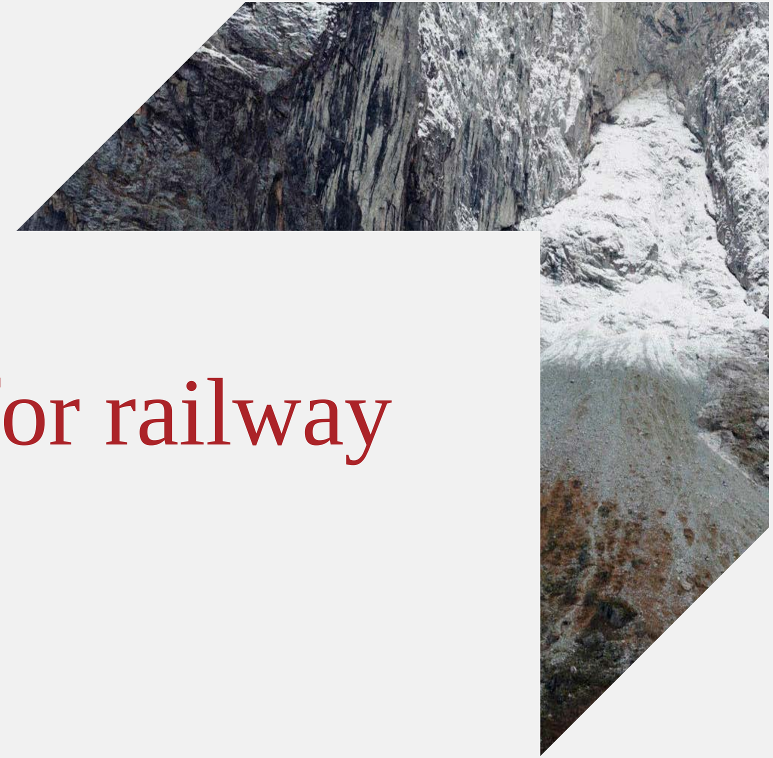


Landslide assessment for railway infrastructure

07.05.2018

Håkon Heyerdahl, NGI/Klima 2050 (hhe@ngi.no)
With contributions from Yme Kvistedal, Kjersti Gisnås, Øyvind Høydal, Pasquale Carotenuto

Content

1. Rainfall triggering of landslides, empirical approach
2. Saturated and unsaturated zone
3. Unsaturated soil properties
4. An example of practical application - Local landslide prediction

1 Rainfall and triggering of landslides

Innfjorden, Northwest coast
of Southern Norway, 1988

«Landslide autumn» – year 2000

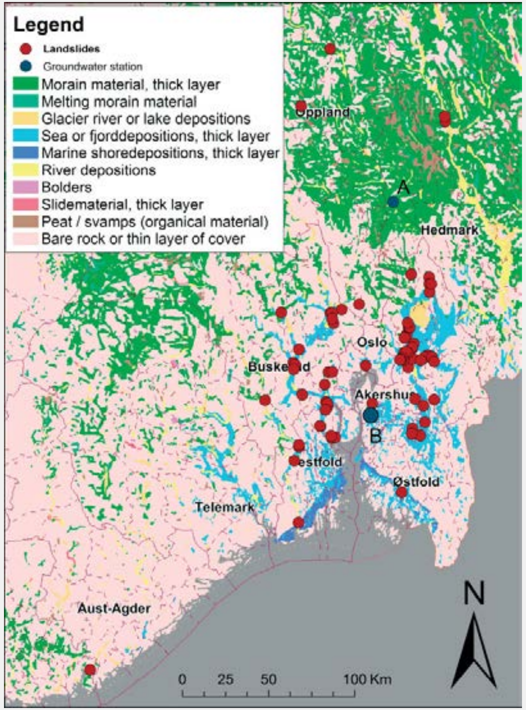
Eastern Norway Oct – Nov 2000

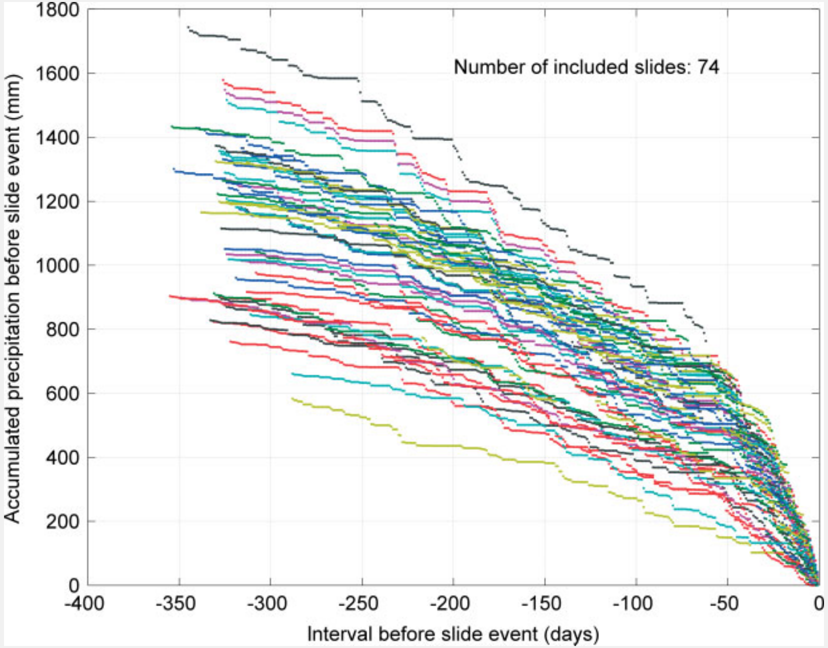
- Hundreds of small landslides (typically 1-2 m depth)
- No casualties, large economic loss
- Slides in sands, silts and clays

Landslide Negarden Sander, autumn 2000

Negarn Sander, hus på raskanten

Landslides, autumn of year 2000





Jaedicke and Kleven, 2007

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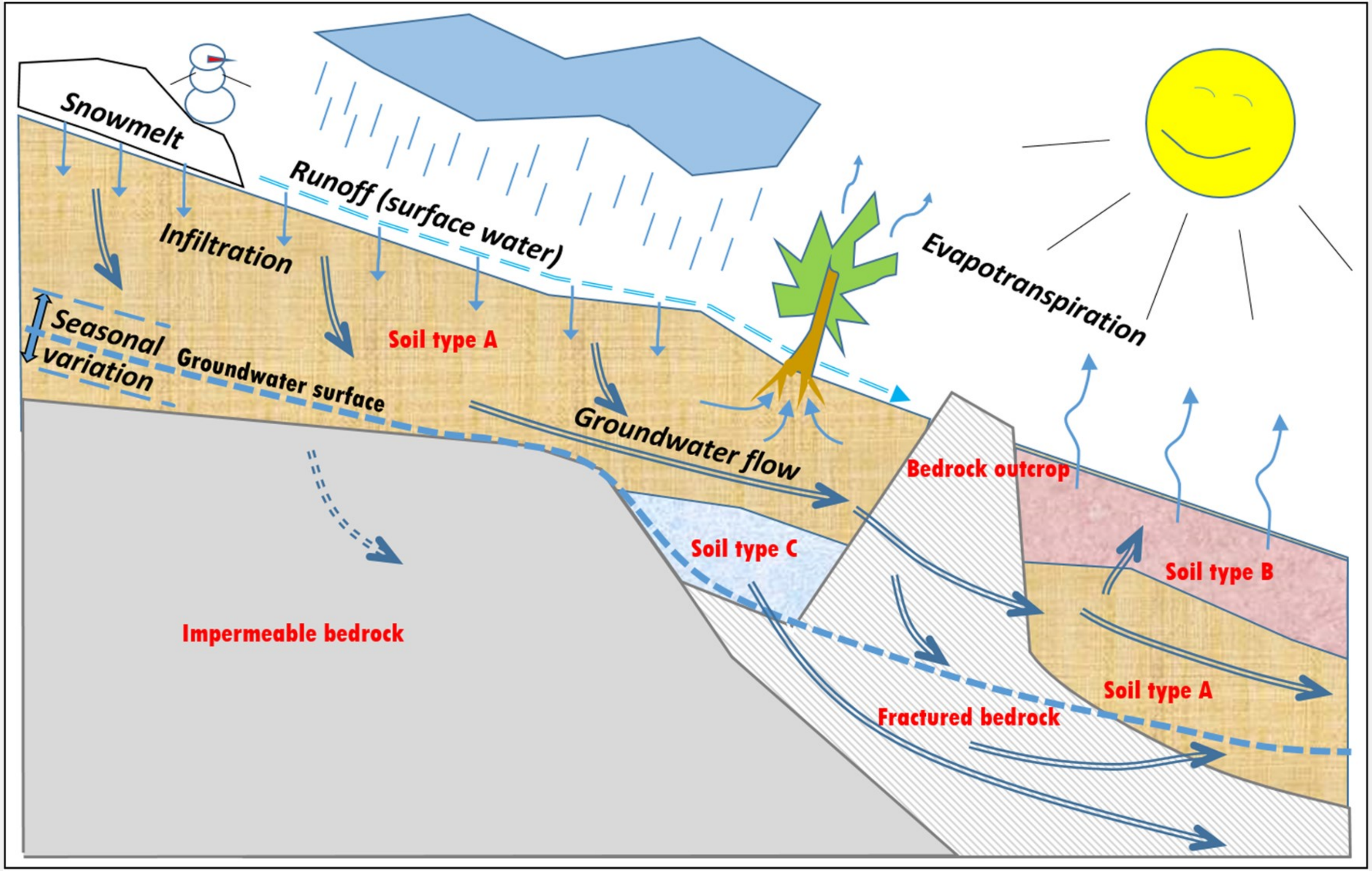
Natural slopes are complex!



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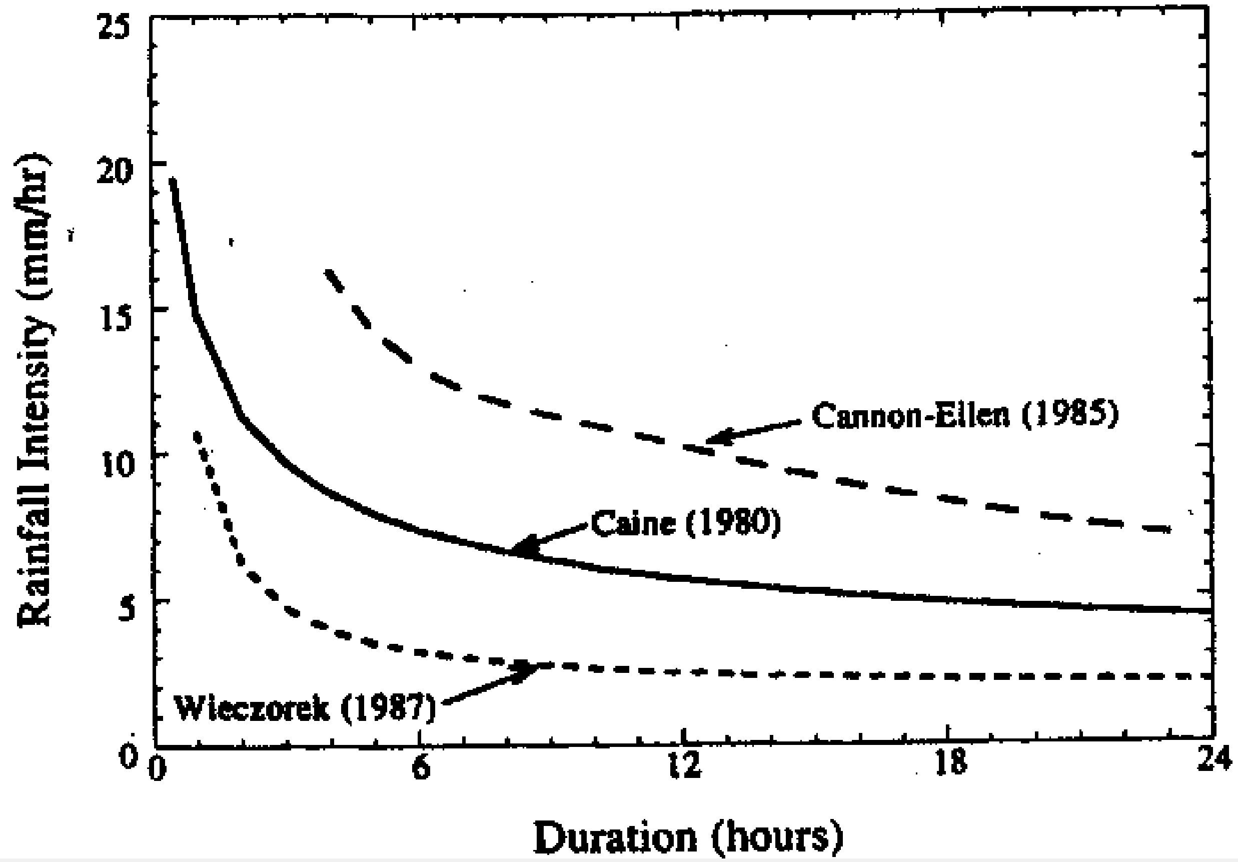
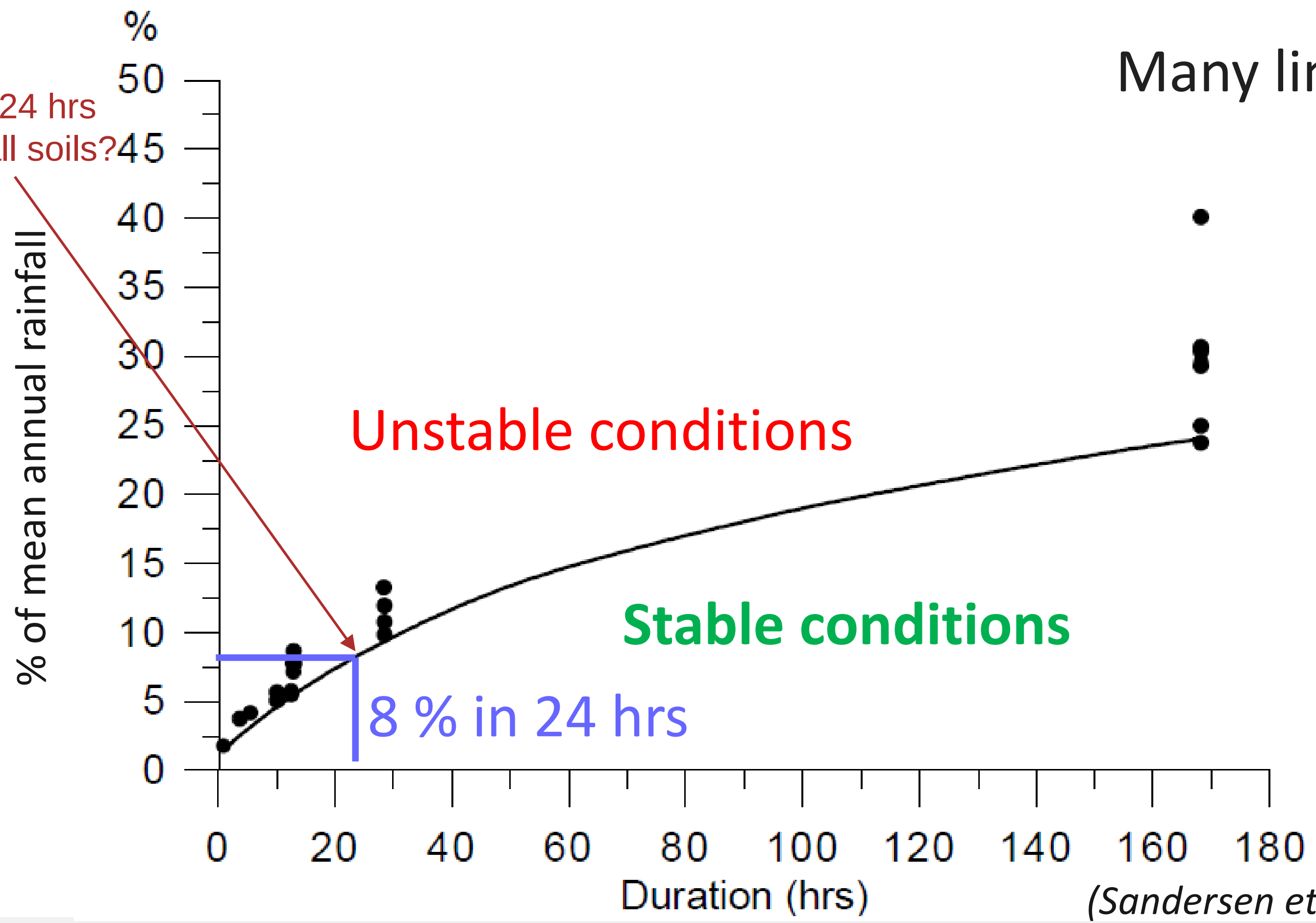
Rainfall Intensity/Duration Relationships

Wilson and Wieczorek, 1995



Example of triggering values from Norway

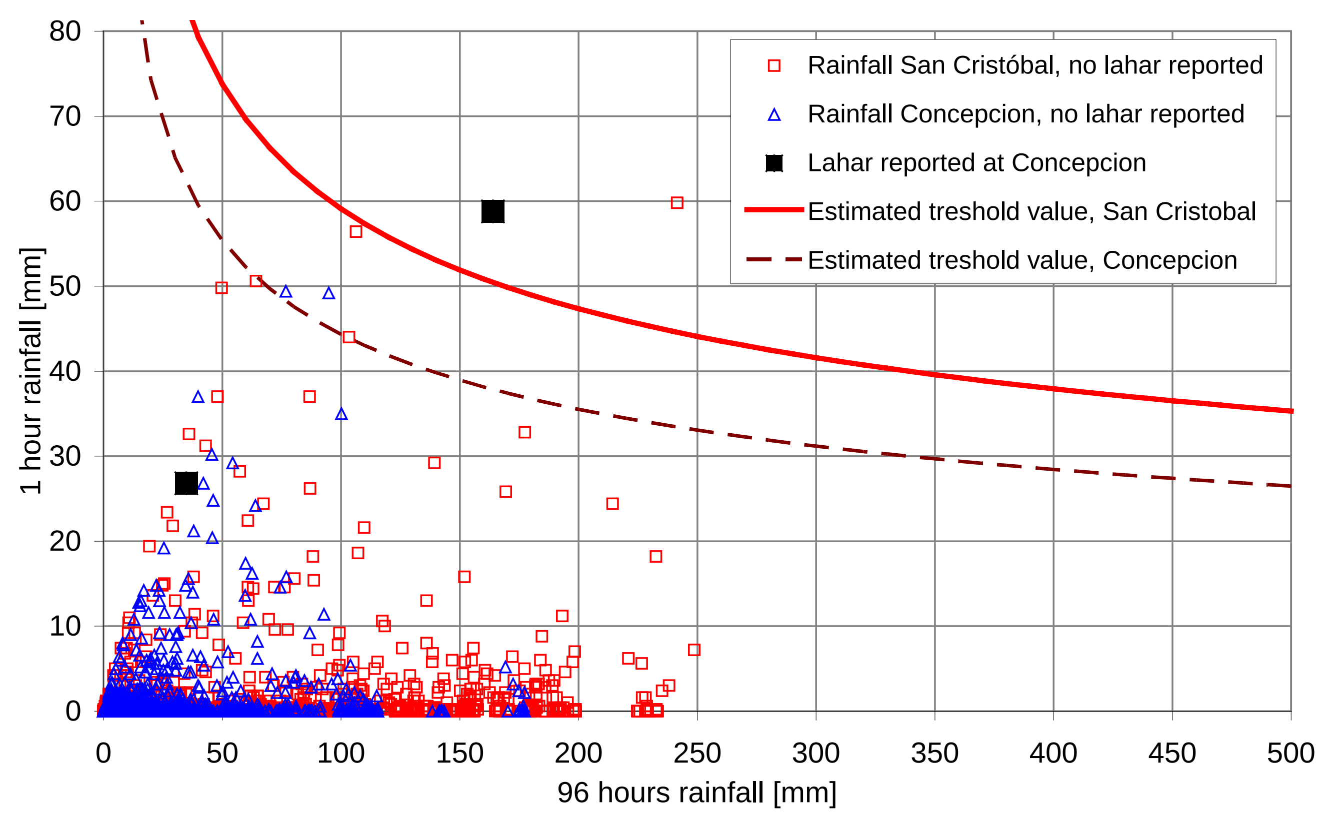
~8% during 24 hrs
But not for all soils?



Many limitations....

(Sandersen et al 1996)

Suggested critical rainfall for a volcano in Nicaragua



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(Heyerdahl et al. 2003)

Empirical criteria are attractive, but need support from understanding of the geomechanics involved!

- Stability of soil slopes
  - Wide range of natural soil types
  - Road cuts, embankments
- Infiltration of rainwater
  - and snowmelt!
- Pore pressures
  - Positive below, negative above the phreatic line
- Effects of climate
  - More rain – longer/more intense scours?

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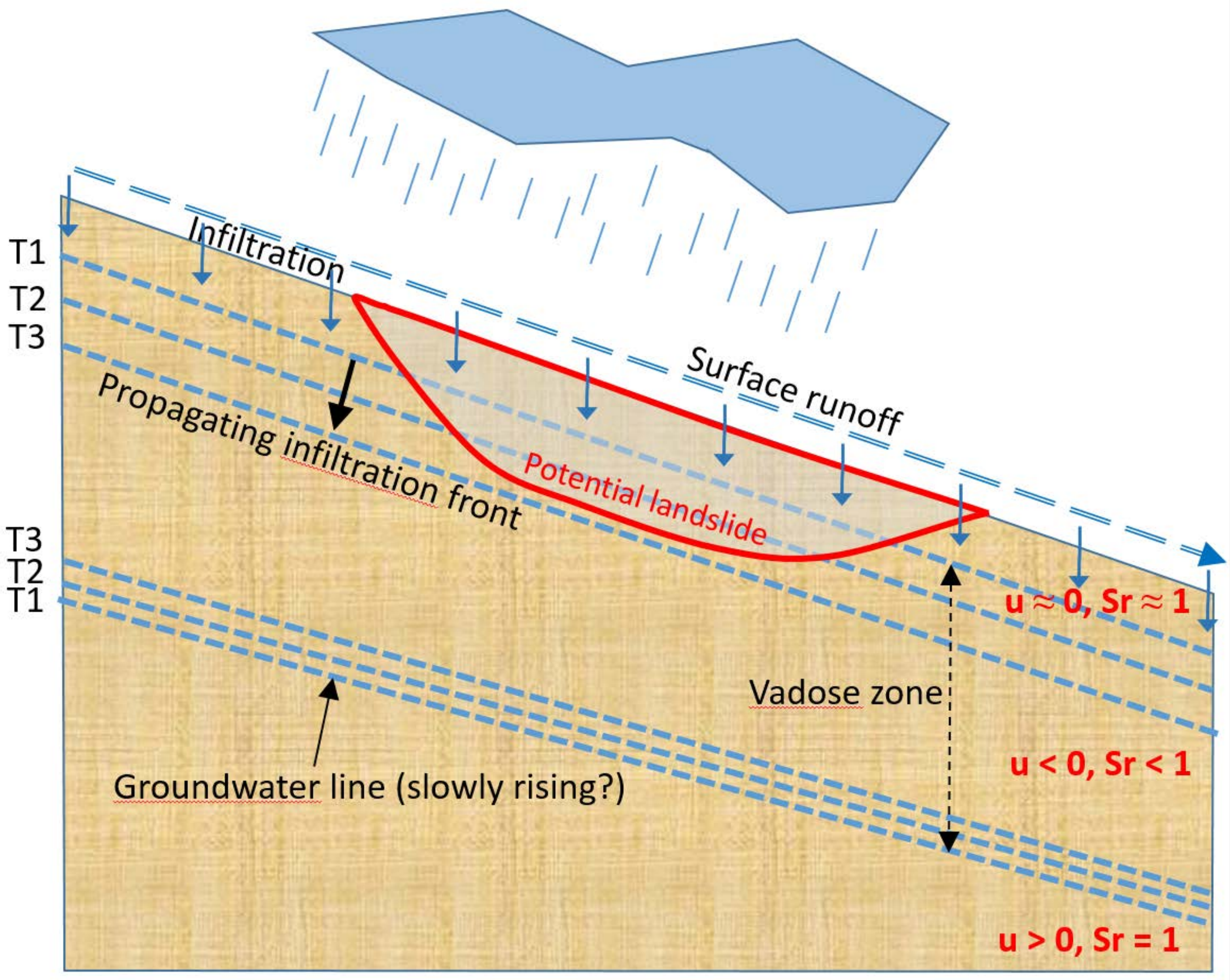
Translational/ rotational slide



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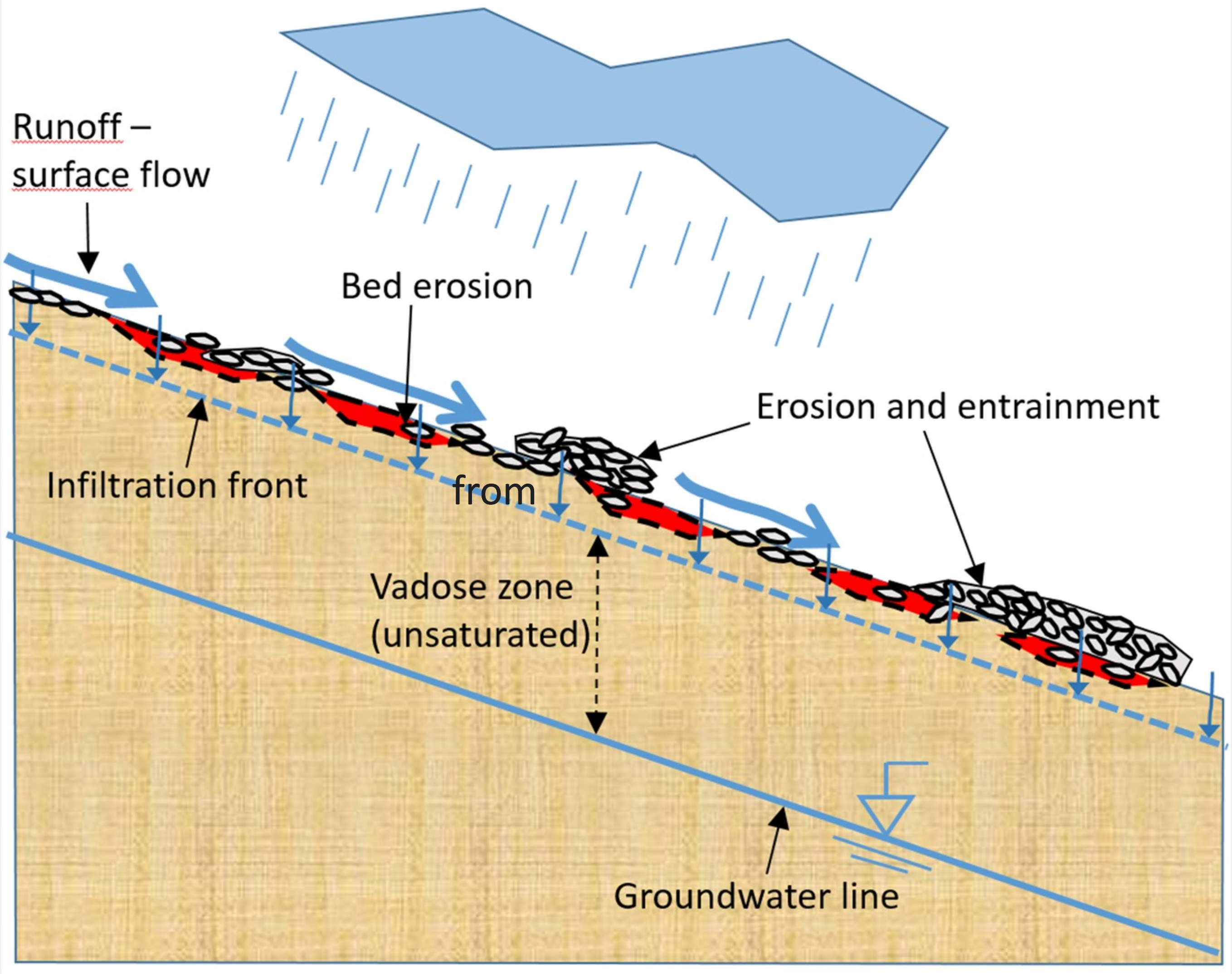
Erosional slide



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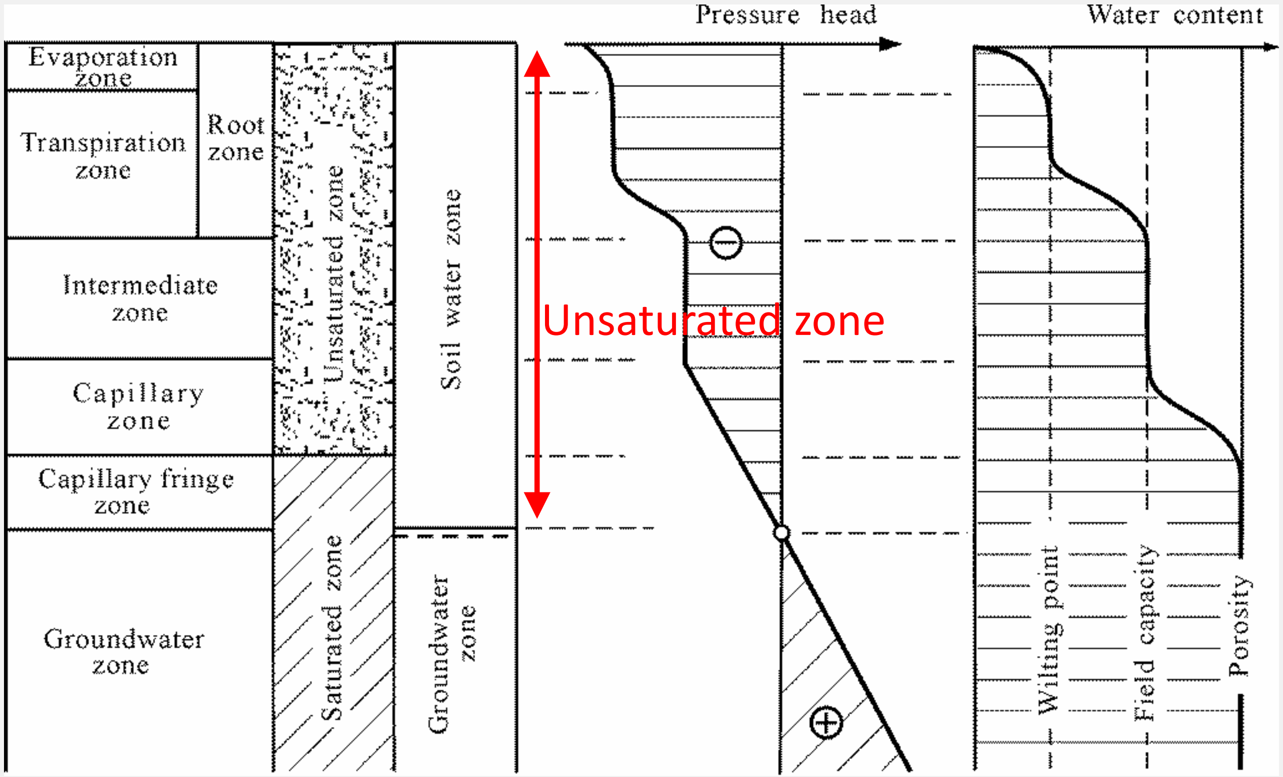
2 Saturated and unsaturated soil profiles

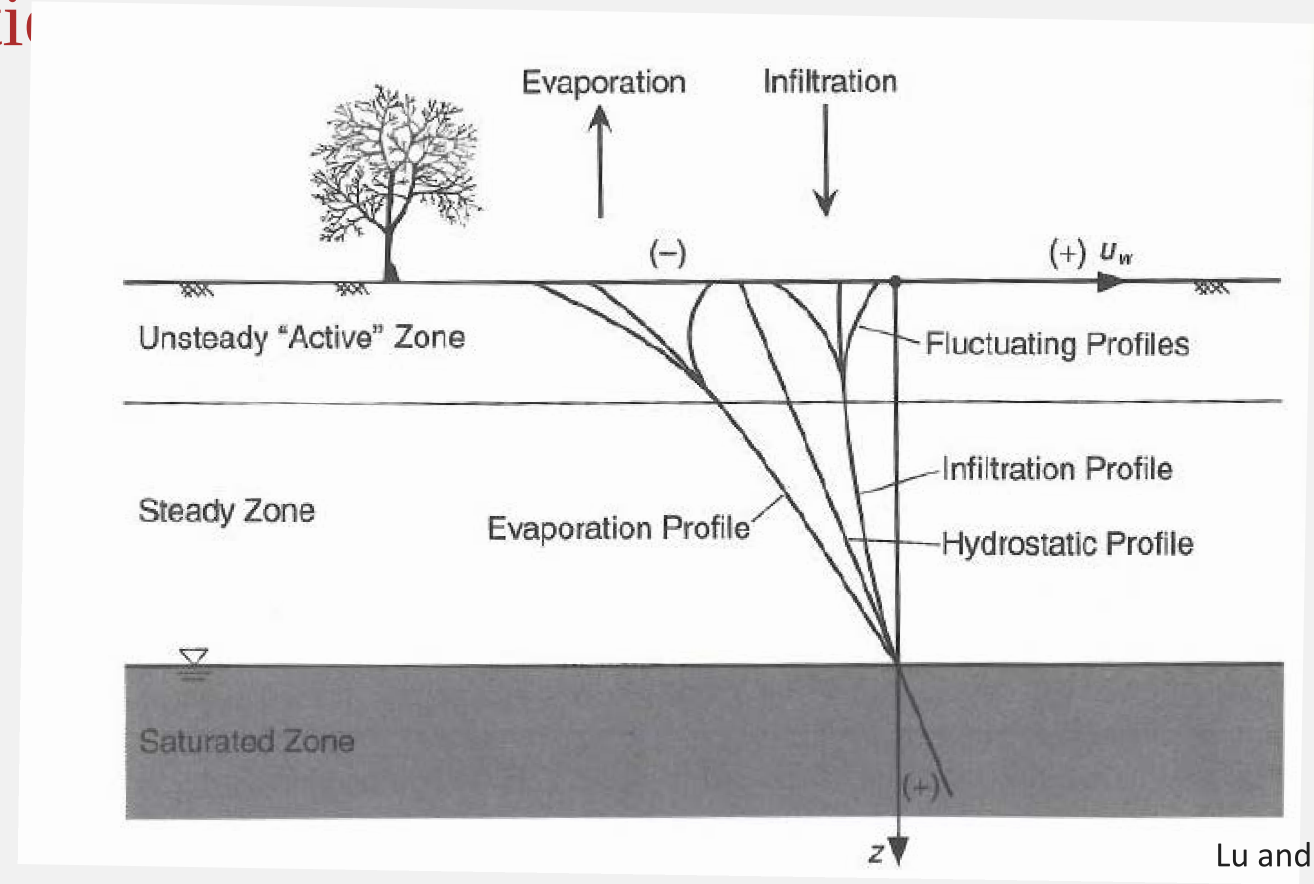
- Unsaturated soil – definition:
  - Negative pore-water pressure
  - Unsaturated soil may however have a saturation rate of 100 %!
- Generally: Soil layer above groundwater surface (vadose zone)
- The extents of the unsaturated layer varies continuously
  - Water flow
  - Climatic impact (rainfall, snowmelt, drying)
  - Geology, soil type, layering

Saturated and unsaturated zone



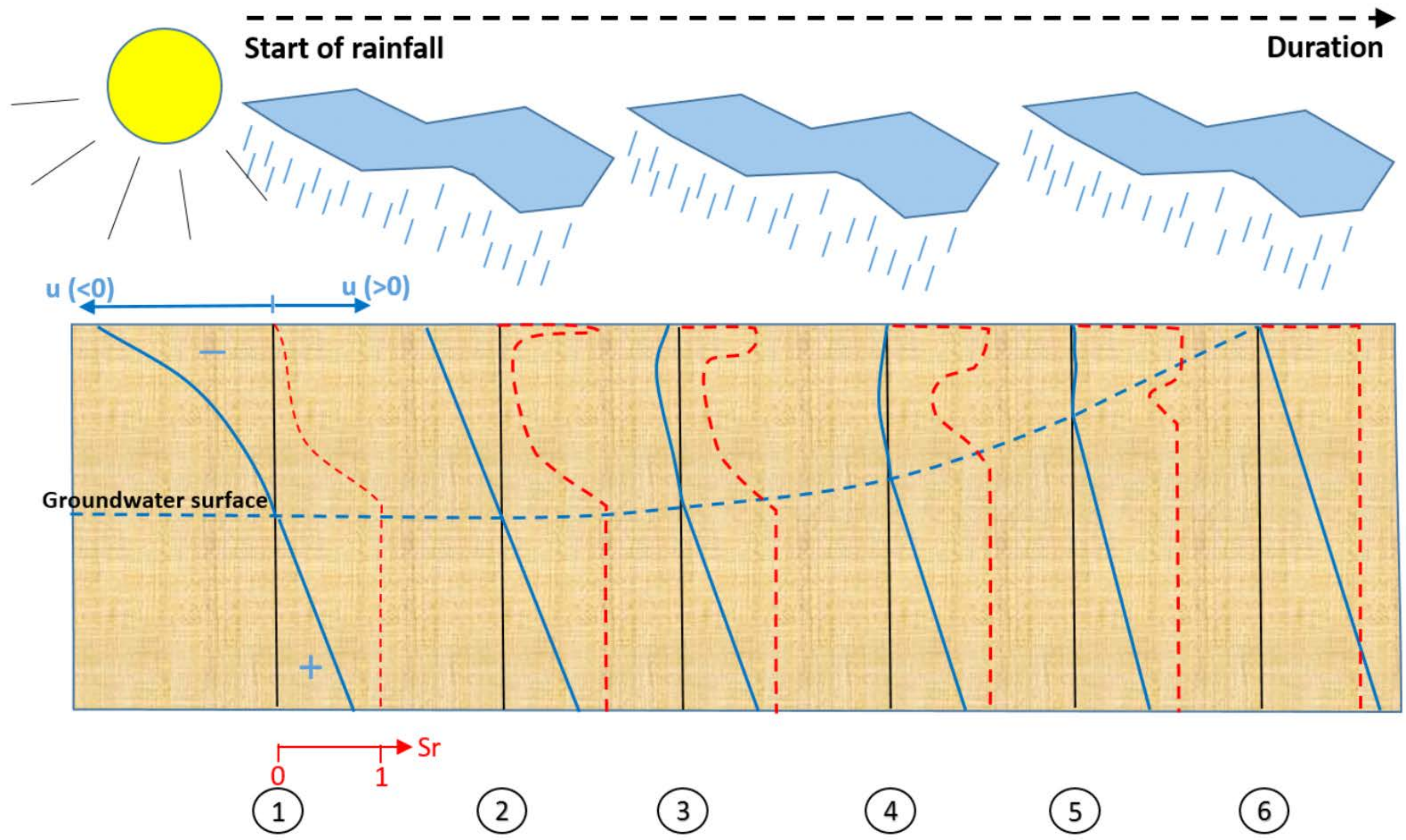
K. H. Jensen, 2001

Pore pressures under various surface flux boundary conditi



Lu and Likos, 2004

What happens in the ground (saturation rate)?



3 Properties of unsaturated soils

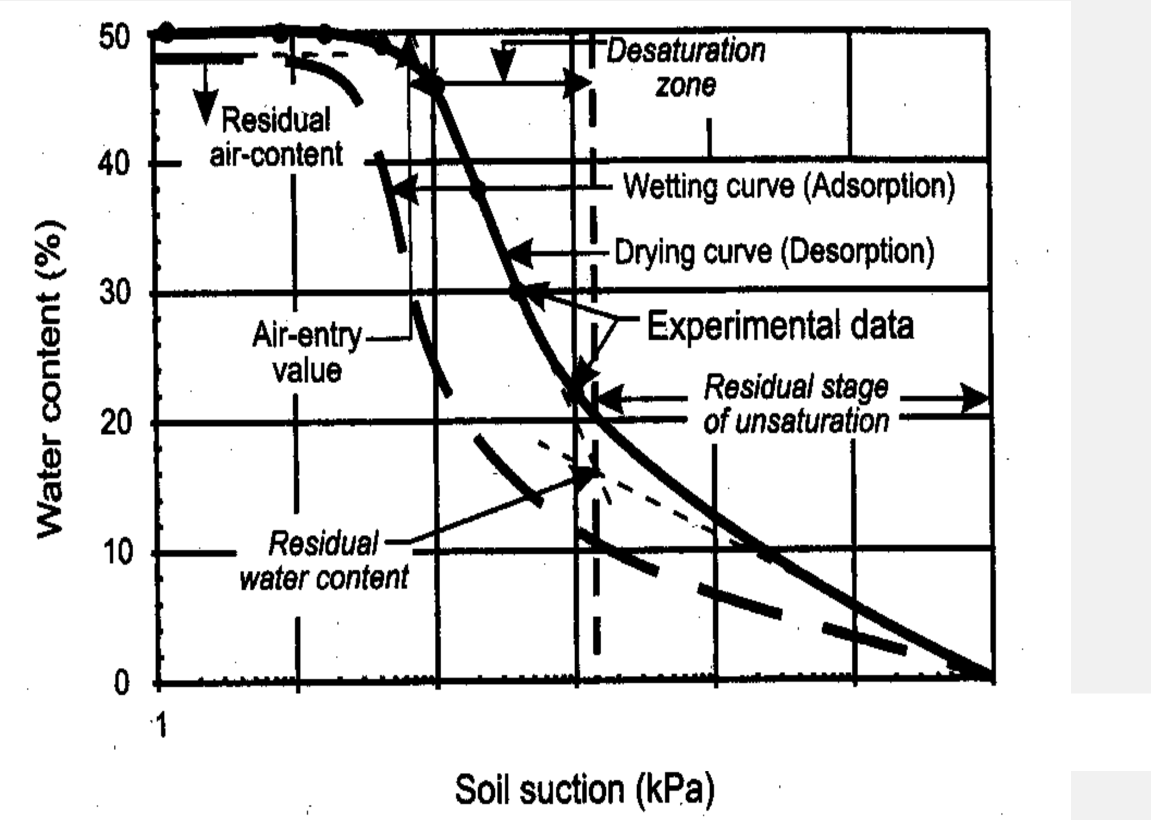
- Water retention (function)
- Permeability (function)
- Shear strength (function)
- (Compressibility) (function)

- Much more complicated than saturated or dry soils!
  - Laboratory work is much more laborious
- Not widely applied in Norway for geotechnical studies
- More commonly used within hydrology/hydrogeology/soil physics
  - Mostly for infiltration, not for slope stability studies

Water retention

(Fredlund, 2000)

- Function relating water content to suction
  - Normalised
  - Volumetric
  - Gravimetric
- Often measured with «pressure plate»
  - Not a very good method



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Water retention

(Fredlund, 2000)

- Function relating water content to suction
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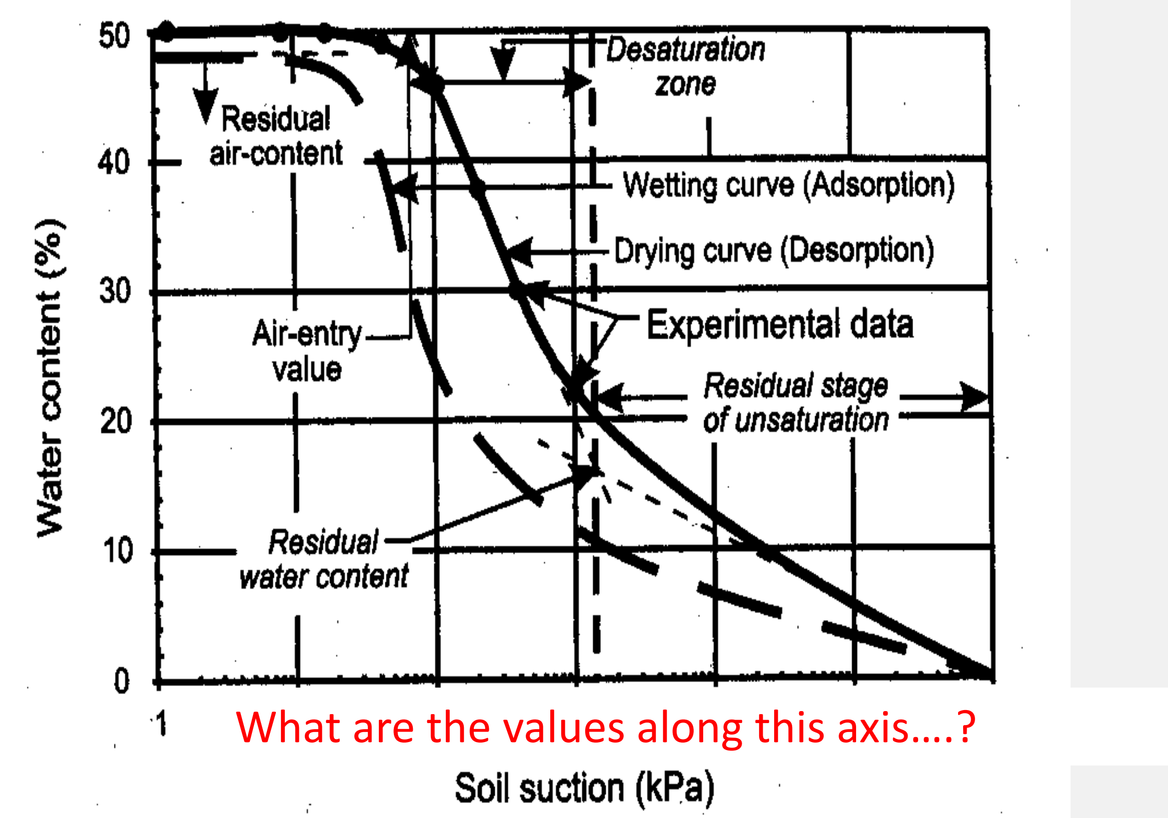

Water retention

(Fredlund, 2000)

- Function relating water content to suction
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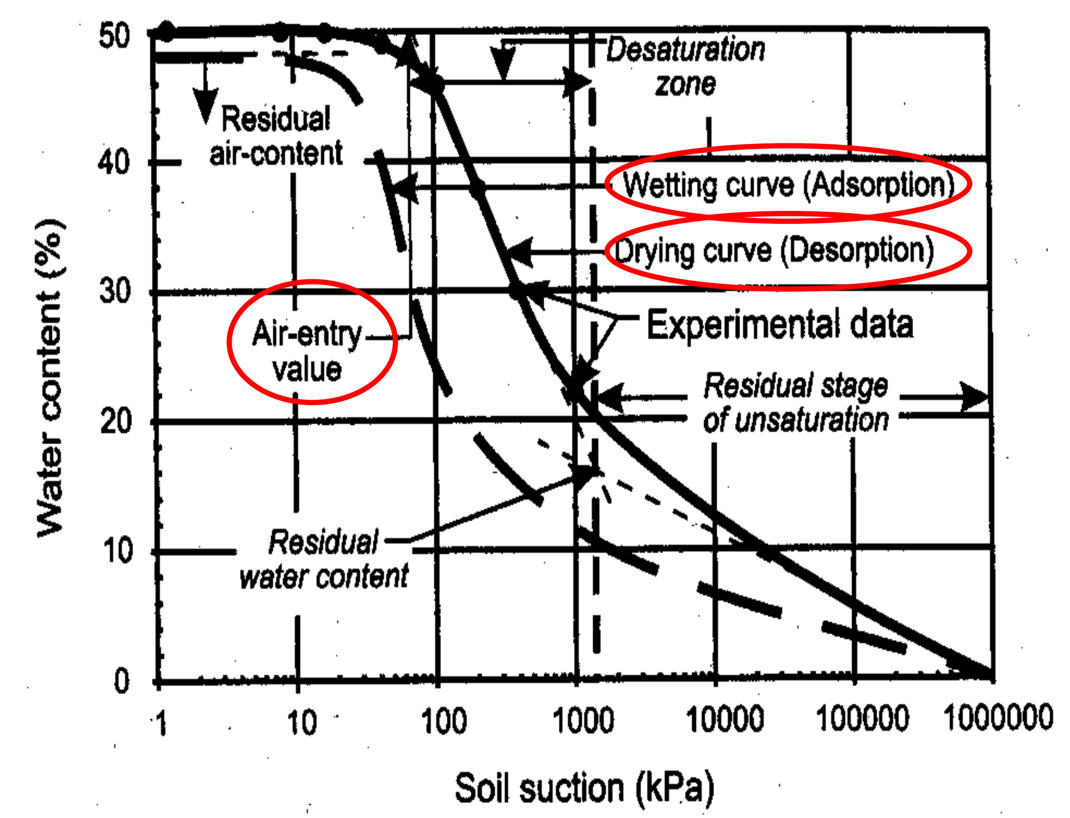
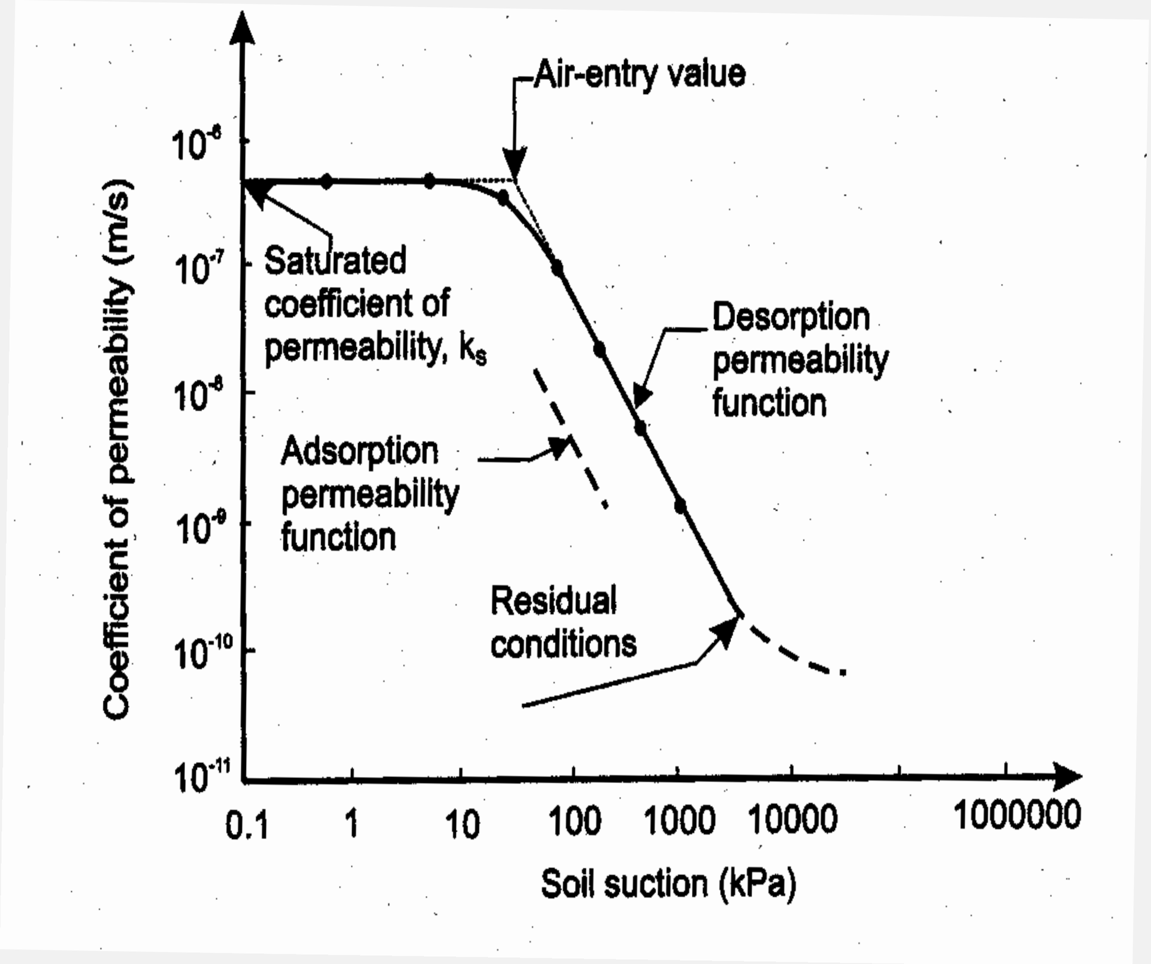


Retention curve functions

- Some common models:
  - Brooks and Corey (1964)
  - Van Genuchten (1980)
  - Fredlund and Xing (1994)
- Only modelling the <u>shape</u> of the curve, no prediction!

Unsaturated permeability vs. soil suction



(Fredlund, 2000)

Soil strength and volumetric behaviour: Governed by stress state variables

- Saturated: One stress state variable

  $(\sigma - u_w)$ Effective stress («Archimedes»)

- Unsaturated: Two stress state variables

  $(\sigma - u_a)$ Total net stress

  $(u_a - u_w)$ Matric suction

- The soil behaviour is governed by the two stress variables (Fredlund and Morgenstern, 1977)

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Classic Mohr-Coulomb model for drained soil strength
One stress variable

$$t_f = c' + (\sigma - u_w)\tan\varphi'$$

Cohesion

Effective stress

Mohr-Coulomb model for unsaturated soil

Two stress variables

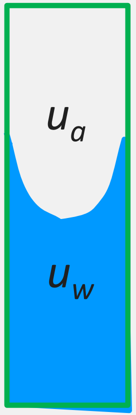
(Fredlund and Rahardjo,1993)

$$t_f = c' + (\sigma - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b$$

Cohesion

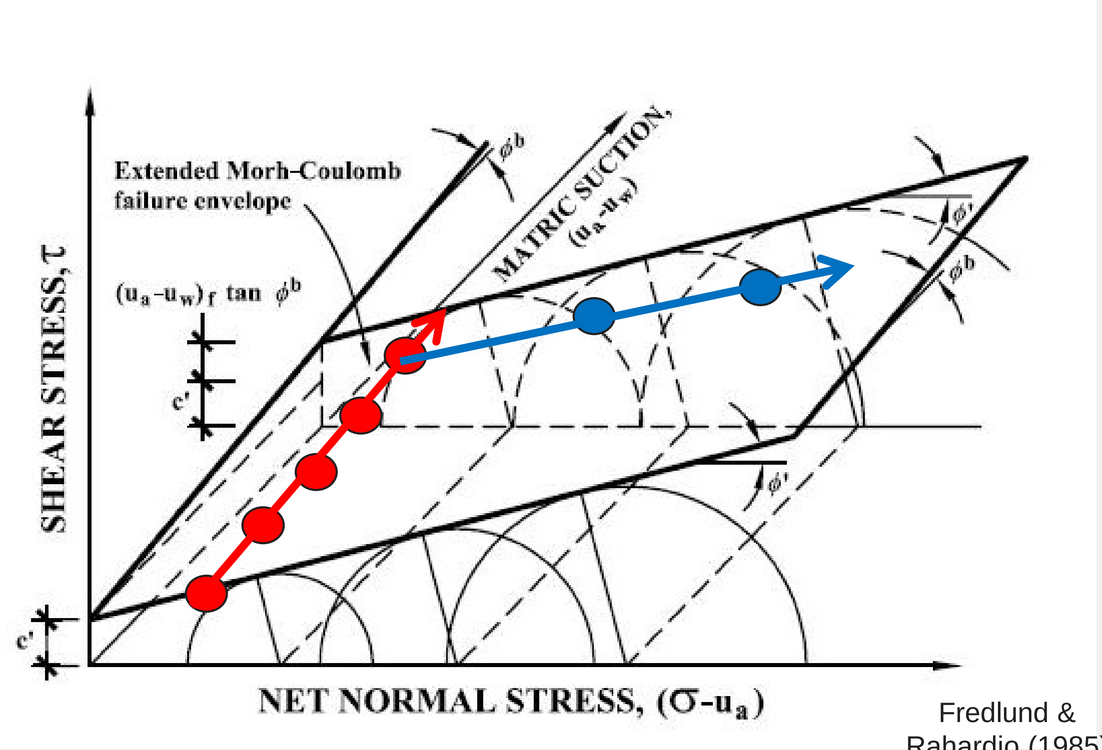
Net normal stress

Suction



Many different suggestions for unsaturated shear strength / suction stress suggested, and new suggestions keep coming!

Shear strength as function of matric suction and net normal stress

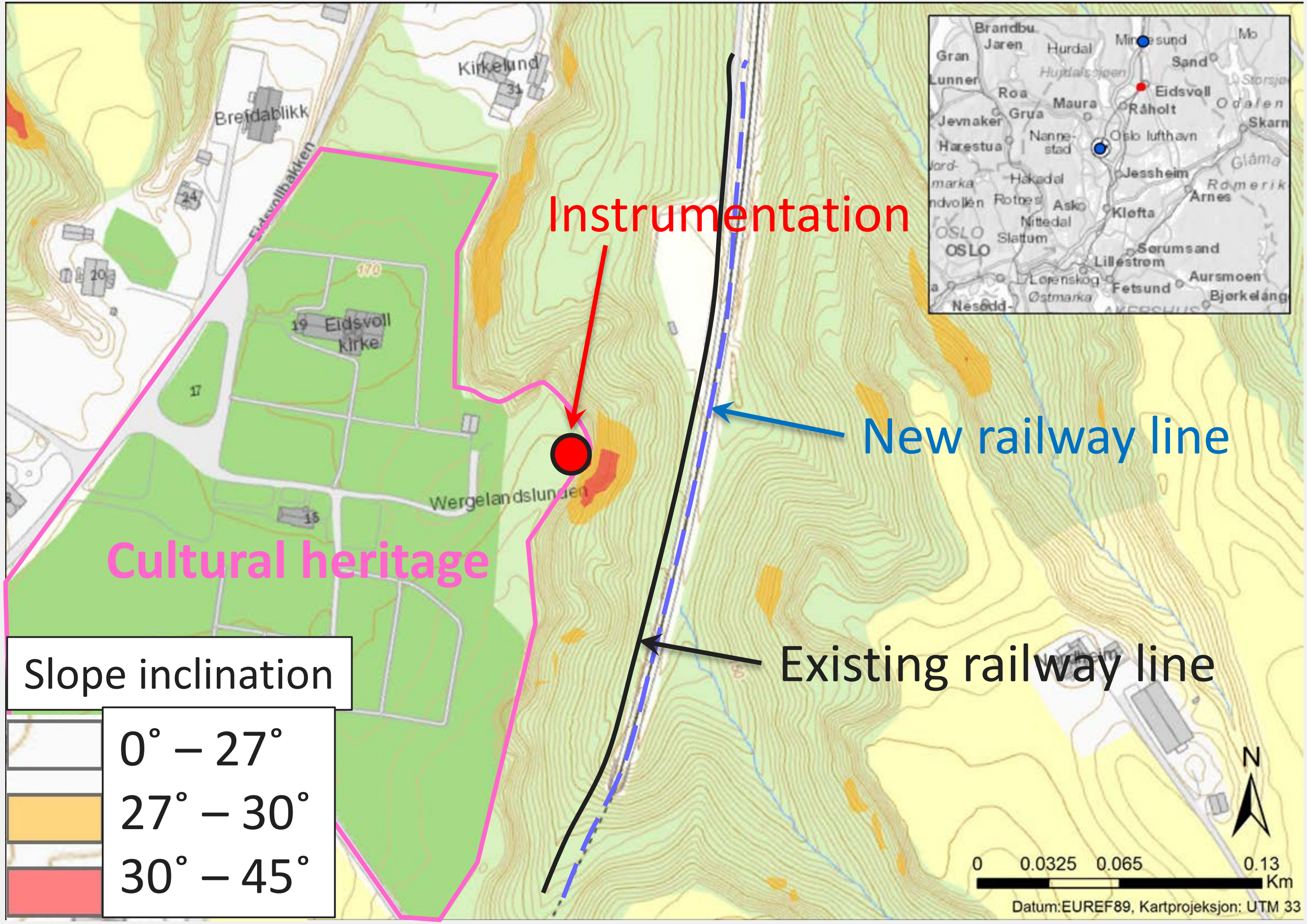


Fredlund & Rahardjo (1985)

4 An example of practical application
Local landslide prediction

- New InterCity railway line, Eidsvoll
  - Constructing new track parallel to existing
- Design criteria for slope stability:
  - Minimum «Safety factor» γ_m (Eurocode 7)
- No space (nor accept) for stabilizing measures
  - Cultural heritage on top of slope: Church, grave-yard, childhood footpaths of Norwegian writers...

Situation



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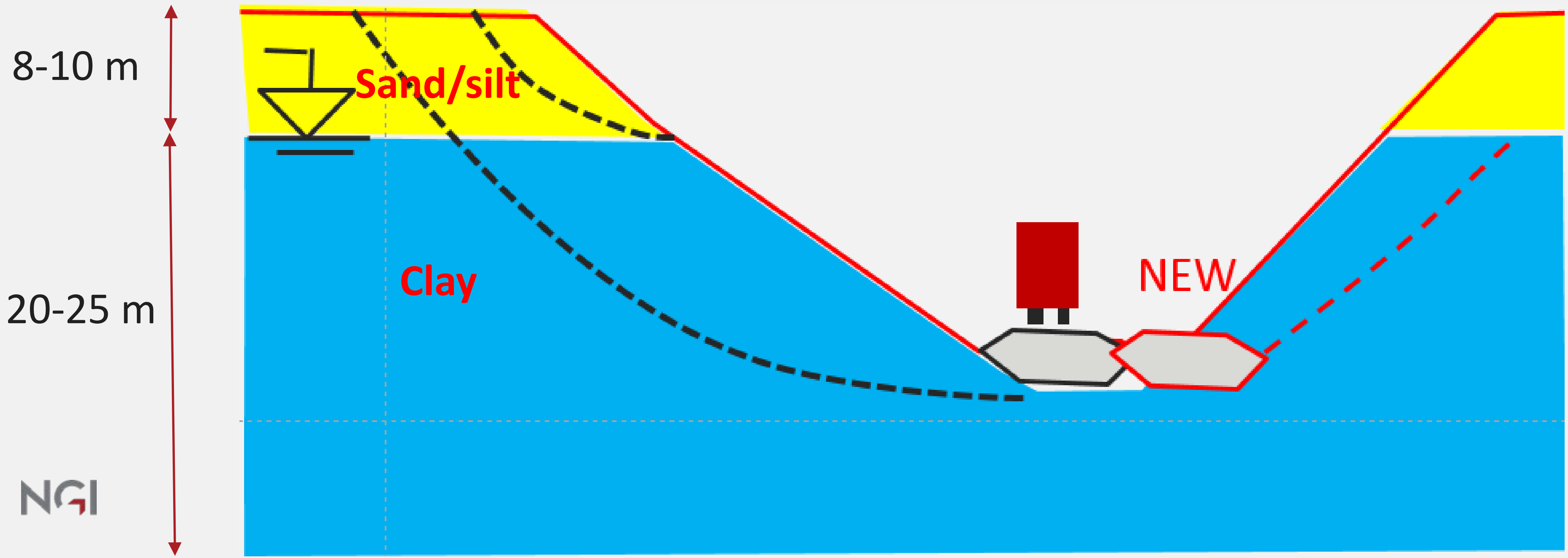
Typical cross section

- Sand/silt above clay
- Deep-seated failures in clay
- Shallow slides in sand/silt



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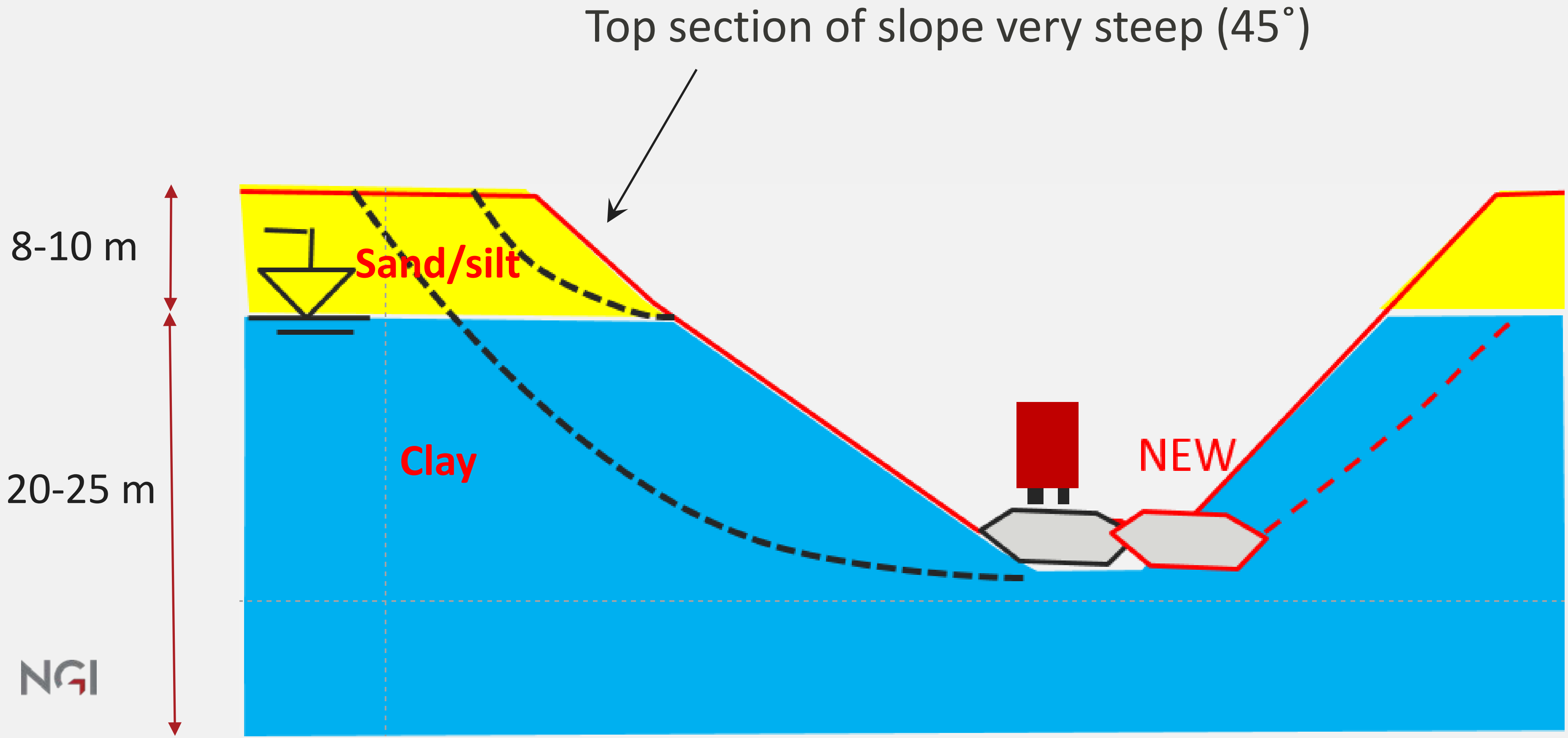
Typical cross section

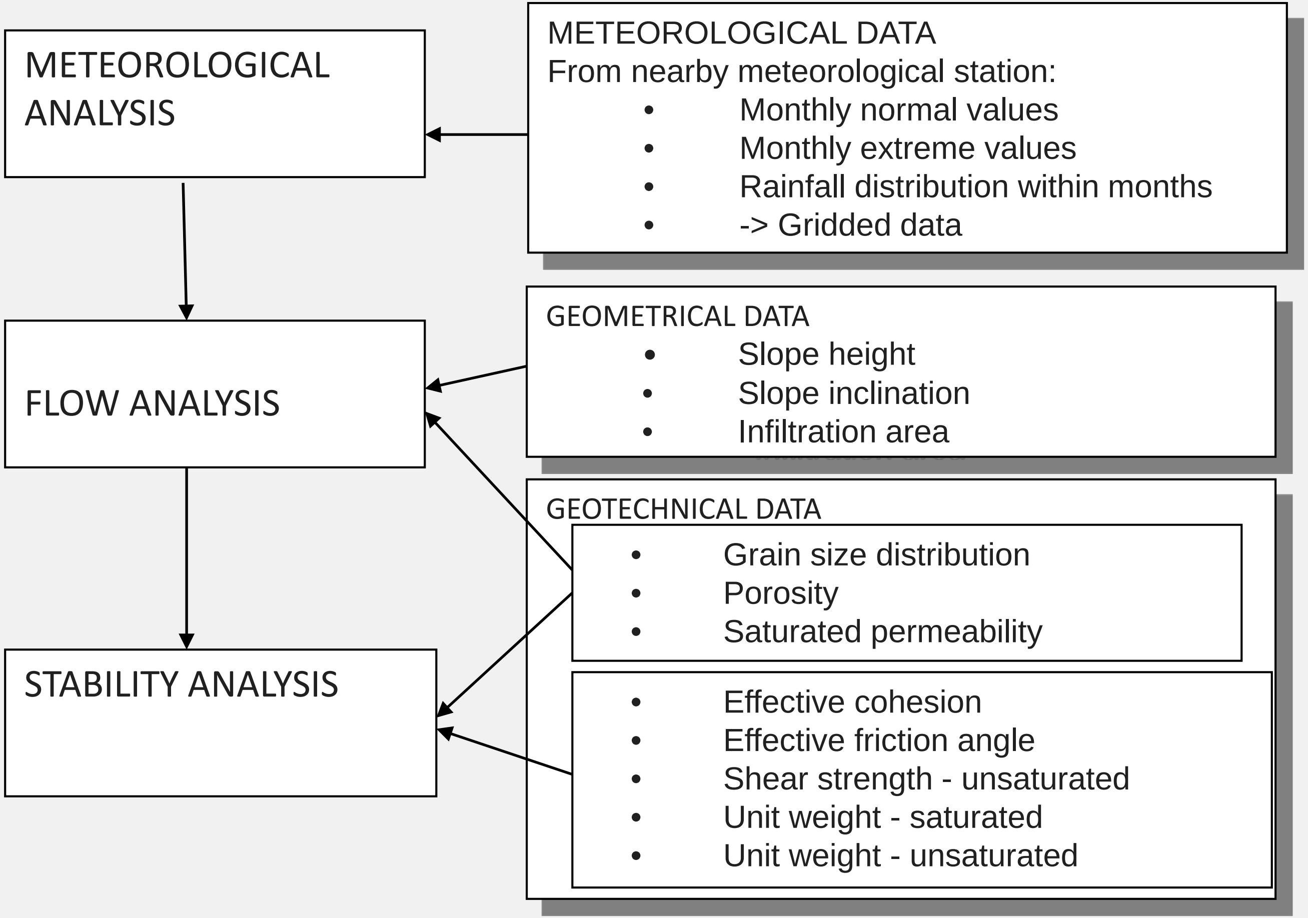


Different approach needed

- Not possible to secure slope by physical mitigation
  - Design criteria cannot be fulfilled! (minimum «safety factor»)
- Question: Can a slide occur from the upper layer?
  - Or - what is the probability?
  - Can we live with that?
- How to perform a prediction?
  - Choose any empirical relation?
  - Or physical model

Physical modelling as basis for site specific landslide risk evaluation

- Consider seasonal variations in ground water and vadoze zone
- What data is needed for reliable evaluation of landslide hazard?
  - Soil layering
  - Water retention properties (drying/wetting)
  - Permeability as function of suction/water content
  - Seasonal fluctuations in ground water
  - «Design rainfall/infiltration»
  - Soil strength (saturated/unsaturated)
  - Field measurements above and below ground-water level


METEOROLOGICAL ANALYSIS
FLOW ANALYSIS
STABILITY ANALYSIS
METEOROLOGICAL DATA
From nearby meteorological station:
• Monthly normal values
• Monthly extreme values
• Rainfall distribution within months
• -> Gridded data
GEOMETRICAL DATA
• Slope height
• Slope inclination
• Infiltration area
GEOTECHNICAL DATA
• Grain size distribution
• Porosity
• Saturated permeability
• Effective cohesion
• Effective friction angle
• Shear strength - unsaturated
• Unit weight - saturated
• Unit weight - unsaturated

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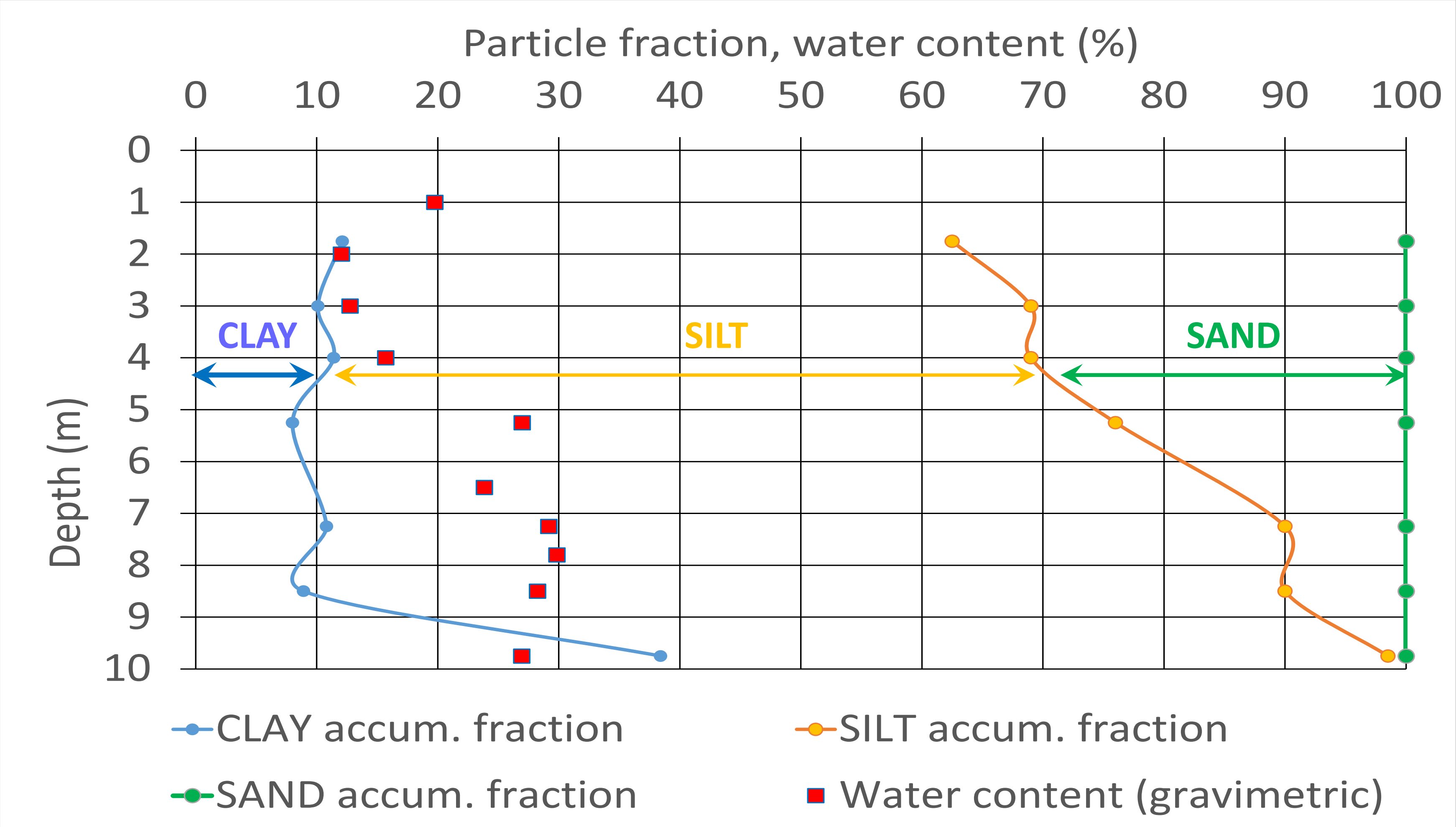
Grain size down to 10 m



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Installed moisture / temperature sensors at Eidsvoll

Sensor (no.)	Depth (m)
1	0.1
2	0.5
3	1
4	2
5	4
6	6

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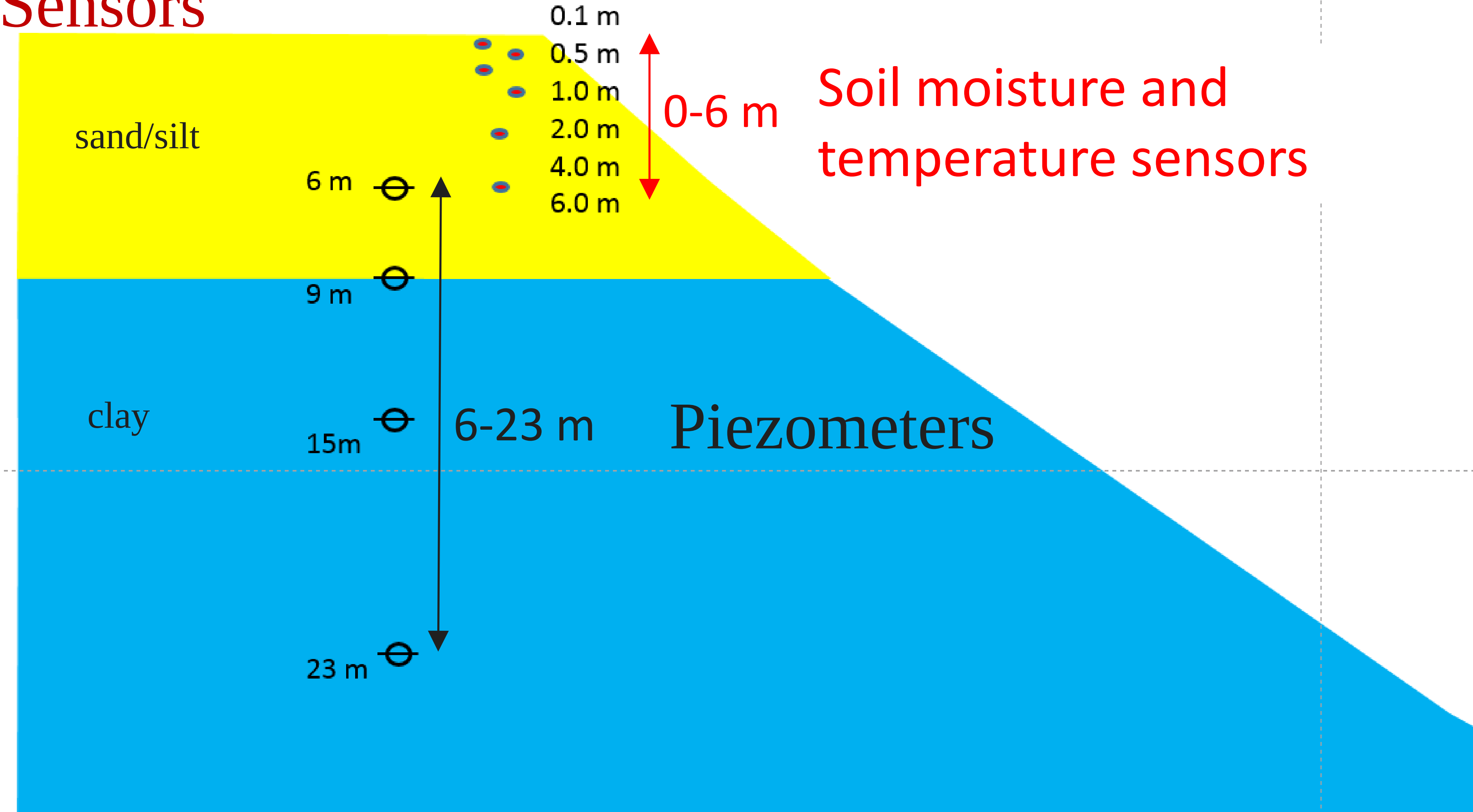
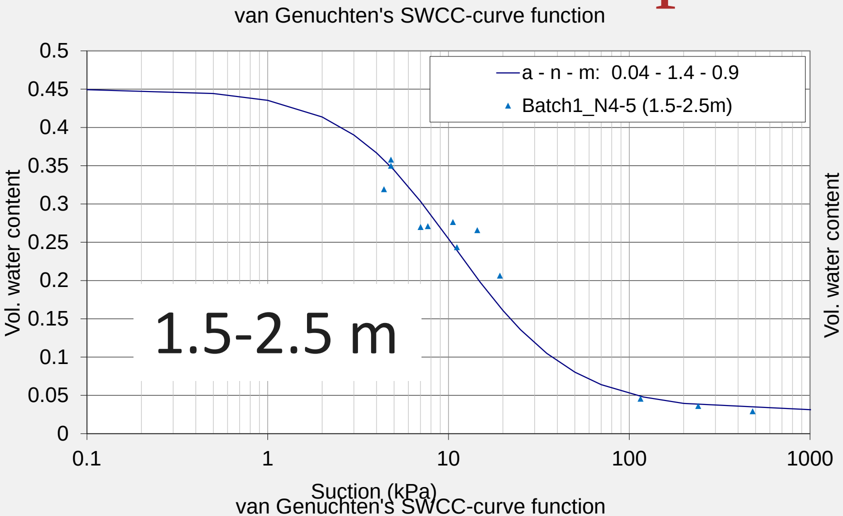
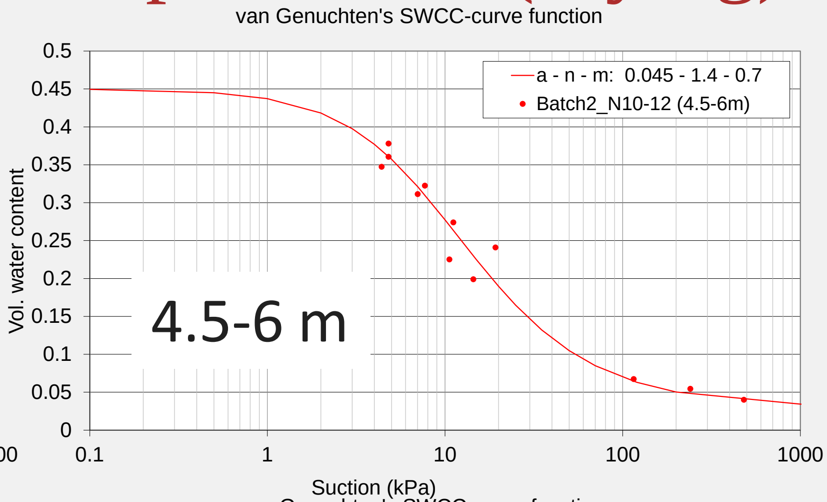
Sensors

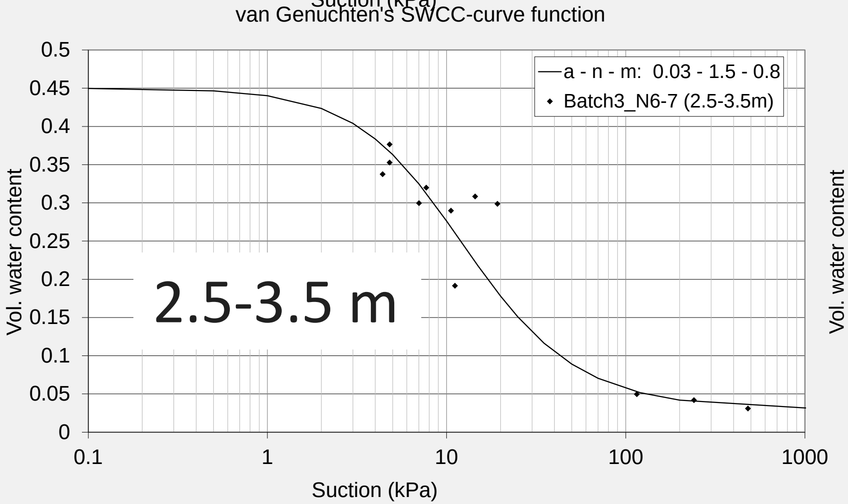


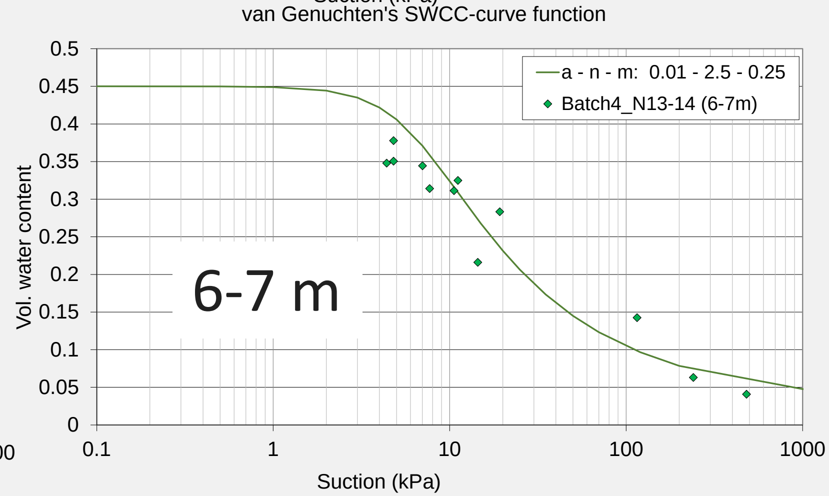
0.1 m
0.5 m
1.0 m
2.0 m
4.0 m
6.0 m
0-6 m
Soil moisture and temperature sensors
sand/silt
clay
6 m
9 m
15m
23 m
6-23 m
Piezometers

Retention curves from pressure plate tests (drying)

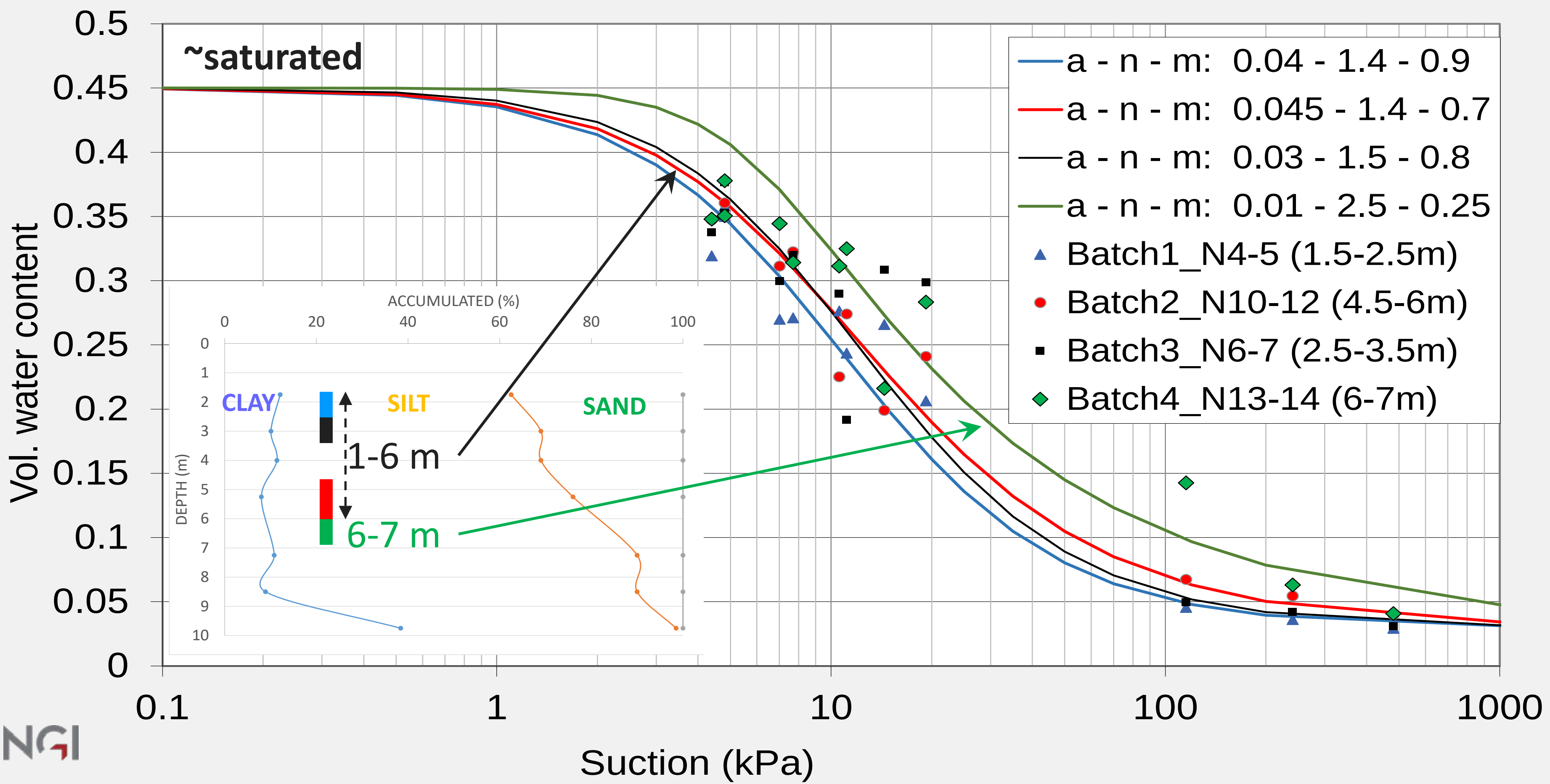








van Genuchten's SWCC-curve function



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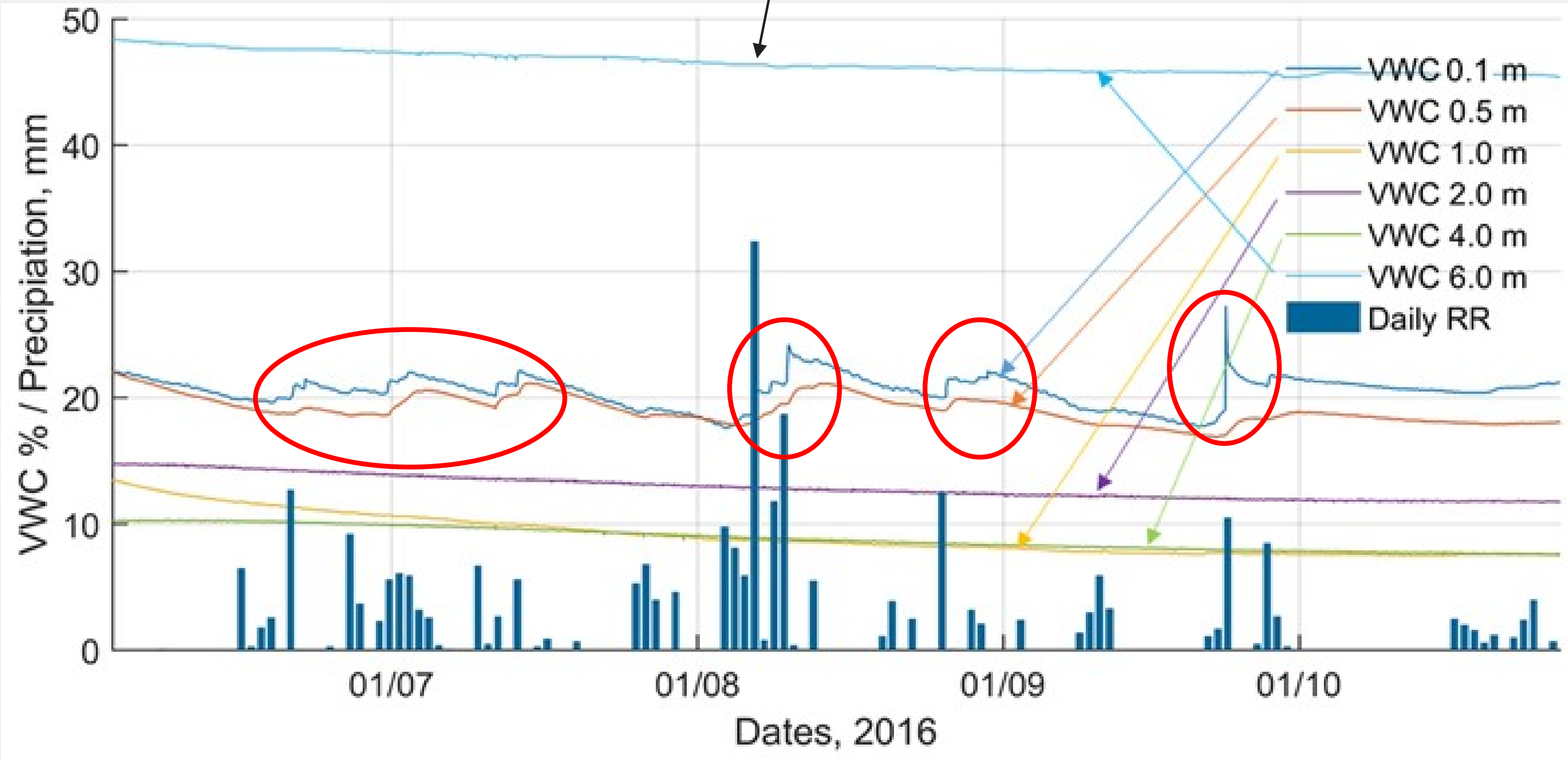
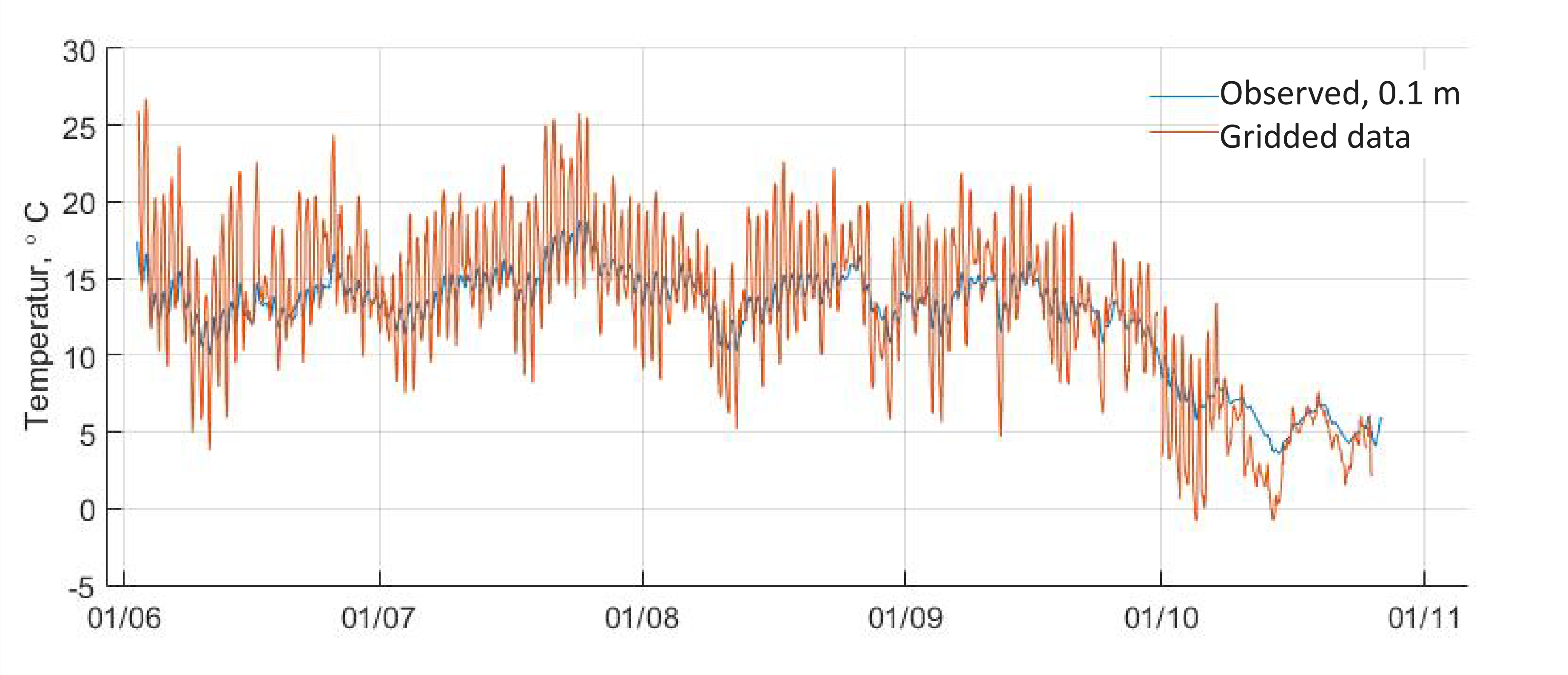
Precipitation and measured water contents

Sensor close to ground water line



Temperature in air and ground



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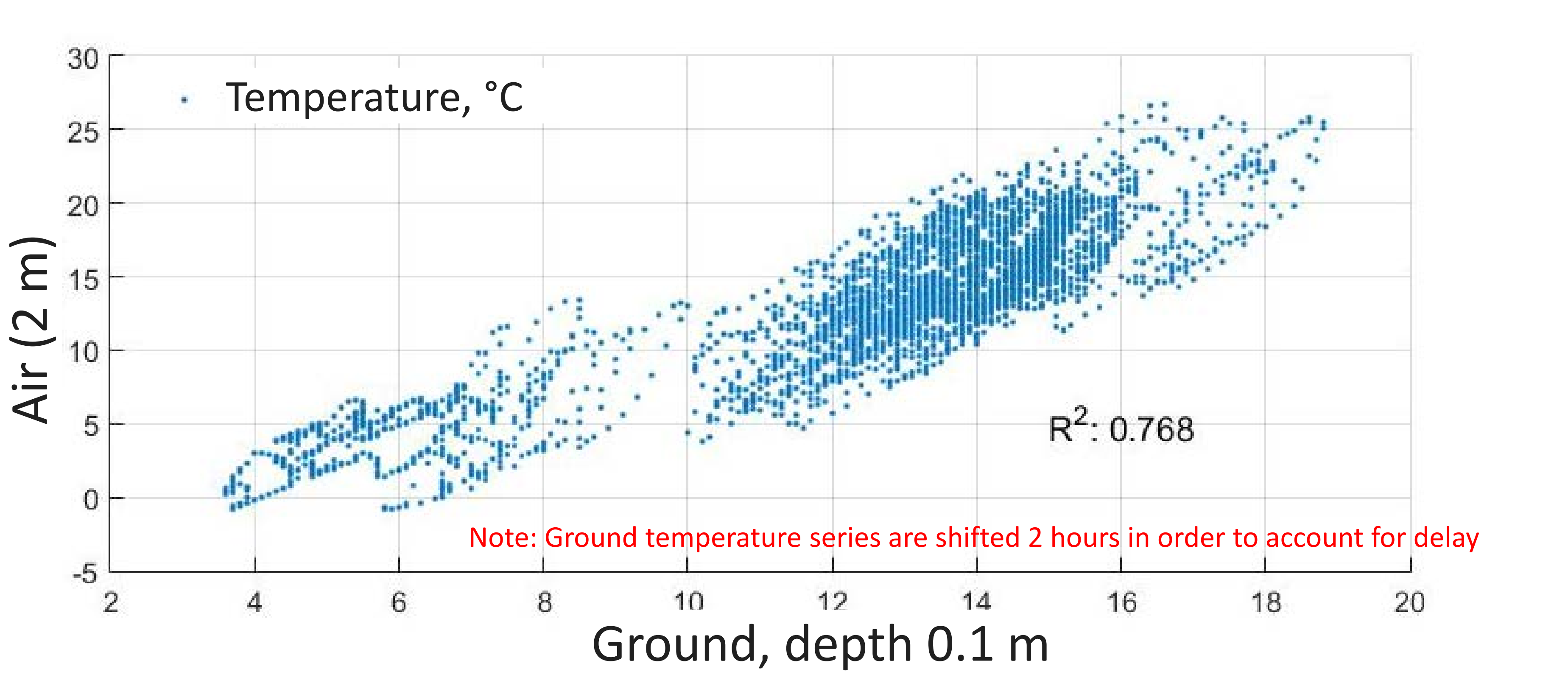
Gridded data from www.senorge.no

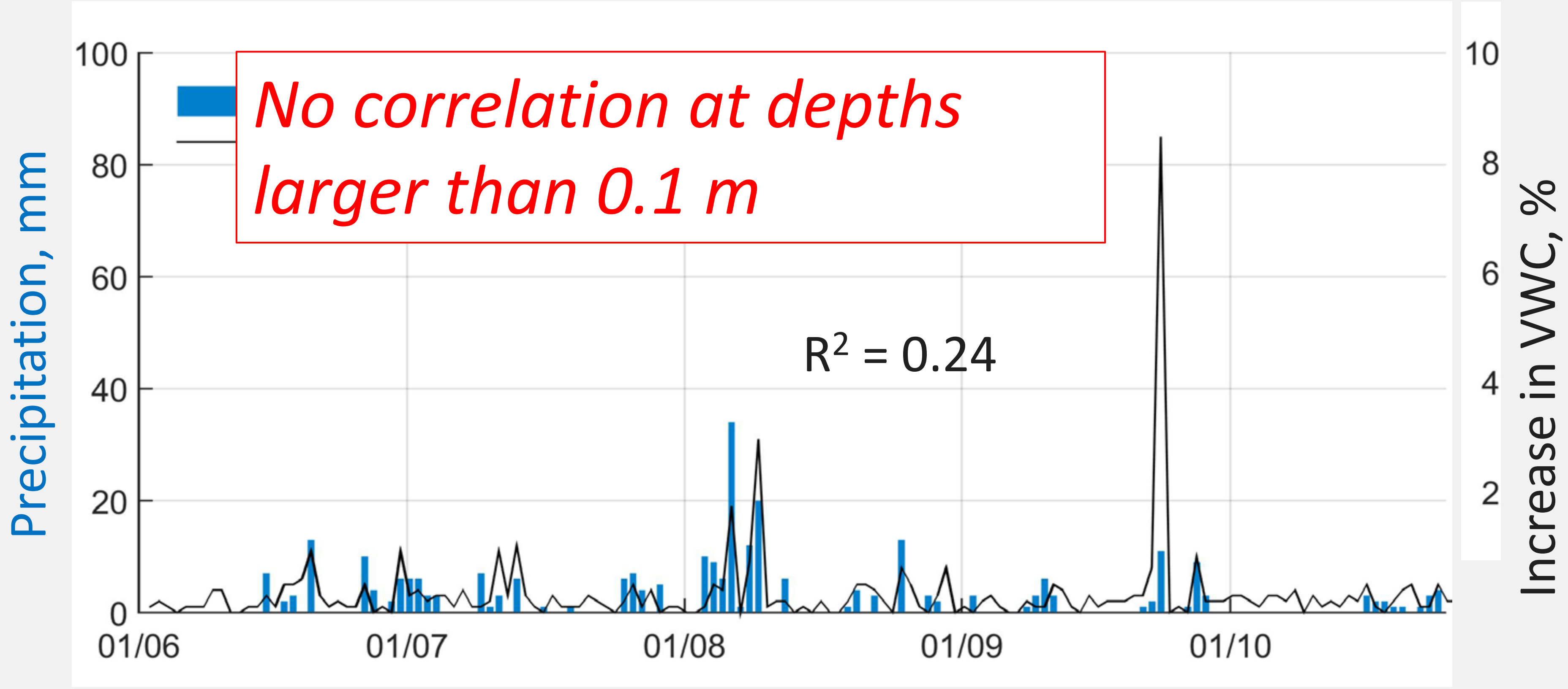
Correlation temperature in air (2 m) and ground (0.1 m)



NGI

Gridded data from www.senorge.no

Correlation between increase in water content and precipitation



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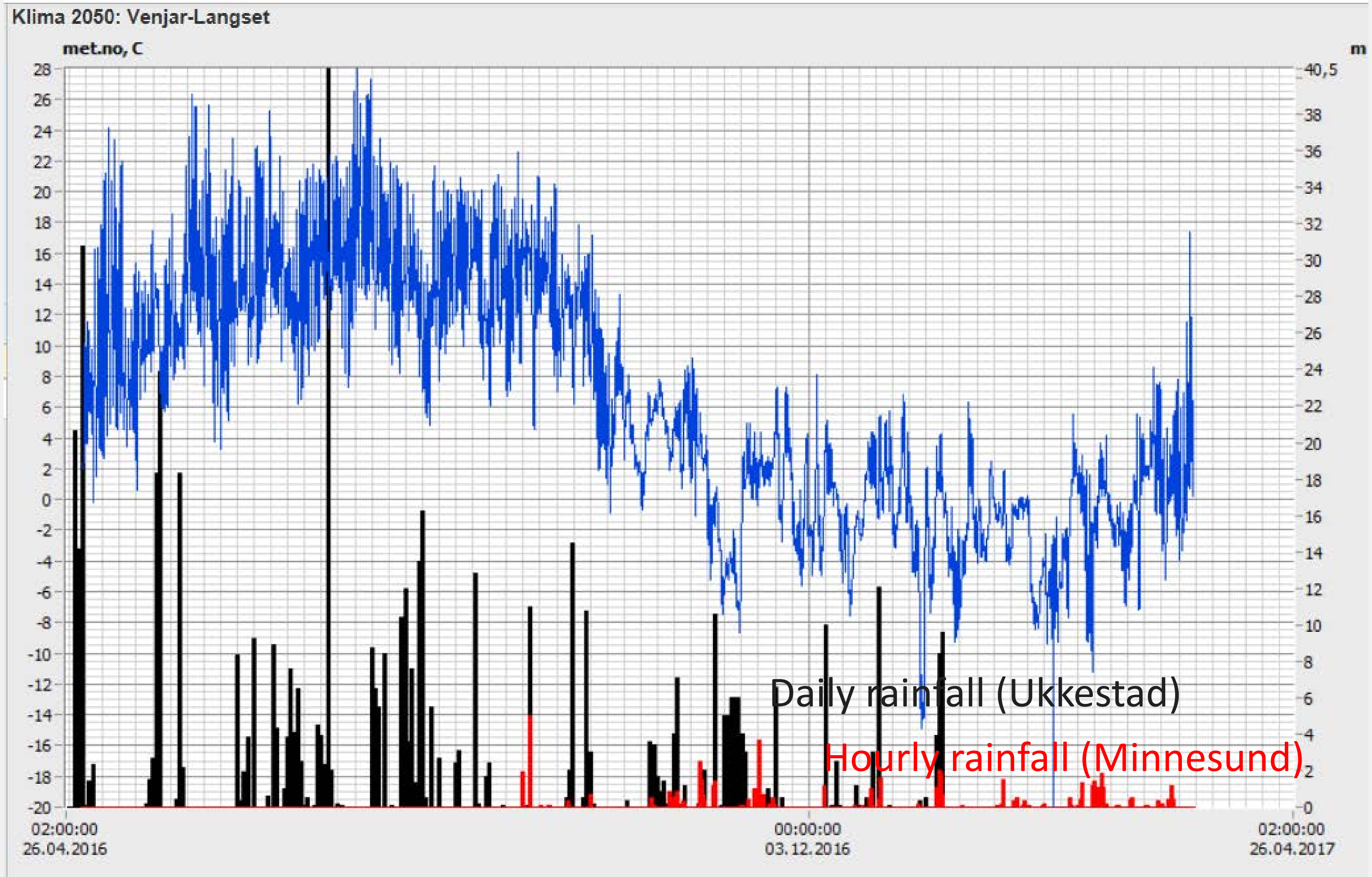
Soil moisture data up to April 2017

? (0.1 m) ? (0.5 m)

Climatic data April 2016-April 2017 (*www.met.no*)



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Ground temperature data up to April 2017

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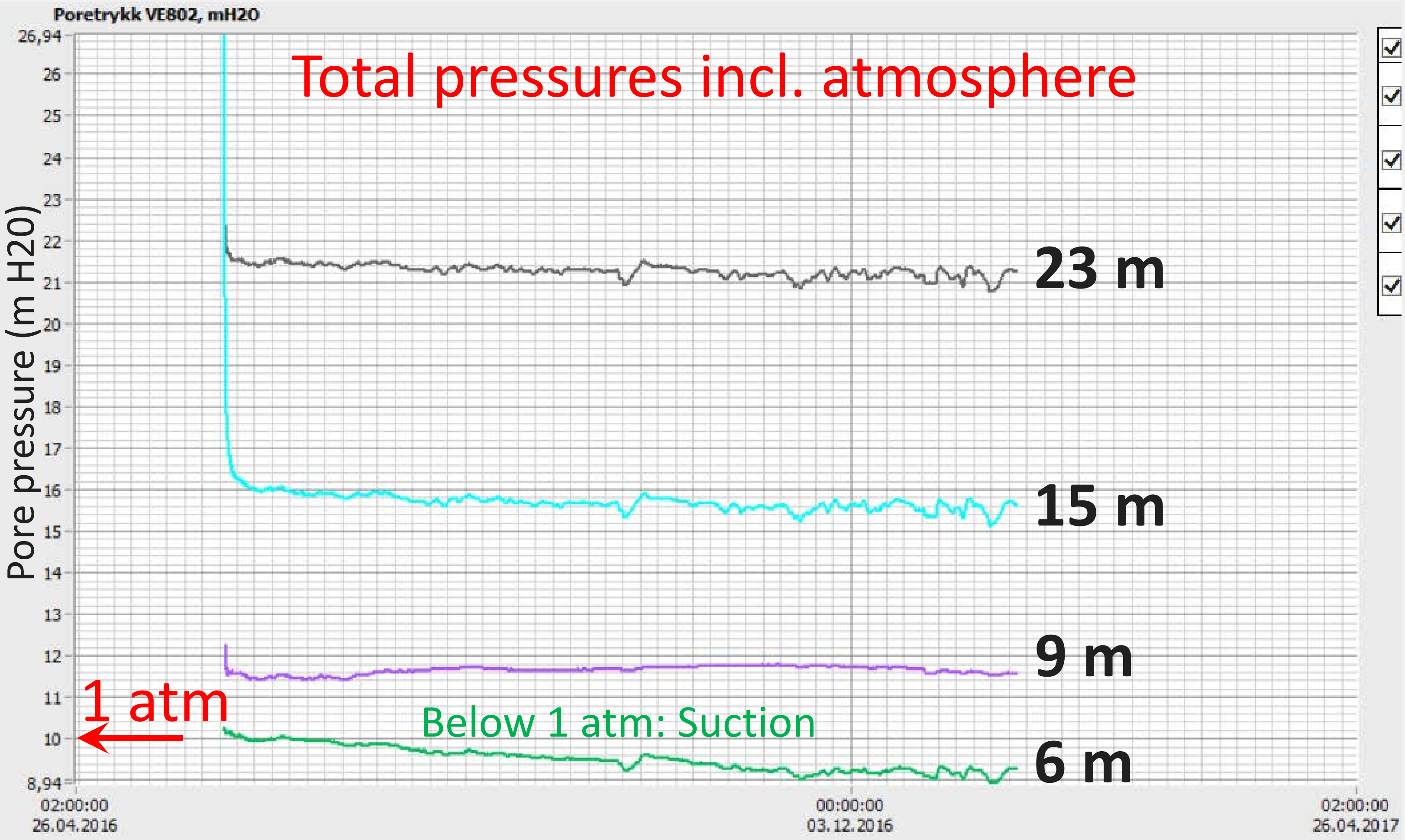

Poretrykk VE802, mH2O
Total pressures incl. atmosphere
Pore pressure (m H20)
26,94
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
8,94
23 m
15 m
9 m
6 m
1 atm
Below 1 atm: Suction
02:00:00
26.04.2016
00:00:00
03.12.2016
02:00:00
26.04.2017

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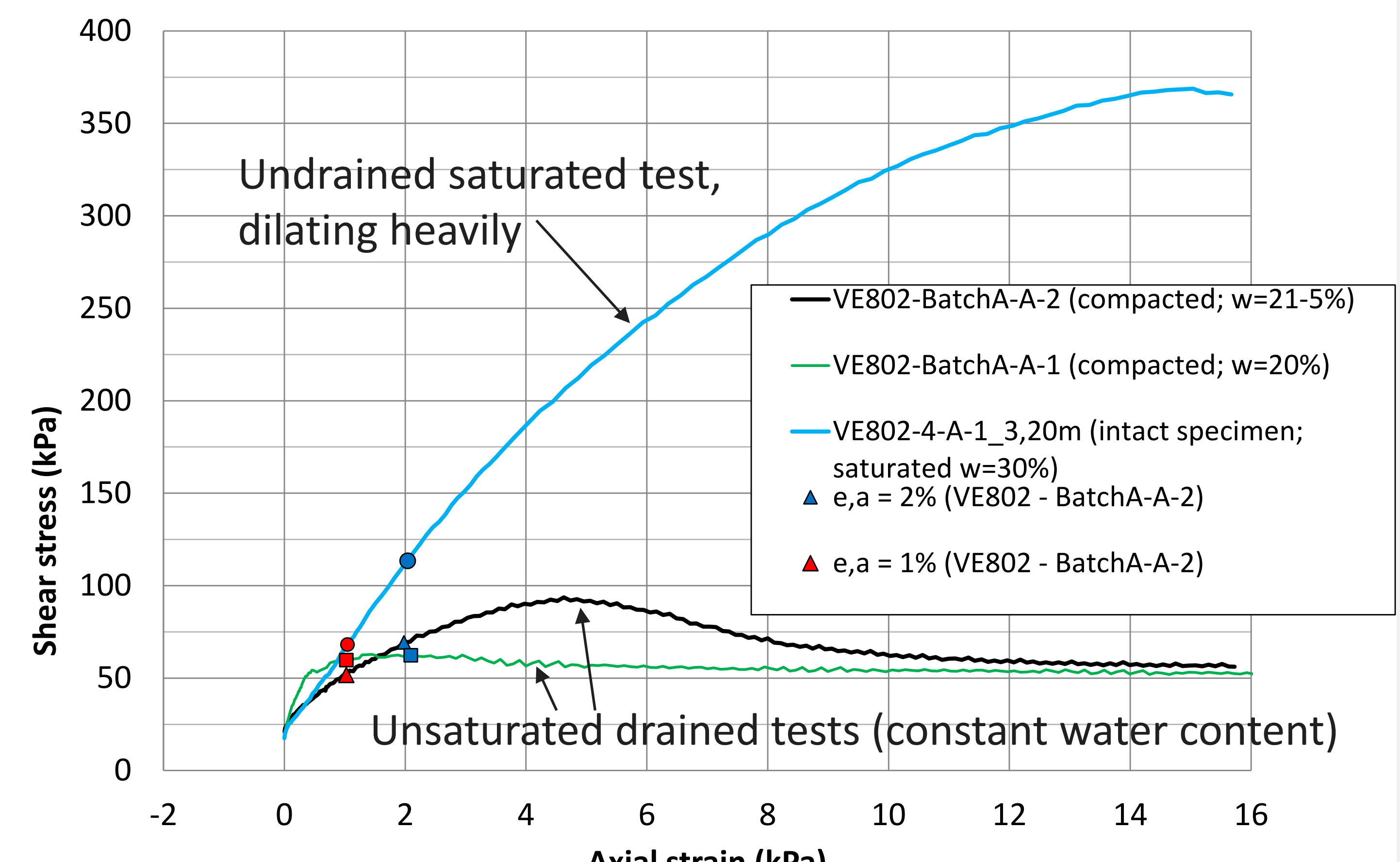
Shear strength – saturated and unsaturated TX



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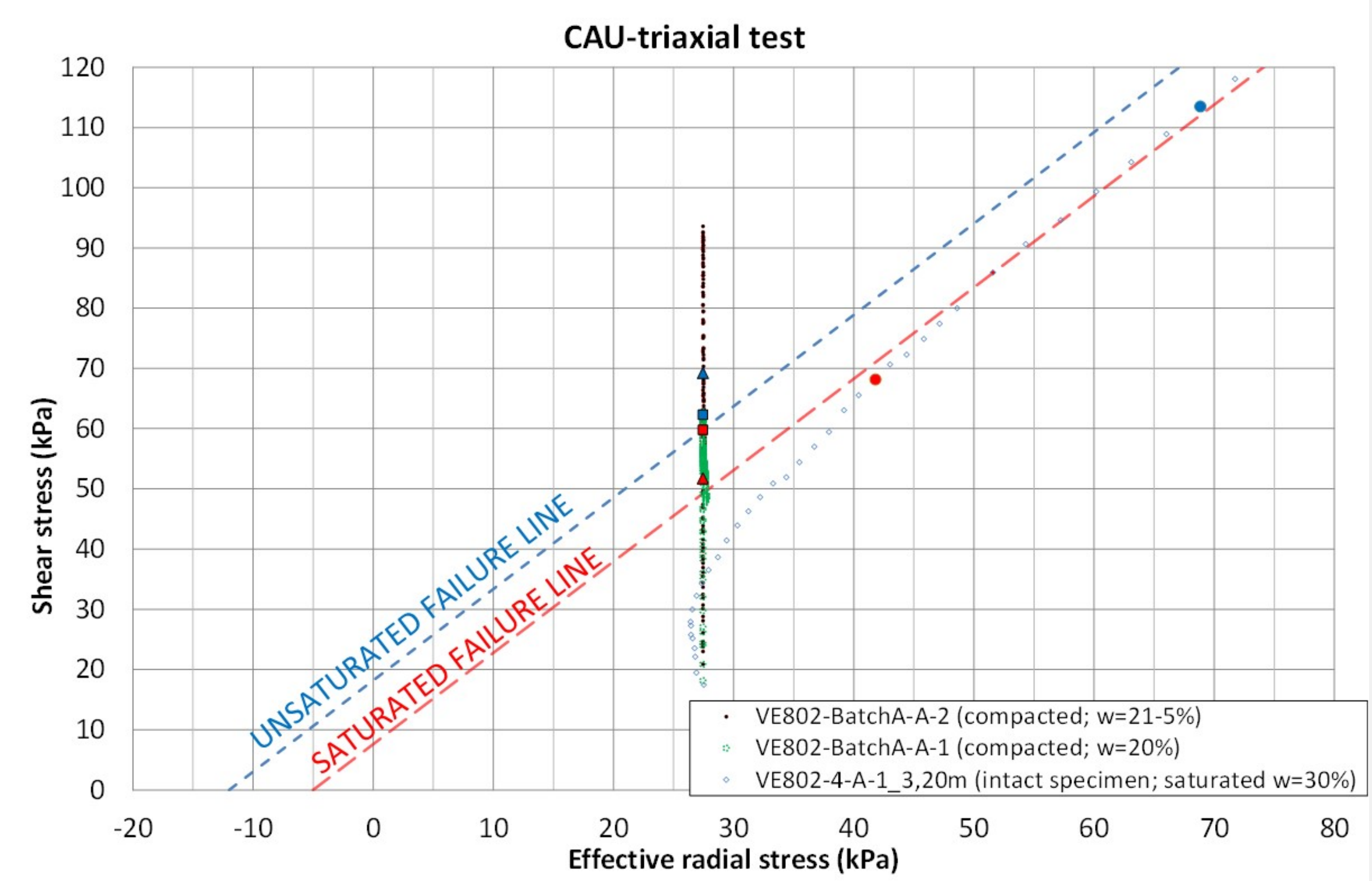
Shear strength from triaxial tests – intact and compacted specimens (saturated and constant water content)



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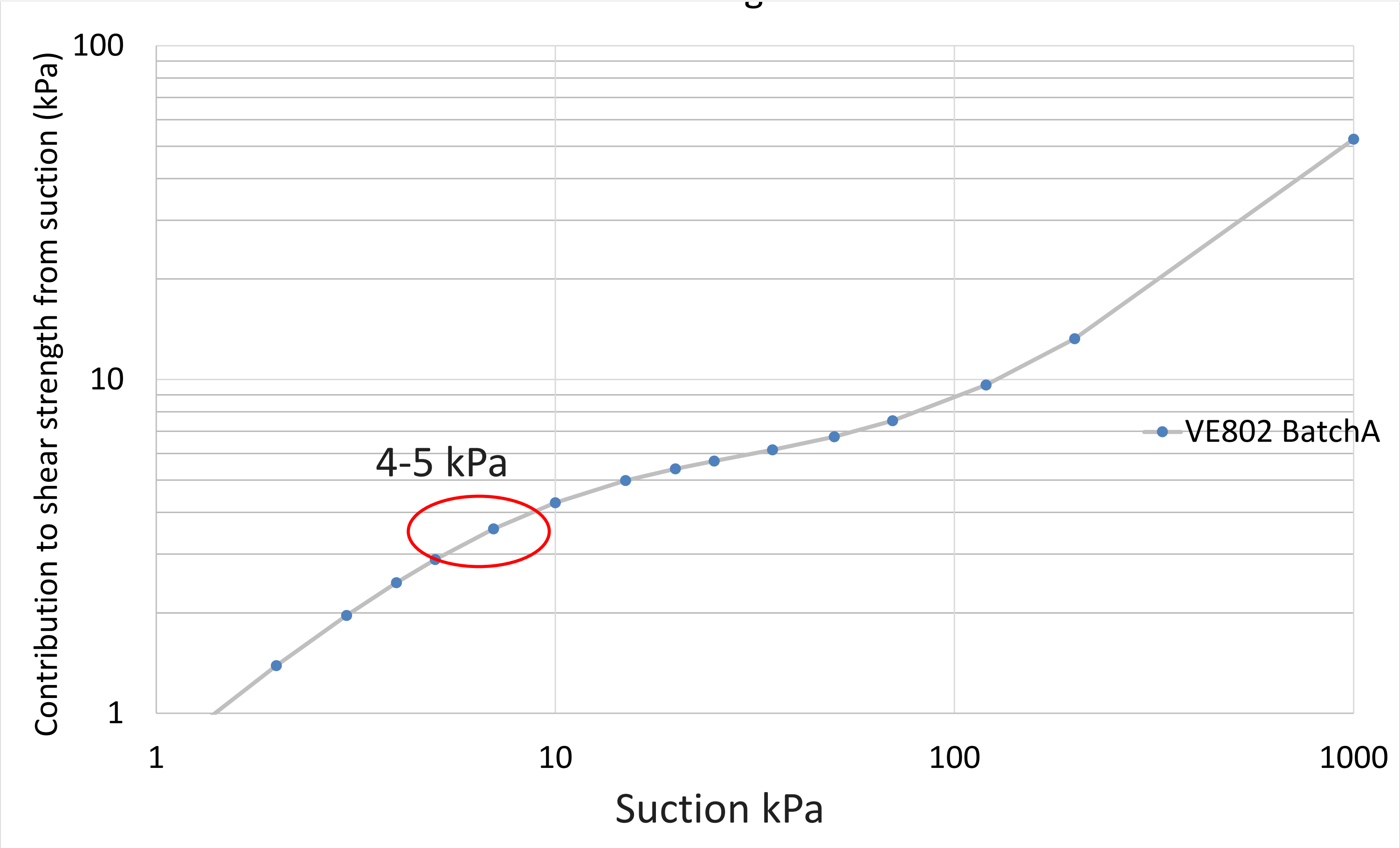
Prediction of unsaturated shear strength

- Prediction model from Vanapalli et al (1996)
- Input parameters:
  - Effective strength paramaters ***c'*** and ***φ'***
  - Normalized water content **Θ** ; exponent **κ** (= 2.5)
  - Soil suction
- Last term in equation assumed to give *suction stress*

$$\tau_{peak} = c' + \tan\phi' \cdot (\sigma_v - u_a) + \Theta^{\kappa} \cdot (u_a - u_w) \cdot \tan\phi'$$

Unsaturated shear strength contribution – predicted minimum effect



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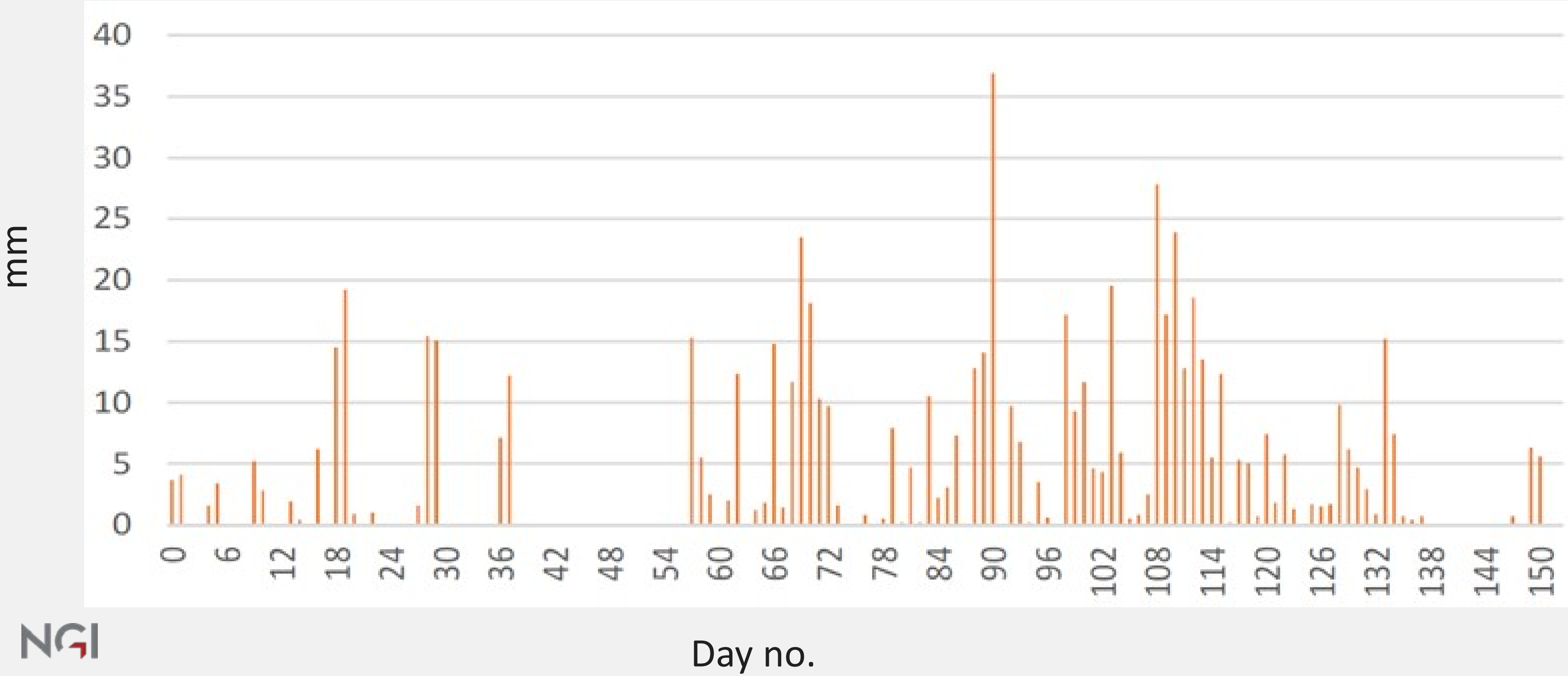
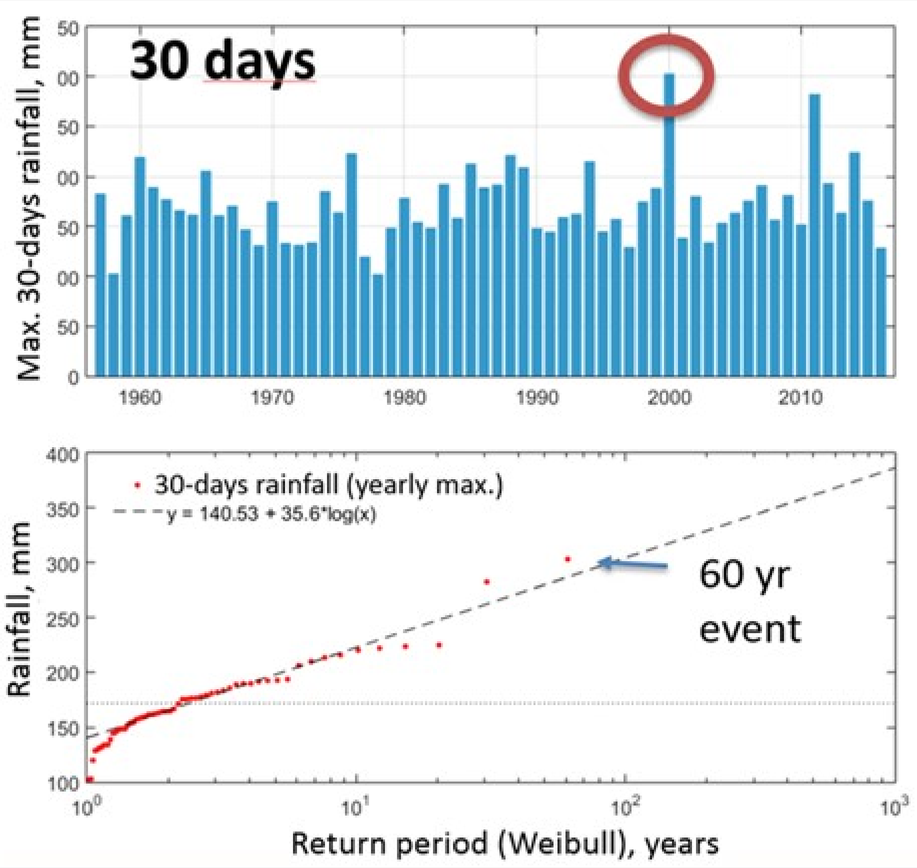
Design rainfall: Daily rainfall, 1 Aug-31 Dec 2000



Return period of rainfall year 2000



Date	mm
27-11-2000	303.1
06-09-2011	282.4
03-11-2014	224.6
13-11-1976	223.5
11-09-1988	221.8
27-07-1960	219.9
12-09-1994	215.6
05-09-1985	213.2
25-08-1989	209.6

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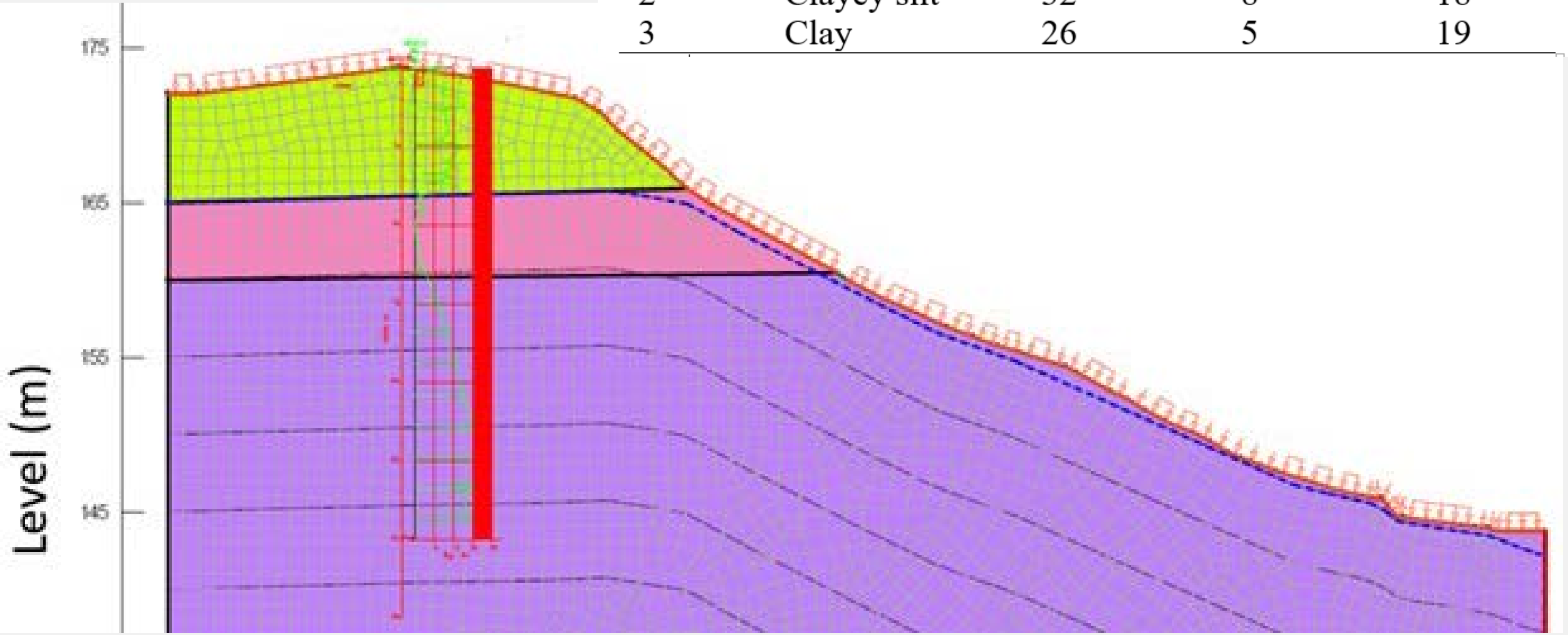
Stability model

Layer	Soil type	ϕ (°)	c' (kPa)	γ_{tot} (kN/m^3)
1	Sandy silt	36	8	18
2	Clayey silt	32	8	18
3	Clay	26	5	19



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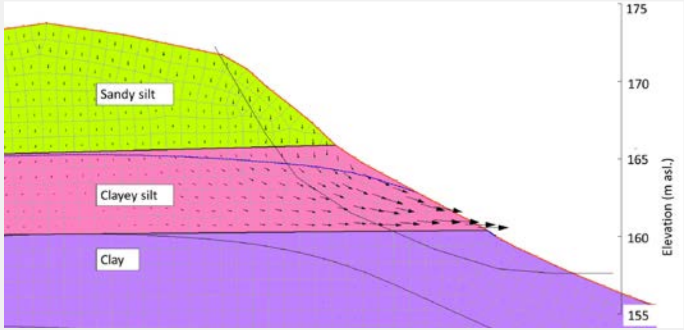
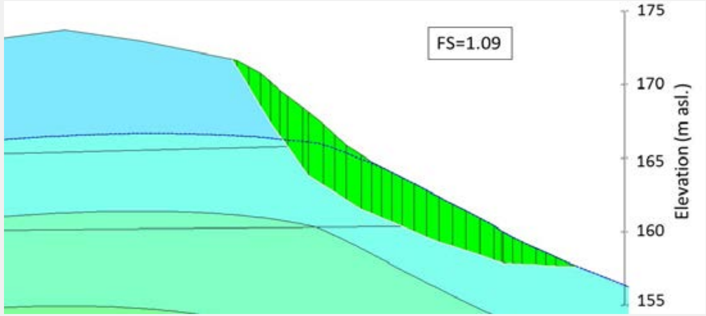
Stability results





Day no.	Safety factor
0 (1 Aug)	1,09
73 (12 Oct)	1,05
115 (24 Nov)	0,96
134 (14 Dec)	0,97

Note: No failure observed in year 2000!

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Conclusions

- Stability of steep natural slopes is not easy to verify
- Evaluation of hydrogeology combined with analyses give increased understanding
- At Eidsvoll, very little change in water content and groundwater during the observation period
- Based on year 2000 rainfall recordss, stability was reduced with ca. 10 %. Bud slope did not fail then.
- Approx. 100 year return period of year 2000 rainfall. Sufficient?
- Protective measures may be built to reduce landslide risk.
- Calibration of hydrogeological model with new data.

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Returning to the task of physical modelling as basis for site specific evaluation of landslide risk

- What data is needed for reliable evaluation of landslide hazard?
  - Soil layering
  - Water retention properties (drying / wetting)
  - Permeability as function of suction/water content
  - «Design rainfall / infiltration»
  - Soil strength (saturated / unsaturated)
  - Seasonal fluctuations in ground water

    -> Field measurements above and below ground-water level

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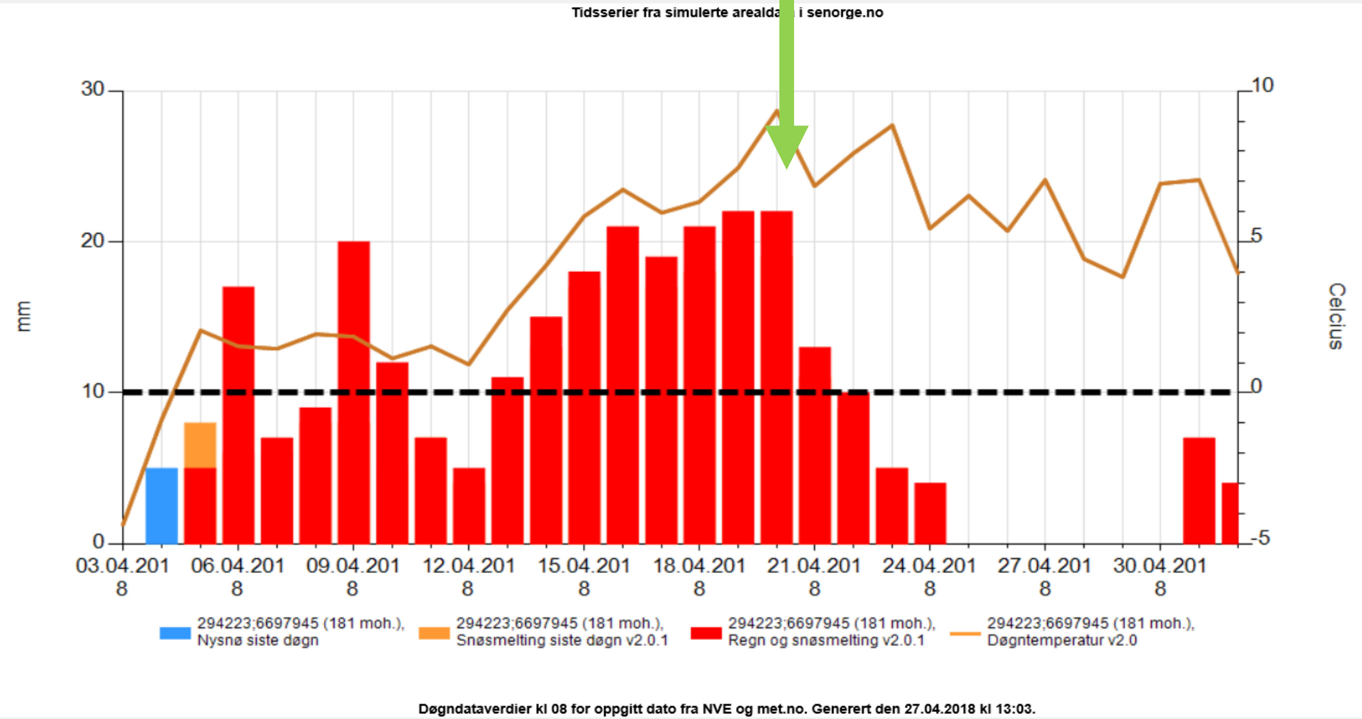
Were we conservative enough?

- Snowmelt in April 2018
- Equivalent to 250 mm rain!

Farm at Eidsvoll:
4 landslides in 4 days



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Sander, Eidsvoll

Thank you for your attention

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