Rock wall retreat and historical back analysis of failures in Alpine limestone cliffs

D. Hantz, Laboratoire de Géophysique Interne et Tectonophysique, CNRS, Université Joseph Fourier, Grenoble, France

M. Frayssines, EGIS SE, Geotechnique, Seyssins, France
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• Introduction: Rock fall / rock slide hazard assessment for land use planning
• Rock fall frequency, rock wall retreat and rock wall age
• Historical back-analysis for modelling stability decrease
Rock fall / rock slide hazard assessment for land use planning

Asked questions

*Where* future landslides are probable in the next 100 years?

What are the *probabilities of occurrence*? (probabilistic estimation of the *time to failure*)

What will be the type of failure (*brittle or ductile*)?

What *area* will be affected?
Large uncertainty about joints persistence, geomechanical parameters and time evolution

Pessimist modelling used for slope design, is not convenient for hazard assessment

→ Rock fall hazard assessment is usually qualitative

Historical approach can improve rock fall hazard assessment by:
• yielding a quantitative time constraint (rock fall frequency) and
• allowing for a better knowledge of the mechanical behaviour (historical back analysis)
Historical approach:
* a time constraint for rock fall hazard assessment

**Historical approach**
(based on inventories, rock wall retreat rate or age)

Rock fall frequency for a homogeneous area and a volume range

Expected fall number for a given period

\[ N \]

**Geomechanical approach**
(based on the observation and analysis of individual rock compartments)

Individual failure probabilities \( p_i \)
(roughly estimated)

Probable fall number in the area:

\[ \Sigma p_i \]
Rock fall frequencies derived from an inventory

Example of the Gorges de l'Arly

RN 212 - Gorges de l'Arly – 1948-1996

Gorges de l'Arly
Rock fall frequencies derived from an inventory

Example of the Gorges de l'Arly

RN 212 - Gorges de l'Arly (upper gorges) – 1954-1976

\[ F = a V^{-b} = 8 V^{-0.45} \]

b: constant
Rock fall frequencies derived from rock wall retreat rate

Relation between the fall frequencies and the rate of retreat of a rock wall

Fallen volume per century:

\[ W_t = \int_0^\infty V df = \frac{a}{(1-b)} V^{(1-b)} \]

Retreat rate:

\[ E = \frac{W_t}{S} \]

Example of the limestone cliffs in the Grenoble area

- Historical inventory (century scale) \( \rightarrow E = 1.5 \text{ mm/year} \)
- Geological history (million years scale) \( \rightarrow \text{retreat of 10-15 km in } 10^7 \text{ years} \)
  \( \rightarrow E = 1-1.5 \text{ mm/year} \)

Strasbourg 2009
D. Hantz
Rock fall frequencies derived from the age of the rock wall surface

Relation between the rate of retreat and the rock wall age

Conceptual two-dimensional models (view from above the cliff)

\[ A_i = \frac{W_i}{E} \]

\[ B_i : \text{Total scar area for the volume range } V_i, \text{ appearing in 1 century} \]

\[ \text{Averaged life expectancy of a scar (and of a rock compartment) } = \frac{A_i}{B_i} \]
### Relation between the fall frequency and the rock wall age

**The model is being tested in the Grenoble area**

<table>
<thead>
<tr>
<th>Volume range ((V_i, V_{i+1})) (m³)</th>
<th>0-(10^2)</th>
<th>(10^2)-(10^3)</th>
<th>(10^3)-(10^4)</th>
<th>(10^4)-(10^5)</th>
<th>(10^5)-(10^6)</th>
<th>(10^6)-(10^7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock fall number</td>
<td>33</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Observed frequency (per century)</td>
<td>51</td>
<td>14</td>
<td>9</td>
<td>1.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td><strong>Fitted mean frequency (per century)</strong></td>
<td><strong>65</strong></td>
<td><strong>18</strong></td>
<td><strong>5</strong></td>
<td><strong>1.5</strong></td>
<td><strong>0.6</strong></td>
<td></td>
</tr>
<tr>
<td>Volumetric erosion rate for the volume range ((V_i, V_{i+1})) (m³/century)</td>
<td>10,893</td>
<td>19,807</td>
<td>55,825</td>
<td>157,336</td>
<td>443,433</td>
<td>2.83 (10^6)</td>
</tr>
<tr>
<td>Total volumetric erosion rate (m³/century)</td>
<td>3.5 (10^6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cliff area (m²)</td>
<td>24 (10^6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Linear rate of retreat (m/century)</strong></td>
<td><strong>0.15</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cliff area (A_i) which is subjected to rock falls in the volume range ((V_i, V_{i+1})) (m²)</td>
<td>0.07 (10^6)</td>
<td>0.1 (10^6)</td>
<td>0.4 (10^6)</td>
<td>10^6</td>
<td>3 (10^6)</td>
<td>19 (10^6)</td>
</tr>
<tr>
<td>Scar appearance rate (B_i) for rock falls in the volume range ((V_i, V_{i+1})) (m²/century)</td>
<td>27,264</td>
<td>14,240</td>
<td>21,677</td>
<td>33,000</td>
<td>50,235</td>
<td>150,769</td>
</tr>
<tr>
<td>Mean life (T_i) of the rock compartments in the volume range ((V_i, V_{i+1})) (year)</td>
<td>272</td>
<td>948</td>
<td>1,755</td>
<td>3,249</td>
<td>6,015</td>
<td>12,812</td>
</tr>
<tr>
<td><strong>Mean life (T_i) of the rock compartments (years)</strong></td>
<td><strong>11,000</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mean age of the cliff surface = 5 500 years**
Surface exposure dating with cosmonuclids

Relation between the fall frequency and the rock wall age

Cosmonuclids: $^{36}\text{Cl}$, $^{10}\text{Be}$
Radioactive lifetime: 430 kyr

Production: $P_0 e^{-\lambda t}$

Erosion: $\varepsilon \frac{\partial C(x,t)}{\partial x}$

Radioactive decay: $-\lambda C(x,t)$

$\frac{\partial C(x,t)}{\partial t} = \text{input} + \text{output}$
Relation between the fall frequency and the rock wall age

Application to the limestone cliffs of the Grenoble area

Samples: 7, 6, 5, 3, 2, 1

11 100 years 2 400 years 14 100 years 5 000 years

Mean age = 8 000 years

Mean age from erosion model = 5 500 years
Historical back analysis of failures

Stability analysis

Geomechanical parameters → Safety factor

Back-analysis

Mechanical parameters ← Failure (safety factor = 1)

The parameters obtained are instantaneous parameters and can be used only to determine the instantaneous stability of existing or future slopes.

The time evolution of the stability cannot be predicted due to the lack of quantitative knowledge of the evolution processes.

Historical back-analysis allows for a better knowledge of these processes.
**Historical back analysis of failures**

**Instantaneous back-analysis**

- Present resisting force
- Failure (safety factor = 1)

**Historical back-analysis**

- Evolution parameters
- Stability under passed earthquakes (safety factor > 1)

*Example in the Grenoble area*

- Statistically, a fallen rock compartment of $10^2$-$10^3$ m$^3$ had been submitted to earthquakes for about 1000 years.
- The acceleration undergone, derived from the seismic hazard in the area, is 2.3 m/s$^2$, with a statistical risk of 5%.
- The *resisting force* 1000 years ago can be estimated (by default), and also its rate of decrease.
Historical back analysis of failures

Rock falls
in the Grenoble area
due to
limestone solution?
subcritical crack
growth?
**Historical back analysis of failures**

**Stability decrease due to limestone solution**

<table>
<thead>
<tr>
<th>Rock fall name</th>
<th>Vierge du Vercors</th>
<th>Chalimont</th>
<th>Pas du Fouillet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (m³)</td>
<td>117</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>Rock bridge area at the time of failure (m²)</td>
<td>0.6</td>
<td>0.1</td>
<td>0.08</td>
</tr>
<tr>
<td>Cohesion derived from failure back-analysis (MPa)</td>
<td>4</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Life time of the compartment (years)</td>
<td>948</td>
<td>272</td>
<td>272</td>
</tr>
<tr>
<td>Probable seismic acceleration (m/s²)</td>
<td>2.3</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Initial rock bridge area (m²)</td>
<td>&gt;0.98</td>
<td>&gt;0.14</td>
<td>&gt;0.11</td>
</tr>
<tr>
<td>Solution rate (mm/year)</td>
<td>&gt;0.05</td>
<td>&gt;0.07</td>
<td>&gt;0.07</td>
</tr>
</tbody>
</table>
Historical back analysis of failures

**Stability decrease due to subcritical crack growth**
*(fracture mechanics theory, Kemeny, 2003)*

\[ a(t) = \left[ a_0^{1+n/2} - \left( 1 + \frac{n}{2} \right) At \left[ \frac{2w(\tau - \sigma_n \cdot \tan \phi)}{K_{IIc} \sqrt{\pi}} \right]^n \right]^{1/(1+n/2)} \]
● The knowledge of rock wall retreat rate, rock wall age or historical rock fall frequencies yields a quantitative time constraint to hazard assessment

● Historical back analysis of fallen compartments allows to calibrate quantitative models of stability decrease

● Historical data bases are needed for a better hazard assessment
CONCLUSION

- L'approche historique permet de déterminer la fréquence d'éboulements pour différents volumes dans une falaise homogène, ainsi que le risque associé.

- Le modèle d'érosion proposé permet d'évaluer ces fréquences sans disposer d'inventaire ou à partir d'un inventaire limité.

- Mais pas de déterminer la probabilité d'éboulement d'un compartiment donné.

- Pour cela, elle doit être associée à une approche géomécanique, qui permet de hiérarchiser les compartiments potentiellement instable.

→ Approche HGP (Historique-Géomécanique-Probabiliste)