55th Rankine Lecture

Reprise in New Zealand 11-13 October 2016

Hazard, Risk and Reliability in Geotechnical Practice

by

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Institution of Civil Engineers

3 key questions

- How can reliability and risk concepts help to ensure adequate safety while achieving cost-effective designs?
- What are the advantages and challenges of the hazard, risk and reliability approach?
- Why aren't reliability and risk concepts used more today?

Strategy in answering these questions

Present examples that are so convincing that they will make you want to use some of the methods.

Show that probabilistic and deterministic analyses are, in many cases, necessary complements to each other.

Contents of lecture

1. Basic concepts and early work
2. Reliability analyses to ensure adequate safety and lead to cost-effective design - "Real-life“ cases
    - Design of piles for offshore installations
    - Debris flow in Barcelonnette Basin, France
    - Roşia Montaňa tailings management facility
    - New Orleans levees
    - Debris runout, slope failure due to earthquake
3. ~~Safety factor and definition of characteristic value~~
4. ~~Observational method and Bayesian updating~~
5. Challenges and emerging topics
6. Summary and conclusions

Basic definitions

Risk = f (Hazard and consequences)

Risk = f (H**,** V**,** U)

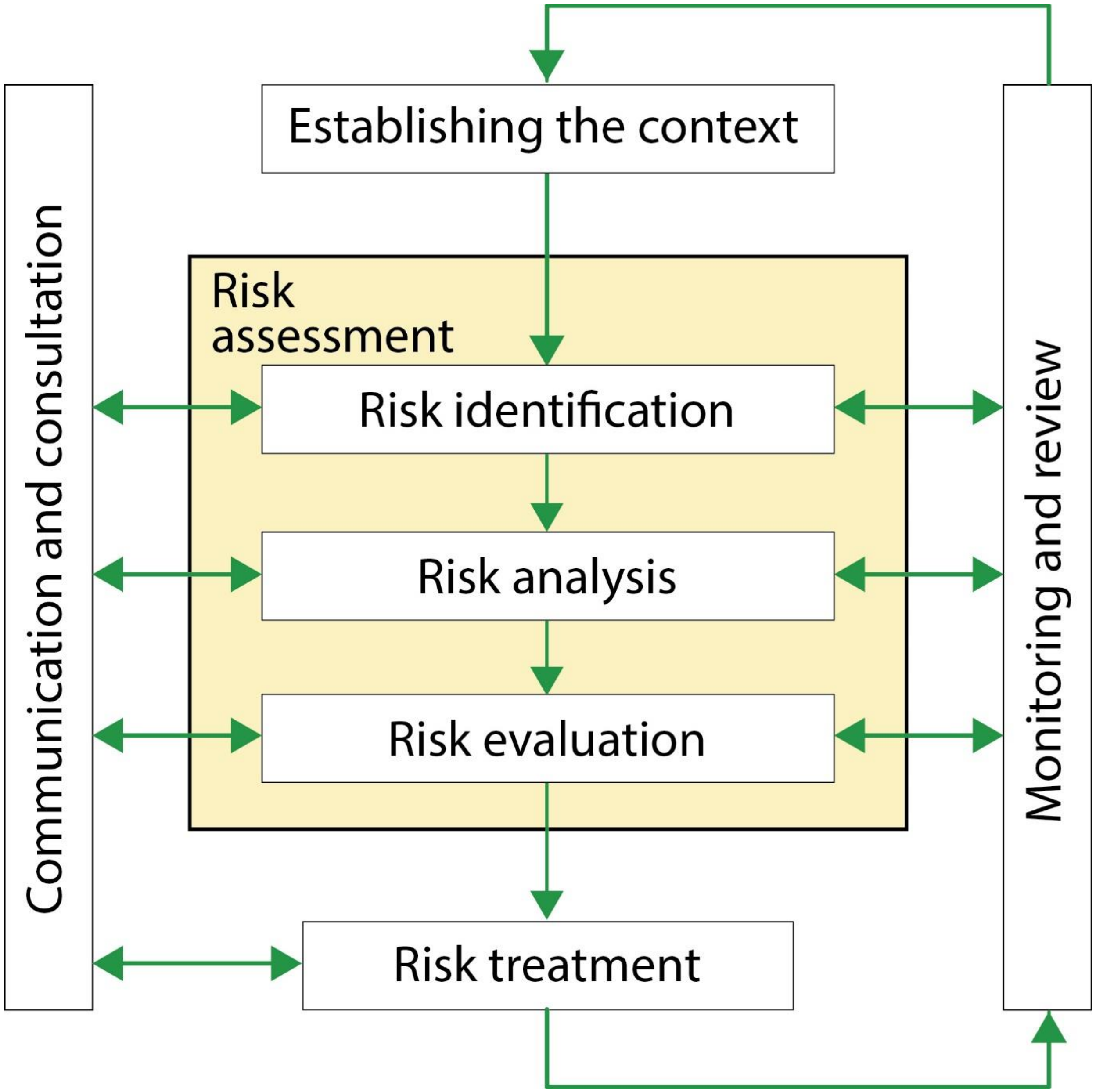
H = Hazard (temporal probability of a threat)

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 [ISO-3100:2009]



ISO’s definition of risk

"Risk is the effect of uncertainties on objectives"

New ISO FDIS 2394 (draft)
«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)

<u>Annex D Reliability of geotechnical structures</u>

Uncertainties

<u>Aleatory uncertainty</u>

Inherent variability due to the natural randomness of a phenomenon (e.g. ocean wave height, wind force, geotechnical pro-perties, earthquake characteristics) etc.

<u>Epistemic uncertainty</u>

Due to lack of know-ledge: it can be reduced by additional measurements or improved theories.

Las Colinas. El Salvador (2001)
Landslide following M = 7.6 earthquake

Uncertainties

In all geotechnical assessments, one needs to deal with uncertainties, either implicitly or explicitly.

[Photo: SVV 2015]

E18 expressway in Norway, February 2015
Slide in quick clay causing bridge collapse

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

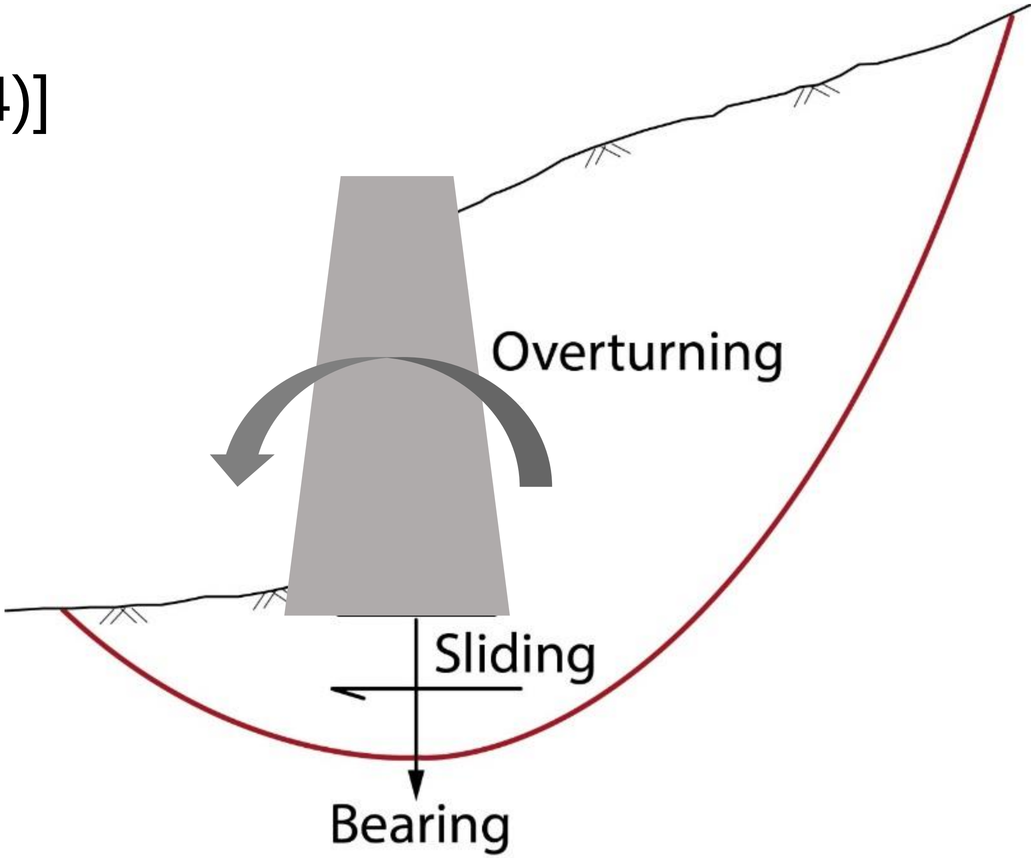
- Excavation in clay
- Bearing capacity failure in clay
- Slope in clay
- Settlement in sand

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."

Early work

[Høeg and Murarka (1974)]

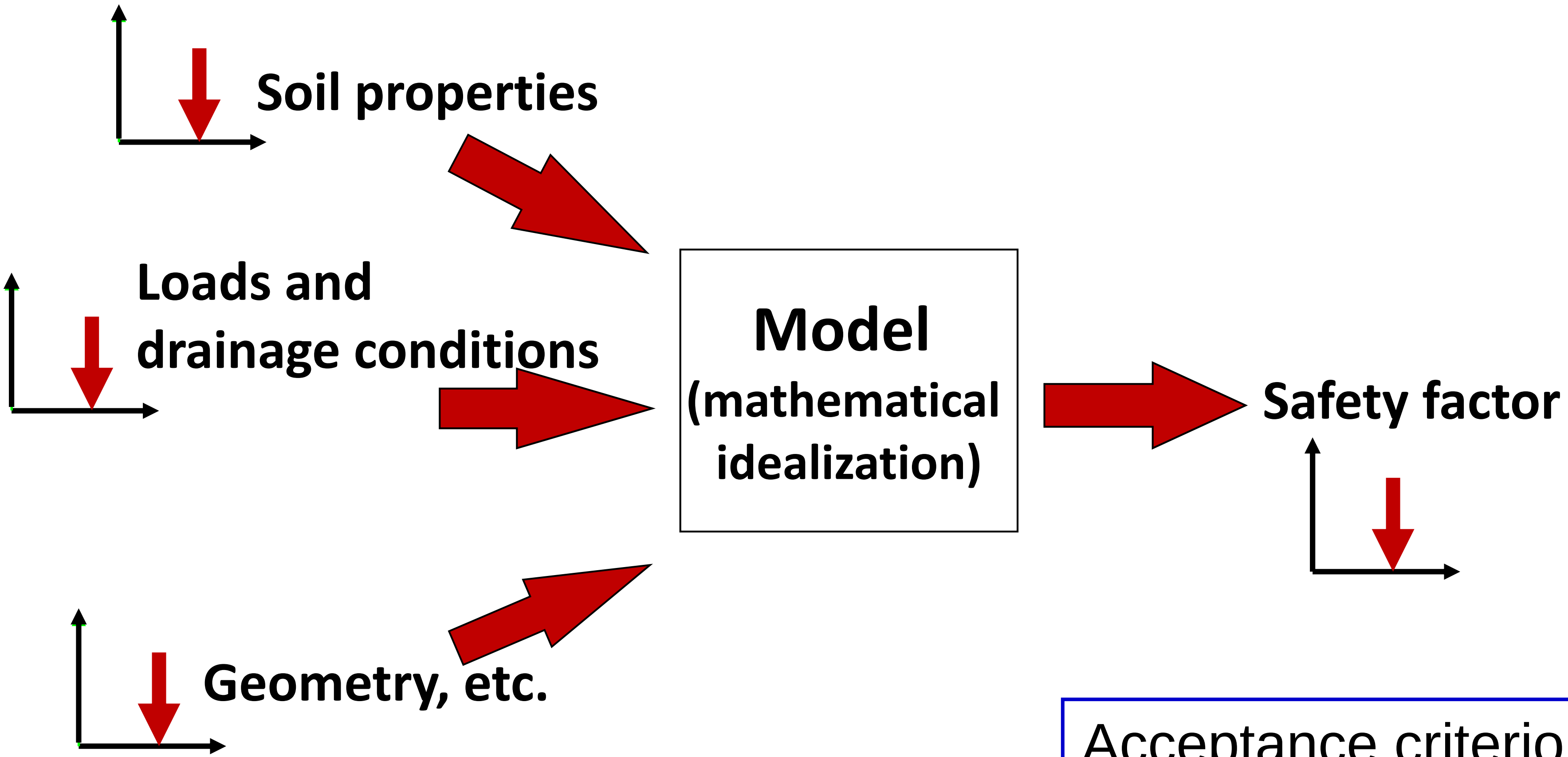


Balanced design
of a retaining wall

The contradiction between the factor of safety and estimated probability of failure was pointed out.

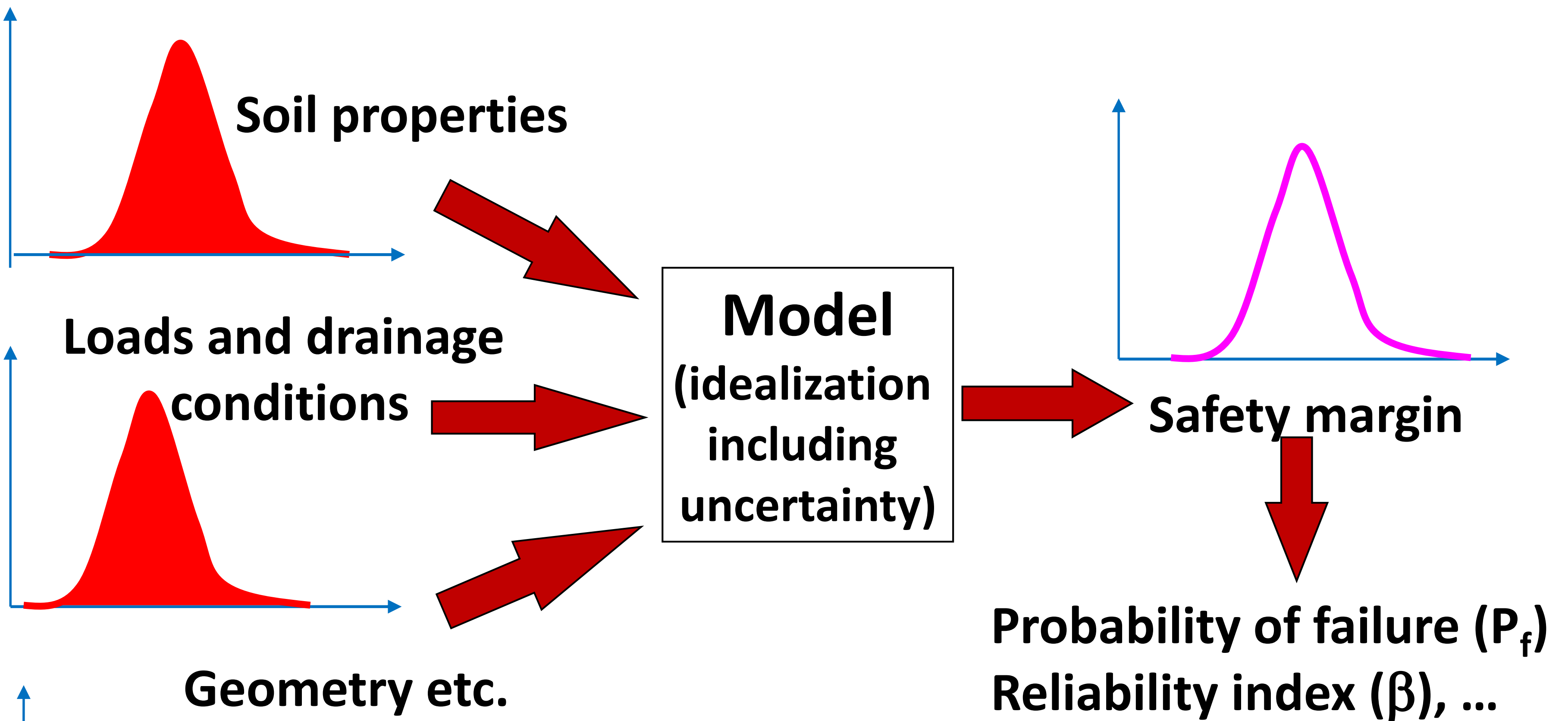
Failure mode	Central FS	P_f
Overturning	1.9	$0.7 \cdot 10^{-4}$
Bearing	3.7	$126 \cdot 10^{-4}$
Sliding	1.6	$26 \cdot 10^{-4}$

Deterministic analysis



Acceptance criterion:
$FS \geq FS_{acceptable}$

Probabilistic analysis

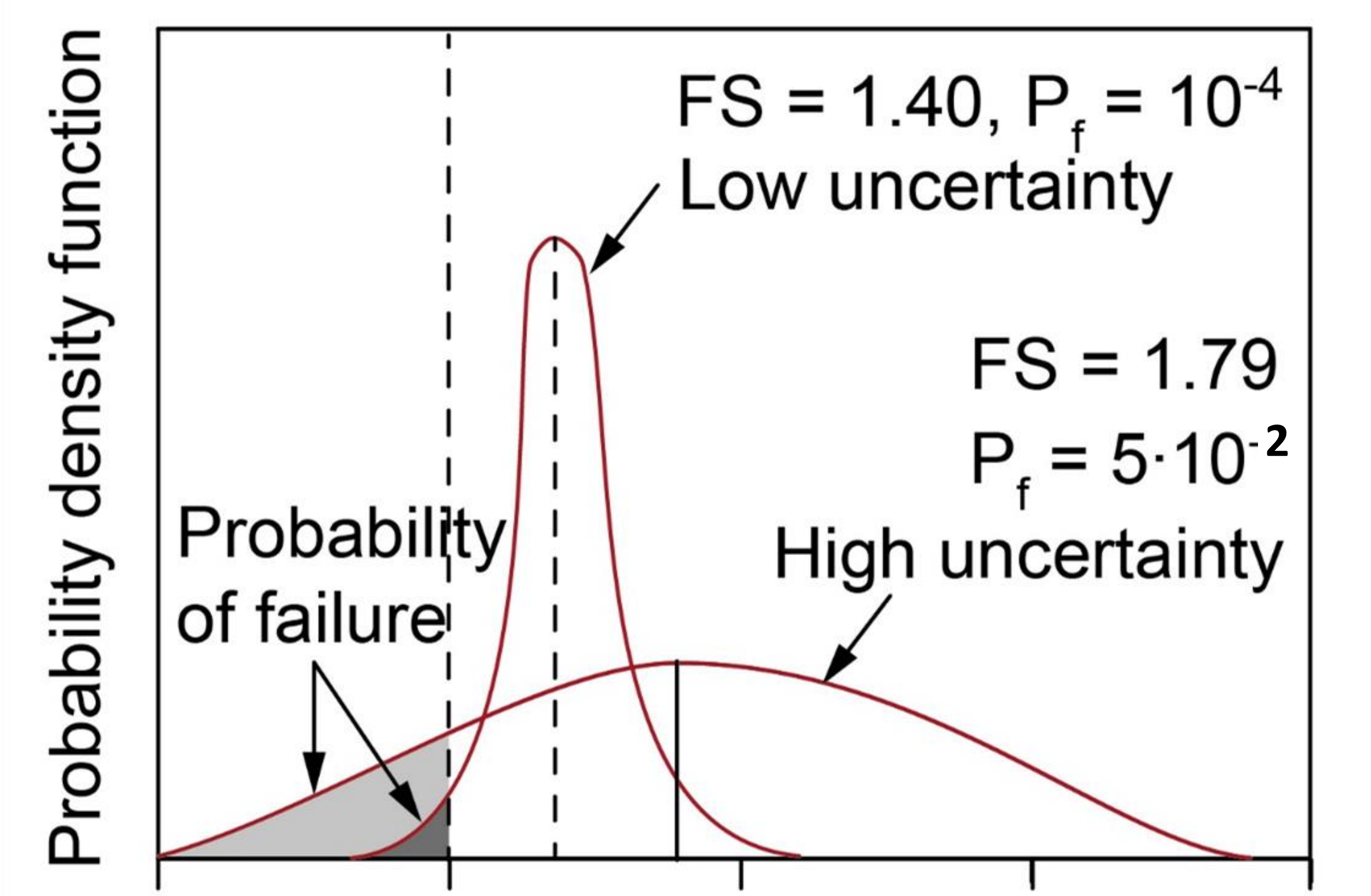


Acceptance criterion:

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

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

Factor of safety and probability of failure



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

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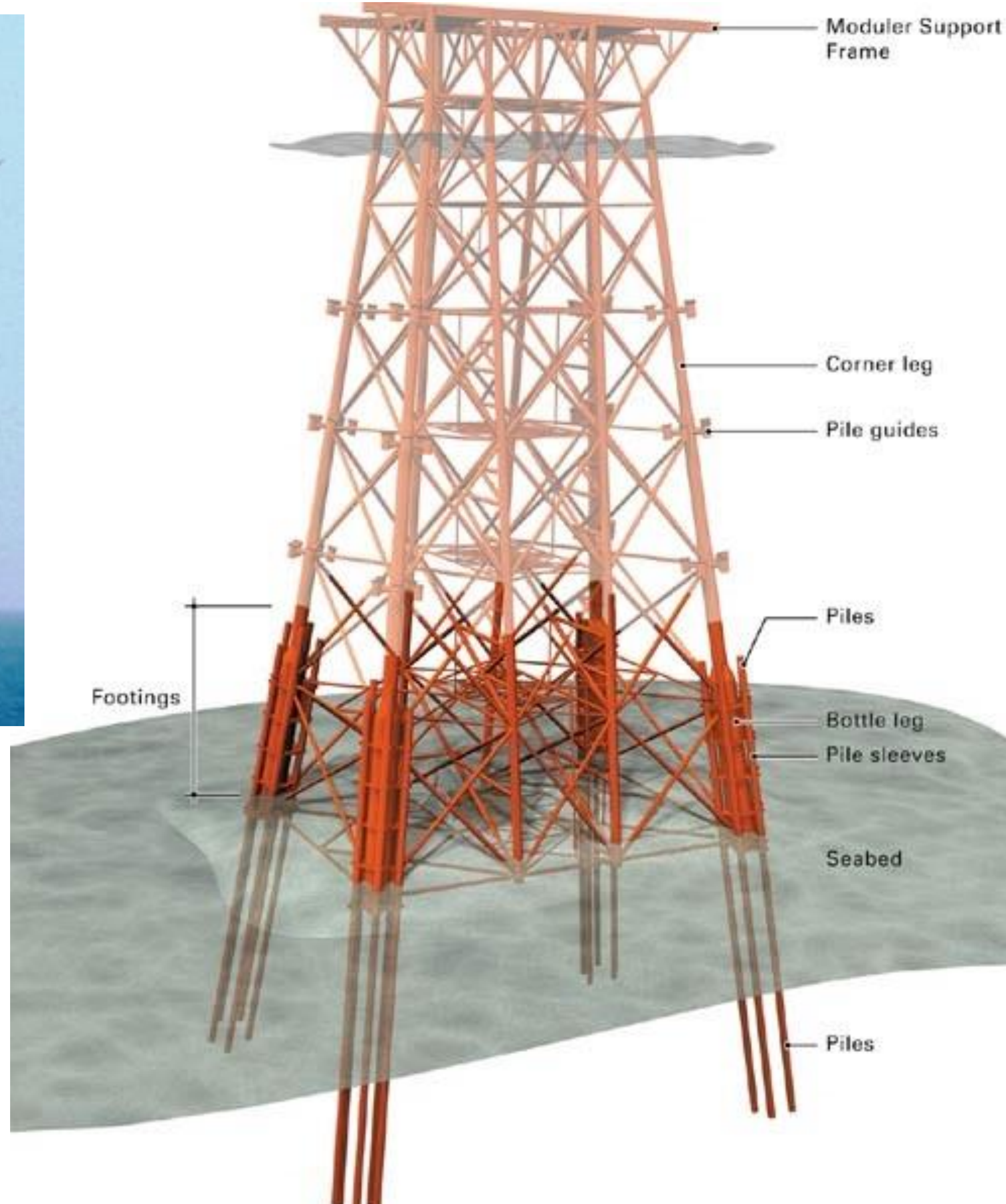

Moduler Support Frame
Corner leg
Pile guides
Piles
Footings
Bottle leg
Pile sleeves
Seabed
Piles

Motivation

- Guidelines require the same level of safety for the new CPT-based pile capacity design methods as for the older API method.
- The designer is required to select an "appropriate" safety factor when using the new CPT-methods.
- The designer can choose to:
  1) be conservative and apply a "high" safety factor or
  2) document the level of safety (“probability of failure").

Load and resistance factors

Design Criterion

$$[\gamma_{l\ stat} \bullet P_{stat} + \gamma_{l\ env} \bullet P_{env}^{100\text{-}yr}] \leq Q_{ult\ char} / \gamma_m$$

$\gamma_{l\ stat}$	=	Load factor on static load
P_{stat}	=	Characteristic static load
$\gamma_{l\ env}$	=	Load factor on environmental load
$P_{env}^{100\text{-}yr}$	=	Characteristic environmental load (typically the 100-yr load, $P_{env}^{100\text{-}yr}$)
$Q_{ult\ char}$	=	Characteristic ultimate axial pile capacity deterministic
γ_m	=	Resistance factor on capacity

Design of offshore pile foundations

- 3 sites (A, B, C), 100 m water depth
- Pipe piles, 2.5 m dia; t= 90 - 100 mm
- Loading in compression was governing

4 'newer' CPT design methods:

ICP-03, NGI-05, UWA-05 and Fugro 96/05.

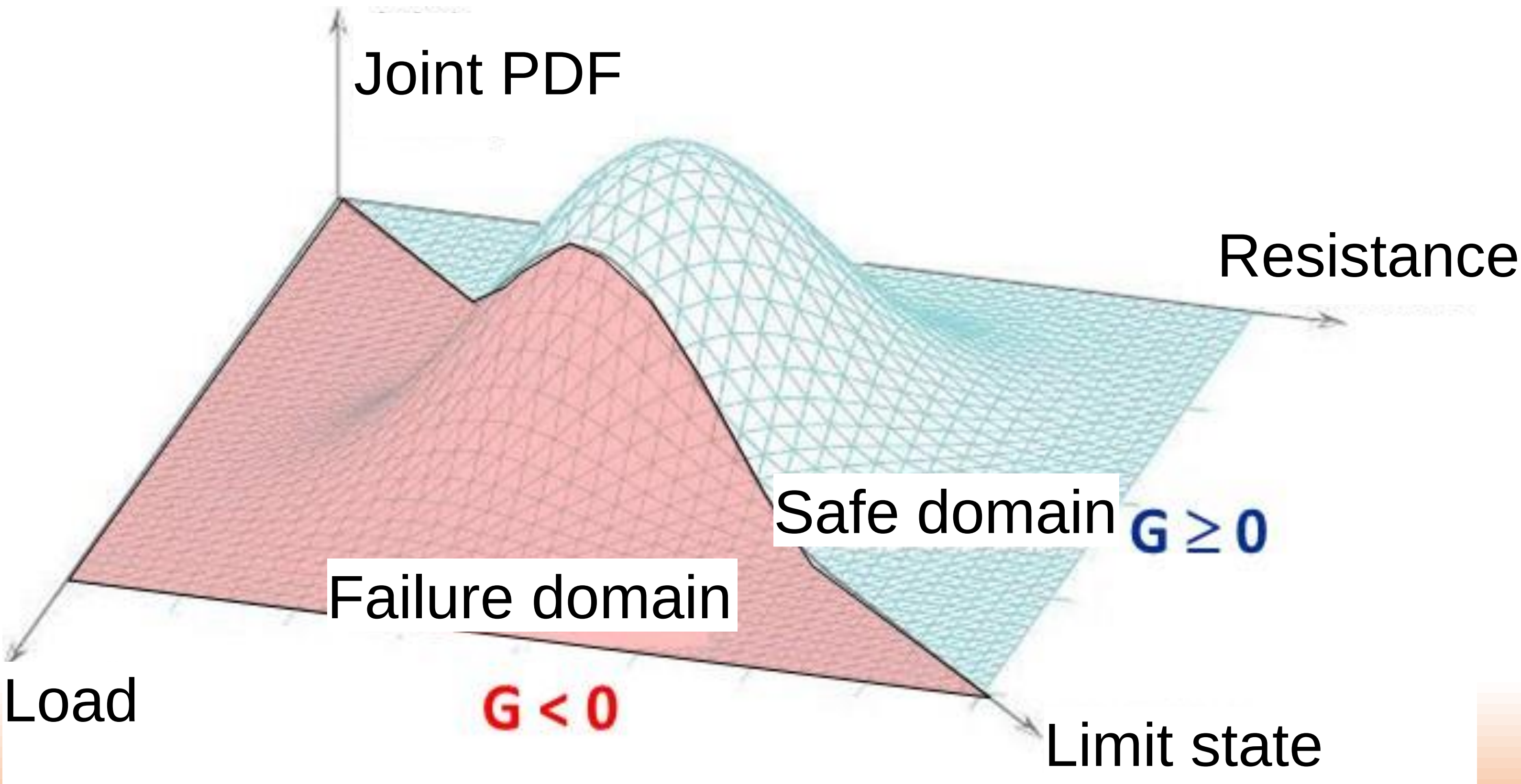
For deterministic analyses, the company required a resistance factor γ_m = 1.5 with the CPT-methods.

For probabilistic analyses, the target annual probability of failure was set to $P_f \leq 10^{-4}$, to follow NORSOK's 'guideline'.

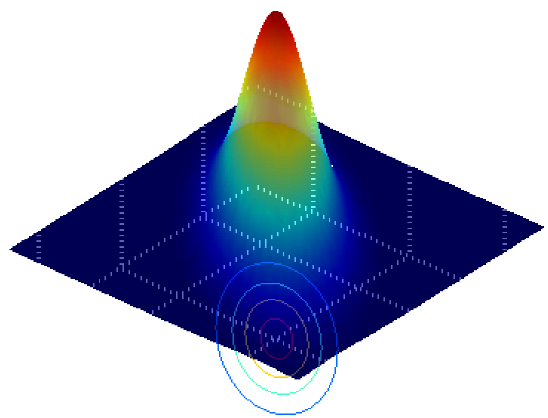
Probabilistic analysis with FORM

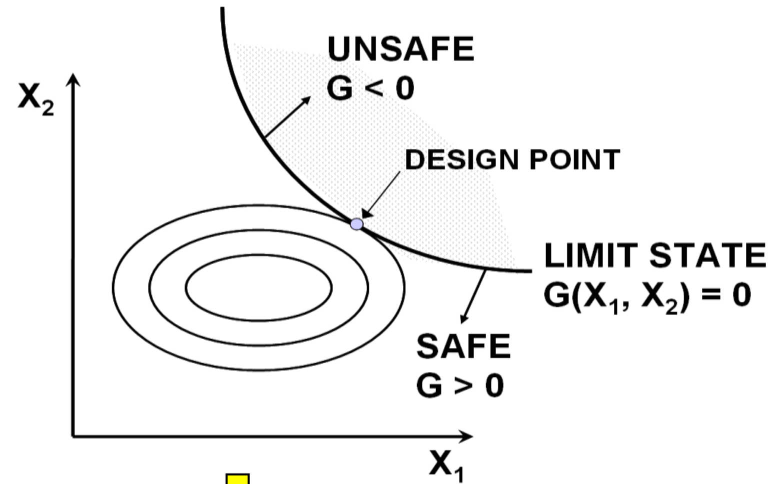
One defines a performance function e.g. $G(X) = R - L$,
where $G(X) \geq 0$ means satisfactory performance
$G(X) < 0$ means failure

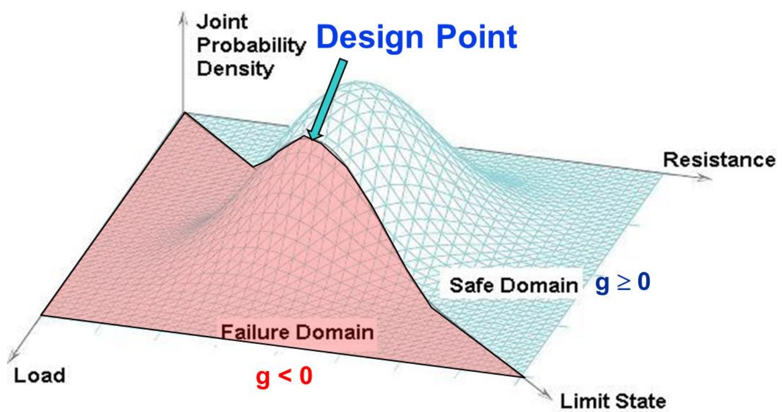
X is a vector of basic random variables (resistance, load effects, geometry and model uncertainty).

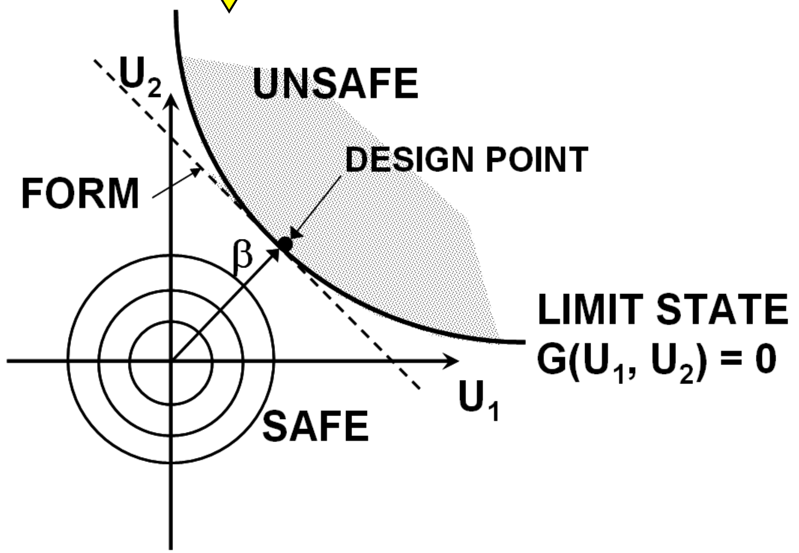


FORM/SORM approach

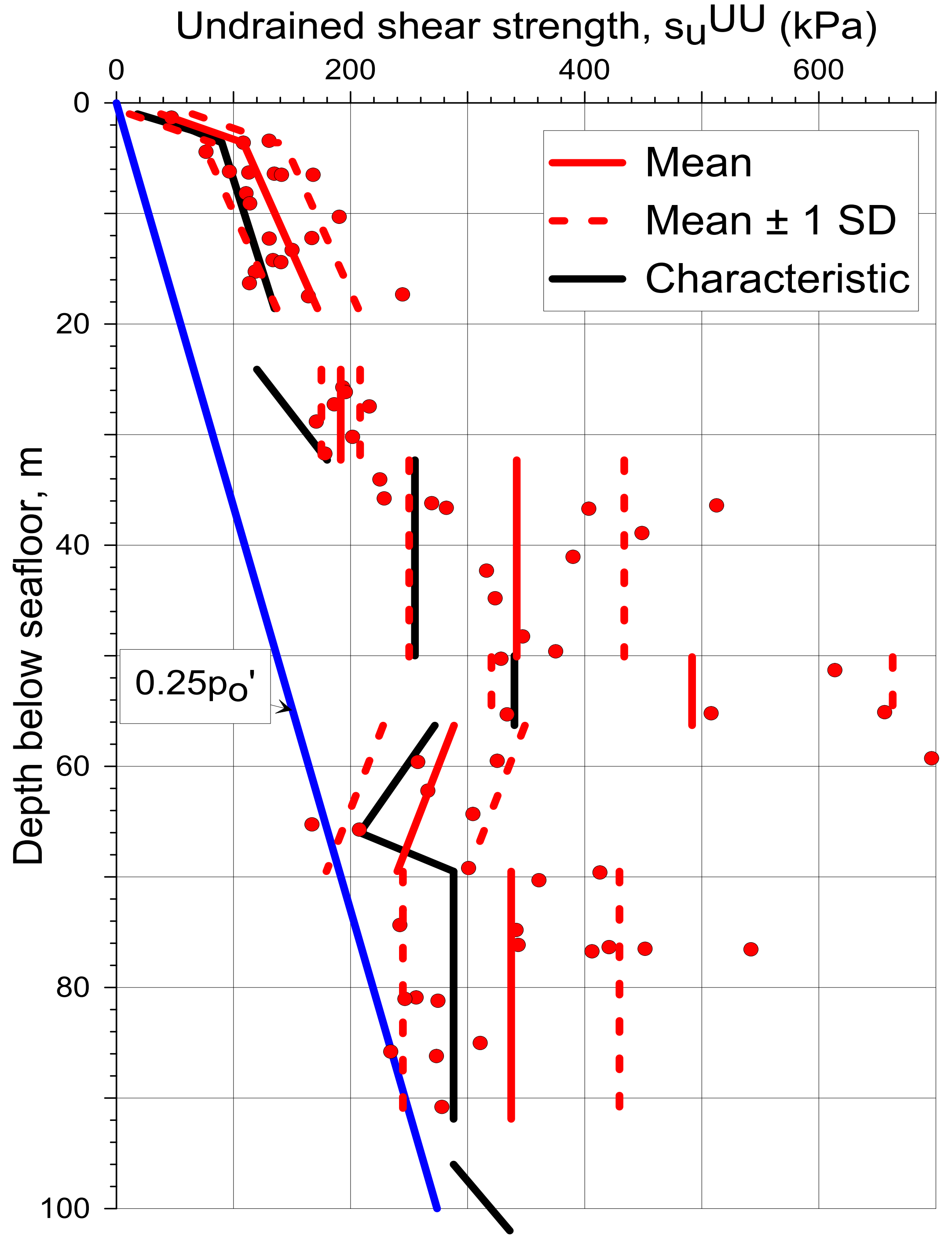




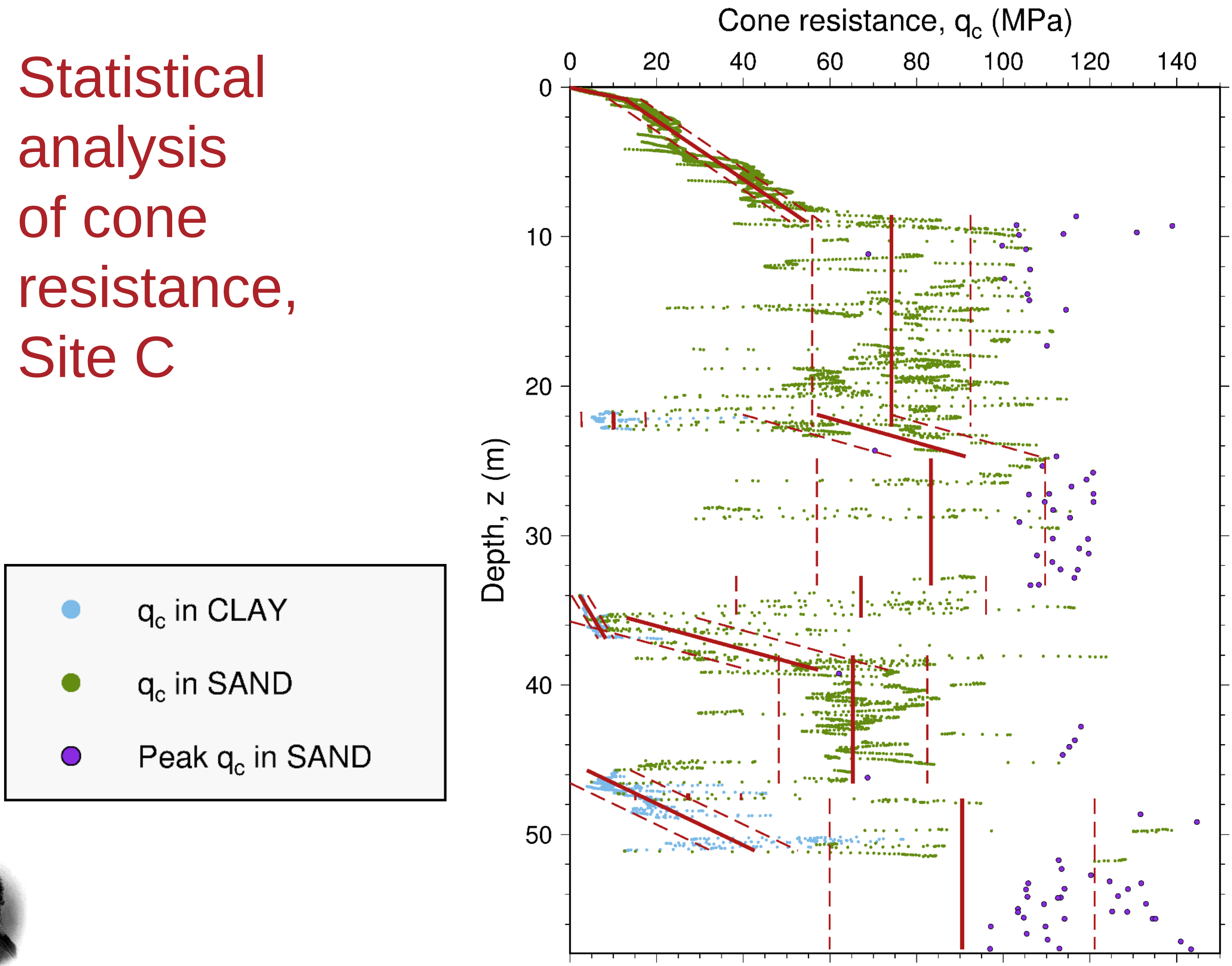




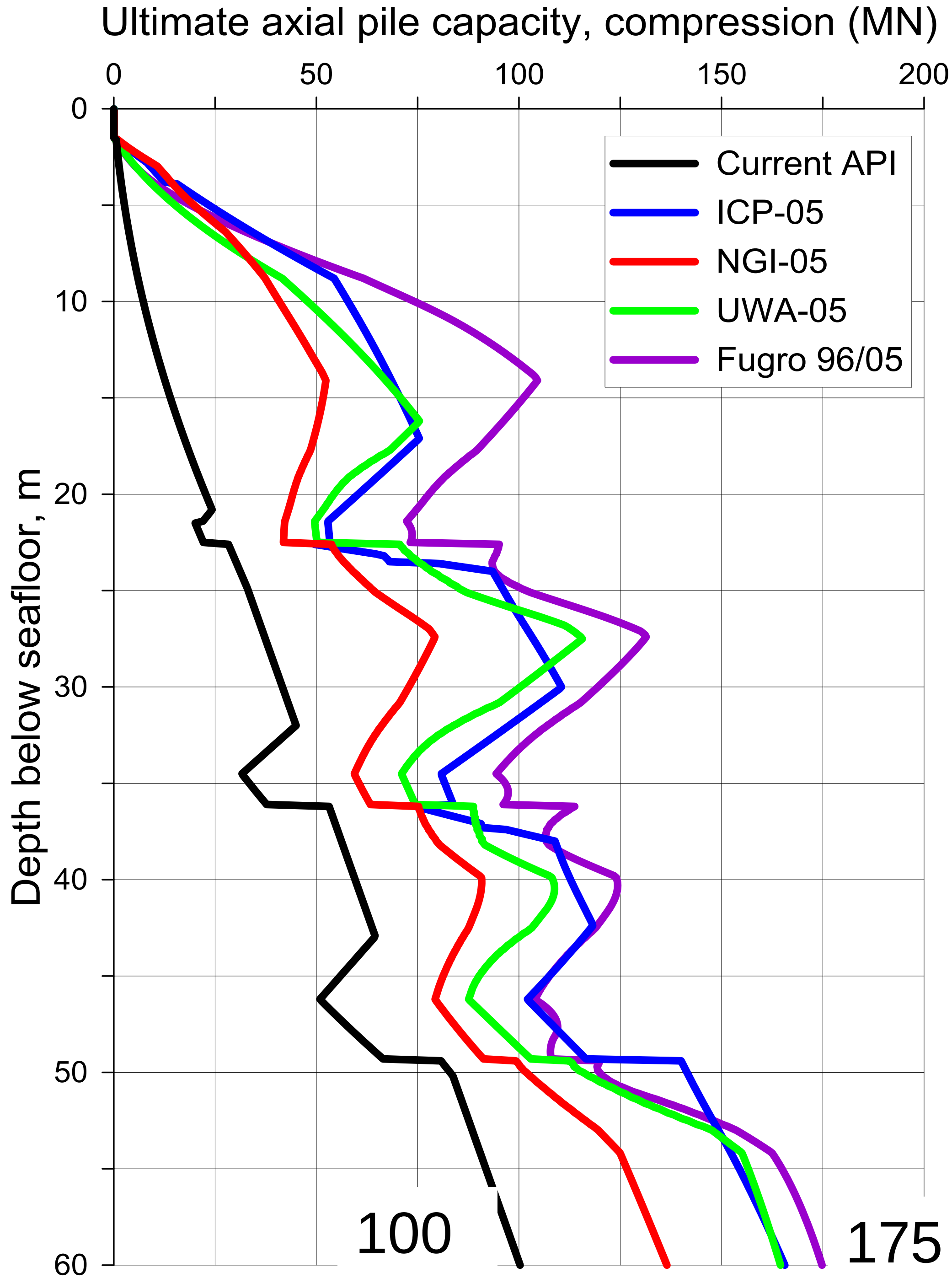
Undrained shear strength, S_u^{UU} Site A "clay site"



Statistical analysis of cone resistance, Site C

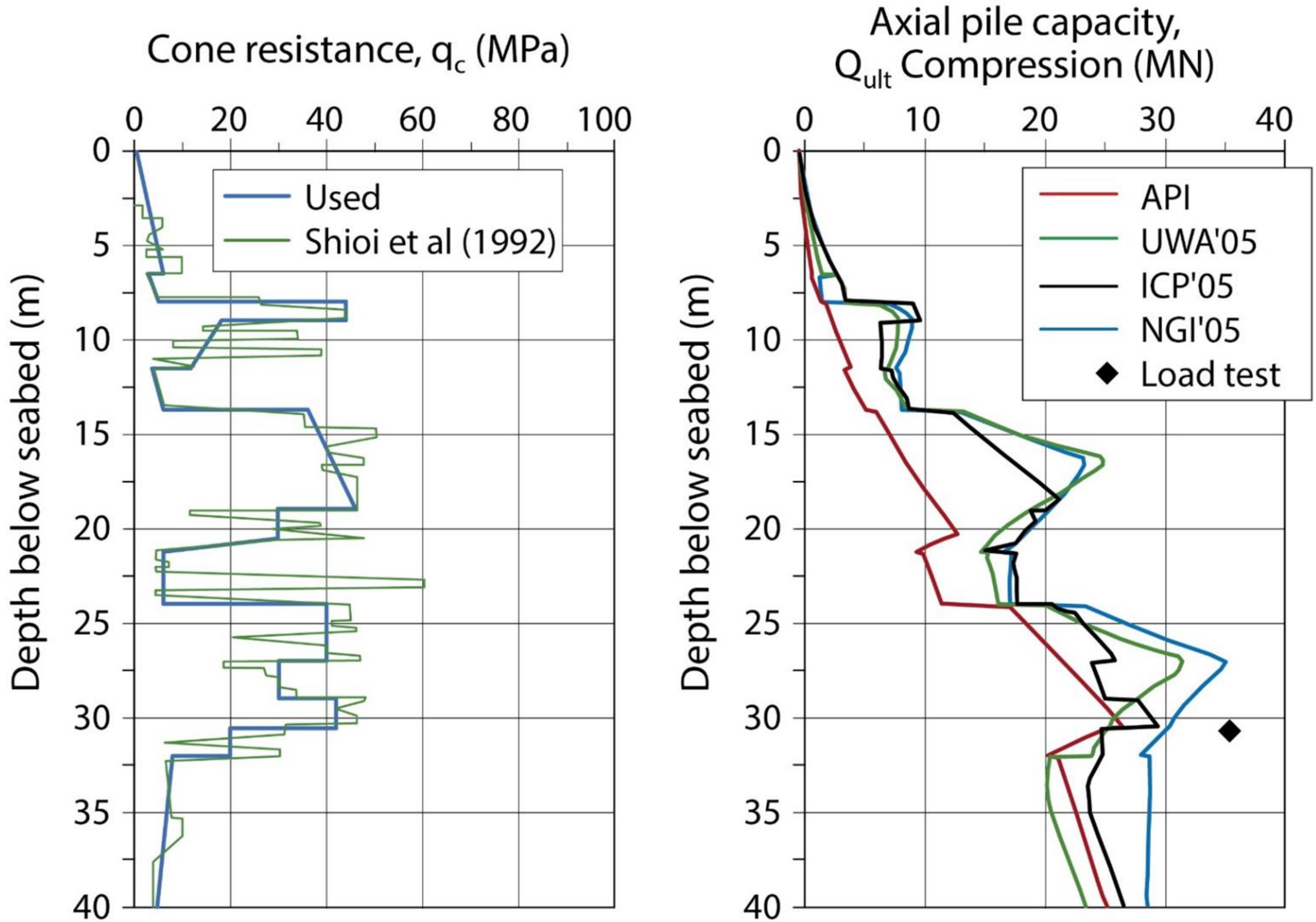


Deterministic Q_{ult} with <u>characteristic</u> shear strength parameters, Site B

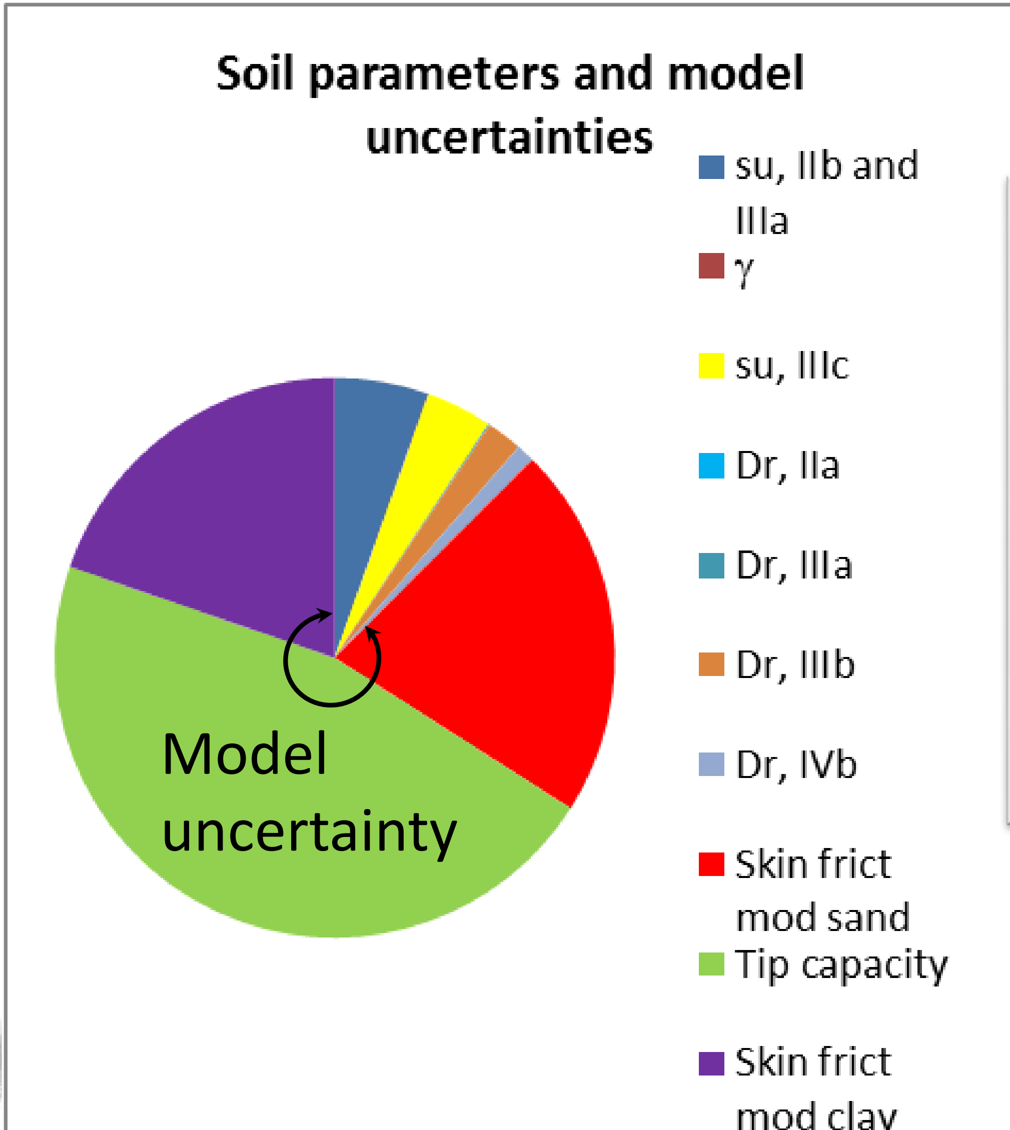


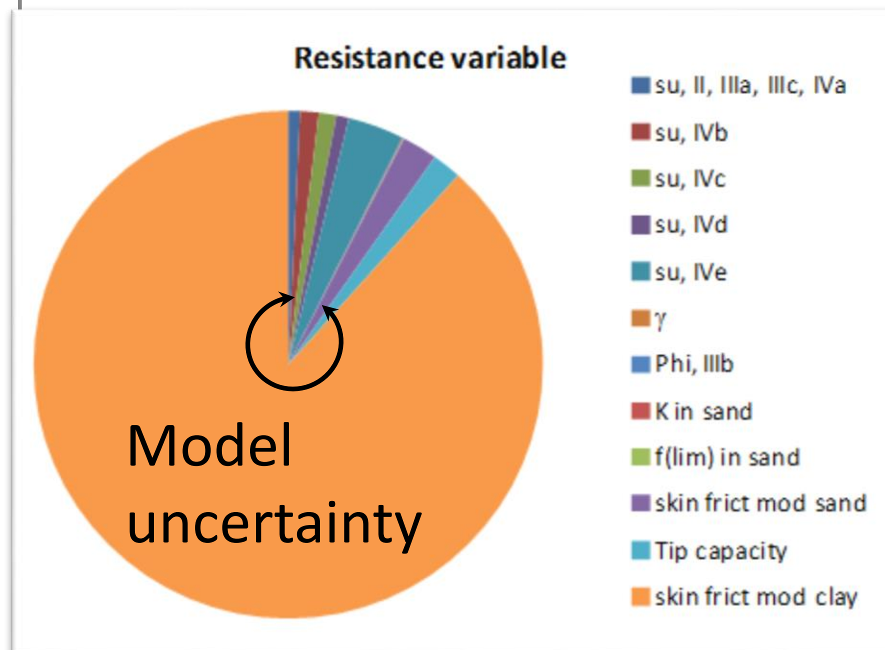
Model uncertainty in skin friction - pile load test

Predicted and measured capacities (dia_{pile}= 2.0 m)

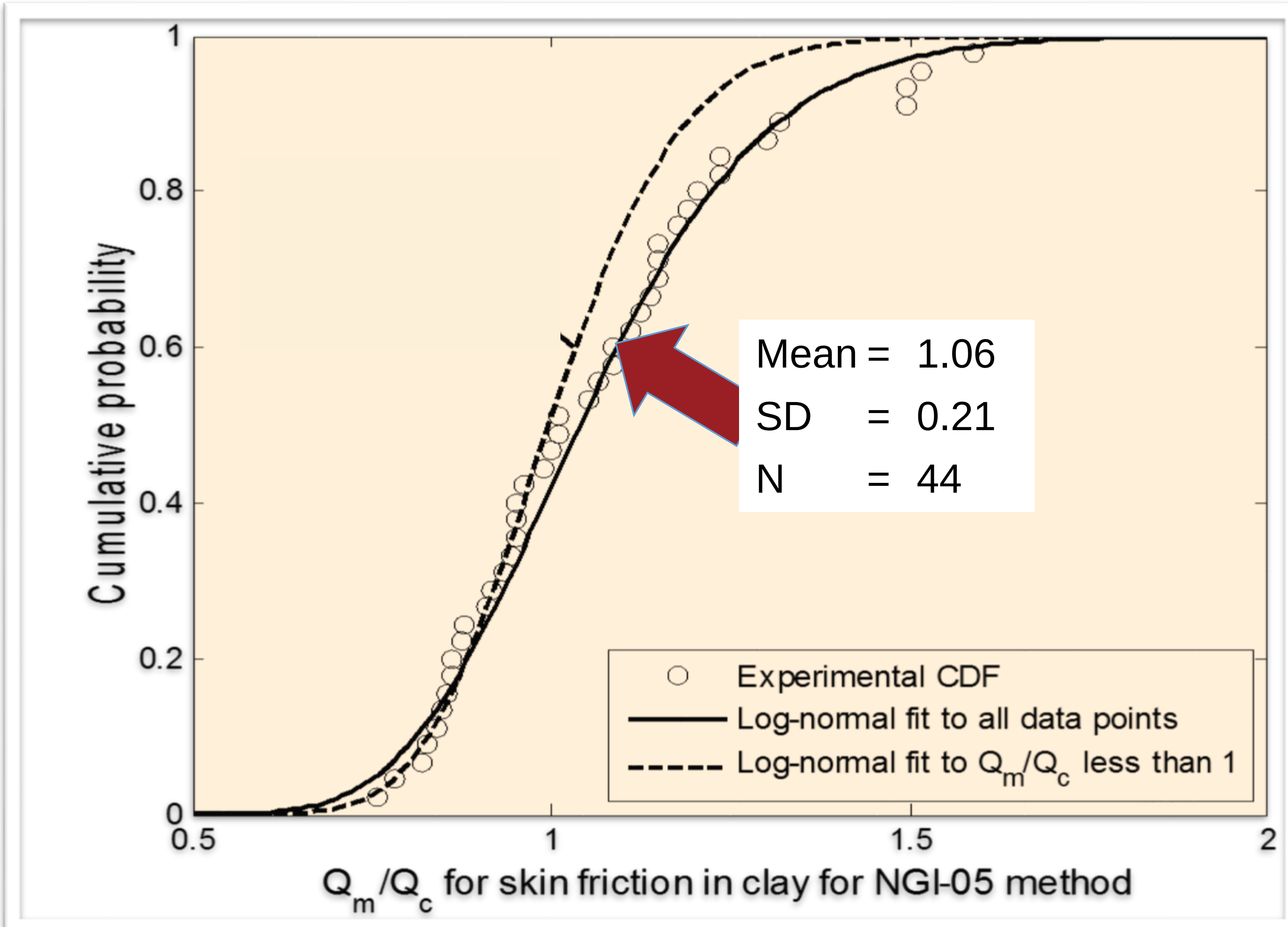


Parameters contributing to uncertainty in Q_u

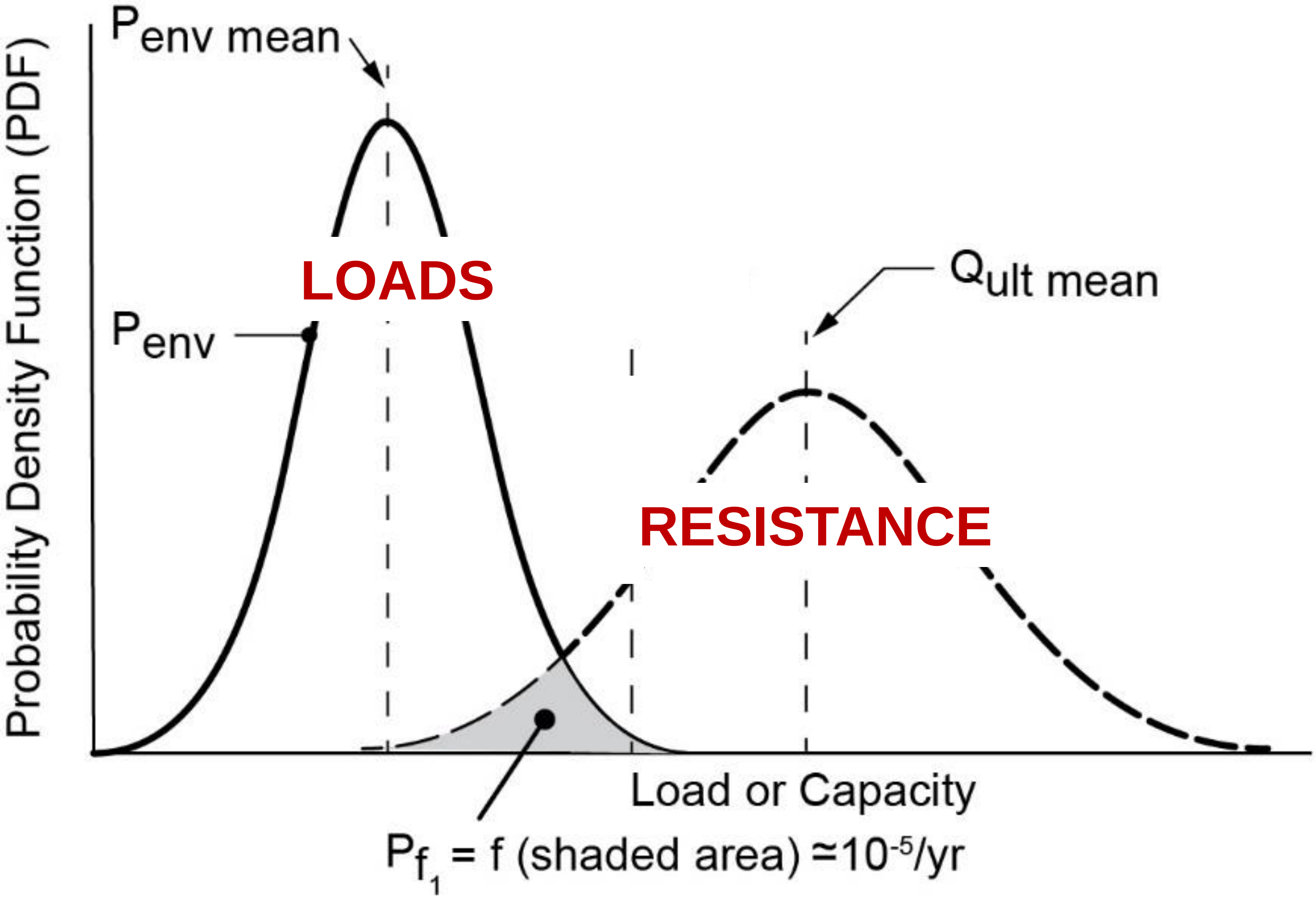




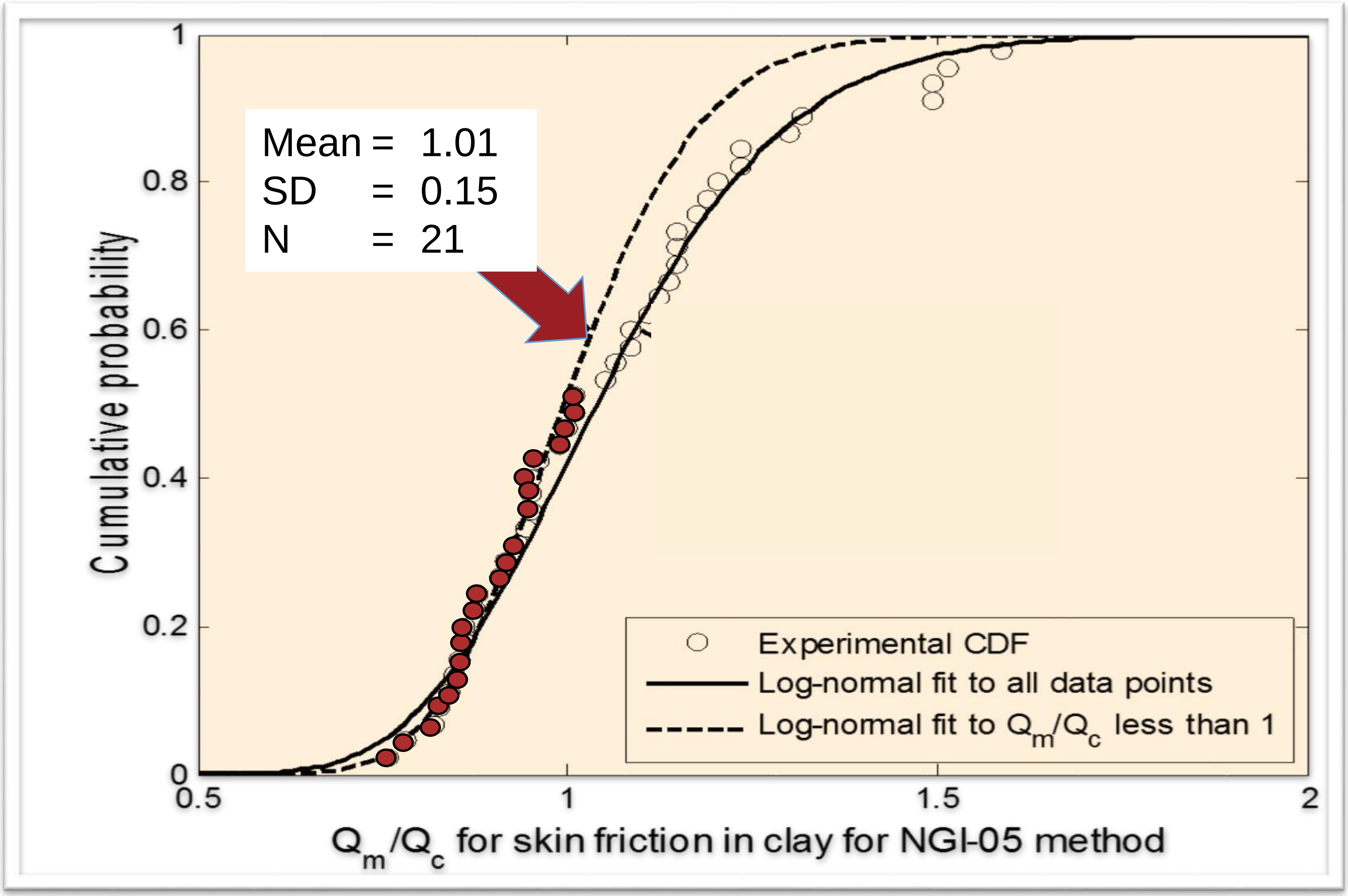
Quantification of model uncertainty



PDF of loads and resistance



Curve fitting only to $Q_m/Q_c < 1$ data points



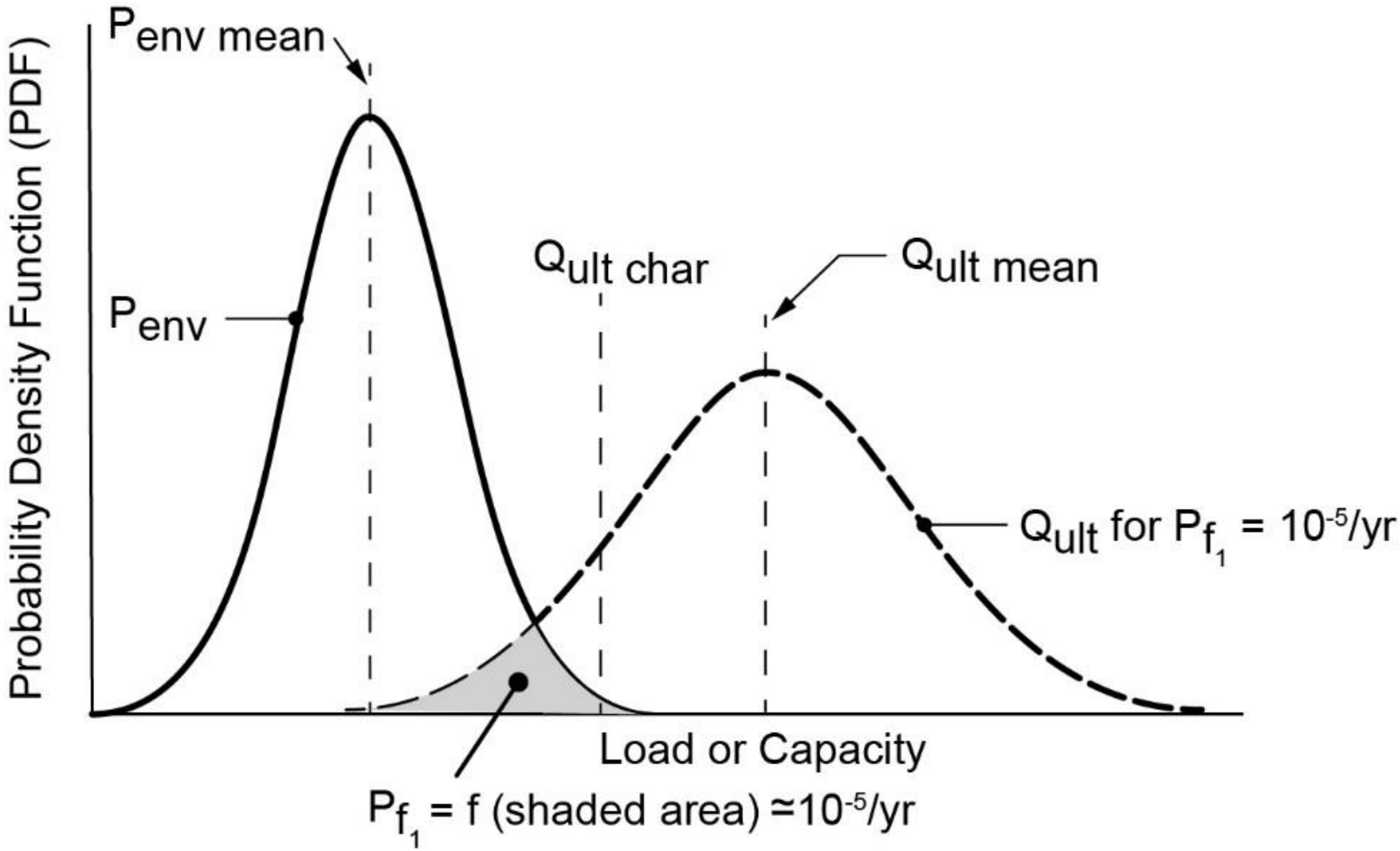
Axial pile capacity and annual P_f

Site A Clay
(NGI-05 method)

Penetr. depth	$Q_{ult\ char}$ (MN)	$Q_{ult\ mean}$ (MN)	Annual P_f - FORM, Q_{LN}
75 m	78	98	**$2.1 \cdot 10^{-5}$**
80 m	84	104	**$2.3 \cdot 10^{-5}$**
90 m	97	119	**$1.2 \cdot 10^{-6}$**

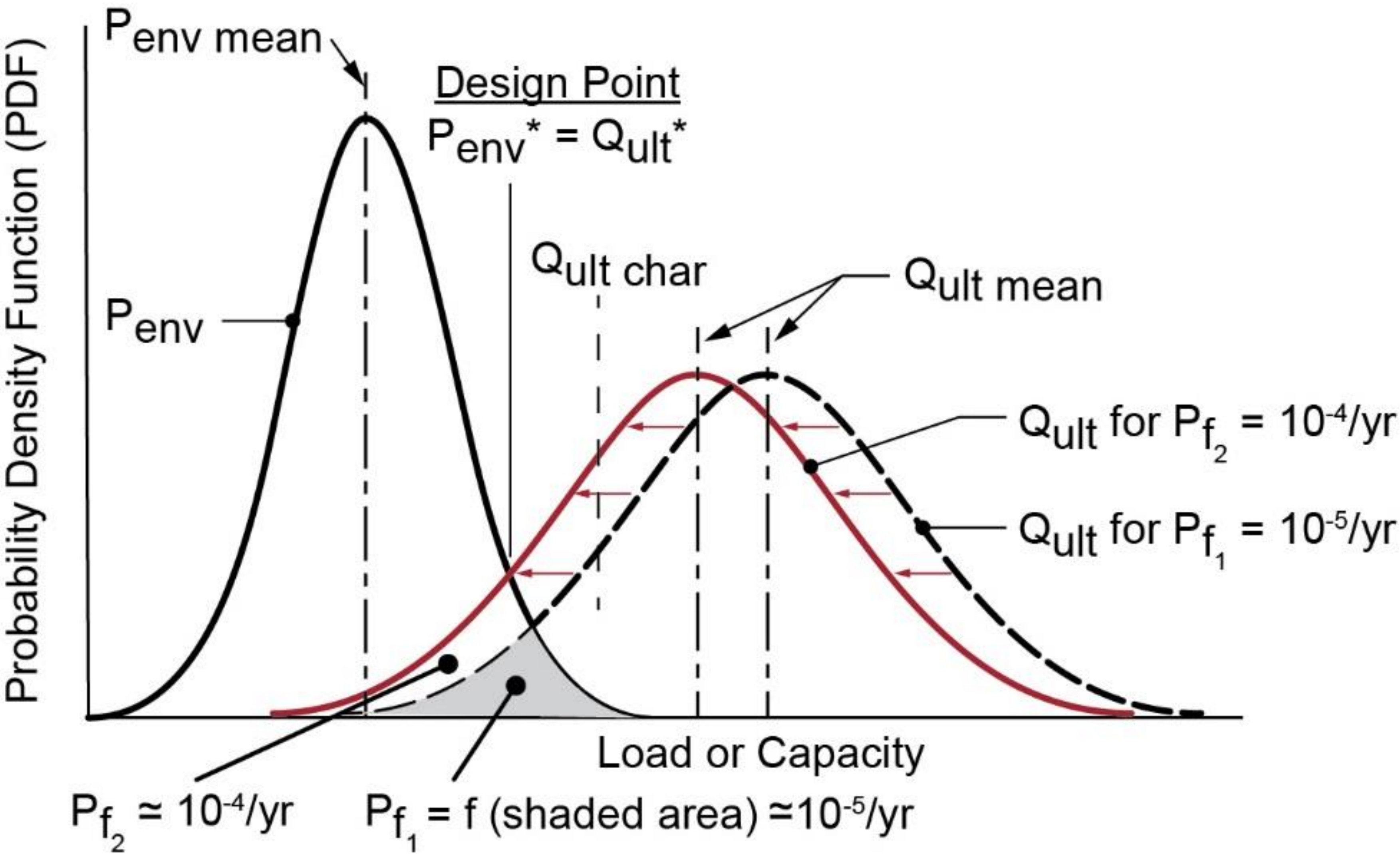
Calibration of partial safety factors

$$[\gamma_{l\ stat} \cdot P_{stat} + \gamma_{l\ env} \cdot P_{env}^{100\text{-}yr}] = Q_{ult}/\gamma_{m}$$



Calibration of partial safety factors

$$[\gamma_{I\,stat} \bullet P_{stat} + \gamma_{I\,env} \bullet P_{env}^{100\text{-}yr}] = Q_{ult}/\gamma_{\mathbf{m}}$$



Calibrated resistance factor, γ_m, related to $Q_{ult\ char}$, for target $P_f < 10^{-4}$/year ($\gamma_{l\ env}$=1.3)

Pile design method	Required resistance factor, γ_m		
	Site A (clay)	**Site B** (sand)	**Site C** (clay and sand)
NGI-05	1.23	1.35	1.20
ICP-05	1.52	1.45	1.32
Fugro-05	1.31	1.72	1.55
UWA-05	---	1.55	1.50
Current API	1.35	2.36	1.93

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.

Added value of reliability analysis?

- The probabilistic design with target annual P_f of 10^{-4} resulted in very significant savings, compared to the deterministic design.
- The reliability approach allows one to design with a uniform margin of safety and to "calibrate" the safety factors prescribed in codes.
- The newer CPT-based design methods are more reliable than the API method.
- The results are most affected by the model uncertainties, especially for piles in sand.

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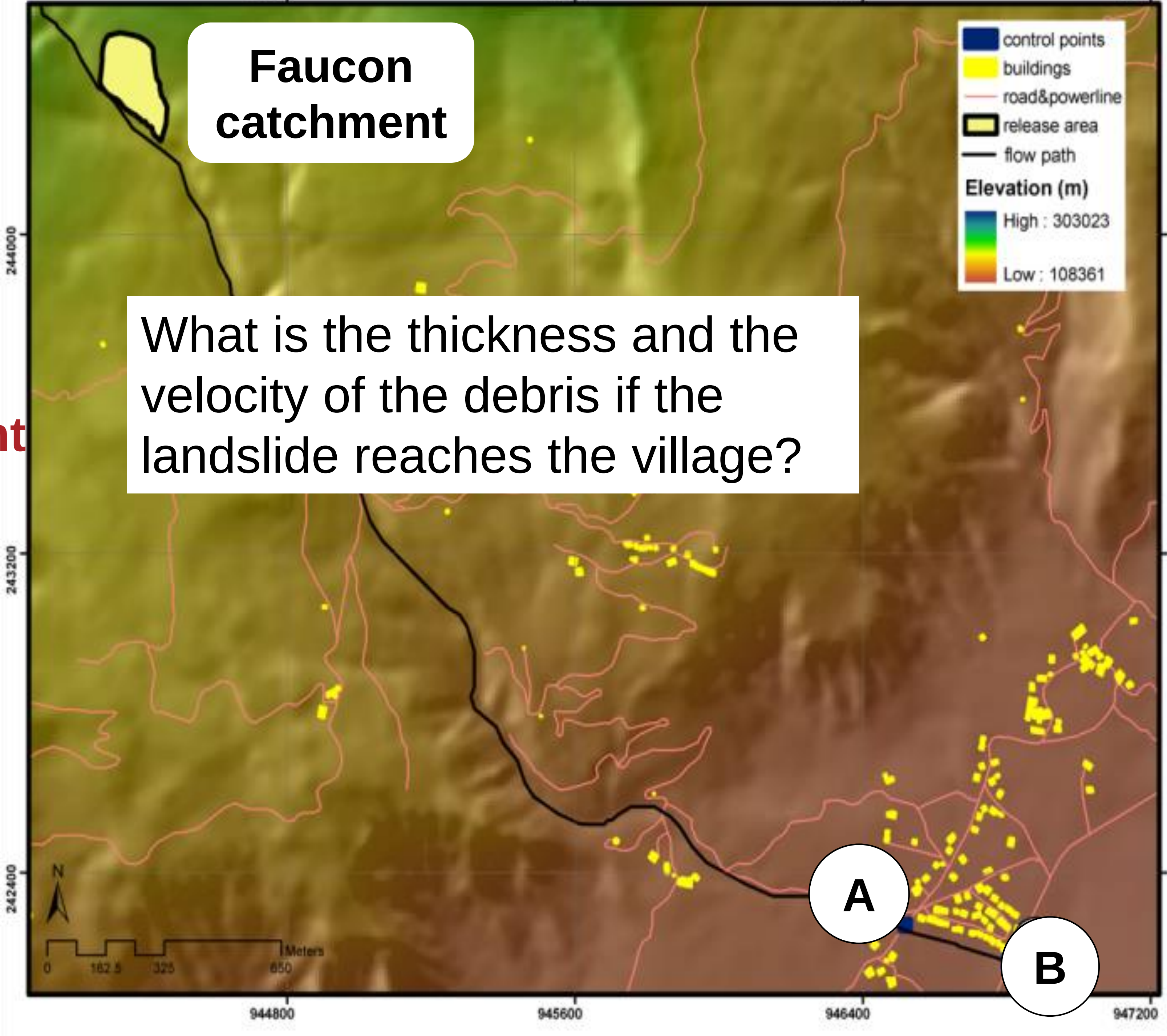
Debris flow

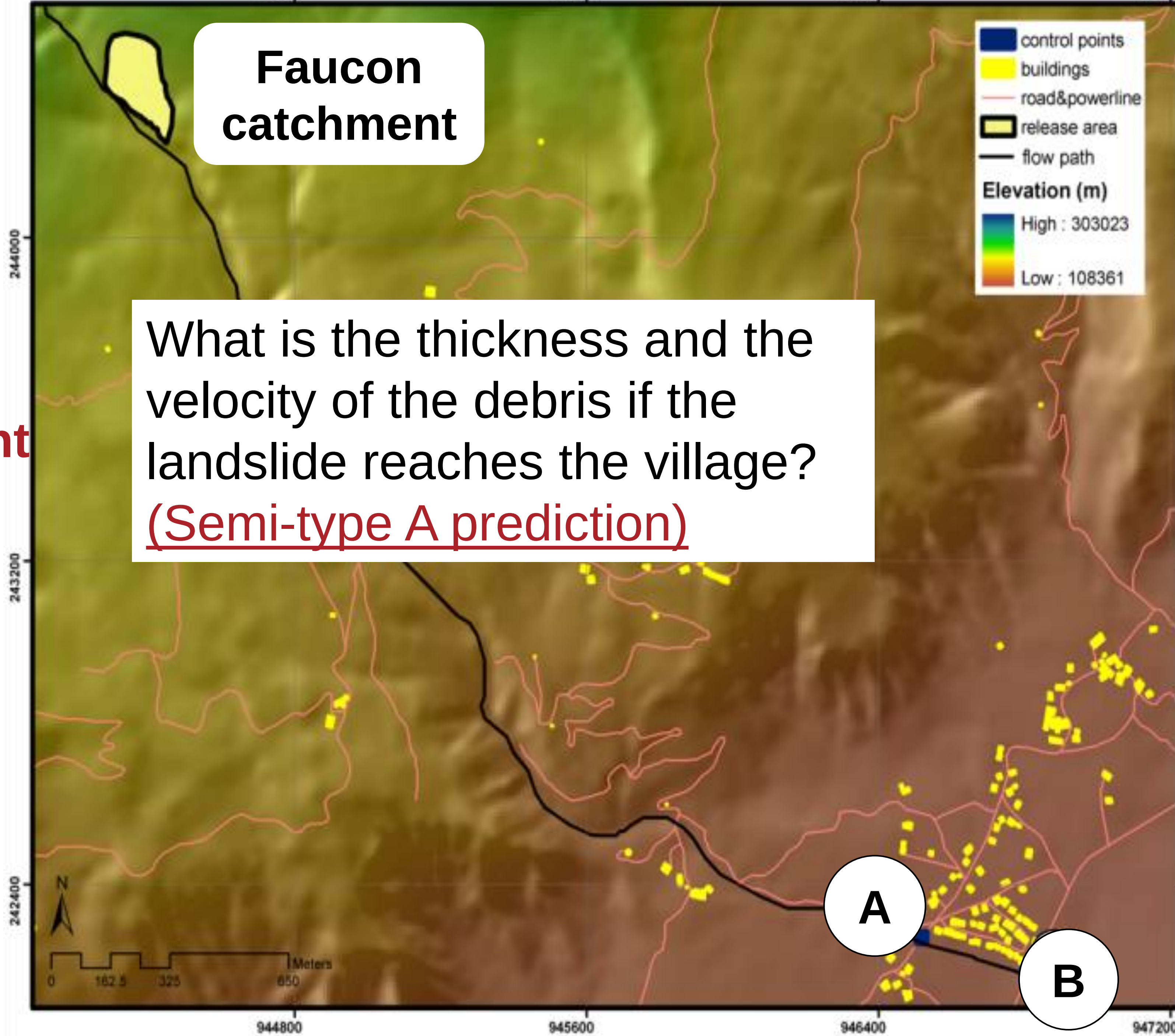
Faucon catchment



What is the thickness and the velocity of the debris if the landslide reaches the village?

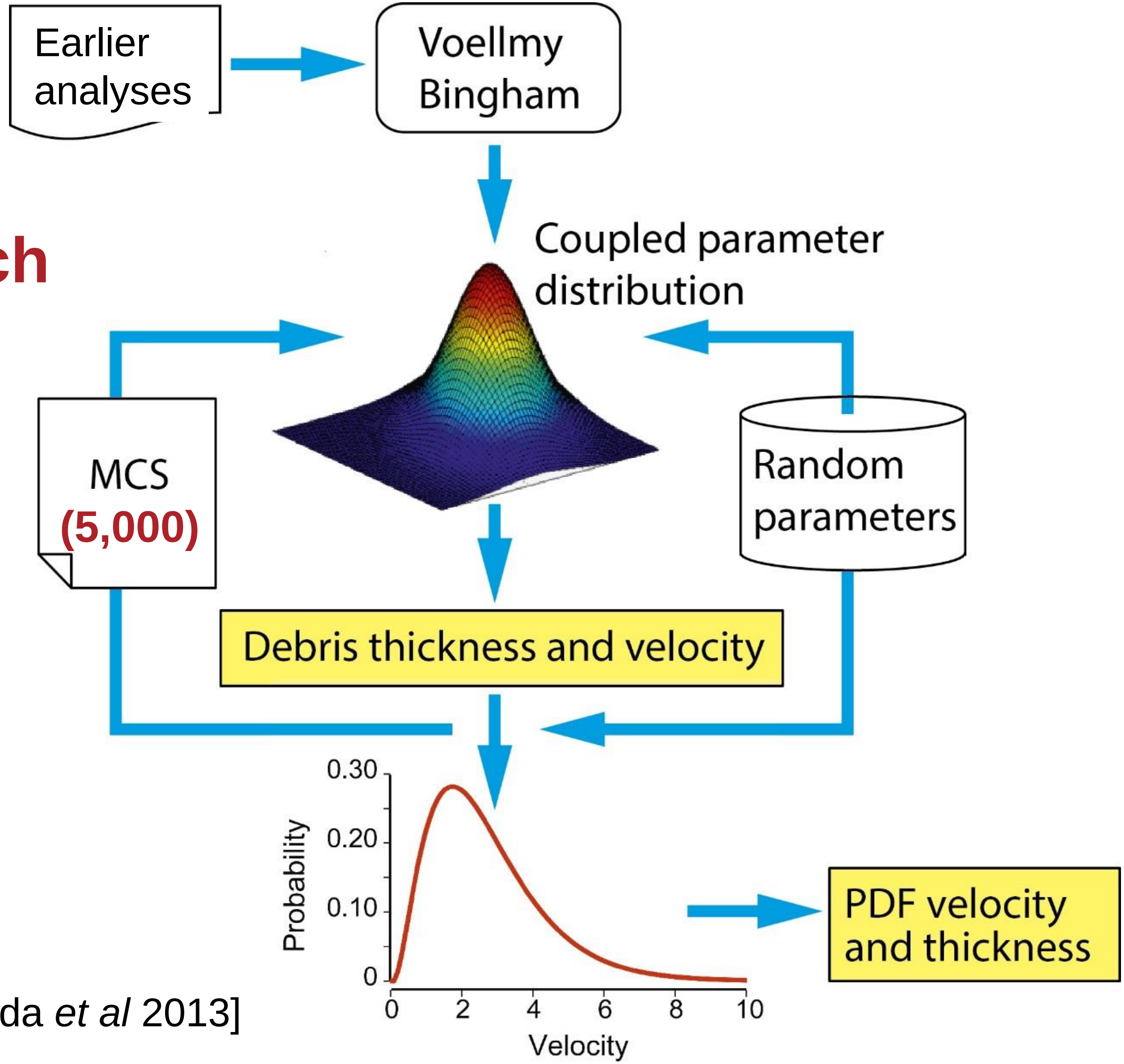
Debris flow

Faucon catchment



What is the thickness and the velocity of the debris if the landslide reaches the village? (Semi-type A prediction)

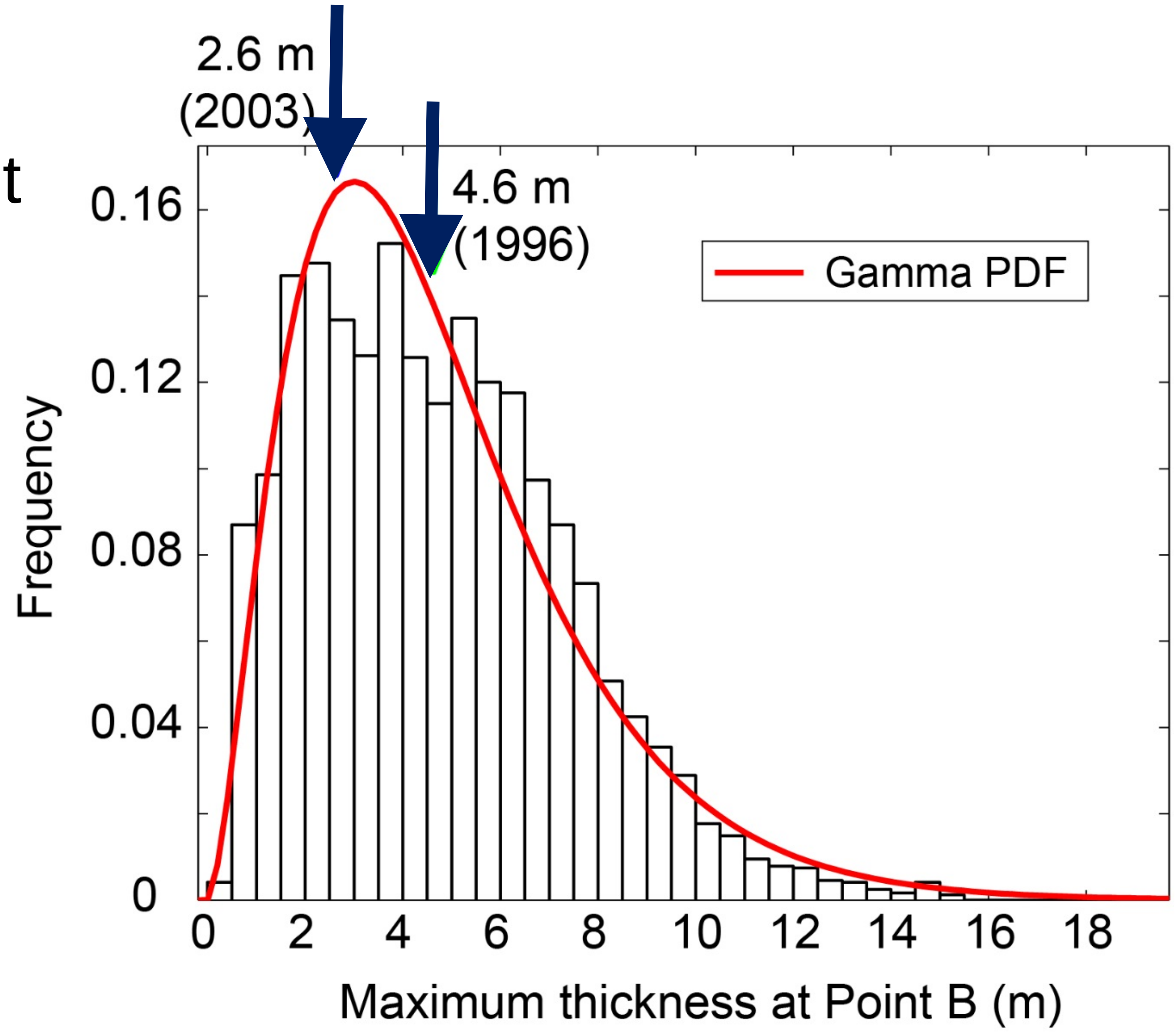
Approach



[Cepeda *et al* 2013]

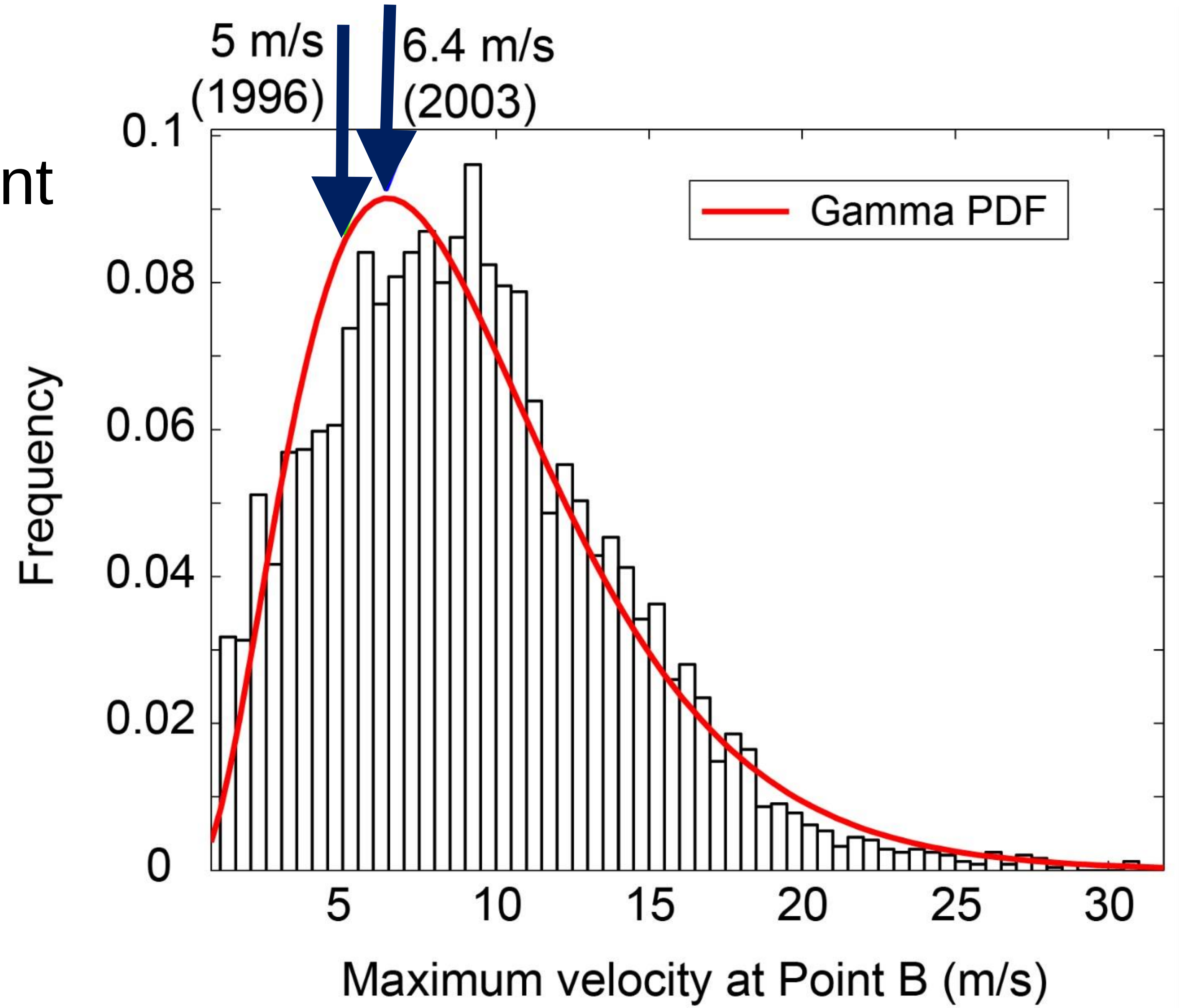
Faucon catchment

Debris thickness Point B



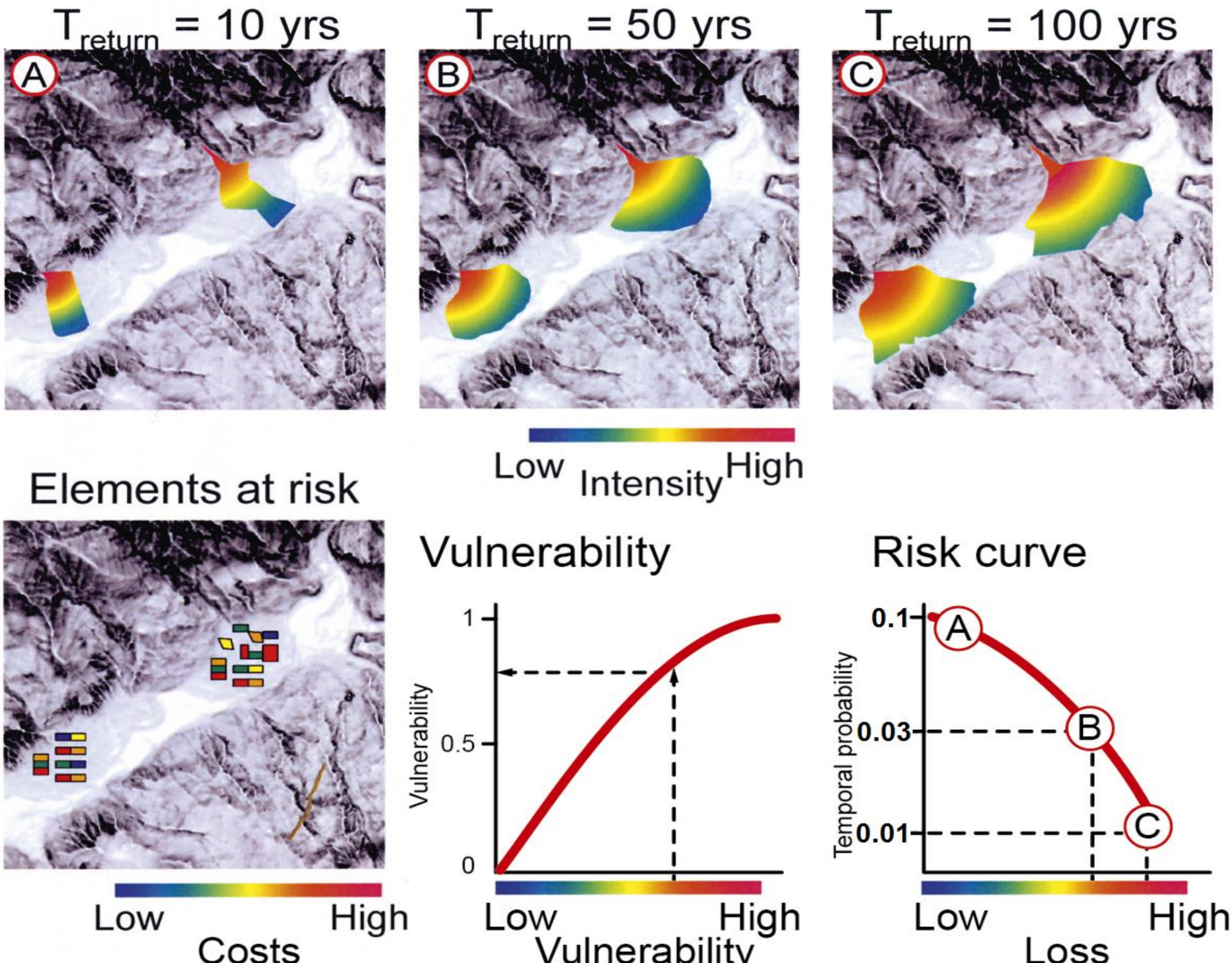
Faucon catchment

Debris velocity Point B



Landslide risk analysis

[After Coro-minas *et al* 2014]



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.

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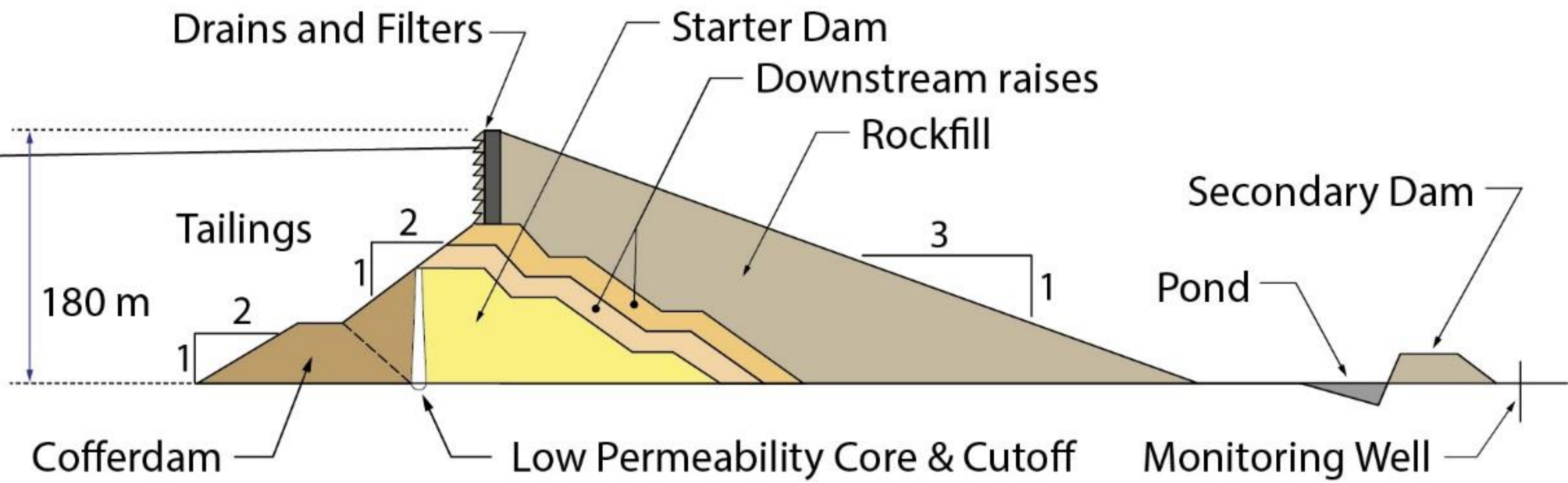
Roşia Montaňa

Design of tailings management facility TMF – the Corna Dam



Tailings dam

Consequence scenarios

The Baia Mare tailings dam failure in Romania (2000) released cyanide in the water, killing tons of fish and poisoning the drinking water of 2 M people in Hungary.

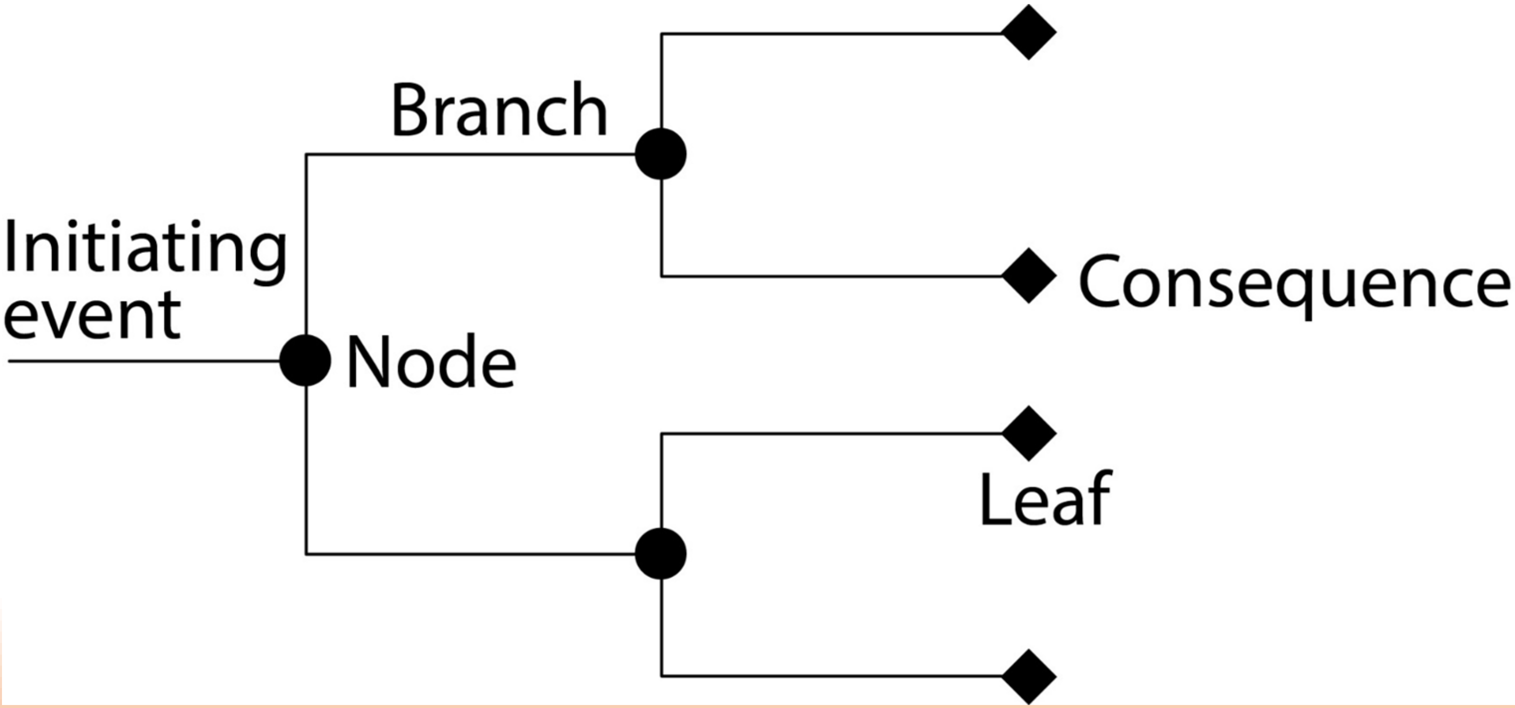
The Aznalcóllar tailings dam failure in Spain (1998) released 68 Mm^3 contaminated material in the environment.

The Mount Polley tailings dam failure (2014): tailings with Se, As ++ escaped: largest environmental disaster in Canada.

Baia Mare

Event tree analysis (ETA)

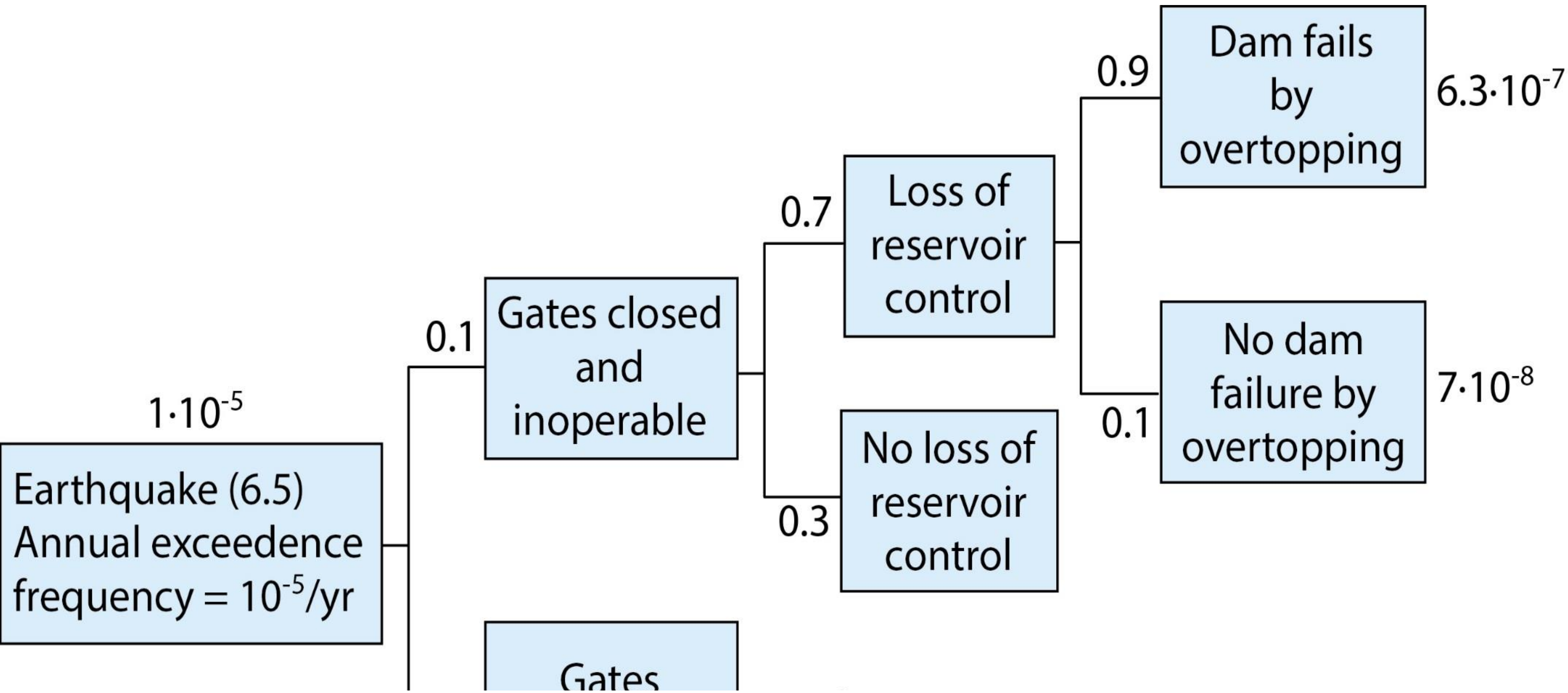
An event tree is a graphical representation of many chains of events that might results from an initiating event, a few of which could lead to system failure. As the number of events increase, the diagram fans out like the branches of a tree.



Event tree analysis (ETA)

A form of "What happens if " type of analysis

Initiation ⇨ continuation ⇨ progression to failure



In an event tree, the events at a node should be defined such that they are mutually exclusive (cannot occur simultaneously).

Event tree analysis of dams

6 steps

1 Dam and site inspection to familiarise review team with structure and site conditions

2 Failure mode screening

3 Construction of event tree

4 Probability assessment

5 Evaluation of results

Usually done with expert teams

The collective judgment of experts, structured within a process of debate, can yield as good an assessment of probabilities as mathematical analyses [Vick 2002].

Event tree analysis (ETA)

Probabilities at a node of the event tree

- Statistical estimates based on observations, test results etc.
- Engineering calculations with models based on physical processes.
- Expert judgment developed through evaluated experience.

The probability estimates should be based on a demonstrable chain of reasoning and not on speculation. Consensus is achieved through discussion, using standard descriptors of uncertainty.

Roşia Montaňa – TMF
Failure mode screening

What would happen to the TMF, the population and the neighbouring environment if

- an earthquake struck
- unusually intense rainfalls occurred
- a slide occurred from the hillsides into the tailings pond
- the dam crest slumped
- two or more of the above occurred at the same time
- …

All plausible triggers/events were examined.

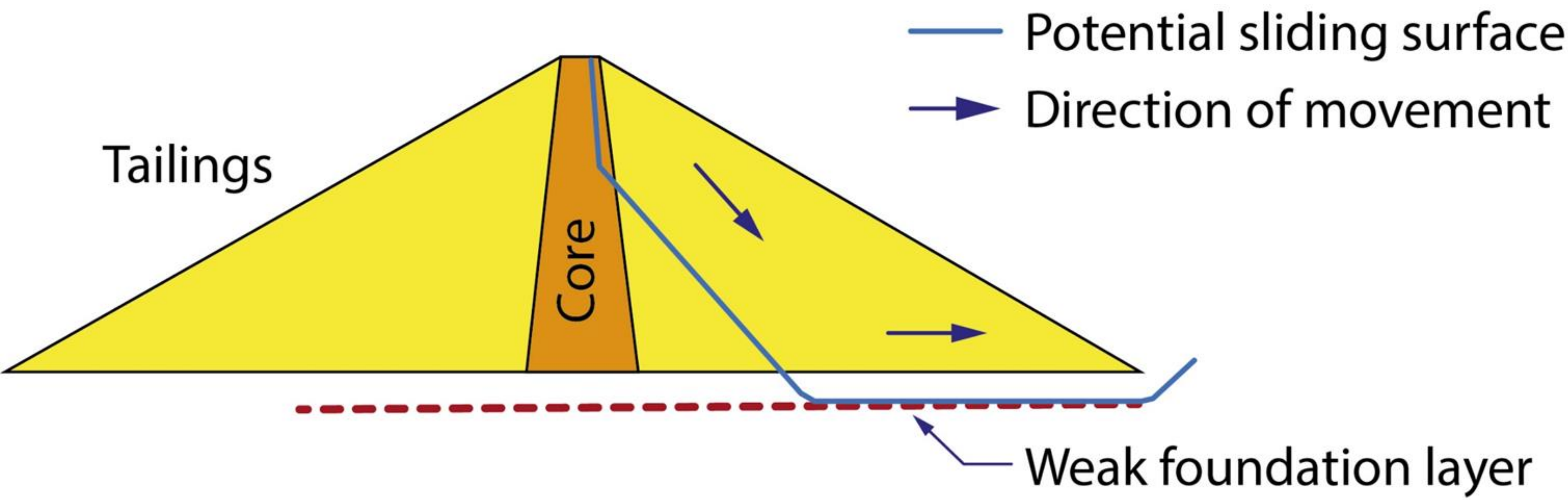
Roşia Montaňa – TMF

How was the evaluation done?

- Assembled dam, geotechnical and risk experts from USA, Norway, Canada and Romania.
- Looked at the failure modes from the start of construction to the closure of the facility, and established the scenarios where the TMF could release tailings and water. Quantified how often each scenario could happen.
- Looked at consequences from "No consequence" to "Small release of tailings" to "Catastrophic tailings release and contamination downstream" to "Loss of life".

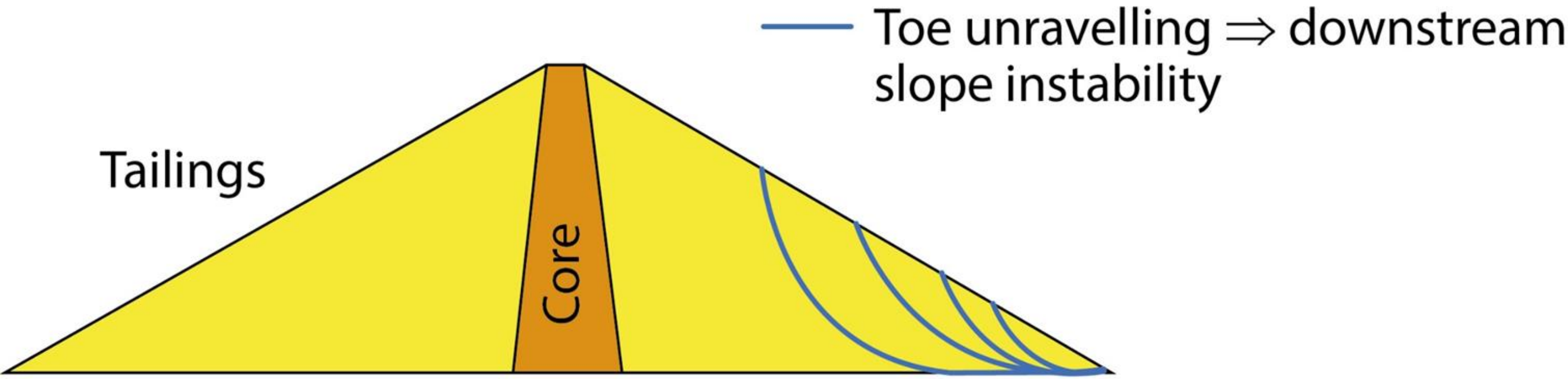
Roşia Montaňa – TMF

Failure scenarios – Starter Dam



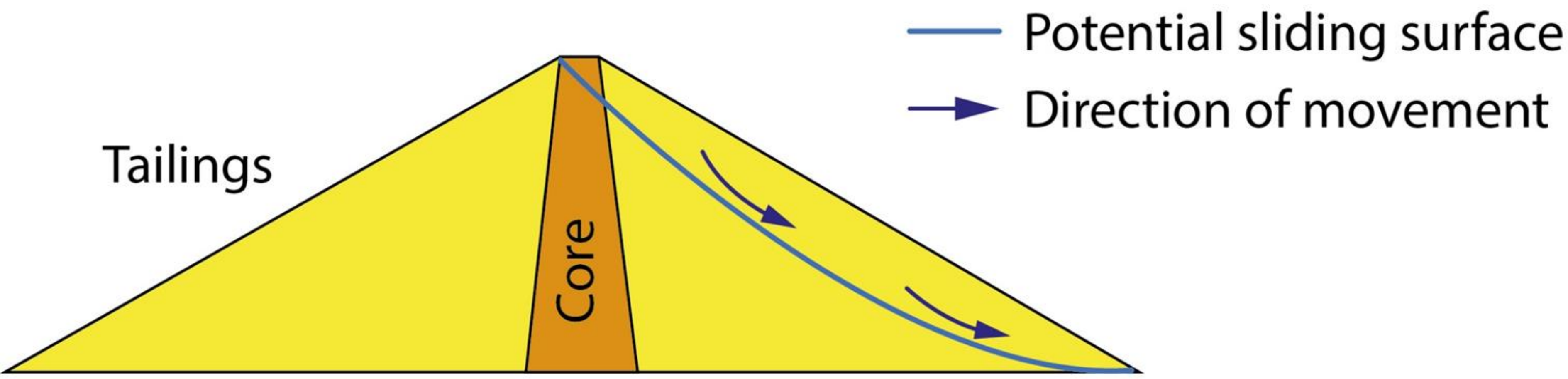
Roşia Montaňa – TMF

Failure scenarios – Starter Dam



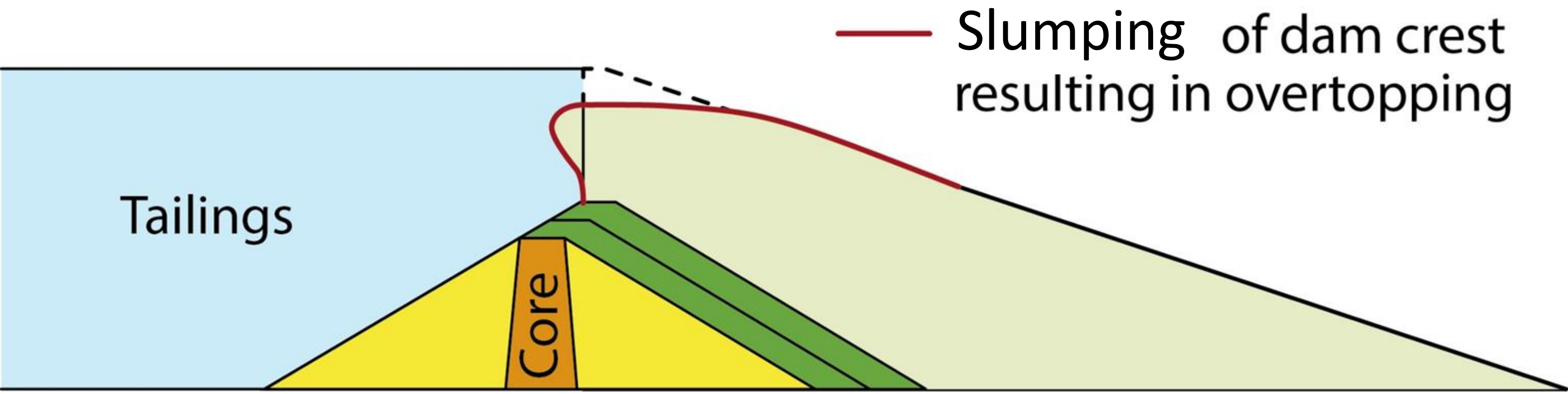
Roşia Montaňa – TMF

Failure scenarios – Starter Dam



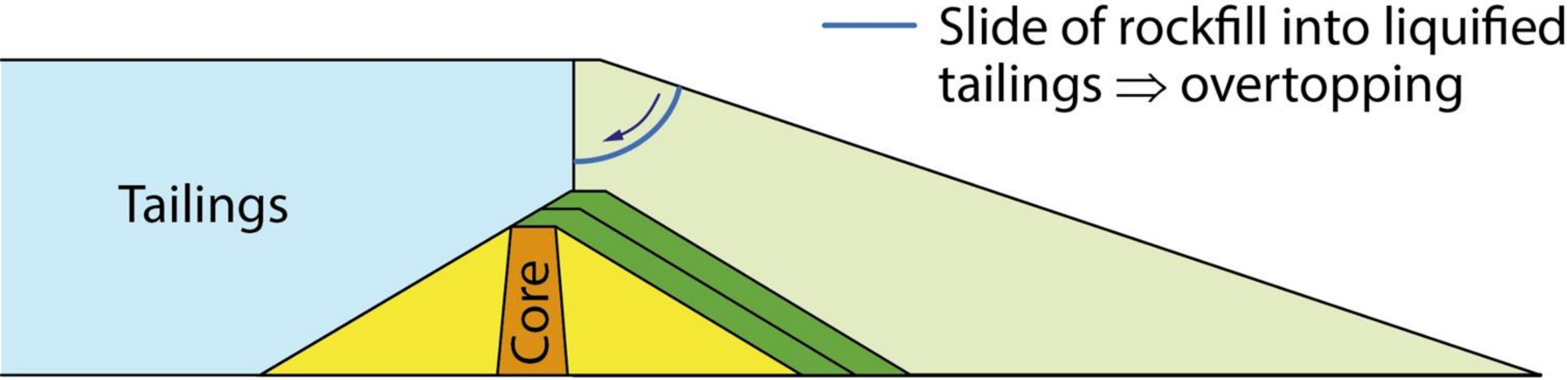
Roşia Montaňa – TMF

Failure scenarios – completed Corna Dam



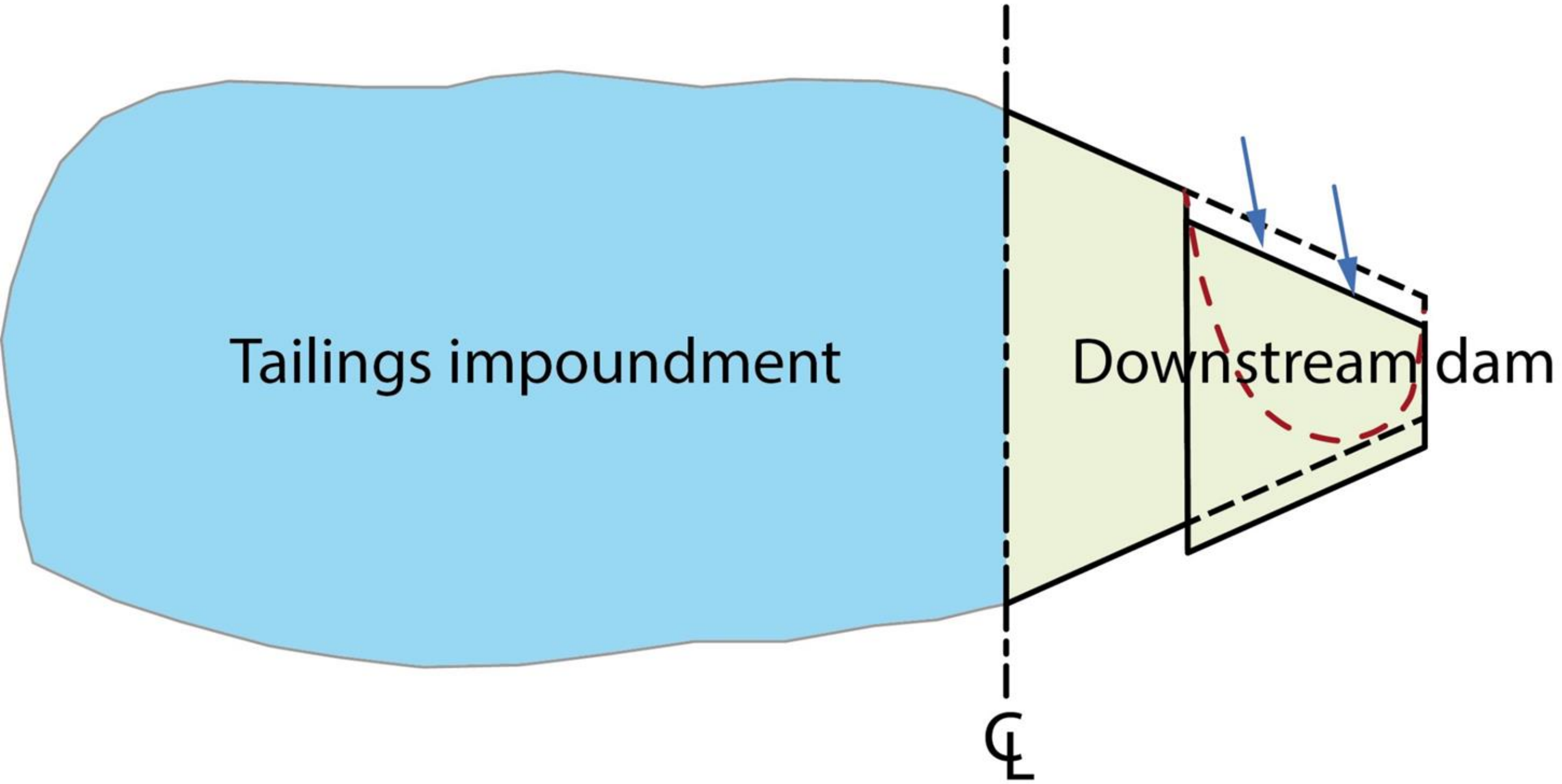
Roşia Montaňa – TMF

Failure scenarios – completed Corna Dam

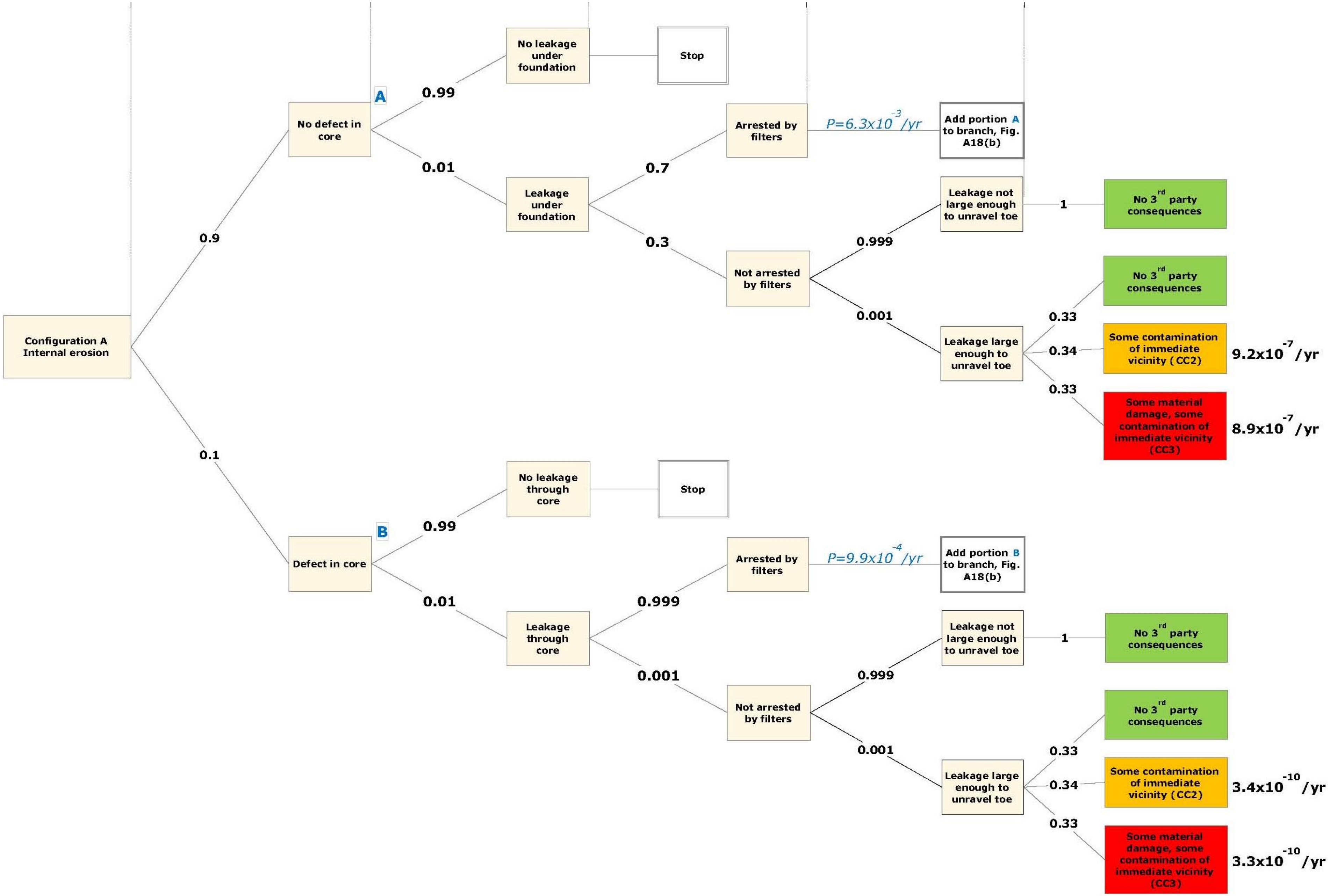


Roşia Montaňa – TMF

Failure scenarios – completed Corna Dam



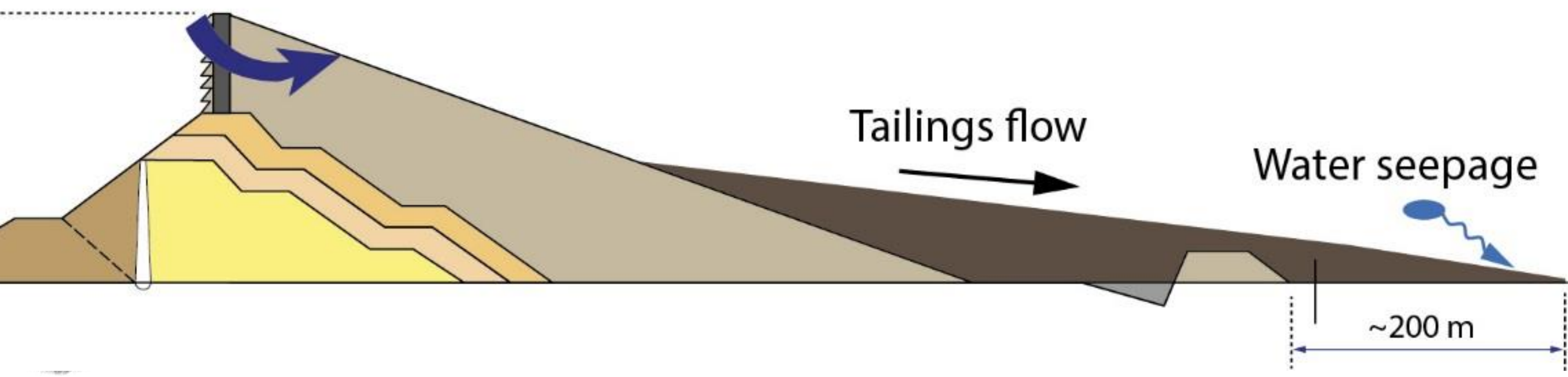
How to quantify the probability?



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

Total probability of non-performance

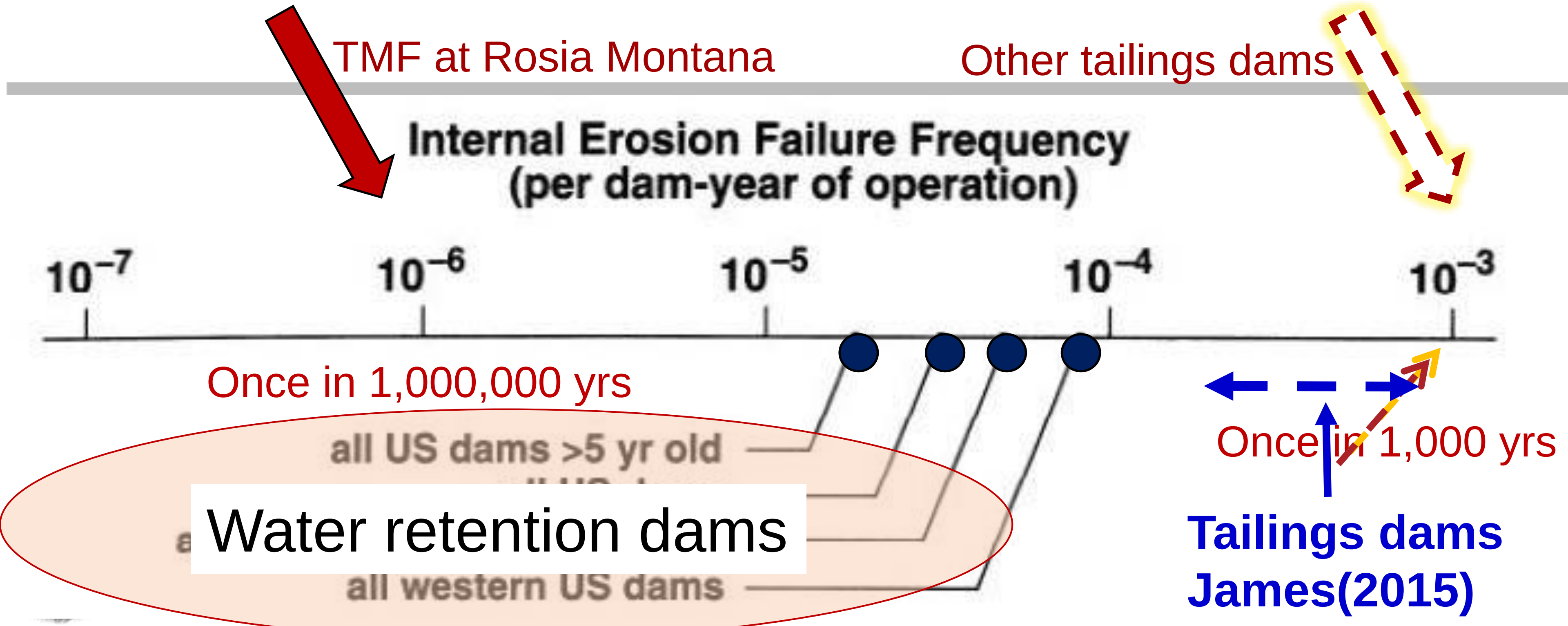
Configuration	P [Non-performance]
Starter Dam (t= 1.5 yrs)	$1.3 \cdot 10^{-6}$ /yr
Completed Corna Dam (t = 16 yrs)	$1.1 \cdot 10^{-6}$/yr
First raise completed (t = 4 yrs)	$7.1 \cdot 10^{-7}$/yr

Starter Dam	No significant release of tailings because of large reserve storage capacity (2 PMP's). Internal erosion was the most critical. Release contained by the Secondary Dam.
Corna Dam	The highest probabilities of non-performance are about equal for earthquake shaking, liquefaction of the tailings and valley slope instability.

Roşia Montaňa – TMF

<u>Addition of probabilities for all scenarios</u>

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.



Why did the Mount Polley tailings dam fail?

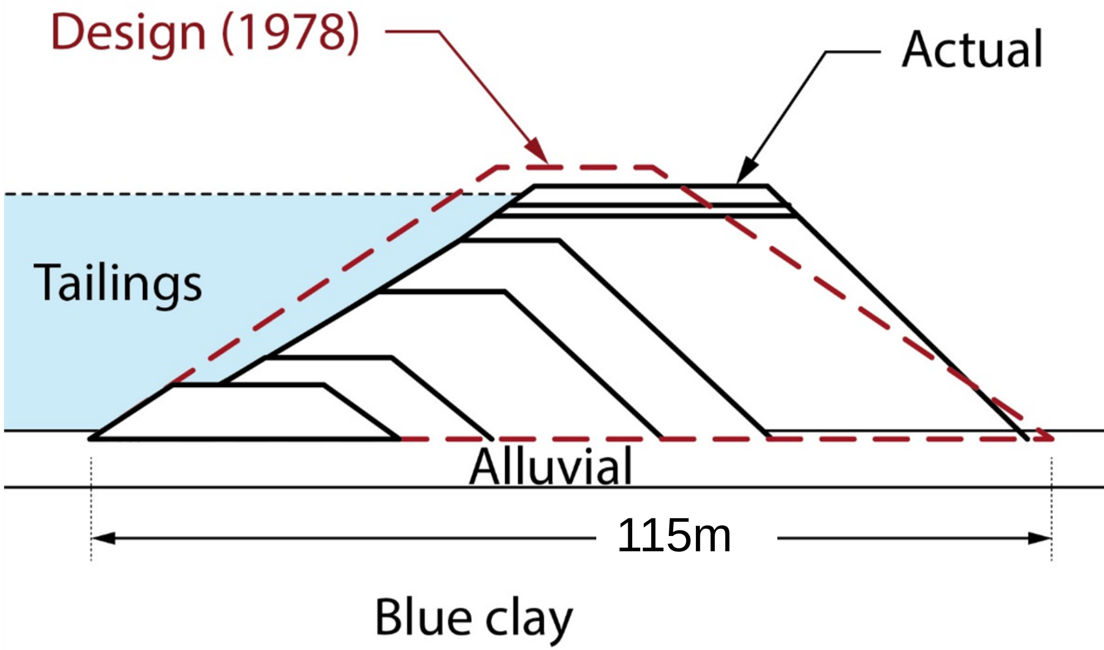
Failure in the foundation of the embankment due to a weak layer that was undetected. In addition, OC clay became NC under construction. Downstream rockfill had very steep slope (1.3H : 1V). Had the slope been flattened to 2H : 1V, as proposed in the original design, failure would have been avoided.

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.

Added value of ETA analyses?

- ETA looks at all potential failure modes in a systematic manner.
- ETA can be used as a diagnostic tool.
- Reliability analyses provide a means to compare the safety of a facility with other facilities and the efficiency of different mitigation measures.
- Probabilistic risk analysis in dam engineering has been coined as a «systematic application of engineering judgment» [Vick 2002; Høeg 1996].

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New Orleans Levees and Hurricane Katrina

Flood control Act of 1965

Flood protection system started in 1965 after Hurricane Betsy

[US Army Corps of Engineers 2005]

Could the failure have been expected and better managed with the help of probabilistic analyses?

New Orleans Levees and Hurricane Katrina

Levees designed for $T_{return} \approx 100$ yrs

$P_f = 1/ T_{return} = 0.01$

What is the probability of a 100-yr hurricane and overtopping for a person living behind the levees for 50 years?

$P(x>0) = 1 - e^{-\lambda t}$ (Poisson distribution)

x = number of events

t = time interval

λ = expected number of events/unit time

λ = 0.01 for P_f = 1 / 100 years

New Orleans Levees and Hurricane Katrina

$P(x>0) = 1 - e^{(-0.01)(50)}$

$P(x>0) = 0.40$ (40%)   *[if T_{return} = 200-yr, P = 22%]*

There is therefore a significant probability of levee overtopping in any 50-yr period.

The 3-4 failures that occurred in New Orleans, even without overtopping indicate that the factor of safety, FS < 1, in some locations.

New Orleans Levees and Hurricane Katrina

In comparison:

The primary dikes protecting the Netherlands are set to heights corresponding to between 2,000 and 10,000-year return periods [Voortman 2003; van Stokkom & Smits 2002]

The interior levees protecting the Rhine are set to a return period of 1,250 years [Vrouwenvelder 1987].

New Orleans Levees and Hurricane Katrina

There are 350 miles (560 km) of levees in New Orleans. Assume that there are 560 reaches (each 1 km long).

What is the annual P_f of each reach?

What is the P_f of the entire levee system?

[US Army Corps of Engineers 2005]

New Orleans Levees and Hurricane Katrina

Assuming that each reach is statistically independent, and if the levee is a series system of *n* reaches (such as links in a chain), the system reliability is the product of the reliability, R, for each link (like combining modes of failure):

$$R = R_1 R_2 R_3 \ldots R_n$$

The probability of failure, P_f, of the system is

$$P_f = 1 - R$$

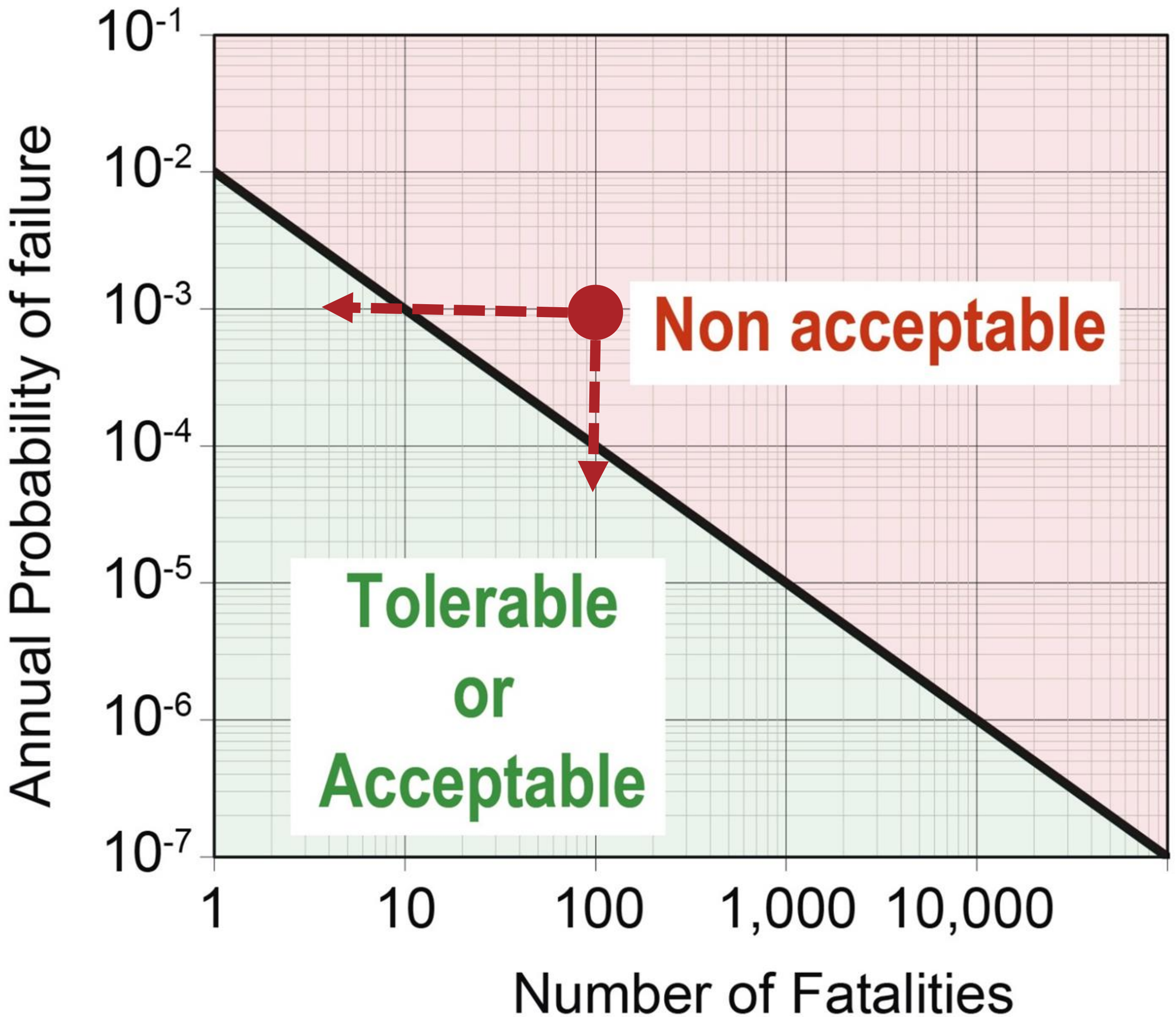
$$P_f = 1 - (1-P_1)(1-P_2)(1-P_3)\ldots(1-P_n)$$

New Orleans Levees and Hurricane Katrina

The probability of <u>at least one failure </u>in the levee system is:

No. of reaches	**Reach length (km)**	**$P_{overtopping}$ (each reach)**	**P_f (system)**
560	1000 m	0.01	**0.99**
280	2000 m	0.01	**0.94**
1020	500 m	0.01	**≈1.00**
560	1000 m	0.001	**0.43**

F-N curves and acceptable risk

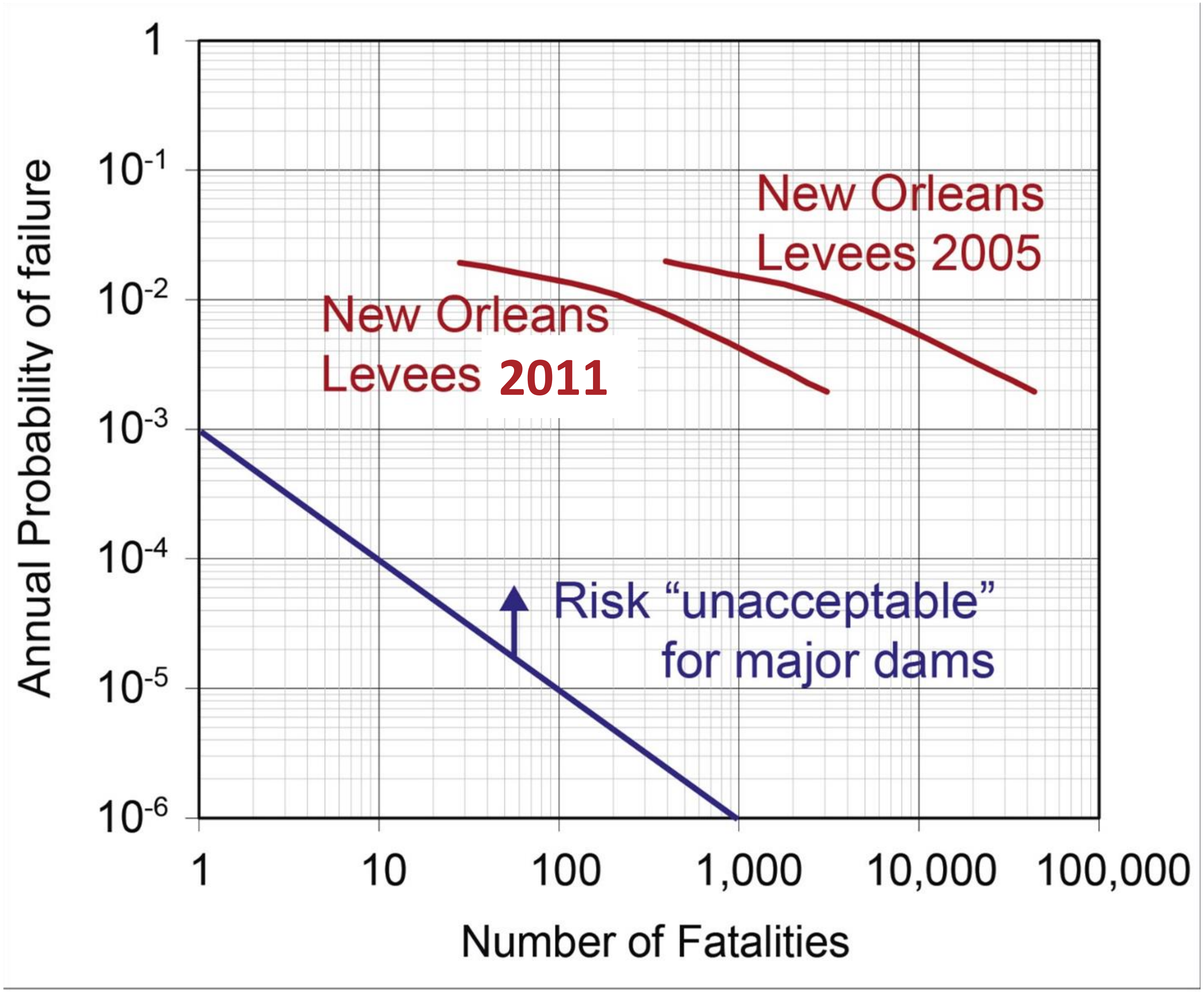


New Orleans Levees and Hurricane Katrina

Risk diagrams (F-N curves) [Gilbert 2014]

<u>2005</u>
"Hurricane Protection System"

<u>2011</u>
"Hurricane Storm Damage Risk Reduction System"



New Orleans Levees and Hurricane Katrina

The risk, even after the 2011 upgrading is much higher than that considered tolerable for major dams in the world.

Why is the risk so much higher for the levee system?

What is considered as “tolerable risk” is not an absolute, but is relative to the context of the costs and the feasibility of reducing the risk. It was not feasible to achieve that low a risk for a long levee system in an urban area [after Gilbert 2015].

Quantitative risk assessment for selection of most appropriate risk mitigation strategy

[US Army Corps of Engineers 2005]

Emerging question:

Should one have used part of the $18 billion USD on measures to evacuate people in advance of a storm, to avoid fatalities, even with overtopping ?

[after Gilbert et al 2008]

Added value of reliability analysis?

- Simple reliability-based analyses predict that the New Orleans levees would most probably fail under a strong hurricane.
- Long levees should be designed for very long return periods.
- Reliability analyses should be used to make decisions on the optimum mitigation measures.

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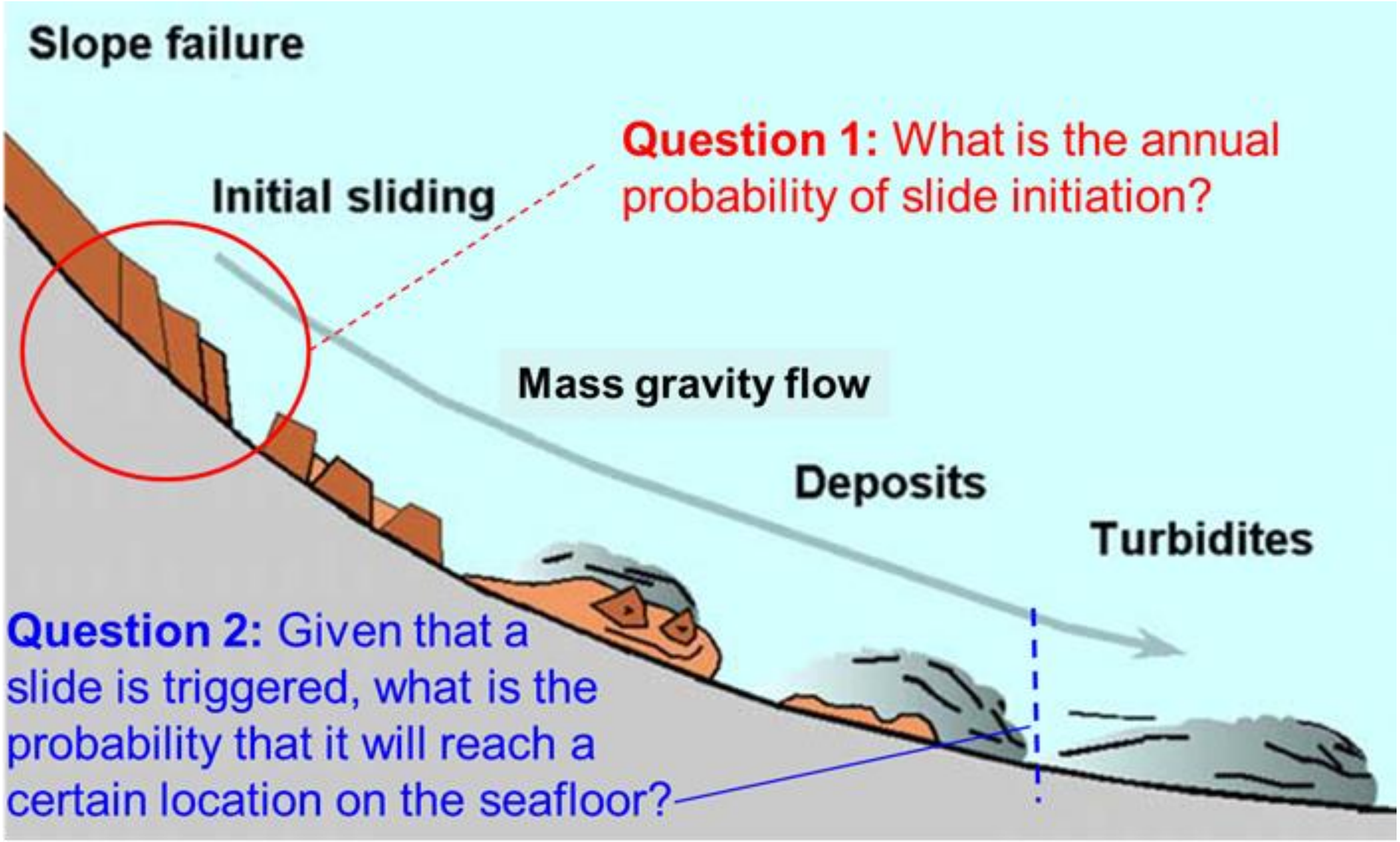
Submarine Landslides

Triggering, propagation and runout



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

<u>Probability distribution of P_f</u>

"r" slides observed during "n" years:

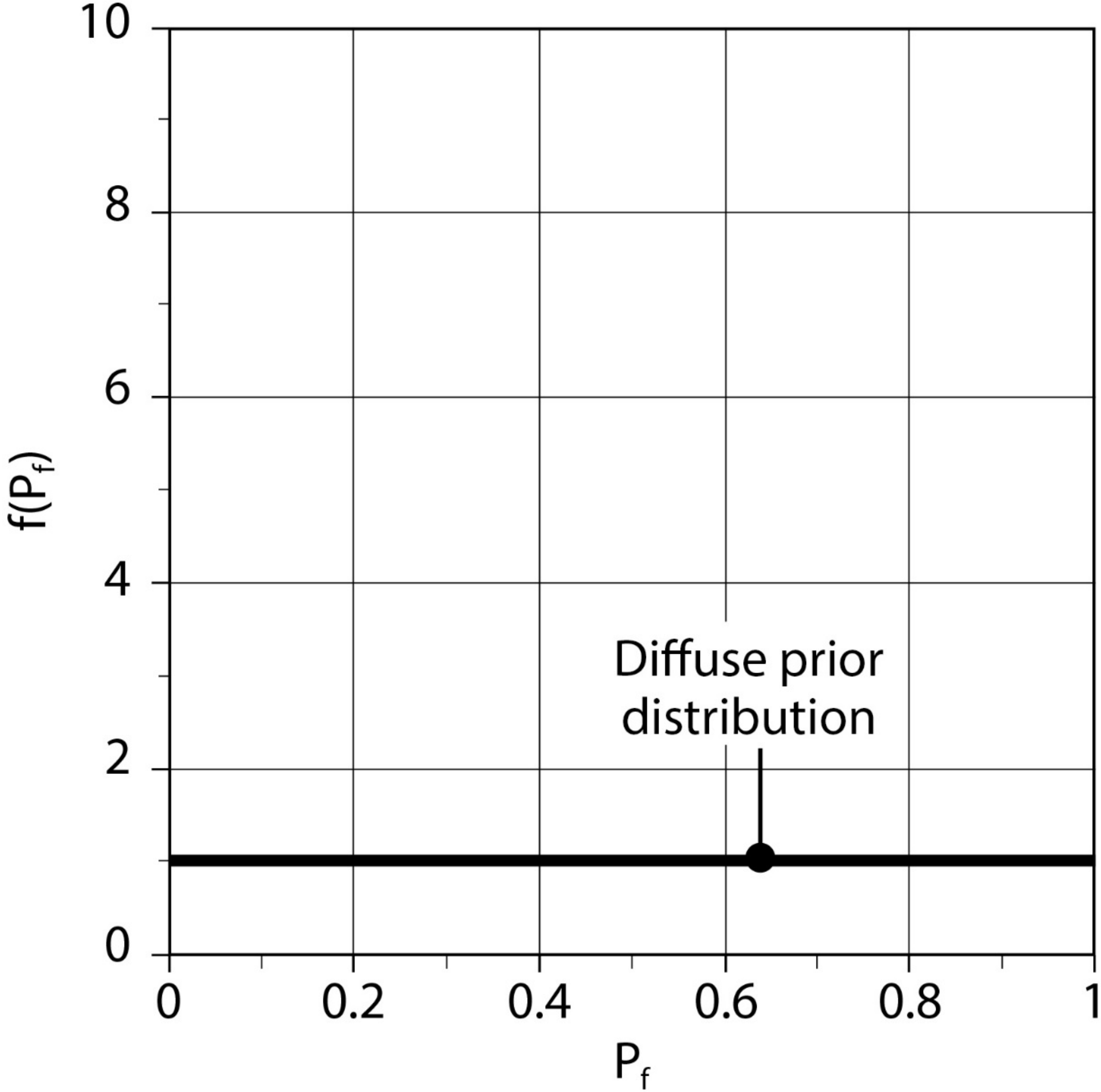
$$f(P_f) = k \cdot P_f^r \cdot (1 - P_f)^{n-r}$$

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

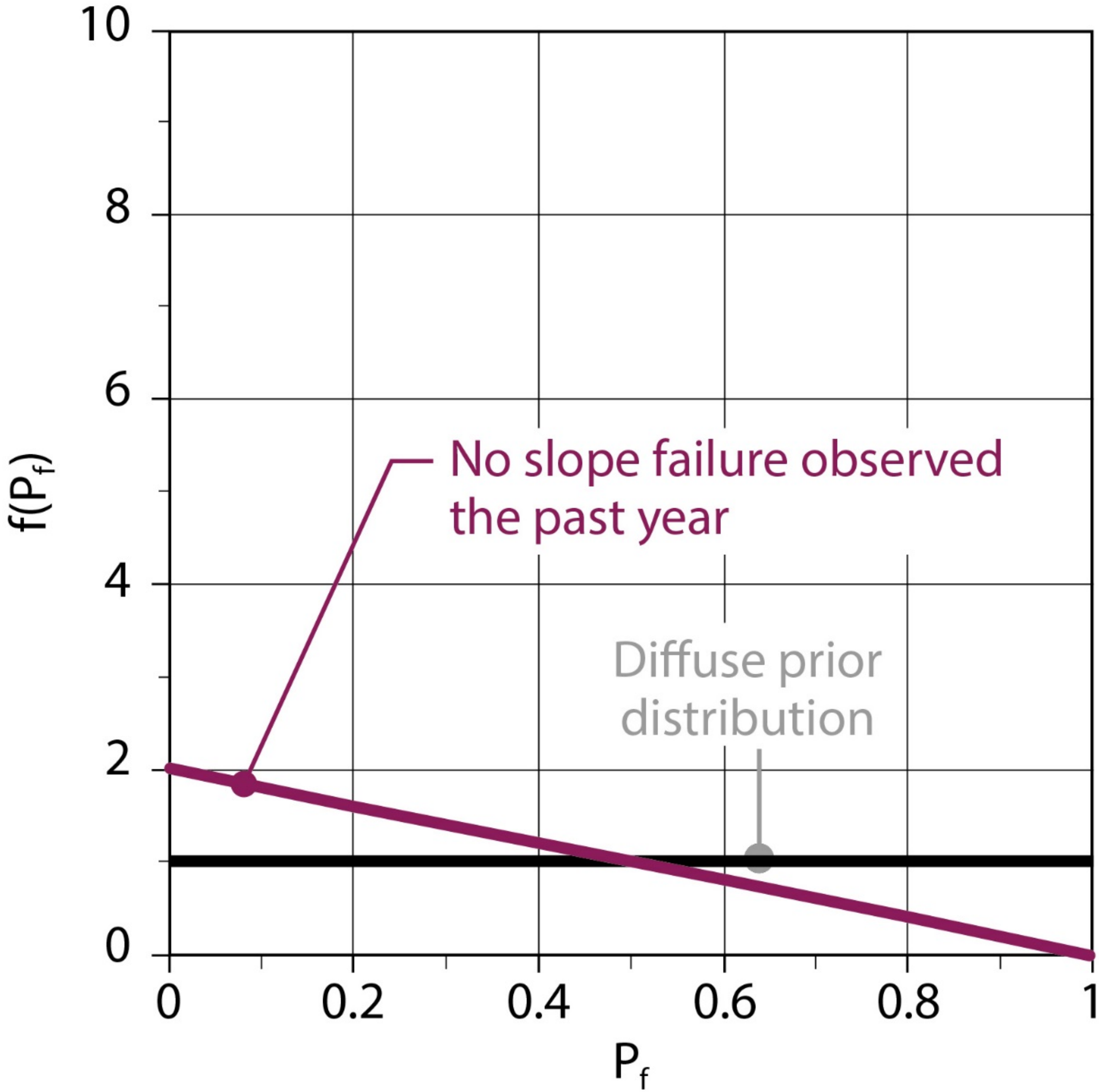
No slides during n = 8,000 years $\Rightarrow$ $E[P_f] \approx 1.25 \cdot 10^{-4}$

No slides during n = 18,000 years $\Rightarrow$ $E[P_f] \approx 0.56 \cdot 10^{-4}$

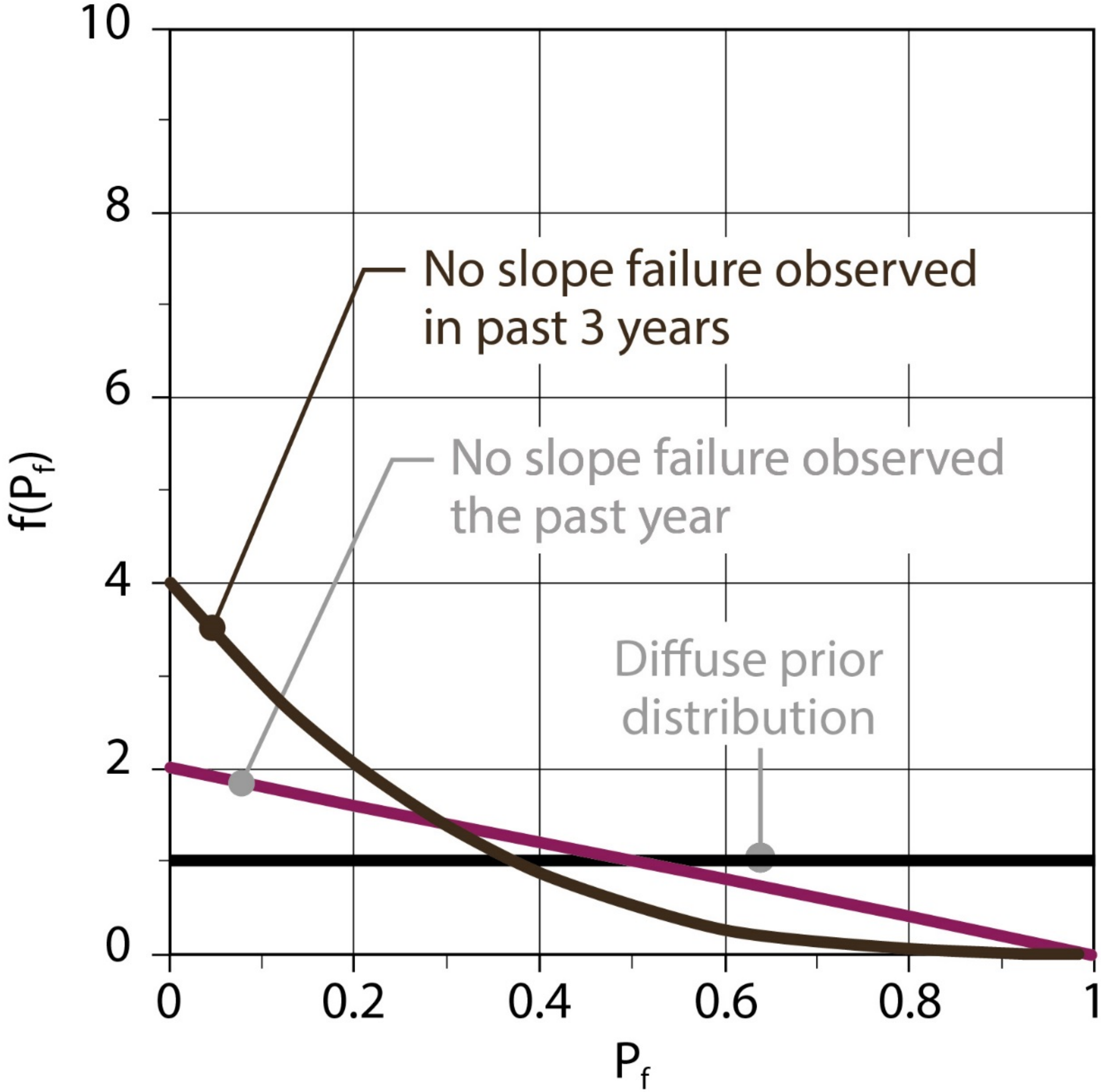
No
information



No
slope failure
in the past
year (1 yr)

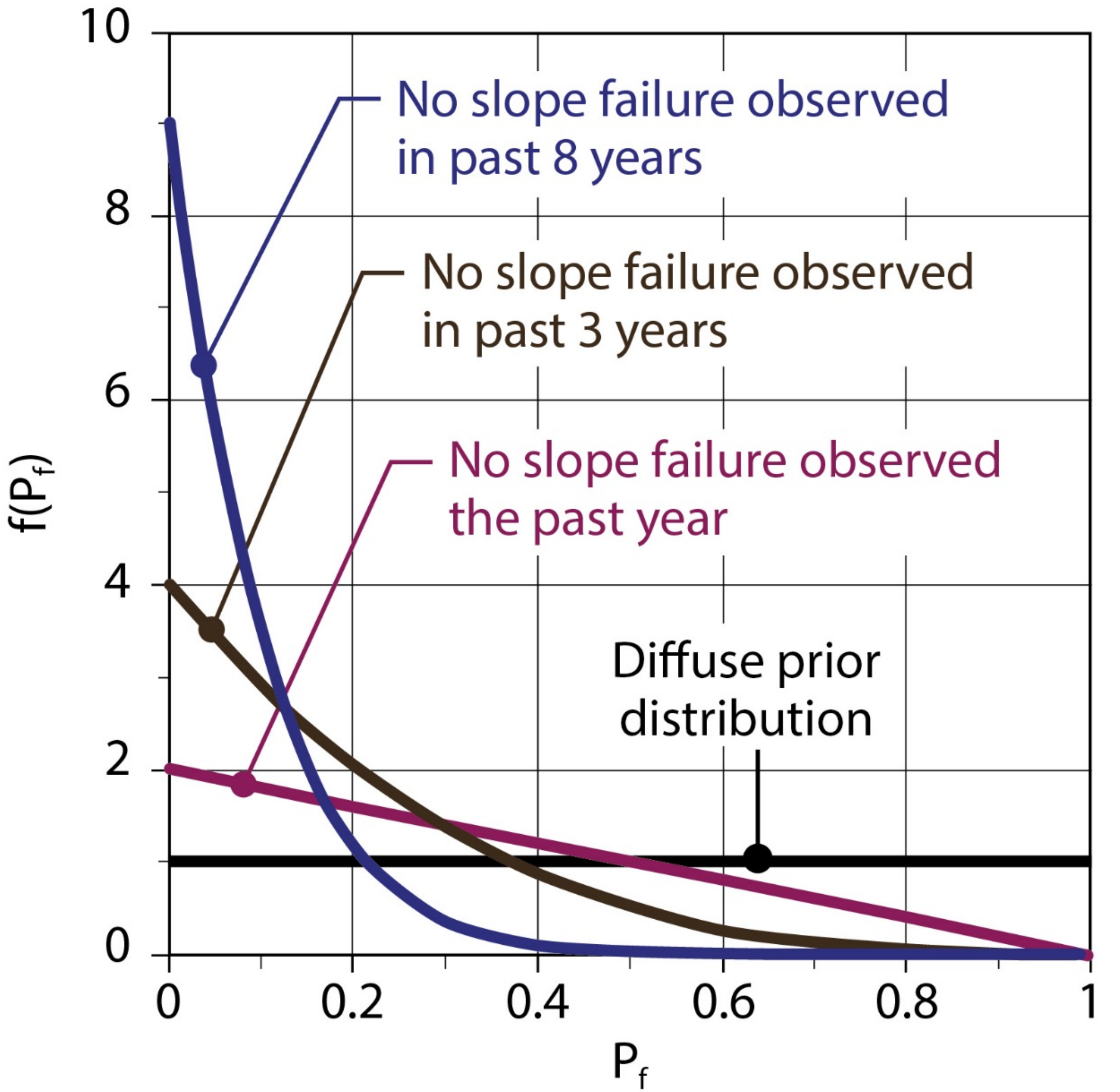


No
slope failure
in the past
3 years



No
slope failure
in the past
8 years

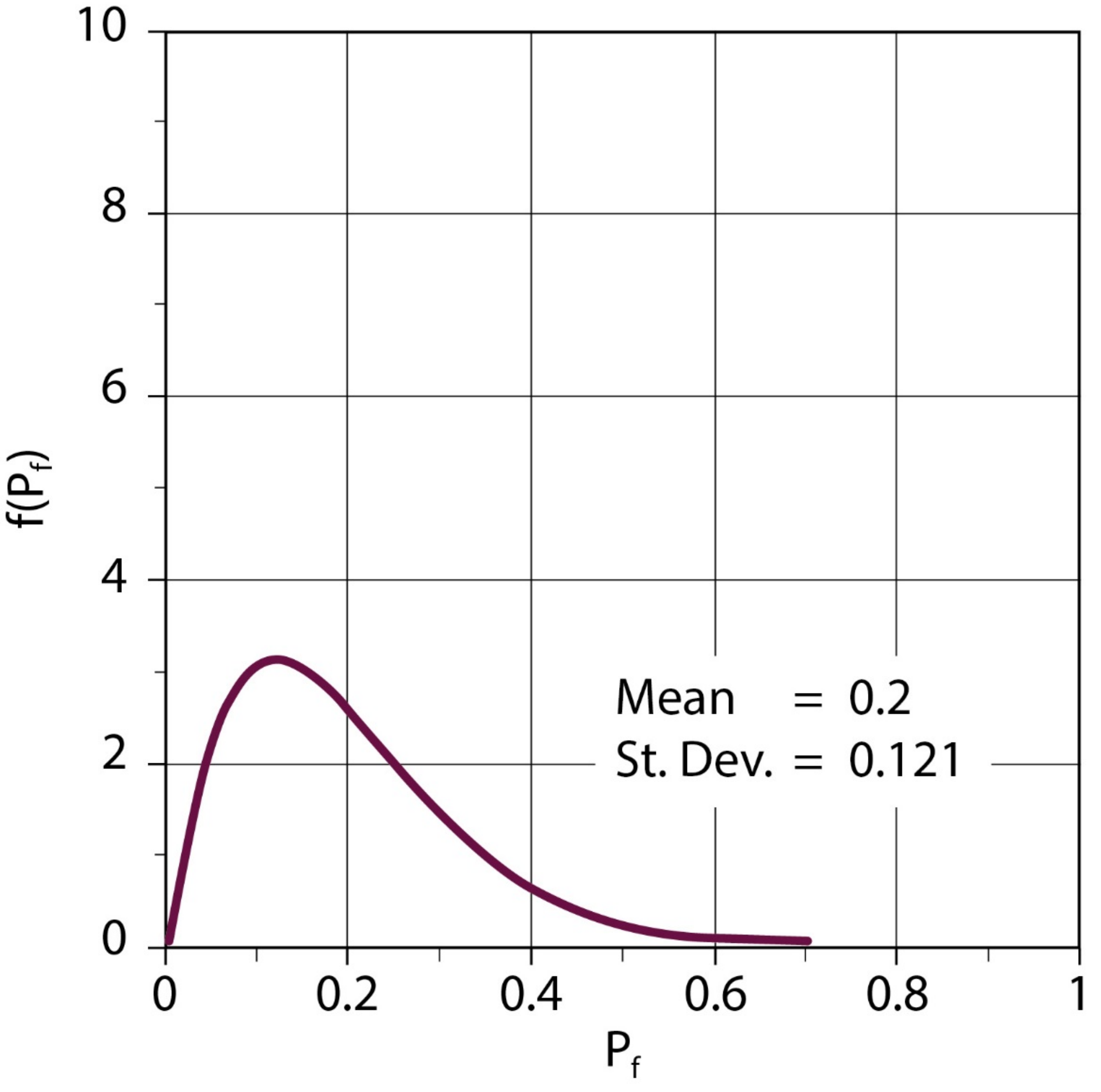
[Nadim
et al 2013]



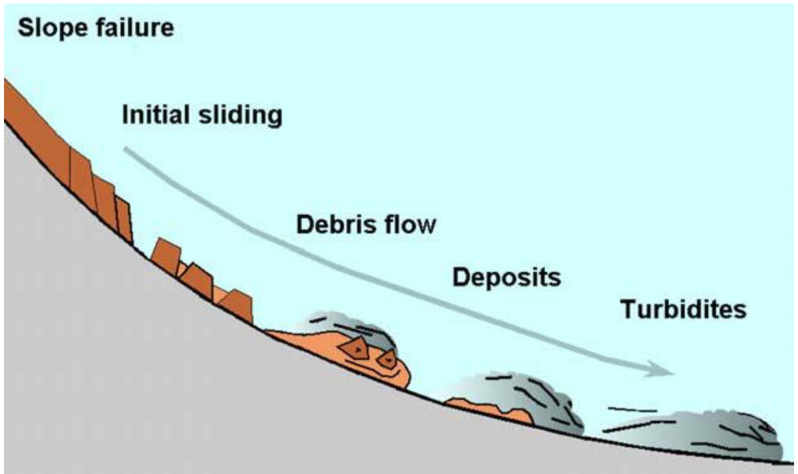
PDF for
$P_{f\ annual}$

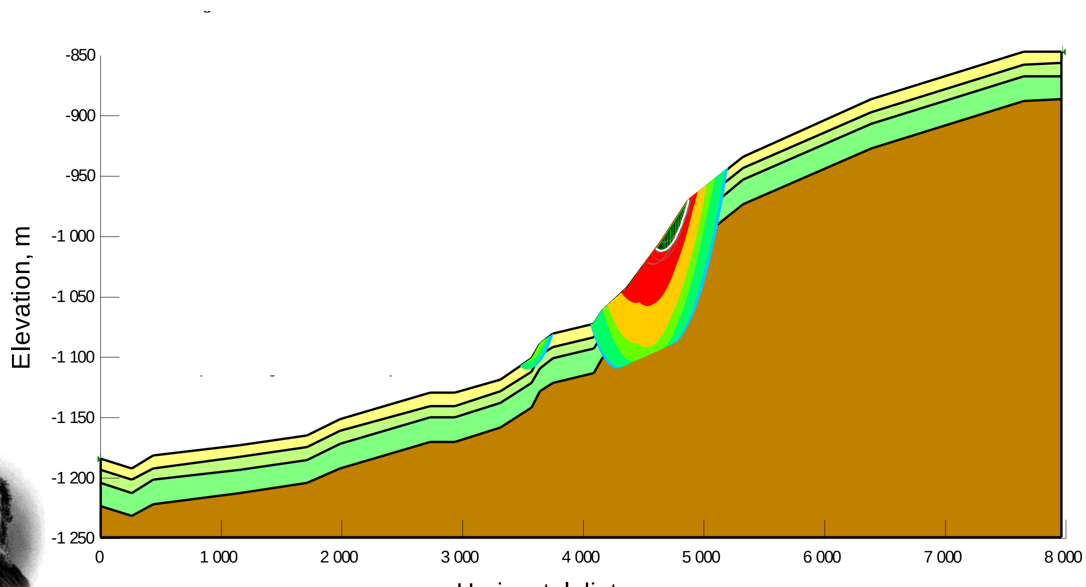
Slope failure
if 2 slides
were
observed
in past 10 yrs

[Nadim
et al 2013]



Submarine Landslides
Propagation and runout





Slope stability

- Resisting vs driving forces
- Excess pore pressure

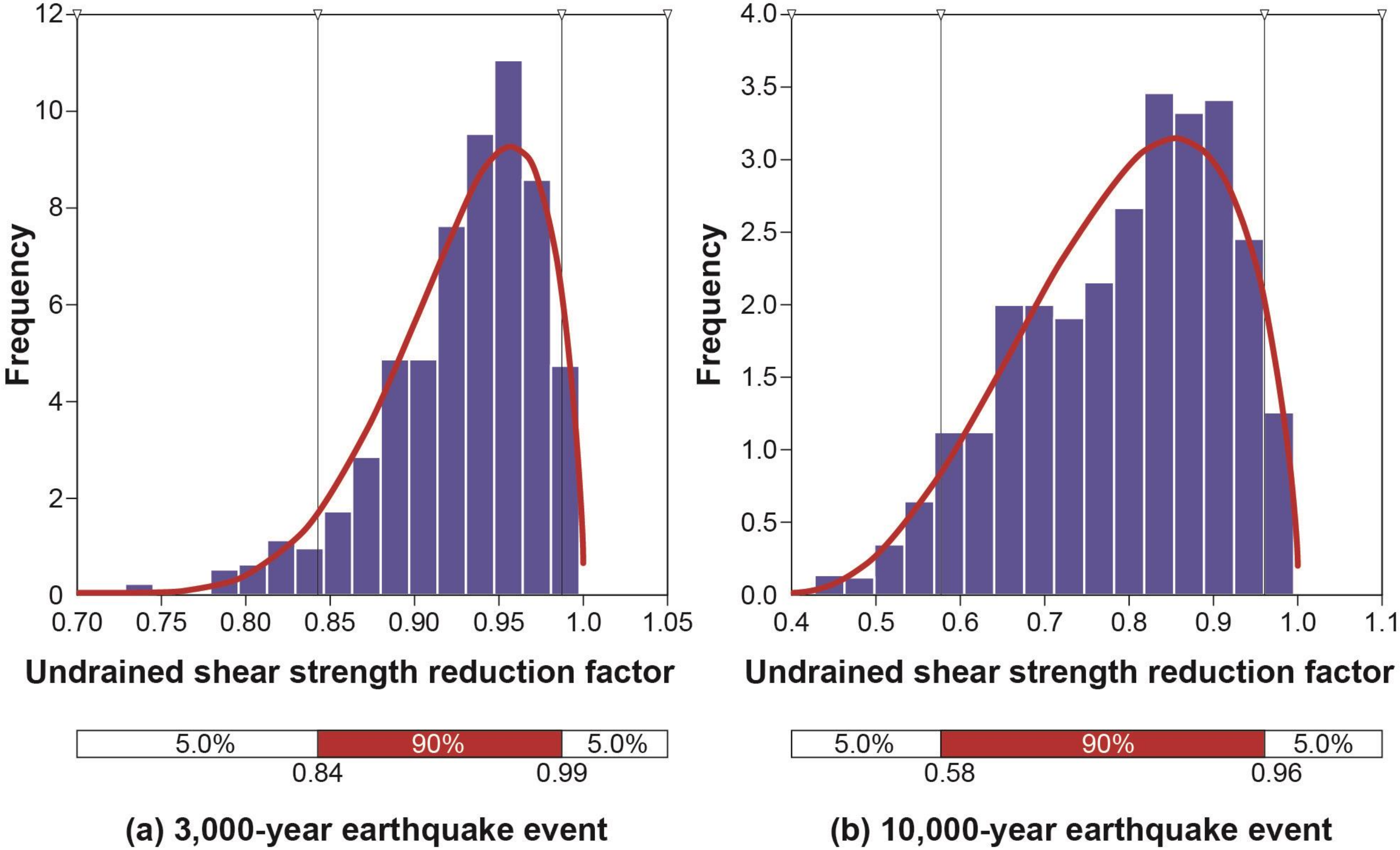
Pre-conditioning, triggers

- Gravity
- Deposition (climate-related sedimentation), erosion
- Pore pressure devel'ment
- Earthquake loading

Hazards and consequences

- Probability of failure?
- Runout, impact, tsunami
- Interaction w/ infrastructure (e.g., pipeline, conductors, subsea structures

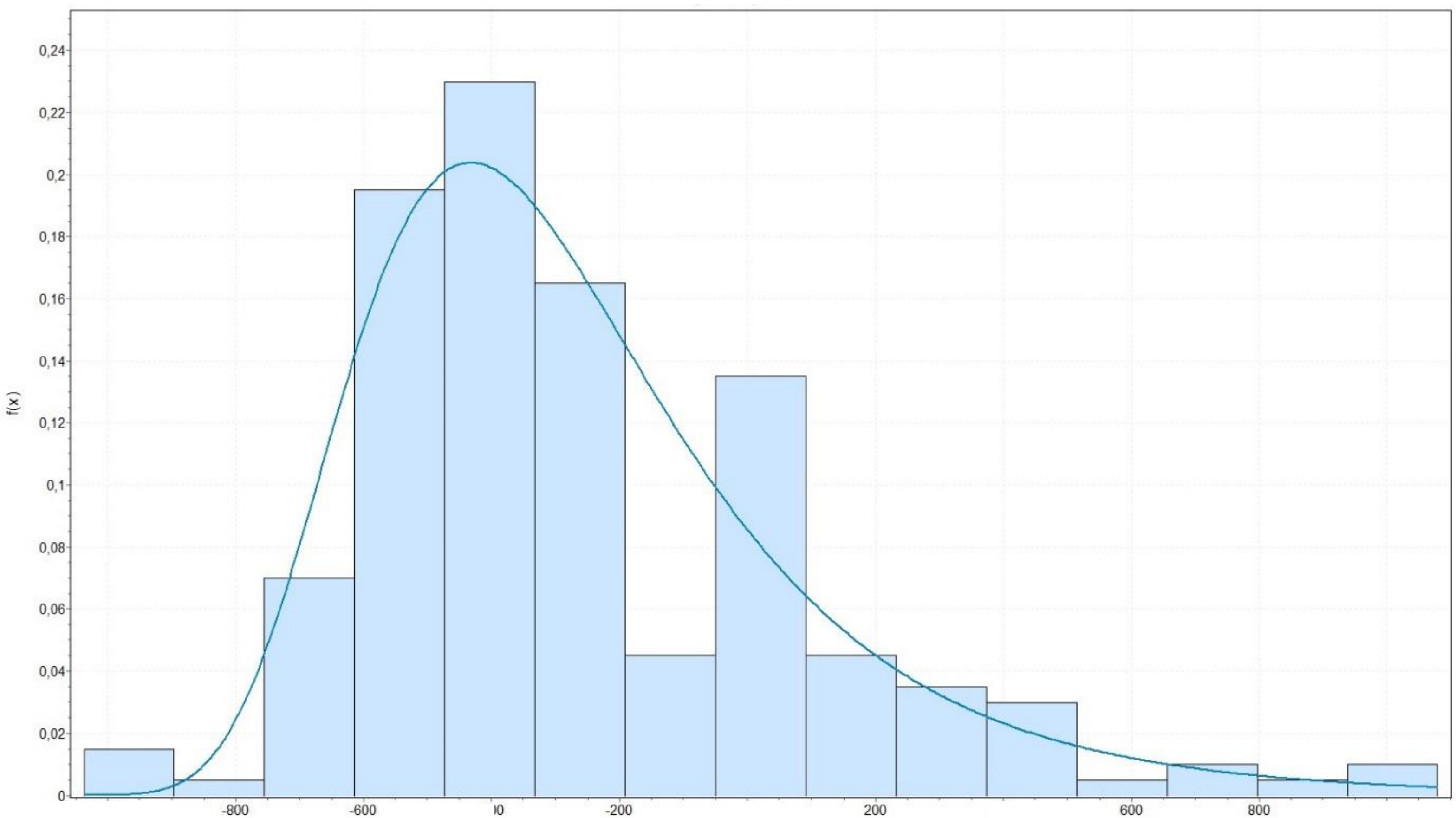
Earthquake-induced shear strength reduction
500 MC simulations and best fit distrib'n functions



3,000-year event: s_u reduction factor between 0.7 and 1.0, mean = 0.93

10,000-year event: s_u reduction factor between 0.4 and 1.0, mean = 0.79

Probability distribution of calculated runout (200 Monte Carlo simulations, plus LHS) Best fit: Generalized Extreme Value Distribution



1000 500 0 500 1000

Maximum runout distance wrt toe of slope (m)

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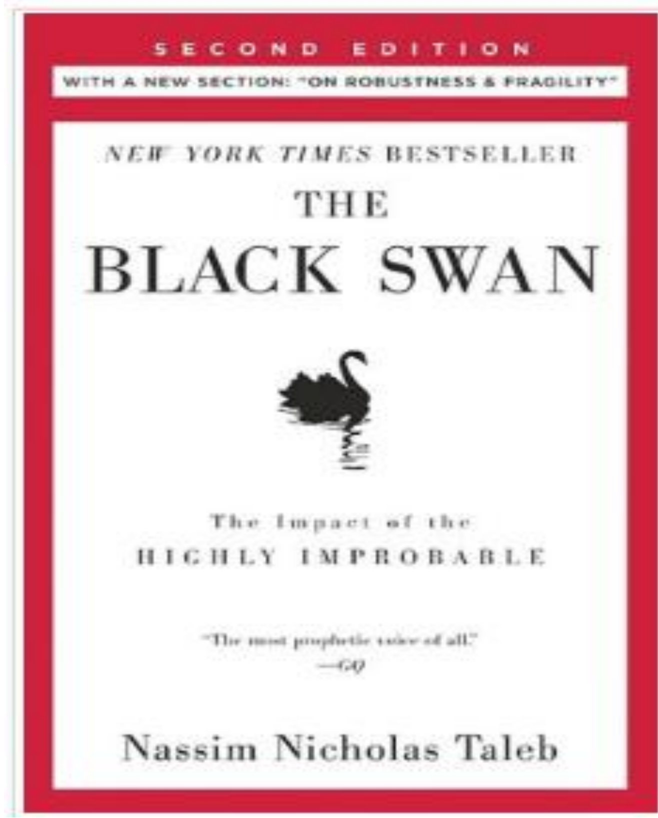
Emerging issues

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)



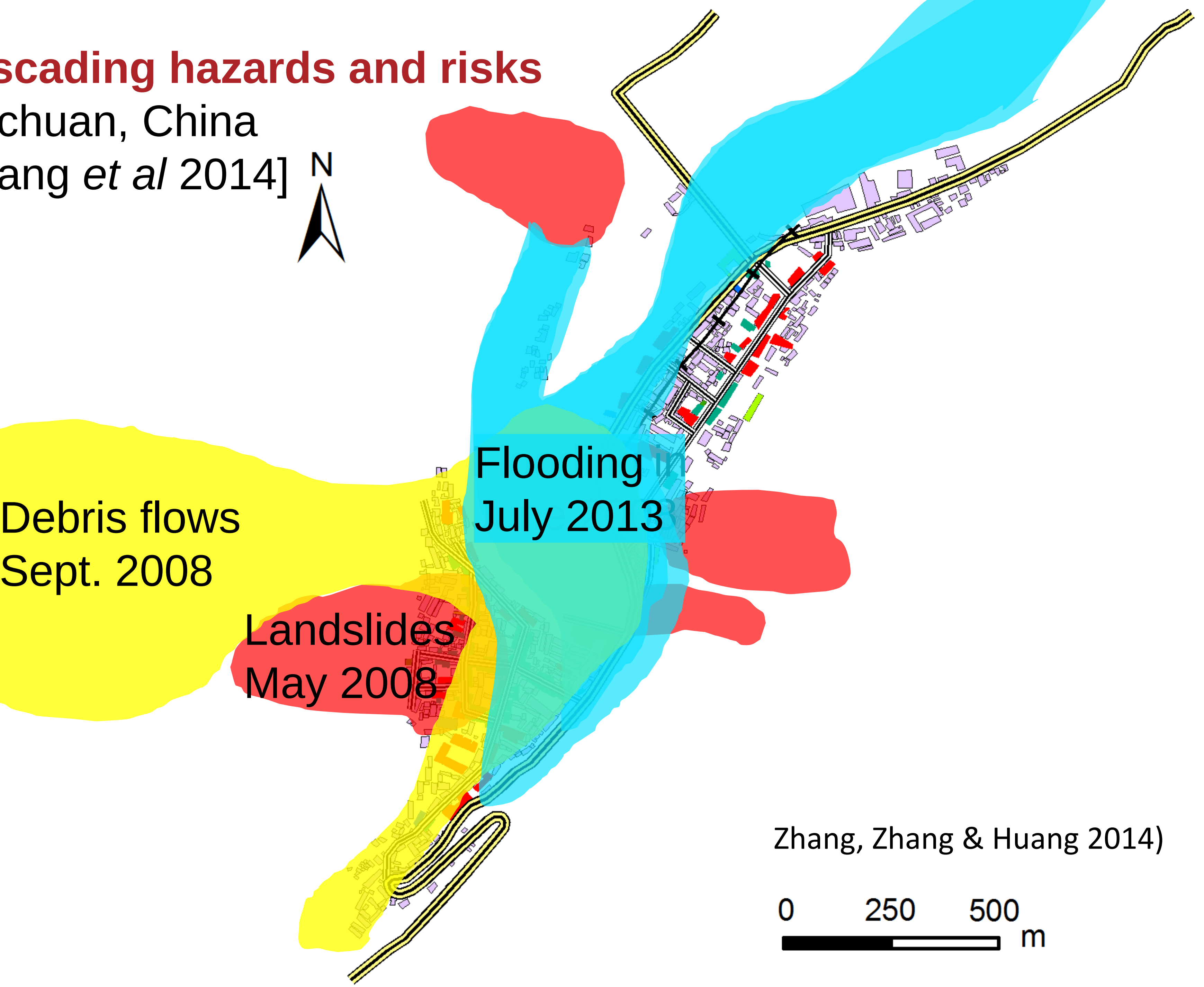
Emerging solution:

"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?

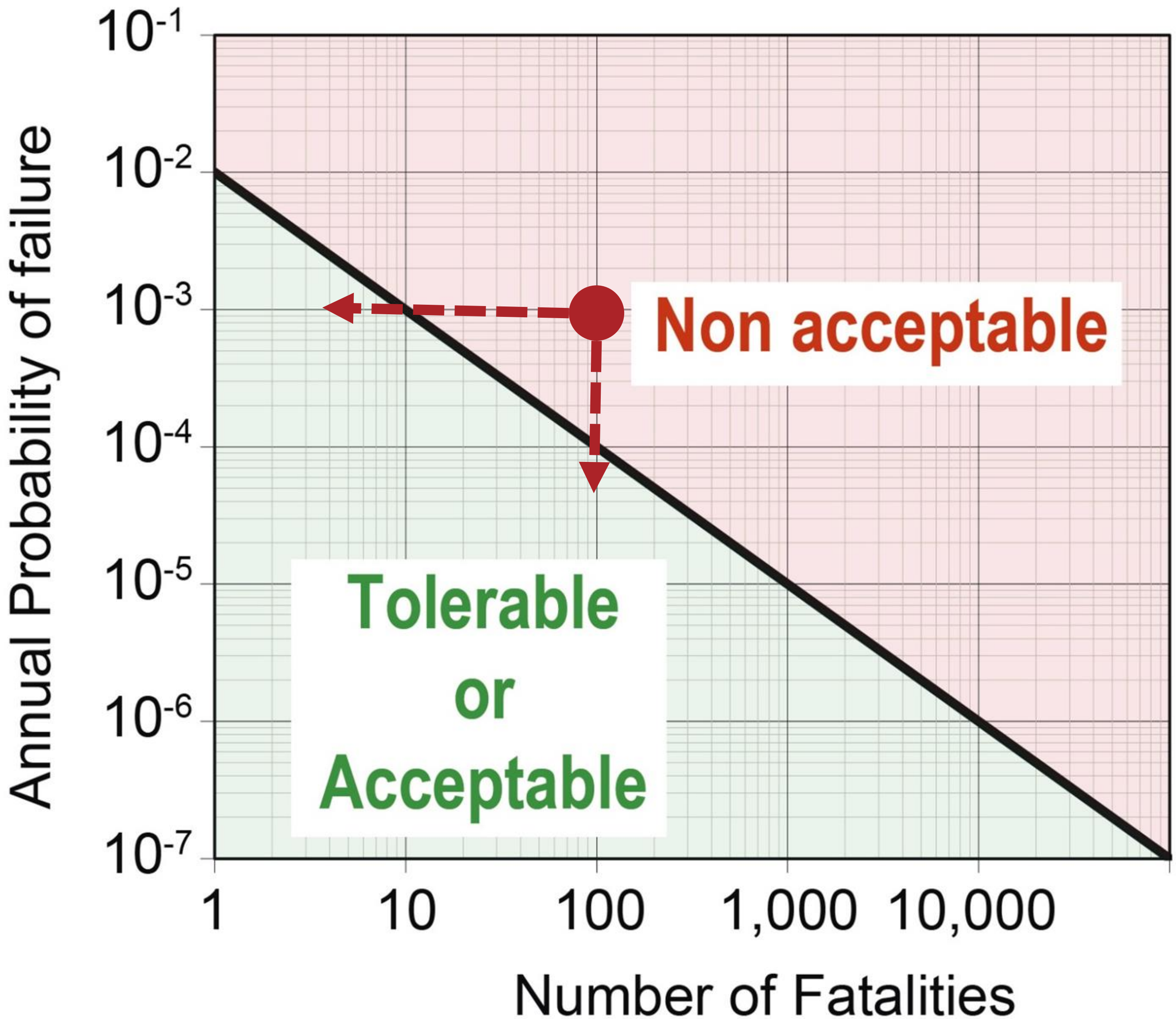
Compared to single risk analysis, the examination of multiple risks poses a range of challenge be-cause of the different characteristics of the hazards.

Emerging solution:

"Bayesian networks" (quantitative)

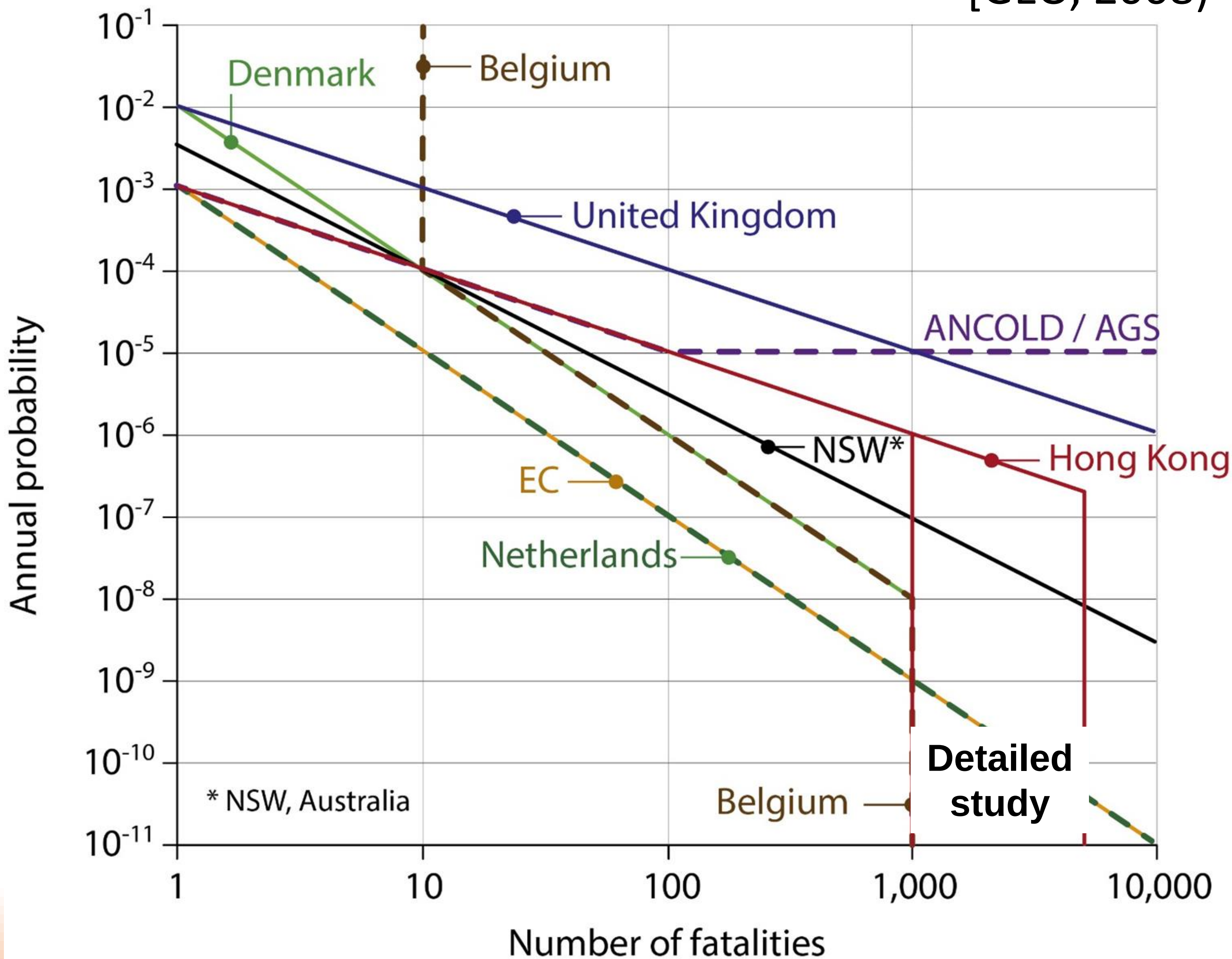
Emerging issues: Acceptable risk

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



Acceptable risk: Requirements

[GEO, 2008)



Emerging issues

<u>Communication</u>

Being a good communicator is <u>today</u> 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 conse-quences reveals the risk-creating factors and the need for remedial changes. It encourages foresight rather than hindsight.

Vulnerability of the geotechnical engineer

From the standpoint of accountability, the geotechnical engineer finds himself in a particularly vulnerable spot.

He/she works at the interface of natural conditions and man-made structures. Often he/she has little hard information and his/her judgment is continuously taxed.

He/she is called upon to identify and define situations that are potentially hazardous and to, at least, initiate a decision process as to whether the hazards are acceptable or not.

Reliability analyses

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

3 key questions

- How can reliability and risk concepts help to ensure adequate safety while achieving cost-effective designs?
- What are the advantages and challenges of the hazard, risk and reliability approach?
- Why aren't reliability and risk concepts used more today?

With all its potential, why is "acceptance" of the reliability approaches slow?

- Reliability theory involves terms and concepts that are unfamiliar to geotechnical engineers. (We, who do such analyses, have to improve how we present the applications of reliability theory.)
- Hazard, risk and reliability applications were perceived to require advanced mathematics. Today, the tools to estimate mean, SD, PDF, β and P_f are standardized, well documented software that greatly facilitate the implementation of the methods in practice.

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

Terminology

-no accepted definition

-“zero risk” and safety

Concerns

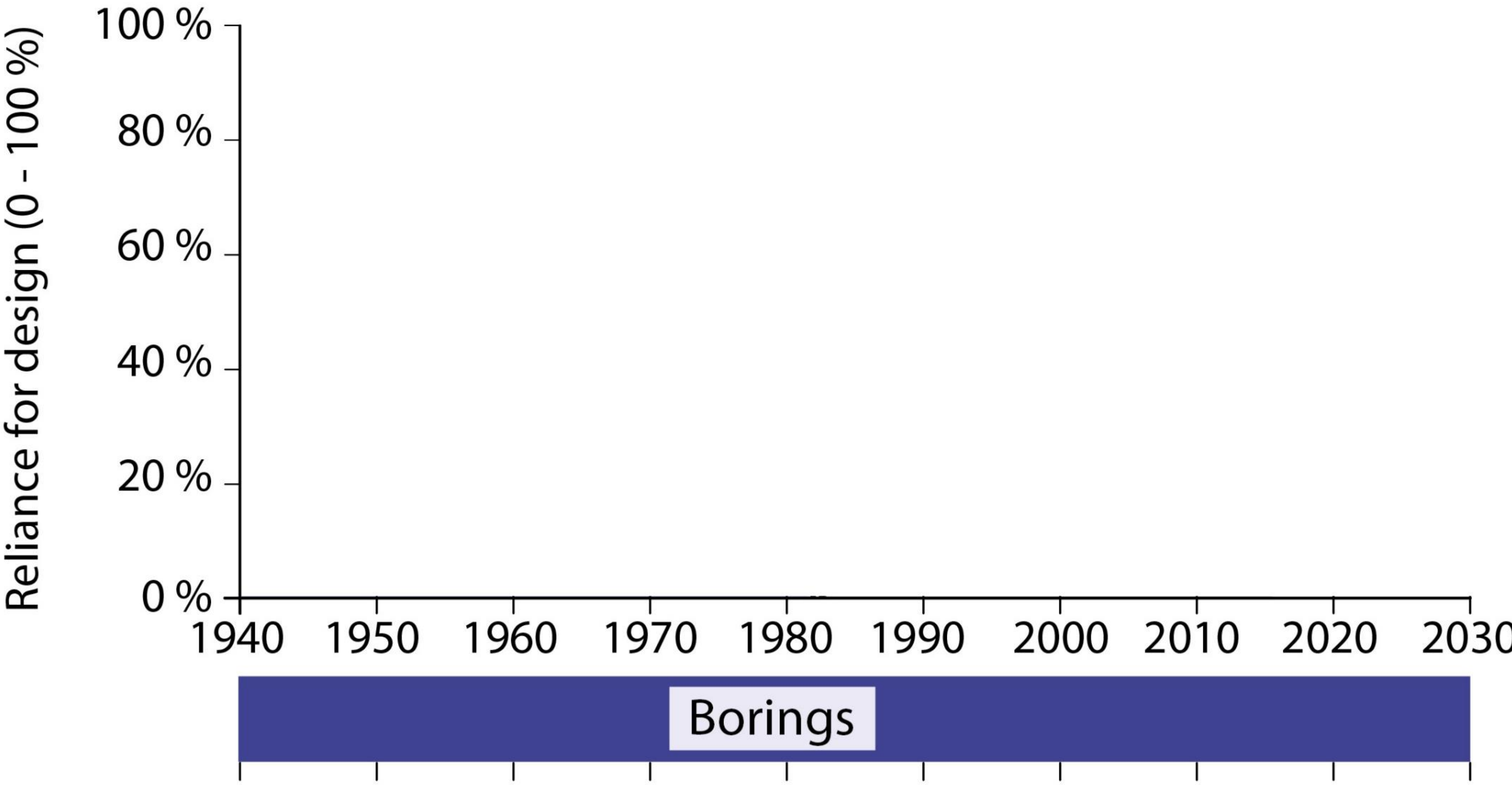
-Complexity/mathematics

-Accepting that there are uncertainties

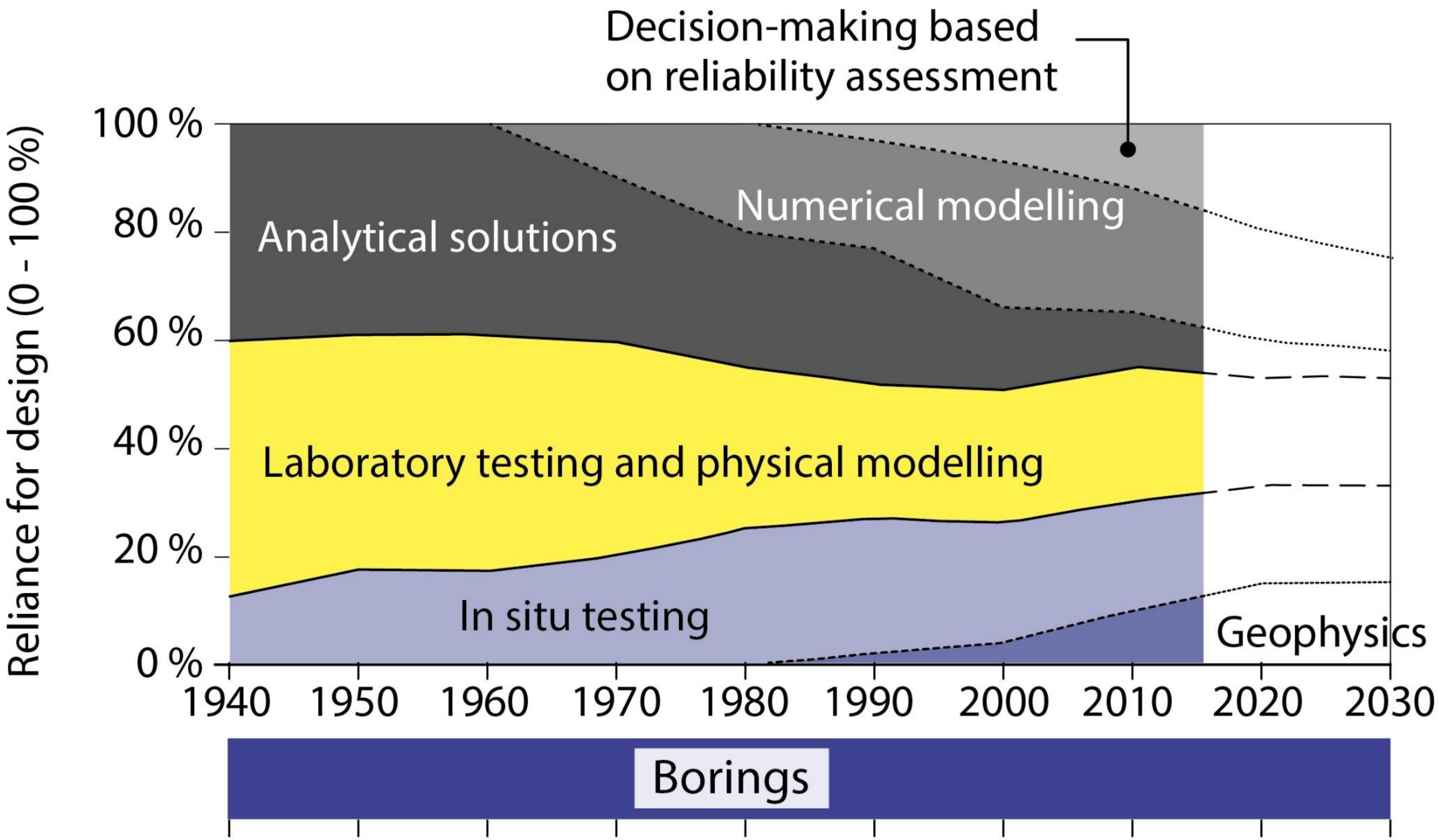
Distrust

-Acceptable/tolerable risk values, and who decides?

Evolution of geotechnical practice



Evolution of geotechnical practice

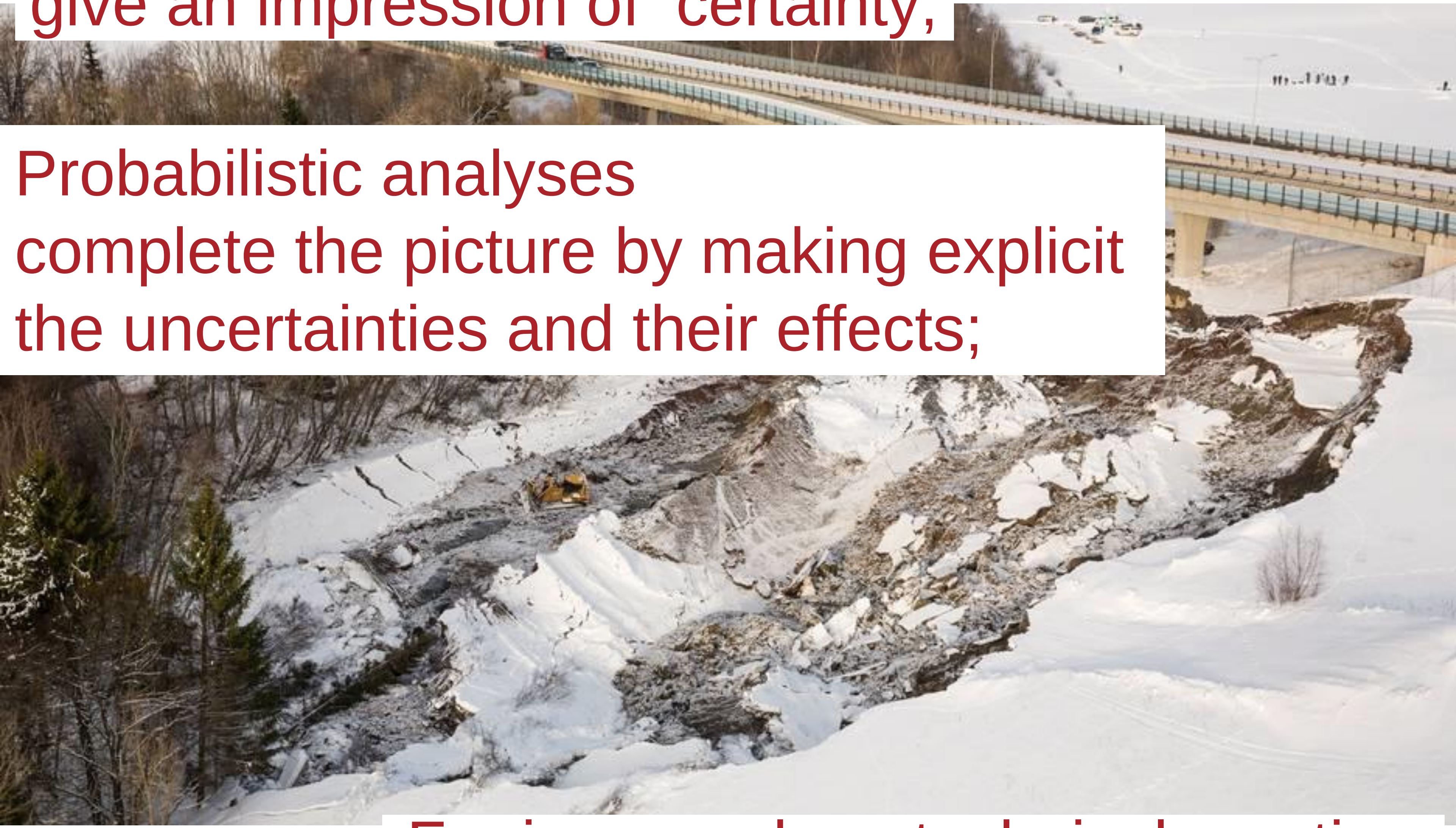


Deterministic and probabilistic analyses

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.

Integrating deterministic and probabilistic analyses in a complementary manner brings together the best of our profession.

Deterministic analyses
give an impression of certainty;

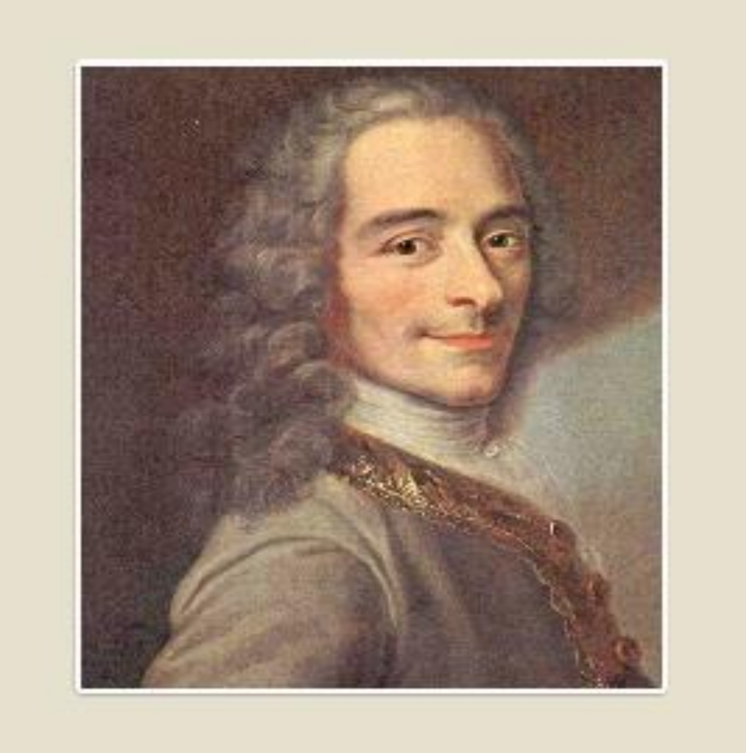


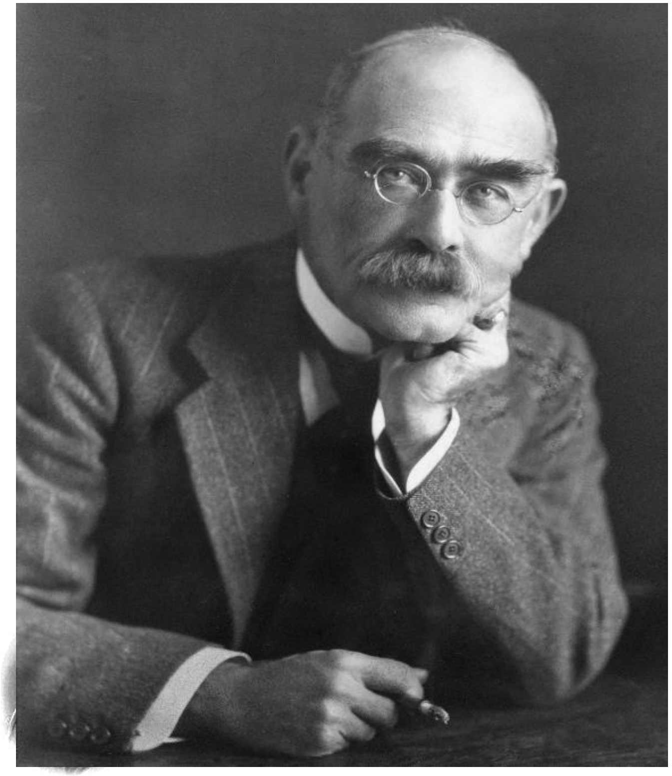
Probabilistic analyses
complete the picture by making explicit
the uncertainties and their effects;

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)

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