Hummock size and alignment in Gadung debris avalanche deposit, Raung Volcanic Complex, East Java, Indonesia

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Abstract. Debris avalanche deposit is formed by the failure of volcanic edifice and has a high potential to directly impact human civilization. The famous characteristic landform of debris avalanche deposit is hummocky hills. To understand the dynamics of avalanche flow, we investigate the morphometric characters of debris avalanche hummocks from Gunung Gadung in Raung Volcanic Complex. The collapse of Gunung Gadung follows two main flow direction with two different kinds of debris avalanche, i.e., freely spreading and valley filling. Our study recorded that there is no significant correlation between hummock size and distance from the source. The distribution of Gadung hummock size is mainly controlled by pre-existing morphologic feature such as Iyang-Argapura Volcanic Complex and Meru Betiri Mountains. We identify four domains area of Gadung debris avalanche flow based on hummock size distribution, which are Toreva domain, Hummock domain, Collision domain, and Oblique collision domain. Hummock orientation and displacement angle of Gadung debris avalanche deposit depend on structural regime existed in certain area. Compressional regime may occur because of collision between Gadung avalanche flow and Iyang-Argapura Volcanic Complex, or shifting of main flow direction. Meanwhile, extensional regime may happen due to decreasing in slope and spreading of avalanche flow.

1. Introduction

Sector collapse is a large-scale landslide of a volcanic edifice that has a high potential to damage human society directly through a debris avalanche or a secondary catastrophe such as lahars and tsunami [1, 2, 3, 4, 5, 6]. Volcanic debris avalanche, as the primary product of sector collapse, could bring few thousand to several million cubic rocks transported in >100 m/s velocity with run outs up to 70 km [7, 8, 9]. Debris avalanche can also produce debris flow due to increasing water content from water incorporation of snow or ice melt [10, 11, 12, 8] or as a result of the breaching of lake-induced debris avalanche deposit [13, 8]. Sector collapse may have more devastating impact if associated with water body such as lake or sea, as occurred at Anak Krakatau Volcano, Indonesia. A small-scale sector collapse of Anak Krakatau in December 2018 has triggered a tsunami that killed almost 400 people [14].

Hummocks are the most prominent characteristic landform of debris avalanche deposit. These conical shaped hills usually associated with the volcanic collapse scars [15, 16, 17, 18, 6]. Hummocks were formed during the failure of volcanic body. The landslide body of volcanic masses are separated
from each other and forms hundred to thousand conical hills depending on the avalanche volume [18]. Hummocks may be characterized based on the basal shape, surface morphology, and orientation with respect to flow and slide direction. Hummock elongation can be parallel, perpendicular or randomly oriented according to the deformation resulting from the flow direction [19]. The geomorphological characters of hummocks might be a key to understanding the formation and of debris avalanche and the dynamics of the avalanche flow.

The aforementioned conical morphology was found around western part of Raung Volcanic Complex, together with the collapse scars that form an elongated horseshoe-shaped caldera opening to the west. The collapse scars have 14 km long and 3 km wide. The hilly area of hummocks located west-southwest of the horseshoe-shaped caldera and covered approximately more than 1000 km² area in the west of Gunung Gadung [7]. This represents a largest caldera collapse that has ever happened in Indonesia and could turn into a potentially disastrous volcanic catastrophe. Therefore, the study of volcanic sector collapse especially in Raung Volcanic Complex is really important to understand the emplacement mechanism as an attempt of disaster risk reduction.

In this study, we examine the geomorphological significance of debris avalanche hummocks of Gunung Gadung in Raung Volcanic Complex to understand the dynamics of avalanche flow through quantitative analysis. Similar studies had been done for some volcano in Japan by [5, 6, 20, 21, 22]. Previous studies on debris avalanche hummocks by [7, 16, 23, 24, 25] mainly focused to hummock morphology as evidence of sector collapse.

![Figure 1. Location of study area.](image)

2. Geology of Raung Volcanic Complex

Raung volcano (3332 masl) is one of the most active Quaternary volcanoes located on the border of 3 regencies in East Java, Indonesia, which are Jember, Banyuwangi, and Bondowoso (Figure 1). The morphology of Raung volcano is represented by a 1.75 x 2.25 km wide and 400-550 m deep caldera, indicating the enormity of highly explosive eruption that has been occurred in Raung history. Raung volcanic complex consists of Gunung Raung (3332 masl), Gunung Suket (2750 masl) on the northern part, Gunung Lempah (2932 masl) on the northeastern part, Gunung Jampit (2338 masl) on the eastern part, Gunung Wates (2796 masl) on the southern part, Gunung Gadung (2290 masl) and Gunung Pajungan (2352 masl) on the western part.

The geology of Raung volcano has been reported by [26] on a 1: 100,000 scale geological map. Raung volcanic activity consists of 3 periods, from the oldest to youngest there are Old Raung Volcanism, Gadung Volcanism, and Young Raung Volcanism. Raung volcanic products generally composed of lava flows, pyroclastic flow deposits, pyroclastic fall deposits, and lahar with cinder cones present on the western flank and peak. Historical eruption records show that Raung volcano is
characterized by the explosive eruption mainly producing volcanic ash and pyroclastic flow. The first activity of Raung volcano has been recorded in the human history since the 16th century (1586), and the last activity of Raung has also been recorded since January 2021. Some paroxysmal eruption documented in 1586, 1597, 1638, 1890, 1953, and 1956 producing an eruption column up to 12 km high, with ashfall distribution reaching a radius of up to 200 km, covering Bali and Surabaya [27]. Eruption record since 1902 shows that the shortest hiatus of Raung volcano activity is 1 year, while the longest hiatus is 15 years [28].

[7] and [24] studied the debris avalanche-sector collapse deposit on Raung Volcanic complex and mentioned that it was the largest known debris avalanche in Indonesia. Based on their research, the debris avalanche deposit extended 60 km from its source on Gunung Gadung, 4 km to the west from the Raung center caldera rim. The latest study has traced the deposit to 79 km from the source [28]. Referring to Java physiographic zone by [29], Raung debris avalanche deposit located on the central depression zone of Java, namely Solo Depression Zone. The debris avalanche deposit is bordered by Iyang-Argapura Volcanic Complex on the western part, Meru Betiri Mountains on the southern part, and Kendeng Anticlinorium Zone on the northern part. The deposits filling a broad valley between Iyang-Argapura Volcanic Complex and Meru Betiri Mountains.

The Gadung debris avalanche deposit has a proximal area extending up to 30 km from the source towards the Jember, consists of abundant hummocks to proximately 75 m in height. On the distal area, the height of each hummock decreased to ±20 m, fewer in size, and more widely scattered [7]. There are no new magmatic material present in the avalanche deposit which indicates that the deposit was produced by non-eruption associated sector collapse [7]. In some areas, a thin unit at the top of hummock resembles a lateral-blast deposit [7] but was not discovered in the interhummock area or outside the avalanche deposit. Post collapse eruptions had construct Pajungan volcano, a new conical-shaped stratovolcano within the horseshoe-shaped caldera [7].

At the proximal area, the hummock deposits are consisted of various segments of lava flows in wide stage of fragmentation and thick sequences of half-litified rock, covered by tephra layers up to tens centimeter thick. Mixed facies are commonly located in distal portion of the deposit that deflected to the south by Iyang-Argapura Volcanic Complex. These facies usually contain subangular clast in fine matrix deposits. At the distal area, hummocks are mainly consist of stratified tephra layers as found at proximal area [7].

3. Methods
We conducted morphological analysis on the Gunung Gadung debris avalanche deposit using DEMNAS digital elevation model published by The Indonesian Geospatial Information Agency. The digital elevation models were processed using multi-directional hillshade visual effect to produce terrain map. Multi-directional hillshade was created using 8 light azimuths (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) with 30° altitude. We trace the outline of each hummock on plan view from the terrain map, referring to DEMNAS, World Hillshade by ESRI, and Aerial Photographs on Google Maps. DEMNAS data has a resolution of 8.5 m with Root Mean Square Error of 2.79 m and -0.13 m bias error, while the ESRI World Hillshade has a resolution up to 25 m in Indonesia, specifically. The parameter of hummock morphometry are examined, such as size of each hummock, major axis, minor axis, elongation ratio, distance of individual hummocks from the sector collapse source, flow direction, and displacement angle. We refer for each hummock parameter to the previous study by [5, 6, 20, 22, and 30].
Figure 2. Morphometric parameter of debris avalanche hummock for (a) freely spreading and (b) valley-filling debris avalanche deposit, adapted from [20]. DAD refers to “debris avalanche deposit”.

We define the hummock size by the boundaries formed by the hummock outline. Major axis is the longest segment that connecting two vertices of hummock polygon while minor axis is the shortest segment (Figure 2). Both major and minor axis were calculated to get the elongation ratio, which is the ratio between major axis to the minor axis [22]. Distance from the source is the length of a horizontal line between the source and the center of each hummock (Figure 2).

The collapse of Gadung edifice follows two main flow direction. The closest flow from the source is MFD 1, categorized as “freely spreading debris avalanche” with the main direction of N273°E. 20 km from the source, the main flow direction shifted to the southwest in the direction of N241°E due to the presence of topographical barrier, which are Iyang-Argapura Volcanic Complex to the west and Meru Betiri Mountains to the south. It is called as “valley filling debris avalanche”, because the flow had been nearly enclosed by surrounding topography. The valley filling debris avalanche is then defined as MFD 2 (Figure 3).

We divide the research area into 3 zones based on the main direction of debris avalanche flow (Figure 3). The area with freely spreading debris avalanche affected by MFD 1 is called MFD 1 zone, while the one affected by MFD 2 with valley filling type is referred as MFD 2 zone. Right in the location where the flow direction change, there is a zone called MFD transition zone. This zone has not experienced direct contact with the topographic barriers; therefore, it is still considered as freely spreading debris avalanche and affected mostly by MFD 1.
Figure 3. Detailed map of Gadung debris avalanche deposit showing main flow directions, hummocks delineation, and MFD zones division.

Figure 4. Topographic profile of Gadung edifice along the (a) MFD 1 Zone, (b) MFD Transition Zone, and (c) MFD 2 zone.

The determination of the displacement angle is carried out in different ways for each different type of debris avalanche. For freely spreading debris avalanche such as in MFD 1 zone and MFD Transition zone, the displacement angle is calculated using "individual flow direction" (IFD) or the orientation connecting the center of each hummock to the center of the source (Figure 2). The displacement angle for the freely spreading debris avalanche is defined as the angle between the major axis of each
hummocks and the IFD. For valley filling debris avalanche such as in MFD 2 zone, displacement angle is calculated using the angle between the major axis of each hummocks and the main flow direction (Figure 2). The extraction of morphometric data was performed on a total of 428 hummocks: 266 hummocks from MFD 1 zone, 92 hummocks from MFD transition zone, and 70 hummocks from MFD 2 zones. A total of 3 topographic profiles were made from the avalanche source, each passing through the MFD 1, MFD Transition, and MFD 2 zones in order to provide an overview of the slope conditions and its effect on the sector collapse mechanism (Figure 4). The processes mentioned above are performed using Software ArcGis 10.4, ArcGis Pro 2.0, and Global Mapper 19.

4. Results

4.1. Hummock size and distribution

We selected the most representative data for hummock morphometry based on the elongation ratio. Elongation ratio is the comparative value between hummock’s major axis and the minor axis. Figure 5 shows the positive correlation between major axis and elongation ratio. Larger major axis and elongation ratio represents more elongated hummock shape, while lower major axis and elongation ratio indicates more equant hummock shape. Data selection was conducted in order to eliminate hummocks with relatively equant shape because of their uncertainty in orientation and displacement angle. We picked the more elongated hummocks with elongation ratio greater than 1, so that the data really represents the accurate hummock size and orientation.

Figure 5. Relation between major axis and elongation ratio of Gadung hummocks shows positive correlation.

The distribution of hummock size in relation to distance from the source has a fairly wide range. The hummock area on MFD 1 zone, located between 12000 to 27000 m from the source, ranges between 14000 to 340000 m². On the MFD Transition zone, which is 18000 to 27000 m from the source, the hummock area ranges from 26000 to 310000 m². Meanwhile, on the farthest area or MFD 2 zone, the hummock area ranges between 27000 to 302000 m² at a distance of 20000 to 35000 m from the source.

Bivariate plot of hummock area and distance from the source not showing any downsizing or enlargement in hummock size, or the positive or negative trend of hummock size with increasing distance from the source (Figure 6). This may be due to the rapid depositional processes of high-flow velocity and dry debris avalanche, so that no significant sorting actually happens. However, it should be noted that the debris avalanche flow velocity does not depend only on the distance from the source. The conditions of pre-existing morphology such as topographic barrier or pre-depositional slope also plays a role on flow velocity. The effect of the pre-existing morphology on flow velocity cannot be pictured only from simple bivariate plot, therefore, we created a hummock size distribution map to evaluate the effect of pre-existing morphology on hummock size.
The hummock size is classified into medium and big based on cumulative probability plot for each zone (Figure 7). Hummocks are considered to be big size if the hummock area exceeds $>52000 \text{ m}^2$ in MFD 1 zone, $>62000 \text{ m}^2$ in MFD Transition zone, and $>100000 \text{ m}^2$ in MFD 2 zone. Hummocks with area below those values are considered as medium size. The hummock size data is then interpolated with Natural Neighbor method to generate the hummock size distribution map (Figure 8).

**Figure 6.** Bivariate plot of hummock area and distance from the source is not showing any significant relation between hummock size and increasing distance.

**Figure 7.** Cumulative probability plot of hummock area to determine the hummock size class for each MFD zone.

**Figure 8.** Hummock size distribution maps of Gadung debris avalanche deposit.
4.2. Hummock alignment and displacement angle

The rose diagram of MFD 1 zone hummock alignment shows that the dominant hummock orientation is in the same direction as the main flow direction (Figure 9a). Meanwhile on the MFD Transition zone and MFD 2 zone, the dominant orientation of hummock is not the same as the main flow direction, even some are aligned perpendicular to the main flow direction (Figure 9b-c). Thus, it can be concluded that hummock alignment is not always exactly in the same direction with the main flow direction.

Figure 9. Hummock alignment rose diagram from (a) MFD 1 zone, (b) MFD transition zone, and (c) MFD 2 zone of Gadung debris avalanche deposit.

[20] and [30] studied the change in hummock alignment in relation to debris avalanche path in Japan by using displacement angle parameter. The displacement angle lower than 45° is considered as parallel to MFD, while the one with value greater than 45° is defined as perpendicular to MFD. Bivariate plot of the hummock displacement angle versus distance from the source shows a broad dispersal of data, suggesting that the displacement angle varies from parallel to perpendicular either at the close or far distance (Figure 10).

Figure 10. Hummock alignment rose diagram from (a) MFD 1 zone, (b) MFD transition zone, and (c) MFD 2 zone of Gadung debris avalanche deposit.

To examine the correlation between distance from the source, debris avalanche type, and displacement angle more clearly, we created a bivariate plot of the average displacement angle versus distance from the source for each MFD zone (Figure 11). The average displacement angle was calculated for 2000 m spacing.
Figure 11. Bivariate plot of hummock average displacement angle and distance from the source of (a) MFD 1 zone, (b) MFD Transition zone, and (c) MFD 2 zone.

Further explanation about the changes in the average displacement angle for each zone is described as follows.

4. 2. 1. **MFD 1 zone.** It covers the area of freely spreading debris avalanche which is bounded to the west by Iyang-Argapura Volcanic Complex. Change in displacement angle in this zone coincides with the change in slope. At 13000-17000 m from source, the hummock alignments are perpendicular to parallel with MFD, slope constant to decreasing. At 17000-25000 m from source, hummock alignments shift from parallel to perpendicular with MFD along with the change of slope from decreasing to increasing.

4. 2. 2. **MFD Transition zone.** Within this zone, there is a shifting in main flow direction to the southwest. The slope is constantly decreasing but the displacement angle undergone several changes.
At 19000-20000 m from source, the hummock displacement angle is perpendicular to parallel. At 20000-24000 m from source, hummock displacement angle changes from parallel to perpendicular, and from 24000-26000 m the displacement angle returns to parallel.

4.2.3. MFD 2 zone. It covers the areas of valley filling debris avalanche, bordered by the topographic barrier of Iyang-Argapura to the north and Meru Betiri to the south. The variation in average displacement angle in respect of distance from source shows an irregular pattern with constantly decreasing slope. At 19000-24000 m from source, the displacement angle is constantly parallel, then begins to decrease at 24000-25000 m. The displacement angle changes from parallel to perpendicular at a distance of 25000-29000 m. At 29000-31000 m, displacement angle shifts again from perpendicular to parallel, then returns to parallel to perpendicular at 31000-34000 m.

Similar to hummock size, the hummock orientation also depends on the pre-existing morphology which cannot be depicted using only a simple bivariate plot. Therefore, we made a displacement angle distribution map to determine the impact of pre-existing morphological conditions to hummock alignment (Figure 12).

Figure 12. Hummock displacement angle distribution maps of Gadung debris avalanche deposit.

5. Discussion

5.1. Relation between hummock size and pre-existing morphology

The volcanic debris avalanche analog model proposed by [31] and [19] divides the failure zone into 2 domains. The upper sliding flank is called Toreva domain, which is the initial part of flank collapse where normal faults are formed and produce huge blocks. On the lower sliding flank, fragmentation of Toreva blocks occur due to the avalanche continuing to spread, forming more abundant normal and transtensional faults so that the hummock is broken into smaller size. These two zones are also observed in Gadung debris avalanche.

We identify the presence of four domains area of Gadung debris avalanche deposit based on the hummock size distribution map (Figure 13). The closest area from source is “Toreva domain” where relatively larger hummocks are clustered in the proximal zone. The large hummocks of Toreva domain were created from Toreva blocks that spread outwards, experience extension force, and teared apart into smaller blocks. Behind Toreva domain we have “Hummock domain” extending from north to the south, which is a region where fragmentation happens more intensively, hence generating smaller
hummocks than those of the Toreva domain. In the area bordered directly by Iyang-Argapura Volcanic Complex, there is a group of large hummocks namely “Collision domain”. This domain is formed by the collision of Gadung debris avalanche flow with Iyang-Argapura Volcanic Complex in the west. The debris avalanche flow velocity drops dramatically due to collision, causing hummocks to merge around each other. Outside the border of the Gadung Amphitheater in the south, there is one region where large hummocks also accumulate. This area is called “Oblique collision domain”, which is influenced by Meru Betiri Mountains. The presence of Meru Betiri Mountains in the south causes an oblique collision with the flow of Gadung debris avalanche, creates friction force, allowing the debris avalanche flow velocity to slow down so that fragmentation did not occur.

Figure 13. The four domains area based on hummock size distribution maps of Gadung debris avalanche deposit consists of (1) Toreva domain, (2) Hummock domain, (3) Collision domain, and (4) Oblique collision domain.

5.2. Relation between hummock alignment and pre-existing morphology

The Hummocks formation model in volcanic setting proposed by [19] elaborates that when an avalanche starts to transport, hummocks initially form through extensional faulting. The avalanche materials are forced to spread further as they slide down from volcano edifice. Depending on the condition of topography and morphology, the traveling down of avalanche material may result in compressional or extensional structures. Extensional regime may be generated in an open depositional environment, while compressional regime may be established if there are any topographic barriers either parallel or perpendicular to the flow direction.

Hummock orientation and displacement angle depend on whether an area is encountered a compressional or extensional regime. Shifts in displacement angle from parallel to perpendicular represents a change in structural regime from extensional to compressional. On the other hand, displacement angle changing from parallel to perpendicular indicates that the structural regime shifts from compressional to extensional [20].

The bivariate plot between average displacement angle and the distance from the source is correlated with the displacement angle distribution map in order to observe the relationship between hummock alignment and morphology. We can divide the displacement angle distribution map into several zones (Figure 14). Red colored zone indicates the dominance of the perpendicular displacement angle with the compression regime. Green colored zone shows the dominance of parallel displacement angle with extensional regime.
Figure 14. The distribution of compression and extension regime from Gadung debris avalanche deposit based on the displacement angle distribution map.

5. 2. 1. Hummock alignment in MFD 1 zone. On the displacement angle distribution map, this zone is shown by a change from compression to extension regime, and then the structural regime changes again to compression on the distal part. This condition is also correlated with the plotting of the average displacement angle versus distance from the source. At a distance of 13000-17000 m from the source, the hummock displacement angle changes from perpendicular to parallel. It shows a change in structural regime from compression to extension. Extensional regime dominates this section due to constant to decreasing slope and the avalanche flow spreads both downslope and laterally. The displacement angle begins to change from parallel to perpendicular at 17000-25000 m. Change in structural regime also occurs from extension to compression. Compression may happen as the avalanche flow is confined by the Iyang-Argapura in the west and causes a significant drop in flow velocity due to the change in slope from decreasing to increasing.

5. 2. 2. Hummock alignment in MFD Transition zone. There is a shift of main flow direction in this transition zone. No dominance of compression or extension regimes because the distribution is relatively similar. Therefore, this zone is also defined as “transition zone” by the character of hummocks displacement angle. At a distance of 19000–20000 m from the source, the displacement angle shows perpendicular to parallel. The structural regime changes from extension to compression at 20000-24000 m, as opposed to the decreasing the slope. This implies that compression possibly occurs because of a factor other than the slope condition, which is most likely the change in main flow direction due to topographic barrier. At 24000-26000 m, the displacement angle changes again from perpendicular to parallel because the main flow direction has shifted to the southwest, so that the extension force is more influenced by the lowering of topography.

5. 2. 3. Hummock alignment in MFD 2 zone. The variation in average displacement angle with respect to the distance from source in MFD 2 zone is very random and irregular, even though the slope is constantly decreasing. This case is similar to Kannongawa valley-filling debris avalanche from [20]. [20] states that the variation in displacement angle in Kannongawa debris avalanche may be attributed to the existence of lateral topographical barriers. In the case of Gadung debris avalanche on MFD 2 zone, which is also a valley-filling debris avalanche, the most influential lateral topographic barrier is the southeast slope of Iyang-Argapura which is directly adjacent to MFD 2 zone. The pre-depositional
6. Conclusion

We classify the area covered by Gadung debris avalanche deposit into 3 zones depending on the main direction of the avalanche flow. The freely spreading debris avalanche zone is referred as the MFD 1 zone, while the valley filling type area is referred to as the MFD 2 zone. Between MFD 1 and MFD 2 zone, right in the location where the flow direction change, there is a zone called MFD transition zone. According to our research, it can be concluded that there is no significant correlation between hummock size and distance from the source of Gadung debris avalanche deposit. The Gadung hummock size is mainly affected by debris avalanche flow velocity, which is controlled by pre-existing morphologic feature such as Iyang-Argapura Volcanic Complex and Meru Betiri Mountains. Based on hummock size distribution map, we could identify four domains area of Gadung debris avalanche flow mechanism, which are Toreva domain, Hummock domain, Collision domain, and Oblique collision domain.

The hummock orientation and displacement angle of Gadung debris avalanche deposit depends on the structural regime existed in certain area. The proximal area of MFD 1 zone is dominated by extensional regime due to constant to decreasing slope and the spreading of avalanche flow downslope and laterally. Change of structural regime from extensional to compressional occurs in the distal part of MFD 1 zone because of the collision between Gadung avalanche flow and Iyang-Argapura Volcanic Complex. In the MFD Transition zone, the change of structural regime from extension to compression is opposed to the decrease in the slope, possibly because of the change in main flow direction to the southwest. As for MFD 2 zone, the irregular pattern of displacement angle with respect to the continuously decreasing slope may happen due to the existence of lateral topographical barriers such as the southeast flank of Iyang-Argapura Volcanic Complex.

Acknowledgments

This work is fully funded by the Ministry of Research and Technology of Indonesia through Penelitian Terapan Unggulan Perguruan Tinggi (PTUPT) funding program for year 2021, entitled “Pengurangan Risiko Bencana Gunung Api Berbasis Integrasi Ilmu Kebumian: Studi Kasus Gunung Raung, Jawa Timur”.

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