THE 2018 UBC GEOENG DISTINGUISHED LECTURE

Landslide Hazard and Risk

Protecting society from landslide risk

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Outline

- Concepts of reliability-based design
- Case studies
  - Railways: setting priorities on where to mitigate
  - Downstream slope of a rockfill embankment dam
  - Factor of safety for strain-softening material
  - Landslide runout, sensitive material
  - Underwater slope stability
  - Snow avalanches
- Target risk levels
  - Stress testing multi-hazards in Hong Kong
- Conclusions

Design approaches

- “Working stress" design (WSD) approach based on an overall factor of safety has been used for a long time.

Level I

- Modern design codes are based on the LRFD approach (Load and Resistance Factor Design) in North America and the characteristic values and “partial safety factors” approach in Europe.

Level II

- Reliability-based design (RBD) using a target annual failure probability or target reliability index.
  - More rigorous, more “complete”
  - Accounts for the uncertainty in the analysis parameters and their correlation(s) explicitly.
  - Will give you a more robust design.

Level III

Concepts of Reliability-Based Design (RBD)

- All predictions are subject to uncertainties.
- Because of uncertainties, it is not feasible (practically or economically) to assure absolute safety or performance of engineered systems.
- Realistically, safety (or serviceability) can be assured only in terms of the probability that the available strength (resistance, capacity) will be adequate to withstand the lifetime maximum load.

Robustness:

Ability to accommodate what is unforeseen

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

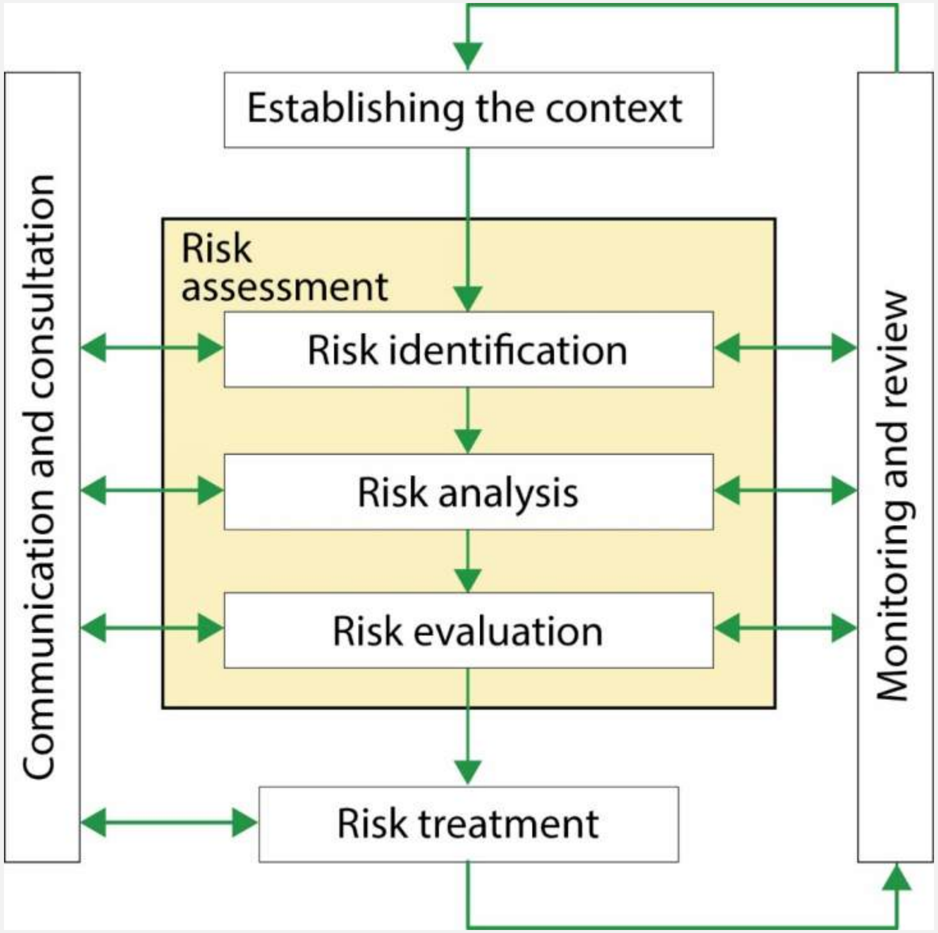
U = Utility (or value) of element(s) at risk

Munkedal Sweden 2006
Unplanned fill placed on top of soft clay

Terminology – What is “Risk”?

Risk term	**Typical denomination**
Hazard	Annual probability, 1/yr Done with a probabilistic analysis
Vulnerability	Dimensionless, between 0 and 1
Consequence	Fatalities Monetary values Contamination
Risk	Number of fatalities/year Monetary value/year Contamination/year

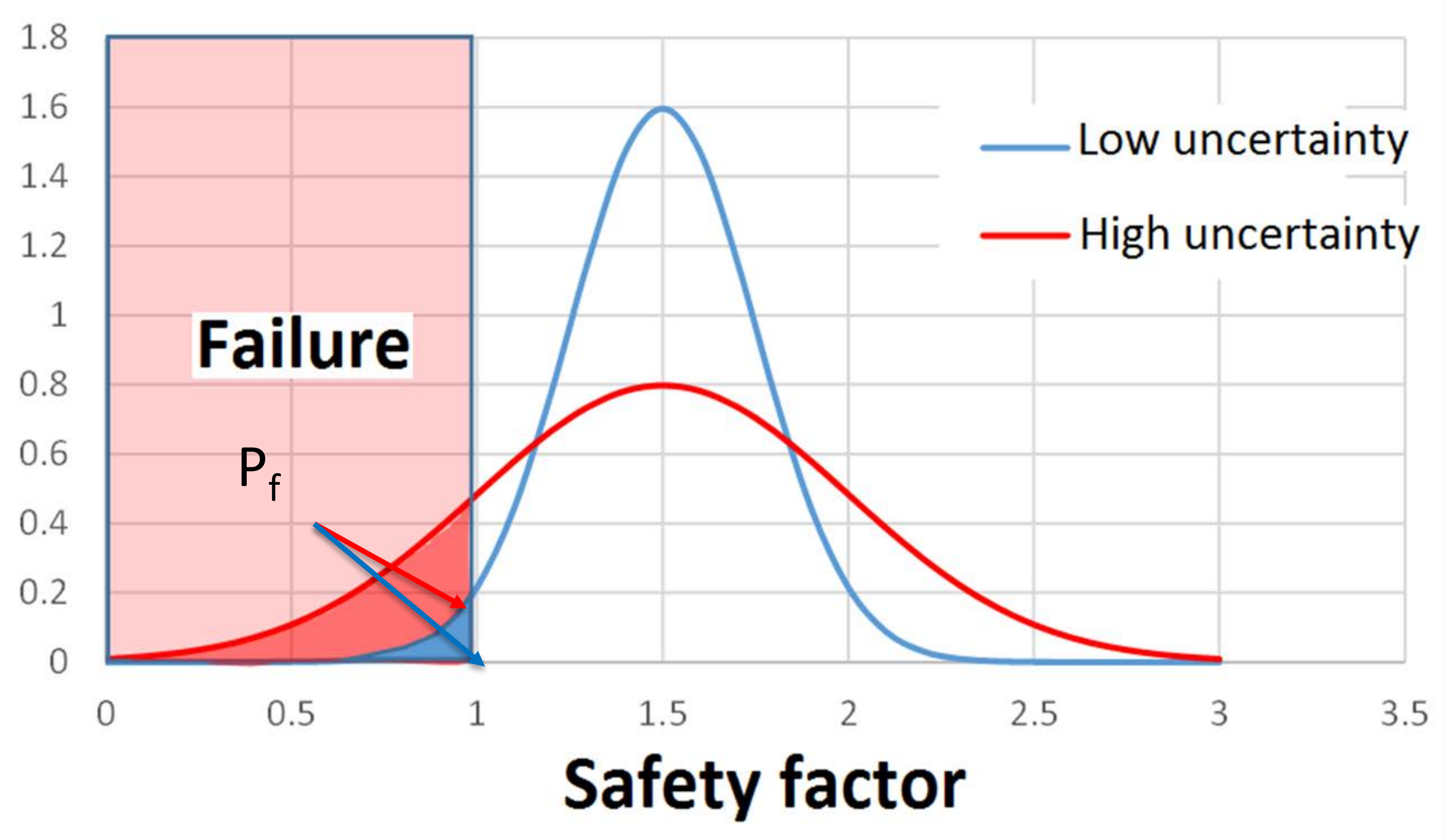
Risk assessment and management [ISO-3100:2009]



"ISO Guideline for Risk Management" (ISO 73:2009) har følgende definisjon for risiko:

"Risk is the effect of uncertainty on objectives."

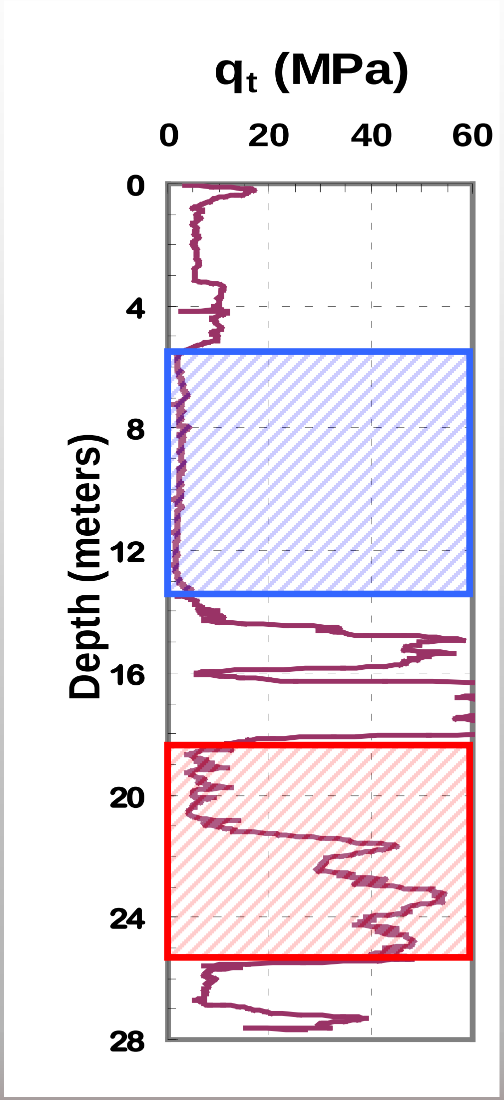
Factor of safety and probability of failure



We need to be aware that P_f is never zero!

Physical homogeneity of soil units

Statistical analyses only on soil units which are physically homogeneous.



OK !

NO !

K_0 from Brooker & Ireland (1965)

- Samples were dried out, sieved and reconstituted from a slurry
- Very high stresses (1-15 MPa)
- I_p calculated rfrm ϕ' !!
- I_P = 0 -> for sand!

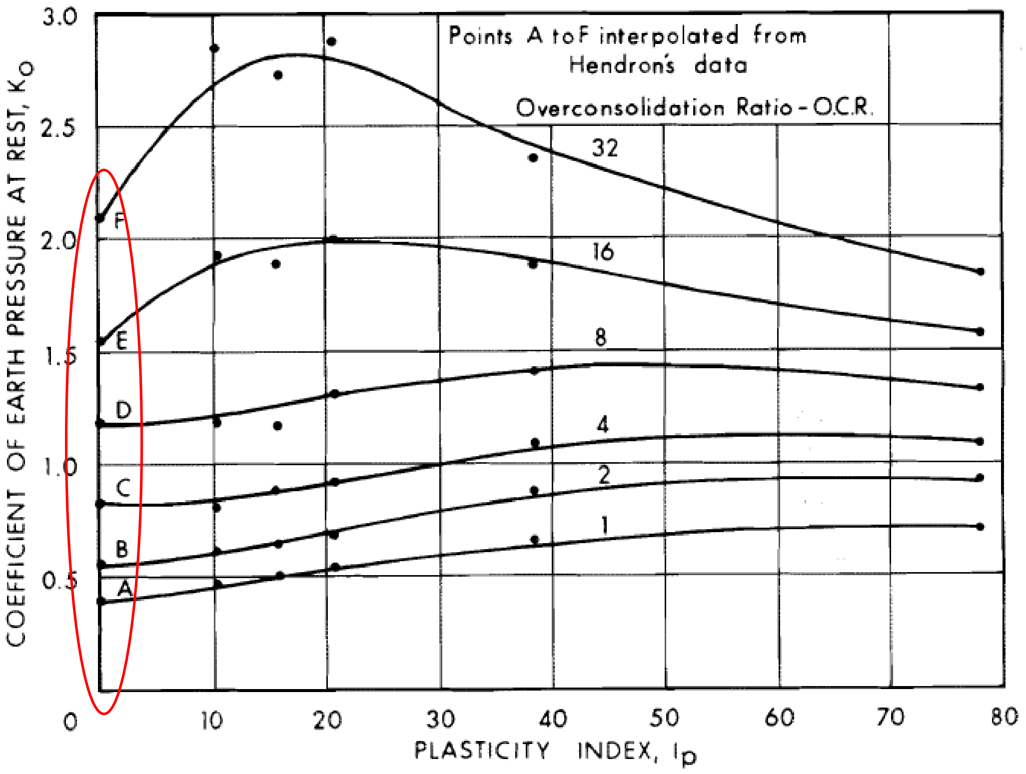
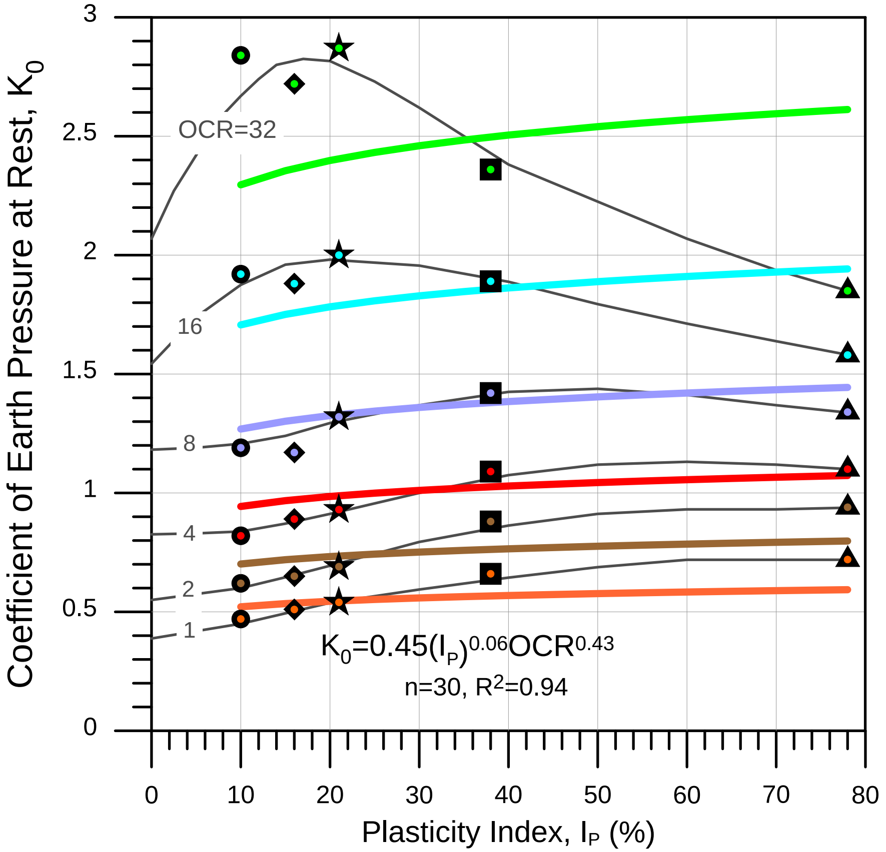


FIGURE 11. Relationship between K_0, I_p, and OCR

Multivariable regression analysis without I_p=0 (sand)



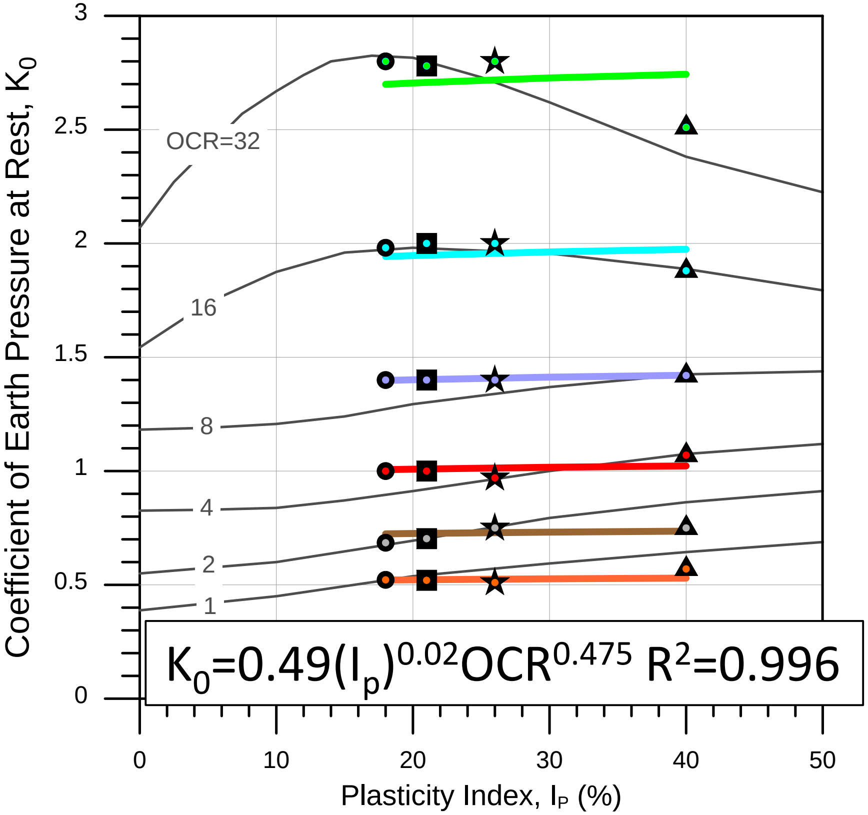
$$K_0=0.45(I_p)^{0.06}OCR^{0.43}$$

$$R^2=0.94$$

Regression analysis - Norwegian clays

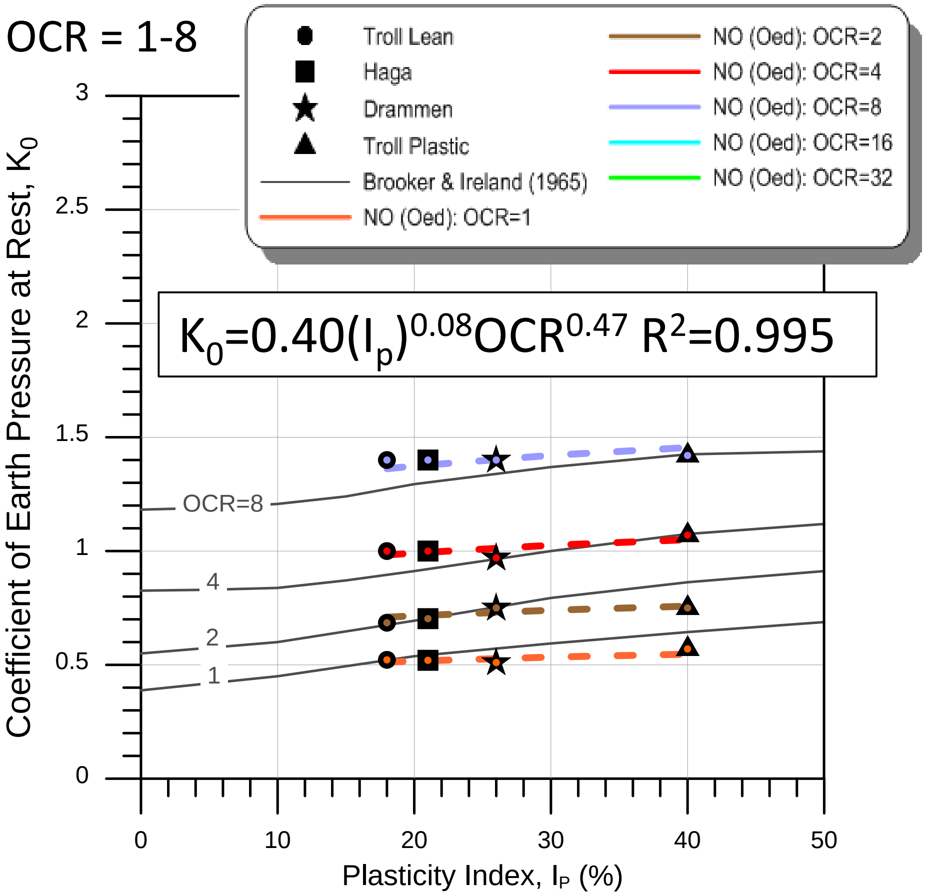
(K_0-Oedometer)

OCR = 1-32



$K_0=0.49(I_p)^{0.02}OCR^{0.475}$ $R^2=0.996$

OCR = 1-8



$K_0=0.40(I_p)^{0.08}OCR^{0.47}$ $R^2=0.995$

Multivariate statistical analysis (Liu *et al* 2015)

Parameter set (s)	**Mean s_u**	**COV of s_u**
LI	$LI^{0.256} \times 1.922$	**0.485**
OCR	$OCR^{0.887} \times 0.338$	**0.253**
LI, OCR	$LI^{-0.004} \times OCR^{0.888} \times 0.338$	**0.253**
S_t, OCR	$S_t^{0.179} \times OCR^{0.238} \times 0.181$	**0.229**
LI, S_t, OCR	$LI^{-0.257} \times S_t^{0.238} \times OCR^{0.821} \times 0.157$	**0.219**

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Risk assessment for railways (for JBV)

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

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

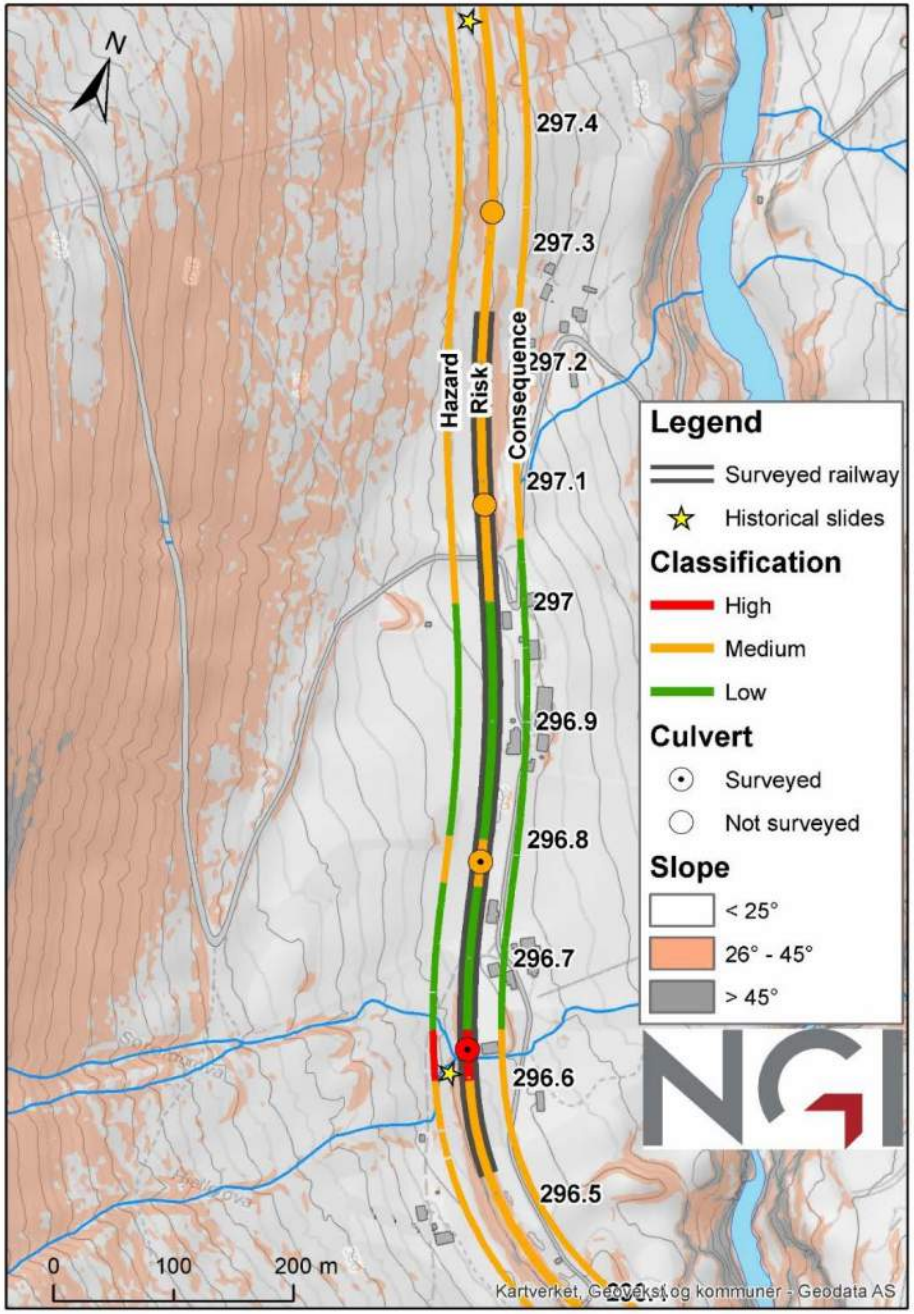
✓elements at risk
✓ terrain conditions at time of potential derailment
✓ impact speed
✓ accessibility for rescue

Risk assessment for railways (for JBV)

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

- one km of railway
- hazard class
- consequence class
- risk class

- high risk: priority for mitigation

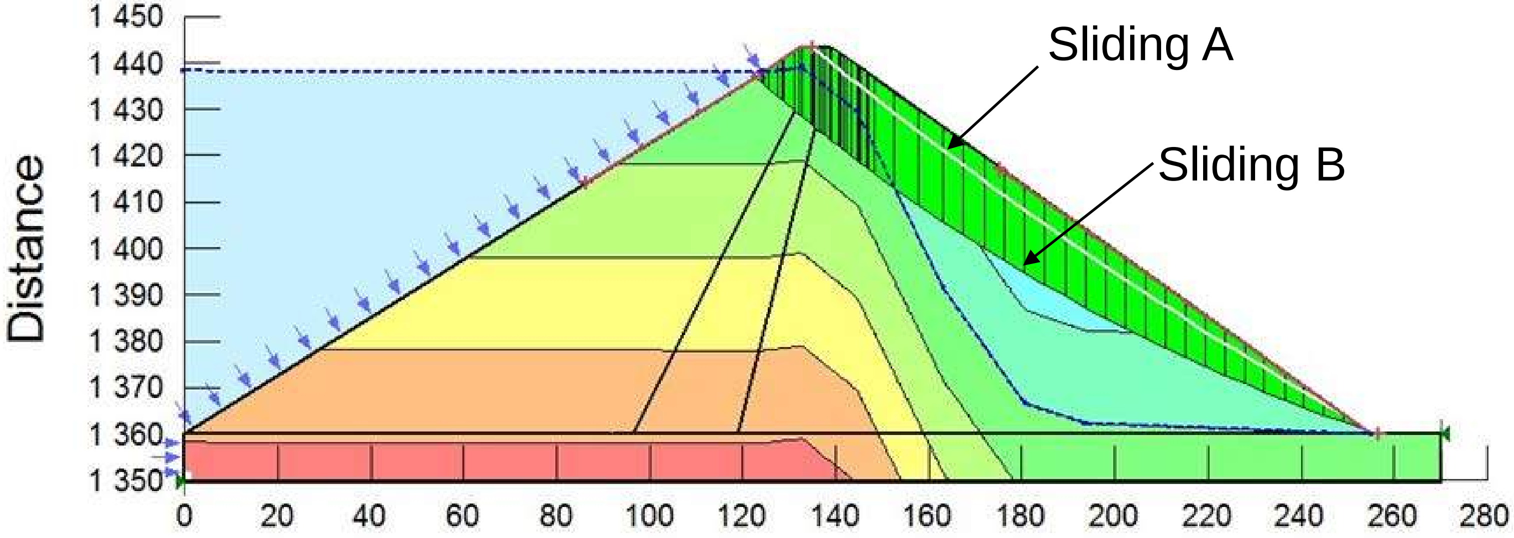


Dam Nyhellervatn - main dam 82,5 m igh

Foto: E-CO

Assessment of downstream slope stability

Limit equilibrium with Monte Carlo simulations (1000 simulations)



Results of deterministic analyses

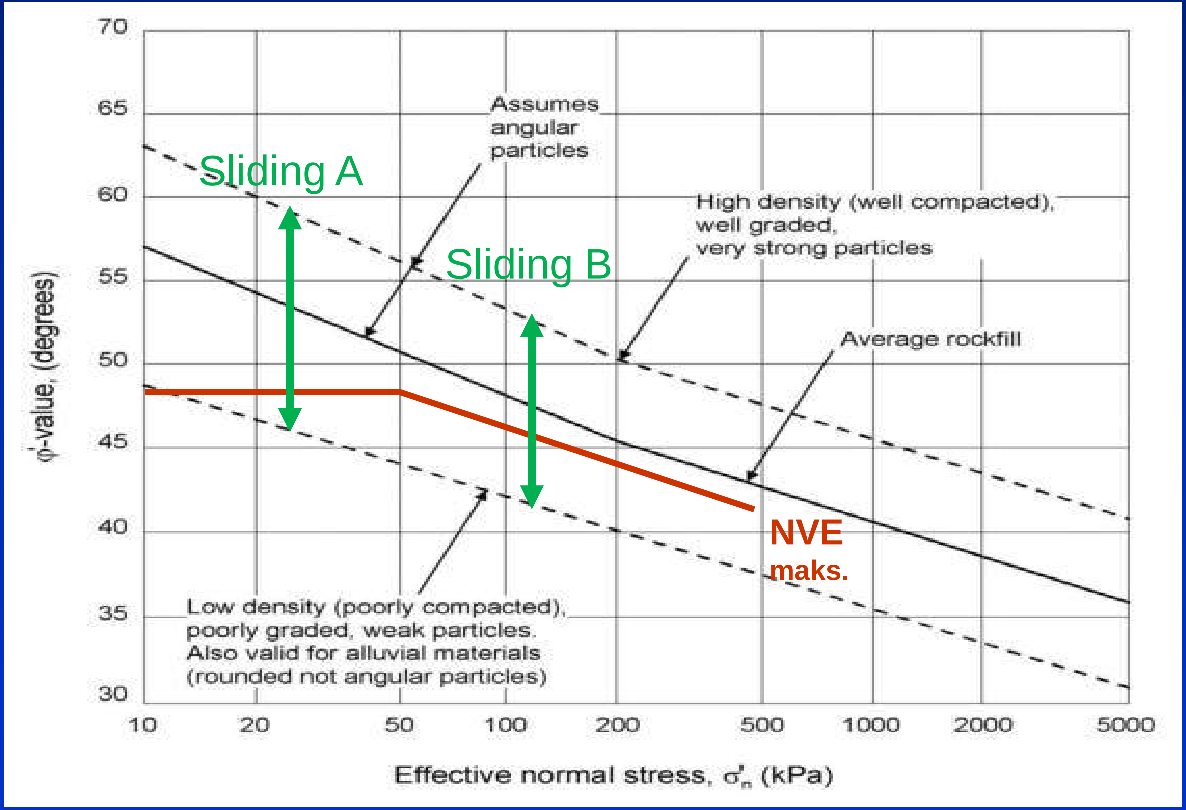
Sliding surface	**Deterministic safety factor, FS**	
	Mean	Standard deviation
Shallow (A)	1.58	0.06
Deeper (B)	1.32	0.05

Friction angle in rockfill

Secant value

of φ'

Depends on effective stress and rock quality



Resultat of probabilistic analyses (1000 Monte Carlo simulations)

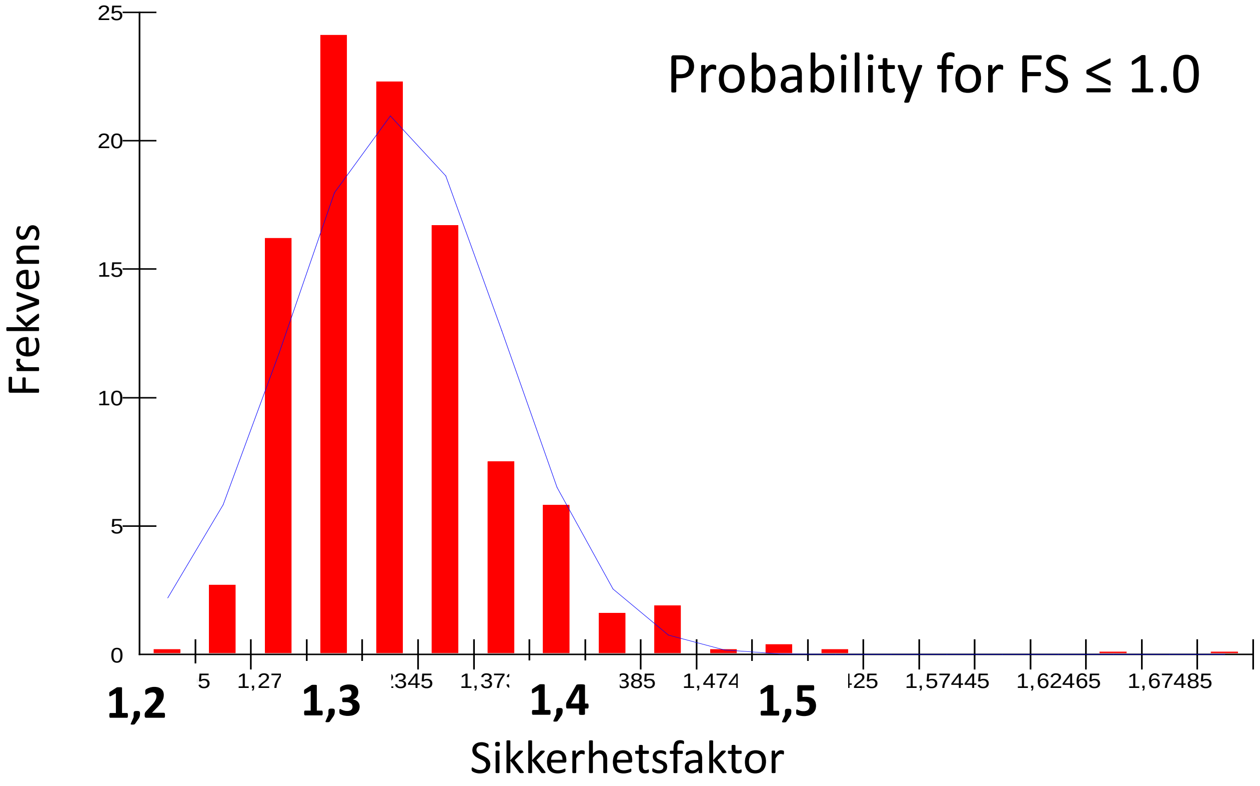
Sliding surface	**Deterministic FS**		**Failure probability**
	Mean	SD	
Shallow (A)	1.58	0.06	$<10^{-10}$
Deeper (B)	1.32	0.05	7×10^{-7}

Selv med en *FS* <1,5 er beregnet P_f meget lav, pga friksjonsvinkelverdiene i steinfylling.

Nyhellervatn – Main dam

Downstrean Slope

Probabilistic distribution of FS



Probability for FS ≤ 1.0

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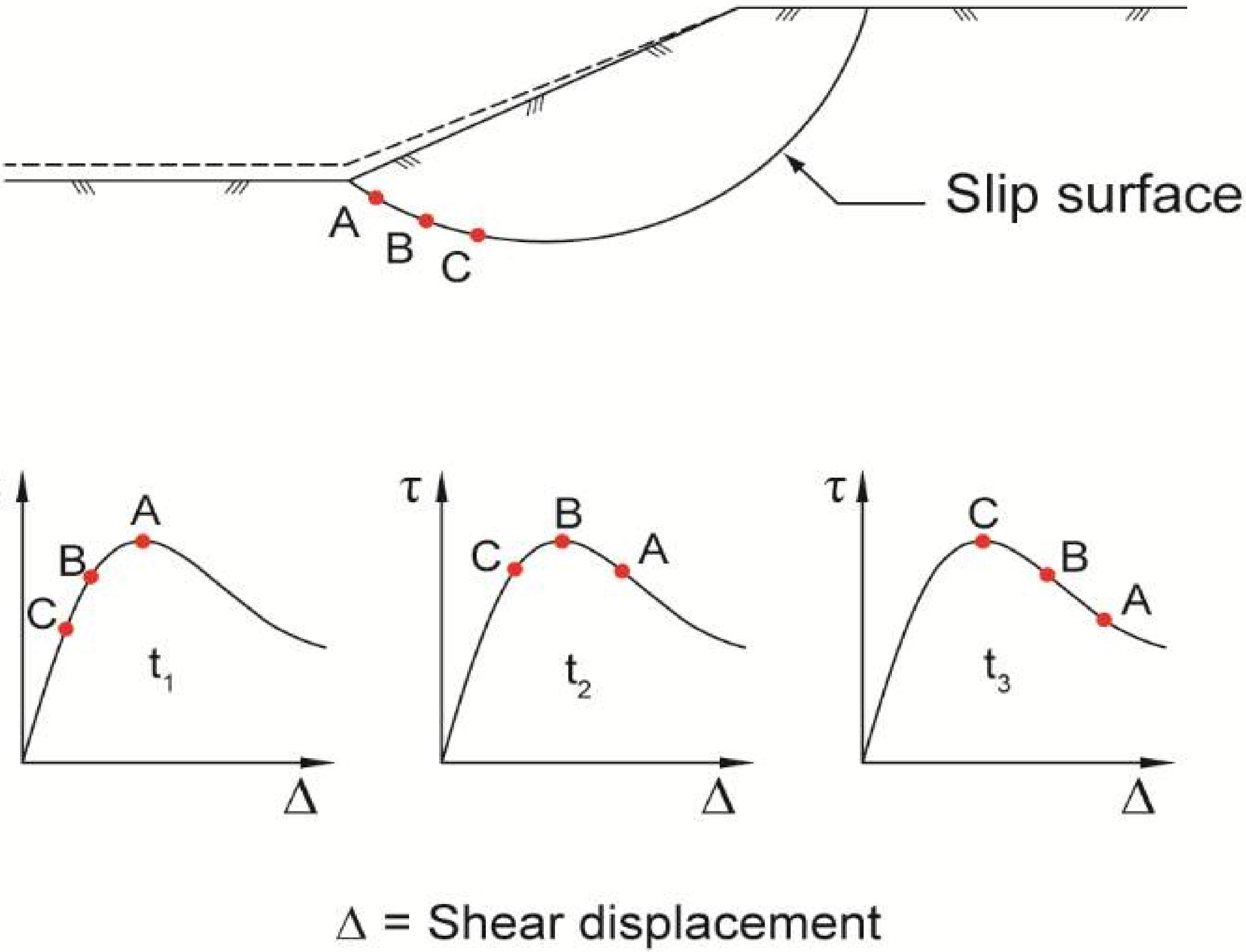
Sensitive clay

- Marine clay
- Leached after deglaciation
- Highly sensitive

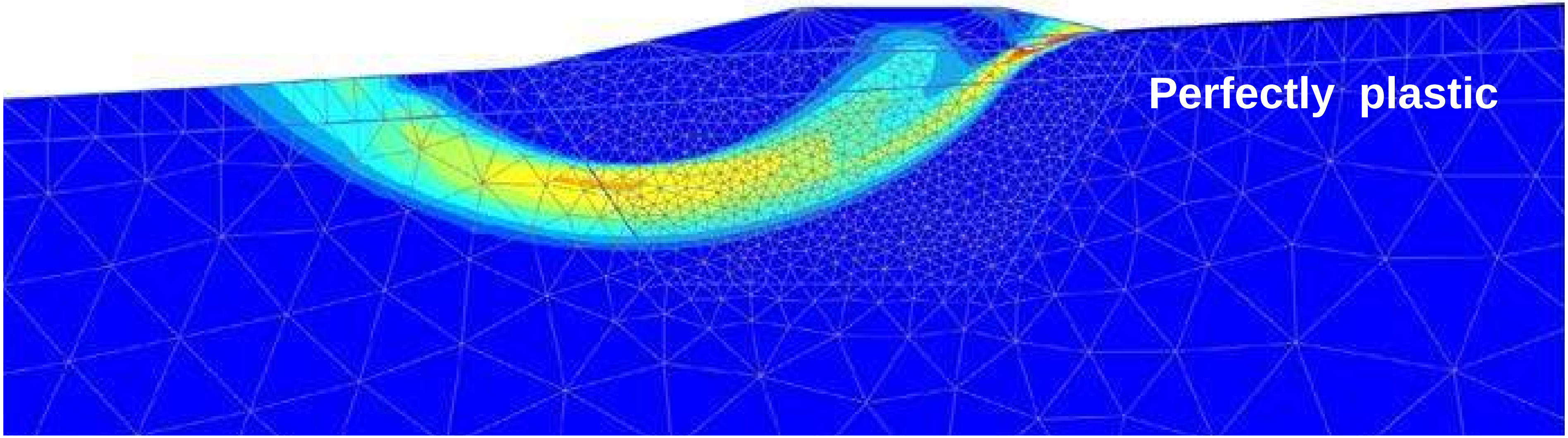
Progressive failure

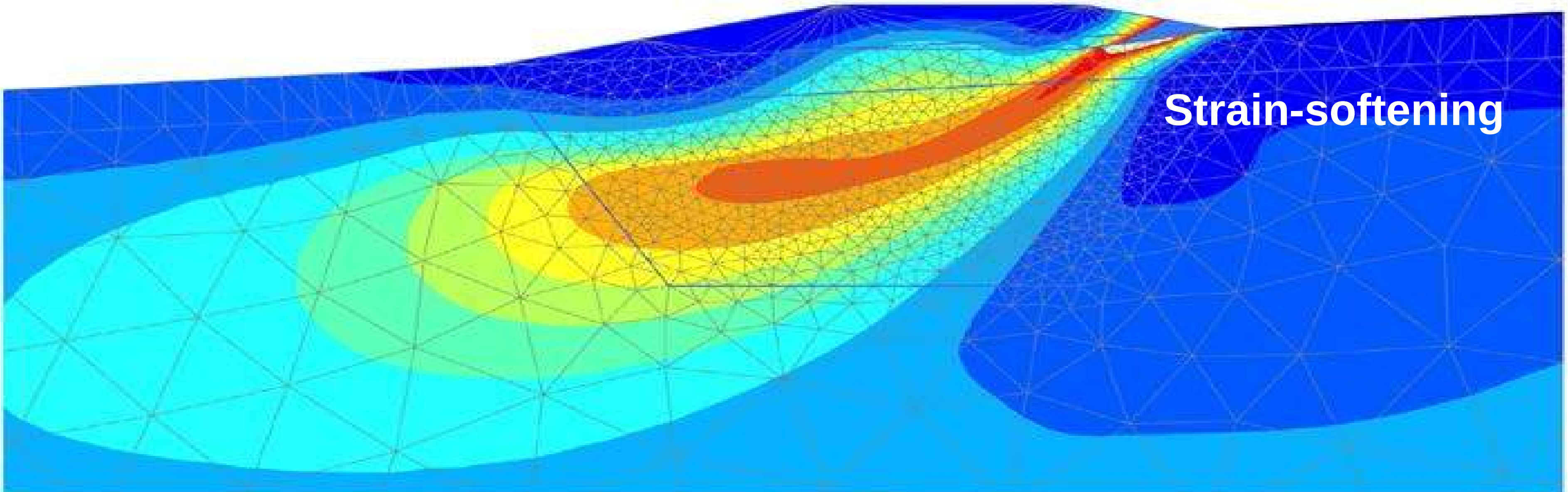
[after Duncan and Wright 2005]



Failure in strain-softening clay
Shear deformations, PLAXIS

[Jostad 2014]



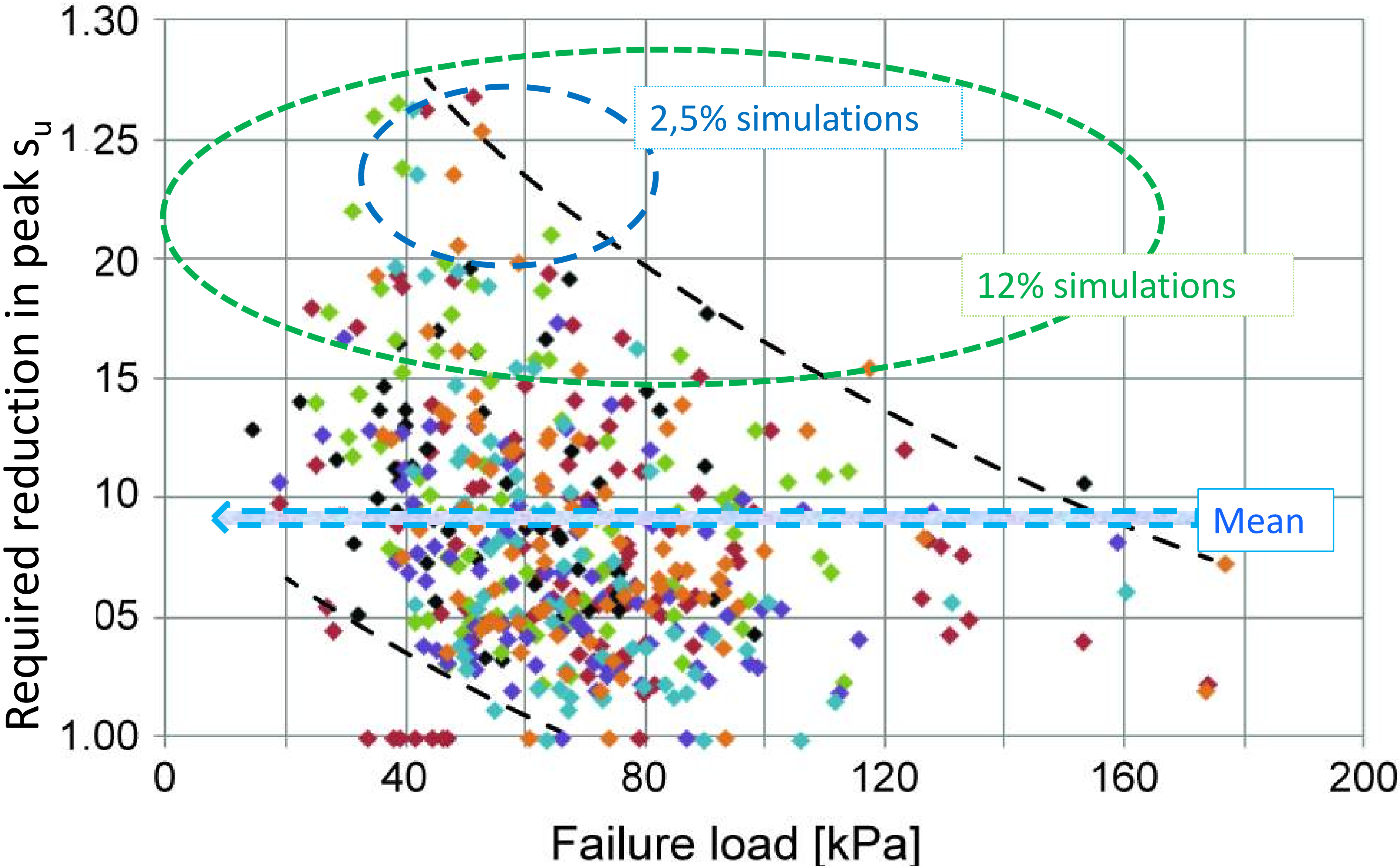


Lessons from back-calculations of earlier failures and finite element modelling

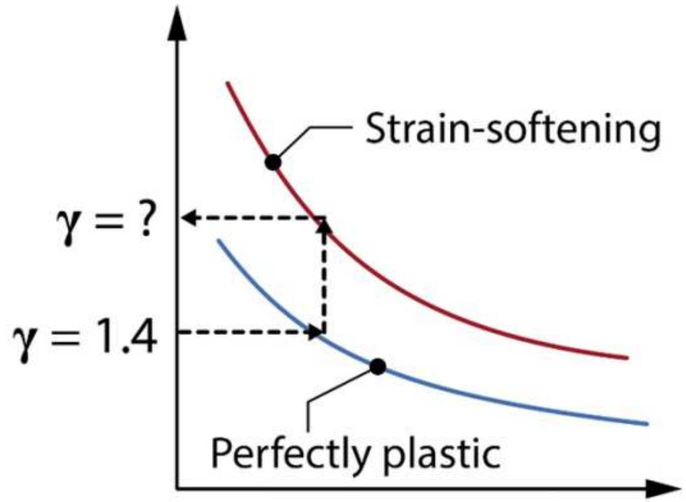
- Limit equilibrium analysis cannot find the critical mechanism of failure and cannot model progressive failure nor ensure strain compatibility.
- If limit equilibrium analysis is used, and they will continue to be used, we need to account for strain-softening and progressive failure.
- How can we find a factor that will be representative of the strain-softening behaviour? Selected to apply a correction factor on the safety factor

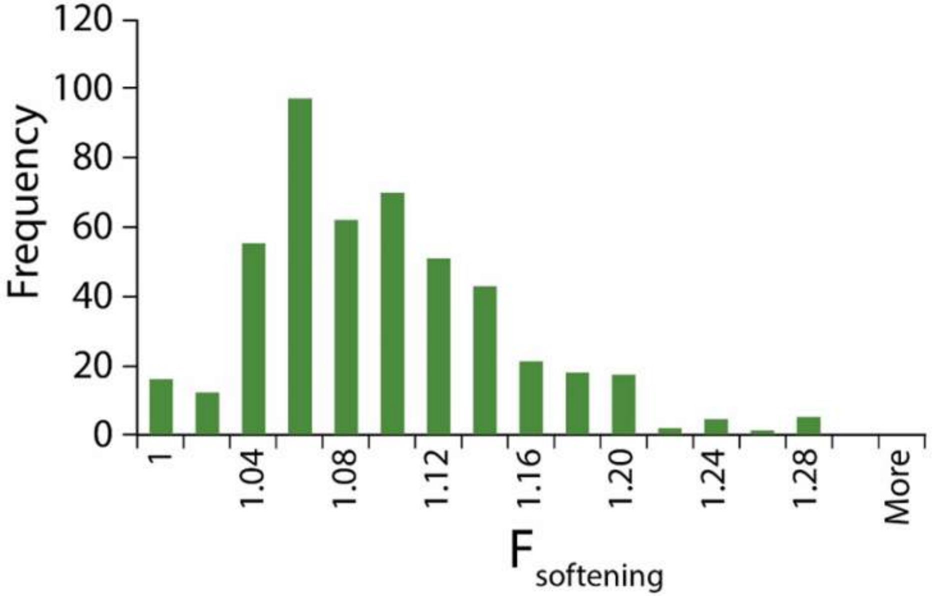
$$\gamma_{M_{\text{strain-softening}}} = \gamma_M \cdot F_{\text{softening}}$$

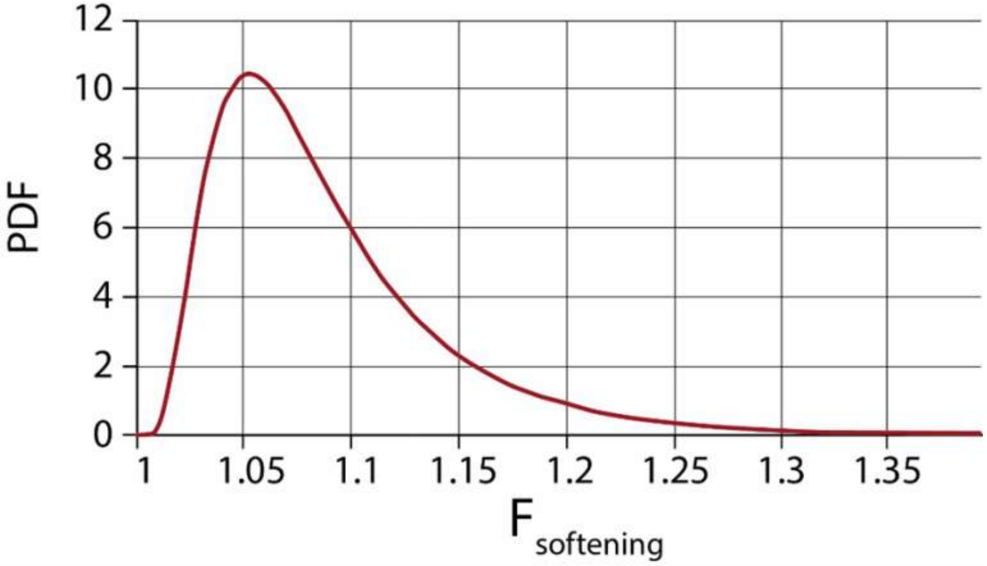
Required reduction in peak undrained shear strength if LE analysis is used [Jostad *et al* 2013]



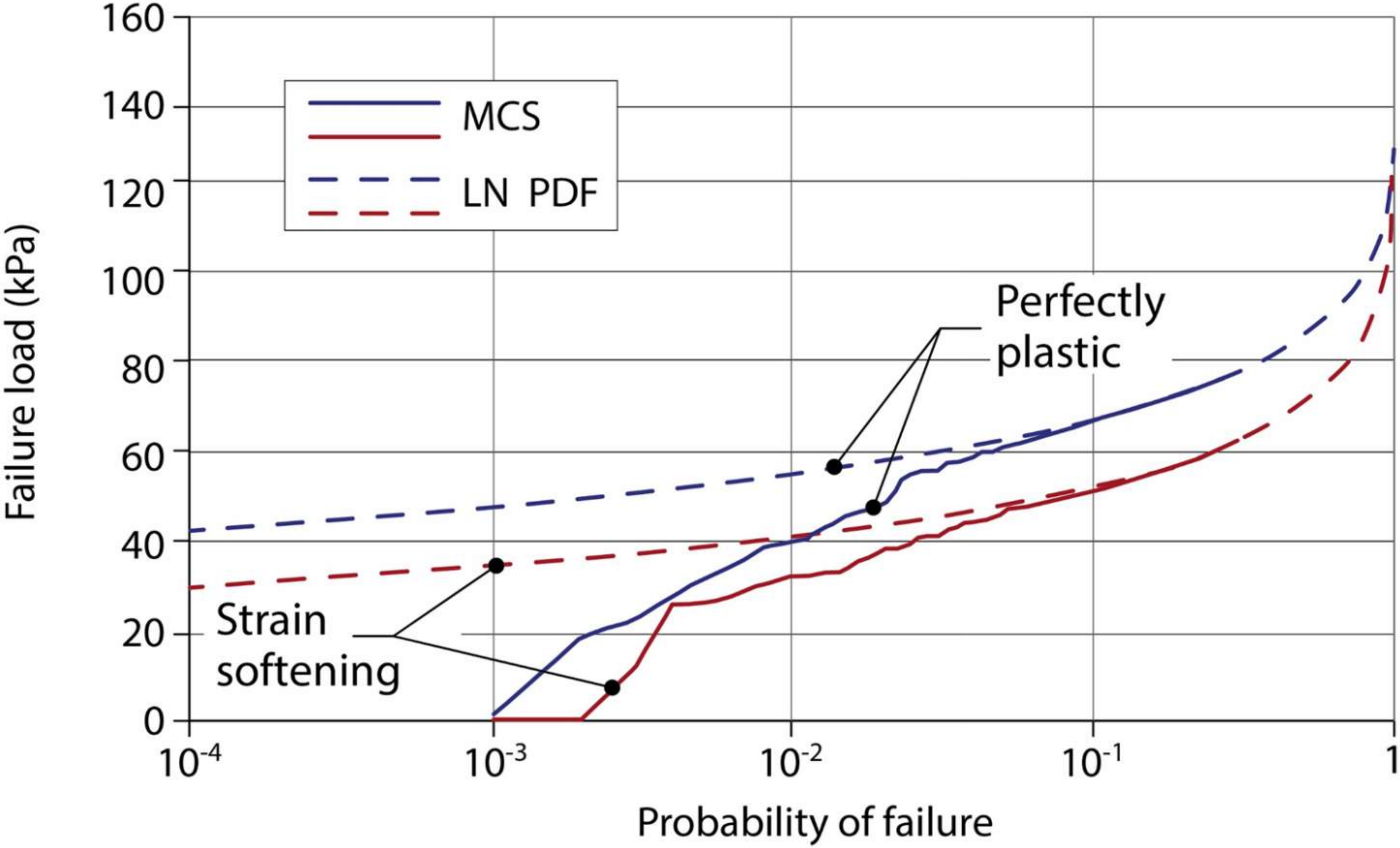
Monte-Carlo simulations to obtain $F_{softening}$



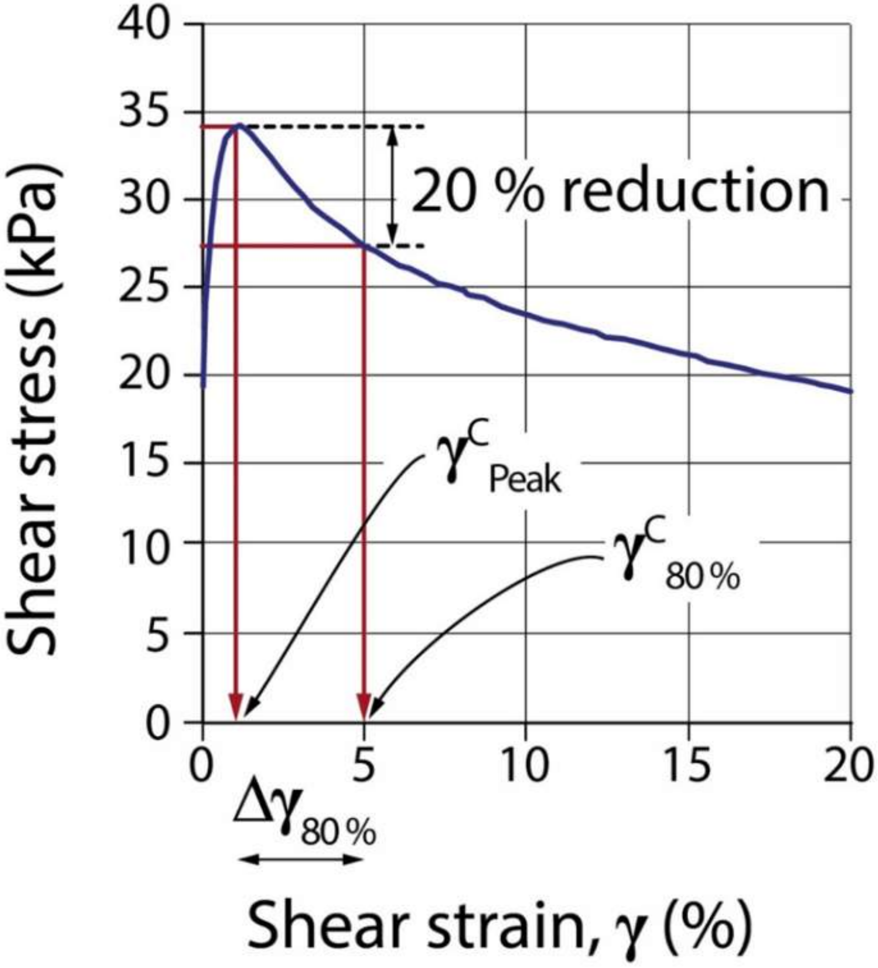


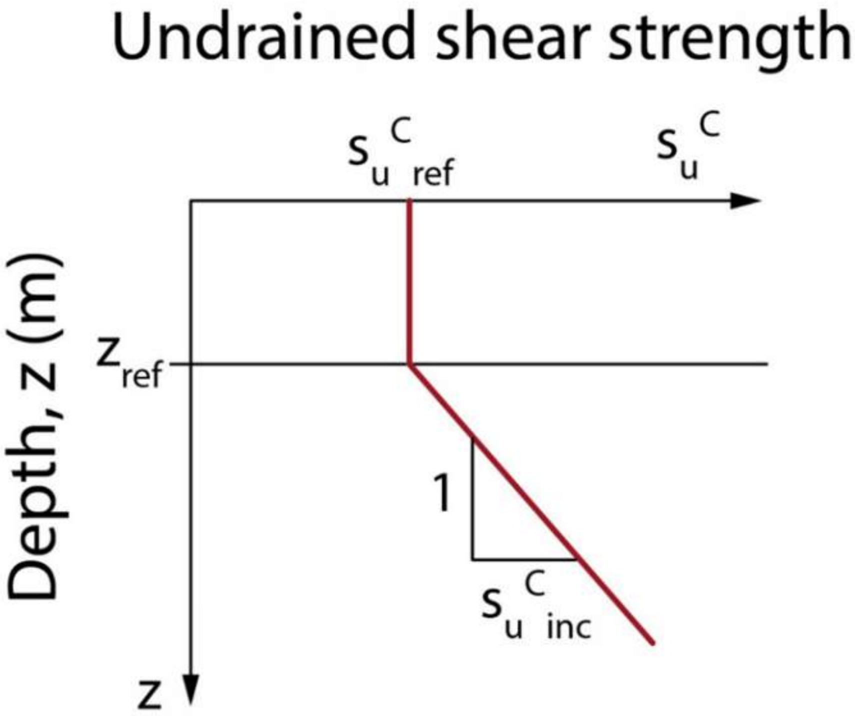


A word of caution: MCS and tails of PDF

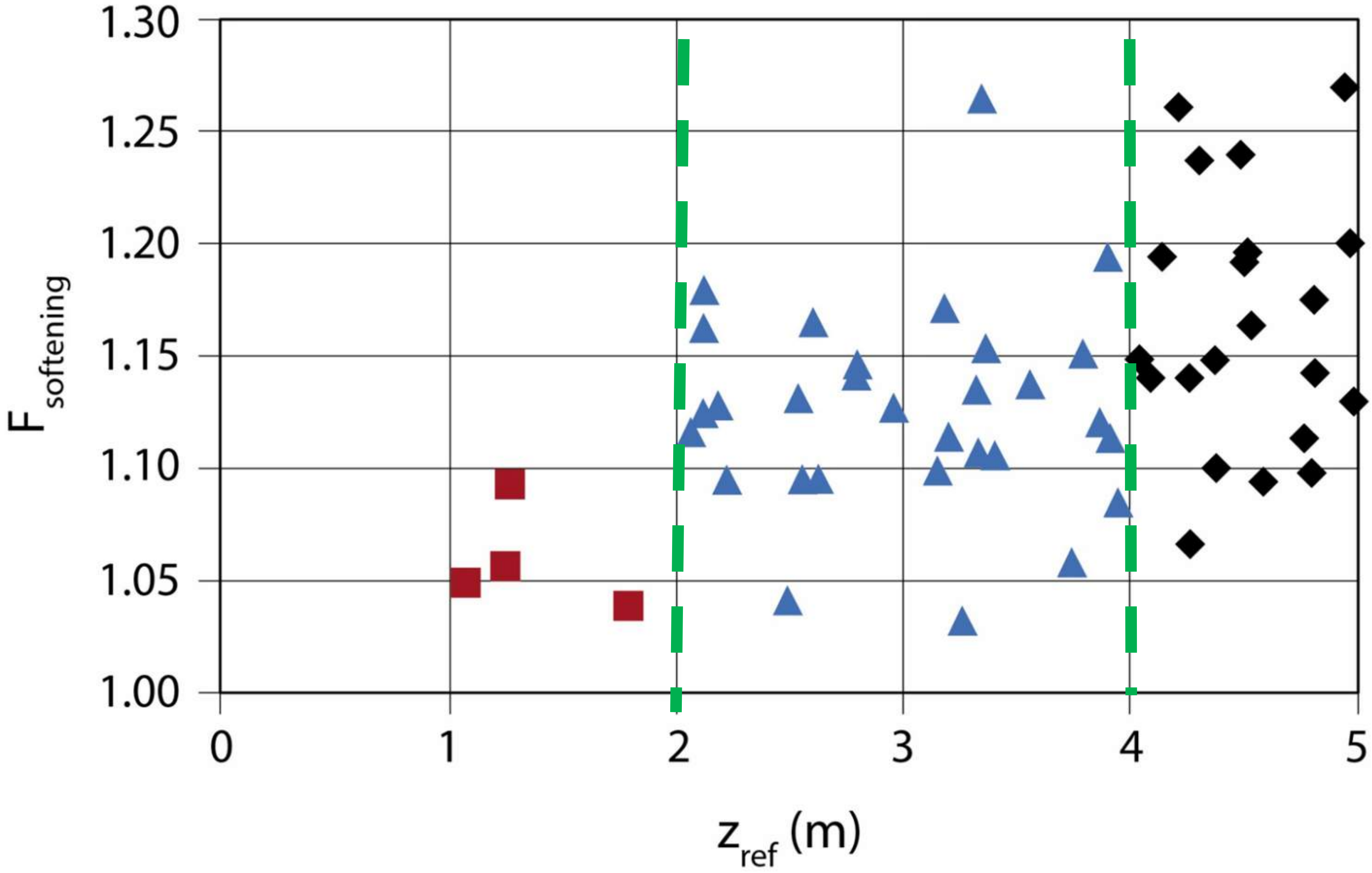


Significant factors in analysis (Jostad *et al* 2015; Dolva *et al* 2016)



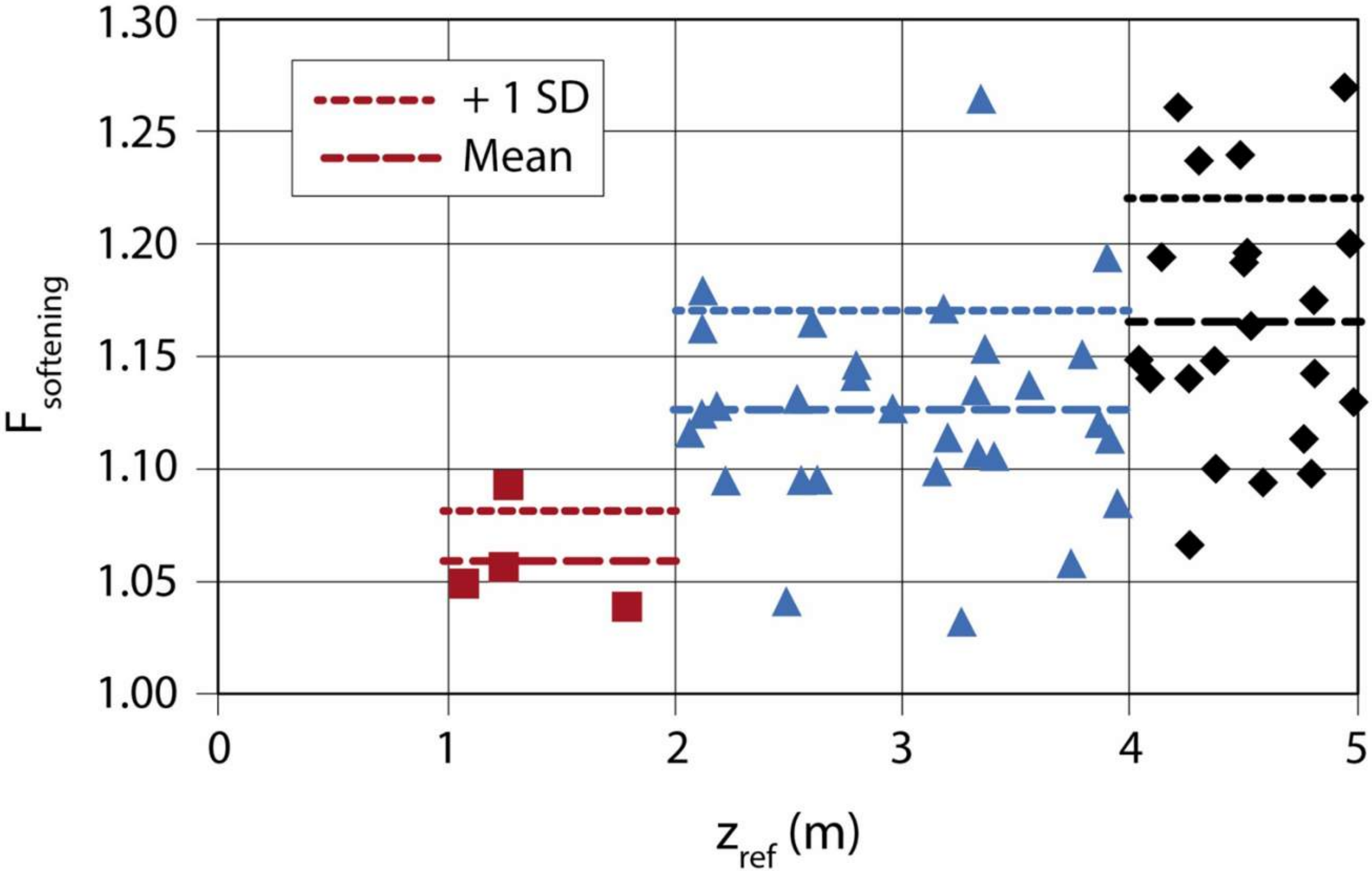


Resulting $F_{softening}$



Correction factor on the safety factor

$$\gamma_{M_{strain\text{-}softening}} = \gamma_M \cdot F_{softening}$$



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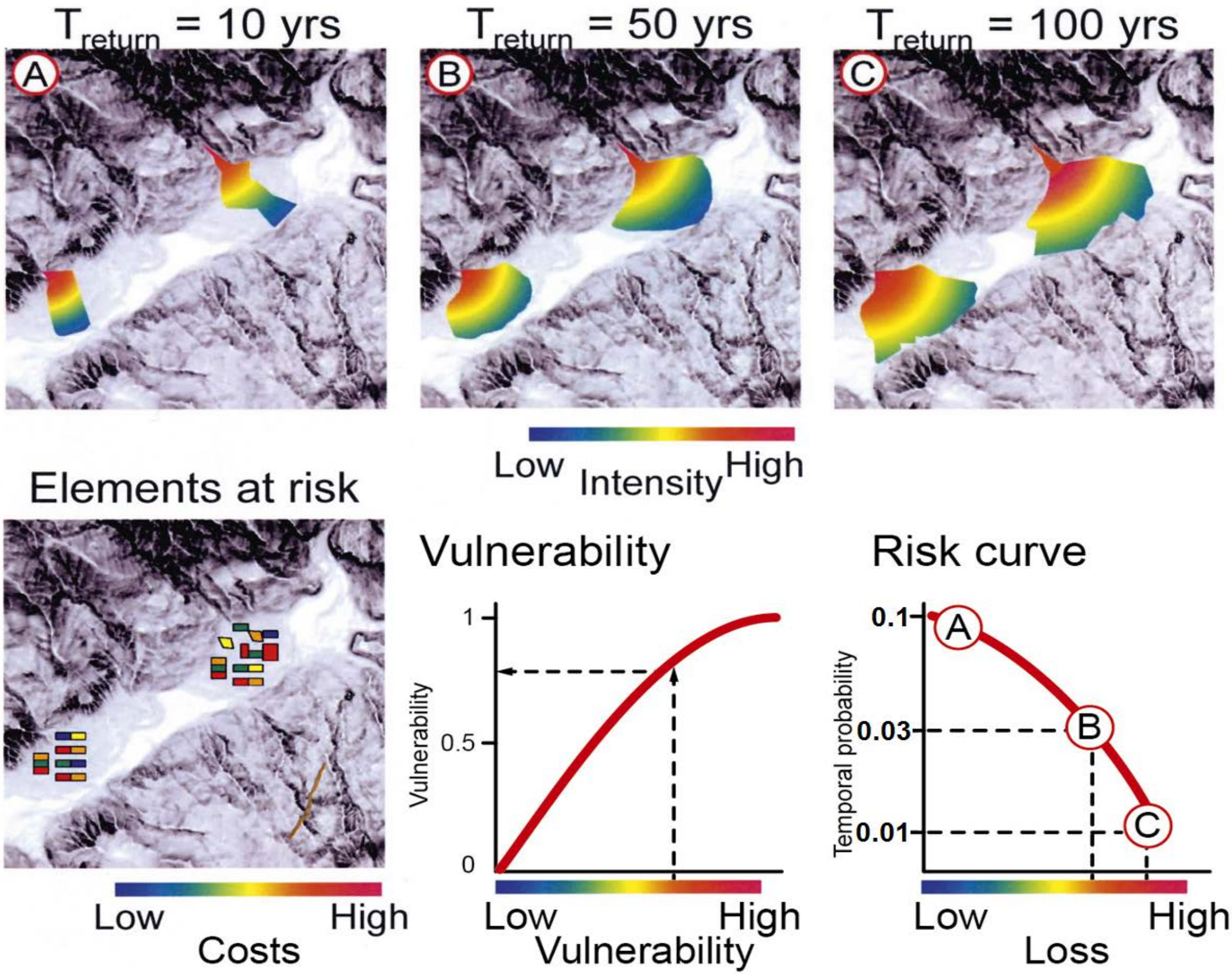
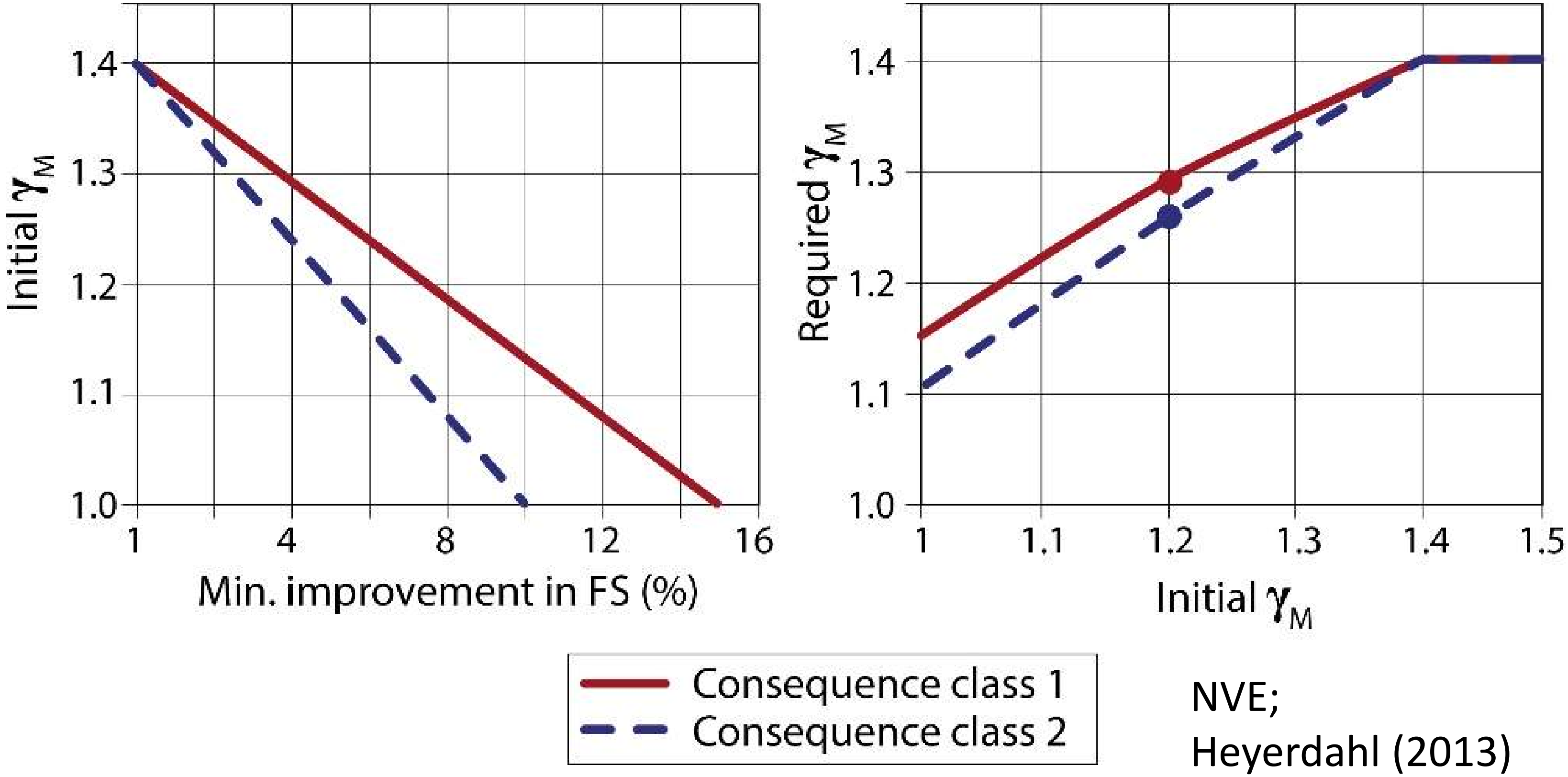


Safety factor for standing slopes

Required γ_M for a standing slope on sensitive clay



NVE;
Heyerdahl (2013)

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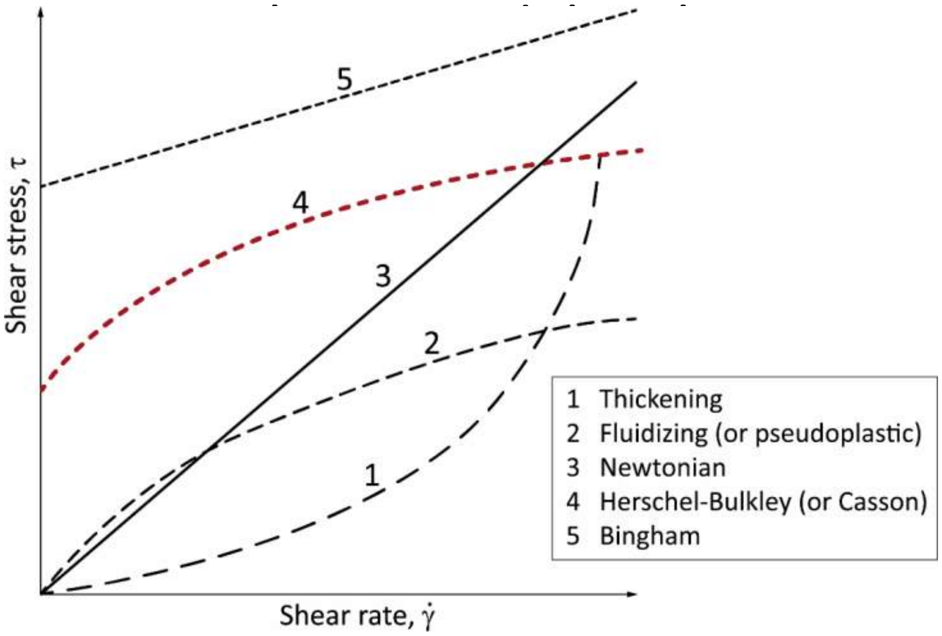
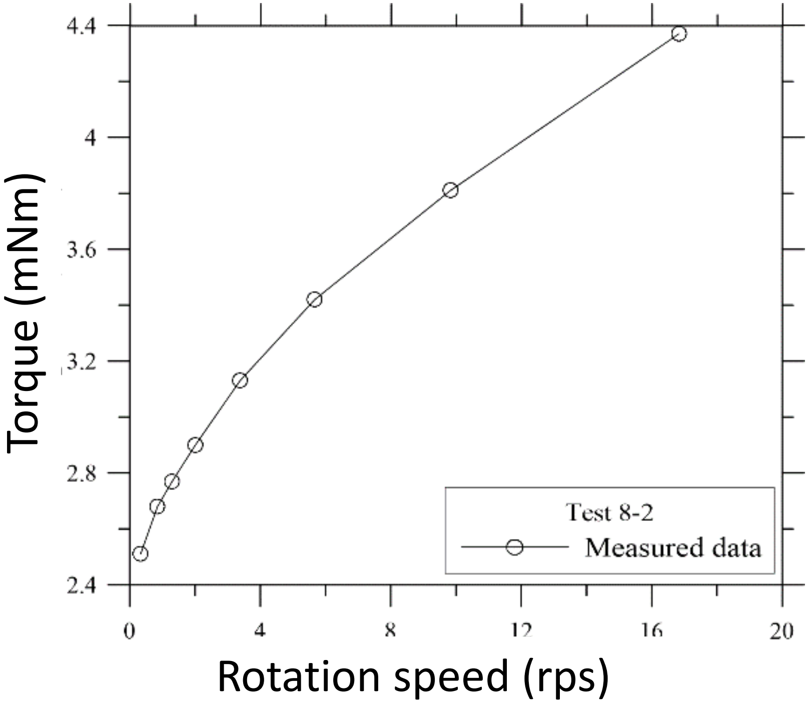
LANDSLIDE RUNOUT
Visco-plastic model
with Herschel-Bulkley rheology ('BING CLAW‘)



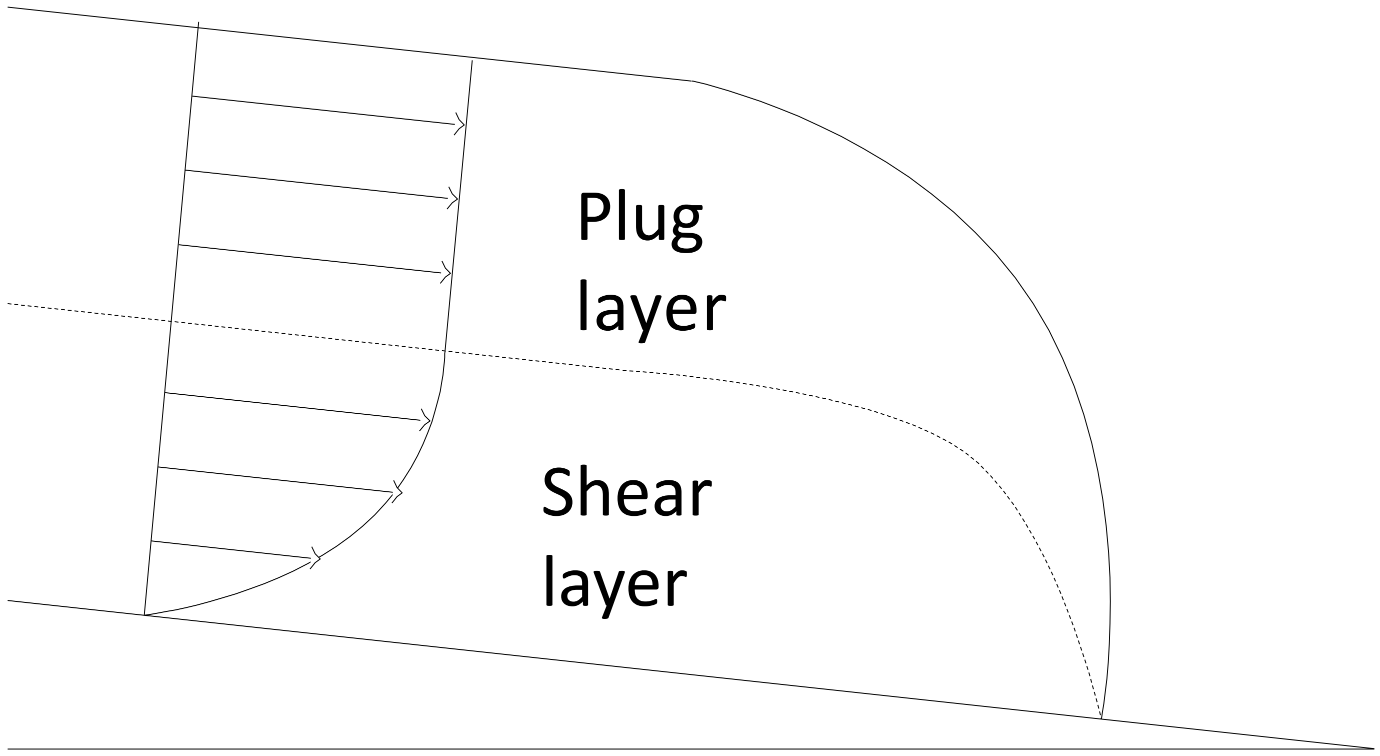
(Locat and Demers, 2018)



(Grue et al 2017)

Herschel-Bulkley model

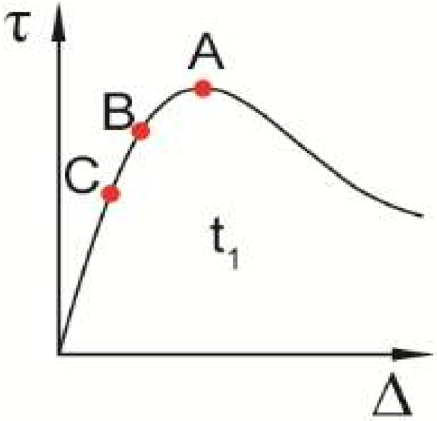
Constant velocity profile for the plug and parabolic velocity profile for the shear layer.



Visco-plastic model parameters

- n : fluid index $(0 < n \leq 1)$
- Strain rate, $\dot{\gamma}_r = \left(\frac{\tau_y}{\mu}\right)^{\frac{1}{n}}$, is fixed
- Remolding varies exponentially with the accumulated bottom shear
- 3 parameters to describe behaviour:

  $\tau_{y,0}$: initial yield stress
  $\tau_{y,\infty}$: remoulded yield stress
  Γ : remoulding parameter



Numerical implementation

Three steps:

(1) the earth pressure is compared to the yield stress in each cell. If the yield stress is larger than the earth pressure, no motion is allowed. If the two adjacent cells do not deform, there is no displacement at the interface;

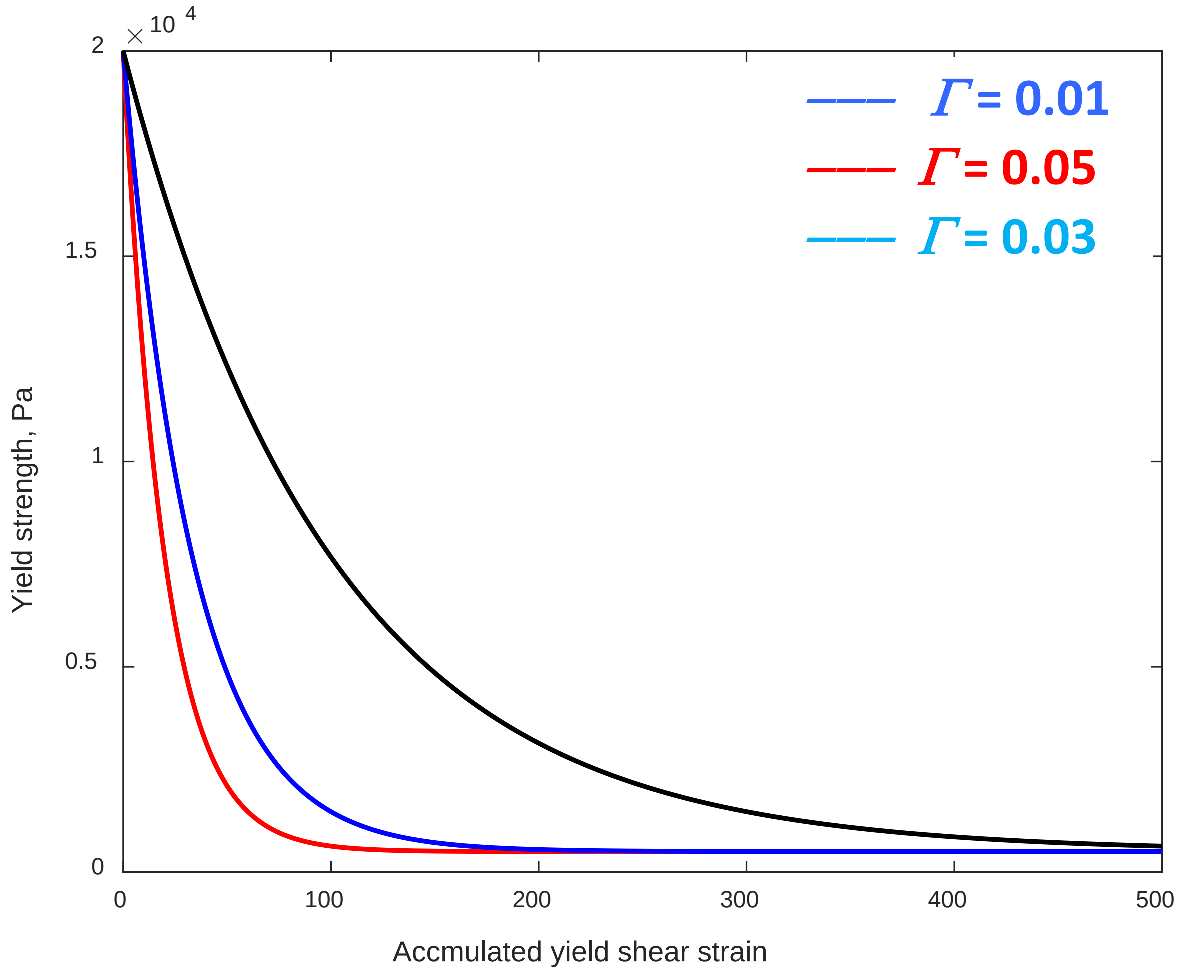
(2) if one of the cells deforms, the equations without friction terms are solved. At each cell interface, a Riemann problem is solved with the wave propagation algorithm of the finite volume method;

(3) The friction forces are then included using a Godunov fractional step method.

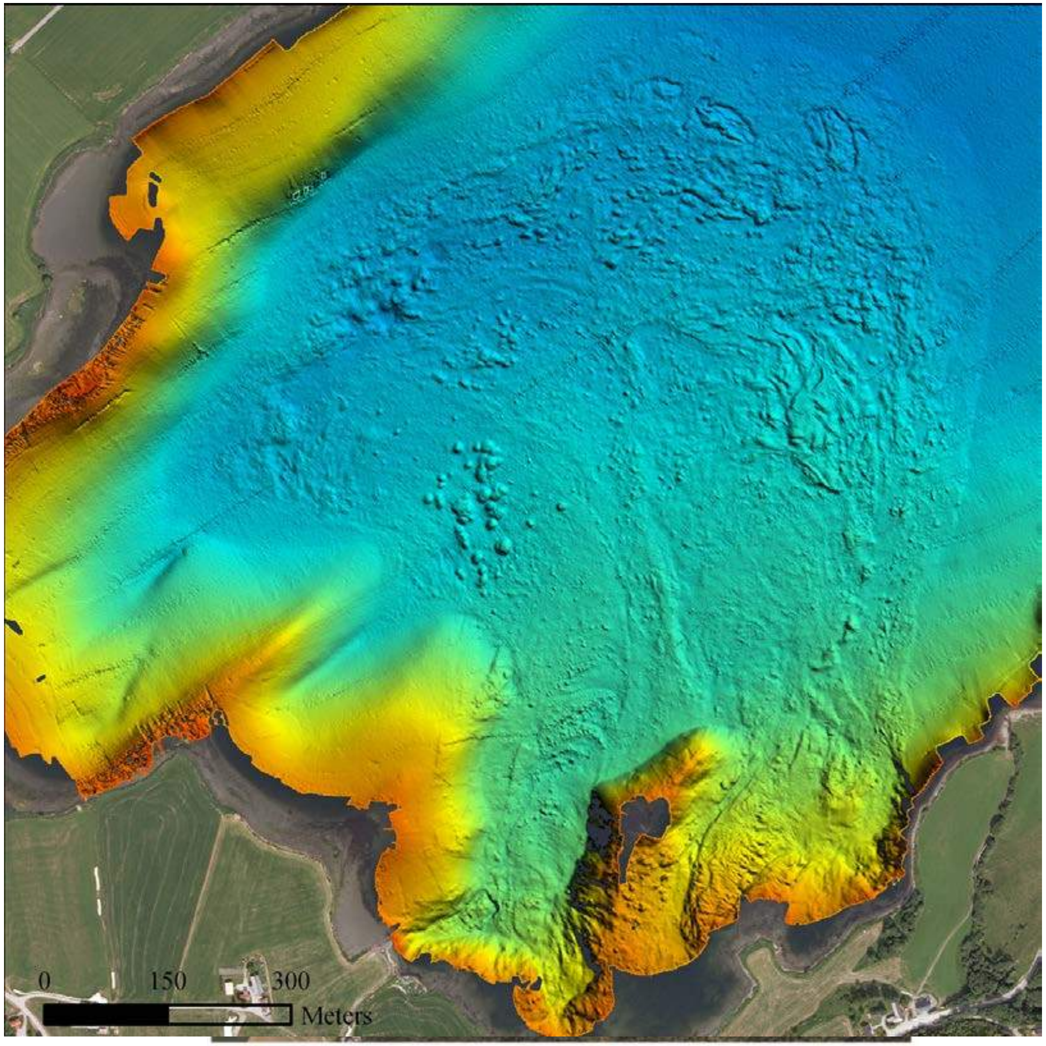
Visco-plastic model parameters

Random variable	Mean	SD	CoV	PDF
Initial yield stress $\tau_{y,0}$ (kPa)	20	3.5	17%	LN
Residual yield stress $\tau_{y,\infty}$ (kPa)	0.5	0.1	17%	LN
Gamma $\mathit{\Gamma}$	??		50%	LN

Influence of Γ-value on averaged yield stress

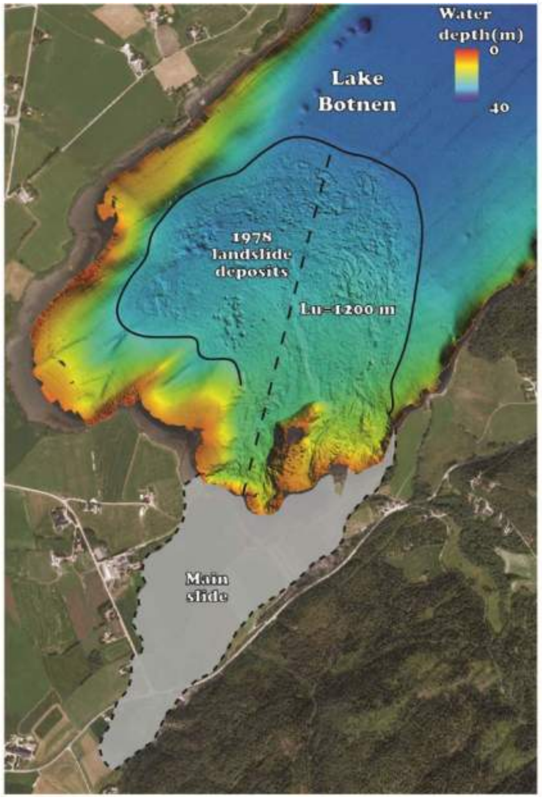


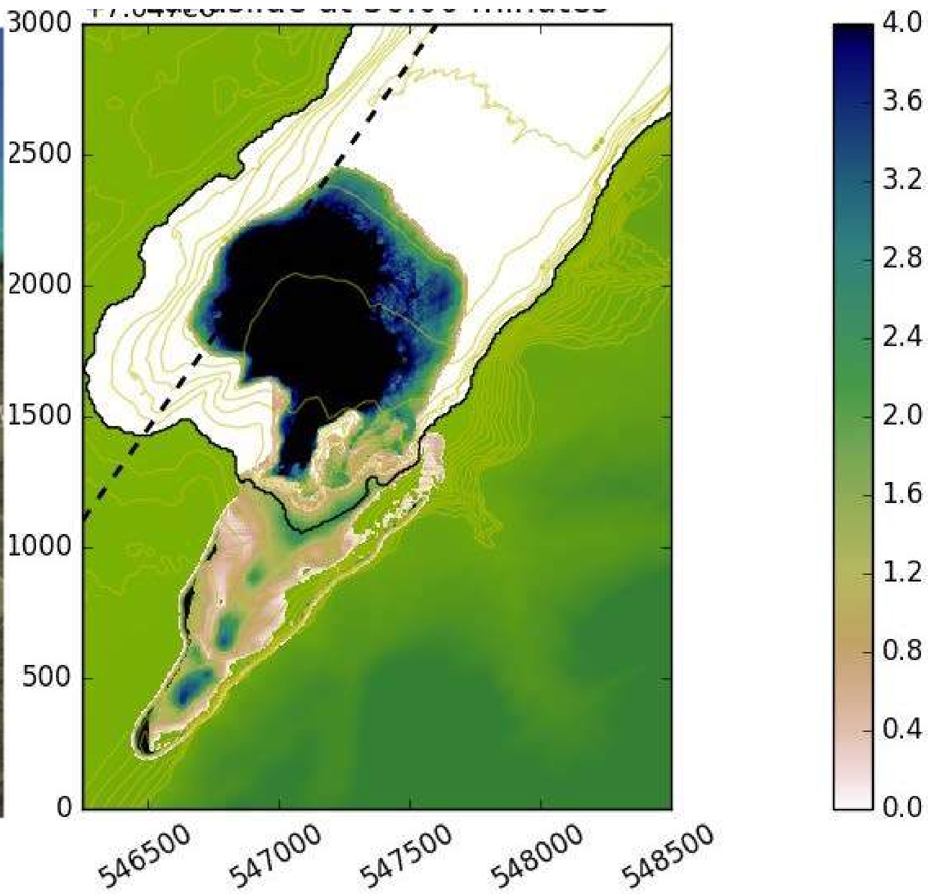
Bathymetry of Rissa landslide



Runout of Rissa landslide

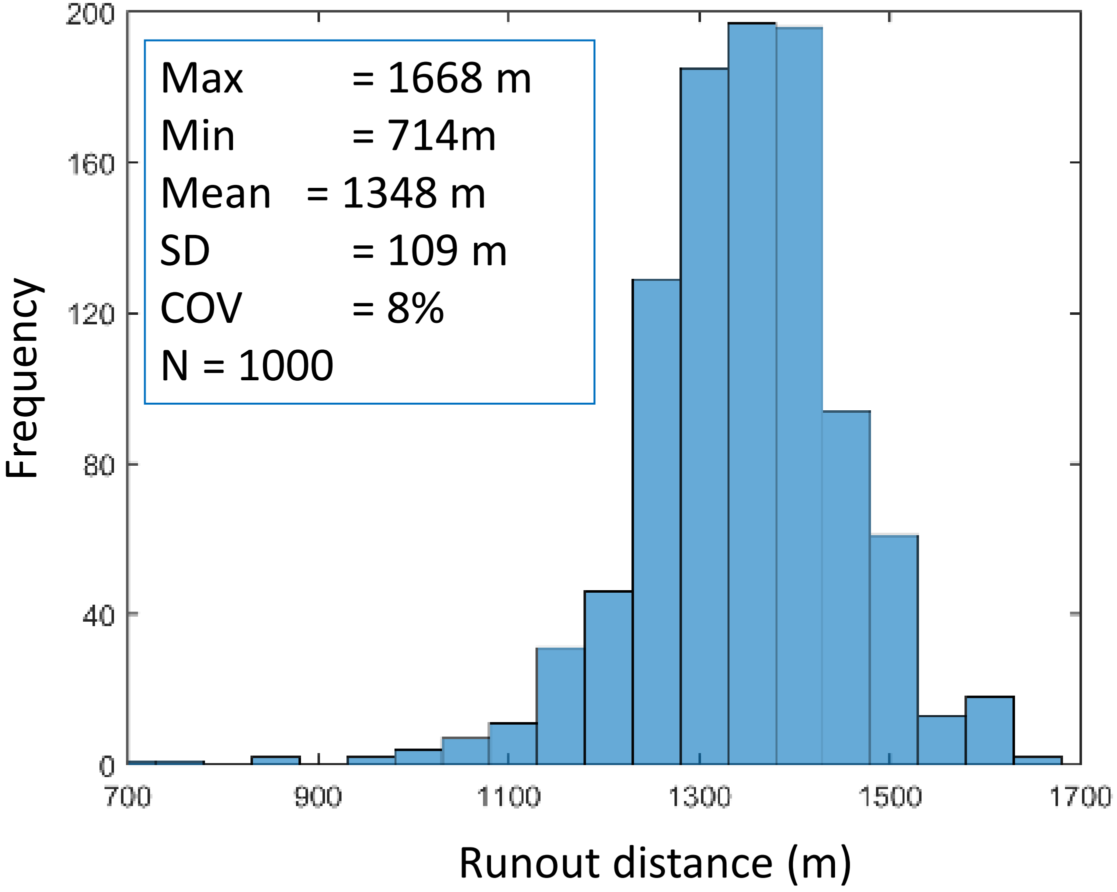
Observed vs calculated runout distance





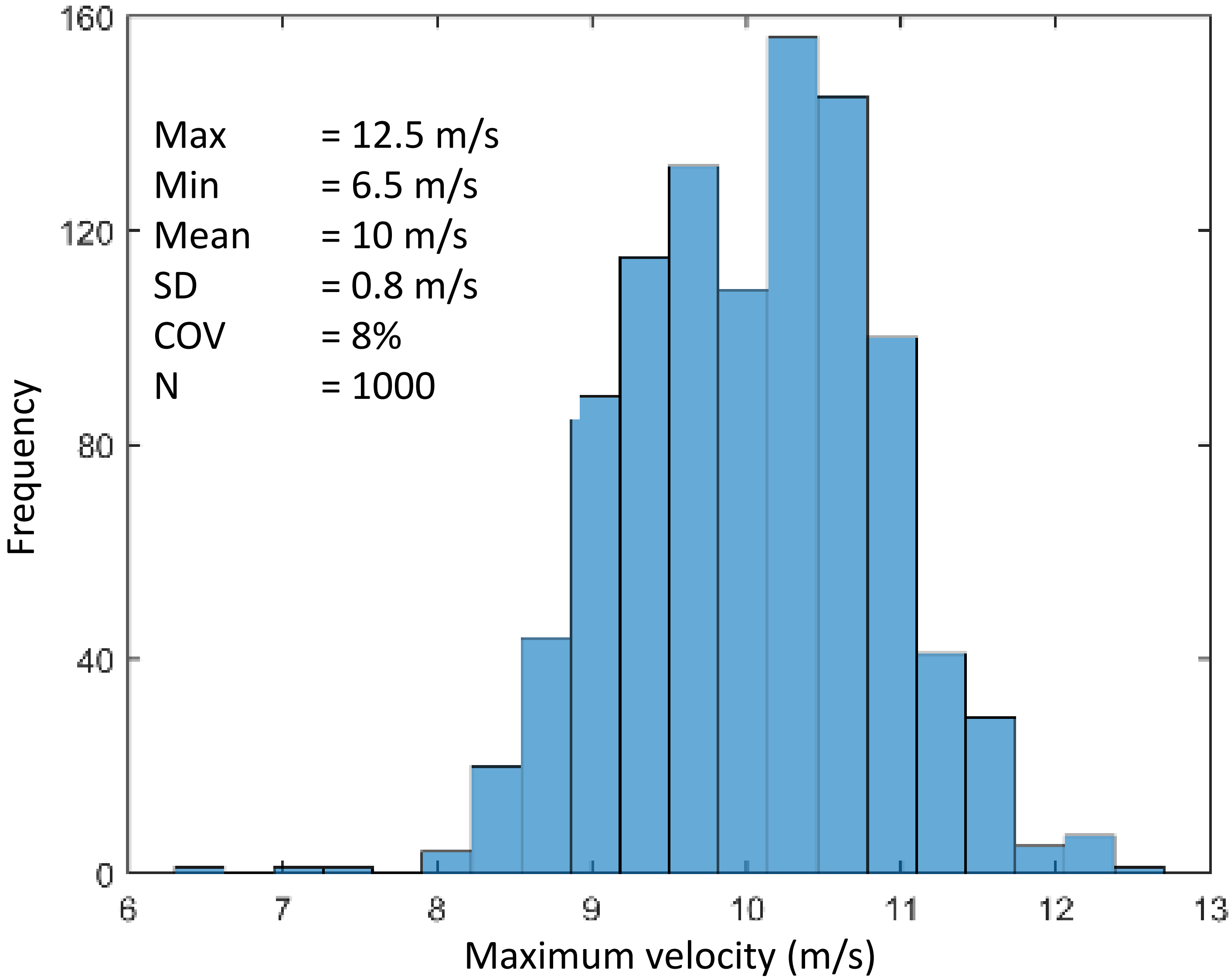
1000 Monte Carlo simulations of landslide movement, Phase 2 Rissa

Runout distance



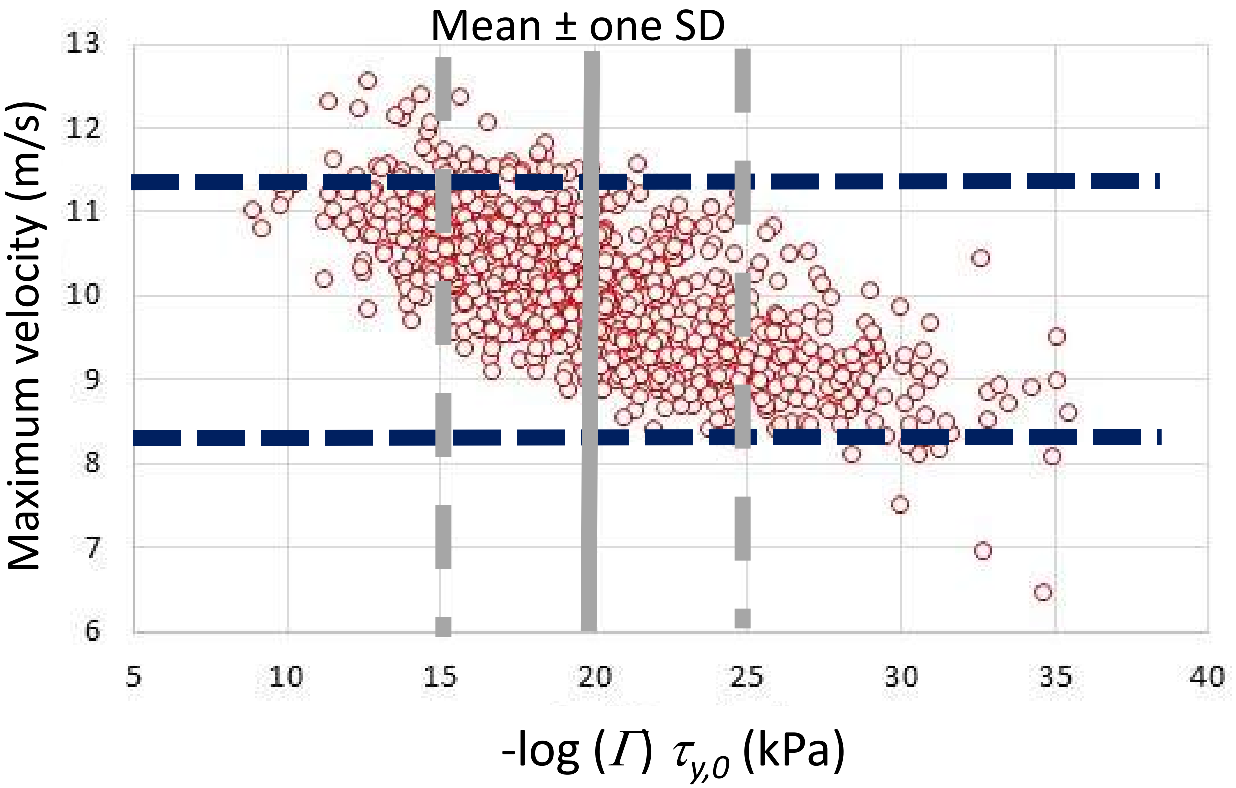
Monte Carlo simulations of runout, Rissa

Maximum velocity over flow domain

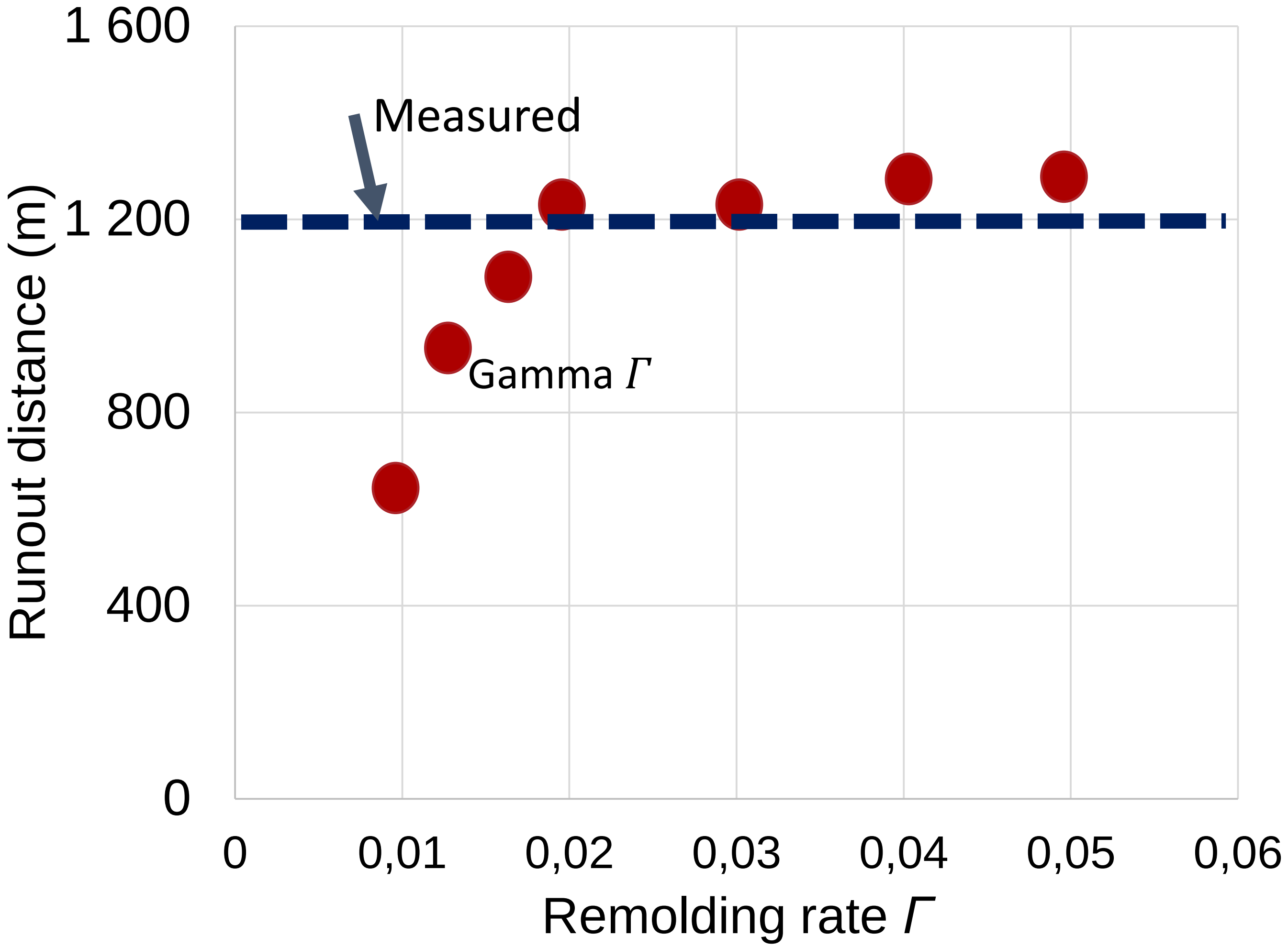


Max = 12.5 m/s
Min = 6.5 m/s
Mean = 10 m/s
SD = 0.8 m/s
COV = 8%
N = 1000

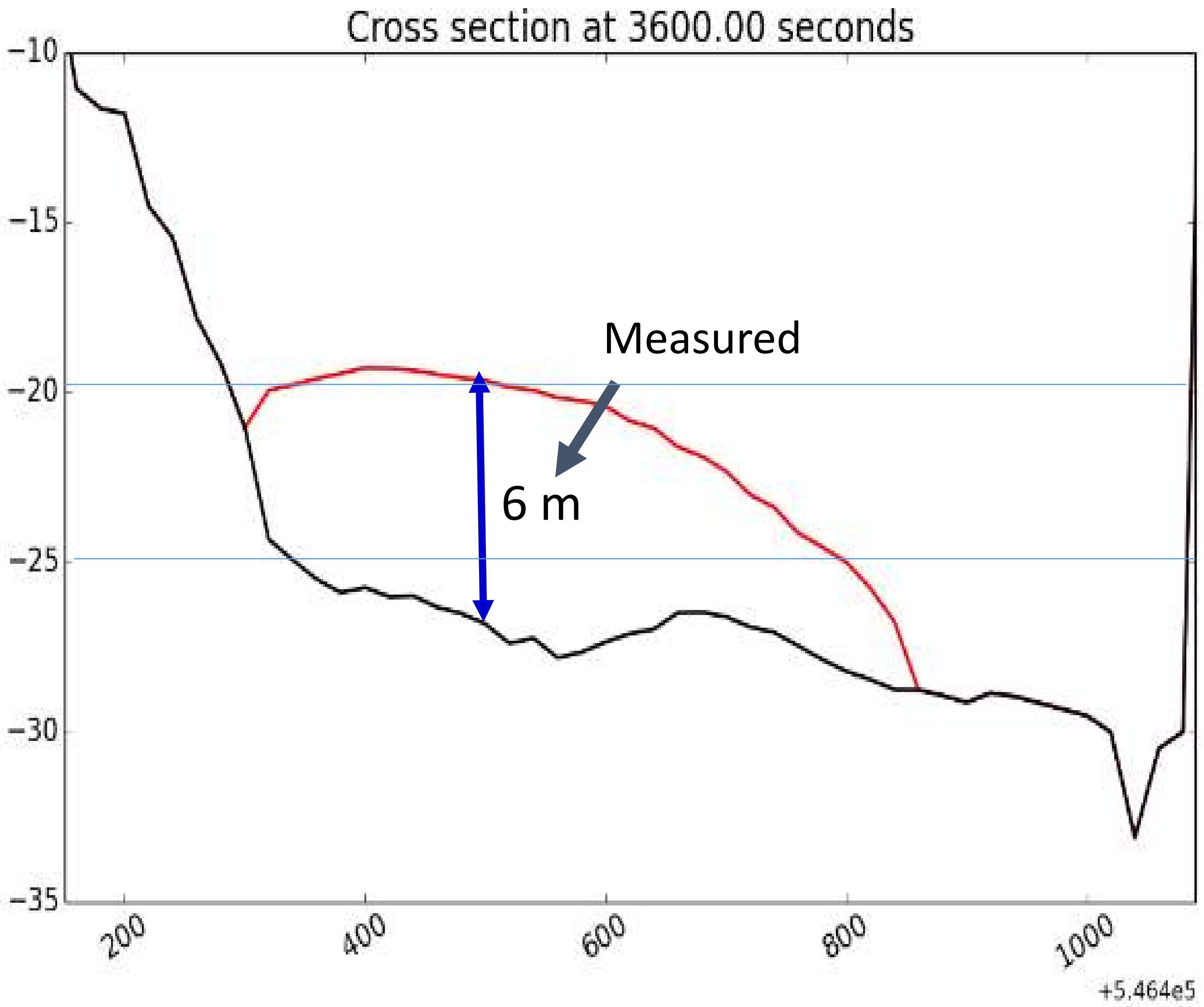
Maximum velocity over flow domain



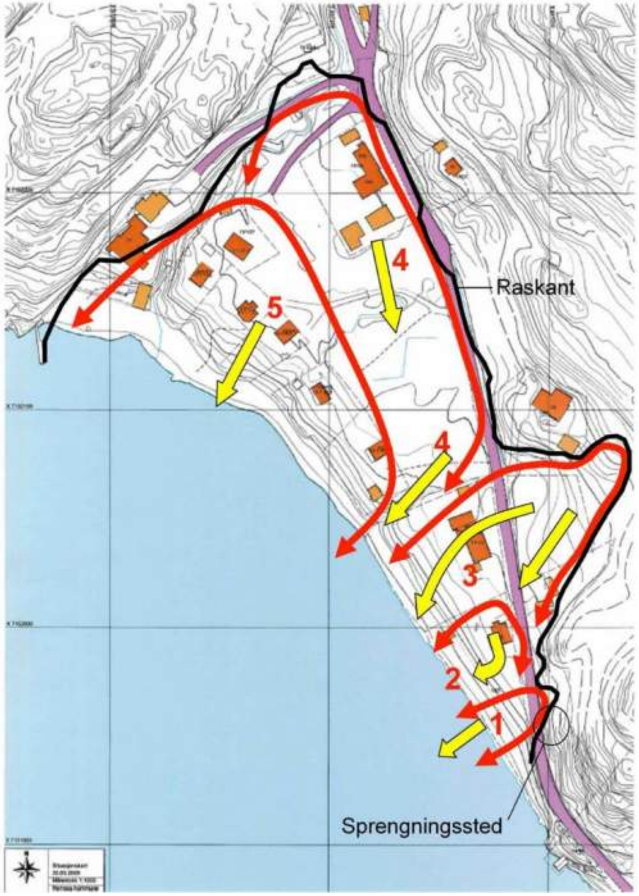
Runout distance = f(Γ)



Deposit thickness (m)

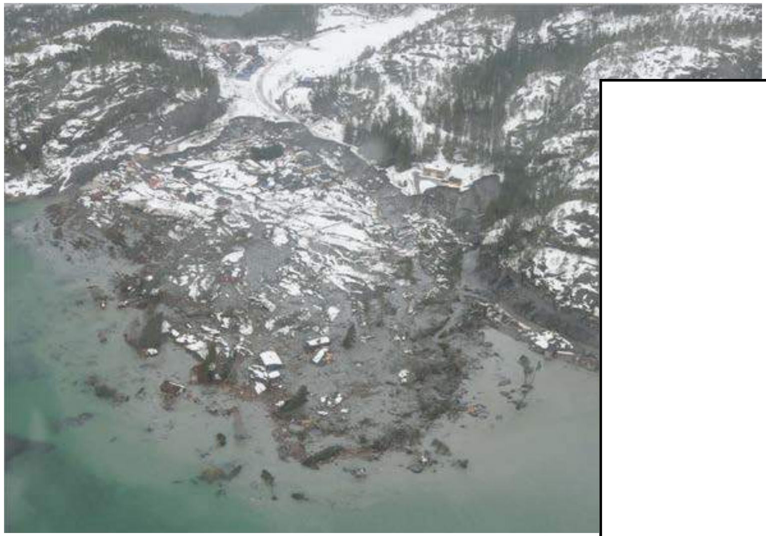


Kattmarka slide



- Retrogressive slide with 5 phases
- Initiated at phase 1 area by rock blasting
- Main slide movement for 10 minutes
- Volume of 300,000-500,000 m^3 in an area of 300 m x 100 m
- Remolded yield strength is 0.6-1 kPa

Back-calculation of the Kattmarka slide



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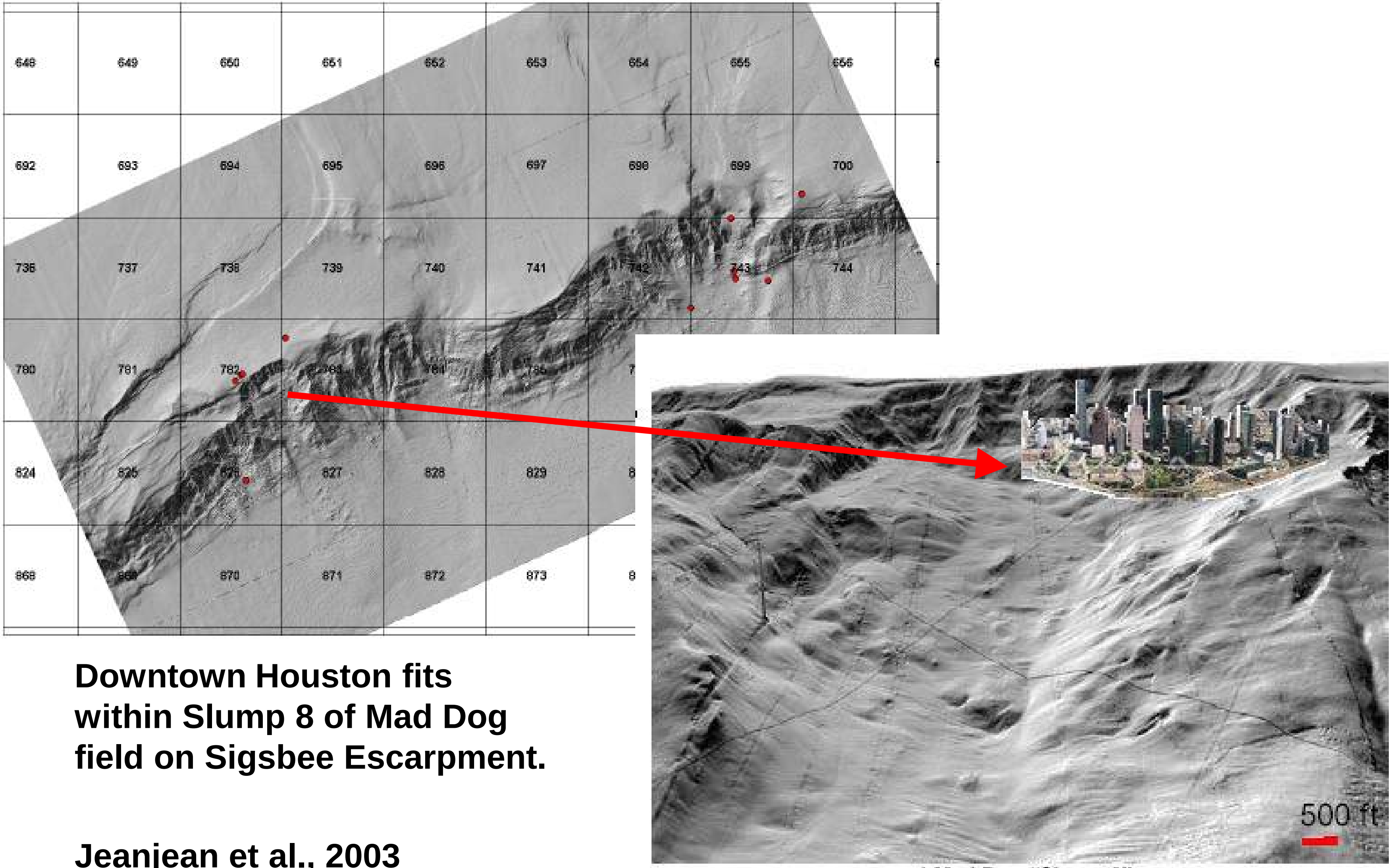
Sigsbee Escarpment – Gulf of Mexico

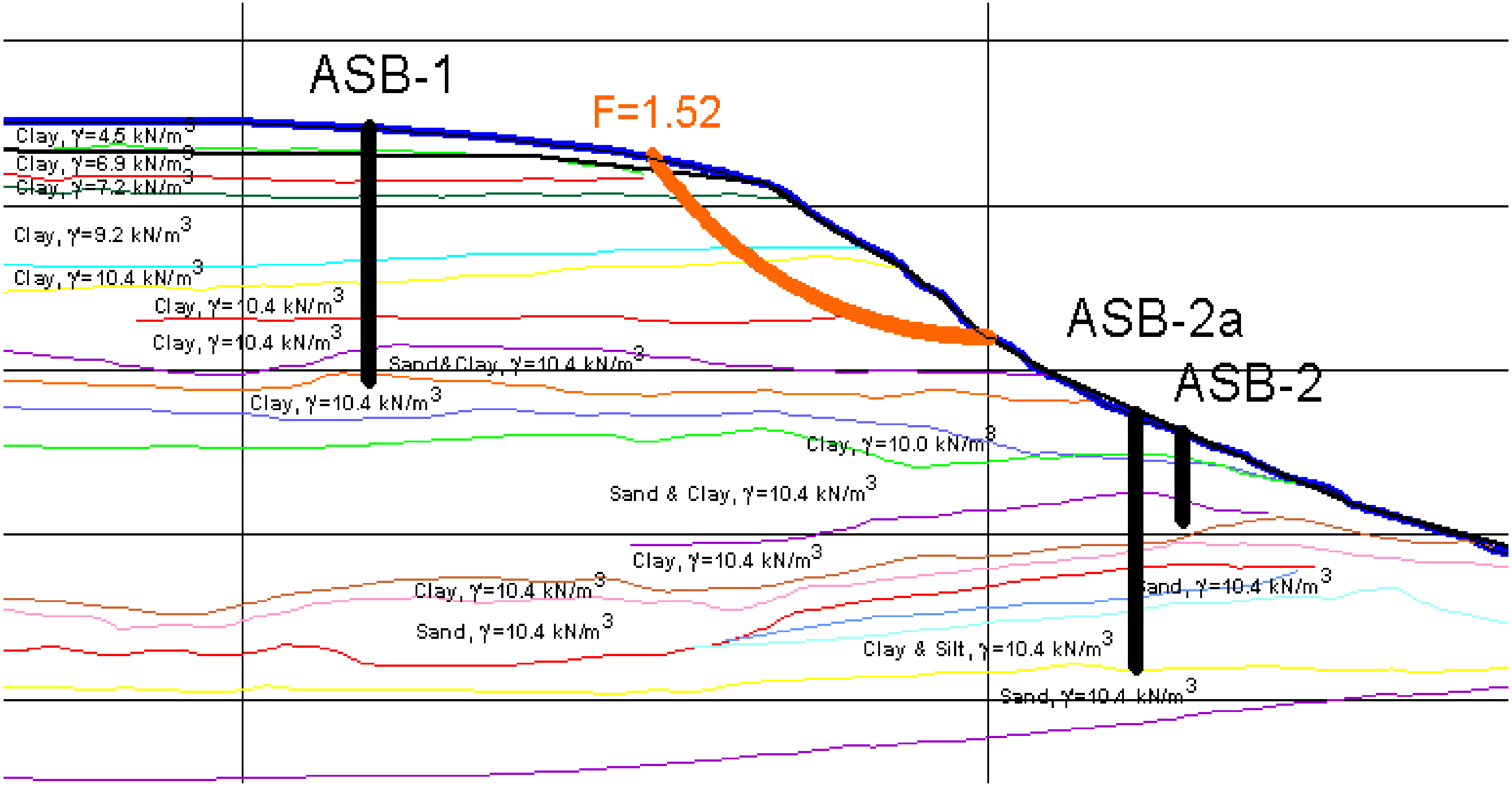


a) Mad Dog "Slump 8"

Downtown Houston fits within Slump 8 of Mad Dog field on Sigsbee Escarpment.

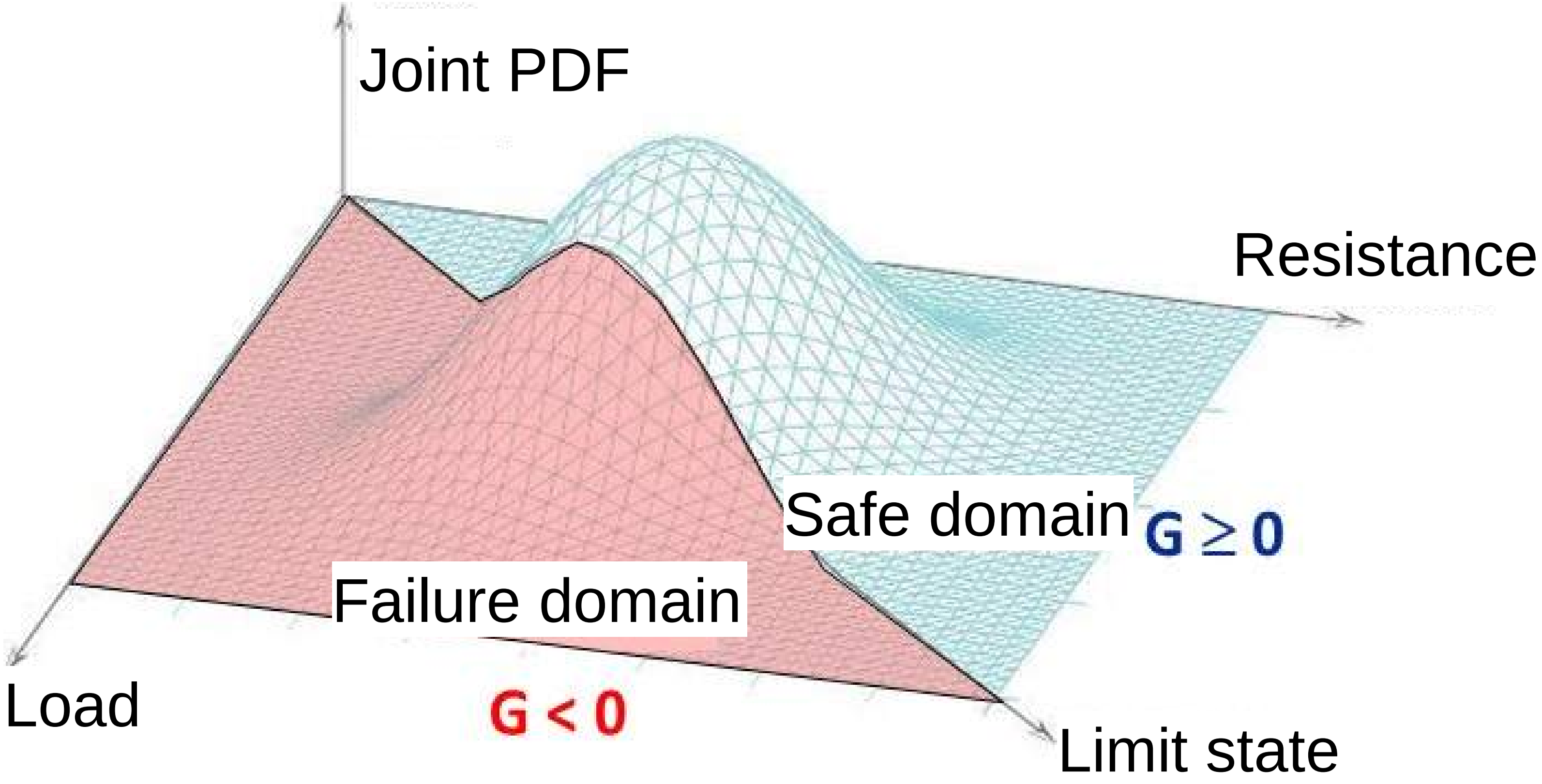
Jeanjean et al., 2003

Atlantis Field, Slump E – Undrained stability



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).

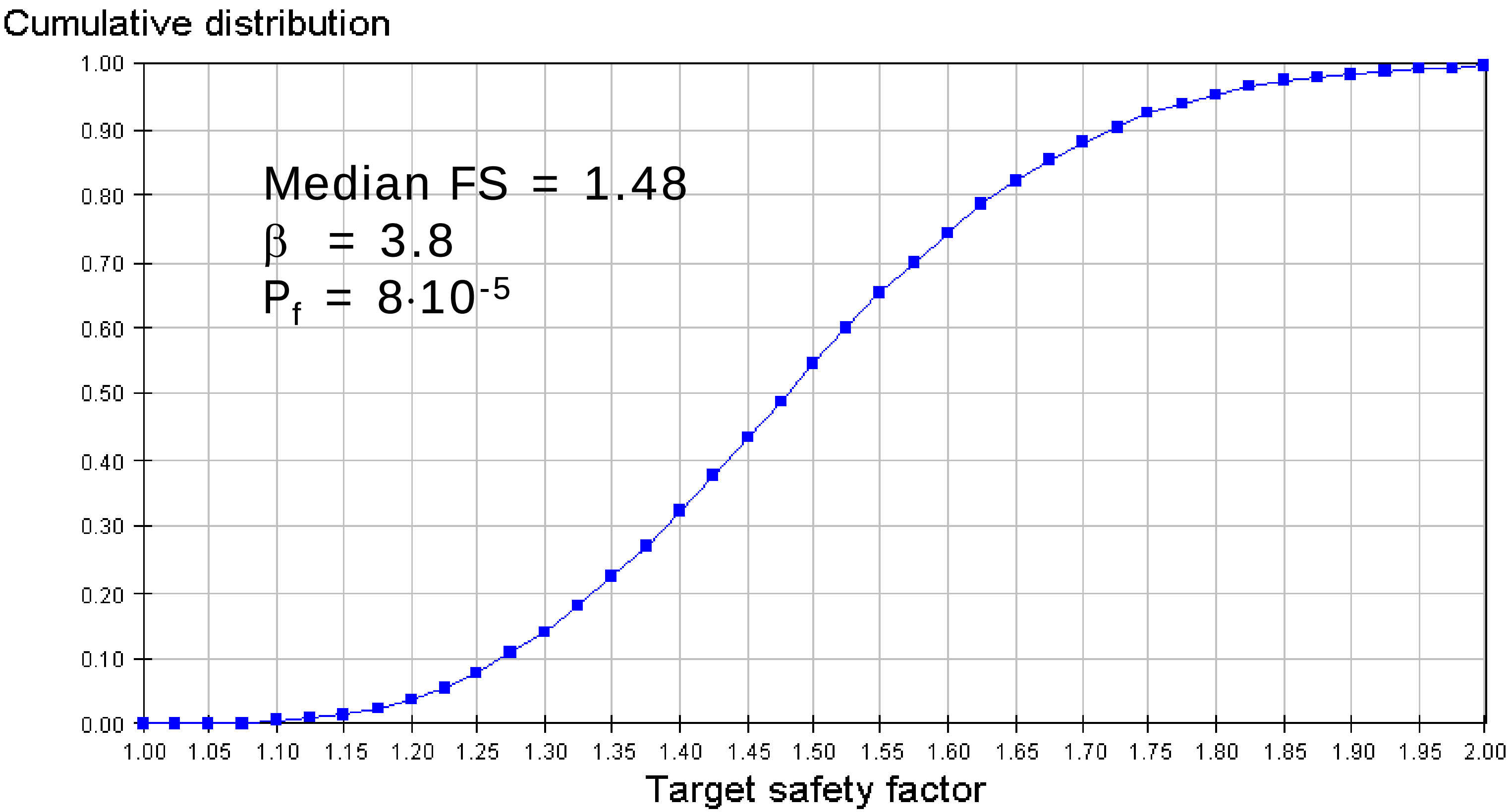


Probabilistic analysis with FORM

- 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.

Distribution of safety factor - Slump E



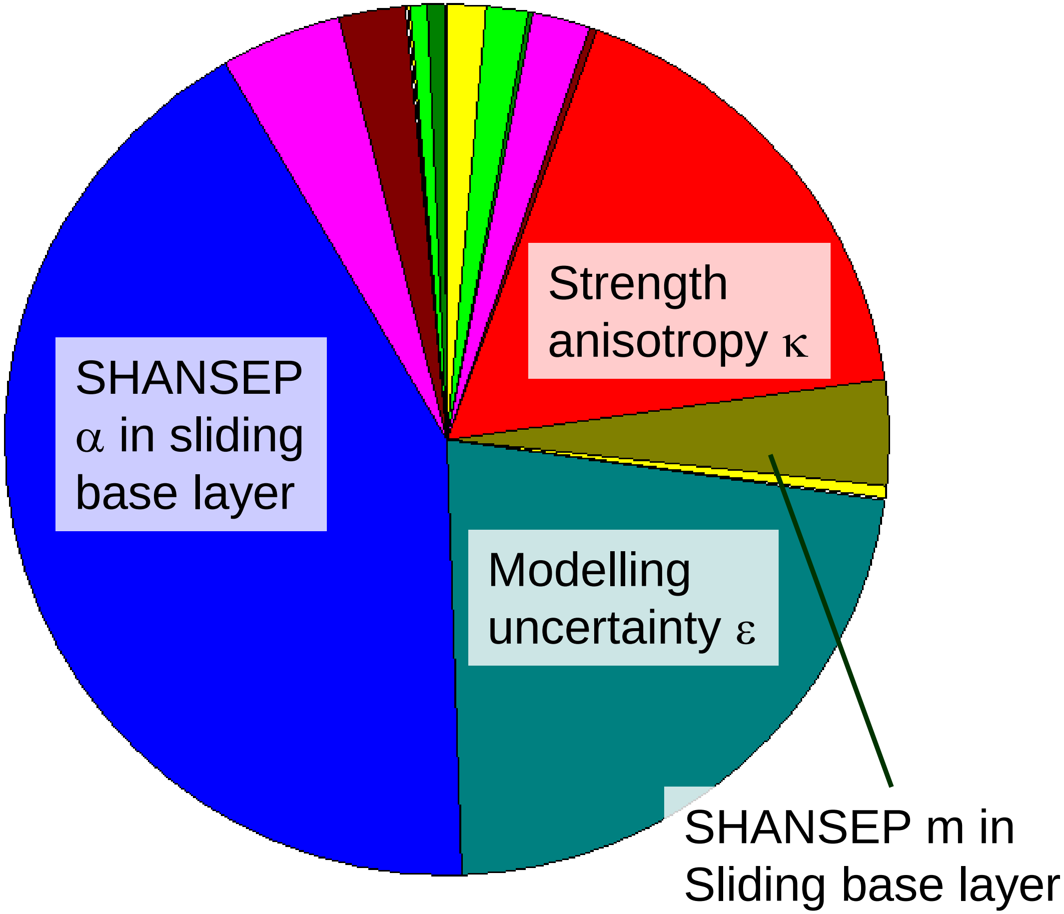
Median FS = 1.48

$\beta = 3.8$

$P_f = 8 \cdot 10^{-5}$

Cumulative distribution function is evaluated numerically using FORM. This was done by varying the target safety factor and evaluating $P[FS \leq FS_{target}] = P[FS - Fs_{target} \leq 0]$

Sensitivity factors for random variables - Slump E



Parameters contributing most to total uncertainty:

1. Soil shear strength parameters α and m (increasing importance with depth)
2. Modelling uncertainty
3. Anisotropy parameter
4. Elevation of seabed prior to previous slide
5. Maximum past pressure in deep layers

Outline

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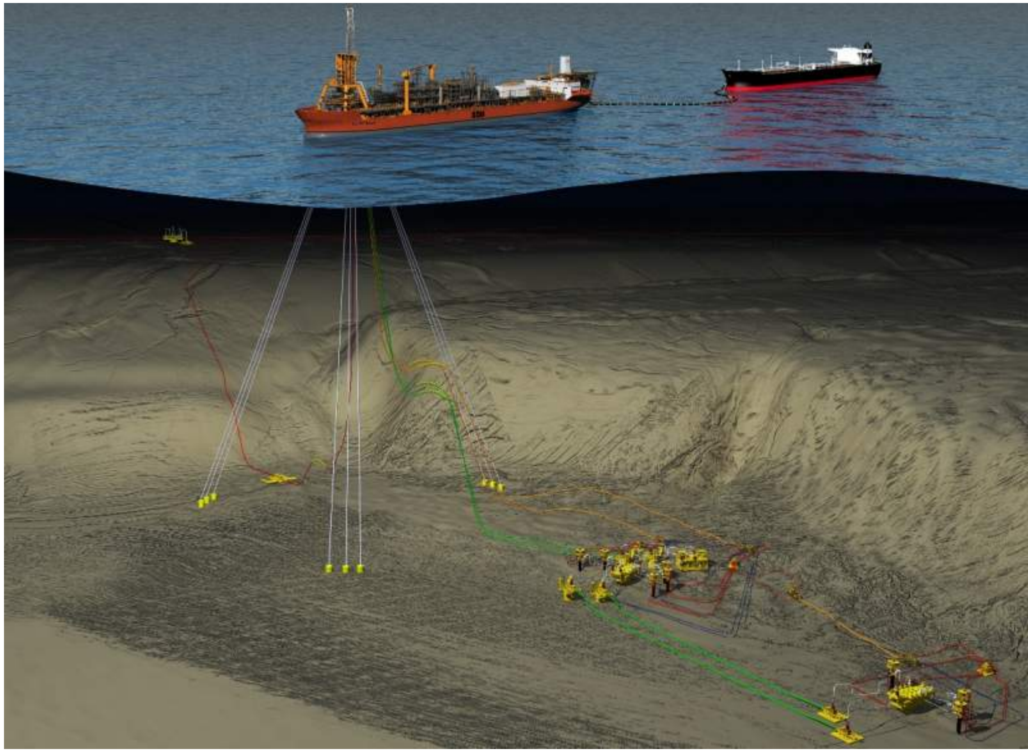
Anonymous Project



- 320 km offshore
- 2900 m water depth
- FPSO & 2 Subsea Drill Centres
- 60,000 bpd capacity
- Disconnectable turret
- Oil export by shuttle tanker
- Gas export / import by pipeline
- 9 mooring lines with suction pile mooring anchors

A floating production storage and offloading (**FPSO**) unit is a floating vessel used by the offshore oil and gas industry for the production and processing of hydrocarbons, and for the storage of oil.

Main objectives & work flow chart

- To determine the annual probability of a debris flow impacting the drill centers (DC)
- To establish annual probability contours of runout distances in the area of interest (DC2)

Critical sections

Slope stability assessment

Volume of possible slide

Calibration of pseudo-3D runout model

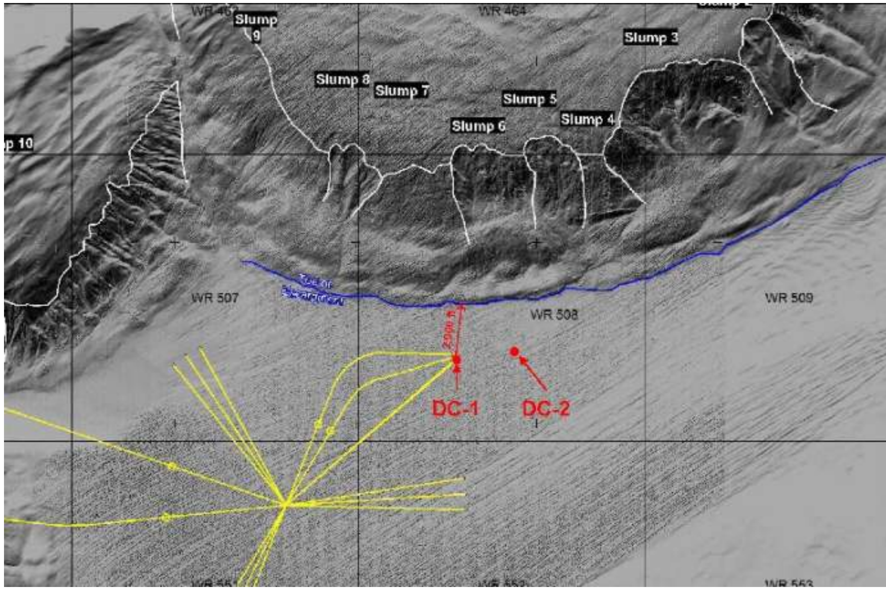
Calibration of 2D model against 3D model

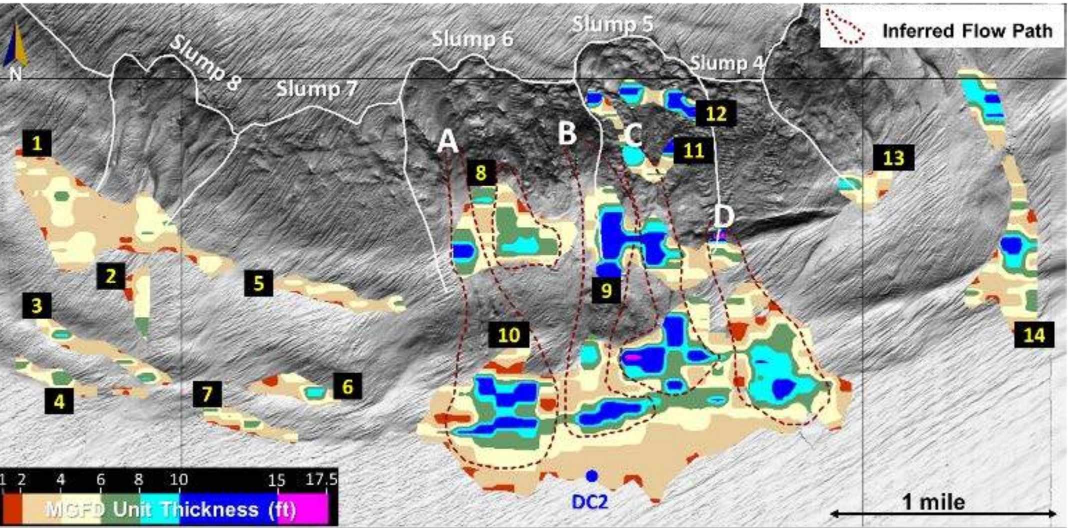
MCS using calibrated 2D model

Fitting probability distribution functions

Calculation of p(debris flow impact)

- The primary geologic processes at the Stones site include: sediment uplift, faulting and slope instability
- Slump zones of interest: Slumps 4, 5 and 6 (Upper picture)
- Main hazard to DC2 is debris flows initiating from slump zone 6
- A best estimate of six debris flow events occurred below slump zone 6 during the past 19,000 years (Lower picture)

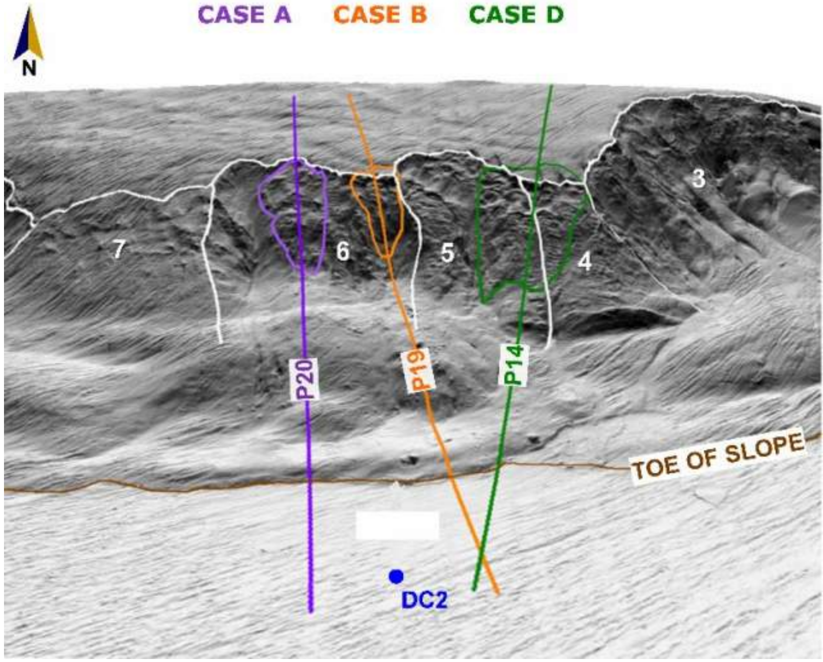




Geological setting

Deterministic slope stability analyses

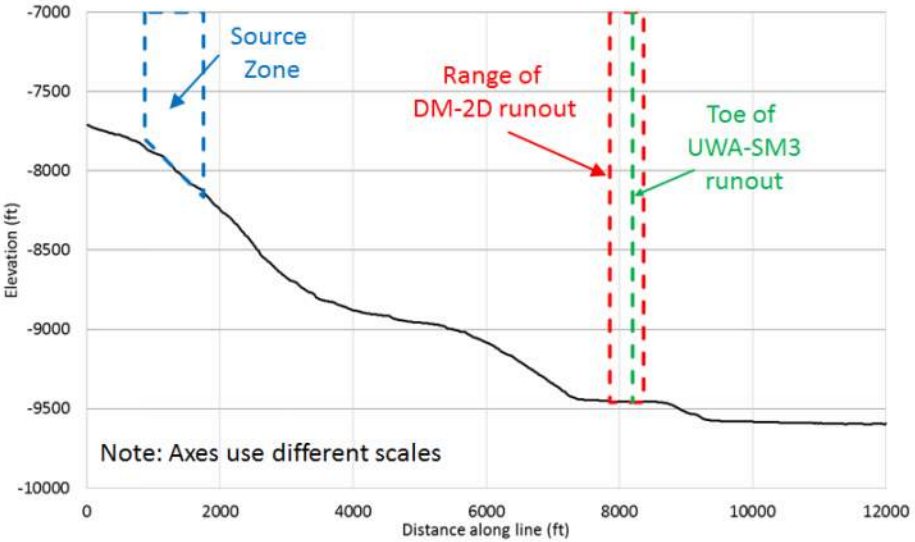
- Used SLOPE/W
- Selected 3 profiles among numerous candidate cross sections
- Drained condition governed
- Drained friction angle of intact soil: 26° and 23° from triaxial tests
- Residual friction angle of faults: 16° and 14° from ring shear tests



Profile	Drained factor of safety	Area of critical slip surface	Deepest depth
P20	1.23	3,270 m^2	27m
P19	1.17	12,400 m^2	48m
P14	1.57	9,860 m^2	37m

Calibration of 2D against 3D models

- Source zone, from the static sl stability analysis
- Range of DM-2D (Niedoroda e 2003) runout, from calibration pseudo-3D model



- UWA-SM^3 (Boylan & White, 2017) from calibration of pseudo-2D model
- Good agreement between results of 2D and 3D models after calibration

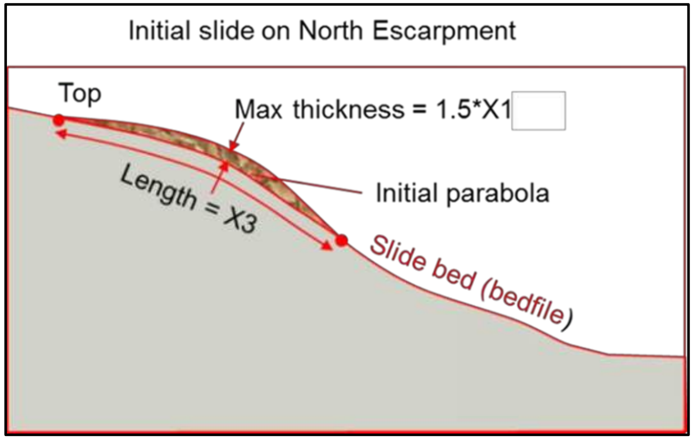
Probabilistic run-out simulations

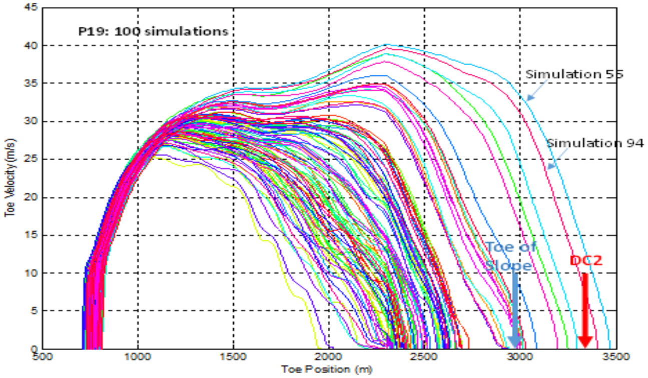
Four random variables selected:

- maximum slide thickness
- yield stress (viscosity assumed to be perfectly correlated with yield stress)
- slide length
- a random modelling error (Normal dist., added to the calculated maximum run-out lengths)

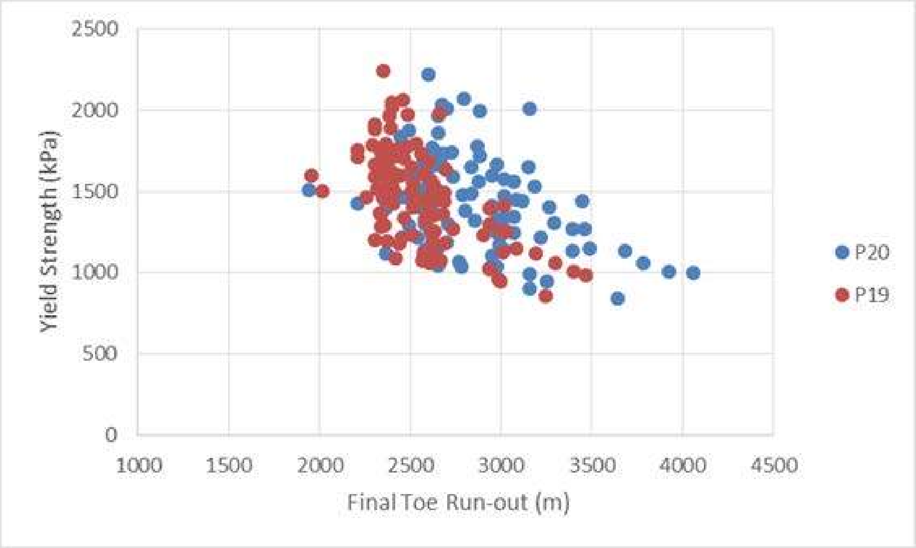
Probabilistic run-out from UWA-SM^3 ,

100 simulations each for P19 and P20

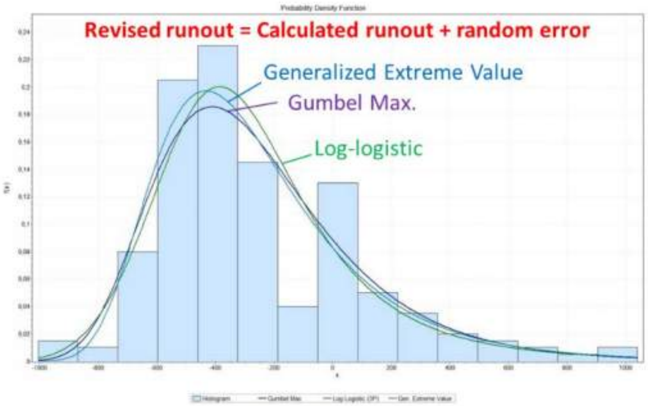




Probabilistic distributions of run-out



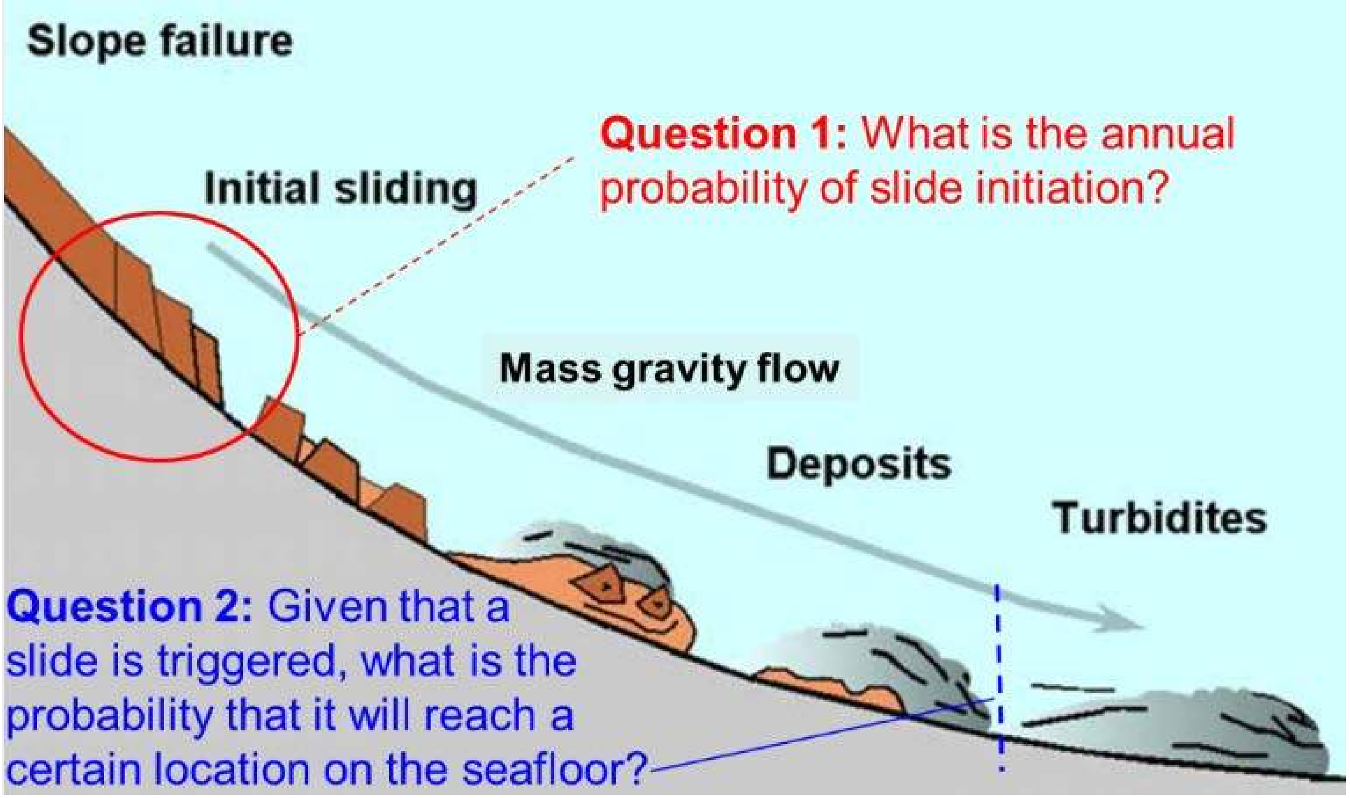
Maximum calculated runout distances



Maximum run-out distances

R	Distribution type	Parameters
1	Gen. Extreme Value	k=0.05858, σ =255.23, μ = -418.96
2	Log-logistic (3P)	α = 5.1077, β = 905.24, γ = -1224.0
3	Gumbel Max	σ = 270.78 μ = -412.3

Probability of run-out reaching a location



Question 1: What is the annual probability of slide initiation?

Question 2: Given that a slide is triggered, what is the probability that it will reach a certain location on the seafloor?

$$P[\text{runout reaching a location}] = P_{\text{slide initiation}} \times P_{\text{runout going past the location}|\text{Slide has occurred}}$$

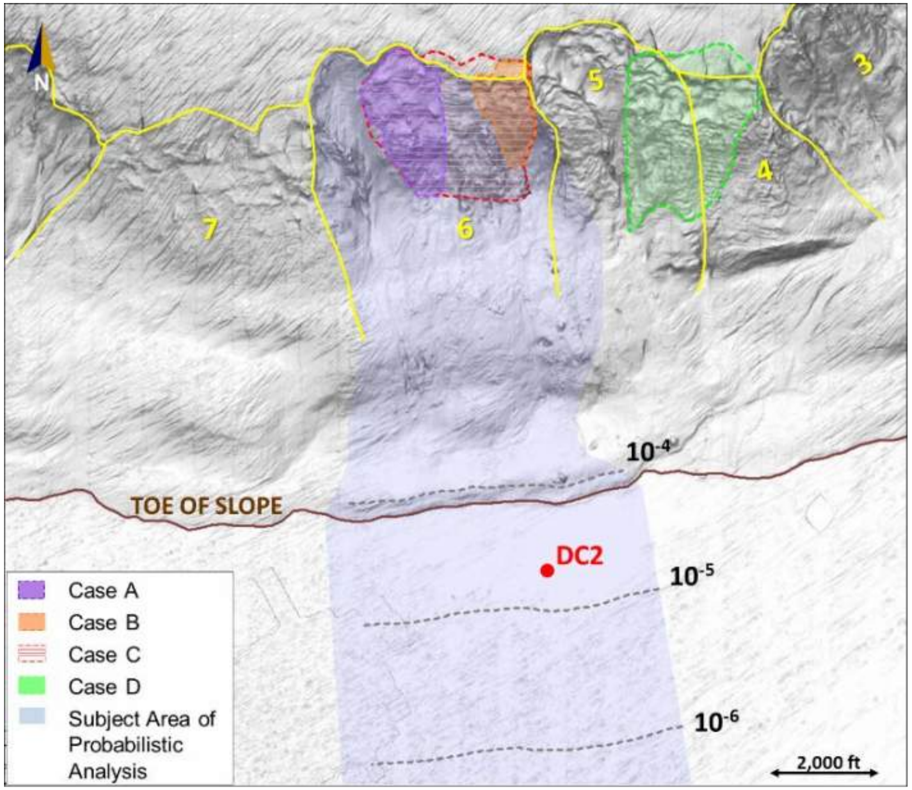
Estimated from dating of previous slide events

where $P_{\text{slide initiation}}$ = Annual probability of slide initiation

$P_{\text{runout going past the location}|\text{Slide has occurred}}$ = Conditional probability of runout reaching a location given that a slide has occurred

Estimated from MCSs of runout

Hazard contours of annual probability of impact by debris flow



Location of contour lines w.r.t. toe of slope

P_{annual}	Generalised extr.	Log-logistic	Gumbel
10^{-4}	-116m	-126m	-101m
10^{-5}	602m	600m	561m
10^{-6}	1383m	1653m	1187m

Conclusions

- Debris flow impact on subsea installations at DC2 represents a significant risk to the development.
- The study required a multi-disciplined approach with close collaboration among experts in geotechnics, geology and geophysics.
- Understanding of past conditions is the key to making reasonable predictions of future events.
- Together with the deterministic analyses, the probabilistic approach provides a good basis for risk-based decision making and was also the key to evaluating the risk to the drill centre location.

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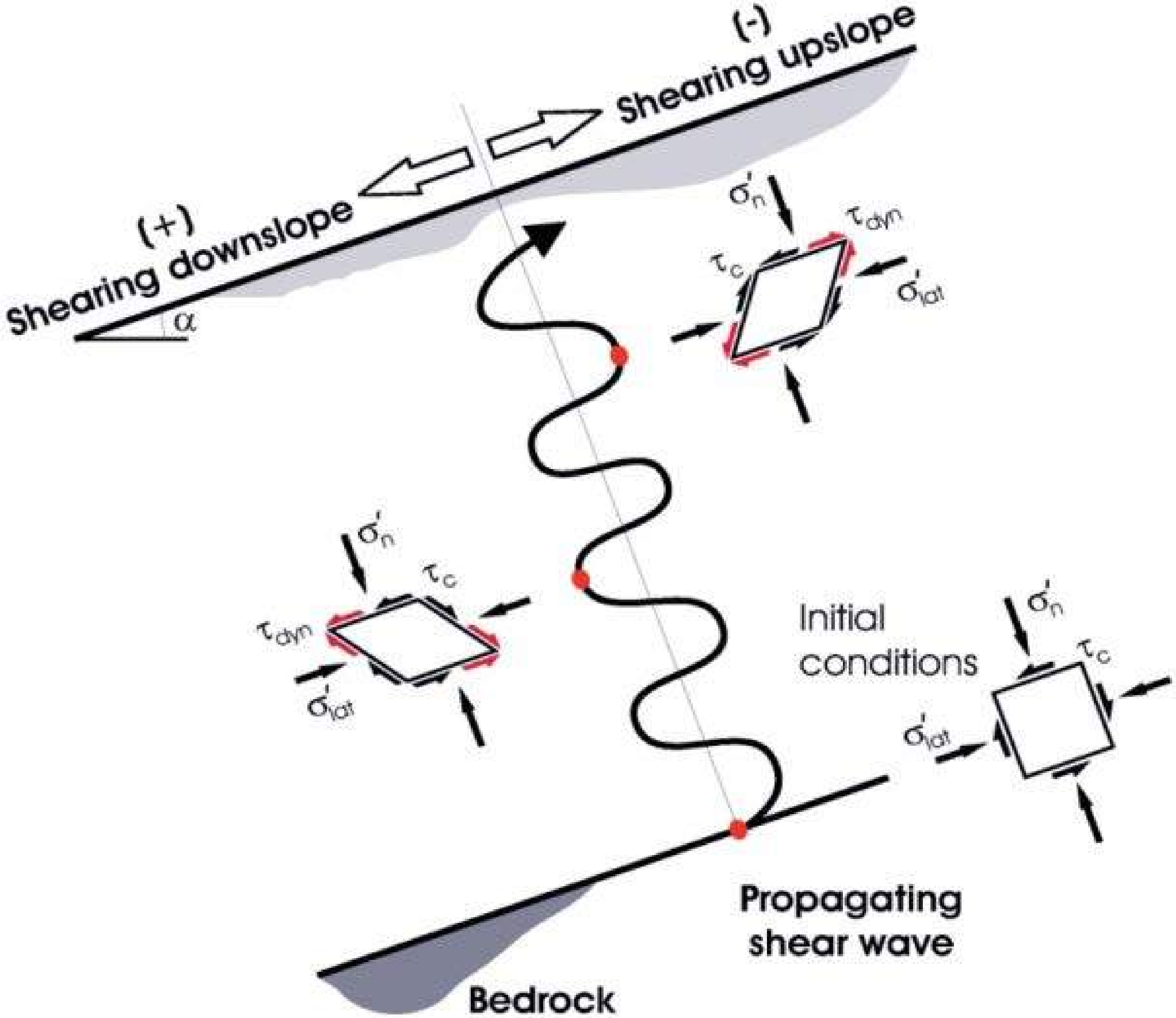
Submarine slope, deepwater Probabilistic slope stability analysis under earthquake loading

1. Identify the critical slopes.
2. Quantify the uncertainty in the soil properties and do probabilistic assessment of static slope stability.
3. Update the probabilistic assessment based on the geological evidence (that the slope has adequate static stability).
4. Evaluate the annual probability of the slide-triggering events.
5. Assess the effect of the triggering event(s) scenarios on the stability of critical slope(s).
6. Combine the assessments in steps 2 through 5 to come up with the annual probability of slope failure and volume and geometry of the potential slide.

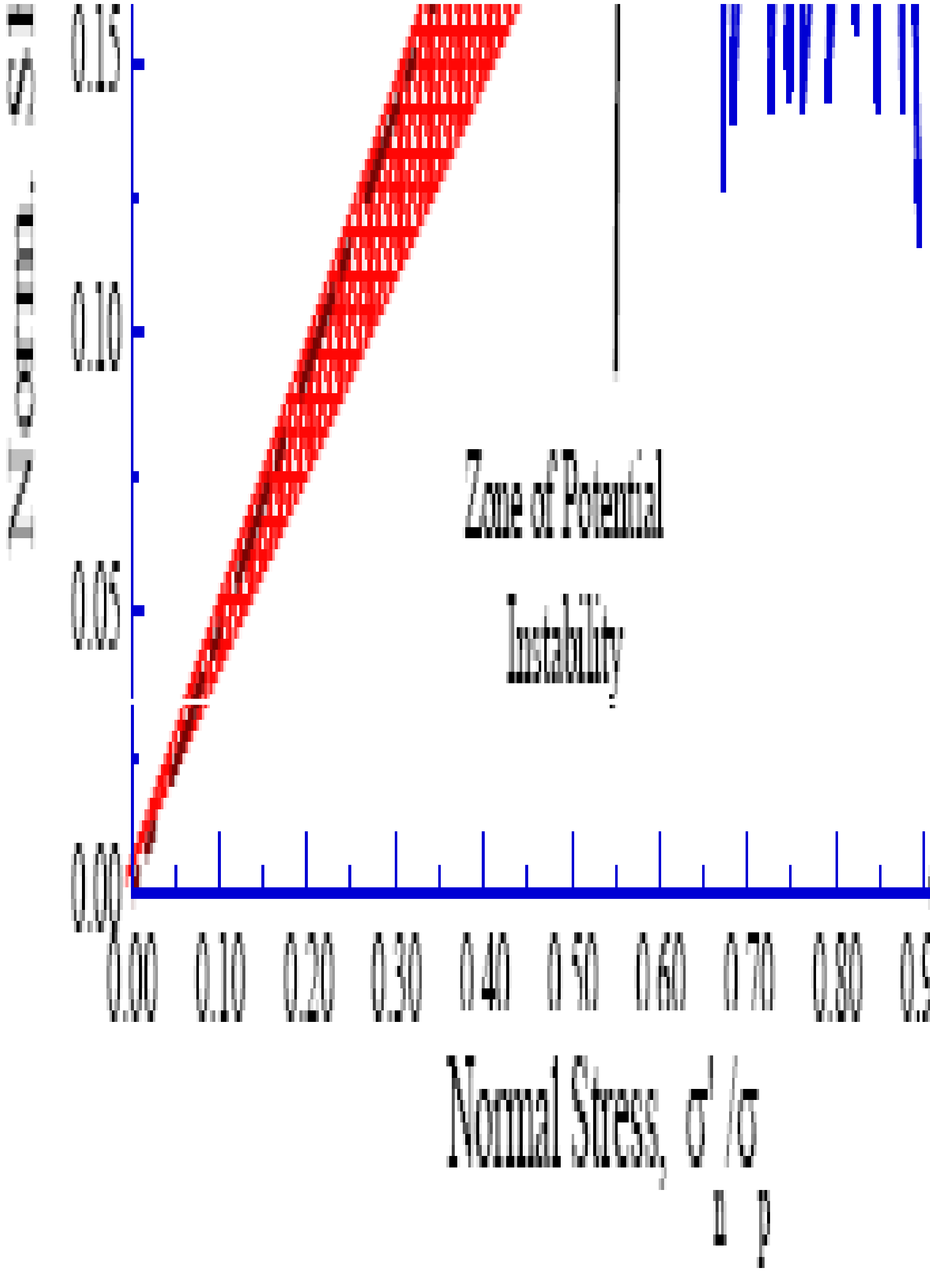
Infinite slope under 1D seismic excitation (Nadim *et al* 2007)

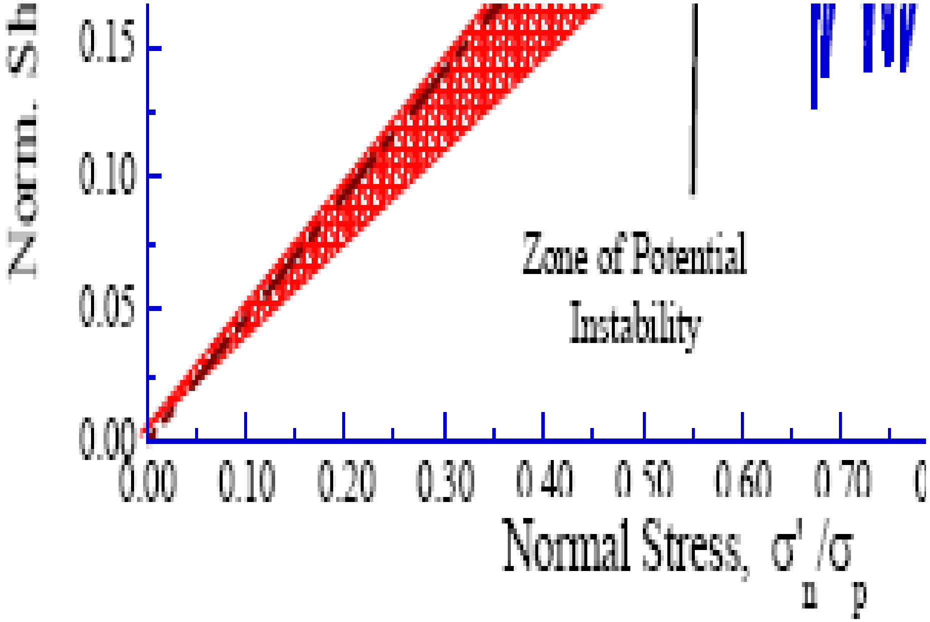


Three scenarios of earthquake-induced slope failure (Biscontin et al 2004)

1) Failure occurring during the earthquake, where excess pore pressures generated by the cyclic stresses degrade the shear strength;
2) Post-earthquake failure due to increase in excess pore pressure caused by seepage from deeper layers
3) Post-earthquake failure due to creep and reduction of the shear strength. Soils with significant strain-softening are most susceptible to failure during earthquake shaking.

Stress paths for elements on slip plane for three earthquake-induced slope failure scenarios





Probabilistic Slope Stability Assessment

- $G(\boldsymbol{X}) = FS - 1$
- $P_f = \int_L F(X)\, d(X)$
- $P_f = P\,[G(\boldsymbol{U}) < 0] \approx P\,[\,\alpha_i U_i - \beta < 0] = \Phi\,(-\beta)$

Estimation of Annual Probability of Slope Failure

- The annual probability for a slope instability may be estimated from the geological evidence, e.g. observed slide frequency, geological history, geophysical investigations, and radiocarbon dating of sediments; while in other situations analytical simulations (e.g.the FORM approach) are more suitable. Ideally, both approaches should be used.

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:

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

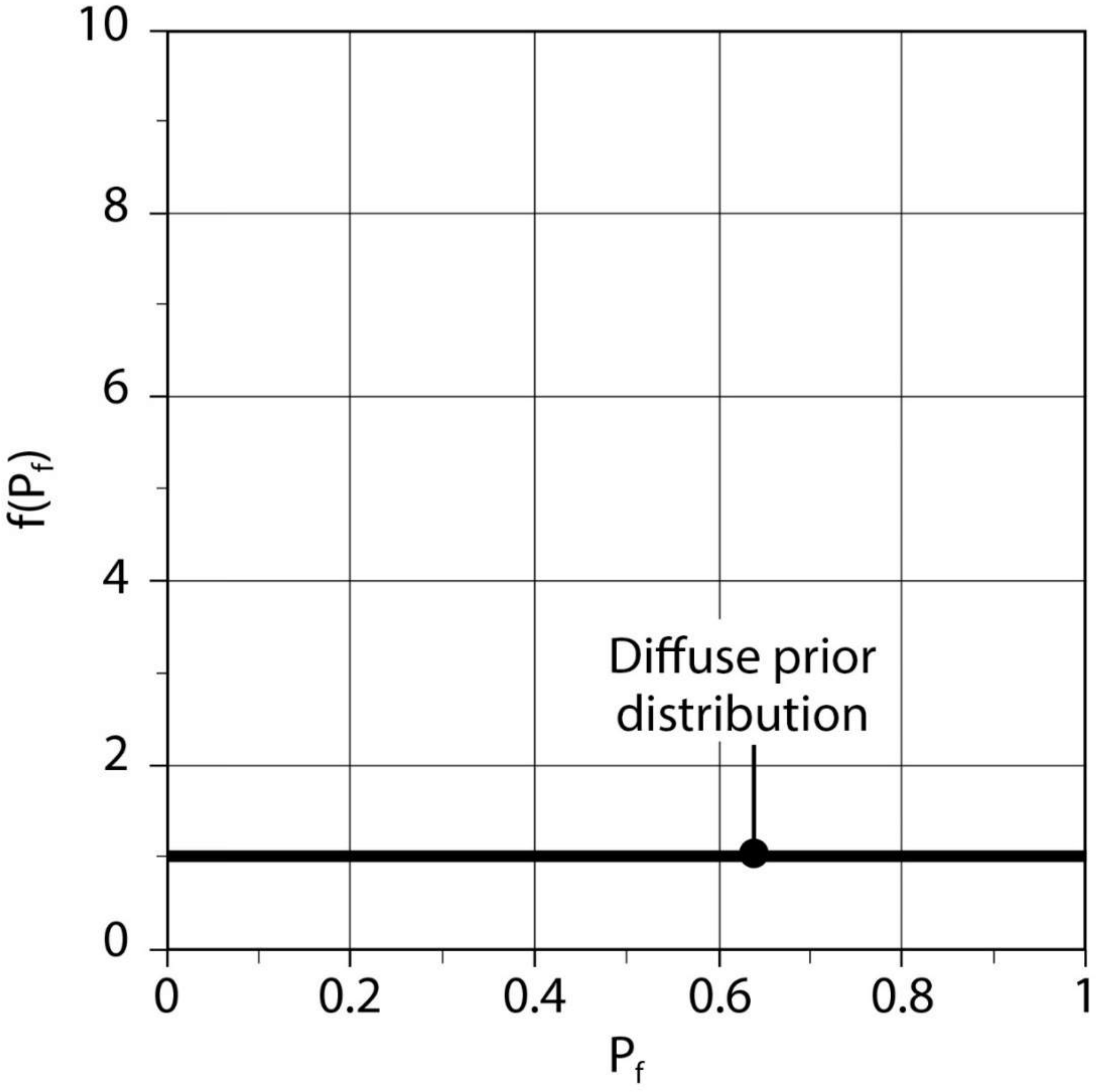
$$E[P_f] = (r+1)/(n+2)$$

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

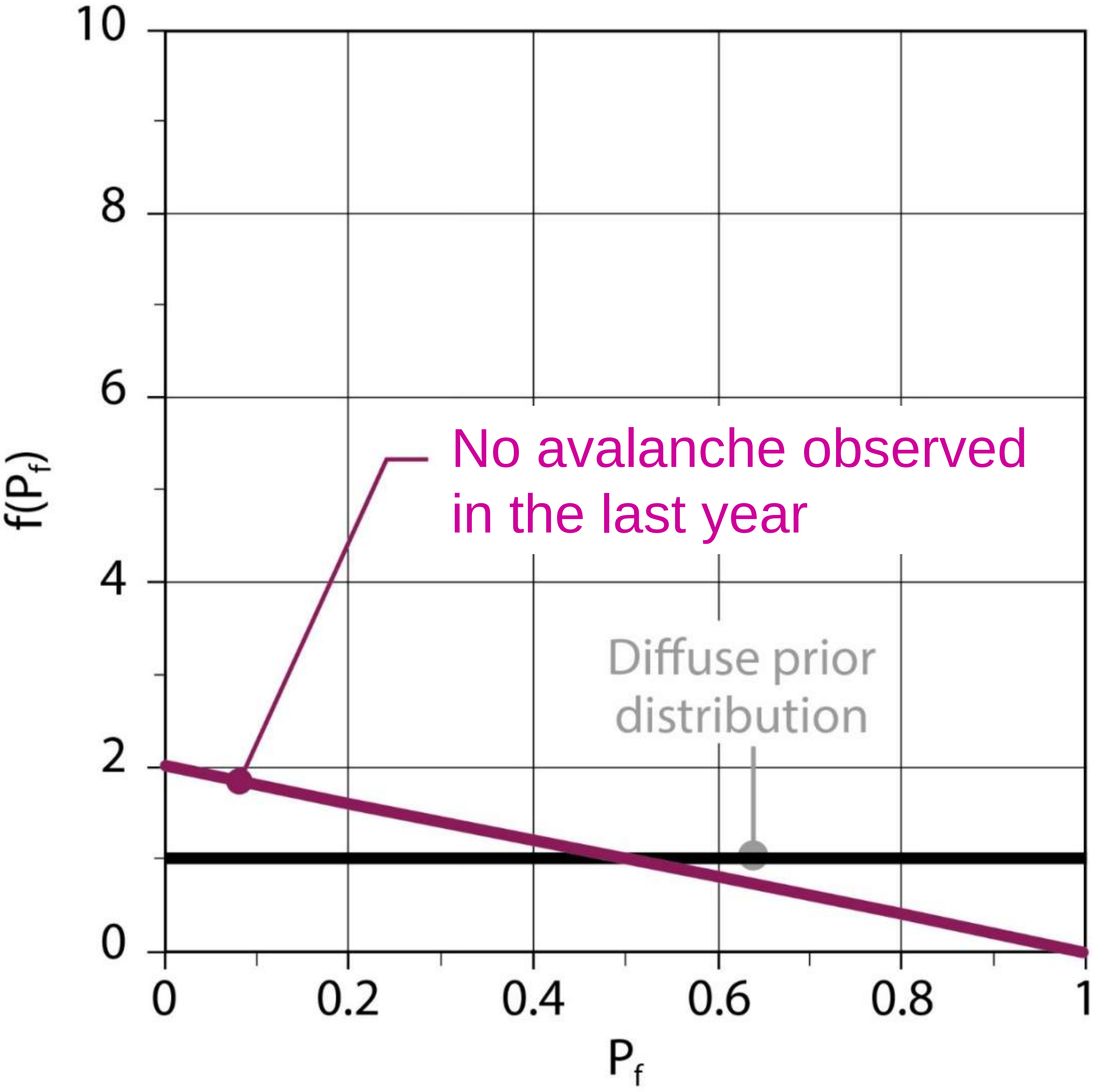
No landslide during past 100 yrs $\Rightarrow$ $E[P_f] \approx 1.0 \cdot 10^{-2}$ /yr

No landslide during past 1000 yrs $\Rightarrow$ $E[P_f] \approx 1.0 \cdot 10^{-2}$ /yr

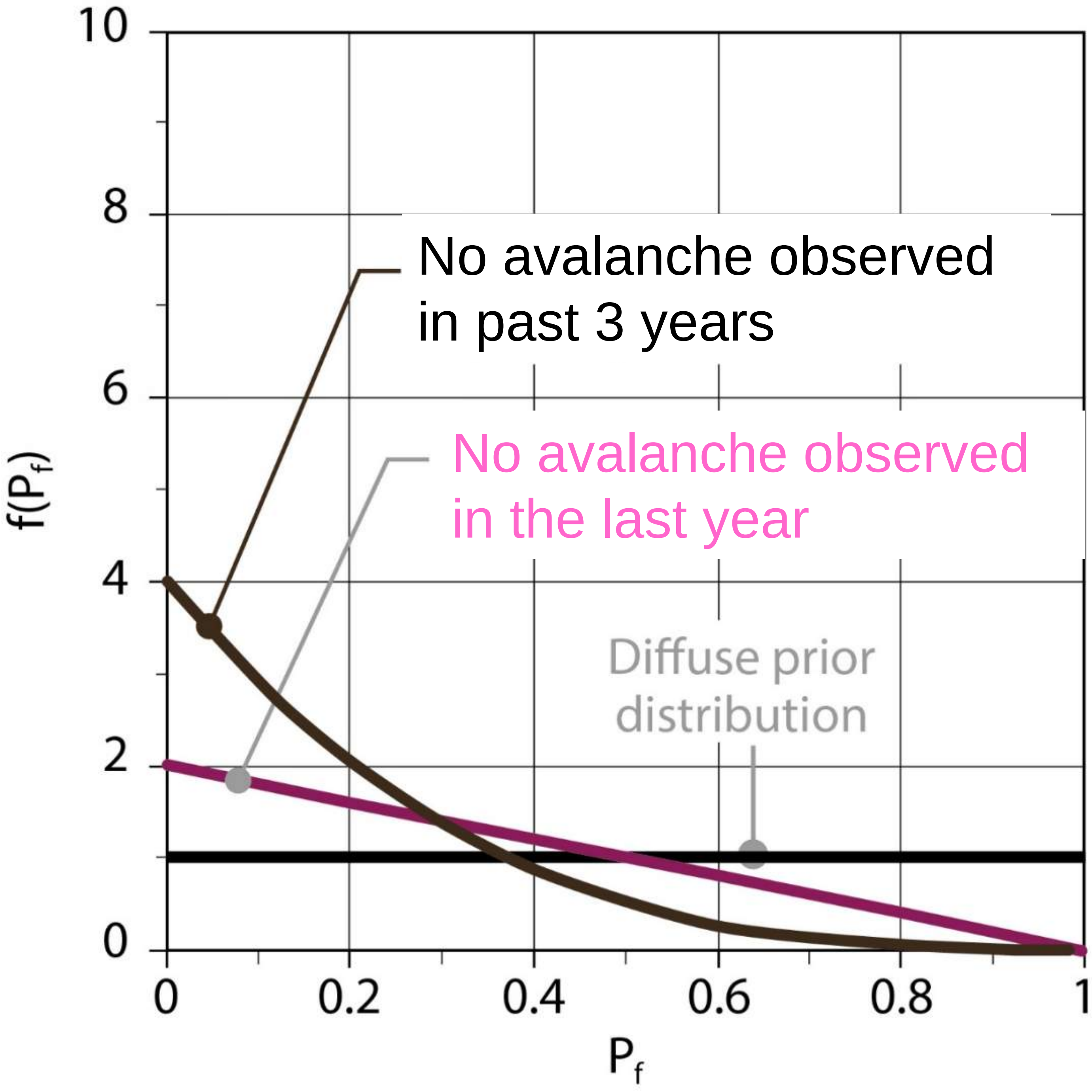
No
information



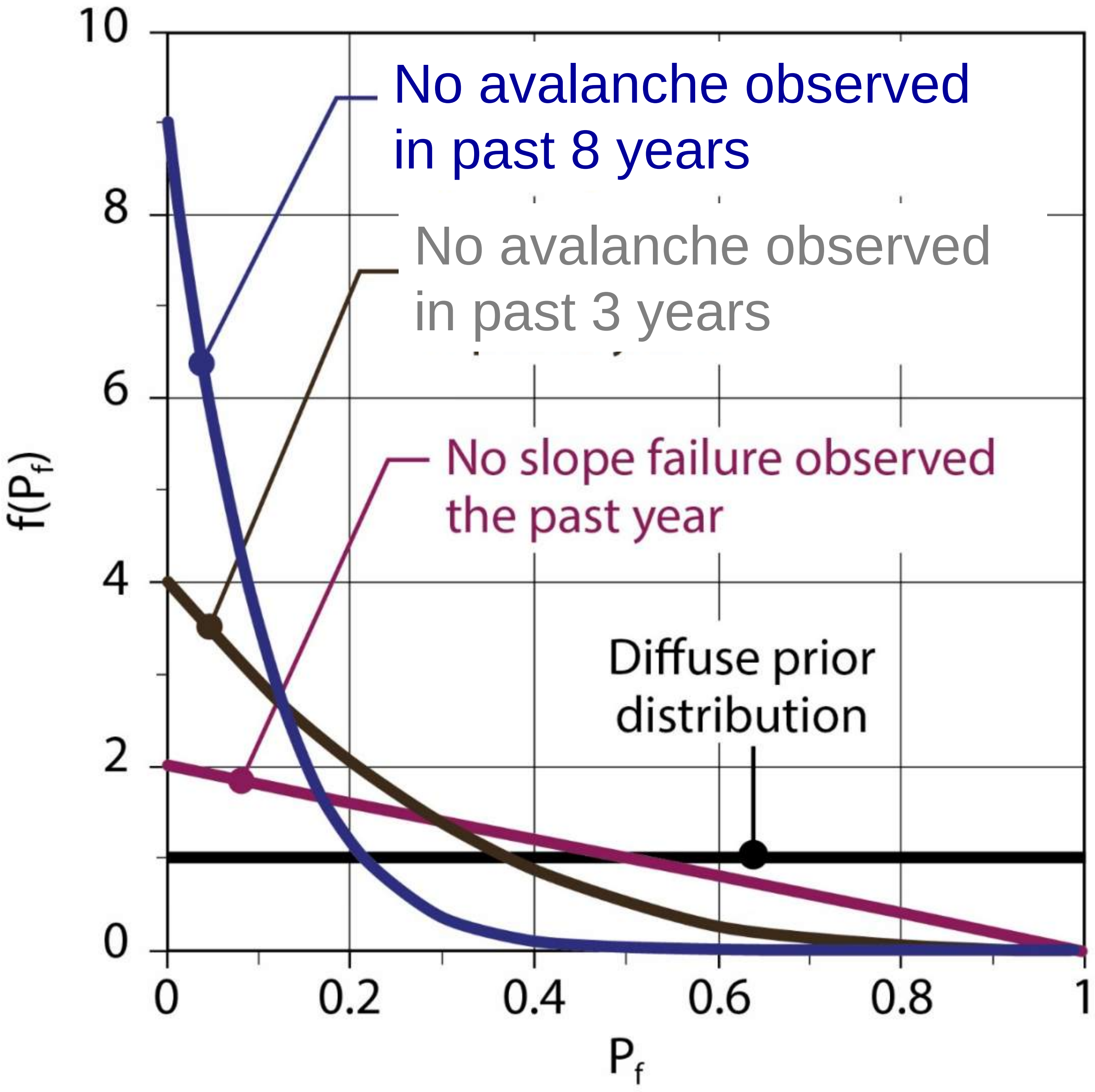
No avalanche in the past year (1 yr)



No avalanche in the past 3 years



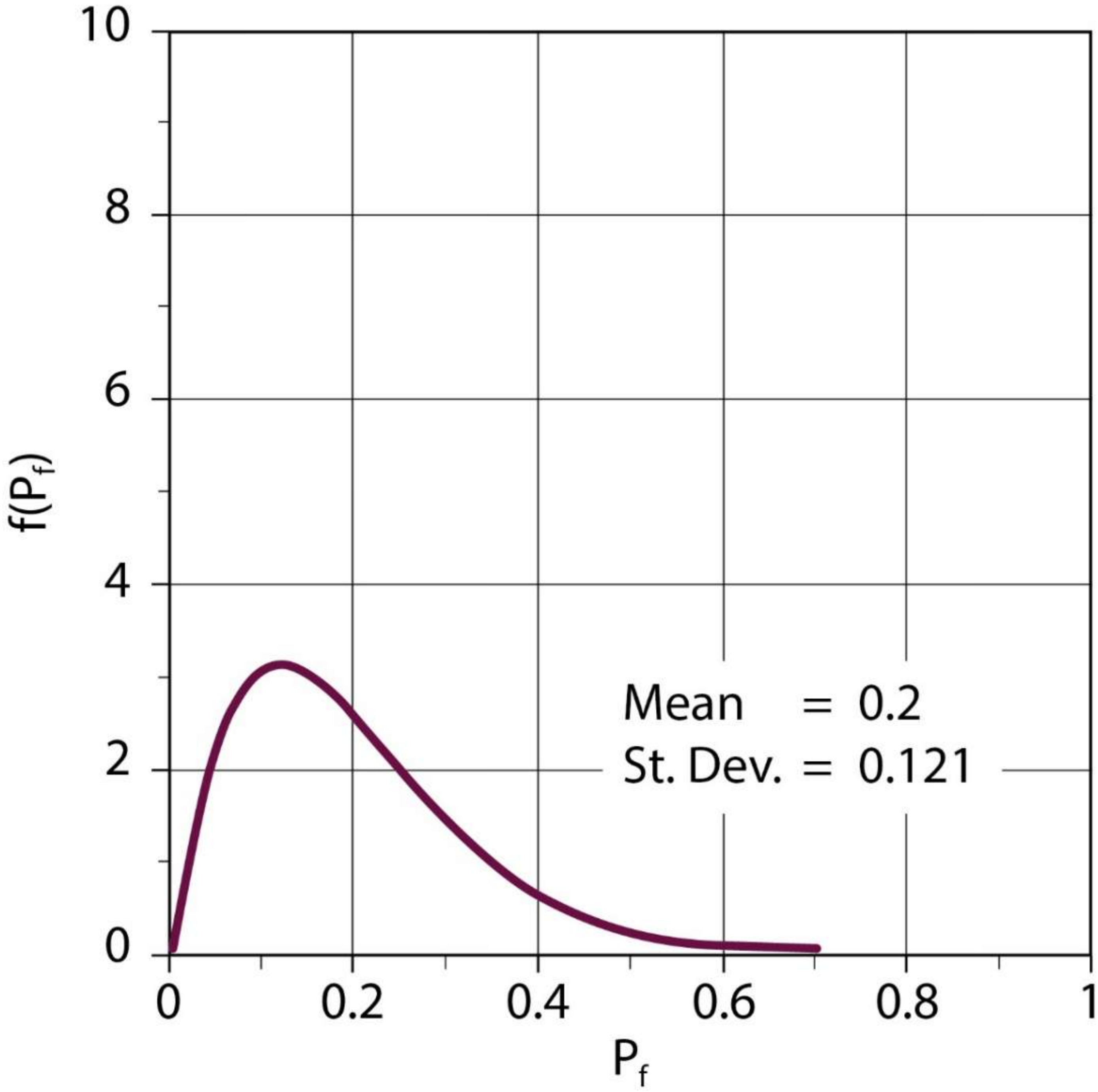
No avalanche in the past 8 years



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

if 2 avalanches observed in past 10 yrs

[Nadim *et al* 2013]

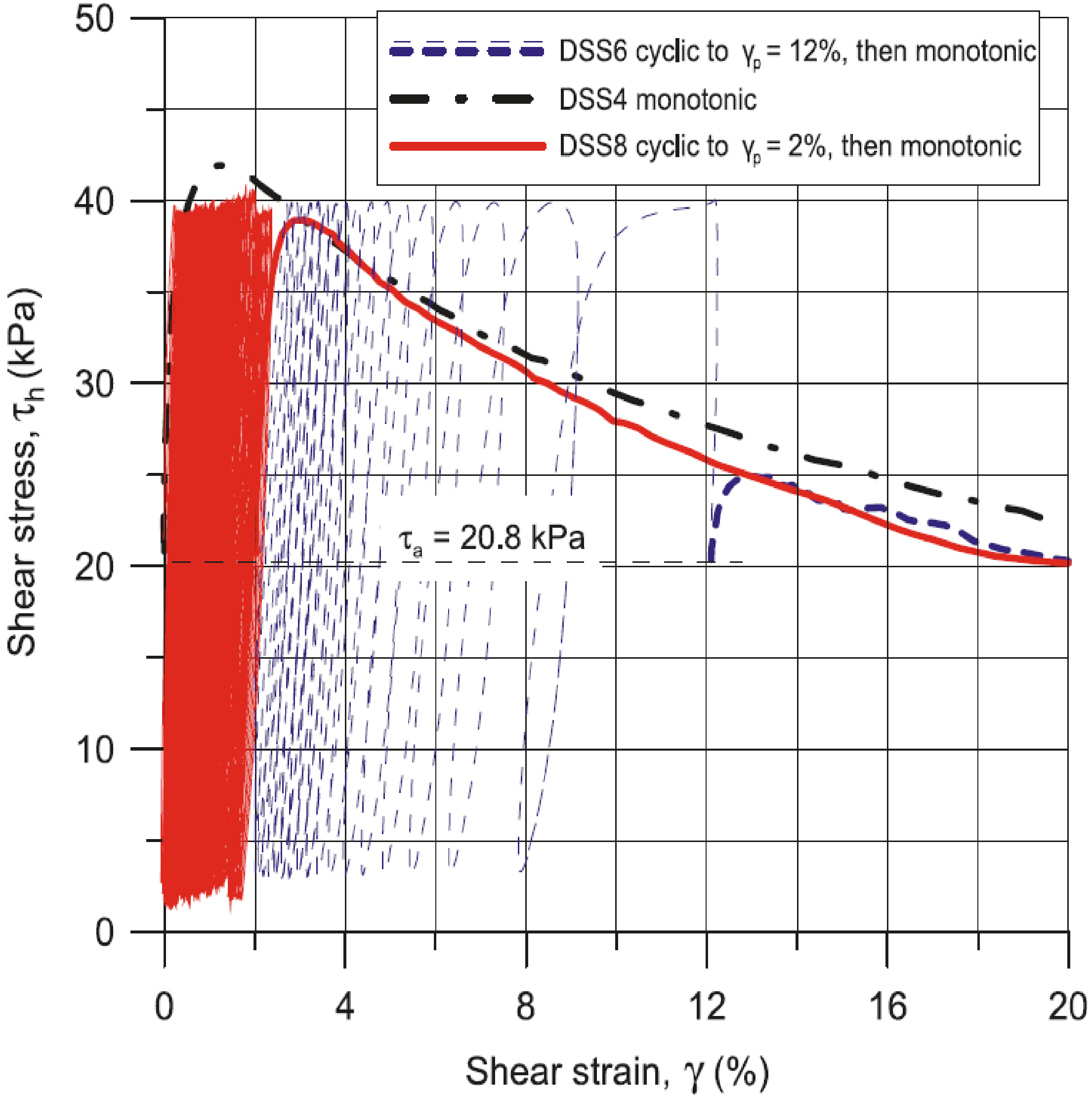


Probabilistic Slope Stability Assessment

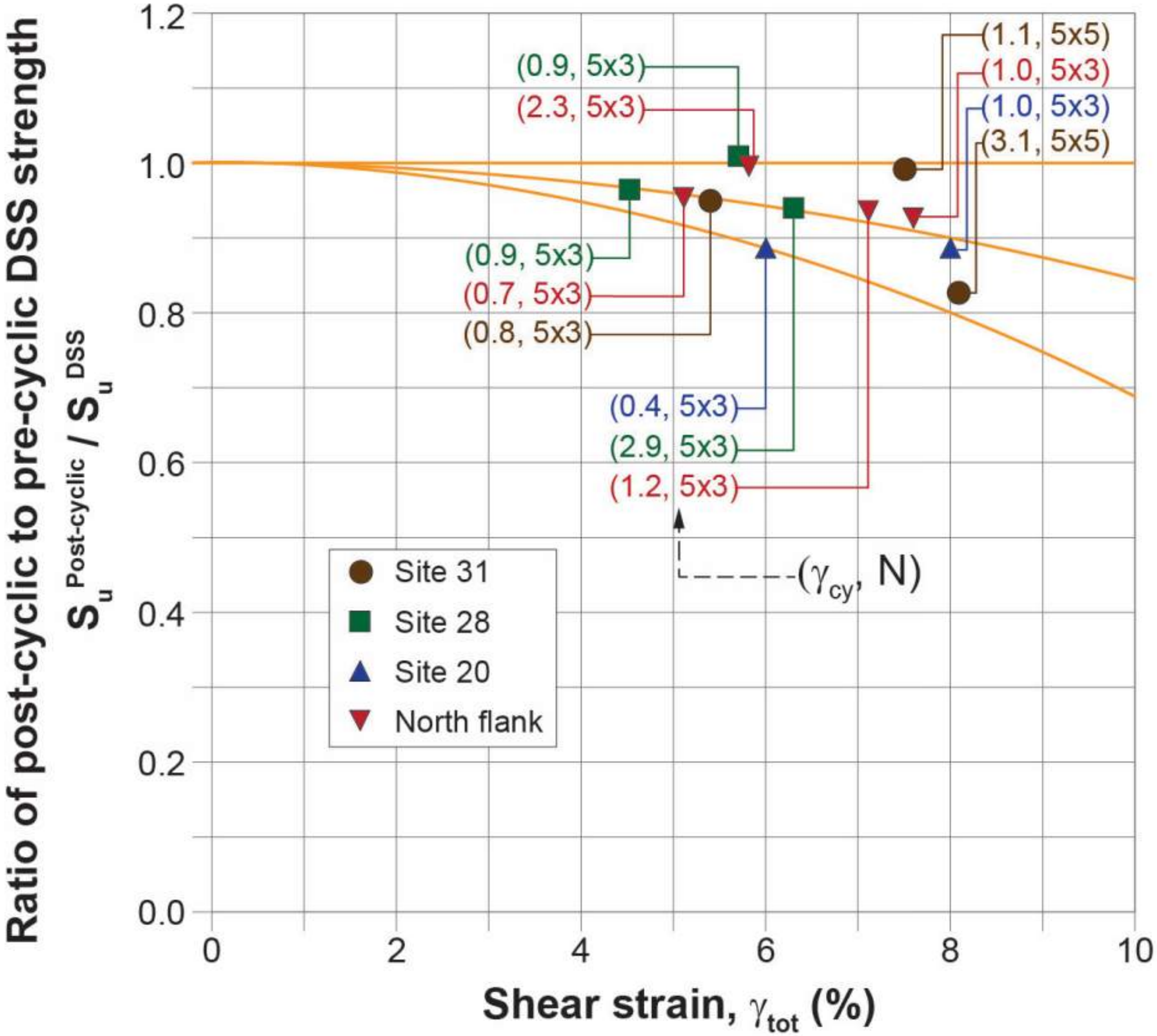
Interpretation of computed static failure probability in Bayesian framework

- The fact that the slope is standing today implies that the current FS > 1.0. The annual probability of failure becomes the likelihood that the current factor of safety will fall below one during next year. The current factor of safety is unknown, but its distribution can be computed (FORM analysis, but truncated distribution to reflect that the slope is stable today). This interpretation is Bayesian updating where the a-priori information is that FS $\geq$ 1. The slope will fail during the next year only if its current value of FS is such that, with the given rate of deterioration, it will fall below unity during one year.

Stress-strain behavior in monotonic, cyclic and post-cyclic monotonic DSS tests (Andersen 2009)

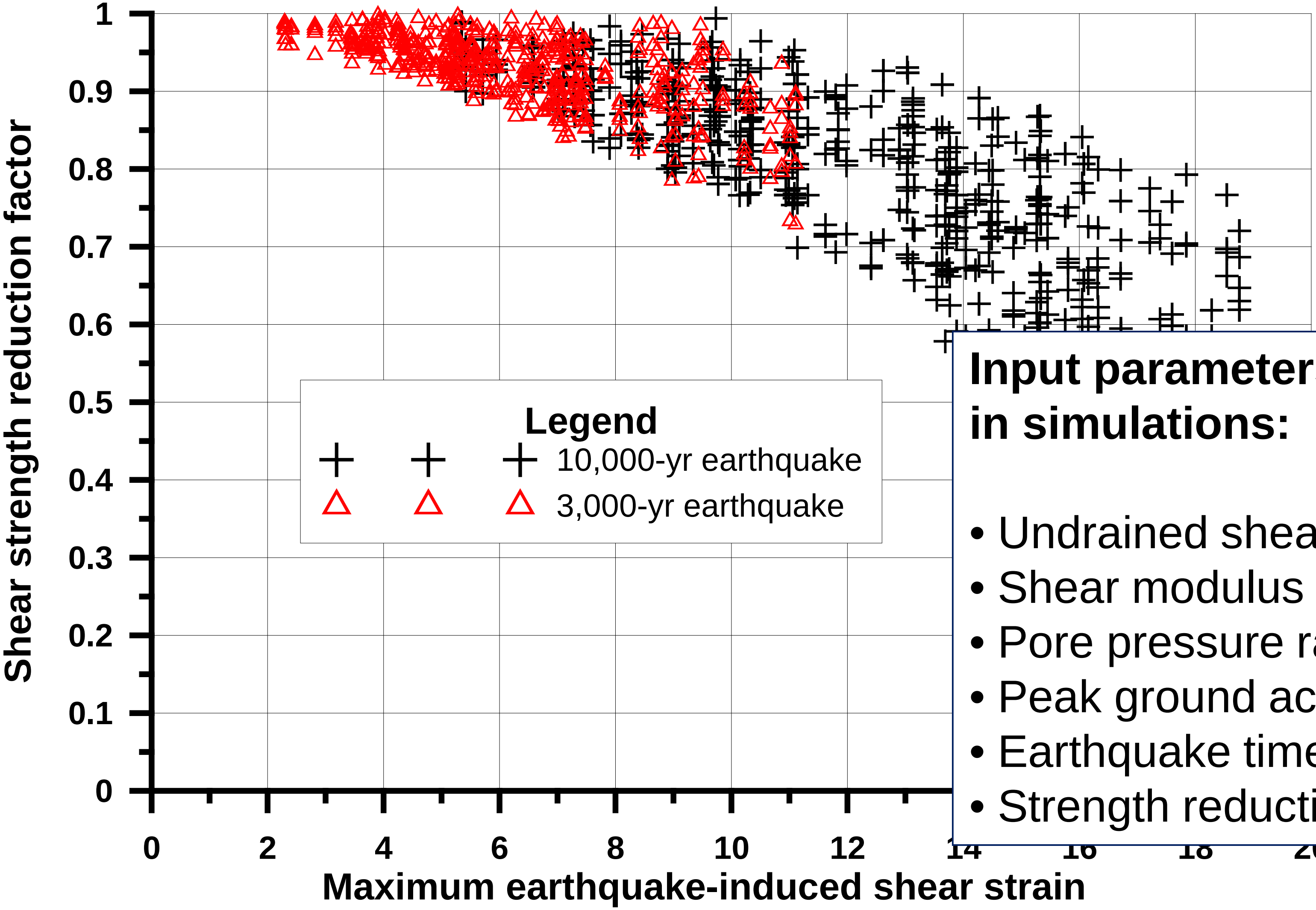


Effects of earthquake-induced shear strains on undrained shear strength of marine clay



Results of 500 simulations with AMPLE

Slope angle = 18°, Average excess pore pressure ratio = 0.1, LHS

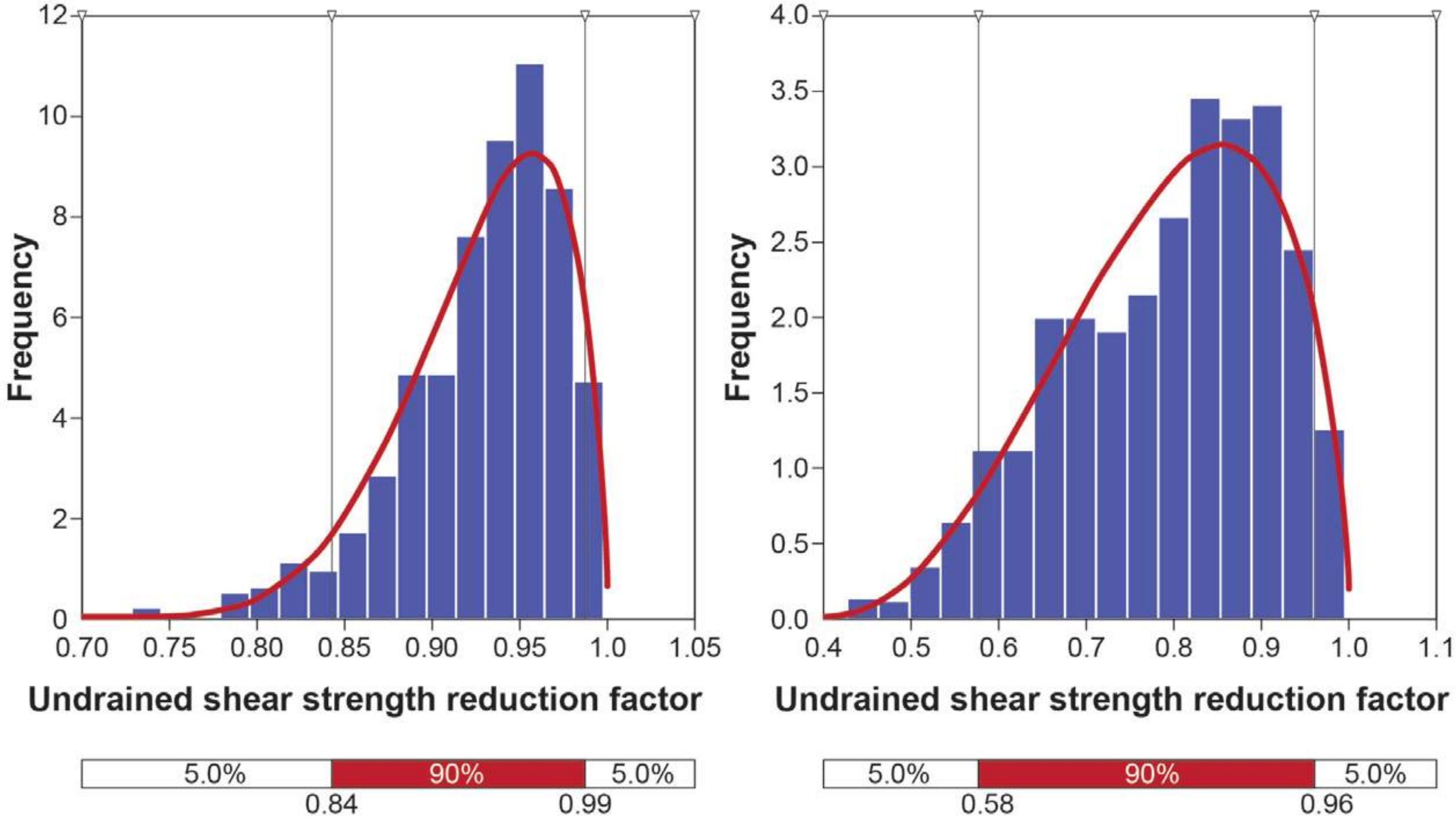


Input parameters varying in simulations:

- Undrained shear strength
- Shear modulus
- Pore pressure ratio
- Peak ground acceleration
- Earthquake time history
- Strength reduction factor

Earthquake-induced shear strength reduction

Results of 500 simulations and fitted distribution functions



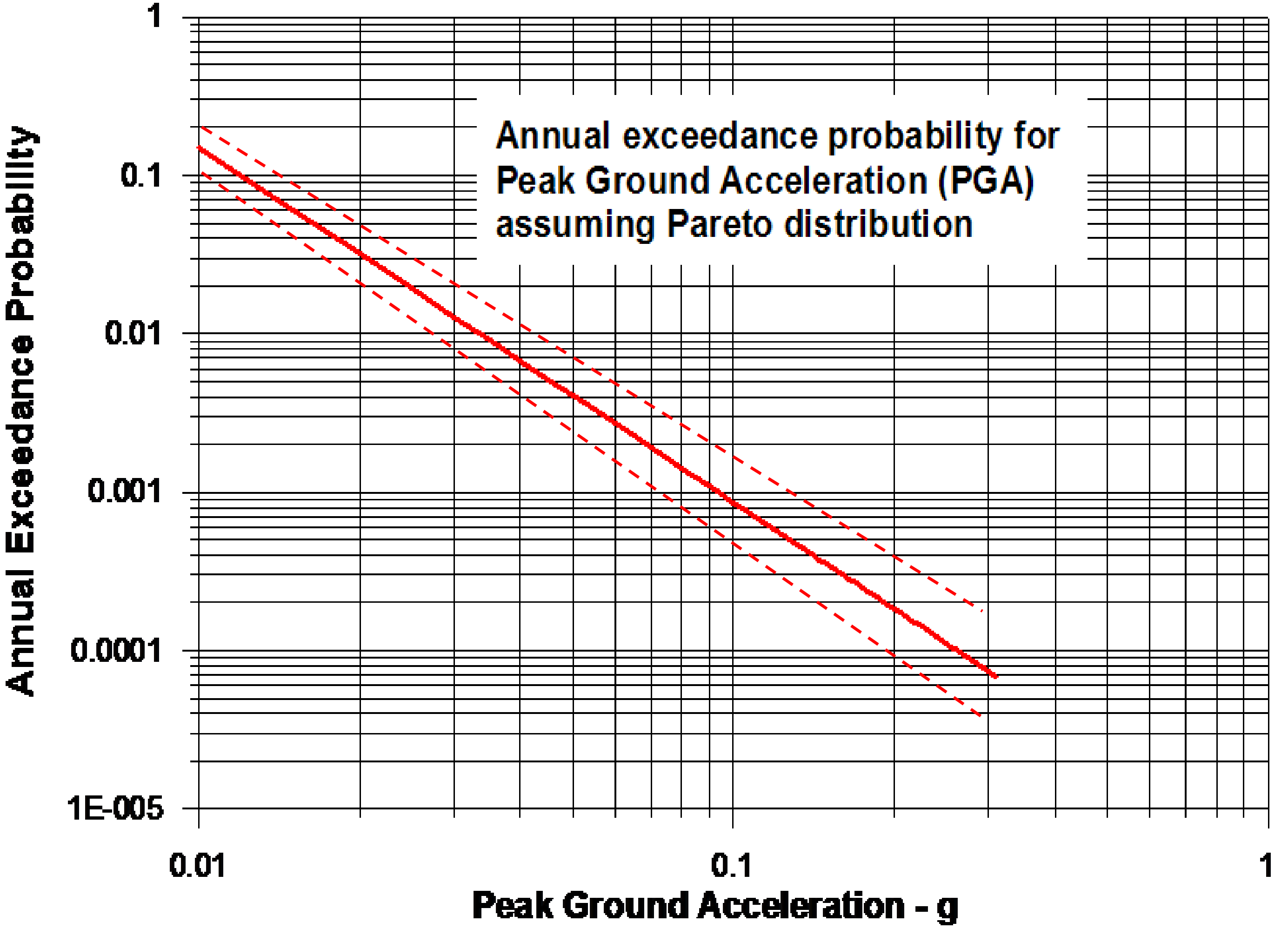
(a) 3,000-year earthquake event **(b) 10,000-year earthquake event**

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

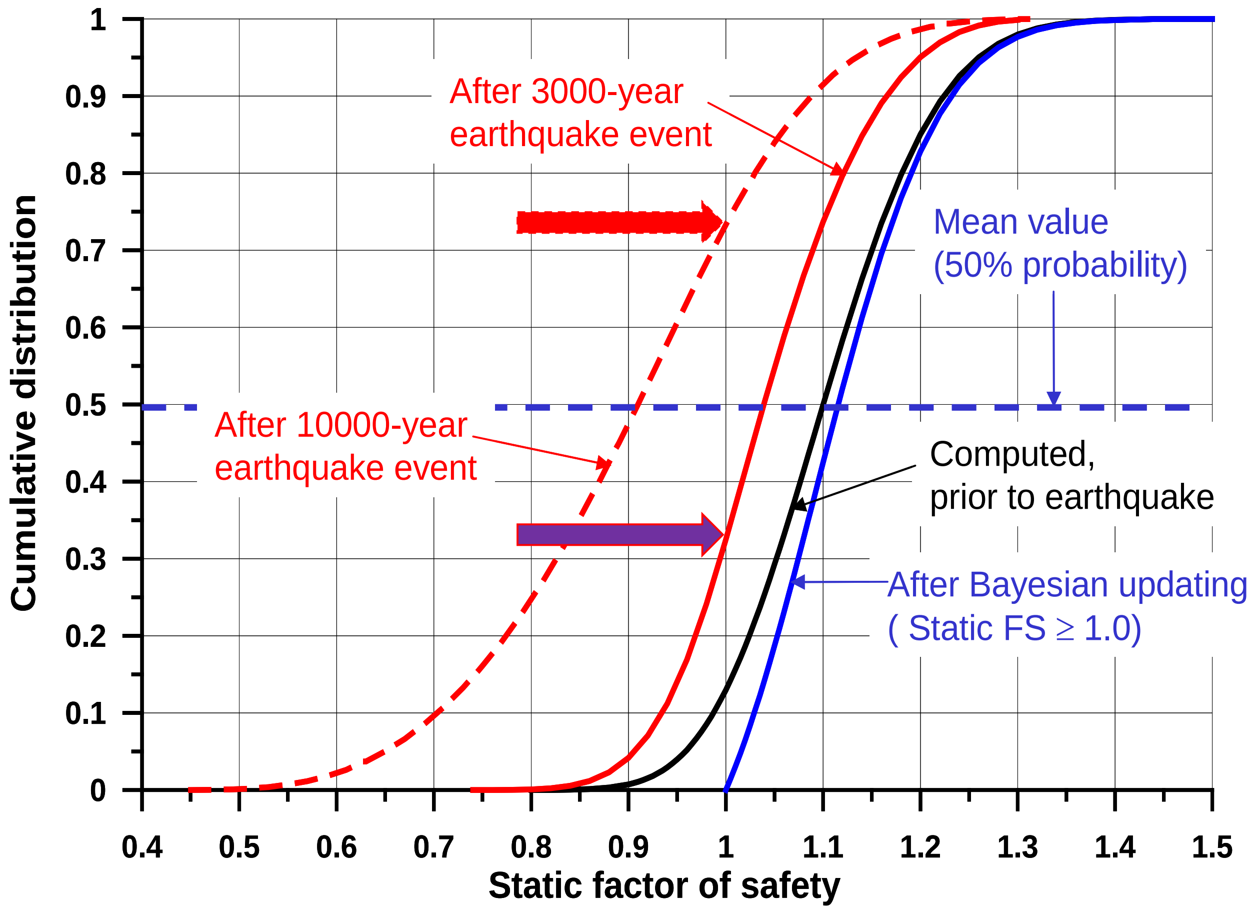
10,000-year event: S_u reduction factor between 0.4 and 1.0, mean = 0.79

Annual peak ground acceleration Amax

Calibrated Pareto distribution with μ = 0.0077 g and SD = 0.0106 g. Distribution is calibrated for 1,000- to 10,000-yr return periods.



Bayesian updating
Probabilistic slope stability analyses under earthquake



Results of probabilistic stability analyses

Slope angle = 18°, Average excess pore pressure ratio = 0.1

Analysis	FS or P_f
Mean (50% prob.) static safety factor, before updating	FS = 1.10
Mean static safety factor, after updating	FS = 1.12
Conditional failure probability under 3,000-yr earthquake	$P_f = 0.33$
Conditional failure probability under 10,000-yr earthquake	$P_{f,} = 0.73$
Annual probability of earthquake-induced slope instability	**$P_f = 3.6 \cdot 10^{-4}$**

The annual failure probability is the integral of all conditional probabilities given the return period, divided by the return period. The earthquake events that contribute most to the annual failure probability are those with return periods between 1,000 and 10,000 years.

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Stability of snow

Avalanche hazard is a combination of:

- precipitation (snow or rain) and wind
- snow pack conditions (probability of avalanche release)
- runout of the avalanche

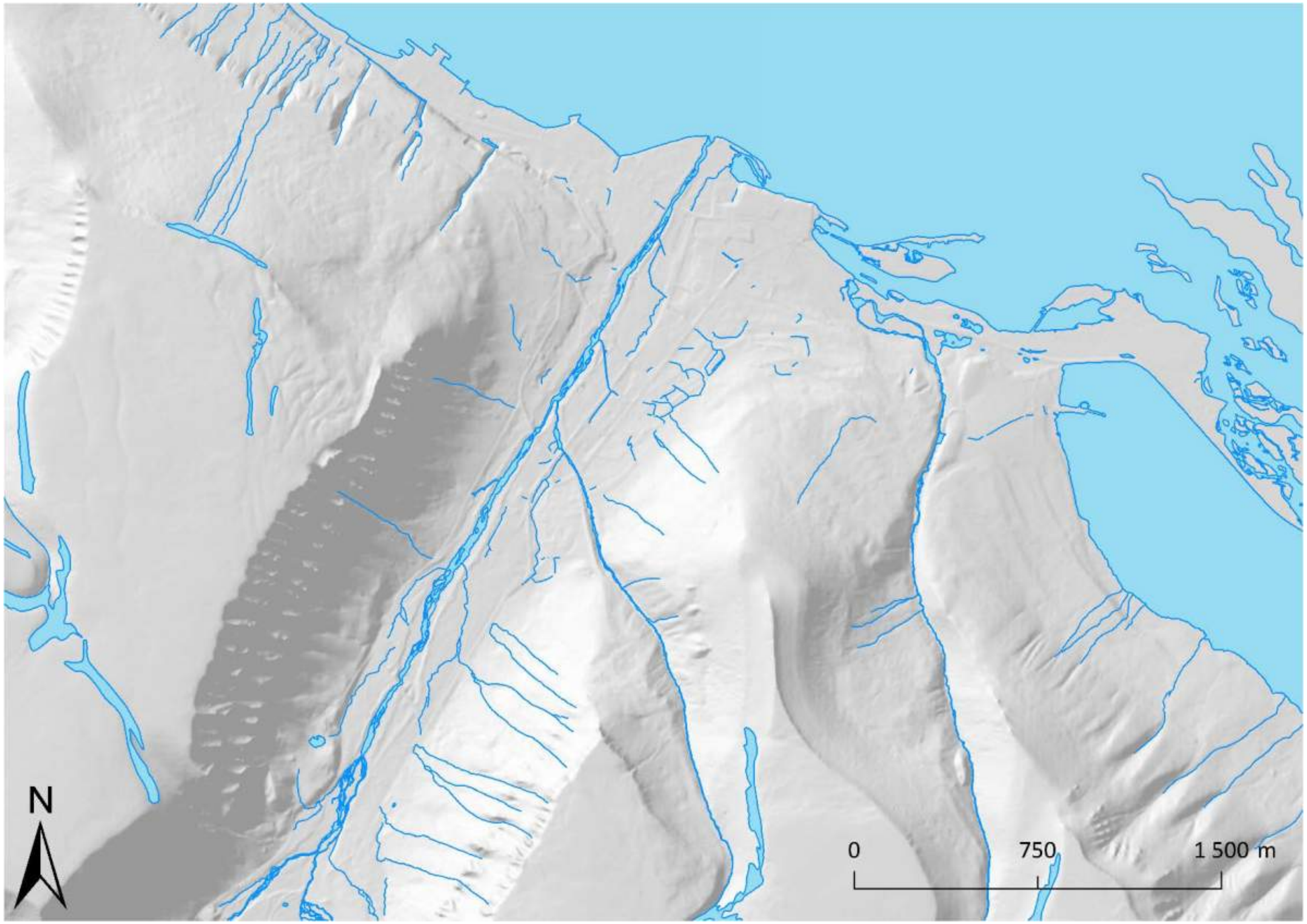
- The reliability approach allows one to design with a uniform margin of safety.
- The most significant uncertainties are singled out.
- The approach allow to use all the knowledge available and to compare margin of safety than include the effect of the uncertainties.

Avalanches on Spitsbergen

Where are we in the world?

- Archipelago of Svalbard
- Largest island is Spitsbergen
- International area under Norwegian government
- Approximately 1000 km from Tromsø, 2000 km from Oslo
- Longyearbyen 78^o North
- In winter only accessible by plane

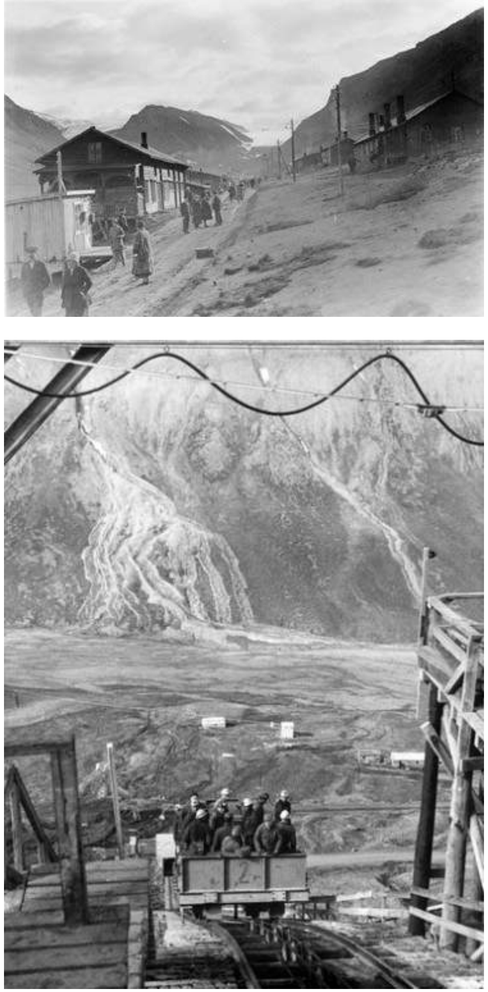
© Eirik Palm


N
0
750
1 500 m

Longyearbyen

- Founded 1906 as a coal mining town
- Tourism, research and education
- Hospital, but no surgeon since 1999
- In 2015 there were 2144 inhabitants
- Average time of residence 5-10 years
- No one born, no one dies!

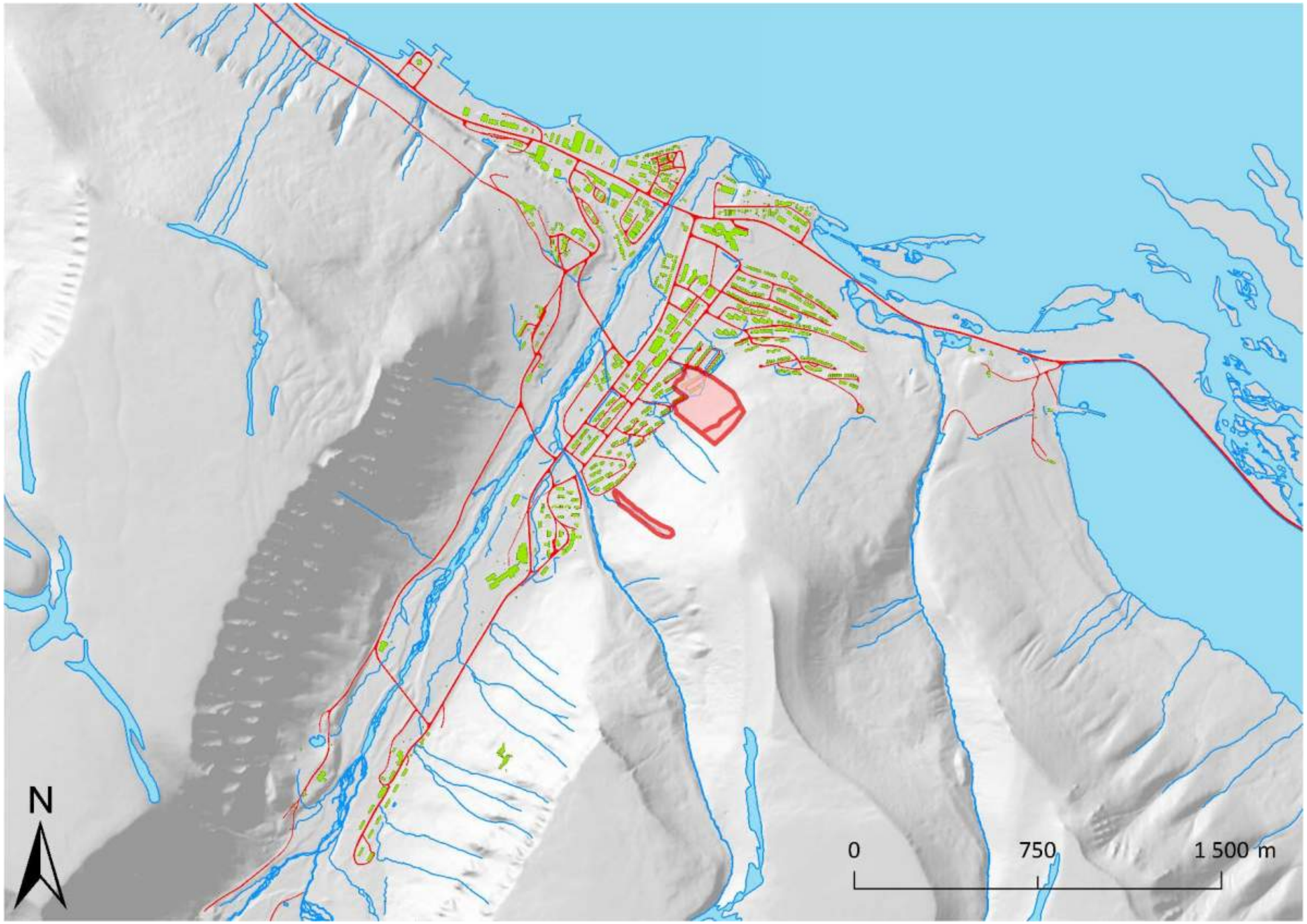
- Some form of snow avalanche occurs nearly every year.



Hazard mitigation

- ~~Blasting of cornices~~
- Removing snow in slushflow path
- ~~Remodelling of the river bed~~
- ~~Observational and~~ evacuation routines for Lia

Discontinued by 2015



N
0
750
1 500 m

Avalanche 19.12.2015

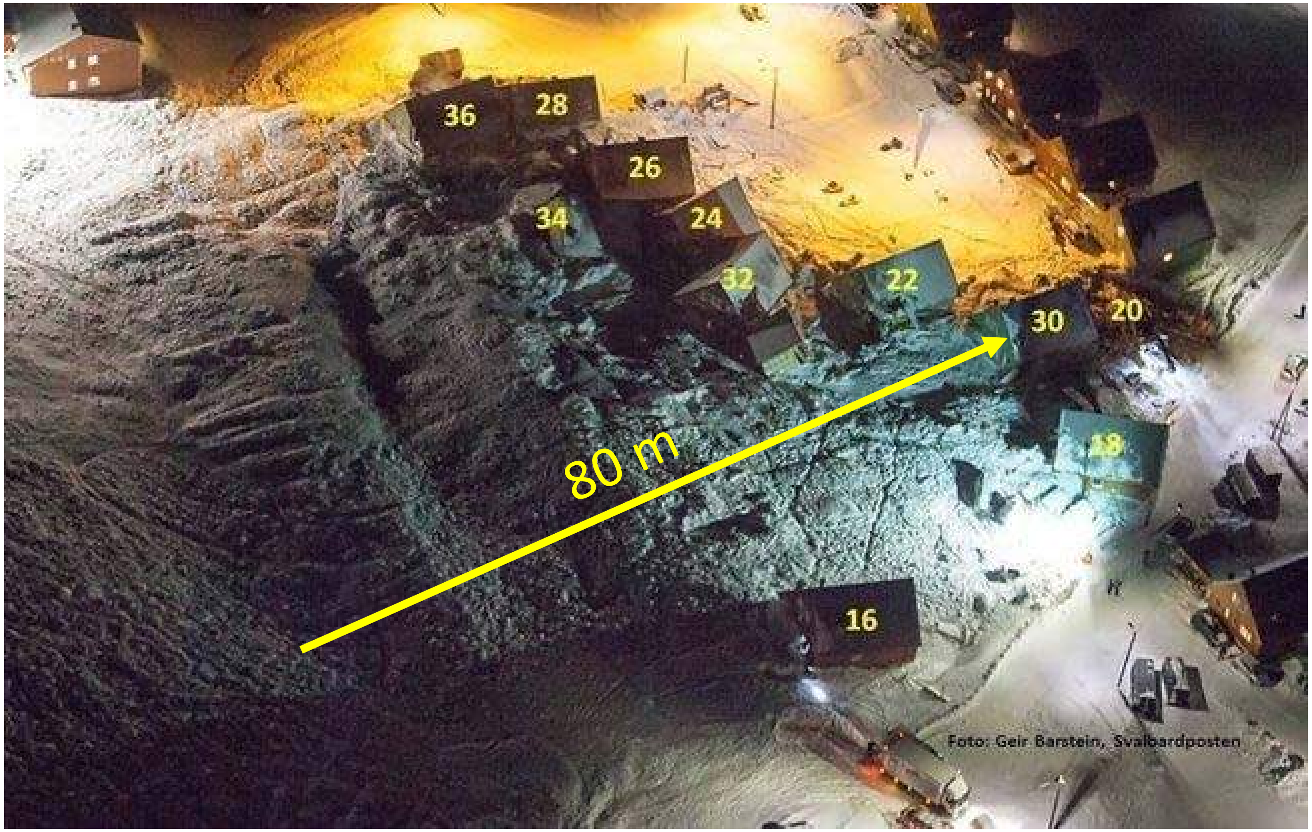


Foto: Geir Barstein, Svalbardposten

Avalanche accident 19.12.2015

- Eleven houses totally damaged
- 2 persons killed, one male (40), one child (2)
- 9 persons injured
- Very few at home
- Extremely difficult search and rescue
- Red Cross voluntary rescuers already on holiday
- The two local rescue dogs on holiday
- Over 100 volunteers

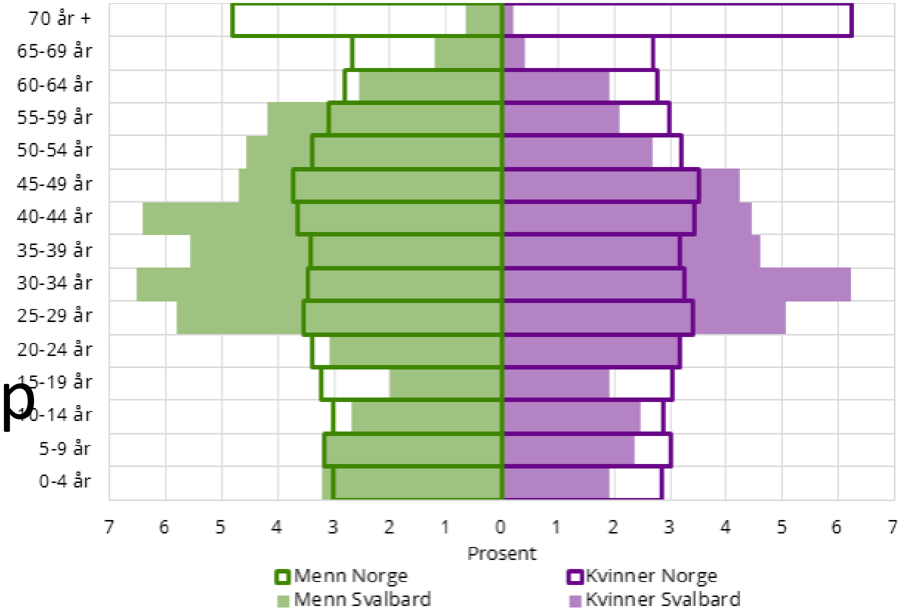
Longyearbyen population

Pros

- Young
- Fit
- Everyone has a shovel
- Everyone has a headlamp

Cons

- No memory
- Little experience



Kilde: Statistisk sentralbyrå.

New measures (>2015)

- New hazard mapping
- Avalanche warning on regional and local scale
- Evaluation of different physical mitigation measures
- Accident inquiry commission (no one did anything wrong)
- Private law suite
- High local awareness

RAPPORT

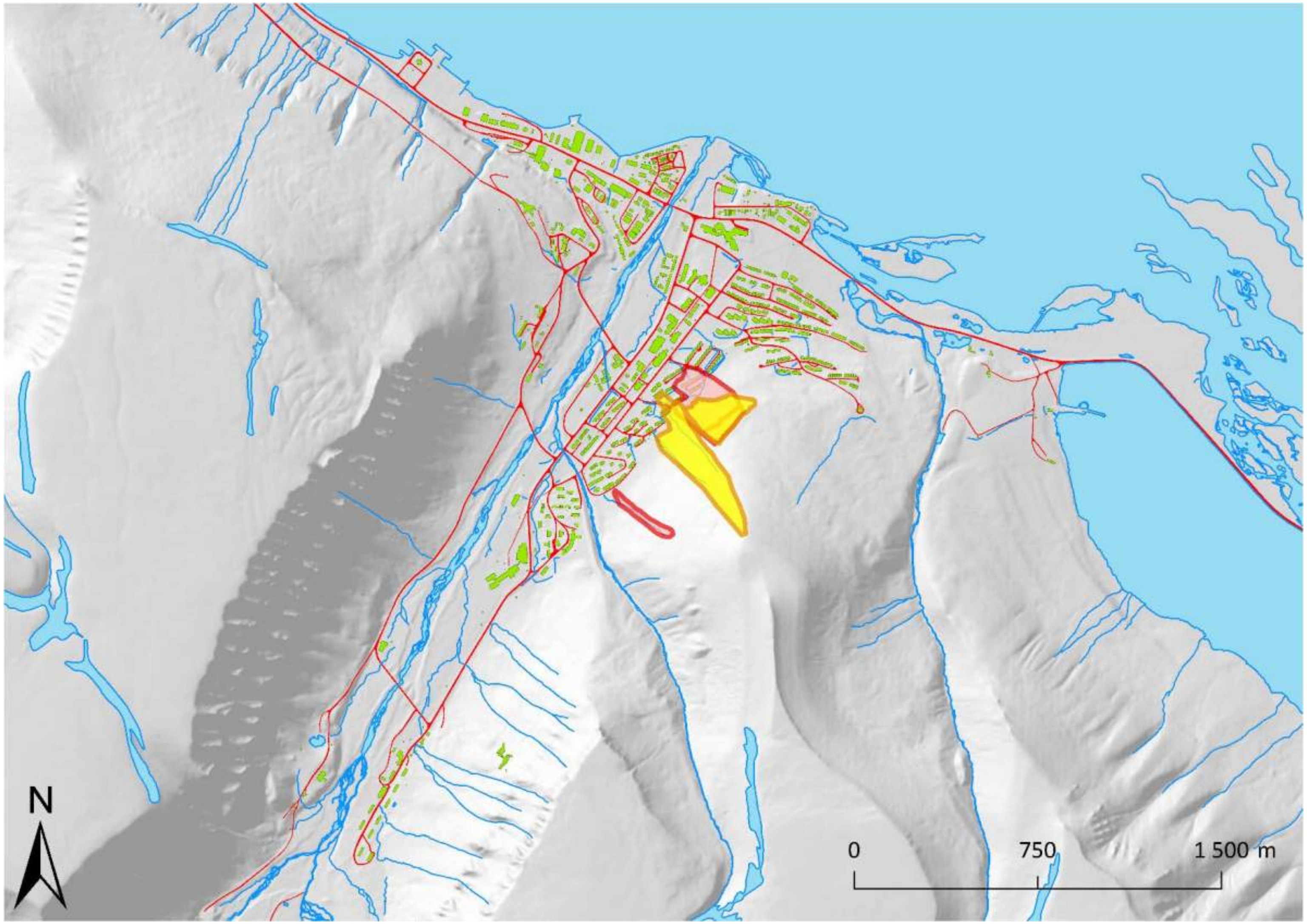
Skredulykken i
Longyearbyen
19. desember 2015

Evaluering av håndtering, beredskap og forebygging

dsb Direktoratet for samfunnssikkerhet og beredskap

Avalanche accident in Longyearbyen. Evaluation of rescue, preparedness and prevention

Avalanche accident 21.02.2017


N
0
750
1 500 m

Avalanche accident 21.02.2017

- Similar weather situation
- Regional avalanche danger level was 4 - high

- Avalanche assessment (authorities): "probability of avalanche reaching settlement: low"
- People were afraid, had expected evacuation
- Dwellers had moved upstairs and taken shovels to their bedroom
- Avalanche hit during the day
- One house destroyed, several damaged
- No persons injured

Lessons learned

- Longyearbyen is highly vulnerable
- The resilience of Longyearbyen is unique
- The type of inhabitants was most likely decisive for the success of the rescue operation(s)
- The same type of inhabitants leads to a short collective memory
- The special role of Longyearbyen in the political framework makes it difficult for the community to find optimal solutions for such challenges

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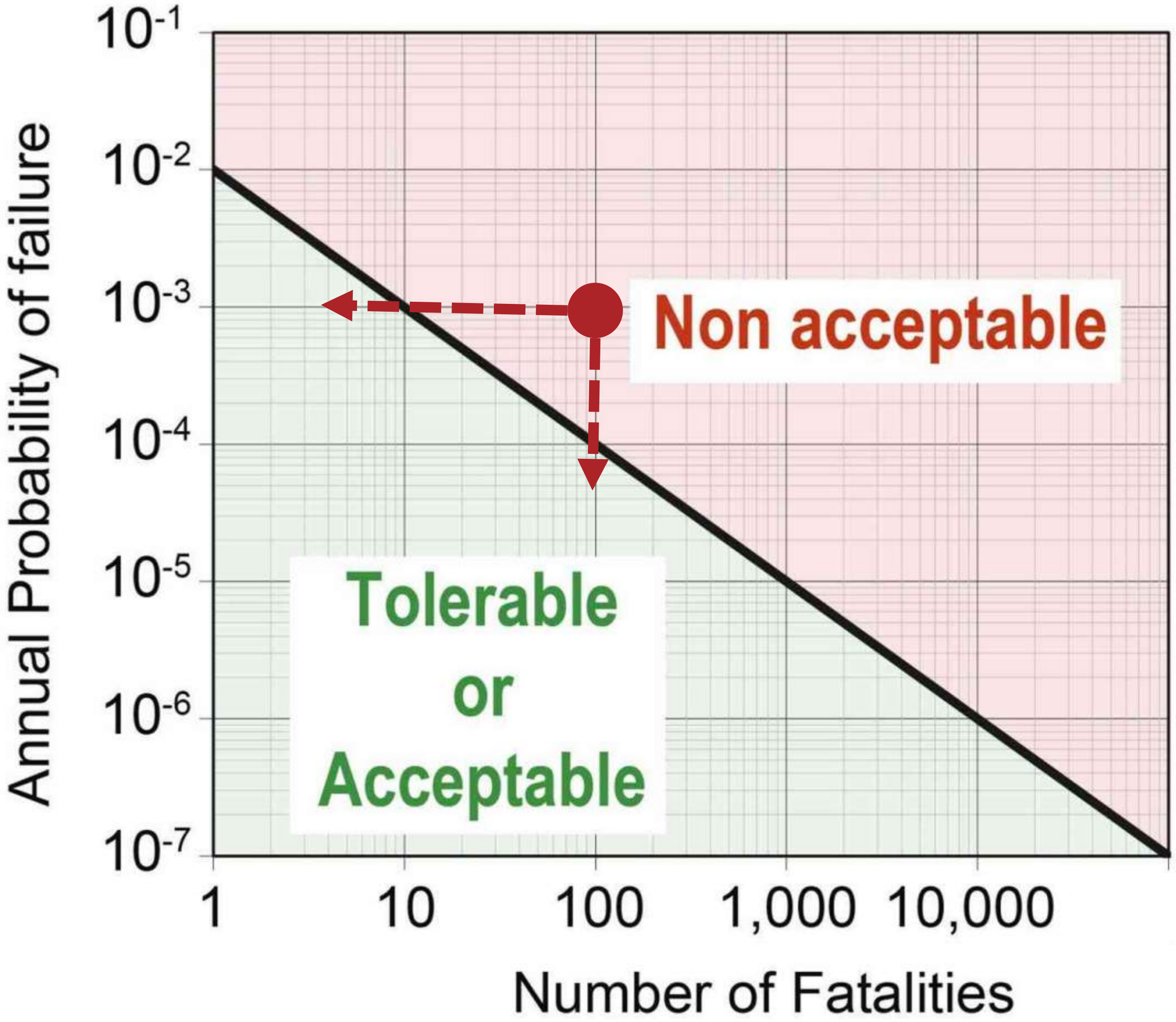
How much risk is acceptable?

How much risk are we willing to accept?

Depends on whether the situation is voluntary or imposed.

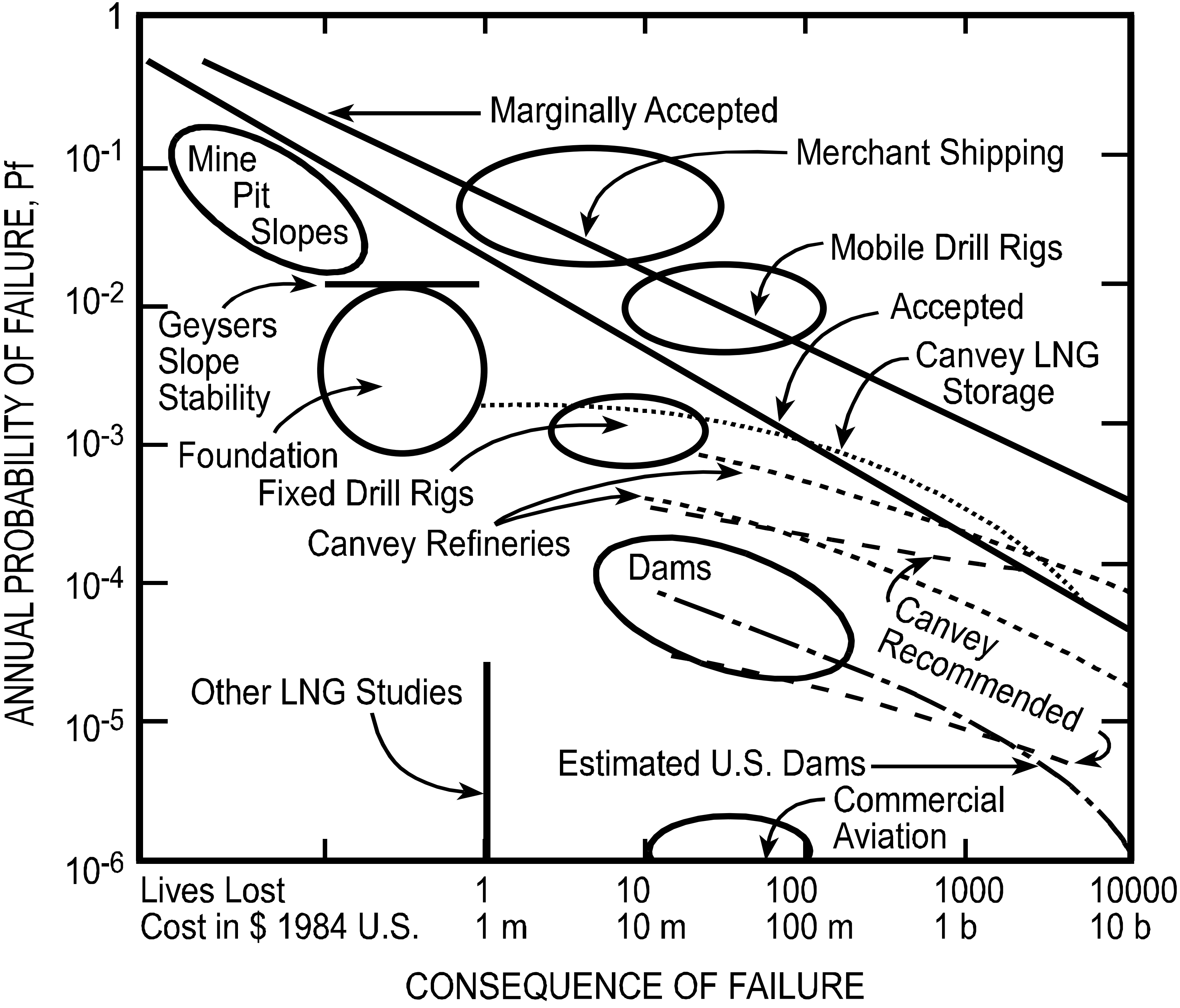
F-N curves and acceptable risk

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



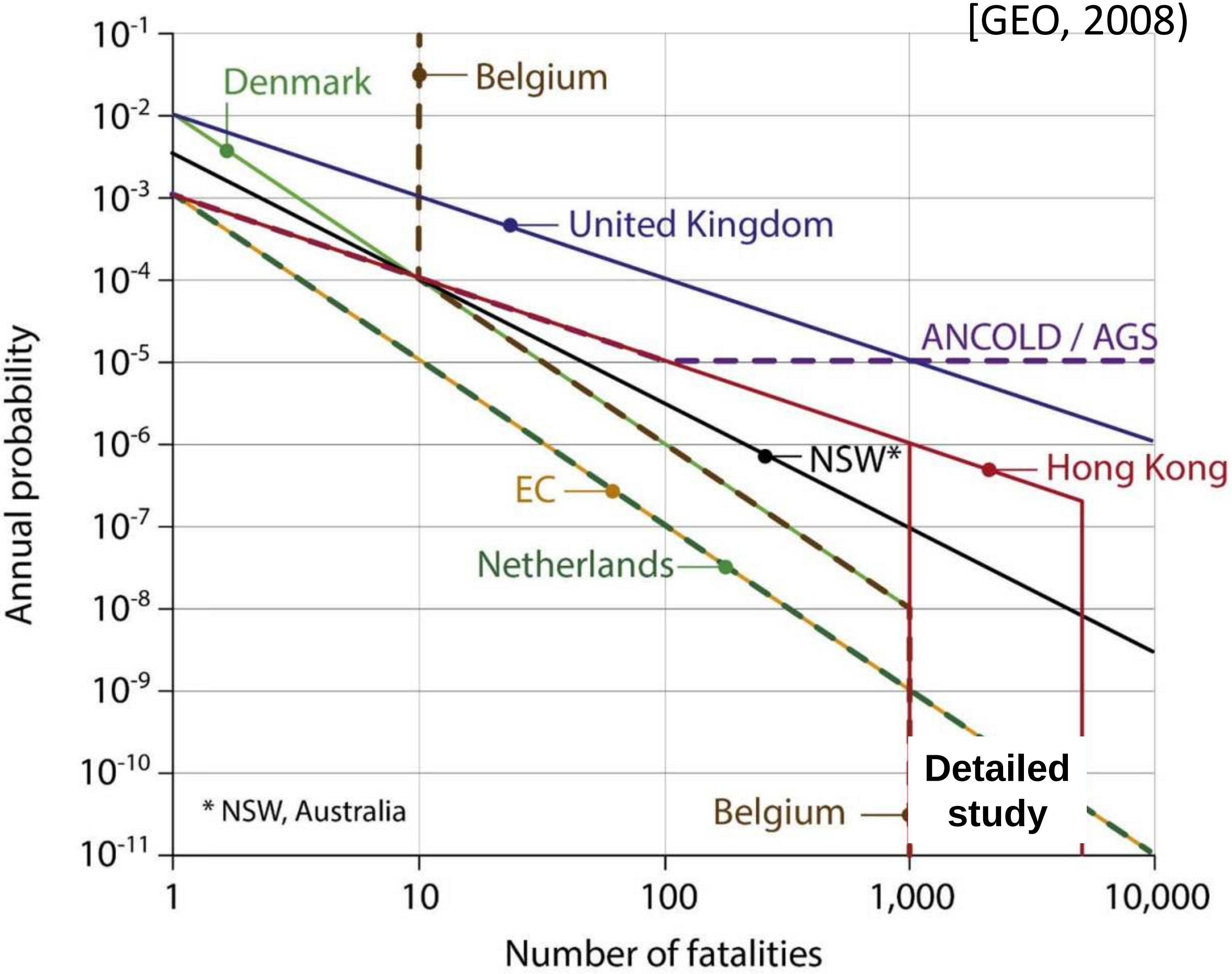
F-N curves

(Whitman 1984)



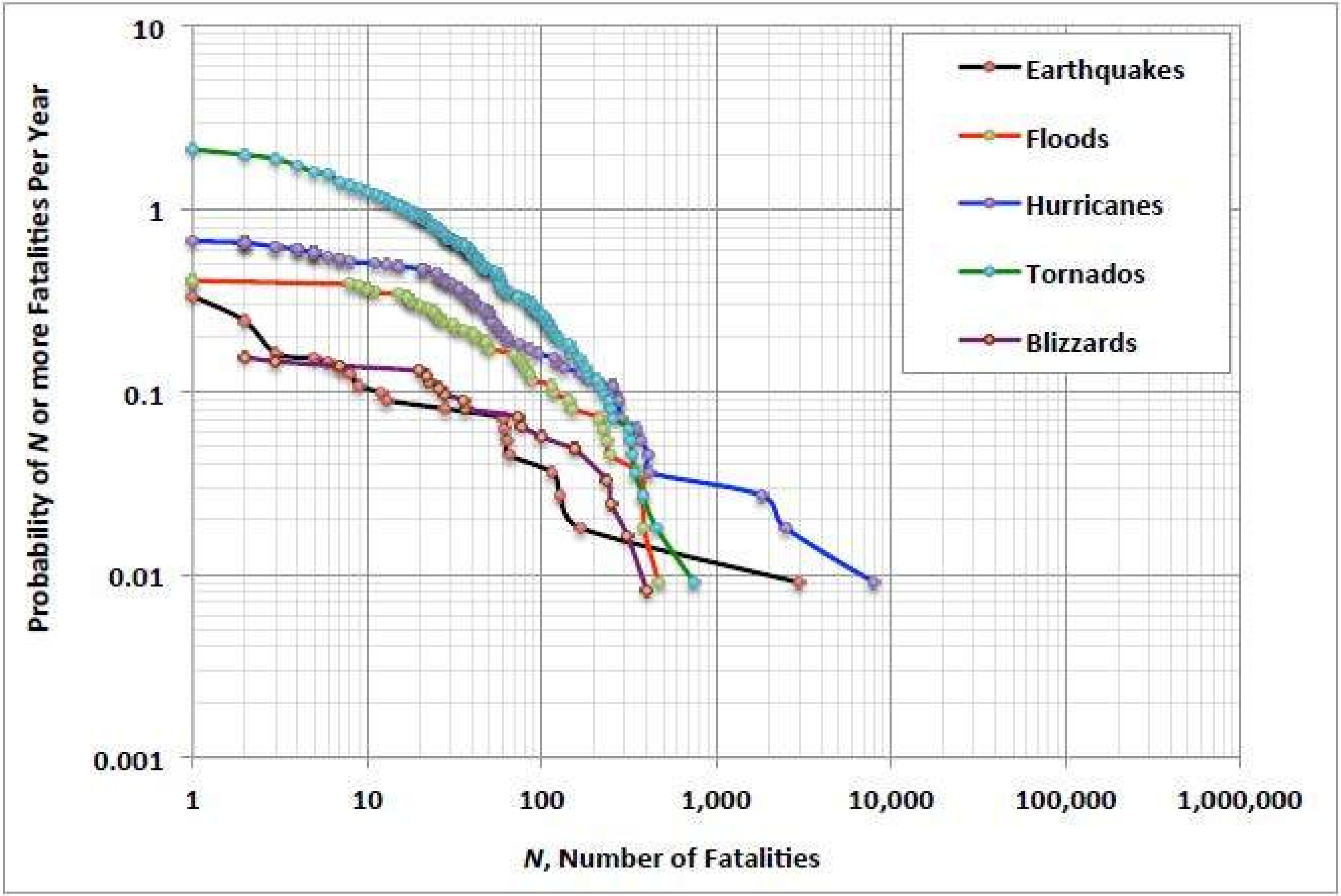
Acceptable risk: Requirements

[GEO, 2008)

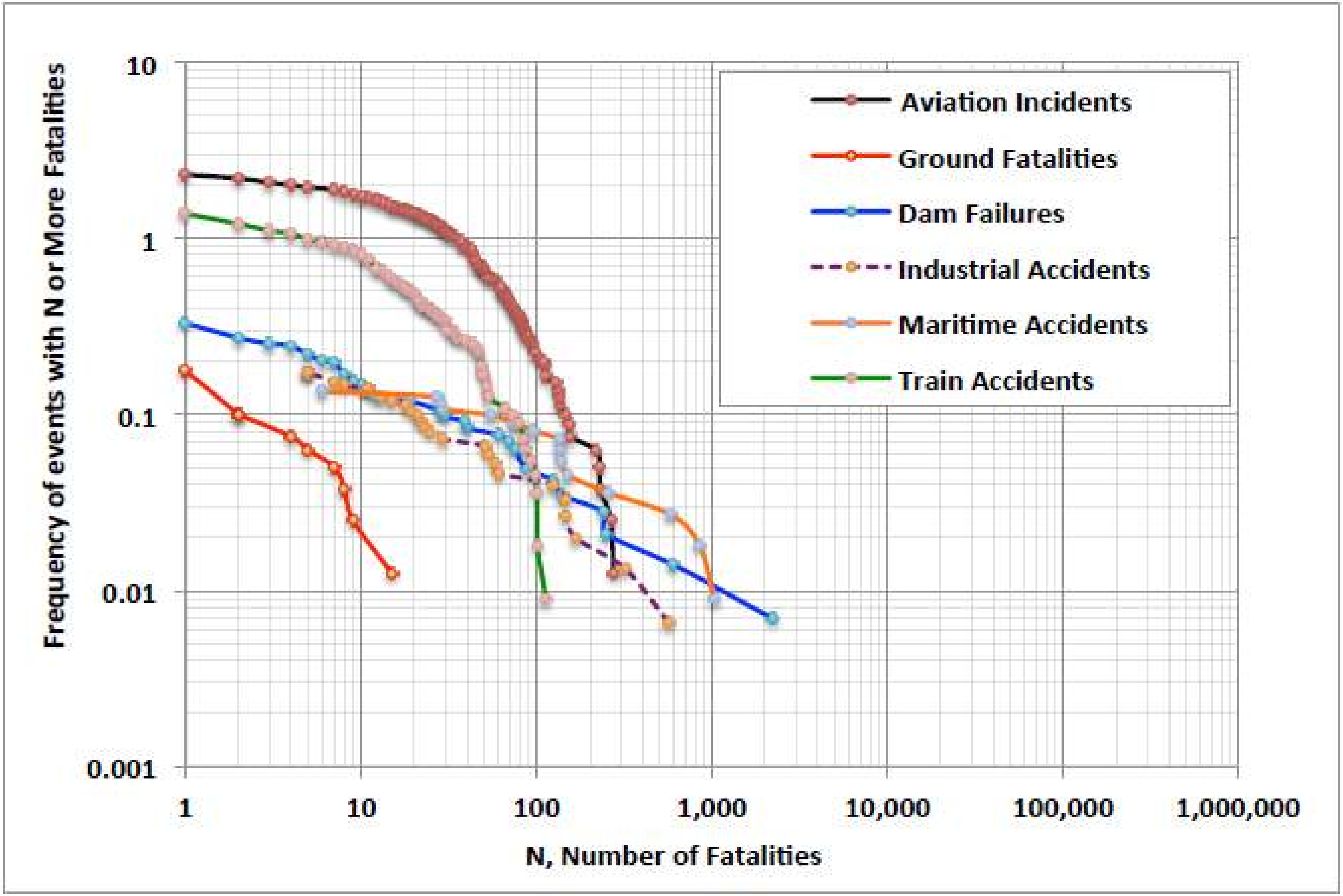


F-N diagram for geohazards USA 1900- 2013

(Abedinisohi 2014)



F-N diagram for man-made accidents USA 1900- 2013 (Abedinisohi 2014)

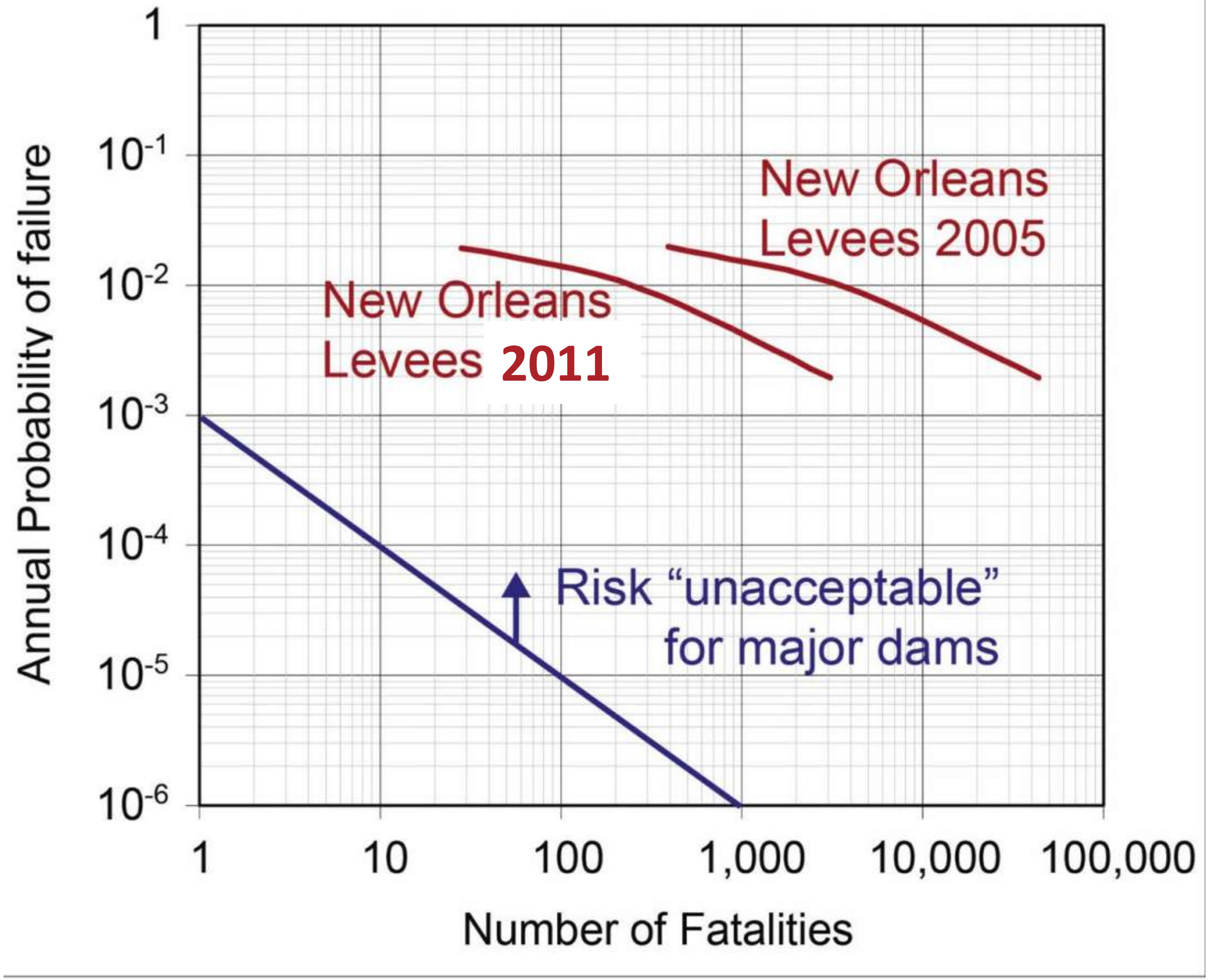


New Orleans Levees and Hurricane Katrina
Risk diagrams (F-N curves)

[Gilbert 2014]

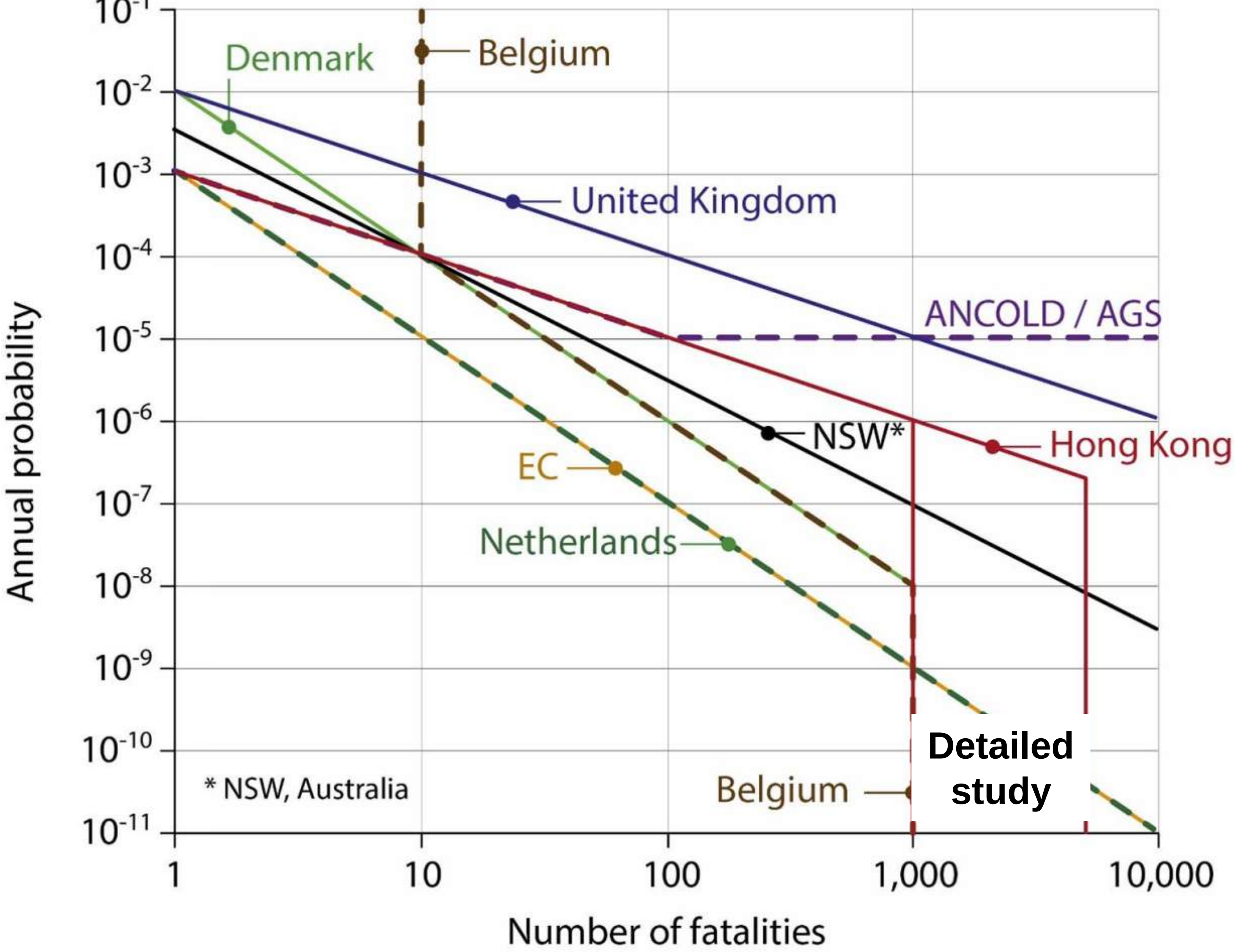
2005
"Hurricane Protection System"

2011
"Hurricane Storm Damage Risk Reduction System"



Acceptable risk: Requirements

[GEO, 2008)



Detailed study

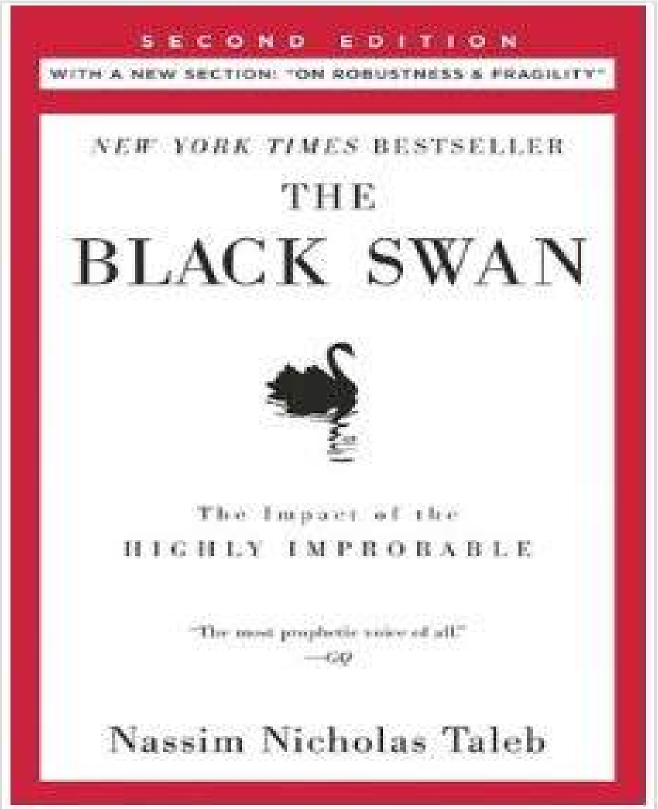
Managing the risk posed by extreme events

- The neglected or residual risk due to very low probability events and epistemic uncertainties pose a threat to the integrity and performance of critical infrastructure.
- This risk is implicitly accepted and knowingly neglected in conventional engineering design.
- Nevertheless, these events can occur, and when they do, they are referred to as extreme events.

⇒ Conventional engineering design is not suitable for dealing with the risks posed by extreme events.

Emerging approach

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)

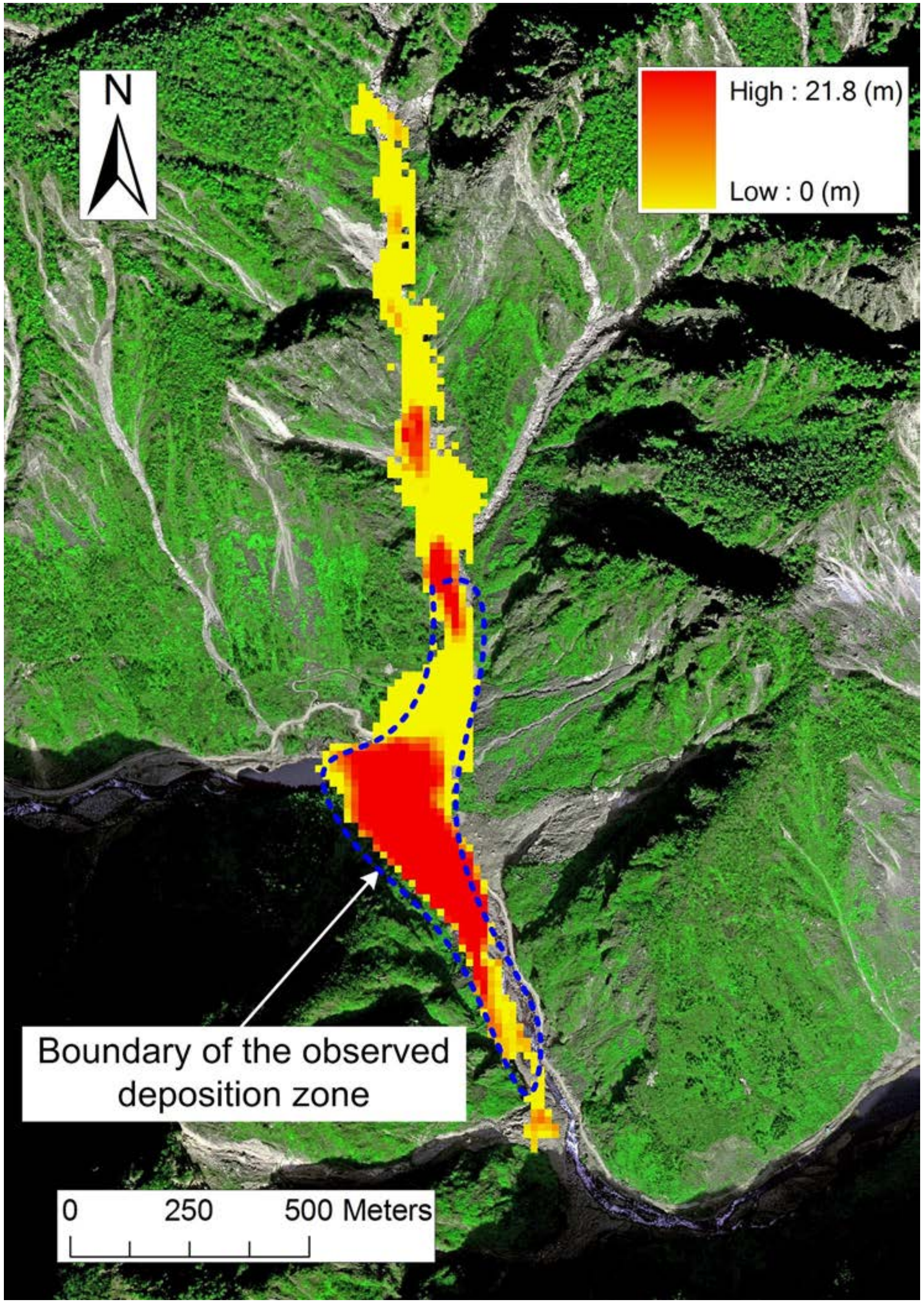


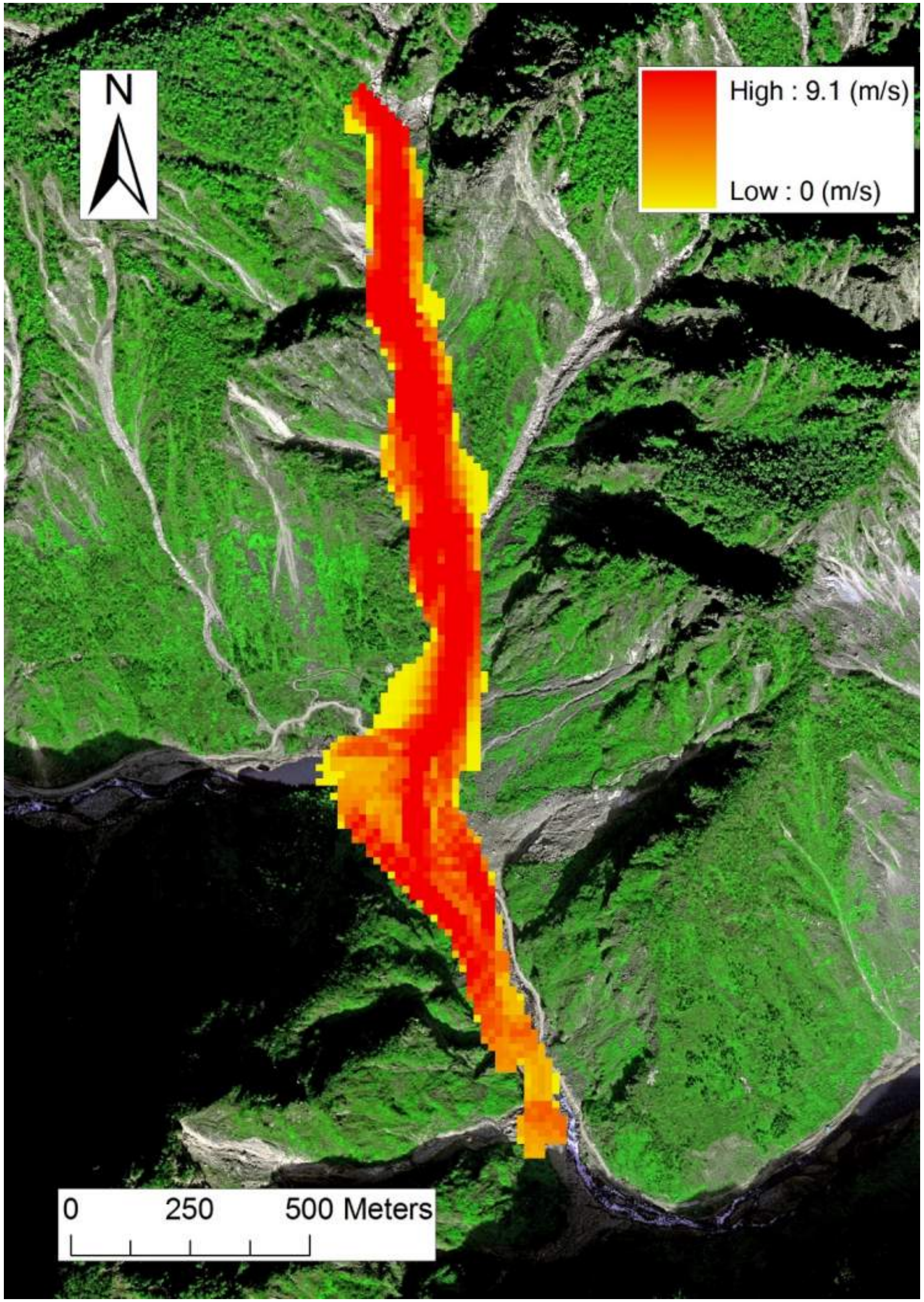
Emerging solution:

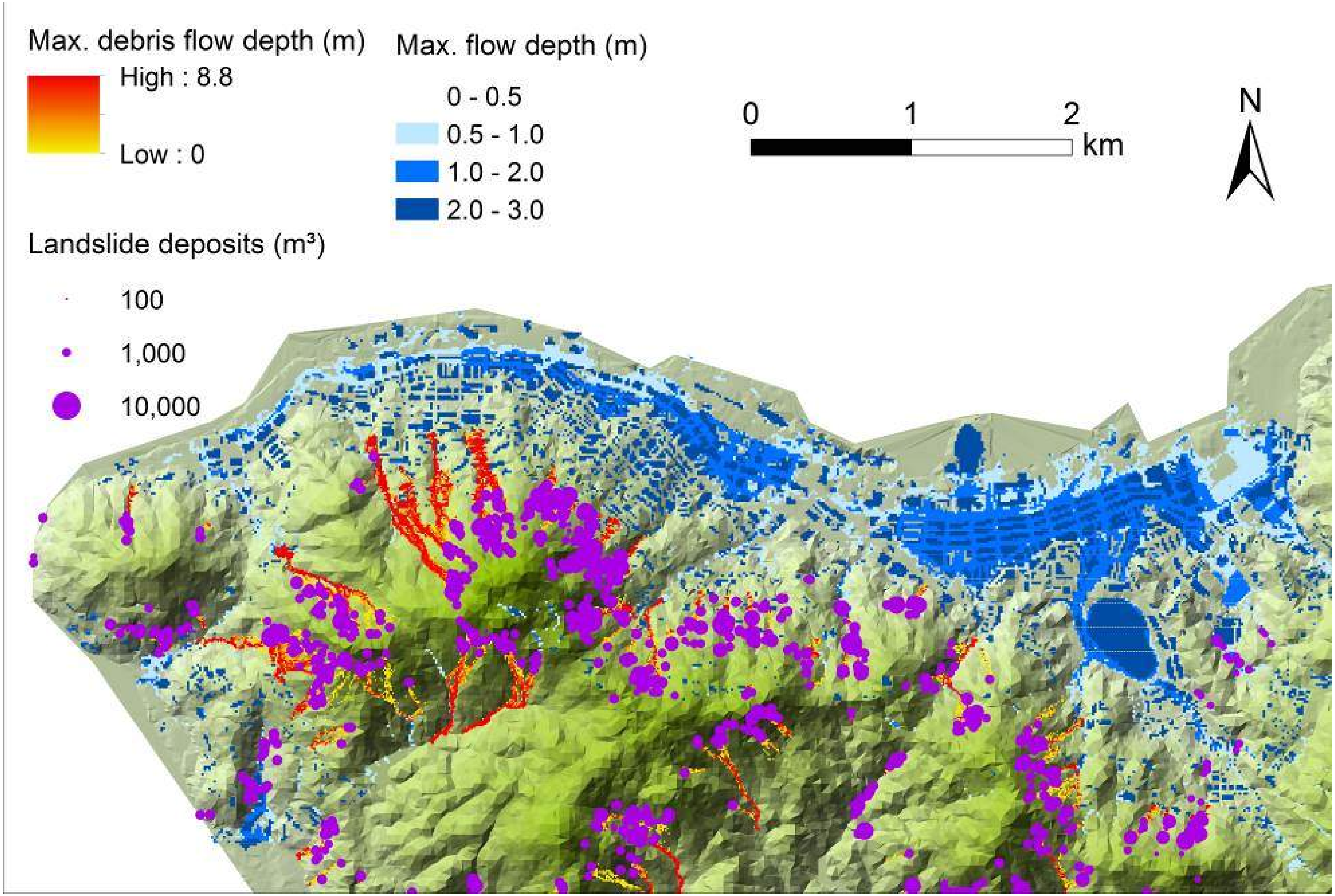
"Stress testing"

Stress-testing for evaluating the Hong Kong slope safety system

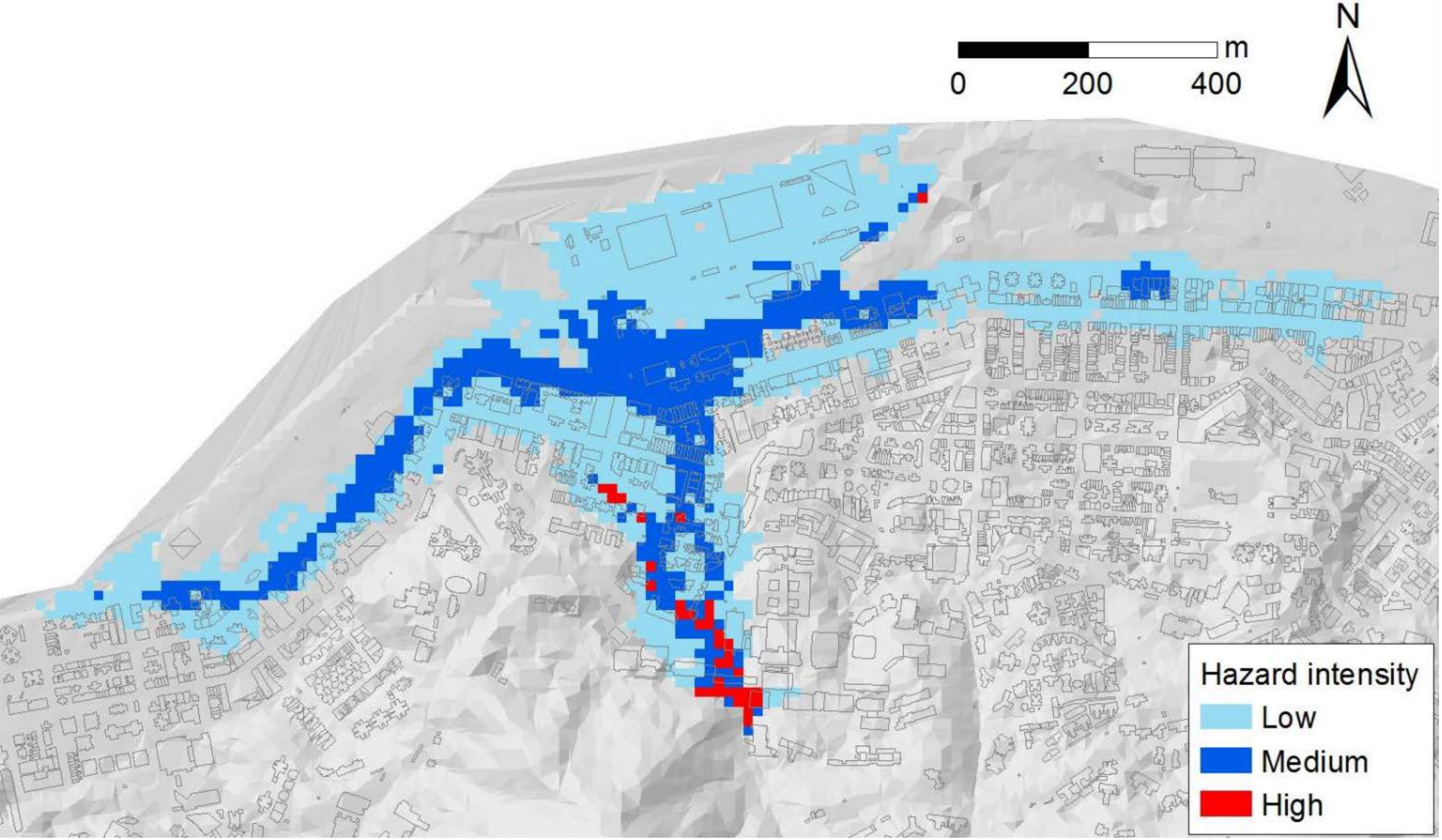
Stress scenarios	Develop critical rainstorm scenarios under the changing climate (earlier experience)
Impact, system response and risks	Evaluate sizes, locations and impact areas of landslides, debris flows, and flash floods. Evaluate response of «slope safety system».
	Assess consequences of multi-hazard events (No. of people and No. of buildings affected)
Management strategies	Mitigation: Find “bottlenecks” and develop strategies to improve performance
	Assess effectiveness of proposed strategies Quantify changes in risk profile due to mitigation


N
High : 21.8 (m)
Low : 0 (m)
Boundary of the observed deposition zone
0
250
500 Meters


N
High : 9.1 (m/s)
Low : 0 (m/s)
0
250
500 Meters



Landslides, debris flows and floods on north Hong Kong Island, extreme storm of 85% PMP (Zhang et al 2017).



Hazard intensity for flooding due to landslide-dam breach (Zhang et al 2017)

Stress testing for

- the identification of future critical rainstorm scenarios considering climate change,
- the evaluation of the slope system response under extreme rainstorms,
- multi-hazard risk assessment

Applicable to all types of hazards (used for aviation, banking, …)

Stress tests were imposed by WENRA on all nuclear power plants in Europe in 2011 and 2012 in the aftermath of Tōhoku earthquake and Fukushima Dai-ichi accident.

Japan,
11 March 2011

Final remarks

- Complex outcomes, uncertain future.
- Landslides, triggered by natural processes or human activity, will happen despite our best efforts to prevent them. Society must learn to live with landslide risk.
- Quantitative Risk Assessment (QRA) is a useful tool for evaluating risk, comparing alternatives and evaluating the need for mitigation. But it need to be "dynamic".
- Vulnerability is increasingly important in risk management. Vulnerability "belongs" to several disciplines and addresses many types of assets.
- Risk and probability tools have reached a degree of maturity 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.

Risk asssessment and management
A tool for the future

- ✓ Cross-disciplinary
- ✓ User-oriented
- ✓ Communication tool
- ✓ Allows to prioritise
- ✓ Serves many objectives: technology, economy, safety, environment, climate, etc
- ✓ Future is not simply a projection of the present

In practice

- ✓ Enables risk-informed decisions
- ✓ Improves safety, cost-effectiveness
- ✓ Shows potential hazards and what could go wrong
- ✓ Seeks to reduce risk

Disasters are seen as fast events…

… but disasters are built up slowly

The role of our profession

Landslide risk assessment, management and governance is about communication.

Our role is not only to act as scientists and engineers providing judgment on factors of safety. Our role has evolved to providing input in the evaluation of hazard, vulnerability and risk associated with landslides. Our profession should be increasingly perceived as reducing risk and protecting people.

Uncertainties

In all our geo-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

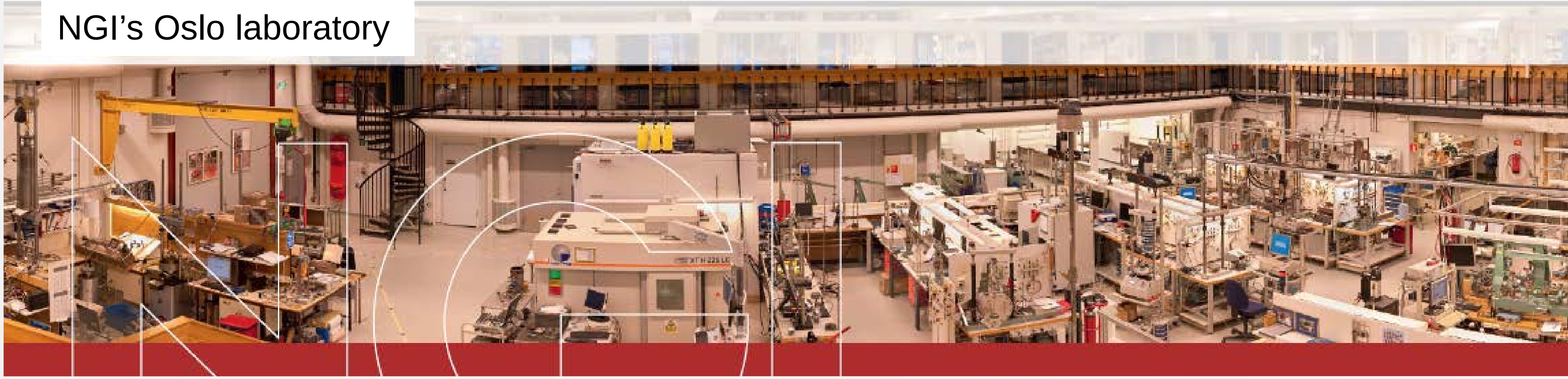
Deterministic analyses and design with a factor of safety give an impression of certainty;

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

For robust and improved geo-design, we need both.

pionér • fundament • forskning og rådgivning • kompetanse • tillitt • handlekraft • innovasjon

Thank you for your attention!


NGI’s Oslo laboratory