8th Terzaghi Oration/8^{e} allocution Terzaghi
ISSMGE Paris 2 September 2013

Lessons learned from landslides

by/par

Suzanne Lacasse

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Karl Terzaghi

NGI

ISSMGE's Terzaghi Orations

Oration	Author	Title
1 (1985)	T.W. Lambe	Amuay landslides
2 (1989)	K. Høeg	Foundation engineering for offshore gravity structures
3 (1994)	V. De Mello	Revisiting our origins
4 (1997)	K. Ishihara	Geotechnical aspects of the 1995 Kobe earthquake
5 (2001)	M. Jamiolkowski	Leaning tower of Pisa: End of an Odyssey
6 (2005)	F. Barends	Associating with advancing insight
7 (2009)	H.G. Poulos	Tall buildings and deep foundations – Middle East challenges

Selection of topic

Over the past decade, our profession has moved in a direction of increased awareness of both its role in society and its contribution to a safer society. The need for targeted communication has emerged more strongly than earlier.

Protecting society from landslide hazard and reducing the exposure and risk to population and property, are some of the issues where we can practice both the art and science inherited from Karl Terzaghi.

Impact of natural hazards in Europe (1900-2000)

Events	Loss of life	Material damage
45 floods	10,000	105 B€
1700 landslides	16,000	200 B€
32 earthquakes	239,000	325 B€

Landslides are frequently triggered by floods and earthquakes and are not statistically recorded as landslides, but as floods and earthquakes in the natural event databases.

Laurits Bjerrum, Karl Terzaghi and Arthur Casagrande at NGI (1957)

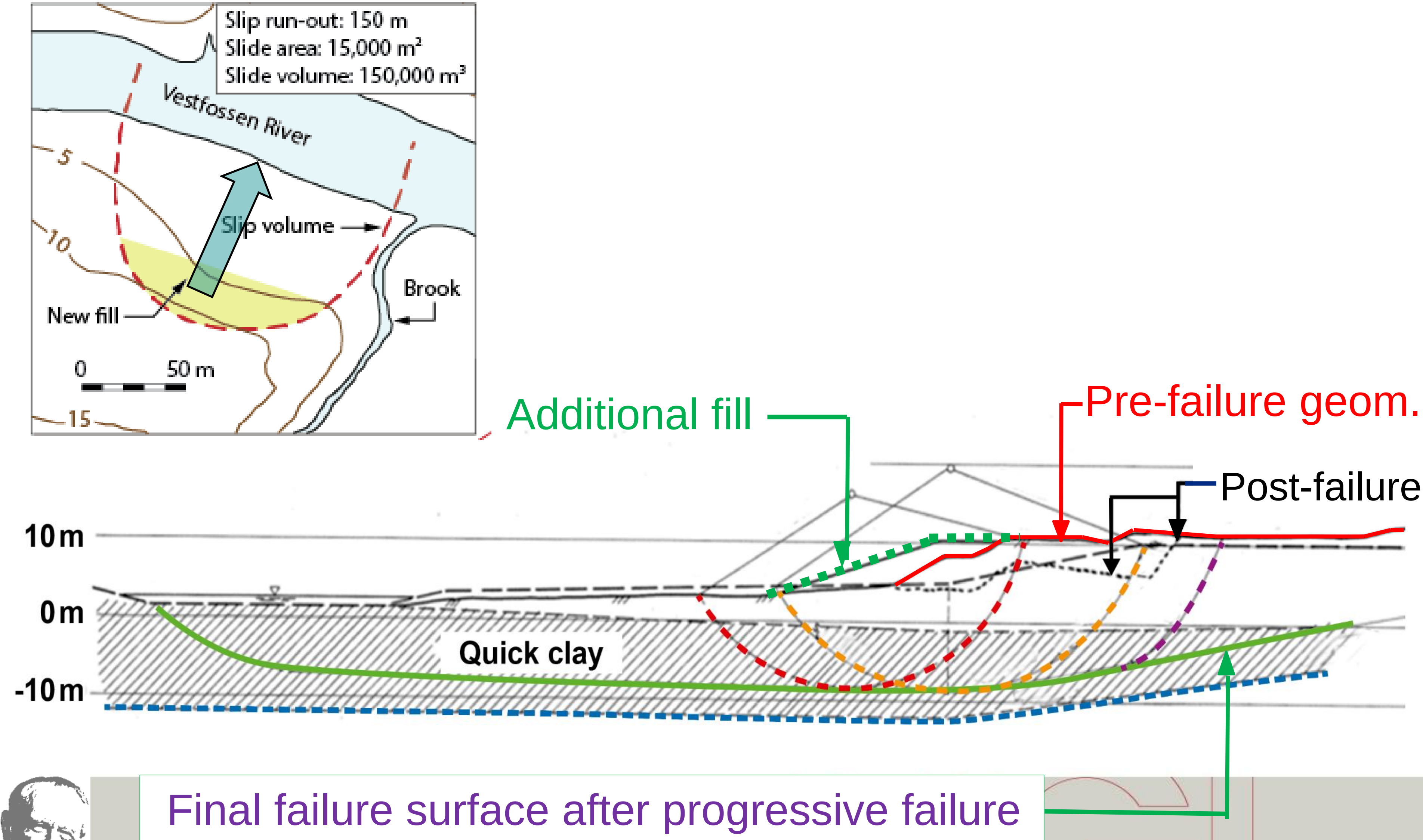
Contents of the lecture

<u>Case studies of landslides</u>

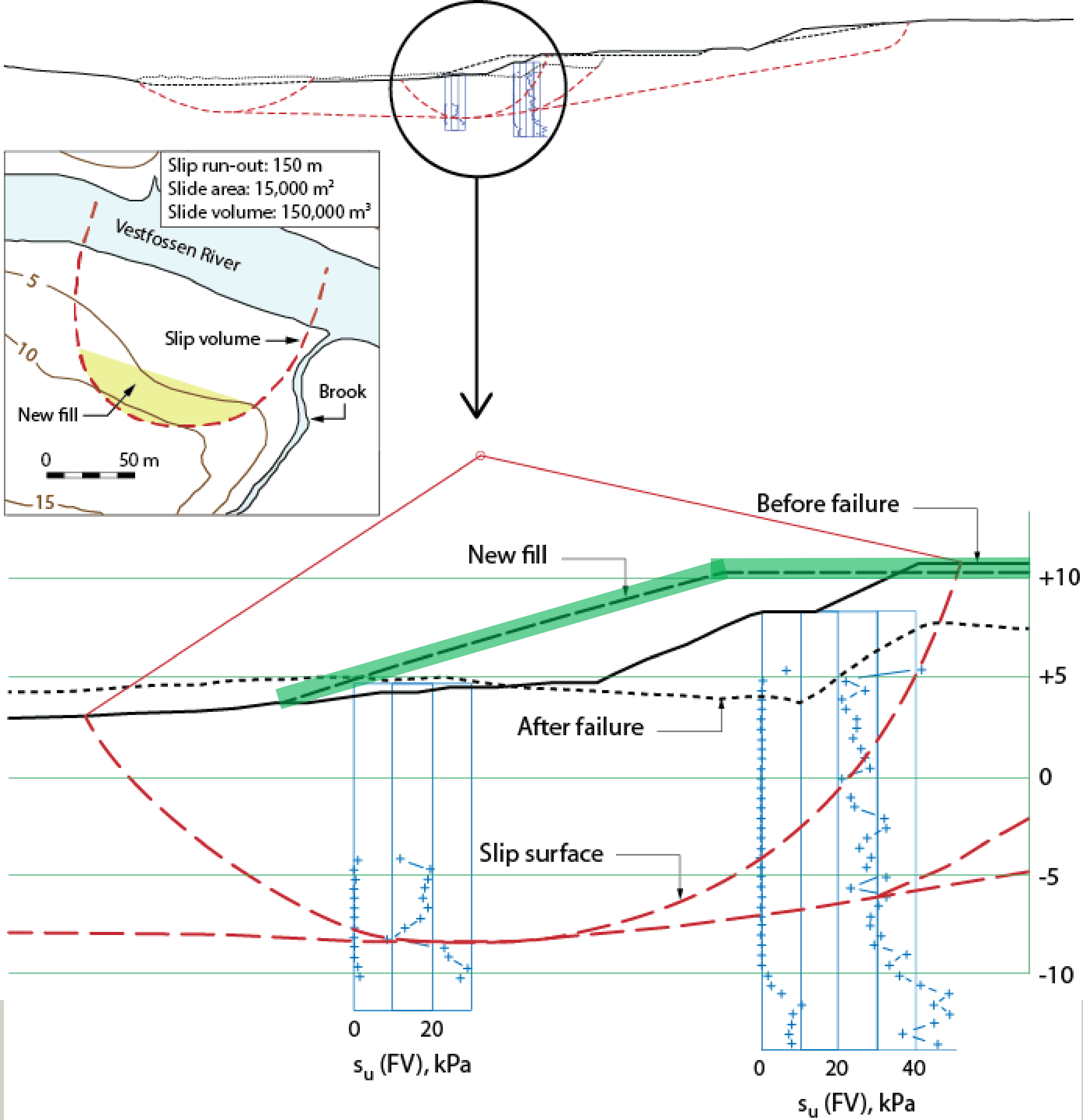
1. Vestfossen Slide, Norway
2. Landslide in Kattmarka, Norway
3. Underwater slide on Cap Lopez, Gabon, Africa
4. Lessons from
   - The Ashcroft Thompson River slides
   - The Aalesund tragedy

<u>Landslide risk management and the role of our profession in protecting people</u>

The Vestfossen landslide (close to Drammen, Norway)



The Vestfossen landslide



Vestfossen soil data

$S_t > 100$

$w = 40\text{-}50\%$

$I_p = w_l - w_p < 10$

$OCR \approx 1.1$

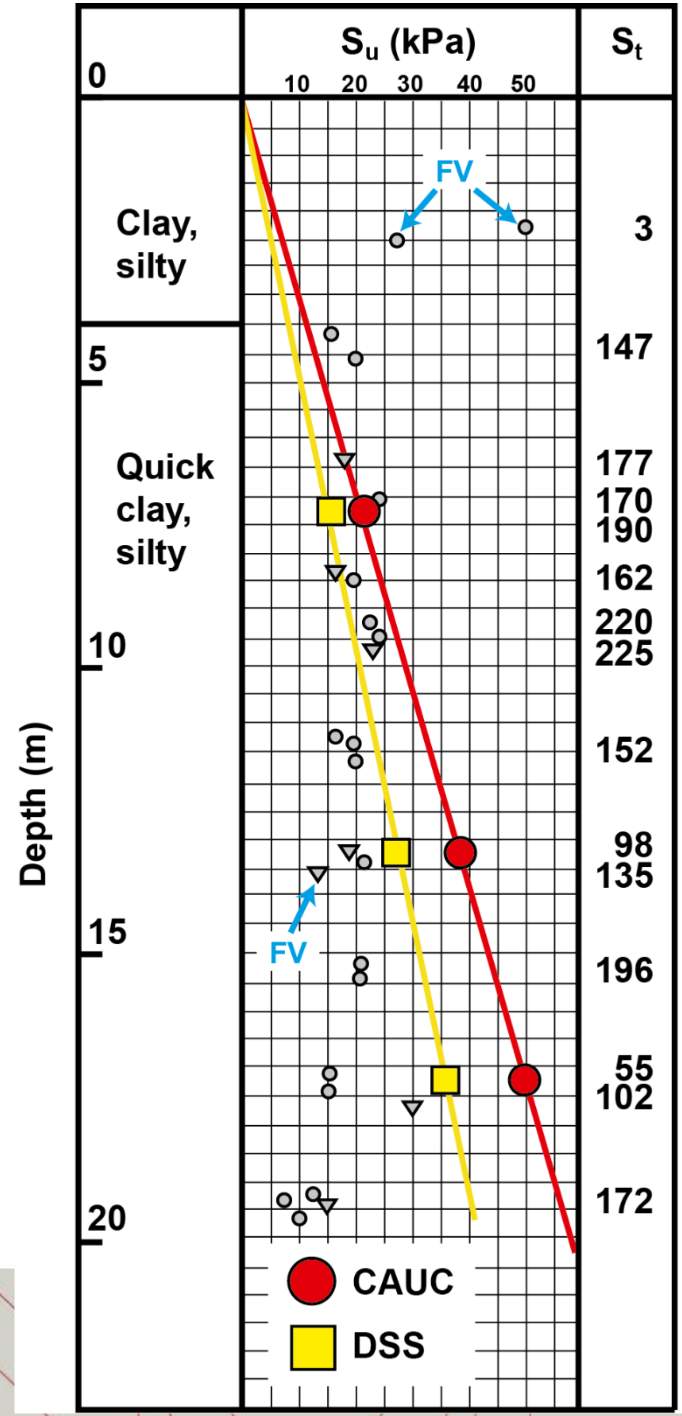
SHANSEP:

$$s_u^c/\sigma'_{vo} = [s_u^c/\sigma'_{vo}]_{NC} \cdot OCR^{\,m}$$

$[s_u^c/\sigma'_{vo}]_{NC} = 0.31$

$m = 0.71$

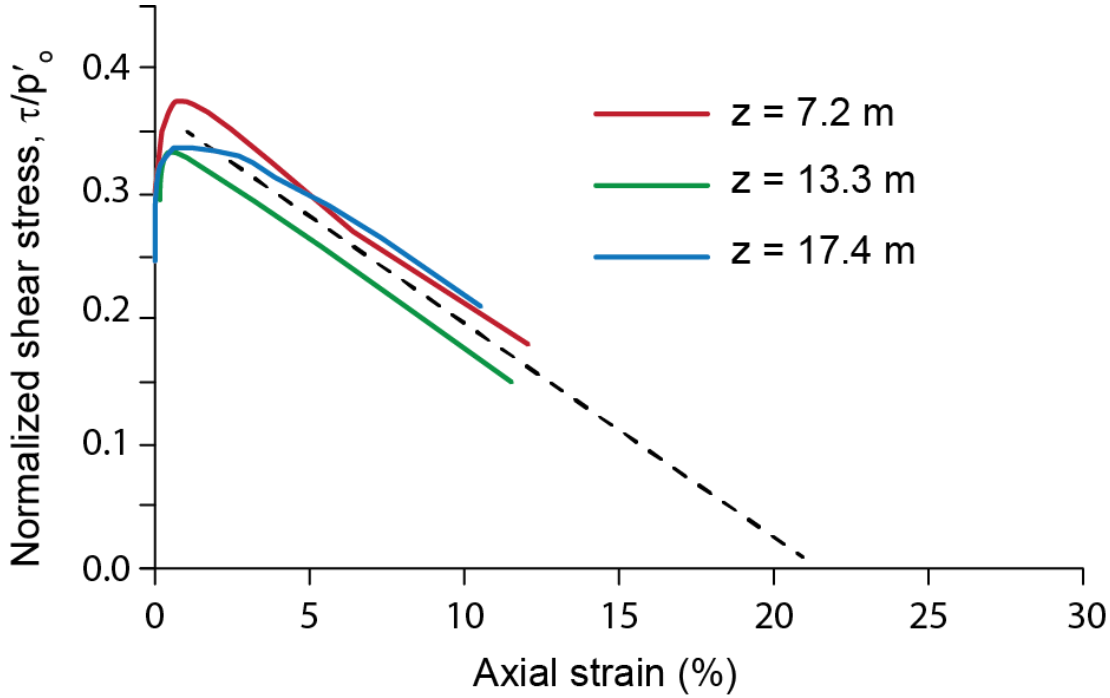
(Karlsrud & Hernandez-Martinez 2013)

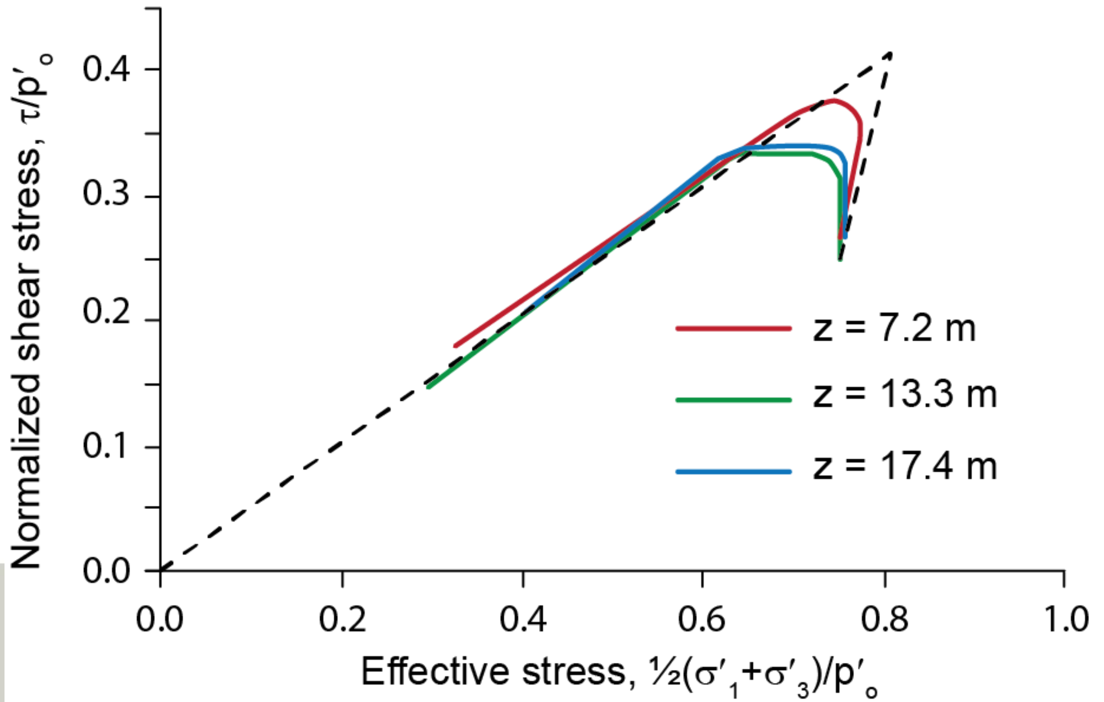


Vestfossen soil data

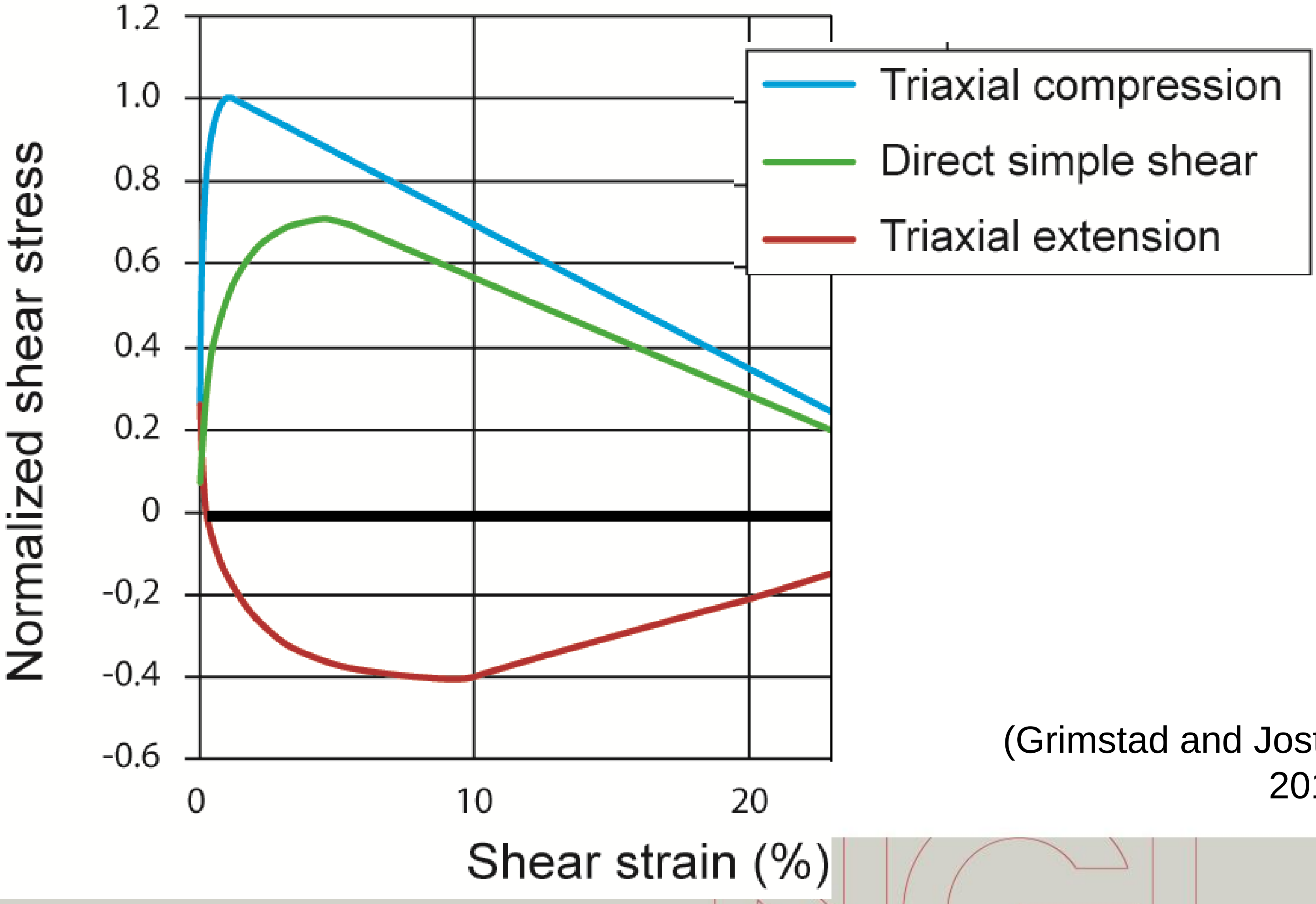
Stress-strain curves and effective stress paths from triaxial compression tests

(Grimstad and Jostad 2011; Berre *et al* 2007).





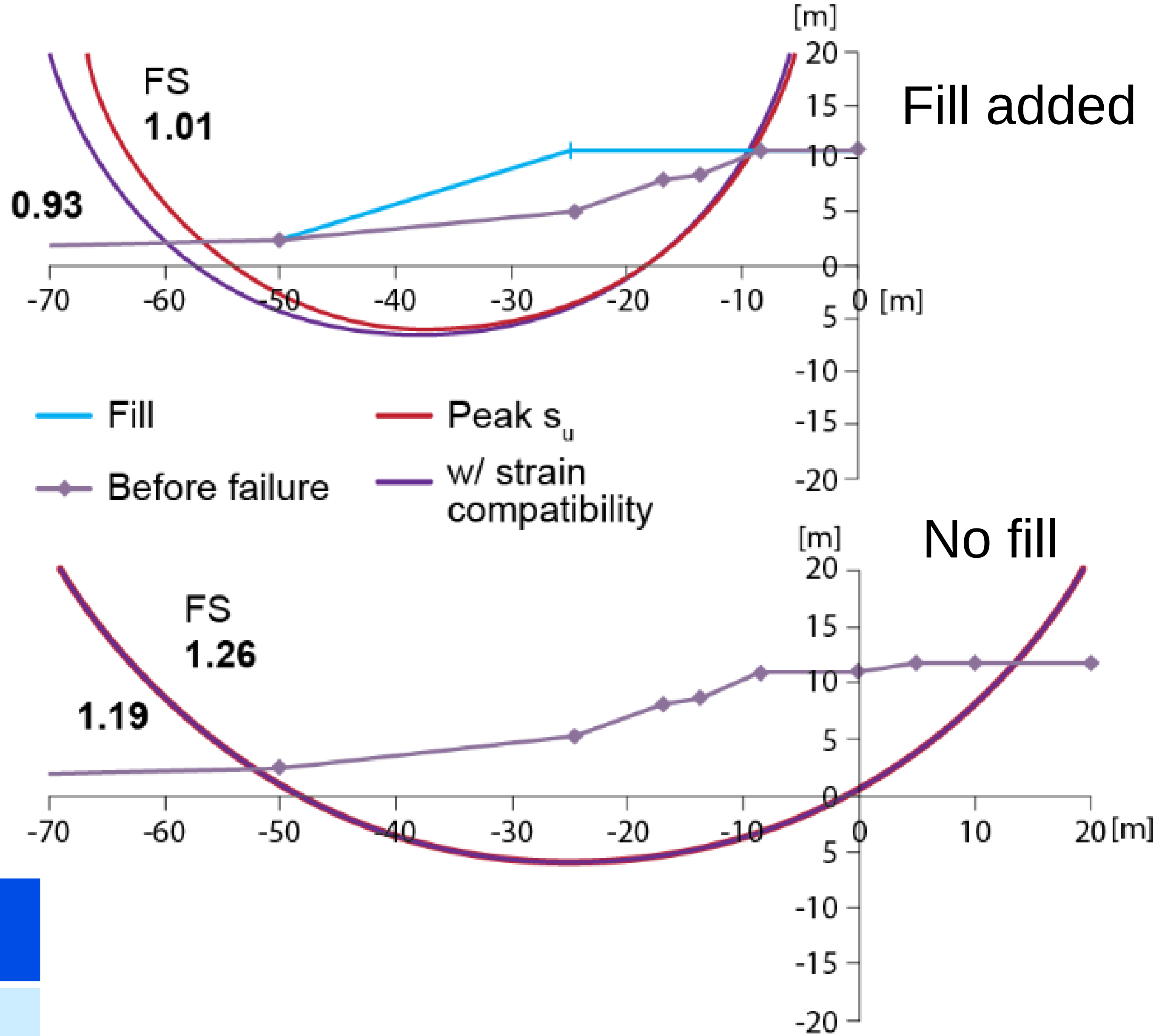
Vestfossen
Analyses of the slide



(Grimstad and Jostad 2012)

Vestfossen

LE analyses of the initial slide

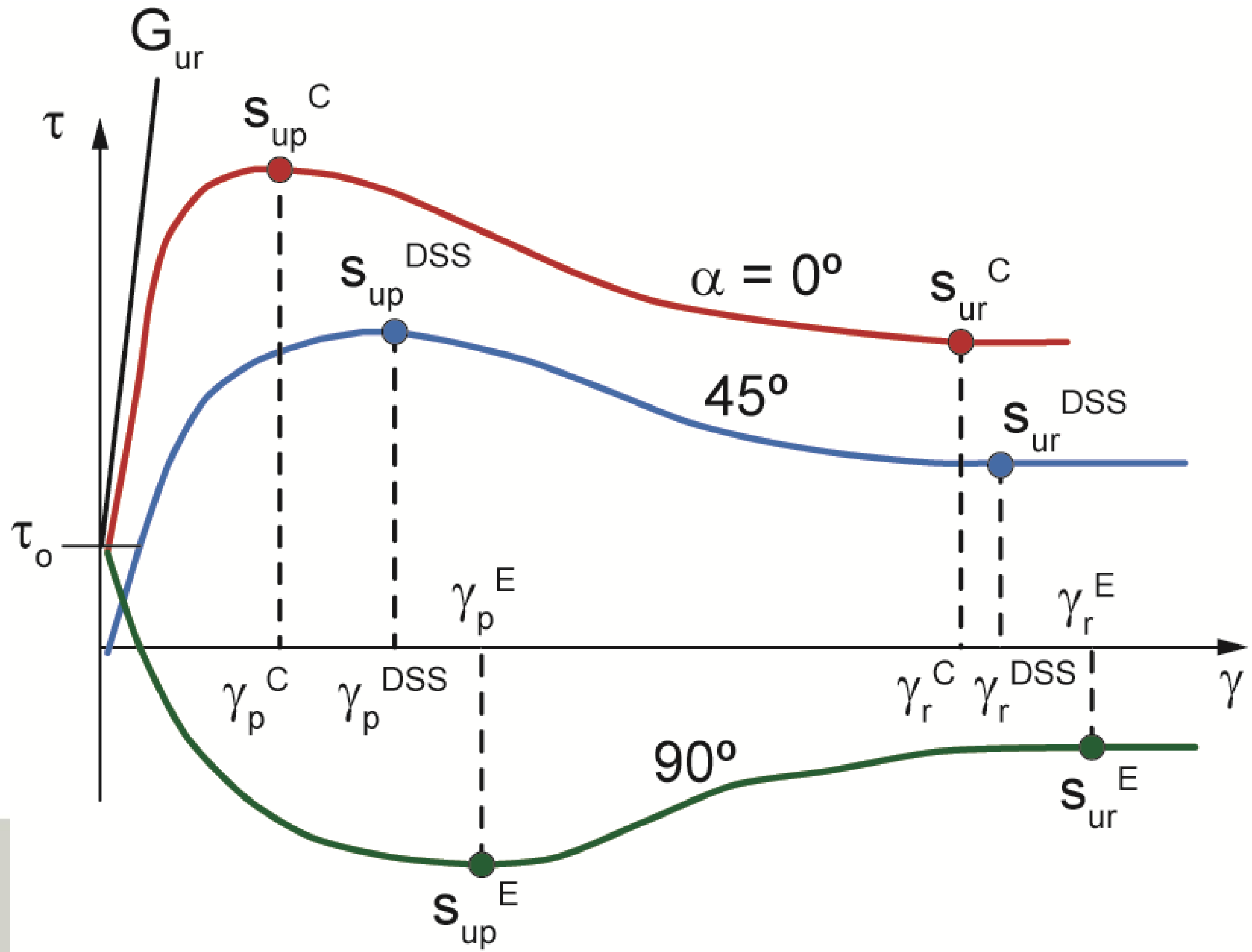


Case	FS
No fill	1.26
Fill added	1.01

Vestfossen - FEM analyses of the slide w/ PLAXIS

NGI ADPSoft model parameters

(Andresen and Jostad 2005; 2007;
Grimstad and Jostad 2012; Fornes and Jostad 2013)



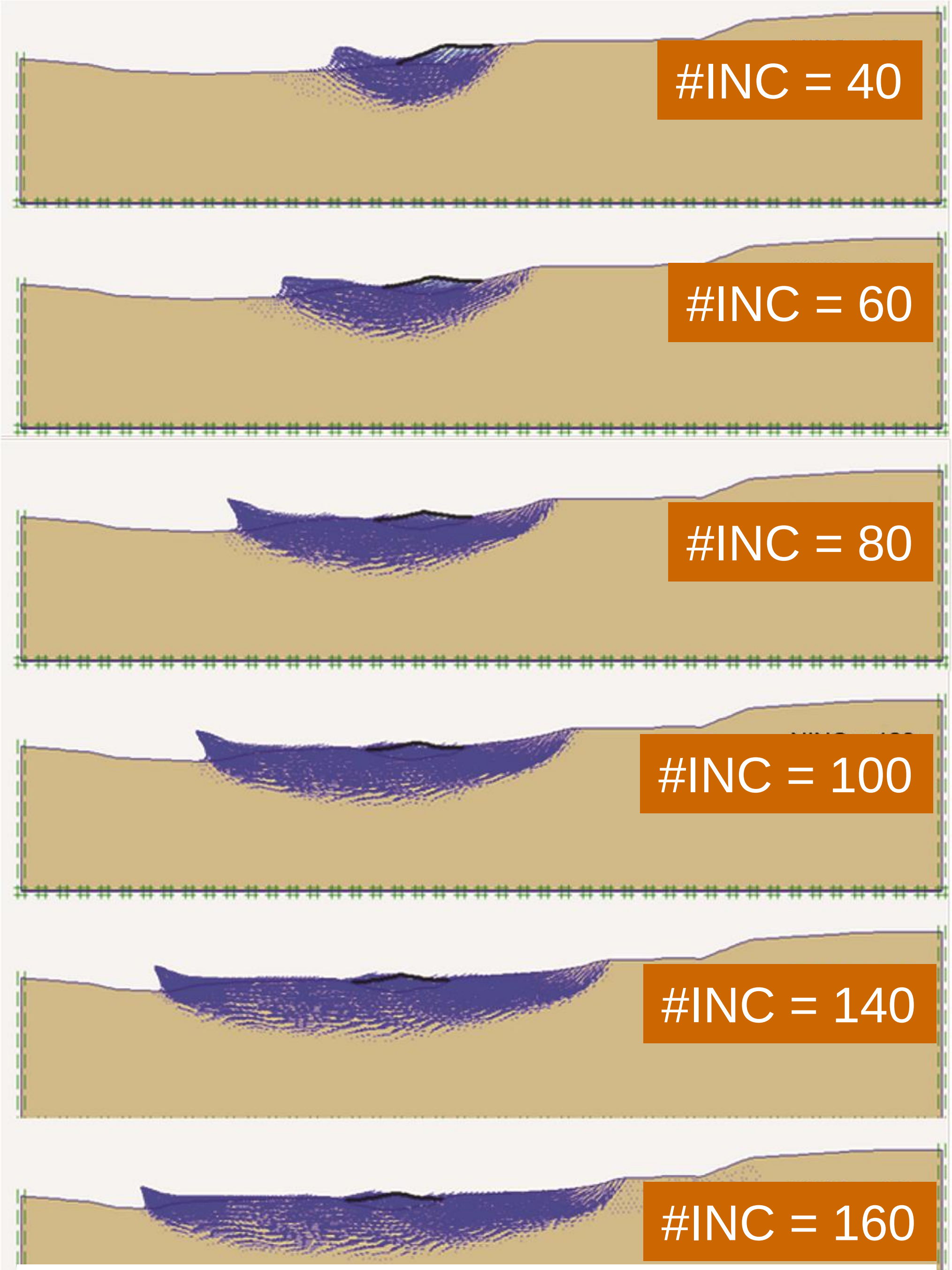
Vestfossen
FEM analyses of slide

Case	Progressive failure	FS
No fill	Yes	1.28
Fill added	Yes	1.00

The strain at which the progressive failure starts is small, and not large enough to remould the clay.

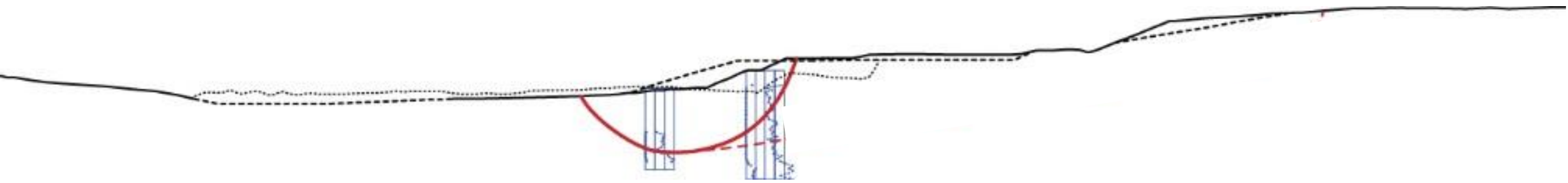
It is the initial part of the stress-strain curve only that determines capacity.

The remaining part of the stress-strain curve towards residual governs the post-failure displacements.

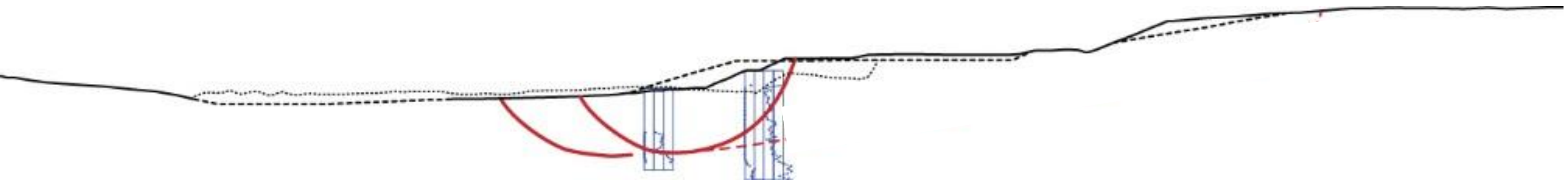


(Jostad and Grimstad 2011)

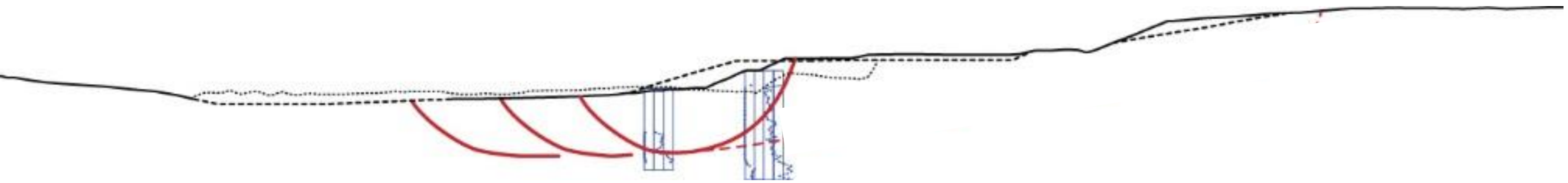
Vestfossen
Analysis of the slide - progressive failure



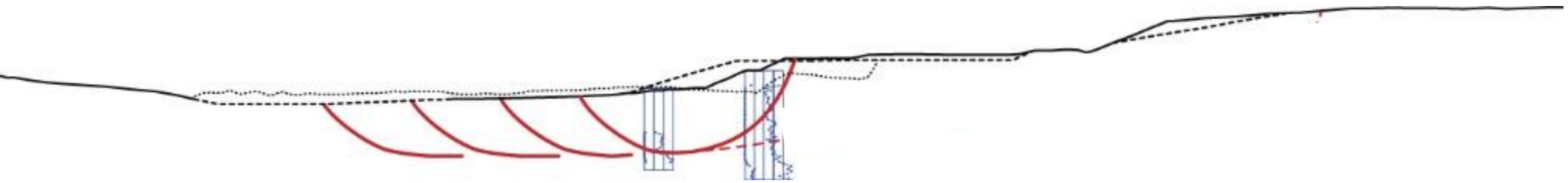
Vestfossen
Analysis of the slide - progressive failure



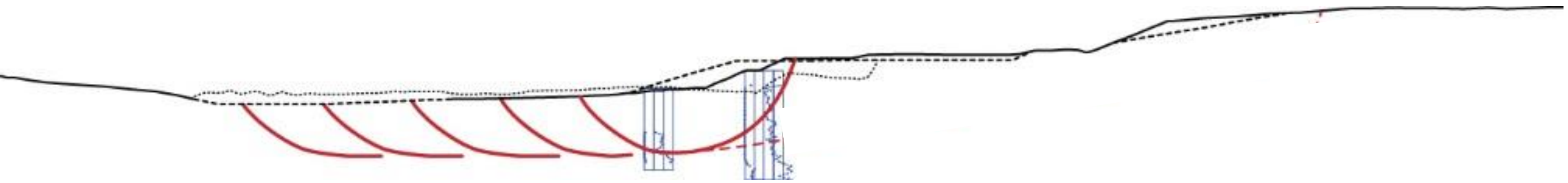
Vestfossen
Analysis of the slide - progressive failure



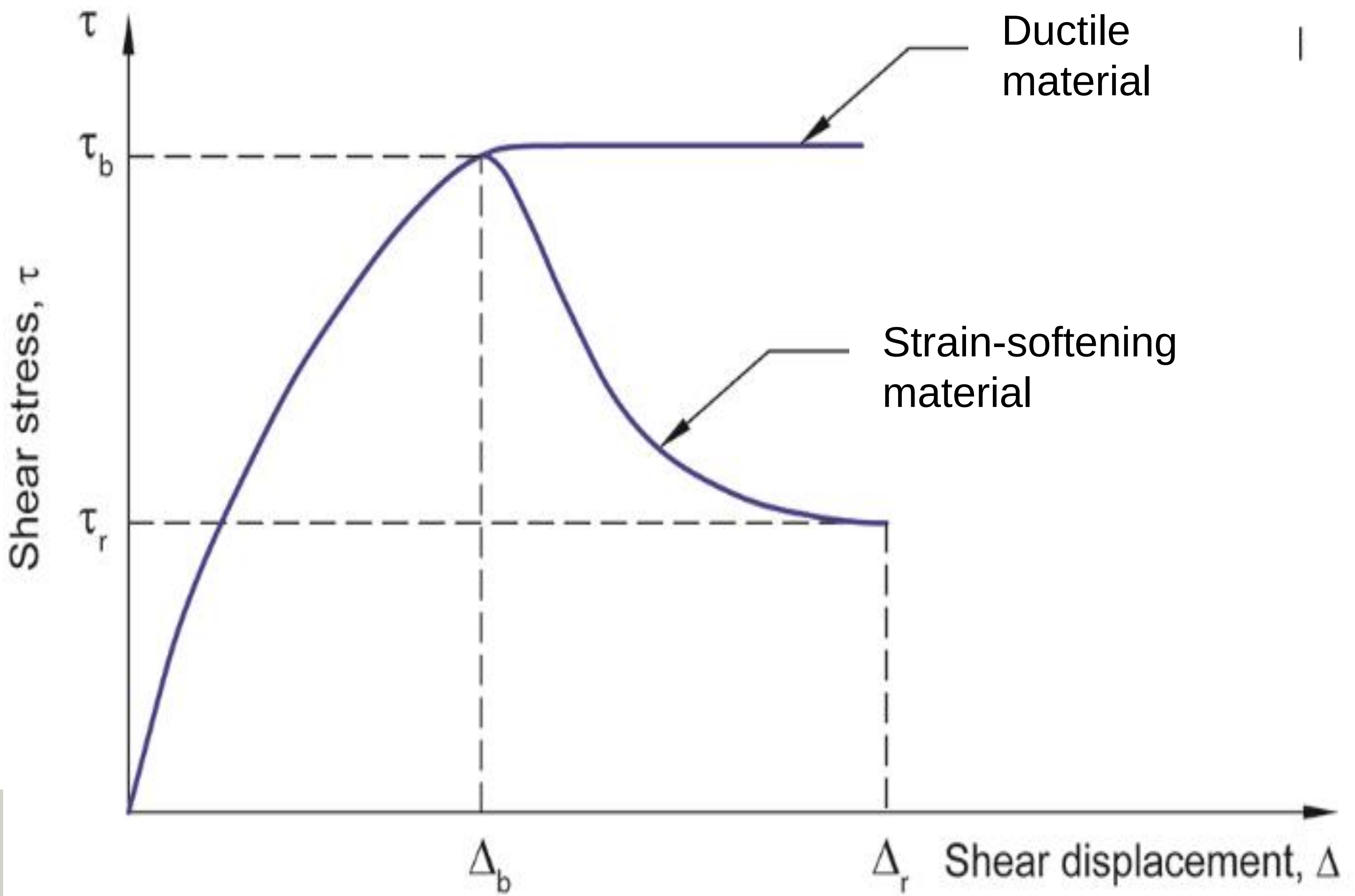
Vestfossen
Analysis of the slide - progressive failure



Vestfossen
Analysis of the slide - progressive failure

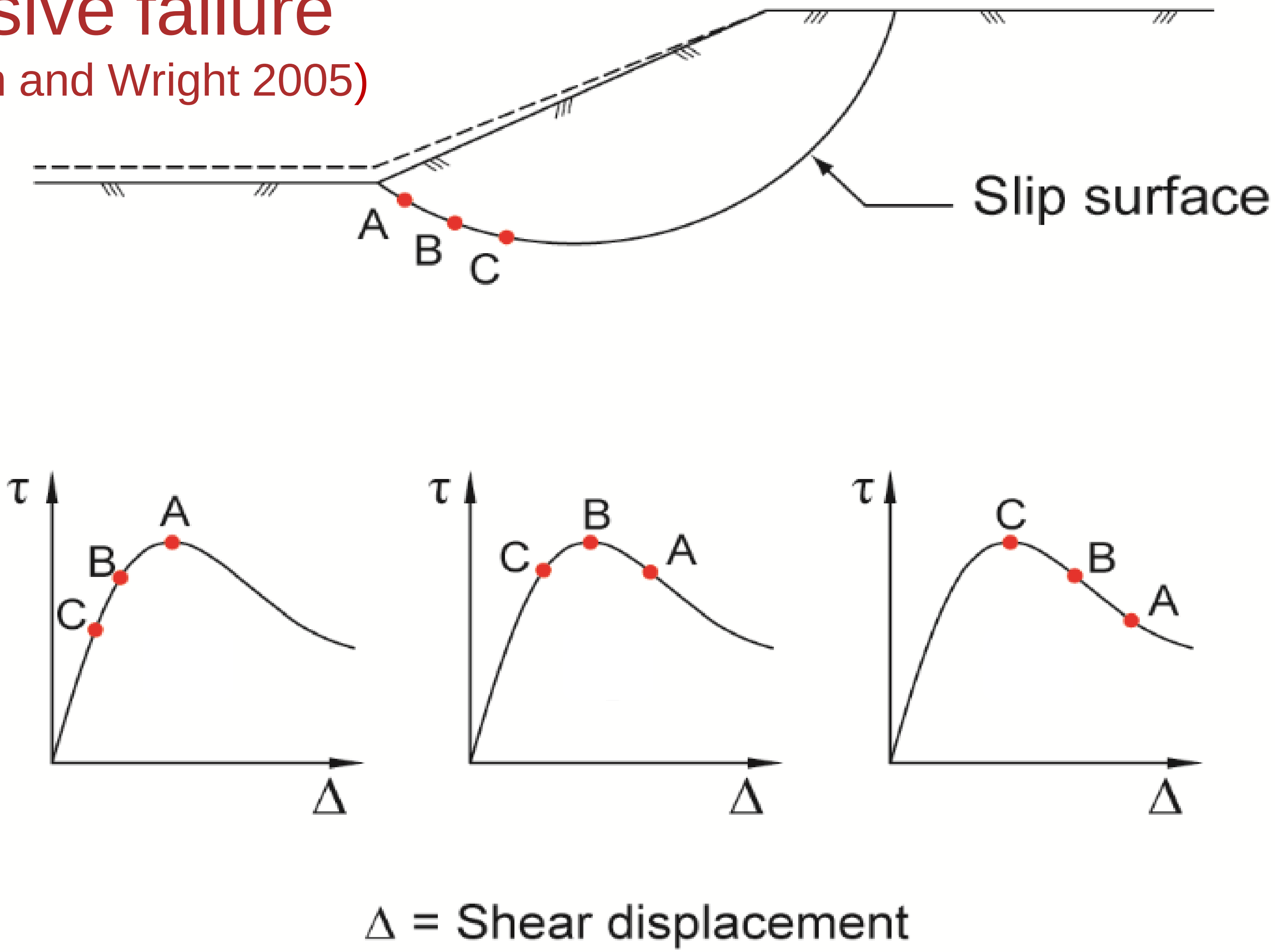


Ductile and strain-softening materials

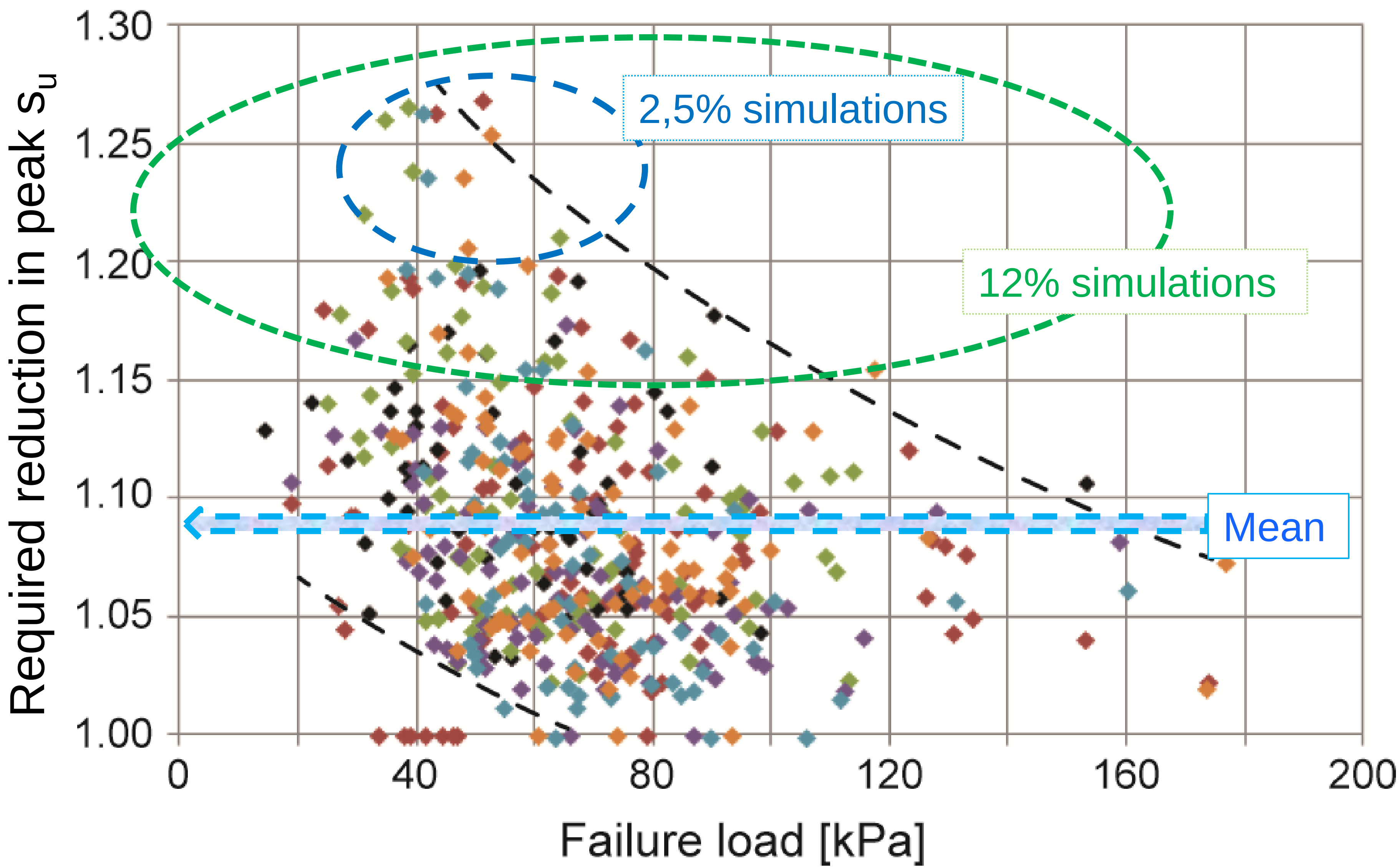


Progressive failure

(after Duncan and Wright 2005)



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



Lessons from the Vestfossen case

- Strain-softening needs to be taken into account in stability analyses. The strain-softening is such that the peak strength measured in the laboratory cannot be used directly in limit equilibrium analyses.
- The shear strength along part of the slip surface reduces significantly, moving towards the remoulded shear strength, while other parts can still be in the pre-peak regime.
- The calculated material coefficient will be overestimated for long slip surfaces to a greater degree than for smaller or local slip surfaces.
- Limit equilibrium approaches will continue to be used to do stability analysis in practice.

Lessons from the Vestfossen case

- The initiation of the failure and the progressive failure were well captured by a large deformation FEM PLAXIS 2D analysis, using the NGI-ADPSoft material model.
- If limit equilibrium analysis is used, one needs to reduce the peak shear strength to account for strain-softening and progressive failure. One can:
  - Apply the same reduction factor on the peak undrained shear strength from TC, DSS and TE tests, or
  - Differentiate the reduction factors for each strength type, e.g. 15% on TC, 10% on DSS and 5% on TE, or
  - Establish a reduction factor as a function of clay strength, slip surface type, loading type or clay sensitivity.
- An average reduction factor between 1.10 and 1.15 may be reasonable. For Vestfossen, it was necessary to reduce the peak shear strength by an average of 10%.

Laurits Bjerrum, Karl Terzaghi and Arthur Casagrande at NGI (1957)

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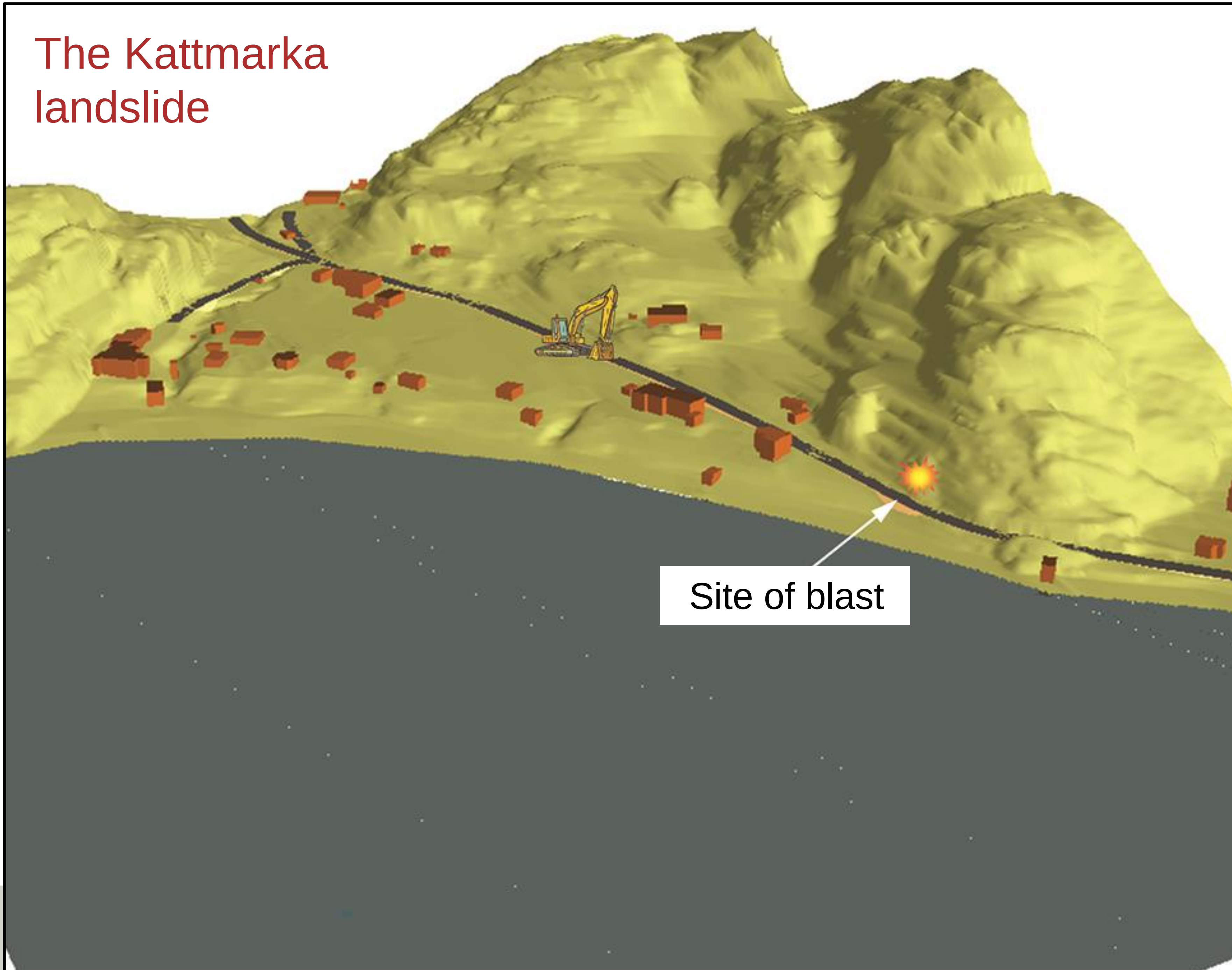
Landslide risk management and the role of our profession in protecting people

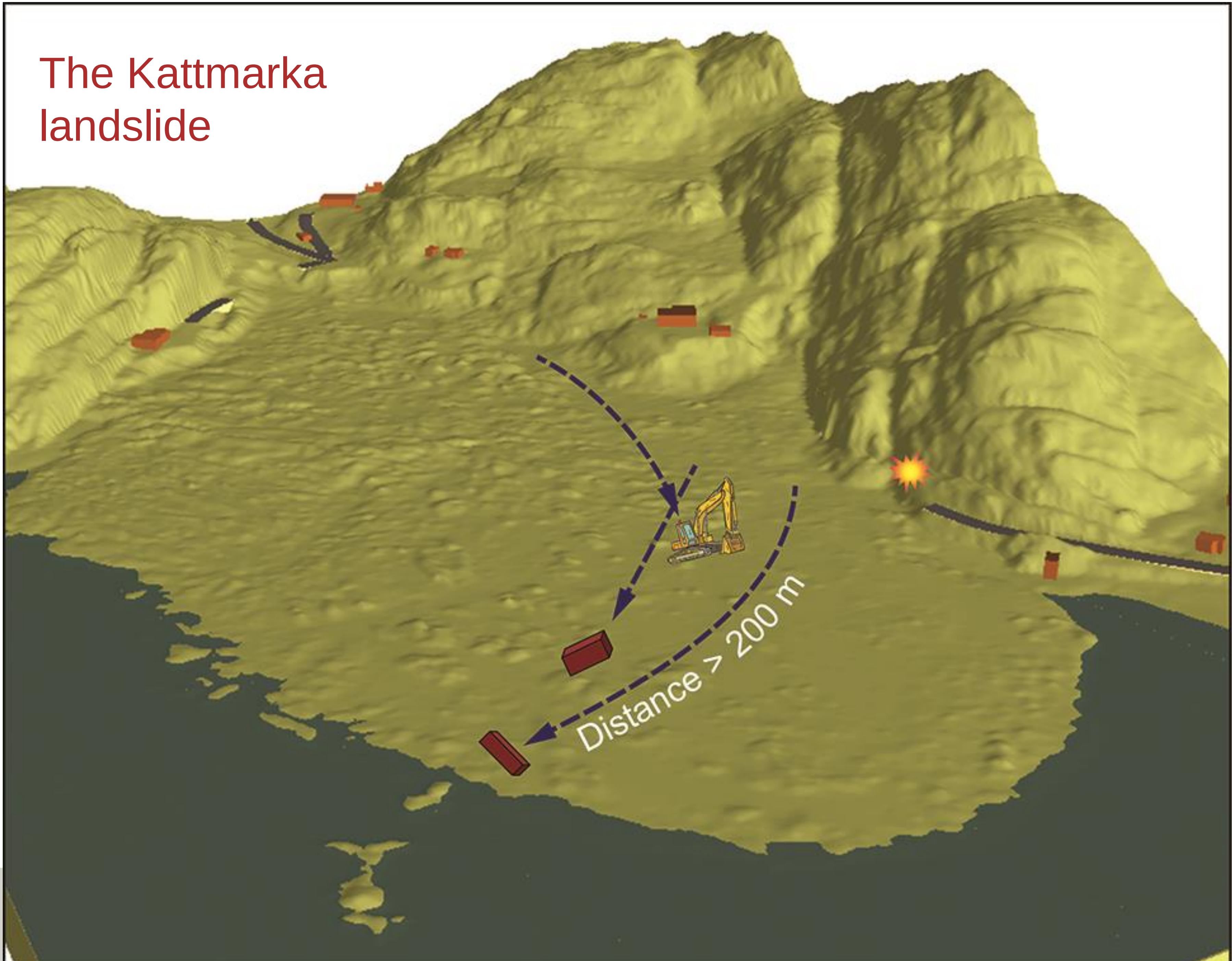

Kattmarkvegen
14 March 2009
Foto: Leif Arne Holme


Kattmarkvegen
14 March 2009

The Kattmarka landslide



The Kattmarka landslide




Construction on
Kattmarkvegen 12 March 2009
Foto: Andre Aglen

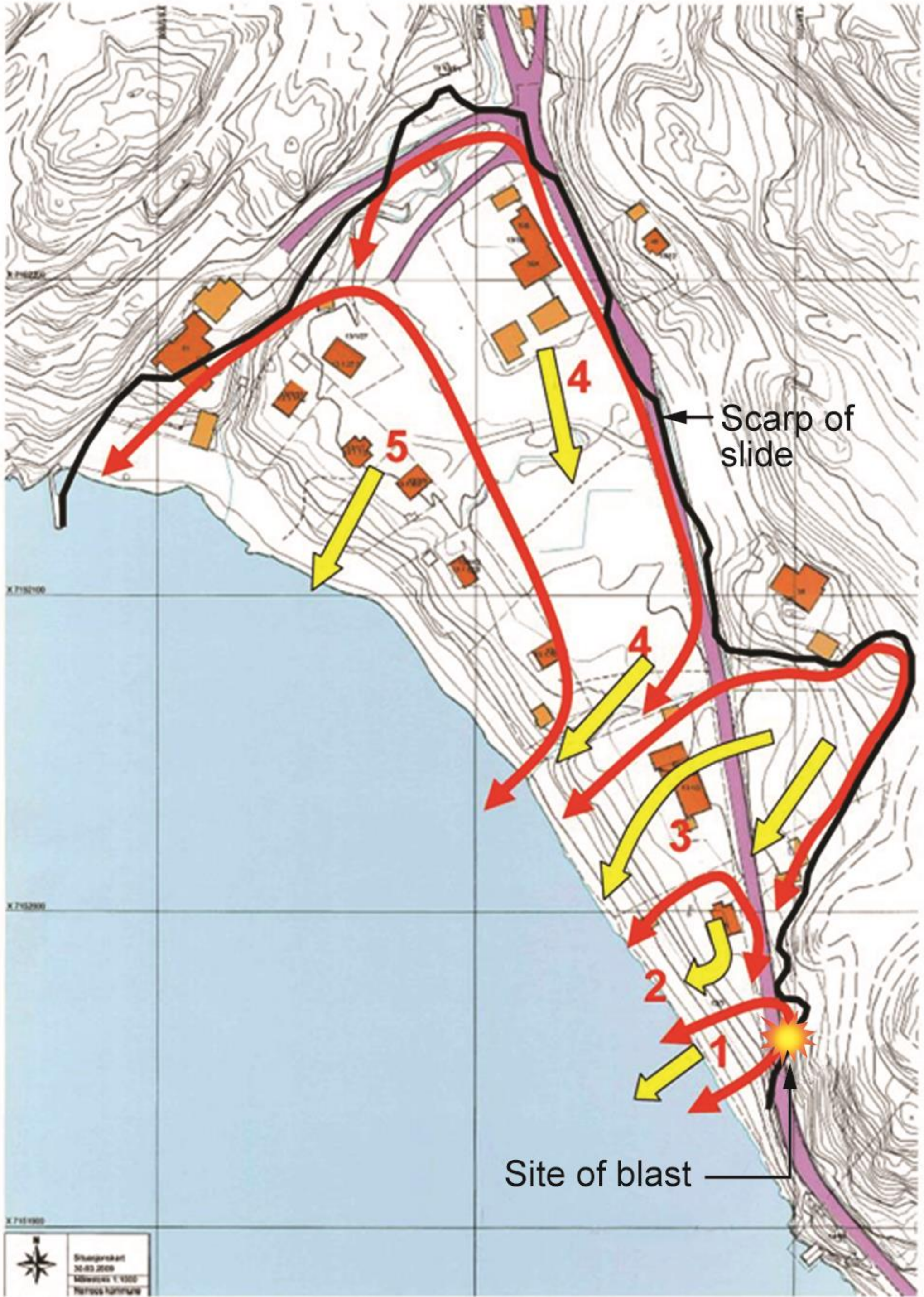
Kattmarkvegen 14 March 2009

: Leif Arne Holme

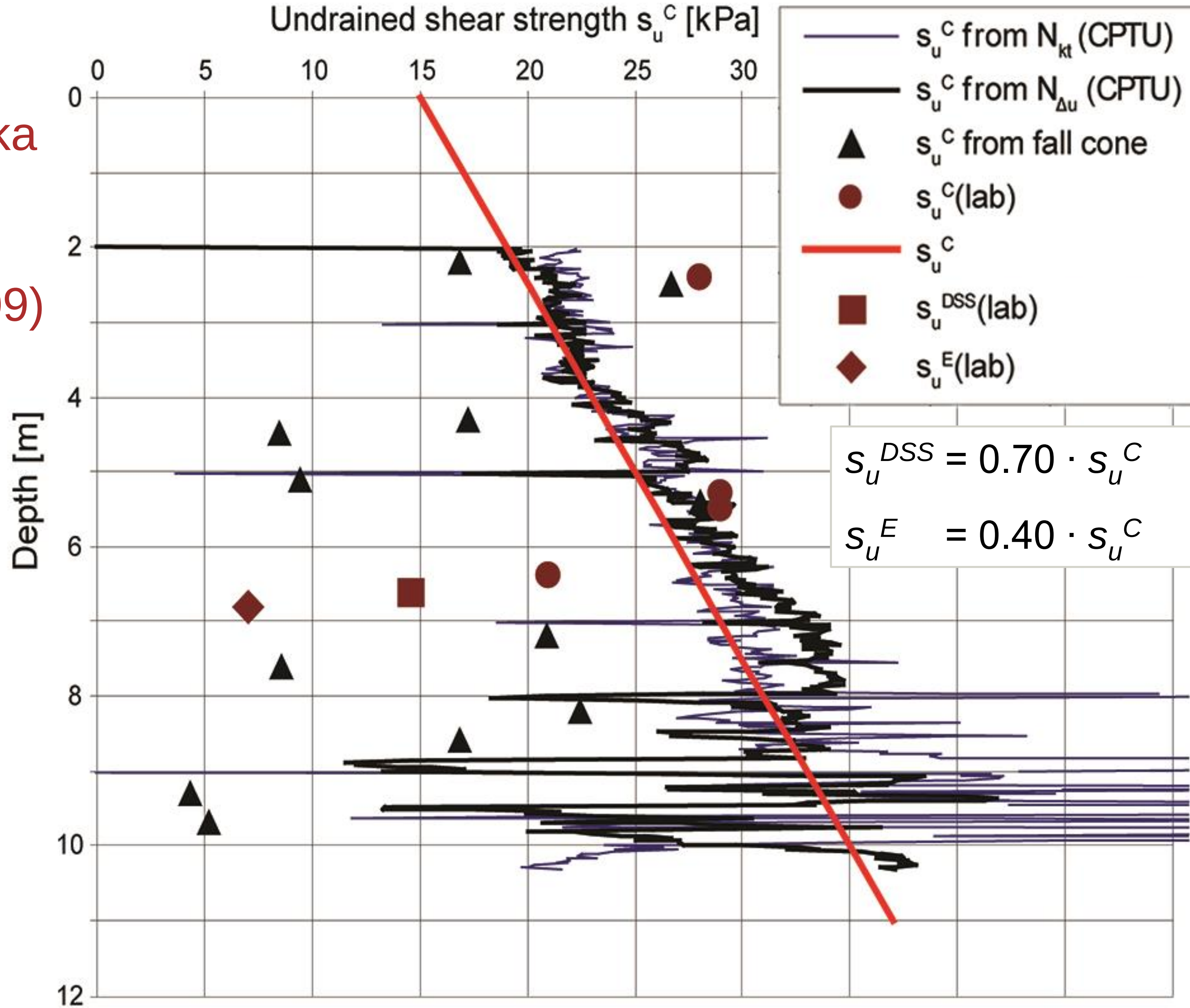
The Kattmarka Landslide (Nordal *et al* 2009)

Sequence of failure:

1 ➡ 2 ➡ 3 ➡ 4 ➡ 5



Kattmarka soil data (Nordal *et al* 2009)



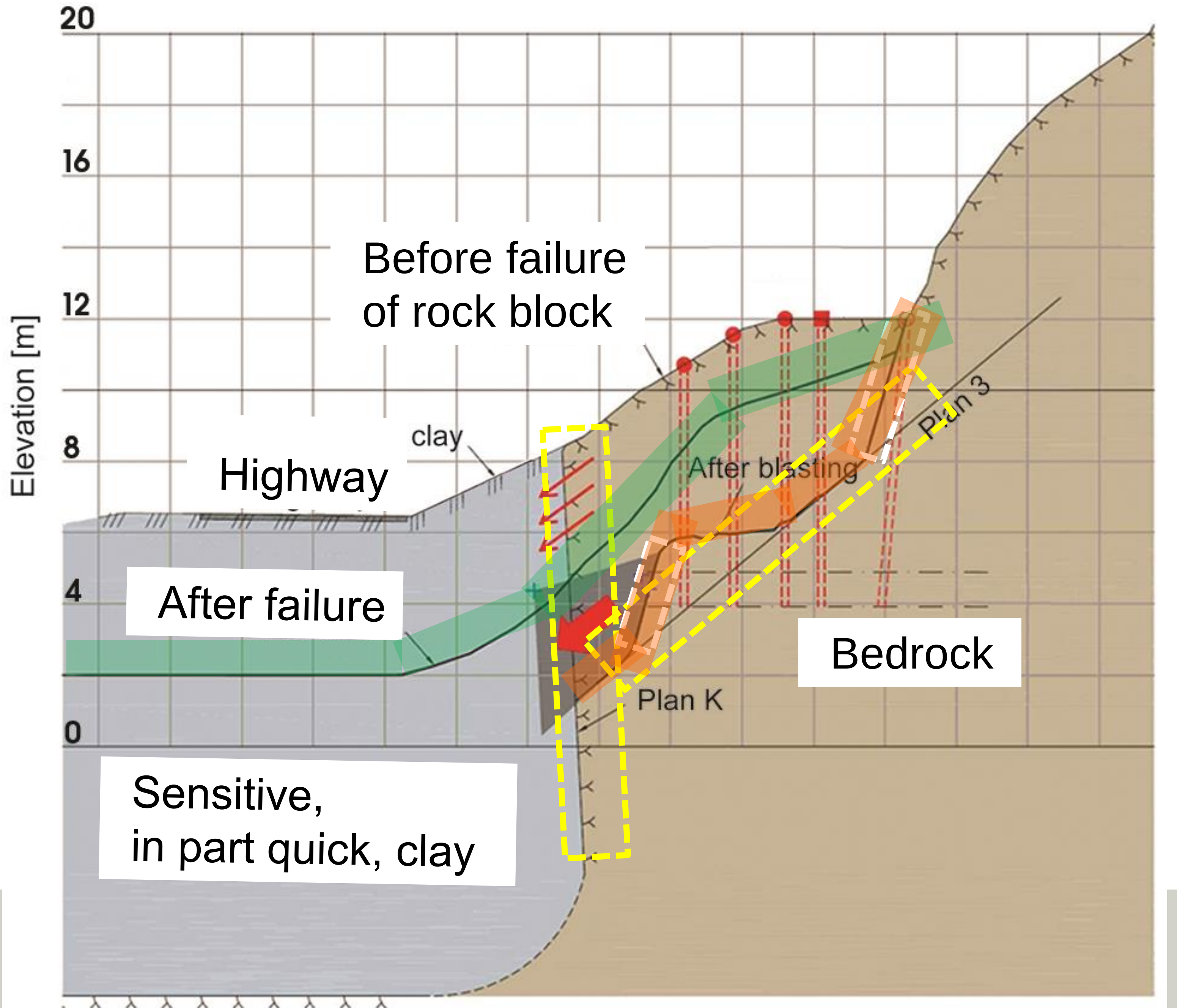
$$s_u^{DSS} = 0.70 \cdot s_u^C$$

$$s_u^E = 0.40 \cdot s_u^C$$

Kattmarka - Analysis of the slide in ZONE 1

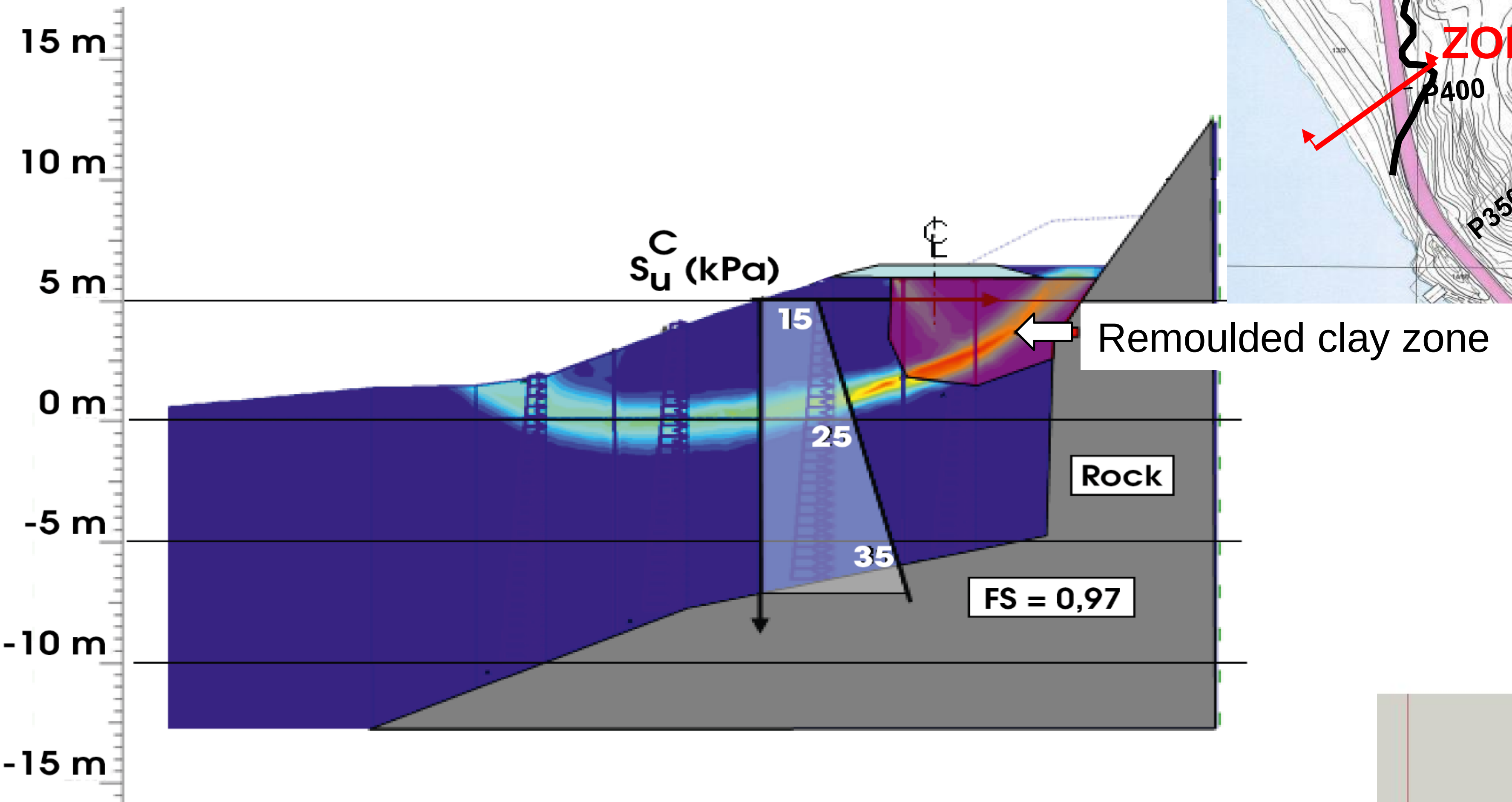
How did the slide start?

Interface rock-clay in ZONE 1 and blast moving the rock face ≈1m into the sensitive clay.



Kattmarka - Analysis of the slide in ZONE 1

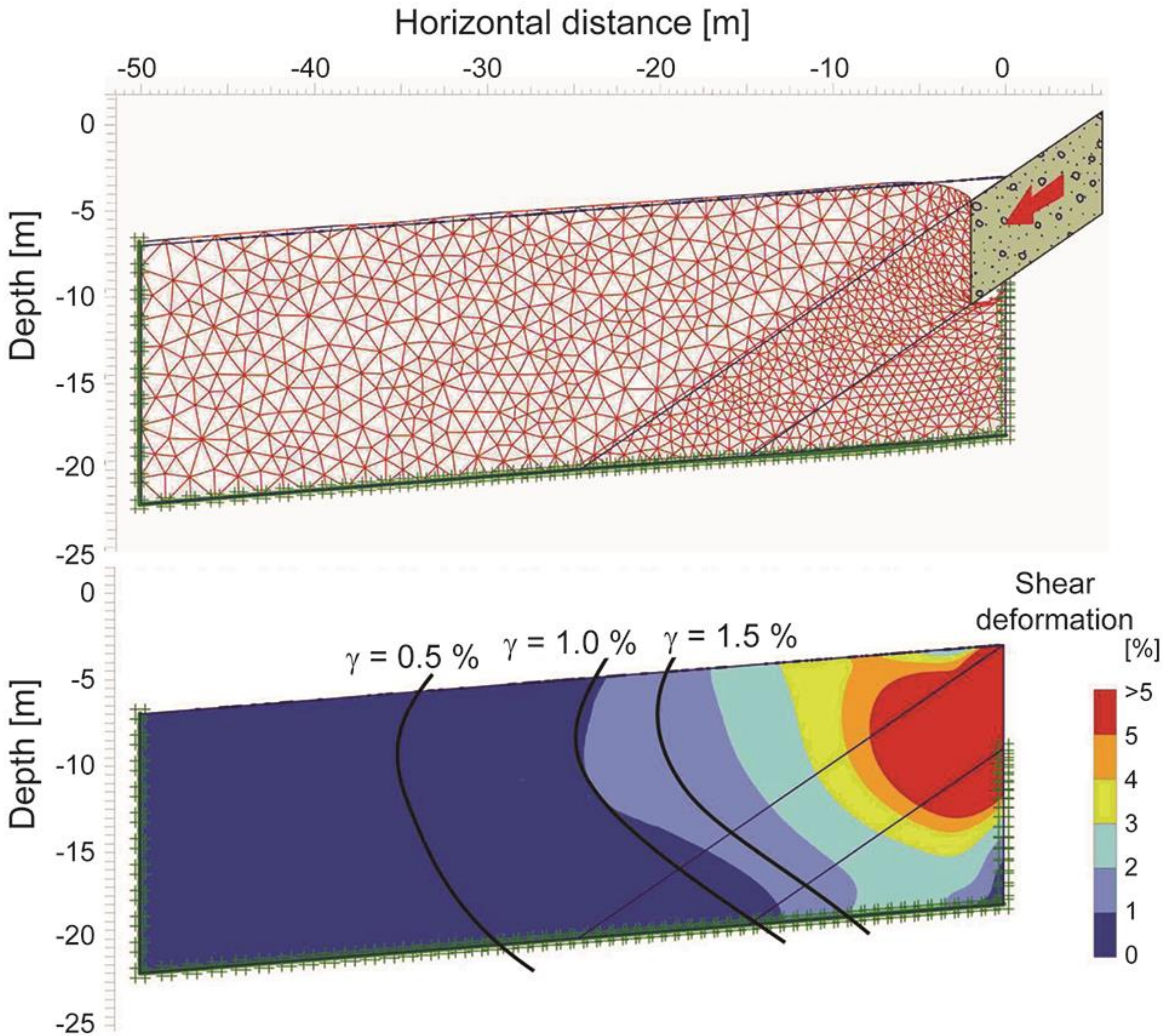
To model “After blasting, before sliding”, a remoulded clay zone was inserted at the rock-clay interface (Nordal *et al* 2009).



Kattmarka - Analysis of slide

Numerical simulation of the rock face penetrating into the clay (Nordal *et al* 2009).

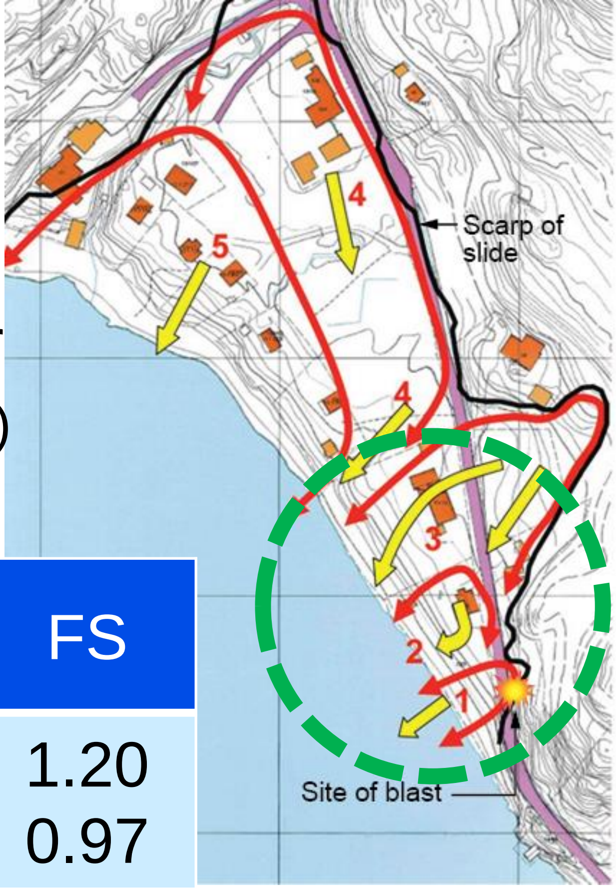
PLAXIS analyses



Kattmarka - Analysis of slide

- 2 software: PLAXIS and GeoSuite
- NGI-ADP soil model for anisotropic clays
- Partial 3-D effects with stabilizing side shear

(Andresen *et al* 2002; Andresen and Jostad 2002)



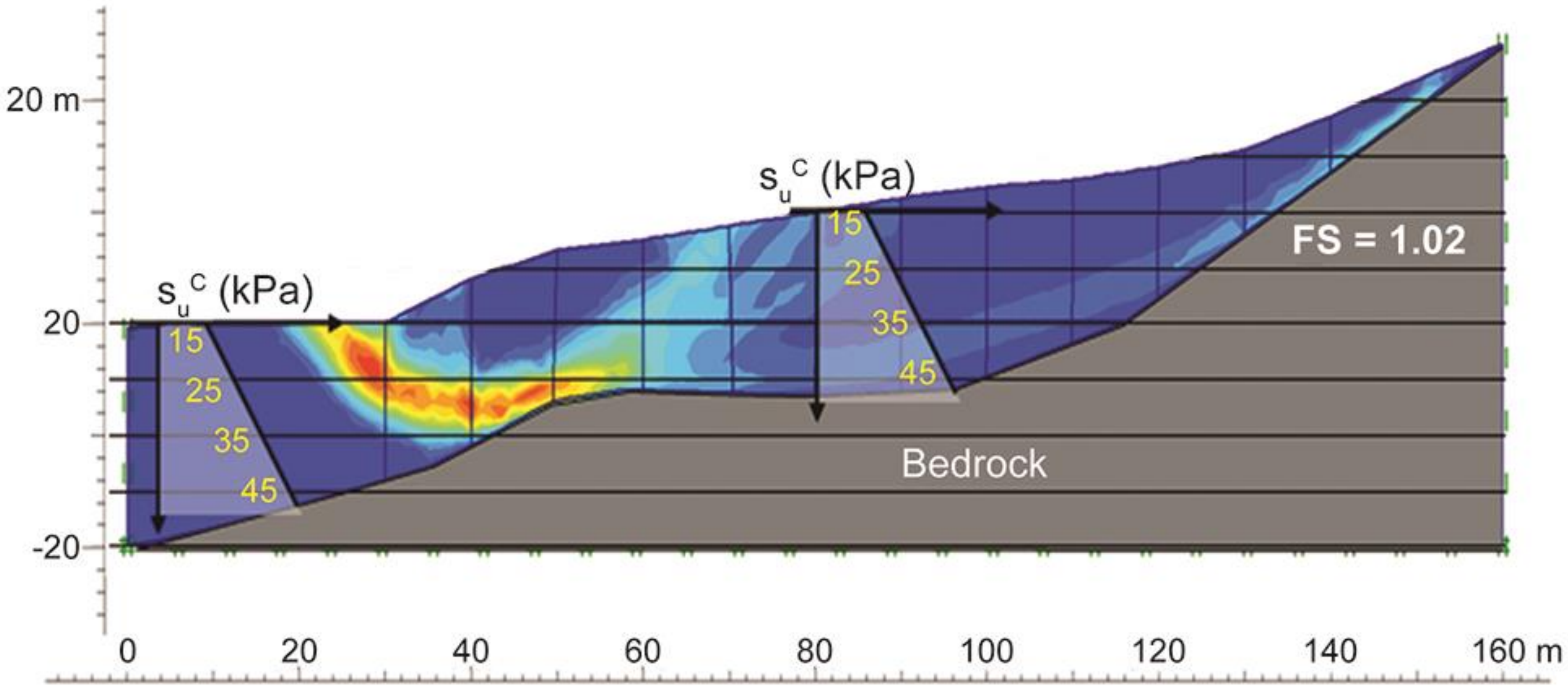
Zone	Stability condition	FS
1	Before blasting After blasting, before sliding in clay	1.20 0.97
2	Before blasting After blasting, before sliding in clay	1.19 1.06
3	Before blasting After blasting, before sliding in clay	1.02 ~0.90

(Nordal *et al* 2009)

Kattmarka - Analysis of the slide

The clay at the top of the slope in ZONE 1 became remoulded under the rock block slipping and pushing into the clay. The clay at the bottom of the slope could not support the added load.

<u>Overstressed area towards bottom of slope in ZONE 3</u>:



Lessons from the Kattmarka case

- The blasting moved the rock face and a block outward into the clay with considerable force and velocity, causing the surrounding clay to liquefy. It was not the high frequency blast vibrations by themselves that triggered the slide.
- The unexpected movement of the rock face was a consequence of two unfavourable conditions: (1) the unknown orientation of the rock-clay interface and (2) planes of weakness in the rock mass. The sensitive quick clays, however, had already, marginal stability.
- The slide had dramatic consequences, and it was just a matter of good odds that no lives were lost.

Lessons from the Kattmarka case

- The work should have been stopped to allow soil investigations, when sensitive clay was found close to the road during the preparation for the blasting.
- The Kattmarka landslide led to new regulations and increased focus on existing regulations, including:
  - Control and mapping of the clay-rock interface when blasting in marginally stable areas.
  - Requirement for geotechnical investigations early in the planning process.
  - Necessity for hazard and vulnerability analyses for projects that can endanger life and property.

Laurits Bjerrum, Karl Terzaghi and Arthur Casagrande at NGI (1957)

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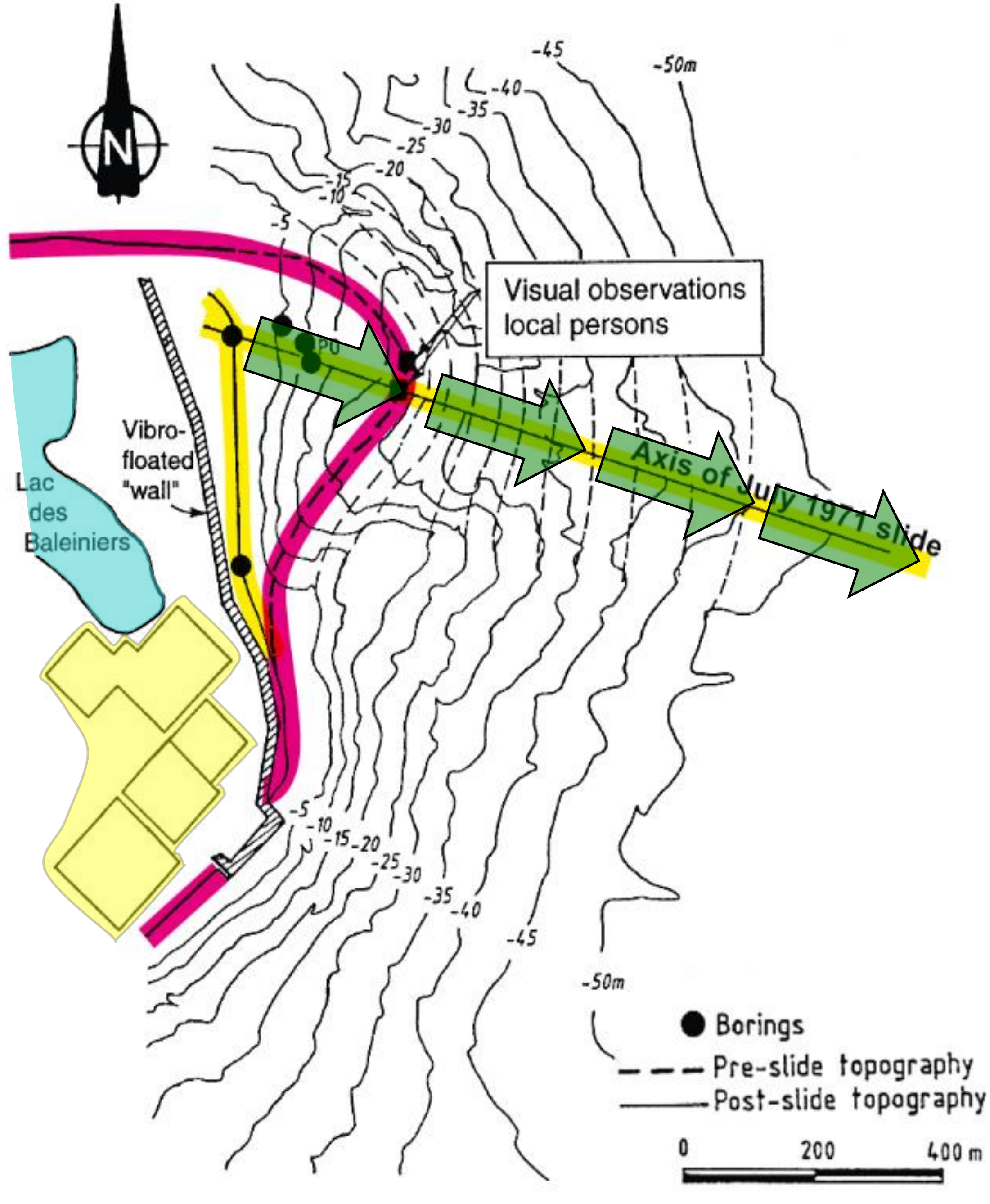
Landslide risk management and the role of our profession in protecting people

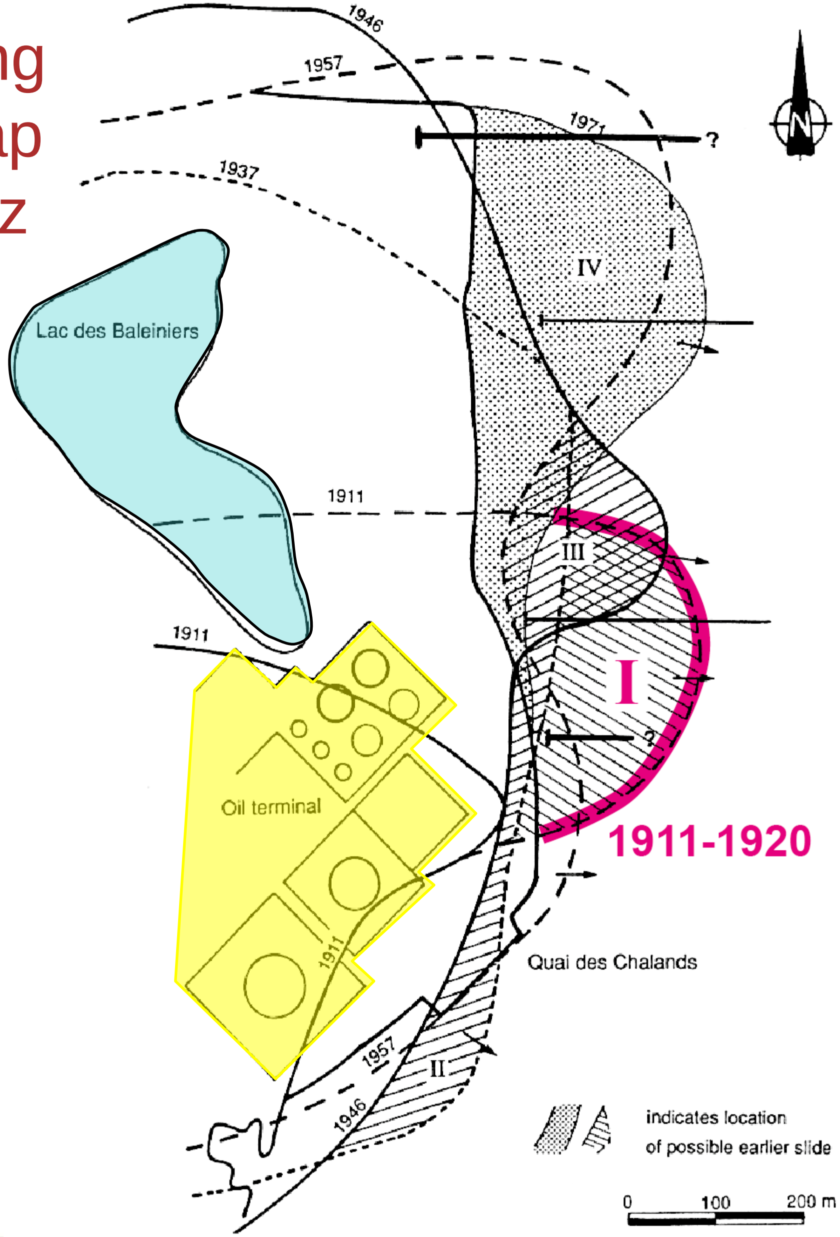
Sliding at Cap Lopez Pointe Odden, Gabon, Africa

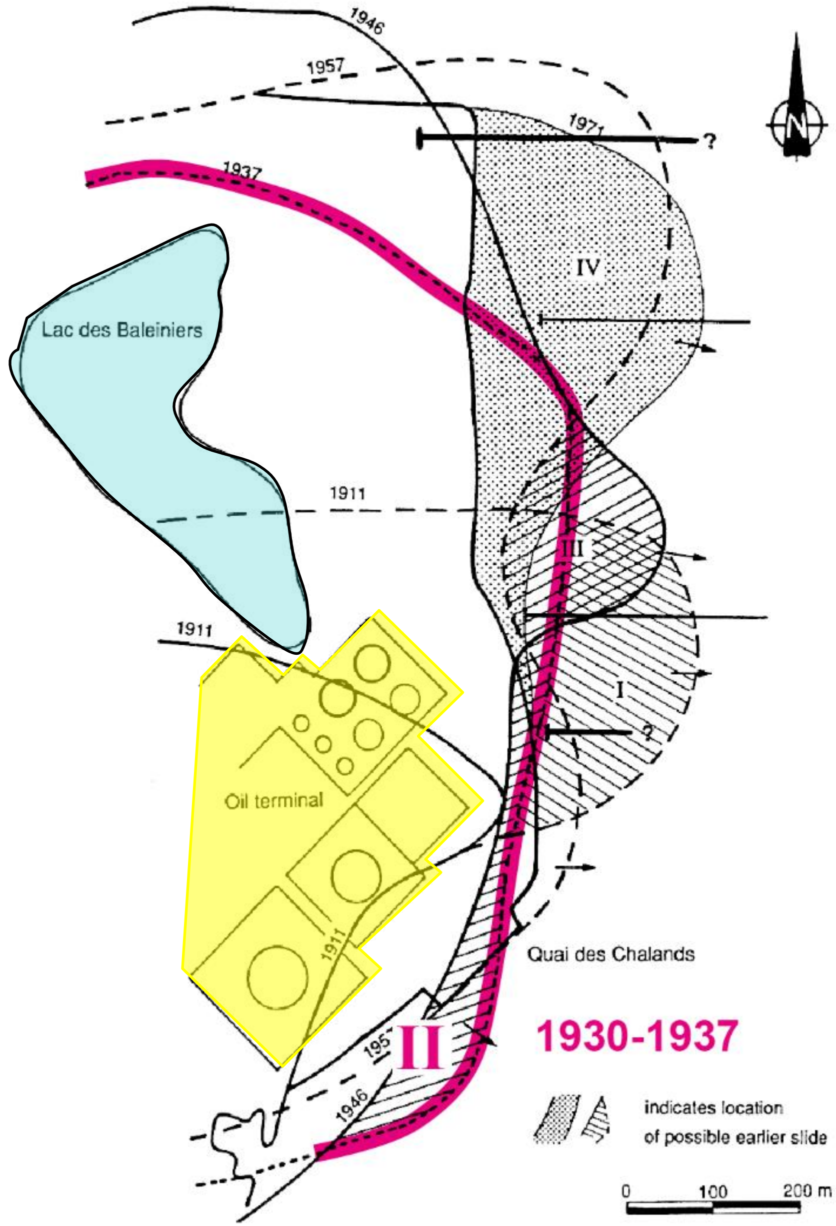
Sliding at Cap Lopez Pointe Odden, Gabon

1971 event

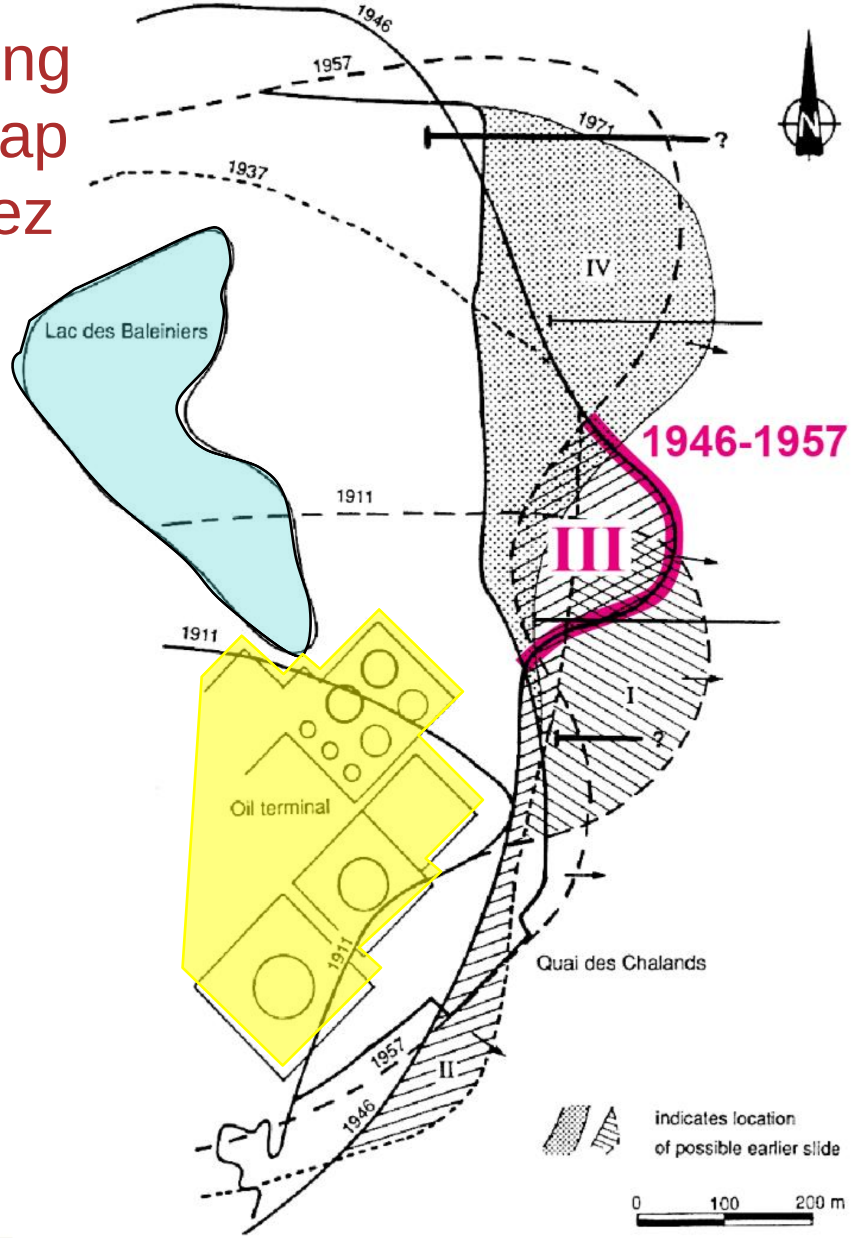


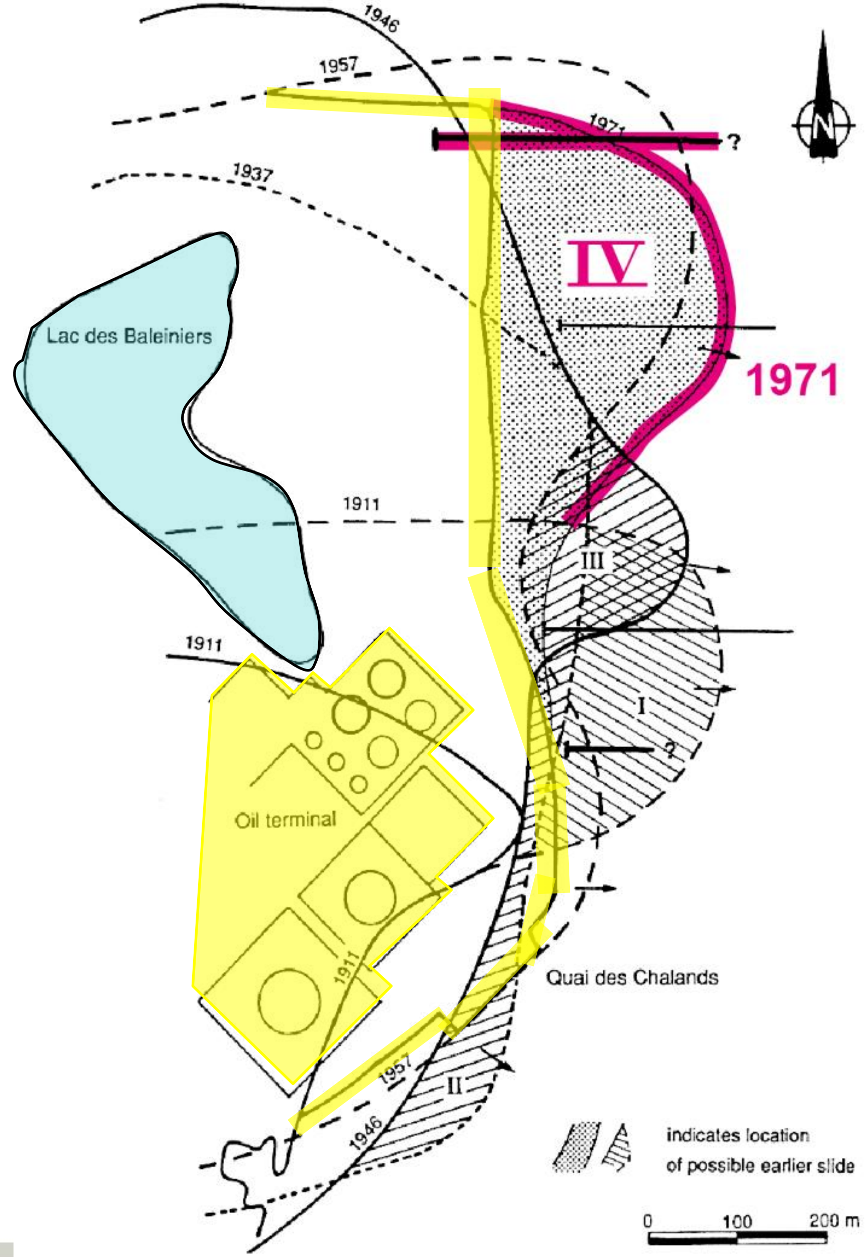
Sliding at Cap Lopez



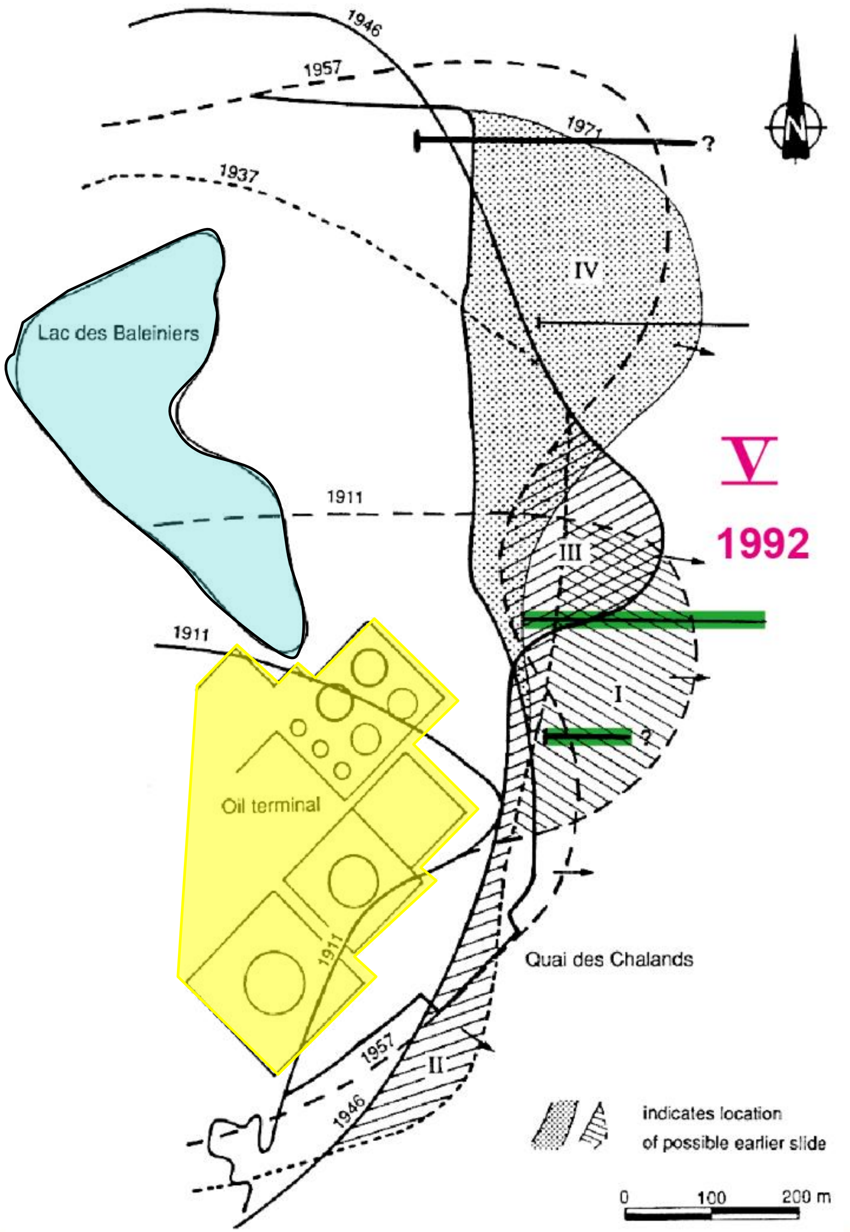


Sliding at Cap Lopez

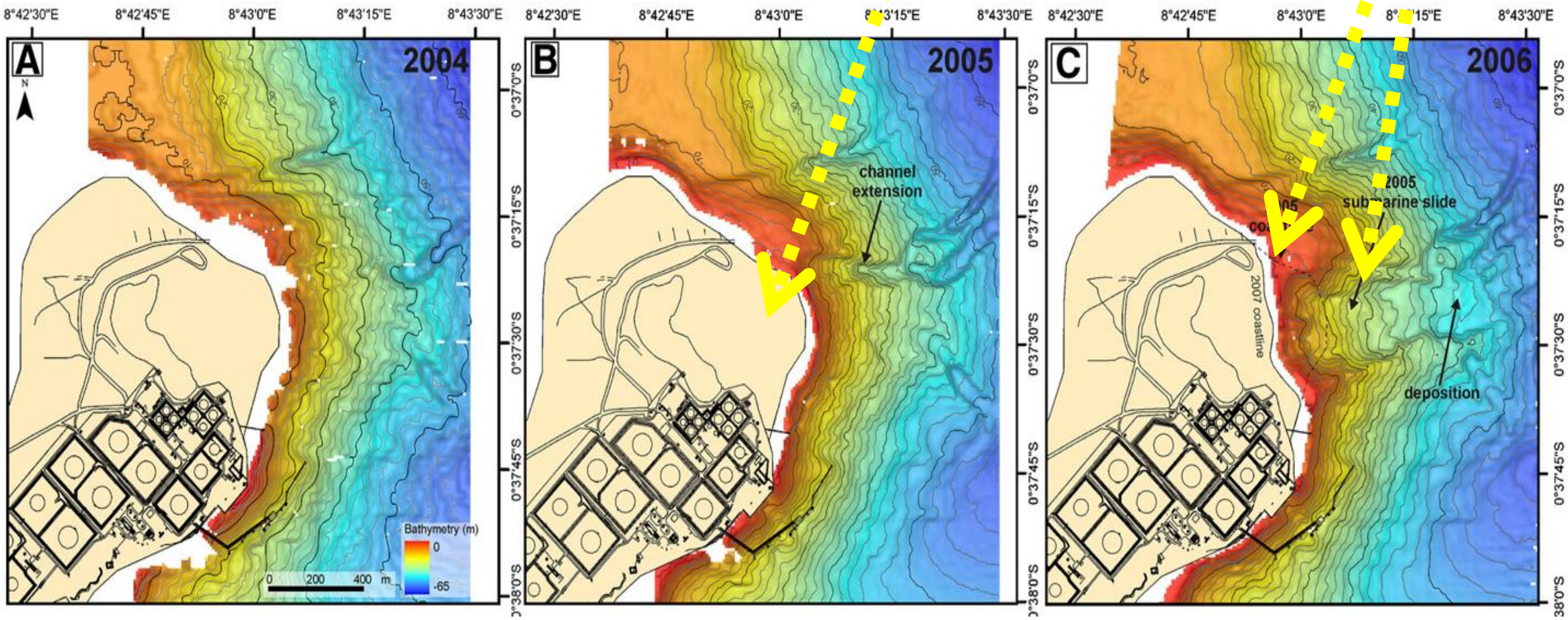




Sliding at Cap Lopez



Sliding at Cap Lopez
Pointe Odden, Gabon



2004 **2005** **2006**

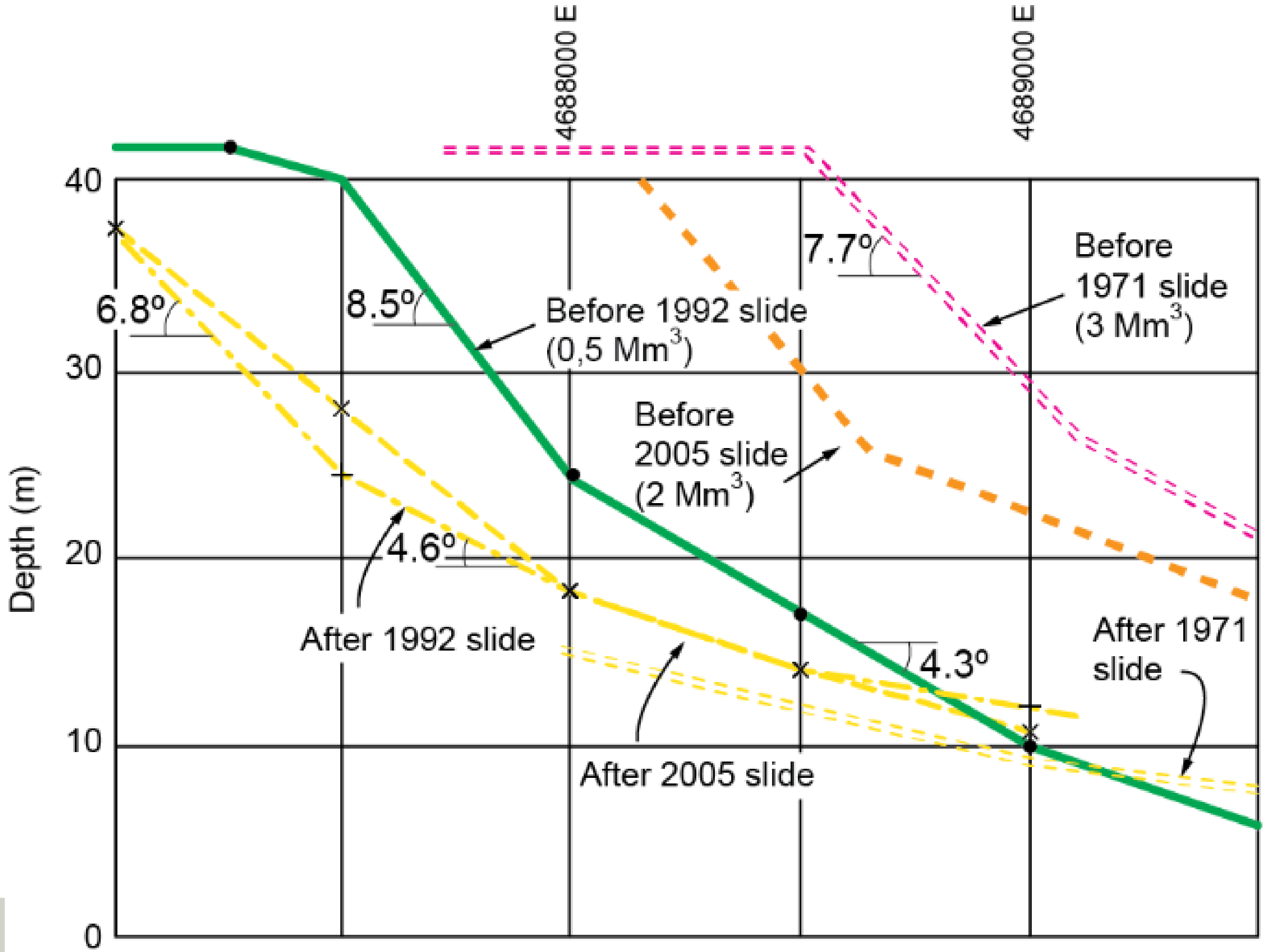
Recent bathymetric surveys (Biscara *et al* 2012)

Sliding at Cap Lopez
Pointe Odden, Gabon

Periodicity of sliding event on Cap Lopez

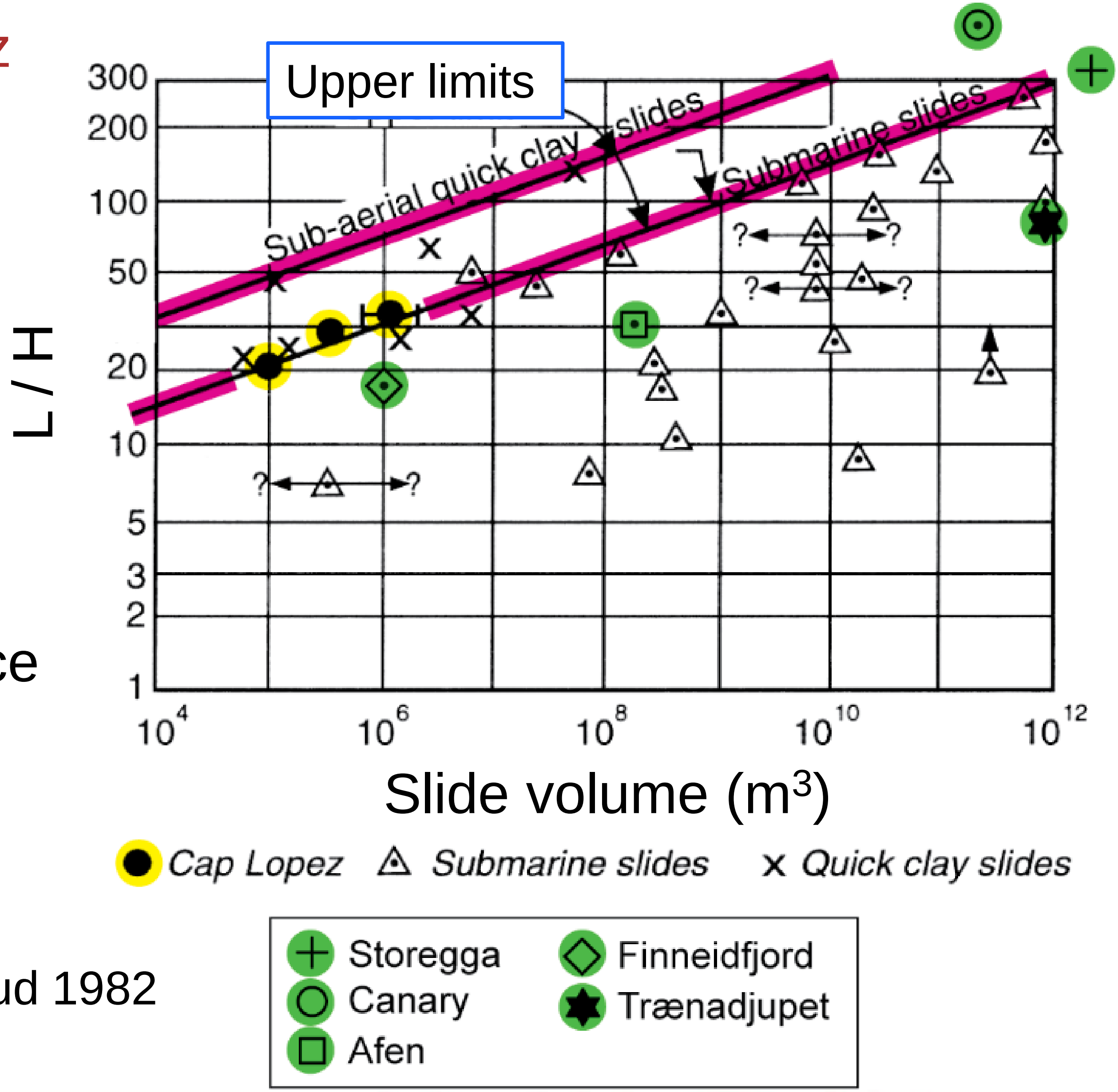
Slide	Approx. date	Time between slides
I	1911-1920	--
II	1930-1937	15-20 years
III	1946-1957	15-20 years
IV	1971	15-25years
V	1992	21 years
VI	2005/2006	13-14 years

Sliding at Cap Lopez
Analyses of slides



Sliding at Cap Lopez
Analyses of slides

H = slope height
L = run-out distance



Edgers and Karlsrud 1982
Canals *et al* 2004

Lessons from sliding at Cap Lopez

Periodicity of sliding event on Cap Lopez

Slide	Approx. date	Time between slides
I	1911-1920	--
II	1930-1937	15-20 years
III	1946-1957	15-20 years
IV	1971	15-25years
V	1992	21 years
VI	2005/2006	13-14 years
VII	???	Shorter periodicity?

Laurits Bjerrum, Karl Terzaghi and Arthur Casagrande at NGI (1957)

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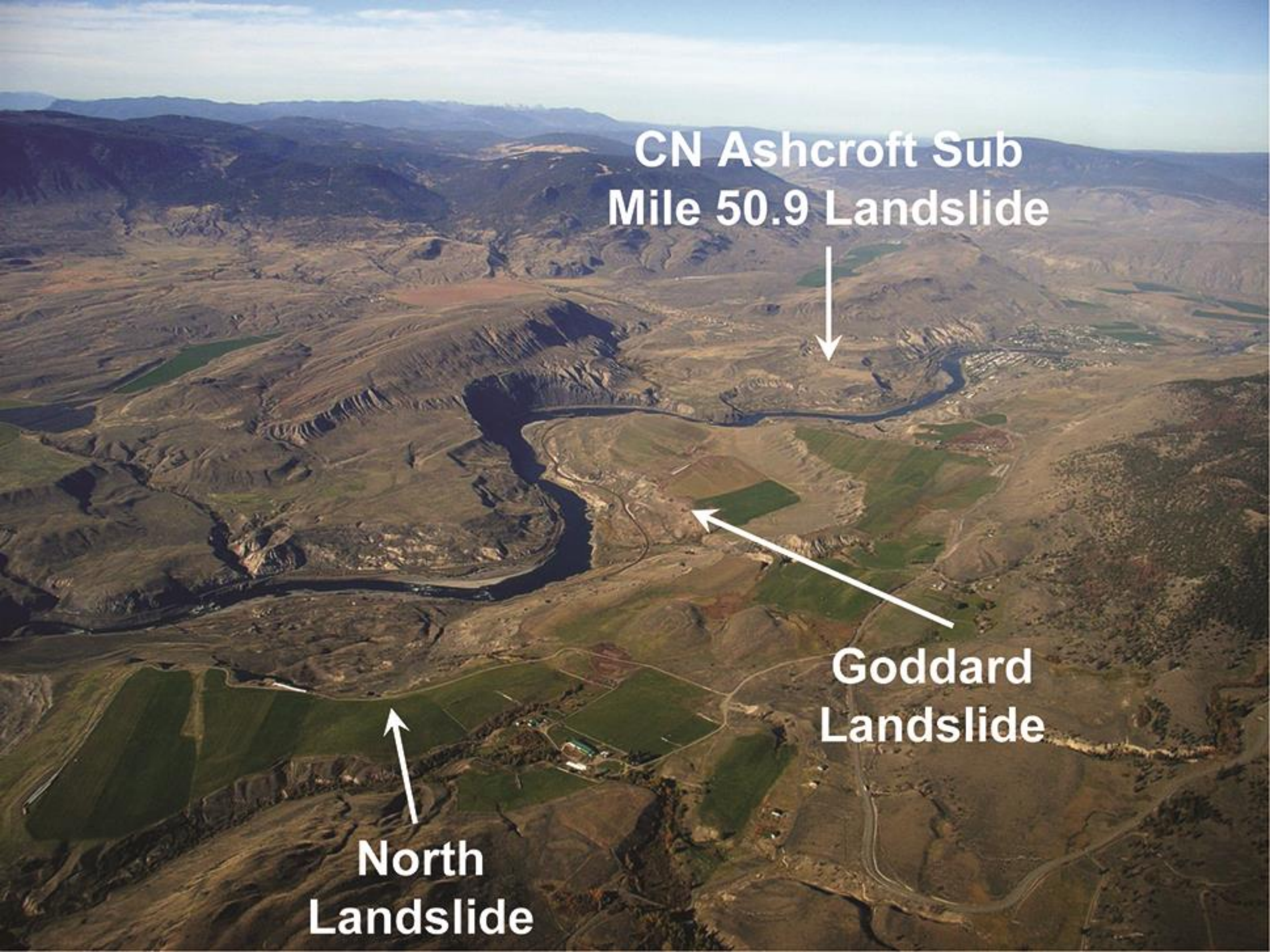
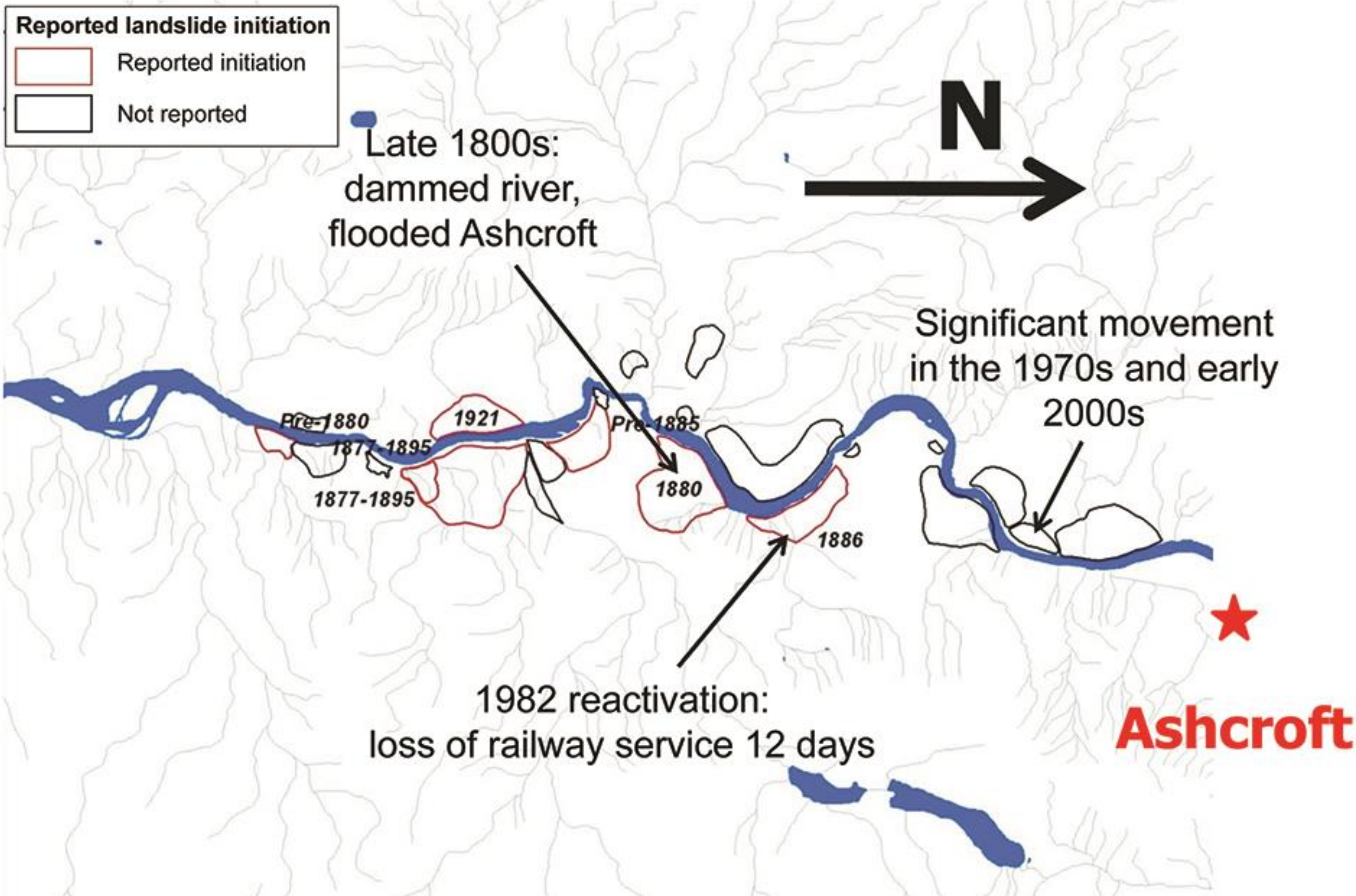
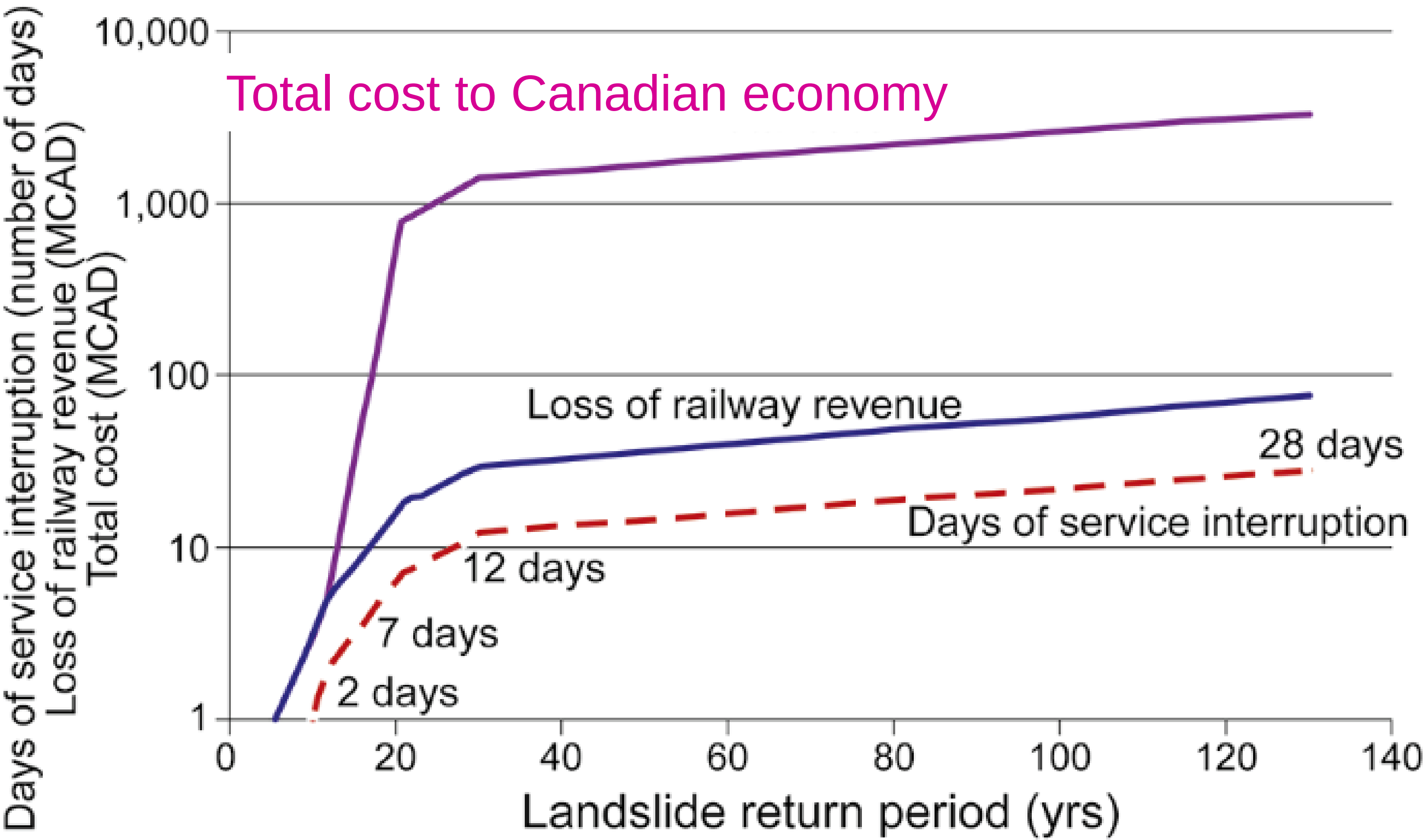
<u>Landslide risk management and the role of our profession in protecting people</u>

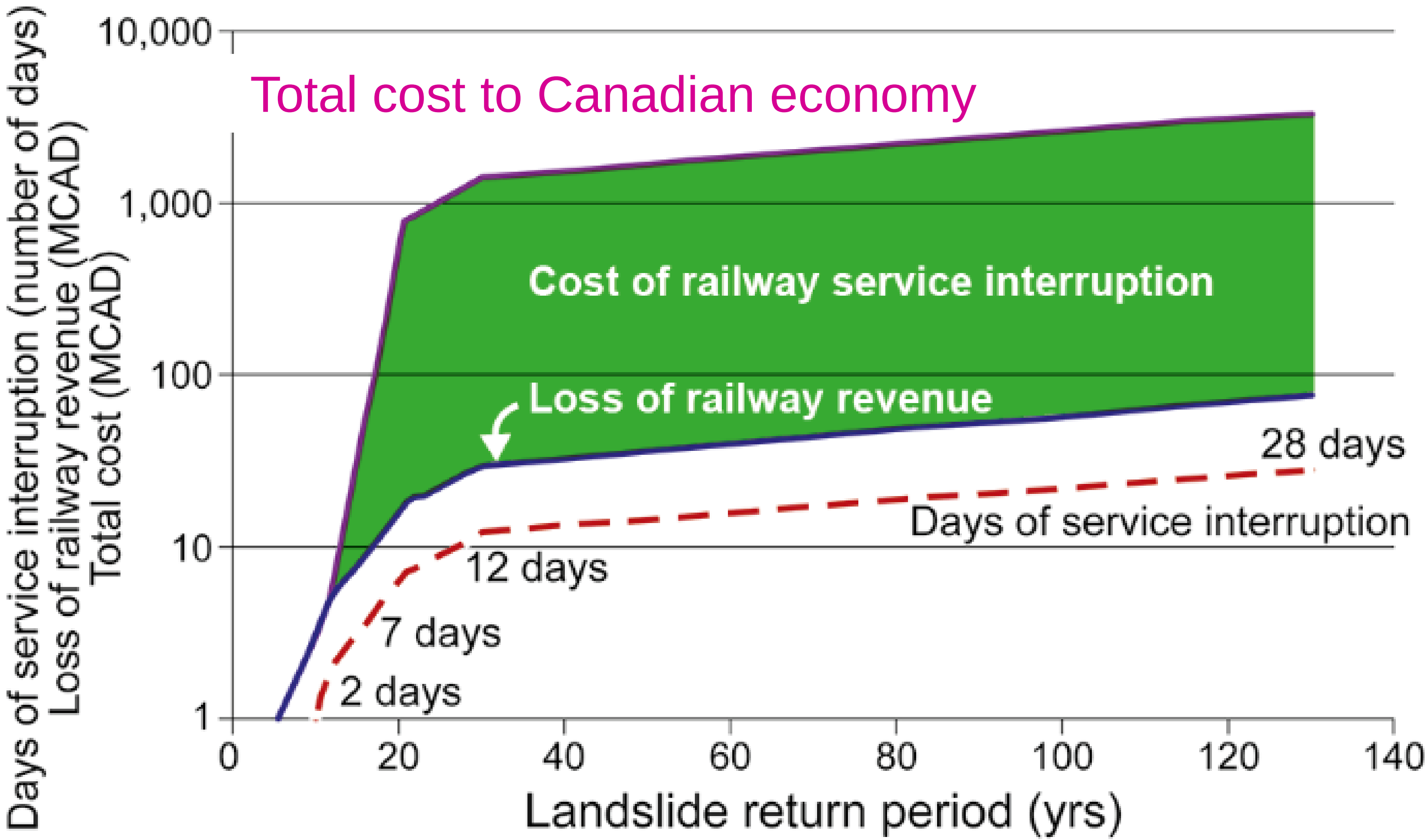

CN Ashcroft Sub
Mile 50.9 Landslide
Goddard
Landslide
North
Landslide


Reported landslide initiation
Reported initiation
Not reported
N
Late 1800s:
dammed river,
flooded Ashcroft
Significant movement
in the 1970s and early
2000s
Pre-1880
1921
Pre-1885
1877-1895
1877-1895
1880
1886
1982 reactivation:
loss of railway service 12 days
Ashcroft

Ashcroft Thompson River
Cost-effectiveness of mitigation (Bunce and Quinn, 2012)



Ashcroft Thompson River
Cost-effectiveness of mitigation (Bunce and Quinn, 2012)



Lessons from the Ashcroft Thompson River landslides

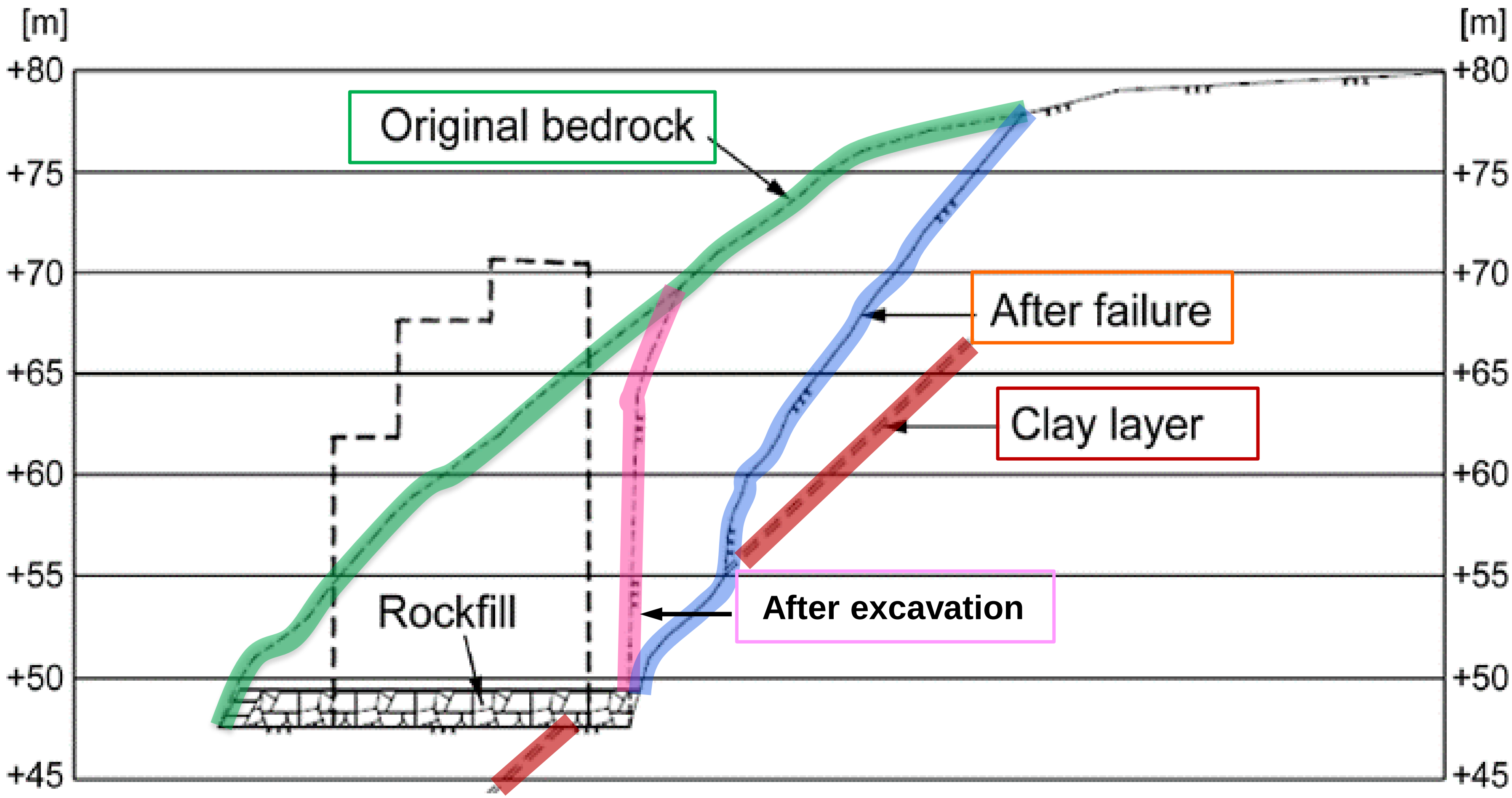
The stakeholders decided to reduce the risk with monitoring and a warning system, thus avoiding the cost of stabilizing the landslides, which also had an uncertain outcome and serious environmental impact (fisheries, First Nations livelihood).

Thinking about future improvement, the stakeholders decided to invest in research and to use the cost estimate shown earlier, to quantify the money they could spend on landslide mitigation.

The stakeholders felt it justified to spend an additional 1 to 2 MCAD/year on research and 2 to 5 MCAD/year per landslide to stabilize known landslides.

The Aalesund tragedy

The Aalesund tragedy -
Undiscovered planes of weakness

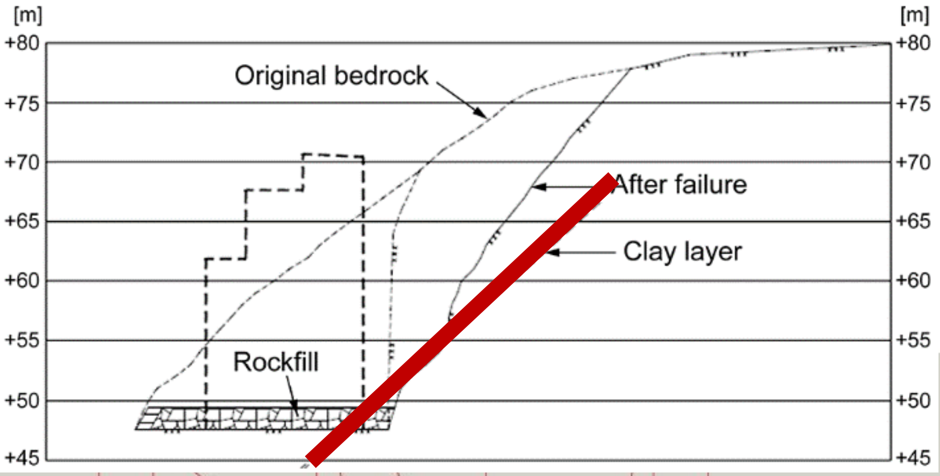


Lessons from the Aalesund tragedy

The accident could have been avoided if an adequate site investigation had been carried out. In particular, geophysical methods should have been used both before and after the blasting for the site preparation.

The geotechnical and engineering geology site investigation reports were insufficient. This omission cost the lives of five persons.

To protect society, we need a closer interaction among geology, geotechnical engineering and geophysics



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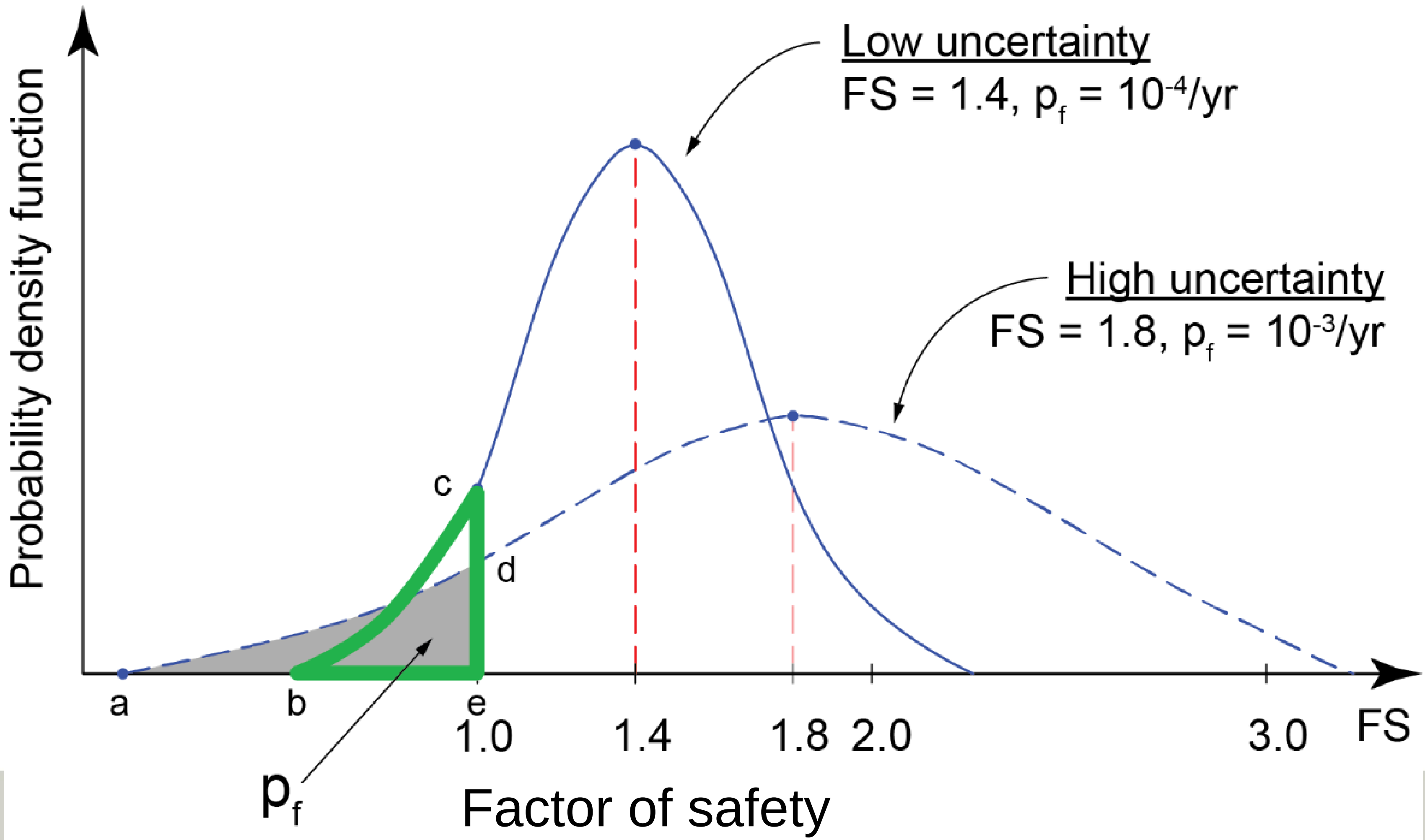
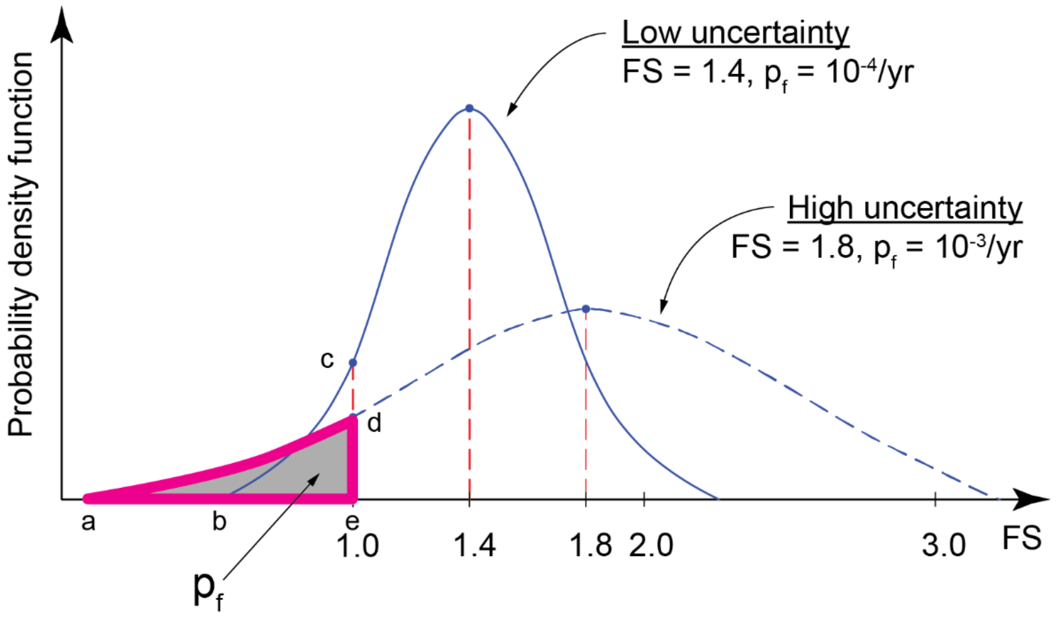
Landslide risk management and the role of our profession in protecting people

Our profession needs to be aware of the significance of safety factor and that the probablility of the occurrence of a failure (P_f) is never zero!



Significance of safety factor



To select a suitable factor of safety, one needs to include the uncertainties involved.

There is no general relationship between factor of safety (FS) and annual probability of failure (P_f).

The safety factor should not be a constant deterministic value, but should be adjusted according to the level of uncertainty. One should calibrate the required FS for different classes of slopes, soils and failure types to ensure a uniform (comparable) annual probability of failure of, e.g., 10^{-3}/year.

Landslide risk management

Risk management
Living with landslide risk - The Safeland Project

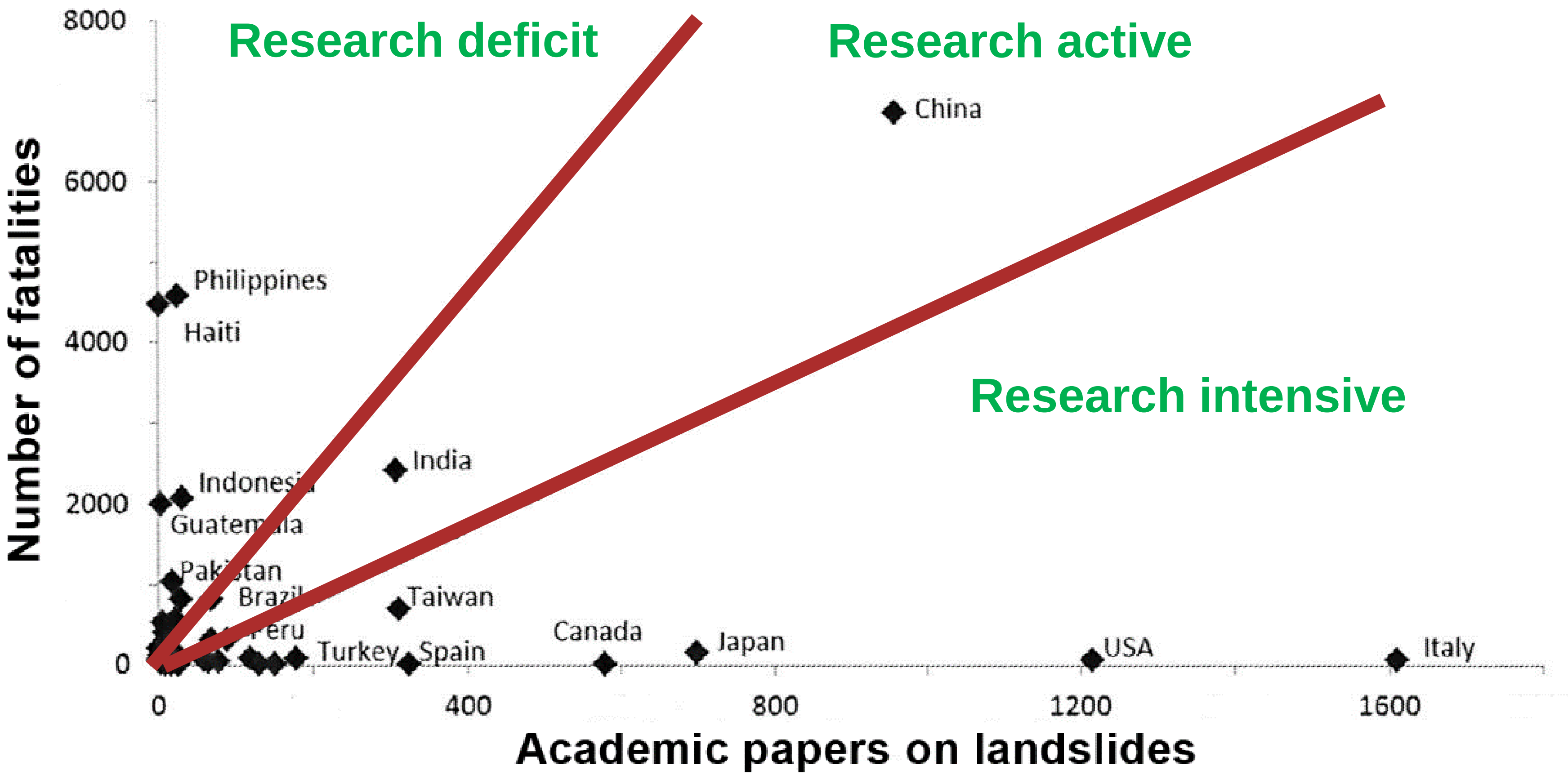
(Nadim et Kalsnes 2013)

- Guidelines on landslide triggering and run-out distance calculation.
- Threshold for rainfall events for landslide triggering.
- Changes in landslide frequency as a function of changes in demography and climate.
- Assessment of physical and societal vulnerability.
- Guidelines for susceptibility, hazard and risk assessment, and for the use of remote sensing and early warning.
- Toolbox for selecting mitigation measures.
- Participatory processes with public and stakeholders for selecting the most appropriate risk mitigation measure(s).

"New" involvement in landslide risk management

- Focus on mitigation solutions rather than the potential for failure (factor of safety calculations).
- Exercises in preparedness with simulation of landslide of national dimension, with fatalities (e.g. Norway, Canada, Hong Kong, and other countries).
- 24/7 emergency service to protect the public (e.g. GEO, Hong Kong).
- Improving building and construction standards and codes.
- Extensive public education on personal safety precautions (e.g. GEO, Hong Kong).

Number of fatalities from landslides against the number of papers with landslide in the title (Petley, 2012)



In conclusion

The role of the geotechnical engineer has evolved from being merely a technologist calculating factors of safety to that of a specialist on the evaluation of hazard, vulnerability and risk.

Inter-disciplinary problem-solving is essential for advancing our practice. Emphasis must be placed on interdisciplinary collaboration in research, consulting and education.

Our geotechnical expertise is essential for protecting society. Safety and life quality depend on us. Our profession should be perceived as reducing risk and protecting people. We can contribute to the prevention of "events" turning into disasters:

hazards are mostly unavoidable, disasters are not.

In conclusion

Civil engineers built the countries we live in

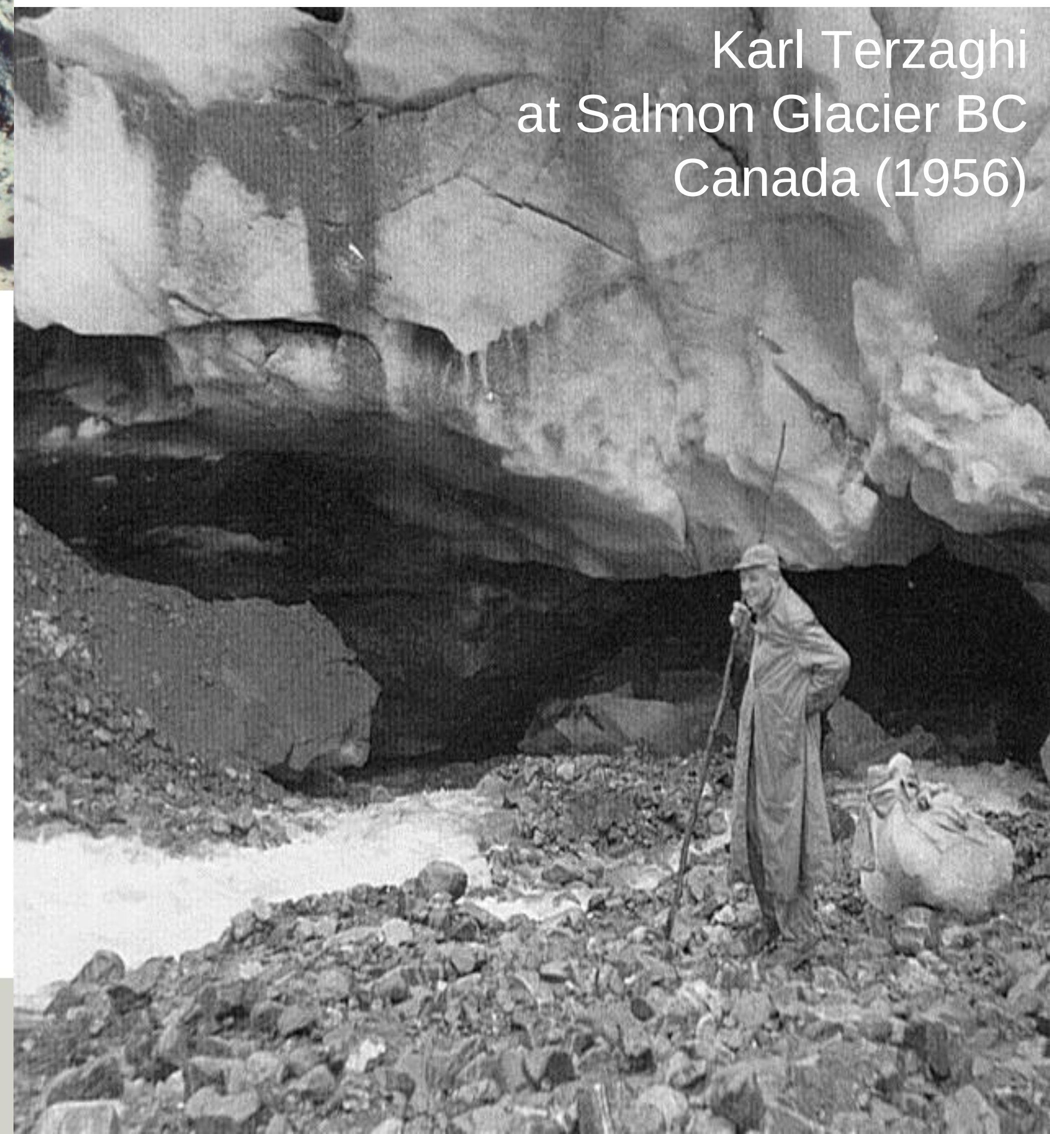
> "when we turn on the tap, we trust that the water is clean; when we drive home from work, we trust that the roads will not collapse."

Over the last 100 years, life expectancy has doubled. The main factor has not been advances in medicine, but advances in clean water and sanitation (after Siegel 2010 and Brandl 2010).

The key to <u>success</u> and <u>happiness</u> is "[...] a love of civil engineering, which, at its core, seeks to do 'good works' for humanity" (Ralph B. Peck 1933, he was 21 years old).

In view of today's needs and our profession's evolution, Ralph could not have been more right.

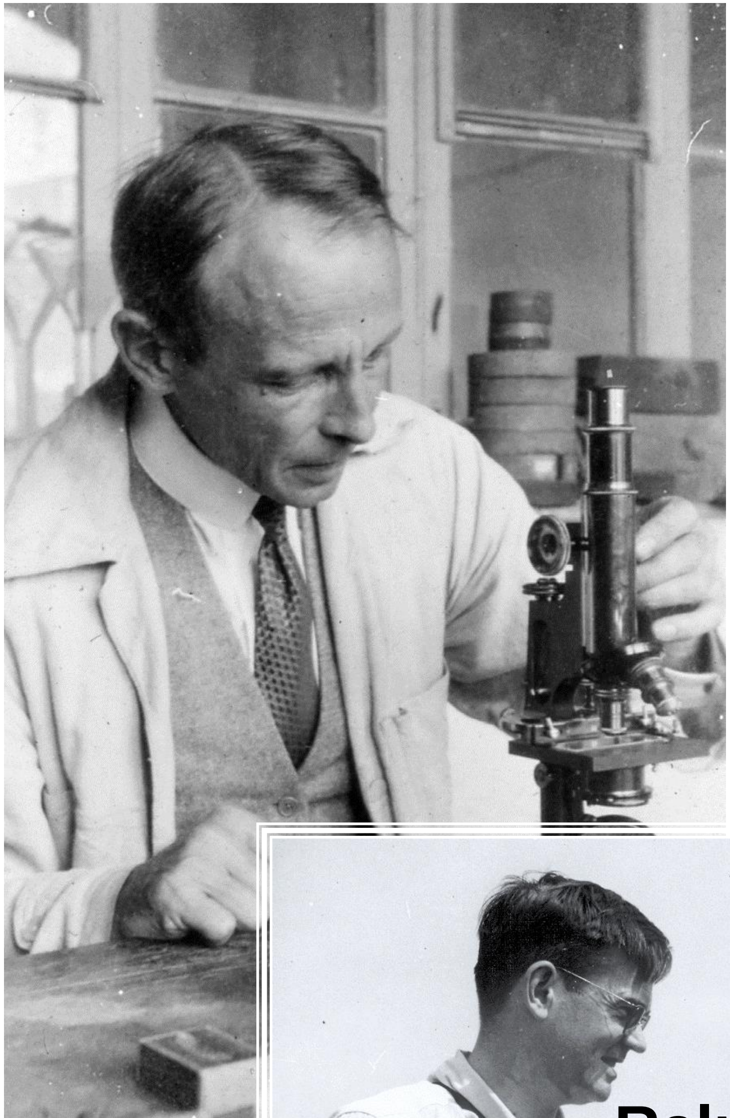
Karl Terzaghi
Loen Norway (1957)



Karl Terzaghi
at Salmon Glacier BC
Canada (1956)

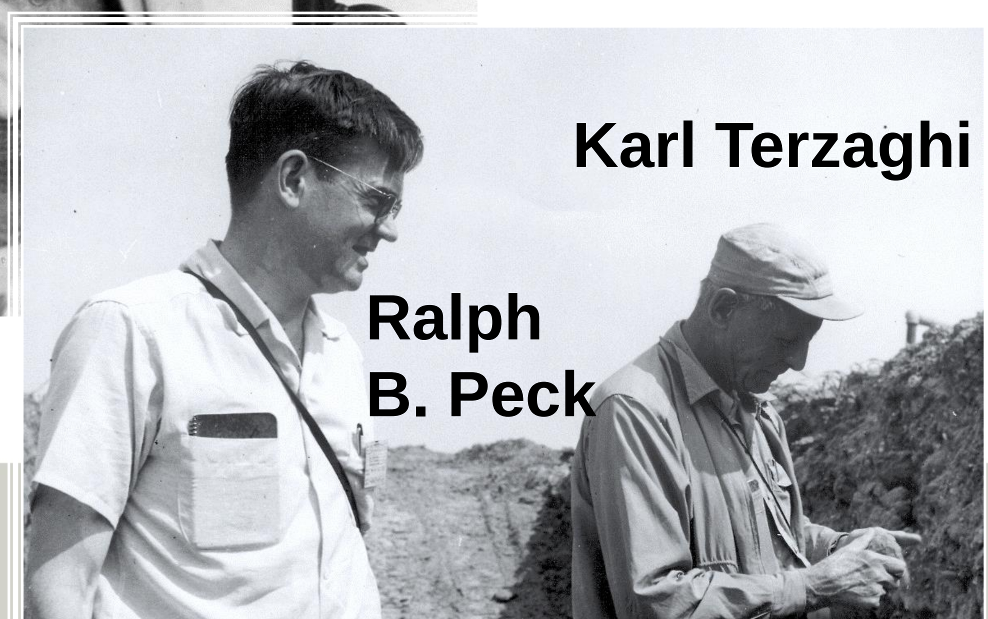
Lessons from Karl Terzaghi (among many lessons):

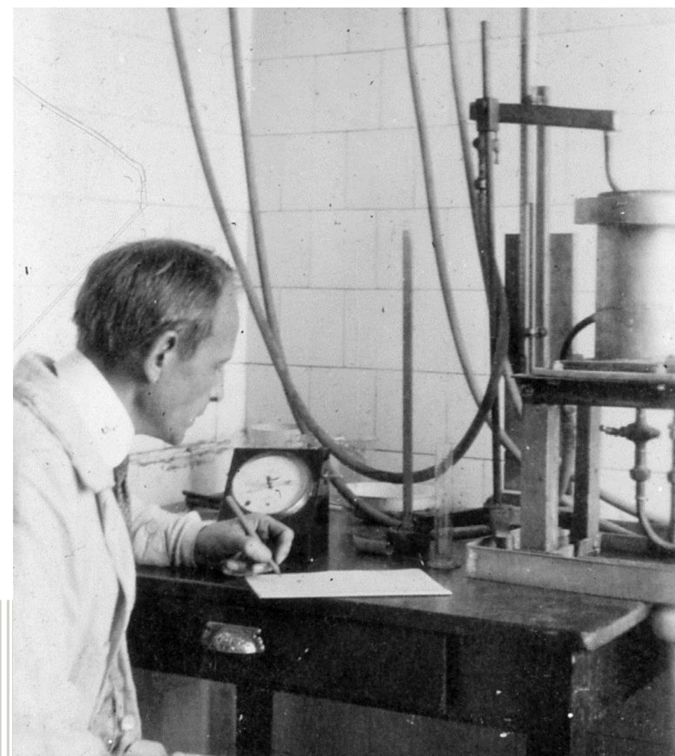
1. Enjoy what you do.
2. For every project, go to the site and see for yourself.



.. «<u>Happiness</u>? I have learned the meaning of the word in this year. Continuous creative activity. Clarification of confused material [case studies, geotechnical profiles] and sympathetic, guiding influence on earnestly striving young men (!)».

Karl Terzaghi 40 years old
Istanbul 31 December 1923





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There is no I in Happ'y'ness