warning system is recommended based on the hourly rainfall measurement [12, 15, 24]. The rainfall intensity reaches the maximum of I_{m3} = 76 mm/day on 26 December 2022 and I_{m5} = 65.2 mm/day on 6 January 2023.

The mean continual precipitation duration was about 4.1 and 3.2 hours per day, respectively, for December 2022 and January 2023. Continuous precipitation commonly generates a sharp increase in rainfall intensity and triggers slope failure [11]. Tables 3 and 4 present the distribution of precipitation events, rainfall amount, and rainfall intensity at a particular time interval. The Tables show that the continual precipitation lasted, on average, 2 to 5 hours. The rainfall amount at the time interval is 217.8 mm and 130.2 mm, respectively, in December 2022 and January 2023, about 63% and 50% of the total. Rainfall events that lasted over 6 hours contributed a relatively sizeable rainfall amount (about 31%) to the total, even though the precipitation only accounted for a small number of events (approximately 3.4%).

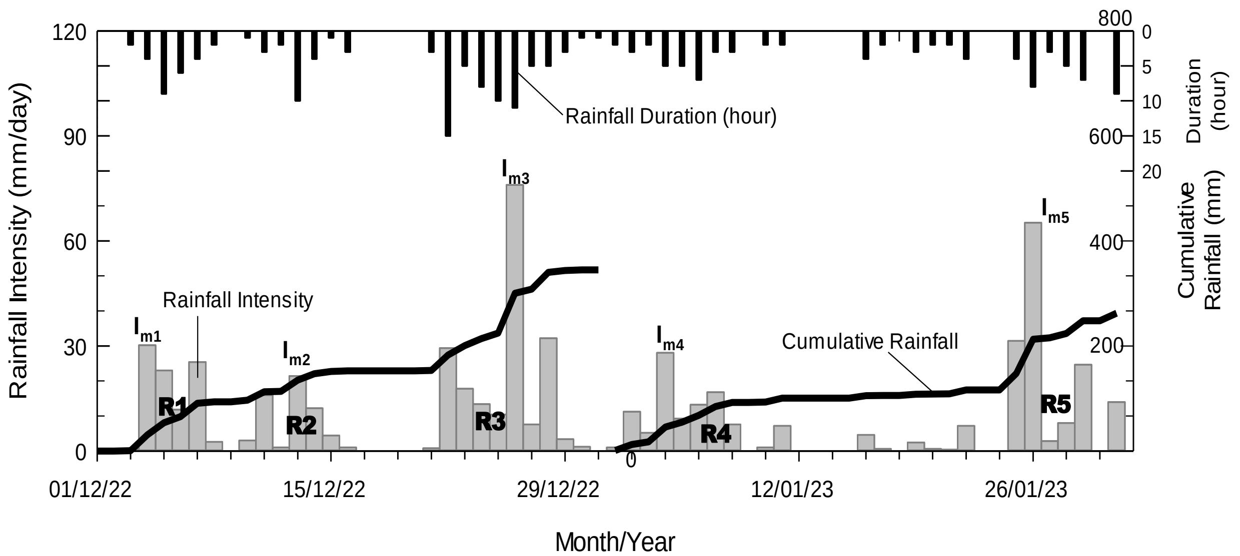


Figure 2. Rainfall Record from the Ground Rain Gauge RG3-M from December 2022 to January 2023

Table 2. Rainfall Duration Characteristics

Criteria	December 2022	January 2023
Number of rain days	19	16
Mean continual rain day	6.3	5.3
Mean rainfall duration (h)	5.3	4.3
Mean continual rainfall duration (h)	4.1	3.2

Table 3. Distribution of the Number of Events, Rainfall Amount, and Hourly Rainfall Intensity for Each Rainfall Duration (T) in December 2023

Criteria	Rainfall duration (T) at time intervals (hours)			Total
	T = 1	2 ≤ T ≤ 5	6 ≤ T ≤ 10	
Number of events	15	17	5	118
Rainfall Amount (mm)	37.6	217.8	64.6	345
Mean Rainfall Intensity (mm/h)	2.2	3.5	1.7	3.1
Maximum Rainfall Intensity (mm/h)	23.0	21.4	9.2	24.6

Table 4. Distribution of the Number of Events, Rainfall Amount, and Hourly Rainfall Intensity for Each Rainfall Duration (T) in January 2023

Criteria	Rainfall duration (T) at time intervals (hours)			Total
	T = 1	2 ≤ T ≤ 5	6 ≤ T ≤ 10	
Number of events	13	18	2	87
Rainfall Amount (mm)	39.4	130.2	91	262.2
Mean Rainfall Intensity (mm/h)	2.2	4.4	5.4	3.2
Maximum Rainfall Intensity (mm/h)	10.2	17.4	43	43

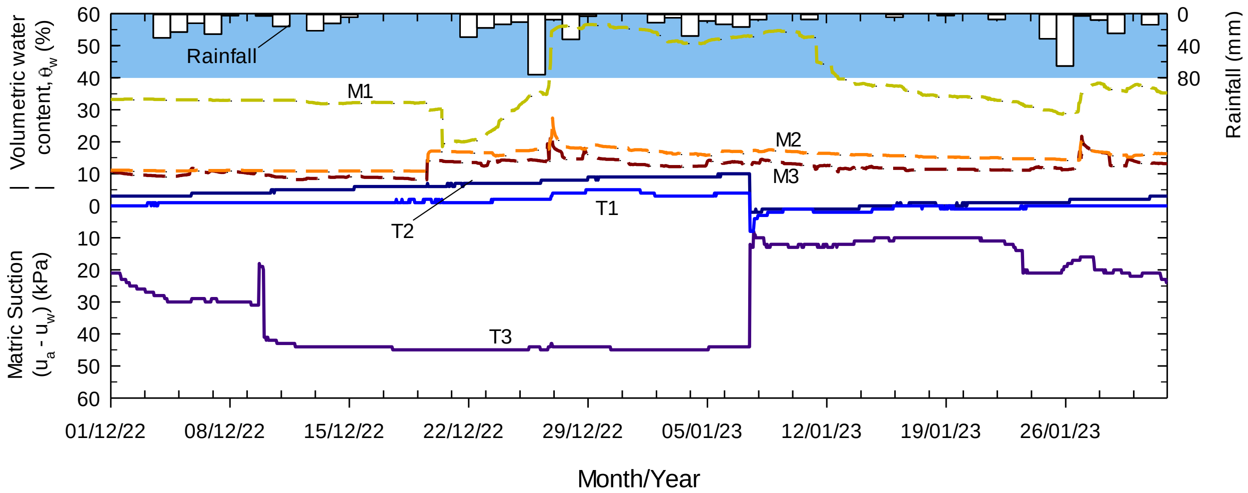


Figure 3. Variation of Matric Suction and Volumetric Water Content with Elapsed Time from December 2022 to January 2023

Suction and Volumetric Water Content Characteristics

Figure 3 shows suction and soil moisture observation for the two months. The variation of the matric suction and volumetric water content is plotted during the rainfall period from December 2022 to January 2023. Figure 3 indicates that rainfall from early December 2022 to early January 2023 increases the suction from 20 kPa to 45 kPa. The graphs show that the suction at a depth of -0.5 m (T3) varies from 10 kPa to 45 kPa, while suction ranges approximately from 1 kPa to 8 kPa at a depth of -1.0 (T2) and -1.5 m (T1). Comparing to the results at the T1 and T2, response of matric suction is slower at the T3. The suction does not change with the rainfall intensity. From 12 December 2022 to 9 January 2023, the accumulated rainfall was recorded as much as 436.6 mm. However, rain has a time lag to decrease the suction at T3. The observation is unlikely to the previous investigation, e.g., Muntohar et al. [8], Xue and Gavin [18], Kim et al. [7], Liu et al. [10], and Liu et al. [25], that the suction decreases and moisture increases as the rainfall intensity increases. Several reasons can be highlighted to elaborate on the result at T3. Atmospheric temperature and humidity can affect the high suction variation at the near surface. Changes in atmospheric temperature affect the rainwater infiltration and seepage field of a slope. The higher the atmospheric temperature is, the higher the rainfall infiltration rate; the deeper the infiltration depth is [25].

The variation of volumetric moisture content (θ_w) during rainfall can be classified into two patterns. Similar patterns of moisture response were observed at T2 and T3. The volumetric moisture content varies from 11% to 39.4% at M2 and 8% to 31.6% at M3. The highest θ_w was attained when the precipitation reached the maximum intensity at I_1 and I_2. The volumetric moisture content changes dramatically at T1 after the rainfall intensity reaches the maximum on I_1. The increase in volumetric moisture content is associated with decreases in suction. Figure 4 shows the relationship between suction and volumetric moisture content based on field observations. The van Genuchten model [26] (see blue line in Fig. 4) can be developed as a soil-water content characteristic curve (SWCC), which

$$\theta_w(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left(1+|\alpha\psi|^n\right)^m} \tag{2}$$

θ_r is residual volumetric water content = 8.7%, θ_r is saturated volumetric water content = 73.6%, α = 210.2, n = 1.417, and m = 0.295. The SWCC model in equation (1) improves the result obtained by Muntohar et al. [8]. Figure 4 plots the laboratory test of SWCC obtained by Muntohar et al. [10]. The data series agree with the SWCC model of equation (1). Hamdany et al. [27] found that the field measurement will not go into a very high suction range; the measured field data can be used to pinpoint the location of the scanning curve.

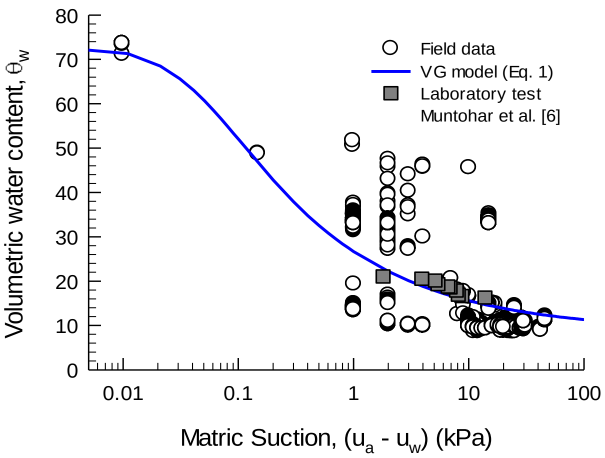
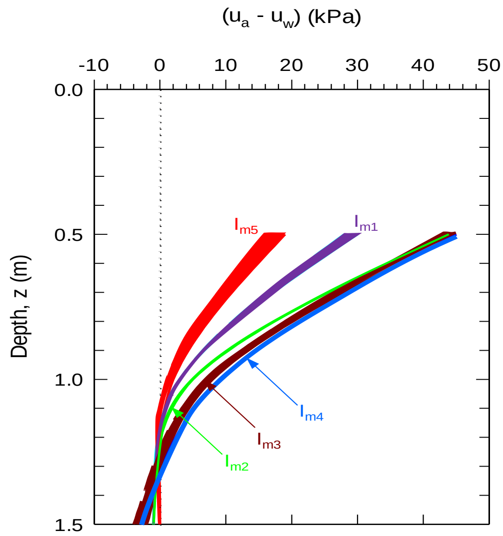


Figure 4. Suction and Volumetric Moisture Content Relationship

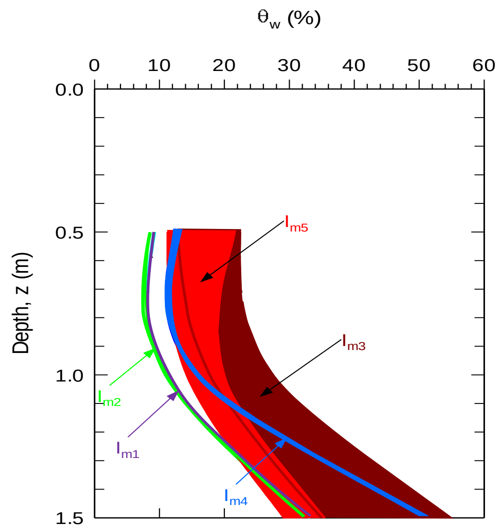
Matric Suction and Volumetric Water Content Profiles

Figure 5 illustrates the variation of pore water pressure and volumetric water content with the depth at different precipitation events (R1 to R5). It is noted that the $(u_a - u_w)$ and θ_w is recorded hourly, and the values fluctuate correspond to the elapsed time. Hence, the $(u_a - u_w)$ and θ_w varies in a day from the lowest to the highest, as shown by the shaded area in Figure 5. A wide range of the θ_w was observed during R3 and R5 rainfall events. At those corresponding rainfall events, the precipitation in a day was relatively high and long-duration rainfall. The rainfall event at I_{m3} is 76 mm/day for 11 hours, while at I_{m5} is 65 mm /day for 8 hours rainfall duration. Tu et al. [28] found that the soil layer would not be wet enough to saturate if the rainfall intensity was not high and prolonged enough to cause a change in the matric suction at a certain depth.

The suction profile in Fig. 5 shows a general pattern: the matric suction decreases with depth, but the volumetric water content increases with depth. The matric suction profile indicates the rainwater infiltrates deeper and forms a wetting front at 1.3 – 1.5 m (Figure 5a). During long-duration rainfall events and higher intensity, the soil layer becomes saturated, and the wetting front advances to a more profound depth. This characteristic is shown by the increases in volumetric water content at the deeper depth, as illustrated in Figure 5b. The advancement of the infiltrating rainwater to deeper depths is affected by its initial matric suction [29]. At deeper depths, it is also found that the suction delay is due to the rainwater infiltration requiring minimum rainfall to cause changes in soil suction and water content at the deeper depth [30].



(a)



(b)

Figure 5 Variation of the Pore Water Pressure with Time and Depth (a) Pore Water Pressure Profile, (b) Change of Volumetric Water Content (notation: I_{m1} = 4 December 2022, I_{m2} = 13 December 2022, I_{m3} = 26 December 2022; I_{m4} = 4 January 2023, I_{m5} = 26 January 2023)

Figure 5a shows low matric suction at I_{m1} and I_{m5}. The lowest matric suction at I_{m5} is almost definitely due to the cumulative event rainfall and antecedent rainfall. Nevertheless, low matric suction at I_{m1} is likely induced by the antecedent rainfall solely, although there is no rainfall record. The rainfall and duration at I_{m1} are 30.2 mm and 4 hours, respectively. The observation agrees with the field monitoring conducted by Li et al. [31]. The antecedent rainfall strongly affects the reduction of matric suction and inducing the perched water table. Some research indicates that subsequent rainfall, including five days of antecedent rainfall, would significantly saturate the soil and cause the slope stability to decrease by 30% [6, 8, 28, 31, 32]. Bishop and Blight [30] stated that if the matric suction of soil is positive, the effective stress of the soil is lower than that of soil with negative matrix suction. Thus, the slope becomes prone to collapse. Applying the empirical equation 1 to evaluate the factor of safety due to rainfall infiltration for a typical slope, the factor of safety trends to decreases by about 37%-38%, which is slightly higher than the previous research [6, 8, 28, 31, 32].

Conclusion

A set of instrumentation, including automatic rain gauge, tensiometers, and soil moisture sensors, has successfully monitored the slope response to the rainfall. Each data has been analyzed and elaborated to have a consolidated conclusion. The conclusion can be summarized as follows: (1) Rainfall events that lasted over 6 hours contributed a relatively sizeable rainfall amount (about 31%) to the total, even though the precipitation only accounted for a small number of events (approximately 3.4%). The cumulative rainfall was about 63% and 50% of the total precipitation in December 2022 and January 2023, respectively; (2) The matric suction varies with the depths. The matric suction value in deep soil has a prolonged duration for altering the matric suction value. A higher amount of precipitation is necessary for the increase in matric suction value, with the depth of the soil playing a role in this relationship. Specifically, the matric suction value increases as the soil depth increases. However, it is worth noting that at a depth of 1 meter, the suction reading is higher than at a depth of 1.5 meters; (3) The antecedent rainfall strongly affects the reduction of matric suction and inducing the perched water table. During long-duration rainfall events and higher intensity, the soil layer becomes saturated, and the wetting front advances to a more profound depth.

Acknowledgment

This research is part of the grant entitled "The relationship of soil suction and moisture content of the volcanic soil triggered by rainfall," funded by Universitas Muhammadiyah Yogyakarta under contract number 56/R-LRI/XII/2022. The authors are thankful to the Landslide Research Center for supporting the instrumentation.

References

1. Guo, H., Understanding Global Natural Disasters and the Role of Earth Observation, *International Journal of Digital Earth,* 3(3), 2010, pp. 221-230.
2. Cruden, D.M., A Simple Definition of a Landslide, *Bulletin of the International Association of Engineering Geology,* 43(1), 1991, pp. 27-29.
3. Wieczorek, G.F., Preparing a Detailed Landslide-Inventory Map for Hazard Evaluation and Reduction, *Bulletin of the Association of Engineering Geologists,* 21(3), 1984, pp. 337-342.
4. Angeli, M.G., Pasuto, A., and Silvano, S., A Critical Review of Landslide Monitoring Experiences, *Engineering Geology,* 55, 2000, pp. 133–147, doi: 10.1016/S0013-7952(99)00122-2.
5. Chae, B.G., Park, H.J., Catani, F., Simoni, A., and Berti, M., Landslide Prediction, Monitoring and Early Warning: a Concise Review of State-of-the-Art, *Geosciences Journal,* 21(6), 2017, pp. 1033-1070, doi: 10.1007/s12303-017-0034-4.
6. Toll, D., Lourenço, S., Mendes, J., Gallipoli, D., Evans, F., Augarde, C., Cui, Y.J., Tang, A. M., Rojas, J., and Pagano, L., Soil Suction Monitoring for Landslides and Slopes, *Quarterly Journal of Engineering Geology and Hydrogeology,* 44, 2011, pp. 23 - 33, doi: 10.1144/1470-9236/09-010.
7. Kim, K.S., Jeong, S.W., Song, Y.S., Kim, M., and Park, J.-Y., Four-Year Monitoring Study of Shallow Landslide Hazards based on Hydrological Measurements in a Weathered Granite Soil Slope in South Korea, *Water,* 13(17), 2021, doi: 10.3390/w13172330.
8. Muntohar, A.S., Fata, N., Jotisankasa, A., and Yang, K.H., Suction Monitoring and Stability of Volcanic-Residual Soil Slope During Rainfall, *Civil Engineering Dimension,* 22(2), 2020, pp. 68-74, doi: 10.9744/CED.22.2.68-74.
9. [Tohari, A., Variations of Pore-Water Pressure Responses in a Volcanic Soil Slope to Rainfall Infiltration, *Jurnal RISET Geologi dan Pertambangan,* 23(2), 2013, doi: 10.14203/risetgeotam 2013.v23.73.
10. Liu, G., Zha, X.Y., Guan, J.K., and Tong, F.G., Field Experiment of Rainfall Infiltration on a Soil Slope and Simulations Based on a Water-Air Two-Phase Flow Model, *Journal of Mountain Science,* 18(8), 2021, pp. 2159-2167, doi: 10.1007/s11629-020-6322-x.
11. Aleotti, P., A Warning System for Rainfall-induced Shallow Failures, *Engineering Geology,* 73(3-4), 2004, pp. 247-265, doi: 10.1016/j.enggeo.2004.01.007.

12. Caine, N., The Rainfall Intensity-duration Control of Shallow Landslides and Debris Flows, *Geografiska Annaler: Series A, Physical Geography,* 62(1-2), 1980, pp. 23-27.
13. Muntohar, A.S. and Soebowo, E., Stability Analysis of A Shallow Slope Failure During Rainy Season in Kulonprogo, Indonesia, in *International Conference on Landslides and Slope Stability (SLOPE 2015)*, Bali, Indonesia, P.P. Rahardjo and A. Tohari, Eds., 27-30 September 2015 2015: Parahyangan Catholic University, pp. F5.1-F5.8.
14. BMKG, *Forecasting of the Onset of Rainy Season in 2022/2023*, Meteorology, Climatology, and Geophysical Agency (in Bahasa Indonesia), Jakarta, 2022.
15. Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C.P., Rainfall Thresholds for the Initiation of Landslides in Central and Southern Europe, *Meteorology and Atmospheric Physics,* 98, 2007, pp. 239–267, doi: 10.1007/s00703-007-0262-7.
16. Muntohar, A.S., Hairani, A., Nabila, K.A., and Agrina, N., Potensi Penggunaan Intensitas Hujan Hasil Pengamatan Satelit untuk Ambang Hujan Pemicu Tanah Longsor, *Jurnal Teknik Sipil,* 17(1), 2022, pp. 12–17, doi: 10.24002/jts.v17i1.6125.
17. Muntohar, A.S. and Liao, H.J., Factors Affecting Rain Infiltration on a Slope Using Green-Ampt Model, *Journal of Physical Science,* 30(3), 2019, pp. 71–86, doi: 10.21315/jps2019.30.3.5.
18. Xue, J. and Gavin, K., Effect of Rainfall Intensity on Infiltration into Partly Saturated Slopes, *Geotechnical and Geological Engineering,* 26(2), 2007, pp. 199-209, doi: 10.1007/s10706-007-9157-0.
19. Holtz, R.D., Kovacs, W.D., and Sheahan, T.C., *An Introduction to Geotechnical Engineering*, Pearson, New York, 2011.
20. Dairaku, K., Kuraji, K., Suzuki, M., Tangtham, N., Jirasuktaveekul, W., and Punyatrong, K., The Effect of Rainfall Duration and Intensity on Orographic Rainfall Enhancement in a Mountainous Area: A Case Study in the Mae Chaem watershed, Thailand, *Journal of Japan Society of Hydrology and Water Resources,* 13, 2000, pp. 57-68, doi: 10.3178/jjshwr.13.57.
21. Kuraji, K., Punyatrong, K., and Suzuki, M., Altitudinal Increase in Rainfall in the Mae Chaem Watershed, Thailand, *Journal of the Meteorological Society of Japan,* 79(1B), 2001, pp. 353-363, doi: 10.2151/jmsj.79.353.
22. Dairaku, K., Emori, S., and Oki, T., Rainfall Amount, Intensity, Duration, and Frequency Relationships in the Mae Chaem Watershed in Southeast Asia, *Journal of Hydrometeorology,* 5(3), 2004, pp. 458–470, doi: 10.1175/1525-7541(2004)005<0458:raidaf>2.0.co;2.
23. WMO, *Technical Regulations (WMO-No. 49) Volume III Hydrology*, Publications Board World Meteorological Organization, Geneva, Switzerland, 2021, p. 40.
24. Keefer, D.K., Wilson, R.C., Mark, R.K., Brabb, E.E., Iii, W.M.B., Ellen, S.D., Har, E.L., Wieczorek, G.F., Alger, C.S., and Zatkin, R.S., Real-Time Landslide Warning During Heavy Rainfall, *Science,* 238(4829), 1987, pp. 921-925, doi: 10.1126/science.238.4829.921.
25. Liu, G., Tong, F., Tian, B., and Tian, W., Influence of Atmospheric Temperature on Shallow Slope Stability, *Environmental Earth Sciences,* 78(632), 2019, pp. 1-9, doi: 10.1007/s12665-019-8649-6.
26. Genuchten, M. T. V., A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *Soil Science Society of America Journal,* 44(5), 1980, pp. 892-898, doi: 10.2136/sssaj1980.03615995004400050002x.
27. Hamdany, A.H., Shen, Y., Satyanaga, A., Rahardjo, H., Lee, T.T.D., and Nong, X., Field Instrumentation for Real-time Measurement of Soil-water Characteristic Curve, *International Soil and Water Conservation Research,* 10(4), 2022, pp. 586-596, doi: 10.1016/j.iswcr.2022.01.007.
28. Tu, X., Kwong, A., Dai, F., Tham, L., and Min, H., Field Monitoring of Rainfall Infiltration in a Loess Slope and Analysis of Failure Mechanism of Rainfall-induced Landslides, *Engineering Geology,* 105(1-2), 2009, pp. 134-150.
29. Rahardjo, H., Lee, T.T., Leong, E.C., and Rezaur, R.B., Response of a Residual Soil Slope to Rainfall, *Canadiann Geotechnical Journal,* 42, 2005, pp. 340-351, doi: 10.1139/T04-101.
30. Bishop, A.W. and Blight, G., Some Aspects of Effective Stress in Saturated and Partly Saturated Soils, *Geotechnique,* 13(3), 1963, pp. 177-197.
31. Li, A., Yue, Z., Tham, L., Lee, C., and Law, K., Field-Monitored Variations of Soil Moisture and Matric Suction in a Saprolite Slope, *Canadian Geotechnical Journal,* 42(1), 2005, pp. 13-26.
32. Jotisankasa, A., Mahannopkul, K., and Sawangsuriya, A., Slope Stability and Pore-Water Pressure Regime in Response to Rainfall: A Case Study of Granitic Fill Slope in Northern Thailand, *Geotechnical Engineering Journal of the SEAGS & AGSSEA,* 46(1), 2015, pp. 45-54.