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Simulation of Kalirejo Roadside Slope based on Altered Andesite Characters, Kulon Progo Regency, Indonesia

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ABSTRACT. This study is performed to investigate the characteristics of the Kalirejo Roadside Slope that consists of intrusive andesite rock in the Kulon Progo Mountains. The rocks consist of slope identified by making a visual observation of hand specimens in the field, petrographic and X-ray Diffraction (XRD) analyses of the rock samples in the laboratory, upon which genetic rock classification was determined. The presence of specific minerals identified in the petrographic and XRD analyses determined the altered rock types. Comparing secondary minerals to the primary minerals observed in the petrographic and XRD analyses examined the alteration intensities. The development is determined in the field through GSI classification based on the visual characteristics and in the Laboratory-based Chemical Index of Alteration (CIA) and engineering properties of the altered rocks. The results showed that the rocks typically consist of 33.20 to 59.20% plagioclase, 1.40 to 5.10% quartz; therefore, they are classified as andesite. The presence of halloysite, montmorillonite, kaolinite, and secondary quartz as secondary minerals in the altered andesite indicated that the parent andesite rocks had undergone argillic alteration. Meanwhile, the percentages of primary minerals to secondary minerals indicate that the andesite rocks have undergone moderate to high alteration intensity. Based on the visual characteristics, the research area consists of fresh, slightly weathered, andesite rocks, and complete weathered residual soil. The field determined GSI values of the samples decreased with the increase of rock weathering. The CIA values of the samples increased with the increase in rock weathering. Identification of visual characteristics of rock weathering appeared to be in good agreement with the classification based on the CIA and engineering properties analysis results. Point load tests determine the uniaxial compressive strength (UCS) of rocks and soils. Engineering properties of the residual soils are performed by using ASTM standard procedures. Besides, the results also showed that the lower part of the roadside slope consists of fresh and slightly weathered andesite rocks, which have relatively high strength and are classified as medium strong rocks. Meanwhile, the upper part of the slope profile contains completely weathered residual soil, which had very low compressive strength, and is classified as very weak soil.

Keywords: Andesite · Argillic alteration · Geological Strength Index (GSI) · Hydrothermal alteration · Roadside slope · Weathering.

1 INTRODUCTION

The research was performed at the Kalirejo Roadside Slope. The roadside slope is located on the opposite side of Masjid Sabillal Muhtadin, Kalirejo area, Kulon Progo Mountains,

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Central Java, Indonesia (Figure 1). The 7 m high, 30 m wide slope appeared with a very steep angle of 65°. Referring to the Regional Geological Map of Yogyakarta by Rahardjo *et al.* (1995), the area mainly consists of intrusive andesite, which was formed by the activity of Tertiary magmatism (Figure 2). Besides, the humid tropical climate causes widely distributed very weak weathered rocks in Kulon Progo Mountains (Novianto *et al.*, 1997).

In the past, the Kalirejo road section was a naturally steep hill slope. However, the slope was then excavated as a road to fulfilling local transportation access need in rural research areas. Andesite commonly has very high compressive strength and exists as steep slopes. However, numerous studies, such as Pratama *et al.* (2018), showed that the intrusive rocks exposed at several locations in Kulon Progo Mountains had undergone hydrothermal alterations, particularly propylitic and argillic alteration types. In addition, a humid tropical climate has caused the weathering of intrusive rocks into soil formation. These two processes were likely to have changed in several characteristics and behaviors of the parent igneous rock. Identification of characteristics of the altered andesite is an essential need for understanding strength reduction processes controlled on slope stability.

This paper presents the detailed results of the study to investigate and examine the slope stability based on the characteristics of altered andesite and for installing the most suitable and cheap slope reinforcement that prevents the additional weathering and to reinforce the altered rock at the Kalirejo roadside slope in Kulon Progo Mountains. Results of the study are expected to provide information for choosing the most effective, long-life stable slope reinforcement in altered andesite of the research area.

2 METHOD

Field investigation and laboratory tests were conducted in the Kalirejo Roadside slope. The slope was divided into twelve profiles during the field observation using GSI classification (Hoek, 2007) at which characteristics of rock masses were carried out by photographic mapping (Figure 3a). With the increase of rock weathering, GSI values decreased. Characteristics of the primary minerals, including the roadside slope, were identified by visual observation of hand specimens in the field, petrographic and X-Ray Diffraction (XRD) analyses of primary and secondary minerals of the rock samples in the laboratory, upon which genetic classification has been determined based on the igneous rock classification proposed by Streckeisen (1978). The presence of specific minerals identified in the petrographic and XRD analyses determined the types of hydrothermally altered and weathered rocks. The number of primary minerals to the secondary minerals observed in the petrographic analyses of thin sections by the point-counting method determined the intensities of rock alteration, following the Byers (1990). The percentages of the rock alteration intensities are then divided following classification proposed by Gillis *et al.* (2014), as shown in Table 1.

TABLE 1. The intensity of hydrothermally altered rock classification (Gillis *et al.*, 2014).

Alteration intensity	Secondary minerals to primary minerals (%)
Fresh rock	<2
Weak	2–9
Moderate	10–49
High	50–95
Intensive	>90

Rock weathering has been investigated in the field and laboratory. In the field, rocks weathering has been examined based on the visual characteristics, following classification proposed by ISRM (2007, in Martin and Stacey (2018)), as shown in Table 2.

Two rock samples and two residual soil samples were selected for XRD and XRF analyses. Laboratory-based Chemical Index of Alteration (CIA) of the rock samples, following classification proposed by Nesbitt and Young (1982), determined the soil formations, as shown in Table 3. The procedures of ASTM standard classifications also perform the engineering properties analyses of residual soil. The CIA values of the altered rock samples calculated for determining the rate of chemical weathering based on four major oxides obtained from XRF analy-

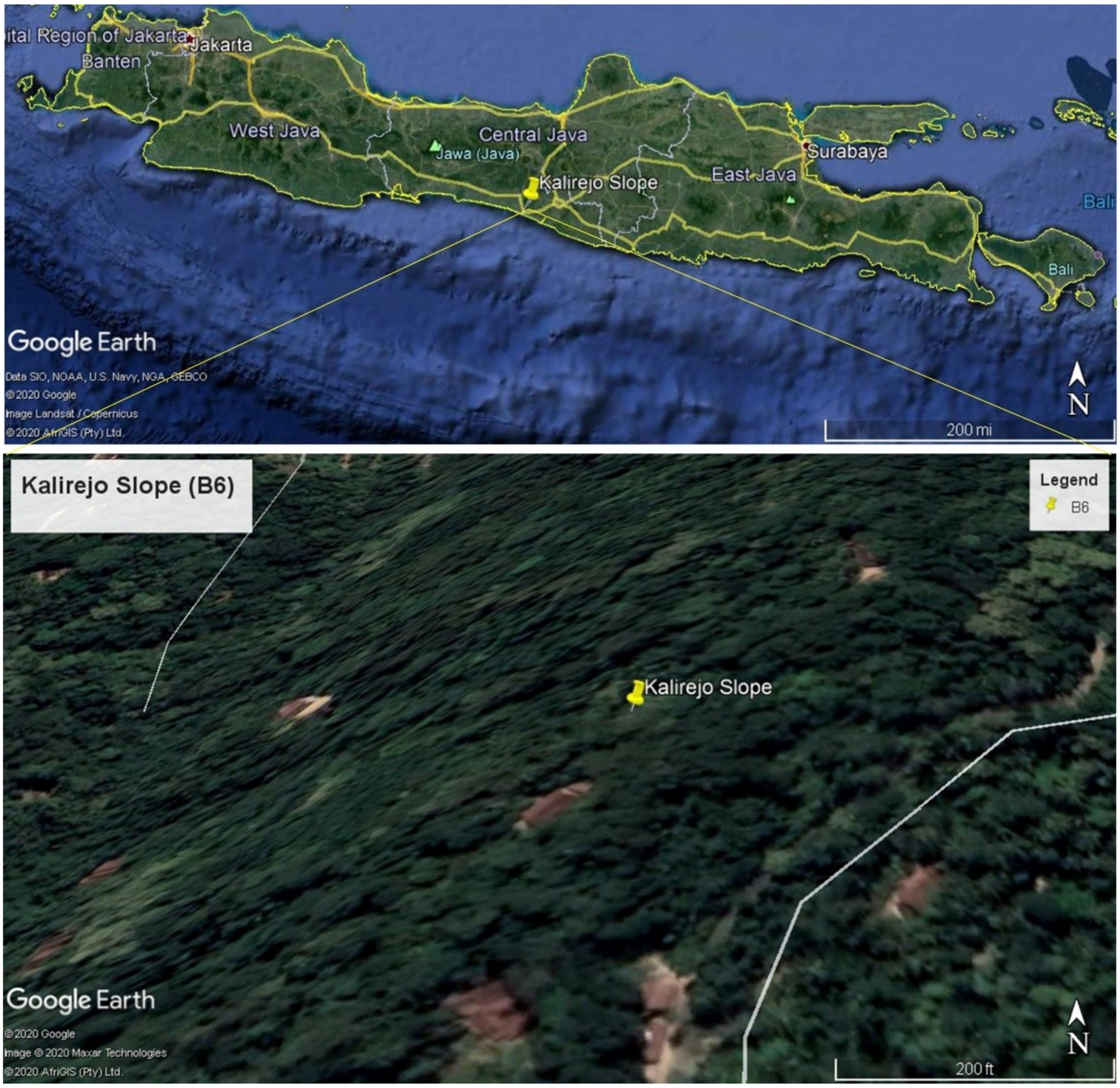

FIGURE 1. Research location at Kalirejo Road of Kulon Progo.

TABLE 2. Weathered rock classification based on visual characteristics (ISRM, 2007, in Martin and Stacey (2018)).

Term	Symbol	Description
Fresh	FR/W1	No visible sign of weathering
Slightly weathered	SW/W2	Partial (<5%) staining or discoloration of rock substance, usually by limonite. The color and texture of fresh rock are recognizable. No discernible effect on the strength properties of the parent rock type.
Moderately weathered	MW/W3	Staining or discoloration extends throughout all of the rock substance, and other signs of chemical or physical decomposition are evident. The color and strength of the original fresh rock are no longer recognizable.
Highly weathered	HW/W4	Limonite staining or bleaching affects all of the rock substance. The original color of fresh rock is no longer recognizable.
Completely weathered	CW/W5	Rock has soil properties (i.e., it can be remolded and classified according to the USCS, although the texture of the original rock can still be recognizable.

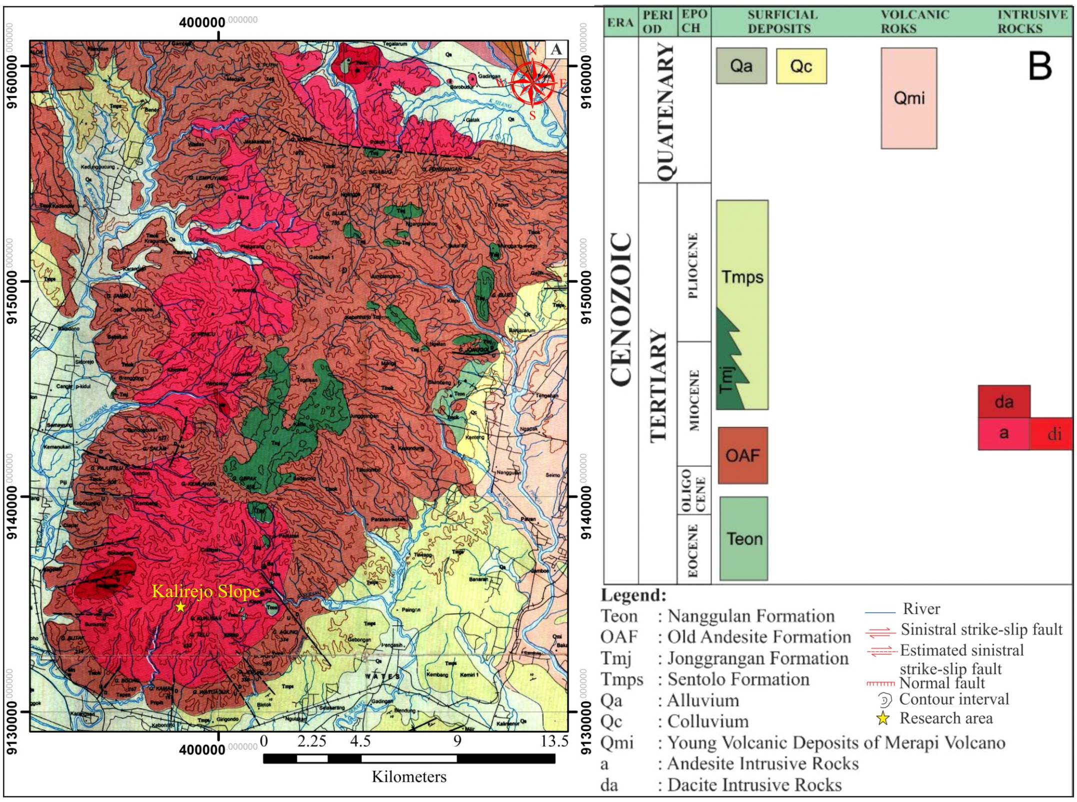

FIGURE 2. Part of the regional geological map of Yogyakarta and the stratigraphic sequence, according to Rahardjo *et al.* (1995).

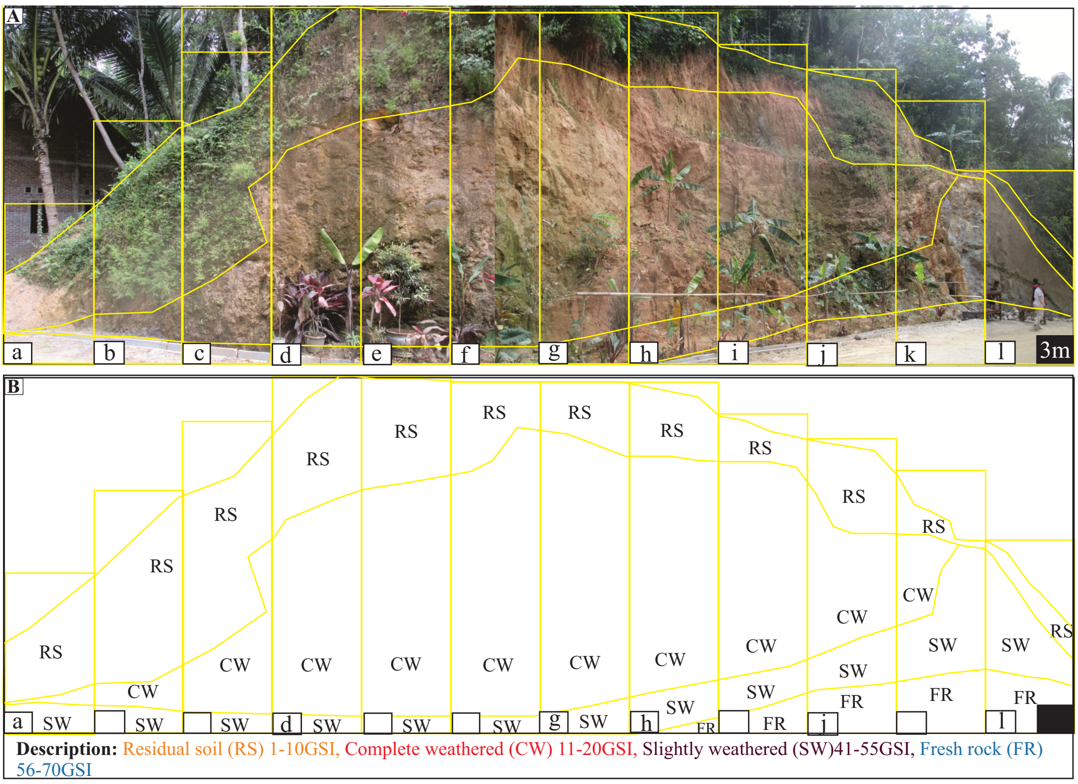

FIGURE 3. Overall view of the Kalirejo Road Side Slope: (A) Photograph of the slope; (B) Weathering profiles.

ses using the following equation originally proposed by Nesbitt and Young (1982):

$$\mathrm{CIA} = \frac{\mathrm{Al_2O_3}}{(\mathrm{Al_2O_3} + \mathrm{CaO} + \mathrm{Na_2O} + \mathrm{K_2O})} \times 100 \quad (1)$$

where Al_2O_3 = aluminum oxide; CaO= calcium oxide; Na_2O= sodium oxide; and K_2O = potassium oxide.

TABLE 3. Chemical weathered rocks classification (Nesbitt and Young, 1982).

CIA (%)	Weathering degree
50–60	Fresh rock
61–74	Slight weathered rock
75–80	Moderate weathered rock
81–85	High and Complete weathered rock
>85	Residual soil

The disturbed soil samples were analyzed in the laboratory to know the index properties of residual soil. ASTM D (2000), 422-63 (Reapproved 1998) was applied to divide the fine materials that are less than 75 µm size from larger particles using the wet sieving method. ASTM D 4318-00 (2000) examined liquid limit, plastic limit, and plasticity index of homogeneous soil. After knowing the liquid limit and plasticity index of the residual soil, ASTM D 2487-00 (2000) classified the suitable soil particle size of the residual soil.

ASTM D 854-02 (2002) used to calculate the specific gravity of the solids phase in soil. The specific gravity can know the relationship of void ratio and saturation degree. Point load tests are proposed by Broch and Franklin (1972), ASTM D 5731-02 (2002), and compression tests can determine the uniaxial compressive strengths (UCS) of altered rocks, following procedures described in ASTM International (2002). Residual soil strengths are examined through direct shear tests (ASTM D 5731-02 (2002)). The measured strengths of residual soils are cohesion (c), and friction angle (ϕ) that were plotted in Mohr-Coulomb failure criteria. Two rock samples are collected for petrographic and UCS analyses. The cohesion (c) is controlled by the composition and types of secondary minerals, distribution, and density in the residual soil. Whereas the internal friction angle (ϕ) is the failed angle that formed the shear stress exceeded its rock strength. The residual soil type found in the research area that was very problematic, called fat clay (CH), that mainly controls on the altered rock slope stability by the reaction of water and soil.

The analysis of shear strength values of altered andesite is the main input data to simulate the slope stability of the research area. The strength of altered rocks are controlled by the parent rock textures and mineral composition (Bell, 2007), the presence of discontinuities and their tightness, filling with expansive clay and orientation to the excavated surface (Hoek, 2007), while the weathered products, mechanical properties of the residual soil depend on the percentage and types of secondary minerals, their changed properties under wet condition act as the resisting shear strength along the assumed circular slip surface. Whereas the shear stress performs as a load that promotes downslope movement. The safety factor (SF) value was calculated at the lower bound slope surface proposed by Frohlich (1955). The SF values are the index factor of slope stability conditions that cause for easily understanding civil engineers. Bishop's simplified method (1955) considered the slope stability of the slip surface that was divided into several vertical slices. The SF values of residual soil can calculate from the following Equation (2) that is the ratio of the measured shear strength of altered materials and shear stress required for equilibrium along the circular slip surface:

$$\mathrm{SF} = \frac{c + (\sigma - u)\tan\phi}{\tau_f} \quad (2)$$

where c = cohesion; σ' = effective stress = $\sigma -$ u; ϕ = internal friction angle τ_f = shear stress at failure

The causes of slope failure are divided into; internal causes, which decrease in shear strength (e.g., progressive failure, weathering, seepage, and erosion) and external causes, which increase in the shearing stress (e.g., geometrical changes, unloading the slope toe, loading the slope crest, shocks, and vibrations, drawdown, changes in water regime) described by Terzaghi *et al.* (1996).

Three stages of slope conditions depend on SF values are stable, marginally stable (critical), and actively unstable. Stable slopes (SF>1) mean that the shear strength of rock/soil materials is higher than shear stress acting along a circular sliding surface. The marginally stable (SF=1), also called limit equilibrium, shows the balancing of both the resisting shear strength and shear stress. The actively varying stage (SF<1) occurs when the residual soil strength becomes very weak by hydrothermal alteration and weathering processes to withstand the promoted shear stress by gravity or pore water pressure rising. The standard SF values are; SF = 1.3 to 1.5 for stable rock slopes, SF = 1.0 to 1.3 for temporary mine slopes operation, and SF > 1.3 for a long-termed span of roadside slopes were suggested by Sivakugan *et al.* (2013). The slopes can be more susceptible to failure in the weak zone consists of highly altered rocks.

Interpretation of slope stability analysis is simulated based on the strengths of altered andesite using Slide V.6.005 (2019) software (RocScience package). The most suitable Bishop Simplified method is selected for its reliable and straightforward simulation results among several limit equilibrium methods (LEM) and depends on the most often experience failure mode in the research area. Slope stability analysis and interpretation of altered andesite are made along the assumed curvilinear surfaces.

3 RESULTS

3.1 Mineralogical characteristics

The photographs of typical outcrops and thin sections of the igneous rocks consisting of the Kalirejo roadside slope are shown in Figure 4 and Figure 5. In contrast, the corresponding results of XRD analysis of the altered rocks and residual soils are described from Figure 6 to Figure 9. The rock samples typically consist of 33.20 to 59.20% plagioclase, 1.40 to 5.10% quartz (Table 4). Adopting the IUGS classification proposed by Streckeisen (1978), the outcrops of the Kalirejo roadside slope are classified as andesite based on the compositions of rock-forming minerals. The rock samples have the aphanitic textures with clay minerals such as halloysite, montmorillonite, and kaolinite forming groundmass; therefore, the parent andesite rocks have undergone argillic alteration in addition to weathering. Based on the results of the petrographic analysis, the percentages of primary minerals to secondary minerals indicated that the rock samples have undergone moderate to high alteration intensity (Table 4).

3.2 Geochemical characteristics

Based on the visual characteristics, the Kalirejo roadside slope consists of fresh and slightly weathered andesite rocks (Figures 4 and 5). Geochemical data of major oxides in the rock and soil samples are obtained from the XRF analyses described in Table 5. The calculated CIA values indicated in Table 5 that the rock mass of roadside slope consists of slightly and moderately chemical weathered andesite rocks and residual soil, adopting the classification proposed by Nesbitt and Young (1982). The CIA values of the andesite increase with the increasing of rock weathering. The visually identified rocks weathering shows good agreement with the CIA classification.

3.3 Engineering properties of altered rocks

The UCS values of the altered rock samples have been demonstrated in Table 6 that decreased with the increasing of rock weathering. The roadside slope consists of fresh and slightly weathered andesite rocks with relatively moderate strengths and is classified as strong and medium-strong rocks based on (ISRM, 1981 in Hoek, 2007). Meanwhile, the residual soils occupy very low compressive strengths. According to Figure 3, there is completely weathered residual soil massively in the upper part of the roadside slope profile.

Based on engineering property's results of rocks weathering, the residual soils had no gravel with 21.40 % sand and 78.60% silt/clay, are classified as fat clay (CH). The thickness of residual soil is ~7 m. Fat clay has a high plasticity index (38.98 %) with a high liquid limit (*LL*, 56.01 %). Moreover, highly porous structures of grain particles (n, 53.58%) caused the road stability problems under high water content (w, 45.42%), high saturation degree (S, 89.72%), and high bulk density (ρ_b, 1.79 g/cm^3). Low dry density (ρ_d, 1.25 g/cm^3) and light specific gravity (G_s, 2.44) result from the complete decomposition of rock-forming minerals in residual soils.

Slightly weathered andesite rocks are shown in Figure 5, consist of joints influenced by the

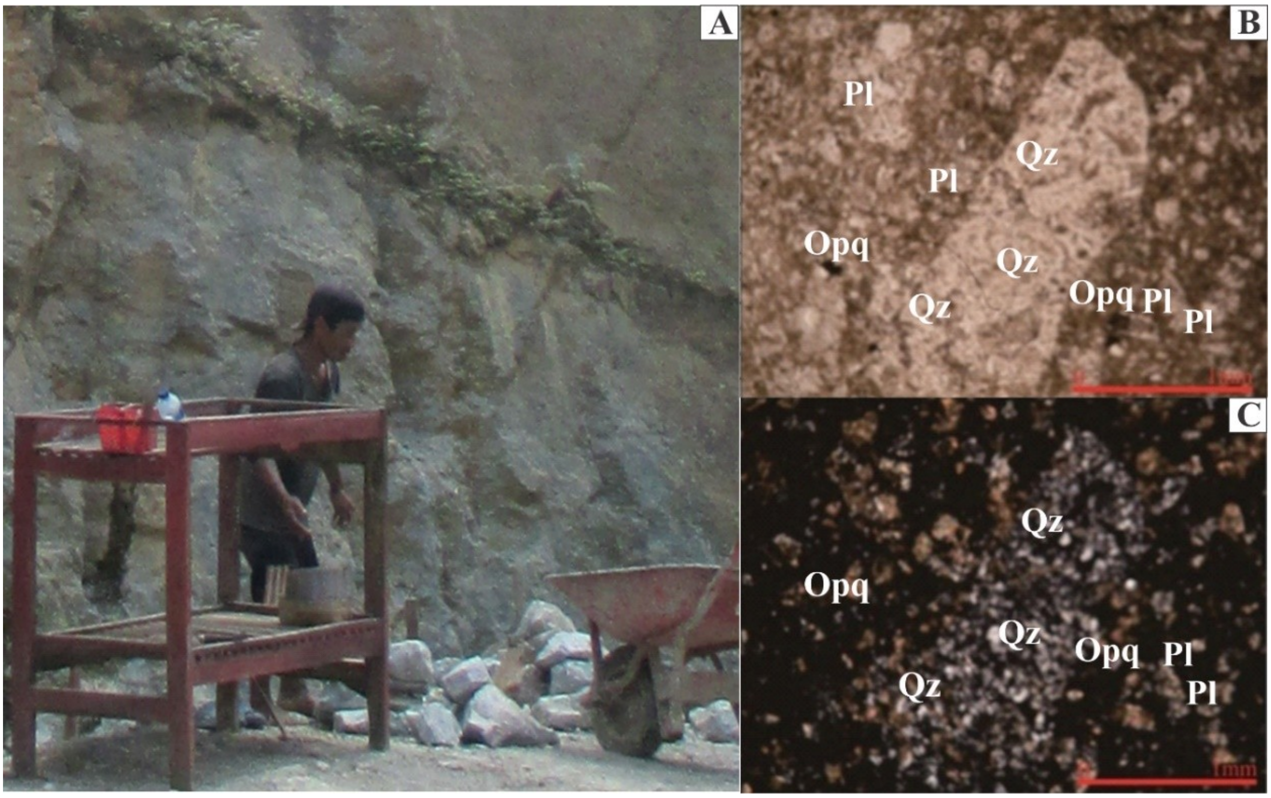

FIGURE 4. Photographs of fresh andesite: (A) Outcrop; (B) Thin sections FR sample under plane-polarized light (PPL) and (C) cross-polarized light (XPL).

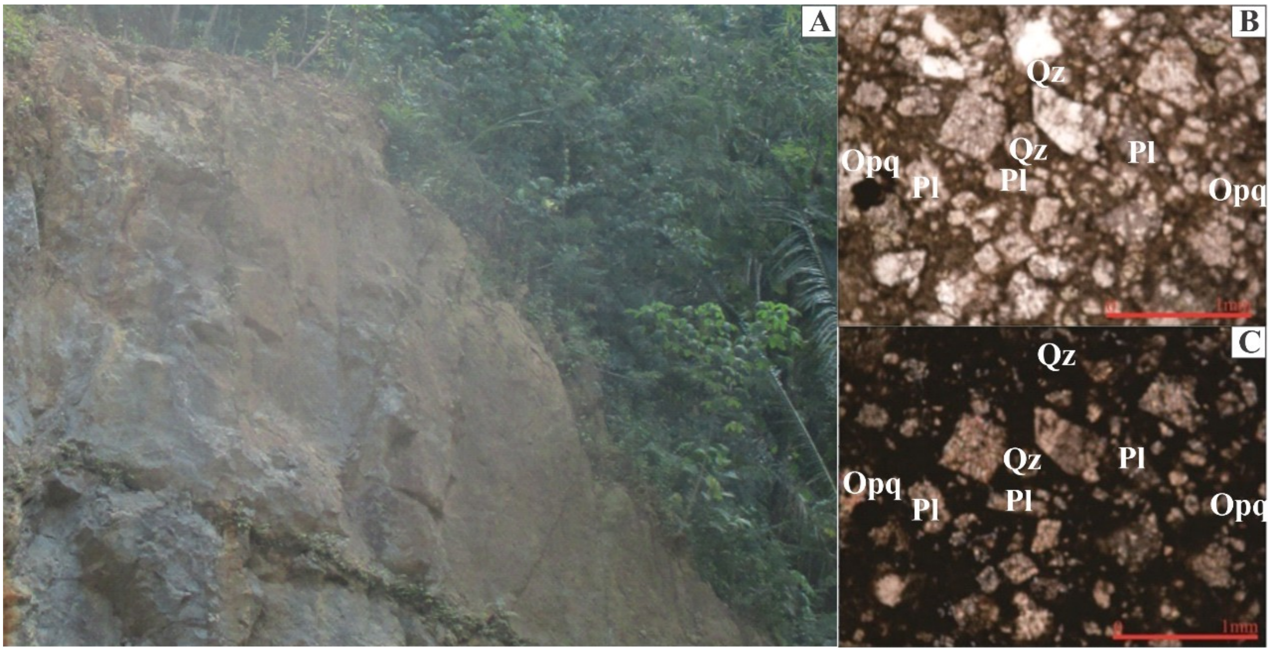

FIGURE 5. Photographs of slightly weathered andesite: (A) Outcrop; (B) Thin sections of SW sample plane-polarized light (PPL) and (C) cross-polarized light (XPL).

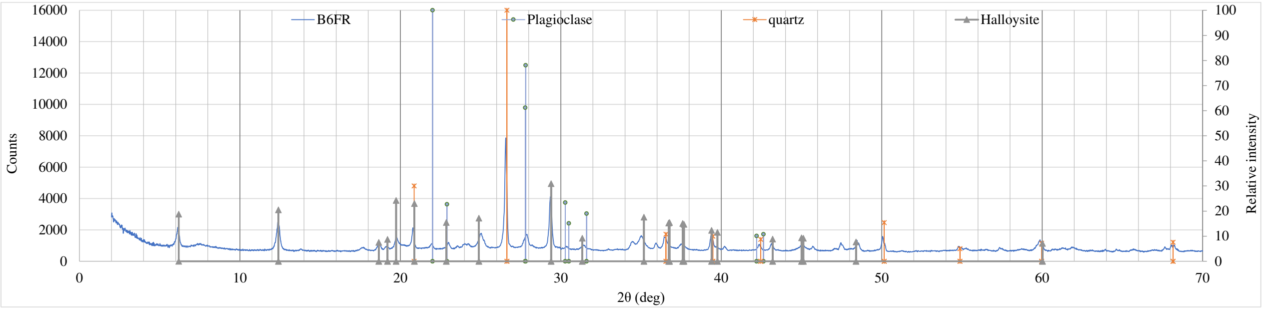

FIGURE 6. The XRD analysis results of the fresh andesite (Sample FR).

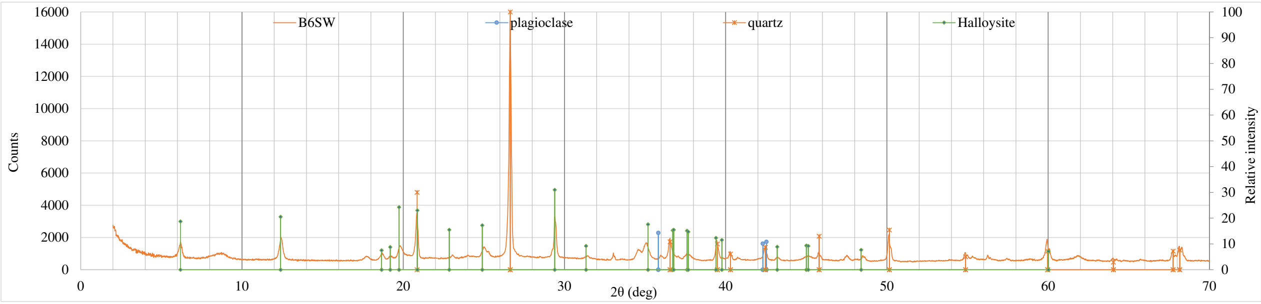

FIGURE 7. The XRD analysis results of the slightly weathered andesite (Sample SW).

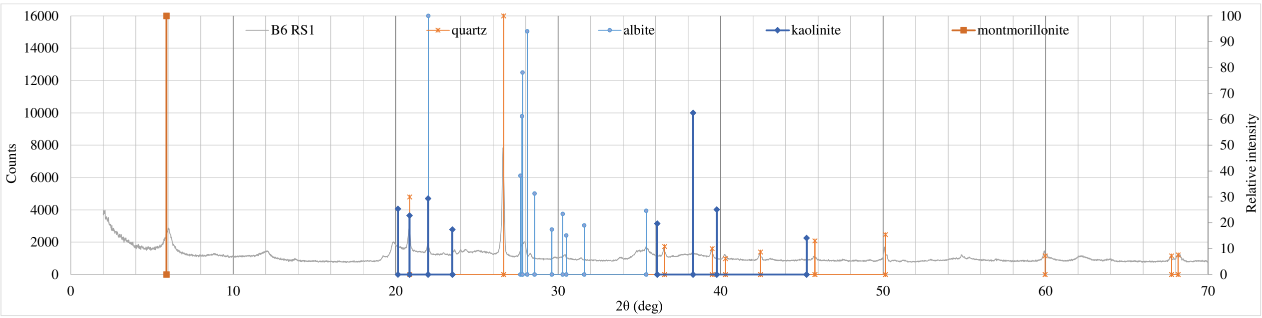

FIGURE 8. The XRD analysis results of the residual soil (Sample RS1).

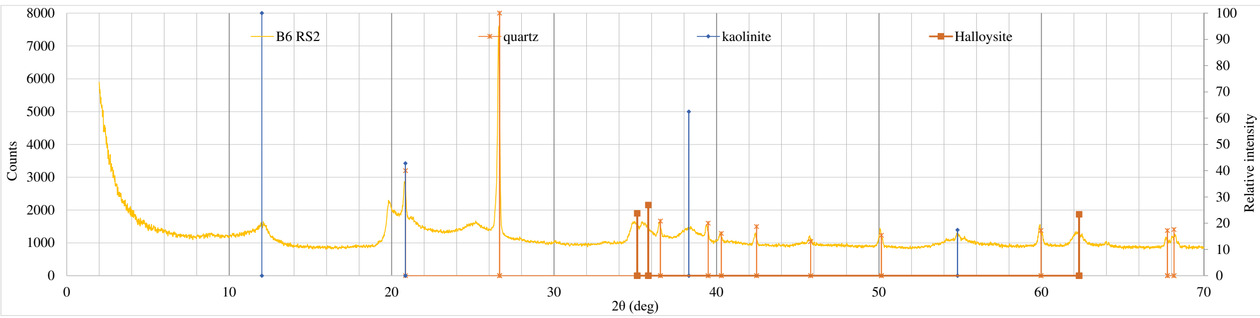

FIGURE 9. The XRD analysis results of the residual soil (Sample RS2).

TABLE 4. Alteration intensities of andesite based on petrographic analysis results.

Sam. Code	Weathering degree (ISRM, 1981 in Hoek, 2007)	Primary mineral (%)			Total primary mineral	Secondary mineral assemblages	Hydrothermal alteration types	Total secondary mineral	Altered intensity (Gillis et al., 2014)
		Pl	Qz	Opq					
FR	Fresh	59.2	5.1	2.8	67.1	Ha	Argillic	32.9	Medium
SW	Slight	33.2	1.4	2.4	36.9	Ha	Argillic	63.1	High
RS1	Complete	1.1	1.9	4.8	7.7	Ha, Kln	Argillic	92.3	High
RS2	Complete	2.8	-	2.9	5.6	2nd Qz, Mmt, Kln	Argillic	94.4	High

Pl = plagioclase; Qz = primary quartz; 2nd Qz = secondary quartz; Opq = opaque, Mmt = montmorillonite, Ha = Halloysite, Kln = kaolinite.

discontinuity characteristics (e.g., orientation, spacing, aperture, and filling materials) on the roadside slope stability. The consideration of slope stabilities in residual soils is likely to control by the altered rock strengths. Hence, further studies need to investigate the characteristics of rocks discontinuities developed in the igneous rocks, and the associated slope stabilities are recommended for engineering slopes.

3.4 Slope stability analysis of altered andesite

The simulation of altered rock slope stability is considered based on the changed slope geometry and the strength reduction of the highest altered rock, residual soil. The calculated shear strength values of Kalirejo residual soil (CH) had cohesion (c, 33.53 kPa) and internal friction angle (ϕ, 16.79°). The safety factor (SF) has been calculated first by changing the slope angle at a fixed slope height. This consideration aims to understand well the stable slope positions. The trial simulated results at 10m height, and 75° inclination gave stable conditions (SF 1.27). The higher the cohesive strength of residual soil, the slope can be more stable even in deep and steep conditions. The Kalirejo roadside slope in the field is situated at 7m height and 65° dip with the fixed mechanical properties and then examined SF values. This situation gave 1.73 SF that was higher than the SF values of the 10m height slope (Figure 10).

The visual observation of the Kalirejo roadside slope took place in the progressive slope failure. Hence, the consideration of strength reduction has been intended to know the minimum SF value that happened. Back analysis of strength reduction of residual soil was applied, and the results were good agreement with the visual observation data. Strength reduction slope instability at 7m height, 65° inclination shows 0.98 SF with cohesion loss (14.53 kPa). The cohesive strength of residual soil controlled significantly on the slope stability, as shown in Figure 11.

4 CONCLUSIONS

The mineralogical, geochemical, and engineering properties of altered rocks are investigated in the Kalirejo roadside slope. The results show that the rocks typically consist of 33.20 to 59.20% plagioclase, 1.40 to 5.10% quartz, and classified as andesite. Secondary minerals such as halloysite, montmorillonite, and kaolinite in the andesite rock samples showed that the parent andesite rocks had undergone argillic alteration. Meanwhile, the percentages of primary minerals to secondary minerals indicated that the andesite rocks have suffered moderate to high alteration intensity.

Based on the visual characteristics, the research area comprises fresh and slightly weathered andesite rocks and complete weathered residual soil. The CIA values of the rock samples increased with the increasing of rock weathering. Grain size decreased with the increasing percentage of clay minerals and soil formation. The visual identified characteristics of rock weathering are good agreement with the CIA classification. Based on the analysis results of the physical and index properties of residual soils, the soil sample consists of high porosity fat clay with high liquid limit, water content,

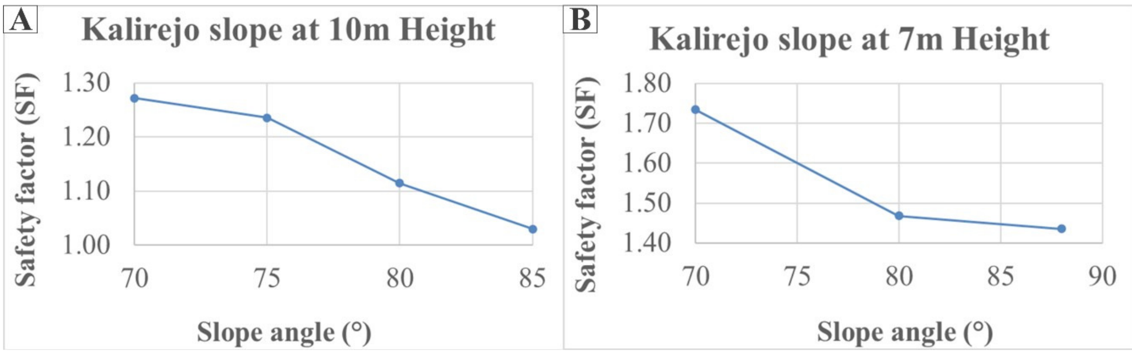

FIGURE 10. The calculated SF values of fat clay residual soil at (A) 10m and (B) 7 m height by changing slope angle.

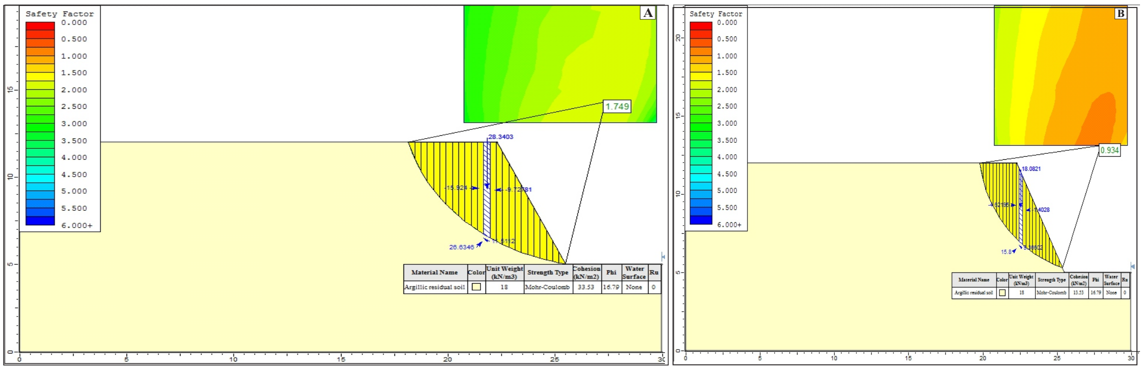

FIGURE 11. (A) 33.53 kPa and (B)14.53 kPa cohesion influence slope stability with fixed ϕ, 16.79°.

and degree of saturation in addition to high bulk density. Whereas, the residual soil had low dry density by complete drying and light specific gravity of constituent altered clay minerals. The very low compressive strength of residual soils exists dominantly at the upper part; meanwhile, strong fresh and moderate strong slightly weathered andesite rocks are found at the lower part of the roadside slope profile. Decreased strength in slope stability result of residual soil (14.53 kPa) gave SF 0.98 under fully saturated condition. Hence, the Kalirejo roadside slope should be installed andesite rock masonry retaining wall (~3m height) with horizontal drained pipe to achieve SF 1.749 as slope reinforcement for long-termed stable slope life.

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TABLE 5. Major oxides of altered rocks and soil samples from XRF analyses.

Sam. Code	Name	Al_2O_3	SiO_2	Na_2O	K_2O	TiO_2	SO_4^{2-}	MnO	Fe_2O_3	ZnO	CaO	Tot. Ox.	CIA (%)	Weathering degrees (Nesbitt & Young,1982)
FR	Fresh	41.73	48.07	1.41	5.2	1.22	0.98	0.34	27.5	0.02	9.42	97.17	72.8	SW
SW	Slight	36.69	56.3	1.09	7.45	0.99	4.01	0.28	20.14	0.02	4.87	97.05	77.2	MW
RS1	Residual soil	50.39	54.99	1.19	0	1.16	0	0.17	30.24	0.02	0.38	131.84	93.7	RS
RS2		59.1	49.99	1.59	0	1.01	0.16	0.15	32.38	0.01	0.23	138.54	99.6	RS
Average		54.75	52.49	1.39	0	1.09	0.08	0.16	31.3	0.02	0.3	135.89	96.7	RS

TABLE 6. UCS values of rock samples.

Sample	Weathering degree*	UCS (MPa)	Rock classification*
FR	Moderate	95.49	Strong
SW	Moderate	35.81	Medium-strong
RS1	Complete	0.61	Very hard clay
RS2	Complete	0.4	Very stiff clay

*According to ISRM (1981 in Hoek, 2007)

TABLE 7. Analysis results of engineering properties of residual soil.

Engineering properties	Soil type	Results
Grain size distribution (%)	Gravel	0
	Sand	21.4
	Silt/clay	78.6
Atterberg's limit (%)	PL	17.02
	LL	56.01
	PI	38.98
Index properties	w (%)	45.22
	ρ_b (g/cm^3)	1.79
	ρ_d (g/cm^3)	1.25
	G_s	2.29
	e	1.15
	n (%)	53.58
	S (%)	89.72
Mechanical properties	c (kPa)	33.53
	ϕ (°)	16.79

Liquid Limit, Plastic Limit and Plasticity Index of Soils, Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, 4(8), p. 14.

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