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Rock slope kinematics analysis by Markland method of the Bener District, Purworejo Regency, Central Java, Indonesia

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ABSTRACT

Bener District, Purworejo Regency, Central Java, Indonesia, located in the Kulon Progo Mountains can be classified as a high-risk area. Many experts and researchers have studied landslides, but there has been little research on rock slope kinematics. In fact, when such a rock slope is unstable and poorly monitored, it has the potential to endanger the community or facilities at the adjacent site. This is why slope kinematics research is required. To complete this study, rock kinematics analysis using the Markland method was performed on six representative slopes. The assessment results show that Kaliwader slope A, Kaliwader slope B, and Argosari slope each tend to collapse with wedge failure, Kaliwader slope D and Wadas slope have the potential for wedge failure and planar slide, but Kaliwader slope C does not. Despite their steep inclination, slopes that are likely to fail are strongly related to the presence of geologic structures, particularly joints, and faults, at the sites. The findings of this study will be helpful in the development of landslide vulnerability zones in the context of disaster mitigation.

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1. INTRODUCTION

One of the environmental issues facing by public facilities such as roads, buildings, and settlements face is a mass movement. This typically occurs in a sloping and hilly or mountainous area. Some hilly morphological areas are frequently confronted with slope instability issues, which can result in mass transfer in the form of landslides or rock collapses [1]. One of the physiographic zones in Central Java that has the potential for mass movements is the Kulon Progo Mountains [2], [3].

The geological condition of the area influences the occurrence of earth movements, which include topography, geomorphology, lithology, and geologic structures. The geologic setting determines whether the slope conditions meet or fail to meet safety criteria. As is well known, the presence of discontinuity planes in general is one of the factors that causes a fresh rock slope to collapse [4], [5]. Many experts and researchers have studied landslides, but there has been little research on rock slope kinematics. When such a rock slope is unstable and poorly monitored, it has the potential to endanger the community or facilities at the adjacent site.

As previously stated, one of the physiographic zones which prone to mass movement is Kulon Progo Hills of which the study area is situated. The area belongs to a relatively dense territory with a population in 2018 equal to 529 person/km^2 [6], and the local government has a plan to develop the area as one of the special interest tourist destinations, namely geo-agro tourism. To realize this plan, information on the security and stability related to the potential for disasters especially mass movements of the area is needed to be collected, and some measures for mitigation are required to be done.

Referring to the backgrounds mentioned above, it is imperative to perform a study on the movement potential of natural slopes built by fresh rock but behaves with various weaknesses. Related to this occasion, a series of engineering geological investigations had been organized, to assess the geological condition, analyze rock slope kinematics, determine the potential for failures and their classification, and identify the controlling factors of slope movements in the study area. It is significant to be held to support the local government measures of establishing landslide vulnerability zonation, in the context of disaster mitigation. The study area is situated in the Bener District, Purworejo Regency, Central Java Province, Indonesia as shown in Figure 1.

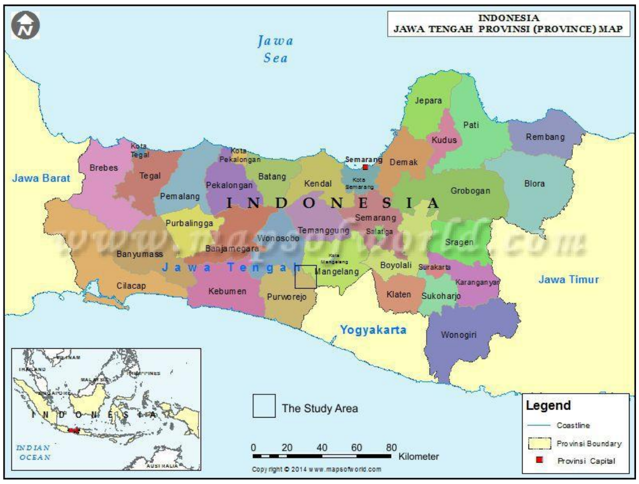


Figure 1. Location map of the study area [7]

2. RESEARCH METHOD

This study used a variety of methods, including descriptive assessments, analytical, geological field surveys and mapping, as well as laboratory testing and analyses. Activities have included the evaluation of secondary and primary data. Secondary data sources include regional geological literature, engineering geological data from previous studies, and satellite imagery. Field investigations were conducted to map geological and geomorphological features, identify rockslide occurrences, and measure the orientation and pattern of geological structures. Rock samples were collected from various locations for petrological analysis and physical/mechanical property evaluation [8], [9]. Laboratory tests on rock samples were done to determine rock properties, which were used in determining the potential of rock failures using the Markland method.

Force is the cause of material movement. Stress is defined as the application of force to a specific area. Disturbance of the balance of force distribution in such a slope causes soil or rock mass movement [10]–[12]. Figure 2 depicts the distribution of stresses acting on a slope. The basic theory of the study states that slopes constructed of hard rock have different characteristics from slopes constructed of soil [4], [9], [10].

The slope's stability in such conditions is entirely determined by rock shear strength [9]. The presence of weak planes or discontinuities, such as layering, jointing, fracturing, faulting, and foliation, or other geological structures, generally influences rock shear strength [13], [14]. An analytical method developed by Markland [4] can be used to predict potential slope failures, particularly those built with massive and fresh rock. To determine the potential slope failures, especially those built by massive and fresh rock, an analytical method by Markland [4] can be applied. The rock failure model on a slope according to Markland in Hoek & Bray [4] is outlined in Figure 3.

Types of failures on a slope comprising fresh rock can be categorized as planar slides, wedges, and topless or topplings [4]. Meanwhile, the slope stability is determined based on its safety factor. In general, the determination of the value of a safety factor is based on the (1).

$$Factor\ of\ Safety = \frac{\text{Resisting Force}}{\text{Driving Force}} \quad (1)$$

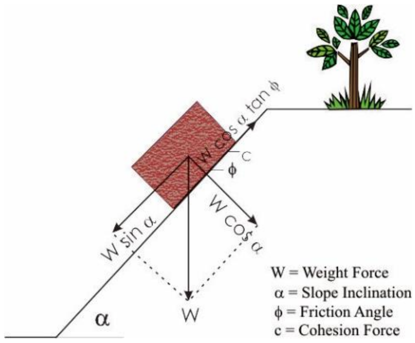


Figure 2. The distribution of stress on a slope [9]

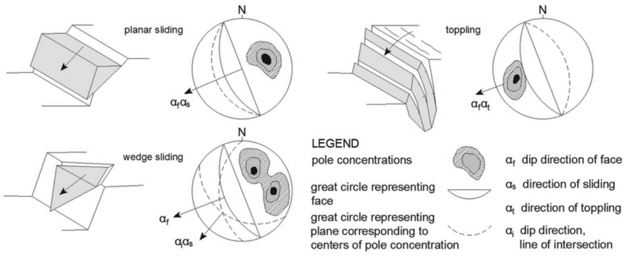


Figure 3. Stereographic projection model of rock slope failures [5]

The resisting force is the total force that retains the slope from sliding, and the driving force is the total force that pushes the slope to slip [15]. If the safety factor value is greater than 1 then the slope is declared to be safe or stable, if the safety factor is equal to 1, the slope is in critical condition, and if the safety factor is less than 1 then the slope will collapse [8], [9], [11], [15].

Despite analyzing some rock slope samples to applying the Markland method, referring to Bieniawski [16], rock mass rating (RMR) was also done by scoring the parameters comprising uniaxial compressive strength, rock quality designation (RQD), discontinuity spacing, discontinuity condition, the orientation of discontinuities, and groundwater condition [16], [17]. The classification of rock mass based on RMR is revealed in Table 1.

Table 1. Rock mass classification based on its RMR [17]

	Rock mass classification				
RMR	Very poor 0-20	Poor 21-40	Fair 41-60	Good 61-80	Very good 81-100

3. RESULTS AND DISCUSSION

Discussion on the geology of this study involves geomorphology, stratigraphy, geologic structures, and the role of these geologic factors in rock failures. The geomorphology of the study area expresses landforms of structural hills, homoclinal valleys, alluvial and floodplains, and river channels as seen in Figure 4. Structural hills have a longitudinal orientation of east-west and are segmented by valleys resulting from crack expansion followed by erosion, influenced by geological structures, especially joints, and faults. The elevation of this unit varies from 112.5–400 meters, sloping from 16°–55° (steep to very steep), with the dominant lithology being volcanic-clastic rocks. The homoclinal valley has a longitudinal orientation of northeast-southeast, influenced by the erosion process, with elevation ranges of 150-200 meters and steep sloping (4°-35°). The alluvial and floodplain display gentle inclination slopes or almost flat (0°-4°), with an elevation of 112.5-150 meters. The river channels have an elevation of approximately 150 meters with sub-dendritic drainage patterns, and the cross-sectional of the valley is "V" to "U" shape. Flow patterns in the study area are closely related to lithology, geological structure, and weathering processes. On the other hand, the topographical slope distribution can be classified into gentle (2%-7%), inclined (7%-15%), moderately steep (15%-30%), and steep (30%-70%), as expressed in Figure 4.

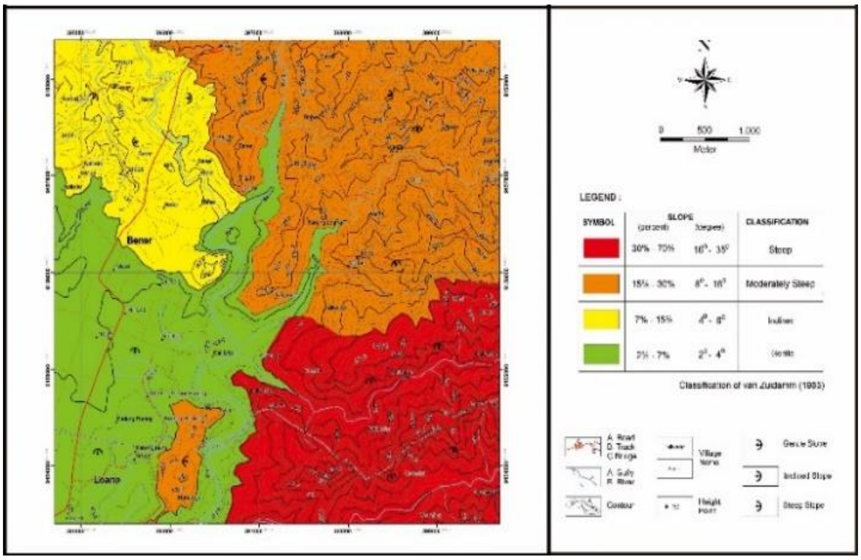


Figure 4. Slope distribution map of the Bener District and surrounding area

Stratigraphy of the study area from the oldest to the youngest comprises Kaligesing Formation composed of volcanic product rocks, Sentolo formation, and alluvial deposits. There is an andesite intrusion that breaks the Kaligesing Formation. The Kaligesing Formation, at the bottom part predominantly consists of andesite pyroclastic breccia and andesite lava (Figure 5), Figure 5(a) shows volcanic breccia of the Kaligesing Formation in fresh condition and Figure 5(b) shows the weathered condition, in Telogoguwa Village, while the upper part is mainly occupied by andesite laharic breccia, with the insertion of volcanic sandstones. The andesite intrusion shows columnar joint and sheeting joint structures, with a position of N 285° E/80° and N 255° E/55°. On the other hand, the andesitic lava shows an auto breccia structure formed during the freezing of the lava. Such vesicular and scoria structures are also found, characterized by the presence of holes formed due to gas release during cooling. In Wadas Village, andesite lava was found with a sheeting joint structure, and in the Pajangan hill andesite lava is observed with a columnar joint structure (Figure 6), locally distributed, and there some xenoliths are found. In weathered conditions, the Kaligesing Formation forms soil reaching more than 5 m of thickness as shown in Figure 5(b).

Conformably overlaying the Kaligesing Formation, there is the Sentolo Formation. It consists of bedded limestone, calcareous sandstone, calcarenite, and sandy marl (Figure 6). In the calcareous sandstone, there are often found lithic fragments, allochem foraminifers, skeletal, calcite matrices, with carbonate mud cement. In general, the slope of this rock unit is trending southwest, with a position of N 155°E/5°. Alluvial deposits are produced by river stream and flood sedimentation, consisting of clay, silt, and sand-sized materials, andesite fragments, volcanic materials, and limestone-sandstone fragments of granule to boulder-sized.

(a) (b)

Figure 5. Volcanic breccia of the Kaligesing Formation at Telogoguwa village in condition (a) fresh and (b) weathered

Figure 6. Andesite lava with columnar joint structure at Pajangan Hill, Sentolo Formation

The geological structures existing in the study area include joints and faults. Statistically, the joint pattern was analyzed utilizing a stereographic net diagram, the results indicated that the major stress trending to Northwest-Southeast (N 350° E/75°). There are some faults found, namely Wader Fault I, Wader Fault II, Kali Wadas Fault, and Kali Bleber Fault. Based on Rickard classification in Fossen [18], it can be stated that Kaliwader Fault I and Kaliwader Fault II belong to reverse left slip fault, Kali Wadas Fault, and Kali Bleber Fault include right-lateral slip fault. There are two main strike directions of faults, tending West-East and Northwest-Southeast. These faults intersect the andesite lava unit and the volcanic breccia unit of the Kaligesing Formation. A map showing the geological condition of the study area is displayed in Figure 7.

The existence of geological structures, especially joints, and faults produce discontinuity planes in rocks. Discontinuities affect the physical properties of rocks in the study area specifically by decreasing their shear strength. The more intensive the presence of geological structures, the smaller the shear strength of the rock, and the greater the potential to fail, particularly if the rock is on a slope with steep inclination. Ultimately, geological conditions will strongly influence the vulnerability of the study area against mass movements.

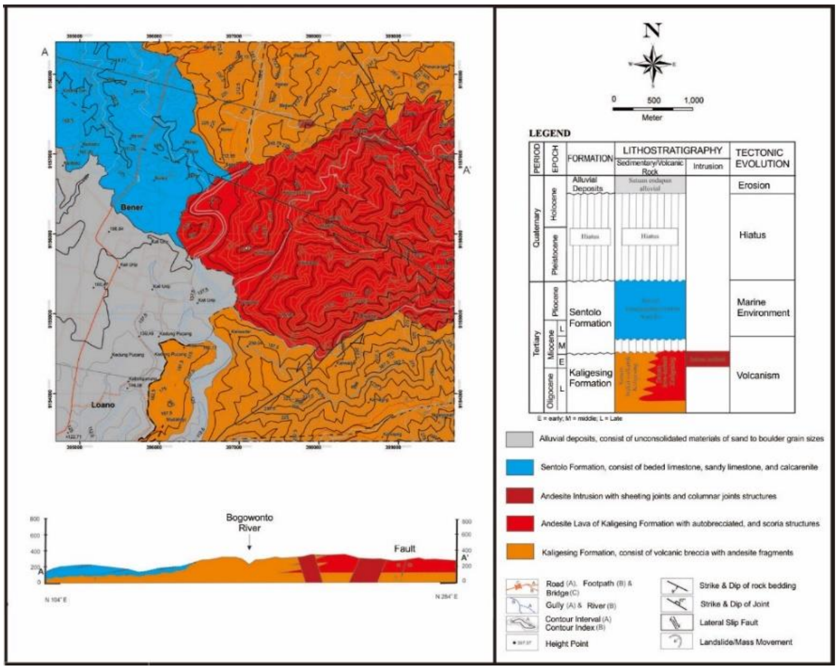


Figure 7. Geologic map of the Bener District and surrounding area [16]

3.1. Rock slope kinematics analysis

To assess the kinematics of rock formations, especially that have the potency to fail, this study was utilizing the Markland method. During applying the method, six slopes samples, mainly consisting of volcanic rocks of Kaligesing Formation, situated in Bener District were analyzed. The physical properties of slope constituent rock were also tested by Uniaxial Compressive Strength Test, and by referring to researchers [17], [19], the results are presented in Table 2.

Table 2. Physical rock properties of six slope samples

No	Location of slope to be analyzed	Lithology	Rock properties			
			Cohesion (Kpa)	Friction angle	Unit weight (g/cm^3)	Uniaxial compressive strength (Mpa)
1	Wadas slope	Andesitic lava	39.1	47°	2.077	6.62
2	Kaliwader slope A	Volcanic breccia	21.8	40°	1.805	12.41
3	Kaliwader slope B	Weathered andesitic lava	15	32°	2.077	6.62
4	Kaliwader slope C	Andesitic lava	39	51°	2.077	6.62
5	Kaliwader slope D	Andesitic lava	39	51°	2.077	6.62
6	Argosari slope	Weathered andesitic lava	15	35°	2.077	6.62

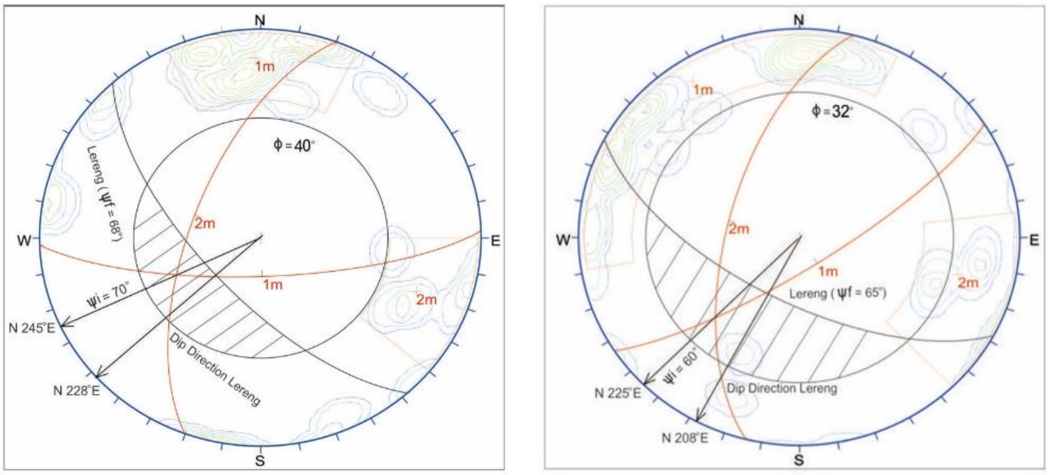
Afterward, RMR was carried out on slope constituent rocks. From the computation of RMR, Kaliwader slopes, Argosari slope, and Wadas slope have an RMR value ranging from 45 to 48, classified as fair rock. It means that discontinuities quite exist on the rock mass. Results of the stereonet plots, kinematics analyses, as well as RMR scorings are displayed in Figures 8-10, Figure 8(a) shows kinematic analysis with potential wedge failure of Kaliwader slope A, and Figure 8(b) shows kinematic analysis with potential wedge failure of Kaliwader slope B. Figure 9(a) shows kinematic analyses of Kaliwader slopes C with wedge failure potential and Figure 9(b) shows kinematic analyses of Kaliwader slope D with no failure potential. Figure 10(a) shows a kinematic analysis of the Argosari slope with wedge failure potential and Figure 10(b) shows a kinematic analysis of the Wadas slope with planar slide failure potential. The consequences of the analyses reinforce that geologic structures, lithological properties, and geomorphography play the main actors in rock slope failures.

Table 3. Results of Markland analysis for slope failures in the study area

No.	Location	Lithology	Rock mass rating	Type of rock slope failure potential
1	Kaliwader A	Volcanic breccia	c = 21.8 Kpa, ϕ = 40°, γ = 1.805 g/cm^3, σ = 12.41 Mpa; RMR = 45	Wedge failure, sliding direction: N 138° E
2	Kaliwader B	Weathered andesite lava	c = 15 Kpa, ϕ = 32°, γ = 2.077 g/cm^3, σ = 6.62 Mpa; RMR = 48	Wedge failure, sliding direction: N 128° E
3	Kaliwader C	Andesite lava	c = 39 Kpa, ϕ = 51°, γ = 2.077 g/cm^3, σ = 6.62 Mpa, RMR = 48	Unpotential to fail
4	Kaliwader D	Andesite lava	c = 39 Kpa, ϕ = 51°, γ = 2.077 g/cm^3, σ = 6.62 Mpa, RMR = 47	Planar slide, sliding direction: N 340° E Wedge failure, sliding direction: N 002° E
5	Argosari	Weathered andesite lava	c = 39 Kpa, ϕ=35°, γ = 2.077 g/cm^3, σ = 6.62 Mpa; RMR = 48	Wedge, sliding direction: N 225° E
6	Wadas	Andesite lava	c = 39.1 Kpa, ϕ = 47°, γ = 2.077 g/cm^3, σ = 6.62 Mpa; RMR = 48	Planar slide, sliding direction N 254° E Wedge, sliding direction: N 271° E

Notes: c = cohesion force of rock sample, ϕ = friction angle, γ = unit weight, σ = uniaxial compressive strength

In addition to analyzing six representative slopes, precautionary measures for the slopes will not be subjected to collapse or failure need to be done. To prevent the occurrence of slope slides in the context of disaster mitigation in the study area, among others by applying slope benching, and decreasing the inclination of the slope. Another method that is better to be applied is improving the slope stability by terracing or benching, horizontal drainage [20], constructing retaining walls, and reforestation with the right plants. This technique is quite effective and efficient to employ on the slope when the first method is difficult to be done. Last but not least, geological conditions, mass movement characteristics, and the factors influencing it are important to be understood by stakeholders and communities, as an inseparable part of disaster mitigation.



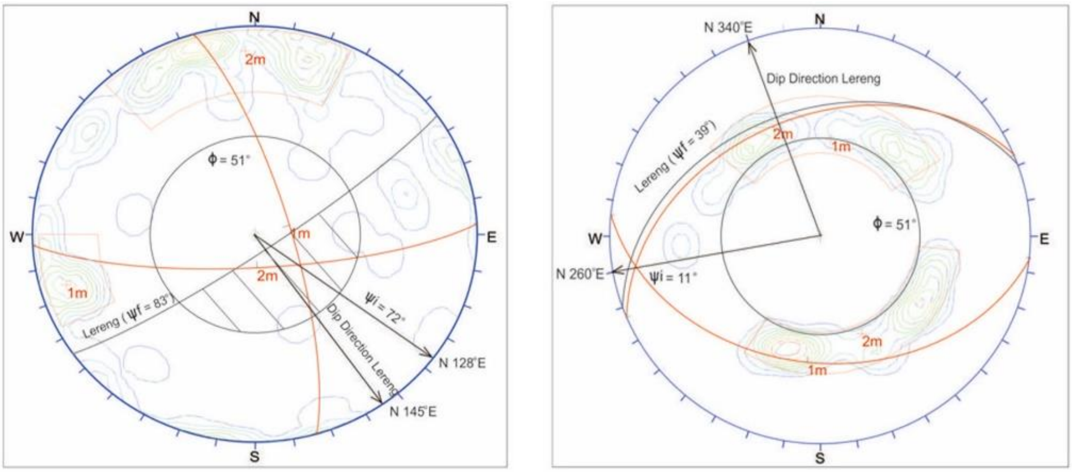
NO.	DATA TO BE ANALYSED				
1.	Azimuth	N 138° E	5.	Sliding direction (ψi)	70°
2.	Slope (ψf)	68°	6.	Friction angle (ϕ)	40°
3.	Joint 1	N 088°E/75°	7.	Slope dip direction	N 228° E
4.	Joint 2	N 200°E/64°			
Slope failure potential: Wedge type with sliding direction: N 245° E					

(a)

NO.	DATA TO BE ANALYSED				
1.	Azimuth	N 118° E	5.	Sliding dip direction (ψi)	60°
2.	Slope (ψf)	65°	6.	Friction angle (ϕ)	32°
3.	Joint 1	N 057°E/78°	7.	Slope dip direction	N 208° E
4.	Joint 2	N 194°E/63°	8.		
Potential slope failure: wedge type, with sliding direction N 225° E					

(b)

Figure 8. Kinematic analysis with potential wedge failure of (a) Kaliwader slope A and (b) Kaliwader slope B



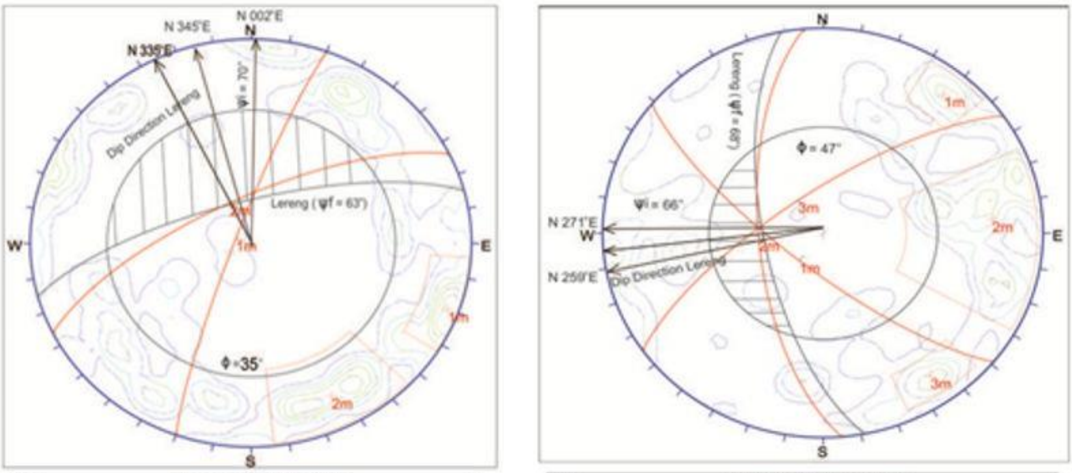
NO.	DATA TO BE ANALYSED				
1.	Azimuth	N 055° E	5.	Sliding dip direction (ψi)	72°
2.	Slope (ψf)	83°	6.	Friction angle (ϕ)	51°
3.	Joint 1	N 350°E/78°	7.	Slope dip direction	N 145° E.
4.	Joint 2	N 087°E/78°			
Potential slope failure: wedge type, with sliding direction N 128° E					

(a)

NO.	DATA TO BE ANALYSED				
1.	Azimuth	N 250° E	5.	Sliding dip direction (ψi)	11°
2.	Slope (ψf)	39°	6.	Friction angle (ϕ)	51°
3.	Joint 1	N 096°E/39°	7.	Slope dip direction	N 340° E.
4.	Joint 2	N 247°E/42°			
The slope is not potential to fail					

(b)

Figure 9. Kinematic analyses of (a) Kaliwader slopes C with wedge failure potential and (b) Kaliwader slope D with no failure potential



NO.	DATA TO BE ANALYSED				
1.	Azimuth	N 255° E	5.	Sliding dip direction (ψi)	70°
2.	Slope (ψf)	73°	6.	Friction angle (ϕ)	35°
3.	Joint 1	N 200°E/84°	7.	Slope dip direction	N 345° E
4.	Joint 2	N 244°E/72°			
Potential slope failures: wedge type with sliding direction N 002° E and planar type with sliding direction N 335°E					

(a)

NO.	DATA TO BE ANALYSED				
1.	Azimuth	N 169° E	5.	Joint 3	N 235° E/74°
2.	Slope (ψf)	68°	6.	Sliding dip direction (ψi)	66°
3.	Joint 1	N 129°E/76°	7.	Friction angle (ϕ)	47°
4.	Joint 2	N 175°E/66°	8.	Slope dip direction	N 259° E
Potential slope failures: wedge type with sliding direction N 271° E and planar slide type with sliding direction N 263°E					

(b)

Figure 10. Kinematic analysis of (a) Argosari slope with wedge failure potential and (b) Wadas slope with planar slide failure potential

4. CONCLUSION

The results of this study conclude that the study area's geomorphology can be classified as structural hills (S1), homoclynal valleys (S2), alluvial plains (F1), river bodies (F2), and flood plains (F3). The drainage pattern is sub-dendritic, that is controlled by the distribution of lithology and geological structures, namely joints and faults. The slope distribution shows a very wide variety, ranging from 0° (flat) to 55° (very steep).

The study area's stratigraphy is made up of rock units, from the oldest to the youngest, namely, the Kaligesing Formation, which consists of andesite-lava, volcanic breccia, pyroclastic, and laharic, the Sentolo Formation, which consists primarily of bedded limestone, calcareous sandstone, and marl, and Alluvial Deposits. Andesite intrusion with sheeting and columnar joint structures exists. The main geologic structures are joints and faults. The faults are Kaliwader Faults 1 and 2, which is a reverse left slip faults with a Northeast-Southwest strike, Wadas Fault, and Bleber Fault, which are both right lateral slip faults with a Northwest-Southeast strike.

According to Markland method analysis, Kaliwader slopes A, B, and Argosari slope have the potential for wedge failure, Kaliwader slope D and Wadas slope have the potential for planar slides and wedge failure types, and Kaliwader slope C is stable. The findings of this analysis can be used by the local government as one supporting data in developing a map of mass movement vulnerability zones. It will also serve as a resource for territorial development and disaster risk reduction and mitigation in communities.

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