Comparative Morphological Differences of Stratovolcanoes in Indonesia

M N Malawani1*, Subandriyo2, T Handayani3, G N Wicaksono3

1Department of Environmental Geography, UGM, Bulaksumur 55281, Indonesia
2BPPTKG (Balai Penyelidikan dan Pengembangan Teknologi Kebencanaan Geologi), Jl. Cendana 15, Yogyakarta 55166, Indonesia
3Research Assistant at Research Centre for Disaster, UGM, Bulaksumur 55281, Indonesia

*Corresponding author: malawani@ugm.ac.id

Abstract. The aims of this research are to identify the comparison of morphological differences of stratovolcanoes and provide information regarding to future hazard prediction. Several stratovolcanoes are compared to investigate the differences in their morphology and then comparison on their morphological parameters are performed. The comparison of stratovolcanoes morphology is based on DEM data from DEMNAS (DEM Nasional). In this study, we see that DEMNAS already present good data for morphological analysis in regional scale. The morphological parameters used for the comparison are landform variation, slope, and drainage pattern. Those three parameters are not directly connected to one another, but they are useful for describing the volcano edifice morphological differences. We suggest that the landform analysis is the best method for identifying morphological differences of stratovolcanoes. In addition, slope and river pattern are useful also for predicting future volcanic hazard such as pyroclastic flow and lahar.

1. Introduction
Indonesia has hundreds of volcanoes due to active subduction zone. Based on Magma Indonesia (Multiplatform Application for Geohazard Mitigation and Assessment in Indonesia), 65 volcanoes are observed and displayed on a realtime observation on https://magma.vsi.esdm.go.id/#. Among of them there are 45 volcanoes on level 1, 15 volcanoes on level 2, 4 volcanoes on level 3, and 1 volcano on level 4, which is Sinabung volcano. Most of volcanoes in Indonesia are stratovolcano, and some of them are cinder, caldera, and shield type [1]. Located on tropical region made Indonesia has the average maximum rainfall at 395 mm/mo [2]. Due to the heavy rainfall, morphology of volcanoes experienced geomorphological processes such as erosion, mass wasting, and debris flow triggered by rainfall [3, 4]. However, human intervention also gave impact to the morphological development of volcanic slope such as mining activities and agriculture. Those various processes as well as volcano-structural elements, volcanic terrains and landform can be recognized by DEM data [5].

The evolution of volcano morphology is always controlled by the constructive and destructive processes both in active and post-eruptive volcanoes. The morphological development of volcanic edifice can be highlighted by morphometry analysis. The characterization of volcano morphometry is one of the efficient methods for describing the general factor that controls volcano edifice development [6]. The development of morphology in volcano edifice assumed to be specific in every volcano. It is
depending on the geological structure, material erupted, frequency of eruption, etc. For example, Sinabung volcano is a long-dormant volcano for a long time, but then it became active again in 2013 triggered by tectonic activities on Sumateran fault [7], but several volcanoes eruptions has been predicted such as Merapi volcano [8] [9]. The eruption processes impact the constructive or destructive volcanic morphology, while on inactive volcanoes destructive processes are always more dominant.

The morphological development of volcano can be summarized into several parameters of geodynamic such as denudational and erosional processes which can be implied from volcanic slope profile [6] [10], landform pattern [11], and regional drainage pattern [12]. Several stratovolcanoes are compared to investigate the differences of their morphology. Previously, comparison of stratovolcano has been carried out, which result in stratovolcanoes morphometrical group, i.e. C-type and P-type [10]. In order to enrich the method for analyzing volcanic morphometry, we tried to compare several stratovolcanoes in Indonesia using other geomorphological parameters especially for identifying morphological differences. Those differences can be used for presumed the morphological development of stratovolcano. We chose one volcano from each big island in Indonesia which are Sinabung volcano (Sumatera), Merapi volcano (Java), Agung volcano (Bali Nusa Tenggara arc), and Gamalama volcano (Ternate and Moluca arc) (Fig. 1). Moreover, the comparison of stratovolcano morphology in this paper also try to highlight some information regarding to morphological variation and similarities [13]. This research also provide information regarding to morphological differences of volcanic edifice and its relation to future volcanic hazard.

Figure 1. The location of four samples stratovolcanoes in Indonesia

2. Methods
The comparison of stratovolcanoes morphology in this research is based on DEM. This DEM data are called DEMNAS (DEM Nasional) and collected from Geospatial Agency of Indonesia (BIG/Badan Informasi Geospasial). DEMNAS can be downloaded at http://tide.big.go.id. The DEMNAS has a
spatial resolution of 0.27-arcsecond using EGM2008 datum, which is suitable for regional analysis. Other data used in this research are topographic map form RBI (Rupa Bumi Indonesia) on the scale of 1: 25,000 and 1: 50,000, and also geological map of Indonesia on the scale of 1: 100,000. There are several parameters presented in this research for comparing stratovolcanoes morphology such as slope profile, landform, and river pattern. Width vs height comparison of volcano edifice also presented in this study [6]. We see that DEMNAS already presents good data for morphological analysis in regional scale.

3. Result and Discussion
The morphological comparison of stratovolcanoes using DEM data only provided three morphological data including the slope profile, landform variation, and river pattern. The slope profile was acquired from DEMNAS data, ranging from north to south in all sampling location. Fig. 2 shows the comparison of slope profile on all four stratovolcanoes. In Sinabung volcano, the slope profile is relatively steep on all 4.5 km profile line. Some breaks of slope can be seen such as in 0.7 and 2 km profile line. The slope profile in Sinabung is relatively similar to Gamalama’s volcano. Both of them are close to convex slope. Consequently, it can be assumed that on the N-S slope aspect, both Sinabung and Gamalama sedimentation processes such as from lava flow or pyroclastic flow are more active than the erosion process.

Two other volcanoes have the different slope characteristic. Merapi and Agung volcano are relatively same within concave slope, but Merapi volcano’s slope is the steepest among the other sampling locations. Merapi volcano has a 50% average slope, while Agung volcano has a 40% inclination. Merapi and Agung volcano can be categorized as C-type volcano [10] according to their slope profile. On the southern side, Merapi volcano has a very wide gentle slope where Yogyakarta located. The break of slope from steep to gentle slope in Merapi is very distinct. At that site, it is very easy to find springs where it formed Merapi springs belt [14, 15]. On the N-S slope profile of Merapi there is no micro relief found, however it appears on Agung volcano. Micro relief on Merapi could be possibly found if the slope profile ranging S-W direction, such as in Muntlan and Godean.

Figure 2. Comparison of slope profile from summit to lower slope of stratovolcano on sampling location. A: Sinabung, B: Merapi, C: Agung, and D: Gamalama.

The ratio between height and width was also derived from DEMNAS data. The ratio between height and base width in three volcanoes (Sinabung, Merapi, and Agung) is relatively similar which is at the scale of 0.2. However, the ratio between summit width and base width is strongly different in all volcanoes. Volcano that are located on the right plotting area are indicating wider summit area (Fig. 3). It can be concluded that Agung volcano has the widest summit area. Gamalama volcano has the most different morphology among them all. Gamalama has the narrowest summit and it also has the shortest shape ratio. We assumed that volcano that has wider summit area they will more susceptible to lahar since they can collect big amount of pyroclastic material on the summit. Fig. 3 showed the comparison of shape ratio.
The next parameter is drainage pattern. The drainage pattern is very useful in describing morphological differences of stratovolcano. The drainage line data in this paper was generated from DEMNAS data at the same scale. Actually drainage pattern data also available on Topographic Map of Indonesia (Peta Rupa Bumi Indonesia), but on different scale. Merapi and Agung volcanoes’ data are available on maps on a scale of 1:25,000, while Sinabung and Gamalama volcanoes’ data are available on maps on a scale of 1: 50,000. The different maps scale leads to the different detail on the river patterns. The intermittent river will appear such as in Merapi and Agung on a map with a bigger scale. Consequently, the comparison are not good at different scale, therefore the drainage pattern then generated from DEMNAS. The different details in river line or drainage pattern comparison are showed in Fig. 4. However, all of those stratovolcanoes have radial centrifugal river pattern. The volcano body or edifice of Sinabung and Gamalama are very easy to distinct due to its drainage pattern, while on Merapi in Agung it is quite difficult in order to separate the volcano body or edifice because on these two volcano the drainage density is relatively high.

The development of drainage pattern strongly depends on derivative process, such as erosion. The volcanic morphology which has more river pattern is assumed to be more erosive. In addition, the surface materials ejected from crater are also influencing. Resistant material will produce a minimum river development. On the contrary, less resistant material will produce more river development due to its erodible materials. Based on the geological map of Indonesia, both Sinabung and Gamalama have andesitic rock type, while Merapi and Agung have tuff and laharc material. However, despite their similar material, Sinabung’s river pattern is more developed than Gamalama’s. It also indicate that the valley development in Sinabung is more developed than in Gamalama. This is presume that the river or drainage patterns in volcanic edifice are more controlled by topography rather than by structural control [16], or its materials. However, the river development that are influenced by the structural control found in Merapi. The red dashed line (Fig. 4) is divided young Merapi and old Merapi where the river upstream also divided. Although Merapi and Agung volcano have quite similar type of river patterns, the river pattern on Agung volcano is not controlled by structural factor.
Figure 4. The comparison of drainage pattern in volcanoes sampling location

Landform delineation is a suitable method to identify the morphological differentiation. The differentiation of stratovolcanoes landform in the sampled volcanoes is generally similar (Fig. 5). They are consist of volcanic cone, volcanic slope (upper, middle, lower) and volcanic foot. This classification also used by Santosa [17] in other stratovolcano. The landform delineation was available on regional scale and was generated from DEMNAS data. The morphoarrangement on all four stratovolcanoes are related to the slope profile. For example, since the gentle slope is wider than the steep slope in Merapi, the formation of volcanic slope are widespread. The steeper slope formed volcanic cone. The variation of landform in Merapi volcano is quite similar to Sinabung volcano. Unlike other sampled volcanoes, Gamalama’s volcanic arc landform formed into orderly arranged volcanic cone, volcanic slope, and volcanic foot. The differentiation of landform also formed into a radial shape following the island shape. In addition, the volcanic foot are elongated only on the northern side. The shape of Gamalama volcano edifice is close to the “ideal” volcanic geomorphometric [11]. We believe that the landform analysis is the best method for identifying morphological differences of stratovolcanoes, especially when performed with a detailed scale (>1: 10,000). Moreover, other data source are also needed, such as high resolution satellite imagery or aerial photograph using UAV/drone and geomorphological survey. The landform or morphological unit identification that we presented in this research are very useful for volcano hazard zoning, especially in stratovolcano [18].
Figure 5. The comparison of landform or morphological unit. A: Sinabung, B: Merapi, C: Agung, and D: Gamalama. 1: volcanic cone, 2: volcanic slope (upper), 3: volcanic slope (middle), 4: volcanic slope (lower), 5: volcanic foot, 6: sea.

4. Conclusion

The comparison of morphology on stratovolcanoes provides some information regarding slope, landform, and drainage pattern. Those three parameters are not directly connected to one and other, but are useful for describing the volcano edifice morphological differences. The slope comparison shows that volcanoes with similar type are not always have similar slope inclination. Generally, the slope shape can indicate that there are more dominant process that happened, such as erosion or sedimentation.

Delineation of landform also provides information on how to divide the slope morphology. Some volcanoes has narrow summit and wider slope, while other has an orderly arranged landform like Gamalama. Moreover, the landform delineation result is useful for preliminary hazard mapping. The hazard mapping can be simply classified as follow: volcanic cone and upper volcanic slope is the high hazard zone; middle volcanic slope is the medium hazard zone; and lower volcanic slope is the low hazard zone. This volcanic hazard zoning can be aligned to Verstappen classification [18], as follow: high hazard zone equal to forbidden zone; medium hazard zone equal to first hazard zone; and low hazard zone equal to second hazard zone. However, this method needs to be evaluated for more detailed hazard zone. The river pattern also provide information on how the volcano edifice influenced by erosion process. In addition, the river channel pattern also useful for predicting the first hazard zone map (KRB 1) in Peta Kawasan Rawan Bencana Gunung Api issued by Directorate of Volcanology and Geologic Hazard Mitigation. Nevertheless, if we combined the drainage pattern with slope morphology or structural control, lahar flow prediction will be more appropriate such as in Merapi where lahar rarely flow to the eastern direction since it is blocked by structural factor. Furthermore, this study also shows that DEMNAS data are appropriate for describing the volcano morphological differences.
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