ANGLE OF SLOPE AND SLOPE SAFETY FACTOR RELATIONSHIP IN GENDOL RIVER, SOUTHERN SLOPE OF MERAPI VOLCANO, YOGYAKARTA

by Eko Tehuh Paripurno

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ANGLE OF SLOPE AND SLOPE SAFETY FACTOR RELATIONSHIP IN GENDOL RIVER, SOUTHERN SLOPE OF MERAPI VOLCANO, YOGYAKARTA

Purwanto[1&2], Zufialdi Zakaria[1], Eko Teguh Paripurno[2], Boy Yoseph C.S.S.S.A[1]

[1]Faculty of Geology Engineering, Padjadjaran University Bandung, Indonesia,

[2] Faculty of Mineral Technology, University of Pembangunan Nasional "Veteran" Yogyakarta, Indonesia

*Corresponding Author: Received: 04 July 2019, Revised: 5 Aug. 2019, Accepted: 18 Aug. 2019

ABSTRACT: The southern slopes of Merapi Volcano in Yogyakarta are mostly the dangerous zone of Merapi. The slope geometry resulted from the Merapi Volcanic eruption forms an area with the potential of mass movement and disturbance of slope stability. On this basis, this study aims to design a control model for slope geometry in the Volcanic Mount of Merapi materials. It used direct lithology observation and geometry measurements in the field, supported by an analysis of the physical and mechanical properties of soil samples. Slope safety analysis was carried out on 35 slope locations, 6 of which were located on the cliffs of the Gendol River. This analysis used Slope W software, and the relationship of slope safety factors that can be formed by certain slope angles follows the equation of $y = 21.4x^{-0.744}$ with a very strong correlation (r = 0.92), where "y" is a slope safety factor, while "x" is the angle of the slope. Based on the research results, it is can be deduced that the relationship between slope safety factors that can be formed by certain slope angles, in lahar deposits is that if the slope angle is increasing then the value of slope stability factor will be reduced. The stable classes are FS>1.25 with slope angles of <43°, the critical class is 1.07> FS>1.25 with slope angles 44° - 54° and labile class is FS <1.07 with slope angles of >55°.

Keywords: Merapi volcano, Angle of slope, Slope safety factor, Lahar

1. INTRODUCTION

Mass movement is a natural occurrence, which will turn into a disaster if it takes victims, both in the form of casualties, property losses and human cultural products. Some part of Yogyakarta territory is comprised of a hilly and mountainous area, causing this region to be prone to mass movements. The high intensity of rainfall and the frequent occurrence of earthquakes will naturally trigger the occurrence of mass movement natural disasters.

Natural disasters may occur abruptly at any moment or through a process that takes place slowly. Some types of disasters such as earthquakes, tsunamis, and volcanic eruptions are almost impossible to predict accurately, especially related to the time of occurrence and excessive strength. On the other hand, some other disasters such as floods, landslides, and droughts are classified as predictable. Nevertheless, the occurrence of disasters always leads to a shock effect and causes a lot of losses of life and material. Such a shock effect is normally due to a lack of vigilance and readiness in facing the looming danger.

Volcanic bows in Indonesia are located in a group of islands ranging from Sumatra, Java, Bali, Nusa Tenggara, Sulawesi and Maluku of 7,000 kilometers in length. This volcanic distribution results from tectonic dynamics in Indonesia in the form of a meeting between the large Indian-Australian plate that moves northward, the relatively stable Eurasian plate and the Pacific plate that moves westward. Merapi Volcano is one of the most active volcanoes in the world. Based on the conception of the morphological unit of Java-based on plate tectonics, this volcanic alignment is the middle part of the Javanese Volcanic Bow Cone [1].

In Merapi Volcano, the lava eruption activity is more regarded as a danger that is detrimental to the community that benefits. Such eruption causes not only losses of lives, but also damaged and lost assets of community livelihoods. The limited understanding of the process and distribution of volcanoes and sediments, in general, has led to the lack of understanding of mass movements in the volcanic slope area. Previous research on this matter tends to assume that the mass movements occurring on the southern slopes of the Merapi Volcano are homogeneous mass movements. These homogeneous movements make it difficult to predict the level of slope stability on heterogeneous slope compositions and varying conditions of compactness. To increase the understanding of the geometry control of the slope against the potential and character of mass movements on the southern slopes of the Merapi Volcano, it is crucial to conduct specific research addressing this matter.

There are some considerations underlying the implementation of this study: the geological condition of the Merapi Volcano, which is in the form of eruption frequency with variations in volcanic rock produced, and the relationships between rocks found in the volcano system. The geomorphological conditions of the Merapi Volcano that are formed by varying slope angles and slope height and shapes determined by their constituent rock units, and quantitative assessment of the relationship between eruption types on the lithology character forming the slope and its level of stability on the southern slopes of Merapi Volcano.

The main problem in this study is that the eruption activity of Merapi Volcano produces lava and pyroclastic deposits. The pyroclastic eruption is the re-deposition of pyroclastic deposits into lahar deposits [1] [2]. In such process, the character of eruption, the eruption of pyroclastic deposits, and volcanic morphological forms may cause the formation of mass movements [3], which is triggered by various human activities in the region. On this basis, the research was conducted by focusing on the relationship between the slope angle and the slope stability factor of the Gendol River, the southern slope of Merapi Volcano, from the volcanic material formed at the time of the Holocene.

On this basis, the purpose of this study was to examine the relationship between the slope angle and the safety factor of the southern slope of Merapi Volcano to mitigate mass movement disaster on the slopes of the Gendol River.

2. METHODS

Overall, the implementation of the study was divided into several stages of activities, namely preparation, field survey, laboratory and studio analysis, data analysis, and analysis of the relationship between slope angles and slope safety factors. Each stage includes synergistic activities to achieve the research objective.

The preparation phase includes the study of literature, determining the location of research, preparing materials, equipment, and research design in the field. The literature study is intended to obtain supporting data and critical studies from previous studies. The literature study produces a research roadmap related to the research theme. The research design in the field is based on studies of secondary data and field conditions. This is intended to determine the general description of the research area which includes estimates of the distribution of rocks, a description of the potential model of soil movement, and the distribution of geomorphological units and rock units.

The field survey stage is a direct research activity on objects in the field. The purpose of this activity is to examine data from previous research results and to complement and add the existing data to solve the research related problems. Field survey activities include determining the observation locations on the base map, description of rocks and soil, measuring elements of geological structures, making a profile of rock units, and taking rock and soil samples for laboratory analysis.

The location studied was the slope of the southern part of Merapi Volcano, which was administratively located in the Sleman district of Yogyakarta Special Region (Fig. 1).

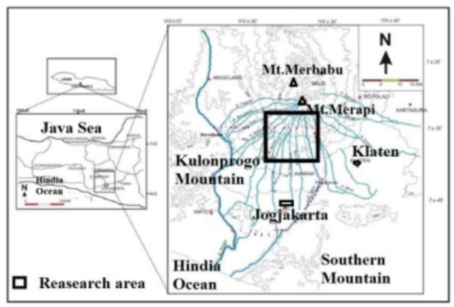

Figure 1 Map of the research area

Laboratory analysis includes morphometric analysis, analysis of physical and mechanical properties of soil, and analysis of slope stability. The soil mechanics analysis especially consists of direct shear analysis (to obtain parameters: cohesion and angle of internal friction), basic properties testing, and grain size analysis.

The method of slope stability analysis was developed prior to the general boundary equilibrium method [4]. This method can be used for all forms of collapsed fields and has met all equilibrium conditions. In this method, a simplifying assumption is made to show the relationship between the shear forces around the slice (X) and the normal force around the slice (E) with the following equation:

$$\mathbf{X = \lambda f(x) E} \tag{1}$$

where : X = the shear force around the slice; E = normal force around the slice; λ = multiplier with assumed value; f (x) = the assumption of a function. f(x) value is an assumption of the value of a function and a multiplier whose value will be assumed in this calculation. The value of unknown assumptions in the Morgenstern-Price method is the factor of safety (F), multiplier (l), the normal force acting (P), the force around the slice plane, which works horizontally, and the point where the force around the slice plane work. The analysis and the equilibrium results in the above assumptions, while the shear force components acting around the slice plane (X) can be calculated using the following equation:

$$P = \frac{\left[Wn - (XR - XL) - \frac{1}{F}(c'(\sin\alpha - ul\ \tan\phi' \sin\alpha)) \right]}{\cos\alpha(1 + \frac{\tan\alpha}{E}.\tan\phi')} \quad (2)$$

where: P = normal force; c ' = cohesion; Wn = force due to the n of soil load; α = the angle between the midpoint of the plane of the slice with the center of the arc landslide field; ϕ'= angle of internal friction; u = pore water pressure; XL, XR = friction force acting on the edge of the slice.

The forces acting on each slice of landslide are illustrated in (Fig. 2).

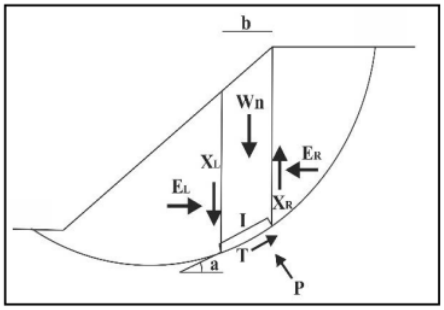

Figure 2 Force working on the sliced area

Based on slope safety factor software-based analysis and studies on slope stability in the field (back analysis), the data were divided into 3 groups of ranges of safety factors (FS) in terms of the landslide intensity (Table 1) according to Bowles (1991) [5]. A stable slope has a high FS while an unstable slope has a low FS value. The slope safety factor depends on the amount of shear resistance and shear stress, where both work opposite each other along the slip plane. The slip plane is located in the weakest zone in the body of the slope. If the price of FS = 1.07, the landslide will stop if the shear resistance of the constituent rock is able to support the new (more sloping) slope geometry and the FS becomes higher. The determination of the value of FS in this research was conducted using Geostudio (Slope/W) software [5].

From the theoretical (scientific) aspect, the results of this study are expected to be useful for the development of engineering geology in volcanic sediment areas, especially lahar deposits in changing the qualitative approach into a quantitative verification approach in determining conclusions.

Table 1 Slope stability classification Bowles, 1991

Safety Factor	Slope Condition
$FS \leq 1.07$	Unstable
$1.07 \leq FS \leq 1.25$	Critical
$FS \geq 1.25$	Stable

In terms of the practical aspects, the results of the study can be applied in mitigation efforts to reduce the danger risk of mass movement more precisely, which is based on changes in physical and mechanical properties and character of lahar deposits due to natural processes and human activities.

3. RESULTS

3.1 Geomorphology

Geomorphic units in the southern slope of Merapi Volcano based on morphological classification [6]. Based on these classifications, unit landforms are strongly influenced by active morphostructural aspects, namely the volcanic activity of Merapi Volcano and erosion in valley areas by the process of fission. The morphometric aspect of the study area is also the basis for the division of landform units. The high difference in the research area is the lowest elevation of 650 m in the southern part and 1,250 m elevation in the highest part in the northwest part of the study area. The slope level ranges from sloping-steep of (8% > 140%).

Based on morphographic, morphometric, and morphogenetic aspects, the study area was divided into one original volcanic formation, which was divided into three landform units namely:

3.1.1 Geomorphic Unit of Upper Volcanic Slope (V2)

This landform unit is in the northwest part of the study area and occupies an area of 15% of the entire study area. The morphological character of this unit is a rather steep slope (14% -20%) and has an elevation between 800-1,250 m, with the shape of the "V" valley. The developing pattern of flow is in the parallel form. Passive morphostructure with lithology is a pyroclastic Deles breccia unit and a Source pyroclastic breccia unit with weak-medium resistance. The active structure that controls the formation of this landform unit is Volcanism.

3.1.2 Geomorphic Unit of Middle Volcanic Slope (V3)

This landform unit is widely spread in the study area and occupies an area of 70% of the whole research areas. The morphological character of this unit is a sloping slope (8% -13%) with an elevation between 588–800 m, and with the shape of the "V" valley. Flow patterns develop in parallel and sub-parallel. Passive morphostructure with lithology is a pyroclastic Deles breccia unit and a Source pyroclastic breccia unit with weak-medium resistance. An active structure that controls the formation of this landform unit is also Volcanism.

3.1.3 Volcanic Valley Geomorphic Unit (V4)

This landform unit occupies an area of 15% of the whole research areas. The morphological character of this unit is valleys with very steep slopes (56 -> 140%) with an elevation between 650-1,250 m, and with the shape of the "V" valley. The flow pattern develops in parallel and sub parallels. Passive morphostructure with lithology is the pyroclastic breccia unit of Deles and the lava Kaligondang breccia unit and the new lava sediment unit with weak to moderate resistance. The active morphostructure that controls the formation of this landform unit is Volcanism.

3.2 Merapi volcano stratigraphy

Volcanic stratigraphy is the study of the sequence of records of volcanic activity with the knowledge of volcanic stratigraphic units, namely mapped layer units consisting of volcanic rocks formed on land (sub-aerial) or in water (subaqueous) by volcanic processes, which was determined based on sources, types of lithology and their genes [1] [2].

The stratigraphic morphology unit is a stratigraphic classification by grouping rocks according to various ways to identify the relationship between one-layer and other layers. Stratigraphic classification based on morphological appearance, sedimentary landscape and volcanic rocks of various successive eruption phases will overlap to result in a stratigraphic value.

As a basic unit, the concept of the stratigraphic morphology unit is morphocet (morphological and facet). The stratigraphy of Merapi Volcano based on lava responses to various types of eruptions can be grouped into 5 stages (Paripurno, 2009), namely: New Merapi, Young Merapi, Mature Merapi, Old Merapi, and Pre Merapi. Based on regional stratigraphy, the study area is the New Merapi volcano stratigraphic unit, the Young Merapi and Old Merapi. The lithology developed in the area around the Gendol River is lahar deposits (Fig. 3).

3.3 Identification of slope safety factors

Slope safety factors identification and potential mass movement in the research area were carried out through a back analysis approach of the slope data based on the field observation. The back analysis was used to determine the slope conditions qualitatively through analysis of symptoms that reflect actual slope conditions. Symptoms found on slopes in the study area are generally bumps and avalanches.

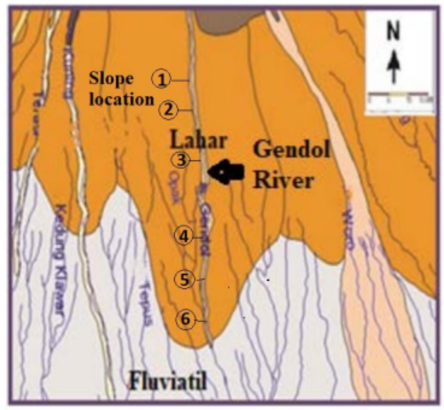

Figure 3 Geological map of the Gendol River

The protrusion is the connection to the body and foot of the slope due to pressure and material loading that makes up the body of the slope. Symptoms of bumps on the slope can indicate that the slope is in poor condition and an avalanche can indicate that the slope has the potential to experience more mass movement.

Field observations were carried out on 6 slope locations (Table 2), all of which were seen as lava deposits, which indicated a potential mass movement in the study area. The slope is on the cliff of the Gendol River. In this study, the identification of slope and potential for the mass movement was done through the Back Analysis approach, which was continued using the Geostudio (Slope / W) software method.

Table 2. Identification of slope safety factors

Loc.	c	ø	ϒ	α	h	FS
1	33,24	19,15	1,98	45	7,7	1,24
2	32,27	20,05	2,06	43	7,7	1,24
3	30,34	21,13	2,20	43	7,5	1,19
4	29,42	22,03	2,30	41	7,4	1,22
5	28,59	21,25	2,17	41	7,2	1,22
6	43,00	11,83	1,70	78	11,2	0,81

Note: Loc: location number, c: cohesion, ø: friction angle, ϒ: unit weight, α: slope, h: height, FS: safety factor.

The Geostudio software method (Slope / W) was carried out to determine the slope stability quantitatively in the form of slope safety factor values by entering the value of geometric parameters and the value of the parameters of physical-mechanical properties. The value of physical-mechanical properties was obtained from laboratory tests on samples that were plastered from each slope with the potential mass movement.

3.4. Effect of rainfall on slope security

Indonesia has a tropical climate with two seasonal patterns, namely the rainy and summer seasons. This condition has resulted in high traffic of erosion and weathering, which affect the physical-mechanical properties of soil and rocks in many areas [6]. Erosion and weathering are caused by rainfall and air temperatures that change in an area [7] [8].

The research area is included in the active volcano area, composed of the main lithology derived from eruption activities, such as pyroclastic breccia and lapilli resulted from pyroclastic flows and falling pyroclastic [9] [10]. Changes in rainfall and temperature will affect the lithological characteristics of eruption activities in the study area. The influences of rainfall and air temperature in the study area are as follows:

High rainfall causes excessive moisture content in each lithology. The addition of water content can reduce the cohesion value which causes a decrease in bond strength between soil grains, making them become easily released and leads to landslide [11] [12].

1. The excessive moisture content can also increase soil density, which adds the driving force on the slope. If the driving force increases, the slope becomes unstable and prone to the mass movement. This situation causes frequent mass movements in the study area in the rainy season [13].
2. Rainfall will affect the water content in each lithology. Sufficient and not excessive water content can increase the cohesion value of pyroclastic deposits and lahar deposits.
3. High air temperature will cause water evaporation, which decreases the water content in lithology. Decreasing water content can reduce cohesion. This decrease in cohesion will cause the lithology to be prone to deflation and mass movements. This situation causes frequent mass movements in the study area during the dry season [13].

The rainfall intensity in the study area over the past 10 years, by referring to rainfall in Pakem Sub-district, overall is pretty high in January-June and decreases in July-August, but it increases again in September-December.

Annual rainfall in several sub-districts in the study area has quite different intensities. Rainfall in Dukun and Srumbung sub-districts is relatively high at>3,000 mm/year. Rainfall in Pakem sub-district is relatively medium, namely 2,000-3,000 mm/year. Rainfall in Turi sub-district is relatively low <2,000 mm/year. Meanwhile, the research area is an area that has medium rainfall of 2,000-3,000 mm/year.

With such rainfall conditions, the identification of slope safety factors in this study is not applicable for the rainy season because the study was carried out during low rainfall intensity is in July - August.

4. DISCUSSION

Analysis of slope stability in the study area was carried out using visual observation methods and computational methods of Geostudio (Slope/W) software. The Back Analysis method was used to determine the level of slope stability qualitatively by observing symptoms that reflect slope conditions in the field. The Geostudio software method (Slope/W) was used to determine the level of slope stability quantitatively in the form of safety factor values by entering the values of geometric parameters and physical-mechanical properties. The value of the safety factor resulted from the software method was then used to determine the slope conditions based on the Bowles (1991) classification.

The level of slope stability will be reflected qualitatively through the symptoms that appear on the slope. Therefore, the Back Analysis method is useful to reduce the risk of slope stability analysis in determining the value of security factors conducted using the software. The different result between the software-determined slope safety factor and the qualitative slope safety factors in the back analysis in the field can be interpreted as an error in slope stability analysis using the Geostudio software method (Slope/W), requiring analysis repeat.

Slope stability in the study area is influenced by controlling factors that can come both from within (internal) or from outside (external). Internal factors are factors that originate from the body of the slope itself, while external factors are factors that originate from the outside (the state of the environment where the slope is located).

The relationship between the slope angle and slope stability factor on lahar deposits on the southern slopes of Merapi Volcano from 35 locations can be grouped and made curves. Of these 35 locations, there are 6 locations that lie on the cliffs of the Gendol River.

Therefore, the lahar unit of the Gendol River on the southern slope of Merapi Volcano is characterized by a slope safety factor with a certain slope angle formation as shown in Fig. 4. The relationship follows the equation of $y = 21.4x^{-0.744}$ with a very strong correlation (r = 0.92), where "y" is a slope safety factor, while "x" is the angle of the slope.

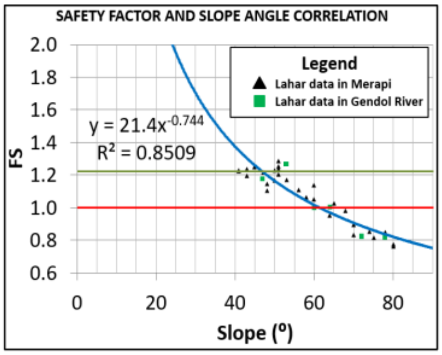

Fig. 4 Relationship curve of safety factor vs. slope angle in lahar deposit units

Based on Fig. 4, it can be seen that the relationship between slope safety factors can be formed by certain slope angles in units of lava deposits. For example, if the slope angle is greater, the value of the slope safety factor will be smaller.

From the data within 35 locations of lahar slopes on the southern part of Merapi Volcano has FS between 0,76 - 2,66 (within the unstable – stable class) and forms slope angle 80° - 53°.

Within 6 locations of slopes in the cliffs of Gendol River from the south to the north, has FS between 0,81 -1,22 with slope angle 78° – 43° (within the unstable – critical class)

Therefore, based on Fig. 4, it can be concluded that Gendol River has a tendency to follow lahar deposits pattern on the southern slope of Merapi Volcano. Generally, within the north to the south area of research possesses greater slope angle, with smaller stability factor of the slope. Within the research area in Gendol River, the FS is in unstable - critical class. The condition on the slope of Gendol River is sand and stone mining area.

The figure shows that the slope angle can form the desired slope safety factor using the formula of $y = 21.4x^{-0.744}$, where "y" is the safety factor of the slope, while "x" is the angle of the slope.

Character relationship between slope safety factor and slope angle is presented in Table 3.

Table 3 Slope stability formula at a certain slope angle

Factor of slopes	Slope stability formula
Slope height	$FS=10.47 \times Xt^{-1.034}$
Slope angle	$FS=21.4 \times Xs^{-0.744}$

Note: Xt: slope height (m), Xs: slope angle, FS: safety factor

5. CONCLUSION

The character of lahar deposits and the relationship of slope safety factors that can be formed by certain slope angles is to follow the equation of $y = 21,4x^{-0,744}$ with a very strong correlation (r = 0.92). In the formula, "y" is the factor of slope stability (FS), while "x" is the amount of slope angle. By applying this formula and the Bowles classification, it is conclusive that the relationship between slope stability factors can be formed by certain slope angles.

In lahar deposits, it is applicable that if the slope angle is large, the value of the slope stability factor will be smaller. The stable classes are FS>1.25 with slope angles of<43°, the critical class is 1.07>FS>1.25 with slope angles of 44° - 54° and class labile is FS <1.07 with slope angles of >55 °. The formula can be used to design slopes that are safe in lahar deposits of the Gendol River.

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