Numerical modelling of pyroclastic flows: a case study from the recent activity of Merapi Volcano, Central Java, Indonesia

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Case study: Merapi Volcano

About 60% of Indonesians live around 16 active volcanoes on the island of Java. Merapi, ranks second after Semeru as the most active volcano of Indonesia, and also second after Kelud in surface area at risk.
Case study: Merapi Volcano

View from the SW
Eruptive history

- ~ 80 eruptions since the mid-1500s and almost half of these have generated small-volume pyroclastic flows of various types, at least 12 of these causing fatalities.

- periods of lava dome growth: → dome-collapse pyroclastic flows
- large vulcanian explosions: → fountain-collapse pyroclastic flows

Merapi: Recent and Historical Activity

- Frequent, quasi steady-state volcanic activity (lava dome extrusion)
- Intermittent gravitational dome-collapse or explosive phases resulting in small-volume pyroclastic flows
Types of pyroclastic flows deposits at Merapi

Four types of pyroclastic flow deposits have been identified in the stratigraphic record of Merapi that can be distinguished on the basis of their characteristic lithologies. These include:

a) Valley-confined block-and-ash flow deposits that comprise dense blocks of pre-existing dome material in an ash matrix,

b) Pyroclastic flow deposits containing characteristic juvenile blocks with cauliflower external morphologies,

c) Pyroclastic flow deposits rich in breadcrust components,

d) Deposits dominated by low density pumice clasts.
Volcanic Hazard at Merapi

- 1.1 million inhabitants in 300 villages above 200 m in elevation.
- Yogyakarta is a city of around 500,000 people located ≈35 km south to the summit.
- 440,000 people are at relatively high risk in areas prone to pyroclastic flows, surges, and lahars.
- At least 80,000 people (maybe twice as much as in 1976) live or work daytime at increased risk in the “forbidden zone”.

Volcanic Hazard Map

Forbidden Zone
- Rock falls
- Pyroclastic flows

Hazard Zone 1
- Surges
- Ash falls

Hazard Zone 2
- Lahars
Modelling approach

Evaluation of geophysical mass flow models → key conditions that control flow behaviour + better assess the potential hazard of different type of flows.

Detailed study of the June 2006 Block-and-ash flow deposits

3D deposit architecture of the flows → key flow parameters + conceptual model of transport and deposition

Integration into numerical simulations of Block-and-ash flows at Merapi + Evaluation of geophysical mass flow models:

TITAN 2D    VOLCFLOW

Case study: The 2006 eruption

The lower Gendol River valley filled with block-and-ash flow deposits from June 2006

- **Volume estimates** covered by:

  - Basal avalanche deposits: ~ $7.7 \times 10^6$ m$^3$ 89%
  - Overbank deposits: ~ $0.8 \times 10^6$ m$^3$ 9%
  - Pyroclastic surge deposits: ~ $0.2 \times 10^6$ m$^3$ 2%

→ Total deposited material: ~ $8.7 \times 10^6$ m$^3$

Short- to medium-runout block-and-ash flows (Post-14 June 2006)

- Restricted to proximal and medial valleys (< 4 km from the summit)
- Deposition on slopes ~20° with unconfined morphologies
- Lobate fronts with coarse margins
The Peak of Activity:
Long-runout block-and-ash flows (14 June 2006)

Summit Seismic Station

Wassermann, pers. comm.

Basal avalanche “overspill” in the Kaliadem area on 14 June 2006

Before 14 June 2006

Kaliadem Overbank deposits

After 14 June 2006

K. Gendol 1 Basal avalanche
### Overbank Deposits

**Transport mechanisms**
- Quasi-steady to unsteady granular flow

**Deposition mechanisms**
- Similar to granular-free surface flow on unconfined planes
- Stepwise aggradation of granular-dominated pulses

**Flow types**
- Basal avalanche
- Overbank flows, Ash-cloud surges

**Associated deposits**
- Channelled, Overbank, Surge

**Deposit morphology**
- Unconfined
- Confined with overbanking

**Lithology**
- > 80% juvenile clasts, outer part of the lava dome
- Accidental lithic content increases downstream
- Overbank deposits enriched in low-density clasts

**Granulometry**
- Bimodal distribution, poorly sorted (c2 from 3.8 to 4), M_d from 5 to 1, ash content from 40 to 55 wt%
- Polymodal distribution, poorly sorted (c2 from 2.9 to 4.2), M_d from -3.5 to -0.2, ash content from 40 to 70 wt%

**Seismic signal**
- Single pulse < 3 mins.
- Multiple-pulses > 3 mins.
### Geophysical mass flow models

<table>
<thead>
<tr>
<th>Geophysical mass flow models</th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>TITAN 2D model</strong></td>
<td><strong>VOLCFLOW model</strong></td>
</tr>
<tr>
<td>➢ Linux platform</td>
<td>➢ Windows with Matlab</td>
</tr>
<tr>
<td>➢ Mohr-Coulomb Frictional</td>
<td>➢ Multiple and user-defined behaviours</td>
</tr>
<tr>
<td>behaviour</td>
<td>➢ Finite volume solver with fast and accurate numerical solutions</td>
</tr>
<tr>
<td>➢ Adaptive gridding with</td>
<td>➢ Single processor simulations</td>
</tr>
<tr>
<td>mesh refinement/unrefinement</td>
<td>➢ No Access to source code</td>
</tr>
<tr>
<td>➢ Parallel (MPI) processing</td>
<td>➢ Flexibility of Matlab</td>
</tr>
<tr>
<td>on supercomputer (2-64 processors)</td>
<td>➢ Multiple output parameters</td>
</tr>
<tr>
<td>➢ Access to source code</td>
<td></td>
</tr>
<tr>
<td>➢ Stopping criteria</td>
<td></td>
</tr>
<tr>
<td>➢ Multiple visualization platforms</td>
<td></td>
</tr>
</tbody>
</table>

### Models evaluation criteria

- A series of evaluation criteria has been developed for the determination of best-fit input parameters that form the basis for evaluating the validity of our models:

1. Runout distance of the simulated flows should match those of the lobe fronts as mapped in the field
2. Distribution of the deposits and deposited volume should fall within the range of those of the actual flows
3. Velocities of the flows and deposit thicknesses should be comparable to those calculated and observed in the field
4. Flow simulations of long-runout flows must escape from channel confines to fill the interfluves area (in particular the area around Kaliadem) and to be re-channeled into the adjacent valleys
Digital Elevation Model adjustments

A. 3D view of the old summit area from the original DEM

B1. Filling of the southwestern flank
B2. Collapse structure on the upper southern slopes
B3. New 2006 lava dome

C. 3D view of the new summit area from the adjusted DEM

TITAN 2D calibration

Internal friction angle: 30 °
Basal friction angle: 16 °

Internal friction angle: 30 °
Basal friction angle: 20 °

None of the simulations using a single bed friction is capable of reproducing the path and extent of the actual events.
TITAN 2D calibration

- GIS-based classified map: Slope map + Elevation profile → Bed-friction map

Charbonnier and Gertisser (2009), Bull. Volc. 71

Short- to medium-runout BAFs: Best-fit parameters

**TITAN 2D**

- **Dimensions of initial pile:**
  - Length: 100 m
  - Width: 70 m
  - Max. Thickness: 10 m
  - Orientation angle: -90°

- **Source characteristics:**
  - Number of flux sources: 1
  - Mean flux: 4 kg/m².s
  - Active duration of collapse: 50 sec

- **Flow parameters:**
  - Internal friction angle: 30°
  - Basal friction angle: 16° - 28°

  **Initial volume:** $0.8 \times 10^6$ m³

**VolcFlow**

- **Source conditions:**
  - Length: 150 m
  - Width: 150 m
  - Number of flux sources: 1
  - Active duration of collapse: 50 sec

- **Flow parameters:**
  - Constant retarding stress: 7 500 Pa
  - Coeff. u²: 0.01
  - Density: 1500 kg/m³

  **Initial volume:** $0.8 \times 10^6$ m³
Short- to medium-runout BAFs: TITAN 2D

Short- to medium-runout BAFs: VolcFlow

Parameters:
- Cst. Ref. Stress = 7500 Pa
- ou2 = 0.01
- d = 1508 kg/m³
Short- to medium-runout BAFs: Results

<table>
<thead>
<tr>
<th></th>
<th>Lobe 5</th>
<th>TITAN 2D</th>
<th>VolcFlow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow duration (sec.)</td>
<td>-</td>
<td>210</td>
<td>275</td>
</tr>
<tr>
<td>Max. cent. velocity (m.s(^{-1}))</td>
<td>-</td>
<td>34.3</td>
<td>33.2</td>
</tr>
<tr>
<td>Area covered (km(^2))</td>
<td>0.21</td>
<td>0.34</td>
<td>0.73</td>
</tr>
<tr>
<td>Deposited volume (10(^6) m(^3))</td>
<td>0.64</td>
<td>0.69</td>
<td>0.61</td>
</tr>
<tr>
<td>Runout distance (km)</td>
<td>3.3</td>
<td>3.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Short- to medium-runout BAFs: Results

### TITAN 2D

![TITAN 2D Image](image)

### VolcFlow

![VolcFlow Image](image)
Long-runout BAFs: Best-fit parameters

**TITAN 2D**
- **Dimensions of initial pile:**
  - Length: 100 m
  - Width: 70 m
  - Max. Thickness: 20 m
  - Orientation angle: -90°
- **Source characteristics:**
  - Number of flux sources: 5
  - Mean flux: 4 kg/m²·s
  - Active duration of collapse: 300 sec
- **Flow parameters:**
  - Internal friction angle: 30°
  - Basal friction angle: 10° - 24°
- **Initial volume:** ~4×10⁶ m³

**VolcFlow**
- **Source conditions:**
  - Length: 150 m
  - Width: 150 m
  - Number of flux sources: 1
  - Active duration of collapse: 150 sec
- **Flow parameters:**
  - Constant retarding stress: 3 500 Pa
  - Coeff_u2: 0.01
  - Density: 1200 kg/m³
- **Initial volume:** 5.8×10⁶ m³

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Long-runout BAFs: Results

<table>
<thead>
<tr>
<th>Time (sec.)</th>
<th>14 June p.m. 2006</th>
<th>TITAN 2D</th>
<th>VolcFlow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. cent. velocity (m/s)</td>
<td>43.8</td>
<td>29.8</td>
<td>44.6</td>
</tr>
<tr>
<td>Area covered (km²)</td>
<td>1.29</td>
<td>1.56</td>
<td>2.03</td>
</tr>
<tr>
<td>Deposited volume (10⁶ m³)</td>
<td>~3.5</td>
<td>3.62</td>
<td>3.50</td>
</tr>
<tr>
<td>Runout distance (km)</td>
<td>7.0</td>
<td>7.5</td>
<td>7.2</td>
</tr>
</tbody>
</table>
Long-runout BAFs: Results

TITAN 2D

VolcFlow

Long-runout BAFs: TITAN 2D
Our Ultimate Aim...

Establish TITAN2D/VolcFlow as predictive tools in future eruption at Merapi

Summary and Outlook

• “Realistic” numerical models require:
  - Model calibration using well-constrained field parameters (thickness variations, velocity, deposit distribution, transport and emplacement mechanisms of associated flows)
  - Incorporation of a suitable empirical law into the model (varying bed friction angles or constant retarding stress)
  - A realistic set of input parameters (incl. Digital elevation model)

• Modelling output:
  - Flow depths and velocities
  - Runout distances, Inundation areas and Volumes of different types of BAFs
  - Key parameters that control flow behaviour

  Basis for estimating the areas and levels of hazards associated with BAFs and for improving disaster mitigation plans at Merapi
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