New individual risk measures for rockfall prone areas:
insights from the French Alps

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**Introduction**

Rockfalls represent a major hazard in mountainous regions, causing damages to buildings and critical infrastructure and/or injuring people. Risk zoning is therefore a crucial issue when planning mitigation measures.

Quantitative risk assessments (QRA) methods applicable in rockfall-prone regions remain scarce:

- This study proposes a holistic QRA at the Le Brocey slope (French Alps).

Approaches are especially lacking for evaluating individual risk as a continuous function of space:

- We aim at proposing an approach for estimating and mapping individual rockfall risk by combining a rockfall simulation model with the physical vulnerability of potentially affected buildings and the complete distribution of block volumes in the range 1–20 m$^3$.

Risk remains in this field of rockfalls always defined as the damage expectation:

- Value-at-risk (VaR) and expected shortfall (ES) quantile-based measures were investigated to better assess the risk due to extreme events.

**I. Study site: Le Brocey, municipality of Crolles (French Alps)**

The pre-alpine conurbation of Crolles is located in the Isère valley, near the city of Grenoble (French Alps). Photograph of a rockfall event occurred in 2012 at Crolles. B. Bourcy. The site is divided into: the protection forest, the agricultural and urbanized areas.

**II. Value-at-risk and expected shortfall**

![Simplified representation of the value-at-risk (VaR) and expected shortfall (ES) for α ∈ (0, 1) on a normal cumulative distribution functions](figure)

- **VaR$_{α}$** = inf {L ∈ R | Pr(L ≥ l) ≤ (1 - α)}
- **ES$_{α}$** = E(L | L ≥ VaR$_{α}$)

**III. Numerical model set-up**

**Figure III.** Rockfall damage distribution at a specific cell of the slope. The VaR and ES risks have been computed for a horizon period $t = 200$ years.

- **Study site**
- **Protection forest**
- **Agricultural area**
- **Urban**
- **Current urban front limit**
- **Protective structures**

**Figure IV.** Distribution of the VaR (a, c) and ES (b, d) rockfall risk (in m$^2$ destroyed per year) at the Le Brocey slope and for horizon periods $t$ set at 100 years and 1,000 years.

- **Current urban front limit**
- **Study site**

<table>
<thead>
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<th>Risk (m$^2$/yr)</th>
<th>0</th>
<th>0.0005</th>
<th>0.001 - 0.005</th>
<th>0.005 - 0.01</th>
<th>0.01 - 0.05</th>
<th>0.05 - 1</th>
<th>&gt; 0.5</th>
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</thead>
<tbody>
<tr>
<td>Study site</td>
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**IV. Results**

![Figure I](photograph of a rockfall event occurred in 2012 at Crolles. ©Bernard Bourcy.)

**Figure I.** a) The pre-alpine conurbation of Crolles is located in the Isère valley, near the city of Grenoble (French Alps). b) A photograph of a rockfall event occurred in 2012 at Crolles. ©Bernard Bourcy. c) Local urban planning scheme of Crolles area. The site is divided into: the protection forest, the agricultural and urbanized areas.

**Conclusion**

Individual rockfall risk map:

**Value-at-risk and Expected Shortfall:**

- Alternative risk measures to the loss expectation.
- Enable the ranking and comparison of risk management options and leave to decision makers the final decision, depending on their personality and on their political, social and/or budgetary constraints.

**Perspectives:**

1) Take into consideration non-stationary environmental conditions, i.e., accounting for potential changes in rockfall activity and propagation related to, e.g., climate fluctuations, landscape evolution, or to urban extent.
2) Replicate our study for other natural hazards.

**REFERENCES**