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The Twelfth Lumb Lecture

Risk assessment and management: Necessary insight to reduce landslide risk

Suzanne Lacasse
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27 June 2022

The foresight of Peter Lumb

Christian and Baecher (2015) wrote: «Probabilistic reliability methods applied to geotechnical problems began to appear in the late 1960's with the work of Peter Lumb", who wrote:

- «It does appear that there is no such thing as *«the»* factor of safety and that when a factor of safety is used, it should be clearly defined» Lumb (1966)
- «It should be obvious that the failure probability will play an important role, and that stability will be dominated by the uncertainties» Lumb (1975

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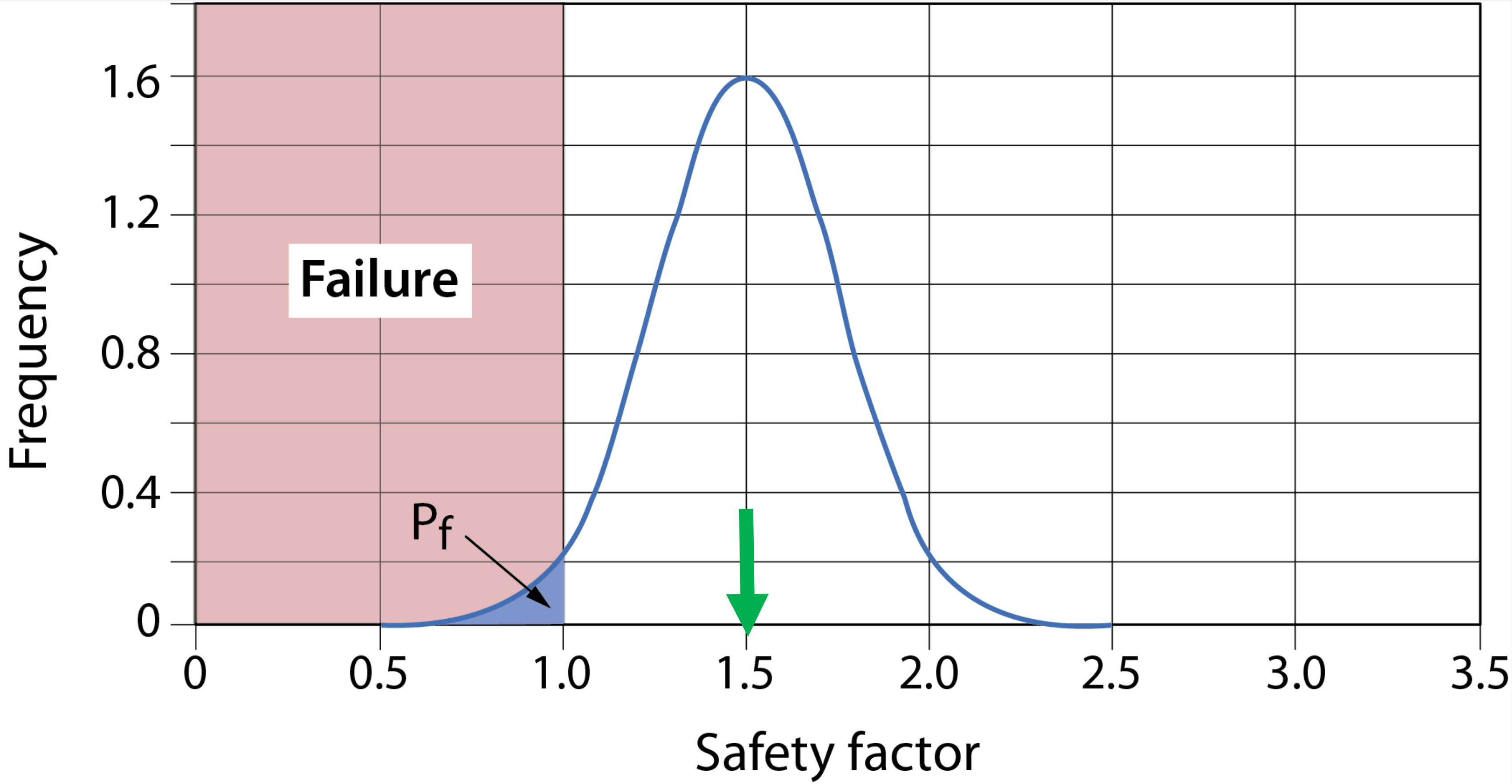
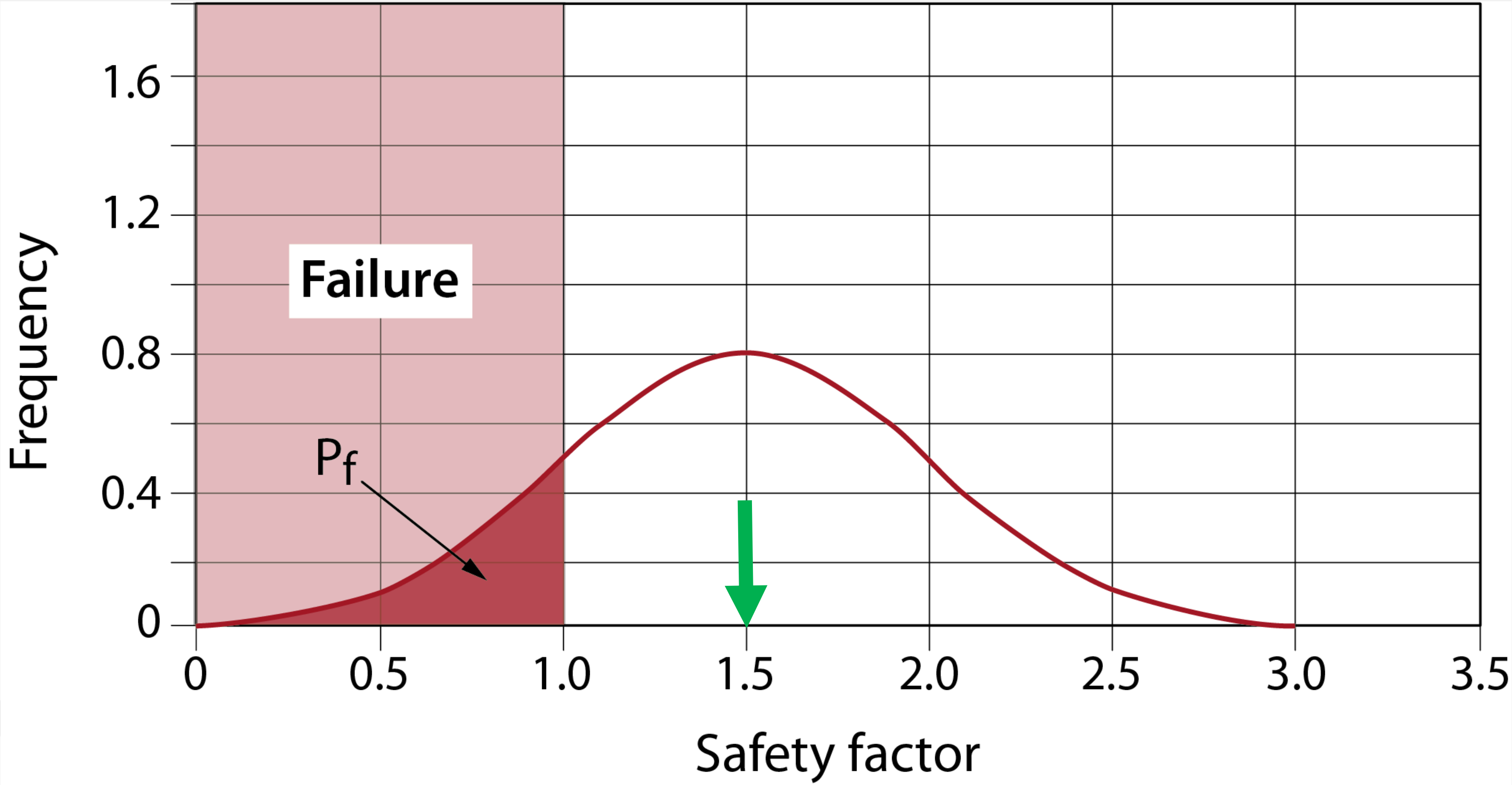
Safety factor of 1.5 and small uncertainty

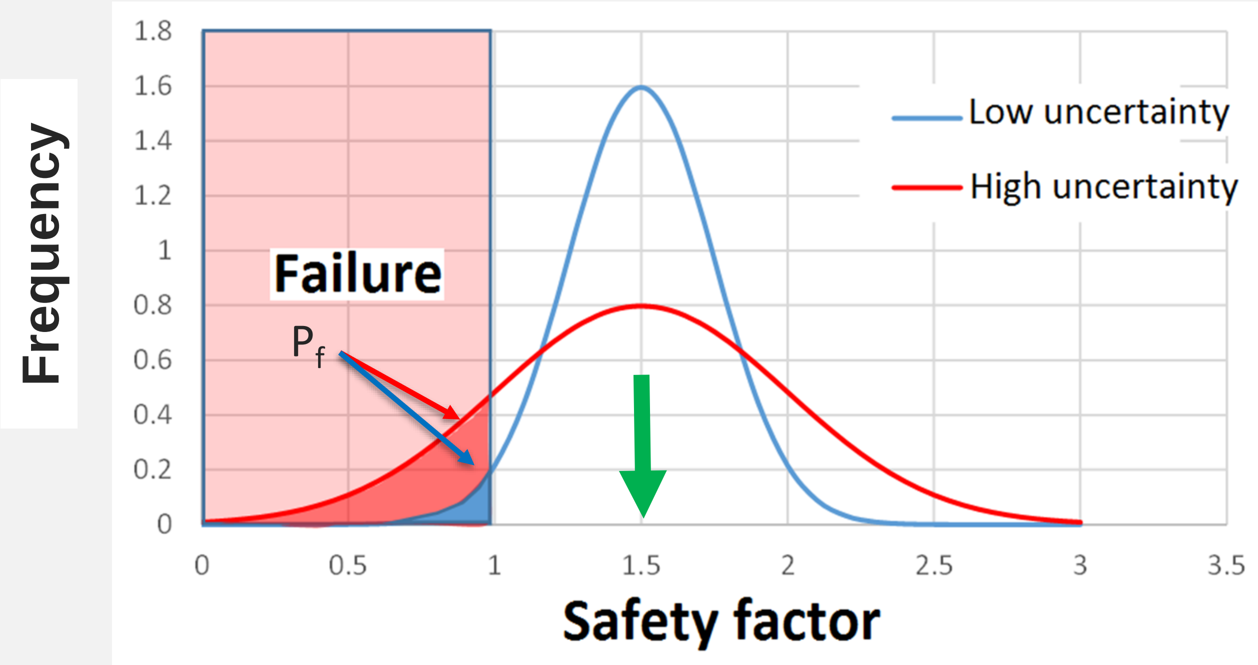


Safety factor of 1.5 and large uncertainty



Same safety factor (FS = 1.5)

Very different safety margins and failure probabilities



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Assessment of safety (3 approaches)

"Prescriptive" (deterministic) approach

Standard-based

Risk-informed Decision-Making

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 a large series of sensitivity analyses.

- uncertainty recognised & acknowledged
- completes the prescriptive approach

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Load and Resistance Factor Design (LRFD) approach - "partial SF"

Contents

- What is Risk-informed decision-making?
  - Concepts of risk assessment and management
  - How to describe risk?
- Applications: reducing landslide risk
- Mitigation of landslide risk
- Framework for risk assessment and management
- Summary and conclusions

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Risk and reliability

Risk combines the *Probability (Likelihood)* and the impact (consequences) of an event.

ISO (ISO 31000:2018):

"**Risk** is the effect of **uncertainty** on objectives"

… ISO recognises the importance of the effect of uncertainties on what we are trying to achieve, which is increased safety

Reliability is the measure of "trustworthiness" (可信度)

Probability
Probability of an event occurring in a period of time

Impact
Fatalities, loss of health, economical losses, damage to infrastructure and environment, loss of reputation, etc

Area with high l
hazard, but very
consequences (c
farmland, desert
low risk

Slope stabilisation
were done in the
reduce the landsl

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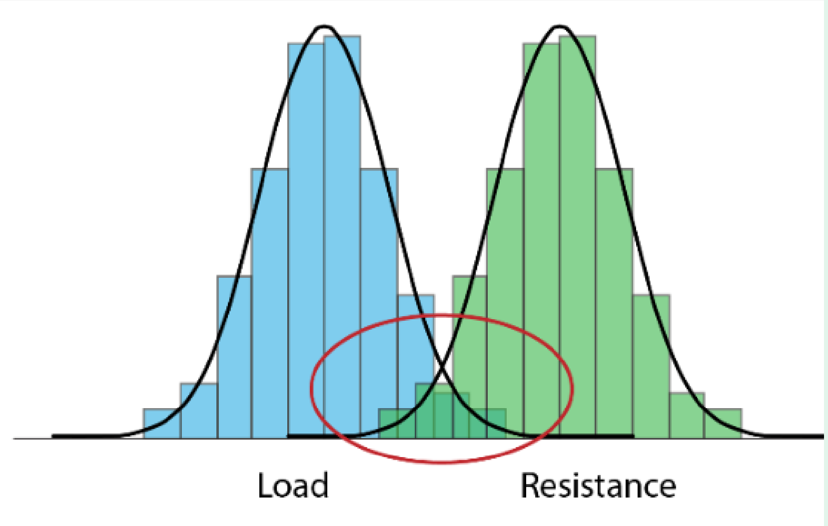
Why not rely on solely the safety factor (SF)?



If a SF of 1.5 is achieved, there is a perception of no uncertainty and that the design is safe.

In reality, a SF=1.5 represents a wide range of failure probabilities, depending on the uncertainties in the parameters.

Through regulation or tradition, today's prescriptive design in codes and standards requires the same SF for cases with differing levels of uncertainty. This is not logical.

A deterministic analysis is not sufficient to describe safety because it does not account explicitly for the uncertainties in the analysis.

Risk-informed decision-making (RIDM) (ISO 2395:2015)

- RIDM is a structured approach in which all insights are considered in reaching a decision, to ensure that a decision is balanced and that all relevant factors have been identified and addressed.
- RIDM encourages a proactive mindset and requires a justified reasoning for the choices made in the analysis and decisions.
- RIDM recognizes that human judgment plays an important role in decisions, and that technical information cannot be the only basis for decision-making. Gaps in knowledge and data are unavoidable, and decision-making is an inherently subjective, value-based task integrating technical and non-technical elements.

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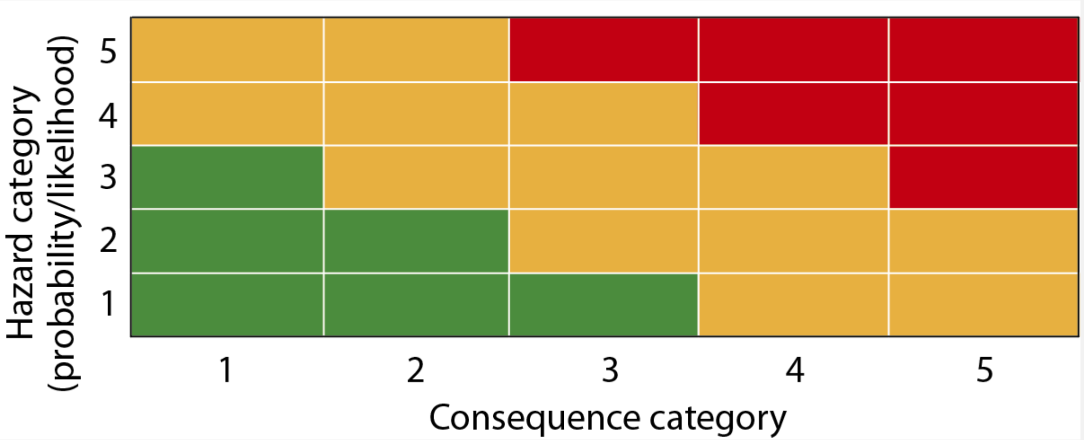
How can we describe risk?

Qualitatively: risk matrix



Green: Low risk

Orange: Medium risk

Red: High risk

A discussion of the uncertainties, even with the simplest methods, provides added insight into the safety and what are the important factors affecting it.

How can we describe risk?

Quantitavely - Risk diagram

A series of temporal probabilities and consequences on a so-called F-N diagram

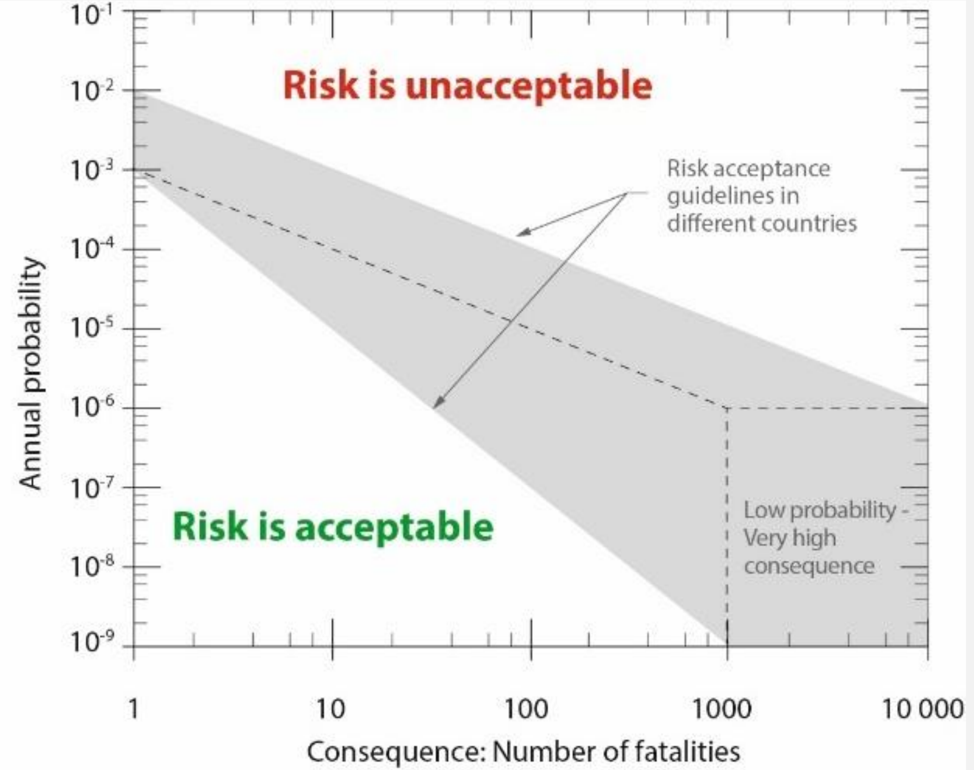
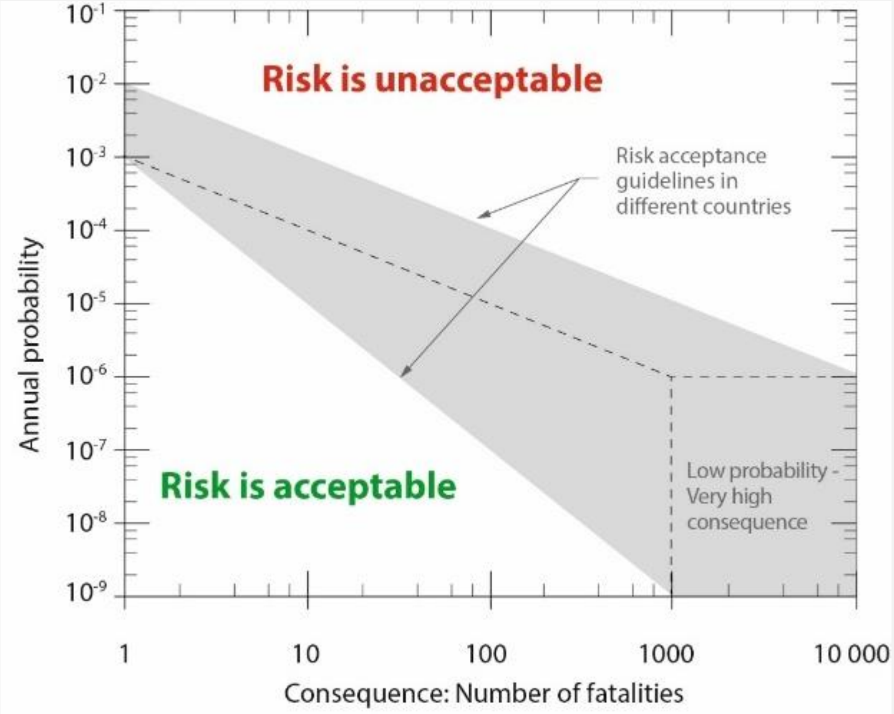
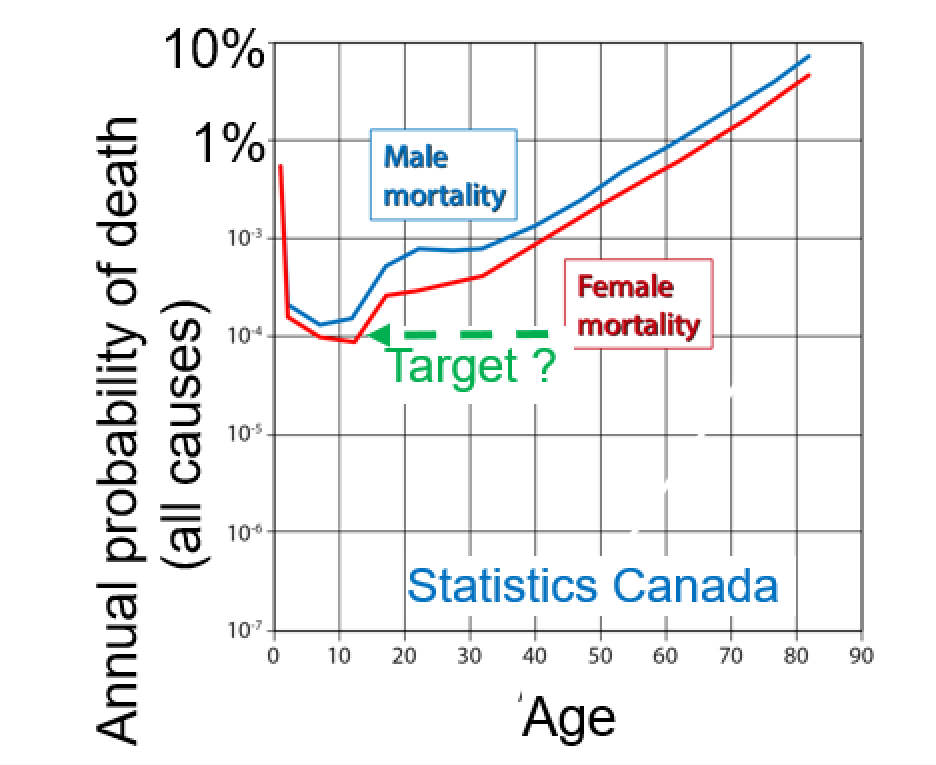


Figure modified from GEO Rpt 75, Ken Ho (1998)

What is acceptable risk?





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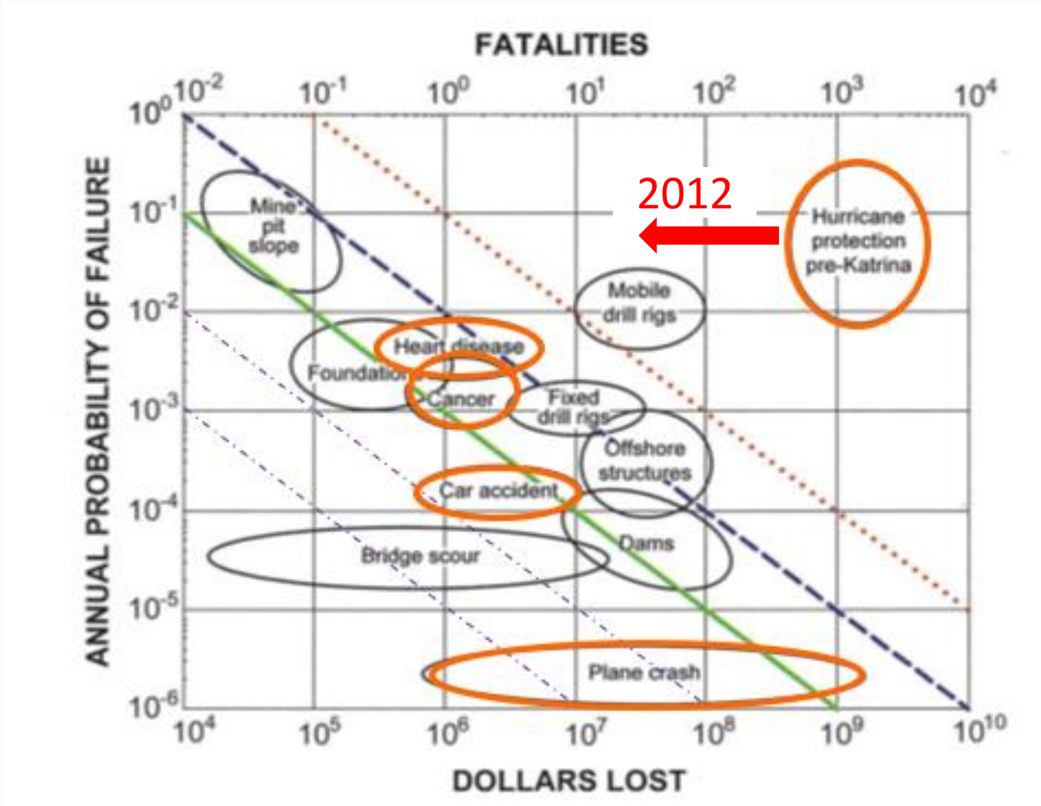
Meaning of probability values?



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Contents

- What is Risk-informed decision-making?
- **Applications: reducing landslide risk**
  - **Gjerdrum**
  - **Alta**
  - **Site A (on-going)**
- Mitigation of landslide risk
- Framework for risk assessment and management
- Summary and conclusions

Application – landslide risk

WHY?

The geoprofessional’s role is not only serves society, its role is also to save lives in landslide-prone regions.

- 3000 registered quick clay hazard zones in Norway
- 75% of the population exposed to quick clays
- > 85% of large landslides in last 20 years have are due to human activity…

Verdal landslide, May 1893

55 Mm^3
116 fatalities

December 2020 Gjerdrum Landslide

Gjerdrum landslide

Ryan et al. 2021

11 fatalities, 1600 evacuated
Volume: 1.4 x 10^6 m^3
Runout ~ 2000 m
Scarp height: 10-13 m
Debris thickness: 5-10 m
Chaos: infrastructure, services, ecosystem (+pandemic).

Gjerdrum Landslide (1,400,000 m^3)

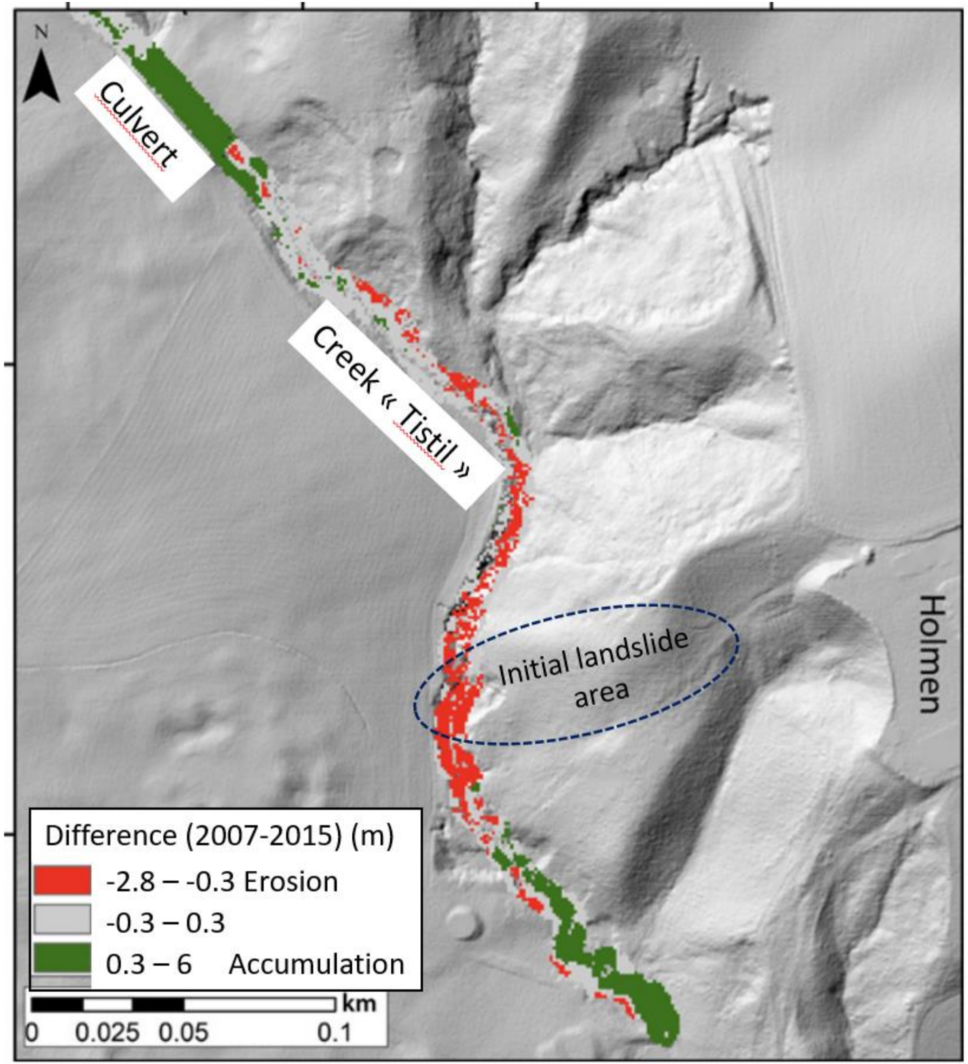
- Thick deposits of marine clay, very sensitive (quick) clay

At Holmen:

- Calculated FS of the slope outside Holmen was very low
- Thick deposits of quick clay
- 25 m high slopes
- This was, however, not sufficient to explain why the landslide occurred, because the slope had been under these conditions already for a long time.

Gjerdrum Landslide

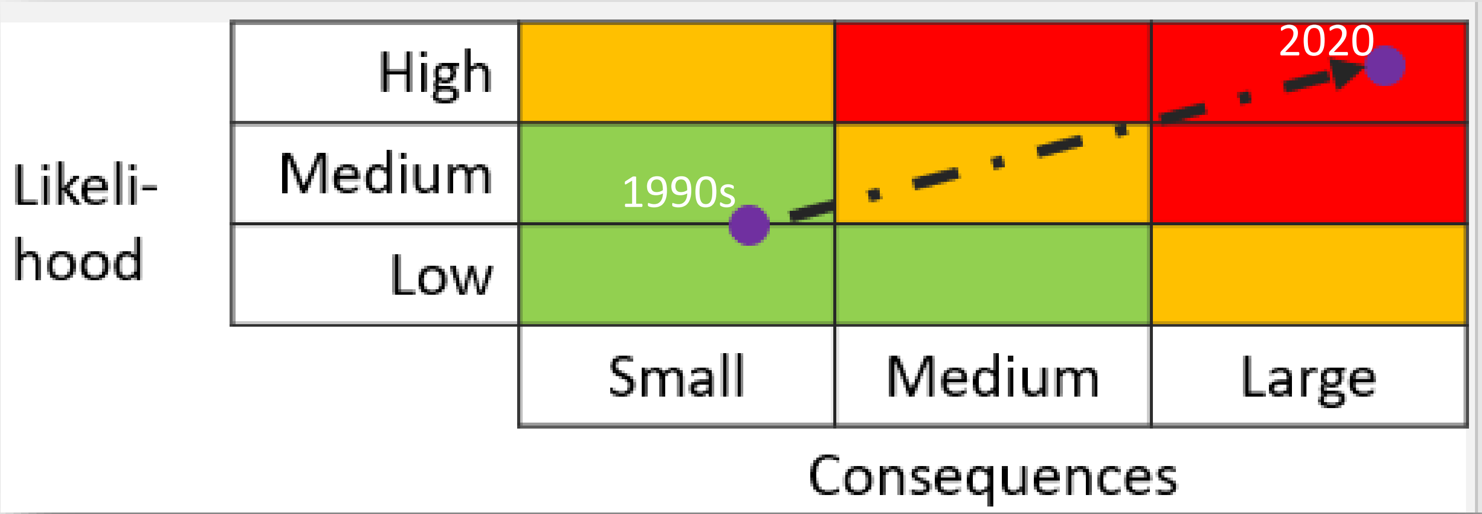
Comparison of terrain model 2007-2015: significant erosion downstream



Gjerdrum Landslide

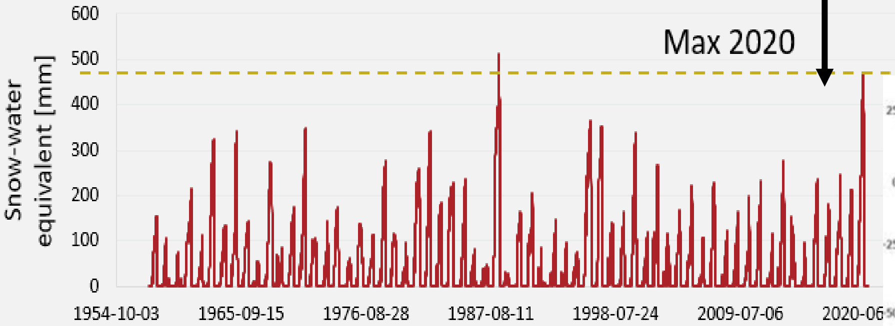
- Erosion was exacerbated by changes in land use in the catchment.
- For agriculture purposes, parts of the creek were laid in pipes. Photographs, witness observations, aerial photos and terrain models document that the creek had broken out of the pipes, starting already in the late 1990s.
- Stabilization was done as part of the urbanization, but the measures did not improve the conditions further down the creek. Urbanization and removal of vegetation increased runoff.
- Several human activities acted in the same direction and contributed to increased erosion at the foot of the slope and the initiation of the landslide.

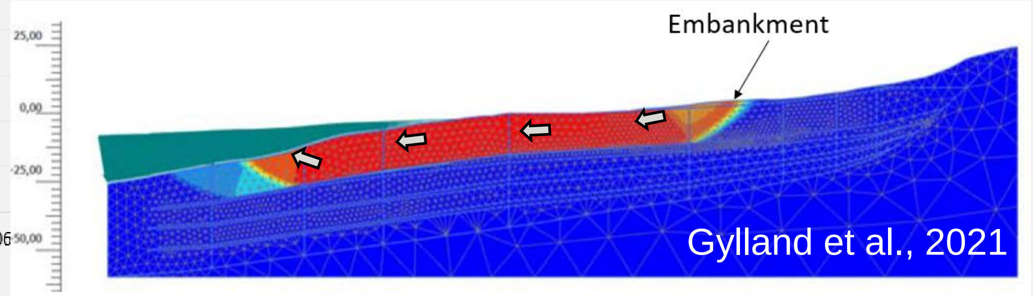
Gjerdrum Landslide - Risk matrix



June 2020 Alta Lands

The Alta landslide



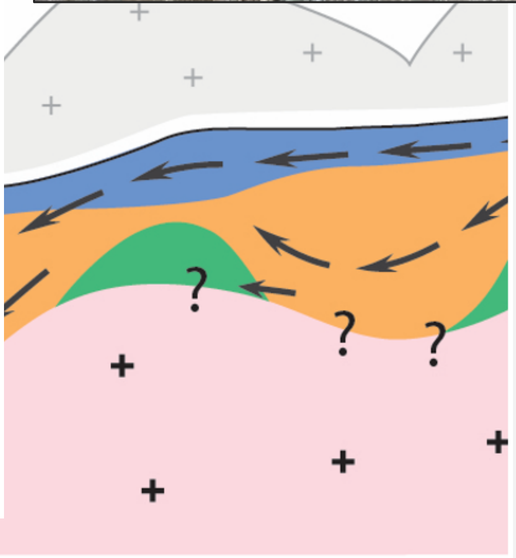


Alta Landslide (900,000 m³)

- 24 m thick clay with interbedded layers of silt and sand
- OC, sensitive clay, sliding partly within ancient landslide scar

- Swept 8 buildings into the sea
- Large flake landslide retrogressing in 2 directions
- Landslide scar: 956 m long and 20 m high
- Tension cracks observed the day before the landslide

- Snow-rich, but not extreme, winter.
- No seismic activity nor any signs of active erosion.
- Lidar revealed increased terrain elevation up to 2 m in 2015, over 600 m²



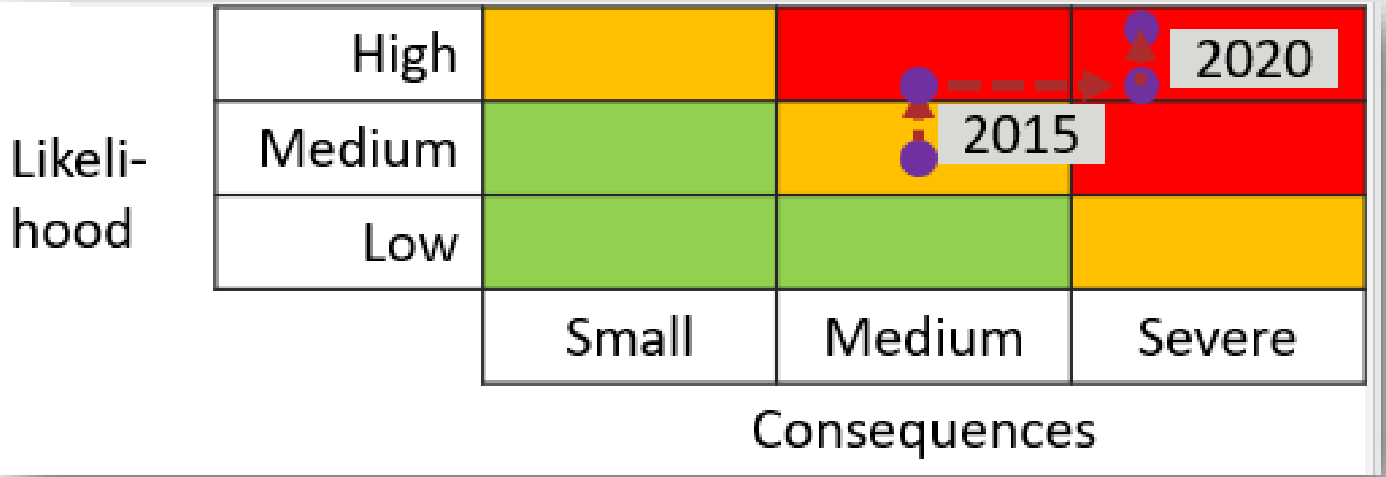
Alta Landslide - Risk matrix

The potential for a landslide at Alta was always present due to (1) the presence of quick clays, (2) the height of the slope and (3) a stratigraphy that made the slope sensitive to changes in porewater pressures.

The fill placed in 2015 increased the likelihood of a landslide. The new house constructed in 2015 increased the number of people living in the area and the potential impact of a landslide. The risk increased (increase in probability and increase in consequences).

The melting of the snow (2020) caused the highest pore pressure experienced by the «new» slope. The likelihood of a landslide increased and therefore the risk increased.

Alta Landslide - Risk matrix

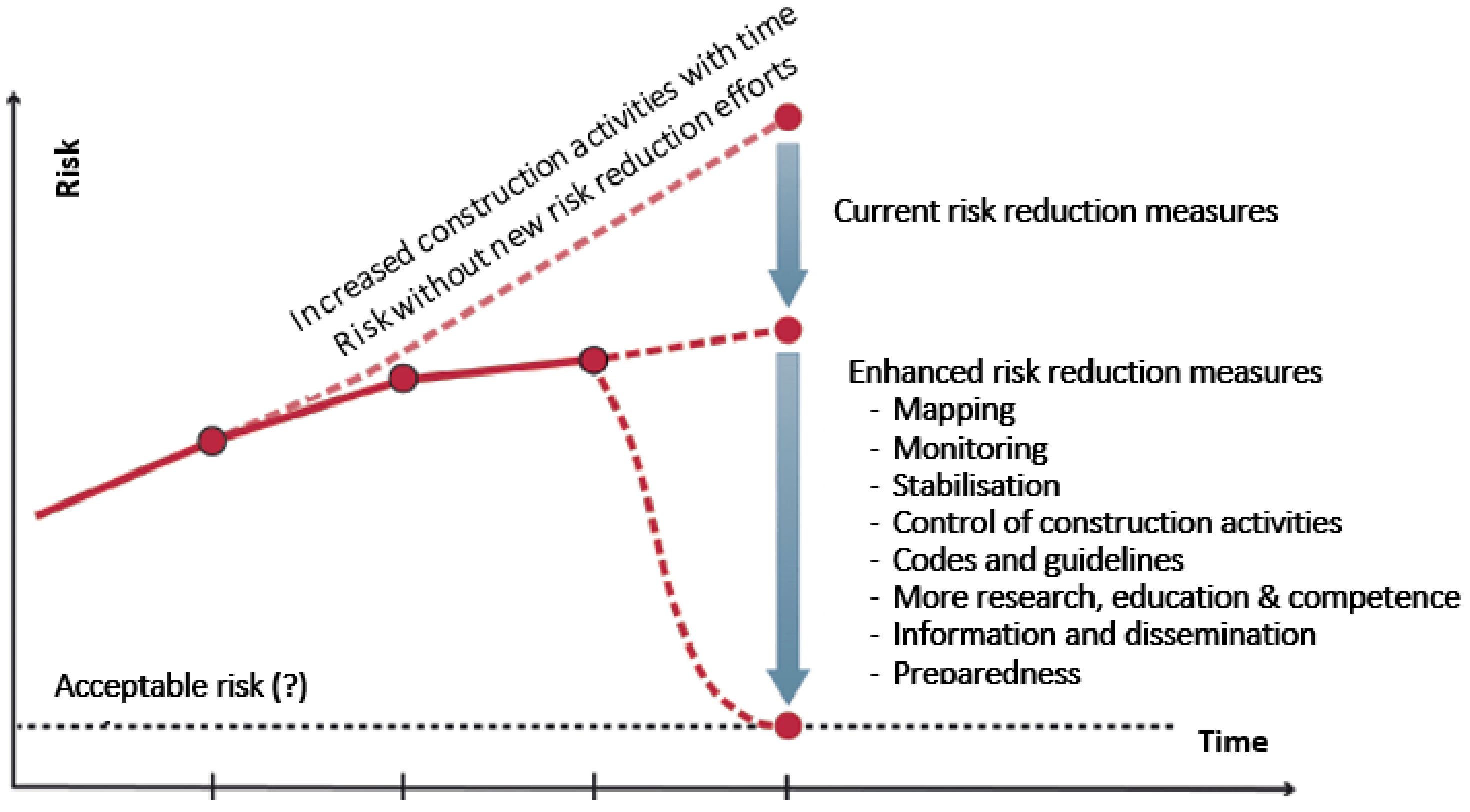


Could these landslides have been prevented?

- The risk assessment methodology for clay areas in Norway is too qualitative and static. Design does not consider changes in erosion over time, climatic variations, land-use changes or urbanisation.
- The stability of slopes depends on a combination of material properties, shear stresses and external factors. Changes/uncertainties in any of these elements will impact the slope stability and therefore the risk.
- The Alta and Gjerdrum landslides occurred following a long history of erosion and/or human activity. New remote sensing techniques allow to create Digital Elevation Models with cm-scale accuracy to monitor aggravating factors. Innovative remote sensing technologies should be used to a greater extent to assess changes in risk with time at a site, including early warning (e.g. crack appearances, animal behaviour).

Illustration of how risk can change with time and how risk reduction measures (and the increase in risk without the measures)

Figure is originally GEO's, adopted by Gjerdrum investigation commission



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Recommendations in the aftermath of the Gjerdrum tragedy

- Focused and strict **new requirements for construction activities** (planning, engineering and control);
- **Monitoring of erosion and other terrain changes**;
- Improving procedures **for follow-up of alerts and citizen reports**;
- Developing a **clear division of responsibilities** for developer, landowner, municipality, state etc;
- Renewed and **improved mapping** of quick clay areas;
- Enhanced **hazard mitigation** of dwellings and buildings in quick clay areas;
- Measures for **enhancing competence and education** on quick clays, the danger and risk they represent and mitigation measures.

Gjerdrum 30.12.2020

Two phases after the landslide:

1- Emergency phase that includes rescue and evacuation

2- Long term risk mitigation phase


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IR WH
117 AUTO 158
DFLT AUTO
UTC+1.0
15
DISARM
Watch in Picture-in-Picture
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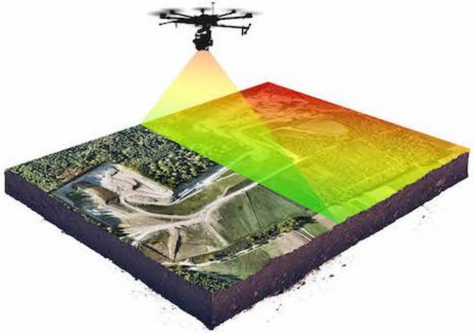
POLITI


GJERDRUM

Immediate response after a landslide

Site assessment and evacuation procedures

- Info on e.g. soil conditions, hazard zones, topography and weather forecast
- Retrogression and runout potential? Who should be evacuated
- Can the landslide be a precursor of a larger landslide?
- Construction activities or elements that can contribute further landslides (e.g. damaged water utility lines)?



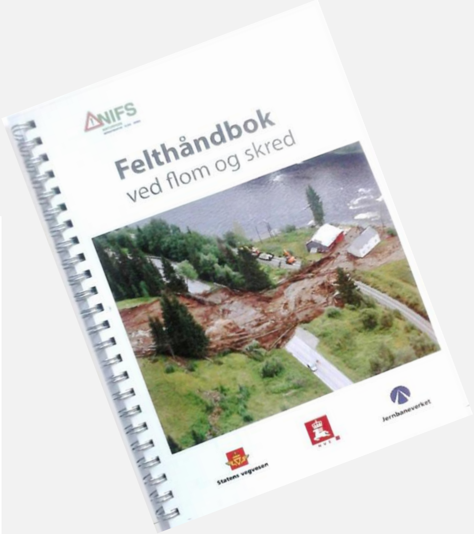
Risk assessment

- Potential hazards should be identified, and security measures should be adopted.
- Monitoring and warning

Immediate response after a landslide

Roles, responsibility and communication

- **Police**: responsibility for emergency management, rescue, evacuation, traffic regulation and implementation of immediate measures necessary to avert further danger and to limit damage.
- **Municipality**: responsible for municipality's infrastructure and residents, and for information to the local community.
- **NVE (government)**: adviser and coordinator of technical advice to the municipalities and the police.
- **Consulting companies**




Gjerdrum 2021/08/22
TLC200 PRO 2021/08/22 12:12:49

Case study , large hazard zone

- Large harbour area (2 km x 1 km), with several slopes that could fail under an external trigger.
- Hazard zone was divided into four sub-areas.
- The lowest calculated SFs (LEM, 2D) in each area were:

Sub-area	Lowest SF
1	1.0
2	1.15
3	1.15
4	1.15

- Varying thicknesses of sensitive clays and of overburden sand over entire area

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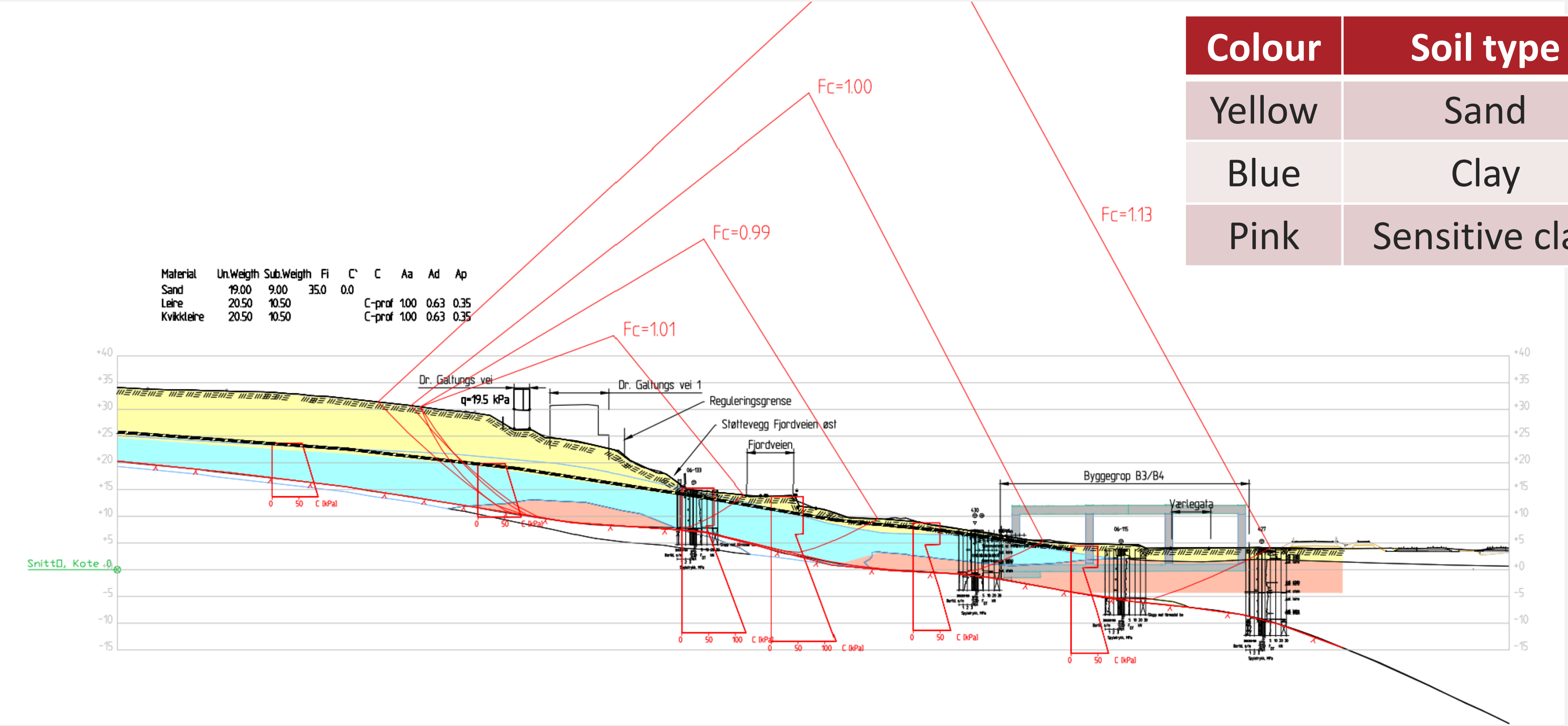
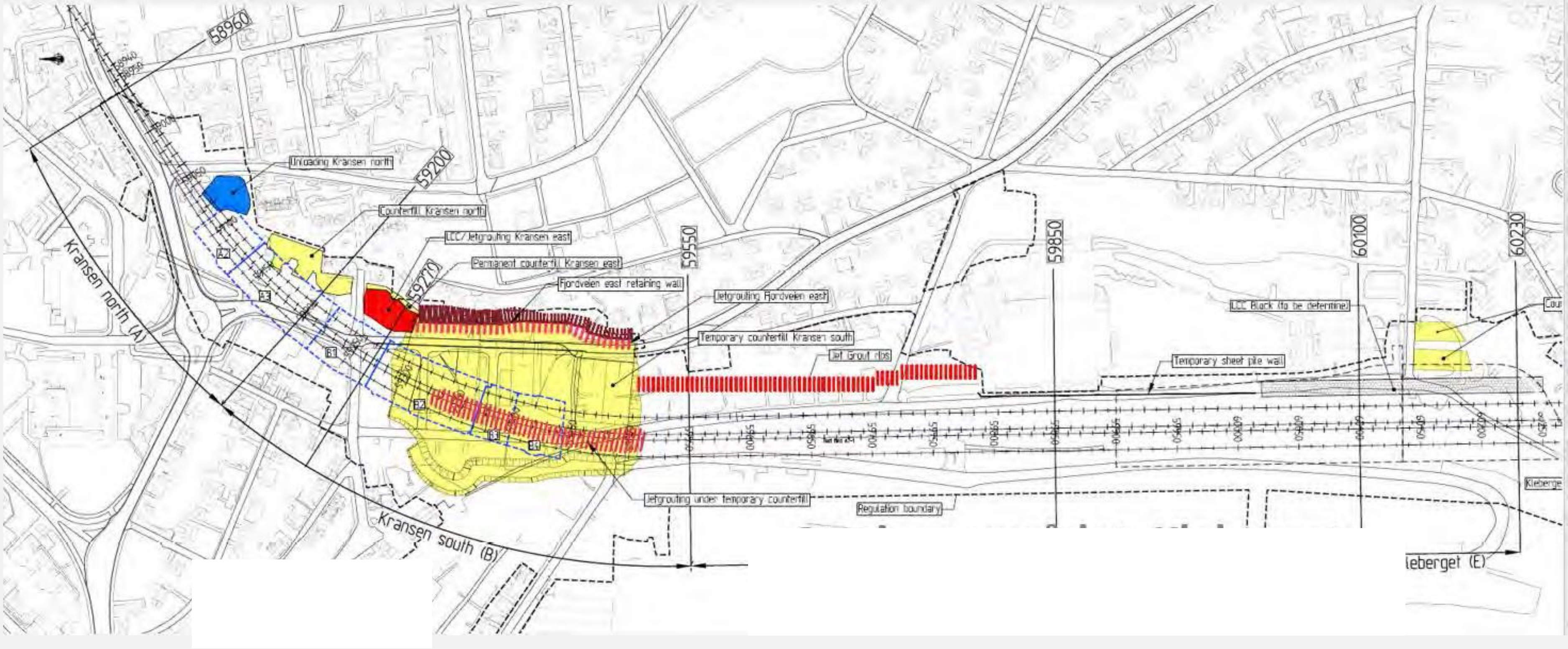
Deterministic stability analyses, example in sub-area 1



Colour	Soil type
Yellow	Sand
Blue	Clay
Pink	Sensitive clay

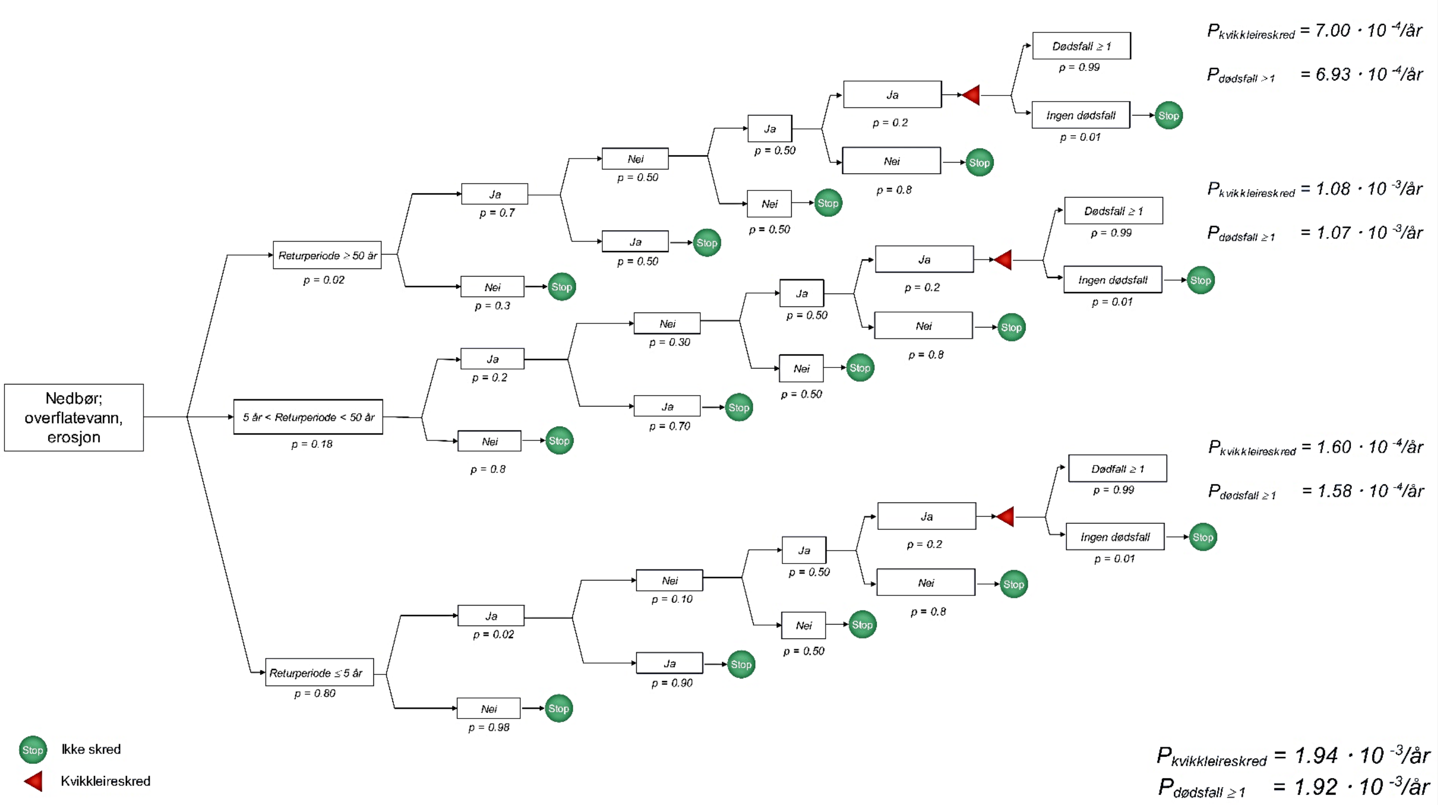
Area with potential for landslide, and mitigation measures



Event tree analysis approach

Sub-area 1, initial conditions, rainfall → surface water and erosion

Nedbør; overflatevann; erosjon	Returperiode av "nedbørhendelse"?	Destruktiv erosjon (som kan påvirke skråningstabilitet)	Utbedres? (tiltak settes i gang og er vellykket)	Utglidning skjer?	Utglidning forårsaker stort kvikkleireskred?	Skred forårsaker tap av liv?



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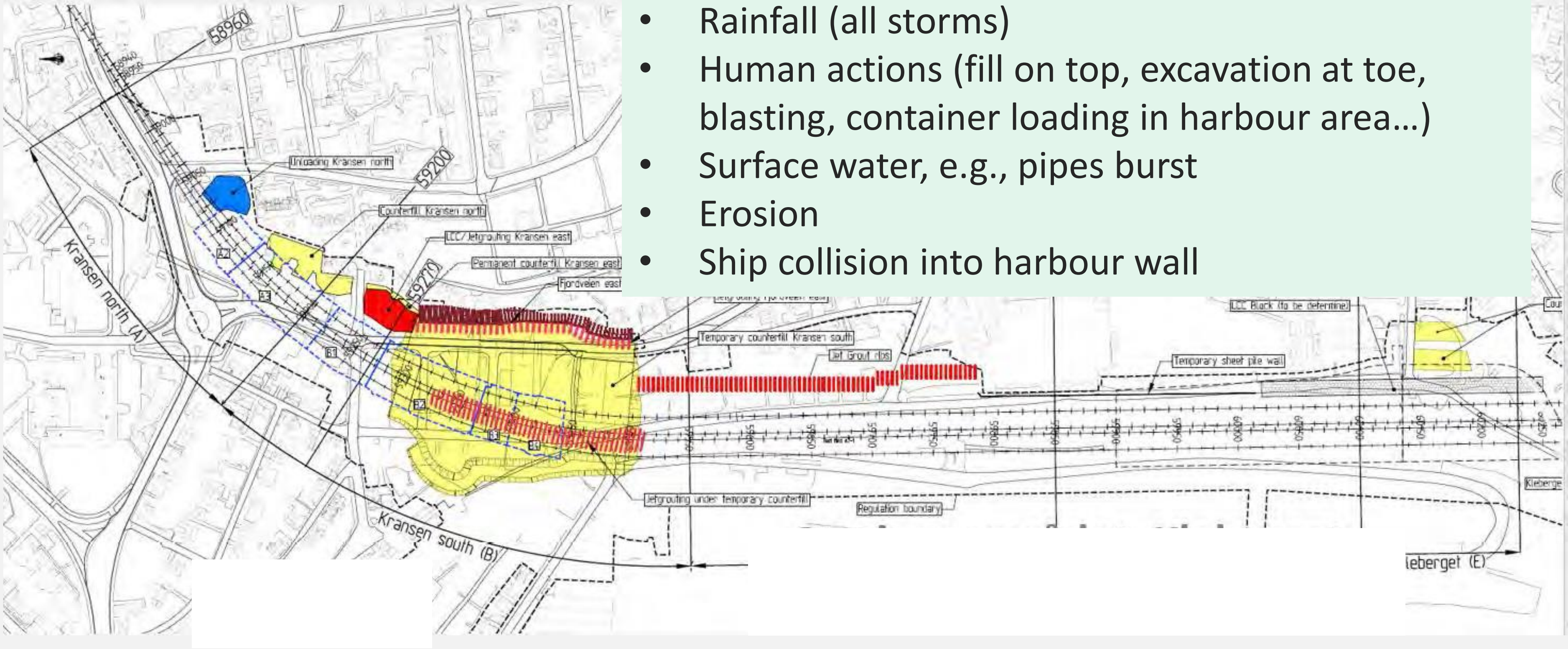
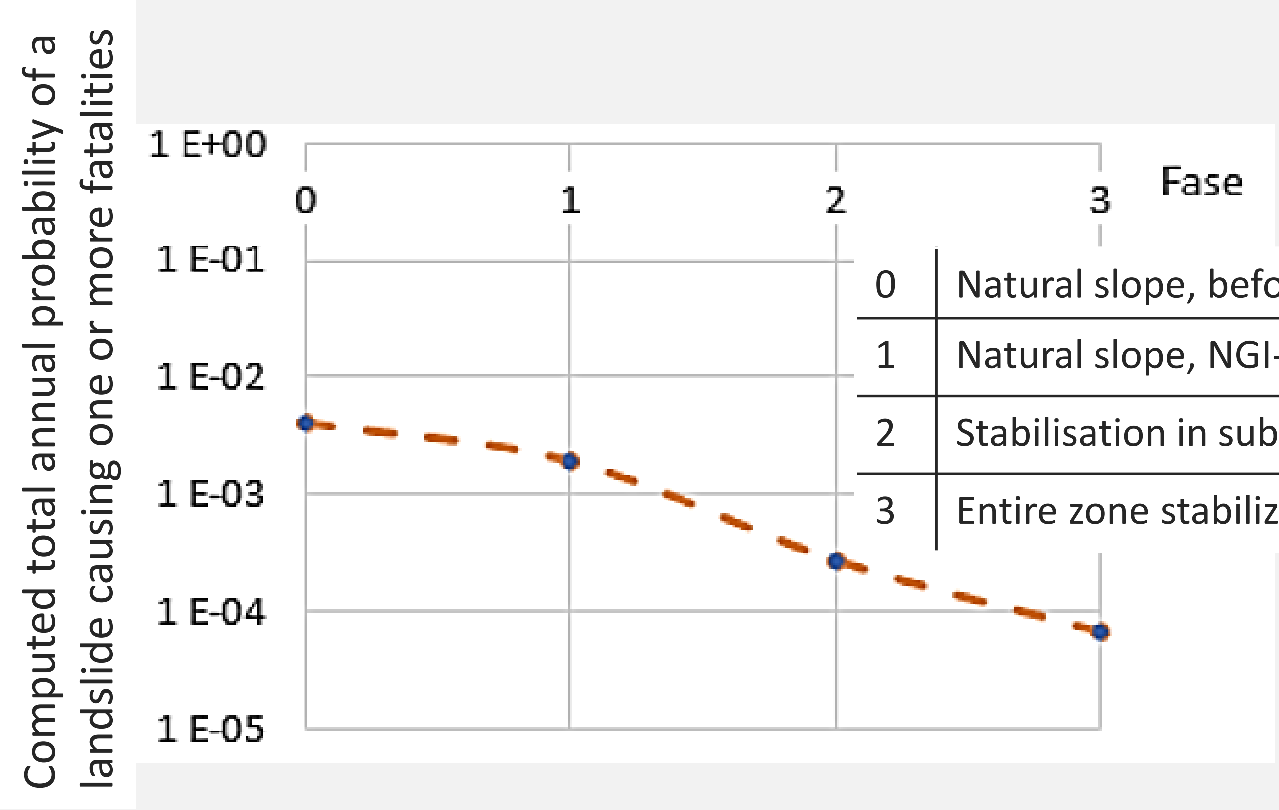


<u>Failure modes analysed</u>

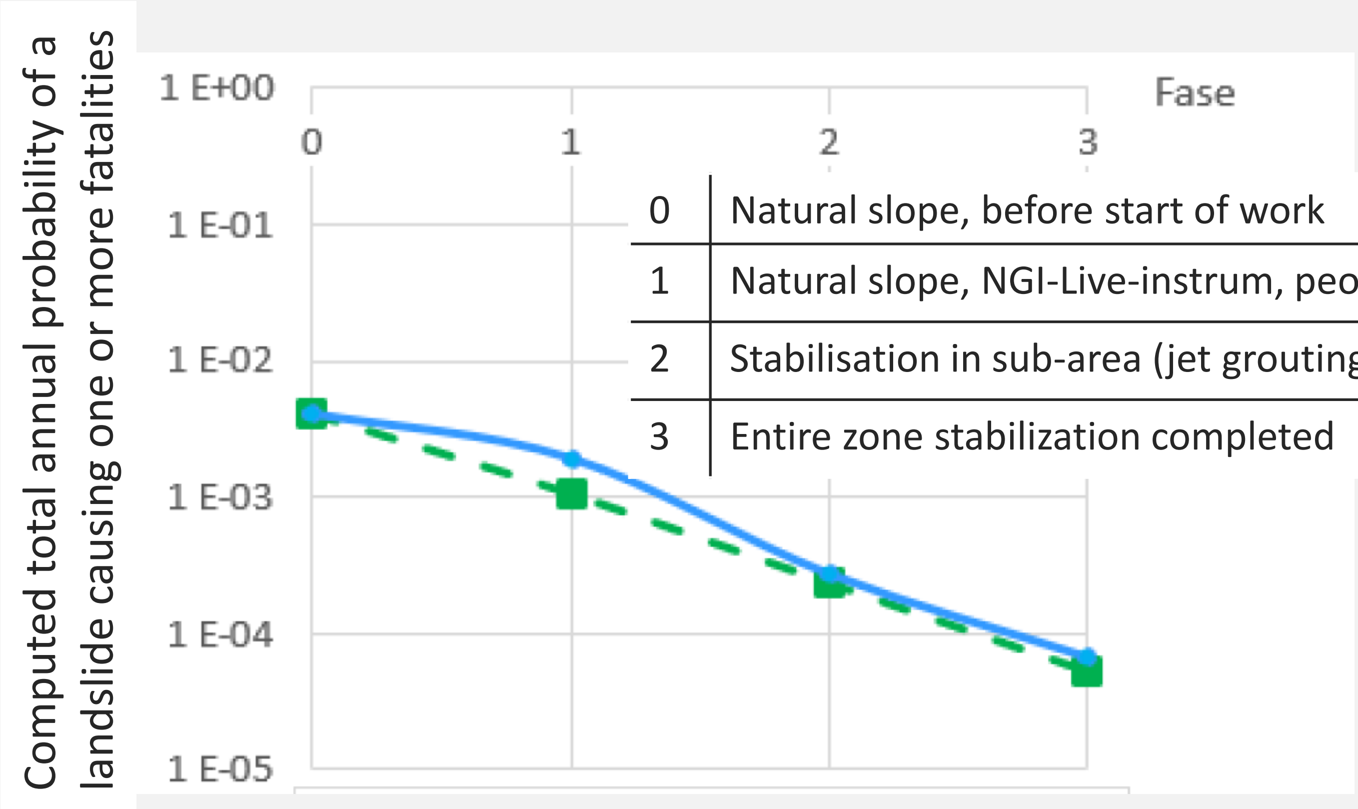
- Rainfall (all storms)
- Human actions (fill on top, excavation at toe, blasting, container loading in harbour area…)
- Surface water, e.g., pipes burst
- Erosion
- Ship collision into harbour wall

Sub-area 1,_with calculated SF= 1.0
Likelihood of a landslide – initial analyses



0	Natural slope, before start of work
1	Natural slope, NGI-Live-instrum, people made aware
2	Stabilisation in sub-area (jet grouting, toe reinf., …)
3	Entire zone stabilization completed

Sub-area 1,_with calculated SF= 1.0
Likelihood of a landslide – addition of erosion protection



0	Natural slope, before start of work
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- Applications: reducing landslide risk
  - Gjerdrum
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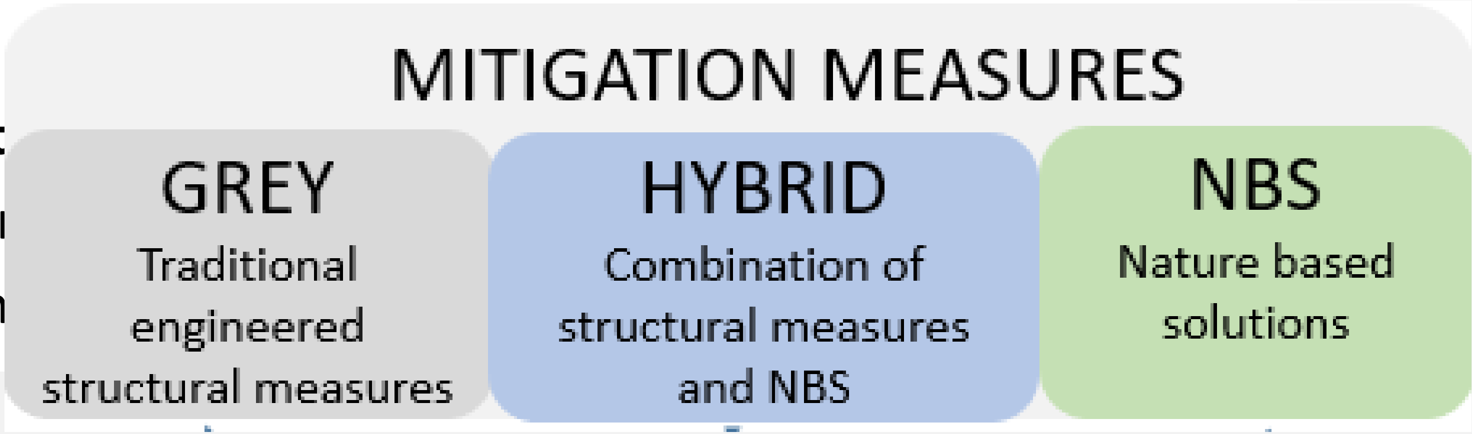
- **Mit**
- Fra
- Sun



Stabilization methods and approaches

- The **most efficient mitigation strategy** usually includes a **combination of methods** that aim at
    - **i)** decreasing the driving forces in the slope
    - **ii)** increasing the strength of the supporting soil
    - **iii)** increasing the resisting forces in the slope.
- The **sequence of work execution** is of great importance.

Example of techniques used for mitigation of landslides in clays in Norway

Landslide	Measures
Kattmarka (2009)	2, 3, 4
Døla (2011)	2, 4
Nittedal (2019)	1, 2, 3, 4
Kvål (2020)	1, 4
Gjerdrum (2020)	1, 2, 4

1 Reduction of the escarpment height from the top

2 Soil improvement with vertical drains

3 Soil improvement with lime-cement

4 Stabilizing buttress

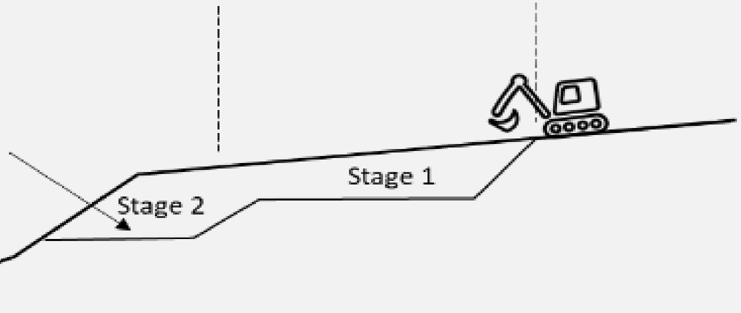
Reducing the height of the escarpment

Gjerdrum: Drone photo (2021)

Reduces the driving forces and increases SF along potential failure plane.

Initiated at a safe distance from the escarpment.

Stop the retrogression process and ensure safety of the workers



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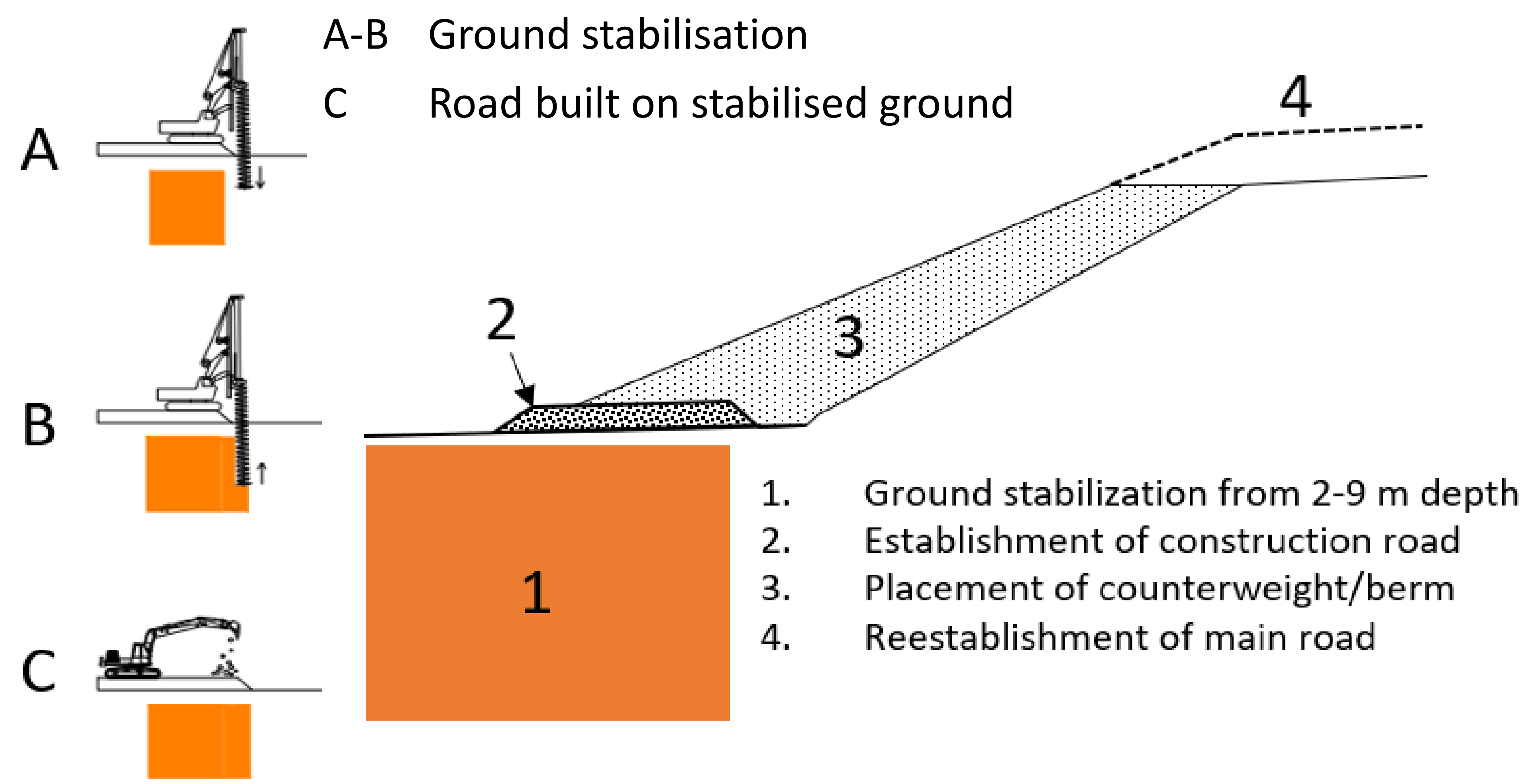
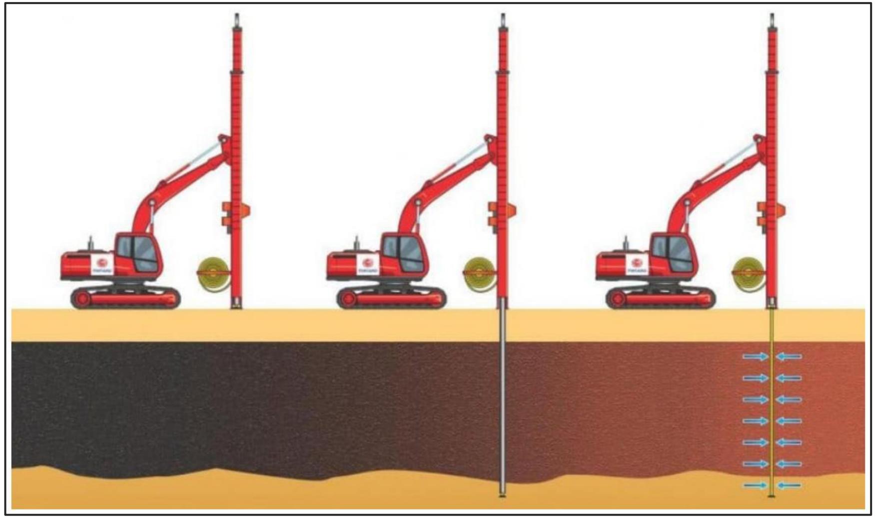

A-B Ground stabilisation
C Road built on stabilised ground
A
B
C
1
2
3
4
1. Ground stabilization from 2-9 m depth
2. Establishment of construction road
3. Placement of counterweight/berm
4. Reestablishment of main road

Soil improvement, PVDs

- Shorten the drainage paths, faster consolidation, strength increase

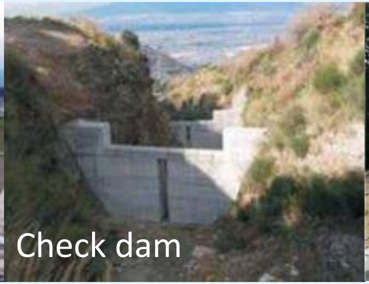
- Installation depths down to 30 m
- Typical ctc distance is 1-2 m.
- A filter layer must be placed on the ground before installing the drains
- Drains can be exposed to larges stresses in the ground – must be considered in the design



Landslide risk mitigation - conventional measures

Active mitigation measures (reduce Hazard)

Passive mitigation measures (reduce consequences)



Fell et al. (2005)

- High costs
- Construction materials
- High carbon footprint
- Maintenance ?
- Visual/environmental impact
- Huge and ‘ugly’

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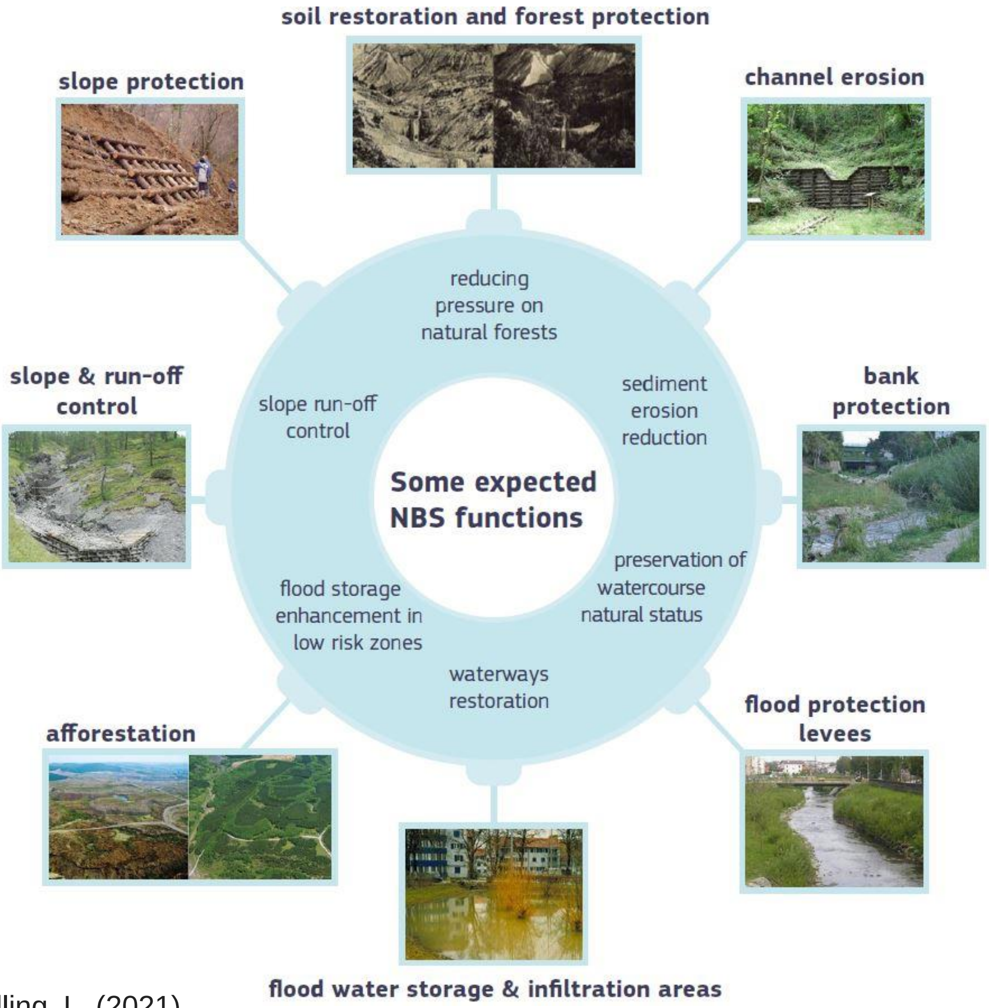
Nature-based Solutions

IUCN (2006)

Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and **biodiversity benefits**



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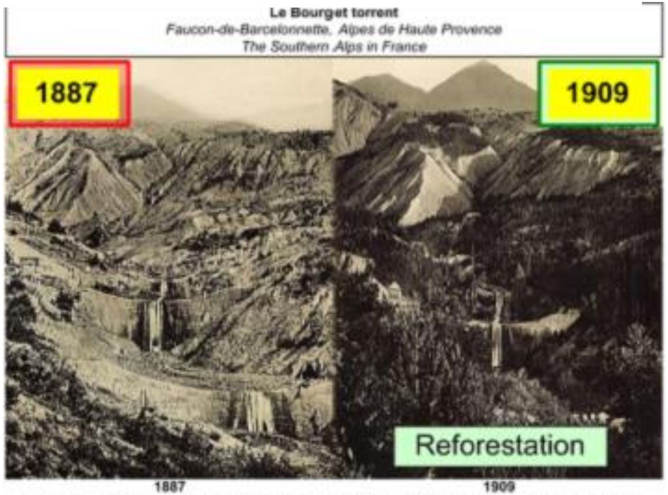
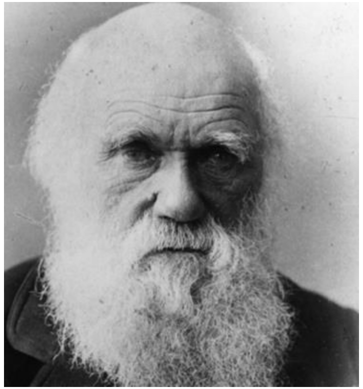
Dumitru, A., & Wendling, L. (2021).

The concept of NBS is not new



From French Forest management school (1911). Restoration and conservation of mountain terrains. Second part, Alps region (in French)



"We believe that there is no structure in plants more wonderful, as far as its functions are concerned, than the tip of the radicle …acts like the brain…"

Ralph B. Peck (1987)
Nature and the Civil Engineer:
"We need to accommodate nature and find nature-based solutions".

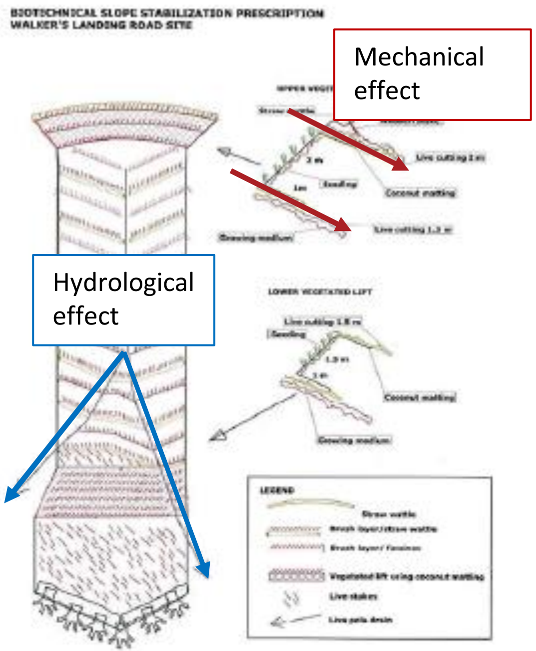
The power of movement in plants
Darwin, Francis, Sir, 1848-1925

Soil-Water Bioengineering – application

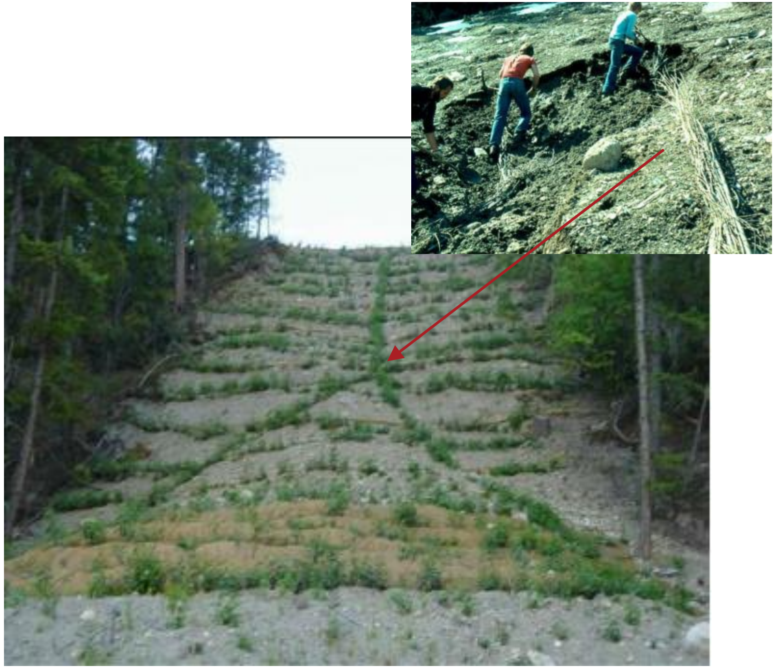
Living plant materials to build structures that provide slope support and erosion protection.

Surficial erosion due to heavy runoff

Design of the installed measures



View of the site after the mitigation



Stokes et al. (2014) - https://doi.org/10.1007/s11104-014-2044-6

LaRiMiT

LaRiMiT (Landslide Risk Mitigation Toolbox) is an "expert-opinion based" Landslide Mitigation Portal to identify cost-effective structural and non-structural landslide risk mitigation options.

- Provide a database of available landslide mitigation measures;
- Assist decision-makers in the selection of 'optimal' mitigation measure(s);
- Platform for sharing experiences among scientists, decision- and policy-makers and other stakeholders

LaRiMiT – Landslide Risk Mitigation Toolbox

https://www.larimit.com/

1) What are the options available?

2) Are they feasible?

3) How expensive they are?

4) What is their environmental impact?

Capobianco et al. (2022) - https://doi.org/10.1007/s10346-022-01855-1

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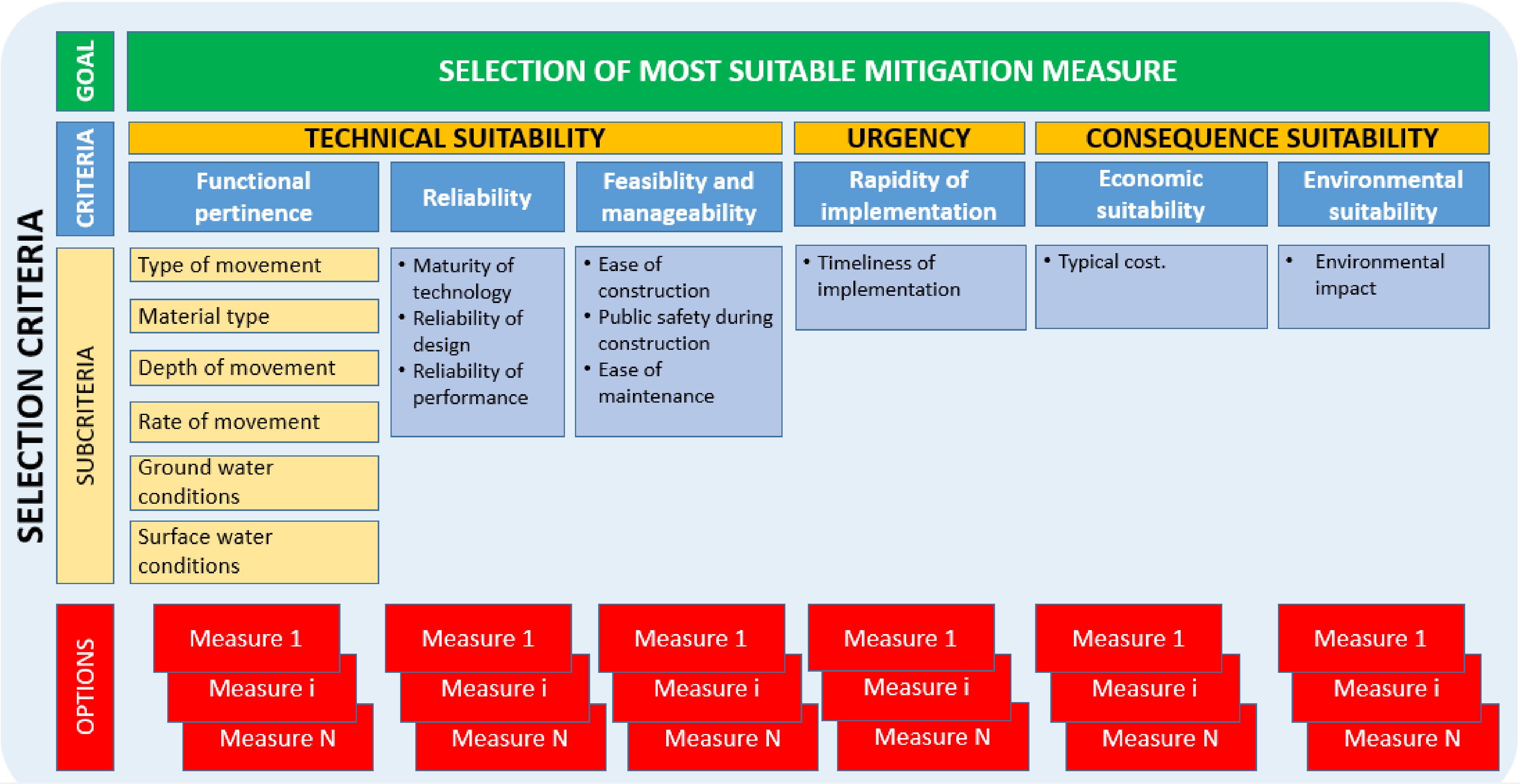
KLIMA 2050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GOAL
SELECTION OF MOST SUITABLE MITIGATION MEASURE
CRITERIA
TECHNICAL SUITABILITY
URGENCY
CONSEQUENCE SUITABILITY
Functional pertinence
Reliability
Feasiblity and manageability
Rapidity of implementation
Economic suitability
Environmental suitability
SUBCRITERIA
Type of movement
Material type
Depth of movement
Rate of movement
Ground water conditions
Surface water conditions
• Maturity of technology
• Reliability of design
• Reliability of performance
• Ease of construction
• Public safety during construction
• Ease of maintenance
• Timeliness of implementation
• Typical cost.
• Environmental impact
OPTIONS
Measure 1
Measure i
Measure N

Hydroseeding

Category: NBS FOR EROSION CONTROL - Living approach

Description | Design methods | Suitability scores

Print

Description

Hydroseeding typically consists of applying a mixture of wood fibre, seeds, fertilizer, and stabilizing emulsion with hydromulch equipment, to temporarily protect exposed soils from erosion by water and wind (Figure 1). Hydroseeding is suitable for areas requiring temporary protection until permanent stabilization is established. It represents a good alternative to normal seeding or to turfing when the area interested is larger than 1000 m^2, or where humans can not reach some places of the slope (by spraying through hydromulch equipment it is possible to reach great distances). They are often combined with bio-degradable geotextiles for a faster vegetation establishment and a better erosion control (BMP, 2009). However the success of this method depends on many factors including the properties and concentration of each component of the mixture, the soil characteristics, the correct choice of plant species, the prevention of seeds to be washed away from water runoff (Albaladejo Montoro et al., 2000). Hydroseeding is increasingly used as combined measure with a principal mitigation measure because of its effectiveness in restoring the area by increasing its aesthetic value (Figure 2).

Advantages

- Easiest way to establish grass on the edges, on wide slopes and other locations where the access is difficult;
- Fast installation time;
- The method can be used both for local and global slope covering.

Disadvantages

- Hydroseeding may be used alone only when there is sufficient time in the season to ensure adequate vegetation establishment and coverage to provide adequate erosion control. Otherwise, hydroseeding must be used in conjunction with mulching (i.e., straw mulch).
- Steep slopes are difficult to protect with temporary seeding;
- Not immediate erosion protection (seeds need to germinate for vegetation to be efficient against erosion);

Figure 1. Aerial Hydroseeding (http://www.ericksonaircrane.com/hydroseeding.php)

Figure 2. Combined rockfall nets with hydroseeding in Orvieto (Italy). On the left: vegetation after one month; on the right: vegetation established after 8 months (source Prati Armati: http://www.pratiarmati.it/).

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Design methods

A preliminary evaluation of site conditions for the selection of the appropriate seed mixtures should be performed with respect to site conditions, site topography and exposure (i.e. sun/wind), vegetation type, season and climate, water availability, plans for permanent vegetation, sensitive adjacent areas.

Some basic instruction should be followed for the implementation:

- The soil to accommodate the seeds must be preliminarly prepared: scarifying the surface to eliminate crust and obstacles improves the water infiltration for the germination of the seeds.
- Hydraulic seed can be applied in single or multiple steps: in single step process seeds and mulch are applied in a hydraulic matrix. A bigger amount of seeds is required to compensate for all seeds not having direct contact with the soil. When multiple step process is adopted, a first layer of hydraulic seed is applied followed by mulch or a geotextile.
- Where seeds fail to germinate, or they germinate and die, the area must be reseeded, fertilized, and mulched within the planting season, using not less than half the original application rates;
- Irrigation systems, if applicable, should be inspected daily while in use to identify system malfunctions and line breaks. When line breaks are detected, the system must be shut down immediately and breaks repaired before the system is put back into operation;
- Irrigation systems shall be inspected for complete coverage and adjusted as needed to maintain complete coverage;
- Growing conditions vary widely across terrain suitable for hydroseeding.

Period of installation: during a season when water availability is sufficient;

Materials: seeds, fertilizers, mulch.

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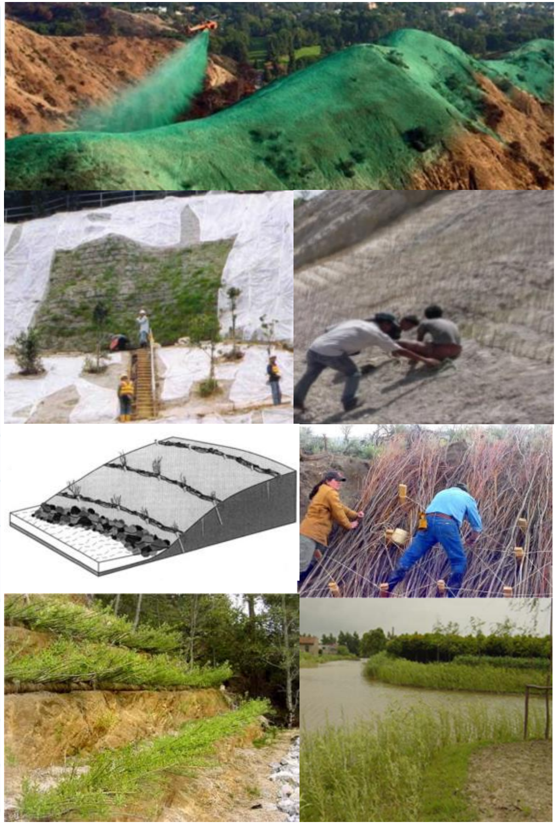
NBS measures in LaRiMiT

Risk reduction	ID	Category	ID	Mitigation measure	Grey	Hybrid	NBS	Update status*
Reduction of the landslide hazard	1	NBS for erosion control — living approach	1.1	Hydroseeding			x	Updated
			1.2	Turfing			x	Updated
			1.3	Tree bushes direct/pit planting			x	Updated
			1.4	Live/inert fascines and straw wattles			x	Updated
			1.5	Brush mattresses			x	Updated
			1.6	Brush layering			x	Updated
			1.7	Live stakes (live poles)			x	Updated
			1.8	Live smiles			x	Updated
	2	NBS for erosion control — living/not living approach	2.1	Geotextiles (rolled erosion control products)			x	Updated
			2.2	Drainage blankets			x	Updated
			2.3	Beach replenishment/nourishment			x	Updated
			2.4	Rip-rap			x	Updated
			2.5	Rock dentition	x		x	Updated



Capobianco et al. (2022) - https://doi.org/10.1007/s10346-022-01855-1

Contents

- What is Risk-informed decision-making?
- Applications: reducing landslide risk
  - Gjerdrum
  - Alta
  - Site A (on-going)
- Mitigation of landslide risk
- **Framework for risk assessment and management**
- **Summary and conclusions**

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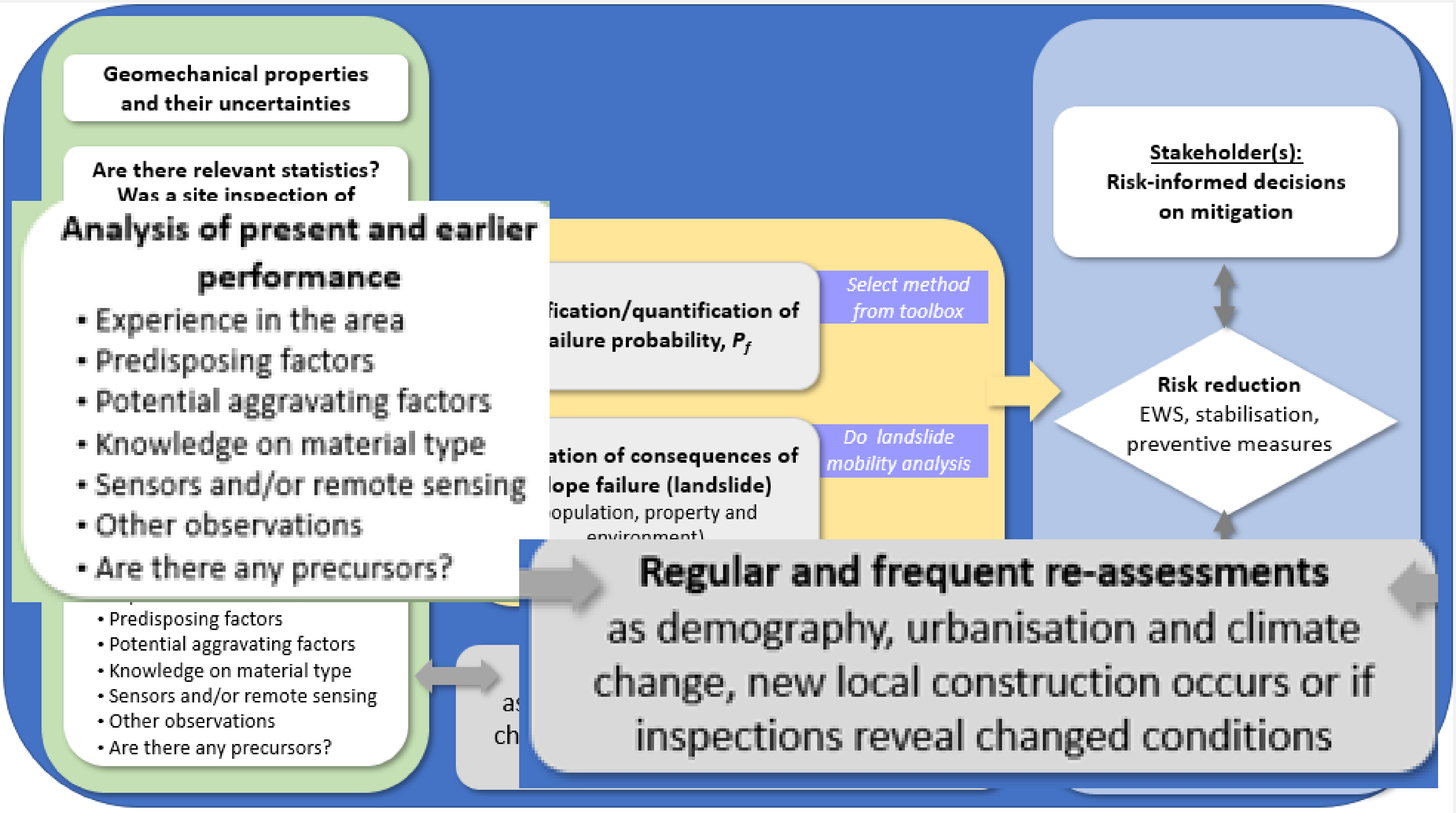
Integrated landslide risk management framework

To do hazard and consequence analysis and systemize the knowledge, uncertainties and their significance on risk. Four components:

1. Assembling the knowledge required for both deterministic and probabilistic hazard assessment and for a consequence analysis and do deterministic analyses;
2. Risk assessment, either qualitative or quantitative;
3. Decision-making and risk reduction;
4. Loop of regular and frequent re-assessments of landslide risk



Geomechanical properties and their uncertainties
Are there relevant statistics?
Was a site inspection of
Analysis of present and earlier performance
• Experience in the area
• Predisposing factors
• Potential aggravating factors
• Knowledge on material type
• Sensors and/or remote sensing
• Other observations
• Are there any precursors?
• Predisposing factors
• Potential aggravating factors
• Knowledge on material type
• Sensors and/or remote sensing
• Other observations
• Are there any precursors?
fication/quantification of ailure probability, P_f
Select method from toolbox
ation of consequences of lope failure (landslide)
opulation, property and
Do landslide mobility analysis
Stakeholder(s):
Risk-informed decisions on mitigation
Risk reduction
EWS, stabilisation, preventive measures
Regular and frequent re-assessments
as demography, urbanisation and climate change, new local construction occurs or if inspections reveal changed conditions

Conclusions – Integrated risk framework

To facilitate risk-informed decisions:

- It is a systematic approach to help decide on the need for mitigation measures.
- As time passes and the area evolves to new stages of its life, the premises for the analyses, the assessment and decisions also need to be updated based on the new information.
- Includes layers of review, recurring risk assessment and performance-based validation

Conclusions

Case studies

- Important take-away: risk changes with time, as predisposing factors become more important by aggravating factors. A design or review should consider changes in erosion, land-use, material properties, stresses, hydrometeorology, etc.
- The Alta and Gjerdrum landslides showed that the events occurred following a long history of erosion and/or human activity over months and years.

Risk-informed decision-making

Key aspects for efficient risk-informed decision-making:

(1) Carry out deterministic analyses;
(2) Carry out a risk assessment;
(3) Identify the most significant factors influencing the safety;
(4) Prepare a risk picture of the slope using risk diagrams; and
(5) Make risk-informed decisions on the need to reduce risk.

Risk diagrams help communicate risk to stakeholders. Risk is not absolute nor static, and is not perceived uniformly by all stakeholders. Risks are perceived as higher when unknown, involuntary, unfamiliar, acute or uncontrollable. RIDM and risk diagrams can help create common ground.

There is a need for RIDM

In terms of responsibility, the geoprofessional engineer is in a particularly vulnerable position:

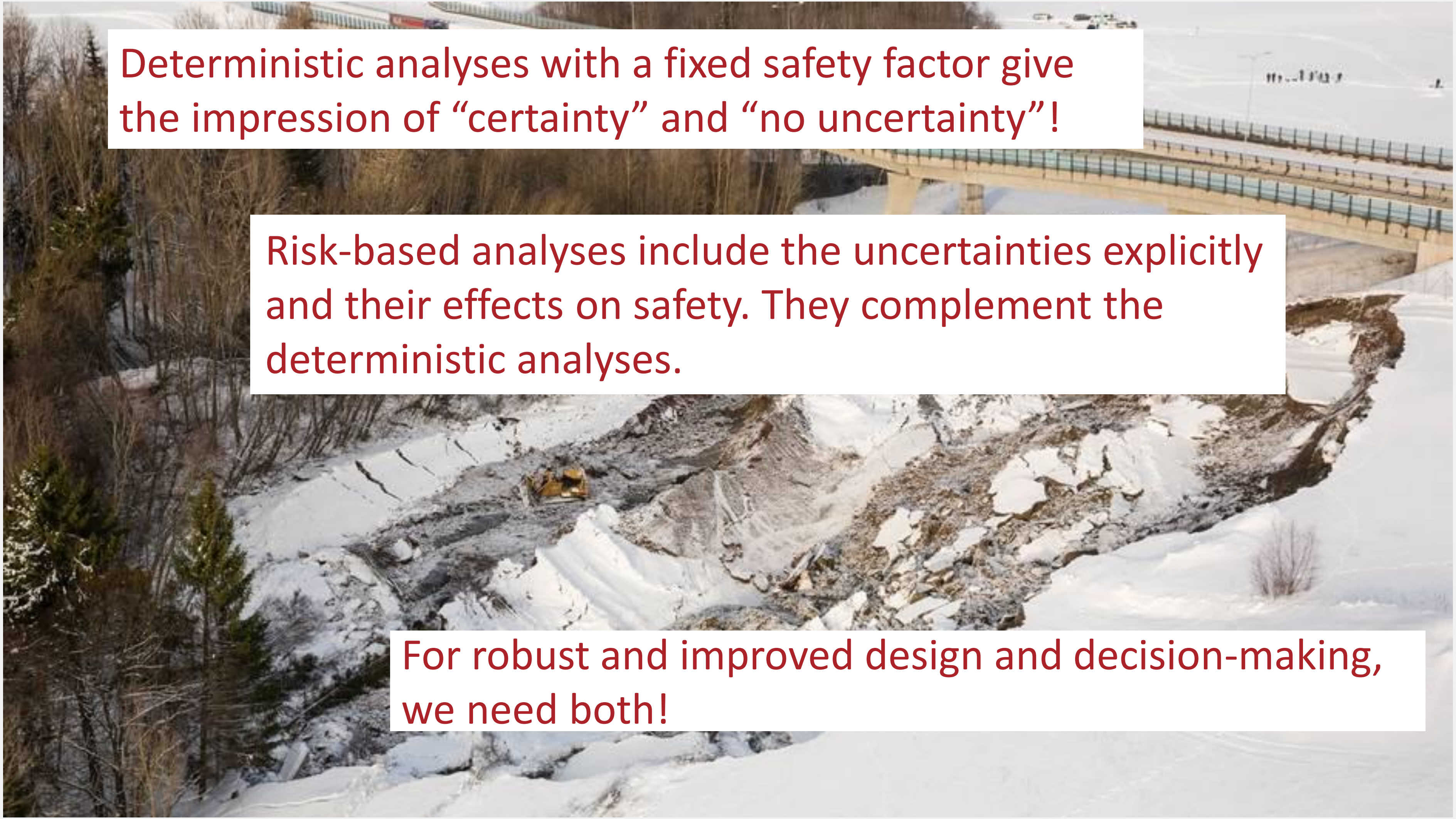
- He/she works at the interface between natural conditions and man-made structures. Often he/she has little information and his/her judgment is continuously taxed.
- He/she must take a stand and identify the situations that are potentially hazardous, and at least initiate a decision-making process about whether the dangers are acceptable or not.

Our profession is continuing to change

Adopting a risk-informed approach, which can be documented and stand the test of time, is one way to improve safety, for both the stakeholders and the population.

A cultural shift has occurred for our profession:

Earlier focus	New trend
Hazard	Consequence
Calculated structural response	Preparedness, resilience
Reactive	Proactive
Science-driven	Multi-disciplinary
Factor of safety decision-making	Risk-informed decision-making
Planning for communities	Planning with communities


Deterministic analyses with a fixed safety factor give the impression of "certainty" and "no uncertainty"!
Risk-based analyses include the uncertainties explicitly and their effects on safety. They complement the deterministic analyses.
For robust and improved design and decision-making, we need both!