Mechanical discontinuities monitoring at Merapi summit using kinematic GPS

G11A-06

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Abstract

Merapi volcano exhibits an almost continuous activity with growth of an andesitic lava dome, which collapses in glowing avalanches, explosions and *nuées ardentes* which are sometimes deadly. Starting 1993, we established a Global Positioning System network and measured it each year using the static method. This allowed us to monitor the evolution of surface displacements and to model the associated magmatic sources. But the poor spatial density of benchmarks and awkwardness of field campaigns did not yield the precise location of major mechanical discontinuities within the edifice. However, identifying precisely these discontinuities is of central importance since they delimit areas of potential instability and provide means to evaluate potential volumes of falling material.

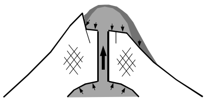
The kinematic GPS method offers a modern means to partially solve the problem of temporal and spatial sampling of the displacement field, but the precision is usually insufficient to monitor small displacements. We propose here a new method of measurement and adjustment which combines kinematic positioning (1-minute) and rapid static baselines (15 minutes) to get a 1.5-cm error (95% confidence). At Merapi summit, a network of about 50 benchmarks have been established (less than 500-m wide), in order to cover the whole area around the main crater. Indonesian teams are performing the campaigns every month since December 1999.

First results show large horizontal displacements (about 40 cm) towards the northwest between June and November 2000. This can be associated with the recent seismic unrest at Merapi, and is probably due to a new magma feeding below the 1998 lava dome. Two active discontinuities have been localized at the summit. Finally, we discuss potential rock slope problem in terms of numerical modeling and hazard mitigation.

Introduction

Volcanic eruption and **rock slope problems** forecasting needs:

- ➔ Direction and magnitude
- ➔ Source type (magmatic / phreatic)
- ➔ Precise area localization (volume)



Answers come from monitoring observations combined with an interpretative model. But numerical models need **boundary conditions**, i.e., internal substructures geometry (magma chamber, duct and fractures) and source parameters (pressure and stress state). Because volcano edifices deform due to fluid transport (magma, gas, or water), these parameters can be partially retrieved from the deformation field analysis.

Merapi Volcano, Indonesia

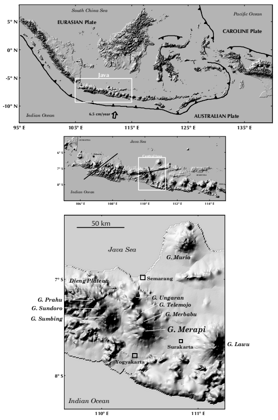


Figure 2. Merapi presents an activity of quasi continuous extrusion of lava which forms a dome in a horse-shoe shaped crater. The dome is continuously and partially destroyed by avalanches and pyroclastic flows. **(up)** View of Merapi from the South-East [*F. Beauducel* photo]. **(bottom)** The January 30, 1992 lava dome: An almost perfect hemisphere of 140-m wide and 40-m high [*J. Tondeur* photo].

Figure 1. Location and geodynamical context of Mt. Merapi (2964 m). Merapi is a young strato-volcano located in Central Java, Indonesia, in a frontal subduction zone. Population of Yogyakarta (25 km from the summit) and around is about 3 millions people, up to 500,000 are living directly on the flank of the volcano, above 500 m of elevation. Merapi is one of the " Decade Volcano " declared by United Nations IDNDR Program.

Summit Deformation 1988-1997

Merapi summit deformations have been observed by American, Indonesian and French teams using EDM since 1988 and GPS measurements since 1993. Before the 1992 dome growth episode, horizontal displacements reached 1.2 m/year, associated with strain rate of 11×10^{-6}/day. Main discontinuities have been roughly localized and modeled from 1993 to 1997 GPS observations, using 3-D mixed boundary elements method [*Cayol and Cornet*, 1997].

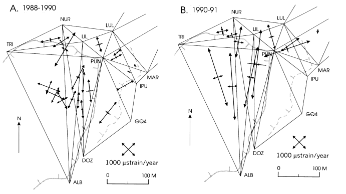


Figure 3. Principal directions and values of the strain tensors for selected triangles of the summit network, computed from EDM measurements: **(A)** June-July 1988 - September 1990 and **(B)** September 1990 - August 1991 [From *Young et al.*, 2000].

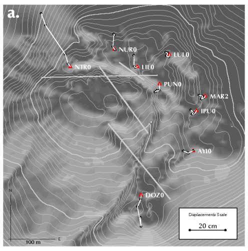
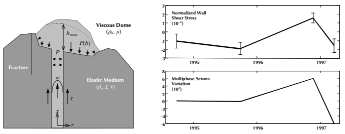


Figure 4. Cumulated horizontal GPS displacements at the summit from 1993 (red triangles) to 1997. An important movement occurred (about 40 cm) on the Northern part of the crater rim. Four " independent " zones separated by fractures (gray lines) with different behavior are observed, presenting a deformation pattern similar to previous measurements (see Figure 3). These fractures have been observed and localized at surface, and introduced into 3-D numerical modeling. The Northern zone did not exhibit an elastic behavior; this was interpreted as a rock slope problem, just before this zone effectively collapsed in July 1998 [From *Beauducel et al.*, 2000].

Figure 5. **(left)** Types of source considered for the summit modeling of displacement field: dome weight effect on the crater floor, magma pressure in the duct and wall shear stress due to flux variation of viscous fluid. Computation of the dome weight effect for 1993-1994 period showed that this effect is negligible on displacements. **(right)** We processed an inversion from the linear combination of the two forward problem solutions (pressure and wall shear stress in the duct) constrained by the 1993-1997 GPS 3-D displacements. The computed wall shear stress variations are compatible with recorded " multi-phase " seismic events variations. Because the two observations are independent, this gives further support that these seismic events are related with shear stress release at the duct wall [From *Beauducel et al.*, 2000].



Methodology

Rock slopes monitoring need a **dense geodetic network** and **brief campaign** at summit. We developed a simple method using the following characteristics:

- ➔ GPS dual-frequency small receivers (*Dassault-Sercel Scorpio*)
- ➔ Very short baselines (< 500 m)
- ➔ Kinematic / rapid-static processing
- ➔ Joint adjustment of kinematic and static results
- ➔ Automatic processing routines for quick interpretation

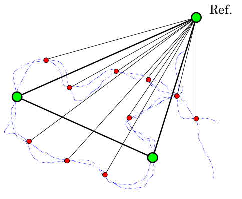


Figure 6. Principle of the measurement method (both 1-s sample rate): **(1)** Kinematic (red dots): ~50 points, 2-min measurements, < 5 cm precision. Points are all measured at least 2 times, along the trajectory which has to be closed (blue dashed line). **(2)** Rapid-static (green dots): at least 3 closed baselines between benchmarks common with kinematic, 15-min measurements, < 1 cm precision.

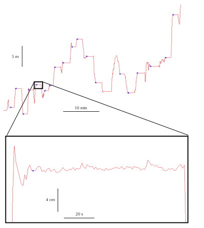


Figure 7. Example of trajectory measurement and processing: marks detection (blue stars), position extraction (3 component average and standard deviation), and automatic point recognition and naming.

$$\mathbf{AX} \approx \mathbf{B}$$

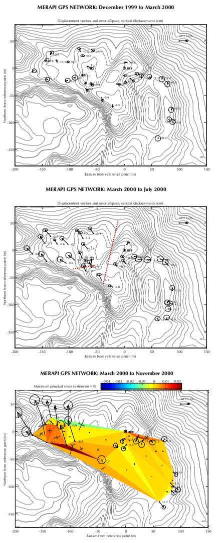
$$\mathbf{X} = (\mathbf{A}^T\mathbf{V}^{-1}\mathbf{A}^T)^{-1}\,\mathbf{A}^T\mathbf{V}^{-1}\mathbf{B}$$

$$\mathbf{X} = \begin{pmatrix} x_i \\ y_i \\ z_i \\ x_{i+1} \\ \ldots \end{pmatrix}$$

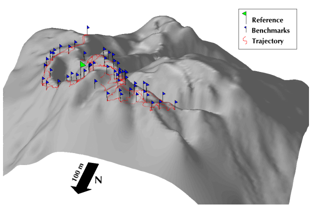
$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 & -1 & \ldots \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \end{pmatrix} \quad \mathbf{B} = \begin{pmatrix} x_i - x_{i-1} \\ y_i - y_{i-1} \\ \ldots \\ x_a - x_b \\ \ldots \end{pmatrix} \quad \mathbf{V} = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \ldots & \ldots \\ \ldots & \sigma_y^2 & \sigma_{yz} & \ldots & \ldots \\ \ldots & \ldots & \sigma_z^2 & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \end{pmatrix}$$

Figure 8. Network adjustment is solved by simple least square linear system, where: **A** = partial derivatives, **B** = observations, **V** = covariance matrix, **X** = unknown (points coordinates *x*, *y*, *z*). Matrix **B** is constructed with differential baselines components (from point *i* to point *i*+1) for kinematic measurements, and baselines components (from point *a* to point *b*) for rapid-static measurements.

First Results: Dec. 1999 - Nov. 2000



The new GPS network has been implanted in December 1999, and measured successively in March, May, June, July, August and November 2000. Automatic *Matlab* routines are used to produce numerical results and graphics, in order to process data within few hours, just after field campaign. Significant displacements have been observed starting July 2000, accelerating in November 2000 (horizontal strain reached 200×10^{-6}/day). A new active fracture is localized.



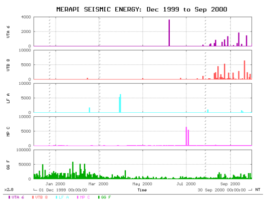


Figure 9. The new GPS network at Merapi summit: reference (green flag), benchmarks (blue flags) and example of trajectory for one campaign (red line). Only Northern and Eastern zones can be monitored, due to strong topography and present dome activity. The Southern zone is unfortunately too dangerous to access due to rock avalanches since 1997.

Figure 10. Number of seismic events per day on the studied period: **VTA** = volcano-tectonic >2 km deep, **VTB** = volcano-tectonic <1.5 km deep, **LF** = low frequency, **MP** = multi-phase (associated with magma production), **GG** = rock avalanches. GPS campaigns are also shown (dashed vertical areas).

Figure 11. Relative displacements and uncertainties (95%). Numerical values correspond to vertical displacements in cm, and are not significant. **(up)** December 1999 to March 2000 : No displacement observed, but this first result allowed us to determine the confidence of our method; joint adjustment of kinematic and rapid-static measurements leads to about 1.5 cm (95%) error on position, for the entire network. **(middle)** March to July 2000 : Western and Eastern zones are clearly opening, revealing an active fracture oriented N10 represented by dashed red line. A known fracture (named Lava 56, oriented N80) shows a right slip movement of about 3 cm. New benchmarks have been added in the active zone. **(bottom)** March to November 2000: Northwestern zone accelerates up to 40 cm, horizontal maximum strain reaches +0.02 (extension).

Conclusions & Perspectives

- ➔ Uncertainties after joint adjustment (kinematic + static) < 1.5 cm for the entire network and 3 components. The method needs at least 2 trajectories and 3 rapid static baselines (1-day campaign).
- ➔ Significant displacements since July 2000, continuing in November 2000, associated with magma production, and revealing a new major discontinuity into the edifice.
- ➔ This new monitoring method will be applied at La Soufrière de Guadeloupe volcano, where fractures play an important role into the dome deformation field.

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