Erfaringer med sprengning nær kvikkleire (Experiences with blasting near quick clay: vibration and pore pressure monitoring)

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Med bidrag fra mange personer

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NFFs 33.e teknisk sprengningskurs

Innhold

- Bakgrunn
- Namsos, Første prosjekt 2010-2012 -> NS8141-3:2014 grenseverdi for vibrasjoner 25 mm/s (uveiet toppverdi)
  - Skråning med god stabiltet
- Eksempel på skred utløst i forbindelse med sprengningsarbeider
- Måledata for vibrasjoner and poretrykk
  - Overflate (pall) sprengning
  - Tunnel sprengning
- Observasjoner så langt

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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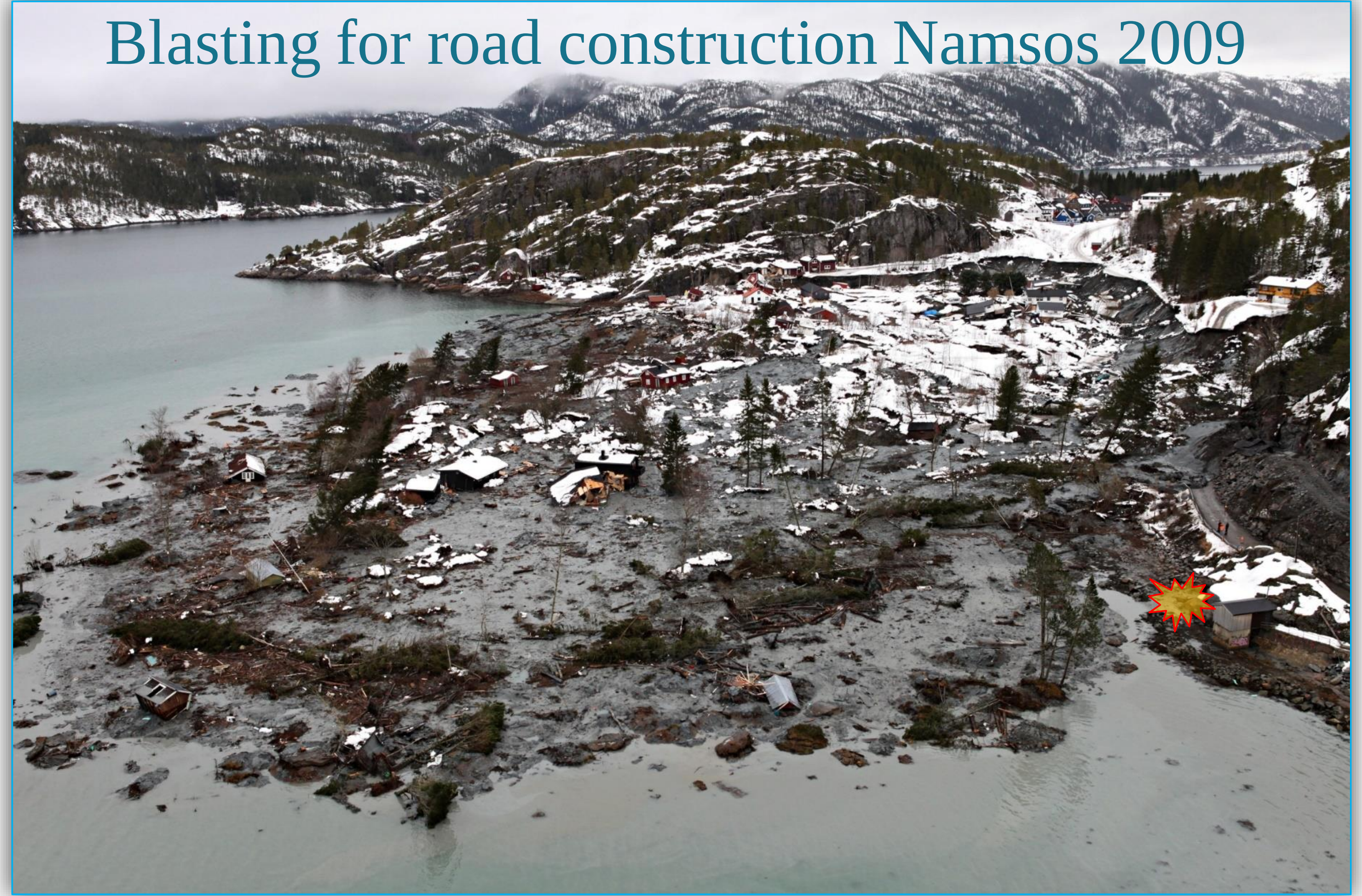
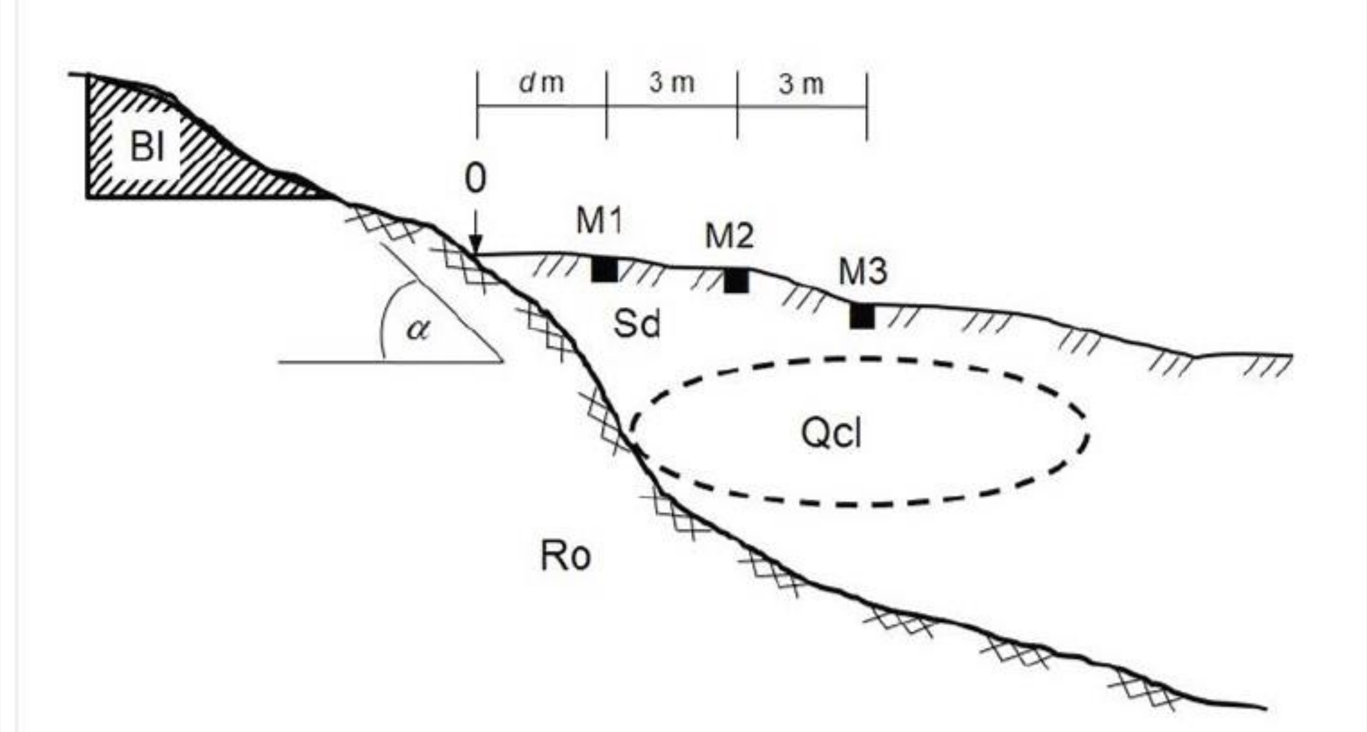
Blasting for road construction Namsos 2009



Standards and guide lines

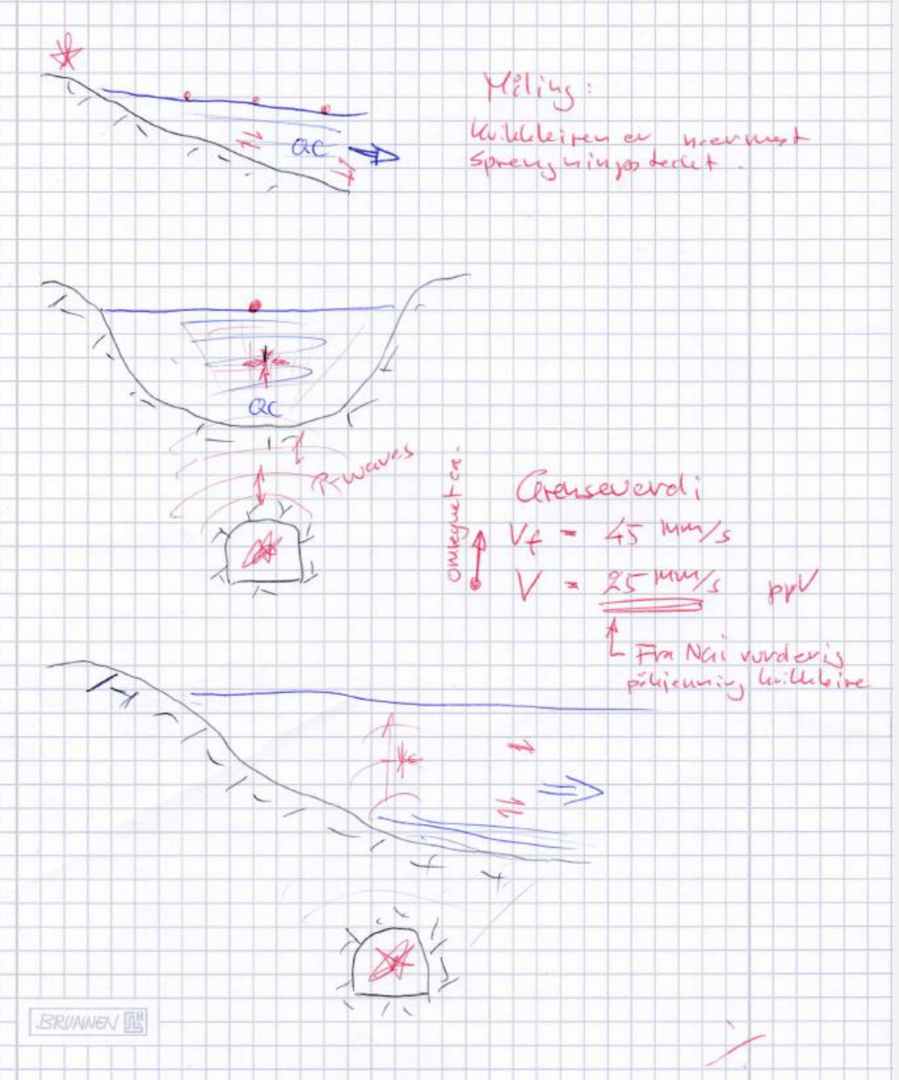
- NGI 20120700-01-R
- SVV HB V220
- 25 mm/s (top value)
- =45 mm/s frequency weighted
- Avoid blasting directly into clay (need to remove clay/soil from blast area)
- Avoid thrown material (e.g. Steinvik Tana!)

Måleopplegg



Surface and tunnel blast

- Surface blast vibration 1-2 s
  - 10-20 holes, 1-3 m distance, arranged in rows, time delays 10-20 ms btw holes, delay between rows 50-100 ms
- Tunnel blast typically 5-6 seconds. (3-4 times longer)
  - 30 horisontal holes
  - Different explosives
- Weakness of current standard
  - Does not give guidance on measurement and vibration limit for tunnel blasting
  - Further guidance with respect to static slope stability



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 (vibrations?) 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, Steinvika); Important with pore pressure measurement

- 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 is already has low stability, even a small blast may be sufficient to trigger a slide (?)

- Faktisk stablitet er vanskelig å vurdere -> overvåking av rystelser og ev. poretrykk på kritiske steder

Slide in Tana, Northern Norway 2021

After blast, a lot of rocks on the road

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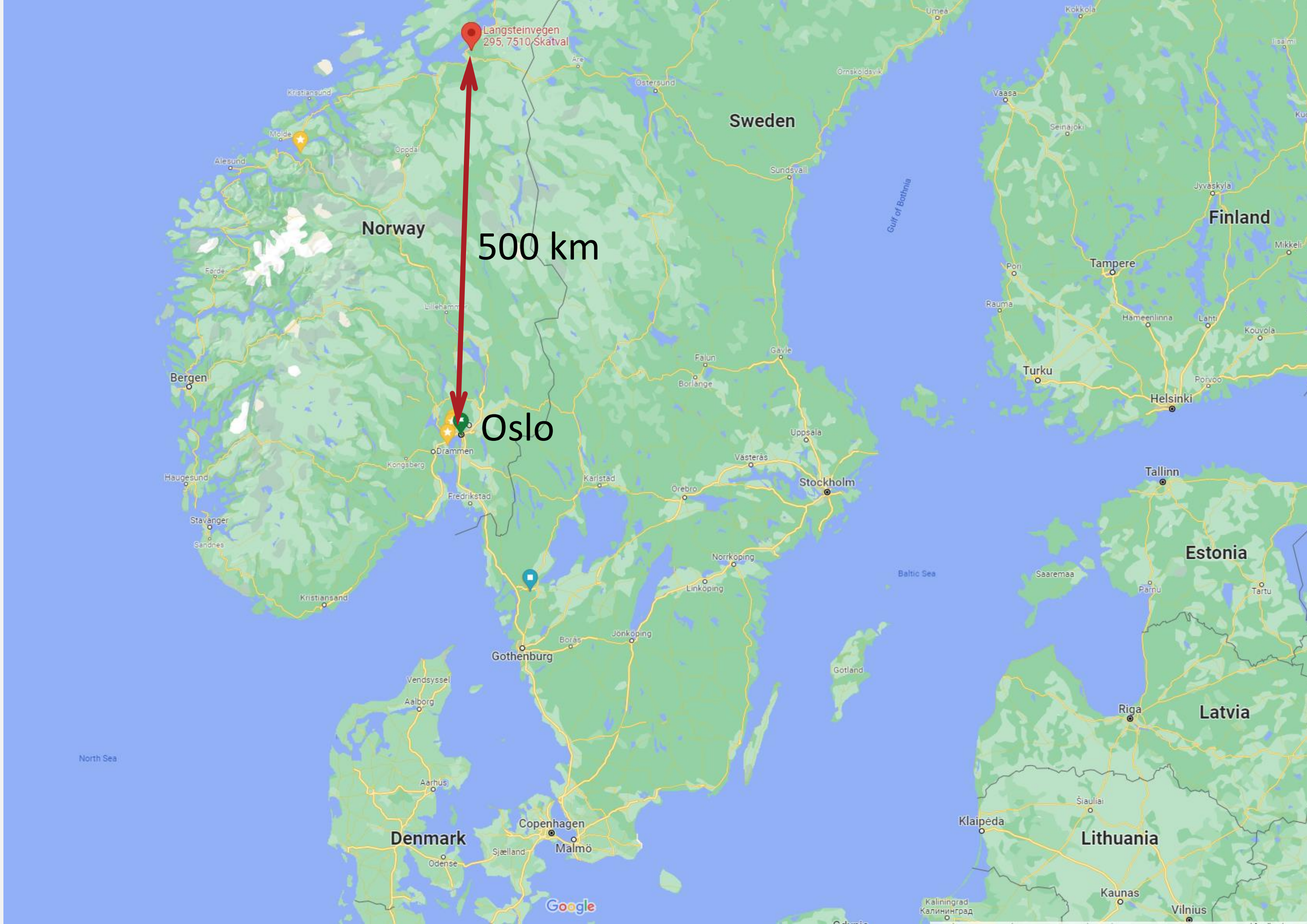
Photo: Stian Hansen, on face book page
Skred i Steinvik, Tana
Hell at ingen ble skadd

Ground water seeping out of layer in slope

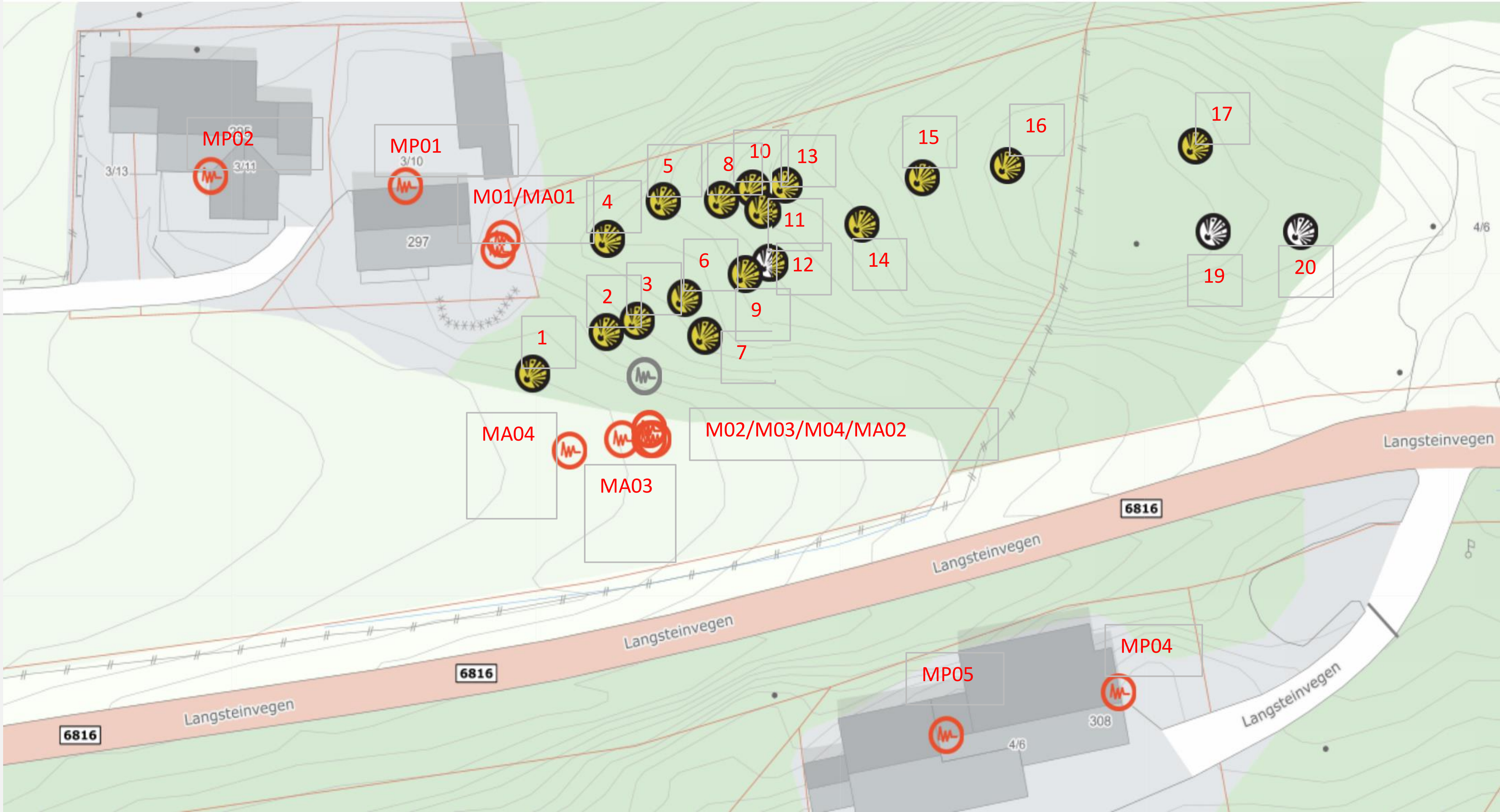
- Vibrations not the cause?
- How large were the vibrations

https://www.veier24.no/artikler/250-meter-av-fylkesvei-98-i-tana-ble-tatt-av-ras/509269

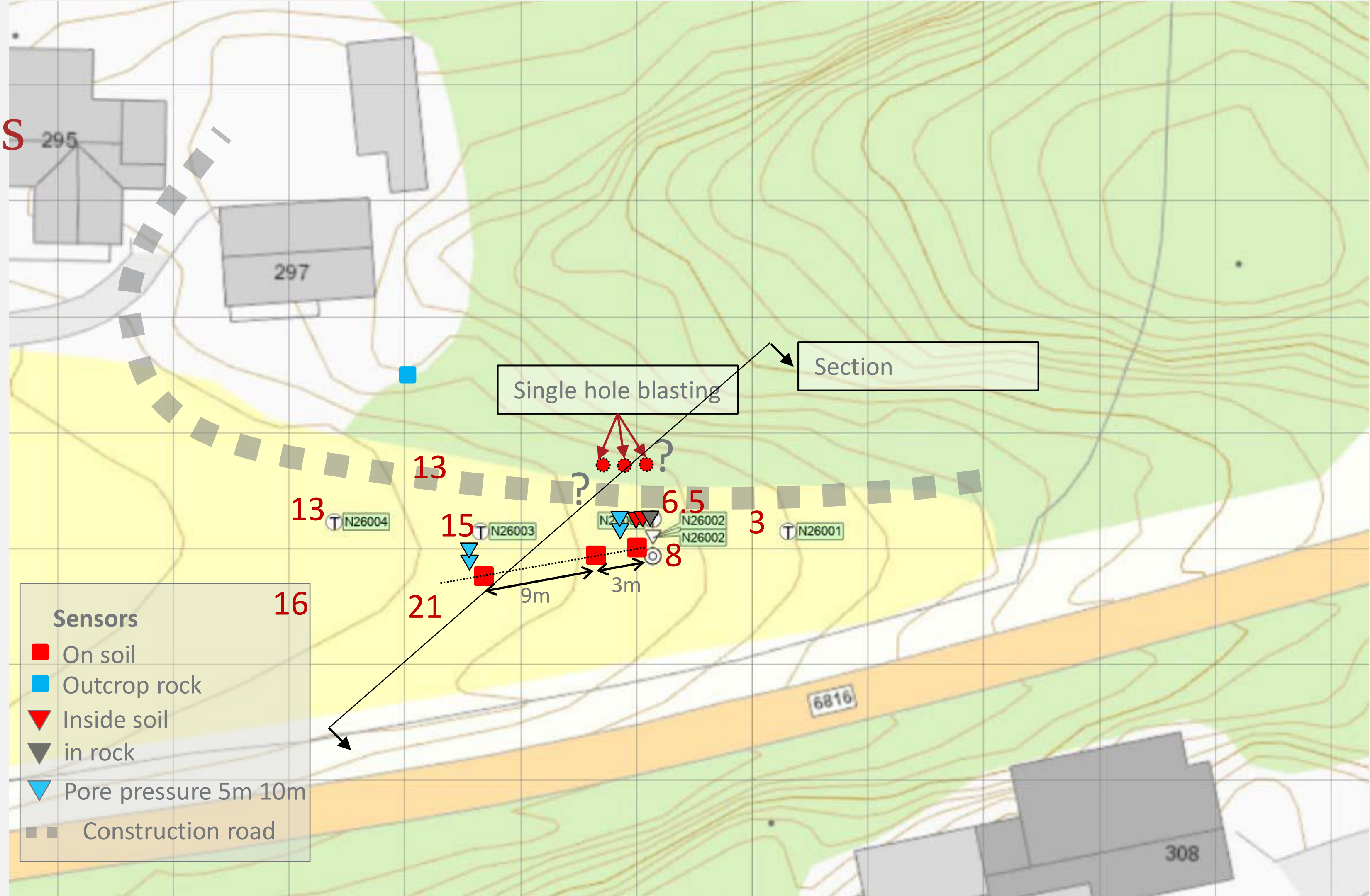
Langsteindalen Blast «experiments»


Langsteinvegen
295, 7510 Skatval
500 km
Oslo
Norway
Sweden
Finland
Estonia
Latvia
Lithuania
Denmark
Bergen
Stockholm
Helsinki
Tallinn
Riga
Gothenburg
Copenhagen
Malmö
Kristiansand
Stavanger
Haugesund
Drammen
Fredrikstad
Uppsala
Västerås
Karlstad
Örebro
Norrköping
Linköping
Jönköping
Turku
Tampere
Kaunas
Klaipėda
Aarhus
Aalborg
Odense
Gotland
Baltic Sea
North Sea
Gulf of Bothnia
Google


MP02
MP01
MA01
M01
MA02
M03
MA04
MA03
M04
MP04
MP05


MP02
3/13
3/11
MP01
3/10
297
M01/MA01
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
19
20
4/6
MA04
MA03
M02/M03/M04/MA02
Langsteinvegen
6816
Langsteinvegen
Langsteinvegen
6816
Langsteinvegen
6816
Langsteinvegen
MP05
MP04
308
4/6

Sensor locations



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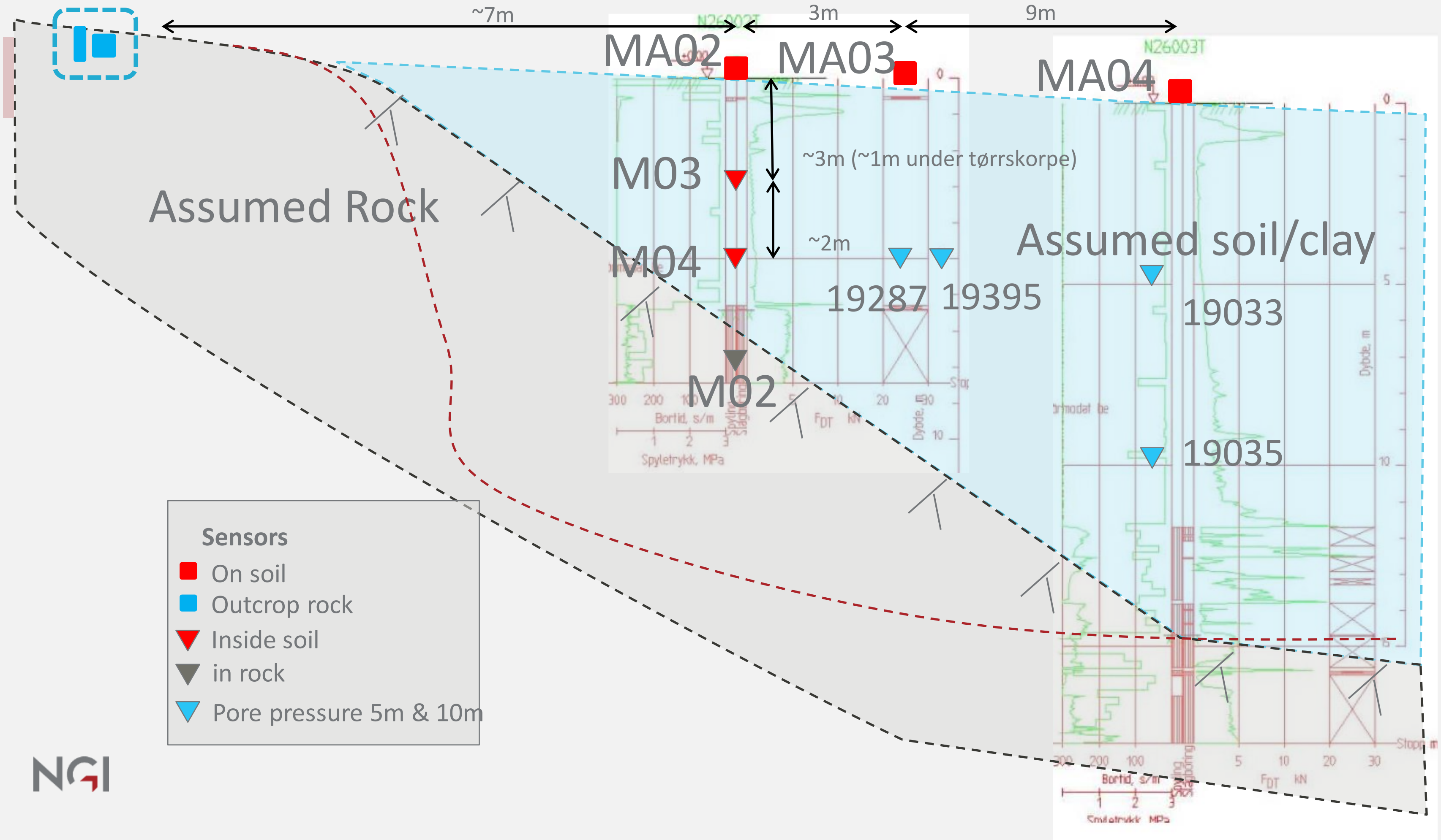
Locations of geophones and piezometers Langsteindalen



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Instrumentation installation

Installation of geophone in clay

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Installation of geophones

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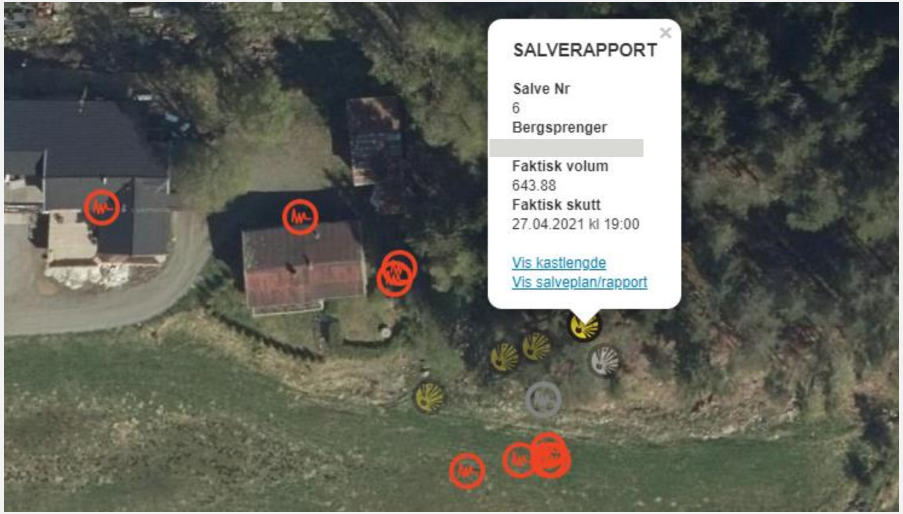
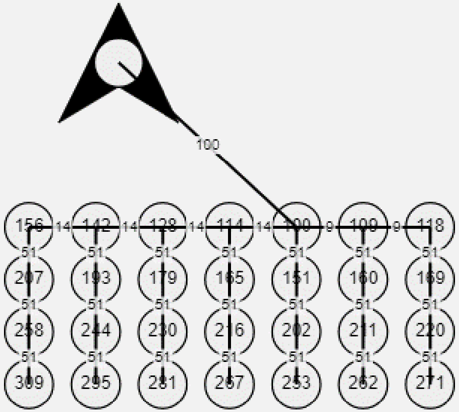
Measurement Results

Example of blast layout

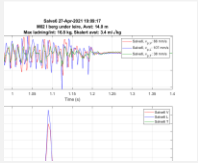
- Blast 6
- Unit charge 8.4 kg, time delay 14 ms

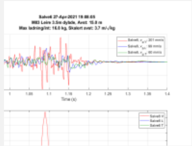




Vibrations blast 6

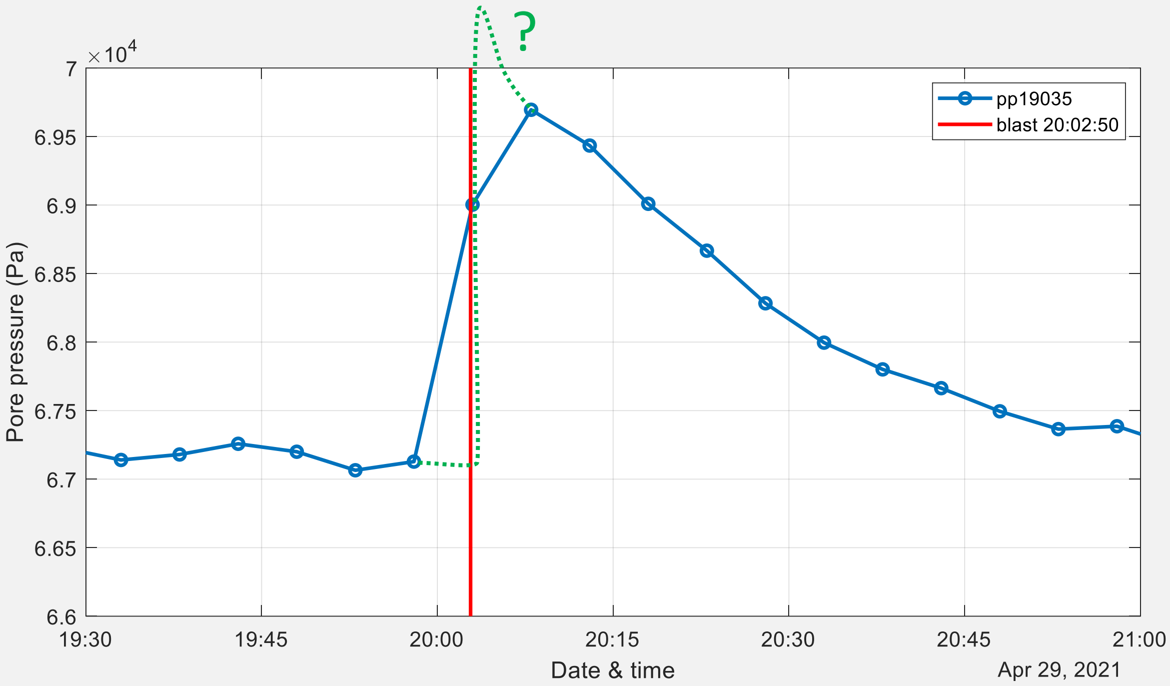
- Rock about 50 mm/s, 1 pulse 100 mm/s
- Soil 3.5 depth several cycles above 100 m/s, max 200 mm/s
- Frequency ~75Hz (some connection to the time delay of 14 ms between charges). Still under investigation





Pore pressure blast 9

- Piezometer 19035 @10 m depth.
- Pressure around 67 kPa, Increase ~2.5 kPa
- Vibrations ~40-60 mm/s at 5 m depth and 30-40 mm/s at 3.5 m depth
- Cyclic strain 0.05-0.1 % (?) at 3,5-5 m depth



Time	Strain (%) @3,5m depth	Strain (%) @5,0m depth	Pore Pressure change (kPa) @10 m depth	Pore pressure Ratio u/σ_v'
14:46:36	0.02	0.01	~0.8	2%
20:02:50	0.03 (0.07%)	0.02 (0.08%)	2.6	6%

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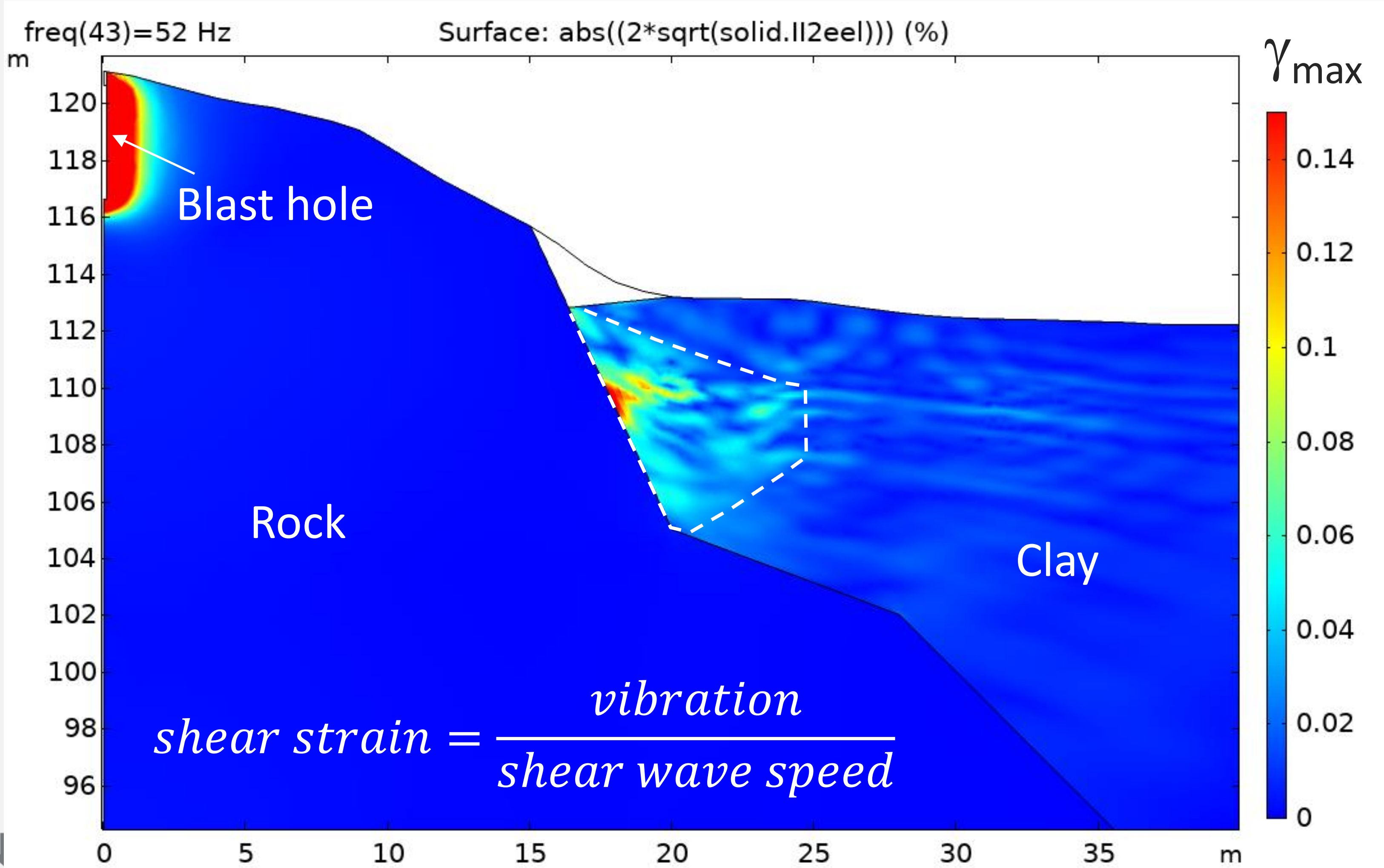
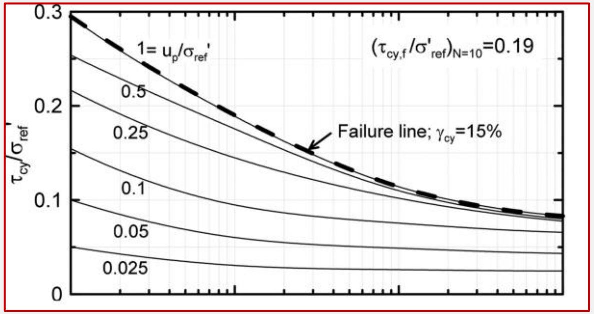
Numerical modelling


freq(43)=52 Hz
Surface: abs((2*sqrt(solid.II2eel))) (%)
m
120
118
116
114
112
110
108
106
104
102
100
98
96
0
5
10
15
20
25
30
35
m
γ_{max}
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Blast hole
Rock
Clay
$$shear\ strain = \frac{vibration}{shear\ wave\ speed}$$

Computed pore pressures



- Based on numerical analysis to evaluate stress and strains and contour diagrams for pore pressure build up for Silt.
- Pore pressure diagram has for quick clay recently been established.
- Pore pressure in relative good agreement with measured values.
- G_{max}=18 MPa, G/ G_{max} =0.5, γ=0.05% give τ_{cy}=5 kPa

Vibration amplitude (mm/s)	20-30	40-60	>100
γ_{cy} (%)	~0.03	~0.1	>0.3
τ_{cy}/σ_{vc}'	0.05	0.09	0.18
τ_{cy} (kPa)	3	5	10
u_p/σ_{ref}' (N=5)	0.038	0.07	0.3
u_p/σ_{ref}' (N=10)	0.040	0.08	0.45
u_p/σ_{ref}' (N=15)	0.045	0.09	0.9
u_p (N=5) (kPa)	**2.2**	**3.9**	**18**
u_p (N=10) (kPa)	**2.4**	**4.5**	**27**
u_p (N=15) (kPa)	**2.7**	**5.0**	**53**

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Vibrasjoner og poretrykk Tunnel sprengning/arbeider

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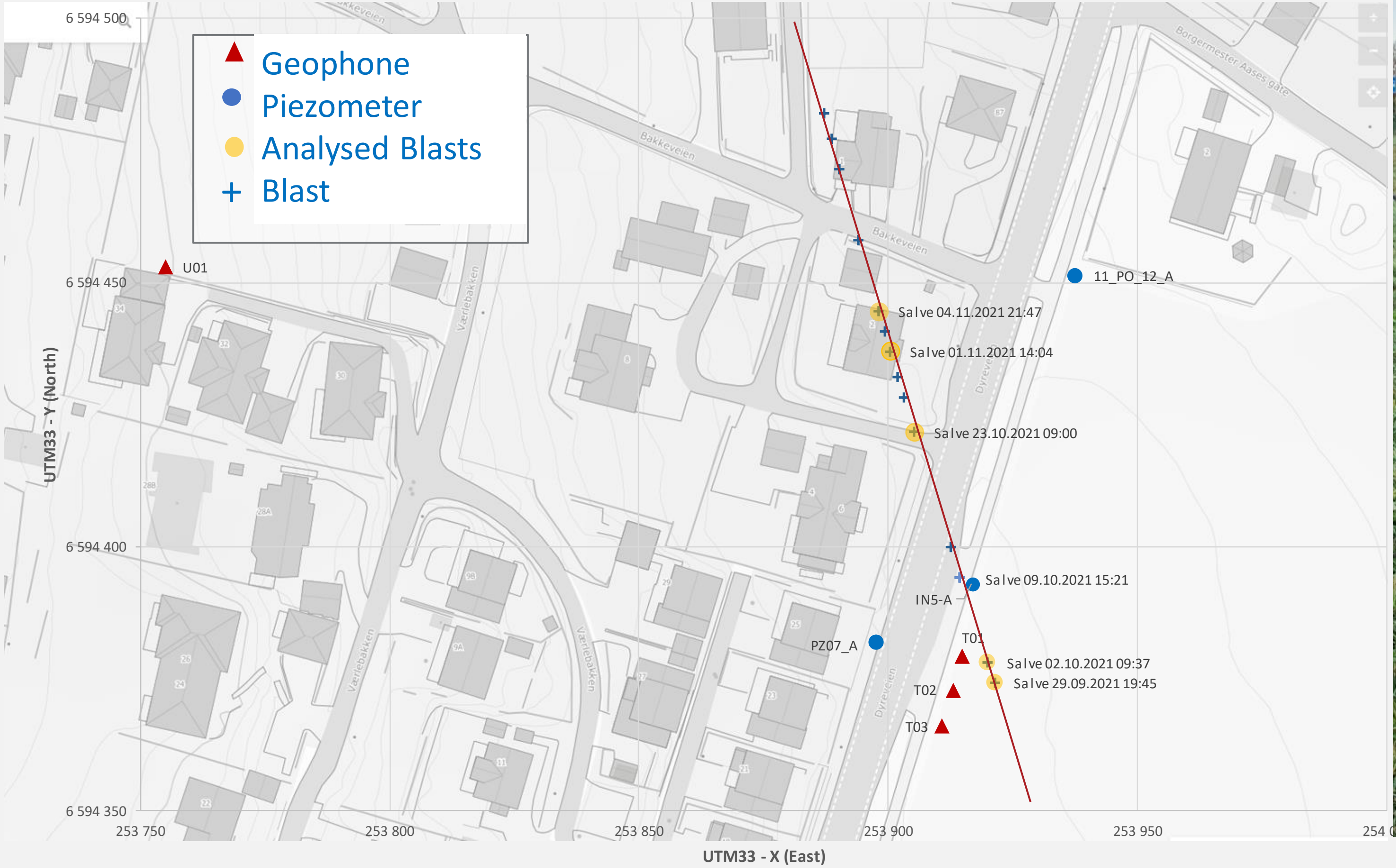
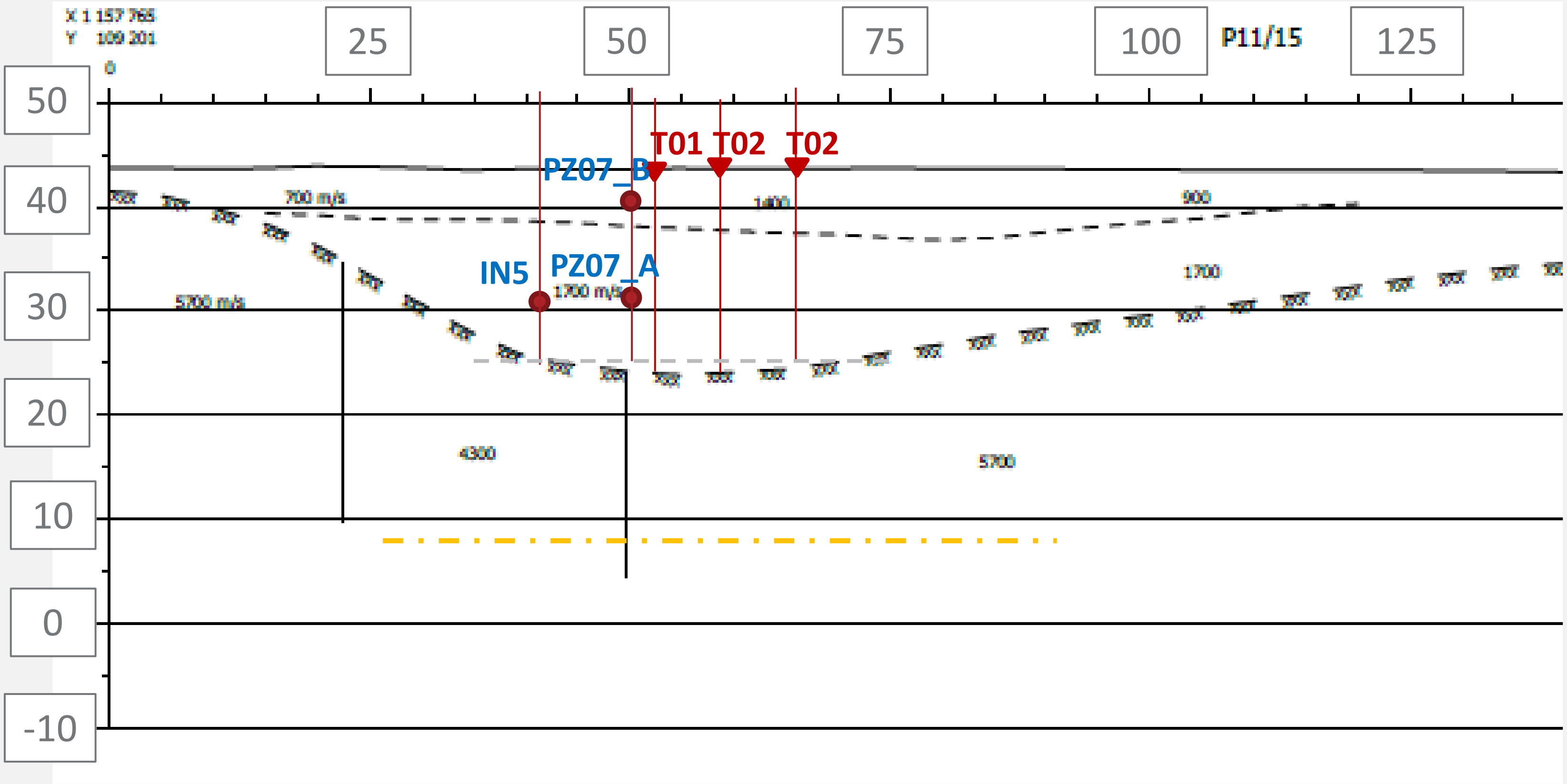
Overview


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
Dyrevelen
Borgermester Aases gate

Seismic profile with locations of sensors



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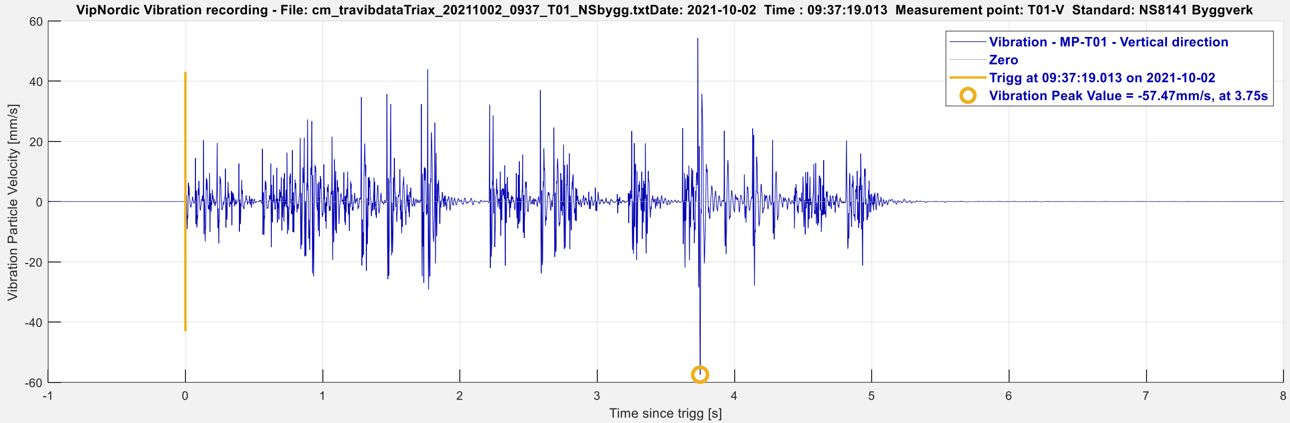
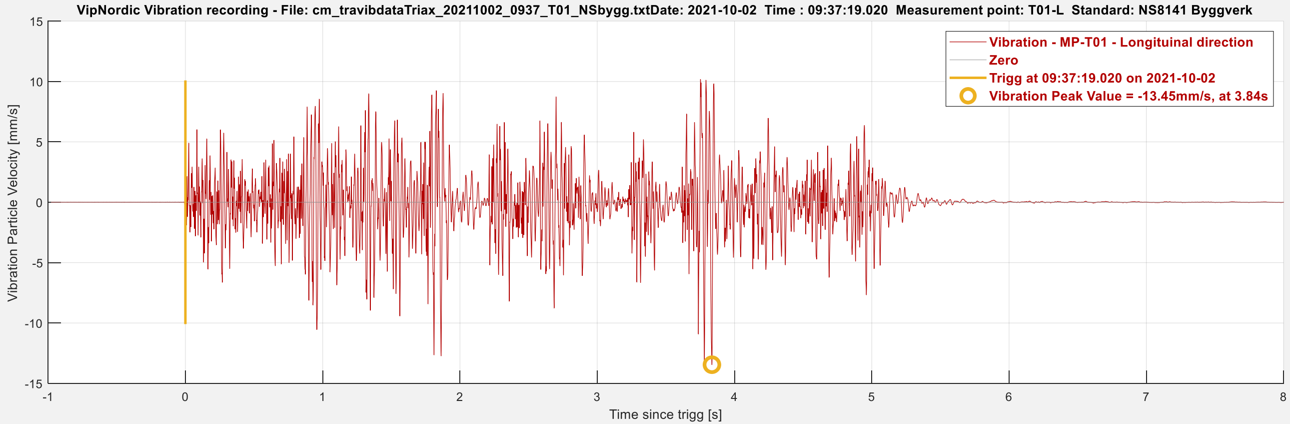
Vibrations





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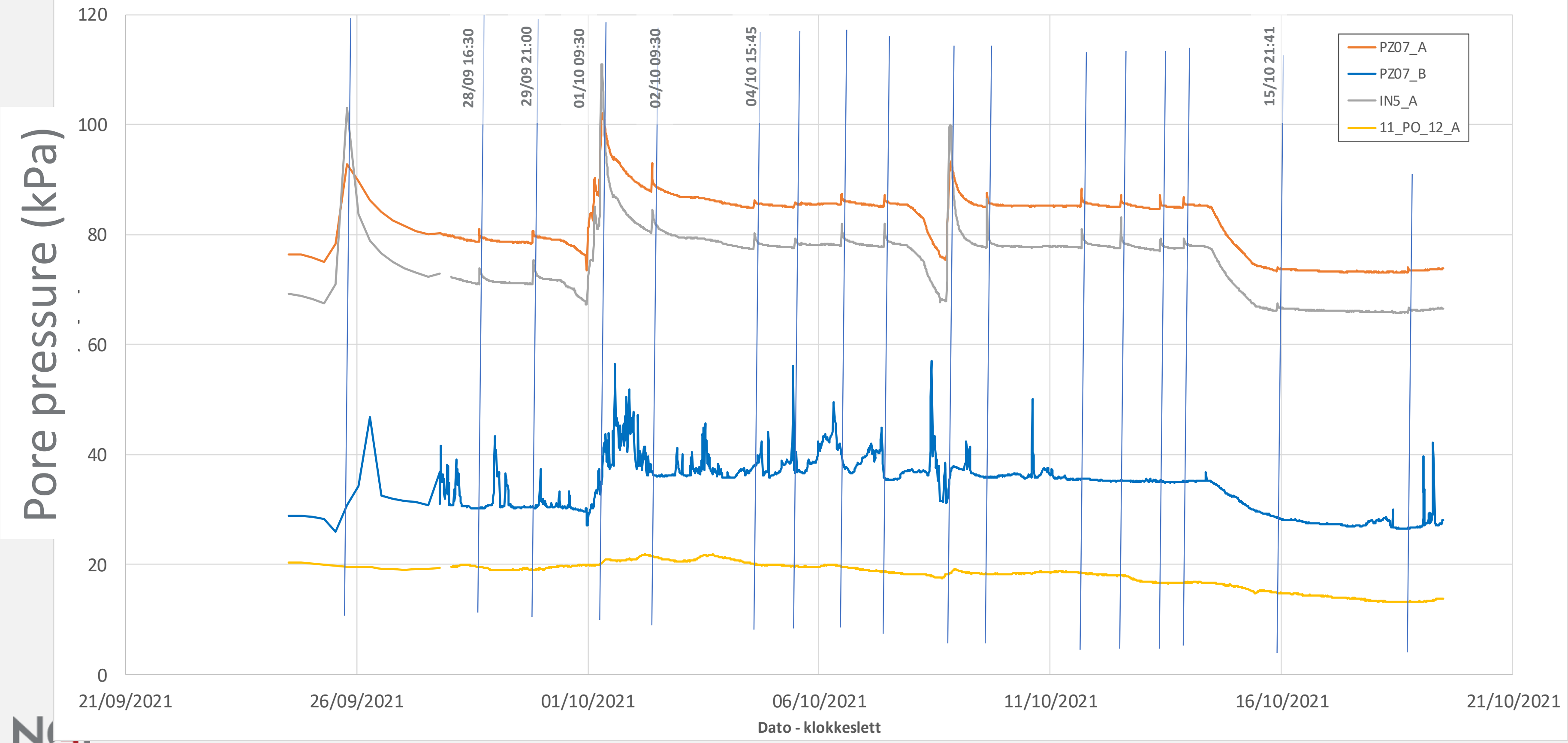
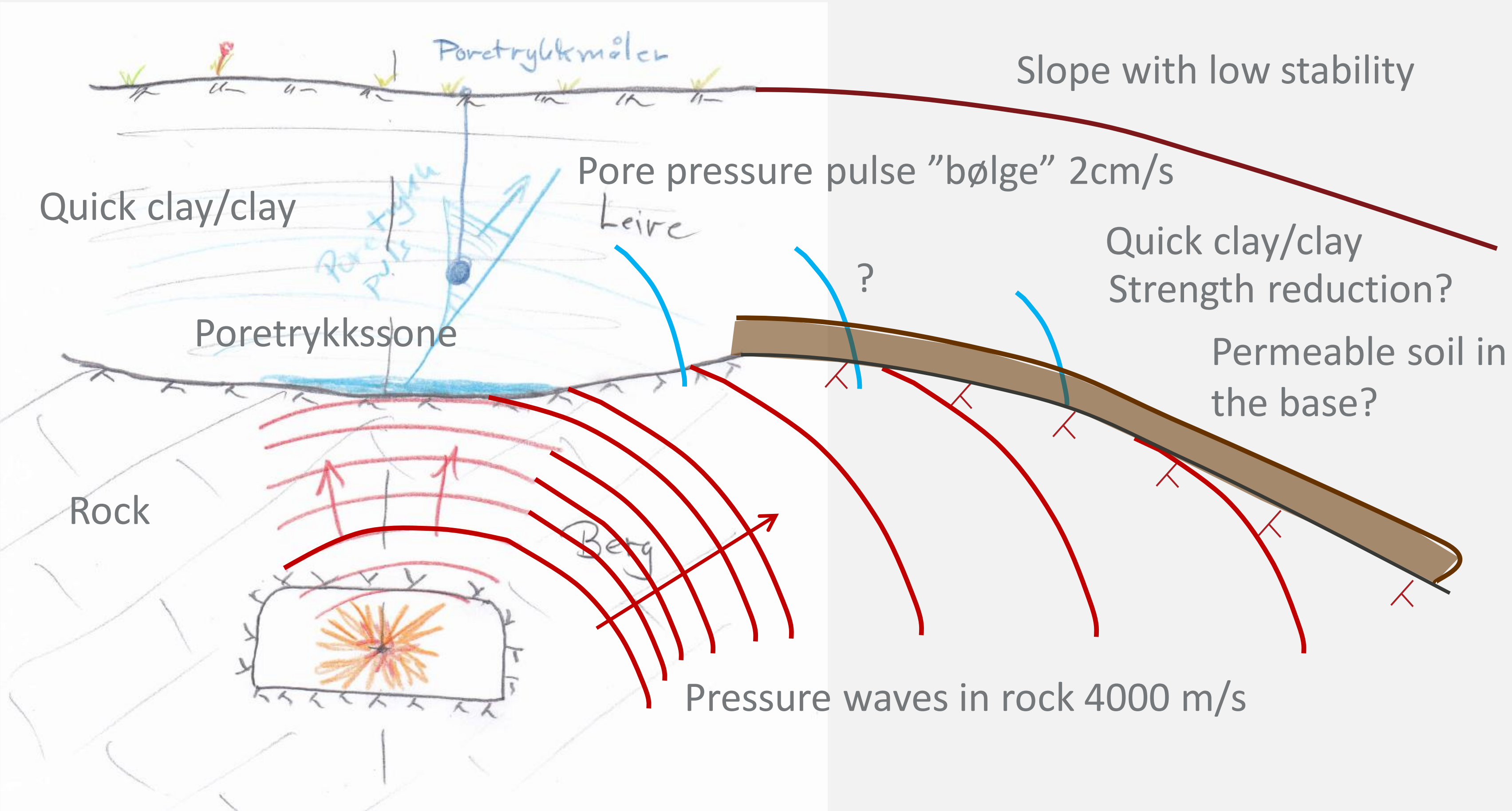
Pore pressures



Sketch of blast induced pore pressure and propagation



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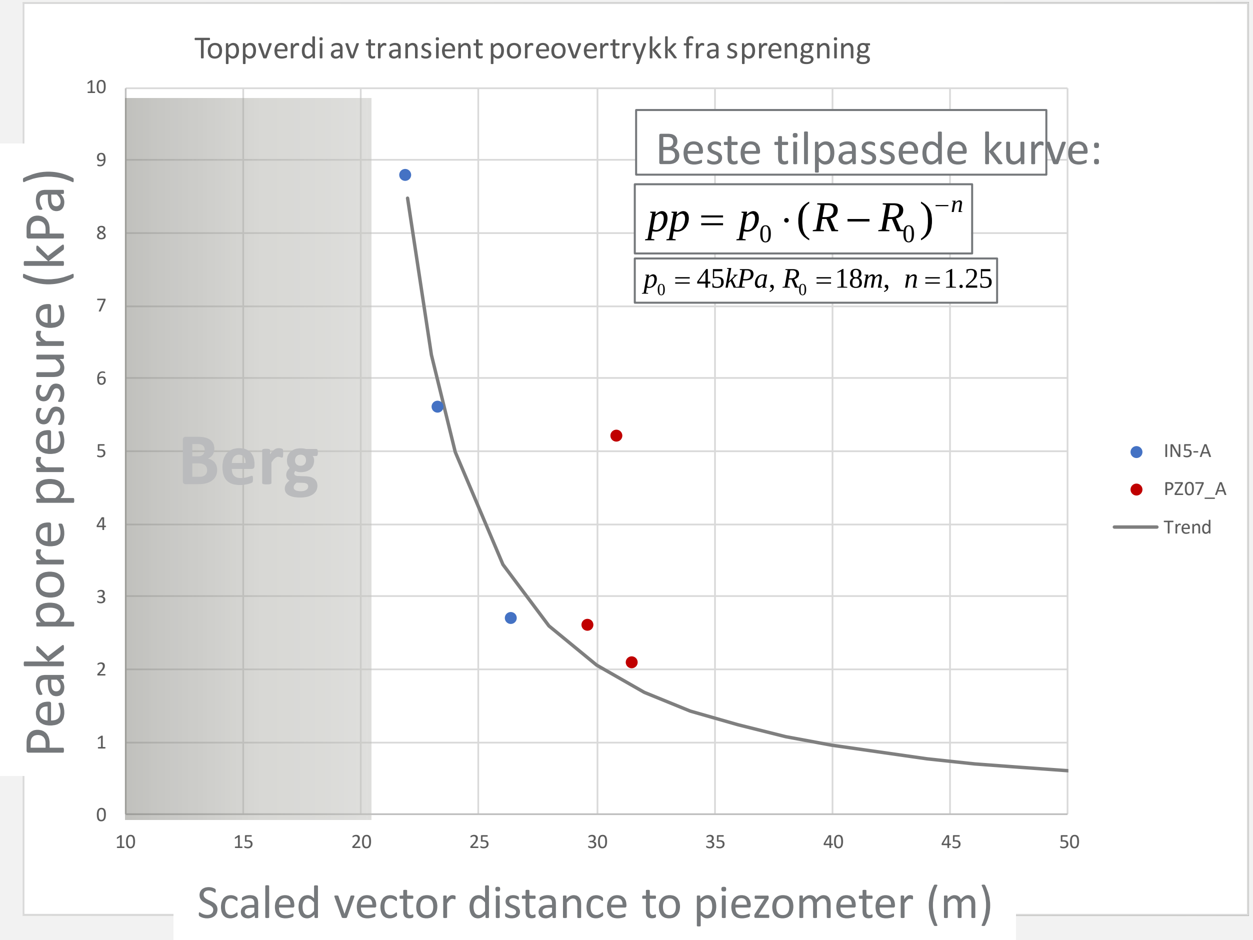
Transient pore pressure peak value vs. distance



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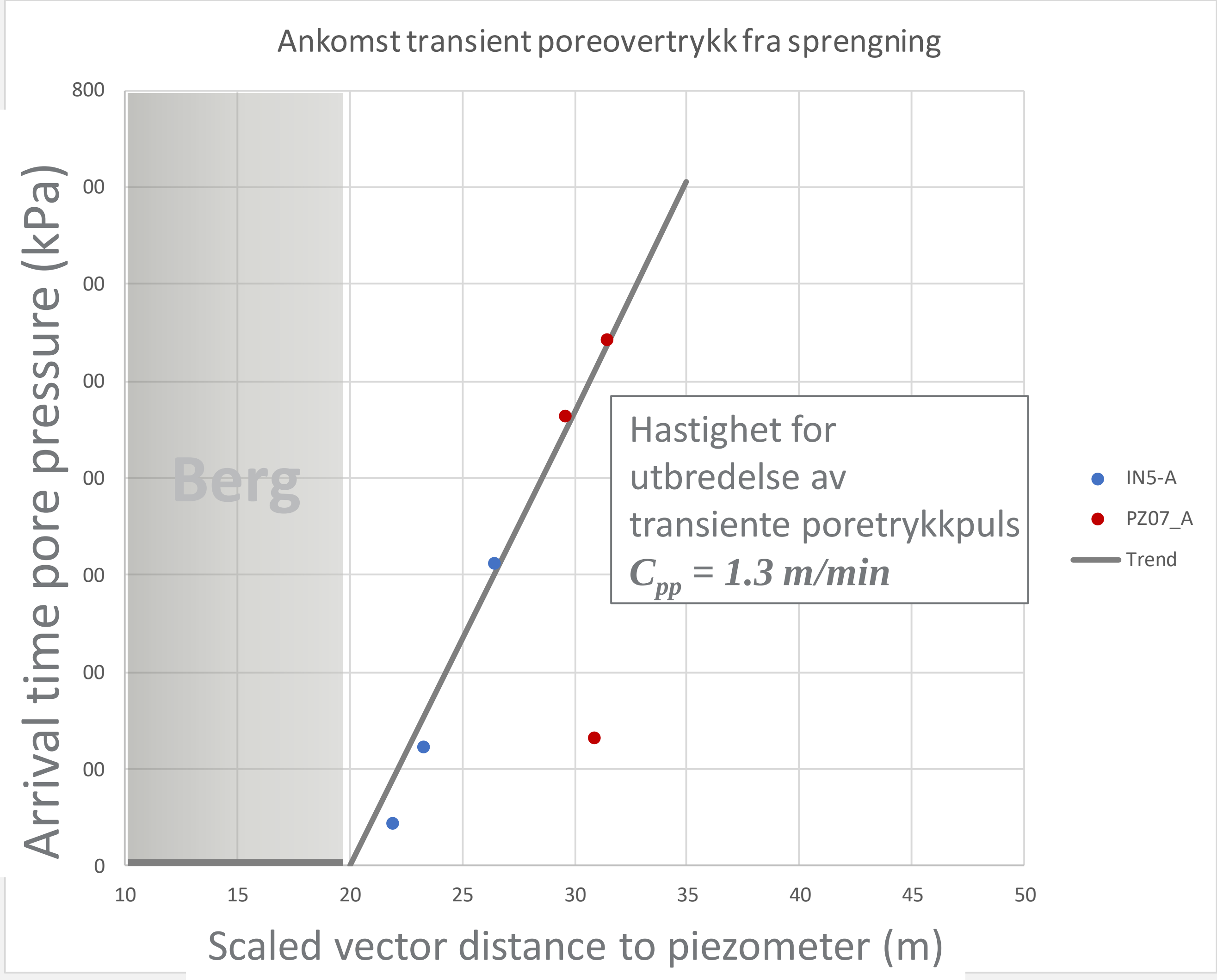
Arrival times pore pressure



Sammendrag

- Behov for å utvide og detaljere NS 8141 standard i forhold til bland annet tunnelsprengning.
- Lykkes å måle poretrykk ved sprengning i tillegg til vibrasjoner.
- Høye poretrykk kan redusere styrken til leire/silt/sand
- Poretrykken avtar raskt 2-4 timer etter sprengning
- Poretrykk spreder seg fra overgang berg/leire til omkringliggende områder
- Kan store nok poretrykk sprede seg til områder i skråning som gjør at skråning blir ustabil?
- Poretrykk fra forinjeksjon er større enn fra sprengning
- Pågående internt FoU prosjekt, ekstern finansiering trenges for å få til et større prosjekt som kan gi mer kunnskap og videreutdanning av spesialister.

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Takk for oppmerksomheten!

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Tack til alle som bidratt så langt!

- A large number of people involved
- Surface blasting
  - Nye Veier (a Norwegian public infrastructure construction company)
  - Hæhre (Road contractor)
  - Sweco (Engineering geologists)
  - Dr. Olav Olsen (consulting company)
  - Nitroconsult (vibrations)
  - Geotech (pore pressure)
  - NGI colleagues
- Tunnel blasting
  - Bane NOR
  - MossIA
  - WSP
  - Forcit and Nexcon (vibrations in clay and on houses)
  - NGI colleagues

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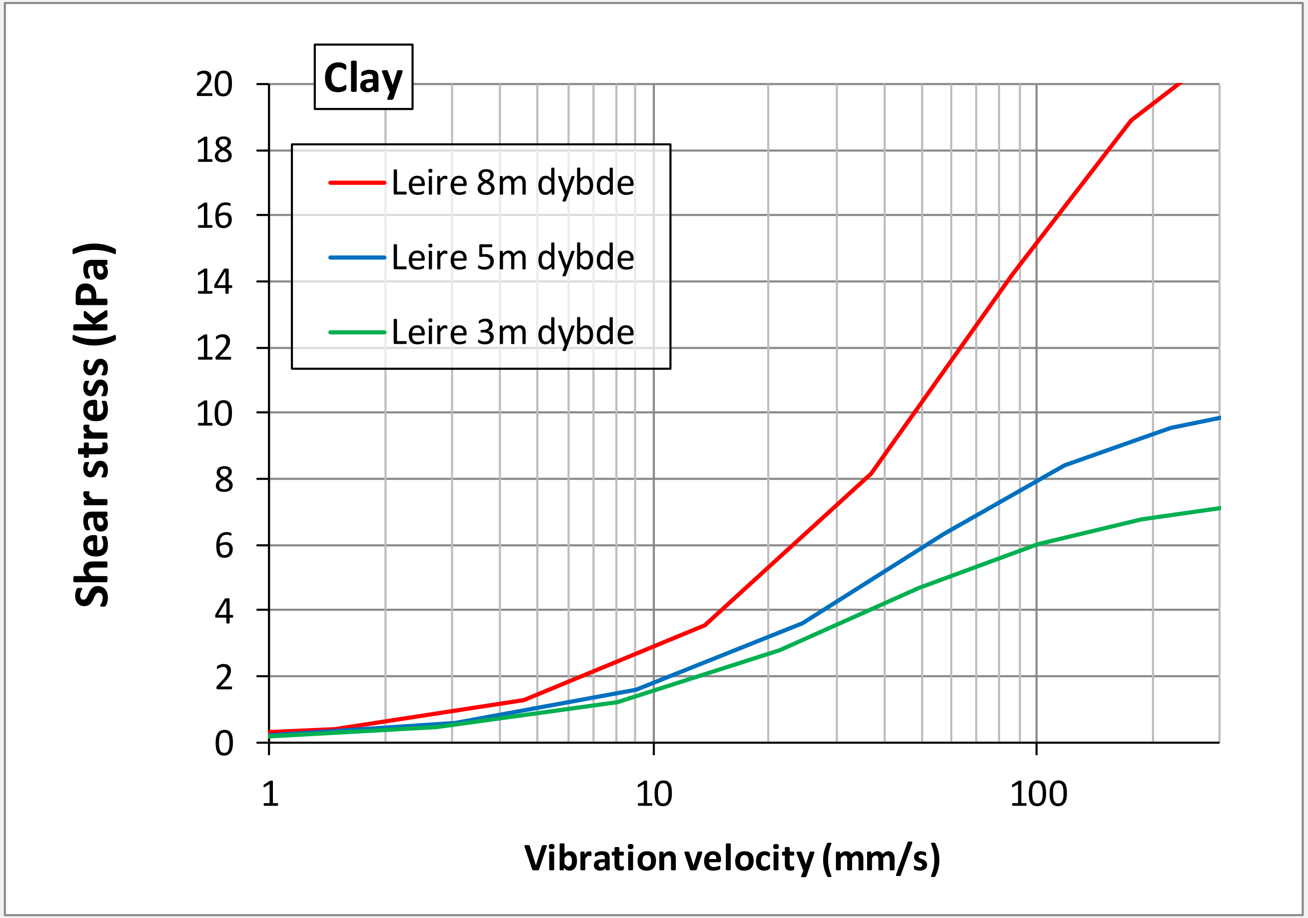
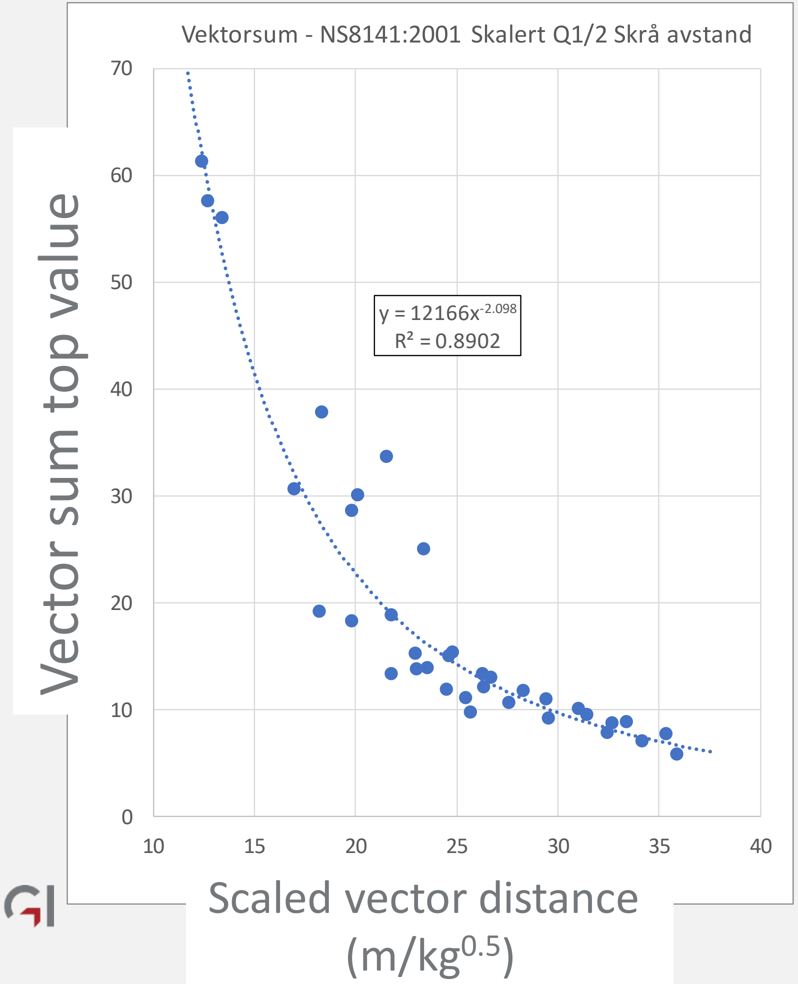
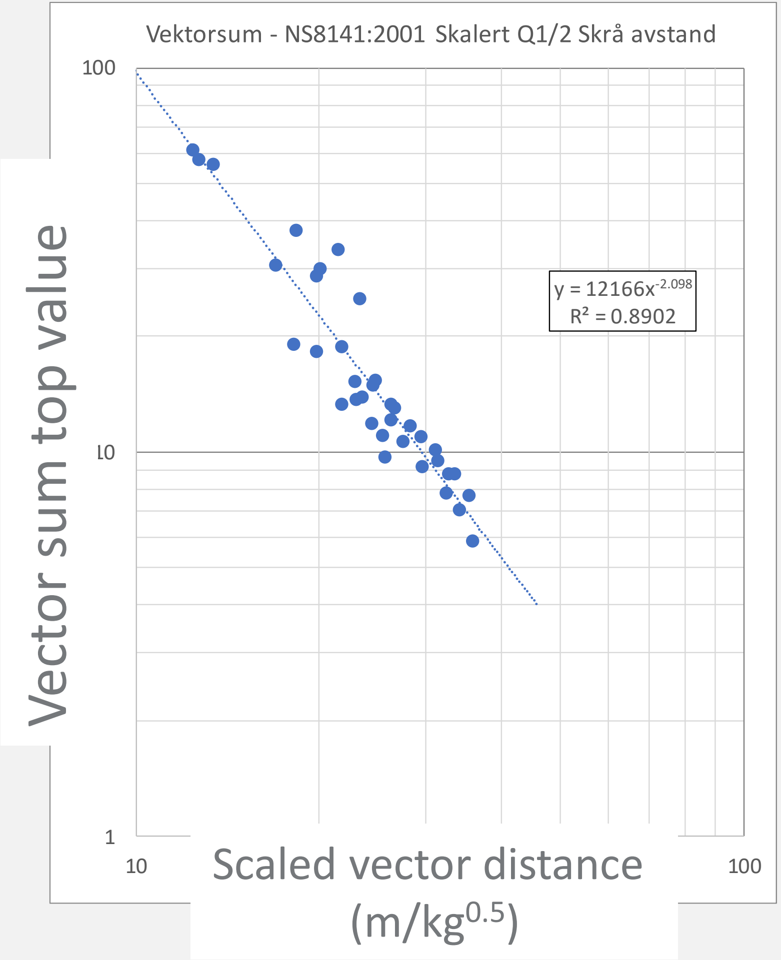
Relation between cyclic shear stress and vibration velocity



Vibration amplitude vs. scaled distances





Implications and future work

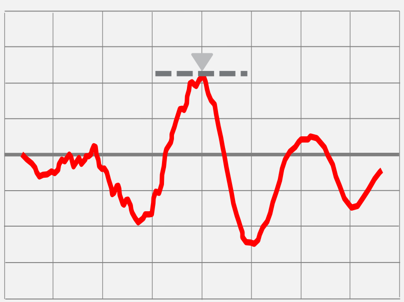
- For tunneling grout injection causes higher pressure than blasting
- Higher pore for highly mobilized slopes?
  - Important to monitor both vibrations and pore pressures
  - Both propagation of pore pressure and vibrations could cause increase pore pressures at highly mobilized parts of slopes at some distance from blast(?)
- Can blast gas pressure in the rock contribute to the pore pressures?
- Detailed processing gather data sets combined with numerical analysis to predict both generation and propagation of pore pressures can shed more light on the observations so far

END

Thank you for the attention!

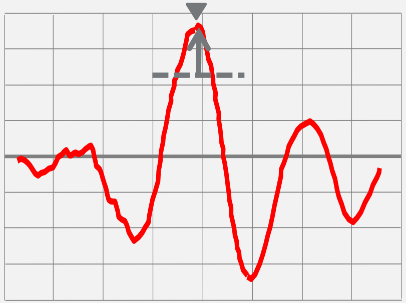
#onsafeground

Hvordan frekvensveiefilteret virker:

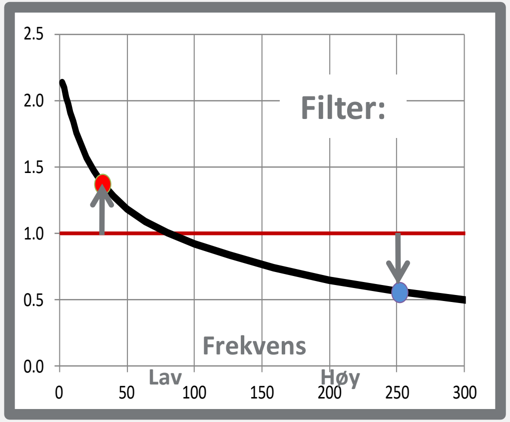


Rystelser med lav frekvens:

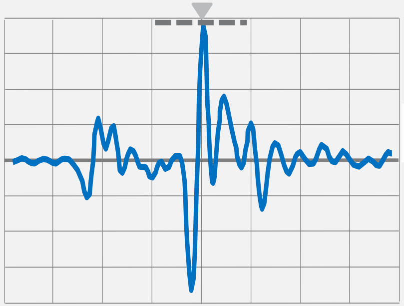
- Bløt grunn
- Lang avstand
- ”Mykt” fundament
- Overflatebølger



Uveid
Svingehastighet –
Toppverdi:

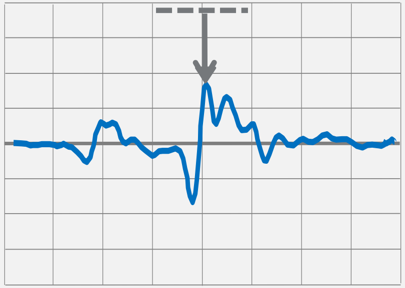


Frekvensveid
Svingehastighet –
Toppverdi:

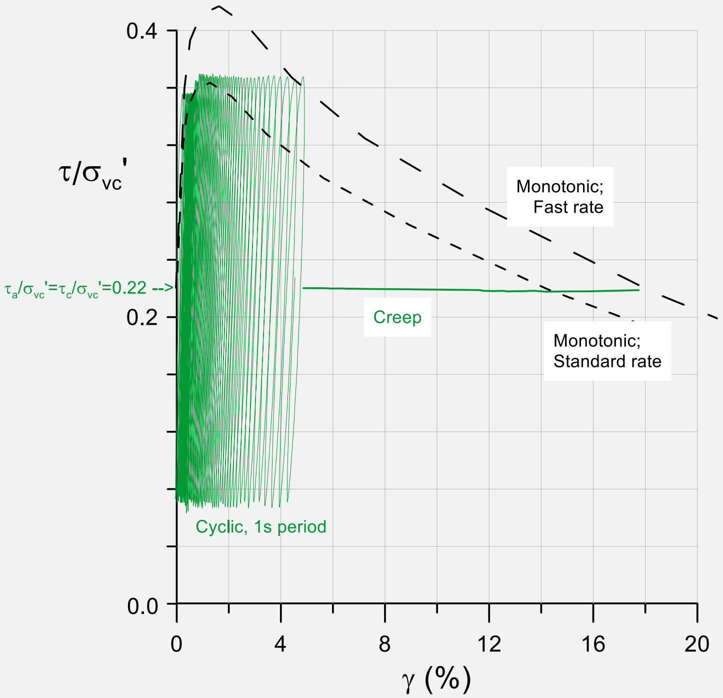


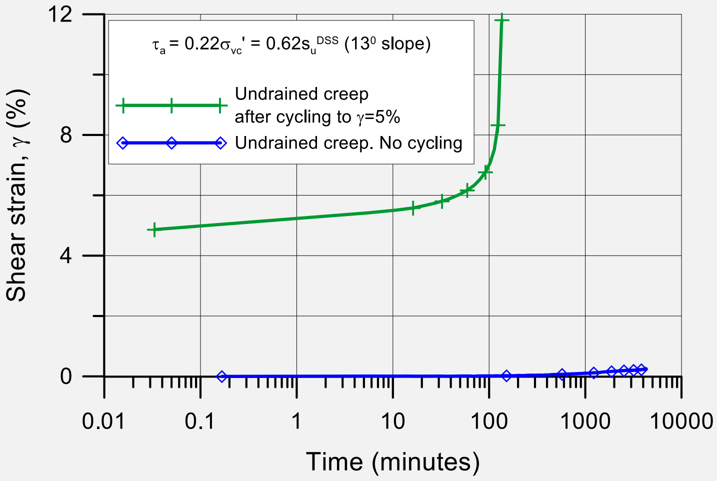
Rystelser med høy frekvens:

- Fast berg
- Kort avstand
- Direkte på berg
- Volumbølger



Explanation of Contour Diamgrams:
Effect of creep after cyclic loading on development permanent deformations





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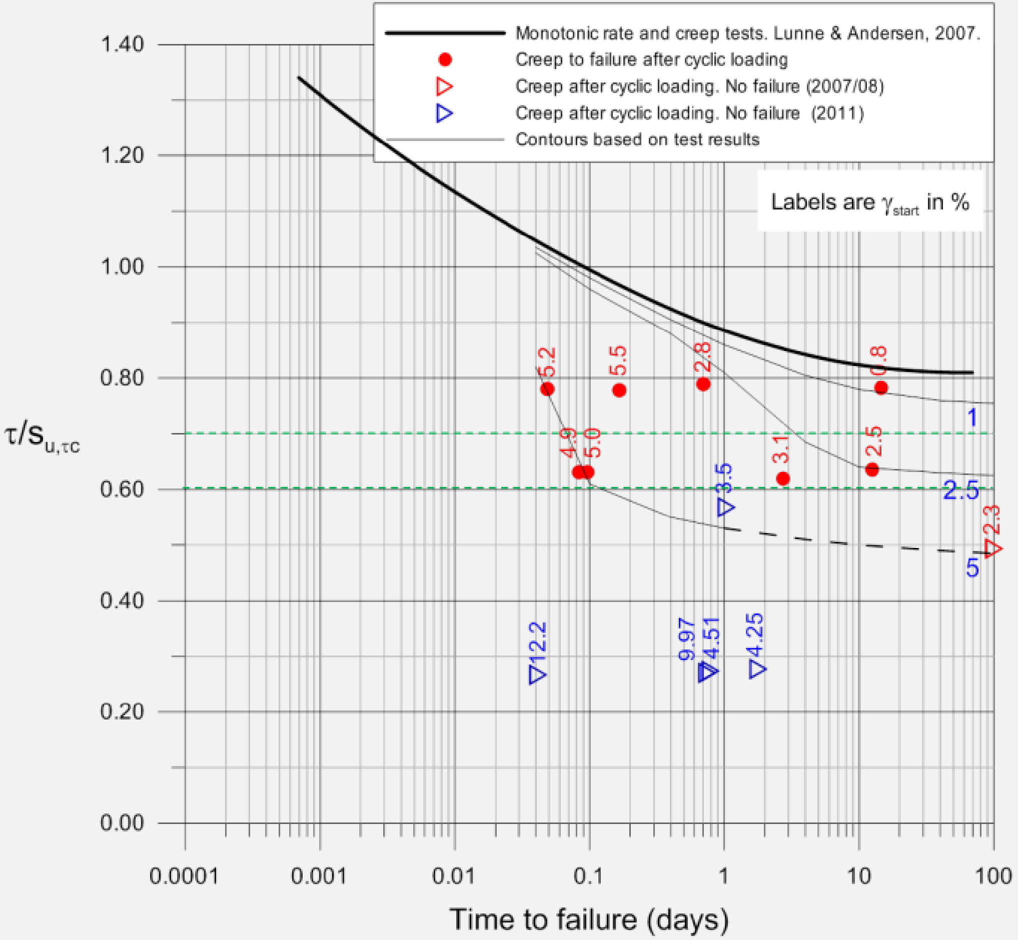
Contour diagram for creep failure after cyclic loading



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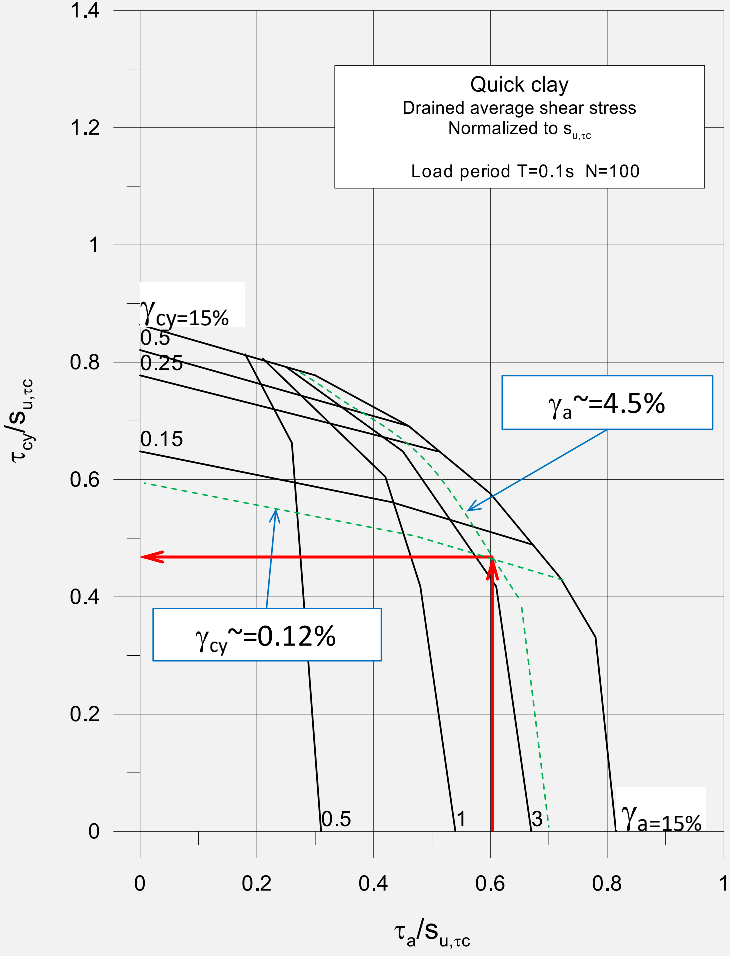
Contour diagram for N=100 cycles and load period of 0.1s (10Hz)



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Vibration amplitude to cause local creep failure in clay

Mobilization degree, (τ_a/s_u)	0.6		0.7	
Permanent strain at end of cyclic loading, γ_p [%]	2.5		1.5	
Consolidation shear strain, γ_c [%]	2.0		4.5	
Resulting average strain, γ_a [%]	4.5		6.0	
Number of cycles, N	10	100	10	100
Cyclic shear strain, γ_{cy} [%]	0,22	0,12	0,13	0,1
Normalized shear stress, τ_{cy}/s_u	0,68	0,47	0,47	0,4
Shear modulus corresponding cyclic strain [MPa]	4,5	5,6	5,2	5,8
Vibration amplitude [mm/s] to cause local failure in clay.	110	67	70	57

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Quick clay slides with vibration as one possible triggering agent

Year	Place	Description
1930	Thamshavn	Flow slide spreading out 20km. Minor earthquake on the west coast (Ref. Emdal, Janbu, Sand). Probably due to landfill.
1955	Hawsebury slide, Ontario, Canada	"The movement occurred as workmen were removing some debris … with dynamite. One b l a s t had been completed and the second charge was being prepared when the movement began.""Thus there could have been five contributing factors to the instability of the bank of the ravine. It is possible that the blast vibrations may have been the trigger to set the unstable bank in motion."
1973	Fröland near Uddevalla, Sweden	Blasting immediately before slide at nearby quarry. Precipitation before slide. Rock blocks/stones landing on soil deposit
1990	Shoreline Slide at Lade, Trondheim	Blasting 3:20 hours before slide, but small vibration amplitudes. Sliding plane consist of very loose sand and silt. Unlikely to be caused by vibrations.
1990	Trestycke vatten, Uddevalla, Sweden	Heavy vibratory roller involved.
1996	Finneidfjord	4 persons killed, filling, large blasting 3 hours before slide. Relatively high precipitation until 10 days before slide.
2009	Namsos, Norge	Block of rock pushed into quick clay when blasting
2011	Vid Hönebäck along E45 Göteborg Trollhättan Sweden	Blasting 30(?) mm/s edge of slide preciptation several days in row before slide, water on field, tractor collecting ensilage.

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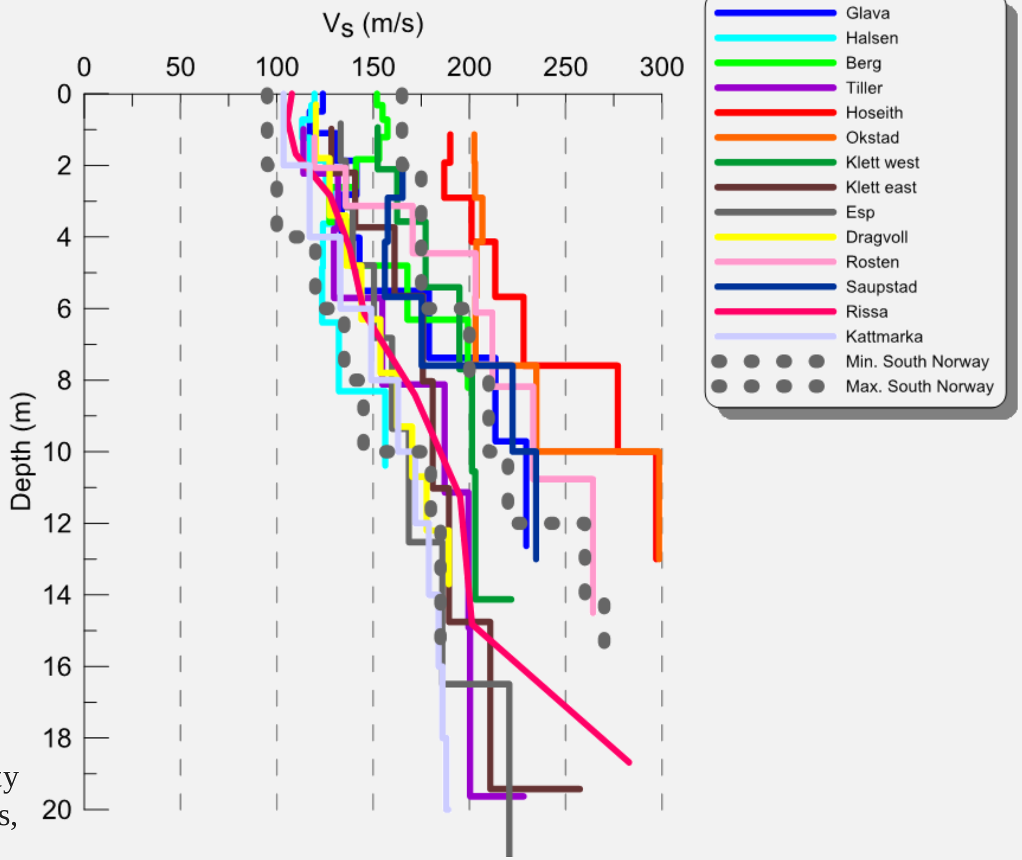
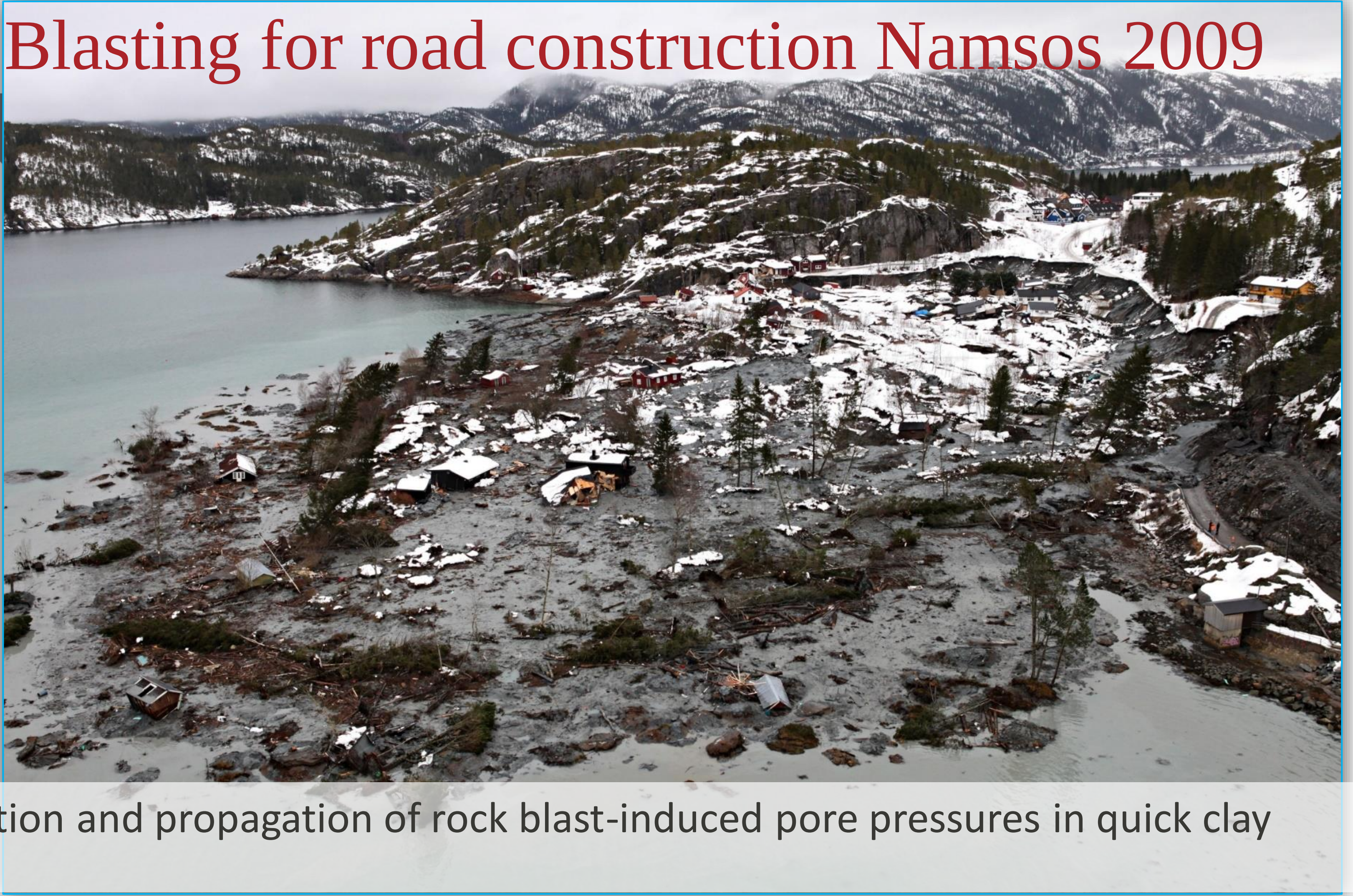
In situ shear wave velocity profile for Norwegian sites



NGI, SP8-GEODIP, Correlations between shear wave velocity and geotechnical parameters in Norwegian clays, 20150030-04-R, 2015-11-02.

Also in paper by L'Heureux et. al. 2016?

Blasting for road construction Namsos 2009

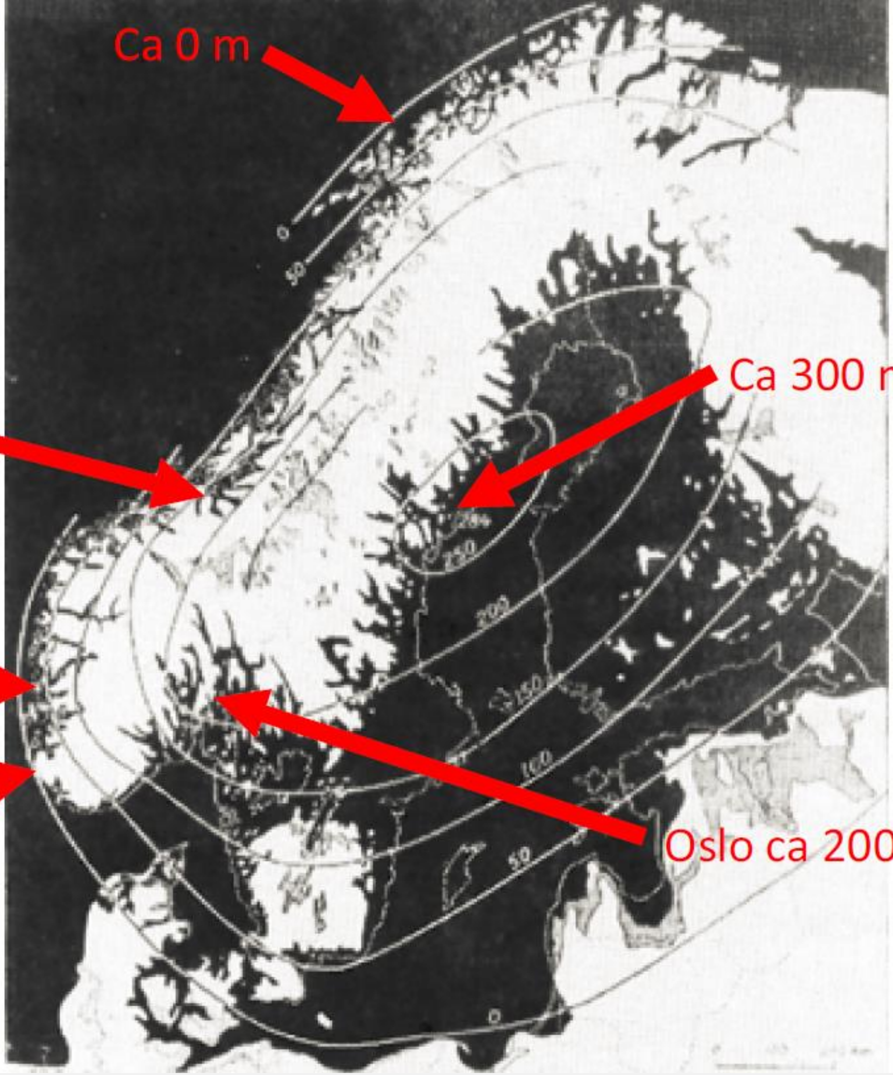


Generation and propagation of rock blast-induced pore pressures in quick clay

Quick introduction to quick clay

- Marine clay with remolded undrained shear strength < 0.5 kPa
- Lifted on-shore after last ice-age
- Encountered up to 200 m above present sea level
- Presence of quick clay coincides with densely populated areas

Result of the last glaciation: Isostatic uplift of after the last ice-age (still ongoing)



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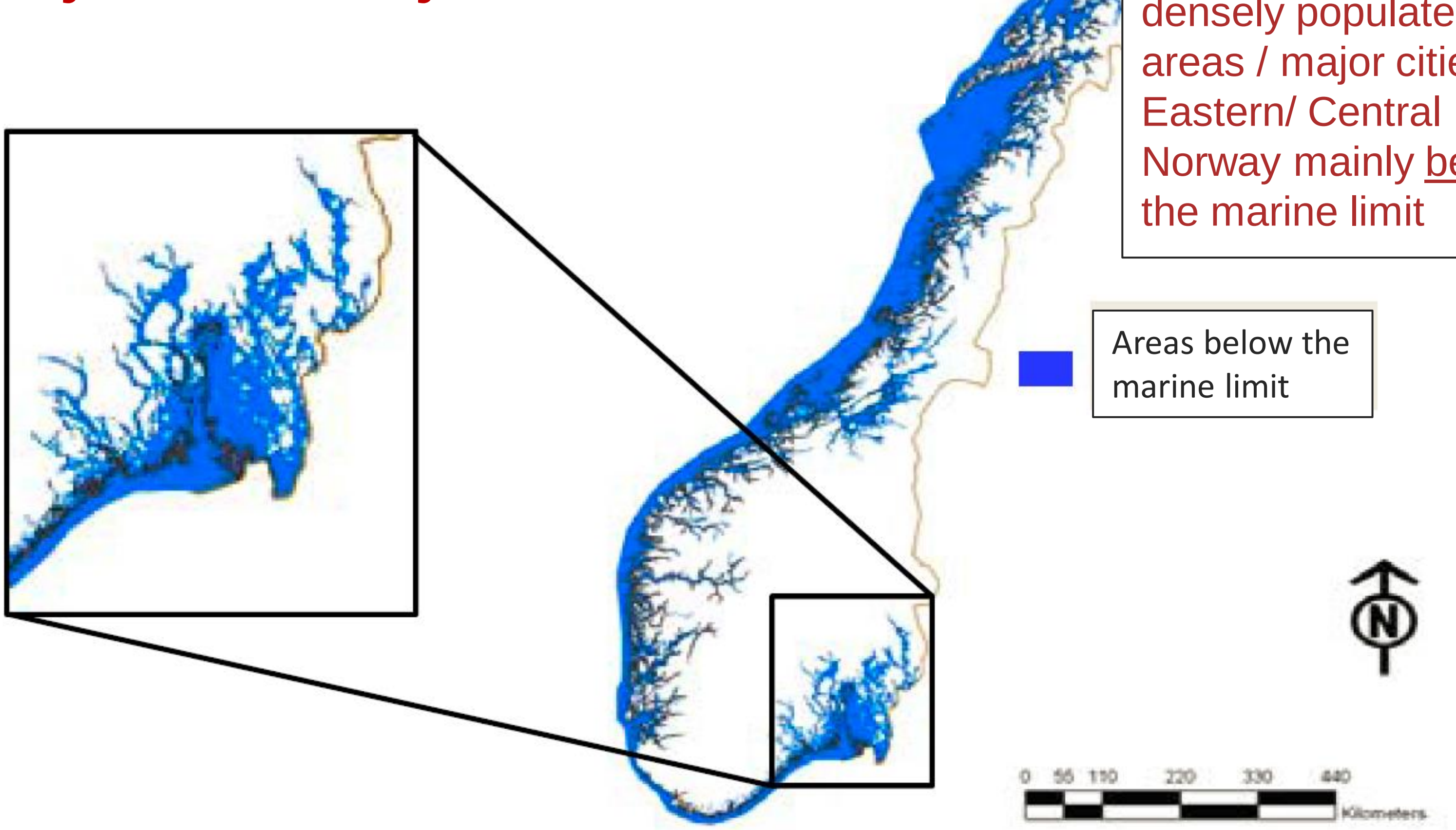
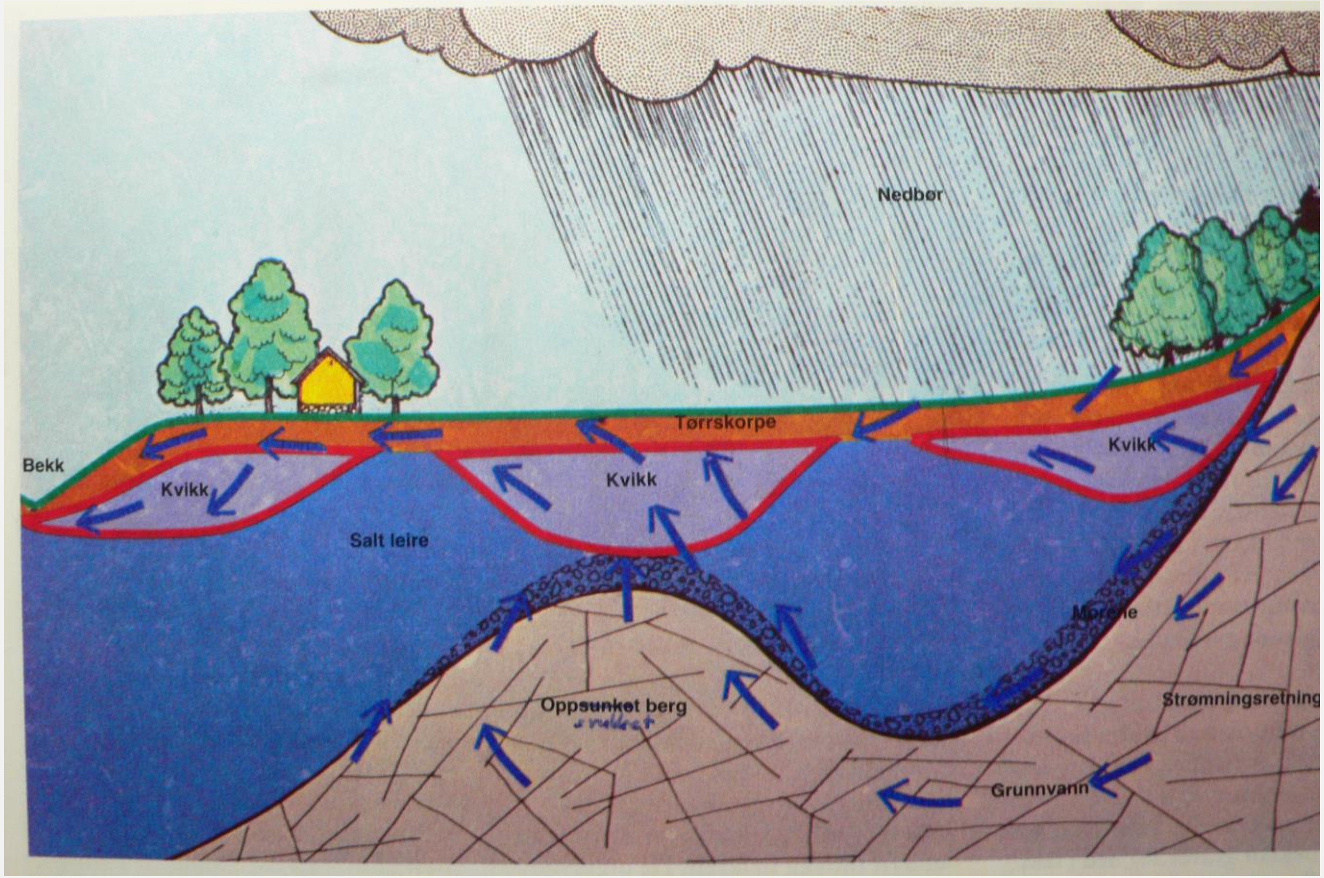
Where do we encounter marine clays in Norway?

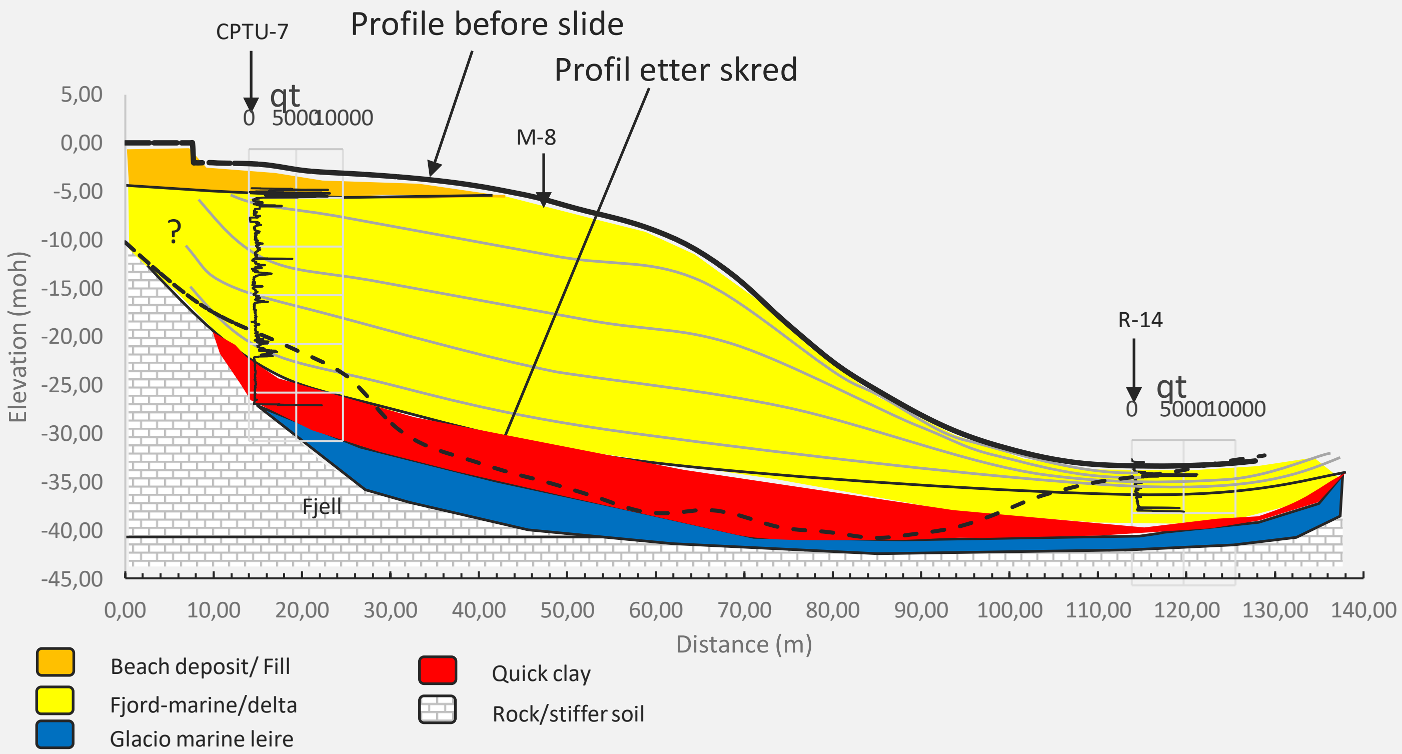
Most of Norway lies above marine limit, but densely populated areas / major cities in Eastern/ Central Norway mainly below the marine limit



Quick-clay: Marine clay leached of salt by percolating fresh groundwater



Example of near shore soil profile



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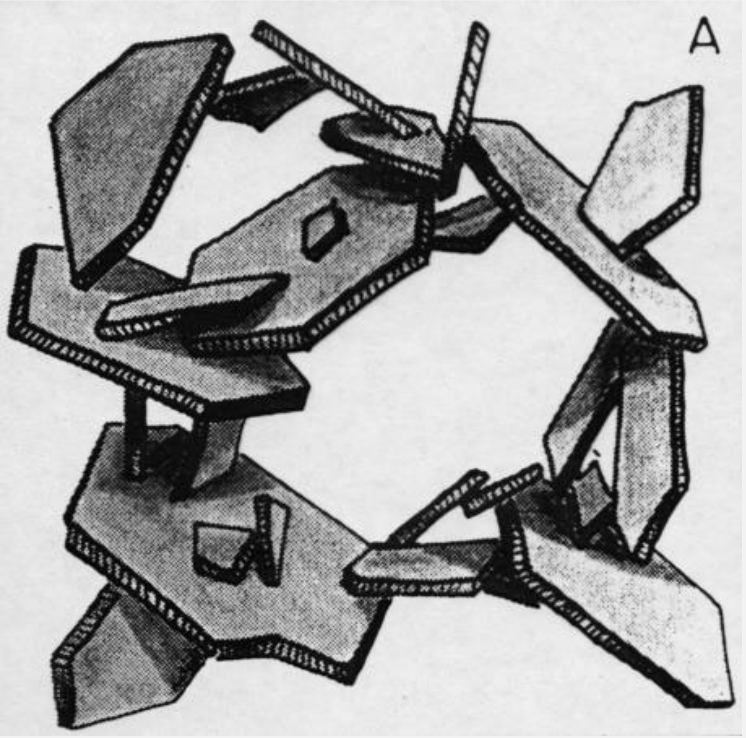
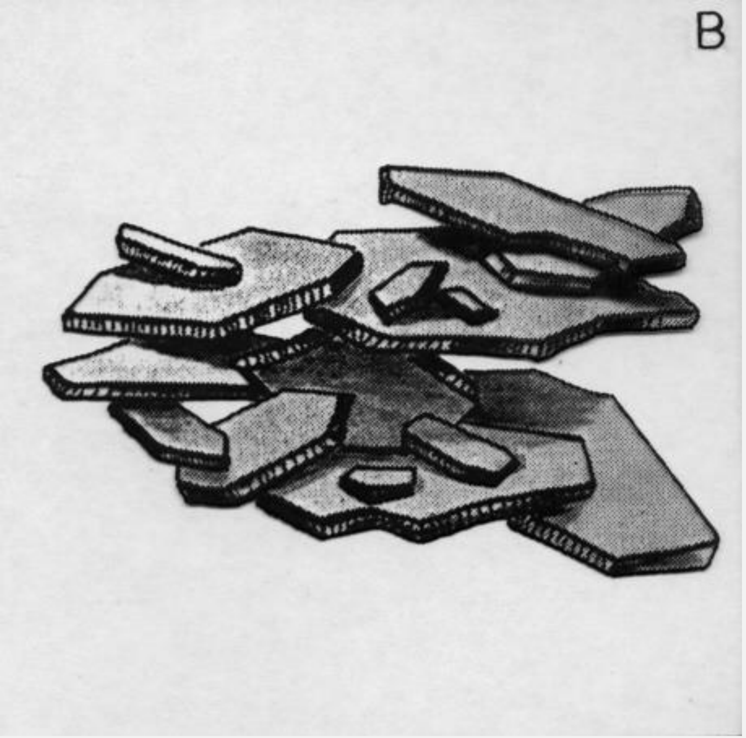
After NVE(Norwegian Water Resources and Energy Directorate) 2014

Salt ions contributes to electric bonding and open structure of marine clays



The structure can easily collapse when salt ions are removed



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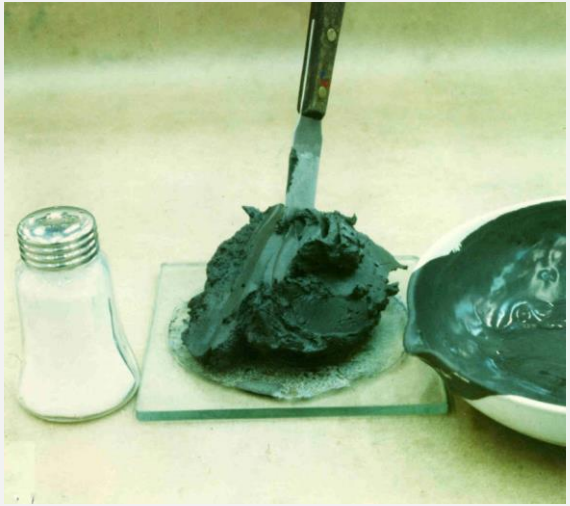
Mechanical behaviour of quick clay

- Undisturbed QC has similar strength as «normal» clay

- After remolding, QC behaves like a viscous fluid

- Increased salt content in porewater stabilises the liquid clay



Tunnelsprengning

- Etter hvert som tunnelfrontene nærmer seg et målepunkt ser vi hvordan vibrasjonene gradvis øker. For hver salve som sprenges (normal framdrift ca. 5 m per salve)
- Skulle vibrasjonene nærme seg grenseverdiene gjøres tiltak for å ikke overskride på neste salve.
- Endringer i salveplanen, bl.a. ved å redusere ladningsmengden. Det gjøres f.eks. ved å redusere salvelengden fra 5 meter til 4 meter, til 3 meter, og så videre.

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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)

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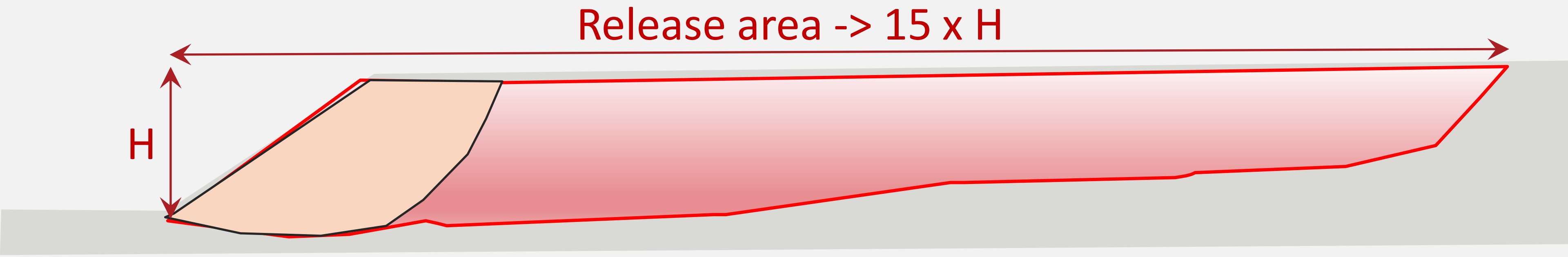
«The quick clay problem» - 1

- 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



«The quick clay problem» 2

- Generally occur without much pre-warning
  - Cracks may develop shortly before, but not often observed
- Lateral propagation of landslide from starting point difficult to assess.
  - 1-2 km lateral propagation seen in Norway and Canada
  - For constant conditions along slope, no natural stop of the propagation
  - Propagation will stop when no quick clay is present in the ground.
  - Narrow ravines that prevent runout is favourable.

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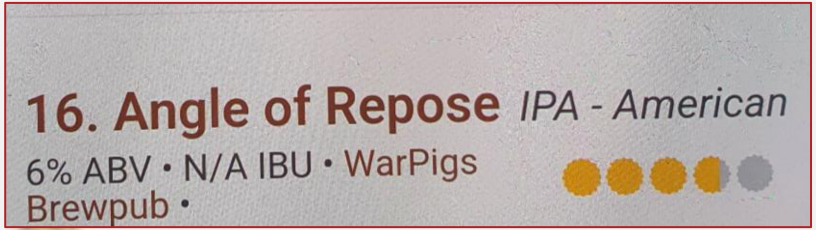
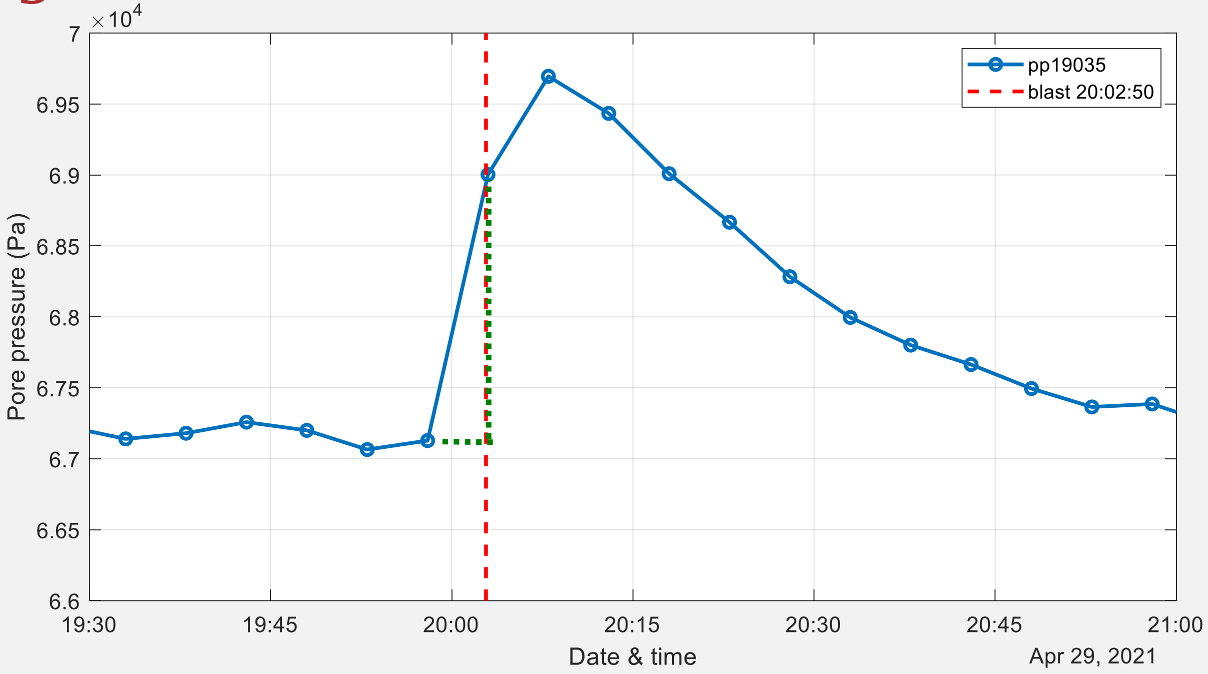
Some rest?


16. Angle of Repose IPA - American
6% ABV • N/A IBU • WarPigs
Brewpub •


ANGLE OF
REPOSE
ALC
6%
VOL
angle of repose

Pore pressure blast 9

- Piezometer 19035 @10 m depth.
- Pressure around 67 kPa, Increase ~2.5 kPa
- Vibrations ~40-60 mm/s at 5 m depth and 30-40 mm/s at 3.5 m depth
- Cyclic strain 0.05-0.1 % (?) at 3,5-5 m depth



Time	Strain (%) @3,5m depth	Strain (%) @5,0m depth	Pore Pressure change (kPa) @10 m depth	Pore pressure Ratio u/σ_v'
14:46:36	0.02	0.01	~0.8	2%
20:02:50	0.03 (0.07%)	0.02 (0.08%)	2.6	6%

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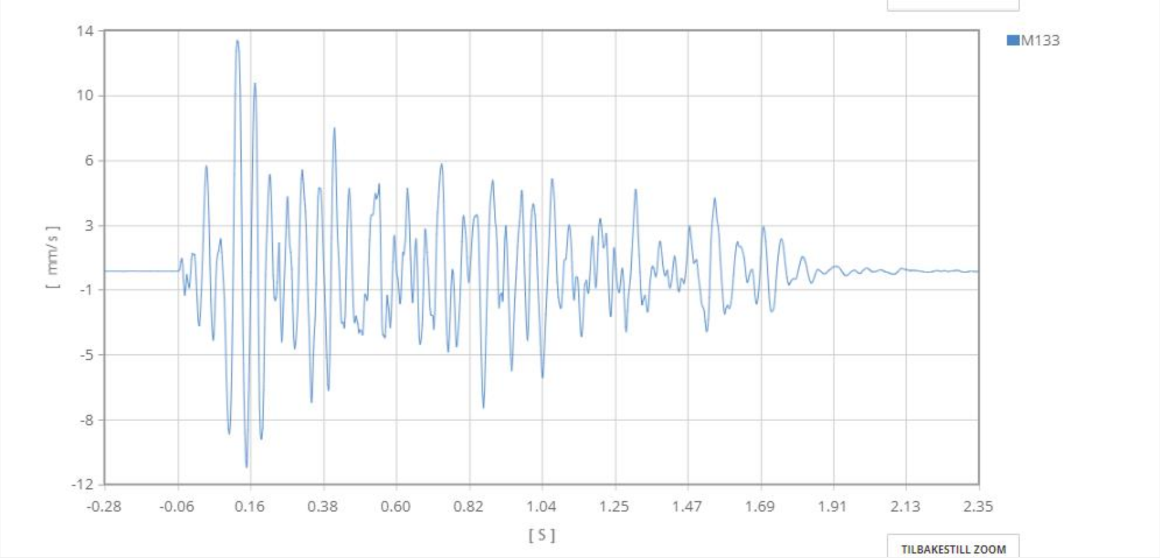
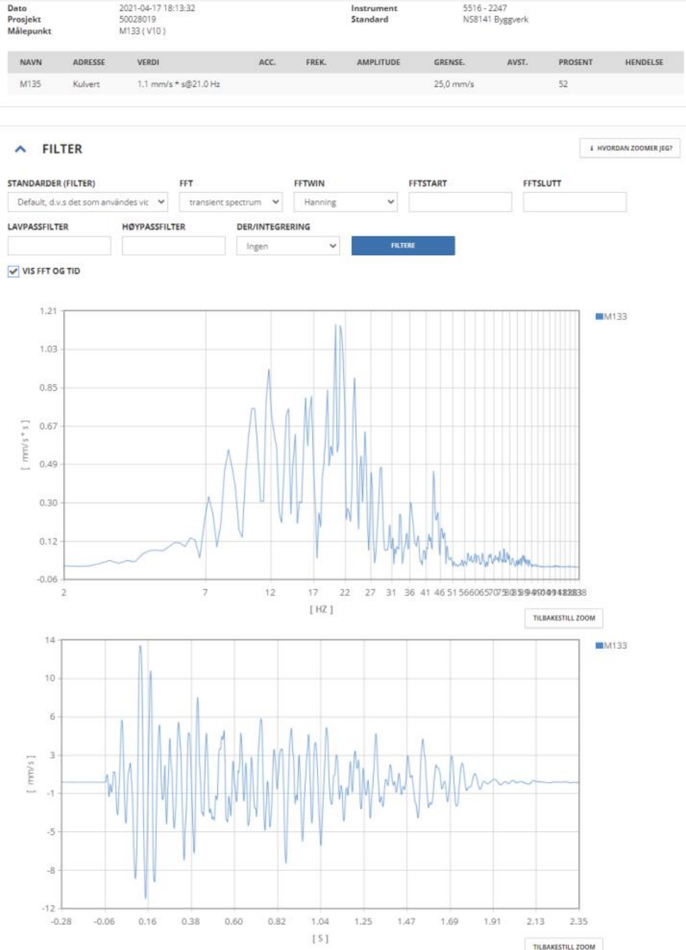
Ground water seeping out of layer in slope

- Vibrations not the cause?
- How large were the vibrations

https://www.veier24.no/artikler/250-meter-av-fylkesvei-98-i-tana-ble-tatt-av-ras/509269

Tana vibrasjon på 100 m fra sprengning





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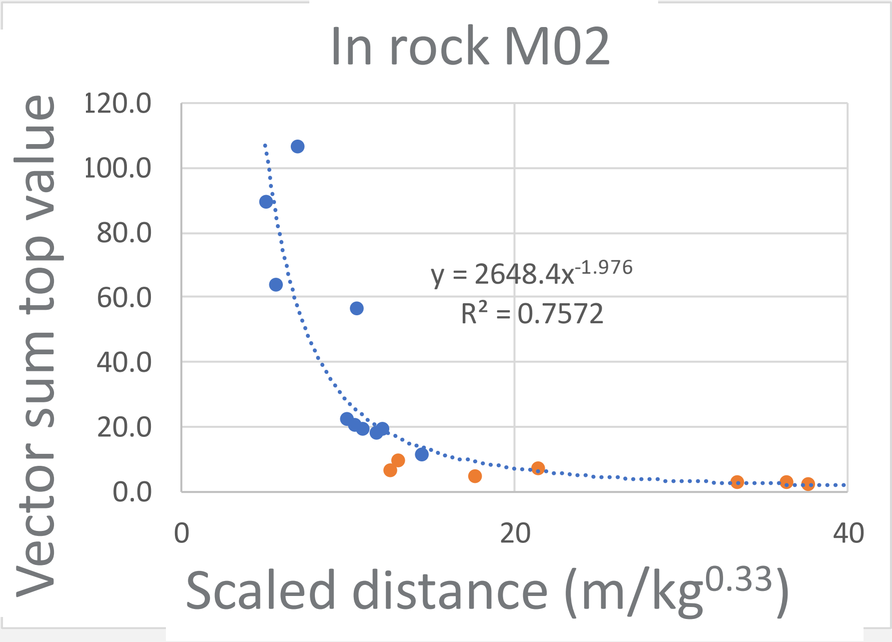
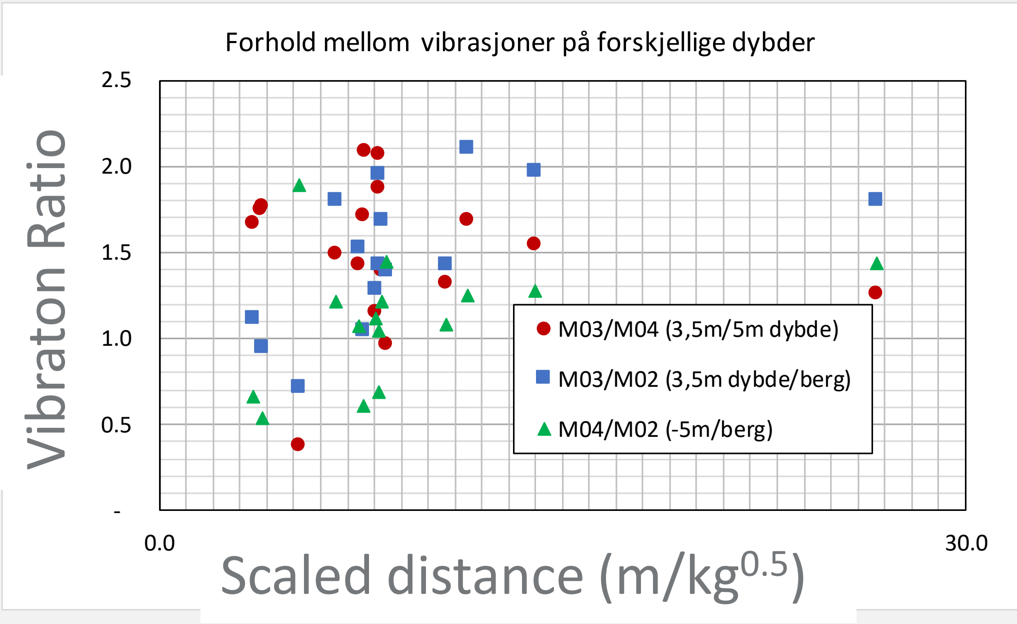
Vibrations brief overview





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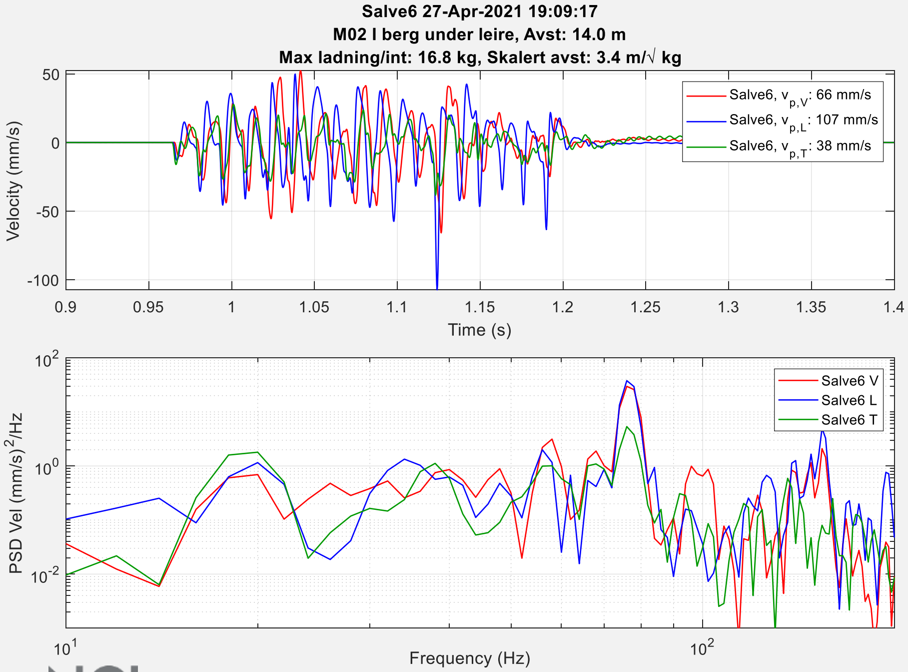
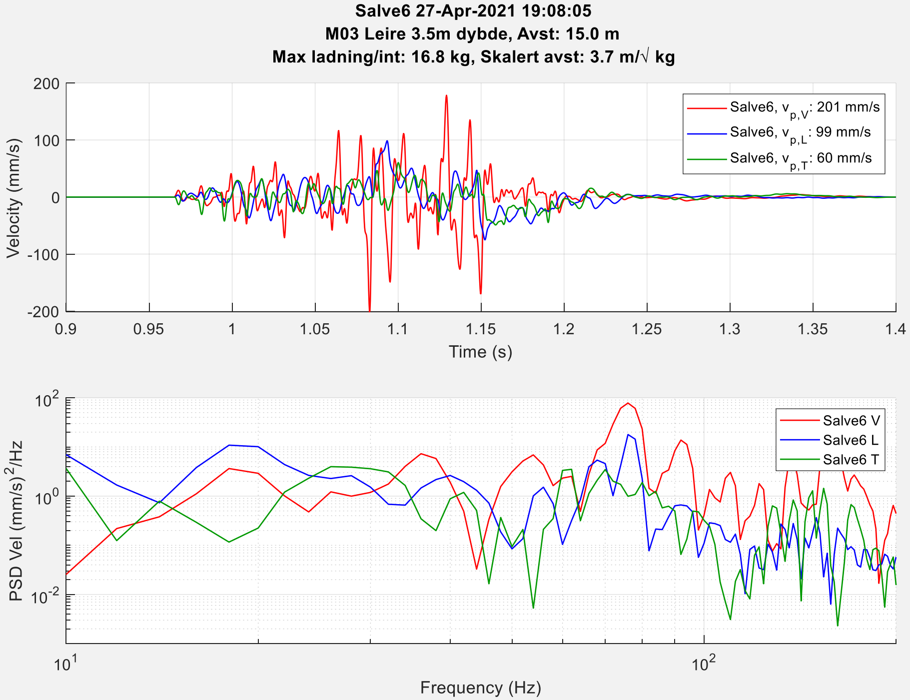
Vibrations blast 6

- 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





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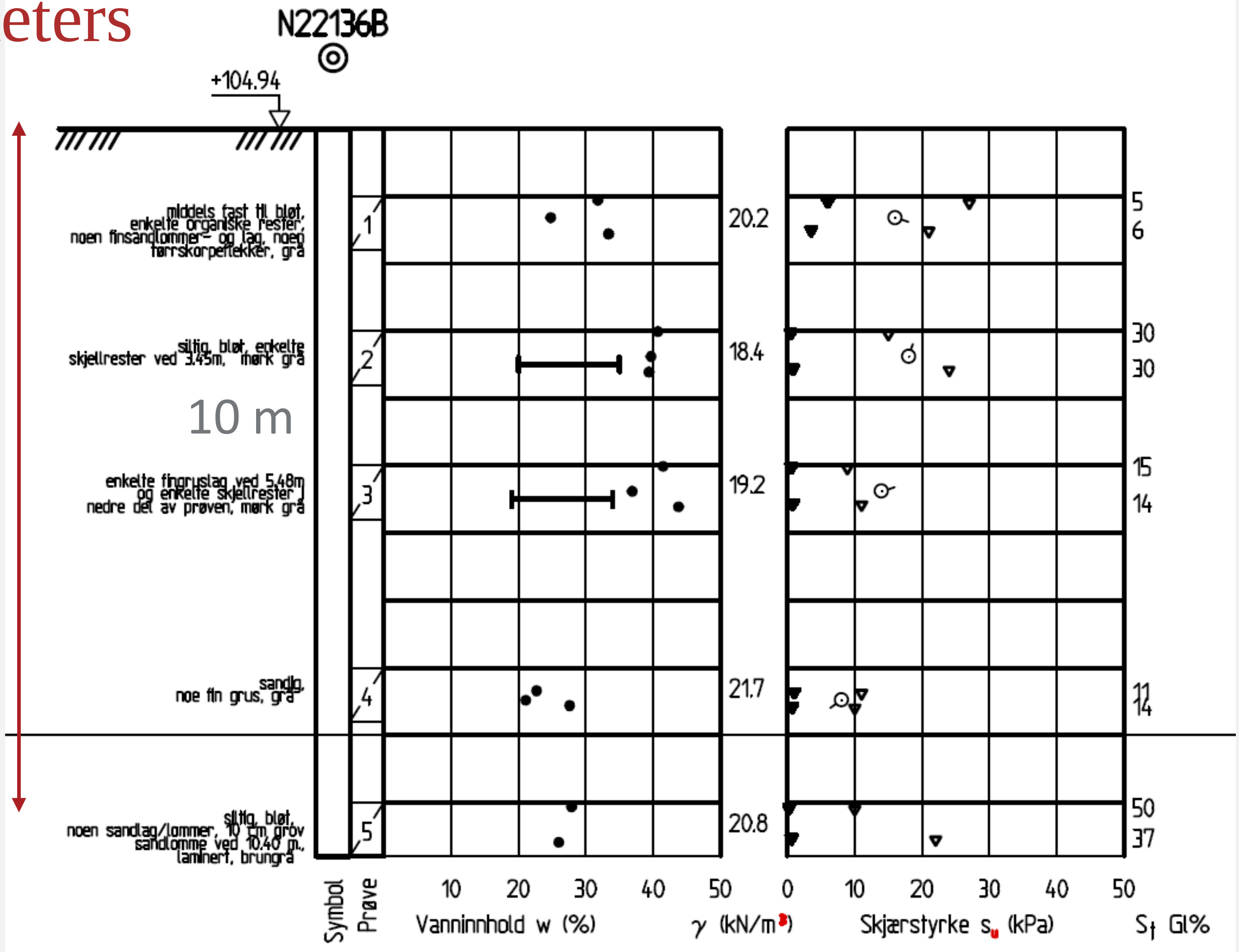
Soil properties

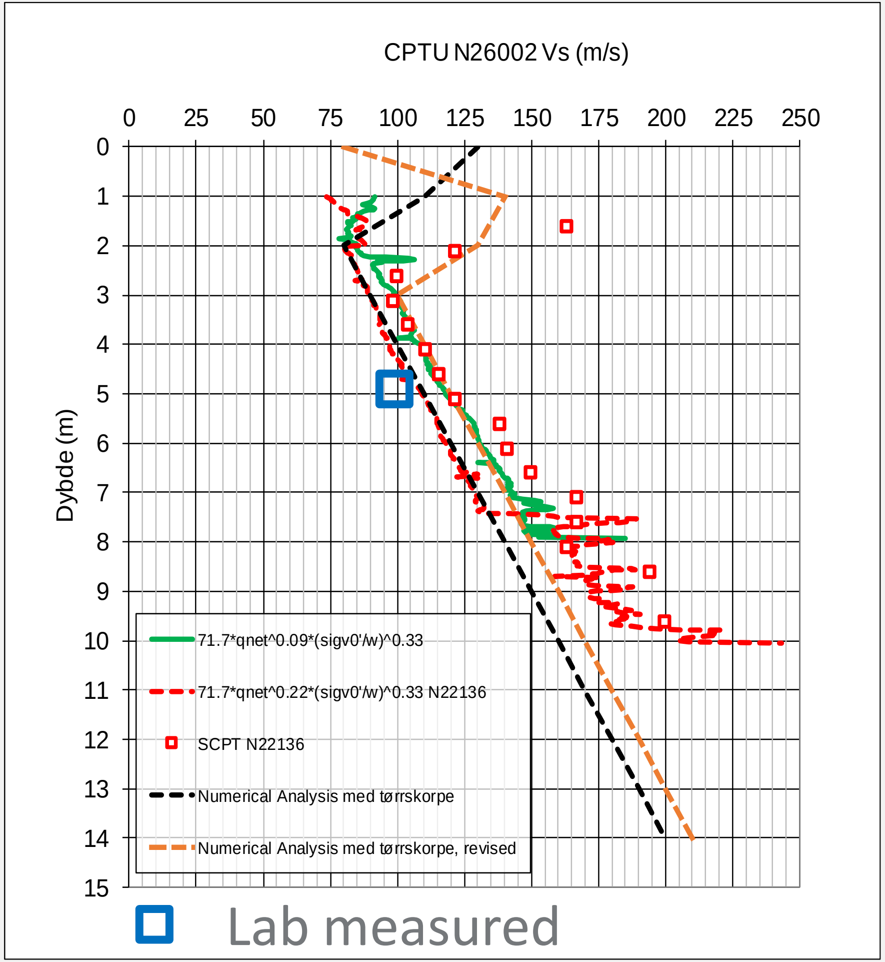
Soil index parameters

- PI=15%
- OCR=1.3
- Rho=19 ton/m^3
- Water content 40%



Estimated and measured shear wave speeds (N26002)

- Shear wave speed estimate at blast site. Dark Red line.
- Measured in lab 100 m/s with bender element (77 kPa eff. vertical stress)
- Varying depth to bedrock
- Assumed linear increase with depth of Vs



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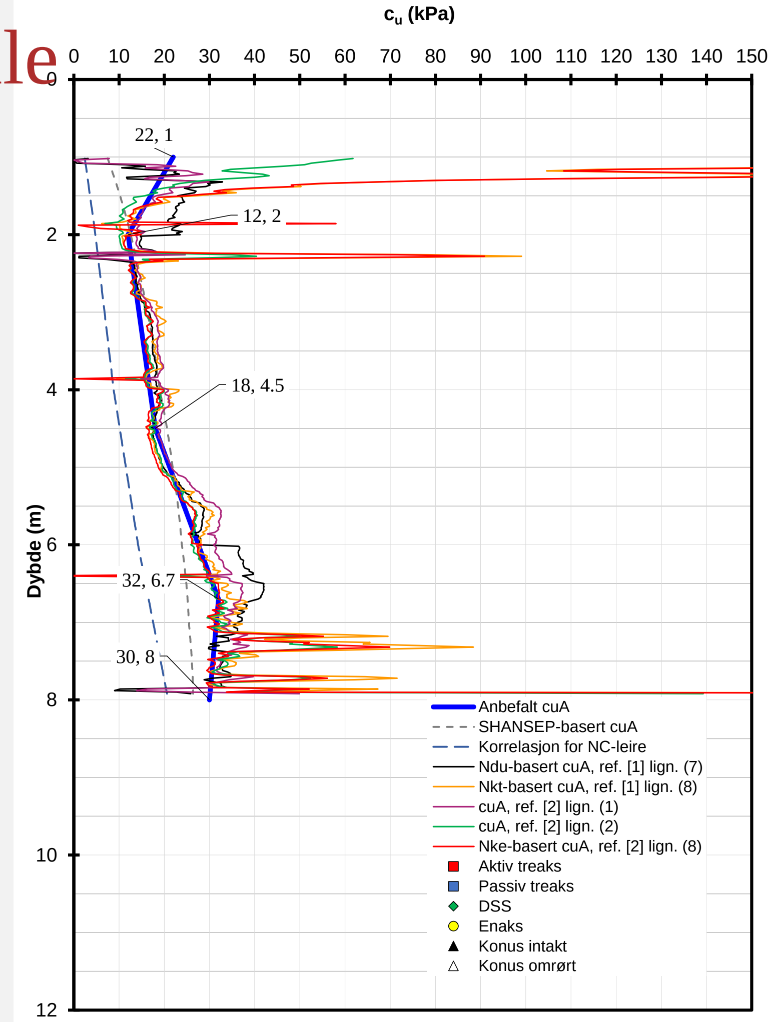
Undrained shear strength, SuA Profile

- Su,DSS=0.65*Su,Active (compression)



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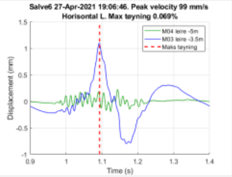
Strains from measurements

- γ=0.1% (from displacement)
- γ=0.14% (from velocity)



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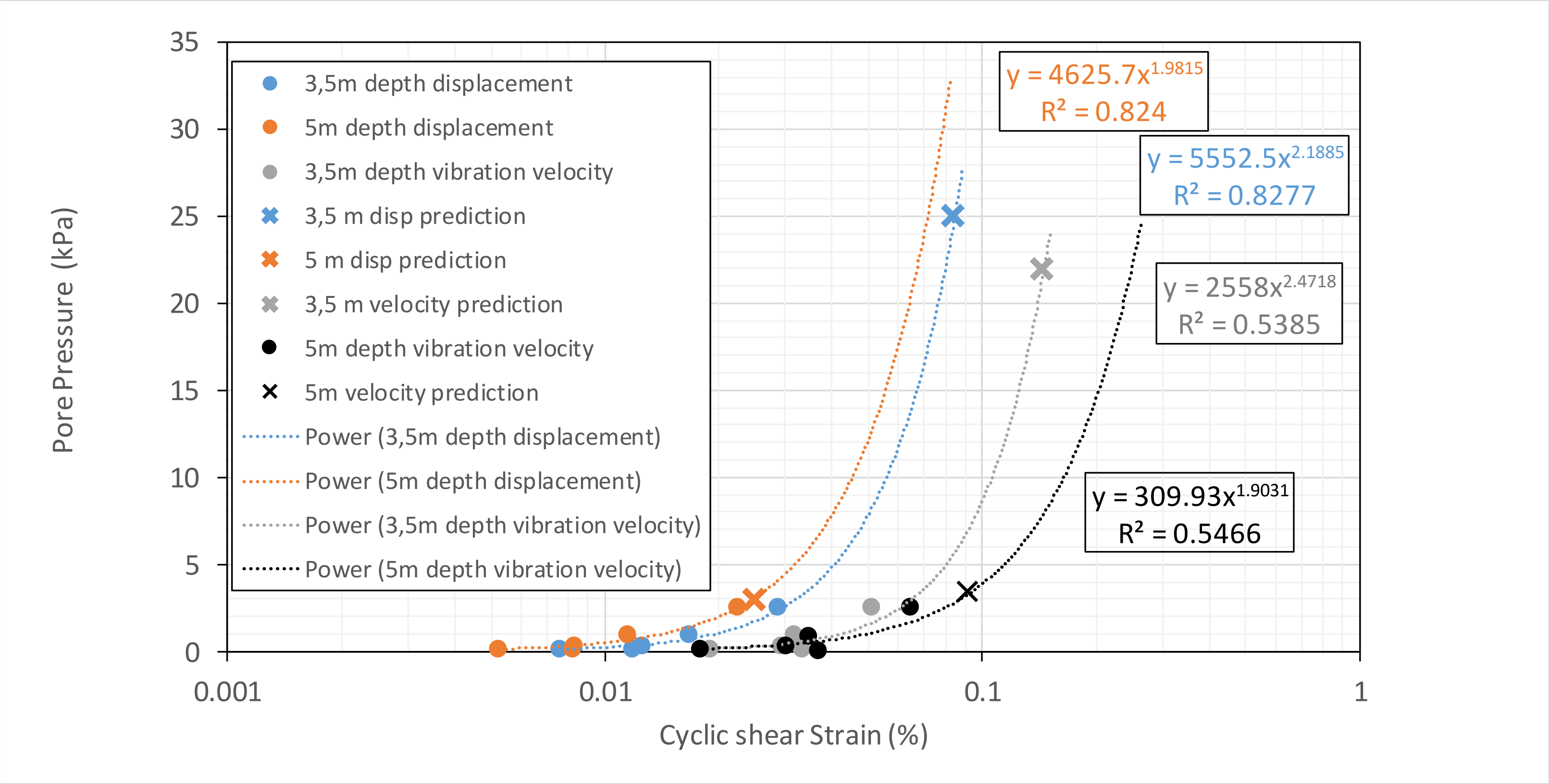
Measured pore pressures



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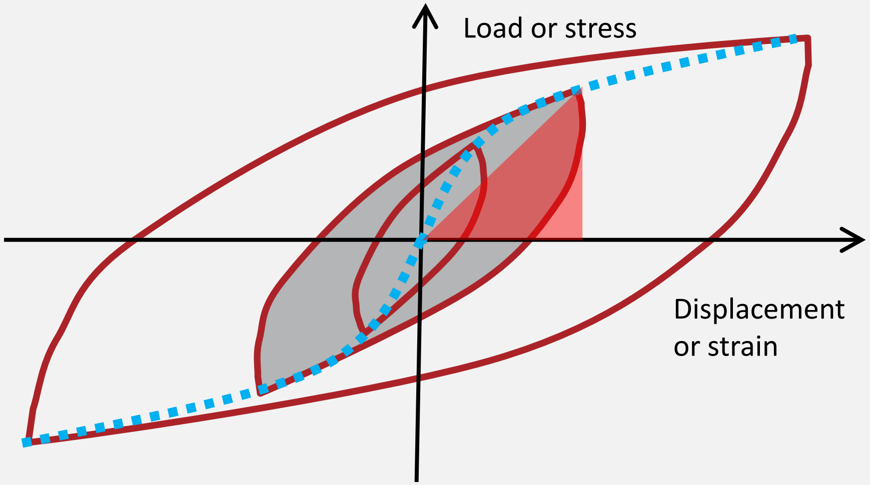
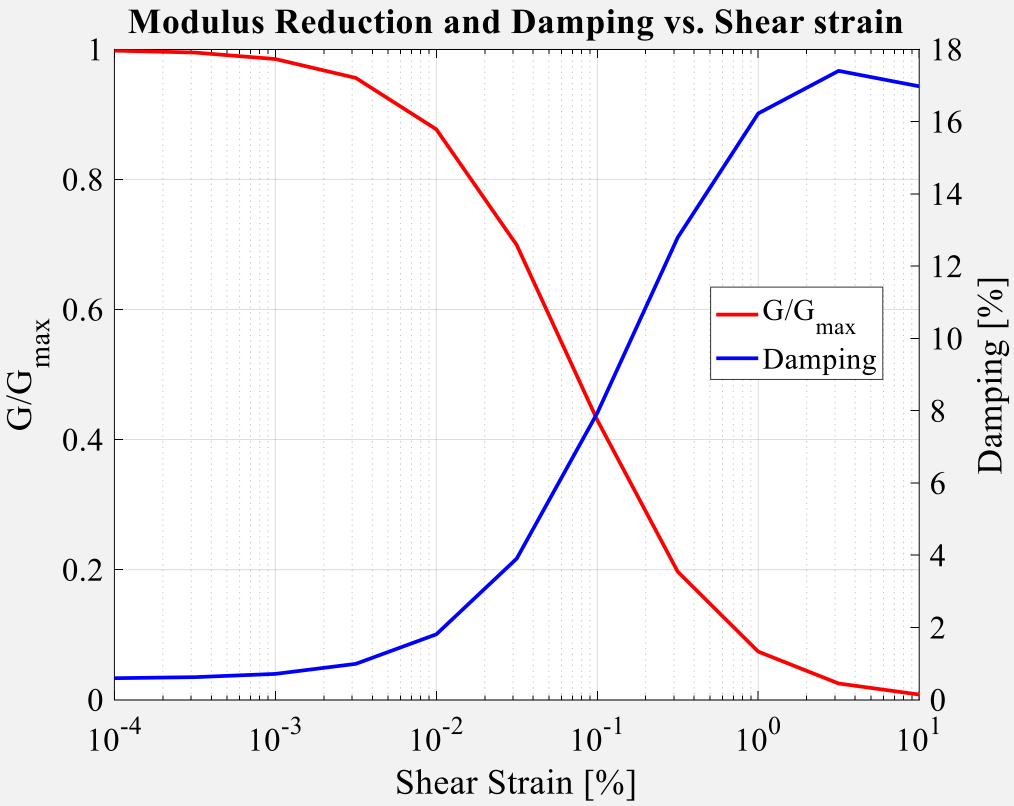
Soil Nonlinearity





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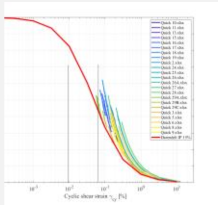
Modulus reduction

- Quick clay test based in this for comparison
- Darendeli G/Gmax in red for overburden effective stress of 60 kPa.
- Quick clay curves for about 80-90 kPa
- G/Gmax curves sensitive due to uncertain Gmax evaluations



Numerical Model

- Equivalent linear model was implemented in the frequency domain in Comsol Multiphysics based on a hyperbolic model
- Shear Modulus Reduction and material damping curve based on laboratory empirical equations

$$-\rho\omega^2 \mathbf{u} = \nabla \cdot S + \mathbf{F}_V e^{i\phi}, \quad -ik_Z = \lambda$$

$$S = S_{ad} + 2G_s \cdot \mathrm{dev}(\epsilon_{el}) + K \cdot \mathrm{trace}(\epsilon_{el})I - \left(\mathrm{trace}(\mathbf{C} : \epsilon_{el})/3 + p_w\right)I, \quad \epsilon_{el} = \epsilon - \epsilon_{inel}$$

$$S_{ad} = S_0 + S_{ext} + S_q$$

$$\epsilon_{inel} = \epsilon_0 + \epsilon_{ext} + \epsilon_{th} + \epsilon_{hs} + \epsilon_{pl} + \epsilon_{cr} + \epsilon_{vp}$$

$$\epsilon = \frac{1}{2}\left[(\nabla \mathbf{u})^T + \nabla \mathbf{u}\right]$$

$$G_s = G\frac{1}{1+\left(\frac{\gamma}{\gamma_{ref}}\right)^n}, \quad G = \frac{E}{2(1+\nu)}, \quad K = \frac{E}{3(1-2\nu)}$$

$$G_s = G\frac{1}{1+\left(\frac{|\gamma|}{\gamma_{ref}}\right)^n}$$

$$G_s^* = G_s(1+i\eta)$$

$\eta = 2D$, where D is the hystertic damping

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Summary and conclusions

- Two data sets of vibrations and pore pressures have been gathered. Preliminary findings are:
- Pore pressures:
  - Surface blasting: Pore pressures of 2-3 kPa for vibrations on the order of 50 mm/s
  - Tunnel blasting 5-10 kPa, for possibly 100 mm/s – 200 mm/s in the boundary between rock and clay
  - Pore pressure dissipate quickly with 1-2 hours for surface blasting, 2-4 hours for tunnel blasting
  - Peak pore pressure occur some time after blast indicate a pressure wave propagating out to surrounding soil
  - Prediction of pore pressure not easy with large number of uncertain variables → monitoring needed preferably with pressure readings every minute or so
- Vibrations
  - Tunnel blast signals last some 4 times the surface blasts → more load cycles to build up pore pressures
  - Tunnel vibrations come from below, depending on soil thickness, larger overburden pressure, soils near rock boundary have higher strength and stiffness, likely less susceptible to vibrations?

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Content

- Bakground
- Namsos, First project 2010-2012 -> NS8141-3:2014 vibration limit 25 mm/s
- Examples of slides by blasting
- Two new data sets with vibrations and pore pressures
  - Surface blasting
  - Tunnel blasting
- Preliminary findings

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