Effect of blasting on slopes with quick clay – overview of ongoing activities

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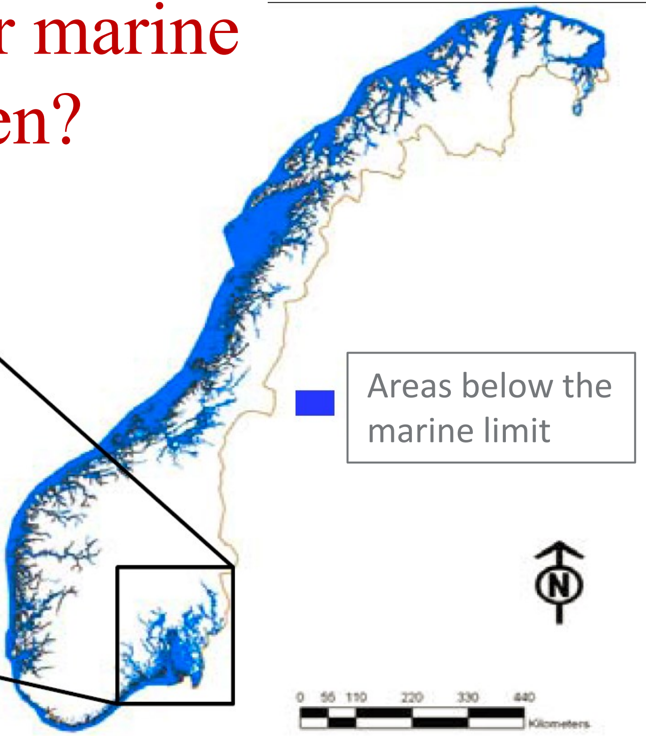
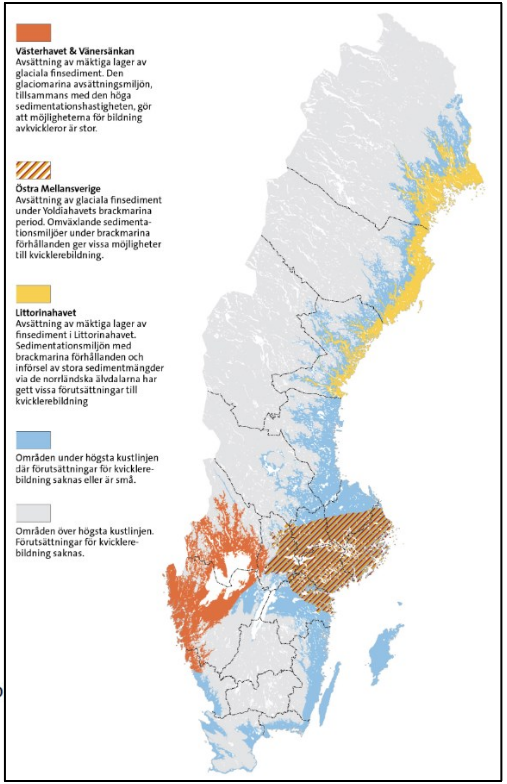
Where do we encounter marine clays in Norway/Sweden?

Most of Norway lies <u>above</u> marine limit, but densely populated areas / major cities in Eastern/ Central Norway mainly <u>below</u> the marine limit



www.grunnvannino

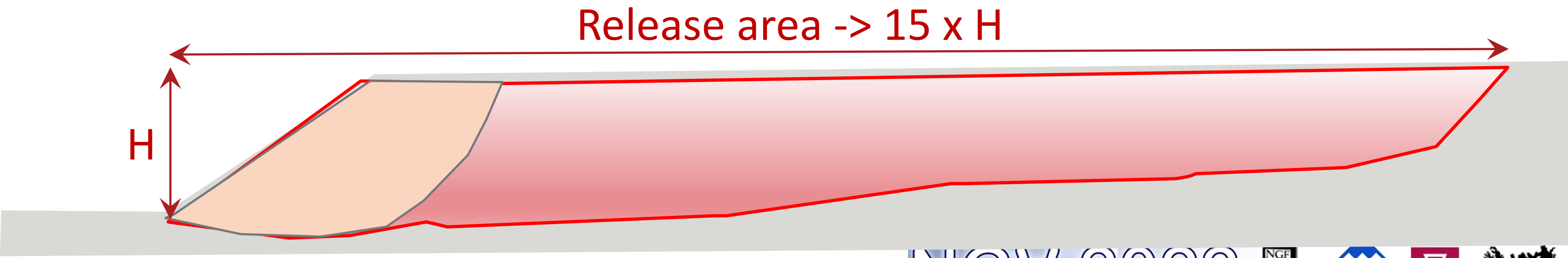


Quick clay landslides in Norway

- 1-2 large quick clay landslides per year
  - > 50.000 m3
- 1 or 2 slides per decade (Last 40 year)
  - > volume 500 000 m3 (Thakur et al. 2014)
- Mostly triggered by human activity
  - Poorly designed mass deposits
  - Accidents (e.g. blasting)
  - Poor geotechnical design
- Also triggered by natural triggers:
  - Erosion in ravines
  - High pore-water pressure
- Landslide volumes up to millions of cubic metres
- High Costs (in millions USD, MUSD)
  - Gjerdrum 2012 (10),
  - Statland 2013 (a few) ,
  - Skjeggestad brigde 2014 (several MUSD),
  - Nittedal (several 10ths MUSD)
  - Gerdrum 2020 (100 MUSD)

«The quick clay problem» - 1

- Small disturbances may initiate large landslides
  - Example soon…
- Landslide release up to 15 x slope height used in mapping;
  - may be more
- Runout can move quick and very far
  - Poses a major threat to downslope areas
- Large areas exposed to risk



Landslide catalogue blasting possible triggering agent

Location:C=Canada, N=Norway, S=Sweden	Year	Consequences	Reference
La Baie (C)	1910	6 casualties	Dion (1986)
Hawkesbury (C)	1955	Damages to the road in construction	Eden (1956)
Toulnustouc (C)	1962	9 casualties [1]	Conlon (1966), Evans (2001)
Sandnessjøen (N)	1967	-	Karlsrud (1979)
Fröland (S)	1973	-	Bjurström (1982)
Finneidfjord (N)	1978	Damages to road	L'Heureux et al. (2010)
Port-Saguenay (C)	~1990	None (preventive evacuation)	Bouchard (2015)
Finneidfjord (N)	1996	4 casualties, 3 houses destroyed	Longva et al. (2003)
Ytterby (N)	~1991	Road damage and closure-	Oset (2015)-
Finneidfjord (N)	2006	Damages to road	L'Heureux et al. (2010)
Kattmarka (N)	2009	Highway, permanent dwellings and 6 summer residences.	NTNU (2009)
La Romaine (C)	2009	Damages to road in construction	Locat et al. (2010), Bouchard et al. (2015)
Lödöse (S)	2011	-	Johansson et al. (2013)
Steinvika, Tana, (N)	2021	Damages to existing road.	-News articles/Social media

Modified after Bouchard et. al (2018)

Quick clay slides blasting possible triggering agent

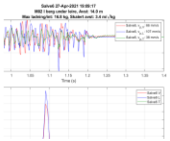
- Landslides have occurred in sensitive clays during or shortly after blasting works (with or without loose silt or sand layers);
- Many of the failures studied were subjected to other aggravating factors (intense rainfall before the event, fill at the top of the slope, bad condition in the blasted rock, and erosion at the toe of the slope), making it difficult to identify the effect of the vibrations alone;
- Some slides happened few to several hours after the blasting operations and could be explained by pore pressure redistribution (Ytterby, Finneidfjord, Lödöse?);
- Blasting vibrations may have led to local failure in the soils near the blasting that could have propagated along bedding planes and also because of the strain-softening behaviour of sensitive clay. Progressive failure may be an explanation for few cases (Toulnustouc, Hawkesbury and La Romaine);
- From the Norwegian experience, it appears that it is not possible to apply a single PPV criterion to clay slope subjected to blasting. It seems to depend on many natural conditions, the frequency content, site effects and other aggravating factors. In particular, if the slope already have low stability, even a small blast may be sufficient to trigger a slide (?).

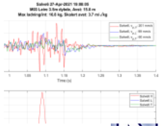

MP02
MP01
MA01
M01
MA02
M03
MA04
MA03
M04
MP04
MP05

Installation of geophones

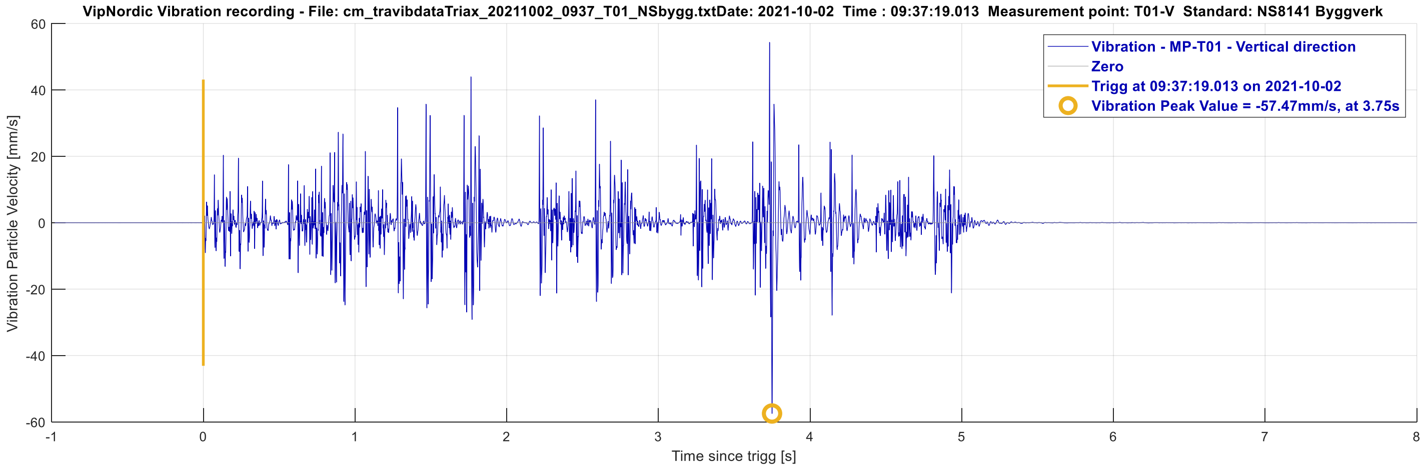
Vibrations blast 6

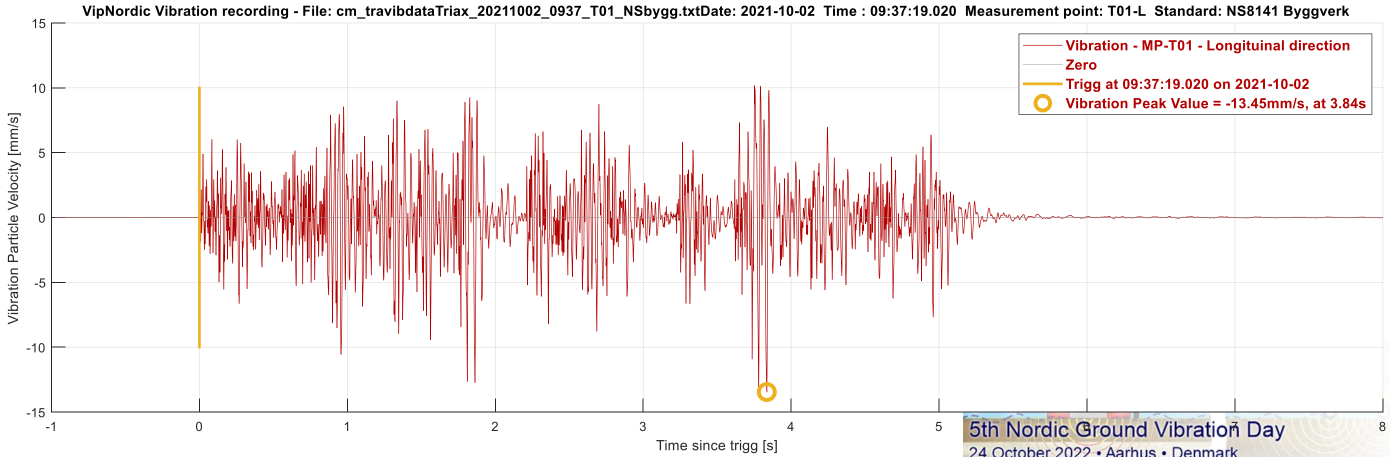
- Rock about 50 mm/s, 1 pulse 100 mm/s
- Soil 3.5 depth several cycles above 100 m/s, max 200 mm/s
- Frequency ~75Hz (some connection to the time delay of 14 ms between charges). Still under investigation





Vibrations tunnel blast

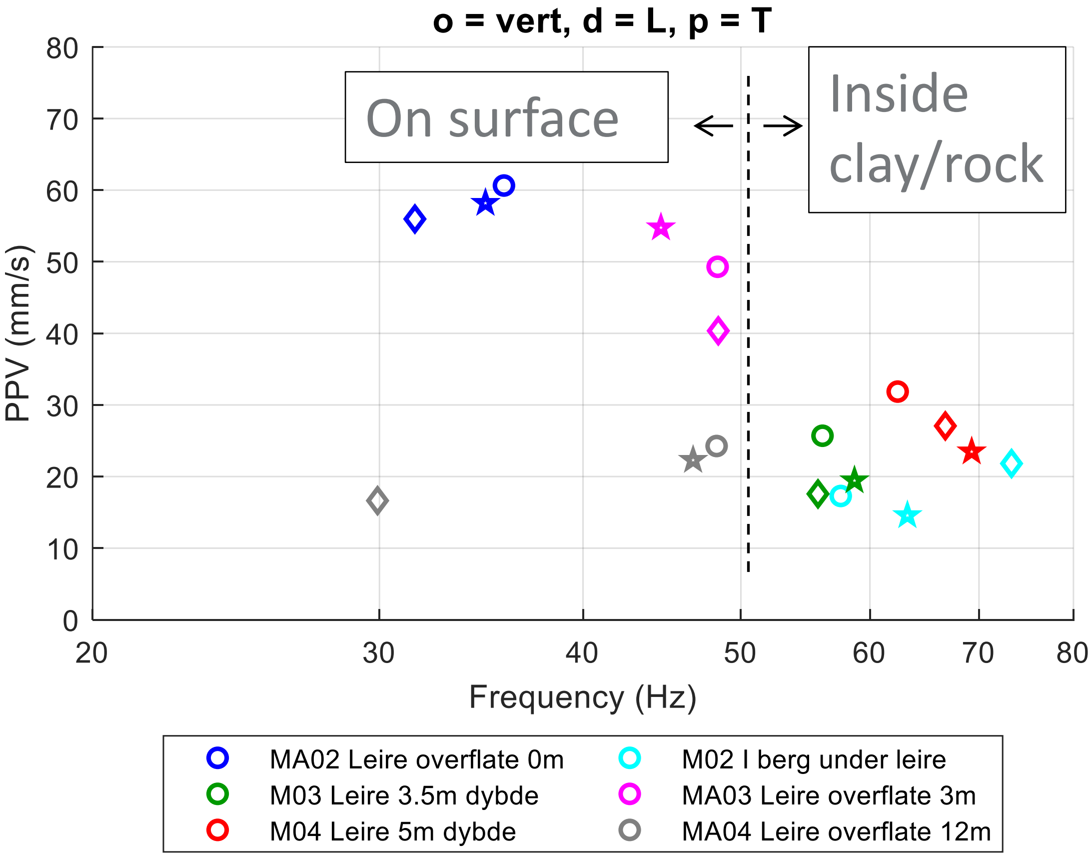




Measuring vibrations

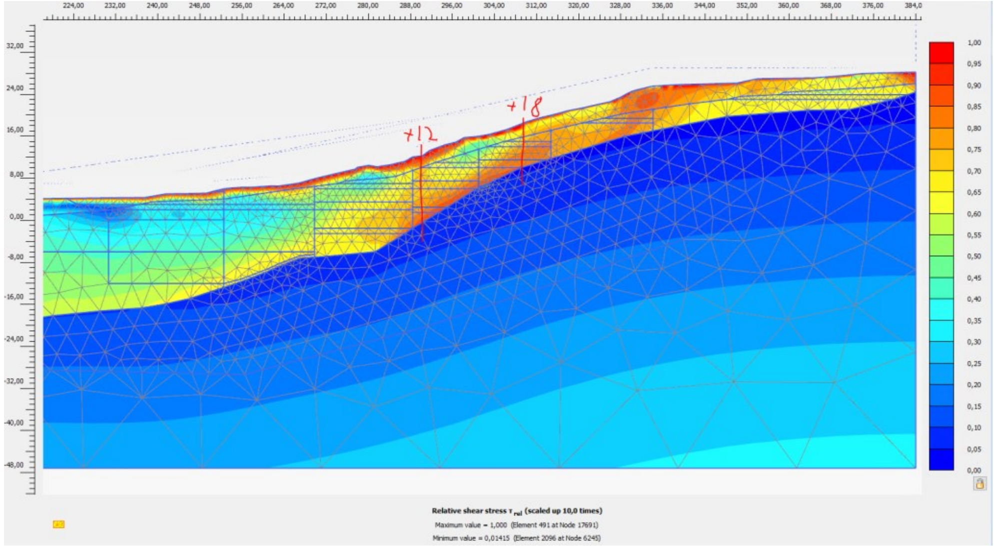
ok?

Not ok



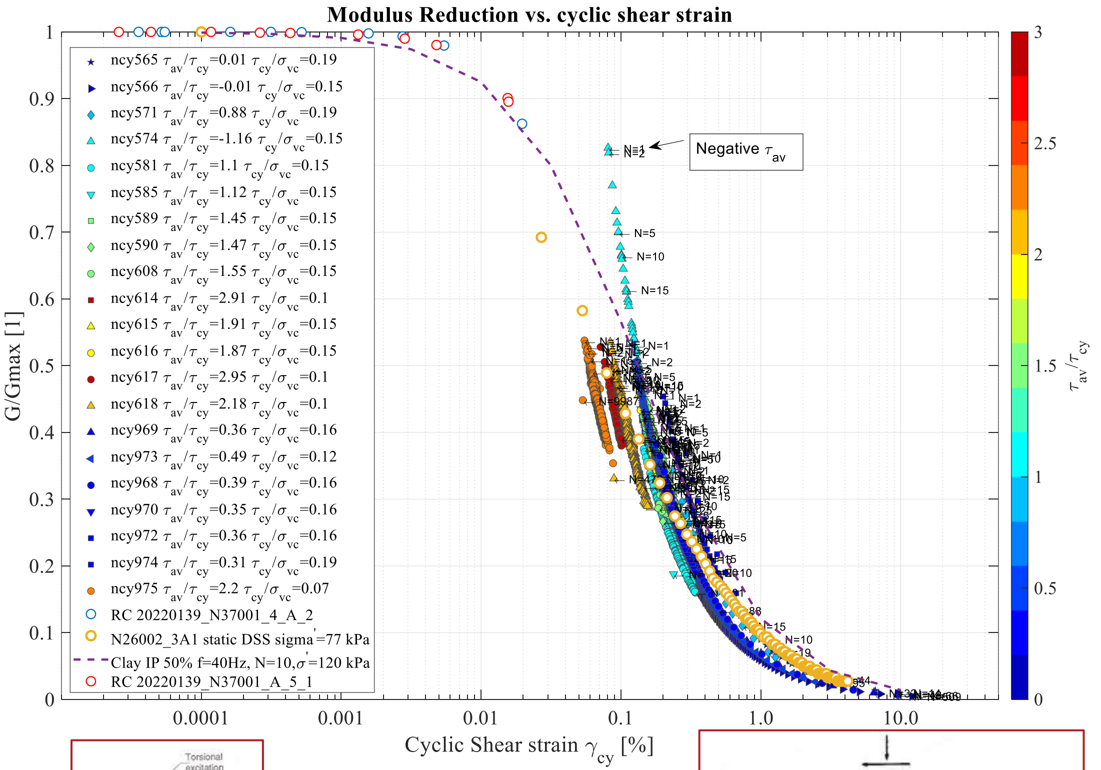
Vibration limits for marginally stable slopes?

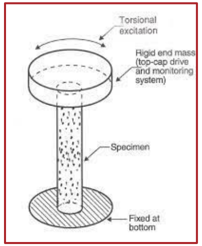
- Computed stress mobilisation is, difficult to apply earlier developed methodology
- Treshold strain (e.g. ISO 14837)
- Connect threshold strain to vibration limit



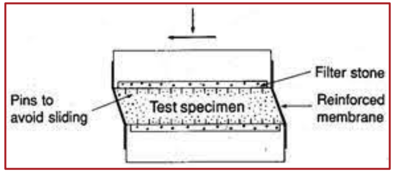
Material properties

- Understanding parameters important for cyclic strength
- Accounting for static shear stress in the slope
- Very small to large shear strains
- Evaluating pore pressure response in RC and DSS give similar results

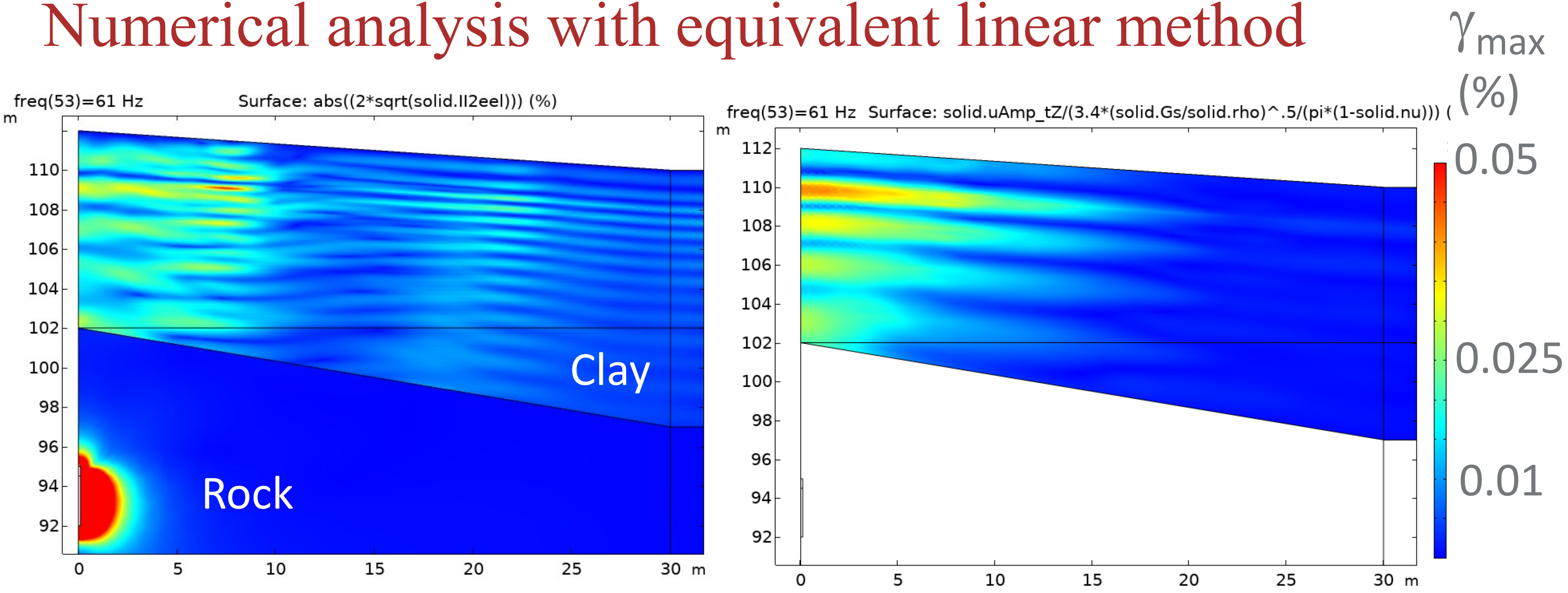




$$\gamma = \tau / G$$



Numerical analysis with equivalent linear method



$$shear\ strain = \frac{vibration\ velocity}{shear\ wave\ speed\ or\ "Lysmer"\ speed}$$

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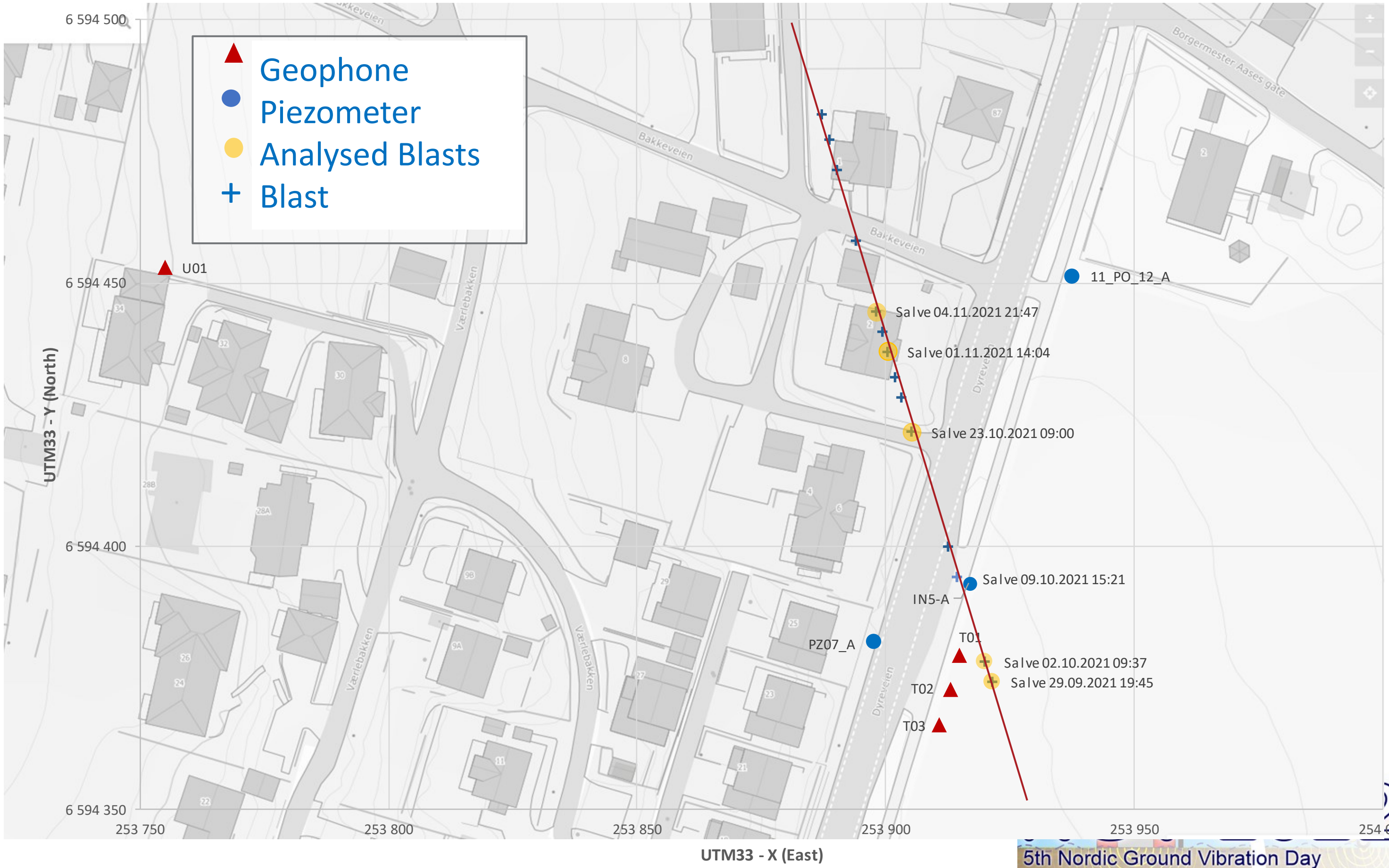
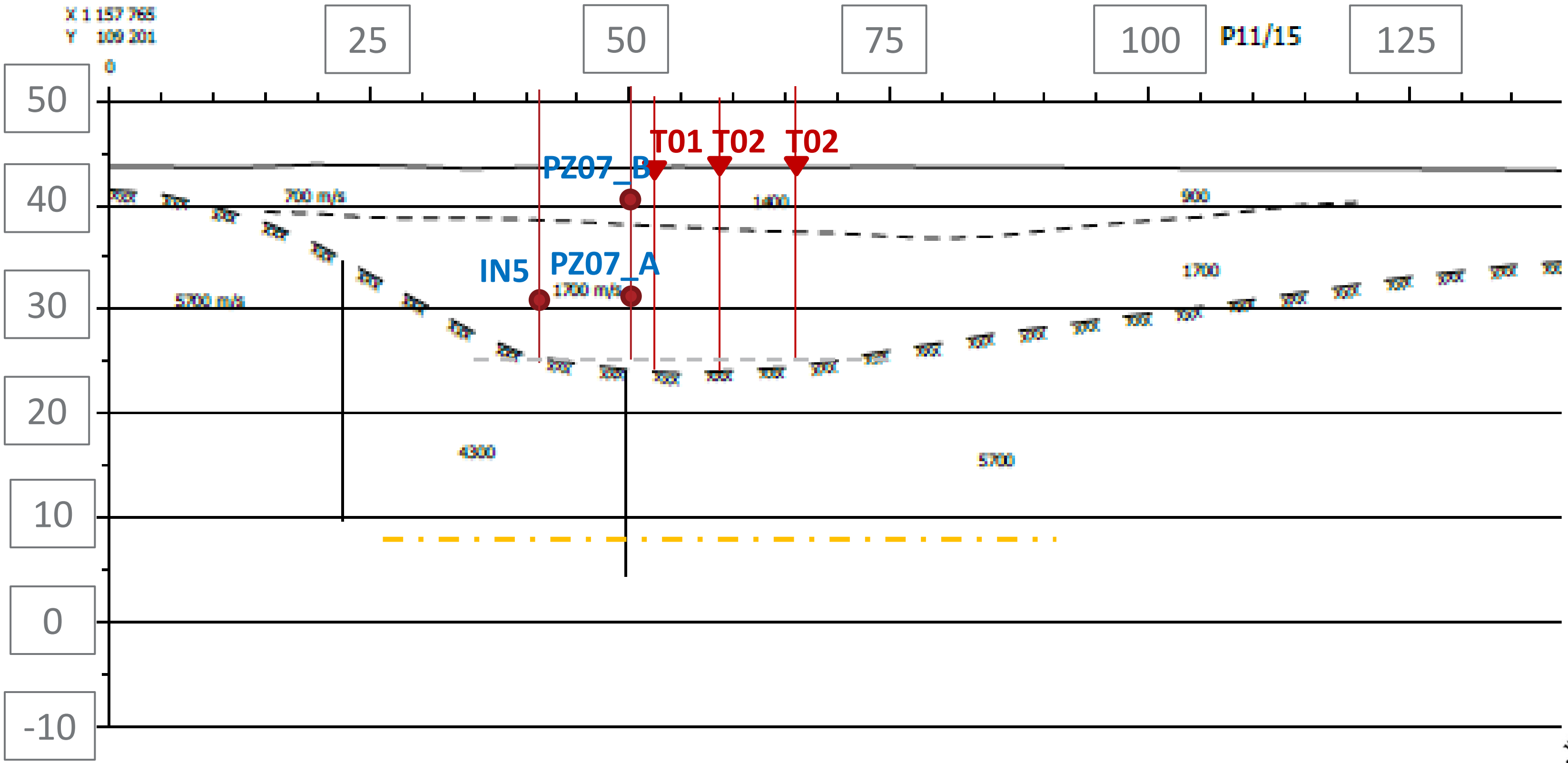
Overview

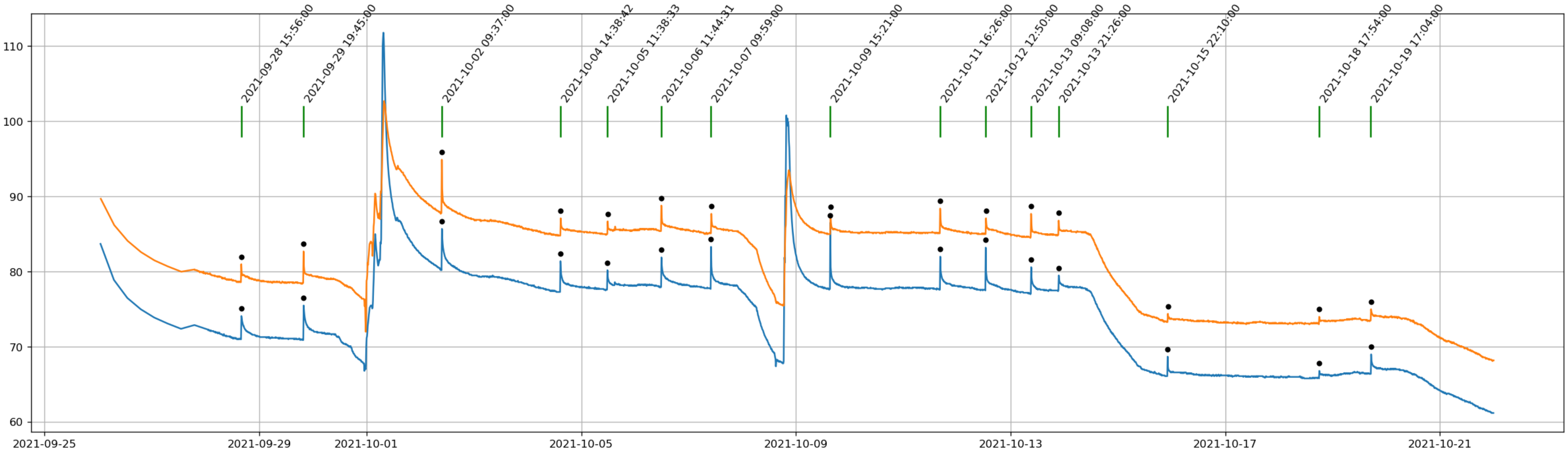


Geophone
Piezometer
Analysed Blasts
Blast
U01
11_PO_12_A
Salve 04.11.2021 21:47
Salve 01.11.2021 14:04
Salve 23.10.2021 09:00
Salve 09.10.2021 15:21
IN5-A
PZ07_A
T01
Salve 02.10.2021 09:37
Salve 29.09.2021 19:45
T02
T03
6 594 500
6 594 450
6 594 400
6 594 350
253 750
253 800
253 850
253 900
253 950
UTM33 - Y (North)
UTM33 - X (East)
Bakkeveien
Værlebakken
Dyreveien
Borgermester Aases gate

Seismic profile with locations of sensors



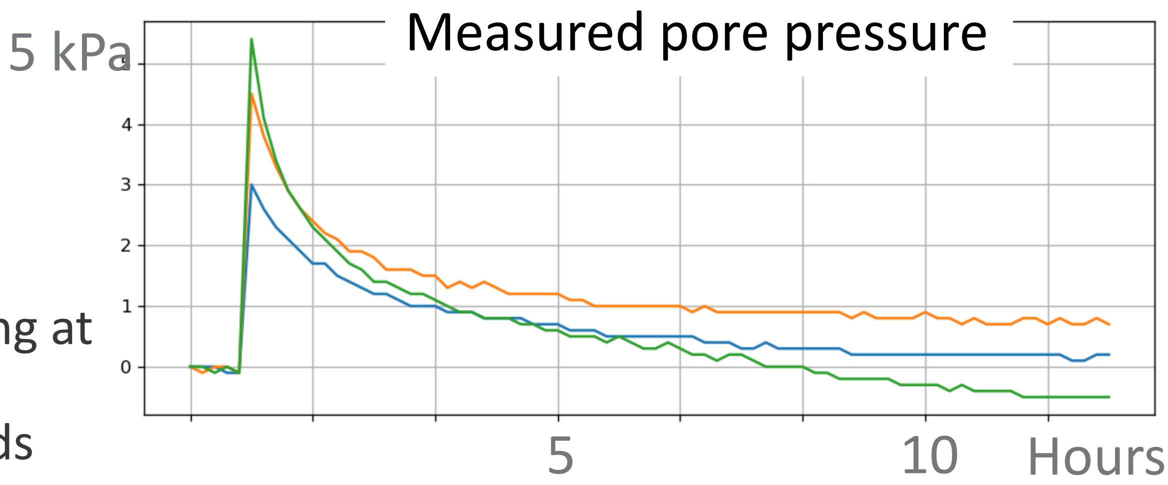
Measured pore pressures in clay in connection with tunnel works

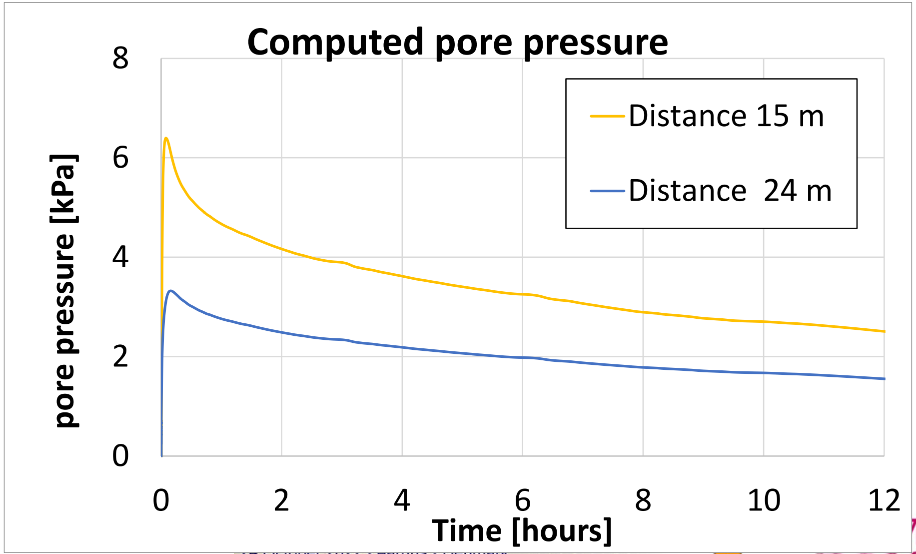


- Large increase due to grout injection!
- Moderate increase due to blasts, but measured at distance from

Pore pressures in quick clay above tunnel

- «Rise time» of pore pressure faster than sampling time -> generated by vibrations arriving at pore pressure sensor
- Arrival times show some trends which could indicate pore pressure generated in clay above rock and propagating to pore pressure sensor
- Need very large hydralic condcutivity in clay to explain the fast dissipation time. On the order of $1x10^{-3}$ m/s, i.e. something more permeable than sand…





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Conclusions/future work

- Safe vibraton limit based on threshold strain
  - Will be to conservative in many cases and putting not necessery restrictions on construction work progress
  - Vibration limit in NS 8141:3 valid for relatively stable slopes (>factor of safety 1.4 ?)
- Vibration limit accounting for site specific conditions will allow better understanding of risks
- Proper monitoring of vibrations and pore pressure
- How much pore pressure increase can we tolerate?
  - Design rules: «no worsening of stability»
- Static stresses in slopes difficult to evaluate, but will affect blast response
- Mechanism for pore pressure generation, propagation (?), dissipation in the field not understood

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Quick clay with thin silt layers

1-2cm clay layers? Silt, fine sand 1-3 mm?
Photo: Harald Sveian, NGU

Remoulded quick clay

”Liquid” quick clay
Video: NPRA

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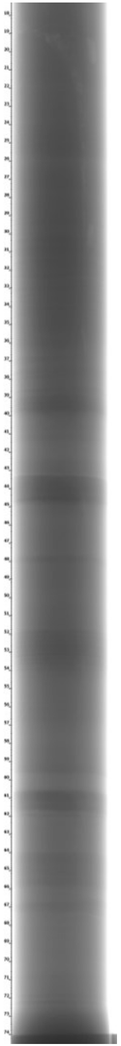
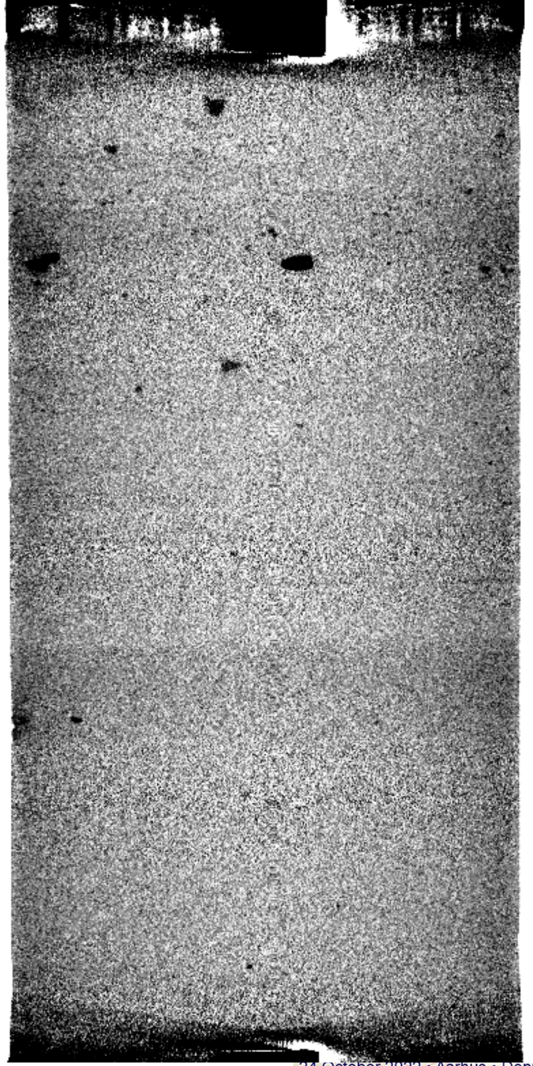
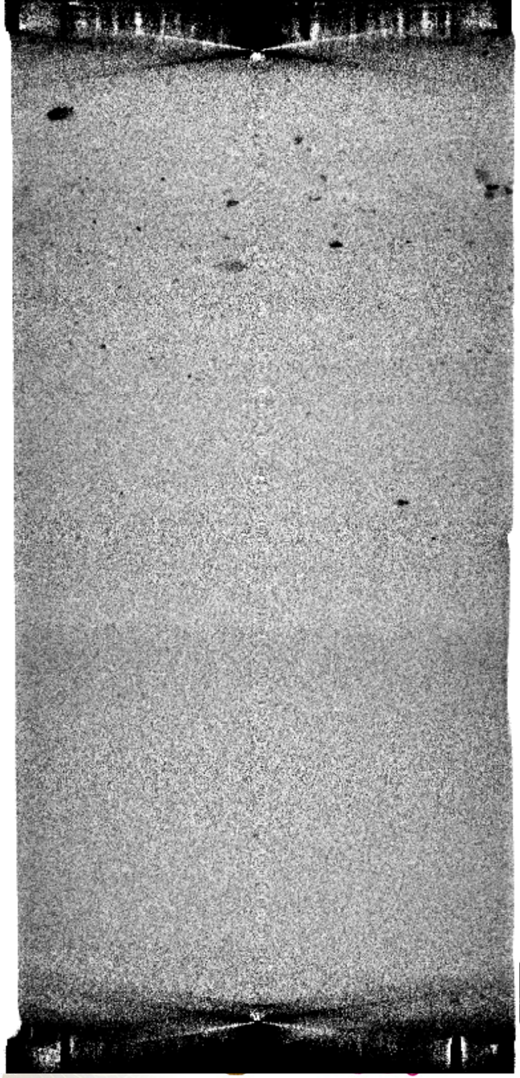
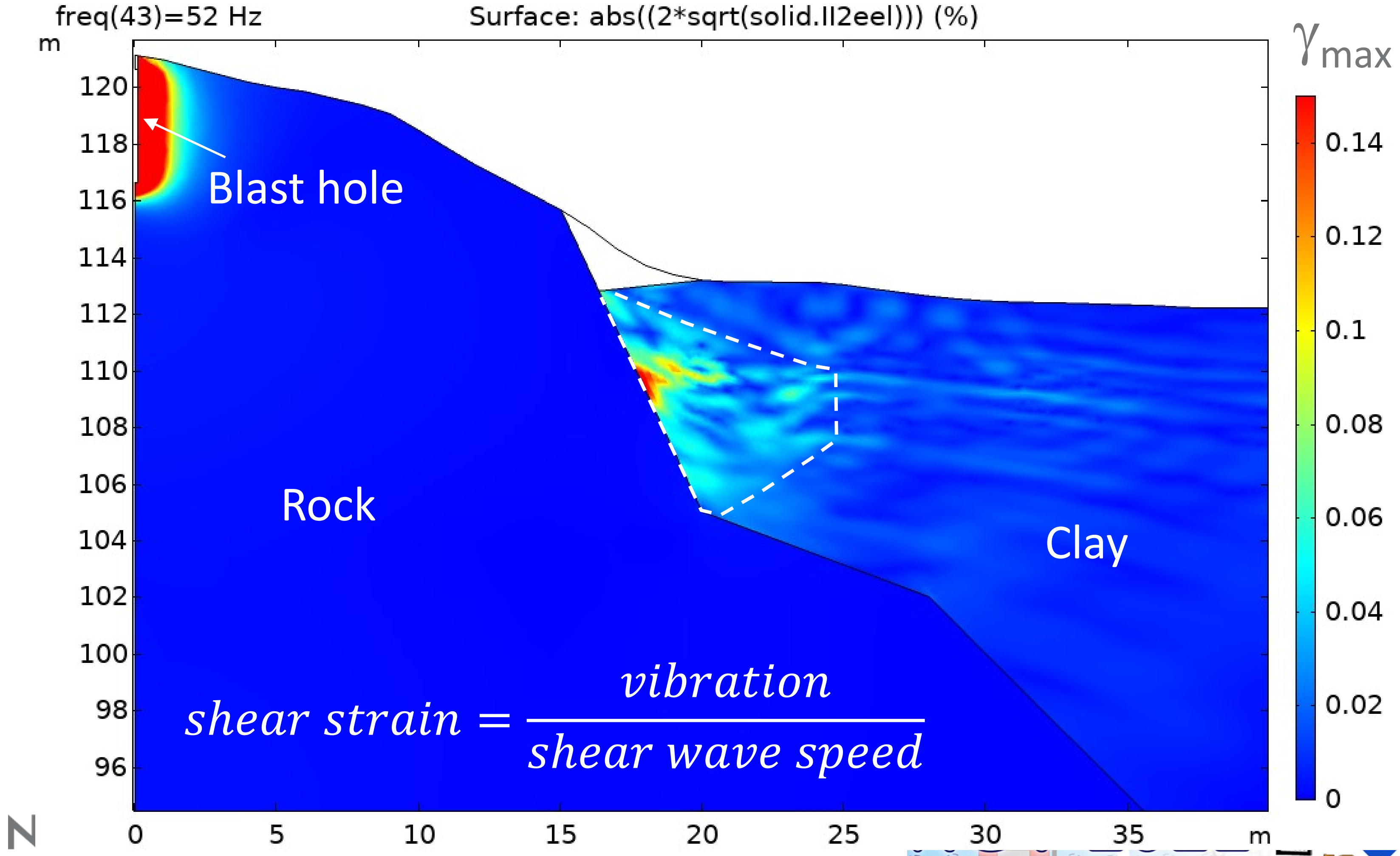
X-ray









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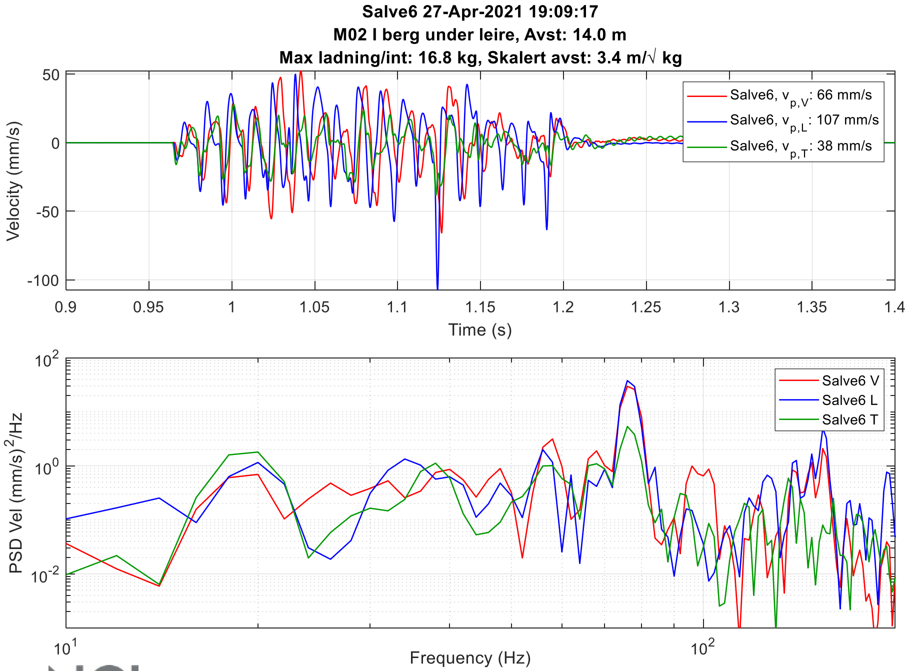
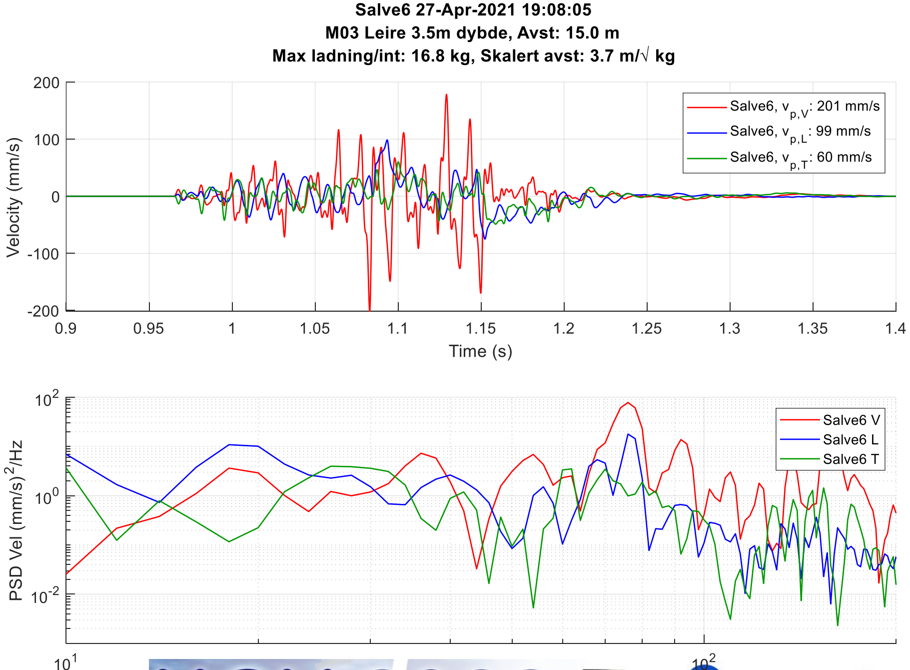
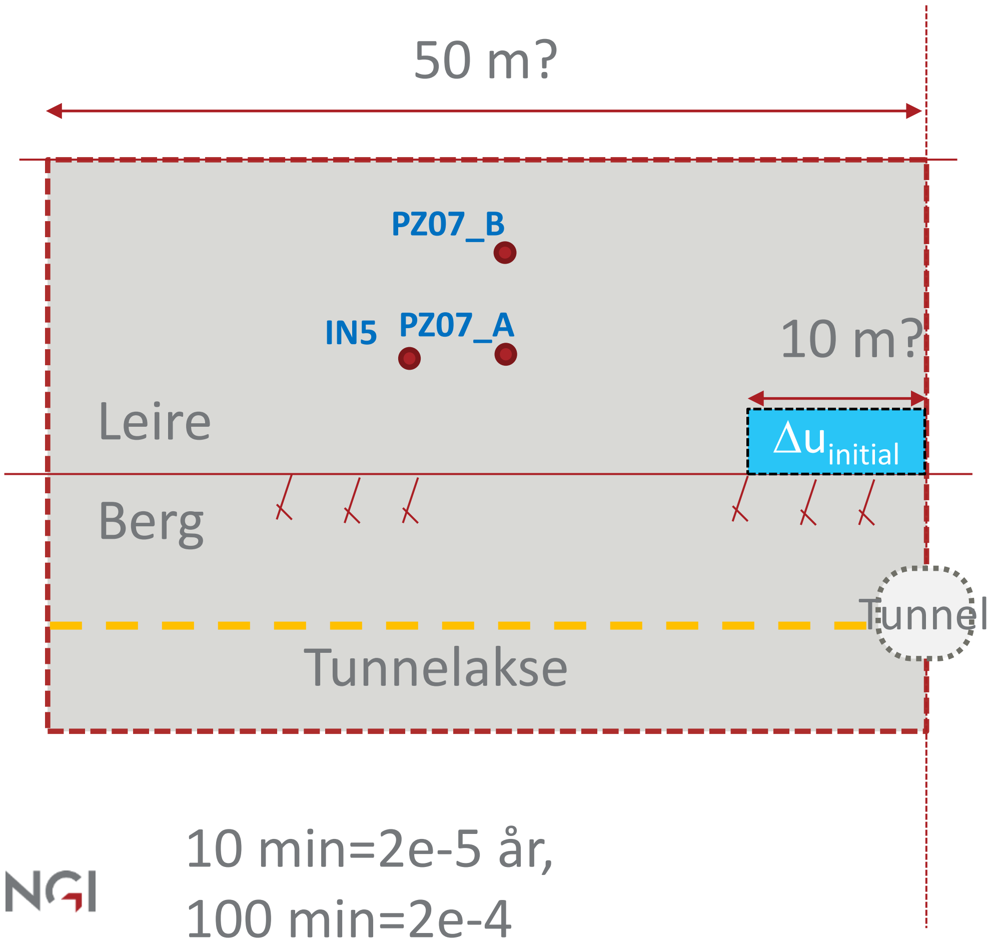




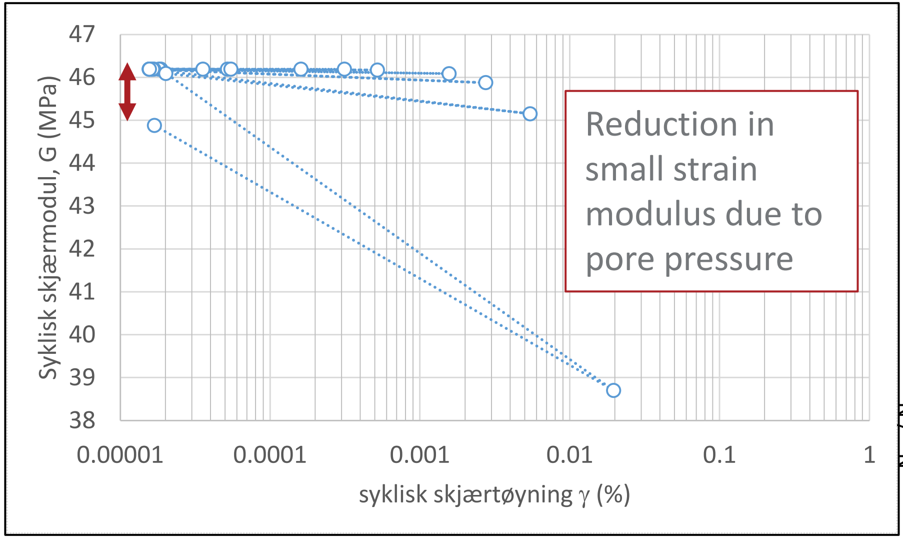
Num. modell i aksesymmetri poretrykksprop

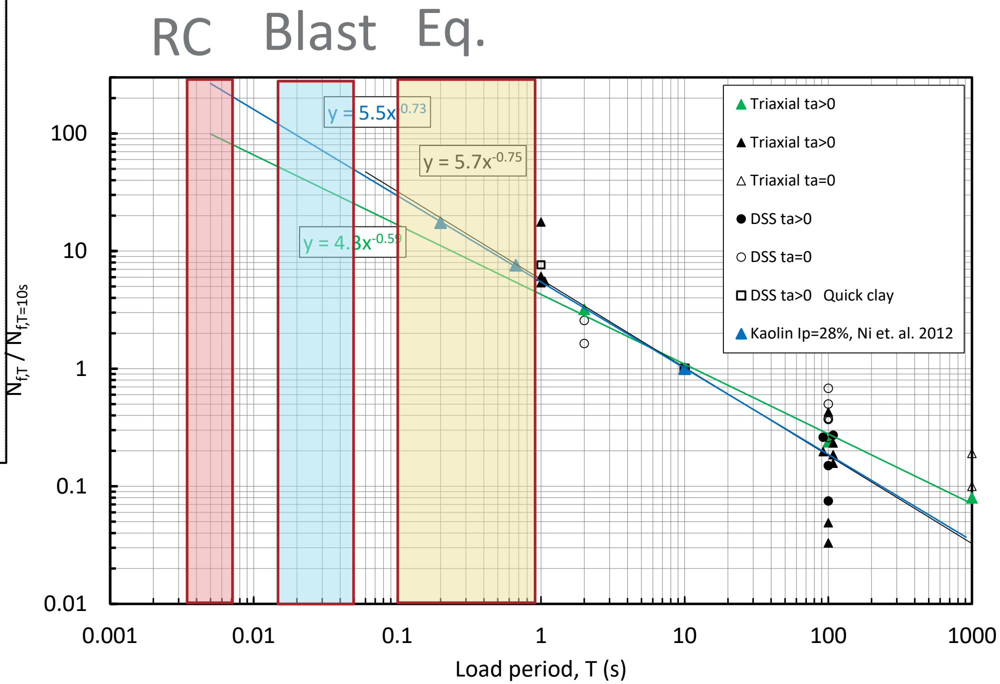


- Virgin Cv10-20 m2/år
- Mo styrt Cv 50-100 m2/år
- Poretrykk 10 kPa?
- Metode 2) Initieres i et kluster, 10 kPa større hydrostat, steady state, deretter udrenert steg fjerner i løpet («null tid») da blir dette et eksses
- Metode 1) Kan sette last på udrenert kluster og drenert utenfor
- Metode 3) Tøyning i kluster
- Linear-elastisk
- Modul utfra Gmax

10 min=2e-5 år,
100 min=2e-4

Evaluating (small) pore pressures from Resonant Column test





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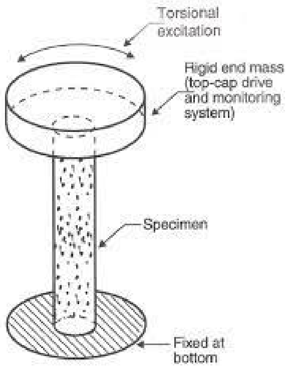

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About me

- Structural/Geotechnical engineer
- Ph.D. on earthquake engineering
- Working with vibration and earthquake induced cyclic/dynamic loading of soil and infrastructures onshore/offshore.