# Activités de l'unité de recherche ETNA d'Irstea en lien avec les questions fiabilistes

N. Eckert
Irstea, UR ETNA &
Université Grenoble-Alpes
38402 Saint Martin d'Hères, France

**Journée du Groupe de Travail et de Réflexion en fiabilité de Grenoble**
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Contributions / ideas:
E. Parent, AgroParisTech, Paris
D. Bertrand, INSA Lyon
J. Gaume, SLF Davos (Suisse)
P. Favier, M. Naaim, I. Ousset, T. Faug, D. Richard, JM Tacnet, F. Bourrier…, Irstea Grenoble

- **Présentation rapide des activités d'ETNA**

- Panorama (non exhaustif) des liens avec les questions fiabilistes

- Analyses « plus ou moins classiques » des structures soumises à « nos » alea
- Courbes de fragilité
- Analyse fiabiliste des conditions d'occurrence des aléas
- Modélisation numérico-probabiliste multivariée des aléas
- Analyse de risque, calcul décisionnels et indicateurs agrégés

- Une application (un peu) plus détaillée : la gestion à long terme du risque avalanche

# L’unité de recherche ETNA

Recherche et expertise en ingénierie pour la prévention des risques naturels en montagne

➡ développer des connaissances et élaborer des outils applicables à l’ingénierie et à la prévention des risques naturels en montagne

# UR ETNA : la démarche (1)

Approche par phénomènes

✓Des mouvements gravitaires rapides

- Ecoulements torrentiels
- Avalanches
- Chutes de blocs

✓ Des phénomènes initiateurs ou induits par les mouvements gravitaires rapides

- Transport de la neige par le vent
- Vague produite par l'impact dans une retenue

# UR ETNA : la démarche (2)

**Pour chaque phénomène sont étudiés:**

- formation et déclenchement
- dynamique
- interaction avec des obstacles ou des structures
- les risques induits

**L'approche est très pluridisciplinaire:**

- Caractérisation des matériaux naturels (rhéologie, etc.)
- Simulation numérique et numérico-probabiliste
- Etude expérimentale sur sites de terrain et en laboratoire
- Données historiques (EPA, CLPA): apprentissage statistique

# UR ETNA : la démarche (3)

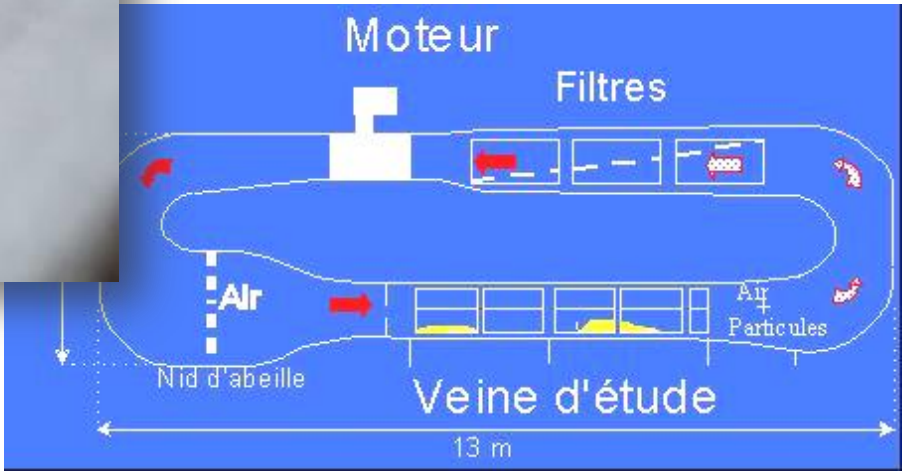
**Les phénomènes et les ouvrages sont étudiés à différentes échelles :**

- **élémentaire: lois de comportement et lois d'interfaces, instabilités**
- **locale : interaction entre un phénomène et une structure**
- **globale : pour étudier le phénomène sur l'ensemble du site à risque**
- **régionale: lien avec le climat, inférence spatio-temporelle**

# UR ETNA : les laboratoires (1)

**Ex 1: La soufflerie**

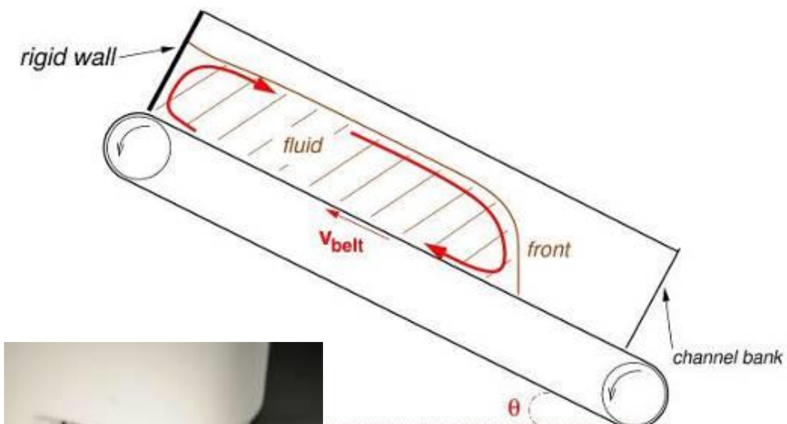
- **Un outil d'étude et de modélisation du transport éolien de particules**



# UR ETNA : les laboratoires (2)

**Ex 2: Le tapis roulant**

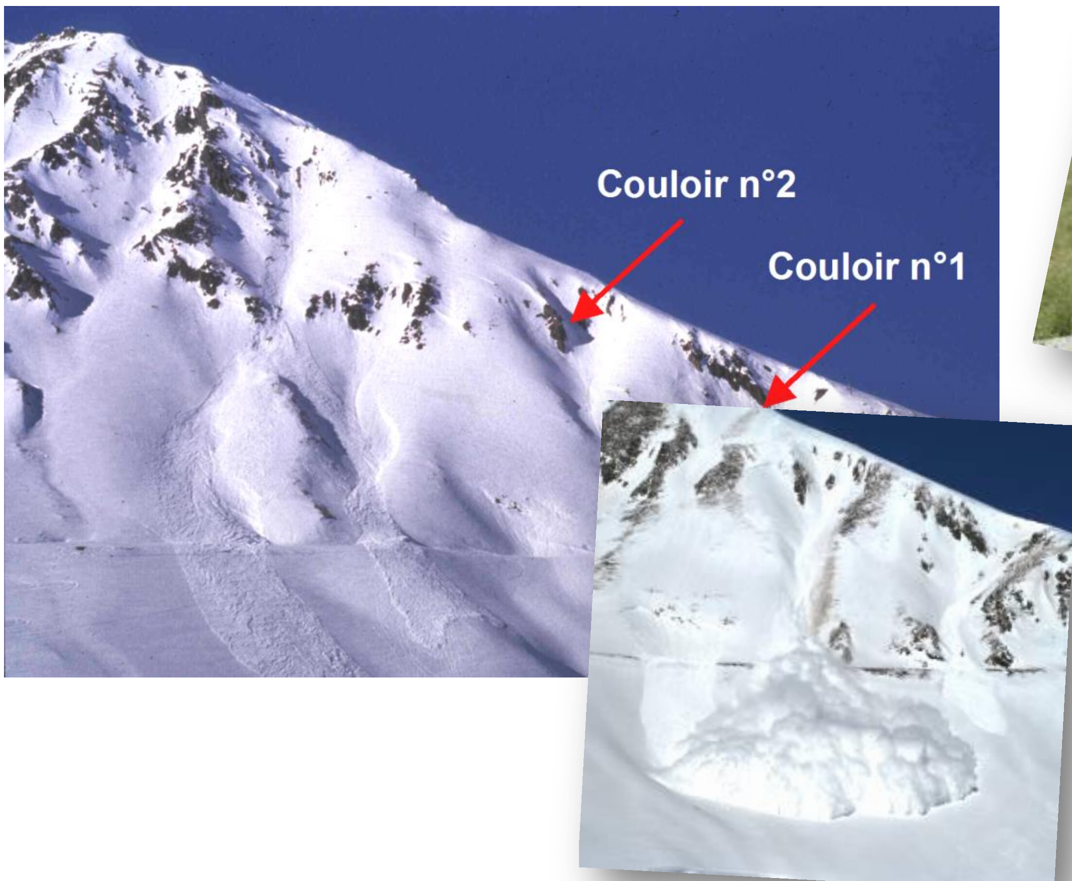
- **Etude des fronts de laves torrentielles**




# UR ETNA : les sites expérimentaux (1)

**Ex 1:: Le col du Lautaret**

- **Un site d'étude et de déclenchement des avalanches grandeur nature**

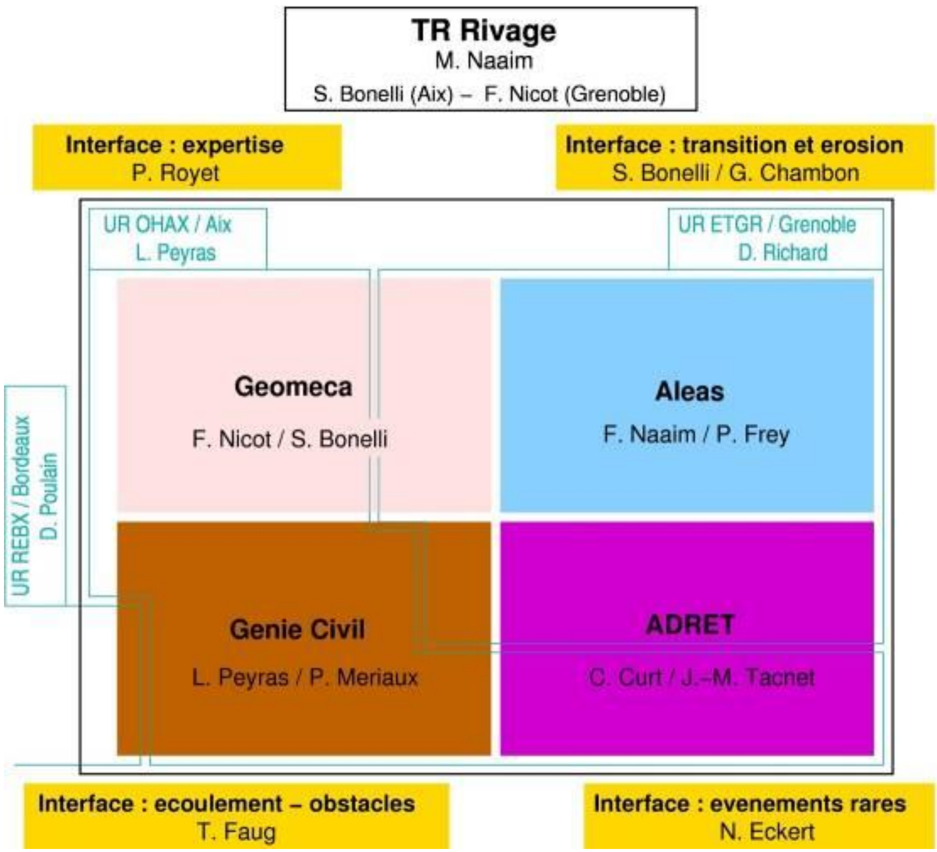



# UR ETNA : les sites expérimentaux (2)

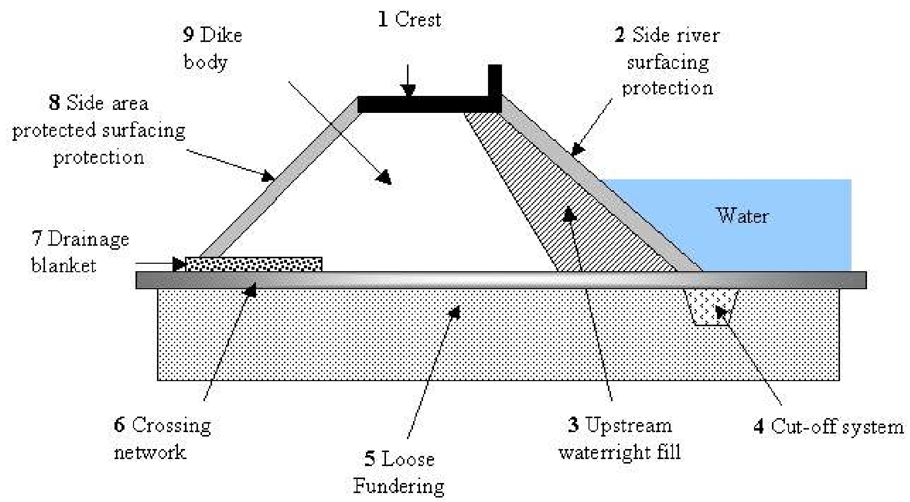
**Ex 2: Le site expérimental du Col du Lac Blanc**

- **Une soufflerie naturelle**

# UR ETNA versus TR RIVAGE




- **Quatre équipes**
- **Lien fort avec l'UR Ouvrages hydrauliques (Aix en Provence)**



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# Vulnérabilité des bâtiments aux aléas

$$\mathcal{V}(\mathcal{E})$$

- Technologie de structure (elements structuraux, assemblage, etc.)

- Propriétés mécaniques des matériaux utilisés

Maçonnerie

Béton armé

Structures métalliques

Structures bois

Exemple de structures de bâtiment

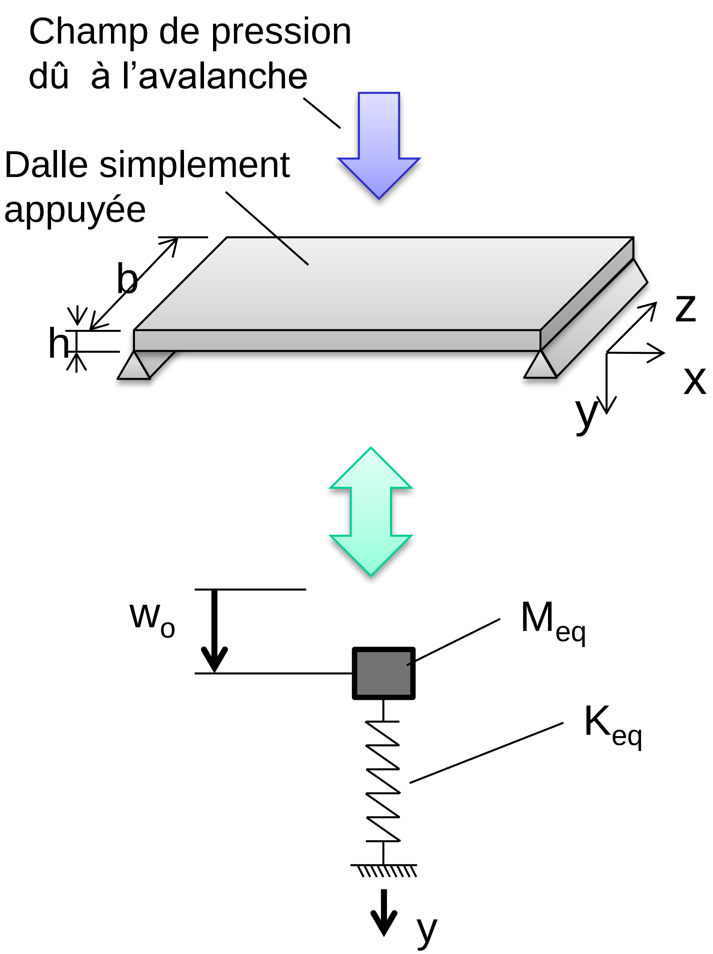
INSA LYON

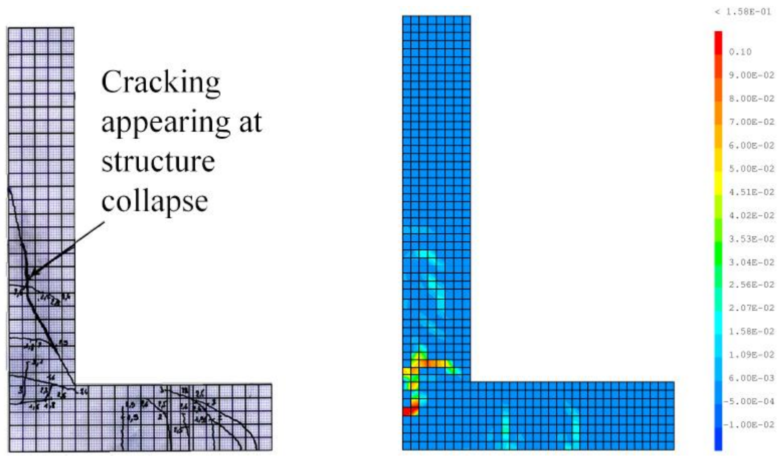
LGCIE
LABORATOIRE DE GÉNIE CIVIL & INGÉNIERIE ENVIRONNEMENTALE

# Modélisation des structures en BA

**Avantages**
- Calcul dynamique
- Prise en compte des effets d'inertie potentiels
- Description dans le temps du chargement (P(t))

**Inconvénients**
- Conditions aux limites réduites (pour le SDOF)
- Problèmes 3D plus complexe à traiter
- Plus couteux en temps de calcul

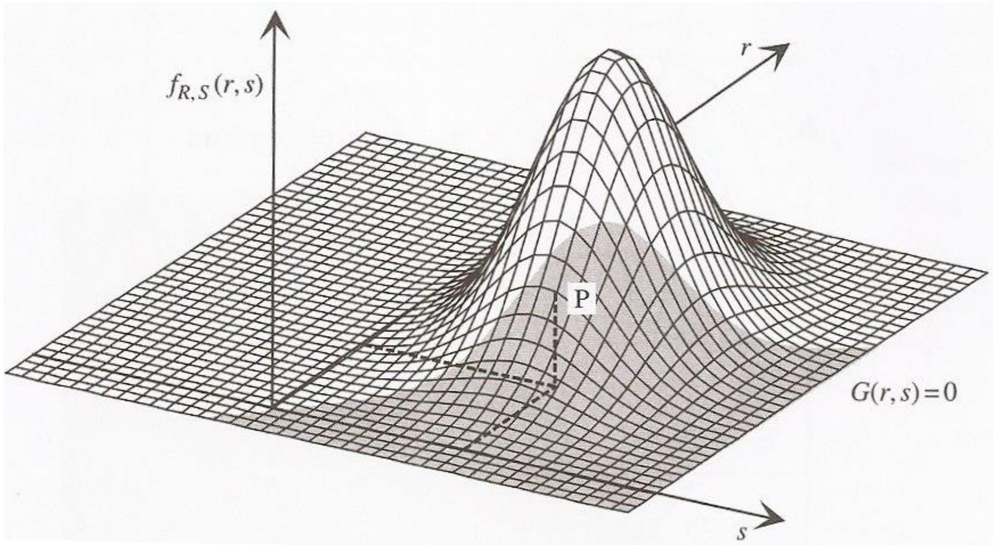


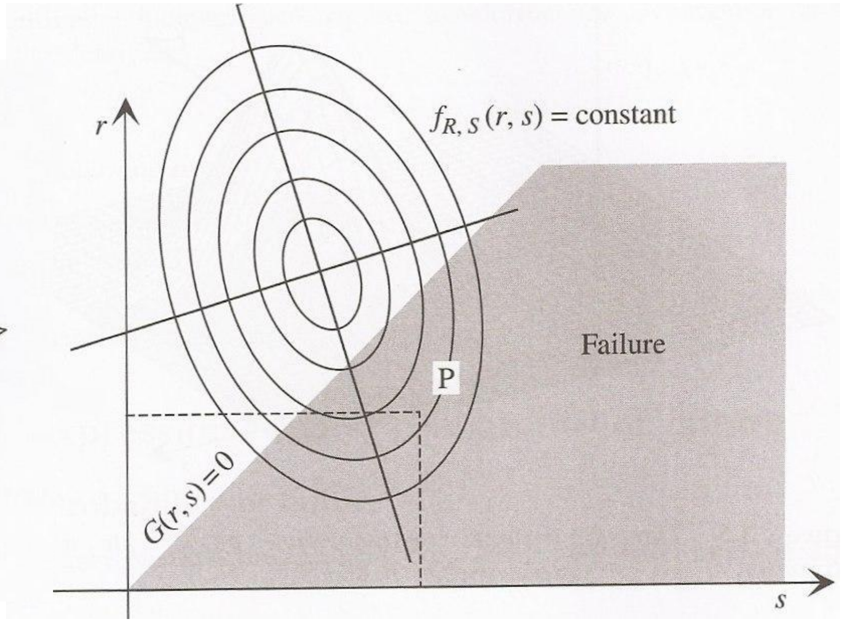




Simulation FEM (Favier et al., 2014)

## Méthodes SDOF (single degree of freedom) et FEM

# Analyse fiabiliste : calcul de la proba. de défaillance




$$\mathcal{P}_f = \mathrm{Prob}[G(\mathbf{x}) \leq 0] = \int_{\mathcal{D}_f} f_X(\mathbf{x}) dx$$

$f_X(x)$ : densité de proba. des variables d'entrées
$D_f$ : domaine de défaillance
$G(x)$ : critère de défaillance

# Vulnerability and fragility

- **vulnerability relations** : **deterministic** point of view, fraction of the studied element at risk destroyed according to solicitation intensity;

- **fragility relations** : **probability** of the entire element at risk to be destroyed according to a given solicitation intensity (a conditional expectation!).

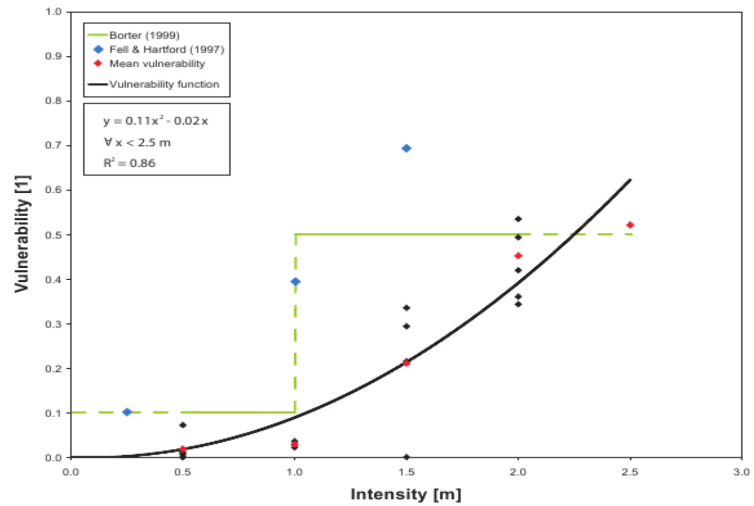



Fig. Vulnerability relationship between debris flow intensity x and vulnerability y expressed by a second order polynomial (Fuchs *et al.*, 2007)

<u>**Fragility definition:**</u>

- Makes sense for humans;
- Enables to take into account uncertainties (physical reliability framework);
- Copes for variability among a class of similar elements at risk: systematic risk assessment.

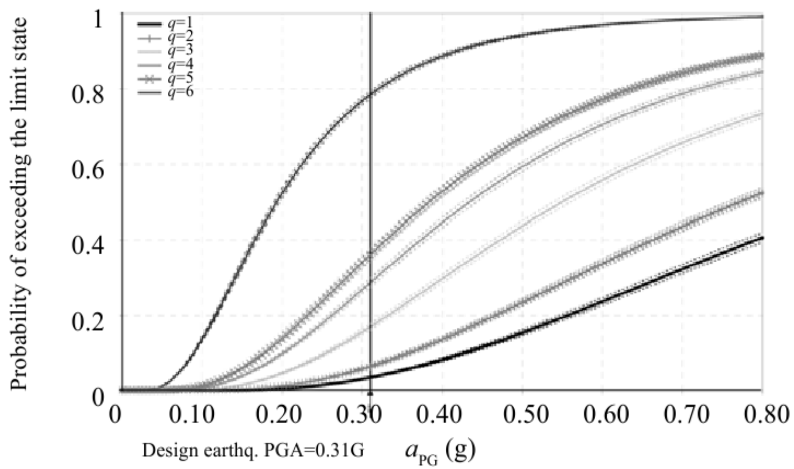



Fig. Fragility curves for a moderate limit state for RC buildings under seismic solicitations (Lagaros *et al.*, 2008)

# Evaluating fragility curves

**A model to summarize the building behaviour:**

- RC slab with different boundaries conditions;
- Quasi-static problem (maximal Pressure is the only critical variable)

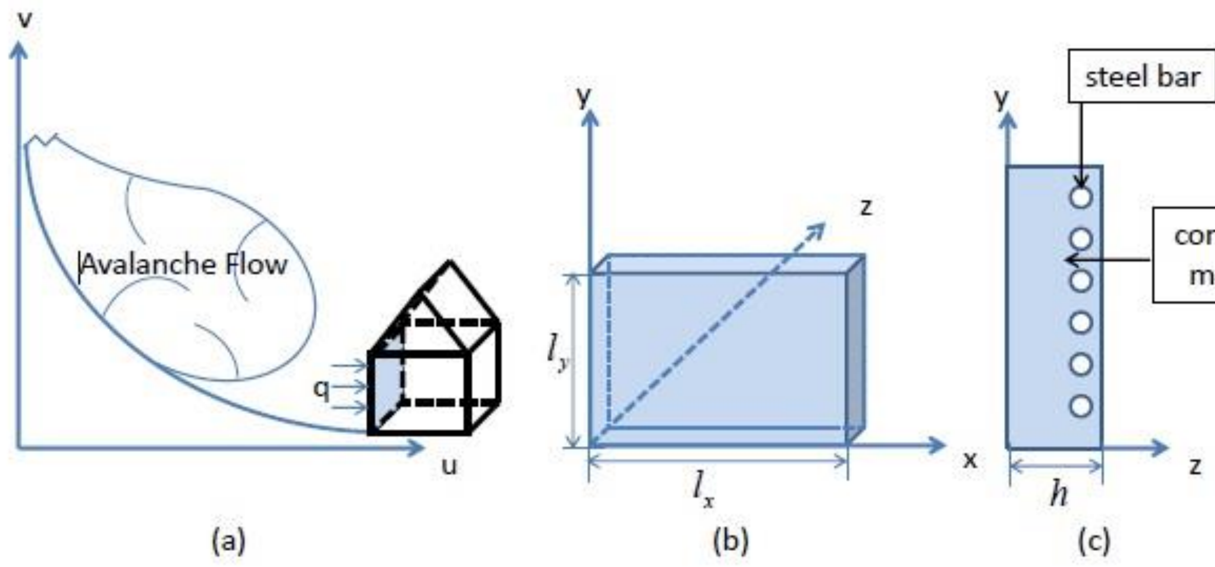



Fig.: Dwelling house impacted by a snow avalanche (a) - RC wall geometry in Favier et al. 2013 (b-c)

**Application of reliability theory:**

- Probabilistic descriptions of renforced concrete are avalaible (Structura safety, 2001);
- Small variability of geometrical variables;
- Reliability techniques to reconstruct the failure probability as function of pressure;
- Specific trick: the *V* function can be seen as a cdf!
- Sobol indexes (variance decomposition) for sensitivity analysis (with independant inputs).

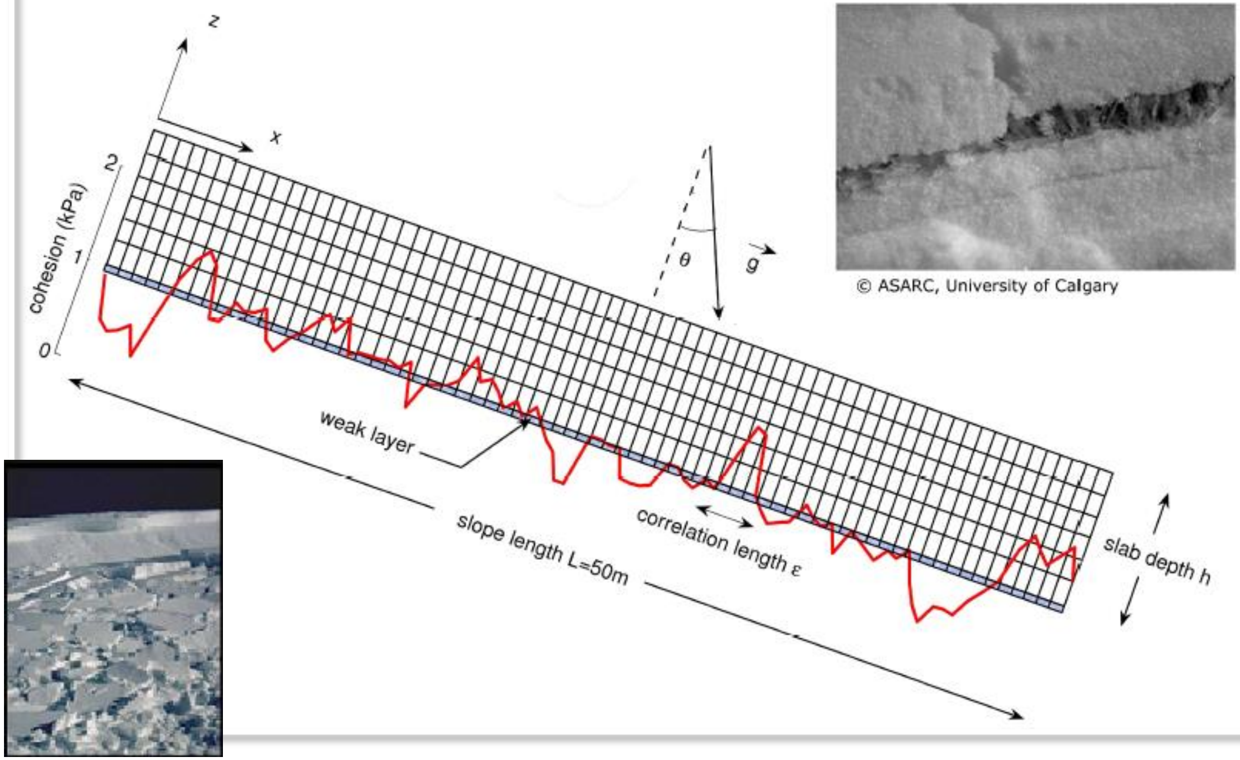
# Probabilistic assessment of rerelease susceptibility

## Objective

Spatial variability → slope stability

## Method

Mechanically-based statistical model of slab avalanche release
Gaume et al. (GRL 2012, JOG 2013)

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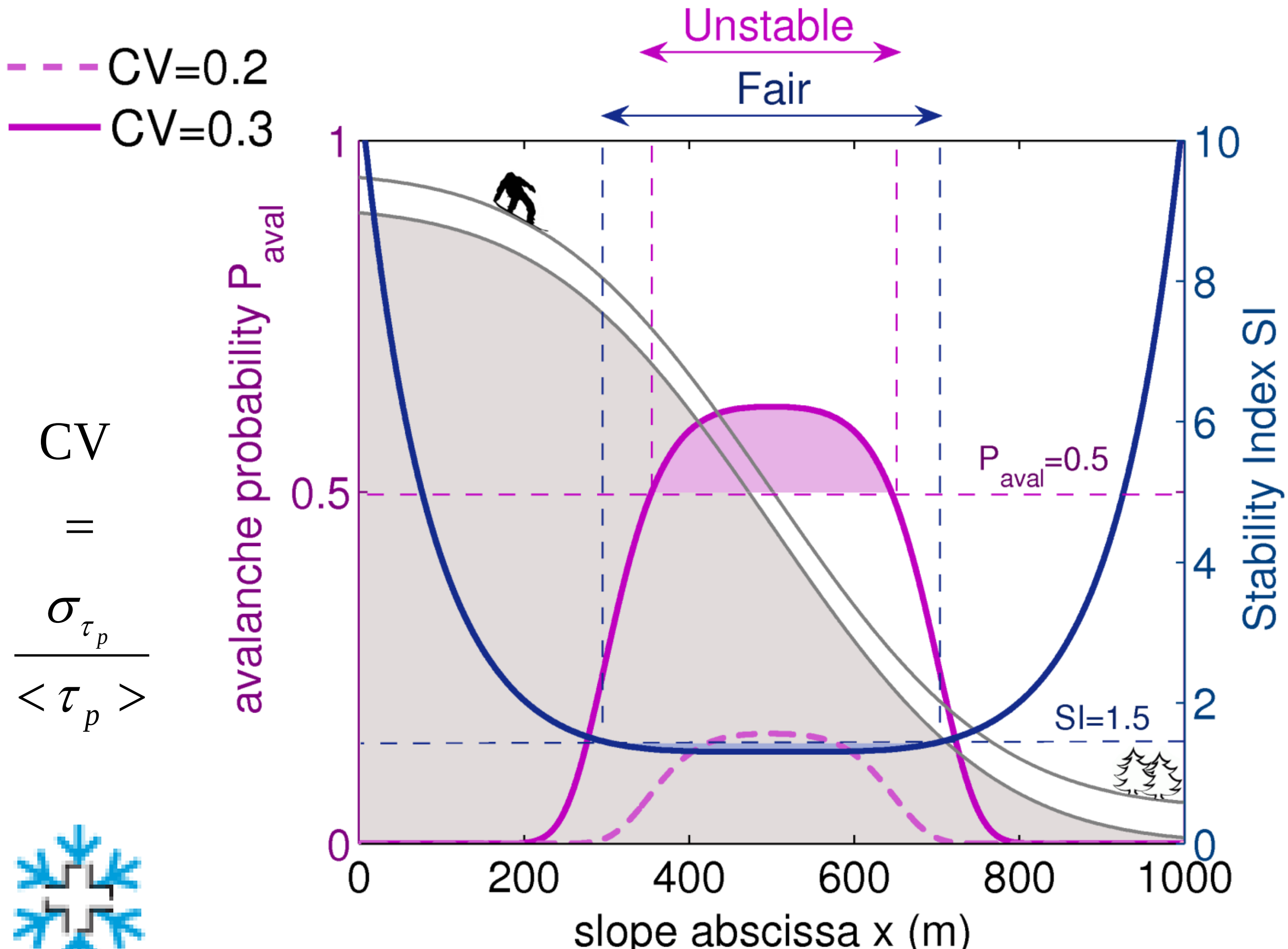
This model takes into account, in particular:

(1) the spatial variations of WL mechanical properties (shear strength)

(2) a shear quasi-brittle constitutive law for the WL

(3) stress redistribution effects by elasticity of the slab

# Slope stability evaluation



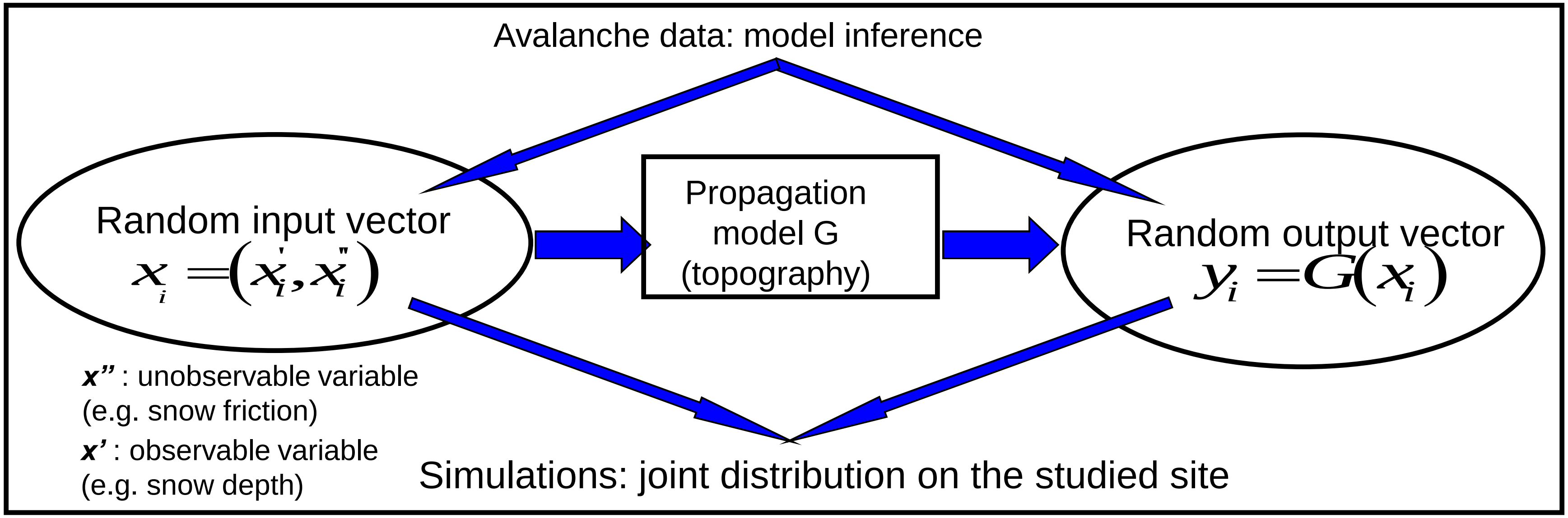

Stability index SI = $\frac{\text{shear strength}}{\text{shear stress}}$ = $\frac{\tau_p}{\tau_{xz}}$

$$CV = \frac{\sigma_{\tau_p}}{<\tau_p>}$$

$h_z$=50cm
$\rho$ =250kg/m$^3$
E=1MPa
**$\tau_p$=800Pa**

Gaume et al. JGR 2014

# Hazard multivariate statistical-numerical modelling




Not " fully explicit", but multivariate and with real topography and "robust" physics to constrain covariance between outputs

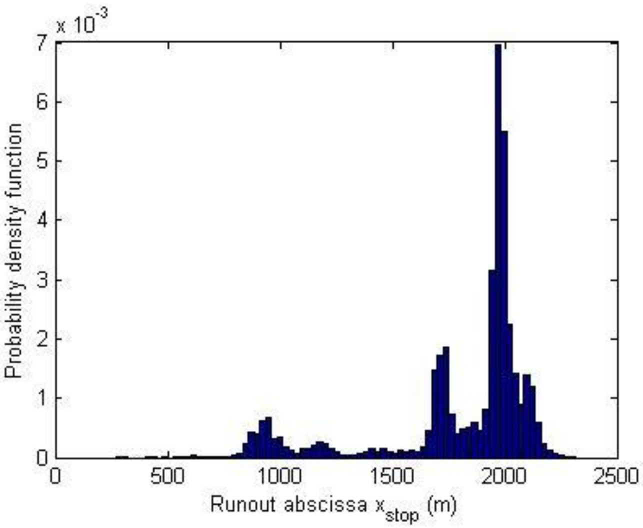
<u>Modelling issues:</u>

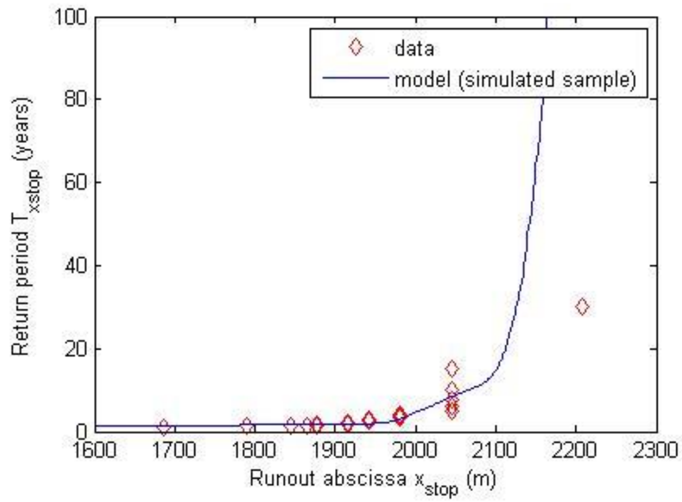
- Deterministic propagation model
- Stochastic modelling of the correlated random input vector (~Multivariate POT / stochastic generator) : variability and/or uncertainty!

<u>Technical issues:</u>

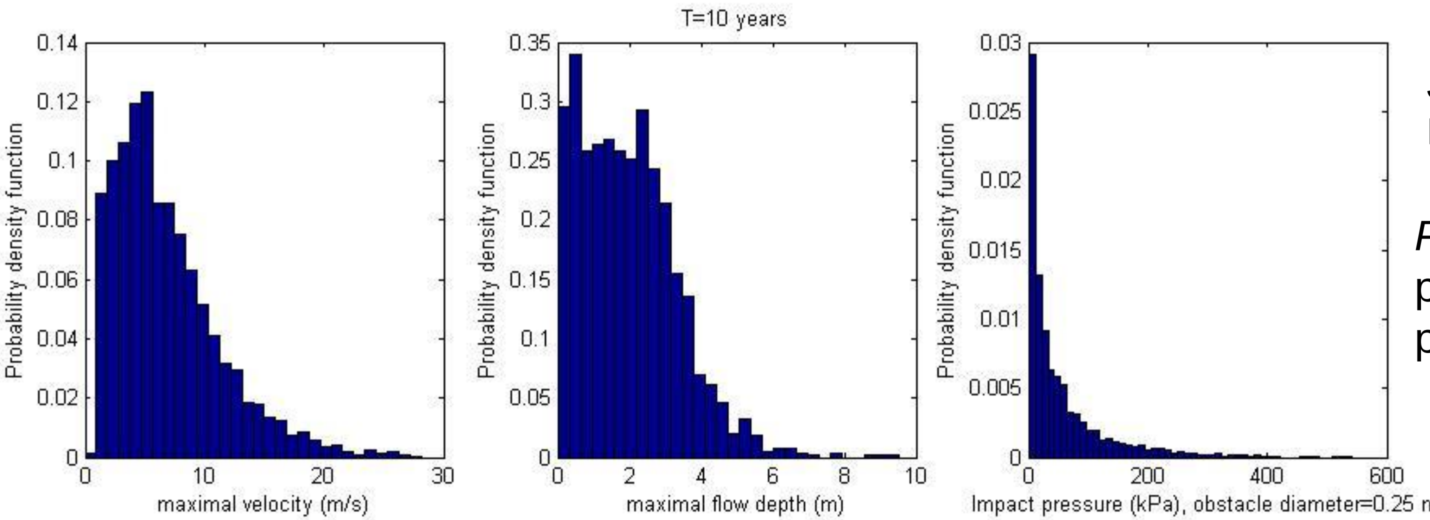
- Inference with a complex model, non invertible model
- Simulation: physical reliability like framework (fast approximation of small probabilities)

# Example 1: snow avalanches




$$T_{x_{stop}} = \frac{1}{\hat{\lambda} \times \left(1 - \hat{F}(x_{stop})\right)}$$

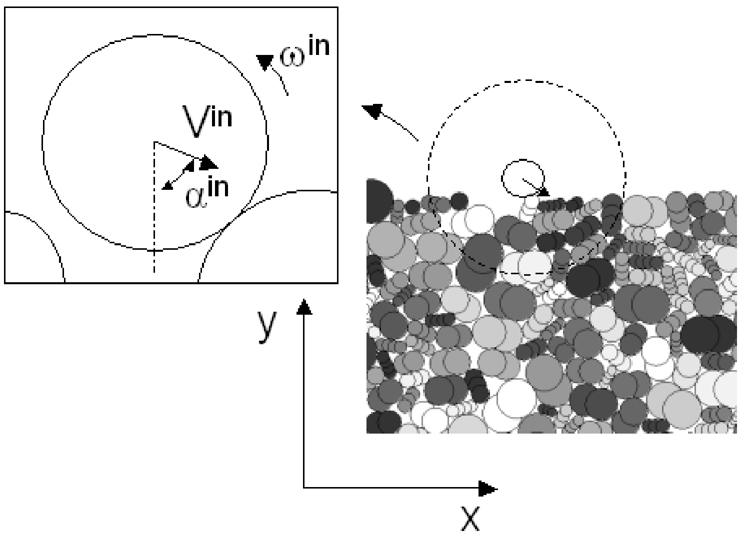


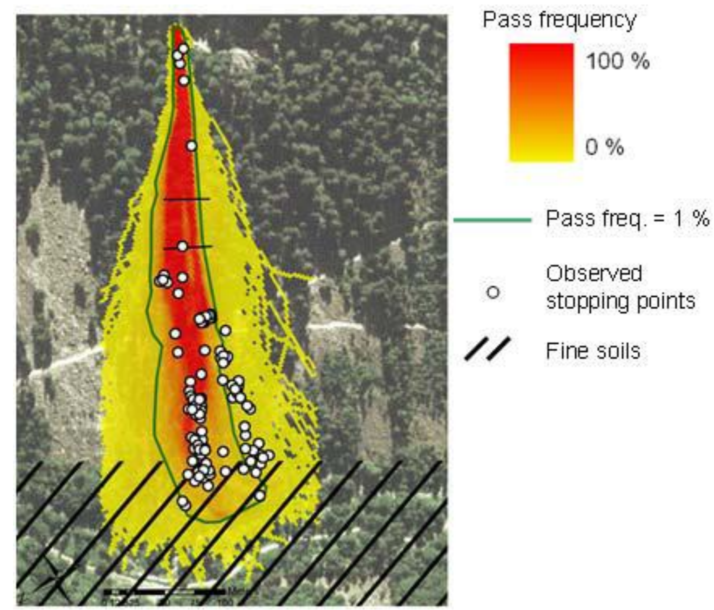

Joint distribution
P($v$,$h$,$Pr$.. I $x_{stop}$ > $x_{stopT}$)

*Posterior* mean (or other point estimates), or predictive simulations

Model and case study from Eckert et al. (2010). The statistical-dynamical model is calibrated on the local data (MCMC techniques). It provides the one-to-one relation between runout distance and return period, and, for each runout distance/return period, the joint distribution of all other variables. Impact pressure is computed following Naaim et al. (2008), taking the rheology of snow into account.

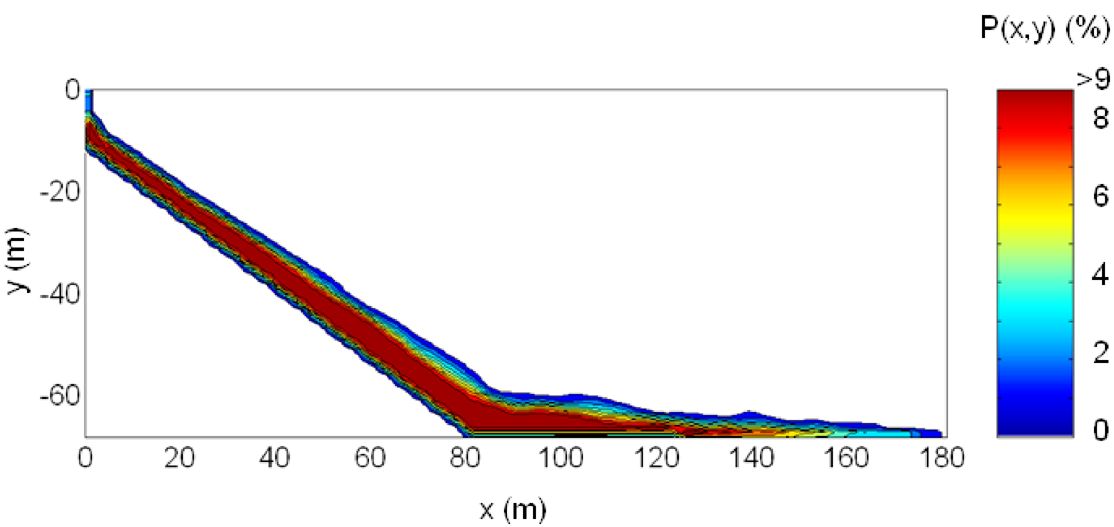
# Example 2: Rockfall



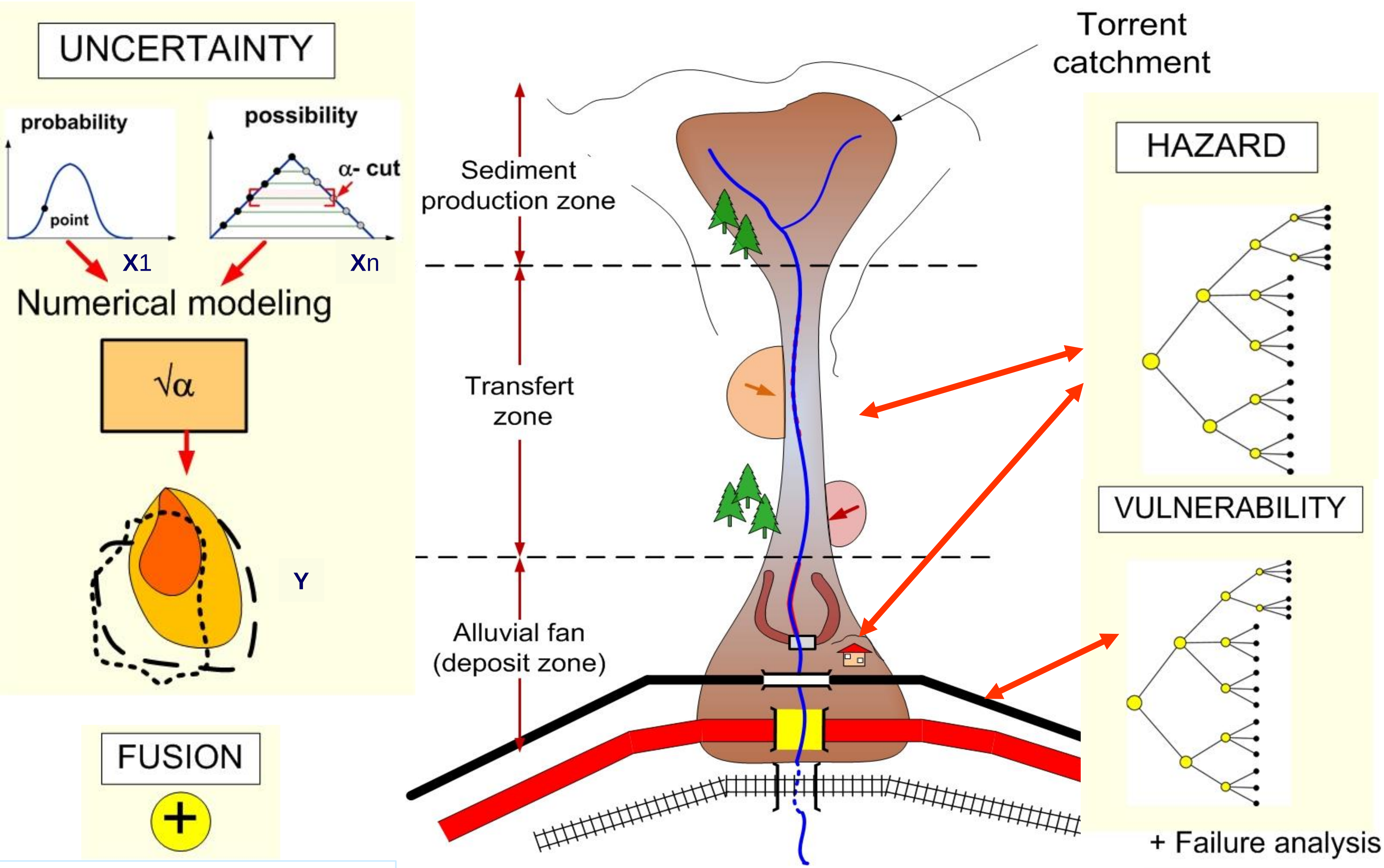

, from

Bourrier et al., EJECE, 2010

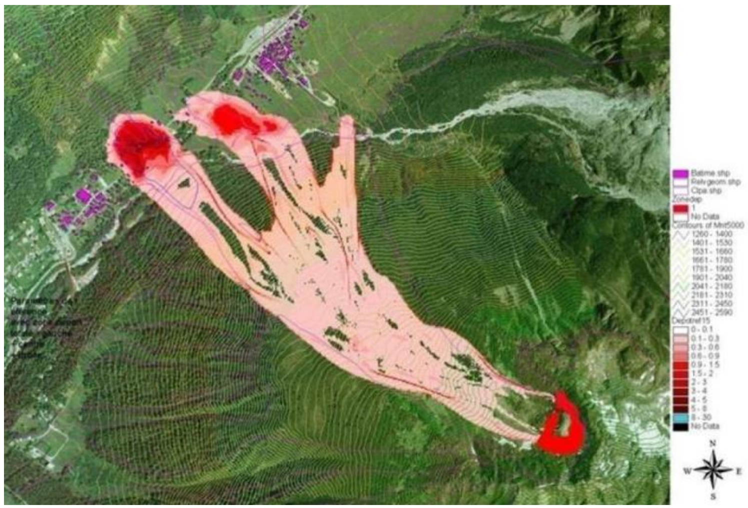



Probability for the occurrence of a rockfall event in all points of the study site, from Bourrier et al., NHESS 2009

# Example 3: debris flows



# Evaluation quantitative du risque



Modèle probabiliste d'aléa multivarié

Courbes de fragilité

$$R_w = \sum_w q(z_w) z_w \int p(y) V(z,y) dy$$

**Théorie statistique (économétrique) du risque :**

- choix d'une statistique résumé de la fonction de perte (ici MLE-CTE)
- Approximations numériques pour des probabilités d'aléa faibles
- Calcul d'incertitudes
- Cadre fiabiliste!

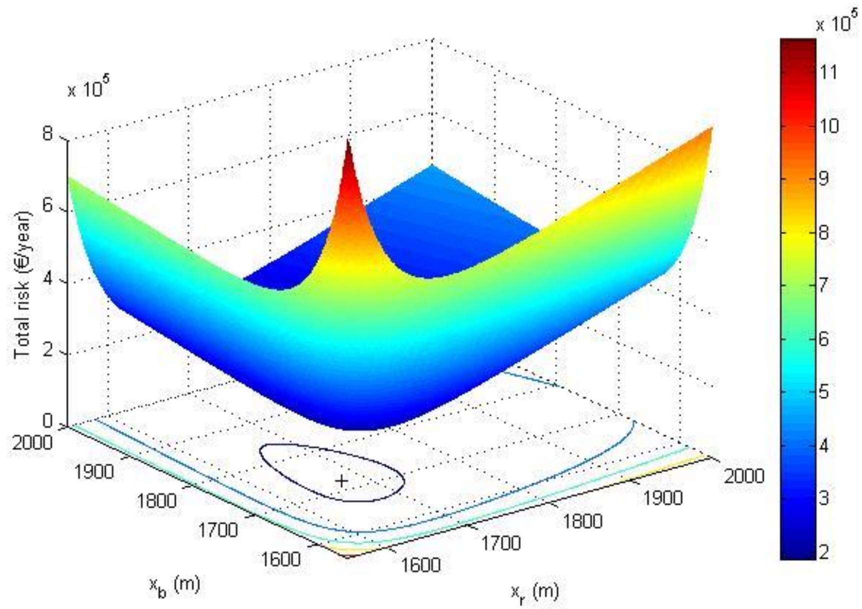
# Decisional framework to risk minimization

- Risk can be modified by a (possibly multidimensional) decisional variable *d*.

Possible additive formulation (inspired by Van Dantzig, 1956):

$$R_w(d) = C_o(d) + \sum_{z \in w} \left(z_w \middle| d\right) q\left(z_w \middle| d\right) \int p\left(y \middle| d\right) V(z, y) dy$$

- Decision may affect hazard, elements at risk, but not their vulnerability
- Optimal decision minimizes the risk (paradigm of maximizing expected utility): Von Neuman and Morgenstern (1953); Prat et al., 1964; Raiffa (1968)
- Classical application: Bayes point estimates: $E_\theta\left[p\left(\theta \middle| y\right)\right] = \mathrm{Argmin}\left(\int (\theta - \theta_o)^2 \, p\left(\theta \middle| y\right) d\theta\right)$
- In general: no analytical solution: fast numerical approximations of the risk function are needed (reliability like methods)




Avalanche risk zoning limits by loss minimisation (Eckert et al., in prep)

# Integrated assessment of protective structures efficiency

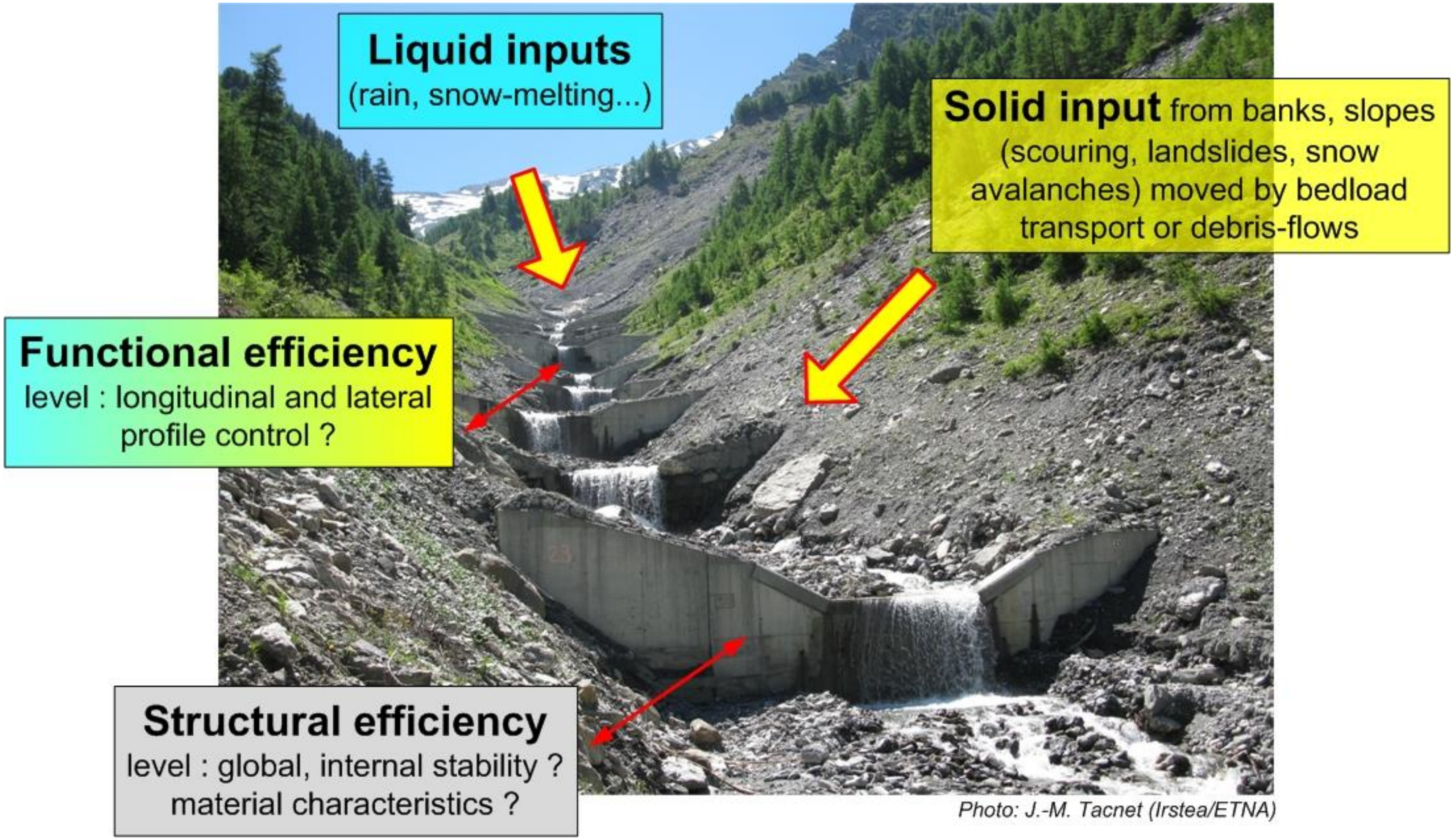
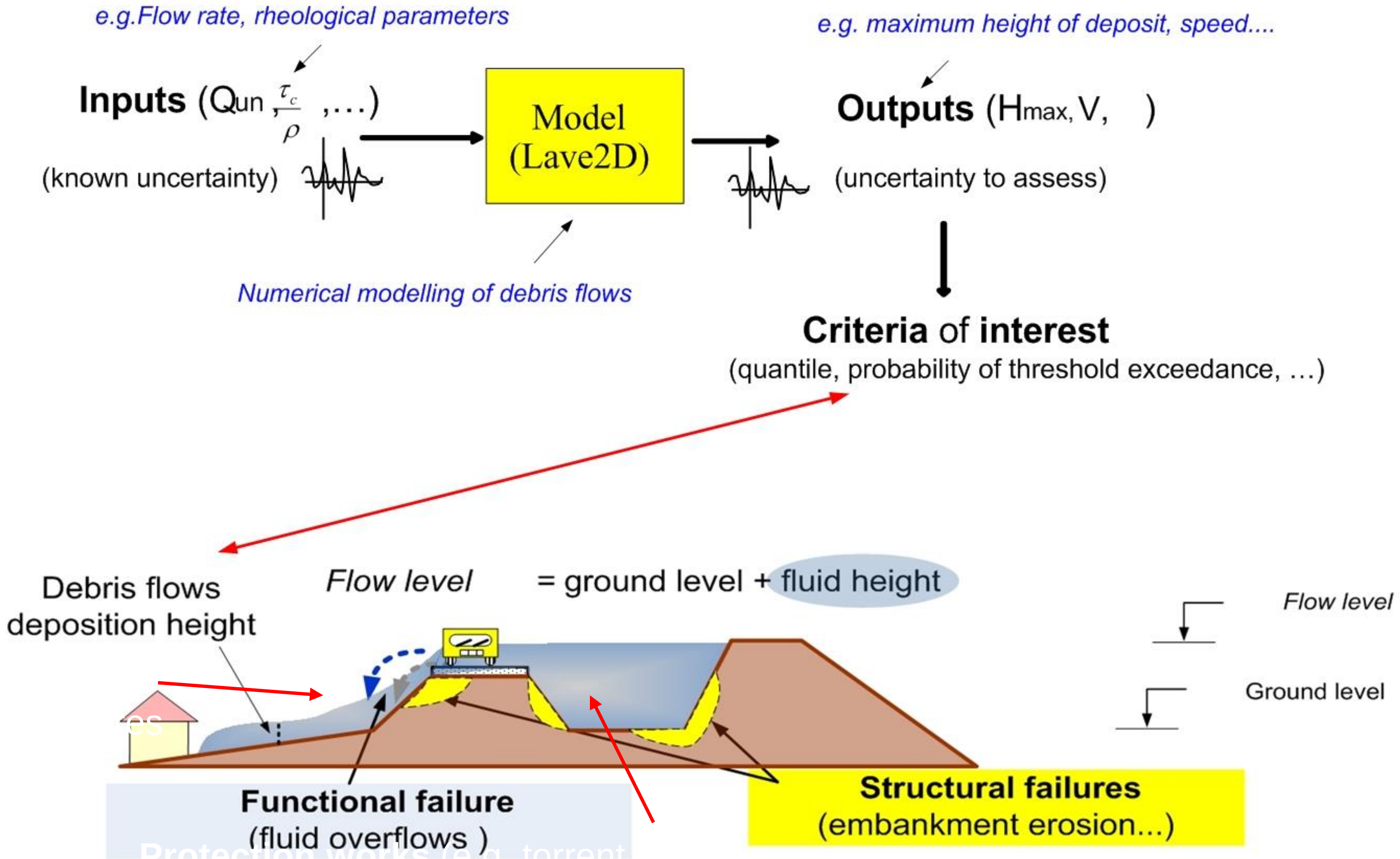



Photo: J.-M. Tacnet (Irstea/ETNA)

➡ Need for integrated indicators mixing information of various nature and quality, results of uncertainty analyses, expert knowledge, etc.

# Application to debris flow risk management




*Indicators, information imperfection, decision-making methods*

(Tacnet and Curt, Annales ITBTP , 2011) *(Tacnet et al., Envt Systems and Decisions, 2014)*

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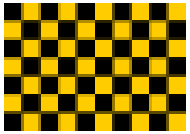
- **Une application (un peu) plus détaillée : la gestion à long terme du risque avalanche**

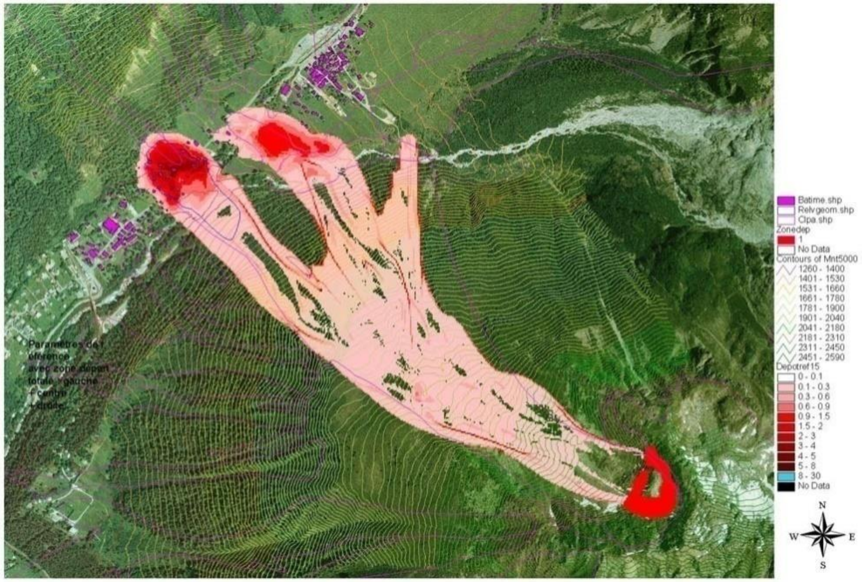
# Avalanche risk mitigation

**Long term land use planning** ≠ avalanche forecasting



- Snow and weather data and snow cover model (real time data assimilation).
- Statistical / mechanical assessment of stable/unstable conditions

Hazard mapping and zoning




Avalanche numerical simulation for hazard mapping

Construction of countermeasures

Passive defense structure

# “Reference hazards” in the snow and avalanche field

Legal thresholds for land use planning based, like in hydrology, on <u>return periods and corresponding return levels</u>: 100 years in France, 30-300 years in Swiss, up to 1,000 years in Iceland…

<u>Multivariate definition</u> : runout distance (travelled distance) / impact pressure

Montroc (Haute Savoie, France), 9 February 1999, building moved and destroyed

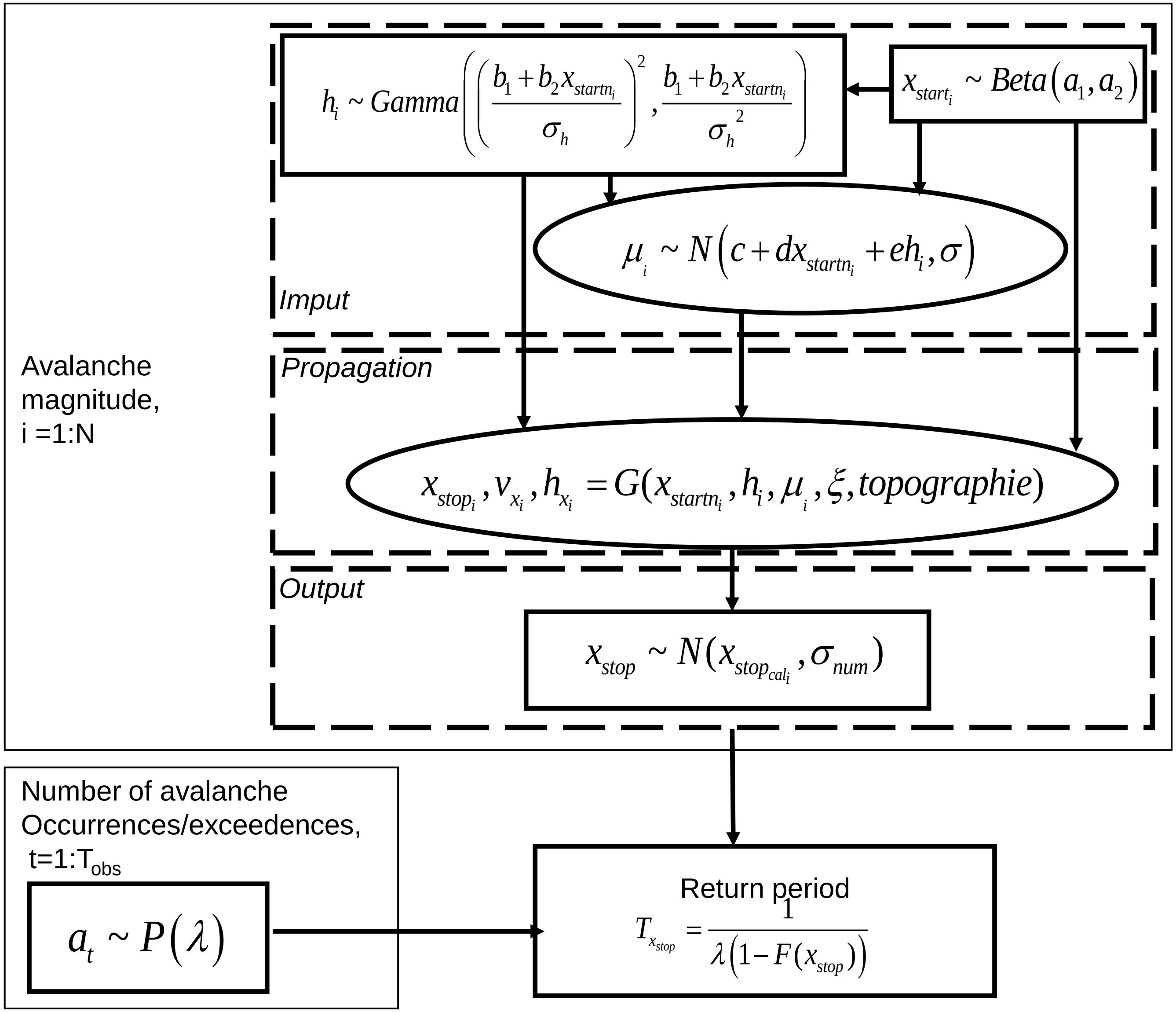
# A statistical-numerical multivariate POT model

Joint modelling of the observable and latent input variables using conditional modelling: release position and depth, and latent friction coefficient

Transfer function: avalanche propagation as a depth averaged fluid (Naaim et al., 2004)

Gaussian differences between observed and simulated runout distances

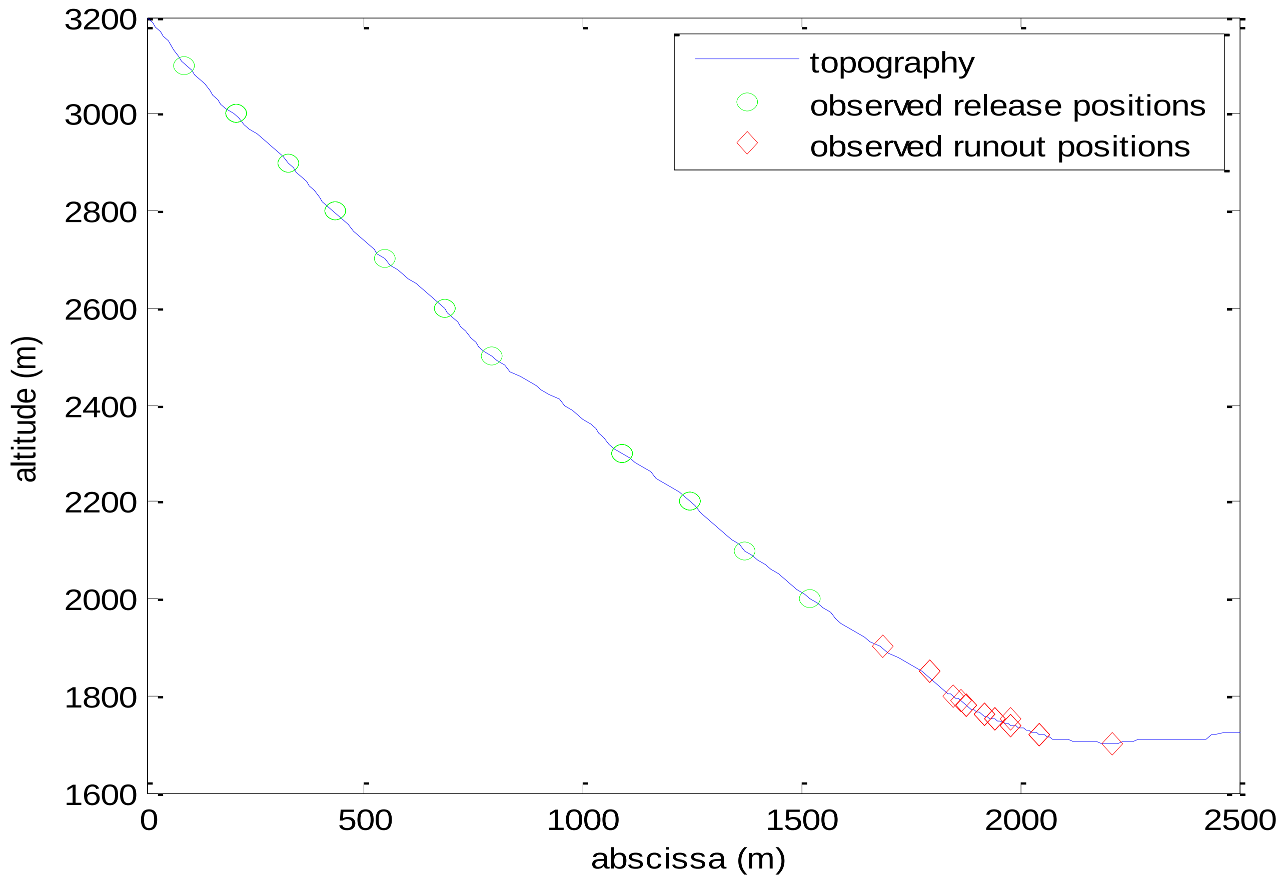
Independent modelling of avalanche magnitude and number of occurrences/exceedences: Efficient "pseudo POT model" (Eckert et al., JOG 2010)




Return period for the runout distance

# Case-study

- Bessans township (Savoie department);
- EPA path number 13;
- 41 occurrence data over 44 winters;
- Among them, 26 reliable release/runout altitudes;
- Deposit volume dimensions;
- Supplemented by Safran/crocus input data (meteo France).

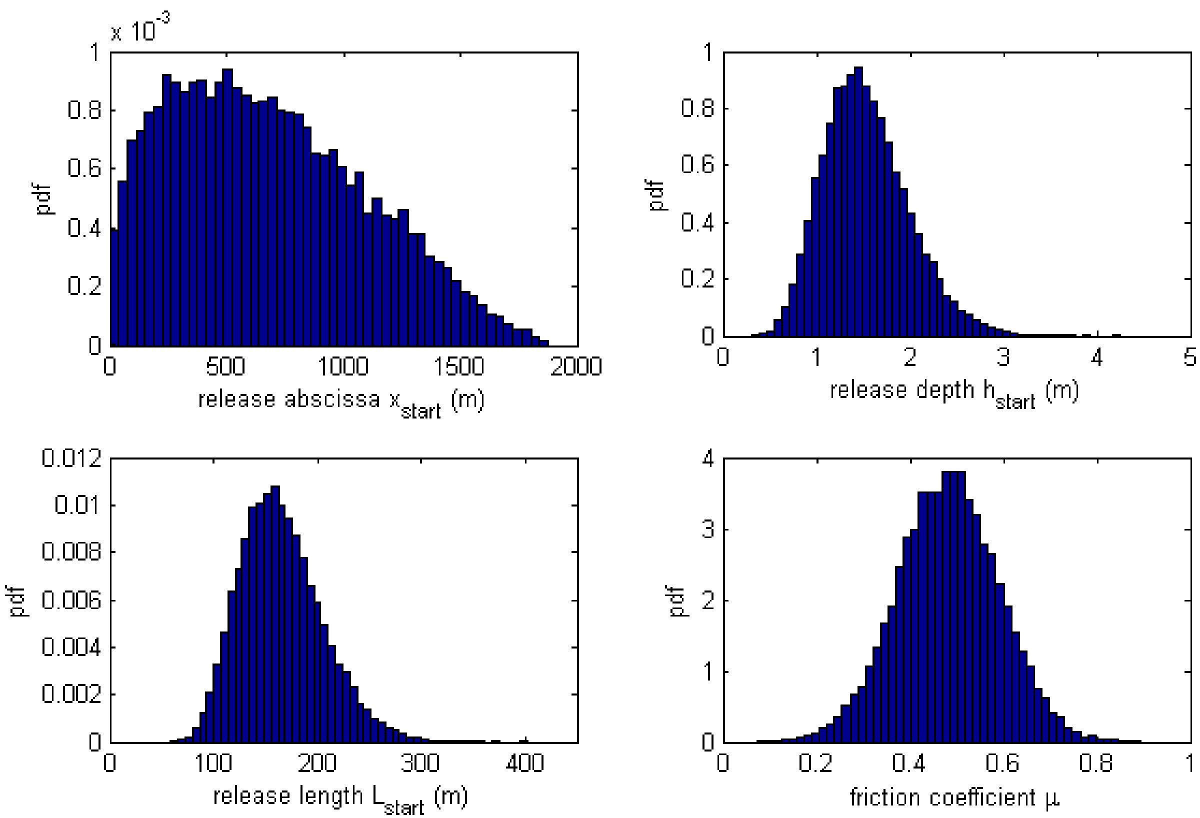


# Simulation: joint distribution of model variables

$$p\left(x_{stop}, v, h... \middle| \hat{\theta}_M\right) = \int p\left(x_{start} \middle| \hat{a}_1, \hat{a}_2\right) \times p\left(h_{start} \middle| \hat{b}_1, \hat{b}_2, \hat{\sigma}_h, x_{start}\right) \times p\left(x_{stop} \middle| x_{start}, h_{start}, \mu, \hat{\xi}\right) \times d\mu$$

Monte Carlo simulations:

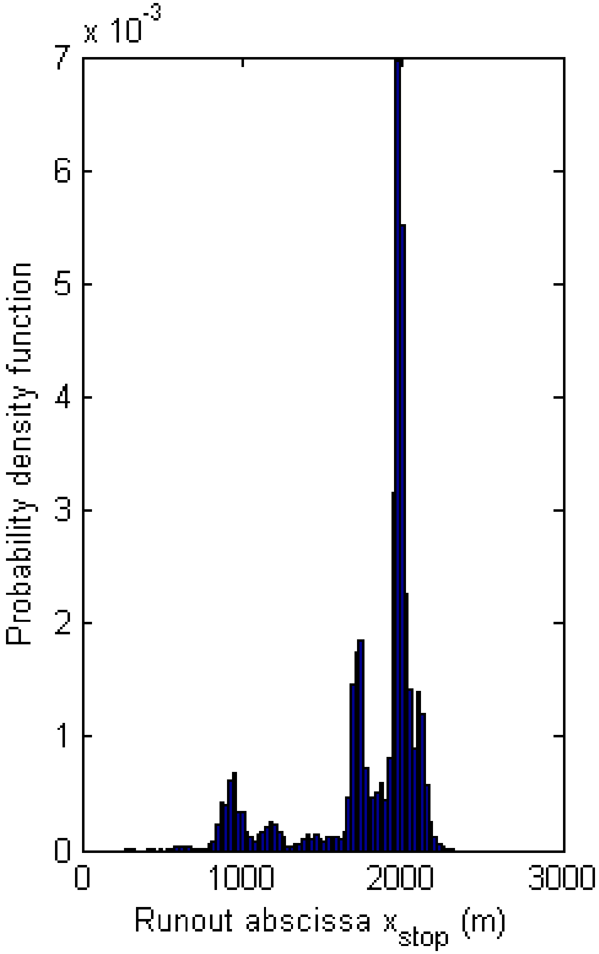
- standard Monte Carlo scheme: slow $\sqrt{n}$ convergence speed
- accelerated (directional or others) Monte Carlo methods: faster convergence
- integration over hidden variables

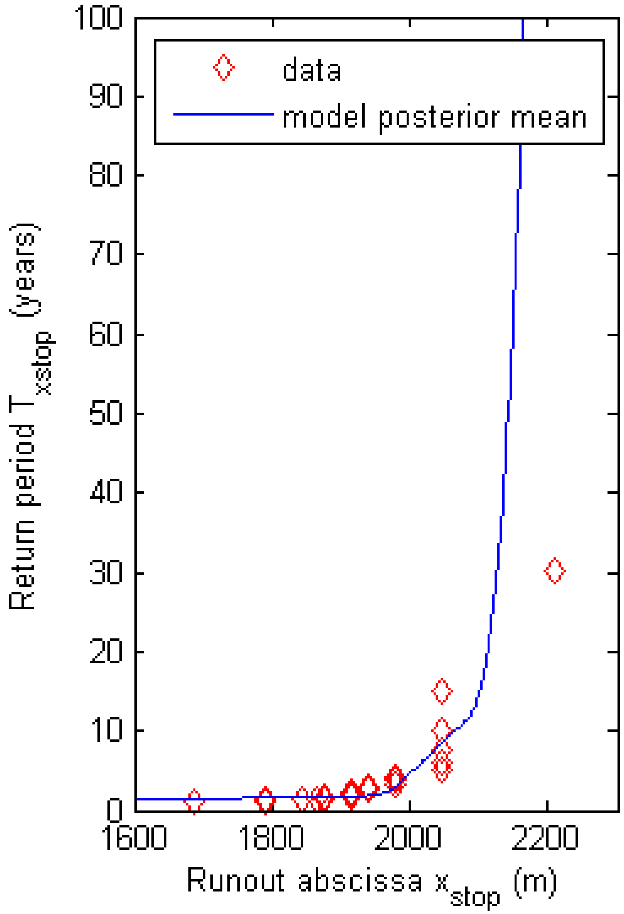



Joint distribution of the variables of the non fully explicit avalanche magnitude model

# Runout distance and return periods

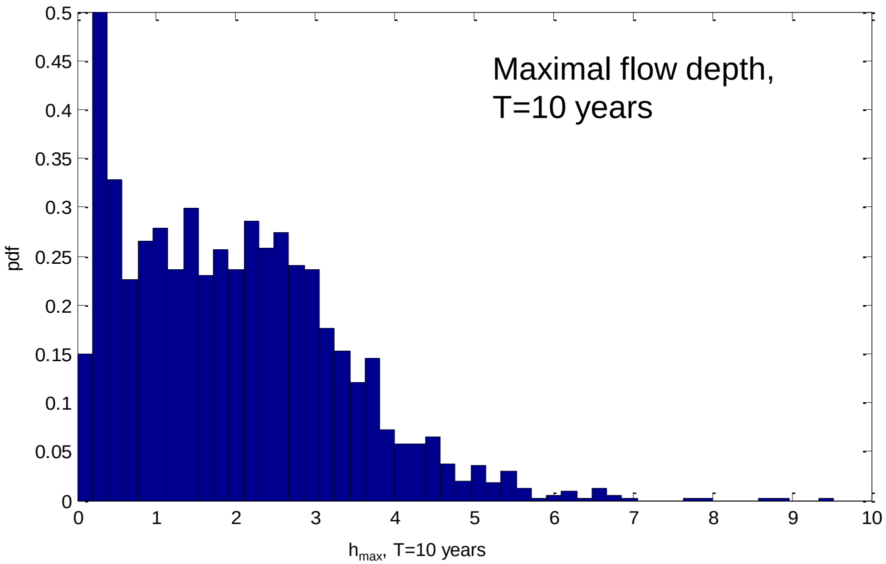
Return period for each abscissa combining:
- a point estimate of the mean avalanche occurrence/threshold exceedence number $\hat{\lambda}$
- the estimated runout distance cdf $\hat{F}(x_{stop})$

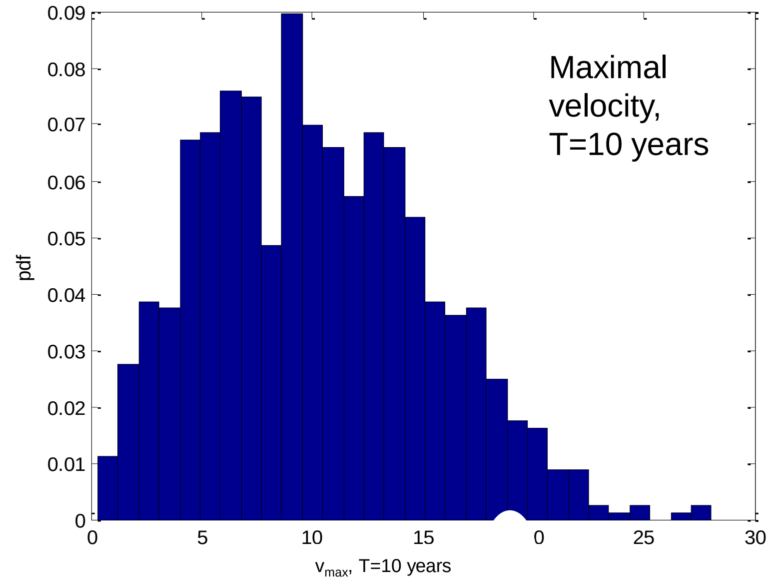


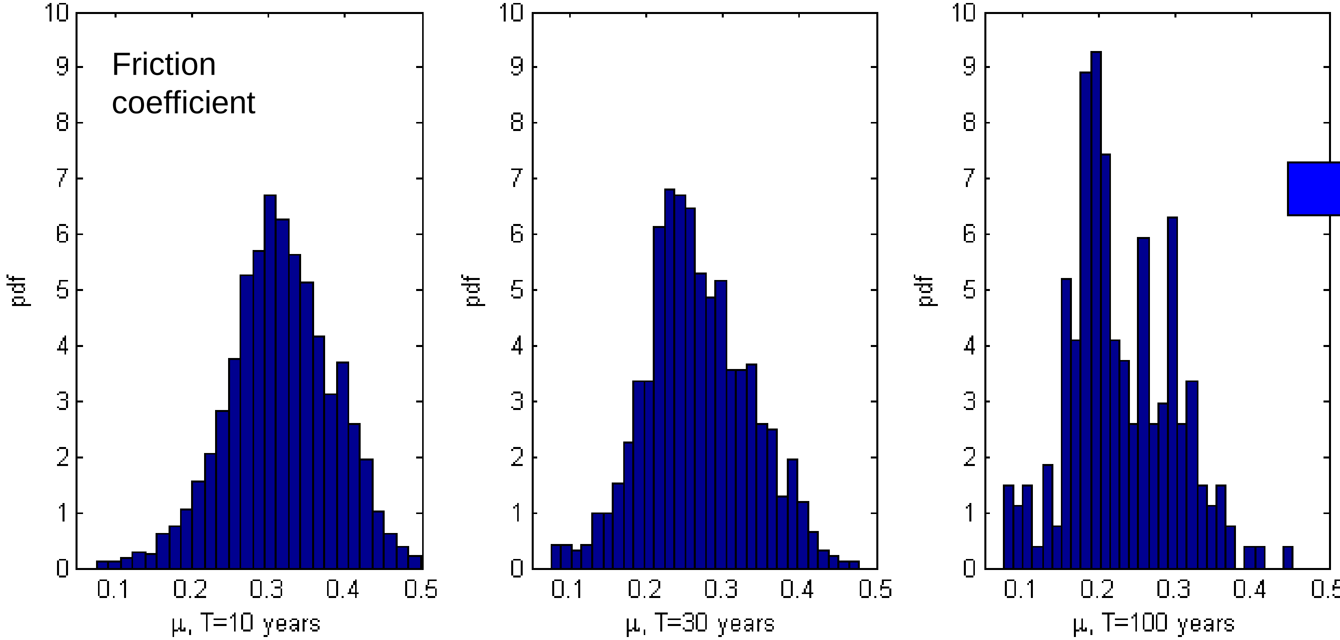




$$T_{x_{stop}} = \frac{1}{\hat{\lambda} \times \left(1 - \hat{F}(x_{stop})\right)}$$

# Joint distribution P($v,h,\mu$.. I $x_{stop} > x_{stopT}$)



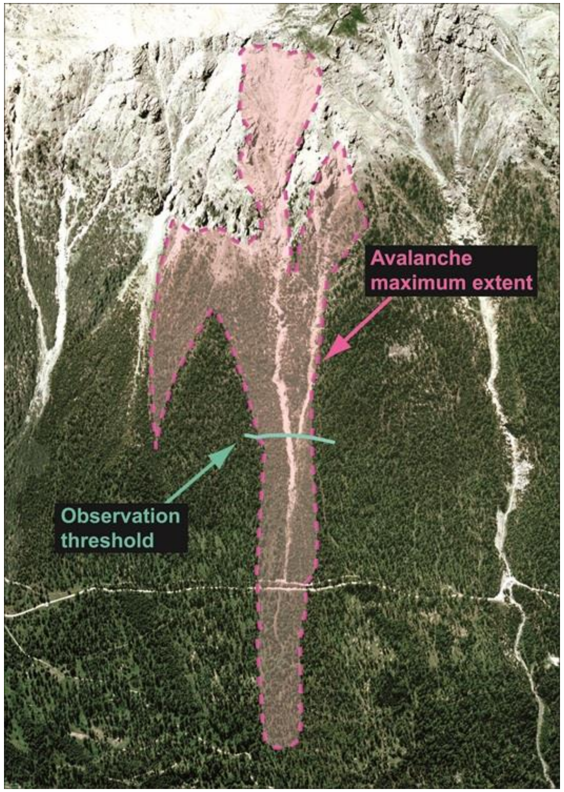




Hazard mapping and zoning, Structural and functional design of defense structures.

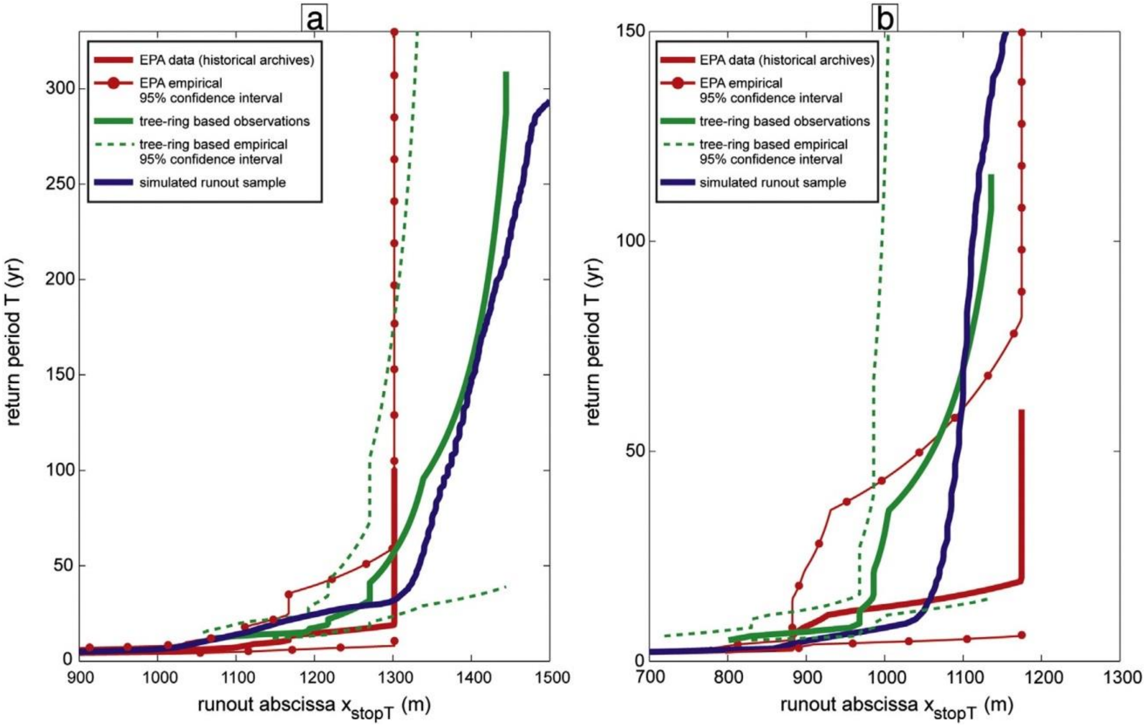
# Validation of model predictions?

Independent “fossil” data from tree ring sampling campaigns :

- Complement EPA database (longer period);
- Can help to validate the statistical- dynamical predictions




*Château Jouan avalanche path, French Alps. Maximal extent and observation threshold in historical chnonicle (EPA database) from Schläppy et al., AAAR 2013*




*Runout distance –return period relationships for two French paths, from Schläppy et al. (CRST 2014). Tree-ring reconstructions versus statistical-numerical predictions.*

# Estimation: Bayesian inference for the magnitude model

Bayes' theorem for parameters and latent variables:

$$p\left(\theta_M, \mu, x_{stop_{cal}} \middle| data, \sigma_{num}\right)$$

$$\propto \underbrace{p\left(\theta_M\right)}_{\text{Prior}} \times \prod_{i=1}^{N} \left( \underbrace{l\left(x_{start_i}, h_i, x_{stop_i} \middle| \theta_M, \mu_i, x_{stop_{cal_i}}, \sigma_{num}\right)}_{\text{Likelihood}} \times \underbrace{p\left(\mu_i, x_{stop_{cal_i}} \middle| \theta_M, x_{start_i}, h_i, x_{stop_i}, \sigma_{num}\right)}_{\text{Distribution of latent variables}} \right)$$

Conditional specification of the model:

$$l\left(x_{start_i}, h_i, x_{stop_i} \middle| \theta_M, \mu_i, x_{stop_{cal_i}}, \sigma_{num}\right) = l\left(x_{start_i} \middle| a_1, a_2\right) \times l\left(h_i \middle| b_1, b_2, \sigma_h, x_{start_i}\right) \times l\left(x_{stop_i} \middle| \sigma_{num}, x_{stop_{cal_i}}\right)$$

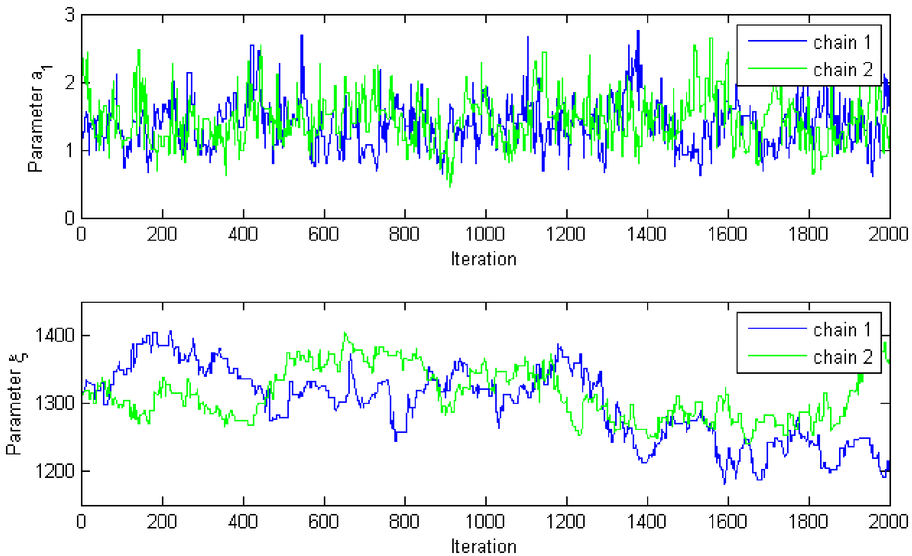
Deterministic propagation:

$$p\left(\mu_i, x_{stop_{cal_i}} \middle| \theta_M, x_{start_i}, h_i, x_{stop_i}, \sigma_{num}\right) = p\left(\mu_i \middle| c, d, e, \sigma, x_{start_i}, h_i\right) \times \delta\left(G(x_{start_i}, h_i, \mu_i, \xi)\right)$$

MCMC simulations:

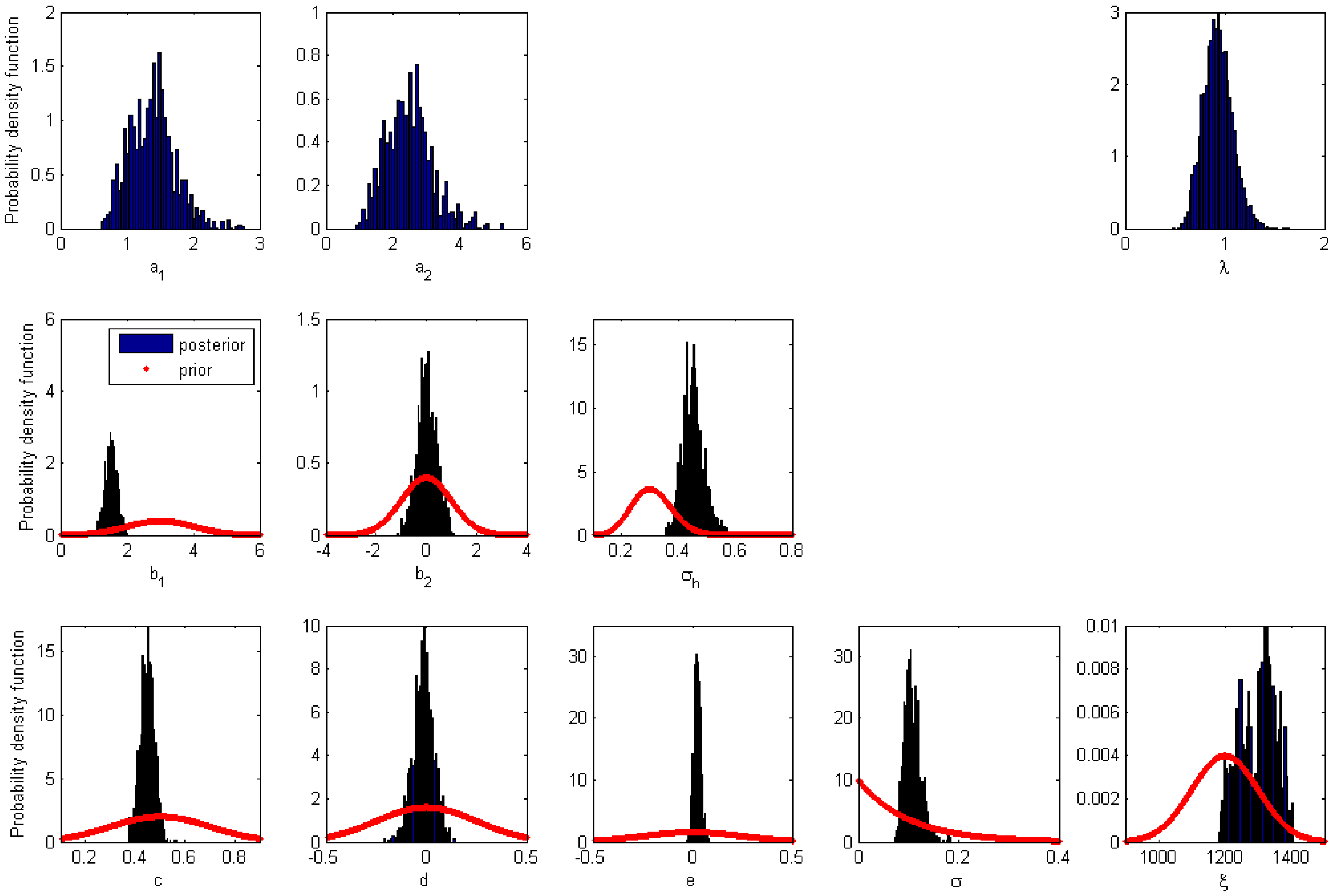
- Gibbs and sequential MH within Gibbs;
- Tuned by adapting jump strength (subtle in practice);
- Converge diagnosis: Gelman and Rubin test.

Computationally intensive, solved in a (rather) efficient way




MCMC sequence for two model parameters with low and high autocorrelation, respectively

# Posterior distributions of magnitude model parameters




- Friction coefficient $\xi$ and parameters describing the variability of the input variables
- Prior / posterior update: introduction of expertise into the modelling!
- Point estimates and associated uncertainty available for simulation.

# Uncertainty quantification : Bayesian predictive percentiles

- Predicted percentile/return period averaged over posterior pdf (Eckert et al., SERRA 2008):

$$p\left(x_{stop_q}\,|data\right)=\int F^{-1}_{x_{stop}|\theta_M}\left(q/100\right)\times p\left(\theta_M\,|data\right)\times d\theta_M$$

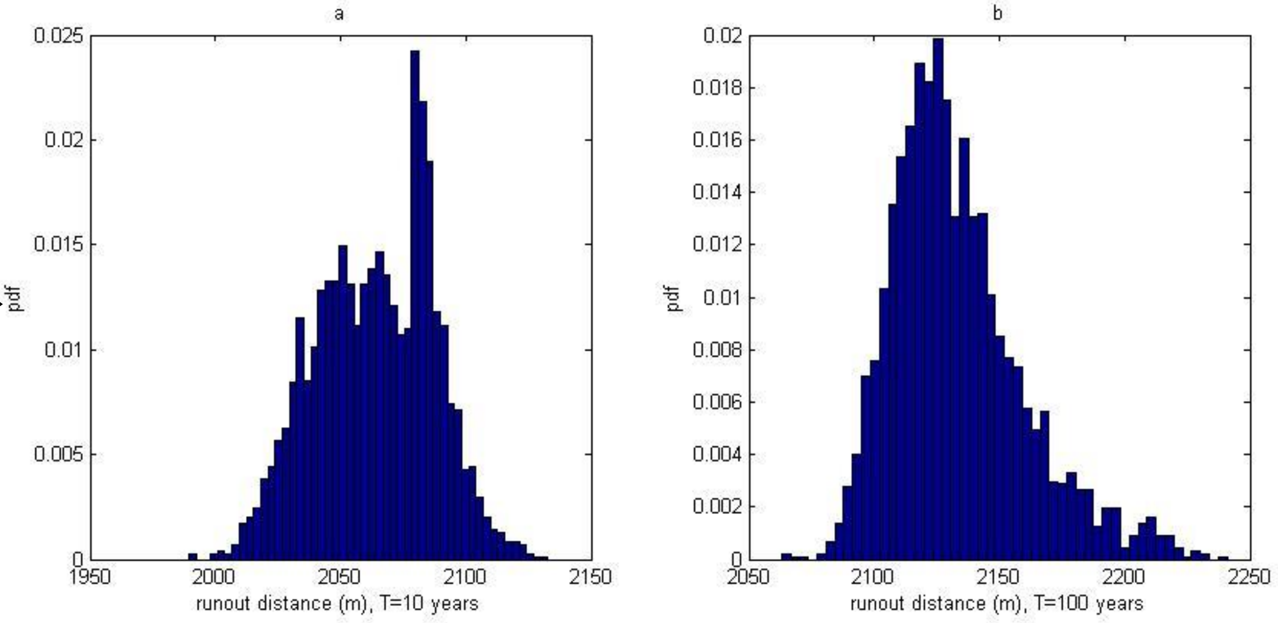
$$p\left(x_{stop_T}\,|data\right)=\int F^{-1}_{x_{stop}|\theta_M}\left(1-\frac{1}{\lambda T}\right)\times p\left(\theta_M\,|data\right)\times p\left(\lambda|data\right)\times d\theta_M\times d\lambda$$

- Fair representation of uncertainty associated to the limited data quantity;

- Alternative method to delta-like methods under the classical paradigm;

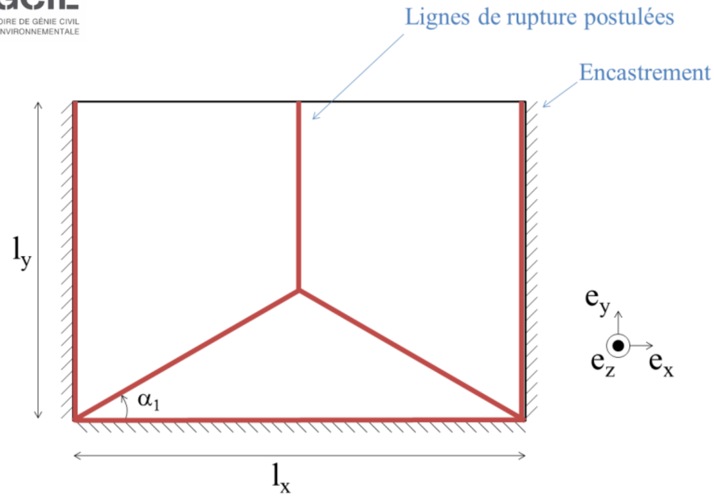
Abscissas corresponding to return periods of a) 10 years and b) 100 years.

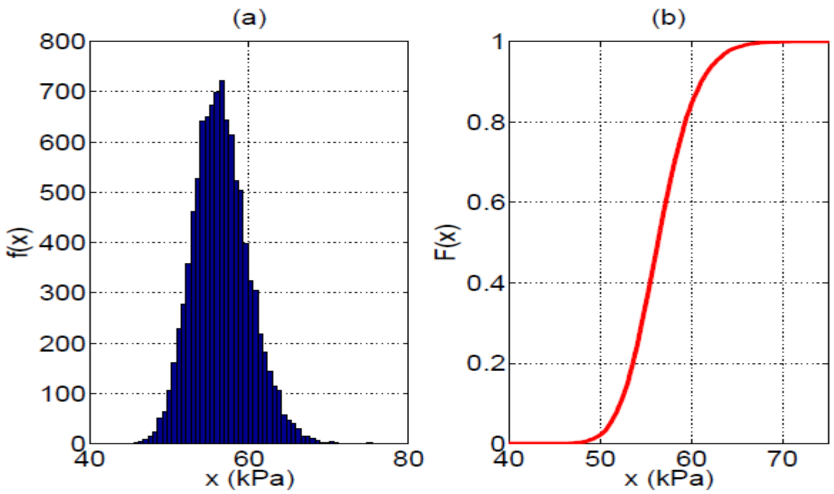
Mean, variance and skewness increase with return period: critical for hazard evaluation



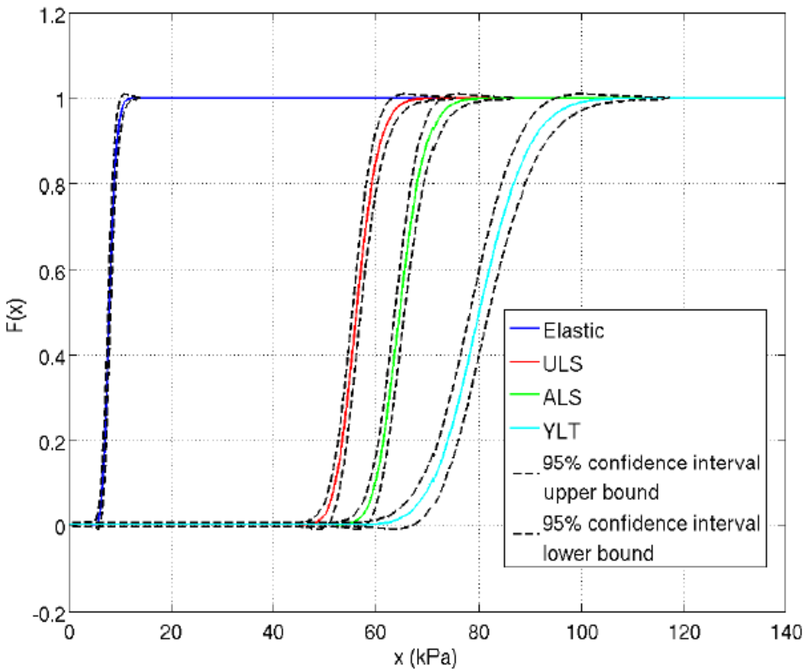
# Courbes de fragilité pour les structures BA (1)

## Un exemple: dalle encastrée sur 3 côtés



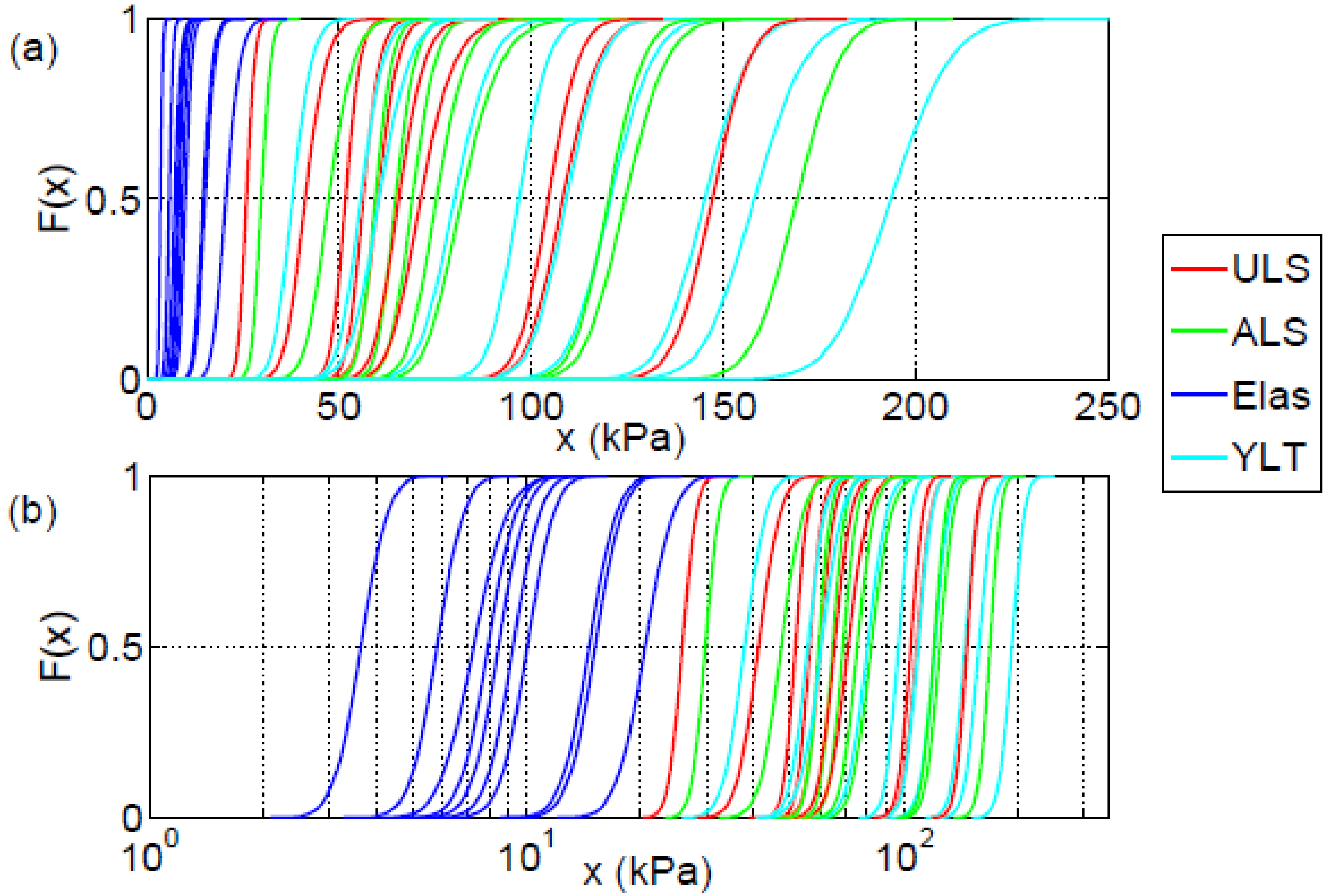

Critère ULS




Courbe de fragilité pour l'ensemble des critères (Favier et al. NHESS 2013)

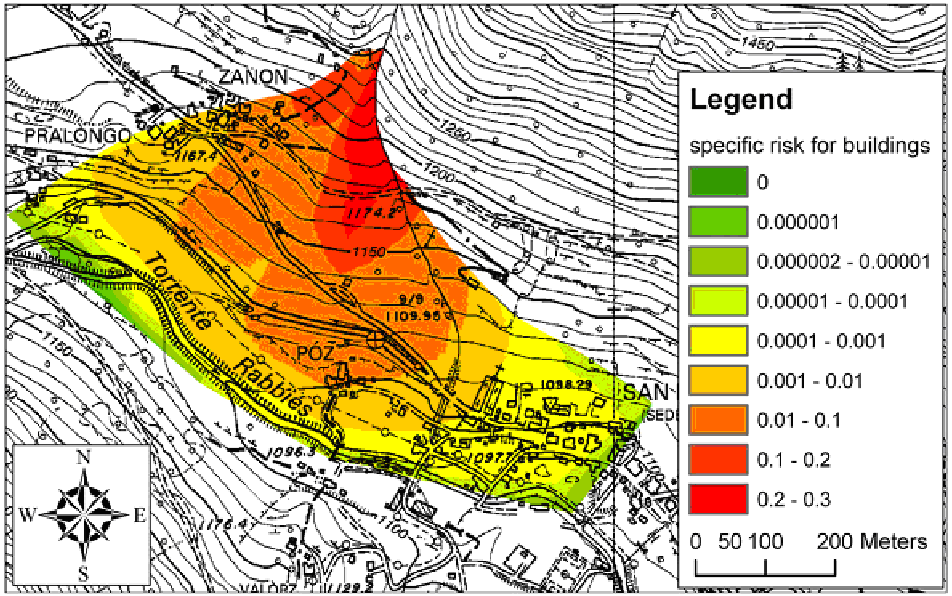
# Courbes de fragilité pour les structures BA (2)

## Effet des conditions aux limites / typologies de structures (Favier et al. NHESS 2013)

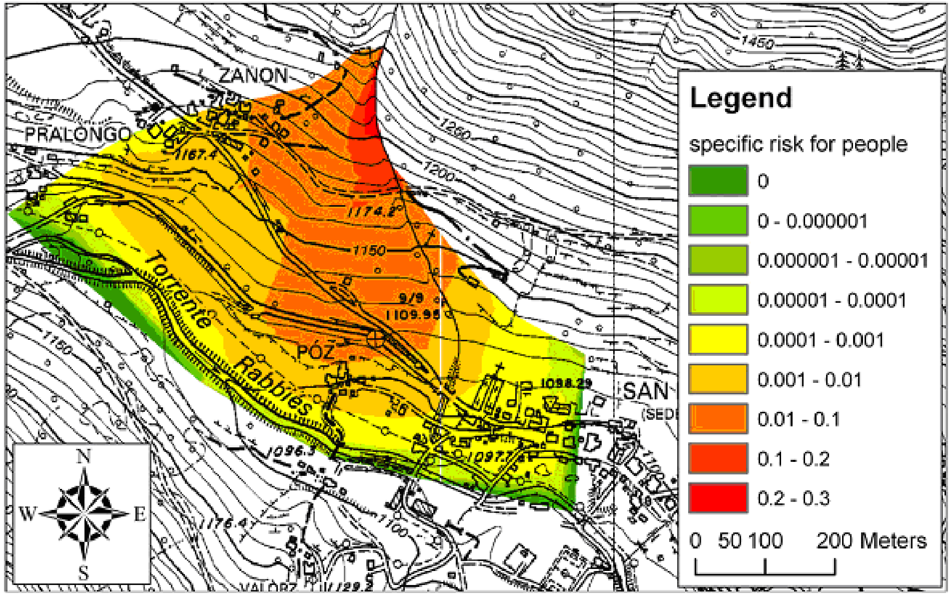


# Application to risk mapping

a




b




Individual risk approach for a fully exposed standalone people or a building :

$$R_z = z\int p(y)V(z,y)dy$$

with z=1 (not dimensionless)

Risk model and case study from Cappabianca et al., 2008. The risk for buildings/people is expressed as an annual probability of destruction/death respectively.

Hazard model is a statistical-dynamical model with simplifying assumptions for input variables randomness, and impact pressure evaluation as a function of the position in the path.

Numerical simulations are performed along a 1-D profile but lateral spread is taken into account.

Vulnerability model links the survival/destruction probability to avalanche impact pressure.

# Vulnerability sensitivity and risk bounds

$$R(x) \propto \int p\left(\Pr \middle| x_{stop}, > x\right) p\left(x_{stop}\right) V\left(\Pr\right) d\Pr dx_{stop}$$

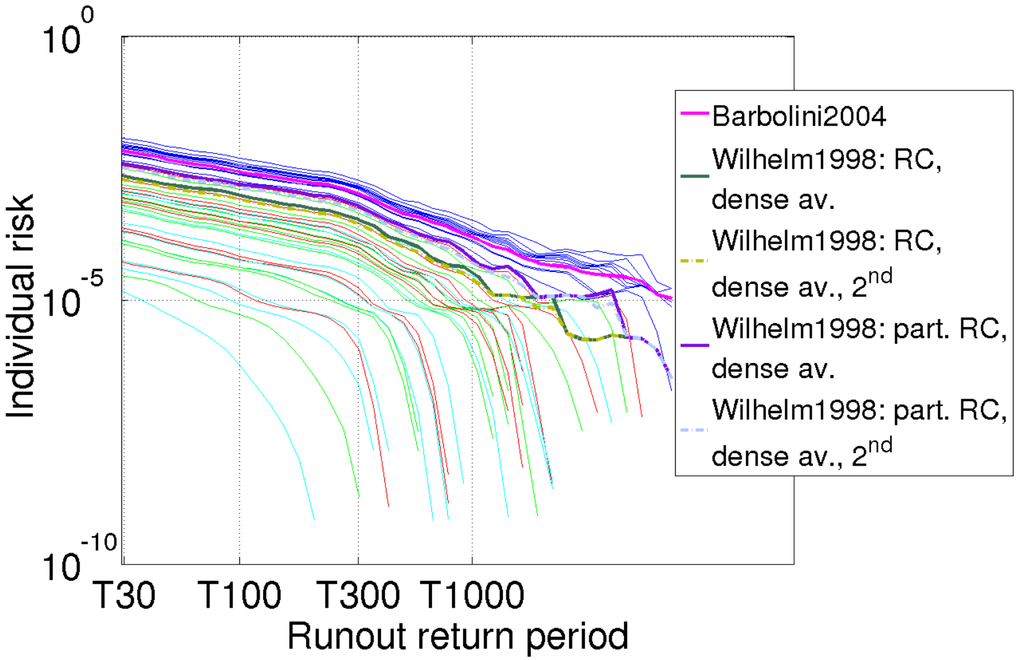



Fig.: Annual destruction rate for buildings with the different vulnerability curves available from Favier et al., 2013

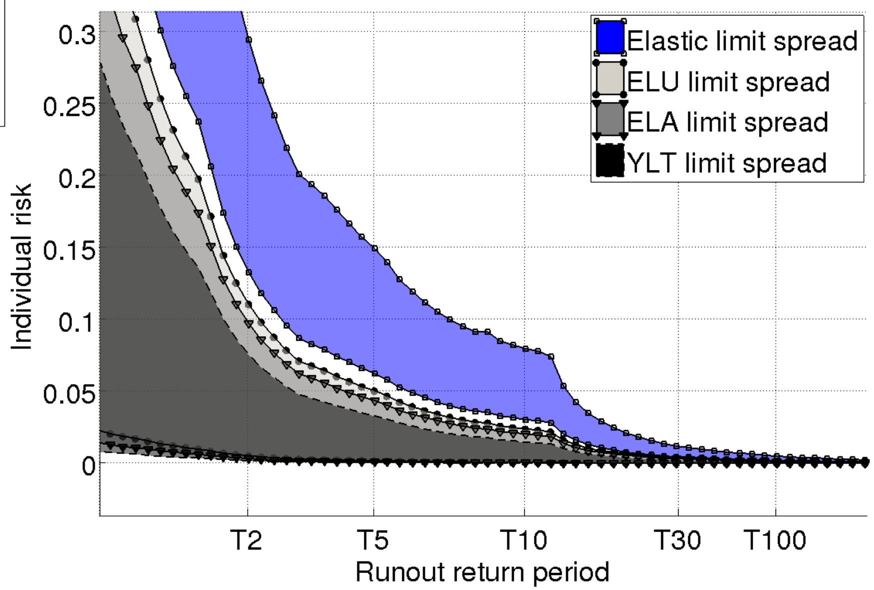
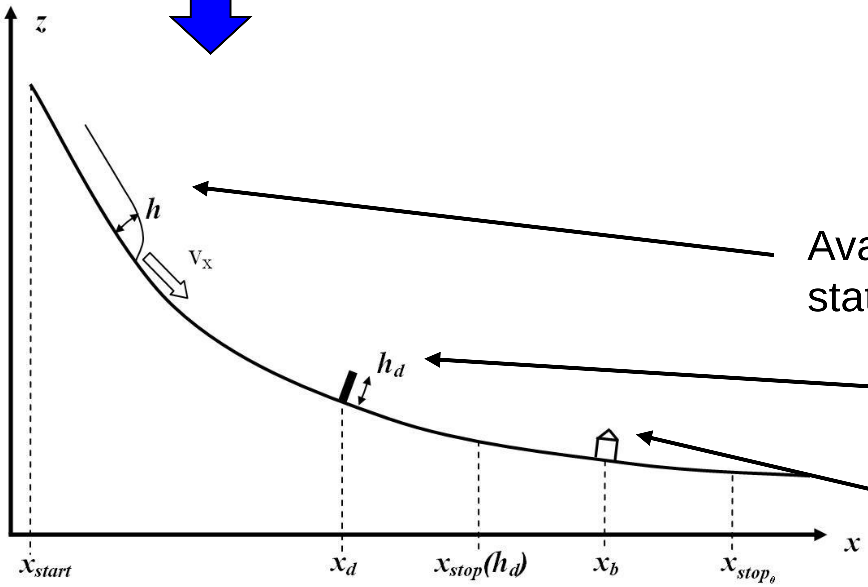



Fig.: corresponding risk bounds from Favier et al., 2013

# Optimal design of an avalanche dam

**A simple case : a vertical dam**

Avalanche dam



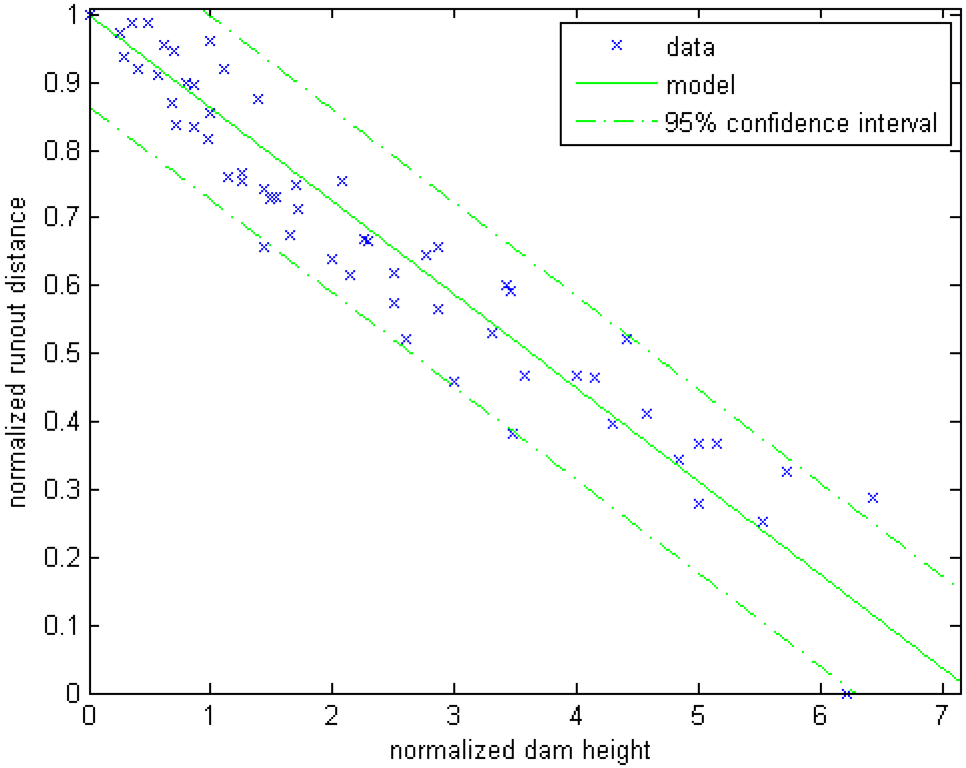

Avalanche model (fully explicit, or statistical-dynamical)

Optimisation of the dam height

One single element at risk (say one building without inhabitants to avoid polemics)

# Model for the dam effects

Small scale experiments : Faug et al. (JGR 2008)




Local energy dissipation :

$$\frac{x_{stop}(h_d) - x_d}{x_{stop_o} - x_d} = 1 - \alpha \frac{h_d}{h}$$

Runout distance shortening

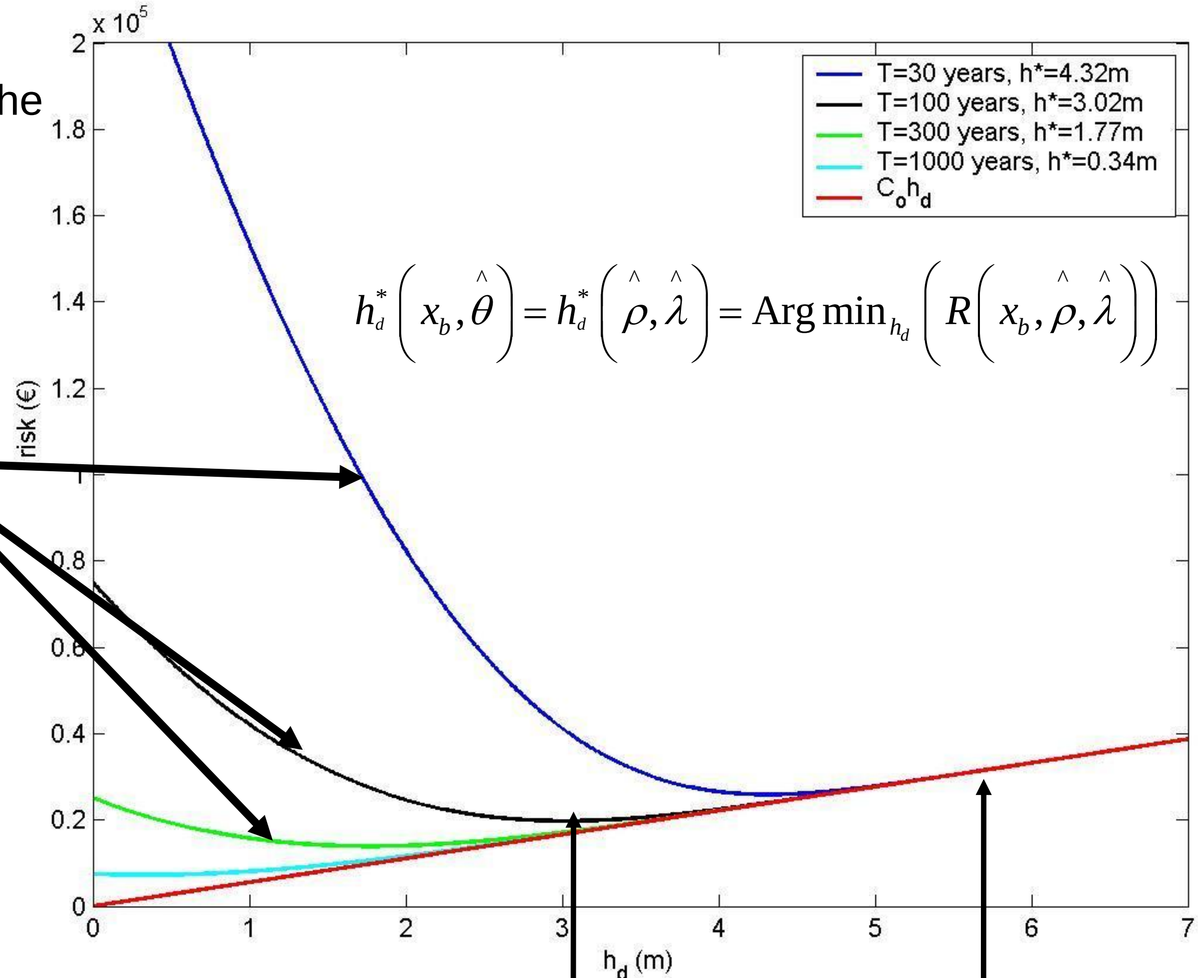
$$\frac{v_{x_d}^2(h_d)}{v_{x_o}^2} = 1 - \frac{\alpha h_d}{2h}$$

Perturbation of the velocity profile

Fast computations for each dam height

# (Frequentist) Optimal design

Looking at fixed positions $x_b$ in the runout zone:




$$h_d^*\left(x_b,\hat{\theta}\right)=h_d^*\left(\hat{\rho},\hat{\lambda}\right)=\operatorname{Arg\,min}_{h_d}\left(R\left(x_b,\hat{\rho},\hat{\lambda}\right)\right)$$

Different building positions $T(x_b)$, the return period without dam

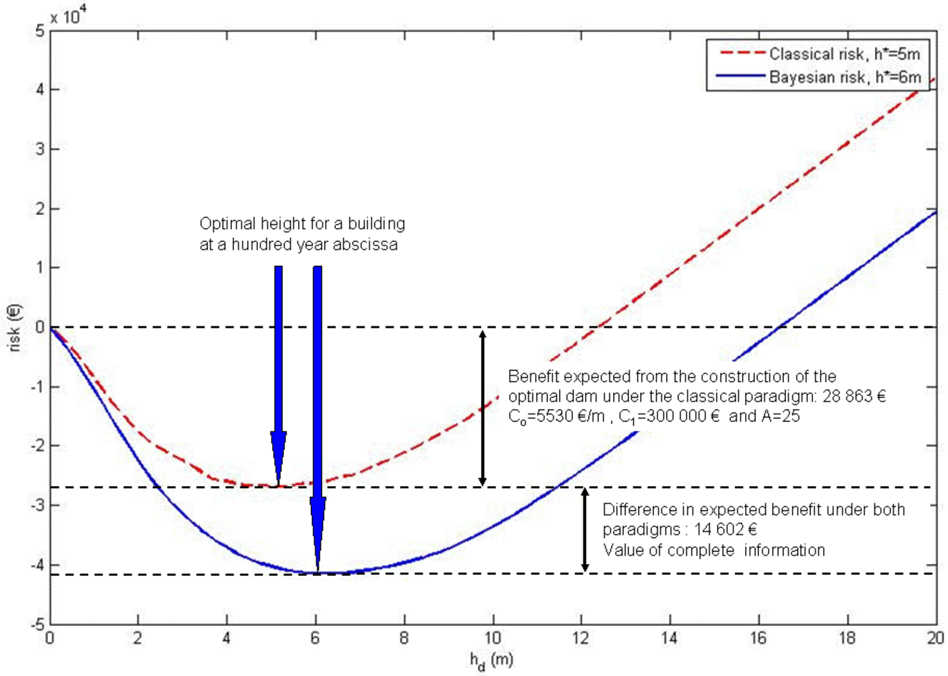
<u>Optimal height (minimum risk)</u>
Here for a 10 year return period abscissa

Asymptotic behaviour (construction cost)

# Calibration, parameter uncertainty and Bayesian risk

<u>Classical optimal design with *plug-in* point estimates</u>:
- separates estimation and decision, and neglects parameter uncertainty;
- do not necessarily respects suitable properties such as *admissibility*.

<u>Bayesian estimation, Bayesian risk and Bayesian optimal design:</u>
- Strong link between Bayesian inference and decision theory (Berger, 1985);
- Specifically, a Bayes rule (average over posterior pdf) is “always” admissible and, reciprocally, an admissible rule is a (generalised) Bayes rule (Complete Class theorem, Wald, 1950);
- Practical way to propagate data uncertainty up to decision (de Groot, 1970);
- Robustness of Bayesian optimal design to loss function choice (Abraham and Cadre, 2004).




Bayesian optimal design of an avalanche dam, Eckert et al. SERRA 2009

# Pour en savoir plus… quelques liens et un peu de pub!

- Le site de l'UR ETNA: http://www.irstea.fr/etgr

- La plateforme www.avalanches.fr, et notamment l'onglet: http://www.avalanches.fr/mopera-projet/


- Soutenance de la thèse de Philomène Favier lundi 1" octobre a Irstea: « **Une approche intégrée du risque avalanche : quantification de la vulnérabilité physique et humaine et optimisation des structures de protection** »

- Merci:
- Pour votre attention
- aux organisateurs (invitation)
- Aux financeurs : ANR, Union européenne, etc.