Deformation and instability at Merapi dome identified by high resolution camera

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Abstract. After phreatic eruptions in May and June 2018, a new dome continuously grows and deforms at Merapi summit. The growth of the Merapi dome progressively causes over steepening, triggers gravitational instability, and then collapses, producing pyroclastic flow. These activities have been observed by our high-resolution camera. Here, we performed high resolution terrestrial photogrammetry to identify deformation and instability at the Merapi dome. The data were collected between 10 and 15 April 2019 by using Cannon EOS 60 D camera and equipped with 200 mm lens. The 200 mm tele lens is able to provide detail morphology and to identify deformation up to sub meter accuracy. The high-resolution images were processed by registering a slave image to a reference image, scaling the images, and applying pixel-tracking techniques. The technique is able to identify deformation of the Merapi dome. Results show a continuous deformation with mean displacement of ~1m during that period. A strong deformation was identified at the south-eastern part of the dome with maximum displacement up to 5 m which might be associated with a dome collapse that produced pyroclastic flow on 10 April 2019. Based on our observation, we infer that the activities of dome growth and gravitational instability triggers dome collapse are recently dominant at Merapi volcano.

1. Introduction
Lava dome is subjected to continuous magma extrusion, deformation, gravitational instability, and collapses that produce devastating pyroclastic flows. In Merapi, gravitational dome collapse produce pyroclastic flows is common and generally occurs, which can be called as “Merapi type” eruption [1]. An example of devastating gravitational dome collapse occurred in November 1994, when the dome failed produced pyroclastic flow that travelled up to 6.5 km to the south – southwest area and killed 60 people [2] and [1]. Therefore, studying the mechanism of continuous deformation and dome instability is vital in Merapi volcano.

Several techniques have been used to investigate deformation and dome instability. Combination of seismic and time-lapse images has been applied to investigate a short-term dynamic of volcanic dome in Mt. St. Helens, USA. Results show a downward displacement associated with tremor, which may indicate a mechanical collapse regularly interrupted the growth of the Mt. St. Helens dome [3]. High-resolution sequence photographs of Merapi summit in 2006 were used to investigate the dome morphology and the results could identify two deformation regions that undergo dome growth and spreading and coulee flow at the south part of the Merapi dome [4]. These studies suggest that high-resolution time-lapse images are a robust technique to identify deformation and instability of active lava domes.

Here, we used high-resolution photogrammetry technique to investigate deformation and instability at the Merapi lava dome between 10 and 15 April 2019. Since August 2018, a new dome has been developed and gradually growth at the middle of the Merapi crater. In July 2019, the dome reached its
maximum size with volume around $\sim475000 \, m^3$ [5] and gradually subjected to partial collapse at the south part of the dome. This study highlights the mechanism of deformation, instability, and partial dome collapse due to continuous magma extrusion at Merapi dome in 2019.

2. Data and Method

2.1. Data acquisition

We conducted photogrammetry field campaign between 10 and 15 April 2019 around 06:30 a.m. The best time for photogrammetry field campaign at Merapi is during summer and early morning as we get the best visibility of the Merapi dome. During rainy season, clouds regularly cover the Merapi edifice and reducing the visibility. For the equipments, we used Canon EOS 60 D camera and CANON EF 70-200 mm f/2.8L IS II USM Tele lens to obtain high-resolution images. The camera was installed in a fix tripod to reduce image shaking and in a safe distance ($\sim5 \, km$ from the summit) (Figure 1). Further information of camera and lens that used in this study is described in Table 1.

![Figure 1](image.jpg)

**Figure 1.** The images were acquired by using Canon and tele lens that installed in a fixed tripod with distance of 5 km from the summit. The distance is relatively safe as the current dome regularly collapses and produces pyroclastic flows with maximum distance of 2 km from the summit.
Table 1. Detail information of Camera and lens that used in this study

| Type                                      | Specifications                  |
|-------------------------------------------|---------------------------------|
| CANON EOS 60 D Camera                     |                                 |
| Weight                                    | 755 gram                        |
| Sensor                                    | 18 MP APS-C CMOS                |
| ISO                                       | 100 – 6400                      |
| Shutter speed                             | 30 – 1/8000 s                   |
| CANON EF 70-200 mm f/2.8L IS II USM Lens  |                                 |
| Weight                                    | 1490 gram                       |
| Lens construction                         | 23/19                           |
| Angel of View                             | 34° - 12°                       |
| Maximum Aperture                          | 70 – 200 mm 1:2:8               |

2.2. Data Processing

We selected the best image quality prior processed the data. After selected the highest quality images, we chose two images as a reference and a slave images. Then, we registered the slave image to the reference image by using register virtual stack slices tool in image software. This tool is freely available and robust as it is able to perform six different techniques to register images [6]. We did not find any obstacles or significant errors during image registration.

After image registration, we scaled the images by setting the actual distance based on georeferenced 3D TLS-SfM point cloud [7] onto the images (Figure 2). Here, we obtained image scale of 3.2 pixels/m or 1 pixel equal with 0.33 m. We then cropped the images only at the new Merapi dome to enhance the visualization (figure 2b). Afterward, we track the similar points between reference and slave images by using manual pixel tracking in ImageJ to obtain displacement of the Merapi dome.
Figure 2. Image scaling was conducted by inputting actual distance from a) 3D registered point cloud that acquired by drone photogrammetry in 2012 [7] onto b) the terrestrial images. Then, we cropped the images based on the region of interest (inset).

3. Results and discussions
Our results show strong deformation at the south part of the Merapi lava dome with maximum displacement of 5.45 m between 10 and 11 April 2019. This strong deformation triggered instability and gravitational collapsed on 10 April 2019. Pyroclastic flow has been reported with maximum distance of 1 km from the summit [8]. The dome collapsed on 10 April 2019 produced two major collapse scars with mean diameter of ~9 m (Figure 3).

The cyclic activities of dome extrusion, deformation, instability, and collapse remained continue from 12 to 15 April 2019. The middle of the Merapi lava dome is subjected to a strong deformation with maximum displacement between 2.1 and 2.7 m. Collapsed scars were identified on 12 and 14 April at the south part of the dome with diameter of 16 and 15 m, respectively. These collapsed scars are relevant with the dome collapsed that produced pyroclastic flows between 11 and 15 April with maximum distance of 1100 m [9].
Figure 3. Pixel tracking of master and slave images which taken from 10 to 15 April 2019 shows strong deformation at the Merapi dome. Strongest deformation occurred at the middle of the Merapi lava dome with range displacement of ~1.4 – 5.4 m. The west part of the dome relatively stable with maximum displacement of 0.5 – 1.2 m. Downward displacement mostly occurred at the dome which may associated with gravitational instability.
Figure 4. Gravitational dome collapsed on 10 April 2019 that captured by our high-resolution camera. The maximum distance of pyroclastic flow produced was 1000 m from the summit of Merapi.

3.1. Dome instability in Merapi
Results of pixel tracking show continuous magma extrusion that deforms, over steepening and triggers gravitational instability at the Merapi dome. These mechanisms may cause partial dome collapse with relatively small volume, possibly less than $1 \times 10^5$ m$^3$, based on loss area (collapsed scar on our images). The partial dome collapse reportedly can produce pyroclastic flows with distance of 500-2000 km from the summit. Therefore, current prohibited area within 3 km distance from the Merapi summit is relevant with the current activities of Merapi. However, some mechanisms may also trigger dome instability such as gas overpressure [10], intense rainfall [11], and hydrothermal alteration that weaken the dome rock [12] and [13].

Overburden gas may accumulate, causes gas overpressure in a shallow conduit, destabilizes the lava dome, and triggers explosive eruption. In the lava dome of Santiaguito, Guatemala, periodic gas pressurization can control the timing of dome explosion, which associated with regular inflation/deflation cycles, very long period earthquakes, and increasing of gas rate up to 2-3 kg s$^{-1}$ during explosion [10] and [14]. Therefore, monitoring gas is vital to mitigate and to anticipate explosive eruption in dome building volcanoes.

In addition, intense rainfall and hydrothermal alteration may also trigger dome collapse. Intense rainfall may cause a rain-saturated dome carapace that increases gas intensity, destabilization, and then resulting in an energetic collapse [11]. Rainfall may also cause hydrothermal alteration within the dome carapace. Interaction between hot fluids and rock can mechanically weaken the rock significantly [15]. The hot fluids, such as meteoric or magmatic fluids, may flow through fractures, pores, and micro cracks of the dome rock, reduce the rock strength and friction, and destabilize the dome rock [16], [17], and [18]. The dome collapses due to hydrothermal alteration that weakens the dome rock is difficult and challenging to predict as no seismic precursor may occur prior the dome collapse. The dome collapse of Soufriere Hills Volcano Montserrat on 3 July 1998 occurred without any seismic precursor and left a hydrothermally altered collapsed scar at the summit area [19].
4. Conclusions
This study shows that the current activities of the Merapi dome are dominated by continuous magma extrusion that deforms, over steepening the dome, and triggers gravitational dome instability. The middle of the Merapi dome is the most unstable area and frequently subjected to partial dome collapse with small volume (<1×10⁶) that generate pyroclastic flows with maximum distance of ~2 km from the summit. Even though, the current activities of Merapi are considered as a small eruption, a devastating explosive eruption such as in 2010 should be considered. As Merapi is located in a tropical country, intense rainfall may trigger gas overpressure, increase the activity of hydrothermal alteration that weaken the dome rock and reduce internal friction. These factors should be monitored to anticipate larger explosive eruption in the future.

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