Hazard, Reliability and Risk Assessment - Research and Practice for Increased Safety

55th Rankine Lecture

adapted for Nordic conditions

by

Suzanne Lacasse

NGI



Contents of lecture

1. Basic concepts, some history
2. Reliability analyses to ensure adequate safety and lead to cost-effective design - "Real-life“ cases
   - Debris flow
   - Strain-softening clays
   - Avalanche occurrence
   - Safety along railways and foundation work
   - Offshore geotechnics and dams
3. Emerging topics and conclusions



Basic definitions

Risk = f (Hazard and consequences)

Risk = f (H, V, U)

H = Hazard (temporal probability of a threat)

V = Vulnerability of element(s) at risk

U = Utility (or value) of element(s) at risk

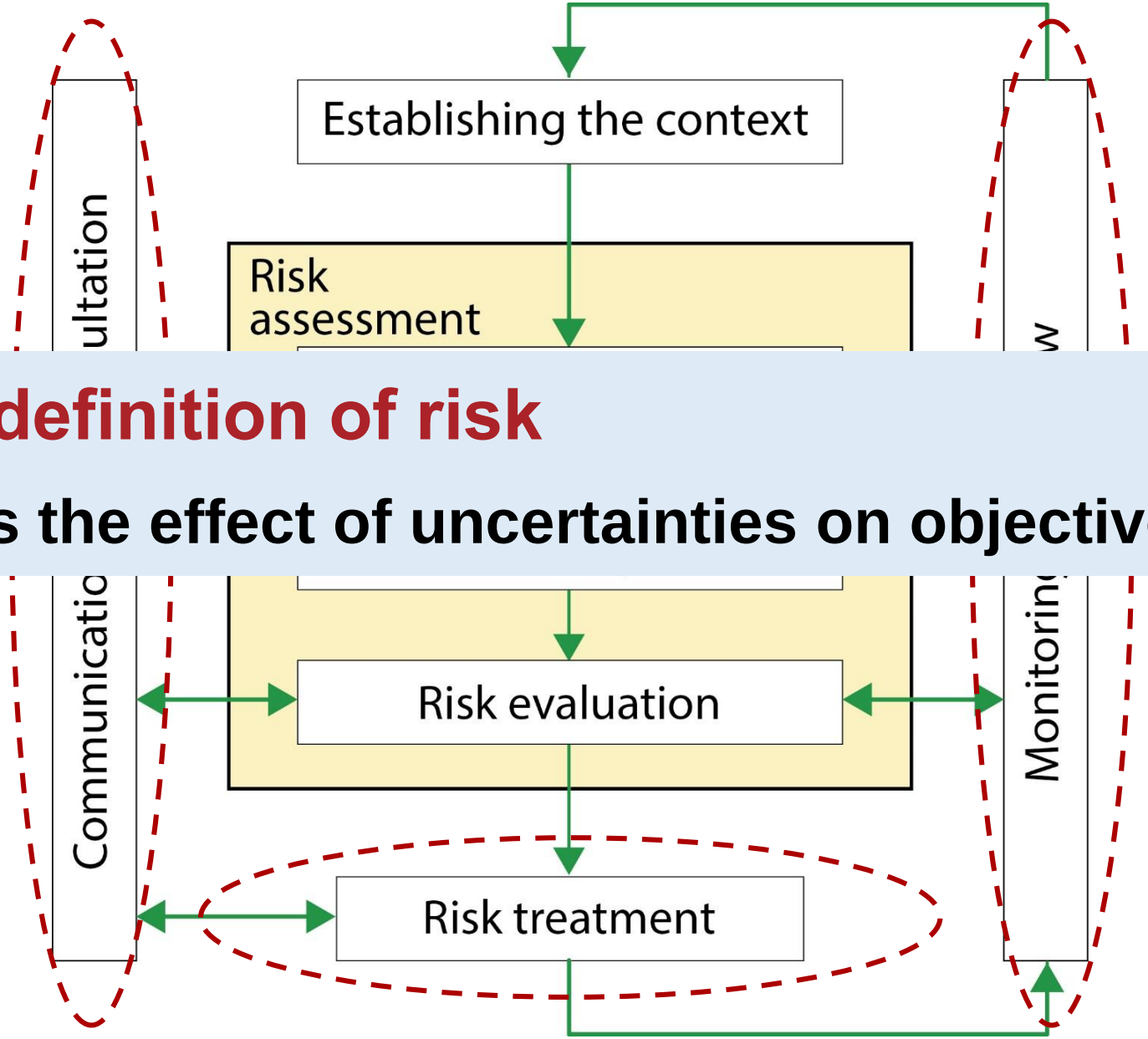


Munkedal Sweden 2006
Thin layer of quick clay was not detected





Risk management process [after ISO-3100:2009]



ISO's definition of risk

"Risk is the effect of uncertainties on objectives"

ISO's definition of risk

"Risk is the effect of uncertainties on objectives"

New ISO FDIS 2394 (March 2015)
«General principles on reliability for structures»

- Spells out the purpose of the reliability approach: ensure a uniform margin of safety (i.e. probability of failure)
- Requires "risk-informed design".
- Outlines the increasing need to "calibrate" the codes (i.e. safety factors)

Annex D Reliability of geotechnical structures



Early work

[Lumb, 1966]

Properties of four natural soils were shown to be random and essentially normally distributed: (grain size distribution, strength (s_u and ϕ') and compressibility characteristics).

Lumb suggested, based on "what never fails":

«a suitable value of probability of failure for design (bearing capacity) should be 10^{-4} to 10^{-5})».



Early work

[Wu and Kraft, 1967; 1970]

Probability of foundation safety

A 'measure of safety' was found probabilistically for

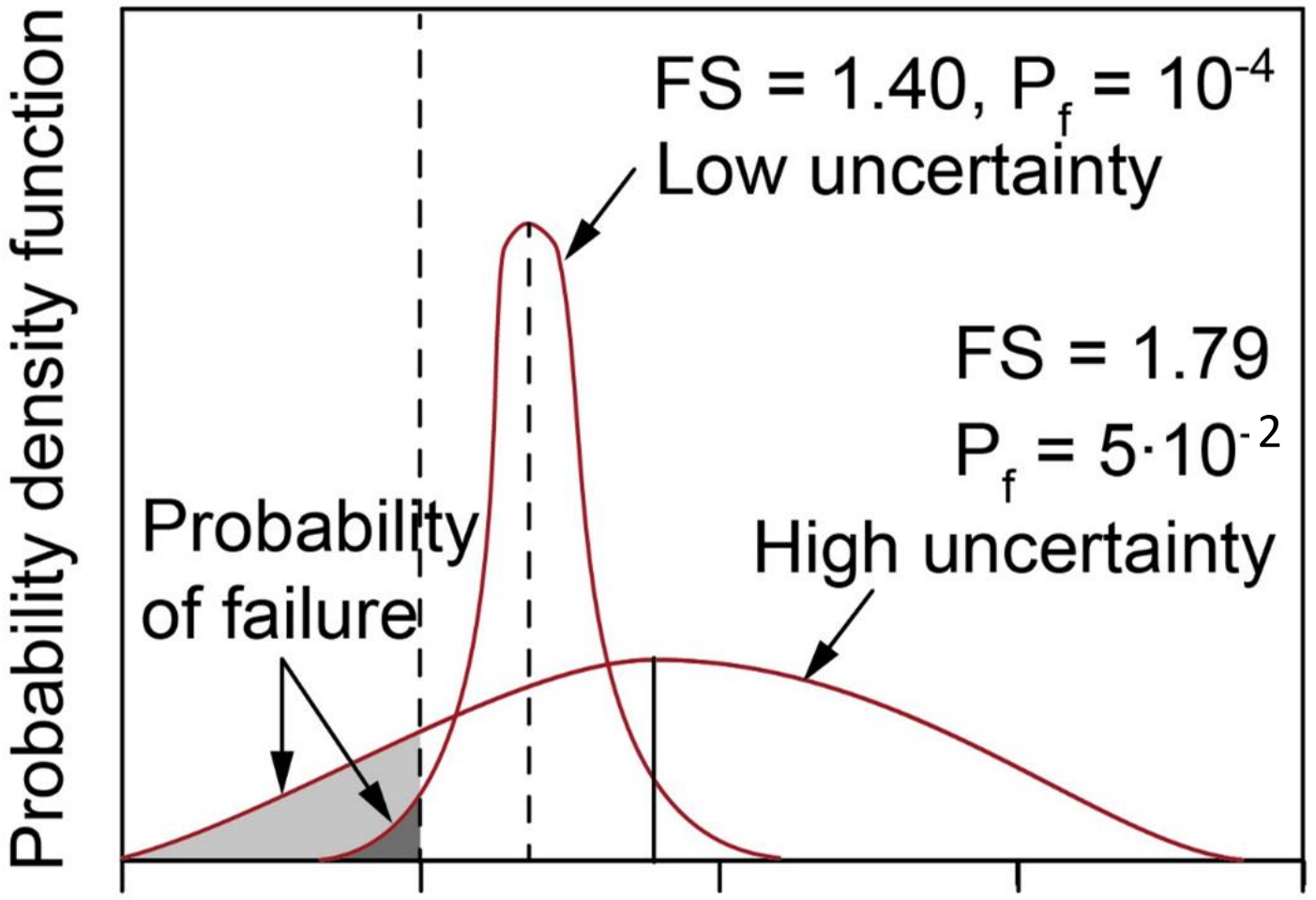
- Excavation in clay
- Bearing capacity failure in clay
- Slope in clay
- Settlement in sand

The factor of safety is not a "unique quantity".

"Probability analysis leads to rational means of foundation design […] and is a step forward to the optimum design of structures."



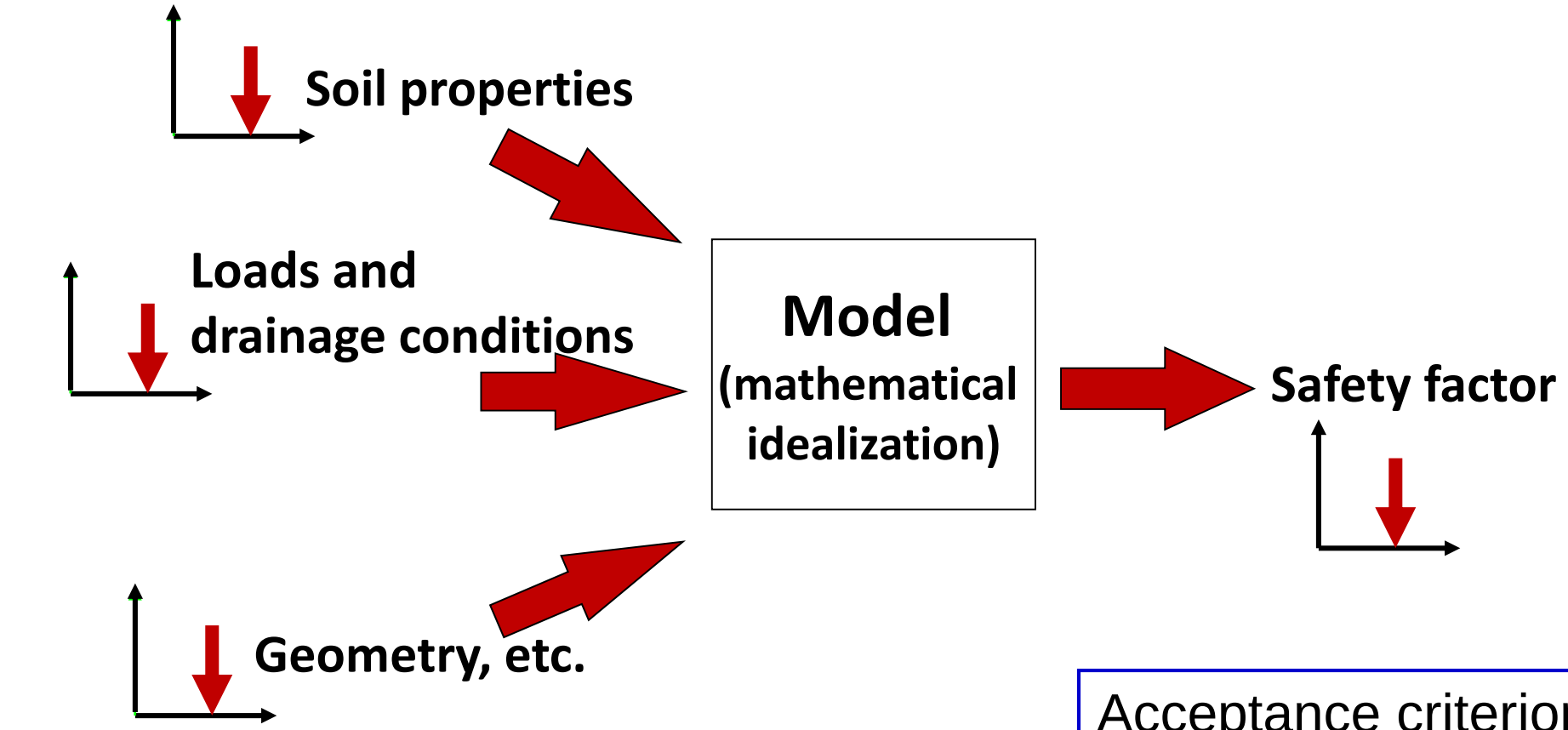
Factor of safety and probability of failure



We need to be aware that the P_f is never zero!



Deterministic analysis

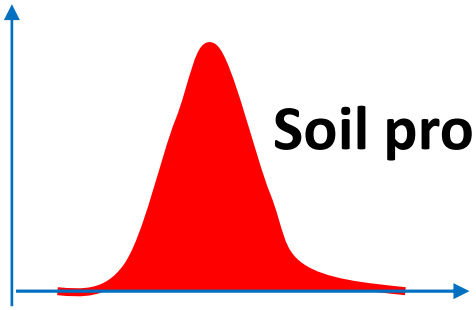


Acceptance criterion:

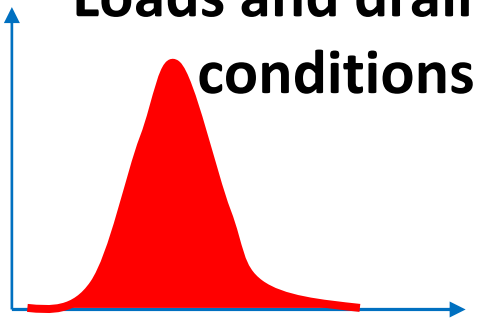
$FS \geq FS_{acceptable}$



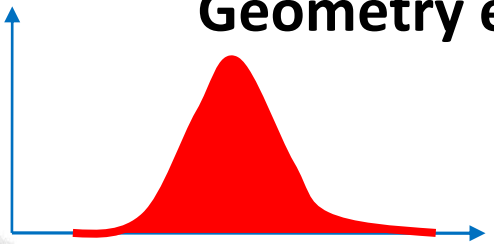
Probabilistic analysis



Soil properties

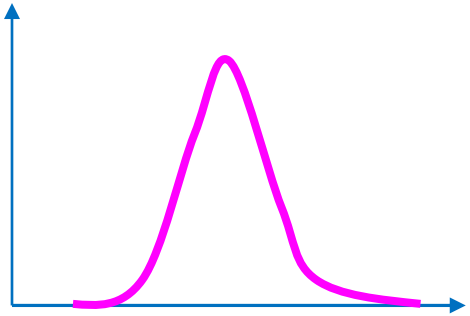


Loads and drainage conditions



Geometry etc.

Model
(idealization including uncertainty)



Safety margin

Probability of failure (P_f)
Reliability index (β), …

Acceptance criterion:

$$\beta \geq \beta_{acceptable}$$

$$P_f < P_{f\ tolerable/acceptable}$$



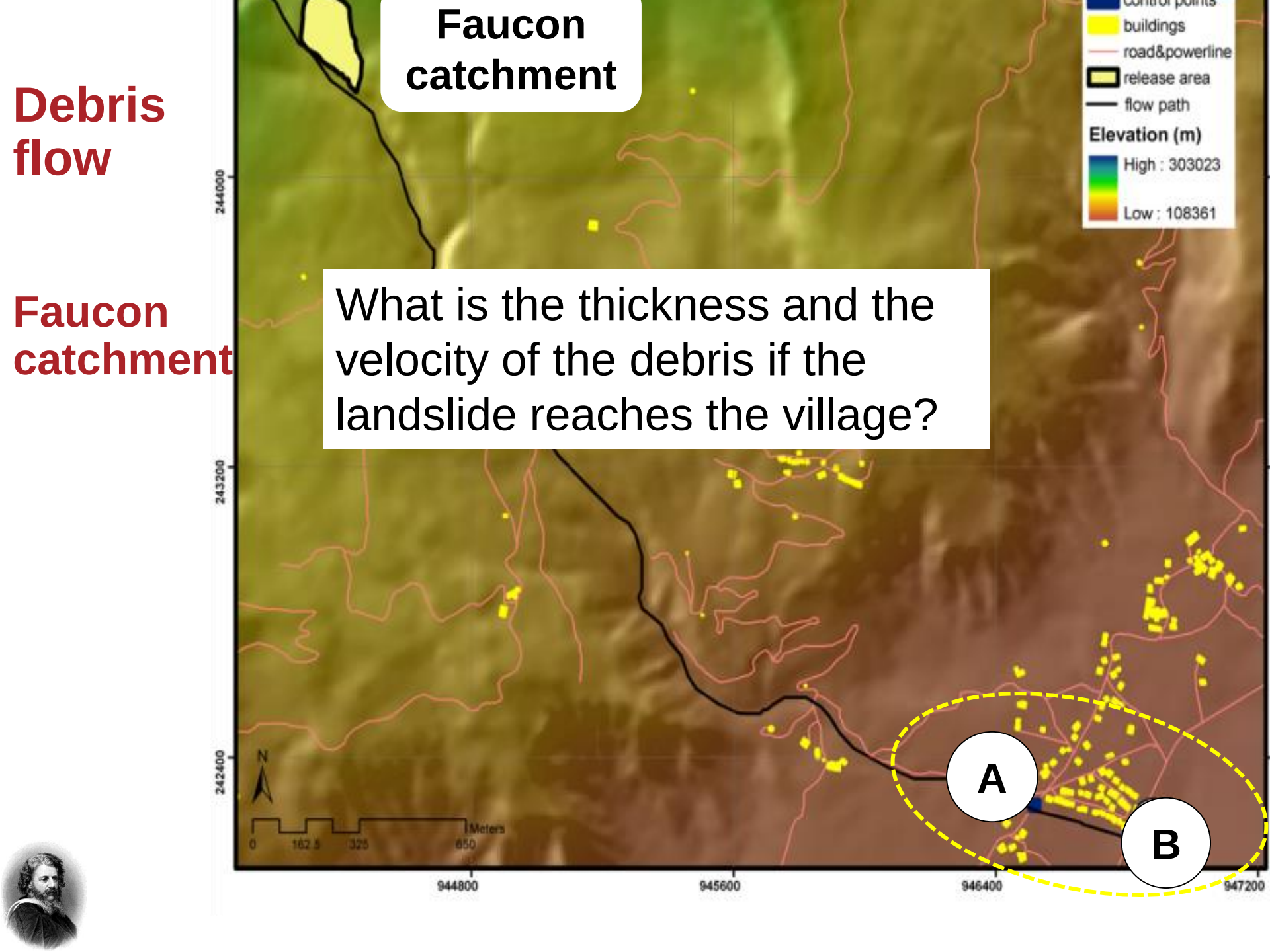
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Debris flow

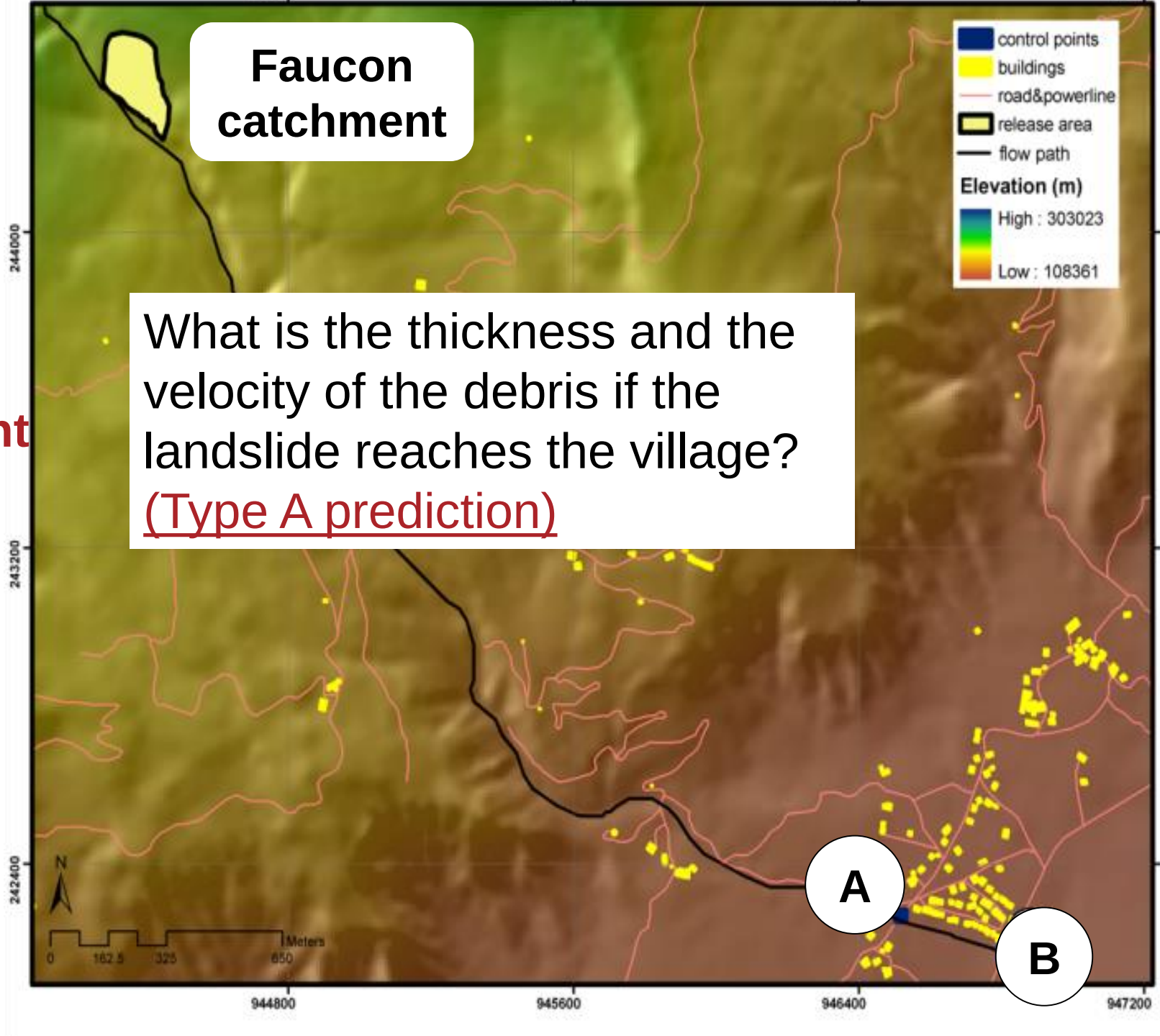
Faucon catchment



Debris flow

Faucon catchment





Monte-Carlo Simulation (MCS)

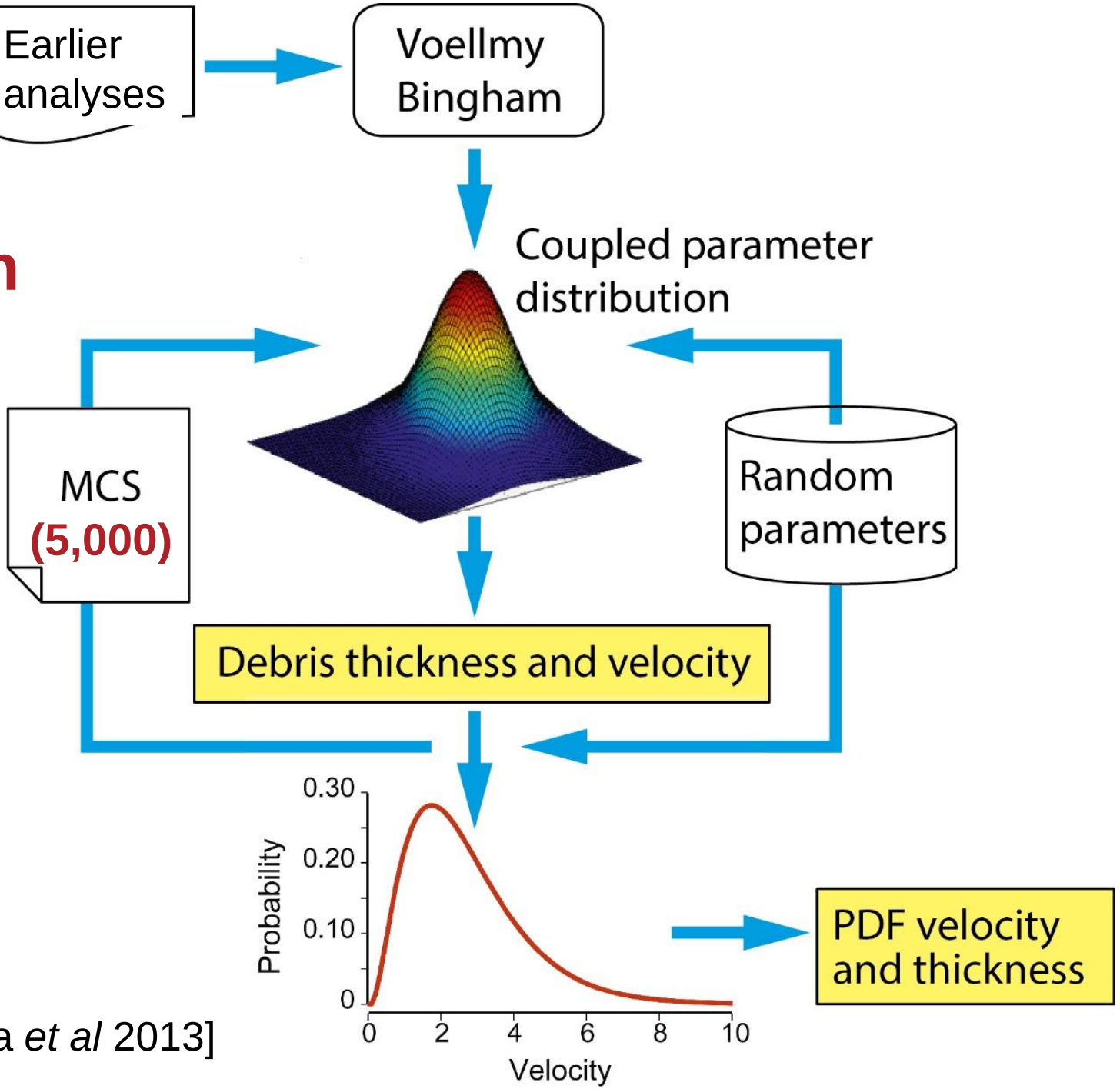
First, one needs an explicit function (or formula) to model the problem.

MCS relies on repeated random sampling to predict the outcome. It uses the sample probability distribu-ion for each random variable to produce hundreds, thousands or millions of possible outcomes and obtain the probability of occurrence of an outcome.

With today's computers, there is no problem in running thousands of simulations. There are also methods to make the random sampling process more efficient, e.g. Latin hypercube sampling.



Approach

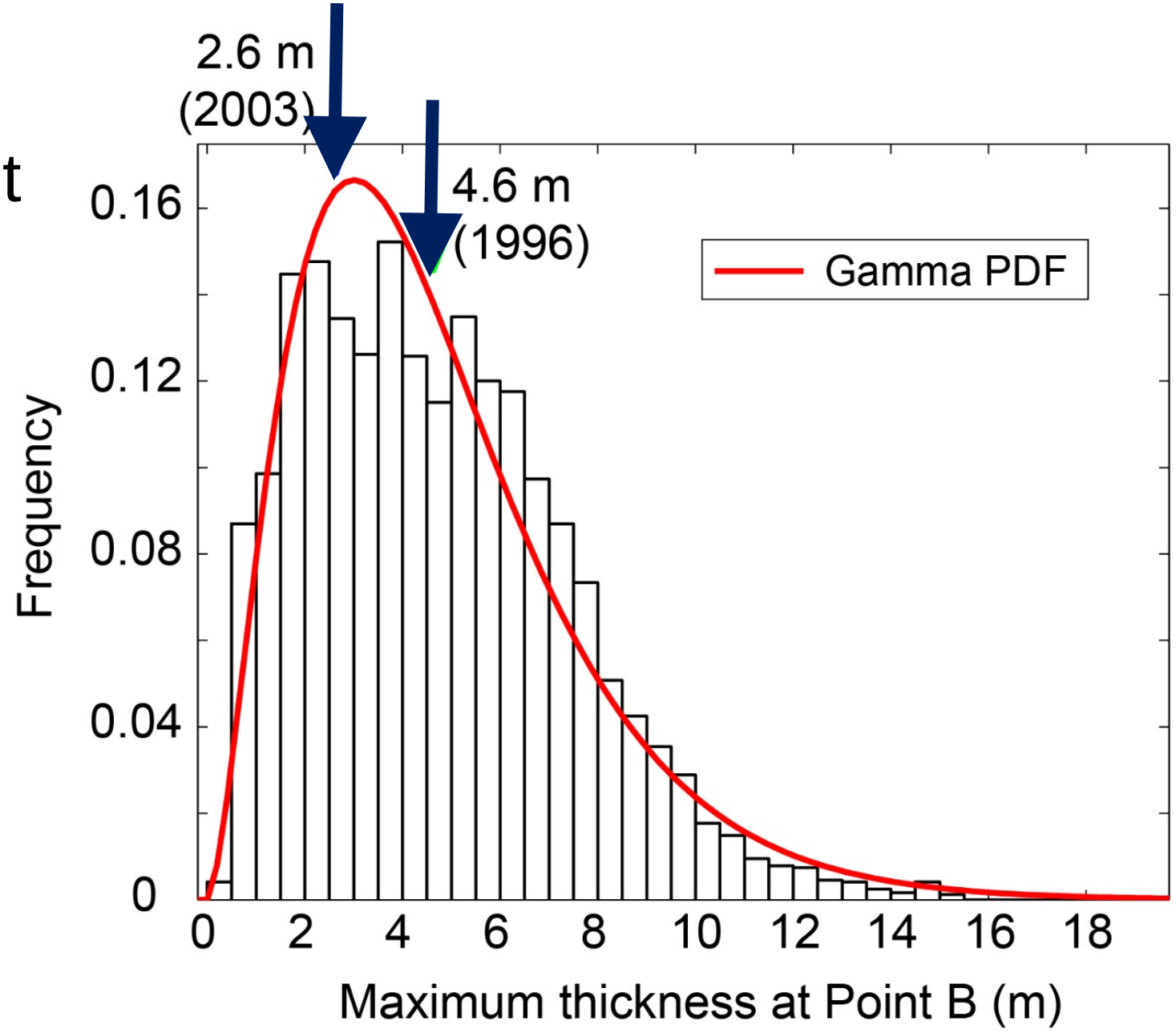




[Cepeda *et al* 2013]

Faucon catchment

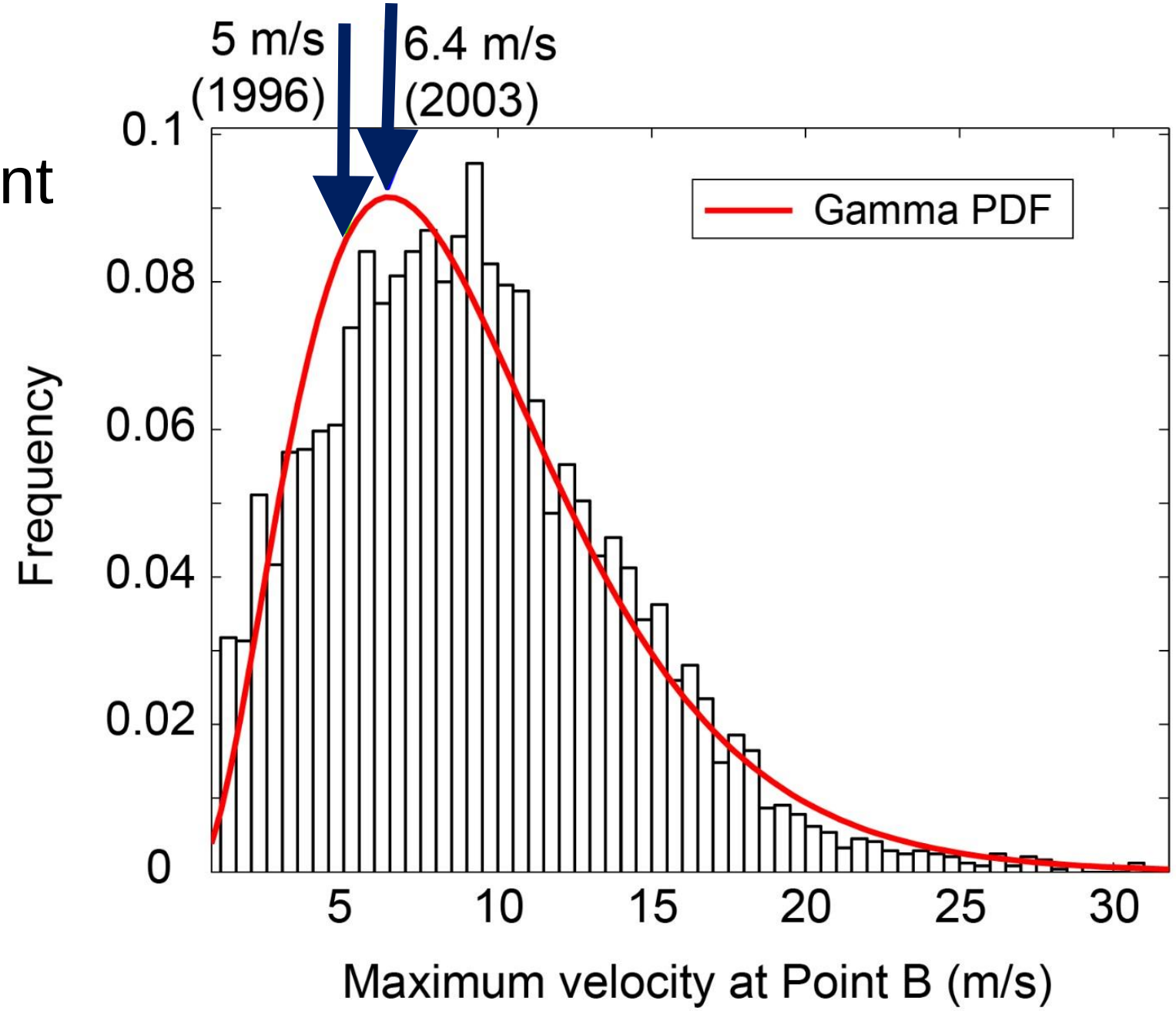
Debris thickness Point B





Faucon catchment

Debris velocity Point B





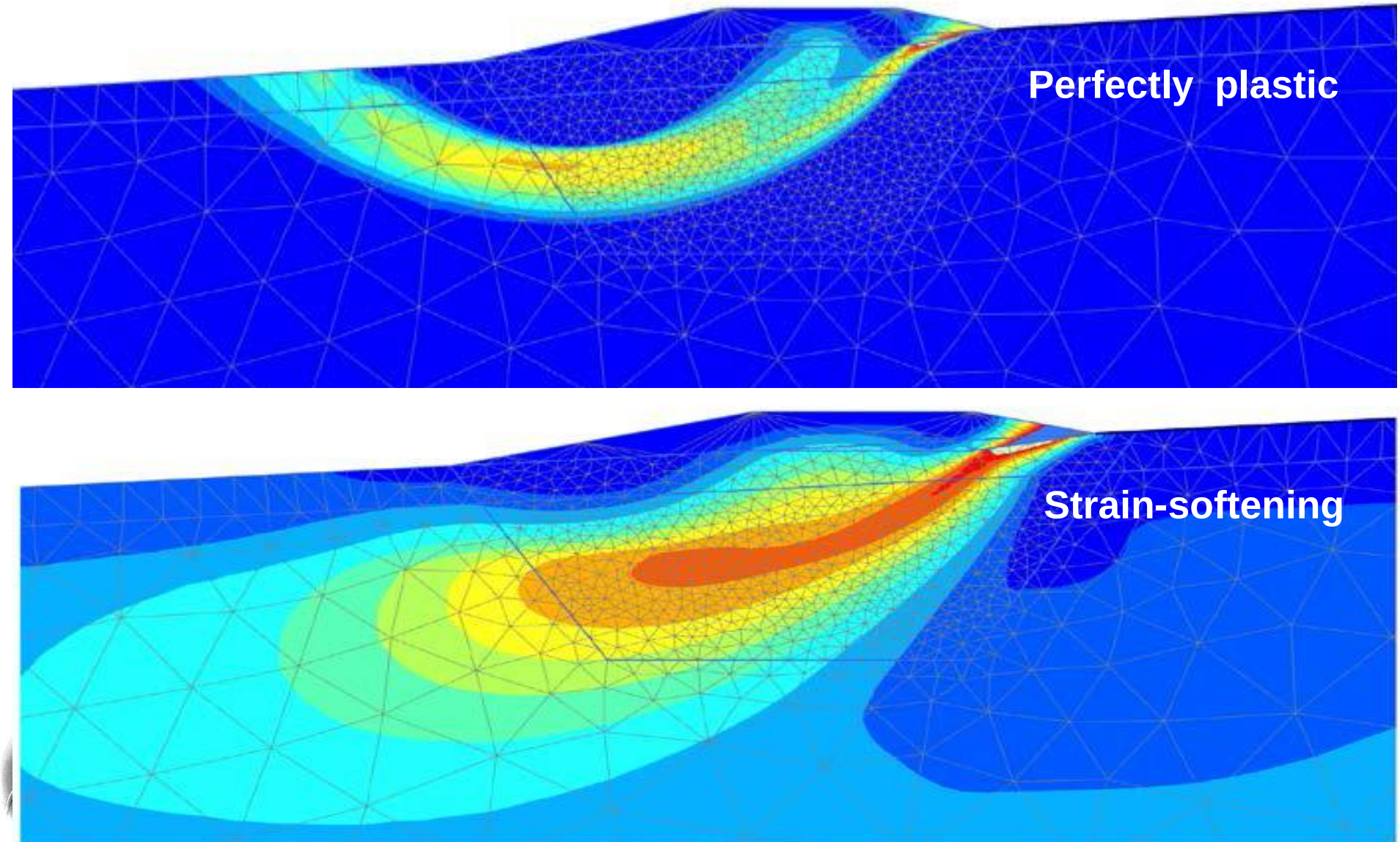
Added value of Monte Carlo analysis?

- Monte-Carlo simulation is an excellent tool if the mean and standard deviation are of main interest. For modelling the "tails" of the PDF (very low P_f), one needs a very large number of simulations.
- MCS can be used to "experiment" and develop new calculation procedures or to model behaviour, for example:
  - Accounting for strain-softening in limit equilibrium analyses.

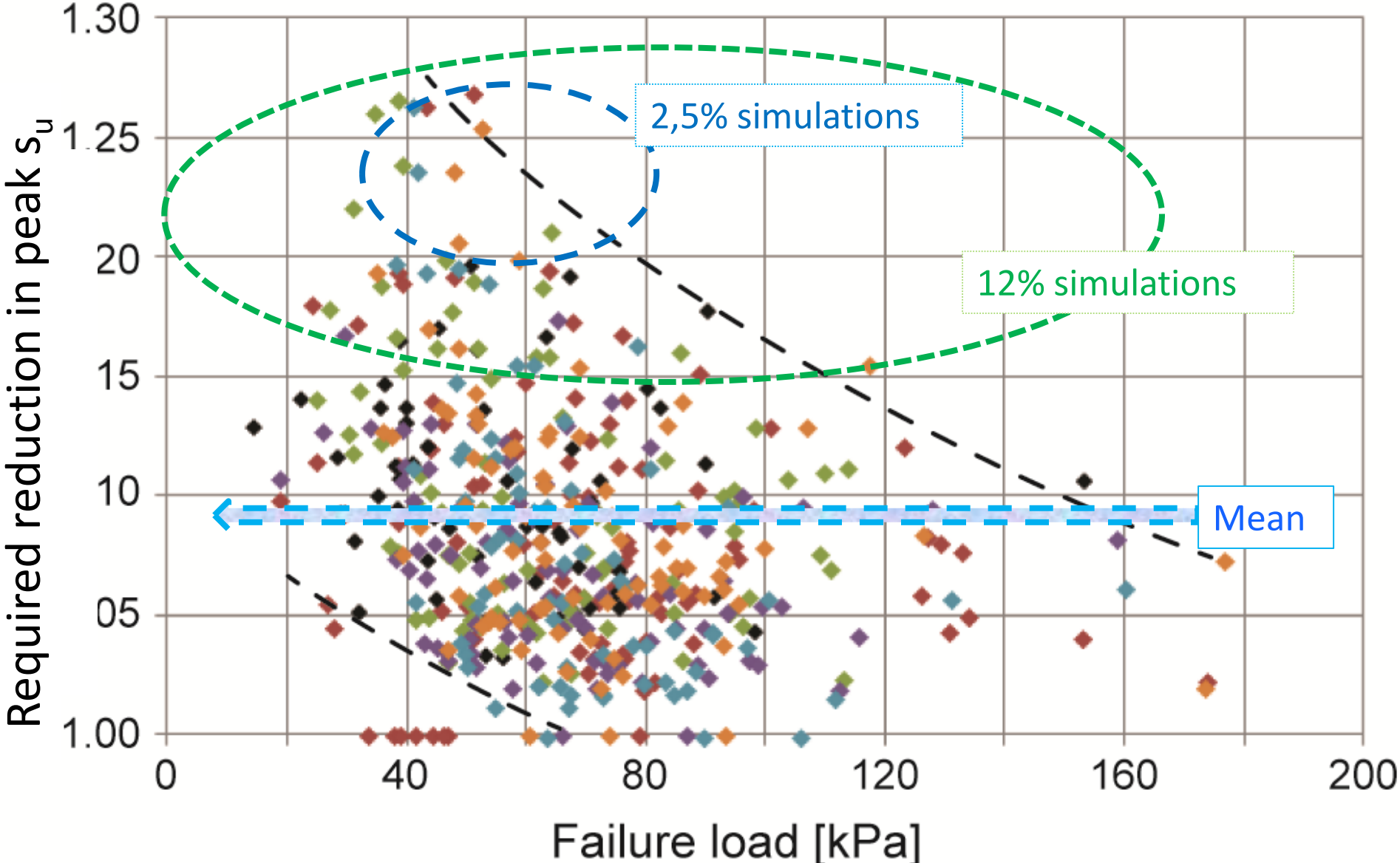


Failure in strain-softening clay

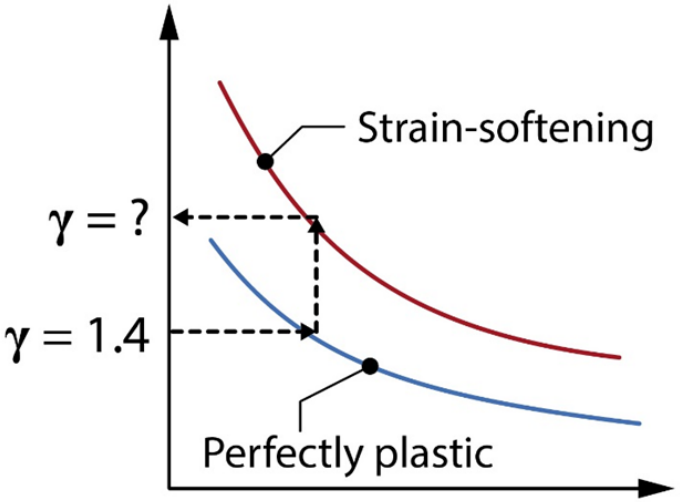
Shear deformations, PLAXIS [Jostad 2014]

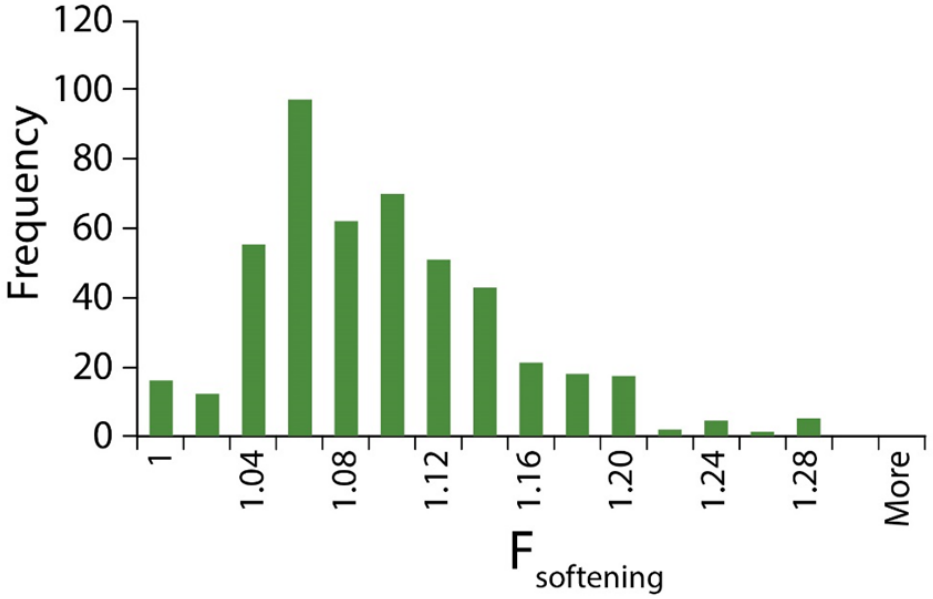


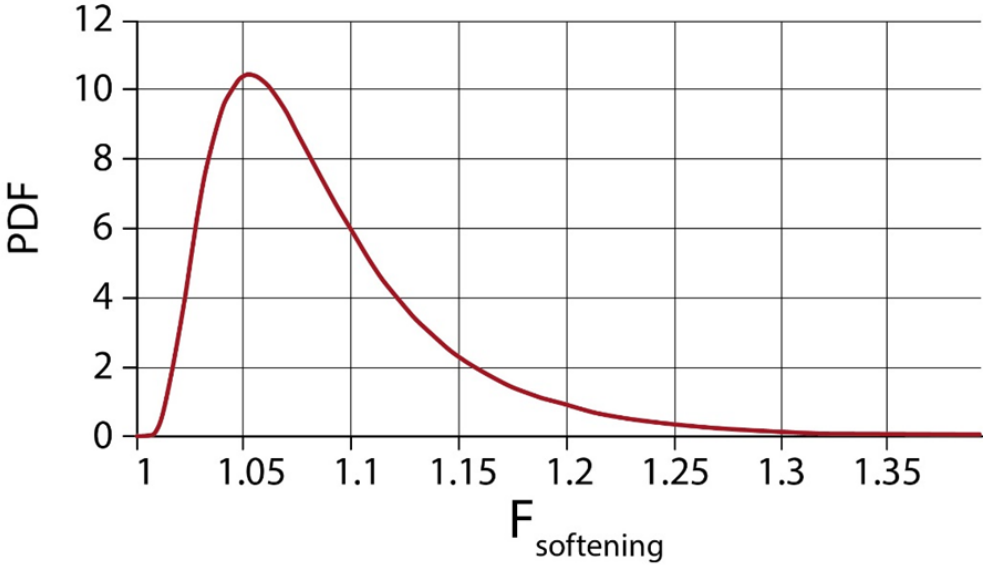
Required reduction in peak undrained shear strength if LE analysis is used [Jostad *et al* 2013 - NIFS-project]



Monte-Carlo simulations to obtain $F_{softening}$

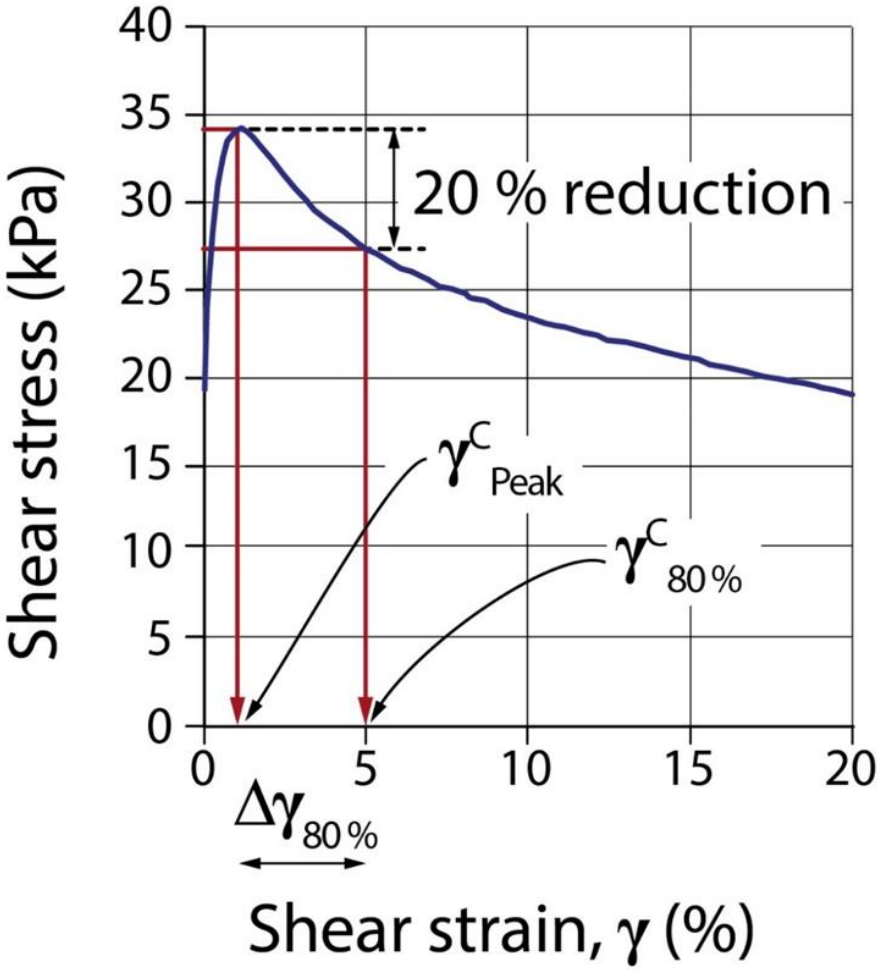


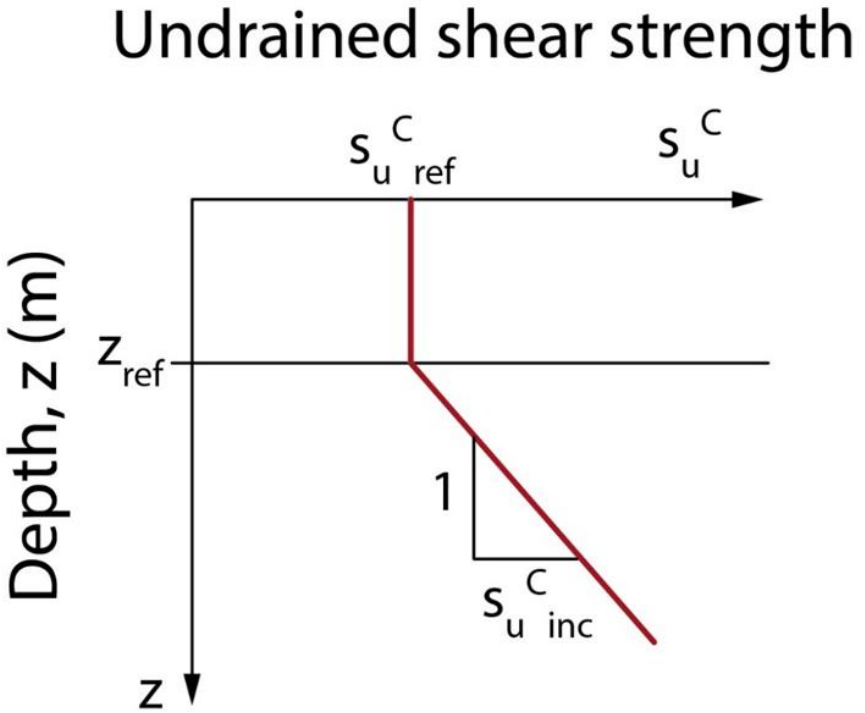






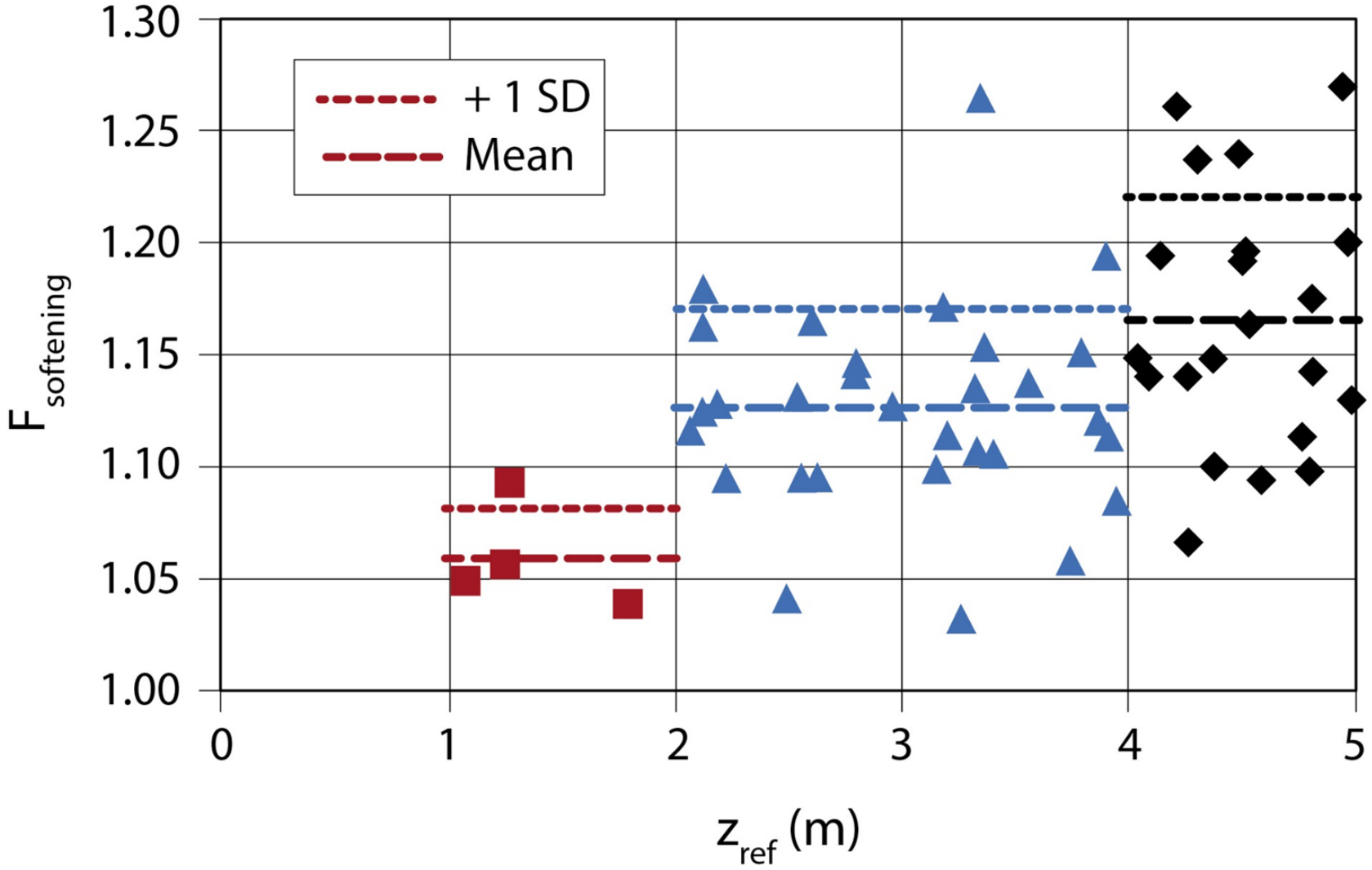
Significant factors in analysis
NIFS-project (Jostad *et al* 2015; Dolva *et al* 2016)





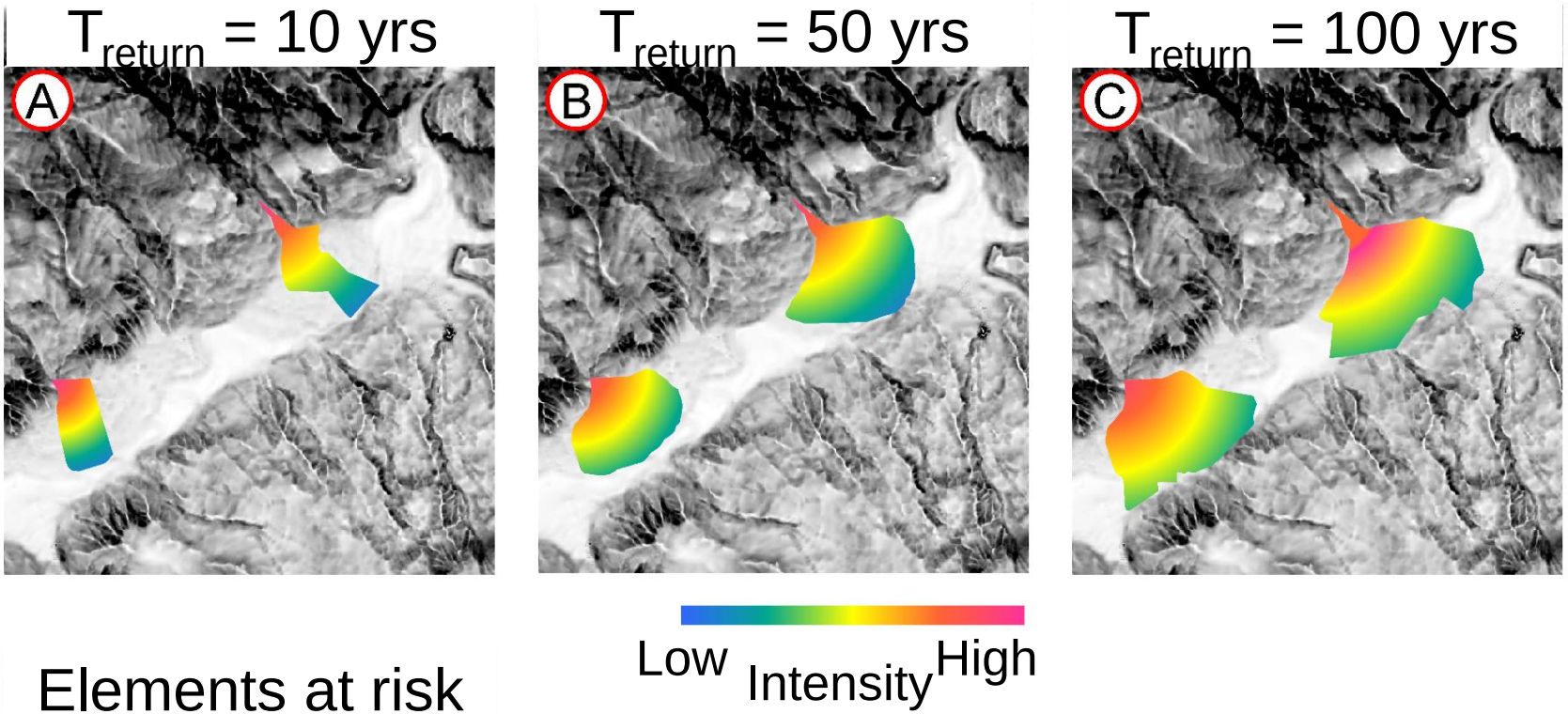


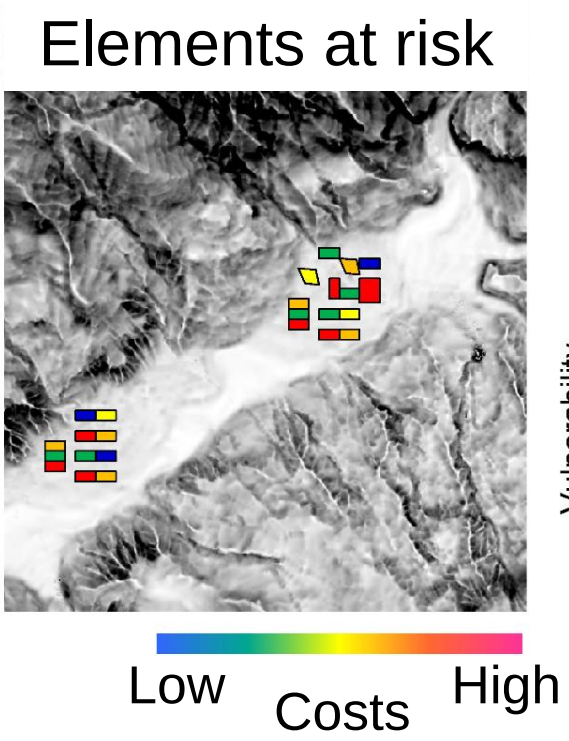
Correction factor on the safety factor (NIFS-project) $\gamma_{M_{strain\text{-}softening}} = \gamma_M \cdot F_{softening}$

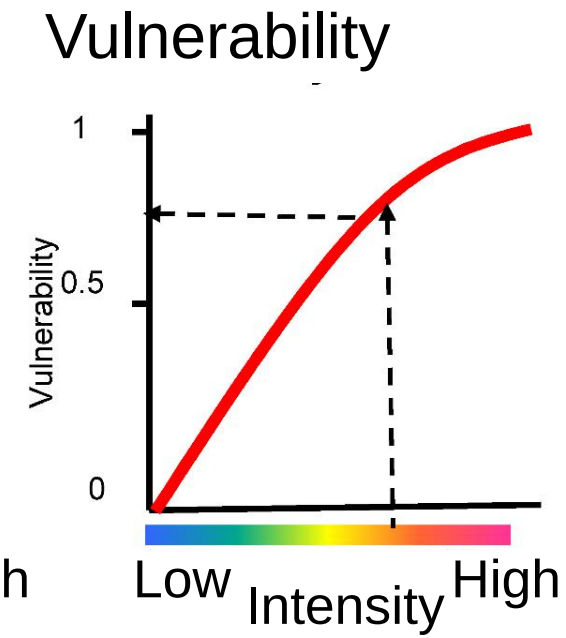


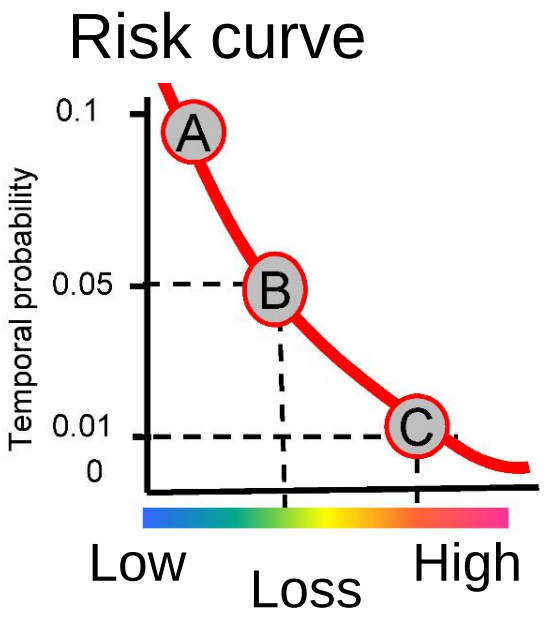


[Coro-minas *et al* 2014]









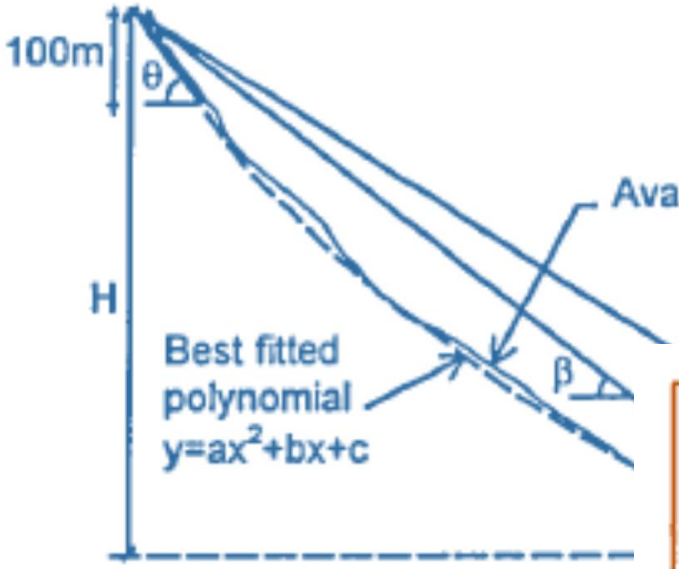


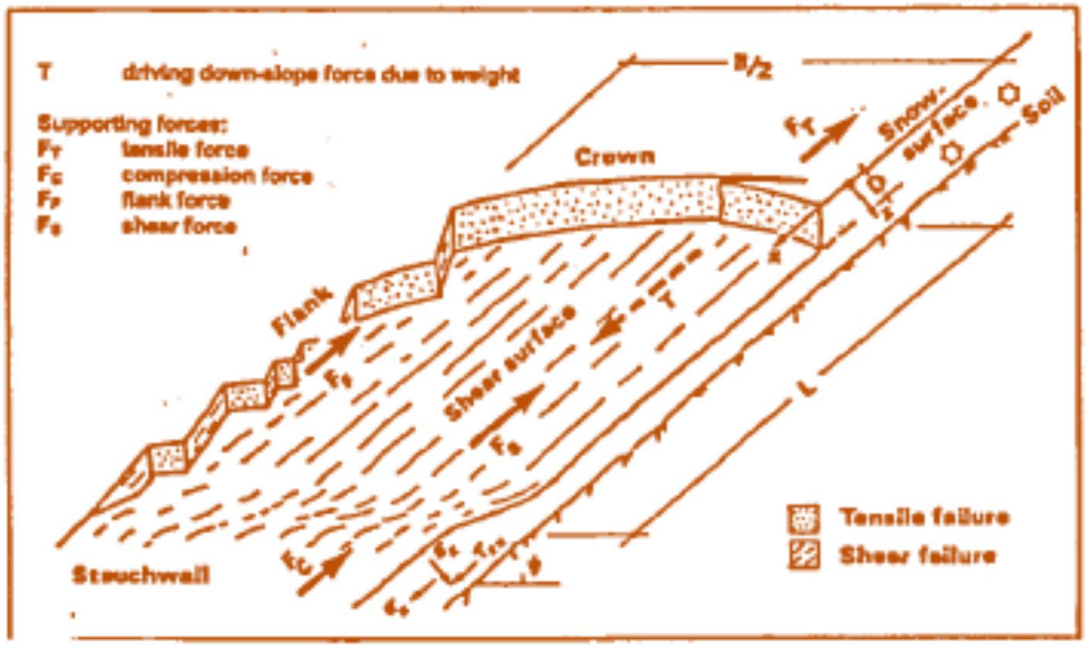
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Analysis of P(avalanche)
Snow slab (Lackinger 1989)







Analysis of P(avalanche)
Snow slab (Lackinger 1989)

$FS = (F_S + F_T + F_C + F_F)/T$

where

F_S is the shear force along the shear surface,

F_T is the tension force at the crown,

F_c is the compression force at the wall,

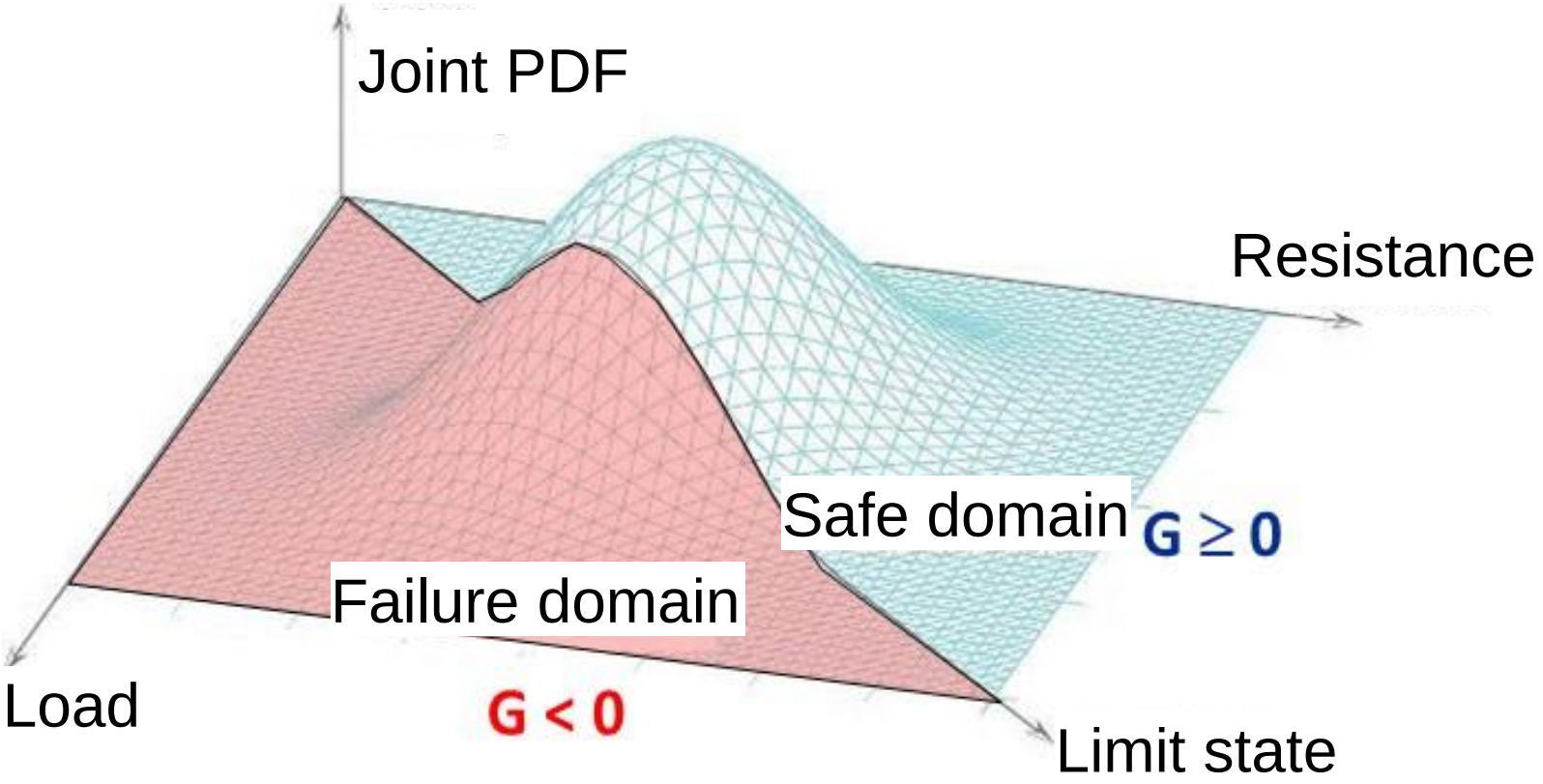
F_F is the flank force,

T is the total weight driving component



Probabilistic analysis with FORM

One defines a performance function e.g. $G(X) = R - L$,
where $G(X) \geq 0$ means satisfactory performance
$G(X) < 0$ means failure
X is a vector of basic random variables (resistance, load effects, geometry and model uncertainty).





Probabilistic analysis with FORM

FORM provides:

- Probability of failure, P_f
- Reliability index, β
- The most probable combination of parameters leading to failure
- Sensitivity of P_f to any change in the random variables (parameters)

FORM allows for explicit consideration of the uncertainties.



Analysis of P(avalanche)
Snow slab (Lackinger 1989)

Random variable	PDF	Mean	SD
Thickness of slab, D (m)	LN	0.7	0.1
Slope angle, ψ (degree)	LN	38°	3
Cohesion-snow, c (kPa)	LN	6	1.5
Tensile strength-snow, σ_t (kPa)	LN	9	2.4
Shear strength on sliding plane, τ_s (kPa)	LN	1.05	0.32
Width of slide, W (m)	LN	50	25
Length of slide, L (m)	LN	50	25
Density of snow, ρ (kg/m^3)	N	220	20
External load, W_{ext} (kN)	LN	10	2



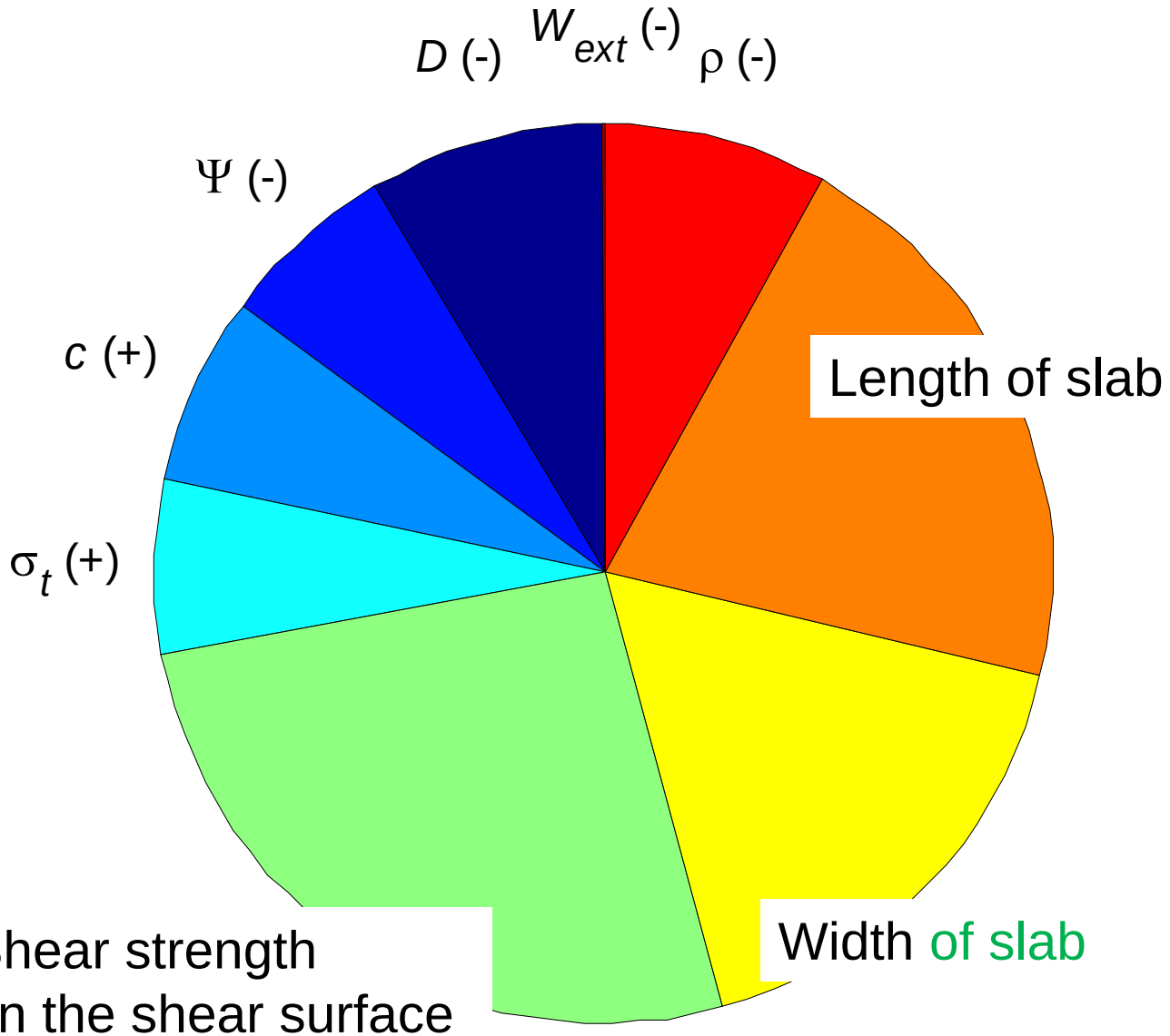
Analysis of P(avalanche)
Snow slab (Lackinger 1989)

$\underline{MCS_{100,000}}$

$P_f = 5 \cdot 10^{-2}$/yr

$\underline{FORM}$

$P_f = 6 \cdot 10^{-2}$/yr





Bayesian approach to estimate annual probability of avalanche P_f [Nadim *et al* 2013]

Probability distribution of P_f

"r" avalanches observed during "n" years:

$$f(P_f) = k \cdot P_f^r \cdot (1 - P_f)^{n-r}$$

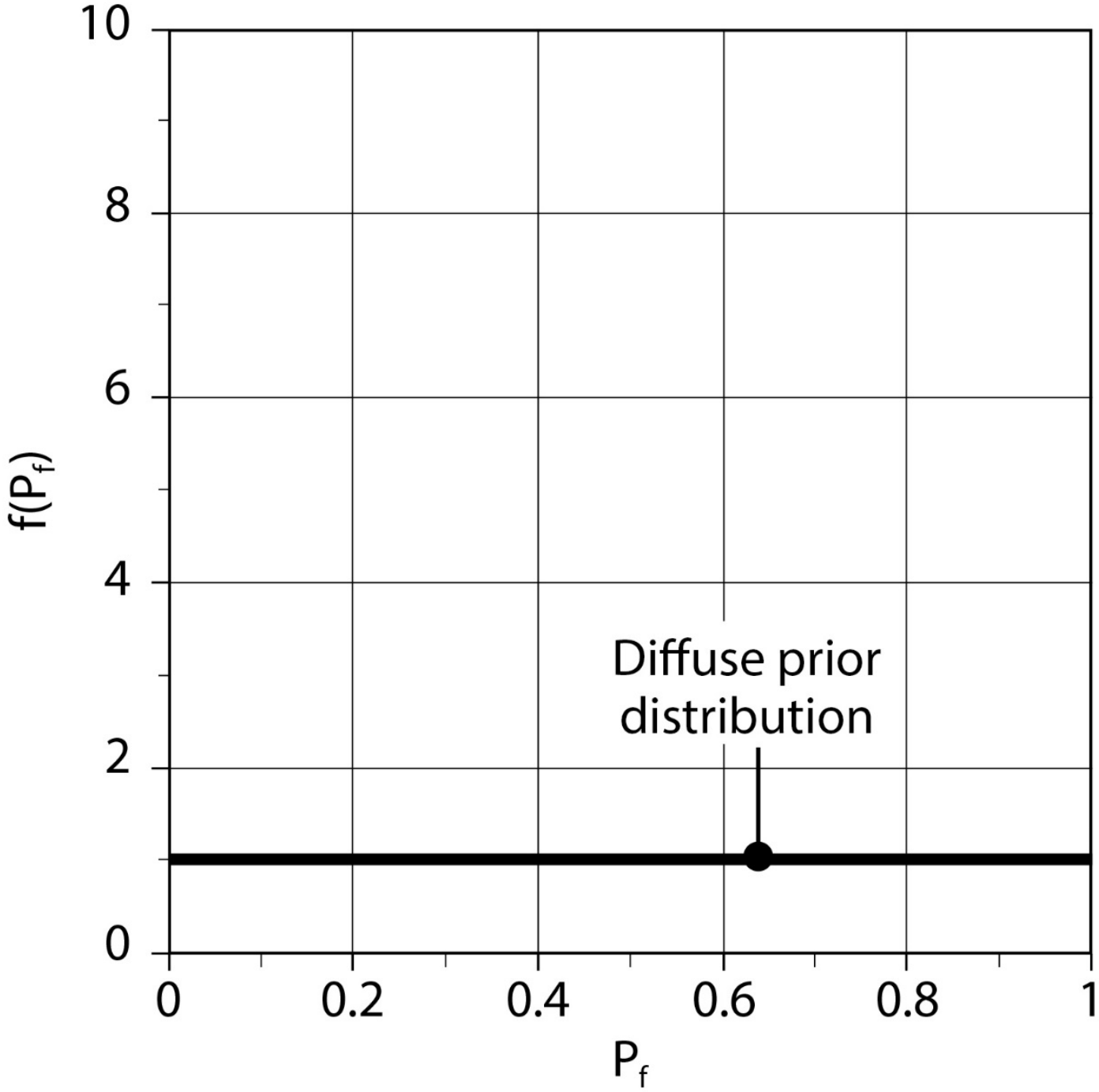
$$E[P_f] = (r + 1) / (n + 2)$$

$$E[P_f] = 1/(n + 2)$$

No avalanche during 100 yrs $\Rightarrow$ $E[P_f] \approx 1.0 \cdot 10^{-2}$ /yr

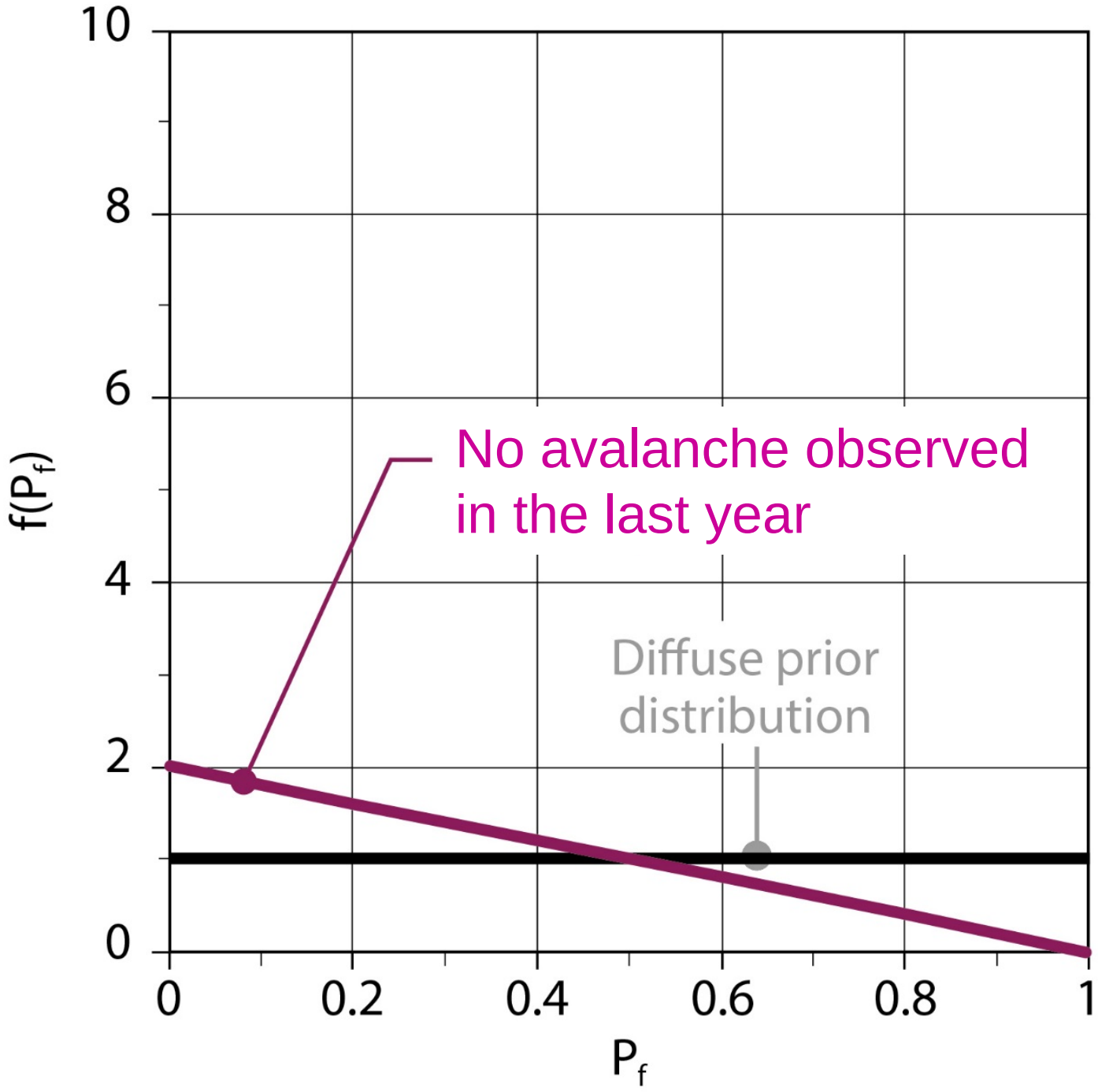


No information



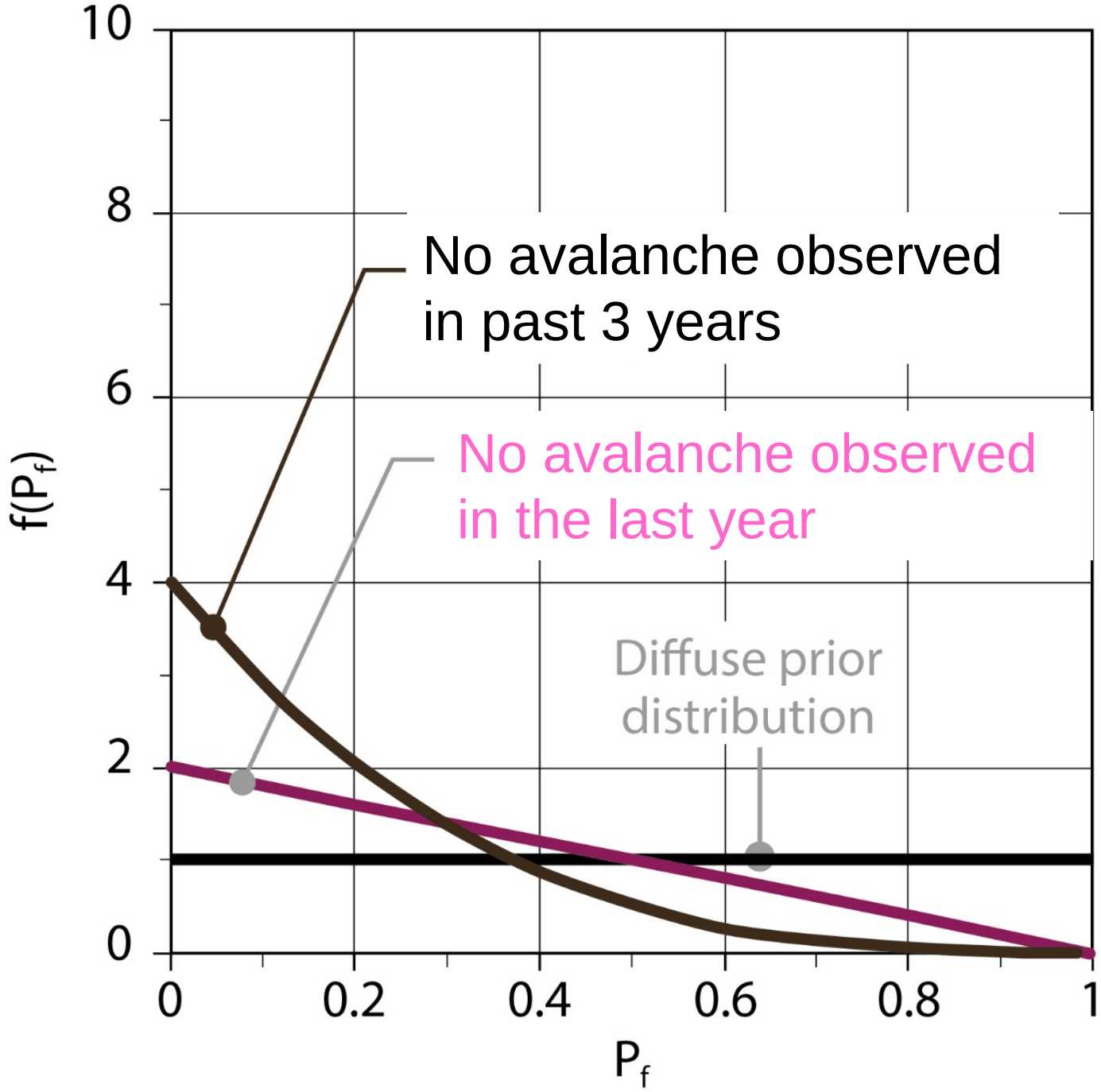


No avalanche in the past year (1 yr)



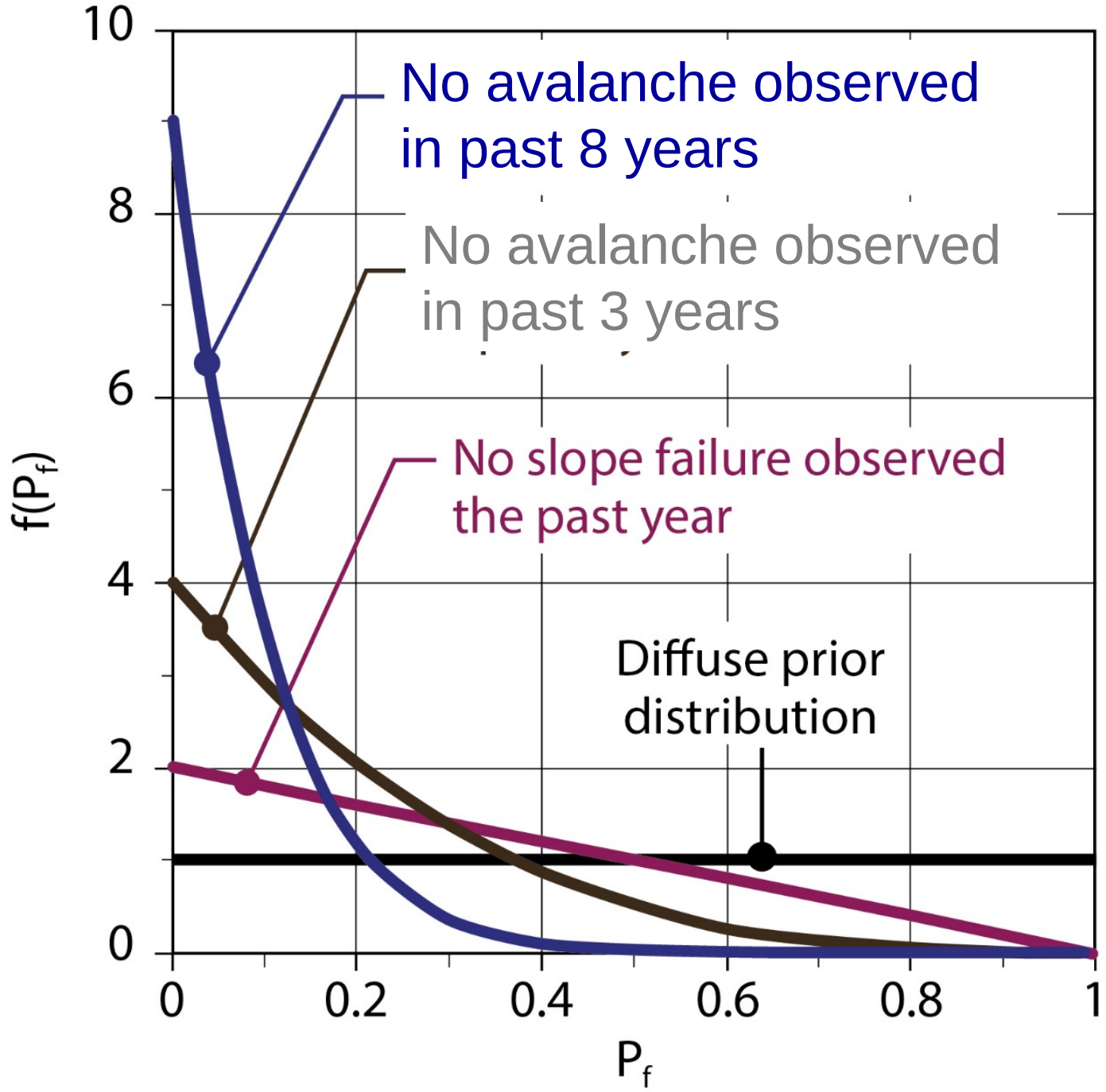


No avalanche in the past 3 years





No avalanche in the past 8 years



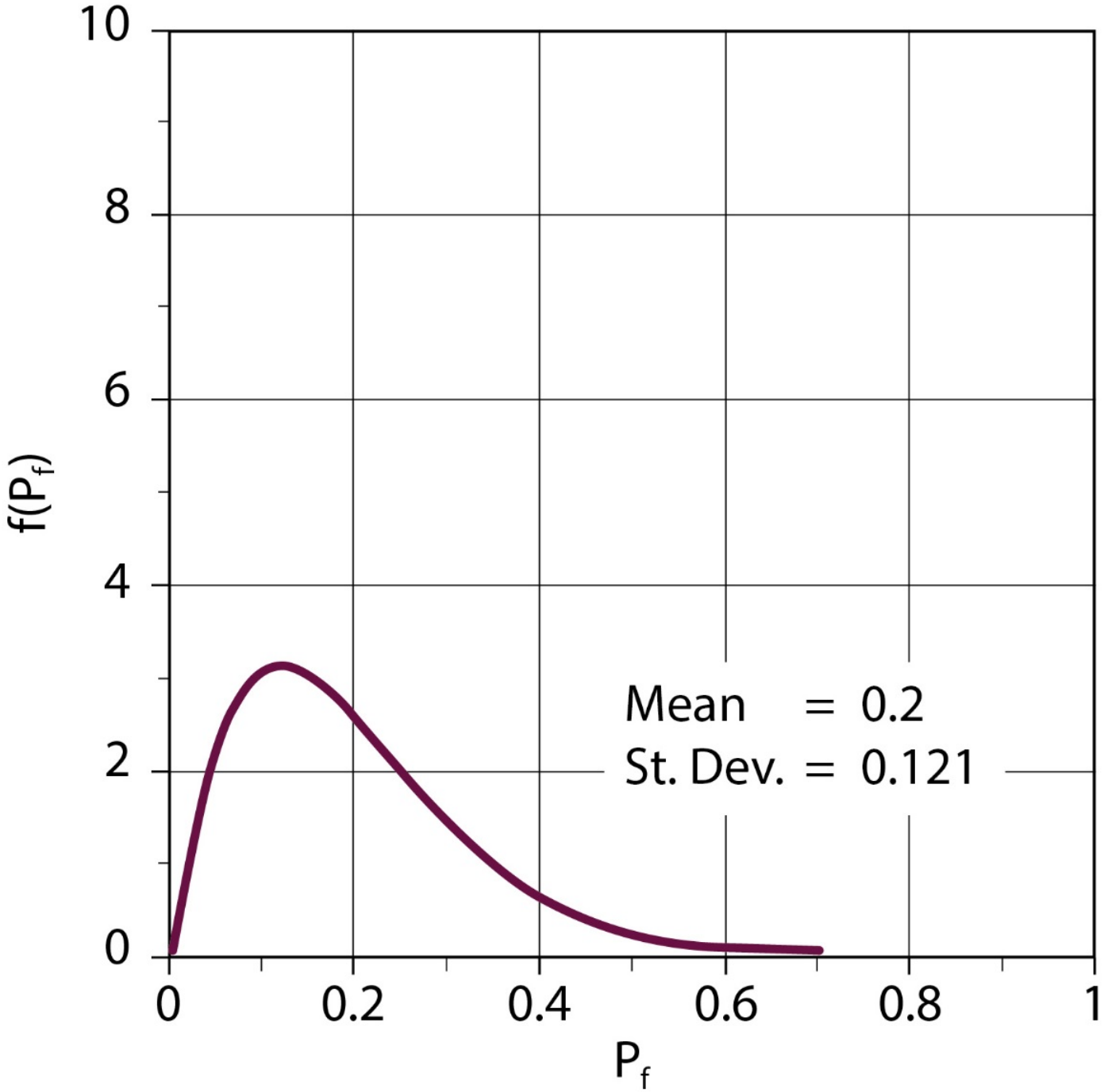


PDF for $P_{f\ annual}$ (avalanche occurring)

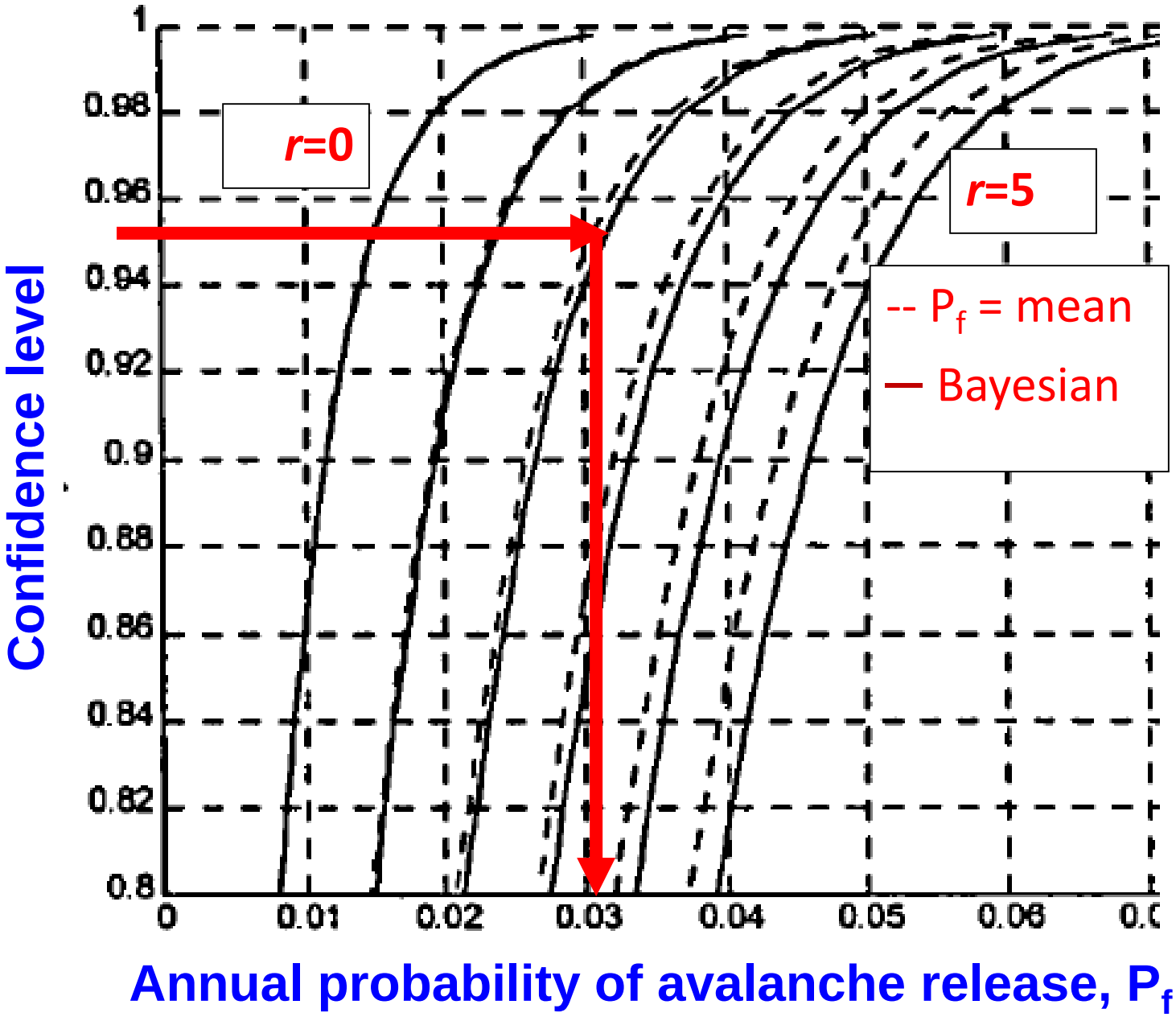
if 2 avalanches observed in past 10 yrs

[Nadim *et al* 2013]





Probability of extreme avalanche along specific path during one year





Added value of reliability analysis?

- The reliability approach allows one to design with a uniform margin of safety.
- The most significant uncertainties are singled out.
- The approach allow to use all the knowledge available and to compare margin of safety than include the effect of the uncertainties.



On avalanche risk

Canadian guidelines on avalanche risk (CAA 2016)
Technical aspects of snow avalanche risk management.

Operational guidelines for:
1) Municipal, residential, commercial and industrial areas
2) Transportation corridors
3) Ski areas and resorts
4) Backcountry travel and commercial activities
5) Worksites, exploration, survey, resource roads, energy corridors and utilities, managed forest land

Guidance tables associating:
- Element at risk
- Avalanche size or impact pressure
- Return period (years)
- Risk management guidelines for planning
- Risk management guideline for operation



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Risk assessment for railways (for JBV)

- GIS-based
- Risk matrix (hazards and consequences) along railway corridors

[Hefre *et al* 2016]



Hazard analysis

✓ average slope angle
✓ slope direction (rel.to railway)
✓ soil type
✓ area of exposed slope
✓ earlier sliding evidence
✓ drainage capacity
✓ potential erosion

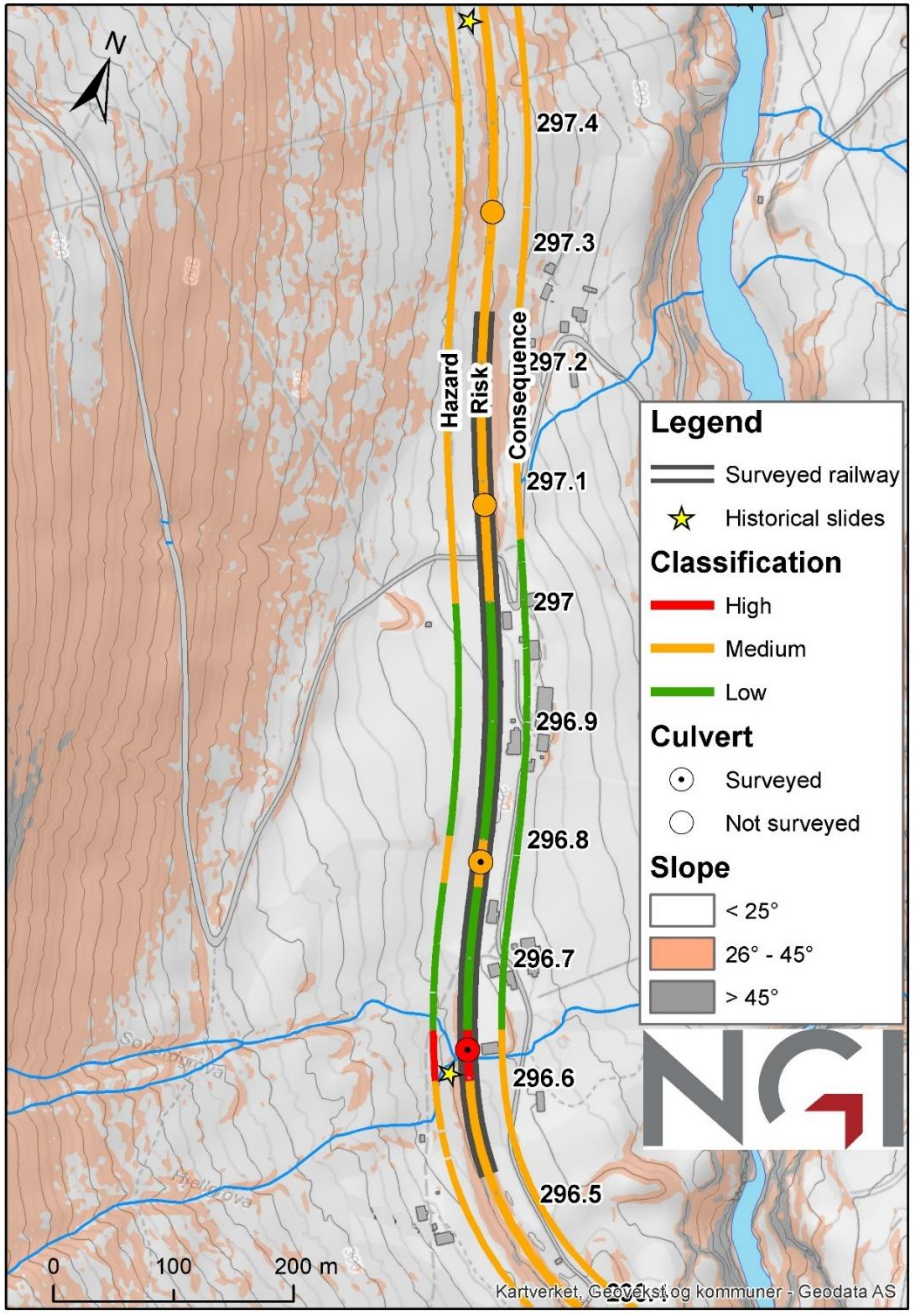
Consequence analysis

✓elements at risk
✓ terrain conditions at time of potential derailment
✓ impact speed
✓ accessibility for rescue

Risk assessment for railways (for JBV)

Illustrative risk map [Hefre *et al* 2016].

- one km of railway
- hazard class
- consequence class
- risk in the middle
- high risk - mitigation





Risk matrix for an excavation
BegrensSkade project

Project phases

1 Design
2 Prepar
3 Pre-ex
4 Sheetp
5 Excava
6 Shorin
7 Local

Sources of uncertainty

1 Material
2 Design
3 Execut
4 Enviror
5 Externa
6 Extrem
10 High gr
11 Fallout on excavated slopes

Consequences

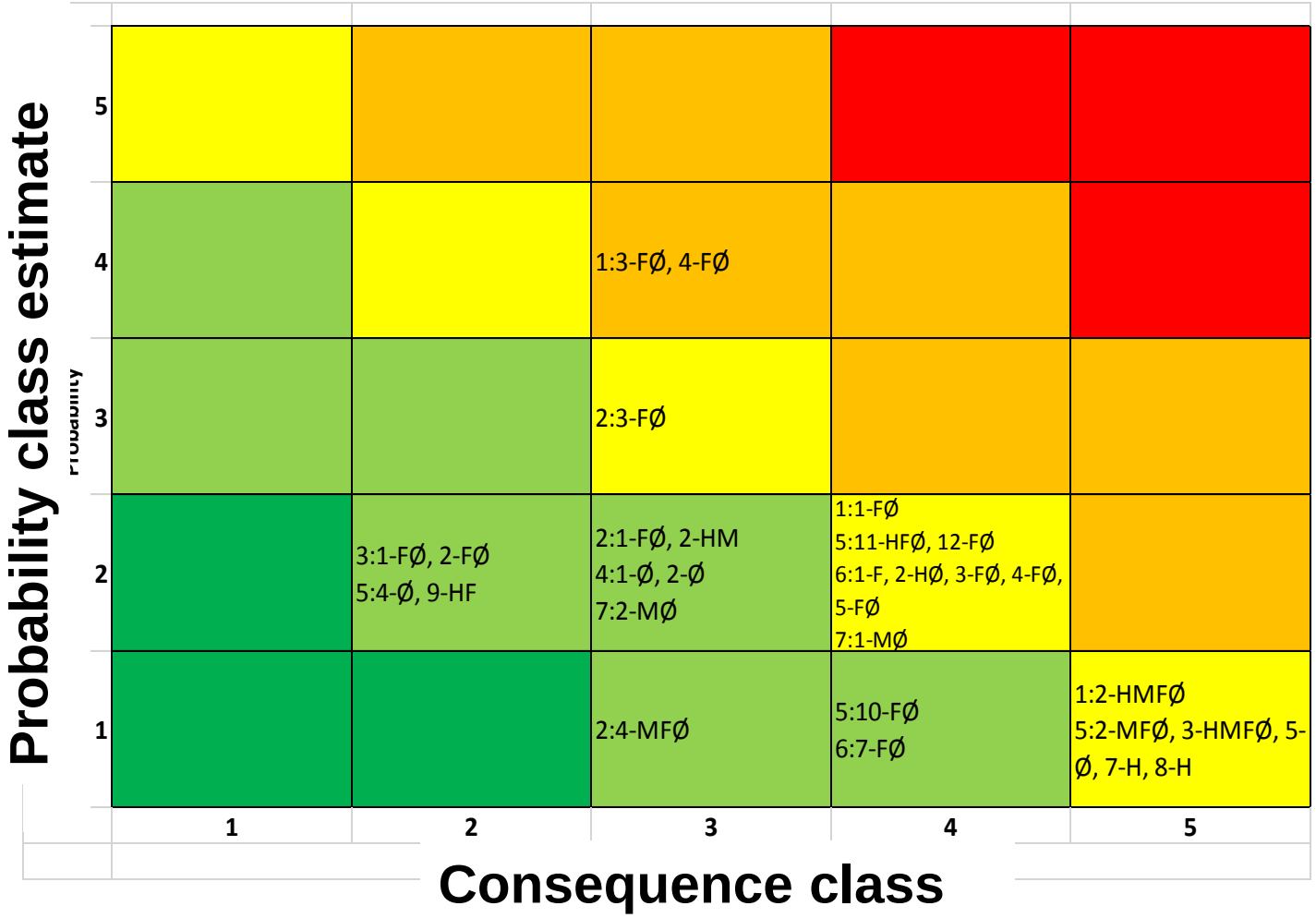
H Health damage or fatality
M Environment
F Progress in execution
Ø Economy



[Engen & Langford 2016; Kalsnes et al 2016]

Risk matrix for an excavation

Hazard and consequence analysed by the project team – system in a EXCEL macro-activated spreadsheet





Risk matrix Excavation BegrensSkade

Each matrix cell
n:m—ccc
1:3—FØ
Constr. Phase : Uncertainty
—Consequences

Probability class estimate	1	2	3	4	5
5					
4			1:3-FØ, 4-FØ		
3			2:3-FØ		
2		3:1-FØ, 2-FØ 5:4-Ø, 9-HF	2:1-FØ, 2-HM 4:1-Ø, 2-Ø 7:2-MØ	1:1-FØ 5:11-HFØ, 12-FØ 6:1-F, 2-HØ, 3-FØ, 4-FØ, 5-FØ 7:1-MØ	
1			2:4-MFØ	5:10-FØ 6:7-FØ	1:2-HMFØ 5:2-MFØ, 3-HMFØ, 5-Ø, 7-H, 8-H

Consequence class

[Engen and Langford 2016; Kalsnes et al 2016]

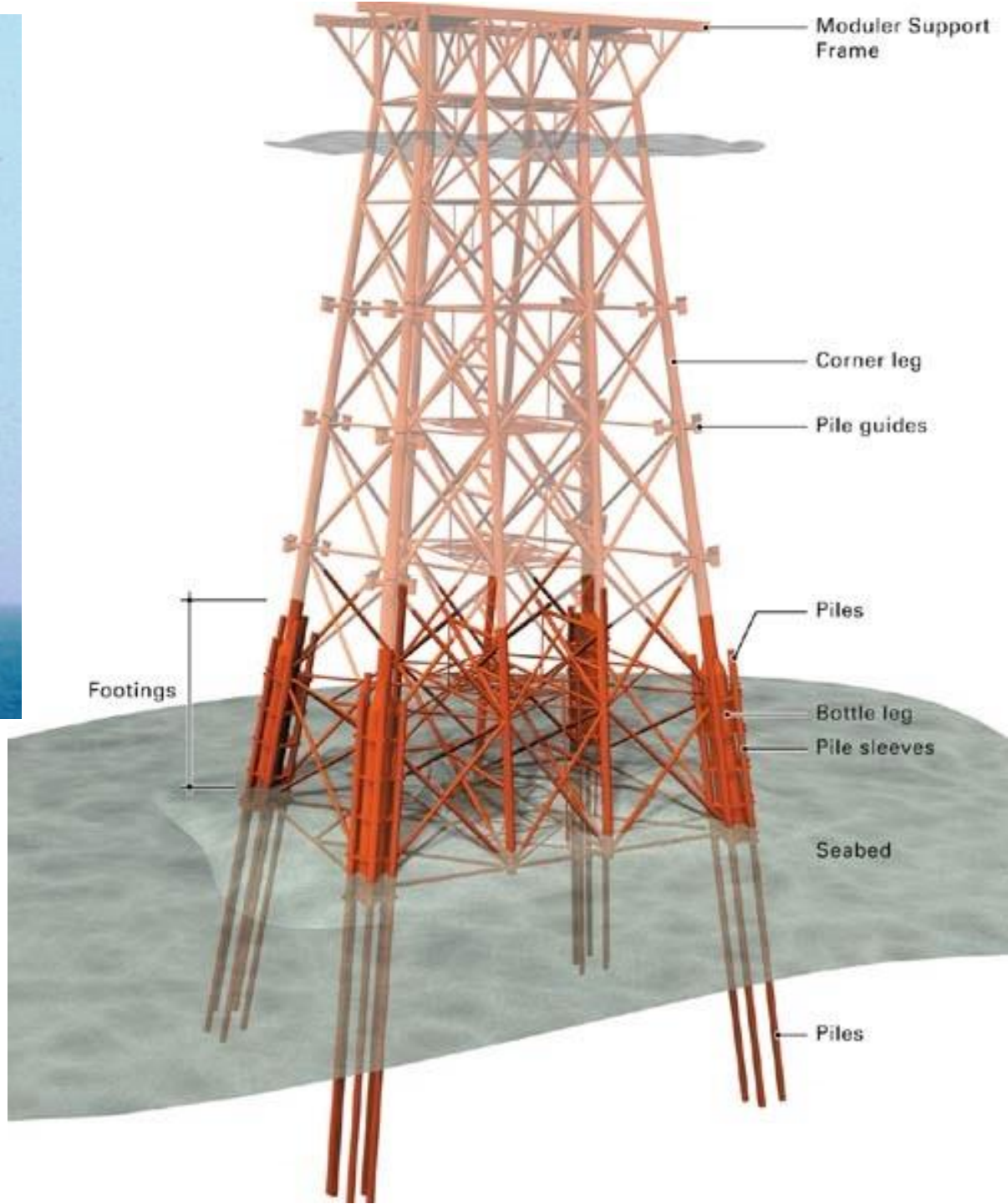


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Moduler Support Frame
Corner leg
Pile guides
Piles
Footings
Bottle leg
Pile sleeves
Seabed
Piles



Consequence for required pile penetration depths at 3 sites

Method	Required pile penetration depths		
	Site A (clay)	Site B (sand)	Site C (clay and sand)
NGI-05	90 m to **75** m	51 m to **27** m	45 m to **36** m

Reduction of the deterministic pile penetration depth (NGI-05 method), because it was documented that $P_f < 10^{-4}$/yr.

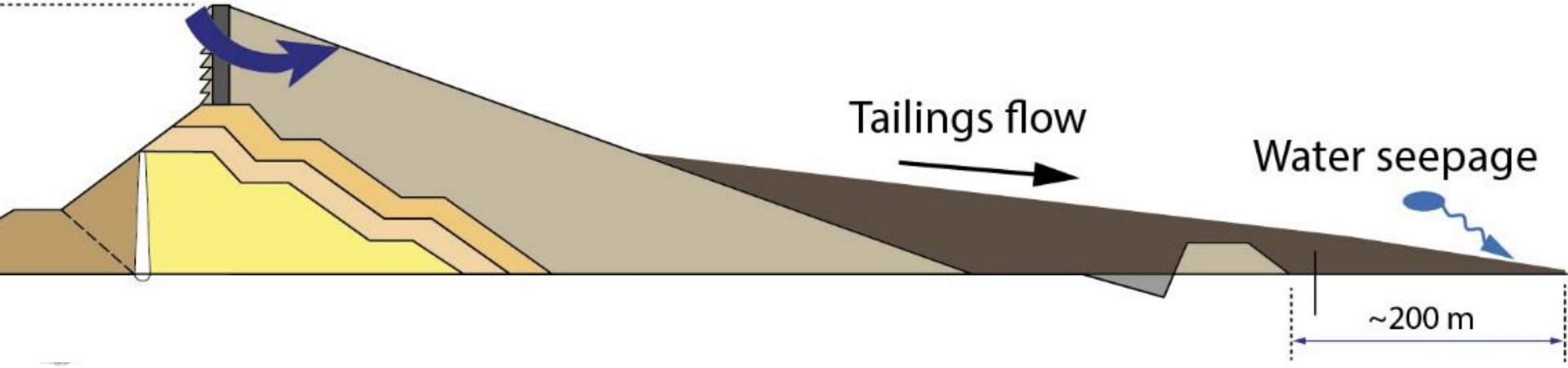


Roşia Montaňa – TMF

Physical impacts

If dam breach occurs:

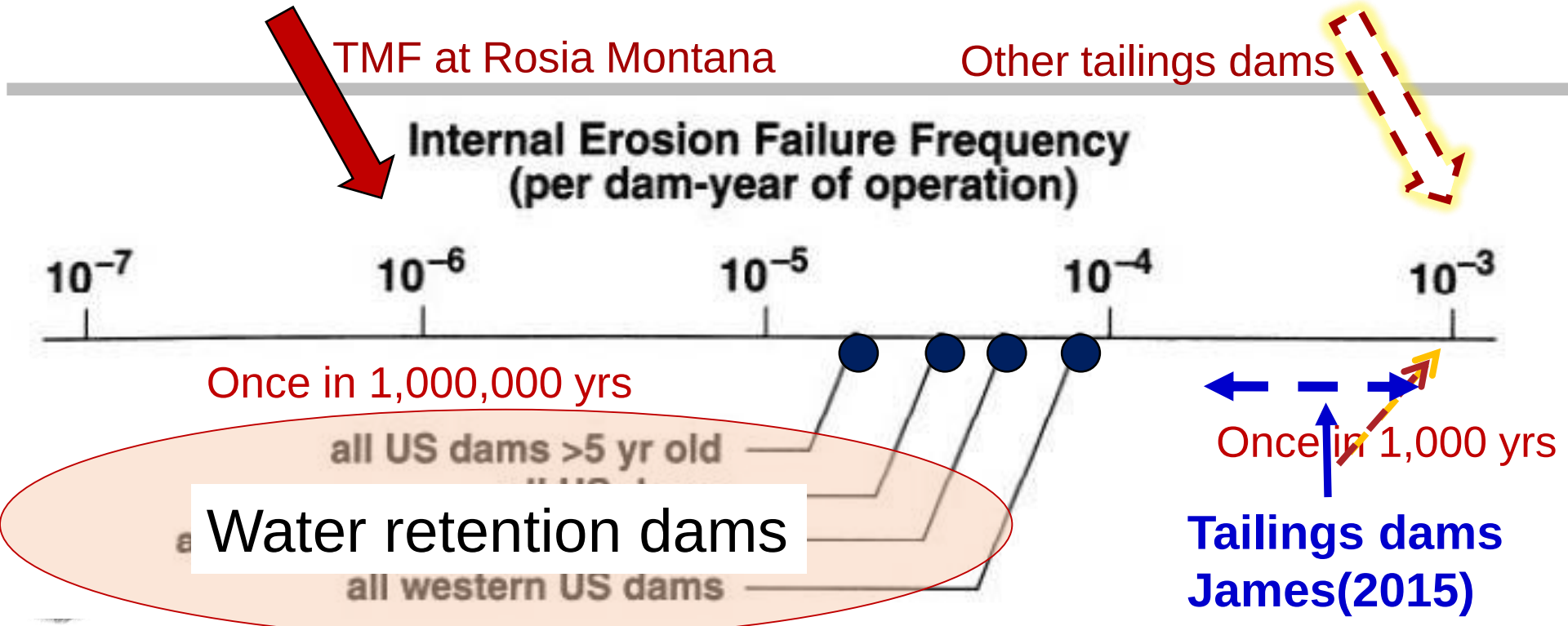
- Tailings would flow about 200 meters past Secondary Dam
- Escape volume: 250,000 m^3 tailings and 26,000 m^3 of water
- Water discharge into nearby Abrud river showed limited cyanide levels above regulated standards in close vicinity only, during low flow period only (1/3 of the year).



Roşia Montaňa – TMF

Addition of probabilities for all scenarios

The highest probability of a breach occurring: once in 1,000,000 years. The TMF is therefore significantly safer than other existing dams containing tailings.



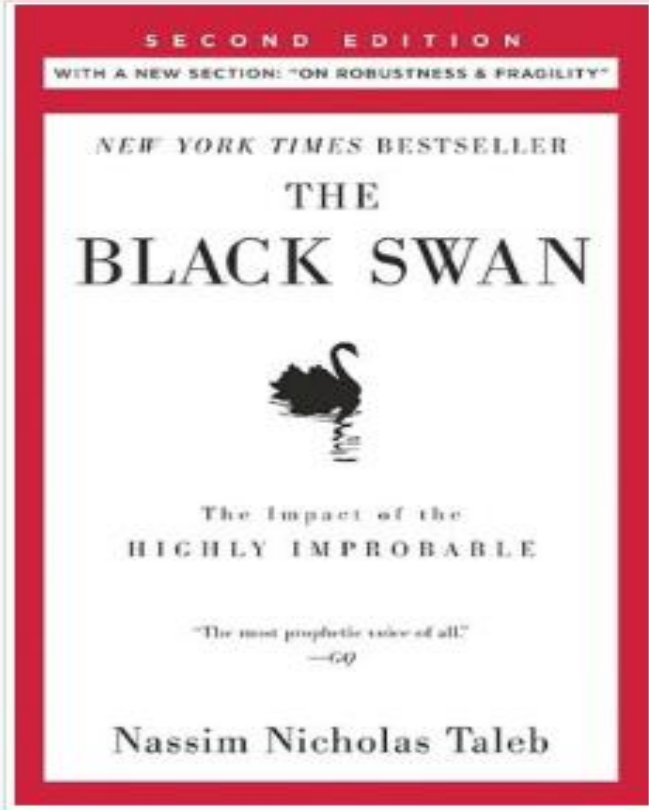
Contents of lecture

1. Basic concepts, some history
2. Reliability analyses to ensure adequate safety and lead to cost-effective design - "Real-life“ cases
   - Debris flow
   - Strain-softening clays
   - Avalanche occurrence
   - Safety along railways and in foundation work
   - **Offshore geotechnics and dams**
3. **Emerging topics and conclusions**



Emerging issues

Critical facilities designed to withstand events with P_f of 10^{-4} - 10^{-6} / yr are not 100% safe. The risk is often governed by **low-probability - high impact** extreme events that occur very rarely. There is, however, usually not enough data to make statistical estimates of the probabilities (also a central concern in UN's IPCC SREX Report 2012)



Emerging solution:

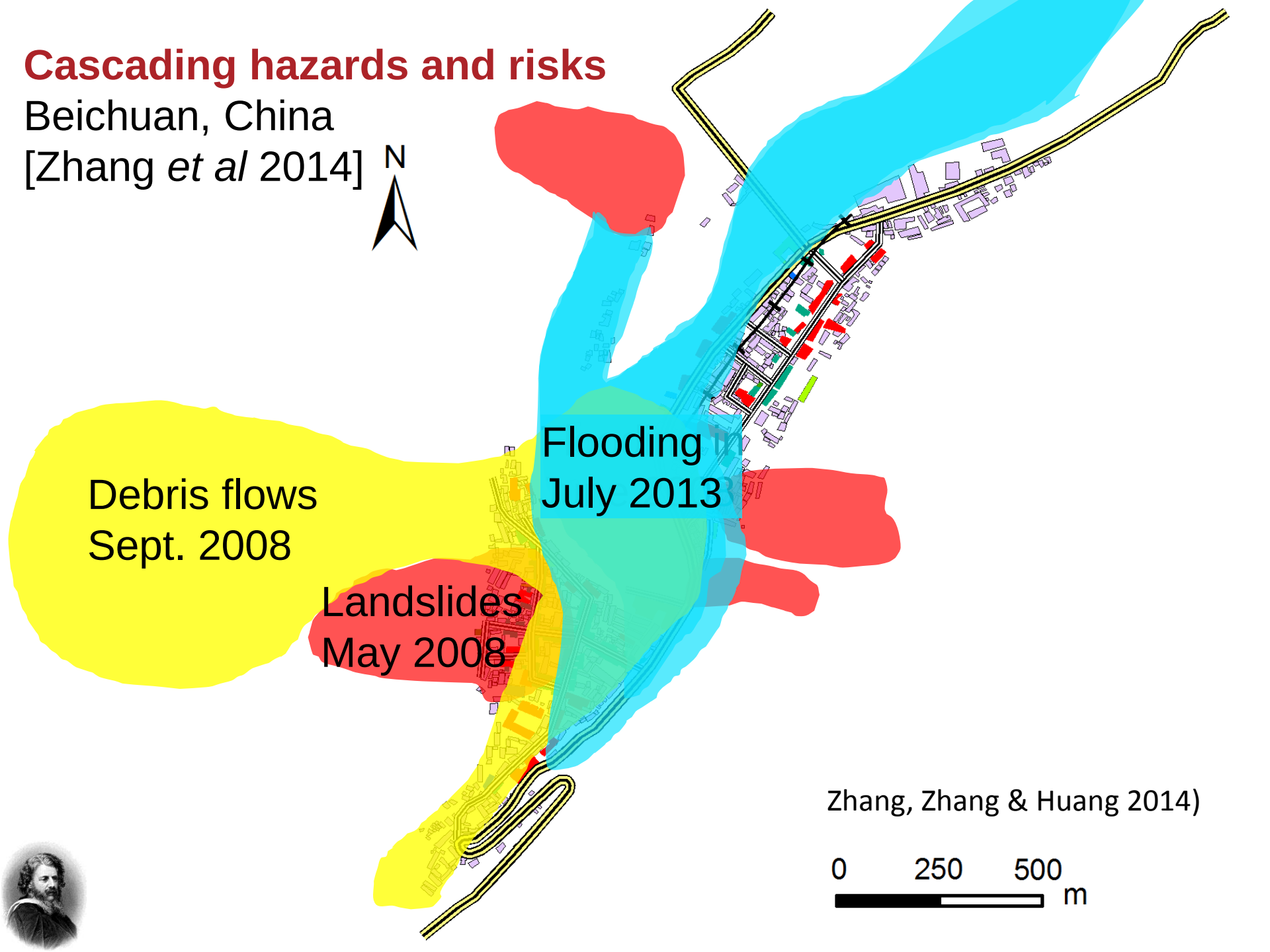
"Stress testing"



Cascading hazards and risks

Beichuan, China

[Zhang *et al* 2014]



Emerging issues

Cascading hazards and multi-risks

How can one consider the interactions among different threats in a systematic way, including the uncertainties?

Compared to single risk analysis, the examination of multiple risks poses a range of challenge be-cause of the different characteristics of the hazards.

Emerging solution:

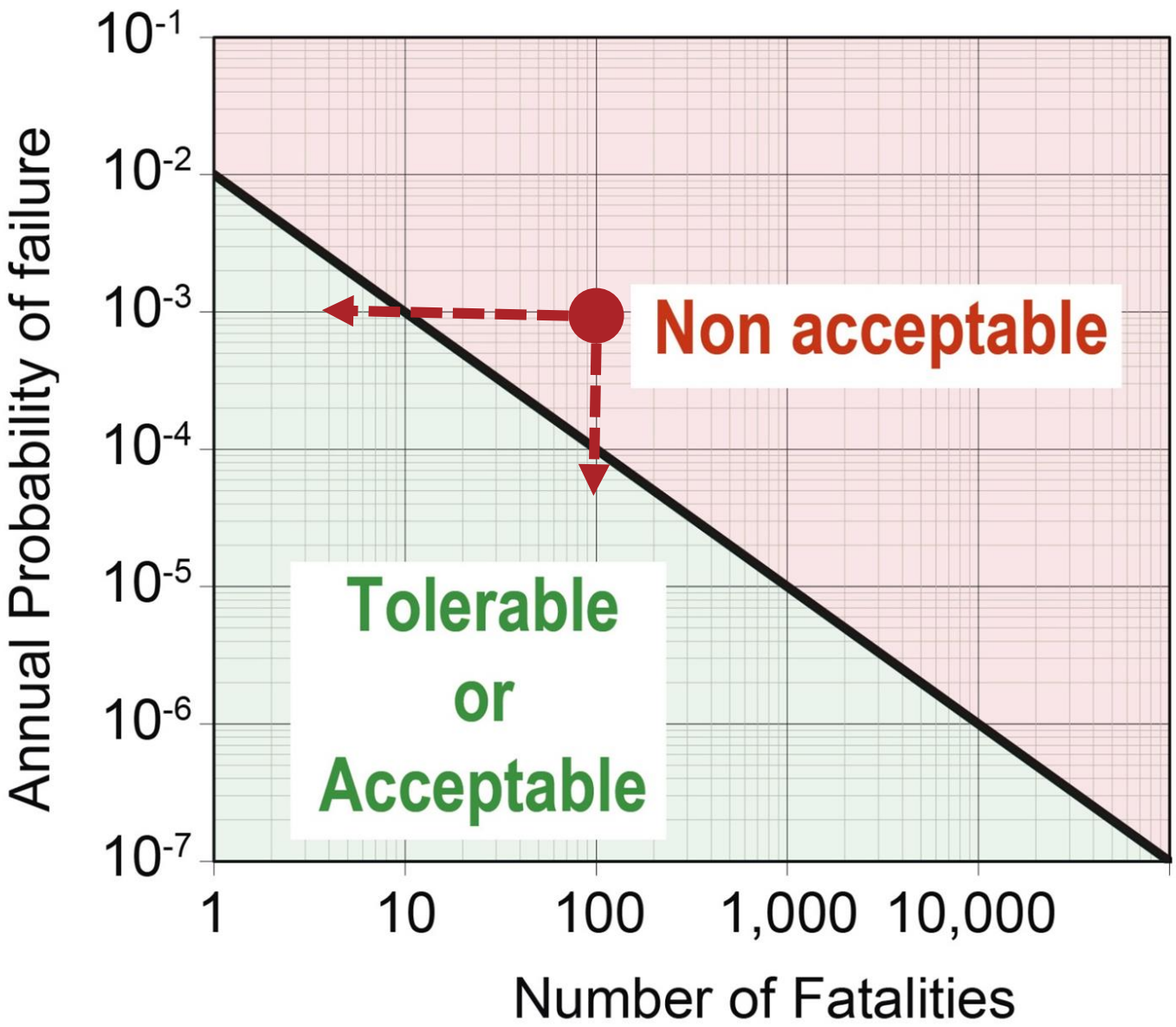
"Bayesian networks" (quantitative)



F-N curves and acceptable risk

The F-N plot is one vehicle for comparing calculated probabilities with, e.g., observed frequencies of failure of comparable facilities.

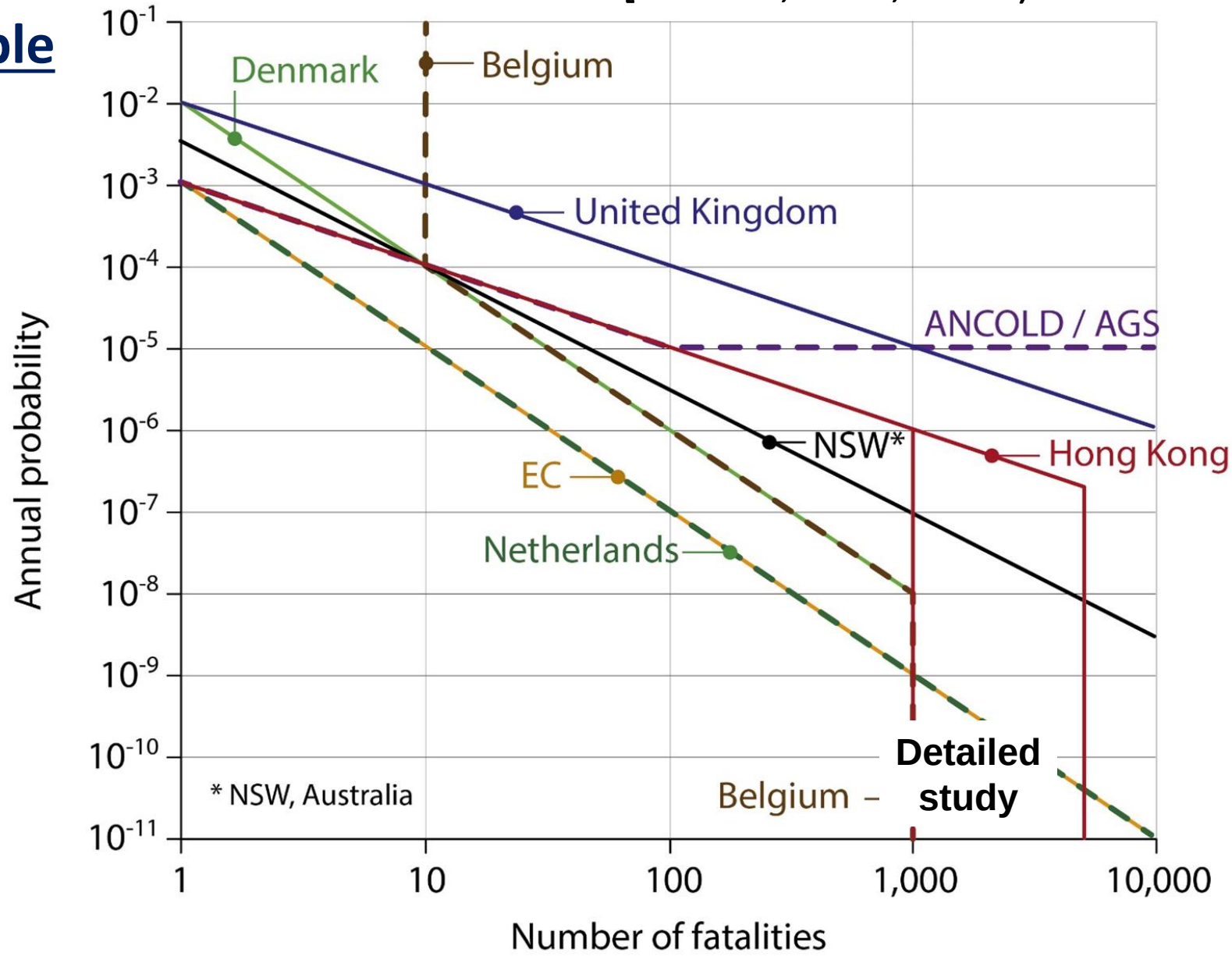




Comparison of requirements (F-N curves)

[Ken Ho, GEO, 2008)

Acceptable risk





Emerging issues

Communication

Being a good communicator is today one of the most empowering skills that we as engineers can acquire. Being able to communicate presupposes understanding the subject, and preparing for the beforehand!

Quantitative assessment of hazard and consequences reveals the risk-creating factors and the need for remedial changes. It encourages foresight rather than hindsight.



Why did the Mount Polley tailings dam fail?



Failure in the foundation of the embankment due to a weak layer that was undetected. In addition, OC clay became NC under construction. Downstream rockfill had very steep slope (1.3H : 1V). Had the slope been flattened to 2H : 1V, as proposed in the original design, failure would have been avoided.

No performance monitoring, although it had been advised.

[Independent Expert Engineering Investigation and review Panel, 30 Jan. 2015]

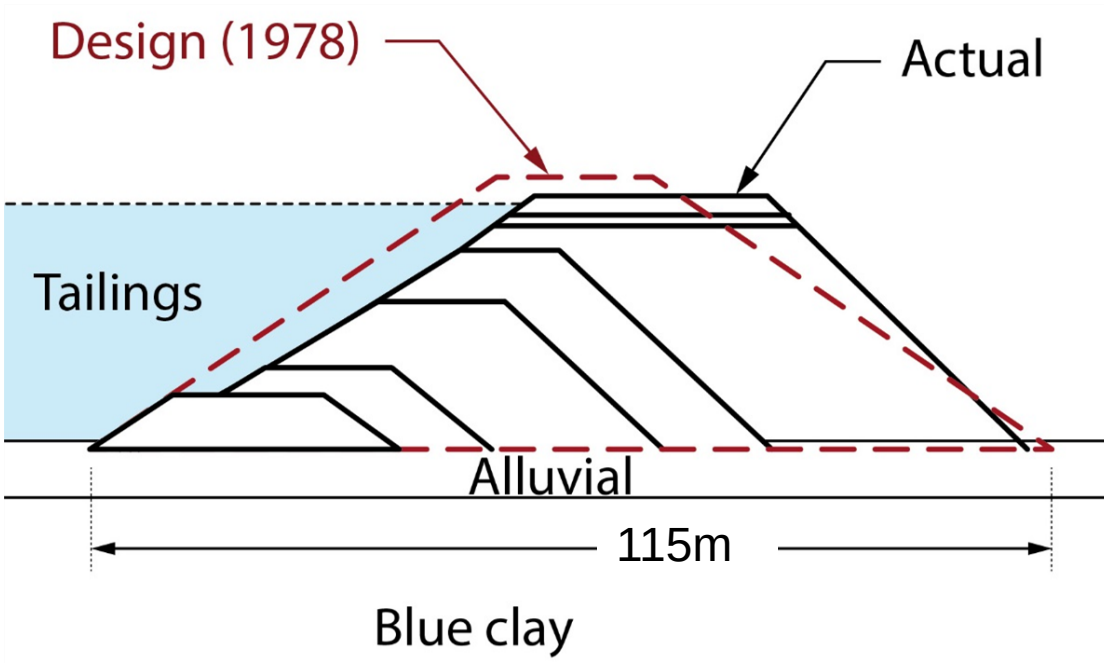


Why did the Aznalcóllar tailings dam fail?



As built cross-section was different from as designed cross-section (1.8H : 1V). Downstream slope was increased to 1.23H : 1V in 1985.

[Gens & Alonzo 2006]





A paradox of our profession

- Time and budget constraints and competition on price bring down the budget for site investigations and design to a minimum, even when there are important uncertainties.
- When a major failure occurs, there seems to be unlimited budget for site investigations (lab and *in situ*), analyses and expert advice (Mount Polley review report: an impressive quantity of tests and analyses in 5 months).

How do we convince clients that:

- More site investigations and more time are needed for design.
- Observational method is the best "insurance".
- Reliability assessments will provide more insight.



Why is risk analysis accepted in concept, but takes time to be put in practice?

Terminology

-no accepted definition

-“zero risk” and safety

Concerns

-Complexity/mathematics

-Accepting that there are uncertainties

Distrust

-Acceptable/tolerable risk values, and who decides?



Reliability analyses

Reliability approaches do not remove uncertainty nor do they alleviate the need for judgment. They provide a way to organise, quantify and handle the uncertainties consistently.

Reliability approaches also provide the basis for comparing alternatives.

Site investigations, laboratory test programmes, limit equilibrium and deformation analyses, instrumentation and monitoring and engineering judgment are necessary parts of the reliability approach.



Deterministic and probabilistic analyses

Risk and probability tools have reached a degree of maturity and breadth that make them effective to use in practice. They provide more insight than deterministic analyses alone. They help reduce uncertainty and focus on safety and cost-effectiveness.



Deterministic analyses
give an impression of certainty;



Probabilistic analyses
complete the picture by making explicit
the uncertainties and their effects;



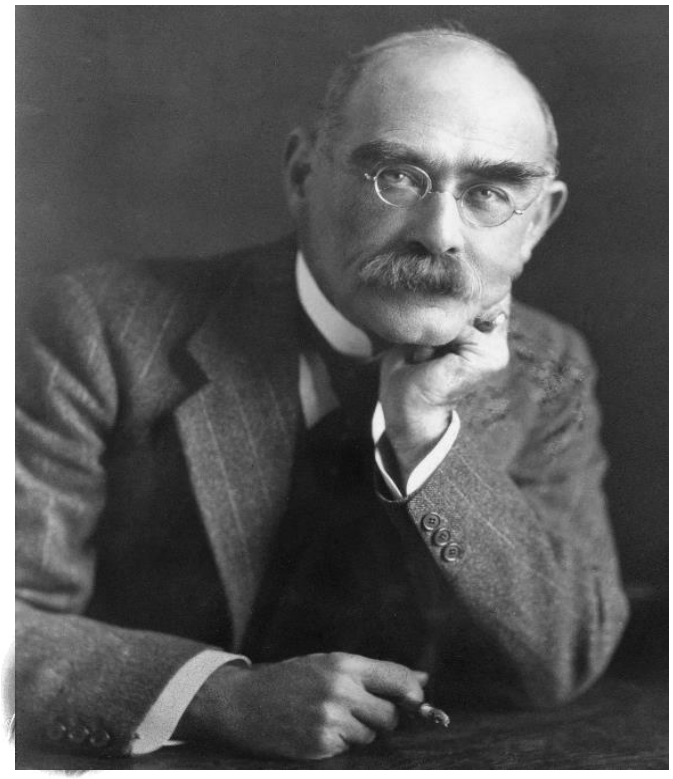


For improved geotechnical practice,
we need both.

“Doubt is an uncomfortable condition, but certainty is a ridiculous one.”

Voltaire
(1694-1778)





“A woman's guess is much more accurate than a man's certainty”.

Rudyard Kipling
(1865-1936)

Thank you, Iceland!

Knight (?) of the Icelandic Order of the Falcon





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