Measuring variability of lime cement columns in lab and field

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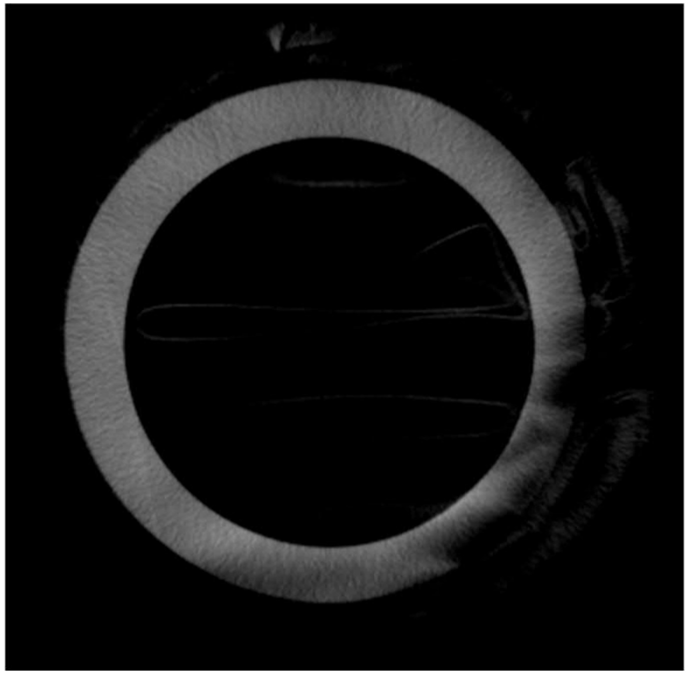
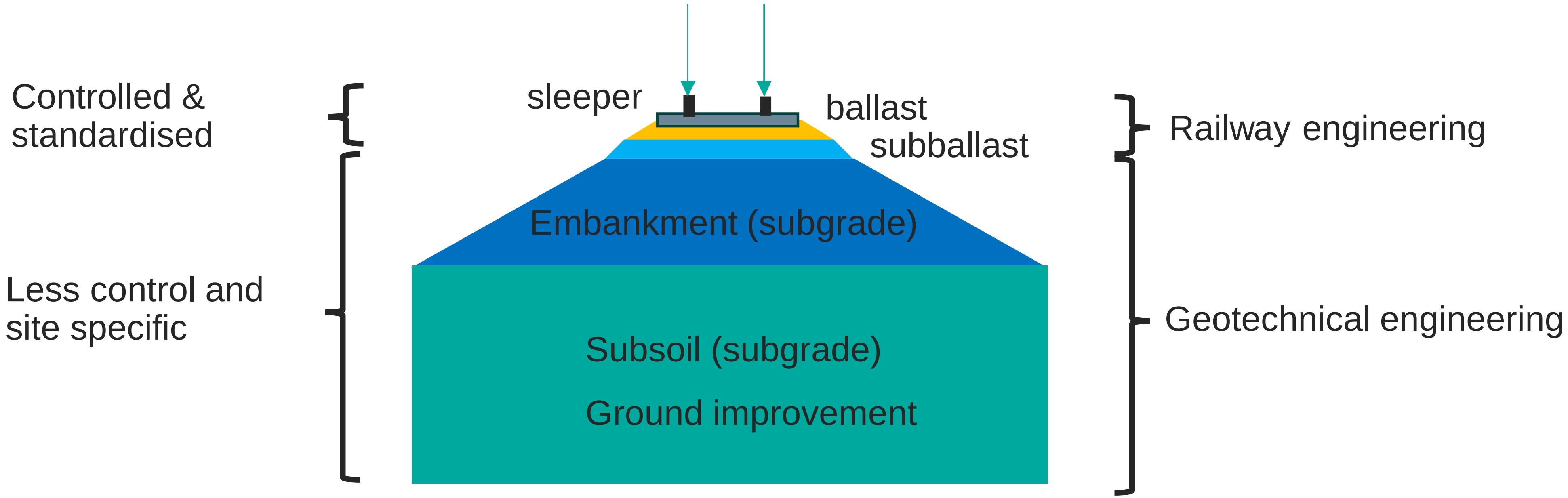
Outline

- Background
- Determination of stiffness
  - E18, Norway
  - Centralen, Göteborg
  - Lärje, Göteborg
- Conclusions & outlook



Background

- Need for system perspective over lifetime of structure
- Track stiffness and alignment is response of more than the track & ballast



Background

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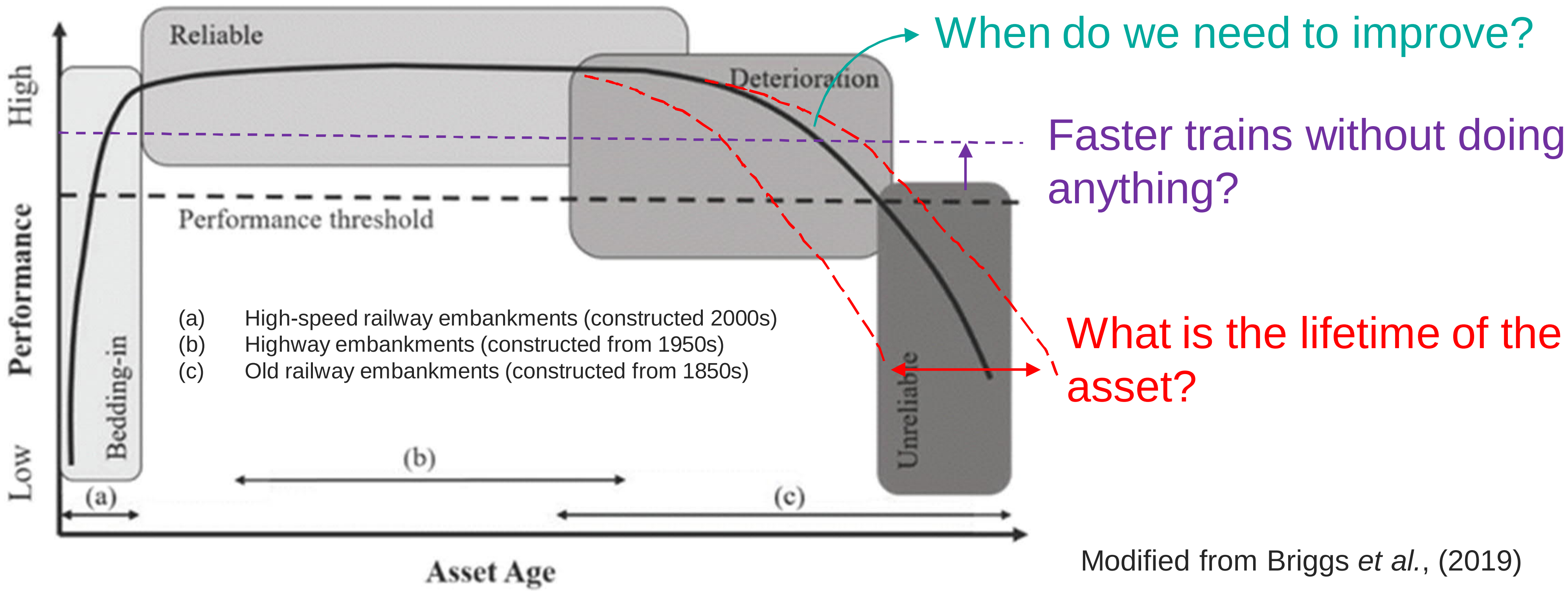


Modified from Briggs *et al.*, (2019)

Background

- Geotechnical design of foundations of physical railway infrastructure focused on assessing
  - Stability (ULS)
  - Settlements (SLS)

- For complex projects complemented with assessment of dynamic response of track-foundation-system
  - Whilst meeting track stiffness (of railway structure)
  - Critical track velocities (ULS)
  - Vibrations in the foundation and the soil (SLS)

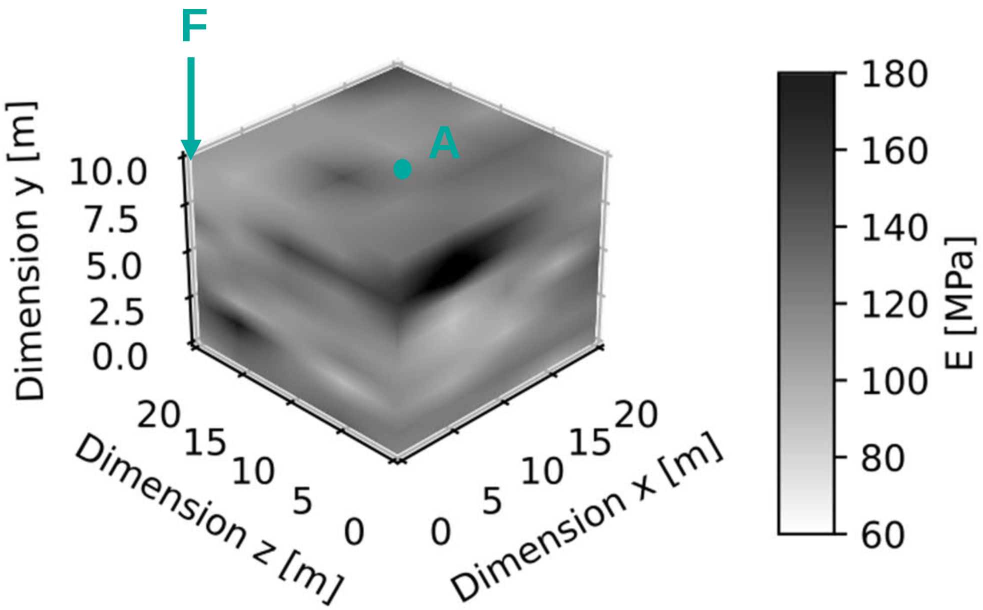
processes physically linked

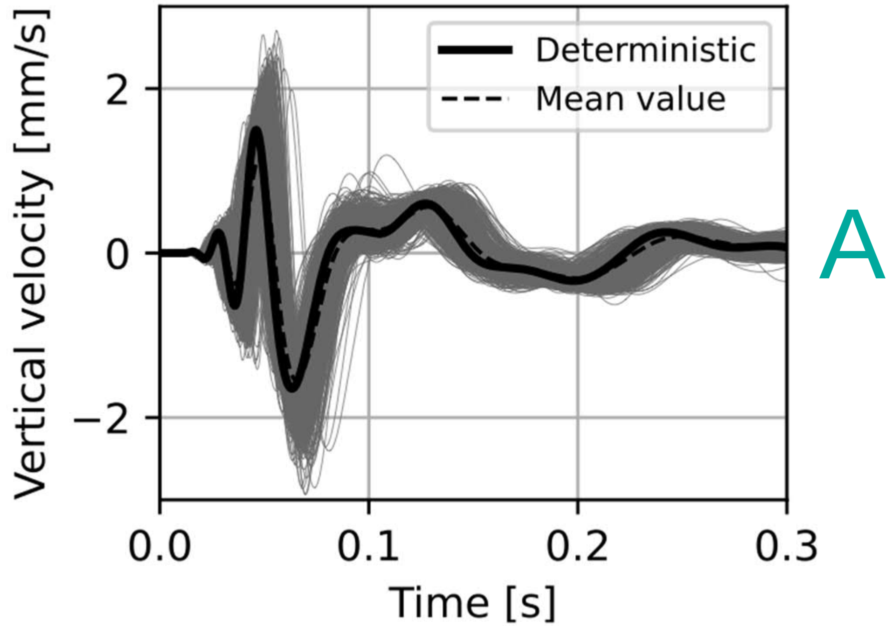
analysis is not

what about guidelines?

Background - vibrations

- Peak velocities and arrival times strongly affected by spatial variation of stiffness





Zuada Coelho *et al.*, (2023)

Background - vibrations

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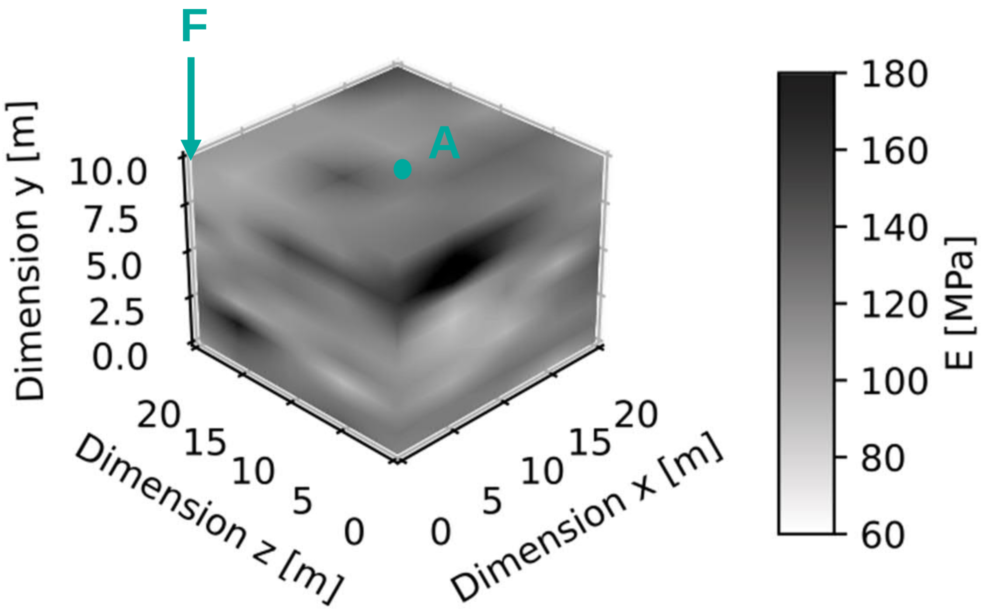
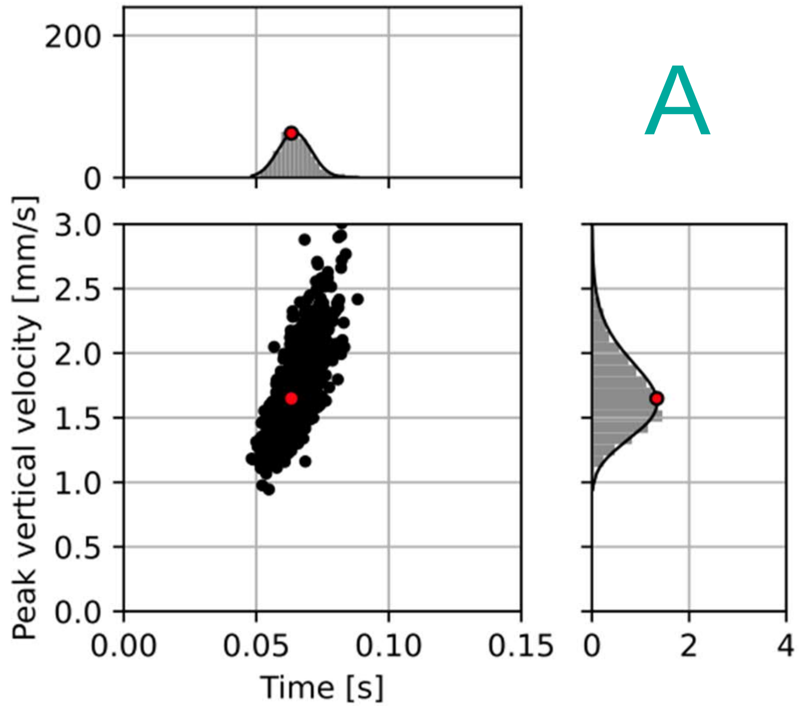


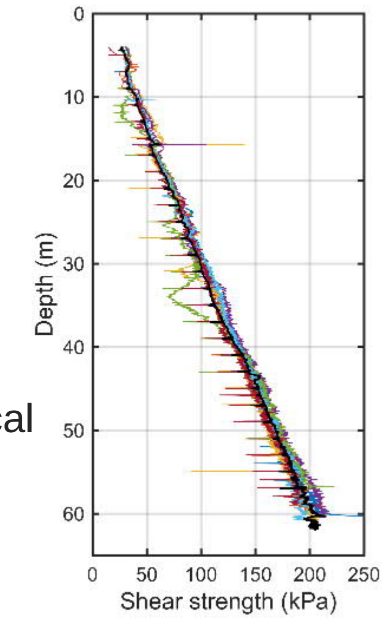


Zuada Coelho *et al.*, (2023)

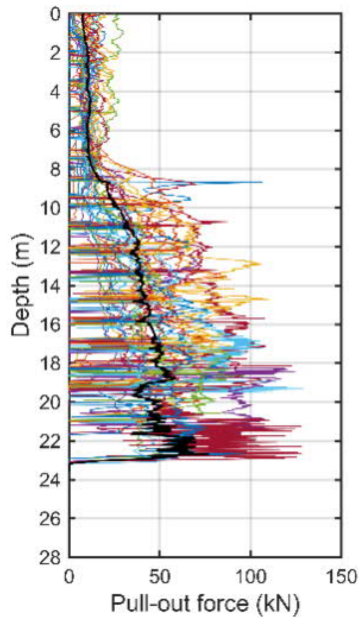
● deterministic result

Background - vibrations

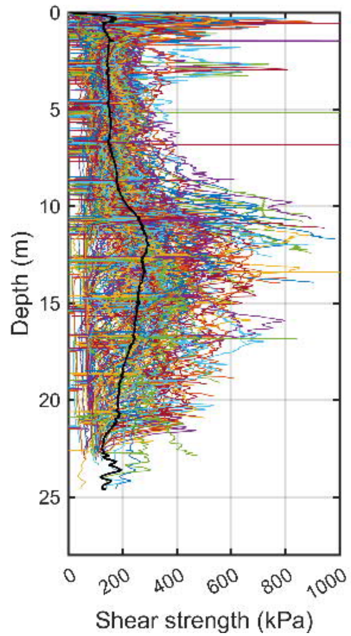
- Soft soils are often improved using Dry Soil Mixing
  - Increase in strength
  - Increase in stiffness
- Method increases spatial variability
  - FKPS
  - FOPS
- What about (small-strain) stiffness
  - Can we measure G_s of LCC with geophysical techniques?
  - Link to strength and variation in density?
  - What about time?



Clay (CPT)



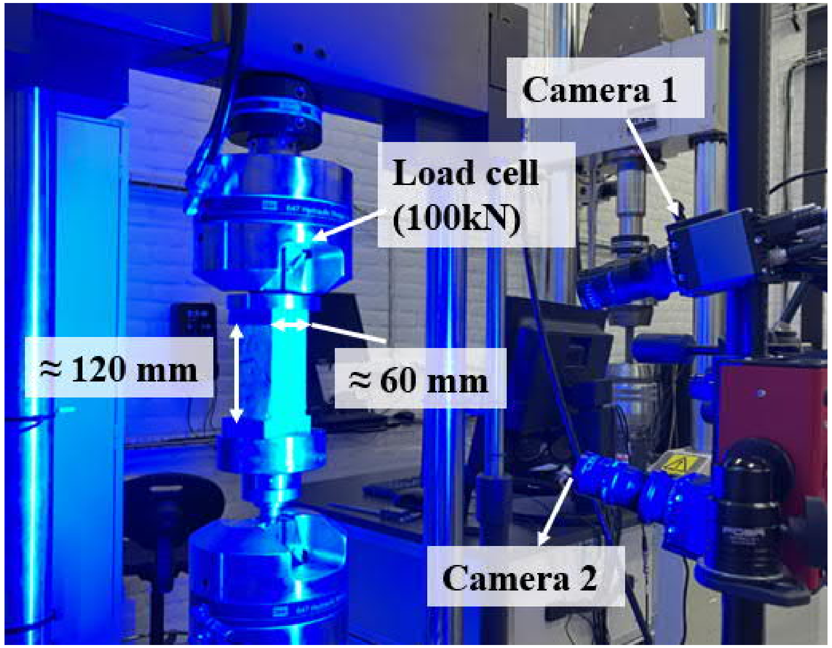
Column (FOPS)



Column (FKPS)

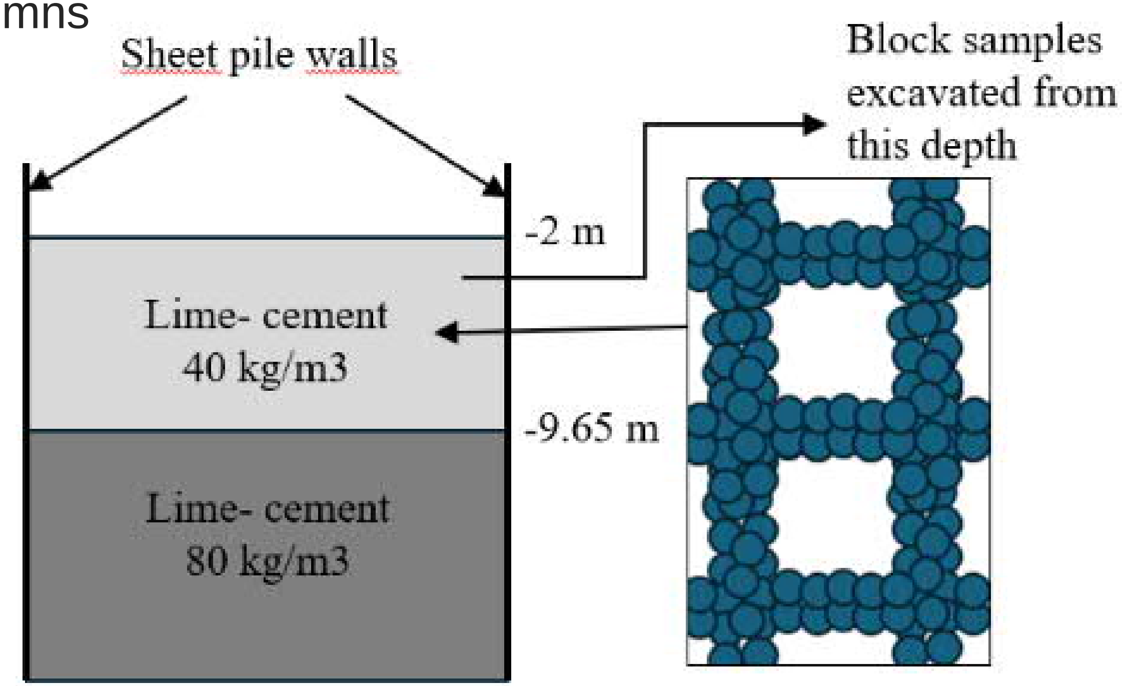
Determination of stiffness (in stabilised clay)

- Seismic methods (non-destructive)
  - Stiffness interpretation is in-direct via measured shear wave velocities
- Laboratory
  - UCT
  - Triaxial test
  - (Cube test, wedge splitting test)
- Empirical via correlation with
  - Strength
  - Fracture energy
  - Electrical resistivity



Centralen Göteborg

- FKPS and FOPS data from production columns
- Block samples from top layer
  - UCT
  - Cyclic triax
  - Prismatic test + DIC



Centralen Göteborg

- **Laboratory scale**

1. Unconfined compressive strength test (UCS)
2. UCS test with Digital Image Correlation (DIC)

Block samples from field (1 year)

6 tests (4 with extensiometer readings)

2 tests

- **Field scale**

1. Predrilled Cone Penetration test (FKPS)
2. Reverse Cone Penetration test (FOPS)

Data from tests (1-5 days)

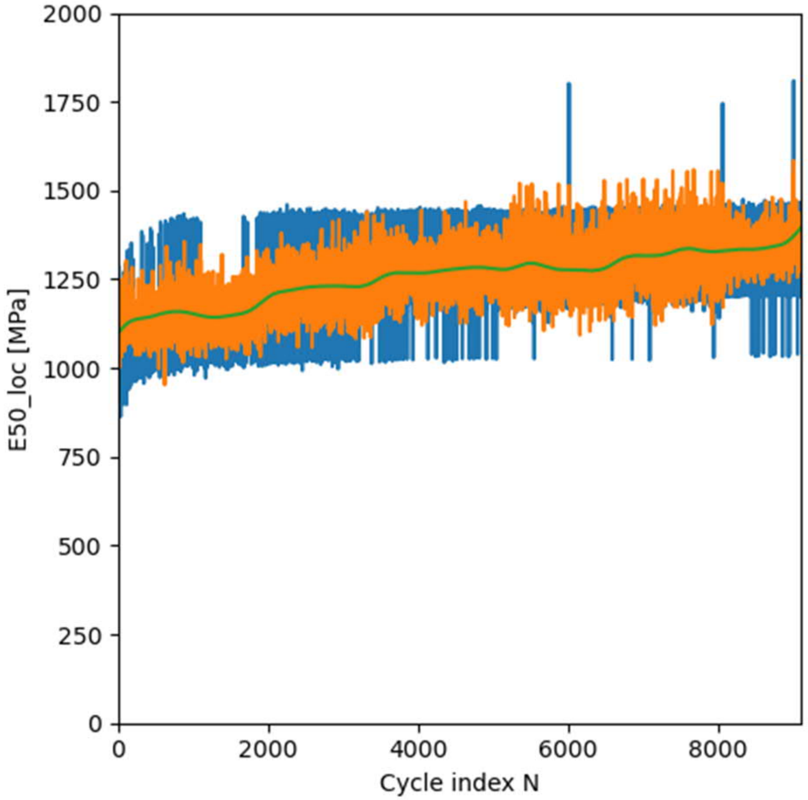
Data from depth 2-8 m ($40\ kg/m^3$ binder content)

Data from depths10 – 18 m ($80\ kg/m^3$ binder content)

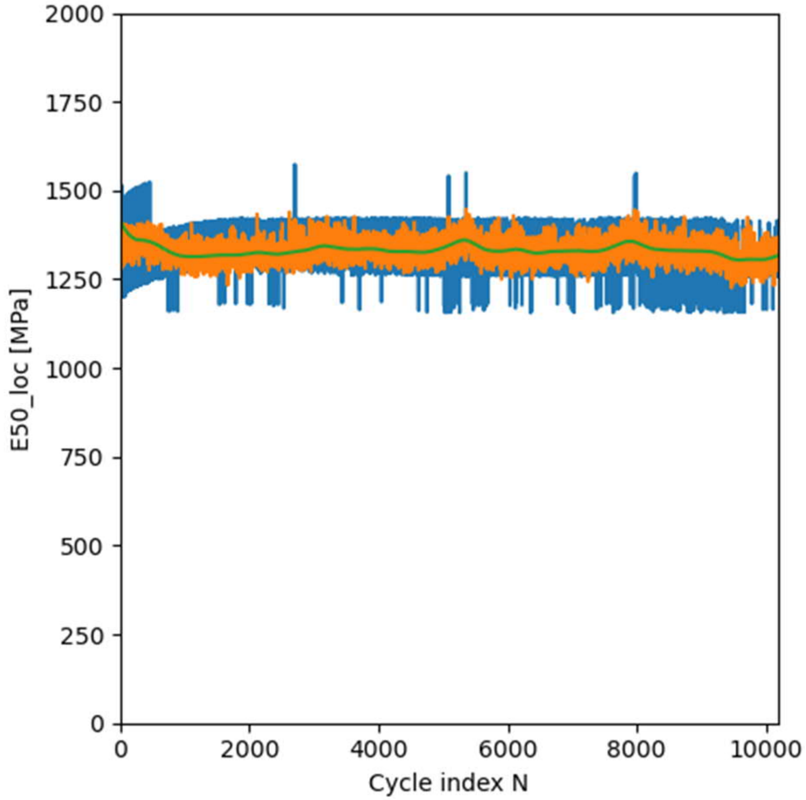
1 year old samples – 6 UCT tests

Parameter	Low [MPa]	High [MPa]	Standard deviation [MPa]
q_u	1.03	2.56	0.65
E	199	398	68
E_{50}	211	319	921
E_{local}	589	3122	921

1 year old samples – cyclic triaxial

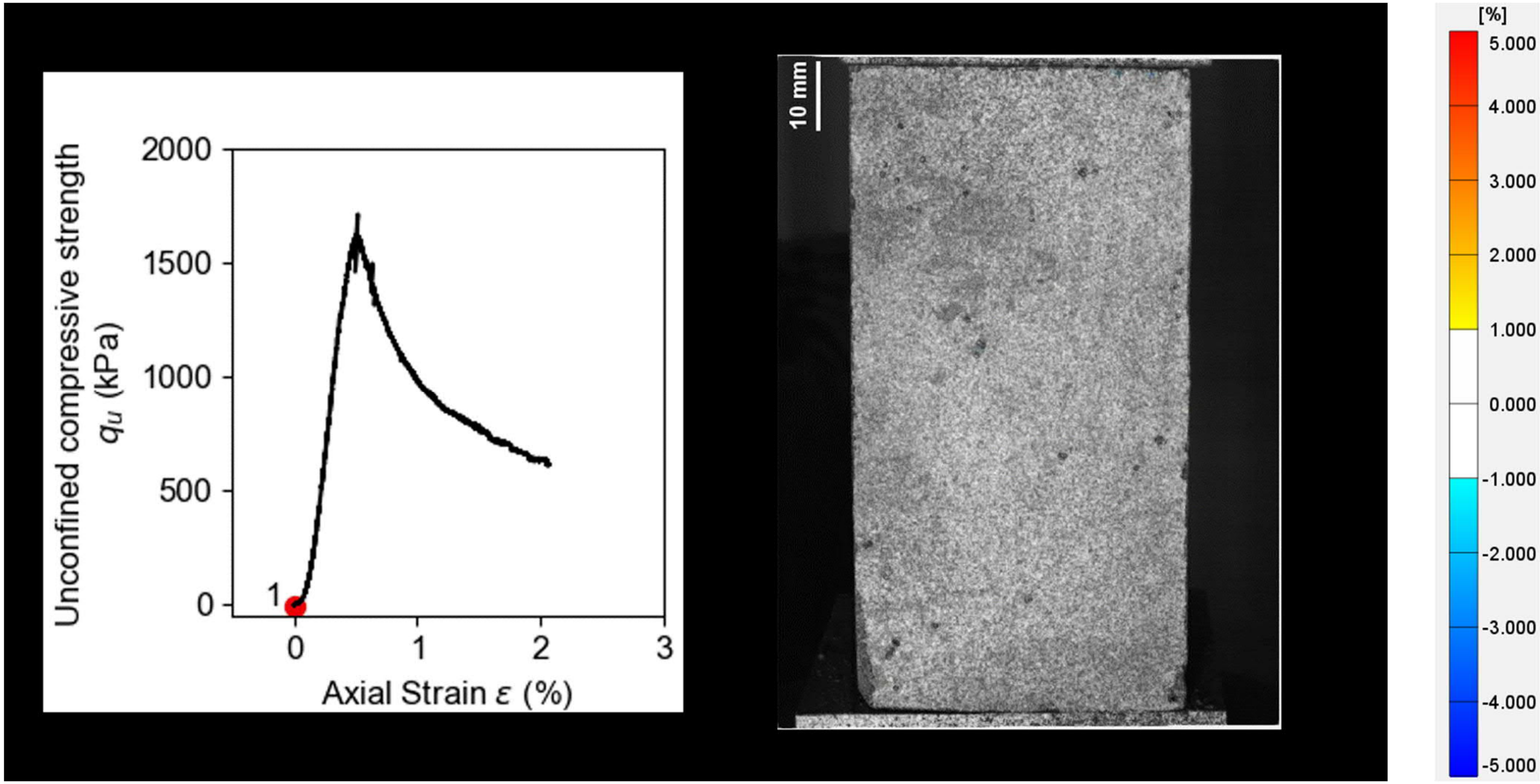


q_{cyc} = 100 kPa



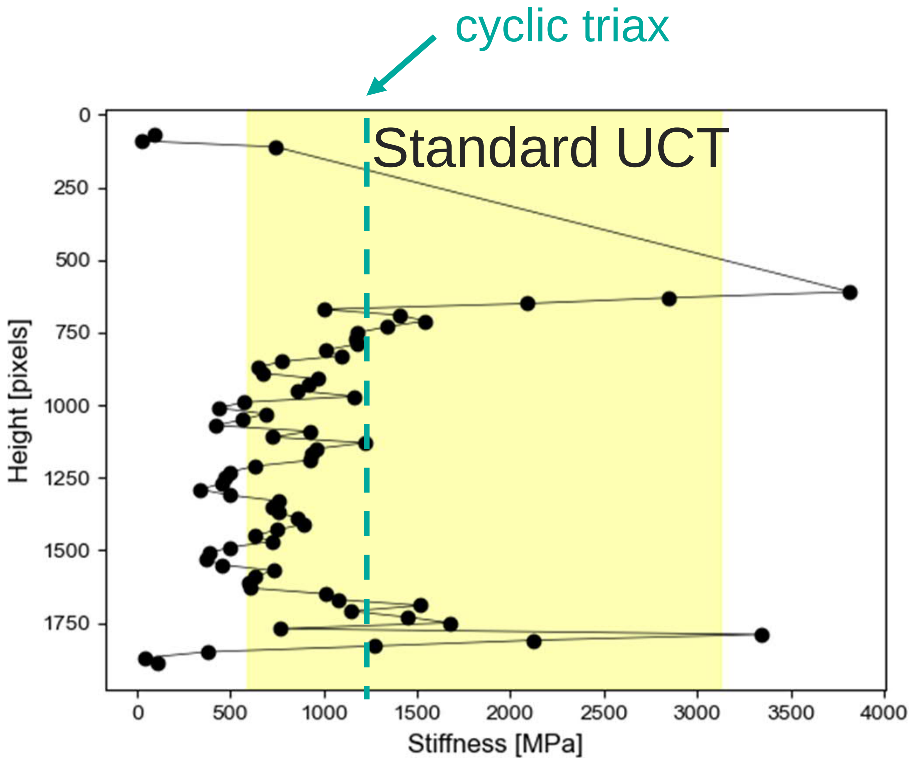
q_{cyc} = 250 kPa

UCS test + surface DIC



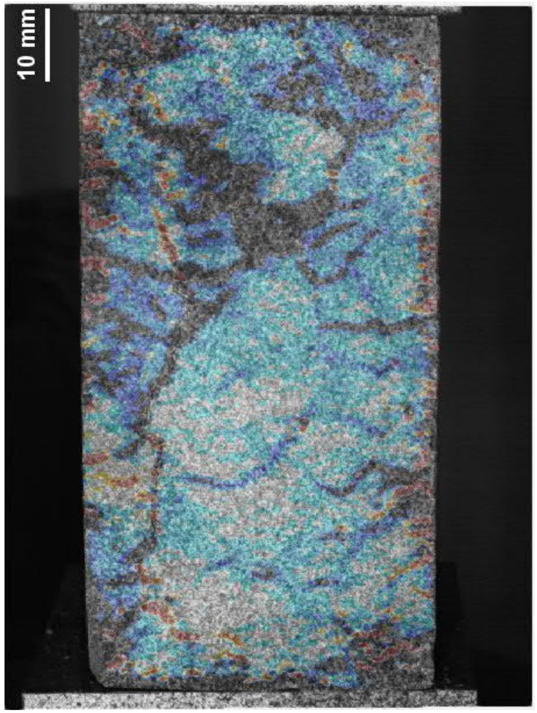
UCS test + surface DIC

- Sample 1

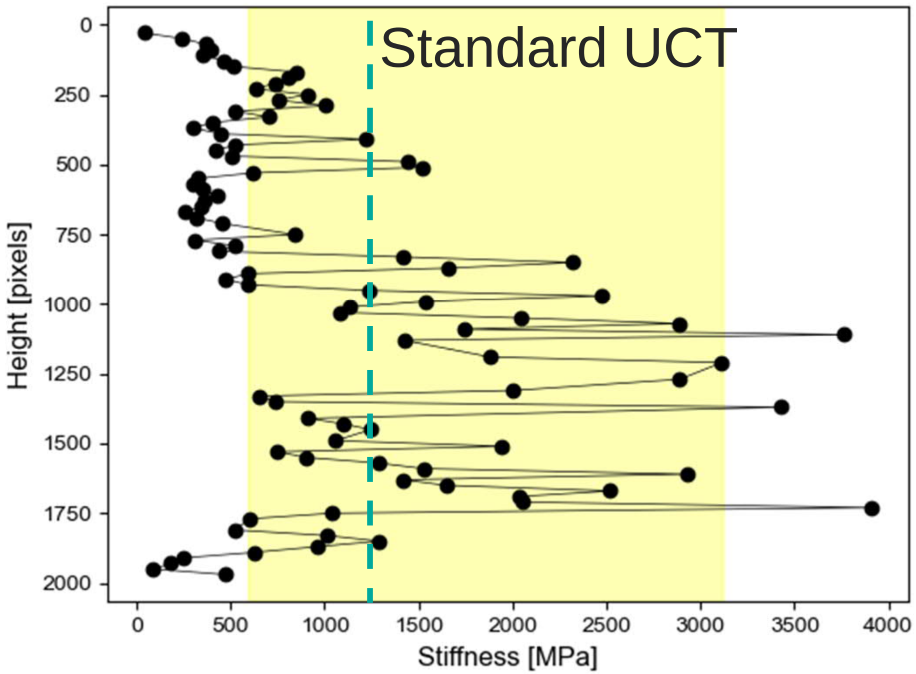


UCS test + surface DIC

- Sample 2



cyclic triax



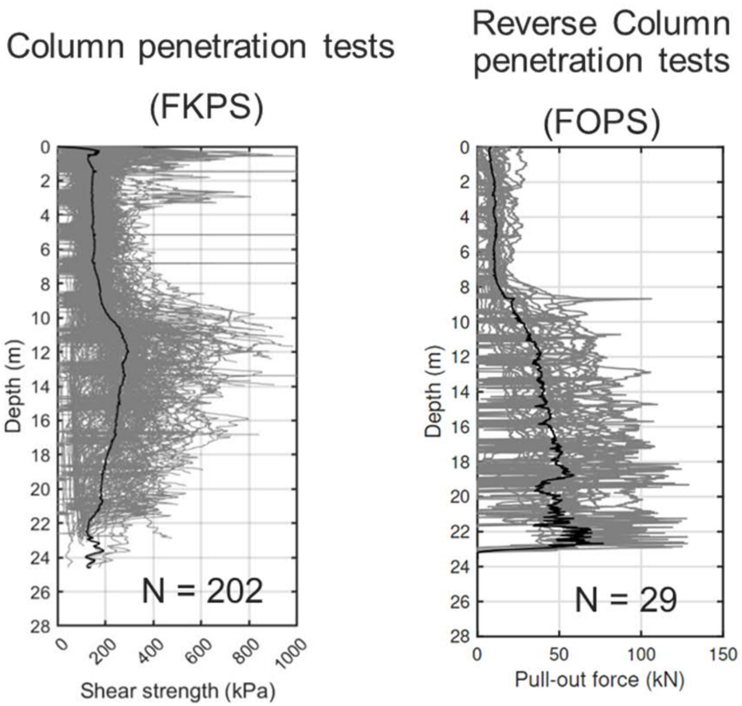
Vertical scale of fluctuation at field scale

- Accurately assessing stiffness is most important for SLS
- Assume SOF strength == SOF stiffness (may not be the case)
- Few existing methods of assessing stiffness of DSM in the field
- Improved MOPS test

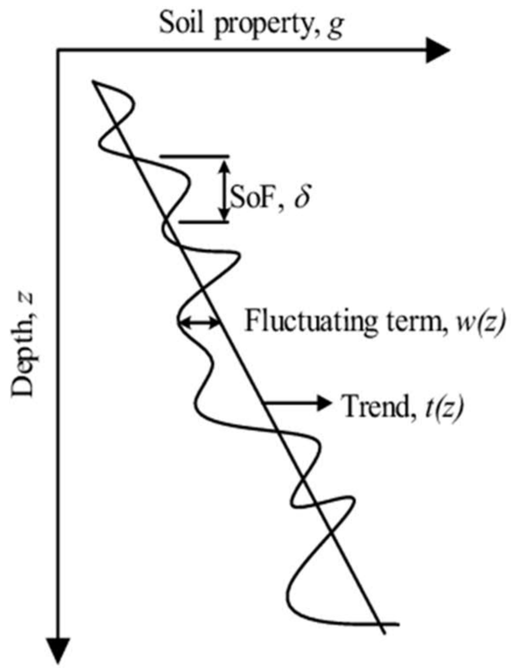
- Field test in collaboration with Dmixab (Nibben Peterzéns & Jorge Yannie)

Spatial variability in LCC

Vertical spatial variability of strength in LCC (Centralen)



Spatial variability is characterized by scale of fluctuation (SOF)



Vertical scale of fluctuation

Test type	Material	SOF_y
DIC	Sample 1	5.4 mm
	Sample 2	13.0 mm
FKPS	LCC	0.4 m to 3.5 m, 1.4 m (average)
FOPS	LCC	0.3 m to 2.0 m, 0.9 m (average)
CPT	*in-situ* clay 3-10 m	2.3 m (average)
	in-situ clay 10-50 m	3.4 m (average)

MOPS Test

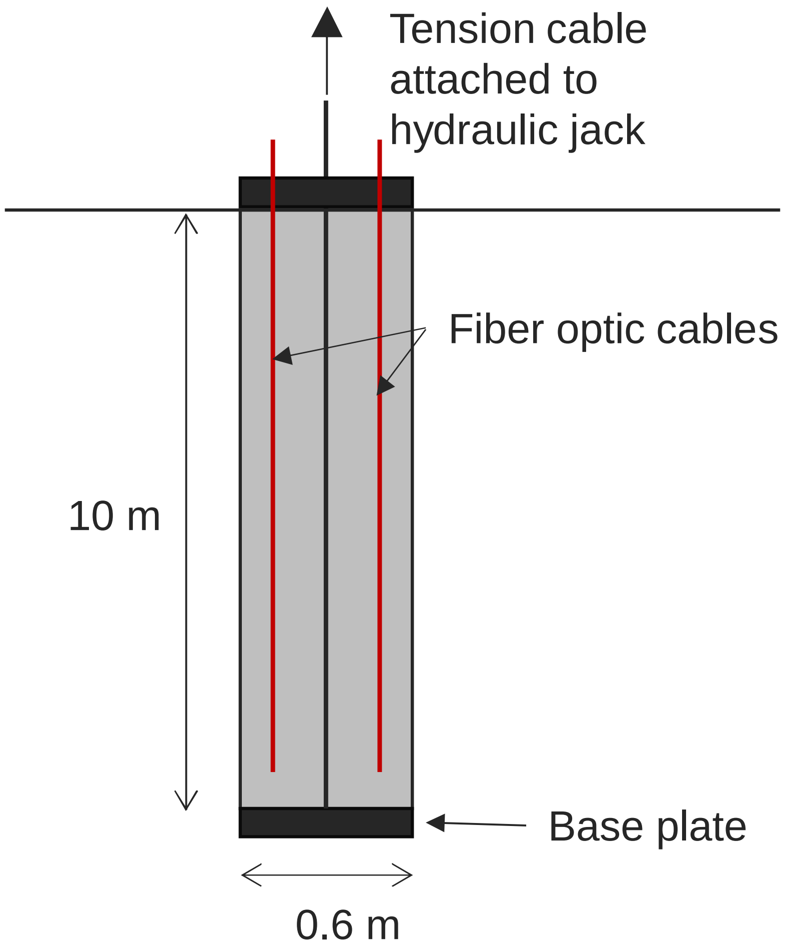
- Reverse pillar probing with anchor plate at bottom connected to a wire which runs through the column to the ground surface

a b

Figure 3 Test arrangement.

(Baker et al., 2005)

MOPS test with DFOS at Lärje

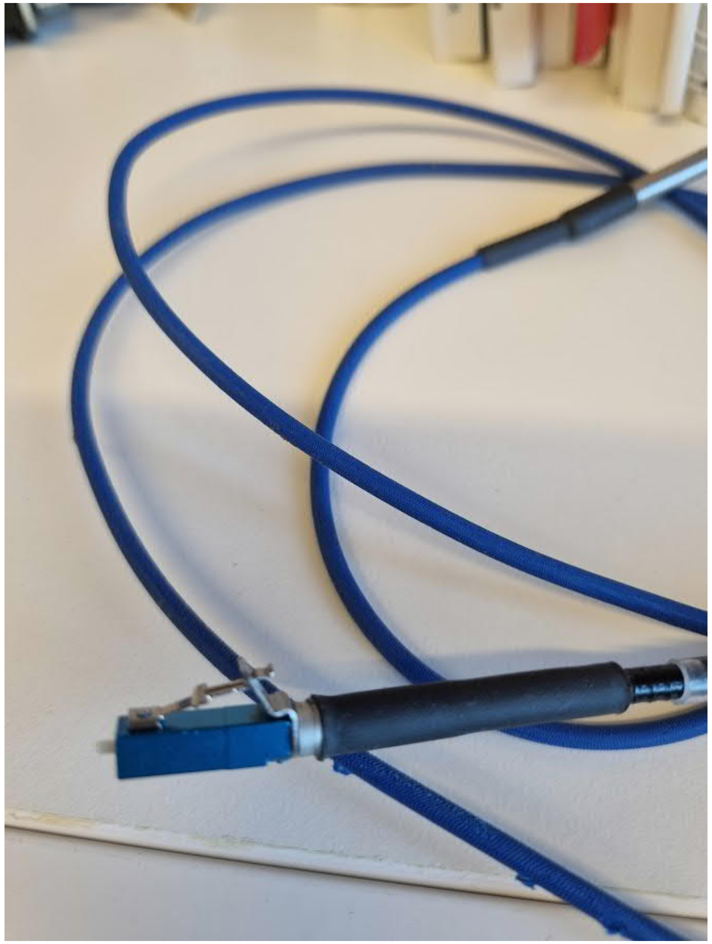


- 28-day old columns
  - 600 mm diameter 10 m length
  - 39 kg/m Multicement
  - Approx ctc 2.5 m
  - Two types of dfos
    - Solifos V1
    - EpsilonSensor 3 mm

Types of sensors

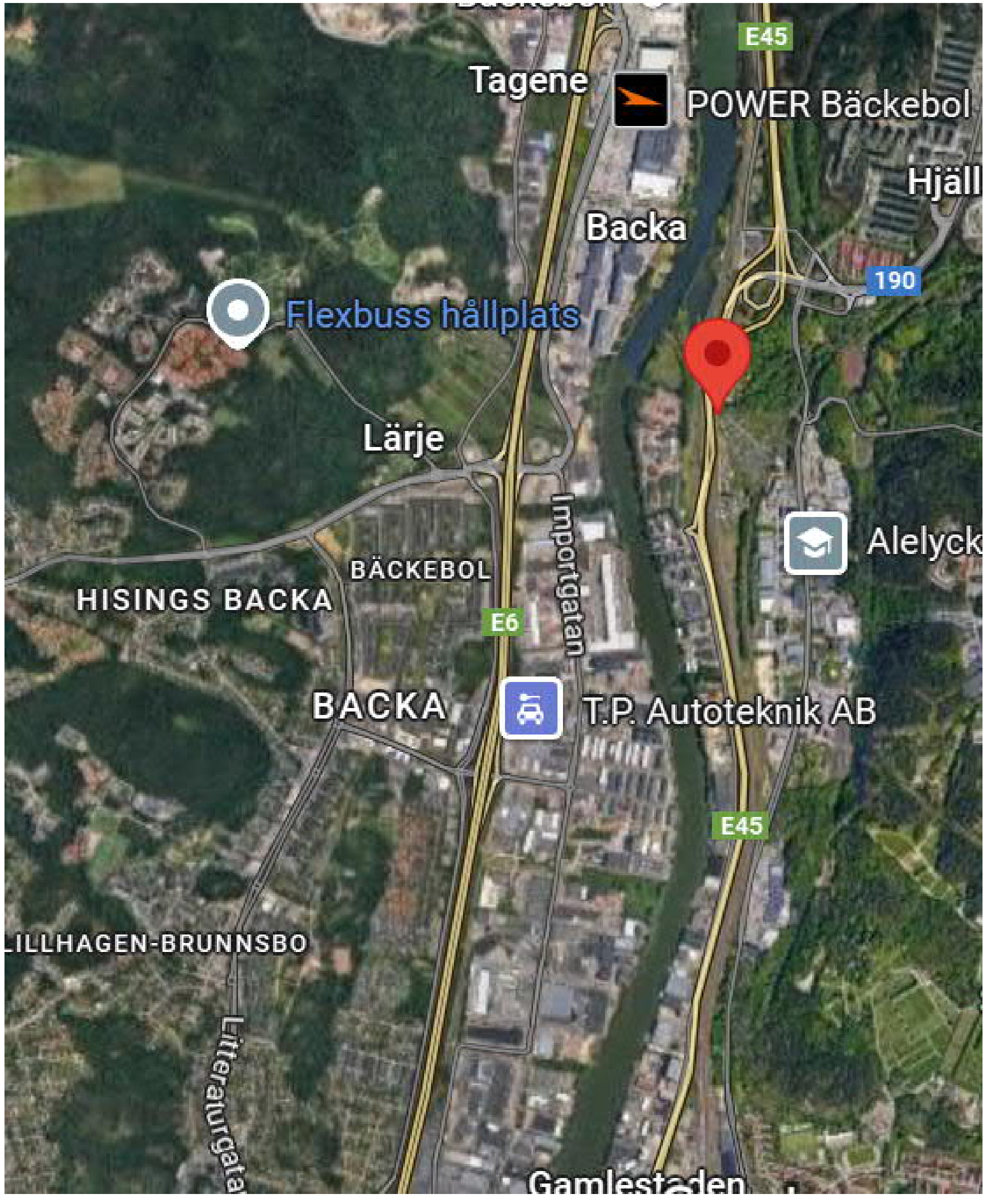
Nerve EpsilonSensor 3 mm diameter

Solifos BRUsens V1



Site location

PEAB site for
Trafikverket project



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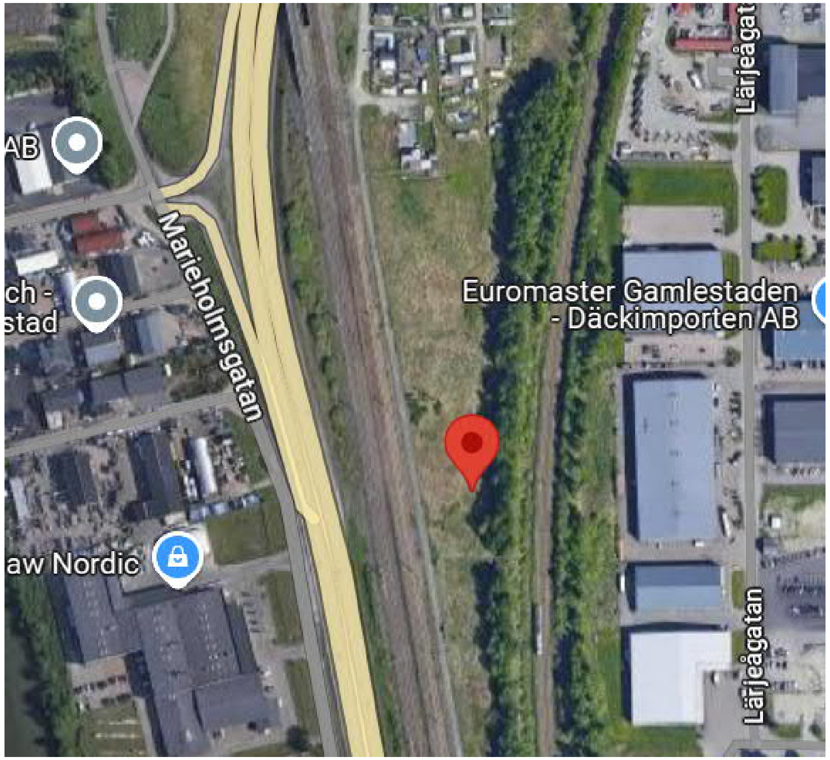
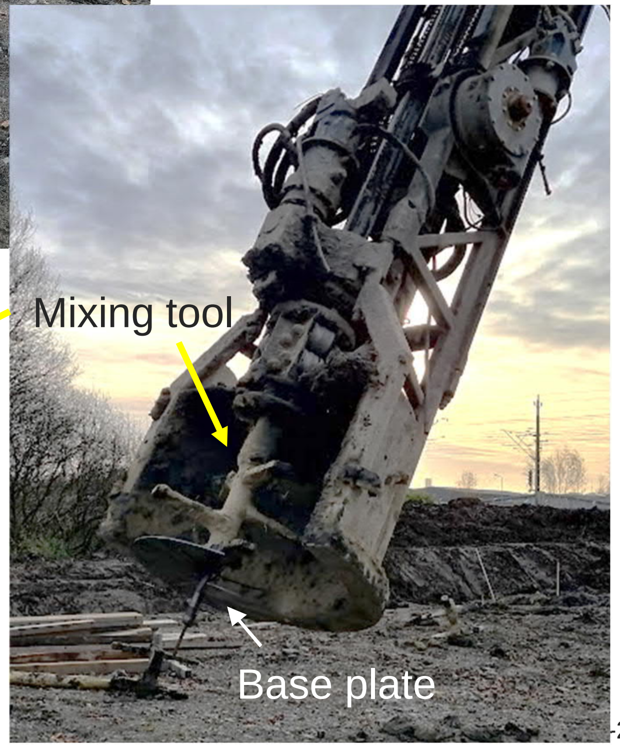
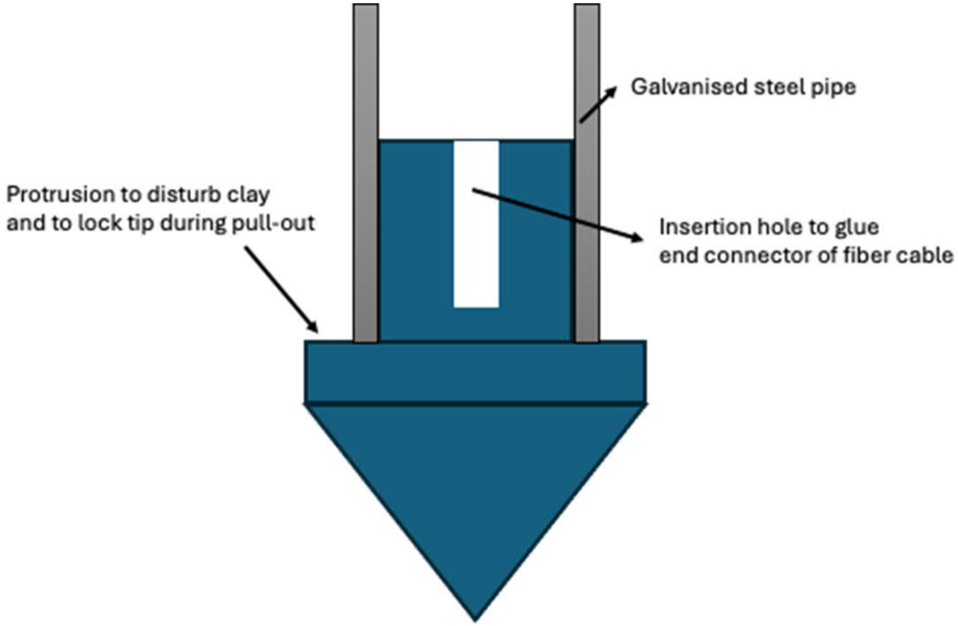
Site location near Lärje

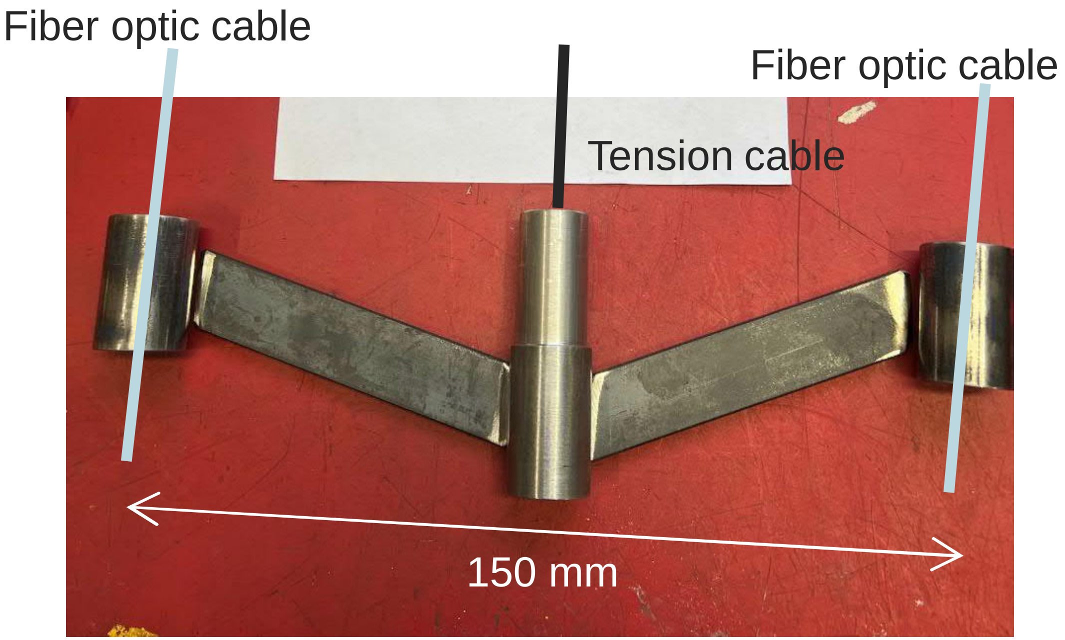


MOPS base plate

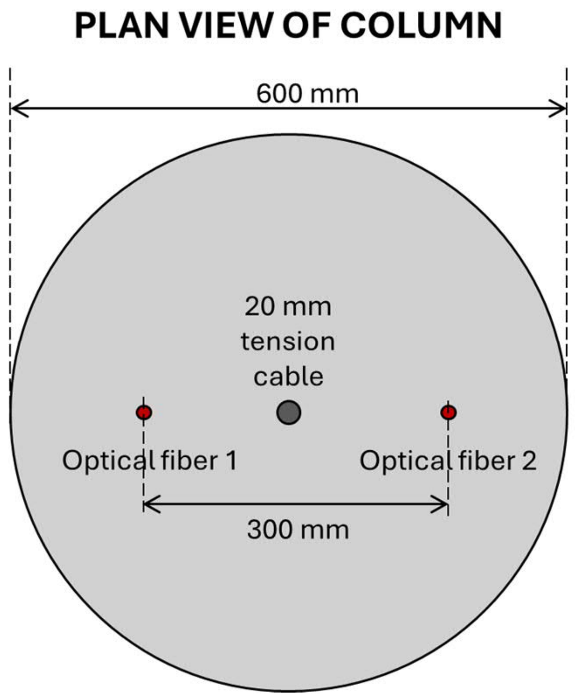


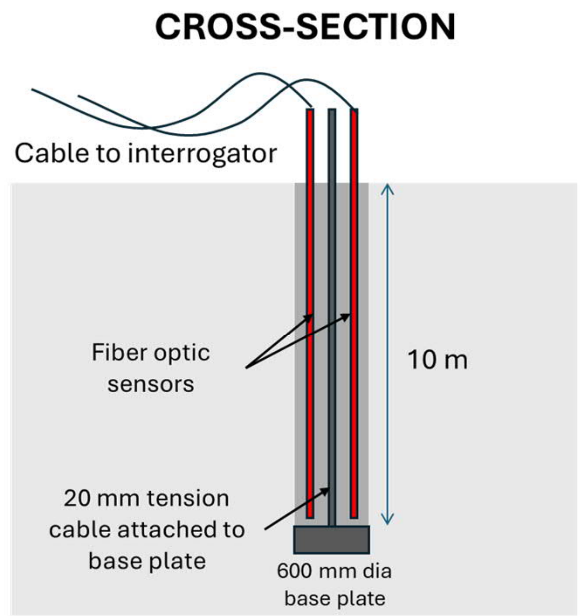
Sensor installation method





Details of sensor layout in column





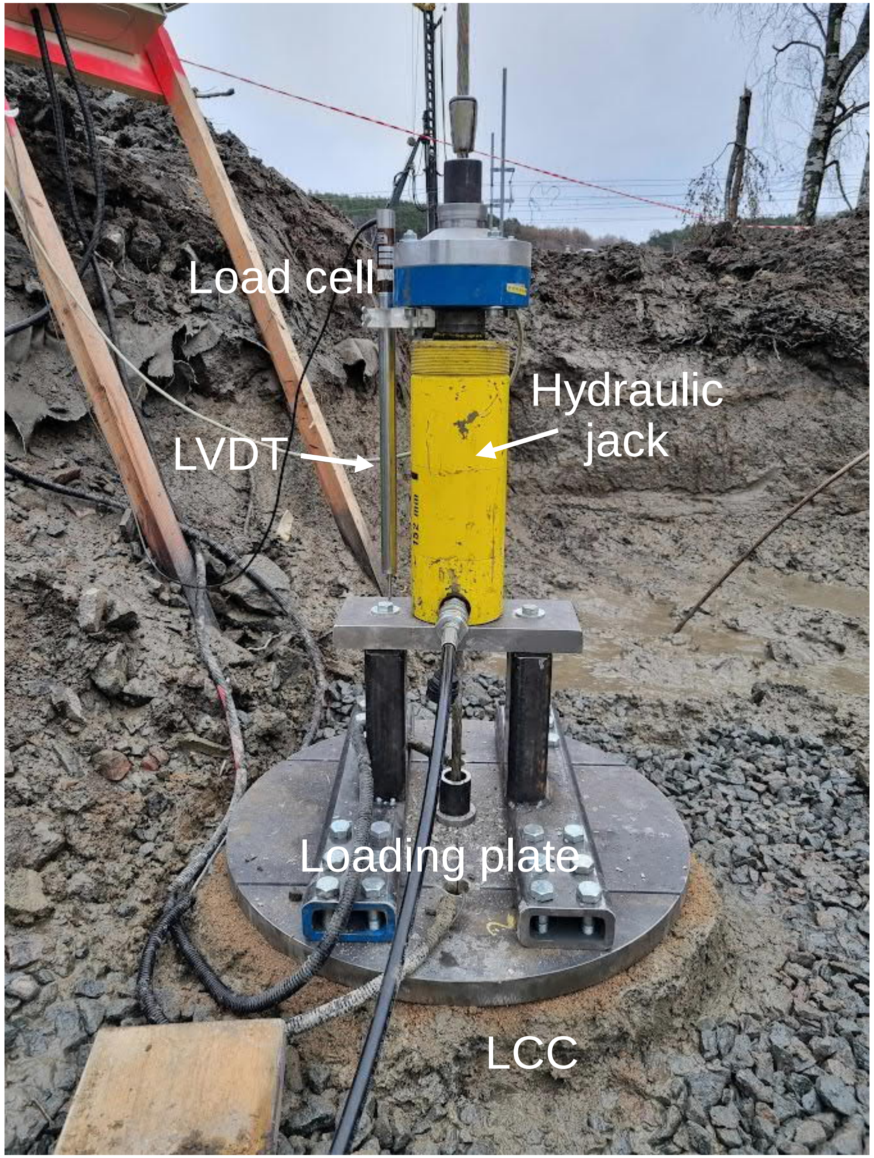
Installation of fibers using CPT rig



Preparing column surfaces for testing (Week 47 – 48)

Preparing column surfaces for testing (Week 47 – 48)

Test set-up



Testing plan

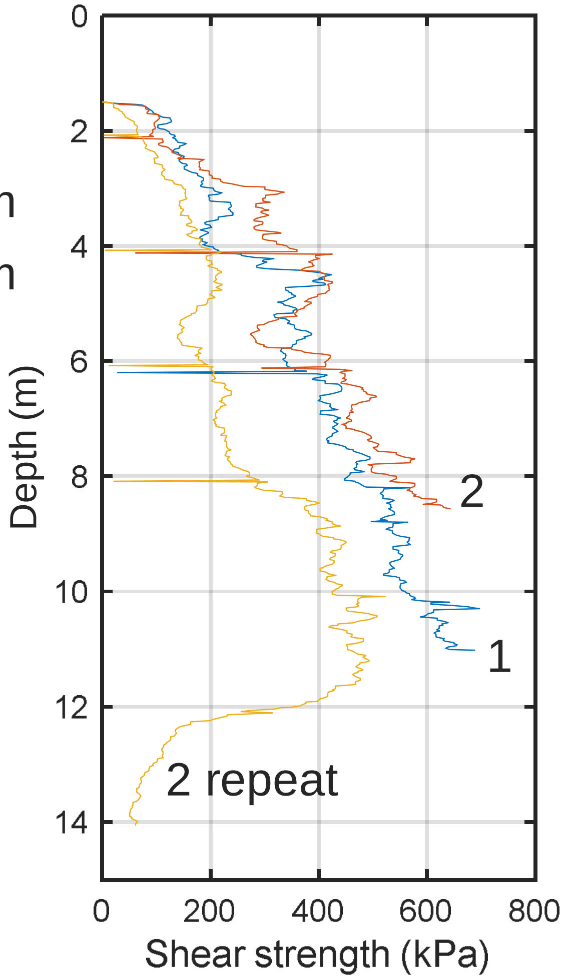
Column id	Sensor type	Test plan
C2	Solifos	Load to failure
C3	Nerve	Load to failure
C4	Solifos	Load to X% of failure and perform load-unload cycles
C5	Nerve	Load to X% of failure and perform load-unload cycles

1. SOFy = 0.42 m

2a. SOFy = 0.55 m

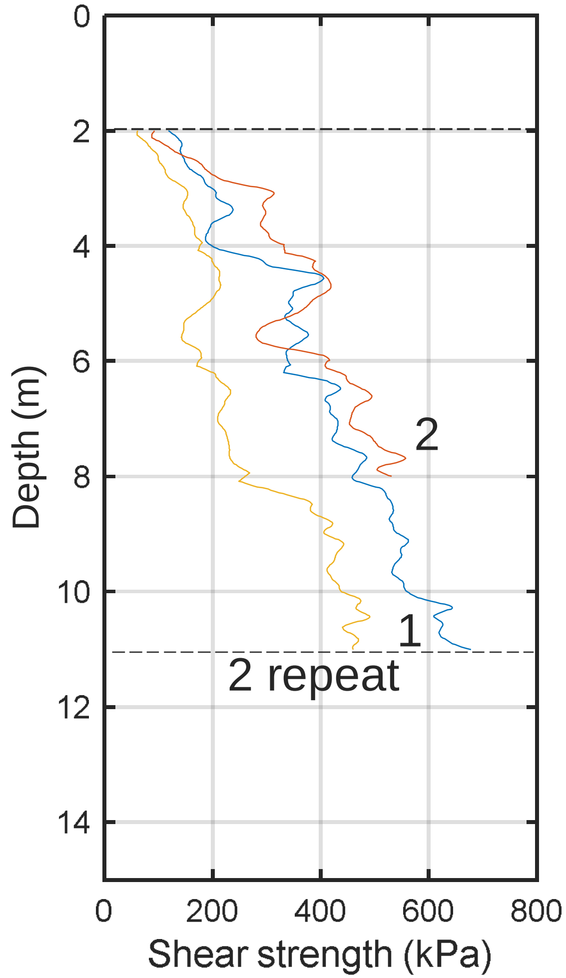
2b. SOFy = 1.28 m

FKPS raw data



Filtered

2 to 11 m depth considered



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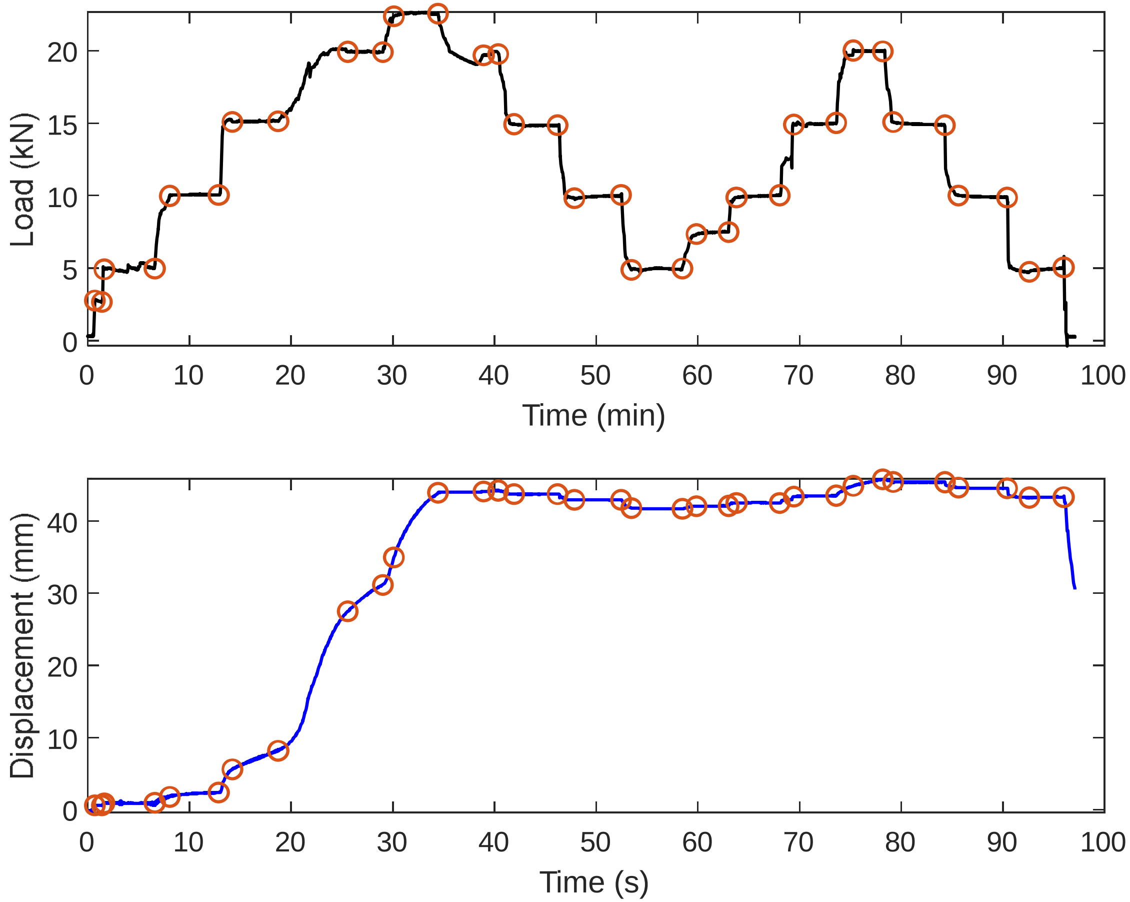
Postprocessing LC and LVDT data

Raw LC and LVDT data from C5



1. Identify start and end of each load step from LC data and wall clock time

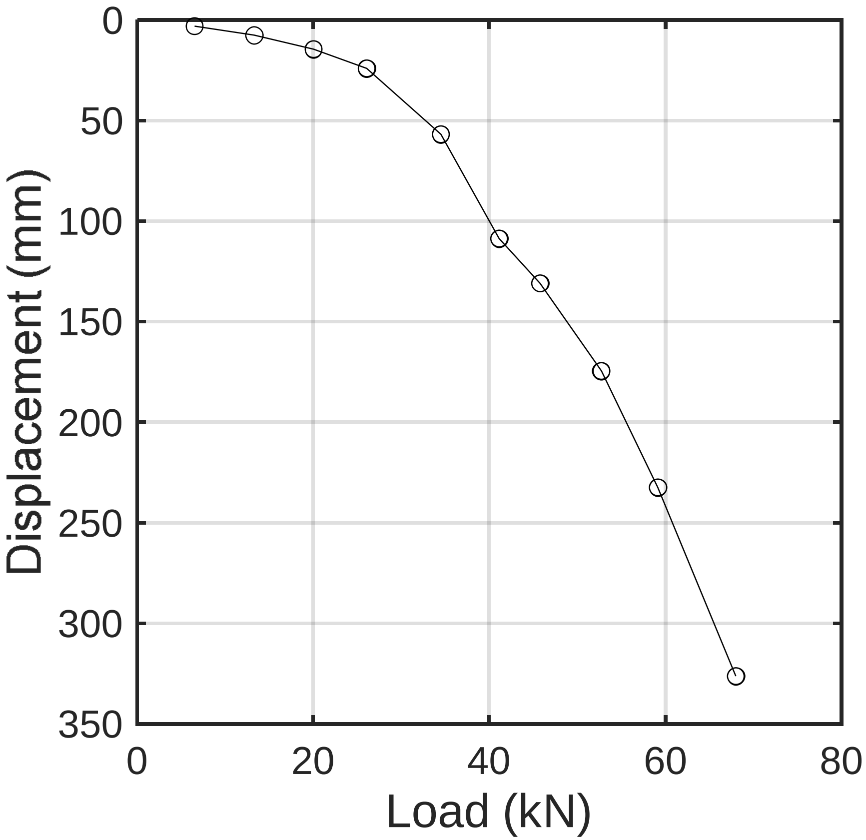
1. Take mean of LC and LVDT readings for each load step
2. Take mean of fiber strains for each load step

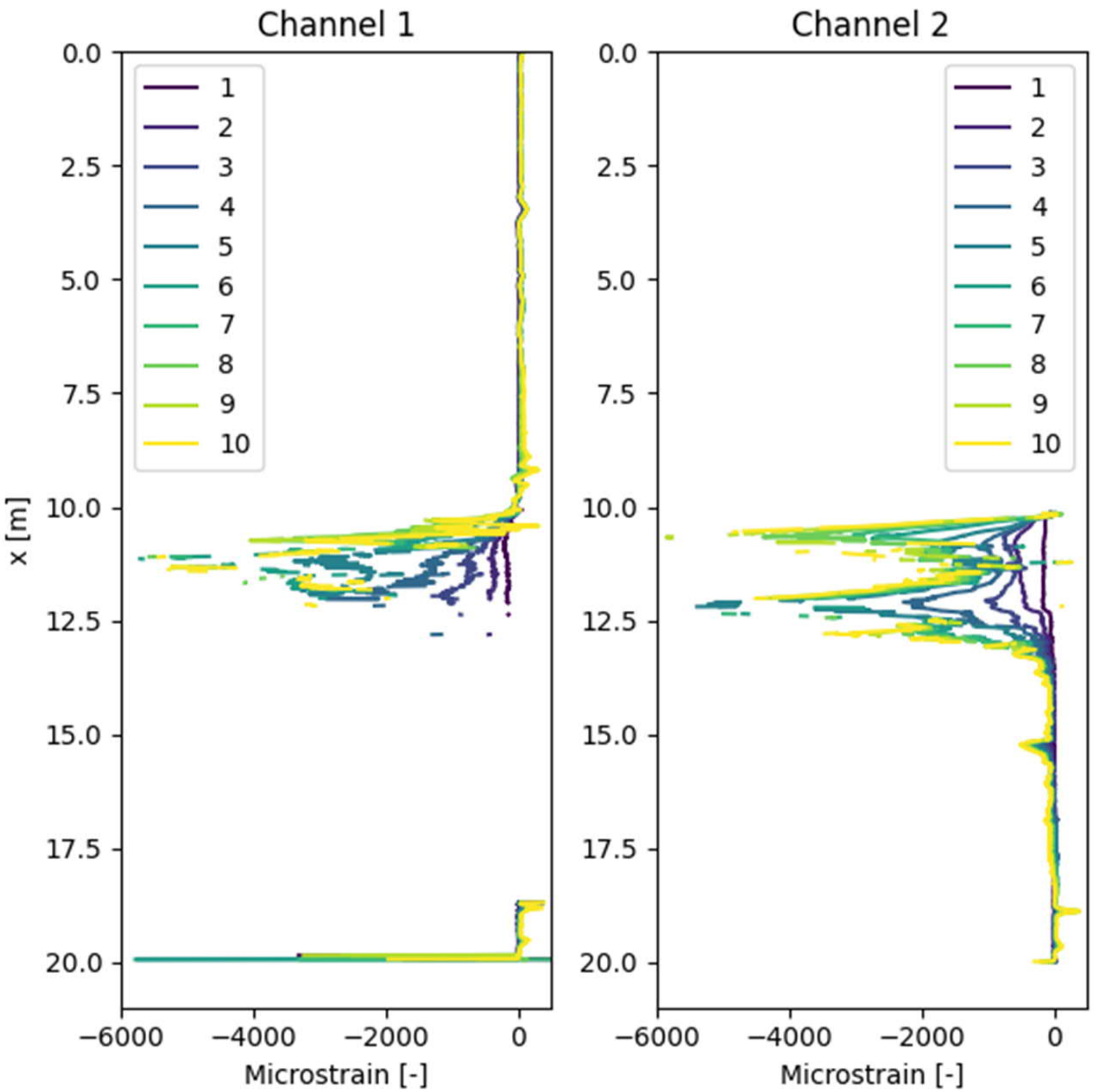
C2 – Before Test

C2 – After Test

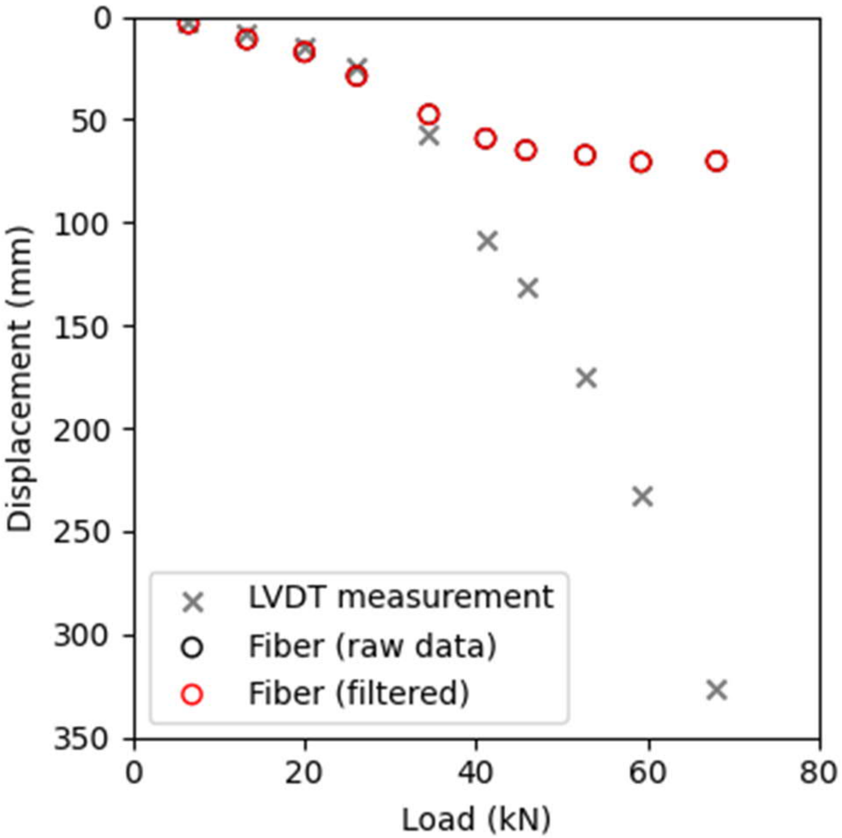
Fibre data

C2, load to failure





C2 load displacement curve



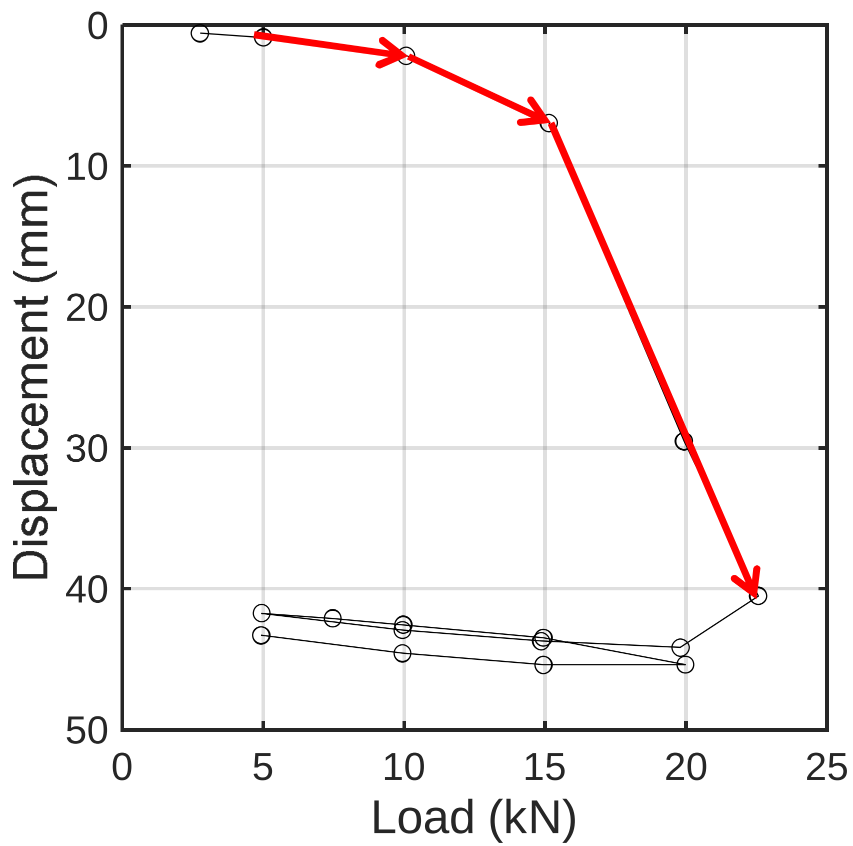
- Fiber channel 2
- Displacement estimated from area under strain curve from fibers
- Displacement from fibers smaller than that from LVDT

C5 – Before Test

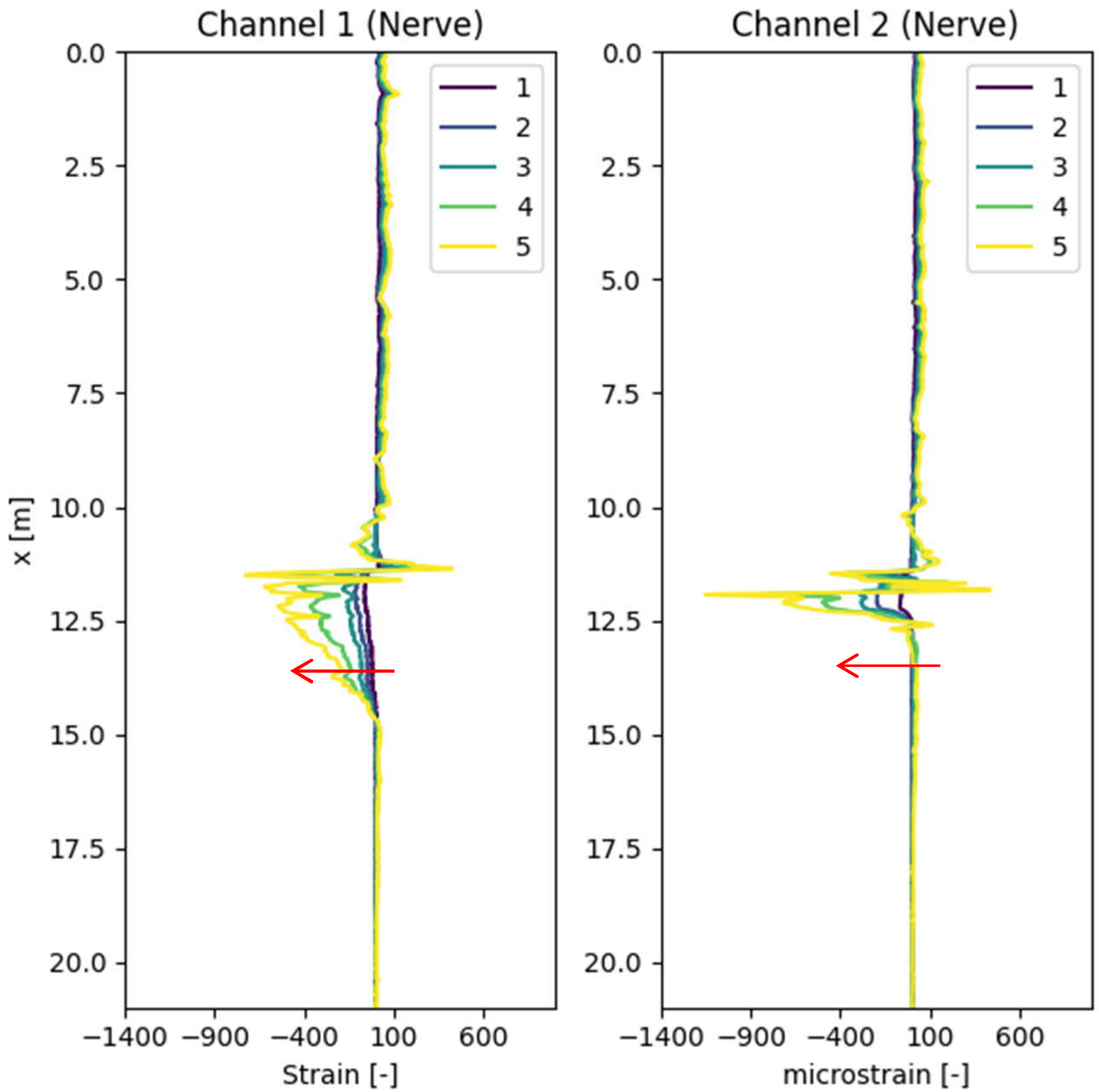
C5 – After Test

2025-08-20

C5, load 1

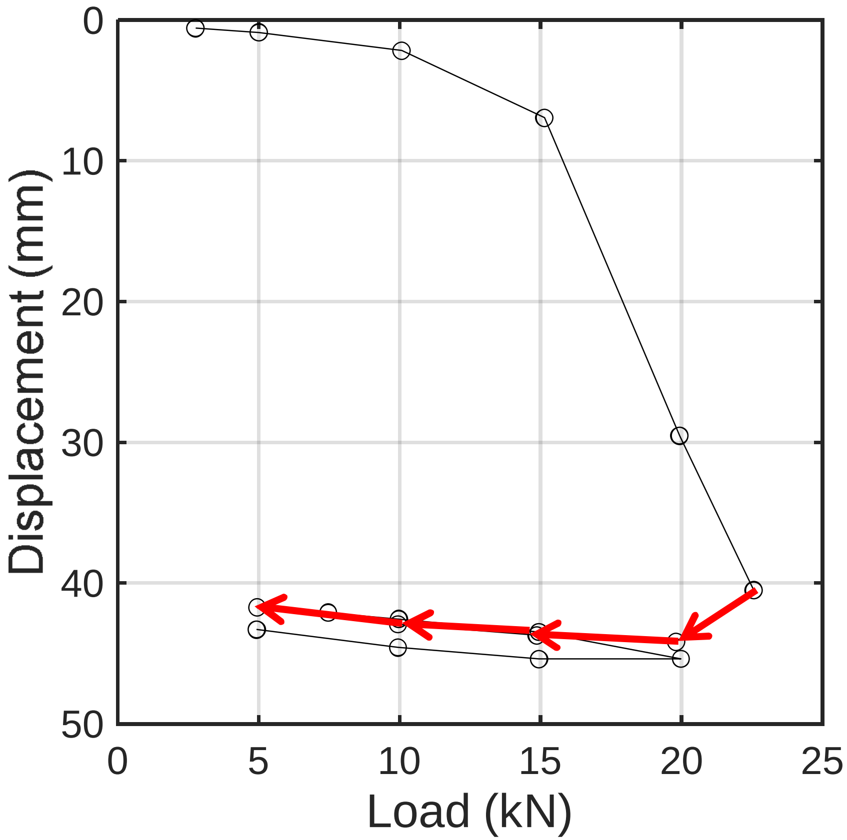


Displacement (mm)
Load (kN)
0
10
20
30
40
50
0
5
10
15
20
25

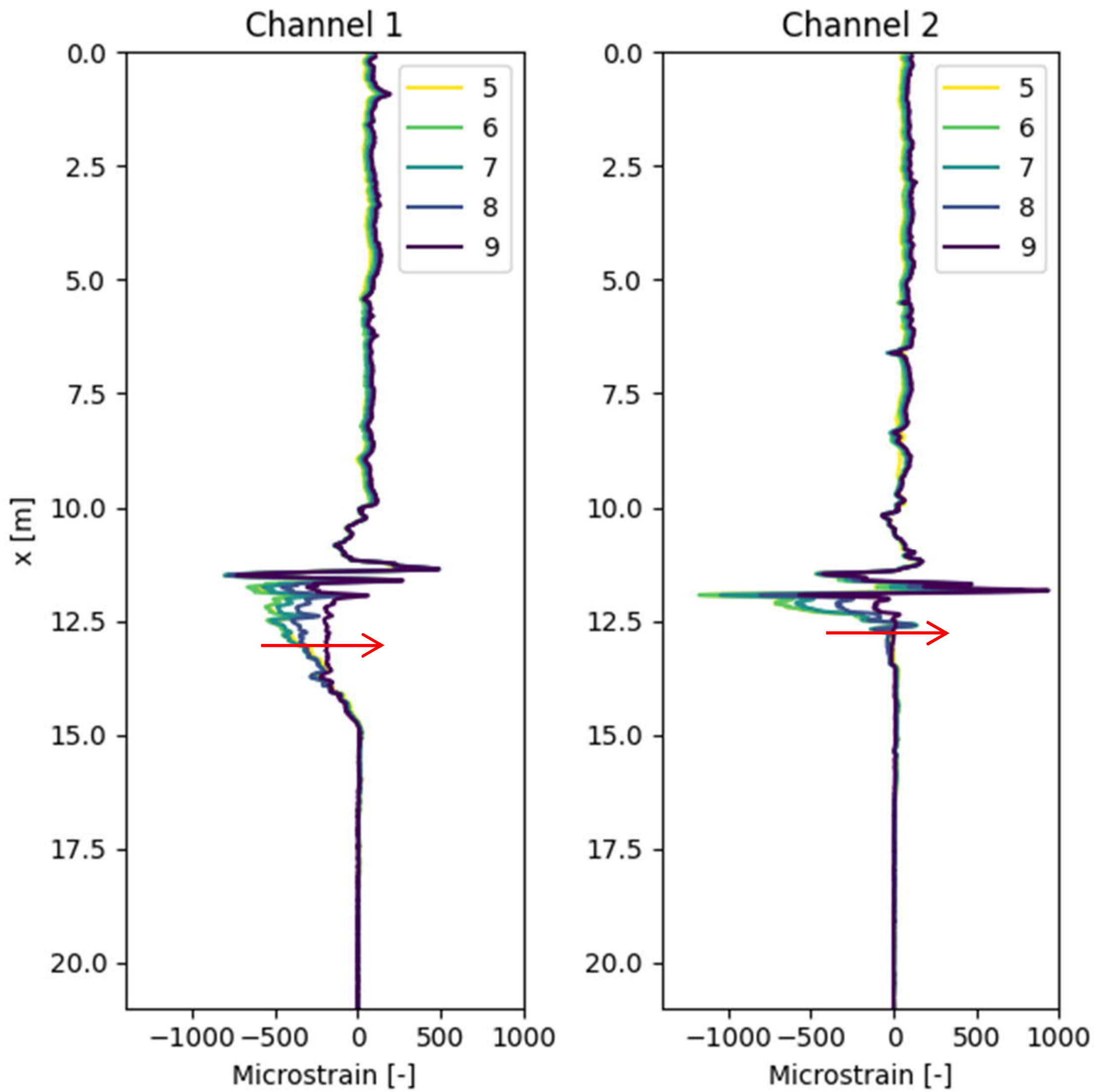


Channel 1 (Nerve)
Channel 2 (Nerve)
x [m]
Strain [-]
microstrain [-]
1
2
3
4
5
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
−1400
−900
−400
100
600

C5, unload 1

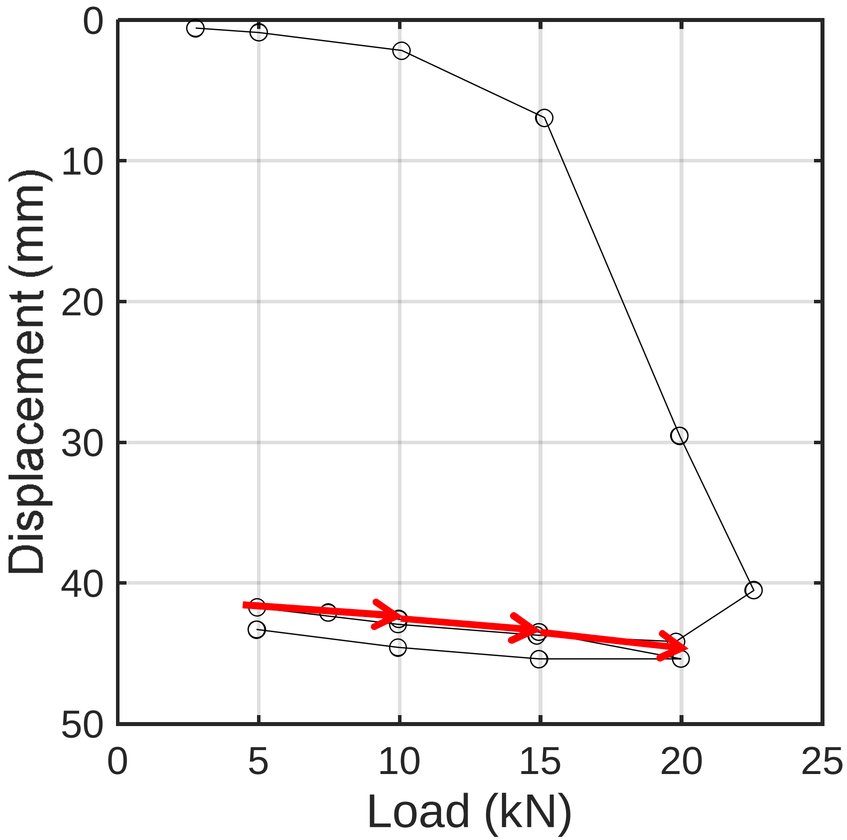


Displacement (mm)
0
10
20
30
40
50
0
5
10
15
20
25
Load (kN)

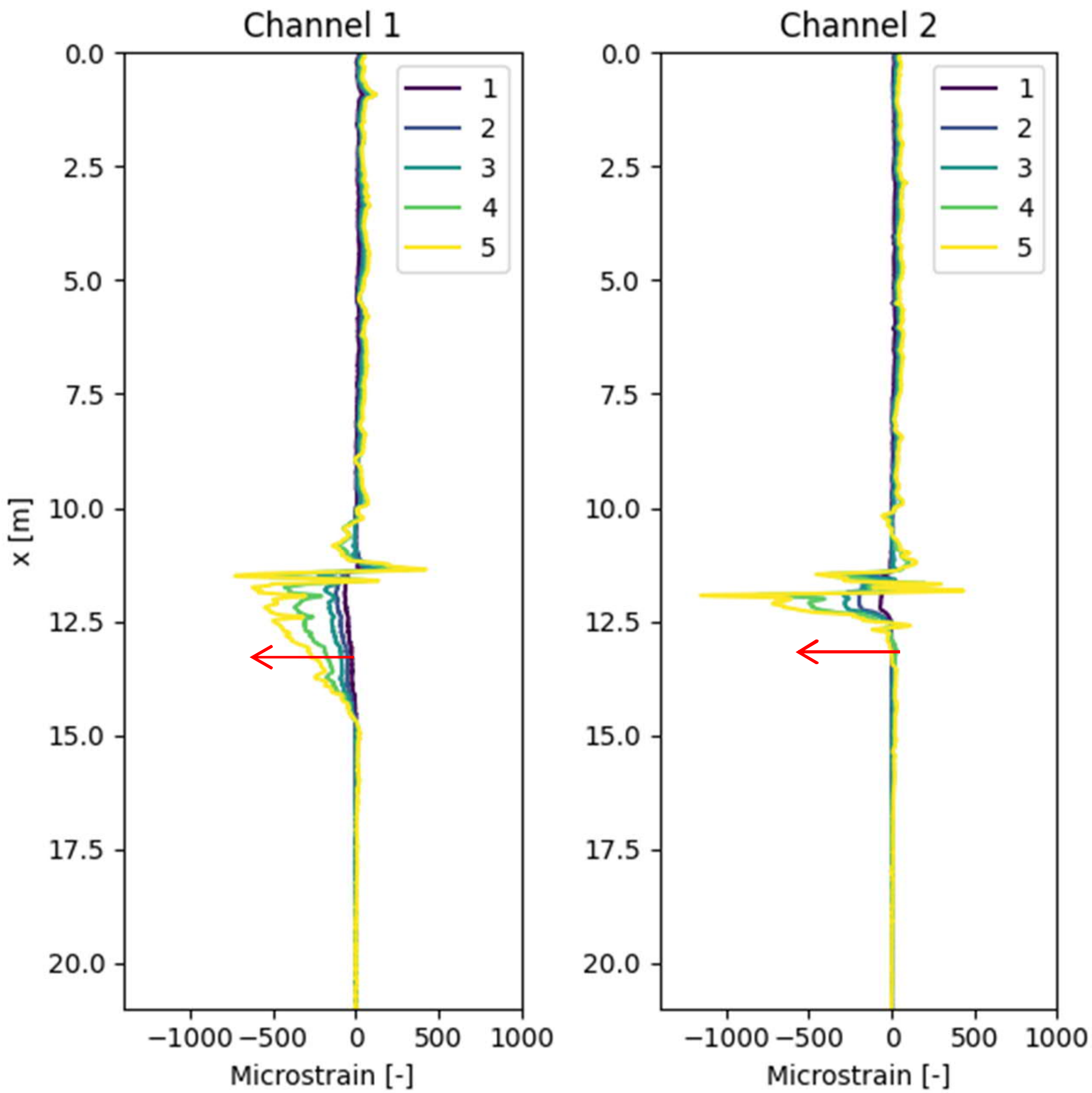


Channel 1
Channel 2
5
6
7
8
9
x [m]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
−1000 −500 0 500 1000
Microstrain [-]

C5, load 2

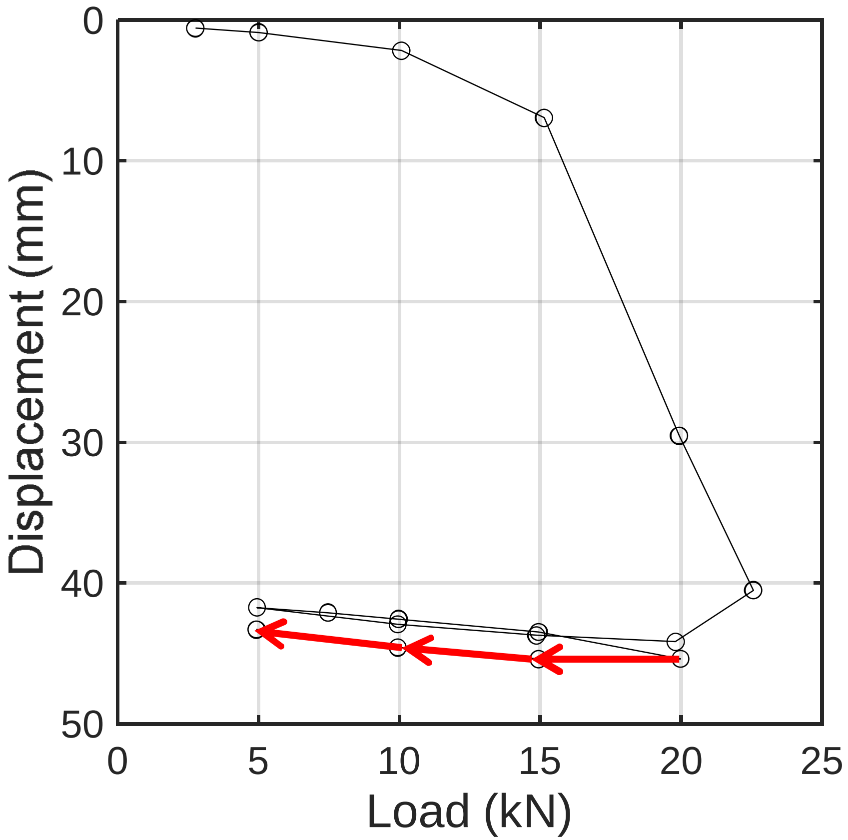


Displacement (mm)
0
10
20
30
40
50
0
5
10
15
20
25
Load (kN)

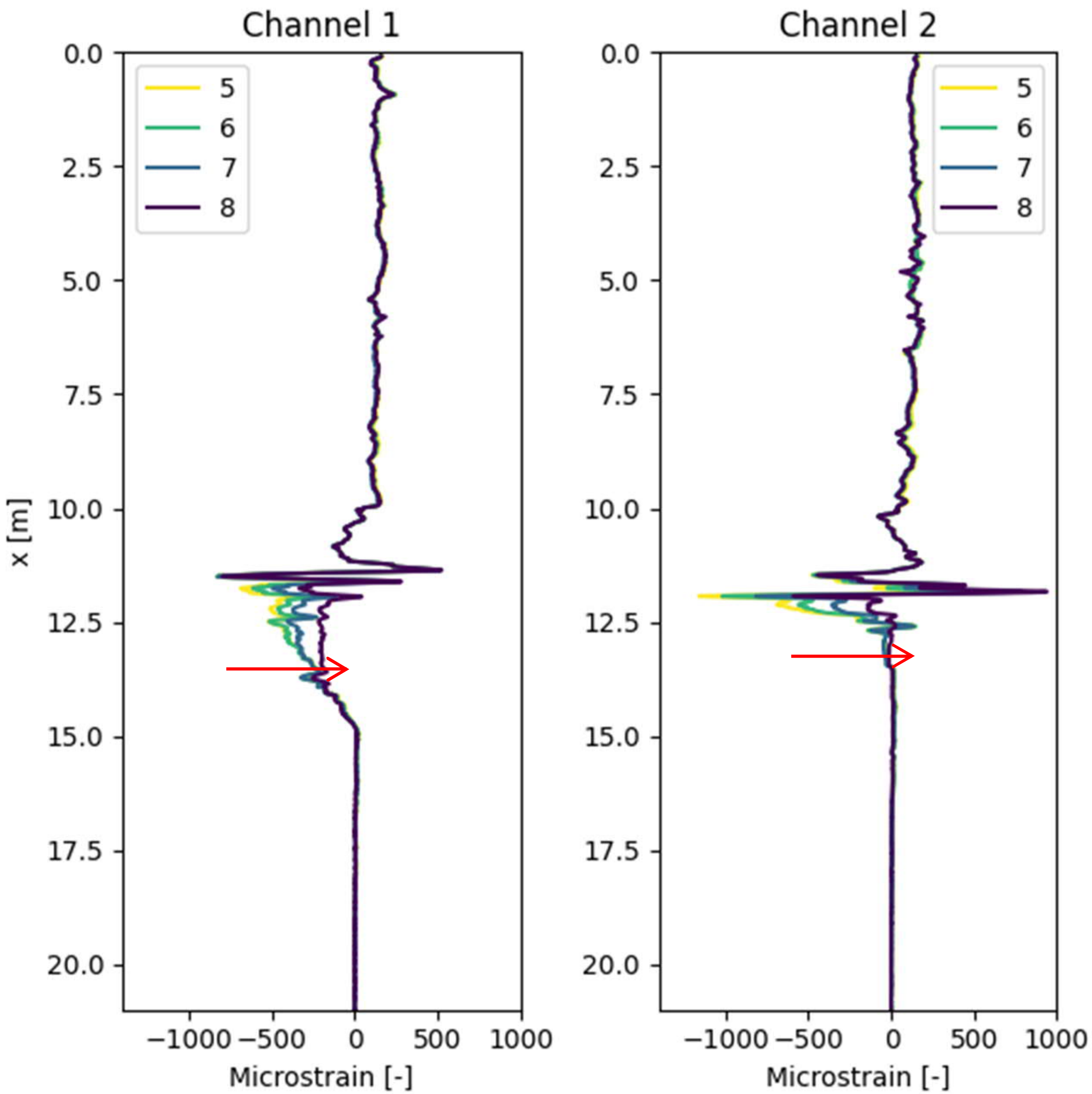


Channel 1
Channel 2
x [m]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
1
2
3
4
5
−1000 −500 0 500 1000
Microstrain [-]

C5, unload 2

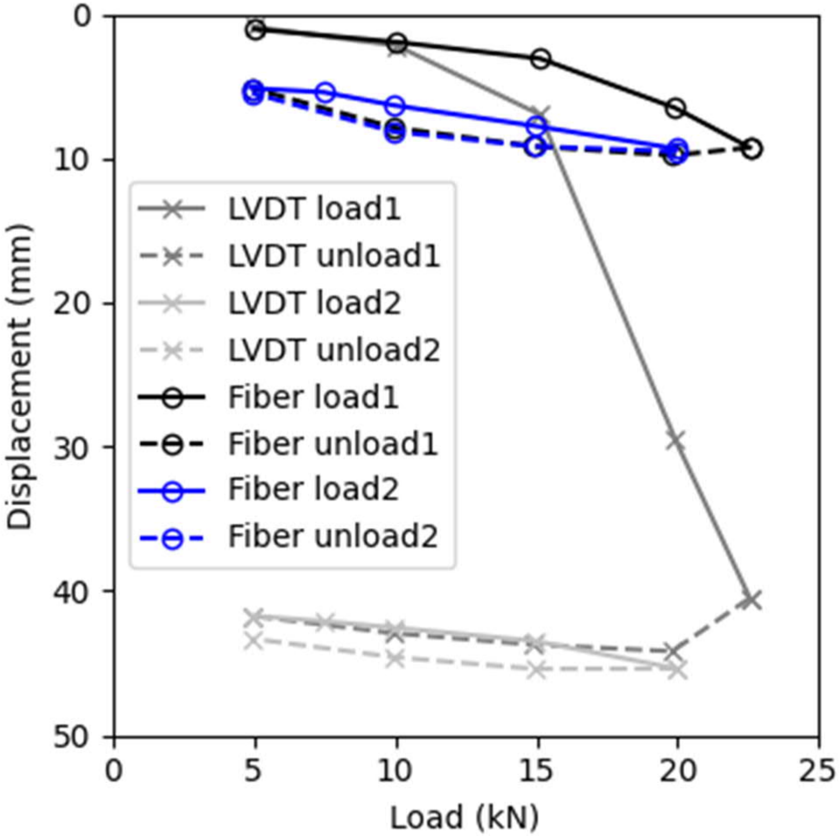


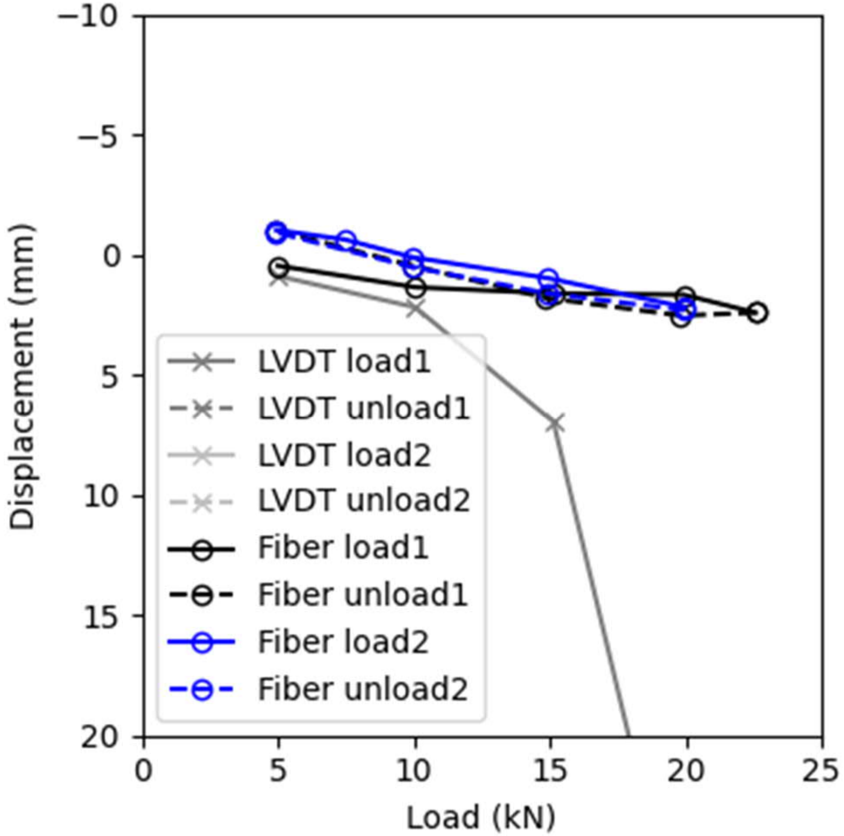
Displacement (mm)
0
10
20
30
40
50
0
5
10
15
20
25
Load (kN)



Channel 1
Channel 2
5
6
7
8
x [m]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
−1000 −500 0 500 1000
Microstrain [-]

C5 load displacement curve, load cycle 1





Conclusions

- Stiffness matters for vibrations
- High spatial resolution required for SOFy, only attained with DFOS at field scale
- Measuring stiffness in Dry Deep Mixed clays is challenging
  - Scale
  - Time
  - Control of environmental conditions
    - Stress level
    - Sample disturbance
    - Column dimensions
    - Binder design
    - Mixing energy
    - etc.

Thanks

- Dawn Wong, Vijashree Sadasivan, Anders Karlsson & Jelke Dijkstra (Chalmers)
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