Hazard analysis and modeling of snow avalanches: recent results from Italy

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And, in sort of cronological order:
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Thanks to: Giovanni Peretti and the AINEVA Personnel, Rangers of Sondrio City
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Ongoing projects


Including: CNR IRSA, TU Wien, SLF Davos, Universidad de Jaume I en Castellon de la Plana, SRDE, Institut Cartografic de Catalunia


Including: SLF Davos, CUDAM University of Trento, University Pavia, Meteo France, CEMAGREF, BOKU Wien, NGI Oslo

2007-2009 CARiPANDA, Climatic change and water resources in the Adamello park, Cariplo Foundation.

Including: Parco dell’Adamello, Università degli Studi di Milano, Istituto di Fisica Generale Applicata, Dip. di Scienze della Terra, ARPA Lombardia, Università di Brescia
The European Alps are characterized by relevant tourism during winter and feature a considerable amount of ski resort areas. Every year, several avalanches occur in the area, and a large number of casualties occurred in the last 20 years all over the Alps; in more than 1/3 of the cases the people involved died.

The number of fatalities has decreased recently due to the new prevention techniques and risk mapping.
0) Rationale

The number of avalanche events is strictly correlated with the snow amount and the presence of people in dangerous areas, the maximum value is in January and February.

The risk involves all the “users” of the mountain areas.

Avalanche accidents Italy

Casualties by activity Italy 1984-2003
1) Criteria for avalanche hazard mapping

\[ R = H E V \]

Hazard: intrinsic to avalanche phenomena
Exposition: value of the properties
Vulnerability: degree of damage

Swiss procedure, also used in Italy

Red zone
\[ P \geq 30 \text{ kPa}, T = 300 \text{ years} \]
\[ P < 30 \text{ kPa}, T \leq 30 \text{ years} \]

Blue zone
\[ P < 30 \text{ kPa}, 30 < T < 300 \text{ years} \]
powder avalanche \[ P < 3 \text{ kPa}, T < 30 \text{ years} \]

Yellow zone
\[ P \leq 3 \text{ kPa}, T > 30 \text{ years} \]
2) Runout of avalanches: AF(A?)S approach.

Runout distance/Altitude

\[ R = x_i - x_0 \vee s_i - s_0 \]

The greatest yearly runout can be modeled According to the theory of extremes

Problems:
1) Topographic control
2) No pressures

Use:
1) Zone mapping
2) Cross check of dynamic models
2) Runout of avalanches: AF(A?)S approach.

A case study: the Vallecetta avalanche site
A number of avalanches were mapped ever since 1886
3) Deterministic-statistic approach for hazard mapping

Input factors: Swiss guidelines, also used in Italy

\[ C_{3d} = H_{72} \] : Maximum annual three days cumulated snow fall

Among other factors, \( H_{72} \) noticeably affects avalanche volume, runout and eventually hazard mapping exercise

\[ C_{3d} = H_{72} \]

\[ \text{Red zone} \]
- \( P \geq 30 \text{ kPa}, \quad T \geq 300 \text{ years} \)
- \( P < 30 \text{ kPa}, \quad T < 300 \text{ years} \)

\[ \text{Blue zone} \]
- \( P < 30 \text{ kPa}, \quad 30 < T < 300 \text{ years} \)
- Powder avalanche \( P < 3 \text{ kPa}, \quad T < 30 \text{ years} \)

\[ \text{Yellow zone} \]
- \( P \leq 3 \text{ kPa}, \quad T > 30 \text{ years} \)

Evaluation of \( H_{72} \):

\[ H_{72} = H_S (\text{day 4th}) - H_S (\text{day 1st}) \]

\[ P_{\text{max}} = C_P \rho U_{\text{max}}^2 \]

\[ C_P = \frac{1}{2} \quad \text{powder avalanche} \]

\[ C_P = 1 \quad \text{dense avalanche} \]

From: Ancey et al., 2004
3) Deterministic-statistic approach for hazard mapping

Design values of $H_{72}$

Single site series analysis is often used for evaluation of T-years design value of $H_{72}$ for hazard mapping procedure. Evaluation of $H_{72}(T)$ for a single site station (20 years of observations). Notice the low predicted return periods using the site observed data ($Y_i=15$ years) and the considerable uncertainty for the highest return periods.

For the design of more reliable estimates one can carry out evaluation of $H_{72}$ using regional approach. Regional approach is often adopted in the field of hydrology for evaluation of floods and storms statistics. This in turn requires assessment of regional homogeneity.

![Diagram showing Bormio area with plotted data points and lines for observed data and different evaluation methods for $H_{72}(T)$ with return periods $T$.](image)
Several avalanches occur in the area, and in the period from 1990 to 2000 at least 7200 avalanche events were mapped, with at least 215 casualties.

The case study area is the Alpine Area of Lombardia region, N-W Italy.
Analysis based on L-coefficients

Evaluation of $H_{72}$ using regional approach (e.g. Barbolini, Natale, Savi, 2002) requires assessment of regional homogenity.

The area investigated is found climatically homogenous according to former studies (e.g. De Michele and Rosso, 2002), and the regime of daily snow precipitation is found to be reasonably homogeneous (Bocchiola and Rosso, 2007).

On this basis, the distribution of $H_{72}$ is investigated.

The approach proposed by Hosking and Wallis (e.g. Hosking and Wallis, 1993) is used here to test the homogeneity of the region in term of $H_{72}$.

$L$-CV $H_{72}$, $L$-coefficients maps are evaluated

$L$-SK $H_{72}$

$L$-KU $H_{72}$
*L-coefficients* charts show the degree of scatter of the *L-coefficients* (e.g. Hosking and Wallis, 1993)

Proper statistical tests show a reasonable degree of homogeneity of the region

$$D_i = \frac{1}{3} (u_i - \bar{u}_i) S^{-1} (u_i - \bar{u}_i)$$  \text{ indicates that the site is homogeneous}

$$u_i = \left[ L_i - CV_{i H2s} \right] \left[ L_i - SK_{i H2s} \right] \left[ L_i - KU_{i H2s} \right]$$

$$S = (N - 1) \sum_{i=1}^{N} (u_i - \bar{u}_i) (u_i - \bar{u}_i)$$

$D > 3$ only for VAM stations ($D = 4.99$)

$$Var_{LCV} = \frac{\sum_{i=1}^{N} Y_i (LCV_i - LCV_{av})^2}{\sum_{i=1}^{N} Y_i}$$

$$Var_{LSK} = \frac{\sum_{i=1}^{N} Y_i [(LSK_i - LSK_{av})^2 + (LKU_i - LKU_{av})^2]}{\sum_{i=1}^{N} Y_i}$$

$$Var_{LU} = \frac{\sum_{i=1}^{N} Y_i [(LKU_i - LKU_{av})^2]}{\sum_{i=1}^{N} Y_i}$$

$$H_j = \frac{Var_j - \mu_{Var_j}}{\sigma_{Var_j}}$$  \text{ for noticeably homogeneous behavior}

<table>
<thead>
<tr>
<th>$L$-coeff.</th>
<th>$n_{site}$</th>
<th>$L$-coeff$_{avj}$</th>
<th>$Var_{obs}$</th>
<th>$\mu_{Var_j}$</th>
<th>$\sigma_{Var_j}$</th>
<th>$H_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L-CV_{H2s}$ ($j = 1$)</td>
<td>1000</td>
<td>0.26</td>
<td>0.0019</td>
<td>0.0017</td>
<td>0.0004</td>
<td>0.53</td>
</tr>
<tr>
<td>$L-SK_{H2s}$ ($j = 2$)</td>
<td>1000</td>
<td>0.21</td>
<td>0.0871</td>
<td>0.0932</td>
<td>0.0116</td>
<td>-0.56</td>
</tr>
<tr>
<td>$L-KU_{H2s}$ ($j = 3$)</td>
<td>1000</td>
<td>0.17</td>
<td>0.0972</td>
<td>0.1088</td>
<td>0.0117</td>
<td>-1.02</td>
</tr>
</tbody>
</table>
Index value approach to evaluation of $H_{72}$

Dimensionless values of $H_{72}$ with respect to an index value can be grouped together to provide a $T$-years quantile growth curve. $F_i$ is the distribution function, valid at each site.

Generally, the index value is given by the single site $i$ sample average

$$\mu_{H_{72i}} = \frac{1}{Y_i} \sum_{y=1}^{Y_i} H_{72i,y}$$

Distribution fitting provides the analytical expression of the growth curve

$$H^*_{72}(T) = \varepsilon_p + \frac{\alpha_p}{k_p} \left(1 - \exp\left(-k_p y_T \right)\right)$$

<table>
<thead>
<tr>
<th>Dist.</th>
<th>$\varepsilon_p$</th>
<th>$\alpha_p$</th>
<th>$k_p$</th>
<th>$AD$</th>
<th>$AD\ 5%$</th>
<th>$KS$</th>
<th>$KS\ 5%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEV</td>
<td>0.785</td>
<td>0.370</td>
<td>-0.005</td>
<td>0.453</td>
<td>0.055</td>
<td>0.029</td>
<td>0.038</td>
</tr>
<tr>
<td>EVI</td>
<td>0.787</td>
<td>0.369</td>
<td>-</td>
<td>0.477</td>
<td>0.055</td>
<td>0.031</td>
<td>0.038</td>
</tr>
</tbody>
</table>
Sensitivity analysis of hazard mapping $H_{72}$

The approaches currently adopted for the sensitivity analysis of the avalanche hazard maps require probabilistic assessment of the distribution of the input value $H_{72i}(T)$, i.e., the design value $H_{72i}(T)$, and a measure of its uncertainty, e.g., its standard deviation, $\sigma_{H_{72i}T}$

The regional approach yields a standard deviation that is smaller than that provided by the approach based on single site distribution fitting

$$\sigma_{H_{72i}T}^2 = \mu_{H_{72i}} \cdot CV \sqrt{Y_i}$$

$$\sigma_{H_{72i}}^* = \frac{\sigma_{H_{72i}T}^2}{H_{72i}(T)} = \sqrt{\frac{\sigma_{\mu H_{72i}}^2 \sigma_{H_{72i}}^2 + \sigma_{\mu H_{72i}}^2 \mu_{H_{72i}}^2 + \sigma_{\mu H_{72i}}^2 \mu_{H_{72i}}^2 \mu_{H_{72i}}^2}{H_{72i}^2}}$$

Here the standard deviation is given with respect to the design value of $H_{72i}(T)$.

This is evaluated against the number of available years of observations $Y_i$ to estimate the local average.

Notice the decrease in the standard deviation using the regional approach.
Increase of $H_{72}$ with altitude

In ungagged sites, the average value of $H_{72}$ has to be estimated using indirect approach. Often, (linear) scaling with altitude is adopted. Use of coupled cluster and scaling analysis showed two areas with defined scaling of $\mu_{H72}$.

<table>
<thead>
<tr>
<th>Region</th>
<th>$N_e$</th>
<th>$c$ [cm/100 m]</th>
<th>$\mu_0$ [cm]</th>
<th>$R^2$</th>
<th>$p$</th>
<th>$\sigma_{H72}$ [cm]</th>
<th>$\delta_{H72}$ [cm]</th>
<th>$\sigma_{\mu_{H72}}$ [cm]</th>
<th>$\sigma_{\mu_{H72}}^*$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-W</td>
<td>15</td>
<td>3.7</td>
<td>5.4</td>
<td>0.59</td>
<td></td>
<td>64.41</td>
<td>15.63</td>
<td>0.069</td>
<td>10.07</td>
</tr>
<tr>
<td>N-E</td>
<td>14</td>
<td>3.3</td>
<td>-9.87</td>
<td>0.72</td>
<td></td>
<td>51.18</td>
<td>9.15</td>
<td>0.066</td>
<td>4.85</td>
</tr>
</tbody>
</table>
The case of Switzerland

- 114 measurement stations
- About 25 E³ KM²
- On the average, 45 years of data
- The data base of the gauging stations is managed by the personnel of SLF Davos

Exporting the regional approach

**REGIONAL EVALUATION OF THREE DAY SNOW DEPTH FOR AVALANCHE HAZARD MAPPING IN SWITZERLAND**

Latenser (2002) used a cluster analysis based on $H_5$.

Here, the homogenous regions were defined according to an iterative procedure with respect to $H_{72}$:

- Homogeneity tests
- Relation of $H_{72}$ to altitude $A$

Region 1, the north west belt crossing the country from west to east, Region 2W, the Rhone Valley, Region 2E, the Gotthard Range, and Region 5, the northern part of Grison. Region 3, the southern valleys of east Valais, Region 4W covering Ticino and Region 4E covering the southern part of Grison.
Region 1 is accommodated by a GEV distribution featuring $k>0$, indicating upper boundary and a slower increase variation with return period.

Regions from 2 to 5 are accommodated by a EV1 (Gumbel) distribution, featuring $k=0$, indicating no upper boundary and a faster increase variation with return period.
A noticeable difference in the regional scaling of $E[H72]$ against altitude is observed. This is confirmed by the available literature and is linked to climatic and orographic patterns leading to heavy snowfall.
Accuracy of the 300 years estimates

A noticeable increase in accuracy of the 300 years quantile is observed. Albeit this might be slightly decreased due to inter site correlation, still a considerable gain is attained.
5) Case studies of hazard mapping: the Lombardia region.

Vallecetta avalanche site, Bormio (So)

Validation of AVAL1D

Vallecetta avalanche events on 1th and 16th May 1983 and Validation of AVAL1D®.

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_s$ [m asl]</th>
<th>$A_r$ [masl]</th>
<th>$R$ [m]</th>
<th>$E_r$ [%]</th>
<th>$H$ [m]</th>
<th>$W_0$ [m]</th>
<th>$L_0$ [m]</th>
<th>$V_0$ [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed 1th May 1983</td>
<td>2950</td>
<td>1174</td>
<td>4877</td>
<td>-</td>
<td>0.9</td>
<td>800</td>
<td>1110</td>
<td>7.99E+5</td>
</tr>
<tr>
<td>AVAL1D® 1th May 1983</td>
<td>//</td>
<td>1176</td>
<td>4838</td>
<td>-0.5%</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
</tr>
<tr>
<td>Observed 16th May 1983</td>
<td>3140</td>
<td>1144</td>
<td>5172</td>
<td>-</td>
<td>1.3</td>
<td>1300</td>
<td>1254</td>
<td>2.118E+6</td>
</tr>
<tr>
<td>AVAL1D® 16th May 1983</td>
<td>//</td>
<td>1149</td>
<td>5110</td>
<td>-1.1%</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
</tr>
</tbody>
</table>
Hazard mapping - sensitivity analysis

Runout [m]

Altitude [m asl]

Blue zone regional (a=1%)
Blue zone single site (a=1%)
Red zone regional (a=1%)
Red zone single site (a=1%)

Single site

Regional

Application of a regional approach for hazard mapping at an avalanche site in northern Italy

D. Bocchini and R. Rocca
Politecnico di Milano, L. De Vani Square 32, 20133 Milan, Italy

Advances in Geosciences
6) A case study in Switzerland

21 January 1951: Samedan avalanche, Engadina
Return period labeled: \( T = 300 \) years

\( H_{72}(T) \) in Samedan

\[
\begin{align*}
H_{72}(T) & \quad \text{Obs 4SD} \\
H_{72}(T) \quad \text{single site} & \\
H_{72}(T) \quad \text{single site +} & \\
H_{72}(T) \quad \text{single site -} & \\
H_{72}(T) \quad \text{reg} & \\
H_{72}(T) \quad \text{reg +} & \\
H_{72}(T) \quad \text{reg -} &
\end{align*}
\]
Samedan avalanche

Data
- Volume at release
- Run out

Model tuning using run out distance:
\[
\begin{align*}
\mu &= 0.15 \\
\xi &= 2500 \text{ms}^{-1} \\
\lambda &= 2.5
\end{align*}
\]

Critical stress
\[
\tau_{cr} \cong 195 - 220 \text{kPa}
\]

Use of regional approach (+ uncertainty)
- \( h_r \), regional analysis = \( H_{72}(T) \)
- \( H_e \), variable with altitude = \( H_{72}(T, Alt) \)

Uncertainty
- \( h_r+s, H_e+s \), variable
- \( h_r-s, H_e-s \), variable
Hazard maps

Sensitivity analysis:
Blue and red zones,
95% reference level

Regional snow-depth estimates for avalanche calculations using a two-dimensional model with snow entrainment

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7) Long term simulation of avalanche frequency

A collection of data related to avalanche events in Bormio region was gathered. Data from 69 avalanche events were gathered, dating back until 1886. These include avalanche type, snow conditions, morphology, release altitude, depth, area, runout length and volume.

In 68% of the events, avalanche cause is related to heavy snowfall.

$h_0$: depth at release
$W_0$: width
$L_0$: length
$V_0$: volume
$L$: runout length
$R$: absolute runout

Reported in:
Regional similarity

Avalanche track geometry. $E[s_0]$ is average track slope including the release area, $E[s_f]$ is average track slope including the flow area, $E[s_r]$ is average track slope including the runout area (average track slope). $L_0'$ is percentage of track length including release area, $L_f'$ is percentage of track length including flow area.

<table>
<thead>
<tr>
<th>CER</th>
<th>GAN</th>
<th>NOV</th>
<th>RAS</th>
<th>VCA</th>
<th>VCE</th>
<th>$E[]$</th>
<th>CV[]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E[s_0]$ [$^\circ$]</td>
<td>30.2</td>
<td>30.3</td>
<td>30.0</td>
<td>30.1</td>
<td>29.2</td>
<td>28.3</td>
<td>29.7</td>
</tr>
<tr>
<td>$E[s_f]$ [$^\circ$]</td>
<td>25.7</td>
<td>28.5</td>
<td>29.2</td>
<td>31.1</td>
<td>28.1</td>
<td>24.2</td>
<td>27.8</td>
</tr>
<tr>
<td>$E[s_r]$ [$^\circ$]</td>
<td>20.9</td>
<td>23.2</td>
<td>25.6</td>
<td>29.7</td>
<td>24.9</td>
<td>21.5</td>
<td>24.3</td>
</tr>
<tr>
<td>$L_0'$ [%]</td>
<td>35%</td>
<td>30%</td>
<td>29%</td>
<td>39%</td>
<td>28%</td>
<td>30%</td>
<td>32%</td>
</tr>
<tr>
<td>$L_f'$ [%]</td>
<td>78%</td>
<td>73%</td>
<td>79%</td>
<td>80%</td>
<td>78%</td>
<td>78%</td>
<td>77%</td>
</tr>
</tbody>
</table>

Reasonable geometric similarity might indicate a possible statistical homogeneity of scaled geometric properties.
Regional similarity

A regional approach based on index value is tentatively adopted to increase sample dimensionality for distribution fitting of the observed avalanche properties.

Avalanche release probability is evaluated as a function of dimensionless snow depth, as

\[ h_0^* = h_0 / \mu_{H72} \quad p_{rel} = F_0(h_0) \]

Release altitude is accommodated as a Normal (NR) distribution.

\[ A_0^* = A_0 / \mu_{A0} \]
\[ W_0^* = W_0 / \mu_{W0} \]
\[ L_0^* = L_0 / \mu_{L0} \]

Avalanche release width and length are accommodated using a GA distribution.
Dynamic model

Dynamic model: Voellmy-Salm (insofar)

\[
f_R = \frac{\rho g}{\xi} V_s^2 + \mu \rho g h_s \cos \theta_s
\]

Turbulent friction

Coulomb friction

topography

Calibration against observed runout

Coulomb friction is evaluated against release altitude and snow depth

\[
\mu = \mu_{av} \mu^*
\]

Reported in:
**A case study**

**Case study: Vallecetta mountain**

**Climatic input:**
$H_{72}$ calculated @ the release altitude

**Avalanche occurrence:**
Input snow depth $H_{72}$ is used to give release probability, $p_{rel}$ Random extraction from a Uniform distribution, $p_{u}$ is used to evaluate occurrence using a binomial approach (yes, $p_{u} > p_{rel}$; no $p_{u} \leq p_{rel}$)

**Avalanche release altitude:**
Drawn from the proposed NR statistical distribution

**Avalanche release width, length:**
Drawn from the proposed GA statistical distributions

**Avalanche release volume:**
$V_0 = W_0^*L_0^*H_{72}^*f(slope)$

Hazard mapping

Release volume, runout

Greatest runout, one realization (195 years, $T=300$ years)

Fitting to the regionalized plotting position is verified to indirectly validate the approach.
Hazard maps

Hazard maps: Sp modified for Italy

**ZONA ROSSA**
- $T=30\text{anni}; P\geq3\text{kPa}$
- $T=100\text{anni}; P\geq15\text{kPa}$

**ZONA BLU**
- $T=30\text{anni}; 0\text{kPa} \leq P < 3\text{kPa}$
- $T=100\text{anni}; 3\text{ kPa} \leq P < 15\text{kPa}$

\[ R(T) = R(H_{72}(T)) \]
\[ P(T) = P(H_{72}(T)) \]
\[ T = 30, 100 \]

Runout length and pressures return period $T$ is directly evaluated from the long term simulated plotting position.

\[ R = R(\hat{T} = 30, 100) \]
\[ P = P(\hat{T} = 30, 100) \]

“Classical” Sp approach
8) A simple developed avalanche model

We preliminarily developed and tested a simple avalanche dynamics model, to be used joint with long term simulation module.

Mass centre, 1D, energy based model

Vallecetta (Again ?????): calibration of observed runout

Edmondo Arena Lo Riggio, Mirko Mura, Daniele Bocchiola, Maria Cristina Rulli, Renzo Rosso, Un modello a formulazione energetica per il calcolo dinamico delle valanghe [An energy conservation based model for avalanche dynamics]. Neve e Valanghe, in press. Paper in Italian language, abstract in english. Available upon request.
9) Some remarks

Land use planning in mountain range requires reliable avalanche hazard mapping, forecasting and design of countermeasures.
Lack of avalanche data requires coupling of dynamic modelling and long term snow fall series for design of extreme events.
Statistical methods based on regional approaches might be used to increase sample dimensionality, so gaining considerable information and decreasing uncertainty in avalanche design exercise.
Long term assessment of avalanche hazard based on synthetic simulation provides a tool avalanche for hazard mapping based on full simulation of avalanche history.
Also, synthetic simulation may provide input for long term assessment of avalanche risk for human settlements, and the impact of countermeasures, in case under climate change scenarios.
EU and nationally fostered projects like IRASMOS are highly necessary to stimulate the debate and provide the researchers with means to bring forward new techniques and concepts.

............and watch your track !!!