Seminário Técnico Internacional sobre Barragens de Rejeitos e o Futuro da Mineração em Minas Gerais

International Technical Seminar: Tailings Dams and the Future of Mining in Minas Gerais State

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International Technical Seminar on Tailings Dams and the Future of Mining in Minas Gerais State

Tailings dams: Design, construction and operation

Uncertainties, hazard and risk with tailings dams

Suzanne Lacasse
Norwegian Geotechnical Institute, NGI Oslo Norway

NGI

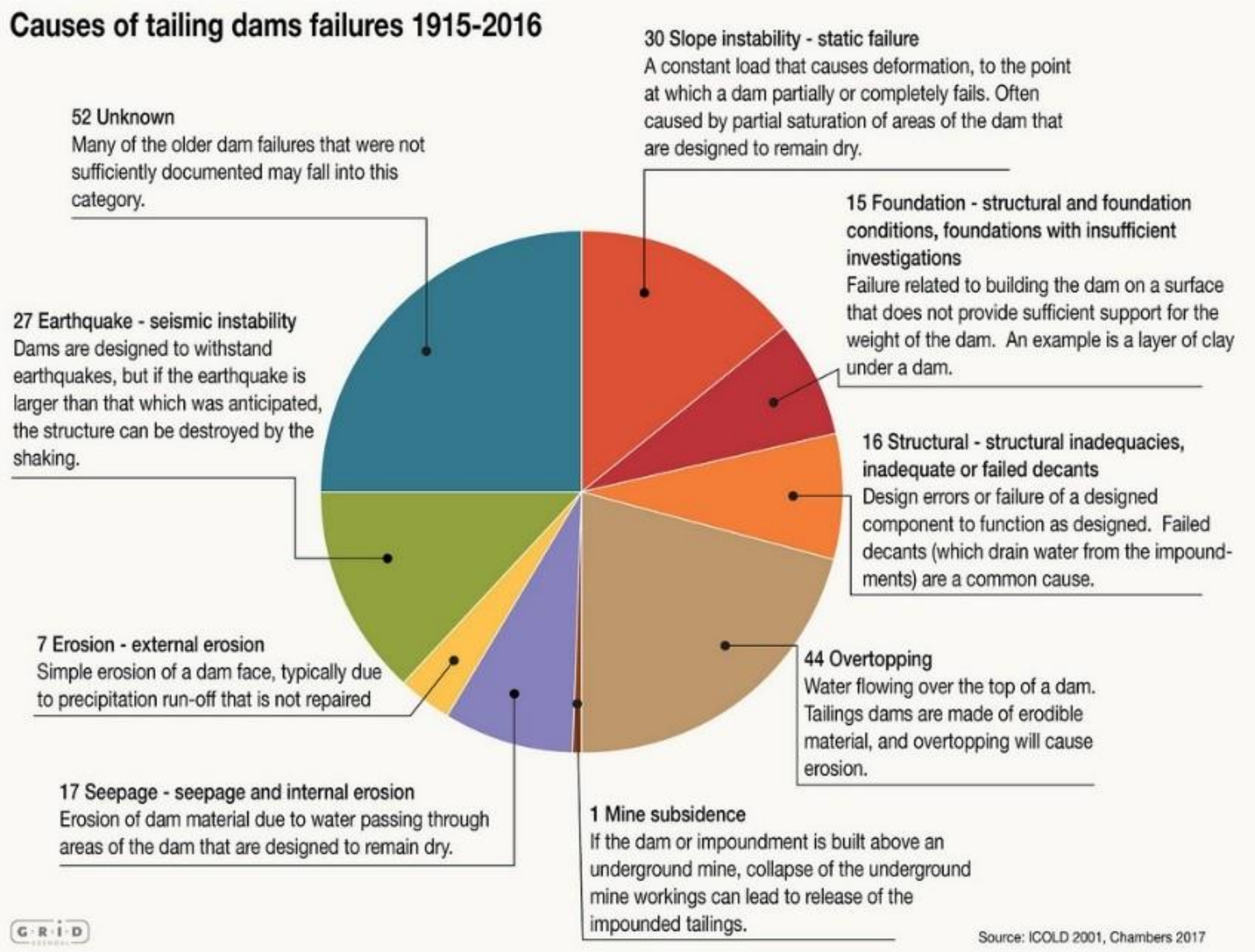
Causes of failure of tailings dams over past 100 years

(ICOLD, 2001)

<u>Mostly due to geotechnical causes</u>

- Slope stability
- Foundation
- Seismic instability
- Erosion
- Seepage, …

Of the 221 failures examined by ICOLD, all were found to be avoidable.



Mount Polley

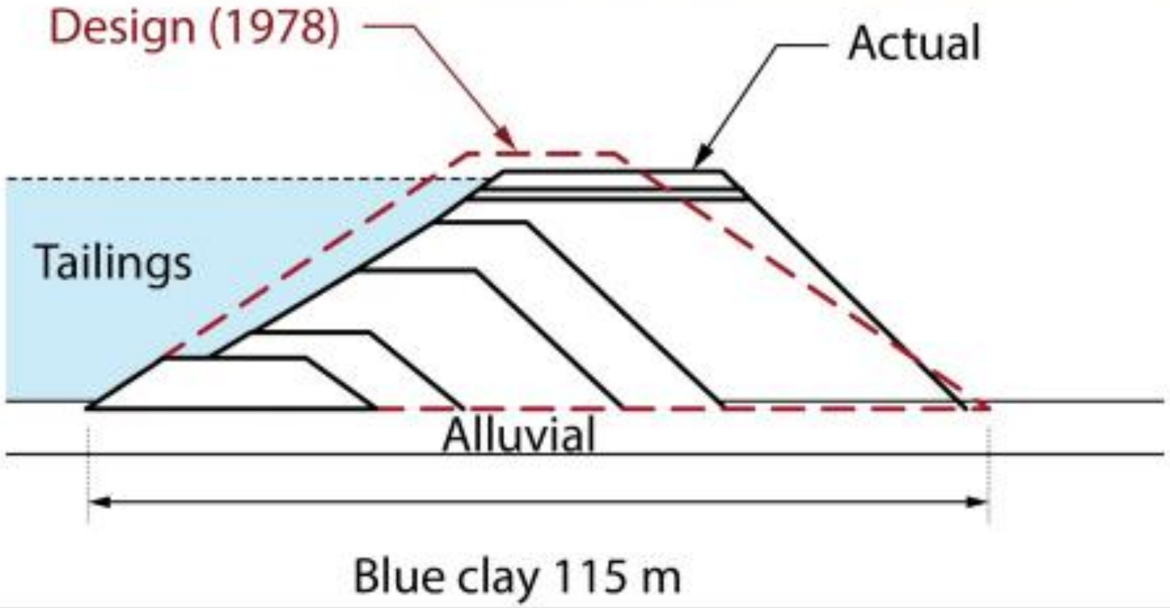
Failure in the foundation of the embankment due to a weak layer that was undetected. The rockfill had very steep downstream slope (1.3H:1V). Had the slope been flattened to 2H:1V, as proposed in the original design, failure would have been avoided.

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

Aznalcóllar

The as built cross-section was steeper than designed (design had already rather steep slopes, 1.8H:1V). The downstream slope was increased to (1.23H:1V) in 1985. After 20 yrs of continuous increase in the dam height, only 15% of the excess pore pressure in the foundation clay had dissipated.

[Gens & Alonzo 2006]



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- Safety margin
- Reliability and risk
- Behaviour of tailings – a challenge
- Examples of reliability-based results and their interpretation
- Conclusions

  What needs to be changed for “risk-informed decisions” to be made in the design, construction and operation of tailings dam to reduce risks (geo point of view)

Safety assessment for a tailings dams

The objective of a safety assessment is to demonstrate that the risk associated with a facility is acceptable.

The conventional way is to use a «deterministic» safety factor, SF. A safety factor of 1.5, for example, is often used to handle the uncertainties in the ground, in the analysis parameters and in the calculation model.

There is a general perception that a design with a safety factor SF ≥ 1.50 has to be «safe». But reality is not so simple. A safety factor of 1.5 represents actually a spectrum of failure probabilities, which depend on the uncertainties in the analysis.

Deterministic (conventional) and probabilistic analyses

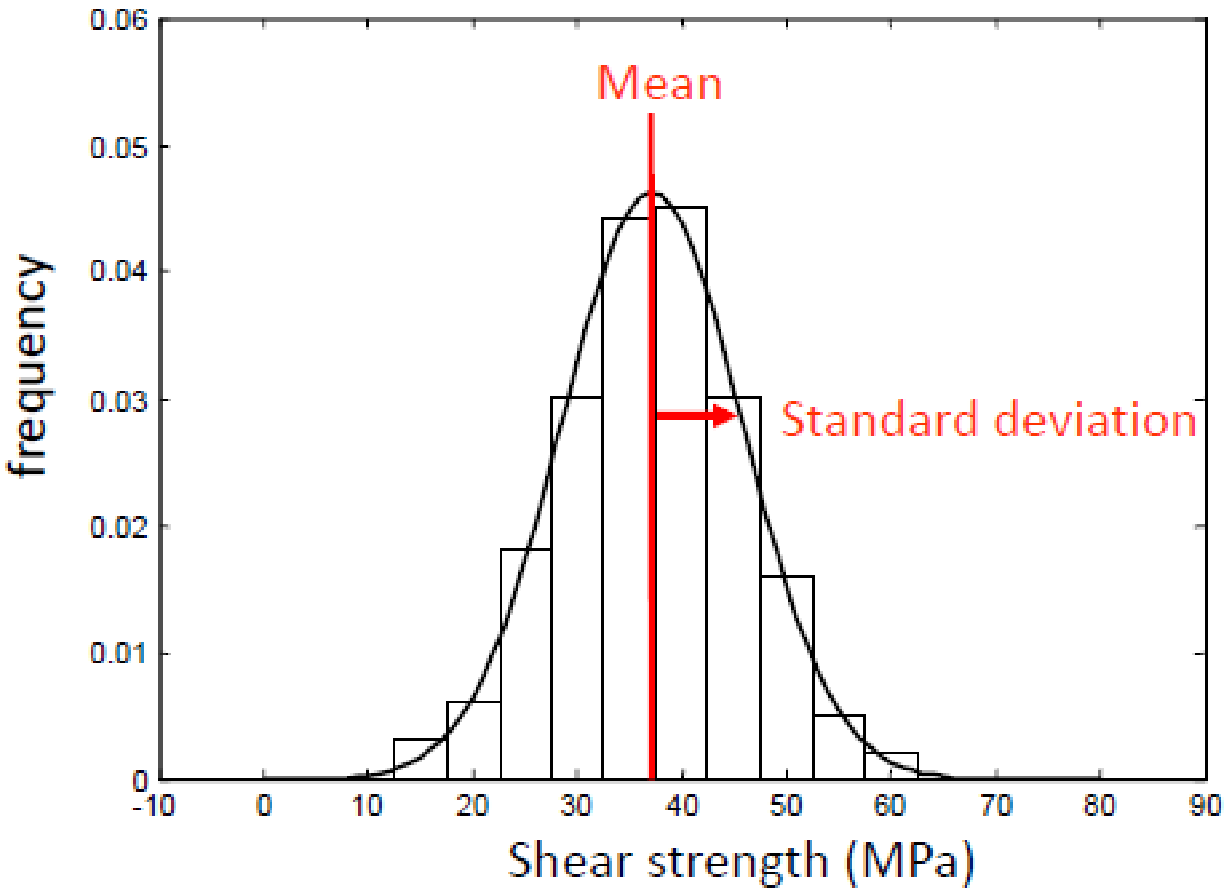
- A deterministic analysis looks at a nominal case, without considering the entire spectrum of plausible outcomes, and does not quantify the likelihood of the outcomes - can therefore under-predict or over-predict the risk.
- A probabilistic analysis evaluates the risk, and identifies the uncertainties that are key for the safety. It brings up a discussion of the uncertainties, which always leads to an improved understanding of what is important for the design and in the monitoring of performance.

While a deterministic analysis looks at one scenario (and one set of input data), a probabilistic analysis attempts to include all the plausible scenarios, their likelihood and their consequences. A probabilistic analysis is like series of sensitivity analyses (many thousands of analyses, on the computer).

Uncertainties
often represented by a normal statistical distribution

A method to express uncertainty:

- Mean
- Standard deviation (SD)



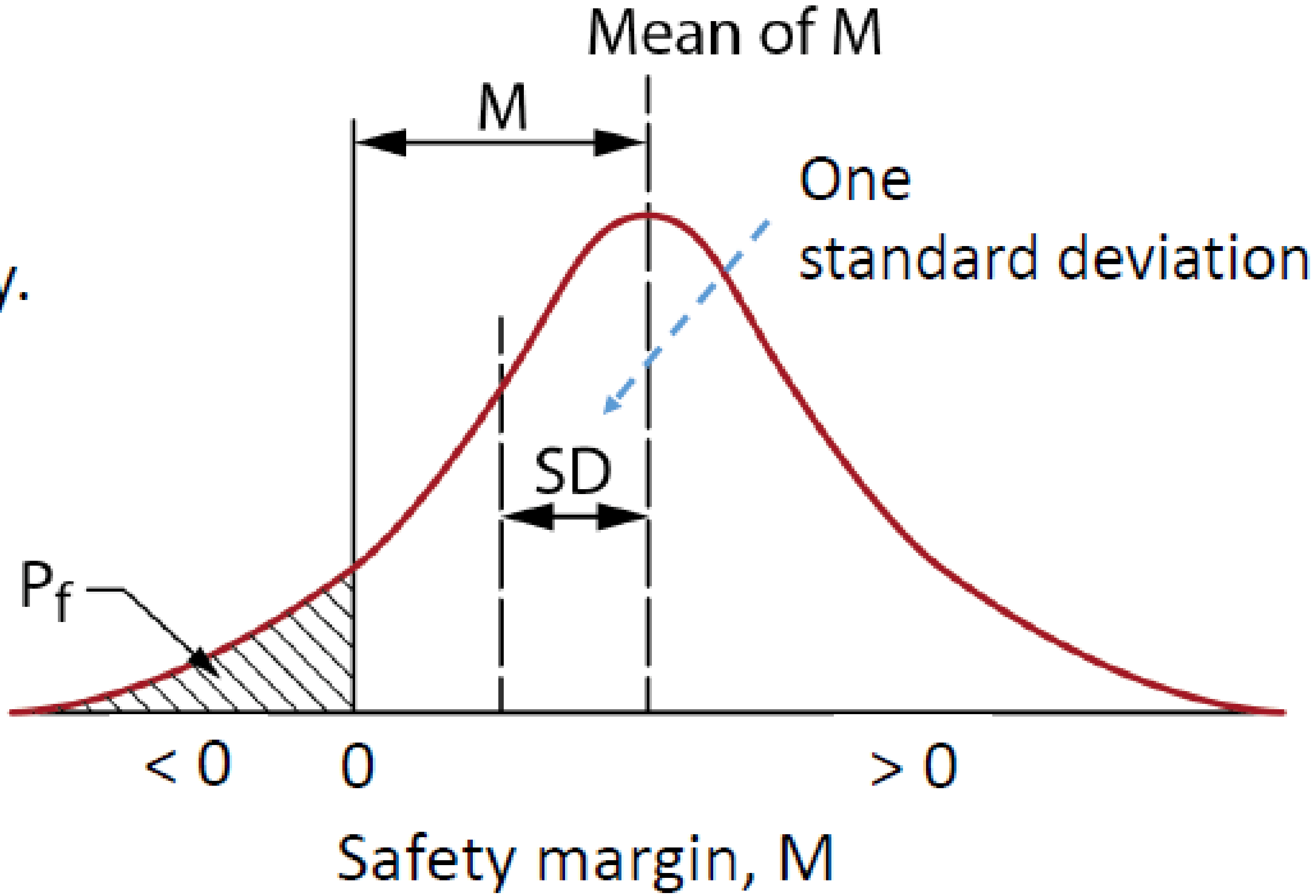
Safety margin throughout the lifetime of a facility

Safety margin, M

$$M = \text{Resistance} - \text{Load} \geq 0$$

Safety margin has an uncertainty.

The likelihood of failure P_f

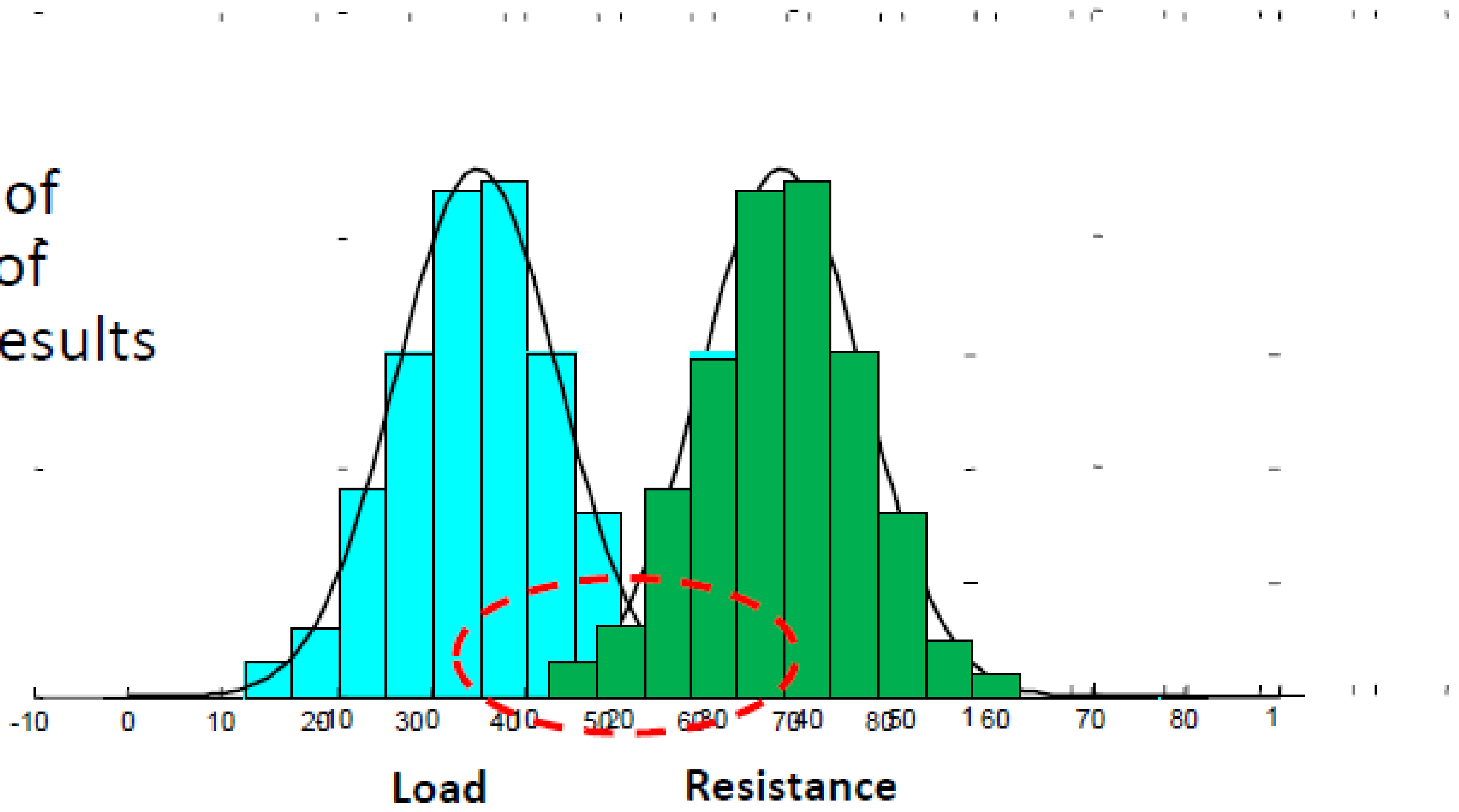


Margin of safety

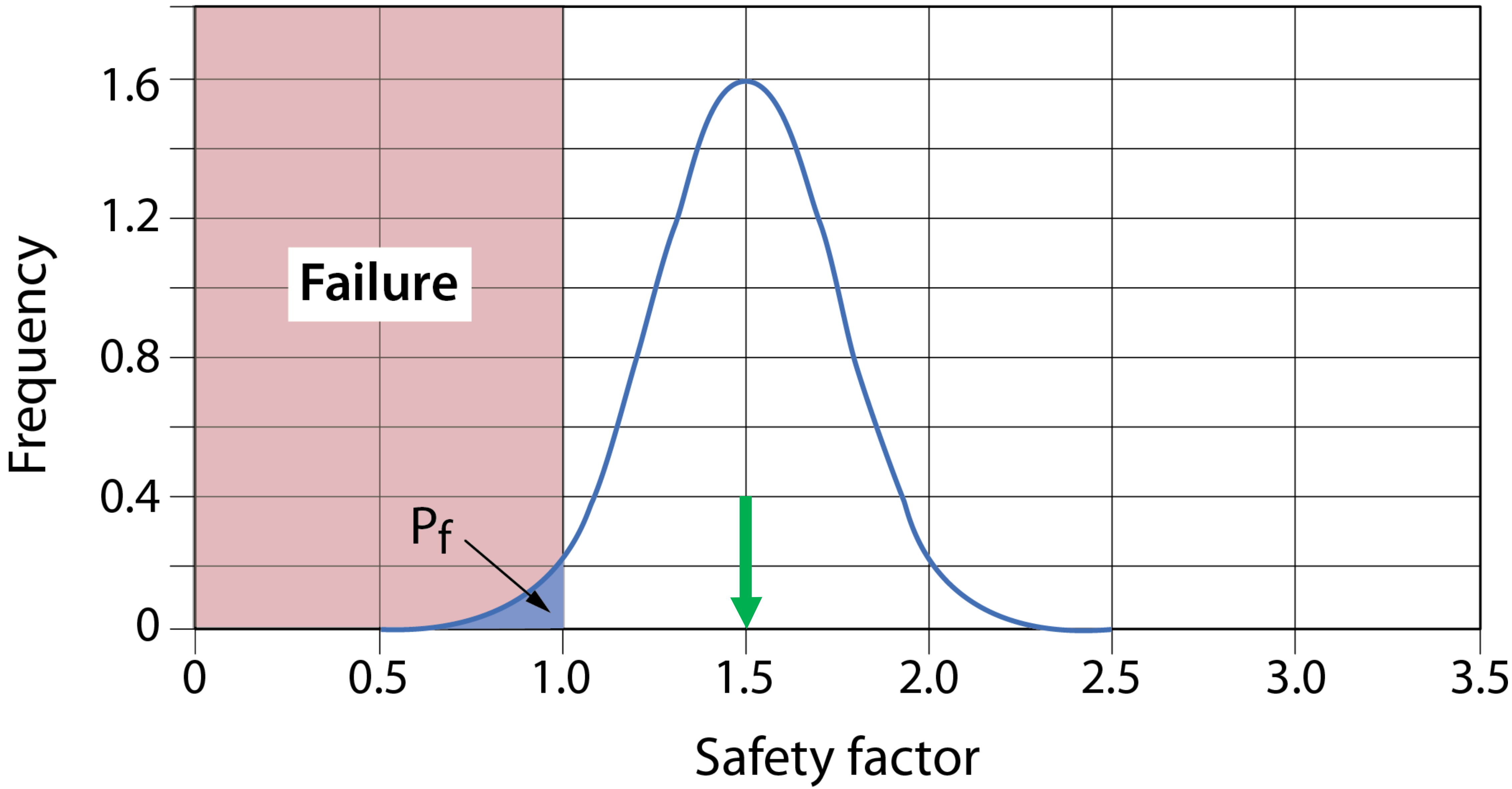
<u>Margin of safety</u>

Resistance – Load

It is the potential overlap of uncertainty distributions of load and resistance that results in a failure probability.



Safety factor of 1.5 and small uncertainty



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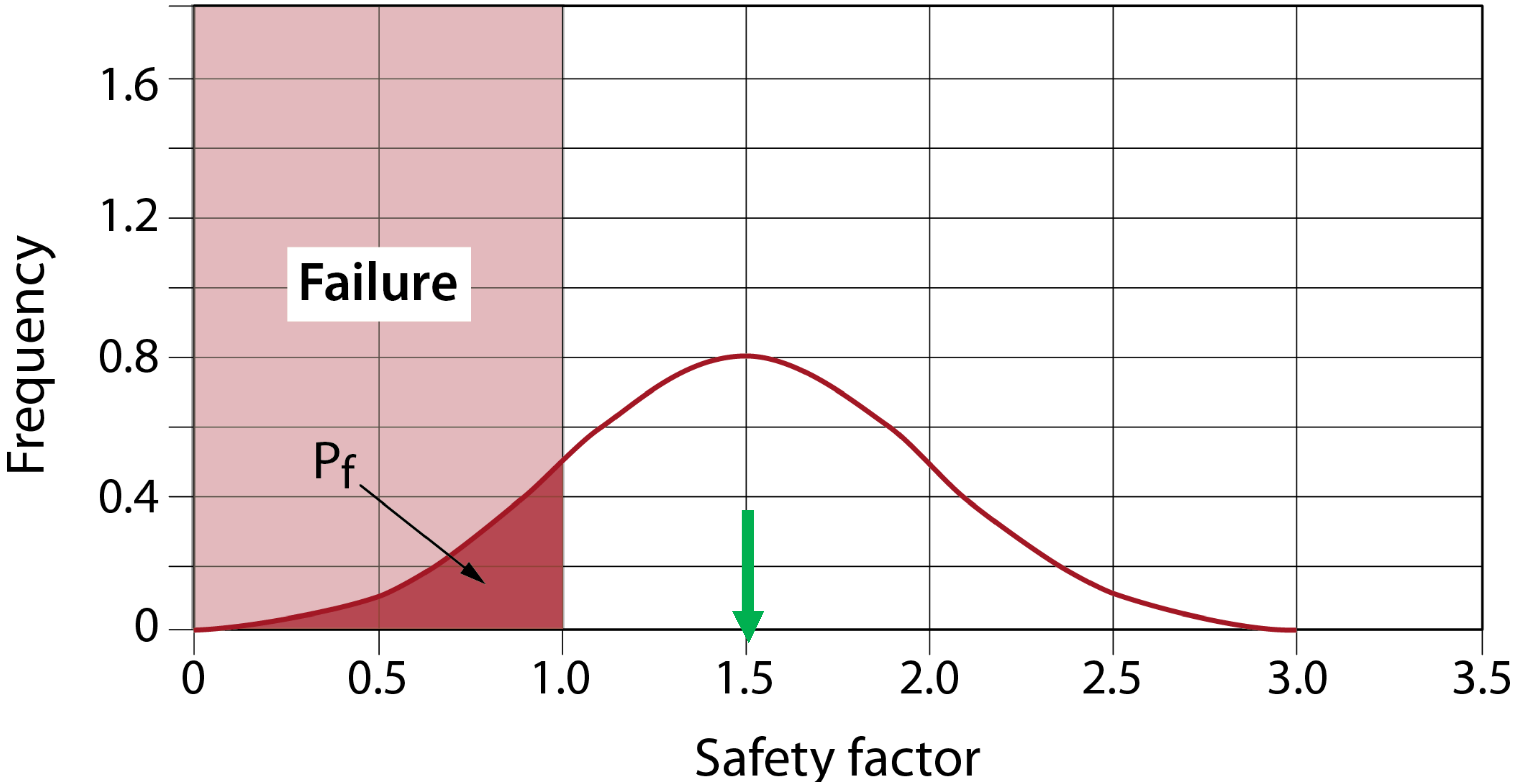
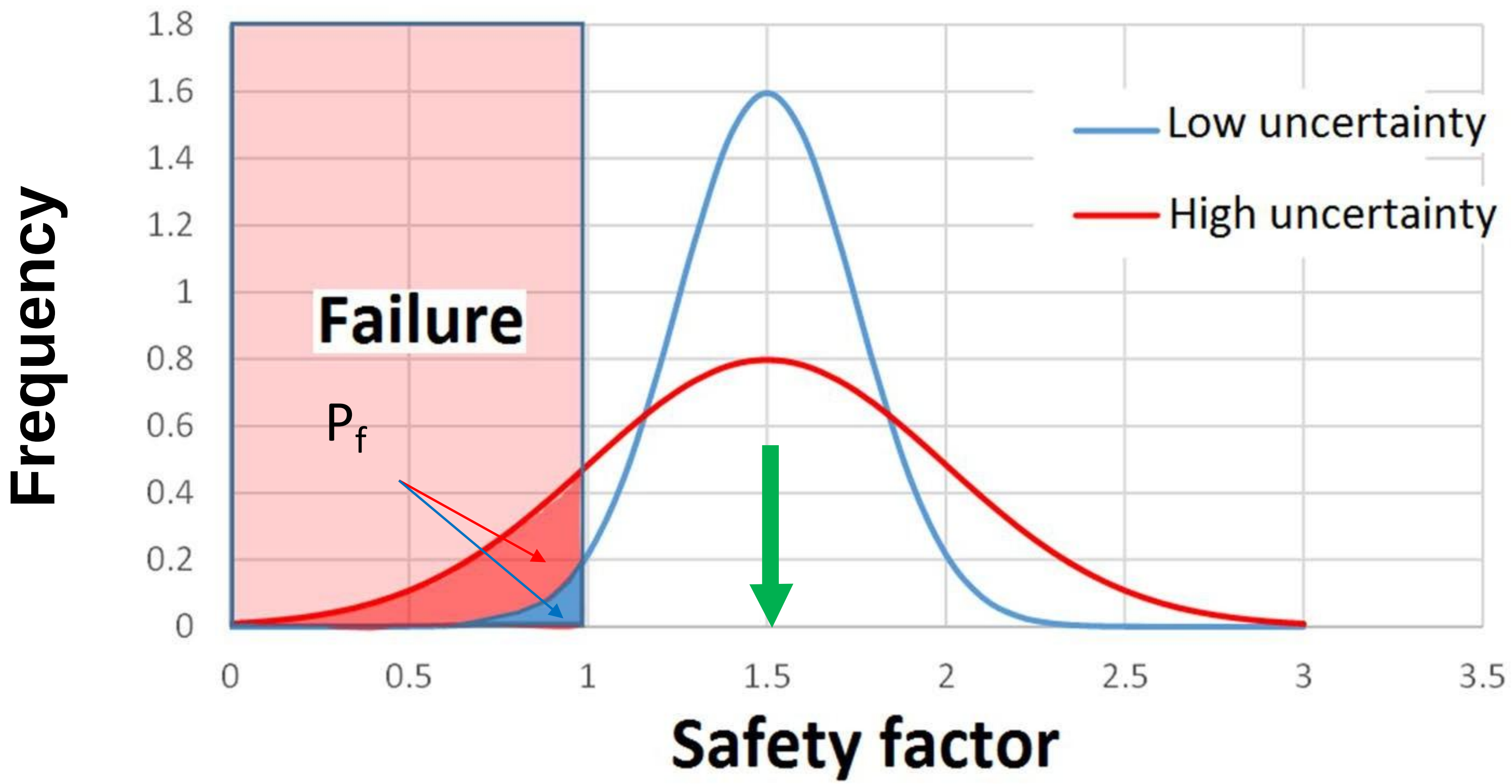


Same safety factor (FS = 1.5), but very different safety margins and failure probabilities



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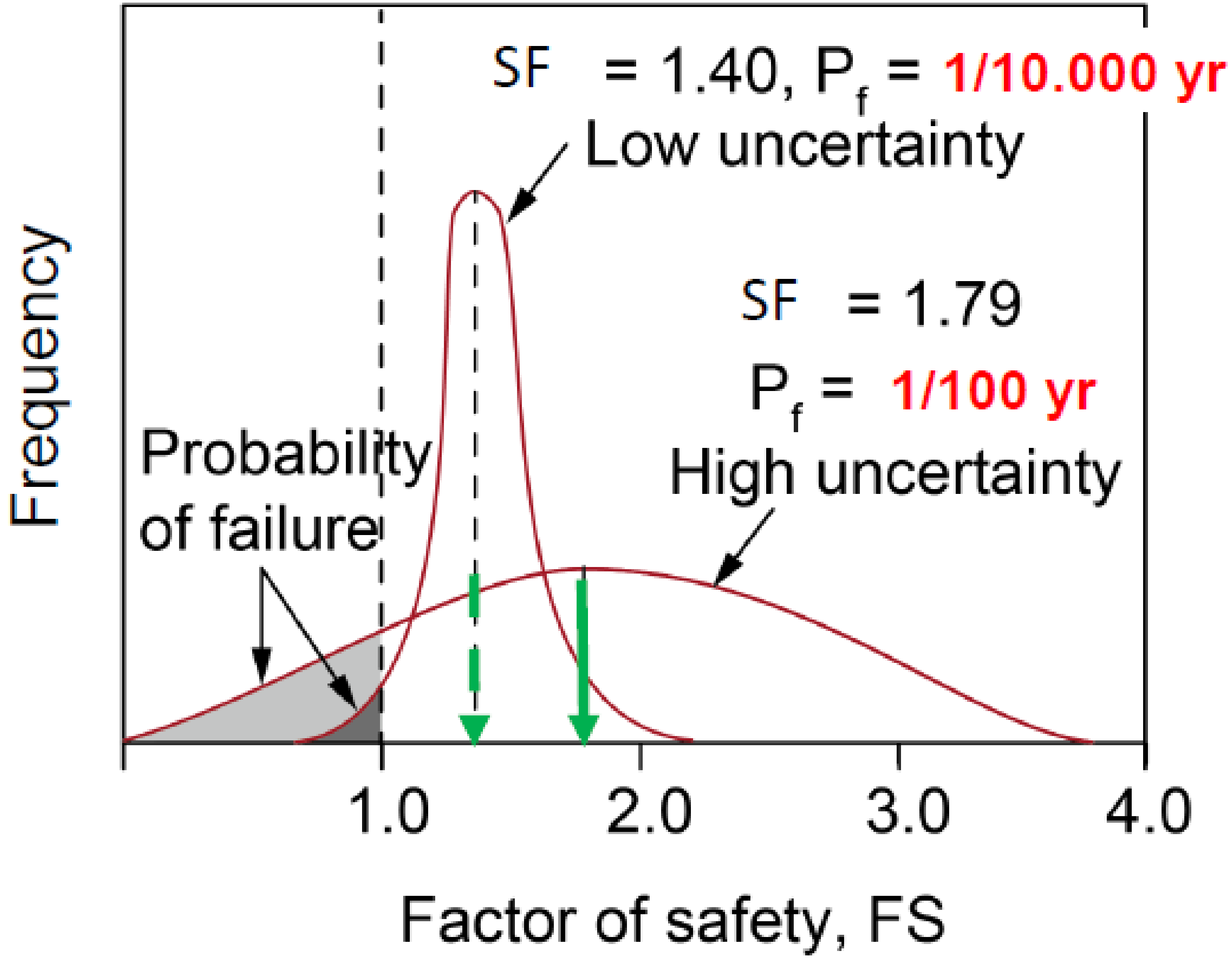
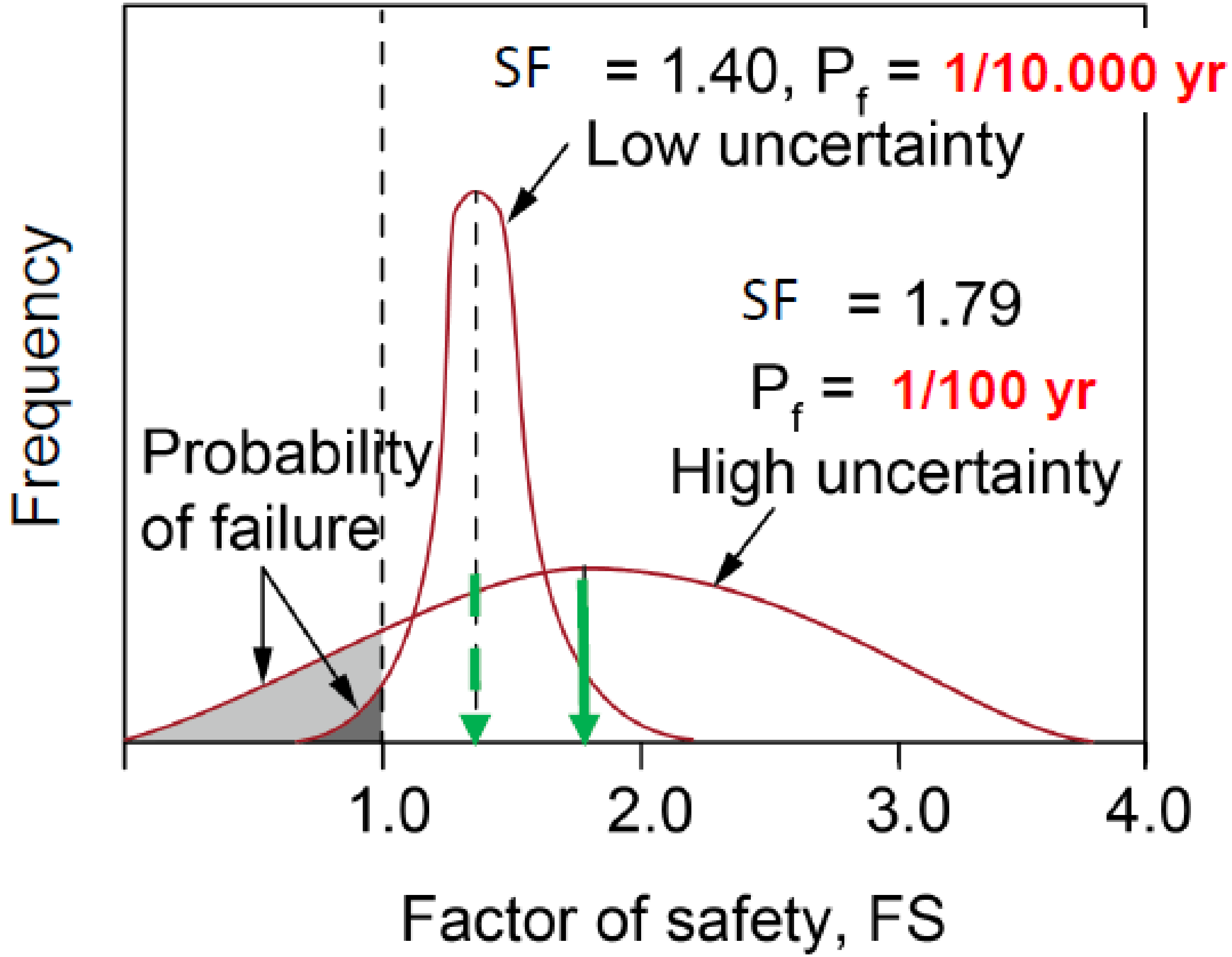
A higher safety factor does not necessarily mean a larger safety margin



A higher safety factor does not necessarily mean a higher safety margin

Failure probability is never zero, and therefore risk is never zero!

This poses a challenge for the communication of risk.

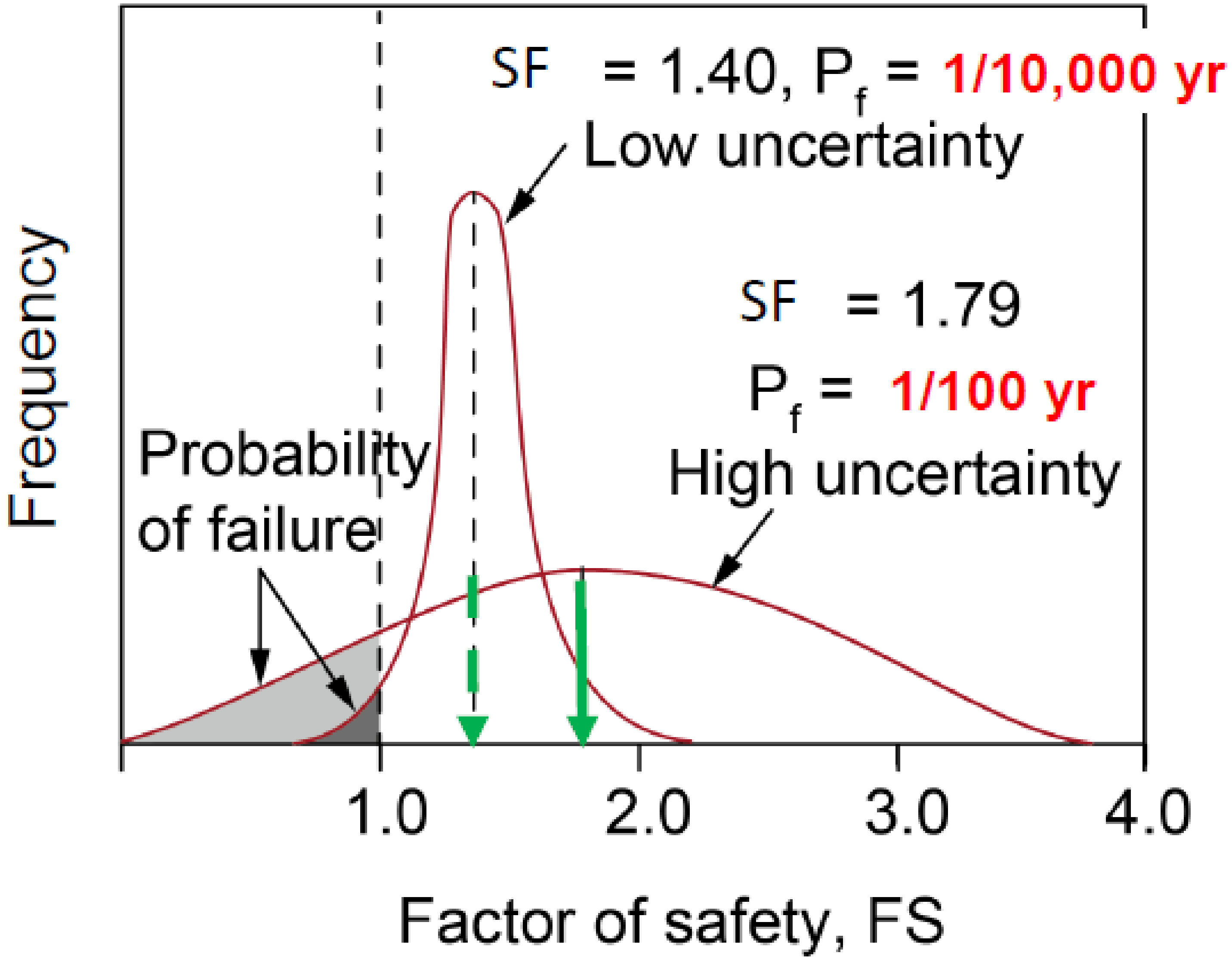


A higher safety factor does not necessarily mean a larger safety margin

More positive wording:

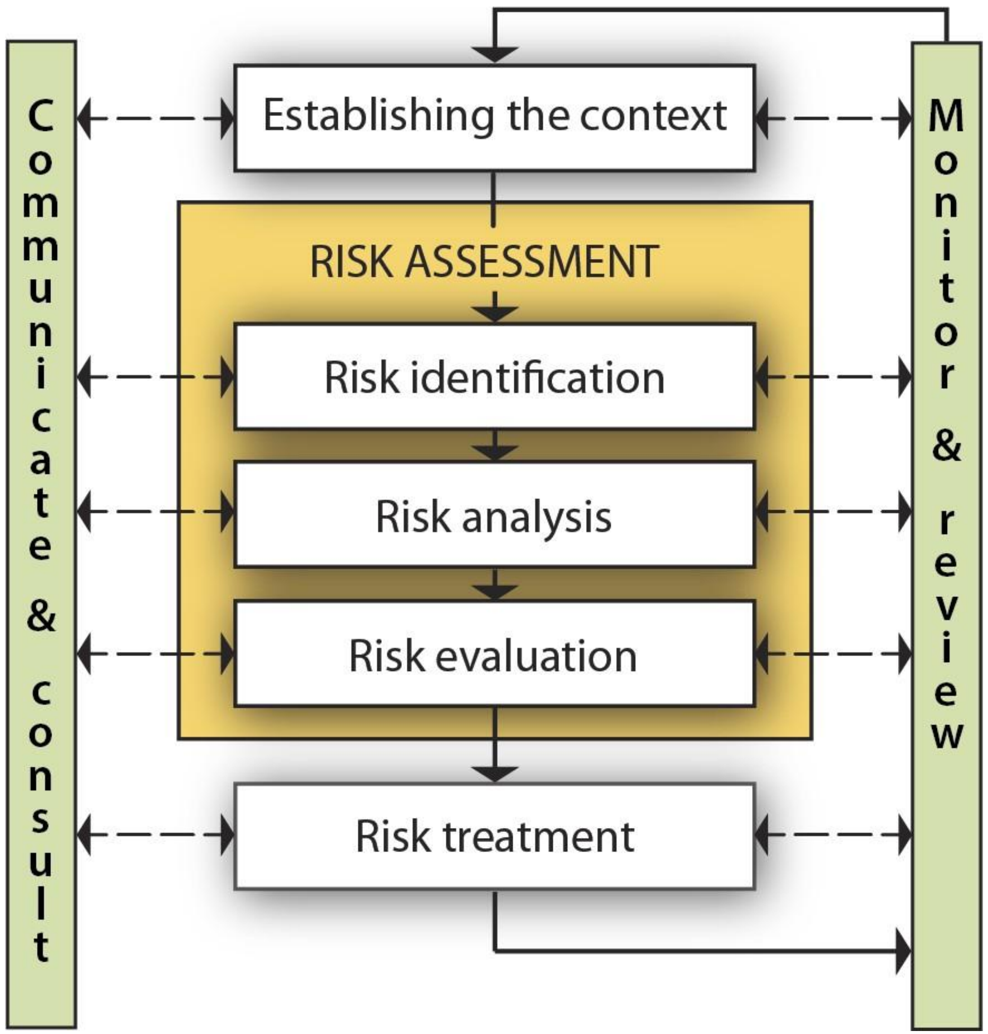
Reliability index, β

$$\beta = \frac{SF_{mean} - 1}{SD_{mean}}$$



__Reliability:__
"fiabilité" in French,
"confiança" in Portuguese

ISO's Definition of risk
"Risk is the effect of uncertainties on objectives"



ISO 2015: 2394
«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", "risk-informed decisions".

How to describe risk?

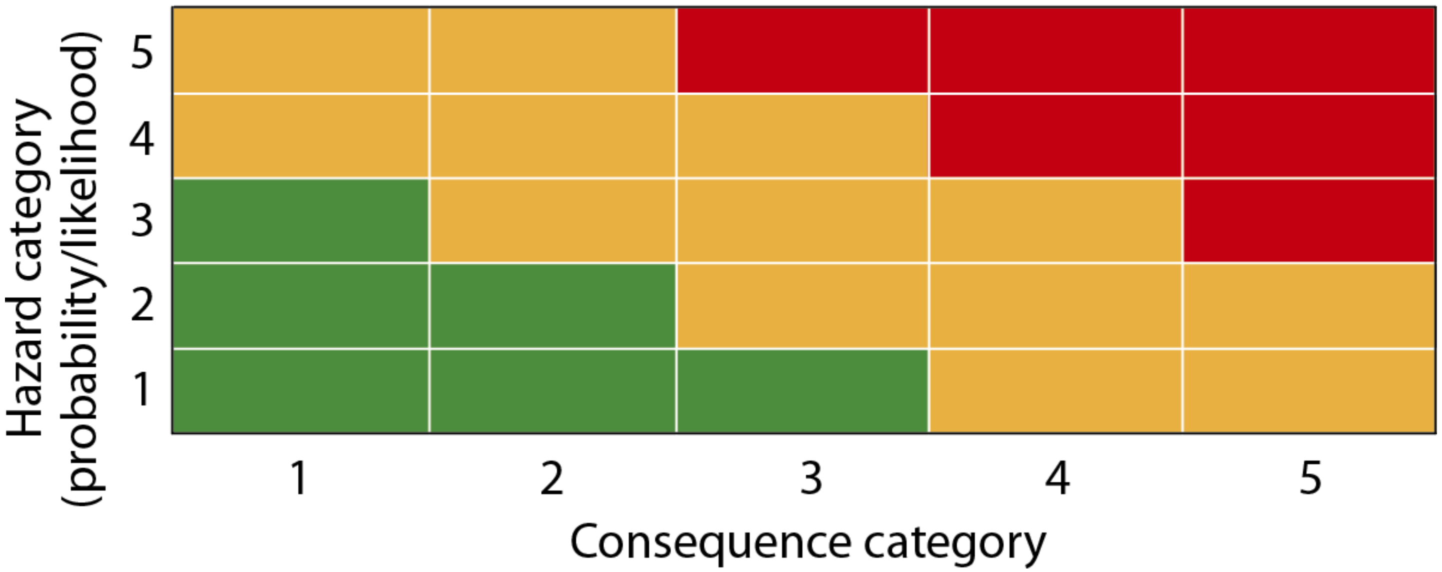
Qualitative risk matrix

- Low risk in green
- Medium risk in orange
- High risk in red

Division among

low, medium and high risk

depends on the problem at hand.

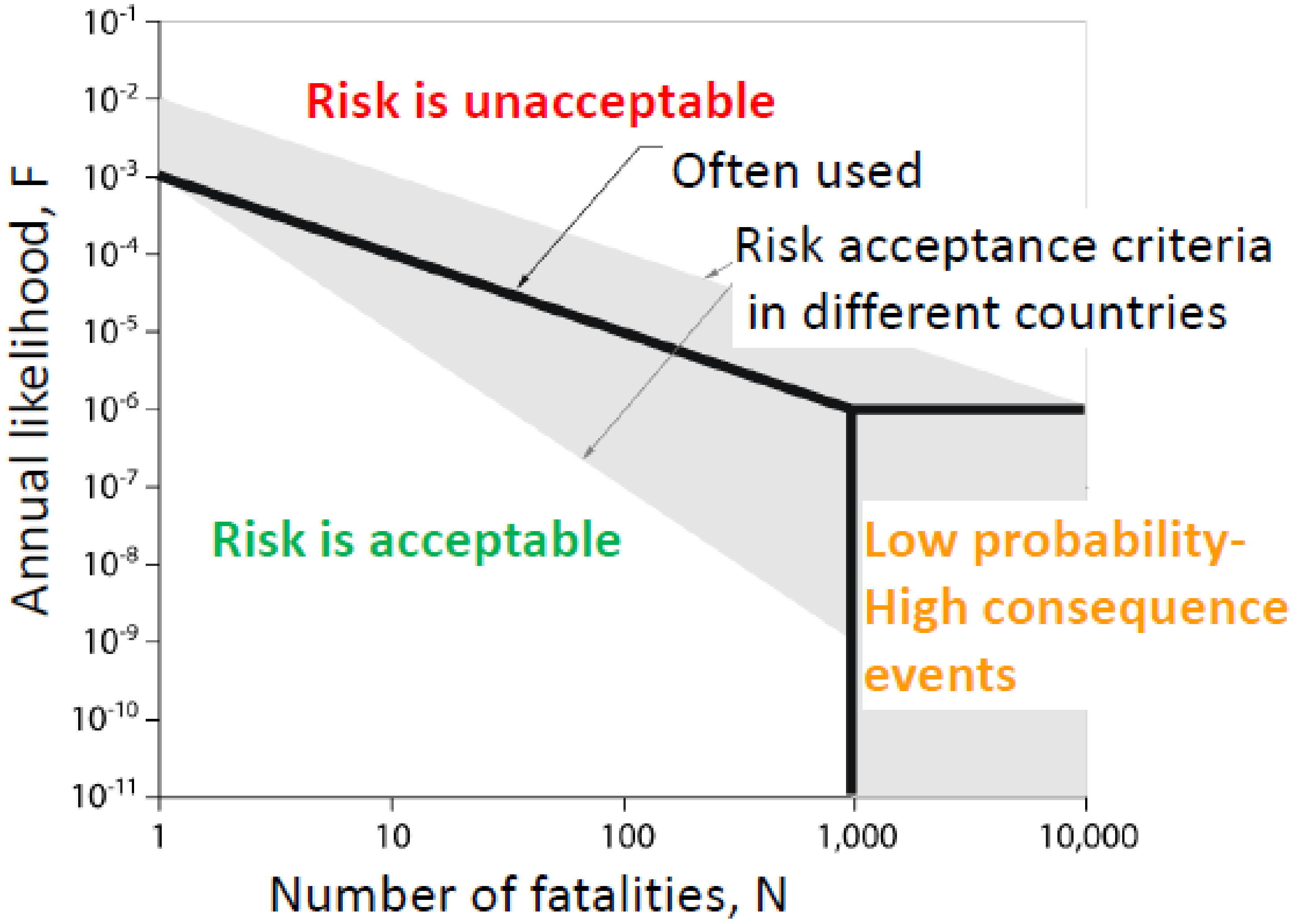


How to describe risk?

<u>F-N diagram</u>

National guidelines published so far (mainly for dams and dikes and man-made slopes).

Quantitative values can be compared to other dams, other facilities in terms of likelihood of occurrence and consequences.



How to describe risk from the results of probabilistic analyses?

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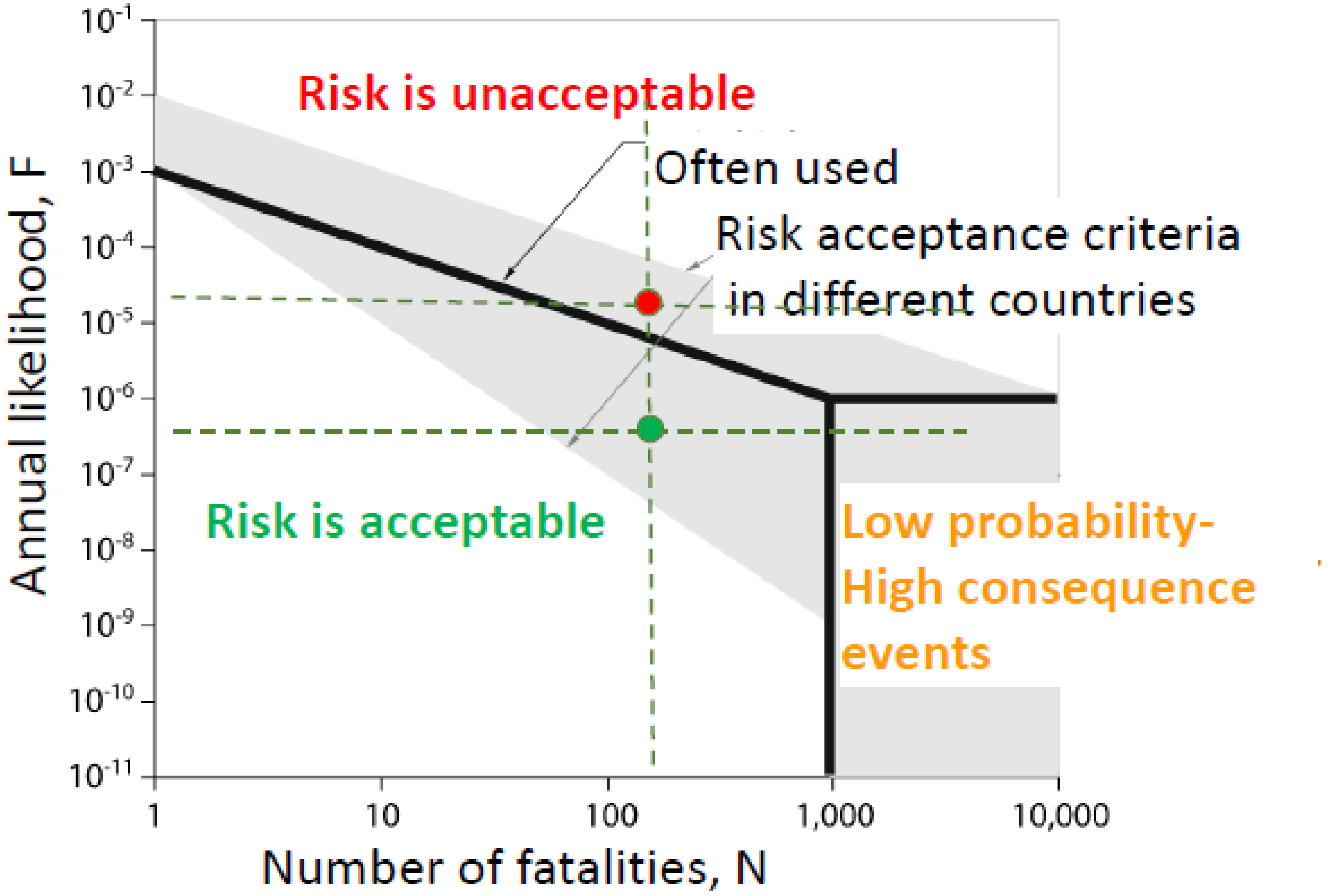

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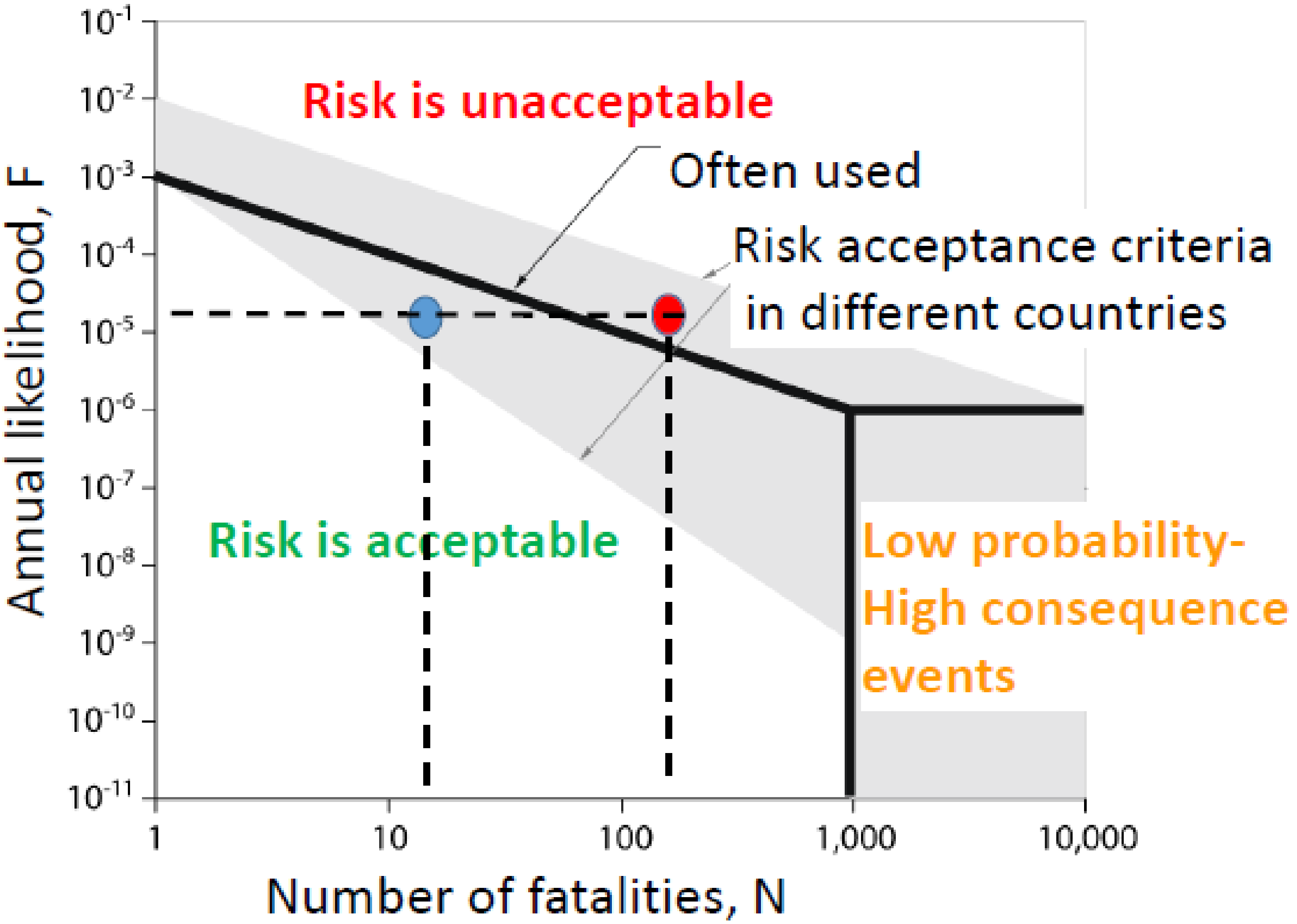
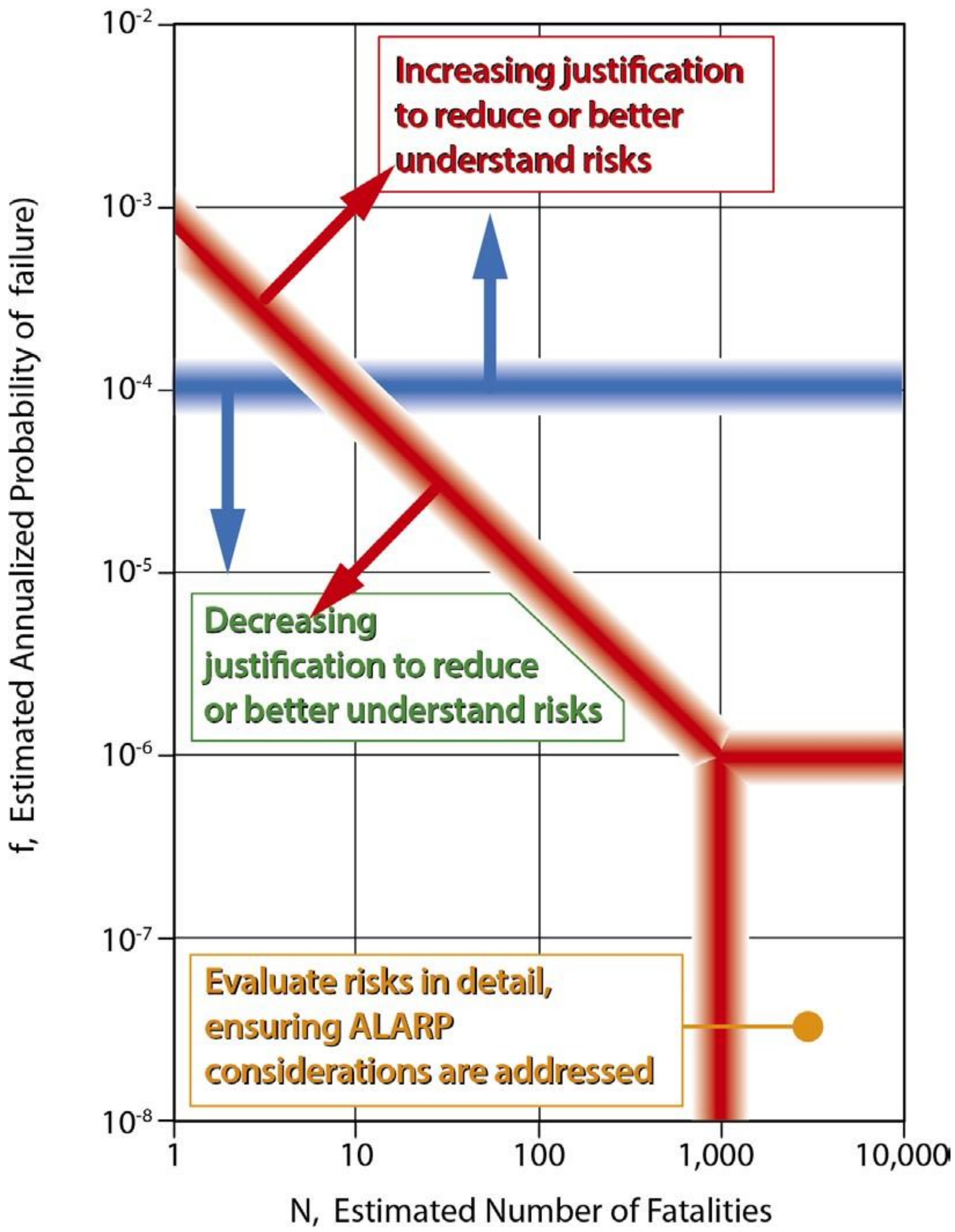


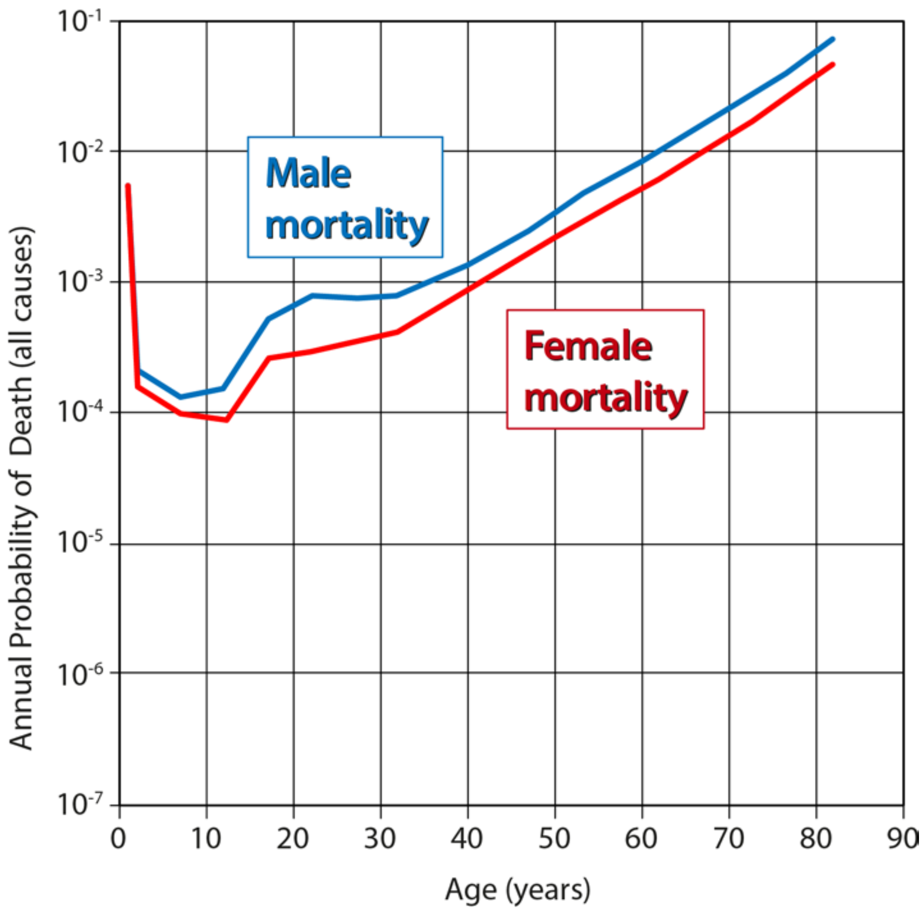
The boundaries between the acceptable and unacceptable zones are gradual.

Guideline for dams under the responsibility of USACE* (2115) and FERC* (2015)

* *US Army Corps of Engineers*
* *Federal Energy Regulatory Commission*



The risk is never zero, but neither is the risk of living



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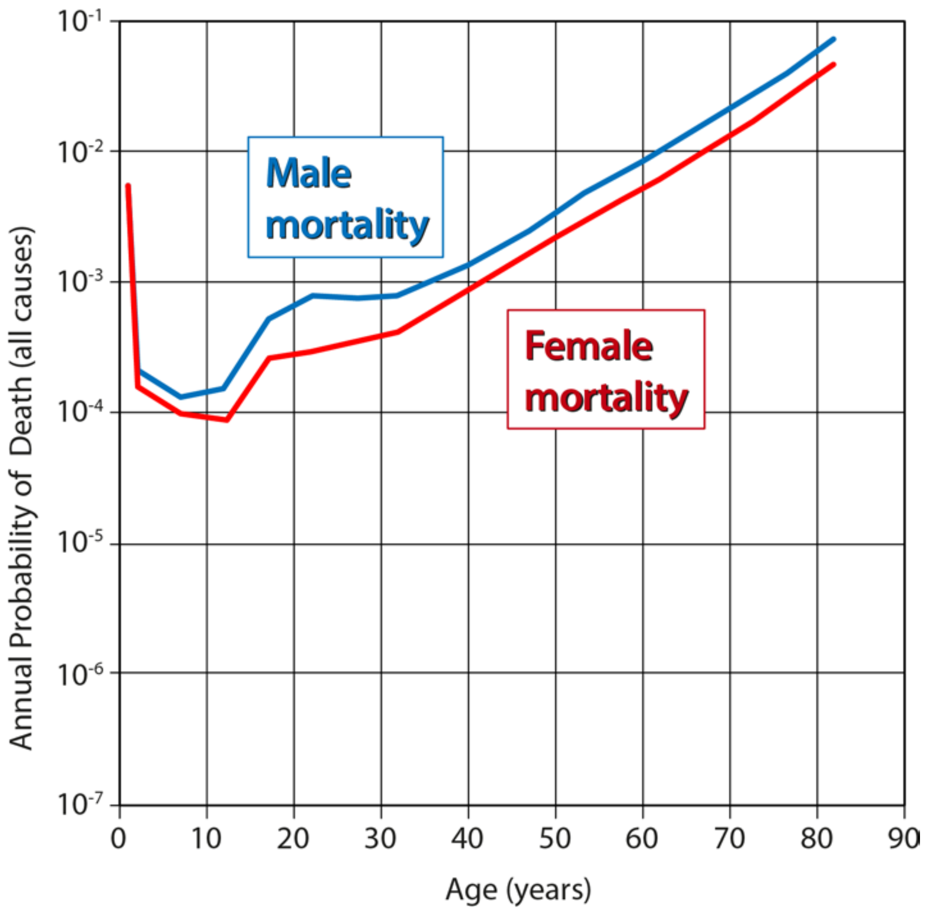

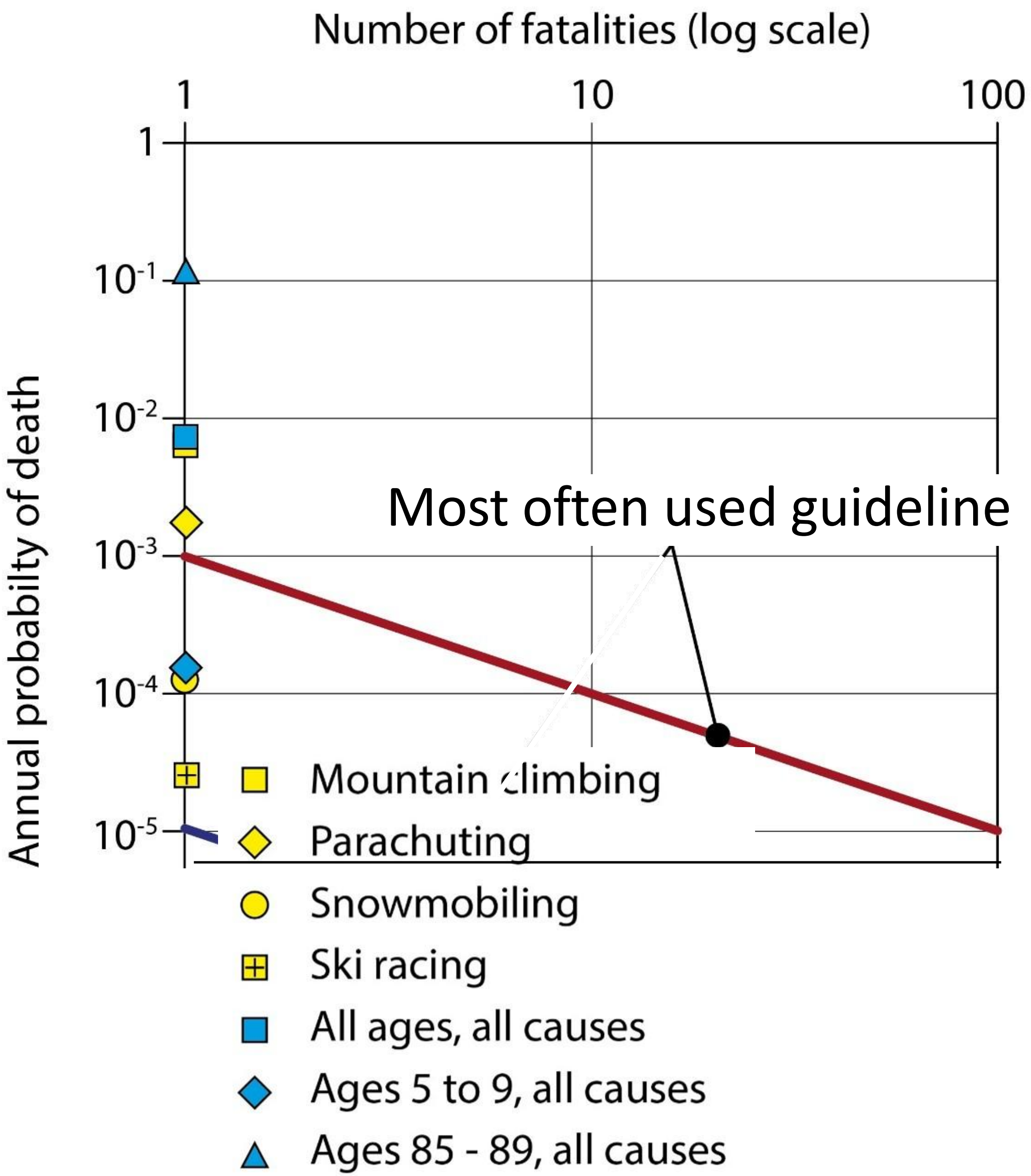

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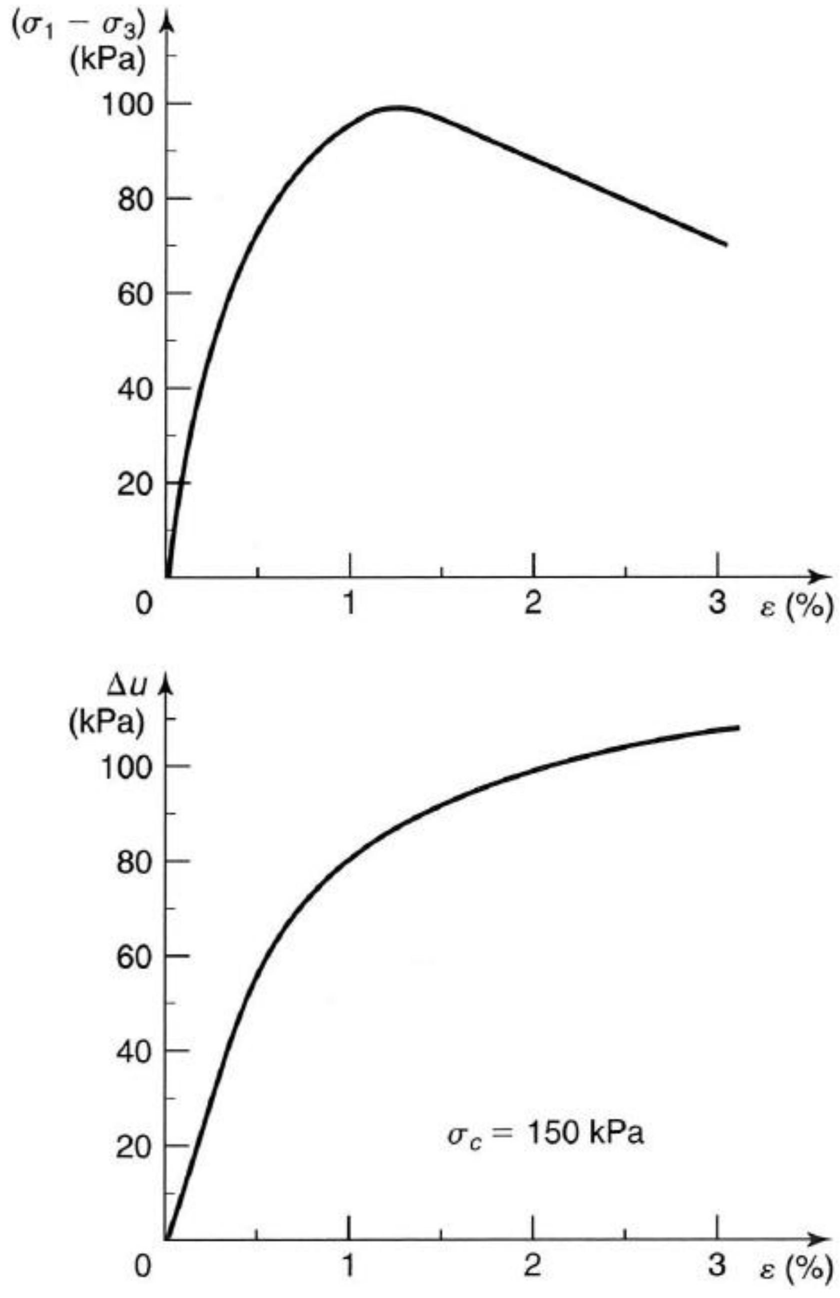
Stress-strain behaviour of tailings



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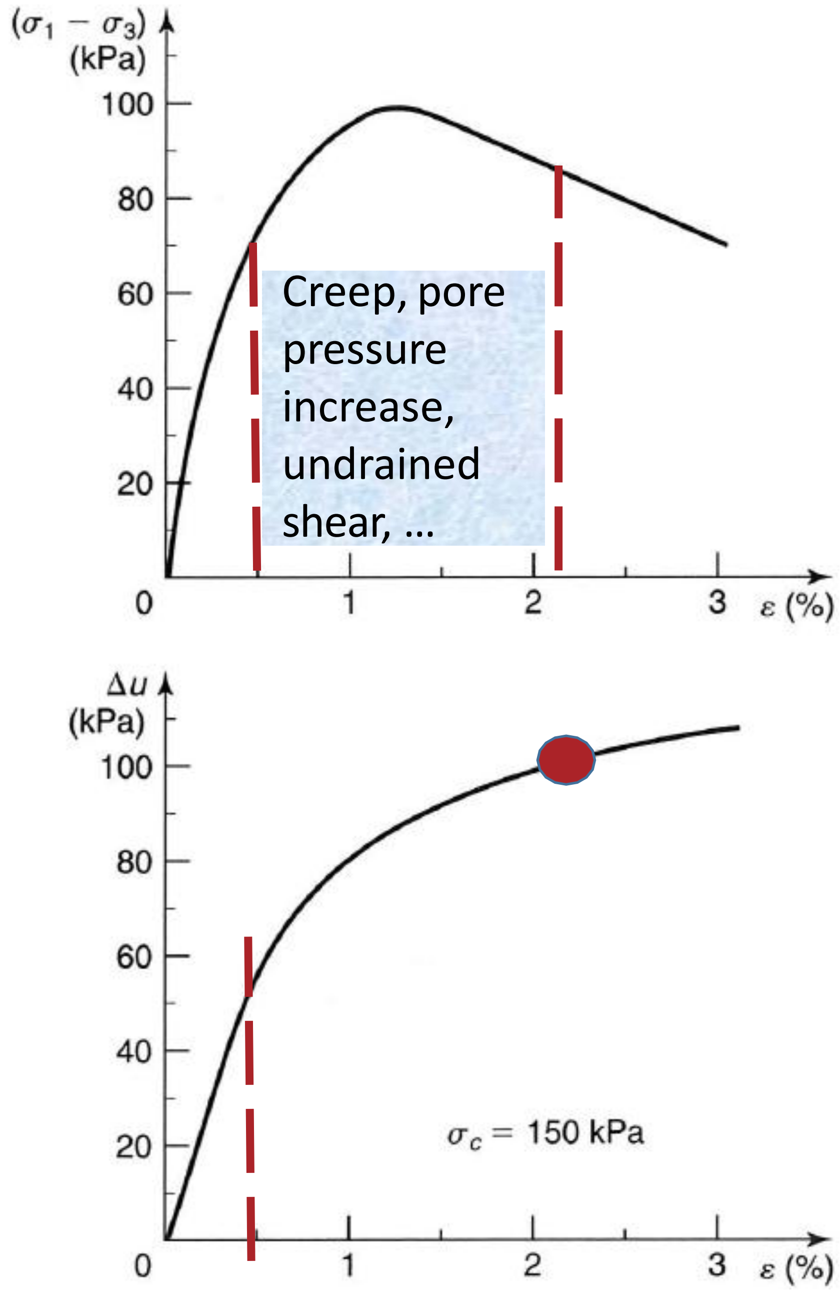
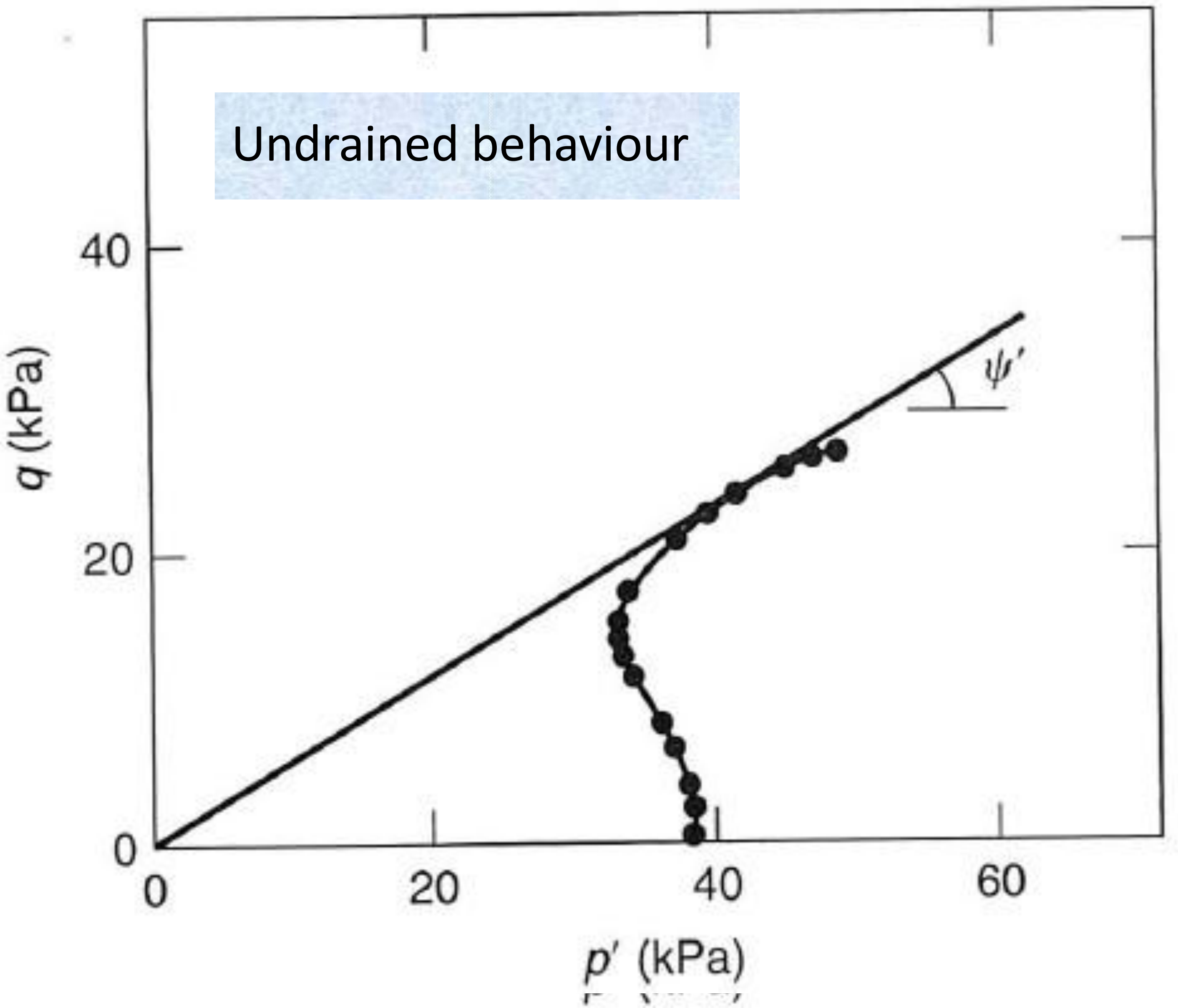


Dilatant vs contractant behaviour of tailings

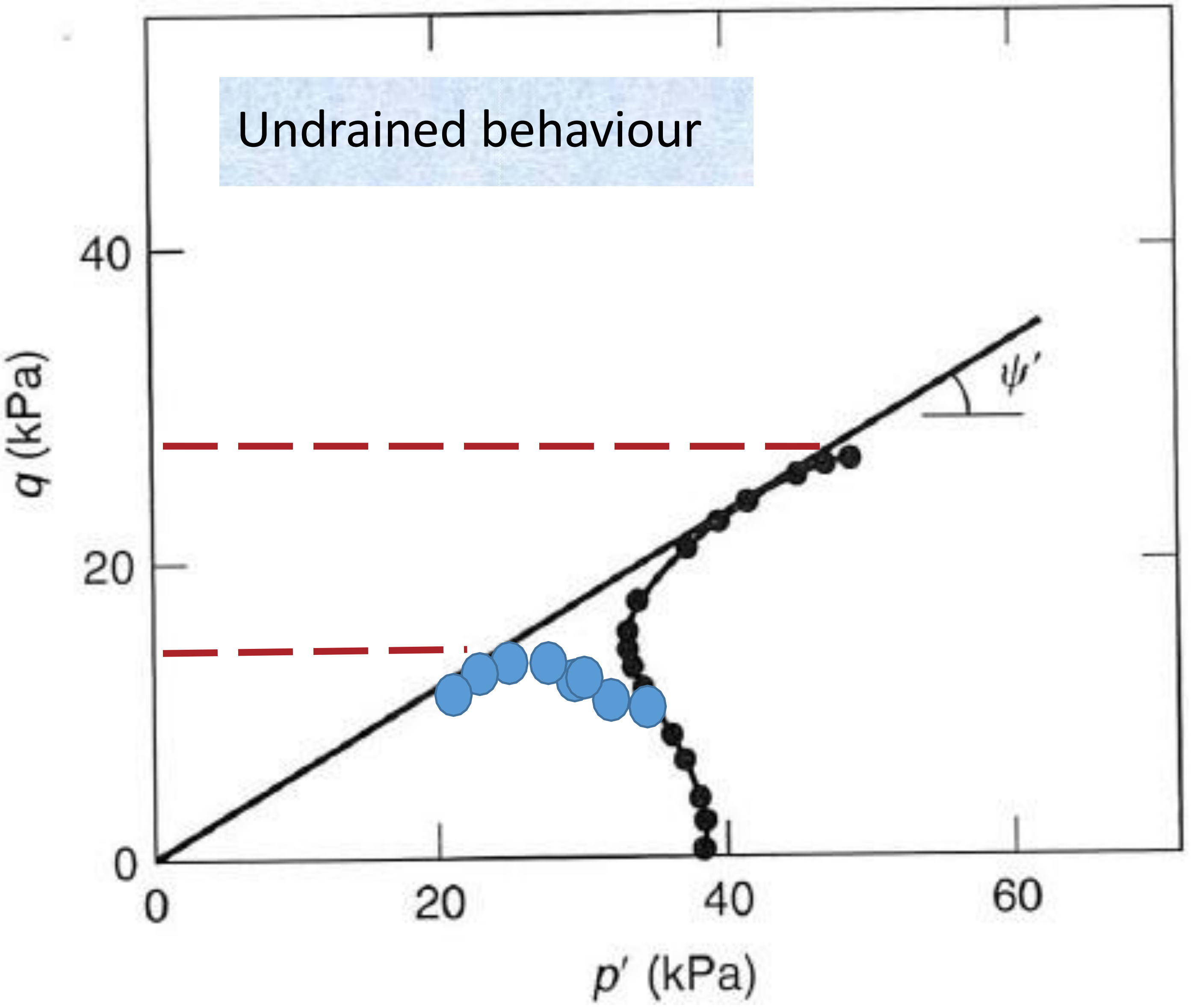


Dilatant vs contractant behaviour of tailings

Very different

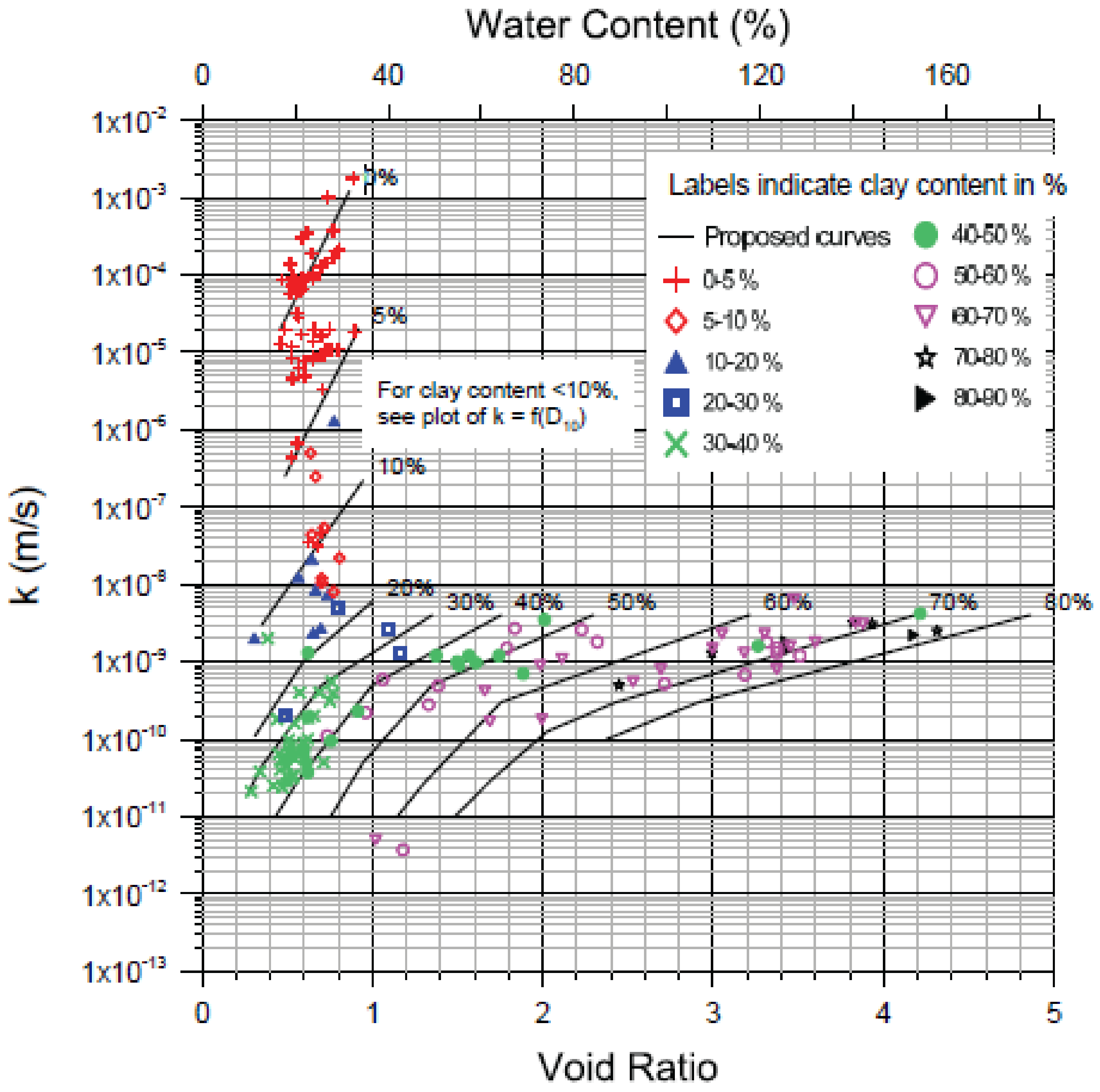
shear strength values

Then some people consider only the drained behaviour (no pore water pressures),,,



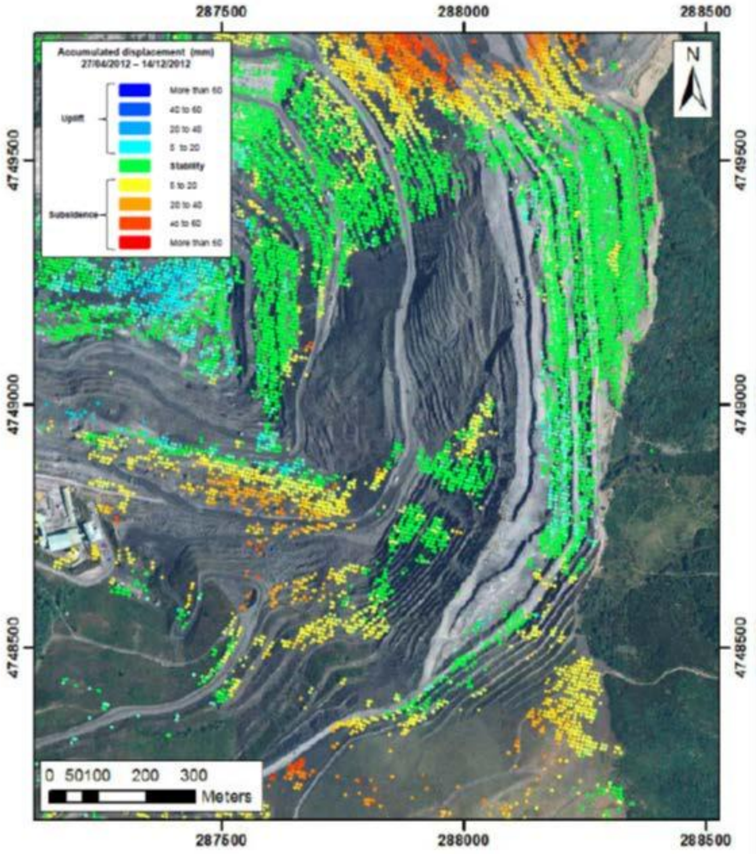
We are gradually reducing the uncertainties with evaluated experience

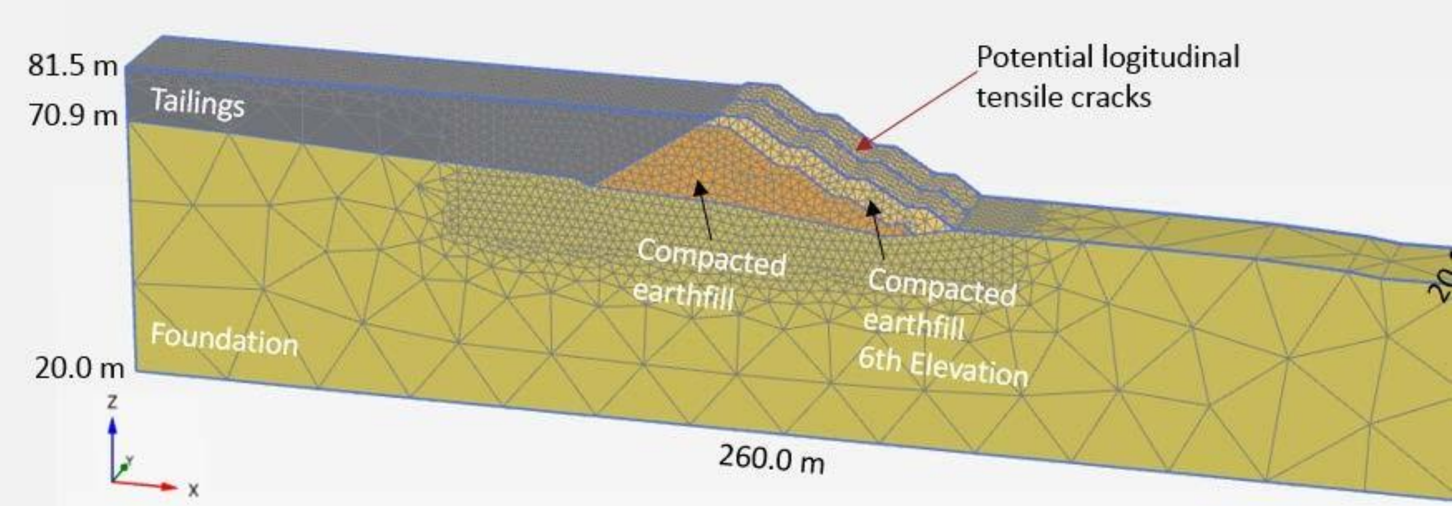
Permeability measurements on 1000's samples from the North Sea, as a function of fines contents and void ratio.



For tailings materials, we need to

- Develop an improved understanding of the behaviour, and the geotechnical and geochemical parameters.
- Develop methods to analyse all dam failure modes (liquefaction, strain-softening and runout, including contaminant transport).
- Instrumented performance monitoring to mitigate risk (InSAR, remote sensing, geophysics, intelligent automated system to screen, sort and interpret data and establish trends).
- Use the Peck Observational Method.





Peck's Observational Method

- ✓ Exploration
- ✓ Most probable conditions and most unfavourable conceivable deviations
- ✓ Design based on a "working hypothesis" anticipated under most probable conditions
- ✓ Selection of quantities to be observed
- ✓ Calculation of values under most unfavourable conditions
- ✓ Selection <u>in advance</u> of course of action
- ✓ Measurement
- ✓ Modification of design

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Risk assessment
Tailings dam in Peru

Quantitative assessment of the risk

Recommended a number of risk mitigation measures to bring the risk level below the internationally accepted norms *(NGI report, 2014).*

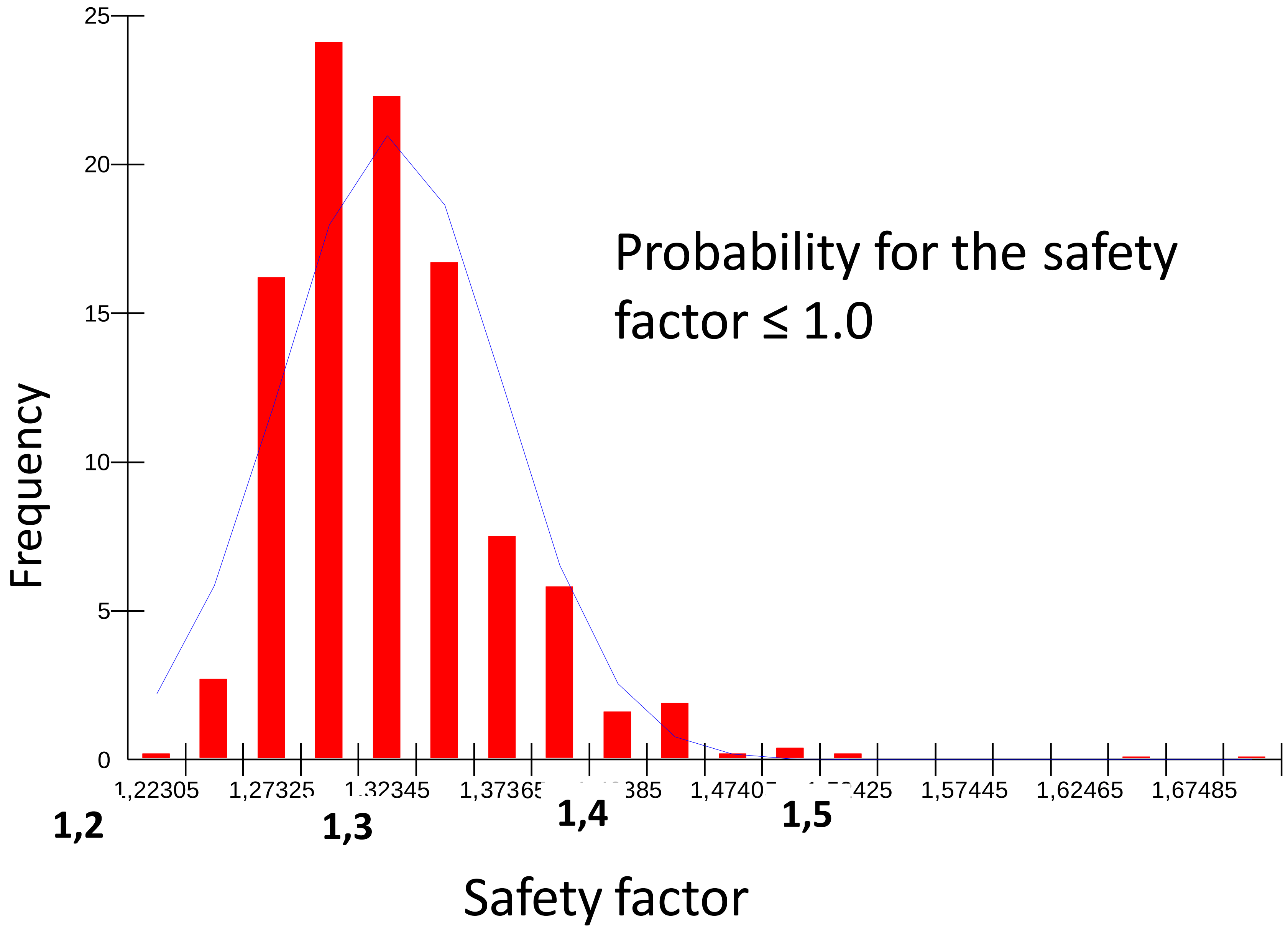
Recommended risk reducing measures (examples):

- Increasing the freeboard to more than 2m.
- Using rockfill, rather than cycloned tailings, for further dam construction.
- Design and construction of erosion protection on the downstream slope if cycloned tailings are used for further dam construction
- Adding an additional spillway to avoid overtopping.

Nyhellervatn
Main dam

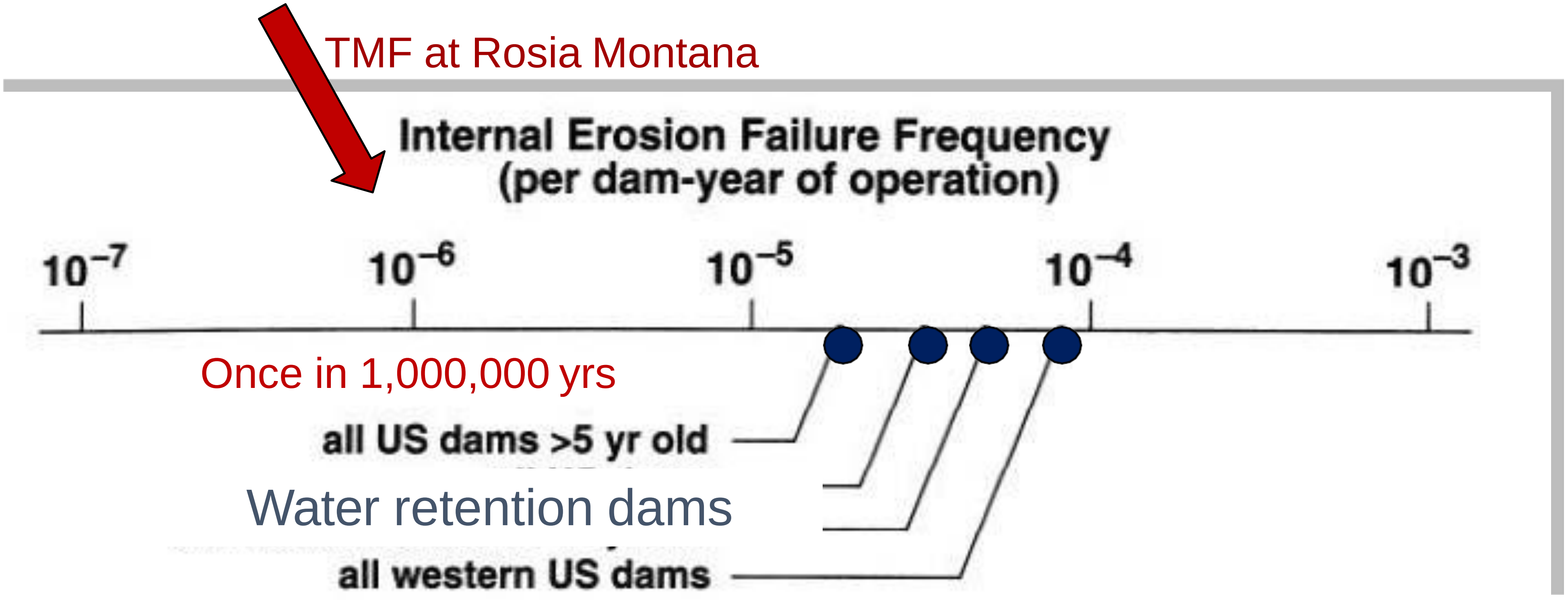
Slope stability

Probability for the safety factor ≤ 1.0



Roşia Montaňa tailings management facility

Compare the risk with other facilities



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Summary

- Failure probability is never 0.
- Factor of safety alone is not enough to give the margin of safety.
- There are uncertainties in the behaviour of tailings materials and how we analyse them.
- We need to quantify and deal with the uncertainties (all aspects, not just “geo”-aspects)
- Mine tailings storage: **“Safety is no accident!”**

Reliability and risk assessments

- Analyse the plausible ways a tailings dam can fail and the consequences.
- Rank dams in a portfolio and help focus monitoring programs and rehabilitation actions on the dams with highest risk.
- Can easily be adjusted over the entire lifetime of a dam, to account for changes (improvement or deterioration).

Probabilistic analyses provide more insight than traditional deterministic approaches alone. They help reduce uncertainty, focus on cost-effectiveness and are an ideal tool for looking at alternatives and help make decisions.

Conclusion

Deterministic

versus

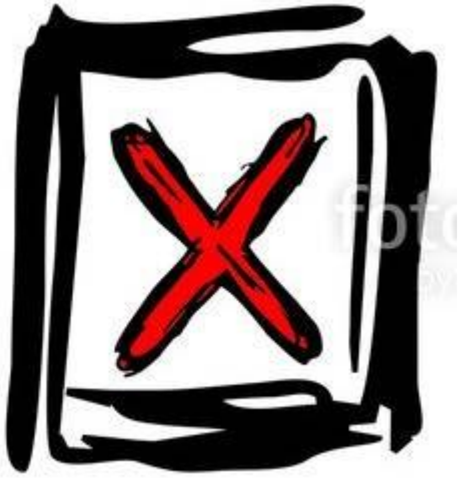
Probabilistic analyses?

Conclusion

Deterministic

versu

Probabilistic a r



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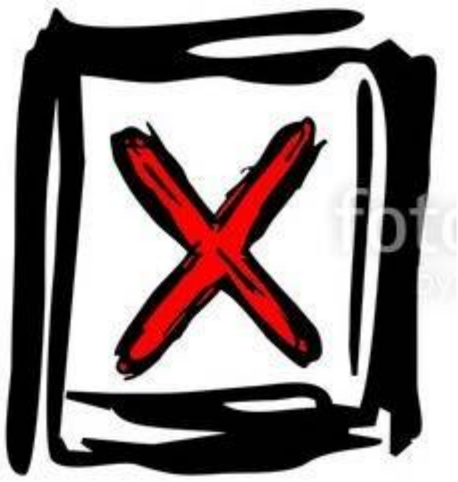

Deterministic

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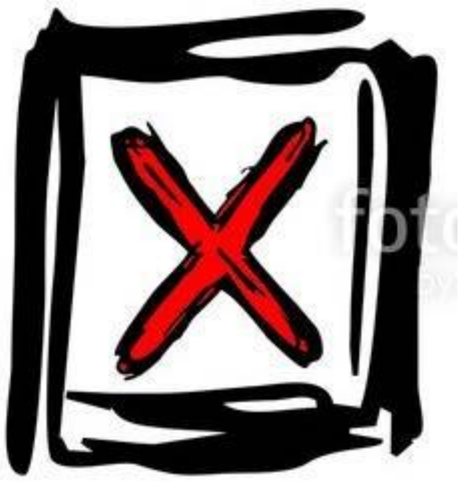

Deterministic

and

Probabilisitic ana

Teton Dam

Deterministic analyses with a fixed safety factor give the impression of “no uncertainty”!

Risk-based analyses include the uncertainties explicitly and their effects on the safety margin. They complete the deterministic analyses.

For robust and improved design and follow-up, we need both!

Teton Dam

How to reduce risk and move forward?

- ✓ We need to learn from our mistakes (good expert reports after recent failures, we reduce uncertainties every day with new findings, …)
- ✓ Important to document the uncertainties and the margin of safety of a tailings dam.
- ✓ Geotechnical risk: It is not only the ground. It is also how we work together in a team.
- ✓ Mining industry has maybe not changed at the same pace as the other engineering sciences that help evaluate the risk (e.g. offshore industry)?
- ✓ Need to develop communication of risk with the people at risk.

Disasters are seen as fast events…









… but disasters are built up slowly

Because

- hazards and vulnerability change with time, and
- we are not adequately prepared.

Perspectives

The cultural shift is needed NOW

Hazard	→	Consequence
Response	→	Preparedness & risk reduction
Reactive	→	Proactive
Science-driven	→	Multi-disciplinary
Response management	→	Risk management
Single agencies	→	Everyone's business
Planning for communities	→	Planning with communities

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