The stability and collapse of lava domes: insight from UAS-derived 4D structure and slope stability models

Brett Carr[1], Einat Lev[1], Loÿc Vanderkluysen[2], Danielle Moyer[2], Gayatri Marliyani[3], and Amanda Clarke[4]

[1]Lamont-Doherty Earth Observatory
[2]Drexel University
[3]Gadjah Mada University
[4]Arizona State University

November 22, 2022

Abstract

Lava domes form by the effusive eruption of viscous lava and are inherently unstable and prone to collapse. Dome collapses can generate pyroclastic flows and trigger explosive eruptions and thus represent a significant natural hazard. Many processes may contribute to the instability and collapse of lava domes, including advance of the dome margins, overtopping of confining topography, internal gas overpressure, and gravitational instability of the dome structure. Collapses that result from these processes can generally be grouped into two types: active and passive. Active collapses are driven by processes associated with active lava effusion, (e.g. dome growth or gas pressurization), while passive collapses are not directly associated with eruptive activity and can be triggered by overtopping of topographic obstacles or weakening of the dome structure. We use data collected by uncrewed aerial systems (UAS, commonly called 'drones') and a slope stability model to both identify and assess the stability of potential collapse sites for both passive and active processes. We collected visual and thermal infrared images by UAS and used structure-from-motion photogrammetry to generate thermal maps and digital elevation models (DEMs) of two example lava domes at Sinabung Volcano (Sumatra, Indonesia) and Merapi Volcano (Java, Indonesia). We evaluate the stability of erupted lava using the Scoops3D numerical model to assess the risk of passive and active collapses, including an assessment of the effect of lava material properties and internal pore pressure on the dome stability. We compare the collapse risk from Scoops3D with UAS-derived temperature maps and DEM differencing to evaluate the stability, size, and location of observed or potential collapses. We test whether Scoops3D can hindcast the sites and magnitudes of passive collapses at Sinabung that occurred in 2014 and 2015 and assess the stability of the remaining lava dome (growth has ended in spring 2018). For both volcanoes. Through application of these techniques, we are able to evaluate the collapse risk due to multiple processes that may act contemporaneously to generate dome instability. This study demonstrates how identification and classification of individual collapse mechanisms can be used to assess hazards at dome-forming volcanoes.

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE
School of Earth and Space Exploration
Arizona State University
Universitas Gadjah Mada
DREXEL UNIVERSITY College of Arts and Sciences

The stability and collapse of lava domes:

insight from UAS-derived 4D structure and slope stability models

V31H-0105

Brett B. CARR[1,4], Einat LEV[1], Loÿc VANDERKLUYSEN[2], Danielle MOYER[2], Gayatri Indah MARLIYANI[3], Amanda B. CLARKE[4]

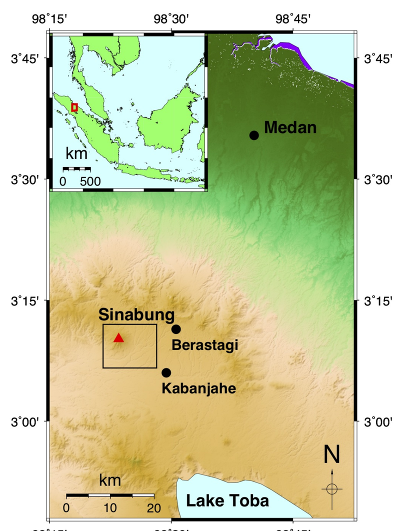
bcarr@ldeo.columbia.edu

1 Lamont-Doherty Earth Observatory Columbia University, Palisades, NY
2 Department of Biodiversity, Earth and Environmental Science, Drexel University, Philadelphia, PA
3 Department of Geological Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
4 School and Earth and Space Exploration, Arizona State University, Tempe, AZ

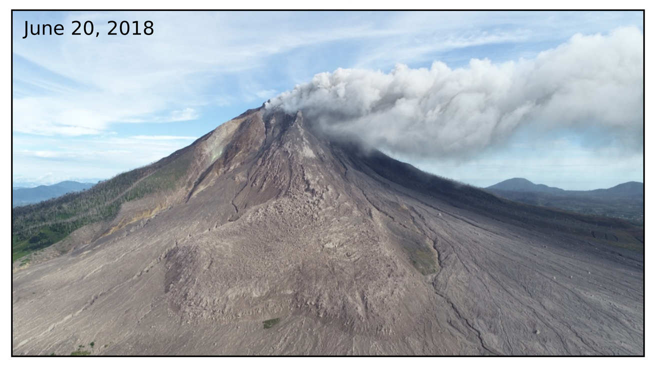
Motivation

- Dome collapse-generated pyroclastic flows are a primary hazard of lava dome eruptions
- Dome-forming eruptions can last for years to decades, creating a persistent hazard
- Improved understanding of collapse mechanisms and how to estimate the risk of collapse can improve hazard assessment for these eruptions

Dome Collapse at Sinabung



The eruption of Sinabung Volcano (2013 - present)[1,2] has included explosions, emplacement of a 3 km long lava flow[3,4], and frequent dome collapse[5]

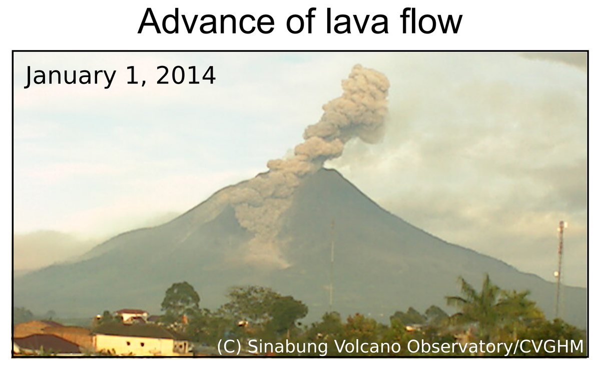


Dome Collapse during the eruption is caused by multiple processes:

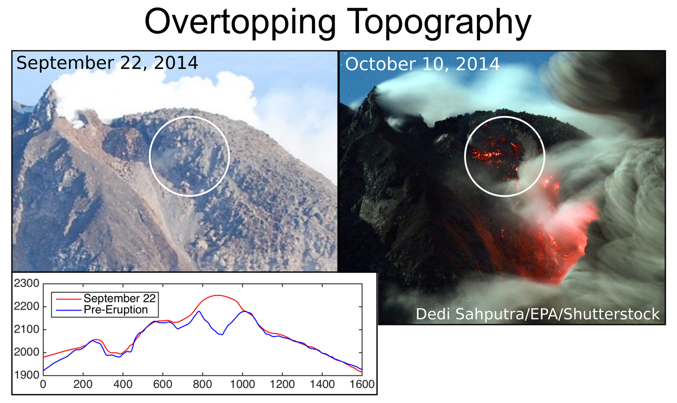
Active Collapse[6]:
- Caused by effusion of lava and growth of domes and/or flows ("pushed")
- Size and/or frequency generally correlates with eruption rate, can be anticipated by monitoring eruption signals

Passive Collapse[6]:
- Caused by weakening of the internal structure of erupted lava ("pulled" by gravity)
- Not correlated to other activity, can occur unexpectedly

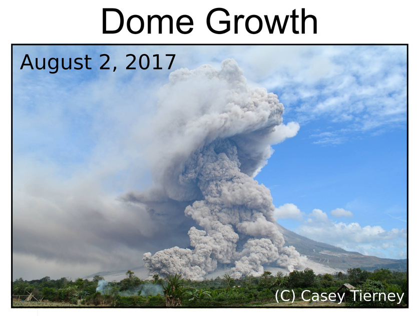
Active
Advance of lava flow



Passive
Overtopping Topography

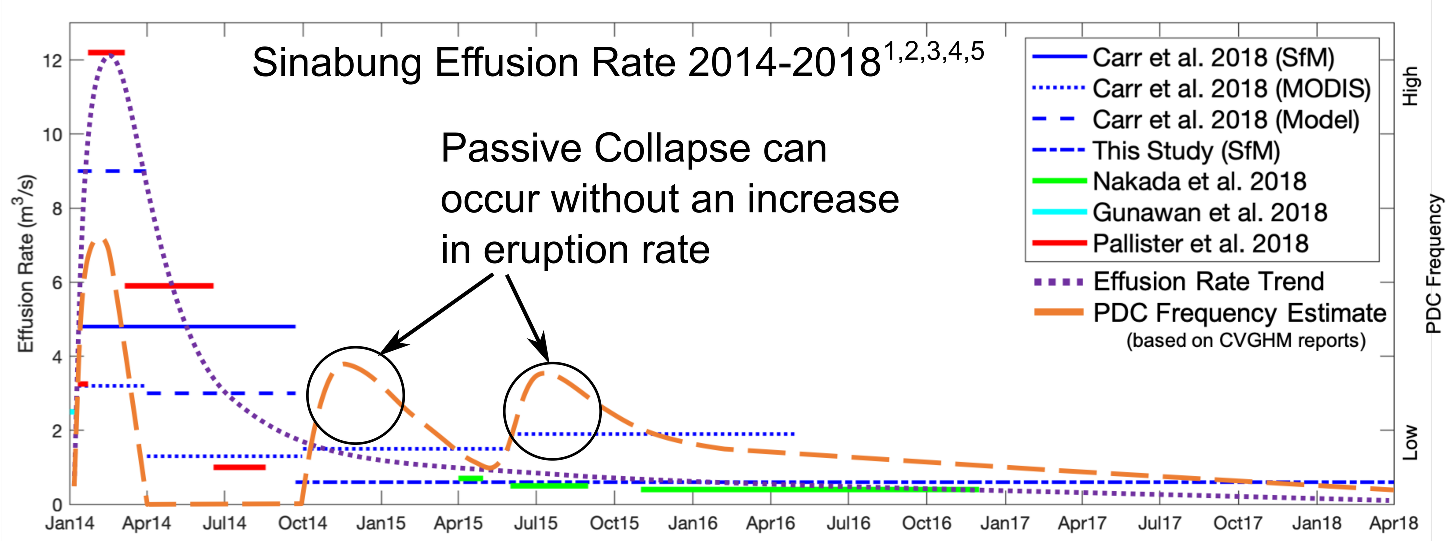


Dome Growth



Gas Pressurization

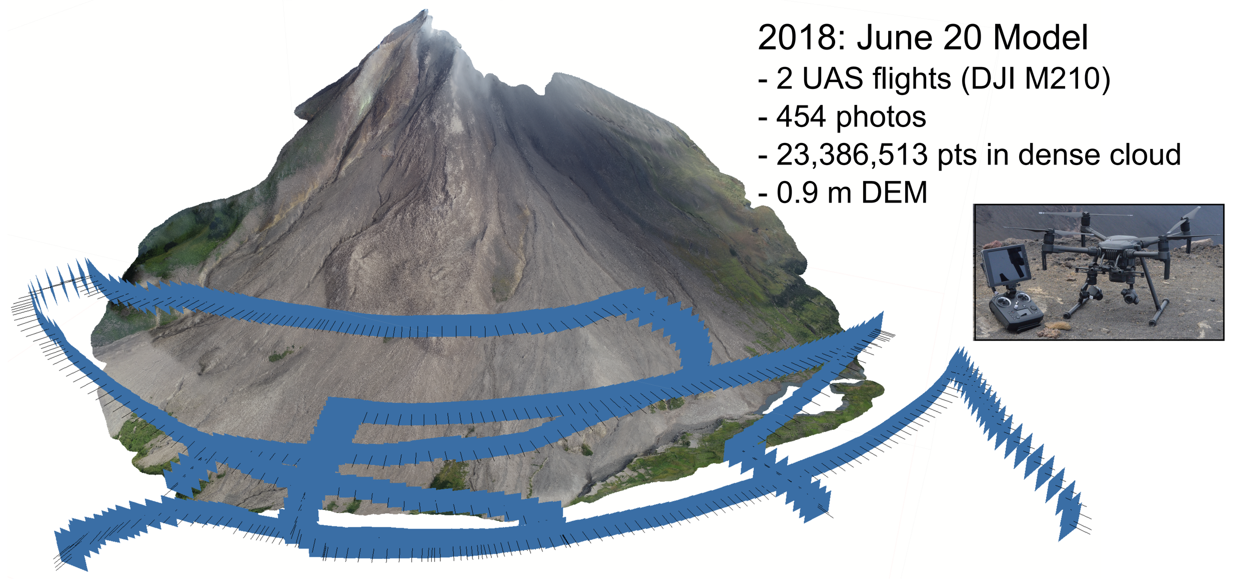
Weakening of material??



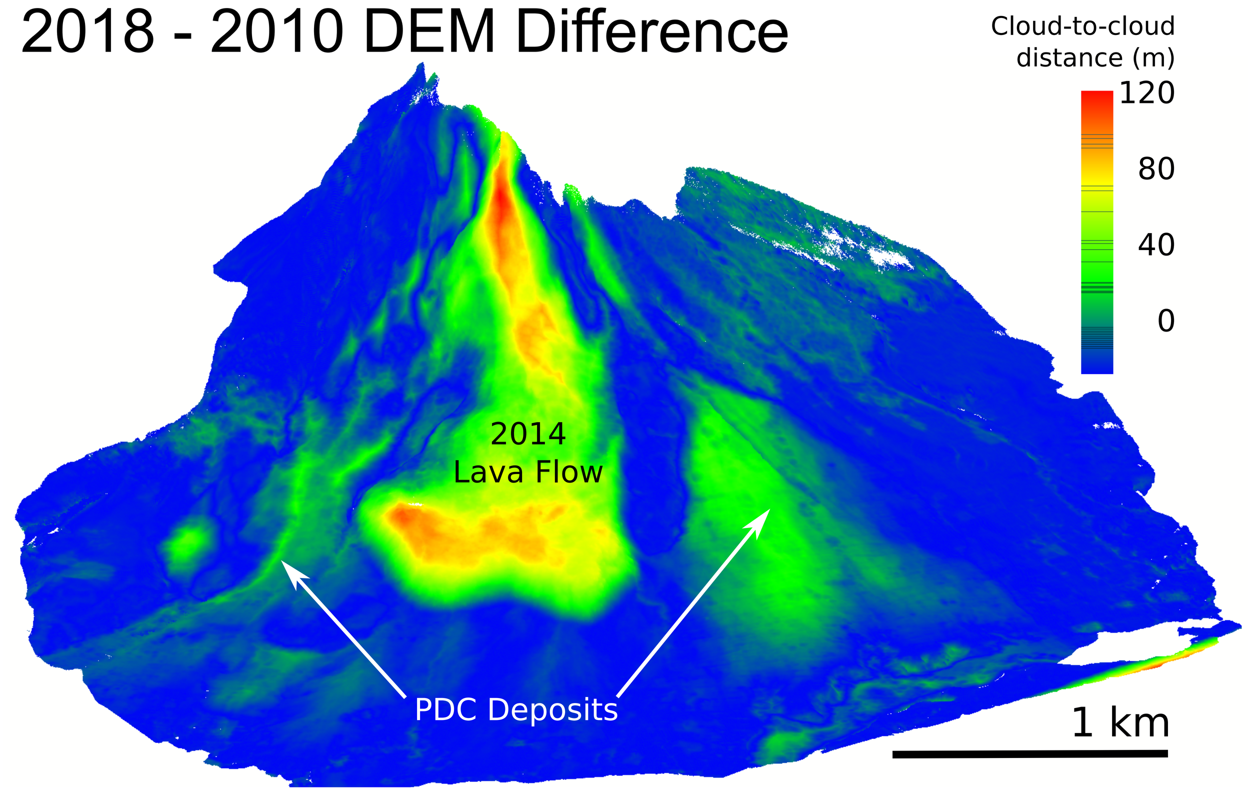
Topographic Change

We create digital elevation models (DEMs) of Sinabung by applying Structure-from-Motion photogrammetry[7] to image sets collected during field surveys in 2014[3] and 2018

2018: June 20 Model
- 2 UAS flights (DJI M210)
- 454 photos
- 23,386,513 pts in dense cloud
- 0.9 m DEM

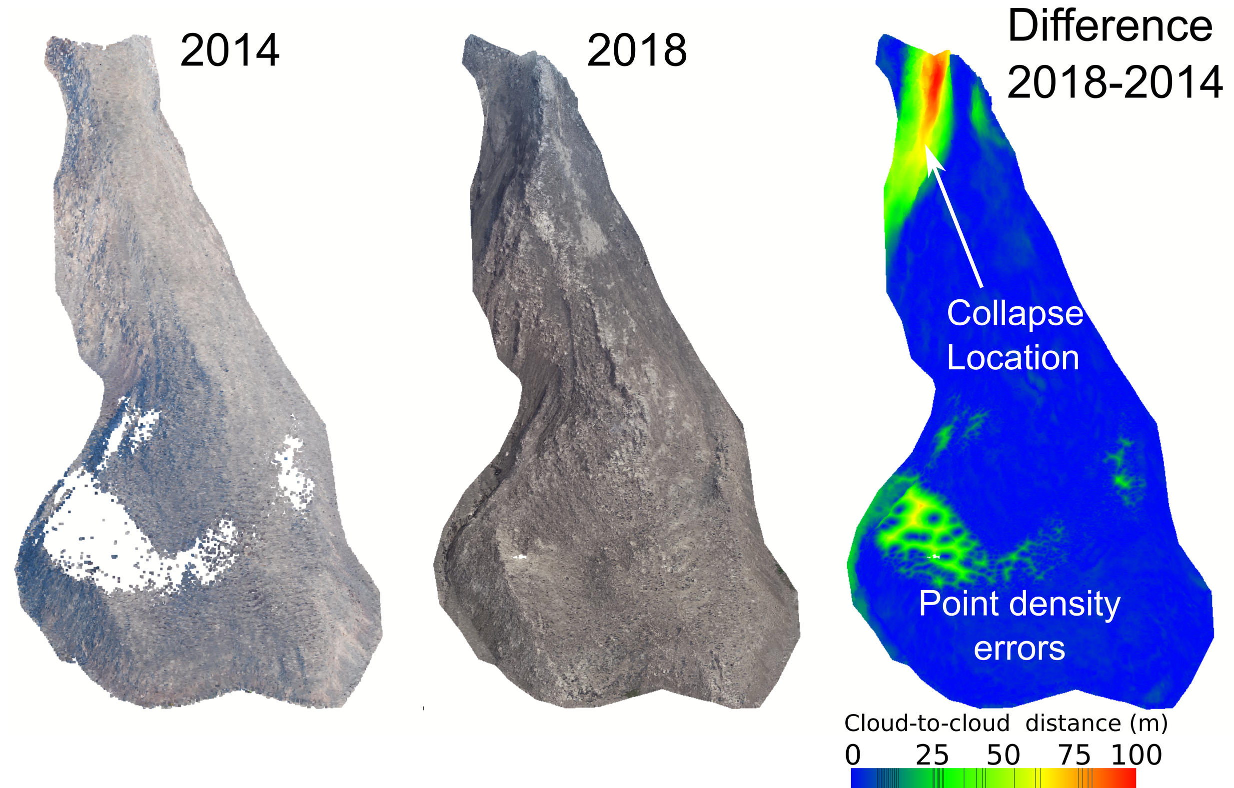


2018 - 2010 DEM Difference



Total Erupted Volume (2013-2018): 173 x 10^6 m^3
Volume of PDC (Collapse) Deposits: 76 x 10^6 m^3

Lava Flow Collapse 2014 - 2018



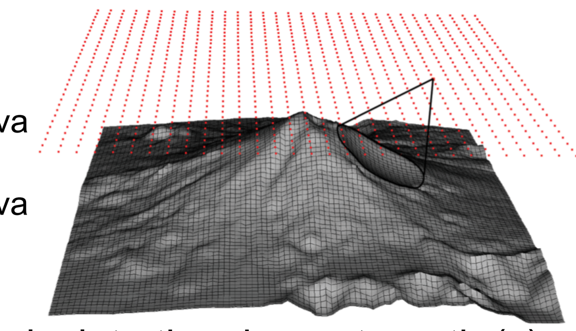
Flow Volume:
Sept 2014[3] (Before Collapse): 103 x 10^6 m^3
June 2018 (After Collapses): 97 x 10^6 m^3
Initial Collapse Volume: 0.2 x 10^6 m^3
Total Collapse Volume: 9.4 x 10^6 m^3

Slope Stability

Scoops3D

We apply the Scoops3D slope stability model[8] to evaluate collapse hazard at Sinabung. For given input parameters:

DEM:	SfM Photogrammetry
Cohesion (c) (kPa):	100 - 500 [8,9,10,11] erupted lava
	1000 [8,9] edifice
Angle of Internal Friction (φ):	25 - 40 [8,9,10,11] erupted lava
	40 [8,9] edifice
Unit Weight (kN m-3):	24.5 [5]

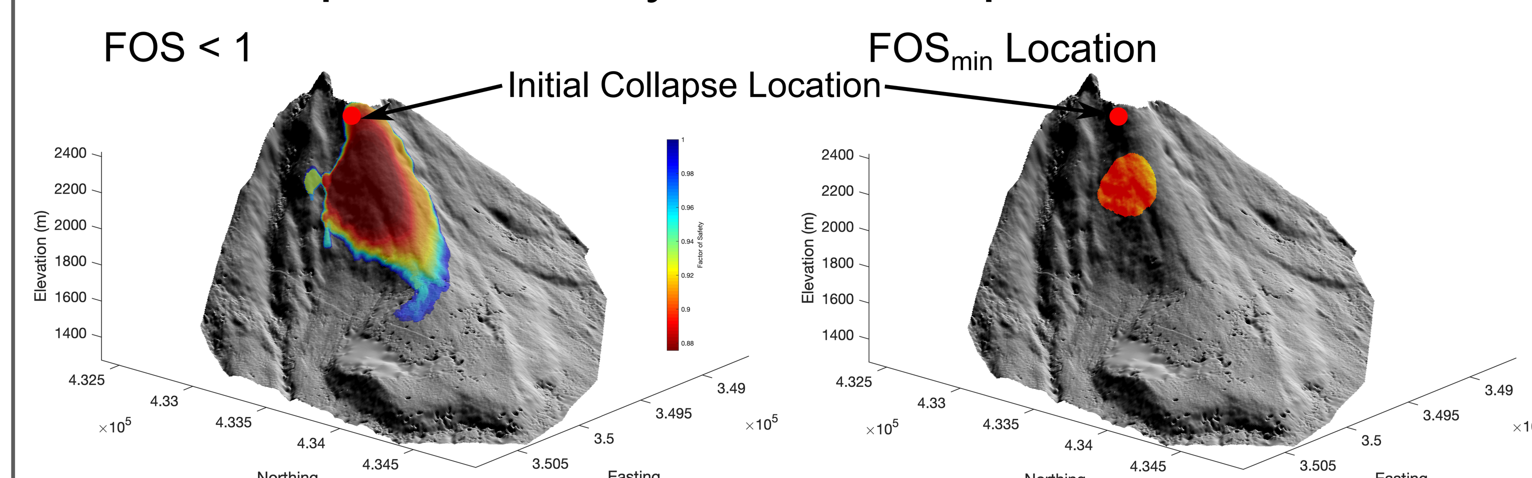


Scoops3D applies the Coulomb failure criteria to calculate the shear strength (s)

$s = c + \sigma_n \tan(\varphi)$ (normal stress) and then the Factor of Safety (FOS) $FOS = \frac{s}{\tau}$ (shear strength / shear stress)

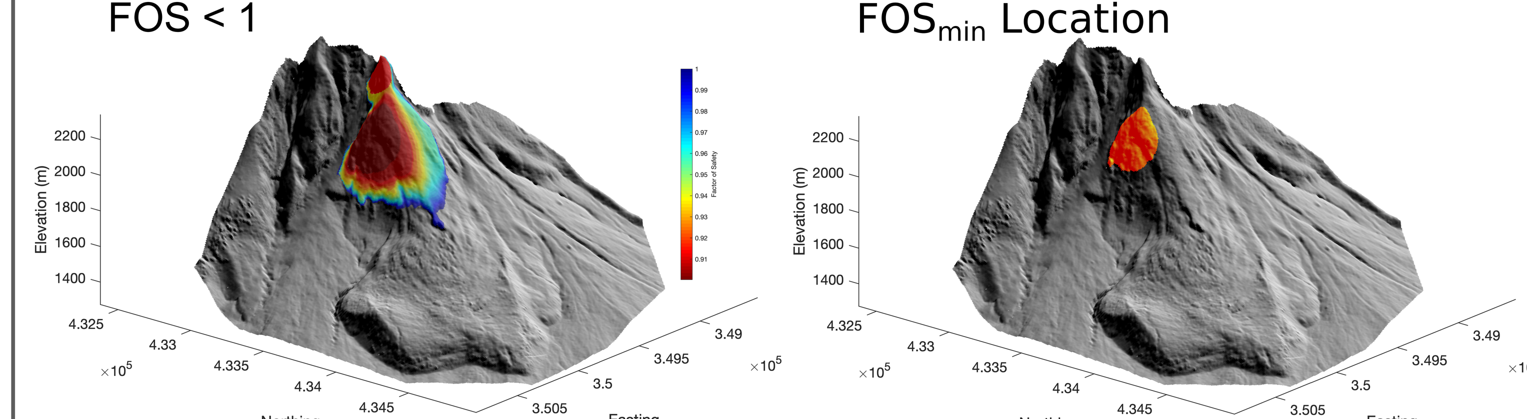
for thousands of potential rotational, spherical slip surfaces.
A FOS < 1 indicates instability. FOS_{min} is the lowest FOS found for the DEM

Can Scoops3D Identify 2014 Collapse?



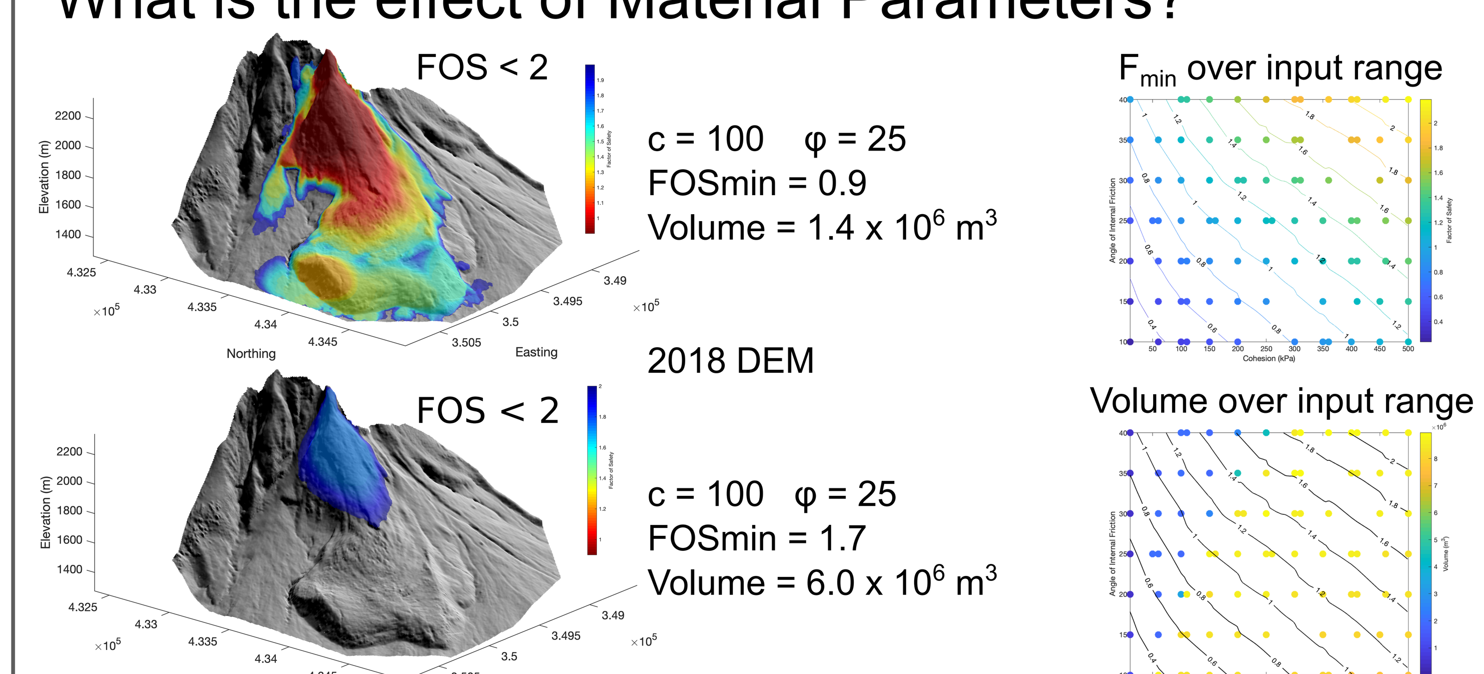
FOS_{min} = 0.87 Volume = 2 x 10^6 m^3

What is the current hazard?



FOS_{min} = 0.90 Volume = 1.4 x 10^6 m^3

What is the effect of Material Parameters?



Accurate constraint of material properties is essential for assessing the FOS of a failure surface. However, the location and volume of the surface where FOS_{min} occurs is not strongly affected by the material properties.

Conclusions

- For the 2014 DEM:
  - The initial 2014 collapse location has FOS < 1
  - The FOS_{min} is located in material that collapsed
  - The FOS_{min} volume is similar to observed collapse volumes
- For the 2018 DEM:
  - A large region of potential instability still exists
  - The potential collapse size is similar to that from earlier periods of active lava effusion
  - The FOS_{min} is located in the same region as in 2014
- Accurate constraint of material properties is needed to determine if FOS < 1 for potential failure surfaces
- The location and volume of the FOS_{min} can still be reasonably assessed without well-constrained material properties
- Application of Scoops3D with SfM-generated DEMs presents a means to assess passive collapse hazards in near-real-time during an eruption

Acknowledgements

Support for author BC came from NSF EAR Postdoctoral Fellowship Award #1725768. Support for author EL came from NSF EAR Award #1654588.

Research and field work in Indonesia is conducted in cooperation with the Geological Engineering Department at Universitas Gadjah Mada in Yogyakarta, Java, Indonesia through a Memorandum of Understanding with the School of Earth and Space Exploration at Arizona State University, Tempe, AZ.

The Center for Volcanology and Geological Hazard Management (CVGHM), Sinabung Volcano Observatory, and Badan Informasi Geospasial generously shared data that contributed to this study.

References

1 Gunawan et al., 2019, J. Volcanol. Geotherm. Res. (382), p. 103-119
2 Pallister et al., 2019, J. Volcanol. Geotherm. Res. (382), p. 149-163
3 Carr et al., 2019a, J. Volcanol. Geotherm. Res. (382), p. 164-172
4 Carr et al., 2019b, J. Volcanol. Geotherm. Res. (382), p. 137-148
5 Nakada et al., 2017, J. Volcanol. Geotherm. Res. (382), p. 120-136
6 Calder et al., 2002, Geol. Soc. London Memoirs (21), p. 173-190
7 James & Robson, 2012, J. Geophys. Res. (117), F03017
8 Reid et al., 2000, J. Geophys. Res. (105), p. 6043-6056
9 Ball et al., 2018, J. Geophys. Res.: Solid Earth (123), p. 2787-2805
10 Schaefer et al., 2019, Earth-Sci. Rev. (192), p. 236-257
11 Voight & Ellsworth, 2000, Geophys. Res. Lett. (27), p. 1-4