FLANK COLLAPSE AND NEW RELATIVE INSTABILITY ANALYSIS TECHNIQUES APPLIED TO VOLCAN DE COLIMA AND MT ST. HELENS

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Colima Volcano - 2011

Mt. St. Helens - 1979
Volcanoes flank collapse

The 1980 sector collapse and debris avalanche at Mount St. Helens triggered the recognition of many similar debris avalanche deposits worldwide (Siebert, 1984; Ui and Glicken, 1986; Siebert et al., 1987; Francis and Wells, 1988; Vallance et al., 1995).

Since then, several studies have revealed that many volcanoes are susceptible to failure caused by exogenous or endogenous processes (McGuire, 1996),
Instability of a volcanic edifice may be caused by many factors:

- direct magmatic intrusion into the edifice (Bezymianny-type activity, Gorshkov, 1962; Day, 1996; Elsworth and Voight, 1996),
- deposition of voluminous pyroclastic deposits on steep slopes (McGuire, 1996),
- hydromagmatic processes (Dzurisin, 1998),
- phreatomagmatic activity (Bandai-type activity, Moriya, 1980).
- faulting and tectonic settings (McGuire, 1996; Siebert, 1984)
- Earthquake (Keefer, 1984)

Gravitational failures may occur in response to progressive weakening of an edifice. Other triggering mechanisms include phreatic explosions and Hurricane-induced rainfall trigger (flank collapse at the Casita volcano in Nicaragua in 1998, Sheridan et al., 1999; Scott et al., 2005).
A **recently developed technique** of analysis applied to stratovolcanoes by Borselli et al. (2011)*, offers **new insights for assessment of degree of instability for flank collapse of volcanic edifices**.


The new technique combines **three methodologies**:  
• 1) slope stability by limit advanced equilibrium analysis (ALEM) of multiple sectors on the volcano using SSAP 4.0 (*Slope Stability Analysis Software*, Borselli 2011) which include fluid internal overpressure or progressive dissipation (Borselli et al. 2011), and rock mass strength criteria (Hoek et al. 2002,2006) for local, stress state dependent, shear strength;

• 2) the analysis of **relative mass/volume deficit in the volcano structure**, made using the new **VOLCANOFIT 2.0** software (Borselli et al.2011);

• 3) **Statistical analysis of major flank debris avalanche ages in the last 10,000 BP**, using **stochastic arithmetic methods** (Vignes, 1993), and calculating the mean time of recurrence of them.
Relative slope stability by advanced limit equilibrium method (ALEM)

Limit equilibrium method (LEM) Slope stability analysis (Duncan 1996):
Calculation of **Factor of Stability (FS)** which is associated to each section of volcanic edifice

Multiple sections of volcanic structure each 30° clockwise

Single section analysis

Factor of stability determination:
- $Fs \leq 1.0$ unstable
- $Fs > 1.0$ stable

According to standard rigorous LEM

Borselli & Sarocchi – “Flank collapse and new relative instability analysis techniques.,” GSA – Cordilleran, Queretaro 30/3/2012
SSAP 4.0 is a full freeware software

http://www.ssap2005.it
(Borselli 1991, 2011)

- Generic shape random search of minimum FS sliding surface by Monte Carlo method
- Fluid pressure function (overpressure and dissipation fields inside volcanic edifice) (Borselli et al. 2011)

\[
\sigma_f = \gamma_w z F_D + U_{0_{MIN}}
\]
\[
F_D = 1 - Ae^{-kD}
\]
ALEM analysis application to Volcan de Fuego, Colima, MX (Approx 3880 m a.s.l.)

Volcan de Fuego, Colima (November 2011)
W view

Saucedo et al. 2010
Volcan de fuego
Colima, MX

Selected area for analysis
The advanced Limit equilibrium method (ALEM) and Relative instability analysis
Scenarios and mechanical parameters

<table>
<thead>
<tr>
<th>Scenario, Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Geomechanical parameters as in Table 2</td>
<td>No seismic effect</td>
</tr>
<tr>
<td>2. Geomechanical parameters as in Table 2 with GSI increase of 50%</td>
<td>No seismic effect</td>
</tr>
<tr>
<td>3. The same as scenario 2, but seismic coefficients $K_h=0.2$; $K_v=0.1$</td>
<td>Seismic effect by LEM pseudostatic analysis</td>
</tr>
<tr>
<td>4. The same as scenario 2, but seismic coefficient $K_h=0.25$; $K_v=0.125$</td>
<td>Seismic effect by LEM pseudostatic analysis</td>
</tr>
</tbody>
</table>
Final results colima with ALEM
The sector with minimum relative stability is W-SW flank (between 270° and 210°)

The Relative stability index

\[ R_{fs_i} = \frac{F_{s_i}}{F_{s_{max}}} \]

(Borselli et al. 2011)
Volcanoid 2.0
WWW. VOLCANOFIT.ORG

\[ Z = a e^{-\frac{\sqrt{(x-x_0)^2+(y-y_0)^2}}{b}} + c \text{ if } Z \leq Z_1 \]

VOLCANOID SURFACE OF REVOLUTION

ALTERNATIVE VOLCANOID’S GENERATRIX

\[ Z = a \cosh \left( \frac{r-c}{b} \right) \]
for \( \forall r < c \) and \( a, b, c > 0 \).

\[ Z = \frac{z_1 - a}{1 + e^{\frac{r-c}{b}}} \]
with \( z_1 > a \) and \( z_1, a, b, c > 0 \).

Fig. A.2. Example of volcanoid with constant negative curvature (Eq. (A.5)).

Fig. A.5. Alternative generatrix function of 3D volcanoid.
Colima Volcanofit 2.0
Result: Using Negative exponential Volcanoid’s generatrix

Fig. 7. a) Upper edifice of Colima volcano DEM (2005) fitted volcanoid 3D surface Eq. (A.5); b) Upper edifice Colima Volcan de Fuego DEM with overlaid volcanoid Eq. (A.5); d) plot of local deficit (negative values) or surplus (positive values) calculated with Eq. (A.6).
Volcanoid

Details overlay DEM and Fitted Volcanoid

Software volcanofit 2.0 (Borselli et al. 2011) www.volcanofit.org

Volume (mass) Deficit in SW flank
The most potentially unstable Flank: Azimuth 270°-210°

Combined results of ALEM (by SSAP 4.0) and VOLCANOFIT2.0
Mt. St. Helens Before 18 May 1980

Mt. St. Helens Now

© National Geographic magazine

USGS DEM 1979

USGS DEM after 18 May 1980

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Mt st. helens 1979 DTM
Analysed by VOLCANOFIT 2.0
(Borselli et al. 2011)

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From Hausback and Swanson (1990)

Figure 7 Northeastern asymmetric distribution of extrusive domes younger than Pine Creek age at Mount St. Helens. Small “x” is pre-1980 summit. These domes include east dome (ED), Sugar Bowl dome (SB), summit dome (SD), and Goat Rocks dome (GR, removed by 1980 landslide and blast). The 1340-m (4400-ft) contour encircles volcano. Dome outlines from unpublished mapping by C.A. Hopson.

DTM by University of Washington, Earth and Space science, 2010.
http://rocky.ess.washington.edu/data/raster/thirtymeter/mtsthelens/OldMtStHelens.zip
View of the "bulge" on the north face of Mount St. Helens, from a measurement site about 2 miles to the northeast 27 april 1980

http://mountsthelens.com/history-1.html

by Jim Nieland, U.S. Forest Service

Photograph by Peter Lipman

Landslide 18 may 1980

© Copyright Gary Rosenquist 1980
Volcan de Colima

time of recurrence of last 5 debris avalanche events (DAE) (Borselli et al. 2011)

<table>
<thead>
<tr>
<th>Data source</th>
<th>Event ID</th>
<th>VEI*</th>
<th>Te1 (years BP)</th>
<th>εTe1 Uncertainty on DAE (years)</th>
<th>ΔTe1 Interval from previous DAE (years)</th>
<th>εΔTe1 Uncertainty on interval from previous DAE (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3</td>
<td>4</td>
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<td>2580</td>
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<tr>
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<td>5</td>
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<td>120</td>
<td>3440</td>
<td>200</td>
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<tr>
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<td>6</td>
<td>7040</td>
<td>160</td>
<td>2631</td>
<td>183</td>
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<tr>
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<td>1</td>
<td>5-6</td>
<td>9671</td>
<td>88</td>
<td>3699</td>
<td>149</td>
</tr>
<tr>
<td>1,2</td>
<td>0</td>
<td>5-6</td>
<td>13370</td>
<td>120</td>
<td>n.a</td>
<td>n.a</td>
</tr>
</tbody>
</table>

Mean interval of last four DAE (expressed as stochastic number)

<table>
<thead>
<tr>
<th>ΔTe Mean interval of last four DAE (years)</th>
<th>εΔTe Standard deviation associated to mean DAE interval (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2698</td>
<td>180</td>
</tr>
</tbody>
</table>

1 Komorowski et al. (1997); 2 Cortes et al. (2005); 3 Cortes et al., 2010; *from Mendoza-Rosas and De La Cruz-Reyna (2008).

Mean interval of last 4 DAE interval is **2698 years** with a mean standard deviation of +/- **180 years**

Using **stochastic arithmetic** (Vignes, 1993; Markov and Alt, 2004)

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USE of Stochastic arithmetic for Debris avalanche recurrence time

The number of DAE is much lower than the number of total explosive events. De la Cruz-Reyna (1993) established a Poissonian model for the recurrence intervals and occurrence frequency of explosive eruptions, and Mendoza-Rosas and De la Cruz-Reyna (2008, JVGR 176, 277–290) analysed the distribution of events with VEI>4, which may be related to large DAEs, finding an 85% probability of a VEI>4 event within the next 500 yr, and an average recurrence time for VEI>=5 over 2500 yr. (this analysis include all events 2<VEI<6)

Instead we use a stochastic arithmetic techniques (Vignes, 1993; Markov and Alt, 2004) adapted to the mean age of DAE and its band of uncertainty. This technique accounts for the error propagation and uncertainty associated with the computation of successive intervals between collapses. The proposed methodology resembles that proposed by Akçiz et al. (2010, Geology 38 (9), 787–790) for the assessment of large earthquake recurrence times at the San Andreas Fault (California, st. Andreas Fault system). In this chase the recurrence time for the Big Ones is much more shorter than previous assessments.
Fig. 6. DAE events vs. time interval from previous debris avalanche event. The projection of a possible scenario for the next DA event is included in the horizontal axis.
Highlights

- **ALEM techniques** applied to Volcán de Colima point to the **W-SW quadrant as potentially the most unstable sector of the edifice** under a wide range of scenarios.

- The VOLCANOFIT application to Colima shows an important deficit of volume in the same W-SW quadrant (approx. 0.4 km$^3$). The VOLCANOFIT Application to Mt. St. Helens pre-eruption1980 DEM shows the distribution of local mass deficit/surplus association that may be easily correlated with the 1980 incipient flank collapse process. **So there is the possibility that Sector Volume Deficit/Excess anomalies may be correlated to a possible mayor relative instability.**

- The recurrence interval of major collapse events in Colima volcano, during the last 10,000 years, calculated here using a stochastic arithmetic approach, yielding a mean recurrence interval of 2698 yrs, with an uncertainty range of 180 yrs.

- Our analysis point out an increased possibility of flank collapse in the interval between -110 yrs and +345 yrs from the present. This generates a series of scenarios ranging from optimistic, considering a collapse within the next 345 years, to pessimistic, derived from the 110-year delay.

- The proposed new approach may be applied to any stratovolcano with a potential of flank collapse and for his future hazard assessments.
Gracias por su atención !!!

Many thanks for Your attention !!!