Slope Mass Rating-based Analysis to Assess Rockfall Hazard on Yogyakarta Southern Mountain, Indonesia

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Abstract

In the Parangtritis Beach tourism area located in the Southern Mountain of Yogyakarta, karst hills were excavated to build the main accessing road and produce some of long and very steep slopes along the sides of the road. But still, there was none of the slope reinforcement installed along the road. Meanwhile, at several nearby locations within Southern Mountain, rockfall incidents have occurred many times even caused casualties. The potential of rockfall hazard could also occur in the main road of Parangtritis Beach as the study area. The purpose of this study is to determine the rockfall hazard assessment along the main road using Slope Mass Rating (SMR) analysis with the additional parameter of the slope height and the rock block size. The necessary data obtained by direct measurement and laboratory test. Geomechanics analysis, stereographic projection analysis, and hazard parameters weighting were carried out to produce the Rockfall Hazard Zonation Map of the study area. Based on 17 measurement stations, there are 4 (four) rockfall hazard classes in the study area, i.e. very low, low, intermediate, and high. The very low class, which also included road segments without slope, has the largest percentage of 83.83%, followed by the classes of intermediate, low, and high with the percentage of 7.16%, 4.28%, and 4.19%, respectively. SMR was assumed as the most significant parameter that influences the rockfall hazard zonation. To validate the predicted hazard zones, historical rockfall points were overlaid over the Rockfall Hazard Zonation Map. Since 91.23% of the rockfall occurred in the intermediate and high hazard classes, the zonation can be considered reliable to predict future rockfall. This study also identified several landslide potential zones and provides the recommendation of slope reinforcement to be installed in the study area.

Keywords: Rockfall, Slope Mass Rating, Hazard zonation, Slope reinforcement, Hills.

INTRODUCTION

Rockfall is one type of mass movement occurred in the form of rock lumps collapsed from a slope and happens quickly both vertically and sub-vertically (Budetta, 2004; Goodman, 1989). The rockfall hazard has the potential to inflict bad and severe impacts on human life (van Westen & Greiving, 2017), but the risks and hazards of rockfall are varying based on the conditions of the area (Ansari et al., 2016; Budetta, 2004). The natural and physical characteristics of the hilly areas were suspected to be the cause of rockfall events and the hazard level will be higher if the area experiencing hills excavation for transportation facilities (Hizbaron et al., 2010). Along the roads produced from excavated hills, rockfall is certainly to be one of the most potential threats that could happen, but not all segments of the roads have the same levels of hazard. Rockfall impacts were identified by Gracchi et al. (2017) as a combination of several functions, one of which is geomechanics conditions. In this study, geomechanics conditions of an area will be analyzed as a significant factor that affecting the hazard level of rockfall.
The rockfall incidents have occurred several times in Yogyakarta. Hizbaron et al. (2010) in his research have identified 16 rockfall events that occurred in 1970-2009 in Yogyakarta. Based on his study, the high vulnerability area of rockfall is located along the transportation route. Afterward, a rockfall incident occurred in 2011 on Yogyakarta Southern Mountain hills which fell into settlements and caused casualties (Mustopo, 2015). In the same district, the rockfall incident occurred again in 2015 on Sadranan Beach and also caused casualties (Jatmikotomo et al., 2015). Also located within the Southern Mountain hills area, Parangtritis Road as the study area of this present study certainly cannot get away from this dangerous threat of rockfall.

Parangtritis Road is the main road to access the well-known Parangtritis Beach tourism site along the coast of the Southern Mountains, Yogyakarta. This road access has considerable tourism activities and frequently accessed by local and international visitors. To support the development of Parangtritis Beach, karst hills were excavated to build the main accessing roads. These cuttings produce several long and very steep slopes along the sides of the road. But still, there was none of slope reinforcement installed along the road. Meanwhile, the road is located near to the Girijati Fault which has 250 meters of steep slope and estimated to be the main trigger of the rock mass movements in the area (Husein et al., 2010). This fault movement activates the Parangtritis Fault as the extension in the west. Both of these faults produced a rock-shaped semi-circular landslide crown (Husein et al., 2010; Prasetyadi et al., 2011) that was traversed by the road access connecting Parangtritis-Giricahyo villages as the two-way route to reach the beach.

The purpose of this study is to assess the rockfall hazard in the study area (Figure 1). The research is carried out by the study of the geological setting, the analysis of geomechanics conditions including Slope Mass Rating (SMR) and other parameters that were considered can affect the hazard level significantly, i.e. slope height and rock block size. As the result, the rockfall hazard zonation will be created using a weighting system of hazard parameters collected from field data measurements.

Figure 1. The maps of (a) Indonesia; (b) Java Island; and (c) the study area. The thick red line on map (c) represents the road segment to be assessed.
MATERIALS AND METHODS

1. Research Equipment

The required field equipment consists of general site survey tools, but there is some equipment that commonly used in geological investigations such as the Global Positioning System (GPS), geological hammer and compass, and Schmidt Hammer. Several software is used in the data analysis and also in the making of output maps, including ArcGIS 10.6.1, Global Mapper 19, and Dips v.5.1.

2. Data Collection

There are four primary data groups obtained through direct measurements in the field, i.e. Rock Mass Rating basic (RMR_b) parameters, dip and strike from the slope and discontinuous plane, slope height, and the size of rock blocks. Secondary data used in the data processing stage is including rock lithology and geological structure obtained from the extracting of Yogyakarta Regional Geological Map on a scale of 1:100.000 (Raharjdo, 1977) published by Geological Research and Development Center that analyzed together with the geological structure interpretation from Shuttle Radar Topographic Mission (SRTM) 1-arc second global (USGS, NASA).

Primary data and rock samples are only taken along the main road, as the study area, from each slope/outcrop that considered could represent the area of rockfall. The outcrops are in the form of slopes that have or have not yet experienced rockfalls and must be on the side of the road. These slopes then become the observation points or called the stations. The stratified random sampling method was used in rock sampling. The population is divided into several groups based on rock lithology, then a random sample will be taken from each group. The rock samples then will be tested in the laboratory to find out the uniaxial compressive strength (UCS) value of the rock to be used in the analysis stage.

**Rock Mass Rating basic (RMR_b)**

The 5 (five) parameters that used to determine the value of the RMR_b are including Uniaxial Compressive Stress (UCS), Rock Quality Designation (RQD), the space of discontinuous plane, the condition of discontinuous plane, and the condition of groundwater (Bieniawski, 1989).

**Uniaxial Compressive Stress (UCS)**

UCS values were obtained through measurements in the field using Schmidt Hammer type NR. Hardness Rebound (HR), the value generated from the Schmidt Hammer, has a scale of 1 to 100 that can be converted into UCS units (the UCS unit used in this study is MPa). Several equations can be used in determining or converting HR values into desired uniaxial compressive strength units. The equation used depends on the type of device used, the size of the media measured, and the position of the tool when taking HR values. In this study, the most suitable equation considered for the acquisition of uniaxial compressive strength values is:

\[ UCS = 2HR \] (Dinçer et al., 2004)

The classification of uniaxial compressive stress from rock materials is shown in Table 1.
Table 1. Uniaxial Compressive Strength (UCS) classification (Bieniawski, 1989)

| Description    | Compressive Strength (MPa) | RMR<sub>b</sub> value |
|----------------|----------------------------|------------------------|
| Extremely strong | >250                       | 15                     |
| Very strong     | 100-250                    | 12                     |
| Strong          | 50-100                     | 7                      |
| Moderate        | 25-50                      | 4                      |
| Weak            | 10-25                      | 2                      |
| Very weak       | 2-10                       | 1                      |
| Extremely weak  | 1-2                        | 0                      |

Rock Quality Designation (RQD)

The determination of indirect RQD is using the volumetric joints method proposed by Palmström (1982), this method is used if there is no borehole core available and measured at the site as illustrated in Figure 2. The RQD value can be estimated indirectly through the calculation of solid volumetric which is calculated per one cubic meter of rock mass with the following equation:

\[ RQD = 115 - 3.3J_V \] (Palmström, 1982)

where

\[ J_V = \sum_{i=1}^{J} \left( \frac{1}{S_i} \right) \]

\( S_i \) is the average value of the joints spacing in meters of the \( i \) number of joints sets, while \( J \) is the total number of joints sets (Palmström, 1982). Table 2 below the classification of RQD values.

Figure 2. There are 3 (three) sets of joints measured in the indirect RQD observation (without borehole). The picture was taken at Station 4 (110°20’53.25”E, 8°0’15.08”S) with an A4 paper as a scale.
Table 2. Rock Quality Designation (RQD) classification (Bieniawski, 1989)

| Description  | RQD   | RMRb value |
|--------------|-------|------------|
| Very good    | 90-100| 20         |
| Good         | 75-90 | 17         |
| Moderate     | 50-75 | 13         |
| Bad          | 25-50 | 8          |
| Very Bad     | <25   | 3          |

The space of discontinuous plane

The discontinuous plane spacing is measured perpendicular to one discontinuous plane until it meets the other discontinuous plane. The form of the discontinuous plane can be a joint, shear zone, minor fracture, or other weak surfaces. Between the discontinuous plane, there are gaps or apertures in general, but sometimes there is a very tight discontinuous plane without visible gaps. There are 5 (five) classes of discontinuous plane spacing as shown in Table 3.

Table 3. The space of discontinuous plane classification (Bieniawski, 1989)

| Description    | Space (m) | RMRb value |
|----------------|-----------|------------|
| Very wide      | > 2       | 20         |
| Wide           | 0.6 - 2   | 15         |
| Moderate       | 0.2 - 0.6 | 10         |
| Tight          | 0.06 - 0.2| 8          |
| Very tight     | < 0.06    | 5          |

The condition of discontinuous plane

Parameters measured in a discontinuous plane condition were including the length, the gaps, the surface roughness, the filling material, and the weathering condition. The 5 (five) criteria have each value according to the conditions found in the field then weighted together to get the overall value of the discontinuous plane conditions. Table 4 will describe the criteria of the parameters.

Table 4. The condition of discontinuous plane classification (Bieniawski, 1989)

| Parameter       | RMRb value |
|-----------------|------------|
| Length          |            |
| <1 m            | (6)        |
| 1-3 m           | (4)        |
| 3-10 m          | (2)        |
| 10-20 m         | (1)        |
| >20 m           | (0)        |
| Gaps            |            |
| -               | (6)        |
| <0.1 mm         | (5)        |
| 0.1-1 mm        | (4)        |
| 1-5 mm          | (3)        |
| >5 mm           | (2)        |
| Roughness       |            |
| Very rough      | (6)        |
| Rough           | (5)        |
| Moderate        | (4)        |
| Smooth          | (3)        |
| Very smooth     | (2)        |
| Filling         |            |
| -               | (6)        |
| Hard            | (5)        |
| Soft            | (4)        |
| Weathering      |            |
| None            | (6)        |
| Slightly weathered | (5)    |
| Moderate        | (4)        |
| Mainly weathered | (3)    |
| Very weathered  | (2)        |
The groundwater conditions

If it is not possible to measure the groundwater discharge and pore pressure in the field, groundwater conditions can be observed generally based on conditions found on rock surfaces. These general conditions can be a dry, humid, wet, dripping, and flowing surface (Table 5).

| Inflow/10 m (l/minute) | <10 | 10-25 | 25-125 | >125 |
|------------------------|-----|-------|--------|------|
| Pore pressure ratio    | 0   | 0-0.1 | 0.1-0.2| 0.2-0.5 | >0.5 |
| General condition      | Dry | Humid | Wet    | Dripping | Flowing |
| RMRb value             | 15  | 10    | 7      | 4     | 0     |

Table 5. The groundwater conditions classification (Bieniawski, 1989)

Based on the total of the RMRb values obtained from the parameters above, the rock mass classification is divided into 5 (five) classes as shown in Table 6 below.

| RMRb value | 81 - 100 | 61 - 80 | 41 - 60 | 21 - 40 | < 20 |
|------------|----------|---------|---------|--------|------|
| Rock quality | Very good | Good | Moderate | Bad | Very bad |

Table 6. Rock Mass Rating basic (RMRb) (Bieniawski, 1989)

Slope height

The height of the slope mentioned here is the vertical slope height. According to Pierson (1991), slope height measurements were carried out from the highest point to the point where the fall of the rock was estimated. The classification method used is the modification of Budetta (2004) classification. The classification of Budetta (2004) was modified because it was considered to give a relatively low value for the hazard rating. Slope with a height of more than 10 meters logically can be categorized as very dangerous especially if their geometry is almost vertical and without vegetation cover as the slopes found in the study area. The classification of the slope height is shown in Table 7.

| Slope height (m) | ≤2,50 | 2,51 – 5,00 | 5,01 – 7,50 | 7,51 – 10,00 | >10 |
|------------------|-------|-------------|-------------|-------------|-----|
| Weight           | 3     | 9           | 27          | 54          | 81  |
| Hazard rating    | Very low | Low | Moderate | High | Very high |

Table 7. The modified slope height classification

Rock block size

Rock avalanches are extremely rapid, moving like landslide flows, and could impact humans and properties far from their source (Aaron et al., 2017). The size of a rock block significantly influences how much of the impact a rock can cause when it falls over an object underneath. Rock block size measurements must be able to represent the type of rockfall that most likely to occur. If at the observation point there is a rockfall in the previous falling rocks location, then the measurement goes into the rockfall volume per event. But if there is no record of falling rocks that have occurred at the observation point, then it can be represented by measurements of the block (diameter) of rocks on the slope that considered to have the most potential to fall (Pierson, 1991). The weighting method used is a modification of Budetta (2004) method as shown in Table 8.
Table 8. The modified rock block size and rockfall volume classification

| Block size (m) | ≤ 0,30 | 0,31 – 0,60 | 0,61 – 0,90 | 0,91 – 1,20 | ≥ 1,20 |
|---------------|--------|-------------|-------------|-------------|--------|
| Rockfall volume (m³) | ≤ 2,30 | 2,31 – 4,60 | 4,61 – 6,90 | 6,91 – 9,20 | ≥ 9,20 |
| Weight | 3 | 9 | 27 | 54 | 81 |
| Hazard rating | Very low | Low | Moderate | High | Very high |

3. Data Analysis

The data analysis stage was preceded by laboratory tests to obtain UCS values which were then converted to MPa units according to the classification of UCS value by Bieniawski (1989). Followed by the geomechanics analysis of RMR₀ and SMR. To obtain the SMR value, the value of RMR₀ are calculated with SMR Adjustment Factors using the formula:

$$SMR = RMR₀ - (F₁ \times F₂ \times F₃) + F₄$$ (Romana, 1993)

SMR Adjustment Factors (F₁, F₂, F₃, and F₄) are additional weights given based on the orientation of the discontinuous plane on an outcrop/slope (Romana, 1993) with the detailed description in Table 9. The SMR Adjustment Factors consist of:

- F₁ which describes the parallelism between the joints direction/strike and the slope direction/strike;
- F₂ which describes the steepness/dip of the slope;
- F₃ which describes the relationship of the joints dip and the slopes steepness/dip; and
- F₄ which is an adjustment score for the excavation method on the slope.

The next step is the making of stereographic projections from discontinuous planes in 2 (two) dimensions to model the discontinuous planes on outcrops/slopes found in the field. This step was intended for determining rockfall types that can occur in a planar, wedge, or toppling type which is then used to calculate the SMR Adjustment Factors.

Table 9. SMR Adjustment Factor classification and the hazard rating (Romana, 1993)

| Slope condition | Very good | Good | Moderate | Bad | Very bad |
|-----------------|-----------|------|----------|-----|----------|
| F₁ P [αᵢ - αₛ] | >30° | 20°-30° | 10°-20° | 5°-10° | <5° |
| T [αᵢ - αₛ - 180°] | 0,15 | 0,40 | 0,70 | 0,85 | 1,00 |
| W [αᵢ - αₛ] | 0,15 | 0,40 | 0,70 | 0,85 | 1,00 |
| T value | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 |
| F₂ P [βᵢ] | <20° | 20°-30° | 30°-35° | 35°-45° | >45° |
| W [βᵢ] | 0,15 | 0,40 | 0,70 | 0,85 | 1,00 |
| P, W value | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 |
| T value | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 |
| F₃ P [βᵢ - βₛ] | >10° | 0°-10° | 0° | 0°-(-10°) | (-10°) |
| W [βᵢ - βₛ] | <110° | 110°-120° | >120° | --- | --- |
| T [βᵢ + βₛ] | 0 | -6 | -25 | -50 | -60 |
| P, W, T value | 15 | 10 | 8 | 0 | -8 |

Excavation Method

| Method | Natural slope | Pre-splitting | Minor blasting | Mechanical excavation | Major blasting |
|--------|---------------|---------------|----------------|------------------------|----------------|
| Weight | 15            | 10            | 8              | 0                      | -8             |
Information:

\( P \) = Planar failure \( \alpha_s \) = slope strike

\( W \) = Wedge failure \( \alpha_i \) = discontinuous plane strike

\( T \) = Toppling failure \( \alpha_i \) = plunge direction of discontinuous plane

\( \beta_s \) = slope dip

\( \beta_j \) = discontinuous plane dip

\( \beta_i \) = plunge dip of discontinuous plane

The score of SMR (Table 10) can be referred to provide recommendations on the required slope reinforcement method. Slopes with very good stability will not need a reinforcement system whereas those with lower levels of stability will require a variety of reinforcement types (Romana, 1993).

| Class | I     | II    | III   | IV    | V    |
|-------|-------|-------|-------|-------|------|
| SMR score | 81-100 | 61-80 | 41-60 | 21-40 | 0-20 |
| Weight | 3     | 9     | 27    | 54    | 81   |
| Description | Very good | Good | Moderate | Bad | Very bad |
| Stability | Very stable | Stable | Moderate | Not stable | Very not stable |
| Structure | None | A few of the blocks | Some or many of the block | Planar or | Big planar plane |

The weighting of rockfall hazard parameters is carried out using rockfall hazard classification which is a modified weighting method of Rockfall Hazard Rating System (RHRS) by Pierson (1991) and Budetta (2004). SMR weight along with slope height and rock block size weights were added up and classified into 5 (five) categories of rockfall hazard. The classification of rockfall hazards based on the total weight is shown in Table 11.

| Total weight | Class   |
|--------------|---------|
| 9,0 – 55,8   | Very low|
| 55,9 – 102,6 | Low     |
| 102,7 – 149,4| Moderate|
| 149,5 – 196,2| High    |
| 196,3 – 243,0| Very high|

Some of the data processing was done with Geographic Information System (GIS) software as well as the maps produced in this study. The verification phase is carried out by confirming the accuracy and the conformity of the data and the resulted map with actual conditions at the study area. The historical rockfall points will be overlaid over the Rockfall Hazard Zonation Map and the number of rockfalls that occurred in each hazard class will be calculated. If there is a discrepancy, repeated field investigation and re-analysis need to be carried out.
RESULTS AND DISCUSSION

1. Geological Setting

The study area is included in a series of Southern Mountains hills along the west to the east of the south coast of Java and the northern part of the area was encountered by a lowland known as Solo Lane (van Bemmelen, 1949). The area is divided into 3 (three) geomorphological units, i.e. the karst hills, the structural hills, and the lowlands. Based on the Geological Map of Yogyakarta sheet (Rahardjo et al., 1977), the western part of the Southern Mountains is composed of volcanic rocks, volcanic clastic rocks, and carbonate rocks. Most of volcanic clastic rocks formed by the deposition of gravity sediment that approximately 4000 meters thick. The study area compiled by the 4 (four) rock formations in the region, namely respectively based on the age are Nglanggran Formation, Wonosari Formation, Young Merapi Volcanic Mount Deposition, and Alluvium Deposition.

Geological structures founded on the Geology Map of Yogyakarta sheet (Rahardjo et al., 1977) are joints, faults, and folds. The folds consist of anticline and syncline which are having a general direction northeast-southwest and east-west and some other trending is northwest-southeast. Faults are generally a normal fault with antithetic fault block patterns (van Bemmelen, 1949). The geological structures developed are shear faults and normal faults (Figure 3). The Opak Fault cut Yogyakarta and Wonosari old andesite as a constituent of fault cutting structures, while in the east of Opak River there are Semilir and Nglanggran Formation which is also involved in the fault system (Rahardjo et al., 1997).

Figure 3. Developed geological structures in the study area. Data used for the structure analysis is NASA Shuttle Radar Topography Mission (SRTM) Version 3.0 Global 1 arc second.
The number of slopes found on the main roadside is 17 slopes with varying height and length. Each slope becomes an observation point so that in total 17 stations were analyzed in this study. The naming of these units is based on the lithology of the rocks. Among the geological units found around the study area, there are only 4 (four) geological units found on the 17 stations (Figure 4). These 4 (four) geological units, i.e. andesite, crystalline limestone, fragmental limestone, and reefal limestone (Rahardjo et al., 1977), used as the analysis unit in the analysis stage.

![Image of lithology and stations location](image)

Figure 4. The map of the lithology and the stations location.

Based on Hardness Rebound (H<sub>R</sub>) values obtained through field measurement using Schmidt Hammer, the andesite unit has the highest UCS value of 131.2 MPa (strong), while the lowest UCS value is owned by the reefal limestone unit of 5.8 MPa (weak). Crystalline limestone unit also includes in the weak class with an average UCS value of 14.92 MPa. The fragmental textured limestone unit has a higher UCS value compared to other limestone units, categorized as the moderate class with the UCS value of 35.33 MPa. These values are equivalent to the UCS value generated by laboratory tests.
2. Stereographic projection analysis

A discontinuous plane and the kinematics mechanism can be analyzed using the stereographic projection (Goodman, 1989). According to Ragan (2009), the stereographic projection is a two-dimensional picture or a projection of a sphere surface that used to describe the geometry position or the orientation of the planes and lines. The method used in stereographic projection in this study is the Equal Area Projection using Schmidt Net as the projection plane and created using Dips v.5.1 software.

In this study, the stereographic projection was also carried out to determine the rockfall types that could or had occurred in the discontinuous plane on a slope, i.e. planar failure, wedge failure, and toppling failure, as mentioned in the Slope Mass Rating (SMR) analysis by Romana (1993). Furthermore, this stereographic projection analysis is also used to find out whether a rock volume from a slope could fall naturally due to the condition of the discontinuous plane or not. If the parallelism of the discontinuous plane orientation to the slope face orientation (resulted from the cutting hills) is known to be in a stable condition, then without any disturbance from natural phenomena or human disturbances the rockfall cannot occur by itself and vice versa.

More information obtained from the stereographic projection of the 17 stations is that the wedge failure of the rockfall type has more potential and occurs more frequently than the planar failure and toppling failure types. This is resulted due to a large number of discontinuous plane sets which have many variations of orientation and causing intersections between discontinuous planes. Some examples of stereographic projections from 3 (three) stations are shown in Figure 5.

![Figure 5](image.png)

Figure 5. The stereographic projections of (a) Station 7; (b) Station 13; and (c) Station 14. Set 1 and set 2 of the projected discontinuous planes in Station 7 show wedge failure type in both sets. In Station 13, set 1 shows toppling failure while set 2 shows planar failure type. Lastly, the types of planar and wedge failure were shown in set 1 and set 2, respectively, in Station 14.

Rose Diagram, which is a graphical form that concludes the entire stereographic projection analysis of 17 stations, is shown in Figure 6. These Rose Diagrams were created using Dips v.5.1 software and used to determine the dominant strike orientation of the discontinuous plane in the rock slope. The diagrams show that the dominant strike orientation...
of the discontinuous plane is trending northeast-southwest (N 60⁰E) in the andesite unit (Figure 6a), northeast-southwest (N 45⁰E) in the crystalline limestone units (Figure 6b), northwest-southeast (N 325⁰E) in the fragmental limestone units (Figure 6c), and northeast-southwest (N 40⁰E) in the reefal limestone units (Figure 6d). In general, the most dominant strike orientation of all discontinuous planes in the study area is trending northeast-southwest (N 45⁰E).

Figure 6. Rose Diagrams of (a) Andesite unit; (b) Crystalline limestone unit; (c) Fragmental limestone unit; (d) Reefal limestone unit; and (e) all units.

3. Slope Mass Rating (SMR) analysis

Road segments without slopes were not given class because the assessment of the slope mass quality cannot be carried out without the rock slopes that being studied. The summary of
measured slopes that classified according to the Slope Mass Rating (SMR) by Romana (1993) is shown in Table 12. Overall, there were none of good quality mass slopes in the study area, the measured SMR score ranged from normal to very bad.

Table 13. The summary of measured SMR

| Sta. | Lithology         | RMR<sub>b</sub> score | SMR Adjustment Factors | SMR score | Class   |
|------|------------------|-----------------------|------------------------|-----------|---------|
|      |                  |                       | F1    | F2    | F3    | F4    |         |         |
| 1    | Andesite         | 60.33                 | 0.72  | 0.56  | -60.00| 15.00 | 51.27  | Normal |
| 2    | Crystalline limestone | 61.33            | 0.72  | 0.90  | -48.33| 0.00  | 30.19  | Bad    |
| 3    | Crystalline limestone | 67.33            | 0.67  | 0.80  | -53.33| 0.00  | 38.87  | Bad    |
| 4    | Crystalline limestone | 61.33            | 0.72  | 0.80  | -56.67| 0.00  | 28.87  | Bad    |
| 5    | Crystalline limestone | 58.00            | 0.70  | 0.85  | -60.00| 0.00  | 22.30  | Bad    |
| 6    | Crystalline limestone | 68.00            | 1.00  | 0.40  | -60.00| 0.00  | 36.50  | Bad    |
| 7    | Fragmental limestone | 60.50            | 0.57  | 0.85  | -60.00| 0.00  | 31.17  | Bad    |
| 8    | Fragmental limestone | 73.00            | 0.85  | 1.00  | -25.00| 0.00  | 51.75  | Normal |
| 9    | Fragmental limestone | 71.50            | 0.57  | 0.57  | -60.00| 0.00  | 51.66  | Normal |
| 10   | Fragmental limestone | 59.50            | 0.15  | 0.75  | -57.50| 0.00  | 53.03  | Normal |
| 11   | Fragmental limestone | 55.00            | 0.57  | 0.70  | -55.00| 0.00  | 35.16  | Bad    |
| 12   | Fragmental limestone | 68.00            | 0.57  | 0.57  | -60.00| 0.00  | 48.16  | Normal |
| 13   | Reefal limestone  | 53.00                | 0.92  | 1.00  | -37.50| 0.00  | 18.31  | Very bad |
| 14   | Reefal limestone  | 48.00                | 0.57  | 0.85  | -60.00| 0.00  | 18.67  | Very bad |
| 15   | Reefal limestone  | 56.00                | 0.85  | 1.00  | -25.00| 0.00  | 34.75  | Bad    |
| 16   | Reefal limestone  | 54.15                | 0.43  | 0.62  | -60.00| 0.00  | 38.15  | Bad    |
| 17   | Reefal limestone  | 53.00                | 0.92  | 0.85  | -60.00| 0.00  | 5.82   | Very bad |

The andesite unit represented by 1 (one) station of observation point has SMR value of 51.27 and categorized as normal class. The RMR<sub>b</sub> value of andesite units was not the largest of the entire sample, but the type of slope excavation method (natural) in this station gives an extra point to the SMR score. Naturally exposed slope was only found at this station.

The crystalline limestone unit represented by 5 (five) stations of observation point had SMR score of 22.30 – 38.87 and categorized as bad class. Furthermore, the fragmental limestone unit represented by 6 (six) stations of observation point has SMR score of 31.17 – 53.03 as categorized as normal to bad class. The highest average score of RMR<sub>b</sub> and SMR was found in fragmental limestone unit, proven by hard and compact rock conditions and non-complex discontinuous plane conditions.

The reefal limestone unit represented by 5 (five) stations of observation point has SMR score of 5.82 – 38.15, which is classified as bad to very bad. This unit has the lowest average score of RMR<sub>b</sub> and SMR, proven by softer rock hardness, accompanied by holes of water dissolution, and complex condition of the developed discontinuous planes. The result of the SMR zonation is shown in Figure 7.
Most of the slopes at the study site need special attention from the community and local government because they have poor slope strengths and unstable conditions. These conditions may affect the risk and hazard level of rockfall which can cause physical and social losses. SMR values obtained here can be used as a reference to find the most appropriate slope reinforcement method. The relationship between the SMR scores with the recommended slope reinforcement method is presented in Table 13.

Slope reinforcement should be installed on a slope with SMR value that less than 80 (good – very bad classes of SMR). That means even though a slope has a stable condition, slope reinforcement still needs to be installed to avoid the rockfall threats from external factors such as natural disasters and human disturbances. Fence, nets, ditch need to be installed on slopes that have the potential to drop small rocks. These types of supports suitable for installation in Stations 8, 9, and 12. Shotcrete is needed to cover fragile and weak parts of the slope and suitable for Station 3, 7, and 10.

Anchors and bolts can be installed on a slope with a solid type of composing rock as in Station 1. Meanwhile, the systematic shotcrete or the concrete coating method can be used on slopes that formed from weathered and/or softer rock types and easily destroyed such as in
Stations 2, 4, 5, 6, 11, 15, and 16. This fragile character is often found in excavated karst hills as on the study area. If the slope has weathered so much and/or has experienced a lot of rockfalls, then the most needed slope reinforcement is an anchored wall or even need re-excavation as in Stations 13, 14, and 17.

Table 13. Recommended support according to SMR score (Romana, 1993).

| SMR Score | Support |
|-----------|---------|
| 91–100    | None    |
| 81–90     | None; scaling |
| 71–80     | None; toe ditch or fence; spot bolting |
| 61–70     | Toe ditch or fence; nets; spot or systematic bolting |
| 51–60     | Toe ditch and/or nets; spot or systematic bolting; spot shotcrete |
| 41–50     | Toe ditch and/or nets; systematic bolting; anchors; systematic shotcrete; toe wall and/or dental concrete |
| 31–40     | Anchors; systematic shotcrete; toe wall and/or concrete; re-excavation; drainage |
| 21–30     | Systematic reinforced shotcrete; toe wall and/or concrete; re-excavation; deep drainage |
| 11–20     | Gravity or anchored wall; re-excavation |

However, not only SMR scores used to assess rockfall hazards in this study. Two other parameters (i.e. slope height and rock block size) were also considered as intrinsic factors that could significantly affect the level of rockfall hazards. Slope height and rock block size will be explained further in the next section.

4. Slope Height and Rock Block Size

Rockfall that occurred from a higher slope possesses greater energy than those that occurred from a lower slope. So it is important to measure the slope height as the higher slope was expected to have a higher level of hazard. Based on the field measurements, the crystalline limestone unit has moderate to high slope height hazard category (Figure 8a). Reefal limestone unit has varied slope height hazard categories from low, moderate, and high. The big difference in slope height between the units will affect the rockfall hazard weight.

The block size is a very significant parameter in rock mass behavior (Barton, 1991) and can be considered fairly affect the rockfall hazard assessment in the study area because of its variations. The rock block size on the slopes varies with the rock diameter size of 0.2 to 1.3 meters. Station 13 has a rock block size with very high hazard categories (Figure 8b). From the evidence and remnants, rockfall is indicated to had occurred in the location. Other stations have various rock block sizes with a very low to high hazard category. Combined with SMR values and slope height, the weighting of rock block size will result in variations of the rockfall hazard assessment.
Figure 8. Figure (a) shows a slope formed by crystallin limestone at Station 6 with a 191 m of length and ± 9 m of height. Figure (b) shows a slope formed by reefal limestone at Station 13 with a 1.3 m of rock block size. Rockfall is indicated to had occurred in both locations.

5. Rockfall Hazard Zonation

The very low class of rockfall hazard zonation has the greatest percentage of 83.83%, road segments without slopes were also categorized in this class. The second-largest percentage is the intermediate hazard class by 7.16%, followed by low hazard class with 4.82% and high hazard class with the smallest percentage of 4.19%. On the different scenario, a different result is shown when the roads that do not have slope is not included. The largest percentage owned by the intermediate hazard class with 36.60%, followed by 24.64% for low hazard class, then high hazard class with a percentage of 21.39%, and very low hazard class with the smallest percentage of 17.38%. The most significant parameter that influences the rockfall hazard zonation is the SMR with a percentage of 53.42% of total rockfall hazard weight. Followed by slope height and rock block size with the percentages of 24.27% and 22.30%, respectively.

Figure 9 shows the Rockfall Hazard Zonation Map.

Most rockfall hazard zonation class at overall stations experience reduced levels compared to their SMR class. Only Station 2 and Station 6 that have the same class level (high) in both the SMR and rockfall hazard zonation classes. This proves that the slope height and rock block size parameters affect the final result of rockfall hazard zonation. For example, Station 3 has a bad SMR class but the size of the rock block at this station has low weight because the largest diameter found is only 0.6 meters (classified as low hazard of rock block size). Therefore, the total weight of the rockfall hazard zonation at Station 3 is classified as low class. Another example is at Stations 8 and Station 9, although both of these stations have normal SMR class, the slope height at both stations has low weight because the slopes did not reach 5 (five) meters (classified as low hazard of slope height). Hence, the final result of rockfall hazard zonation at Station 8 and Station 9 is classified as very low class. Table 1 provides a summary of rockfall hazard classes with the condition of each parameter.
Table 13. The summary of rockfall hazard class and the parameters.

| Hazard class | Lithology                                      | SMR score     | Slope height (m) | Size of rock block (m) | Stations |
|--------------|-----------------------------------------------|---------------|------------------|------------------------|---------|
| Very low     | Fragmental limestone                          | 51.66 – 51.75 | 2.85 – 4.57      | 0.2 – 0.3              | 8, 9    |
| Low          | Andesite, crystalline, and fragmental limestones | 31.17 – 53.03 | 3.52 – 5.28      | 0.2 – 0.7              | 1, 3, 7, 10, 12 |
| Intermediate | Crystalline, fragmental, and reefal limestones | 5.82 – 38.15  | 4.26 – 8.96      | 0.3 – 1.0              | 4, 5, 11, 14, 15, 16, 17 |
| High         | Crystalline and reefal limestones             | 18.31 – 36.50 | 3.62 – 7.82      | 0.7 – 1.3              | 2, 6, 13 |

Figure 9. Rockfall Hazard Zonation Map
There is a 'landslide potential' category with purple color on the Rockfall Hazard Zonation Map. The slopes can be assumed to have landslide potential if there is evidence of occurred landslide and none of slope reinforcement installed yet on the slope. With the occurrence of the landslide, the slope mass quality at the location automatically cannot be measured because the rocks that composed the slope have been destroyed and/or collapsed. Therefore, locations with landslide potential were not included in the rockfall hazard classes, but they still need extra awareness.

The extension of Girijati and Parangtritis Fault which forms a semi-circular crown structure (Prasetyadi et al., 2011) produces paleo-landslides deposits with estimated dimensions of 2,700 m long, 1,500 m wide, and 810 million m$^3$ of landslide volumes (Husein et al., 2010) in a gravel–boulder grain size. These landslide deposits are very prone to move and/or collapse and believed to be one of the causes of most recent landslide events in the study area. On these landslide potential areas, the stakeholders should consider to re-excavating or at least covering the slope with ananchored wall. Figure 10 below shows the occurred landslides in several locations in the study area.

![Figure 10. Landslides evidence at coordinate 110°20′27.60″E, 8°0′16.24″S (a) and 110°22′15.60″E, 8°1′33.60″S (b). None of slope reinforcement installed at the location.](image)

To validate the predicted hazard zones, historical rockfall points were overlaid over the Rockfall Hazard Zonation Map and the number of rockfalls that occurred in each hazard class was calculated. Information about occurred rockfalls was obtained from the local authorities of transportation, facilities, and infrastructure. In some stations without administrative data sources, the number of rockfalls can also be estimated based on observations around the stations and information from residents. The estimation was carried out by observing the holes in the former slope or the rock blocks found on the trench/ditch. From this validation, rockfalls have occurred in the classes of very low, low, intermediate, and high with a percentage of 1.75%, 7.02%, 26.32%, and 64.91%, respectively (Figure 11). Since 91.23% of the rockfall occurred in the intermediate and high hazard classes, the Rockfall Hazard Zonation Map can be considered reliable to predict future rockfall.
CONCLUSION

Based on 17 measurement stations, there are 4 (four) rockfall hazard classes in the study area, i.e. very low, low, intermediate, and high. The very low class, which also included road segments without slope, has the largest percentage of 83.83% that associated with normal SMR score, slope height very low to low, and block size between 0.2 – 0.3 m. Followed by intermediate class with a percentage of 7.16% that associated with bad to very bad SMR score, slope height low to high, and block size between 0.3 – 1.0 m. In the third position followed by a low class with a percentage of 4.28% that associated with normal to bad SMR score, slope height low to moderate, and block size between 0.2 – 0.7 m. The last position was taken by high class with a percentage of 4.19% that associated with bad to very bad SMR score, slope height low to high, and block size between 0.7 – 1.3 m.

Based on the percentage of the total rockfall hazard weight, the most significant parameter that influences the rockfall hazard zonation is the SMR followed by slope height and rock block size, respectively. This study also identified several landslide potential zones which included slopes that have experienced landslide but still have the potential to re-occur and also slopes with destroyed composing rocks and/or easily collapse. To validate the predicted hazard zone, historical rockfall events were overlaid over the Rockfall Hazard Zonation Map. Since 91.23% of the rockfall occurred in the intermediate and high hazard classes, the Rockfall Hazard Zonation Map can be considered reliable to predict future rockfall.

Even in a stable condition, slope reinforcement still needed to be installed on a slope to avoid the rockfall threats triggered by external factors such as natural disasters and human disturbances. Fence, nets, ditch need to be installed on slopes that have the potential to drop small rocks. Spot shotcrete are needed to cover fragile and weak parts of the slope. Anchors and bolts can be installed on a slope with a solid type of composing rock. Meanwhile, the systematic shotcrete or the concrete coating method can be used on slopes that formed from weathered and/or softer rock types and easily destroyed. If the slope has weathered so much and/or has experienced a lot of rockfalls, then the most needed slope reinforcement is an anchored wall or even need re-excavation.
DECLARATIONS

Availability of data and materials
The DEM data utilized in this study are freely available from NASA Shuttle Radar Topography Mission Version 3.0 Global 1 arc second (https://earthexplorer.usgs.gov). The other datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interest
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Contributions
KT conducted field investigation in 2014, took samples, created the maps, analyzed and compiled the research work. KH carried out some geotechnical analyses in the research work. Both authors read and approved the final manuscript.

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