LANDSLIDE HAZARDS DUE TO RAINFALL INTENSITY IN THE CALDERA OF MOUNT BATUR, BALI.

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ABSTRACT

In order to ensure the safety of the visitors, the development planning of tourism areas requires a comprehensive study on the physical condition and disaster risk management, so that it can be applied effectively, efficiently, and in line with the sustainability requirements. In this case, the study on the physical condition focuses on the potential of natural disasters, especially landslide. This research was conducted in Terunyan Village, Kintamani Distric, Bangli Regency, Bali. Landslide often occurs in this village, especially during the rainy season, as it is surrounded by hills with low vegetation and bordered by a lake. Samples were collected from two hand bore points at slopes which have the highest risk to the public facilities and residences. GeoStudio 2012 program was used to analyze the rainfall infiltration, then it was linked to Slope/W to obtain the safety factor. The average rainfall intensity applied in this study was 125 mm/day, and the optimal duration of rain was 5 hours (based on the data provided by BMKG on 9 February, 2017). The results show that the impact of rainfall to the infiltration with the safety factor lower than 1.0 happened in the 2nd hours. The critical safety factor decreased from 0.963 to 0.623. The safety factor decreased drastically in the 4th to 5th hours of rain due to the drastic drop of the resisting force from 167 kPa to 124 kPa and the increase of driving force from 152 kPa to 200 kPa. The high and constant rain volume caused high seepage to the ground. Rain water filled the soil void and increased the pore pressure, then the soil became saturated and the internal friction angle decreased. This problem can be solved by controlling the seepage into the ground, which can be done by closing the open cracks and designing the upperground and underground drainage system.

Keywords: Landslide, rainfall intensity, infiltration, critical safety factor

A. INTRODUCTION

Terunyan is a traditional village which becomes a tourist destination and is also a part of the Batur Geopark. The village is located in the Caldera of Mount Batur, between Longitude 115°13'43"E - 115°27'24"E and Latitude 8°08'30'S - 8°3'07"S. Batur Caldera is located in Kintamani District, Bangli Regency, Bali. The size of the caldera is about 13.8 × 10 km, and it has another caldera structure formed in the middle of it, which has the diameter of 7.5 km. The highest peak of Mount Batur is +1.717 m (Bemmelen, 1949).

Based on the data from the Disaster Management Agency (BPBD) Bangli, in the year of 2012 there were 23 landslides occurred in Bangli Regency. The number of landslide occurrences is about 16.79% of all incidents caused by land movements in Bali (BPBD, 2012). The incident occurred mostly in Kintamani, an area belongs to Gunung Batur Caldera (Figure 1). Thus, it is necessary to study and map the potential threat of landslide disaster around the caldera of Mount Batur.

The geological formations of Buyan Volcano – Ancient Bratan and Ancient Batur in the lower quarter around Mount Batur, including Mount Abang, consists of tuffs and volcanic lava sediment of Buyan-Beratan and groups of Batur rocks.

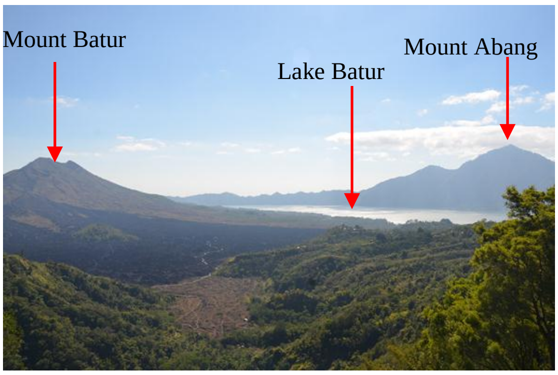


Figure 1. The morphology of Mount Batur Caldera

The outlook of landscape and geological condition was based on Bali geological map (Hadiwidjojo et al., 1998). The geological structures comprise faults and folds and there is also Flores Thrust that stretches from the north to the south of Bali. Meanwhile, the eastern part consists of tuff and volcanic breccia, formed in the Pleistocene era, aged 2.33 ± 0.12 million years to 0.77 ± 0.06 million years. Due to the rain, they can be eroded very quickly (Sinarta et al., 2016).

The application of partial saturated soil concept is the main problem in this study, especially in determining the soil parameters. There are several approaches to determine the partial saturation parameters of the analysis, such as laboratory tests and knowledge-based systems (Fredlund et al., 1996,1997).

The use of computer software in slope stability analysis incorporating water seepage allows researchers to obtain accurate results (Rifa'i, 2011). Before choosing the appropriate method of landslide risk management, it is necessary to investigate the causes of slope instability. Geotechnical and geohydrological data are required in evaluating the stability of the slope. Numerical modeling with Seep/W and Slope/W from GeoStudio can be used for seepage simulation and slope stability (GeoStudio, 2012).

This research was conducted to assess the safety factor due to landslide hazard in Terunyan as the result of the rainfall intensity. This study shows the influence of rainwater infiltration to negative pore-water pressure (suction) alteration and the effect of rainfall infiltration on the safety factor. The seepage and slope stability analysis uses Seep/W and Slope/W.

B. LITERATURE STUDY

Rainfall with particular intensity is the trigger of landslides because rainwater seeps into the slopes then stimulates the soil to slide. In general, there are two types of rain that trigger landslides in Indonesia: 1) Heavy rain, which can reach 70 mm/day or more than 100 mm/day (Premchit (1995) in Karnawati (2005); 2) Normal rain with longer duration that occurs less than 20 mm/day. Heavy rain only triggers a landslide on soil which absorbs water easily, such as clay and sand (Karnawati, 1997, 2000).

The analysis of slope stability is based on the concept of limit plastic equilibrium. This method uses the principle of equilibrium force, also known as the slice method because the slope plane is divided into several parts. This method is analyzed under the conditions of force balance in the vertical direction (or vertical perpendicular direction) and in the horizontal direction (or parallel direction of the landslide); and moment balance at one particular point (Furuya, 2013).

The purpose of stability analysis is to determine the safety factor of a potential landslide area. There are four assumptions in the method of limit plastic equilibrium i.e. the sliding occurring along a certain landslide plane can be considered as a 2-dimensional problem, landslide mass is considered as a massive plane, shear strength is considered isotropic, and average shear strength are considered along the slip surface to determine the safety factor (Abramson,1995).

The simulation program is used to analyze slope stability. In analyzing the slope stability, the researchers used Slope/W, while the method used in this program is the Limit Plastic Equilibrium Method (Mukhlisin, 2016). There are several methods of slice in Slope/W, however, the researchers only used four of them: Bishop, Ordinary, Janbu, and Morgenstern-Price Methods (GeoStudio, 2012a, b).

For the used simulation program in seepage analysis, the equations for the groundwater flow used in the Seep/W software for the analysis of complete 2-dimensional transient and seepage are:

$$m_w^2 \gamma_w \frac{\partial h_w}{\partial t} = \frac{\partial}{\partial_x}\left(-k_{wx}\frac{\partial h_w}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(-k_{wy}\frac{\partial h_w}{\partial_y}\right) + q$$

where: m_w^2 = slope soil-water relationship characteristic curves, γ_w = unit weight of water, h_w = total head, k_{wx} = soil permeability coefficient of water in the x-direction, k_{wy} = soil permeability coefficient of water in the y-direction, q = flux boundary; t = time.

Two important soil parameters used in Seep/W analysis were soil permeability and Soil Water Characteristic Curve (SWCC) coefficients. The shear strength equations for unsaturated soils used in slope stability analysis, Slope/W, are shown in Equation 2. This equation combines the shear forces of the soil as a result of negative pore water pressure and unsaturated soil saturation. In order to obtain the safety factor (SF) in analysis, the Morgenstern-Price method is used.

$$\tau = c' + (\sigma_n - u_w)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad (2)$$

Where: τ = unsaturated soil shear strength, c' = cohesion, σ_n = total normal stress, u_a = pore air pressure, ϕ = internal friction angle, u_w = pore-water pressure, $(u_a - u_w)$ = matrix suction.

C. RESEARCH METHOD

This research analyzes the stability of slope with Limit Equilibrium Method based on field data and compared the results of analysis to the conditions at the field. This research only observes the value of safety factor resulting from rainwater infiltration.

Samples were collected on 5 February, 2017, in Terunyan Village, Kintamani, Bangli, assisted by a team from the Faculty of Engineering, Universitas Warmadewa. The sample collection was conducted on the slopes closest to the public facilities and residences. The groundwater depth calculated in slope stability was based on the condition at the time of sampling, while the groundwater depth position was based on seepage of water on the slopes.

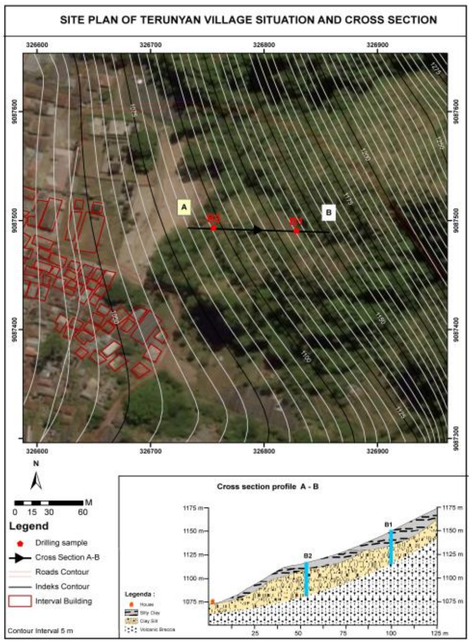
Laboratory tests were primarily conducted to obtain engineering parameters used in landslide analysis. The soil parameters tested in the soil mechanics laboratory are: 1) Water content, 2) Specific gravity, 3) Atterberg limits, 4) Grain-size analysis. 5) Permeability and 6) Shear strength parameters by Direct Shear Test. The soil data parameters used as the input data for slope stability calculation are presented in Table 1.

The investigation results of physical parameters of the soil are based on the description of the geological drill log in the field as seen in Table 1. The rainfall data were based on the extreme rainfall analysis in Kintamani (Bangli) on 9 February, 2017, by BMKG of Jembrana-Bali. The average rain intensity was 125 mm/day and lasted for 5 hours. Additionally, in the infiltration analysis by modeling the seepage into the soil due to the influence of rain, Seep/W program from GeoStudio was used.

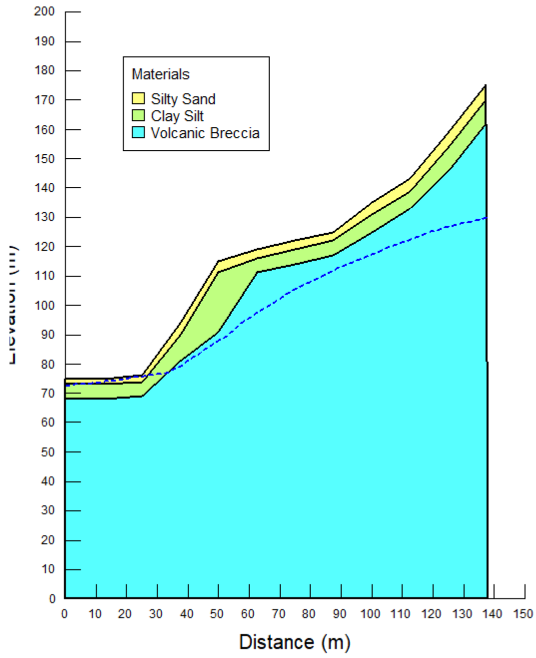
The analysis was carried out by including the physical parameters of the soil and then adjusted it with the geometry measurement data in Terunyan (see Figure 2). Moreover, cross section was done on the contour as shown in Figure 2a to find out the geometry of the slope to be analyzed in GeoStudio 2012. Figure 2b is the geometry model for GeoStudio 2012 simulation on each type of soil layer in Terunyan, which was to be investigated in GeoStudio 2012.

Table 1. Physical and mechanical properties of soil samples

Depth (m)	Soil	(w) (%)	Gs	γ_b (kN/m^3)	c (kN/m^2)	ϕ (^{o})	k (cm/dt)
Borehole B1							
0 – 2.5	Silty sand	22.12	2.65	16.8	8.3	30.45	2.23 10^{-5}
2.5 – 6	Clay Silt	32.18	2.74	21.5	24.65	32.34	2.34 10^{-5}
> 6	Breccia	41.56	2.64	19.4	21.80	45.13	0.06 10^{-5}
Borehole B2							
0 – 2	Silty sand	25.57	2.65	16.8	8.3	30	2.23 10^{-5}
3.5 – 6	Clay Silt	32.00	2.74	21.5	24.0	33.34	2.34 10^{-5}
> 6	Breccia	40.80	2.64	19.4	20.12	42.34	0.06 10^{-5}



a. Cross section A-B and Drilling sample



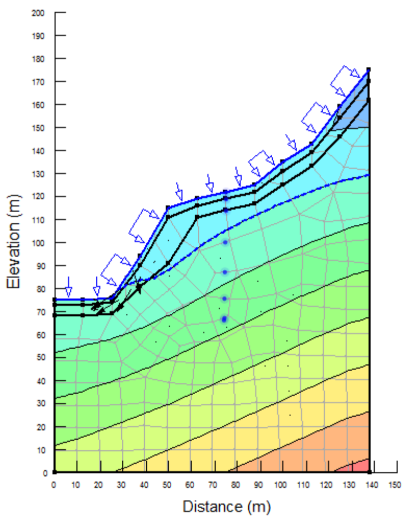
b. GeoStudio geometry model

Figure 2. Site plan and geometry model of the study

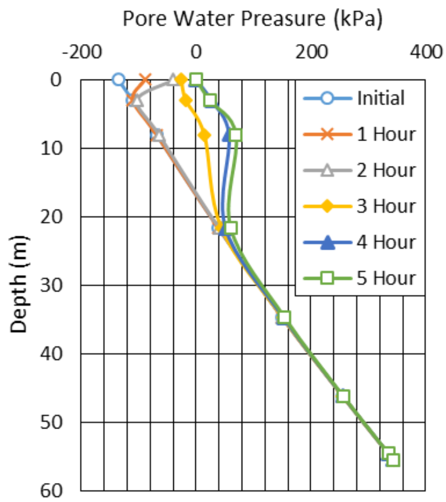
The modeling stage was started by choosing the analytical method. For rain seepage analysis of the slope, the steady-state analysis was used. Additionally, in slope stability analysis, Morgenstern-Price method was chosen using pore-water pressure condition taken from Seep/W analysis. Moreover, the geometry of the slope was drawn by considering the regions having similar geological formation, so that it formed a real slope model. The parameters of each layer were inputted according to the index properties and engineering properties from the laboratory tests. Furthermore, the safety factor was analyzed using Slope/W to find out the value of the safety factor of a slope and the condition of the existing slope stability.

D. RESULTS AND DISCUSSION

From the numerical simulation, the changes in pore water pressure at every rainfall event can be obtained. An overview of pore water pressure changes is shown in Figure 3a, then is plotted on the graph of pore water pressure changes to the depth of sliding mass for each hour as shown in Figure 3b. In general, the pore pressures changes at every rain hour tend to be the same.



a. Overview of pore water (blue dots)



b. Graph of pore water pressure change

Figure 3. Changes in pore water pressure

Based on Figure 3b, the changes of pore water pressure in a steady state conditions begin relatively linear, then nonlinear behavior occurs at the distance of 3 m - 21 m, which are the distance of the sliding surface to the control point. Negative pore water pressure still exists in the 1st hour rain because infiltration cannot be partially saturated. Meanwhile, in 2nd hour to 5th hour rain, pore water pressure approaches a positive value, which indicates the saturation or critical condition in the sliding surface. When the soil is saturated, the rain forms a flow on the surface since the soil is no longer able to absorb the air.

Data processing of physical properties, soil mechanical properties, and infiltration due to rain intensity and duration of rain results in changes on pore water pressure with Seep/W. Moreover, the program is connected to the Slope/W program for slope stability analysis. The results of the calculation are illustrated in a graph that shows the relationship between the safety factor and period of rain as shown in Figure 4, while the value of the safety factor when the pore pressure changes is shown in Figure 5.

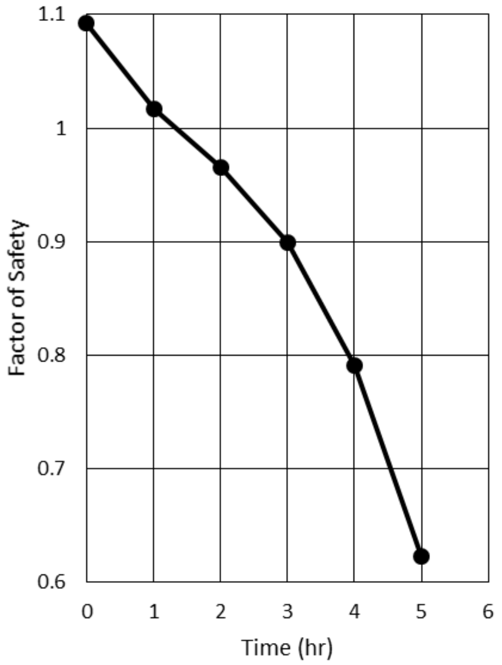


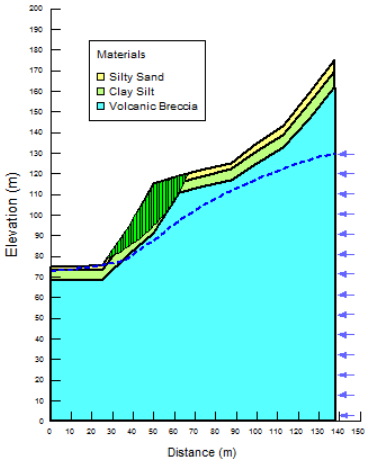
Figure 4. Relationship between Safety Factor and Rain Period

The result of the data processing with the slope/W program the Morgenstern and Price method is shown in Figure 5 a-f. The height and tilt of the slopes, and the changes in water content and degree of saturation are significant influences to the safety factor. According to these conditions, those studies only focus on the most critical condition obtained from the amount of safety factor.

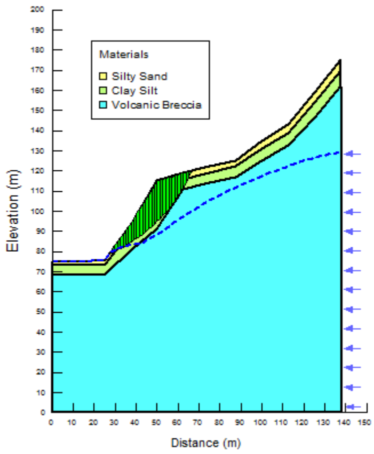
Figure 5a, which shows the early condition of initial water level or field, has already indicated that the slope is in critical condition based on the calculation of the safety factor that reaches 1.093 or slightly higher than 1.0. Evidences of the critical condition before the rain, due to steep site conditions and some places adjacent to the research location where landslide has occurred, can be seen in Figure 6.

Data processing by GeoStudio on rainfall intensity of 125 mm/day and the rain duration of 5 hours, the safety factor <1 already occurs at the 2nd hour. The decrease of safety number occurs along with the increase of rain duration in which the decrease ranges from 0.963 to 0.623. This condition is a result of constant, high volume of rain that causes high seepage to the ground. This water fills the void and creates high pore water pressure on the slopes.

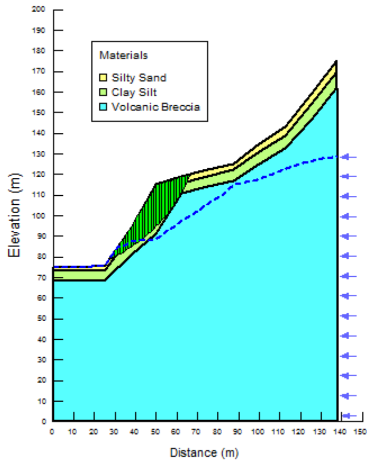
The safety factor decrease is quite drastic in the 4th hour to the 5th hour of rain. This condition can be caused by several reasons: the drastic reduction of resisting force and soil friction angle as the soil becomes saturated. The resisting force at the sliding surface is 167 kPa in the beginning, and it decreases by 124 kPa at the 5th hour, which can be seen in Figure 7a. On the other hand, the driving force in the sliding surface increases by 152 kPa in the beginning and it becomes 200 by the 5th hour. This hourly change can be seen in Figure 7b.



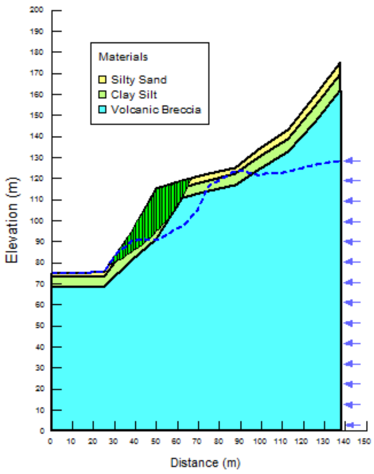
a). Steady state: SF=1.093



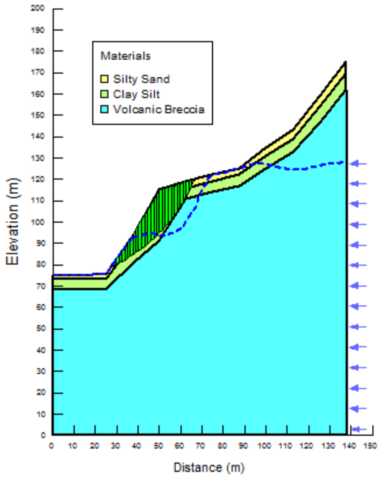
b). Rain on 1st hour: SF = 1.016



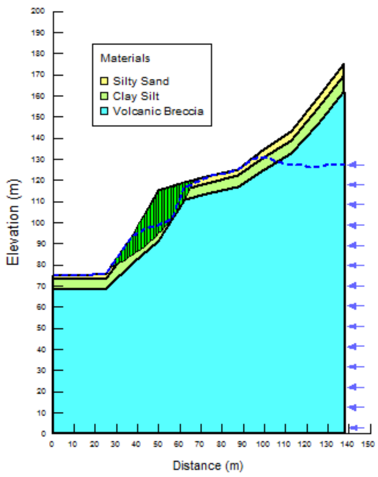
c). Rain 2nd hour: SF = 0.965



d). Rain 3rd hour: SF=0.899



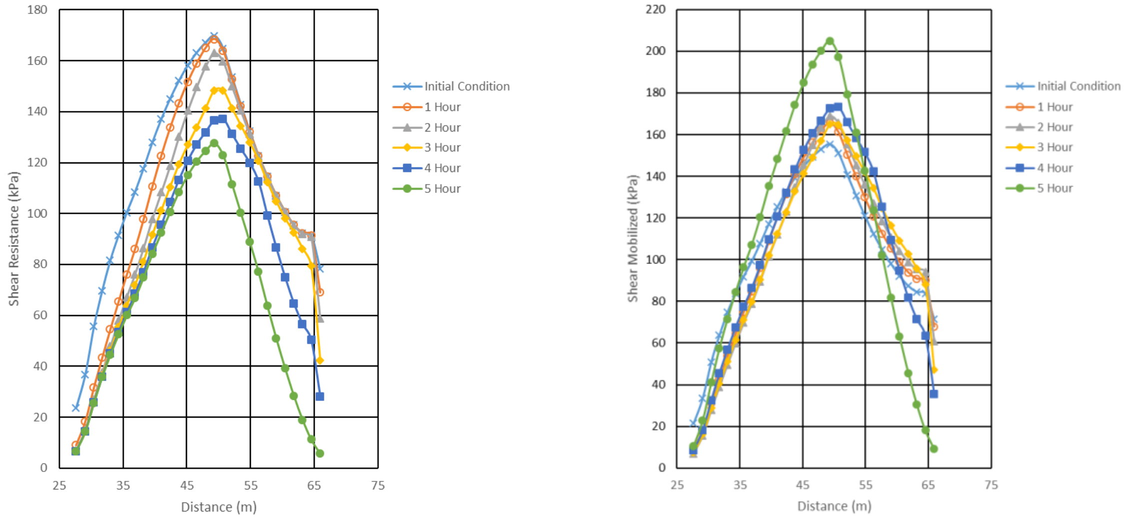
e). Rain 4th hour: SF =0.791



f). Rain 5th hour: SF=0.623

Figure 5. Safety factor and ground water level

Figure 6. Landslide conditions and site location



a. Resisting Force

b. Driving Force

Figure 7. Resisting force and driving force at the sliding surface

E. CONCLUSION

In conclusion, a slope that has higher inclination than the soil friction angle has a critical safety factor nearly 1.0. The duration gives significant influence on the stability of the slope in addition to the intensity of the rain itself. This research shows that the tilt of the slope, the duration of rain, and the intensity of rain on the slopes composed of volcanic rocks affect its stability.

The average rain intensity of 125 mm/day with duration of five hours influences the magnitude of infiltration that causes the slope to collapse. The higher the infiltration, the higher the pore of water pressure and the longer the duration, which makes the inundation or surface runoff that can cause floods. The result shows that on the slope which inclination is about 40°-45°, the infiltration has significant influence to its stability, where the change in 1-hour rain duration occurs from 1.093 to 1.060. Meanwhile, when the slope conditions reach the saturation condition in the 2nd hour to the 5th hour, the infiltration effect is very significant, i.e. from 0.965 to 0.623.

In Terunyan Village, a tourist destination located in the Geopark area of Mount Batur, tourists are warned to avoid steep slopes during the rainy season. It is necessary to make efforts on strengthening the slopes, especially those which threaten infrastructures and residences using bioengineering methods to preserve local flora and fauna. The concept of people-centered early warning system proposed by Fathani et al. (2017) could be effectively implemented by communities vulnerable to landslides, government agencies, and also non-governmental organizations at central, provincial, municipality/district, sub-district, and village levels.

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REFERENCES

Abramson L.W., Lee T.S., Sharma S., and Boyce G.M., (1995). *Slope Stability and Stabilization Methods.* New York: John Wiley & Sons, Inc.

Bemmelen R.W.V., (1949). *The Geology of Indonesia Vol. 1A: General Geology of Indonesia and Adjacent Archipelagoes.* Government Printing Office, The Hague.

Bowles, J.E., (1984). *Physical and Geotechnical Properties of Soil.* Singapura: McGraw-Hil International Editions Civil Engineering Series

Center for Operational Control (Pusdalop), *Regional Disaster Management Agency*, Bali Province, (2012) (in Indonesia)

Fathani T.F., Karnawati D., and Wilopo W., (2017), Promoting a Global Standard for Community-Based Landslide Early Warning Systems (WCoE 2014–2017, IPL-158, IPL-165), *4th World Landslide Forum*, Slovenia DOI: 10.1007/978-3-319-59469-9_30

Fredlund D.G., Xing A., Fredlund M.D. and Barbour S.L., (1996), The Relationship of the Unsaturated Soil Shear Strength Function to the Soil-Water Characteristic Curve, *Canadian Geotechnical Journal*, 33(3): 440- 448.

Fredlund M.D., Fredlund D.G., and Wilson G.W., (1997), *Estimation of unsaturated Soil Properties Using a Knowledge-Based System*, University of Saskatchewan, Saskatoon, Sask., Canada.

Furuya T., (2003), Review and Comparison of Limit Equilibrium Methods of Slices for Slope Stability Analysis, *Bulletin of the National Institute for Rural Engineering* No.43 (2004).

GeoStudio International Ltd., (2012a). *Seep/W, Groundwater seepage analysis GEO-SLOPE International Ltd*., Calgary, Alberta, Canada.

GeoStudio International Ltd, (2012b). *Slope/W, Slope stability analysis.* GEO-SLOPE International Ltd., Calgary, Alberta, Canada.

Hadiwidjojo P, Samodra, H, Amin, T., (1998). *Map of Geology Sheet of Bali, Nusa Tenggara.* Bandung: Center for Geological Research and Development (in Indonesian).

Karnawati D., (2005). *Mass movement natural disaster in Indonesia and its countermeasures. Dept of Geological Engineering, Faculty of Engineering*, Gadjah Mada University, Yogyakarta (in Indonesian).

Mukhlisin M., Aini N., (2016), Study of Horizontal Drain Effect on Slope Stability, *Journal Geological Society of India*, Vol.87, April 2016, pp.483-490

Rifa'i A., (2011). Effect of Matric Suction Changes on Unsaturated Soil Parameter in Slope Stability Analysis Due to Rainfall. *Seminar Nasional-1-BMTTSSI-Konteks 5*: G15-G23.

Sinarta I.N, Rifa'i A., Fathani T.F., Wilopo W., (2016), Geotechnical Properties And Geology Age On Characteristics Of Landslides Hazards Of Volcanic Soils In Bali, Indonesia, *International Journal of GEOMATE*, Oct., 2016, Vol. 11, Issue 26, Japan DOI:10.21660/2016.26.67987

Sinarta I.N, Rifa'i A., Fathani T.F., Wilopo W., (2017), *Slope Stability Assessment Using Trigger Parameters and SINMAP Methods on Tamblingan-Buyan Ancient Mountain Area in Buleleng Regency, Bali*, Geosciences, 2017;7(4):110;doi:10.3390/geosciences7040110

Sinarta I.N., (2014), Landslide Handling Method with Soil Nailing, *Paduraksa*, 3 (2). pp. 1-16. ISSN 2303-2693 (in Indonesian).