PROGETTO UNIMPRESA 2019 – TITANO

SISTEMI INNOVATIVI DI MONITORAGGIO GEOTECNICO MEDIANTE SENSORI IN FIBRA OTTICA

Sala Auditorium dell’Orto Botanico – Padova, June 28th 2022

COMPORTAMENTO DI PALI DI FONDAZIONE IN PROVE DI CARICO E IN ESERCIZIO

(PILE BEHAVIOUR IN DESIGN LOAD TESTS AND IN SERVISEABILITY STATE)

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1. Objectives
2. Distributed Fiber Optic Sensors (DFOS)
3. Static Pile Load Test
4. Pile Behavior During Bridge Construction (Pile in exercise)
5. Final remarks

Many Pile Load tests were already successfully carried out using Distributed Fibre Optic Sensors (**DFOS**) technology for **evaluating the performance** of piles and obtaining information on the soil-pile interaction (e.g. Soga et al., 2015)

- **Open questions**

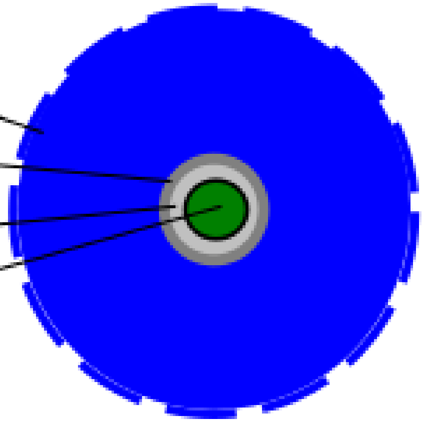
1. How could the measurements obtained with **DFOS** be processed to derive the **load transfer parameters** at the soil-structure interface?

2. Could the **DFOS** be **efficient for monitoring also the long term** of pile foundations?

2. Used DFOS

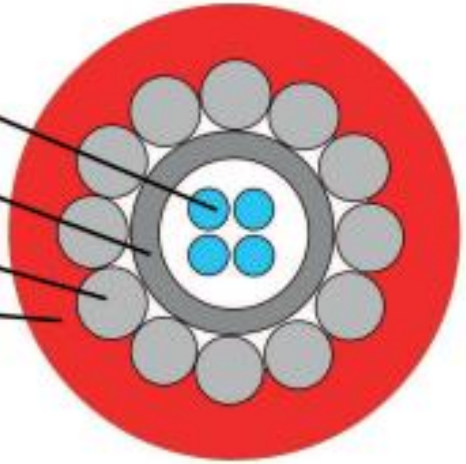
BRUsens© strain V9 cable (ø 32mm) (Brugg Kabel AG)

PA outer sheath with a grip 1
Multi layer buffer 2
Stainless steel tube 3
Fibre core 4



BRUsens© Temperature cable (ø 48m) (Brugg Kabel AG)

Fibre core in gel 1
Stainless steel loose tube 2
Stainless steel wires 3
PA outer sheath 4



- Strain range up to 1% (10000 με)
- Attenuation < 0.5 dB/km for a wavelength of 1550 nm
- Max tensile strength at installation: 260 N

2. Used DFOS

❑ Luna OBR 4600 interrogator

- **One ended** configuration

- Fibres interrogated exploiting **the Rayleigh scattering**, with the **Optical Frequency Domain Reflectometry (OFDR)** technique

Spatial resolution: 0.1 ÷ 10 cm

Distance range: < 70-80 m
Measurement time: 5 ÷ 15 s

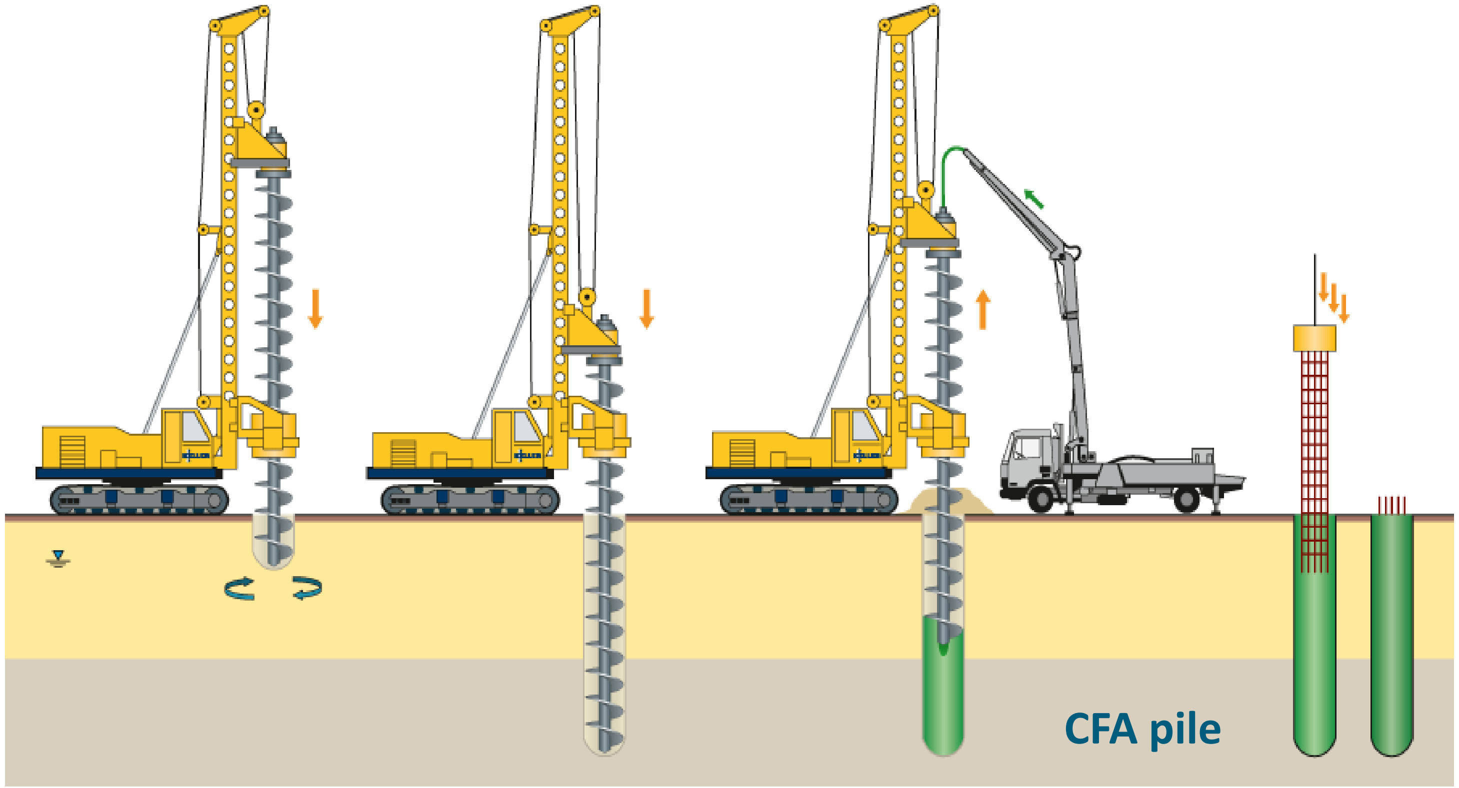
Measurements: strain and temperature variation with respect to a first measurement kept as a reference

Precision strain: 1-3$\mu\varepsilon$
Precision temperature: 0.1-0.5°C

❑ Static load test on a Continuous Flight Auger (CFA) pile

- Pile length: 24.5m
- Pile diameter: 0.64 m

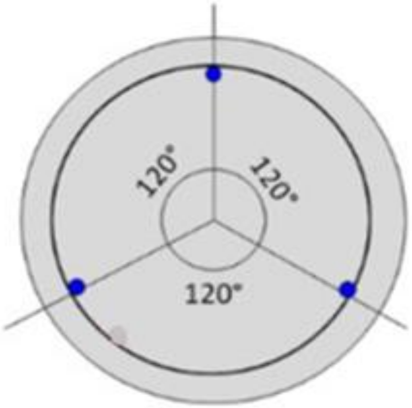
- Q_{max} = 3080 kN (1.5 Q_{ex})
- 2 cycles of loading-unloading

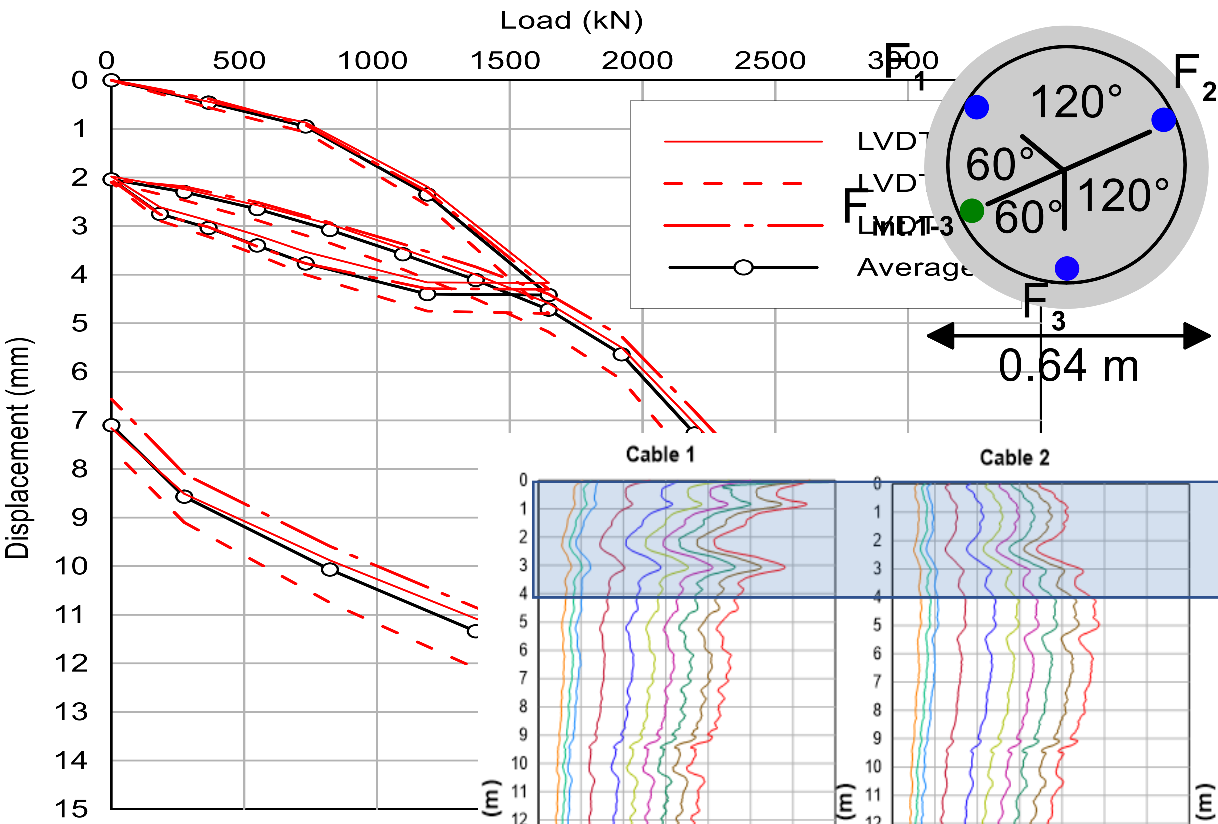


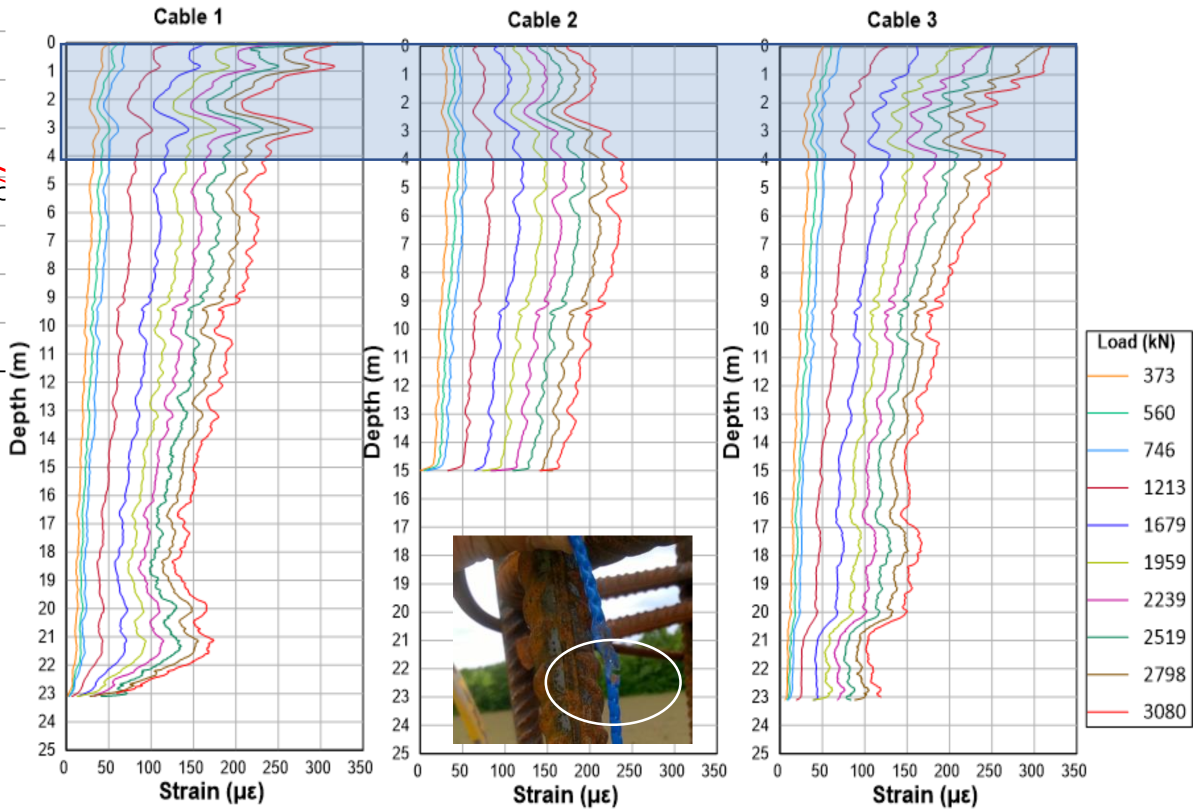
❑ Vertical load test on instrumented CFA pile with DFOS

- 3 lengths of **BRUSens cable V9** and pretensioned with15 kg

- **Three LVDTs** for vertical displacements of the pile head

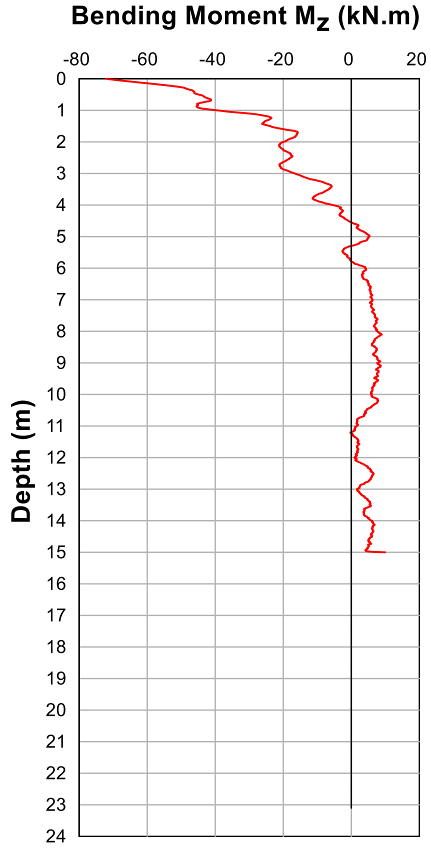


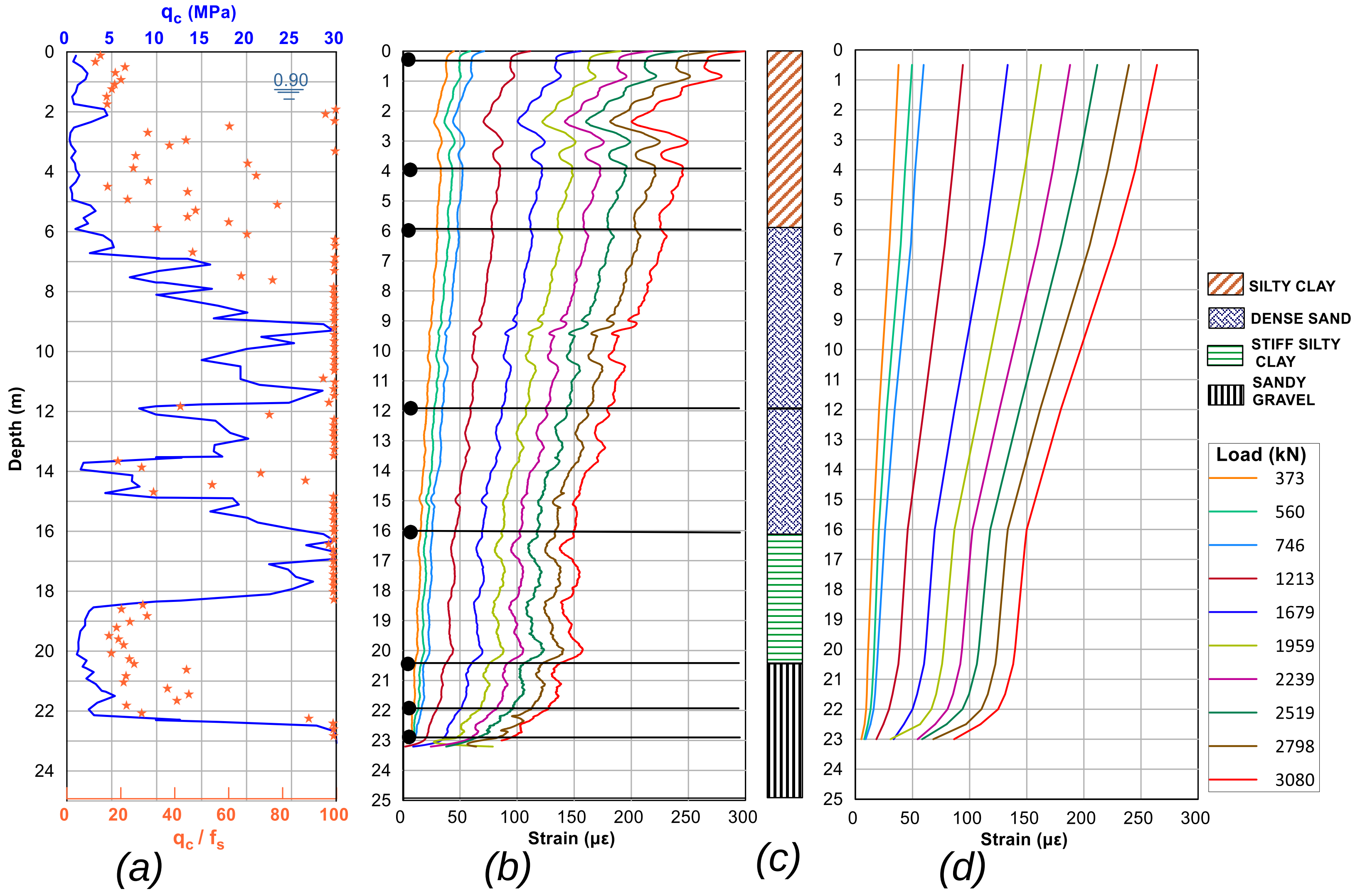




Bending moment:

$$M_z = \frac{EI}{D}\left(\varepsilon_{F_2} - \varepsilon_{F_{int.1-3}}\right)$$





- Assume **pile geometry constant** with depth
- 4 main soil layers are identified from CPT and DFOS strain profiles

a) CPT2 executed at South abutment; *b)* average FO-strain profile for each load applied in the pile test; *c)* soil profile derived from CPT2 and average FO-strain profiles; *d)* approximated axial strain profile at different load steps

Load transfer curves from axial strain measurements

Data for each load step *j*:

(i) Axial strain profile along pile depth y: $\varepsilon_a(y,j)$

(ii) Settlement at pile head $(y = y_0)$: $z(y_0,j)$

1) **Pile vertical displacement**:

$$z(y,j) = z(y_0,j) + \int_{y_0}^{y} \varepsilon_a(y,j)dy$$

2) **Axial force profile**:

$$F_a(y,j) = E(y)A(y)\varepsilon(y,j)$$

3) **Unit tip bearing resistance** at depth $(y = y_L)$:

$$q(y_L,j) = F_a(y_L,j)/A(y_L)$$

4) **Unit shaft friction**:

$$t(y,j) = \frac{1}{\pi D(y)} \frac{dF_a(y,j)}{dy}$$

Interpolation functions for DFOS load transfer curves :

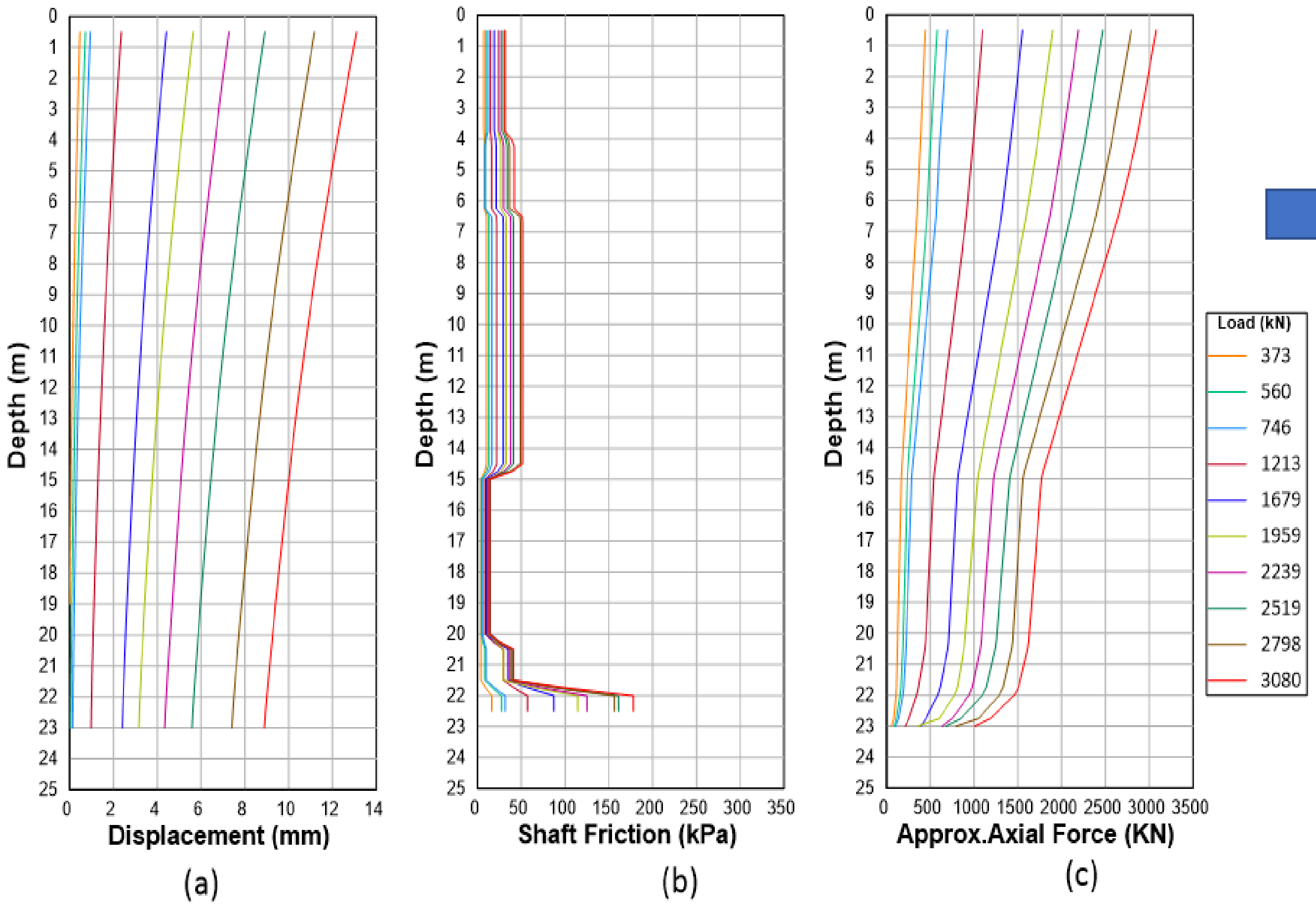
- Chin function for cohesive soils:

$$t = \frac{z(y,j)}{a + b \cdot z(y,j)}$$

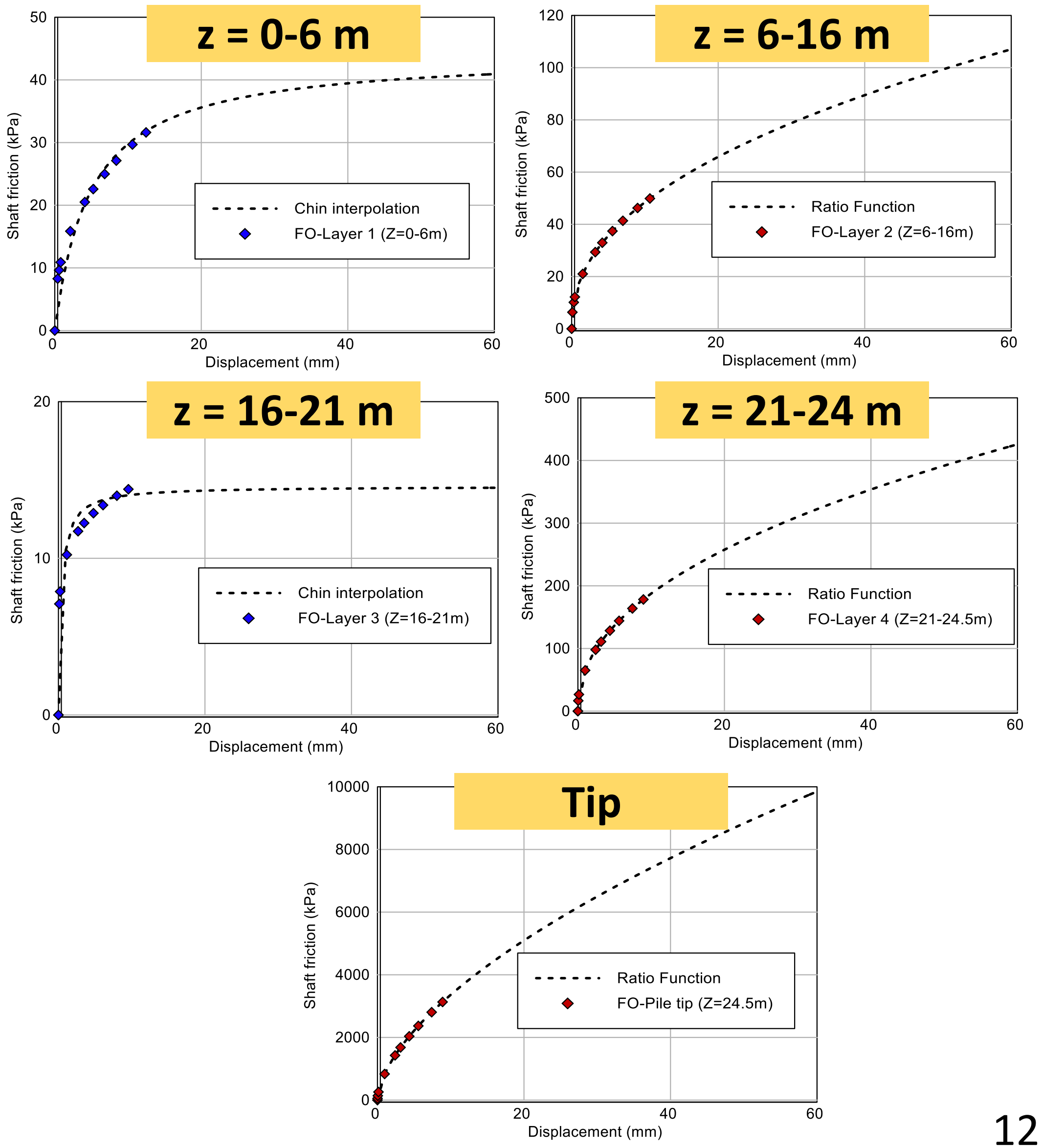
- Ratio function for cohesionless soils:

$$t = t_{trg} \left(\frac{z(y,j)}{z(y)_{trg}} \right)^{\theta}$$

❑ Load transfer curves from DFOS strain measurement



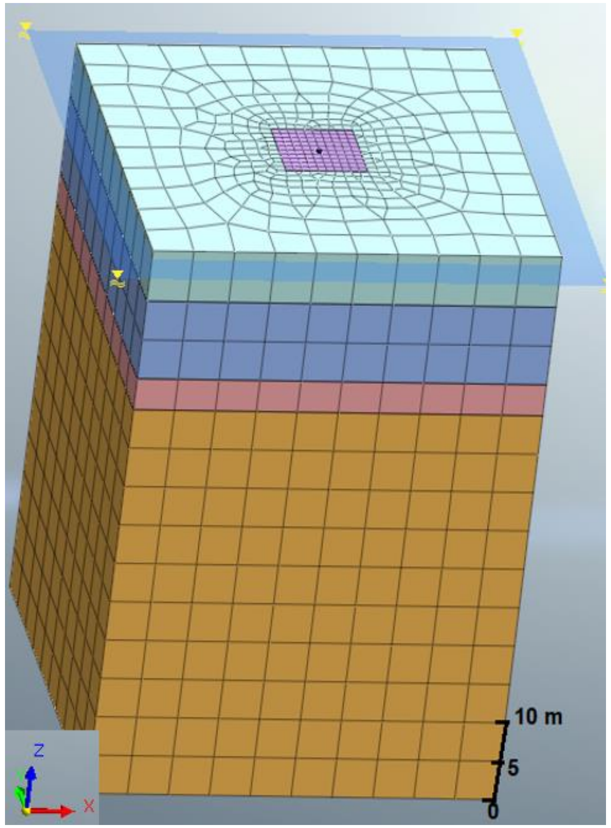
(a) displacement profile, (b) shaft friction profile, and (c) axial force profile

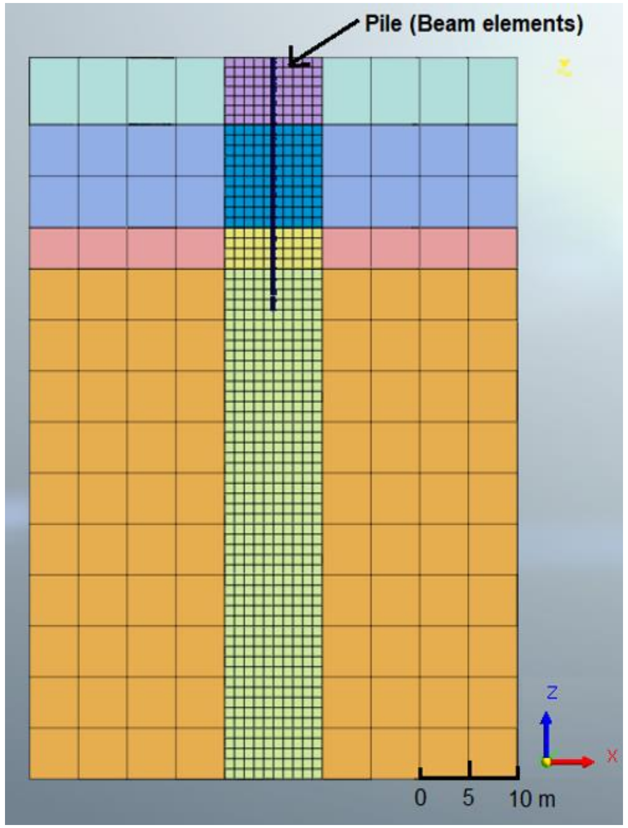


❑ Calibration of FEM with MIDAS GTS NX with the DFOS transfer curves

- Soil Model (50mx50mx70m): **Mohr Coulomb**
- Pile model: Elastic 1D
- Interface: **DFOS *t-z* curves** obtained from the previous load test
- Load condition: 12 load steps
- Load analysis: Construction stage

Soil type	Depth from G.L.	Saturated unit weight γ_{sat}	Effective cohesion C'	Friction angle φ'	Elastic Young modulus E	Poisson coefficient v'
-	[m]	[kN/m³]	[kN/m²]	[°]	[MPa]	[-]
Silty clay	0 to 6	18	1	20	7	0.3
Dense sand	6 to16	20	0	30	30	0.3
Consistent clay	16 to 20.5	19	15	5	10	0.35
Sandy gravel	≥20.5	21	0	35	120	0.3

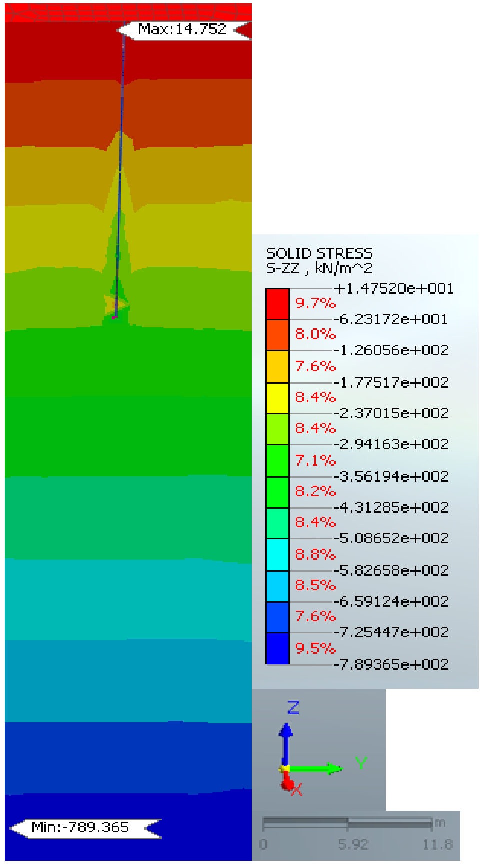




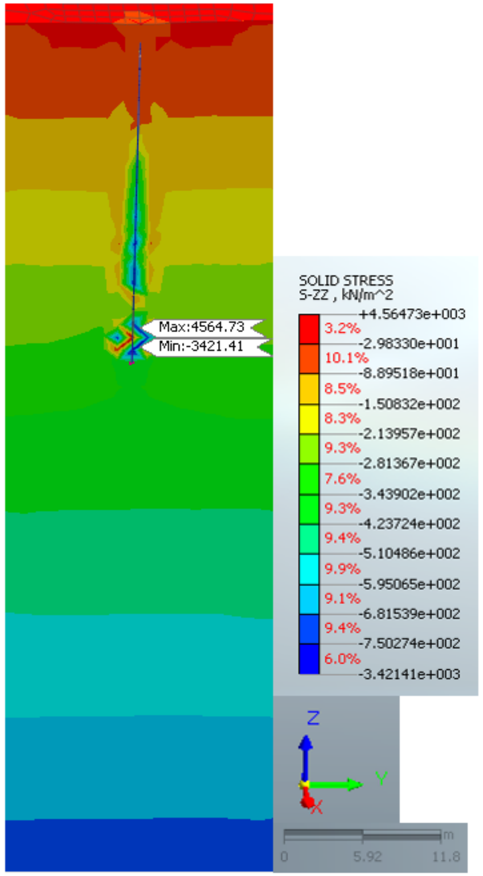
❑ FEM RESULTS

Effective stress state (a) before and (b) at maximum load

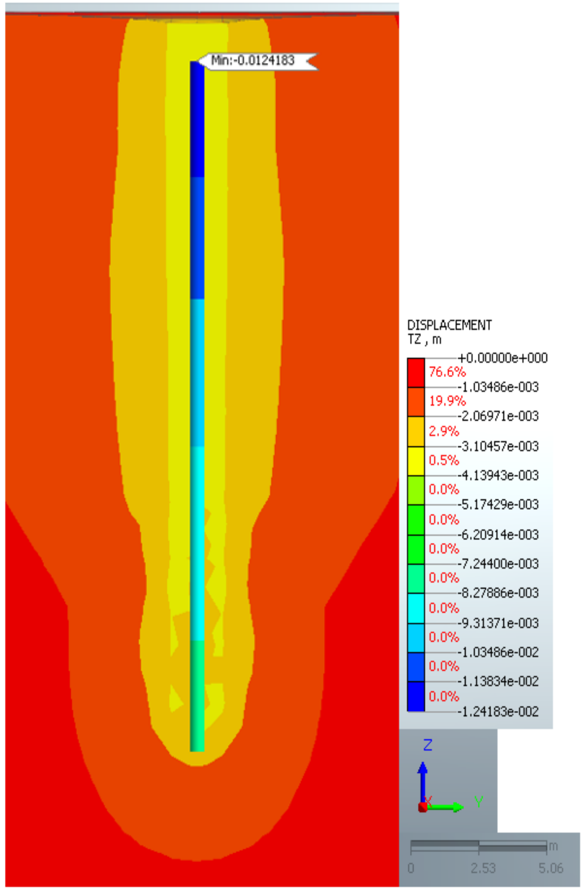
(a)



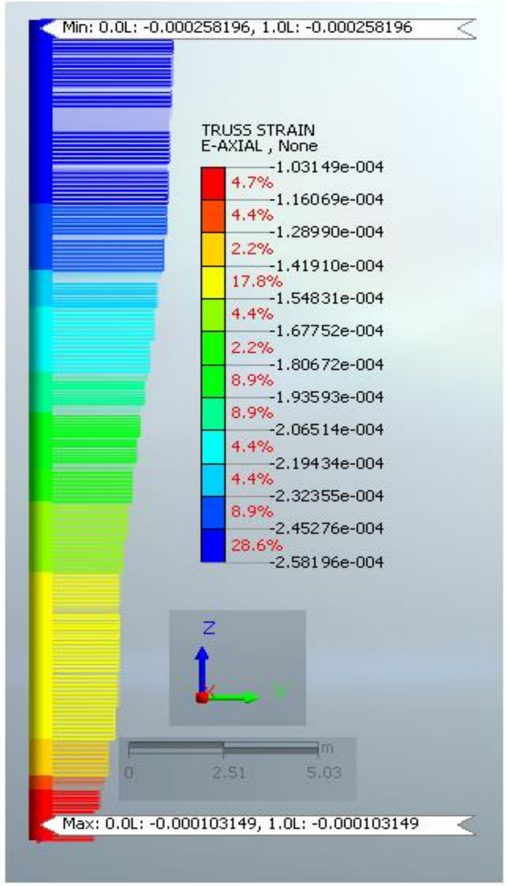
(b)



Vertical displacement at the maximum load

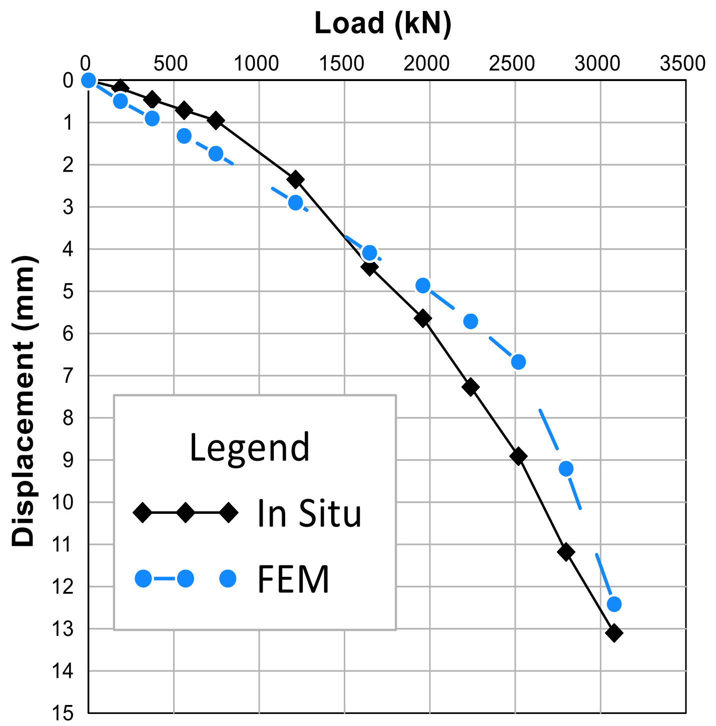


Strain profile at the maximum load

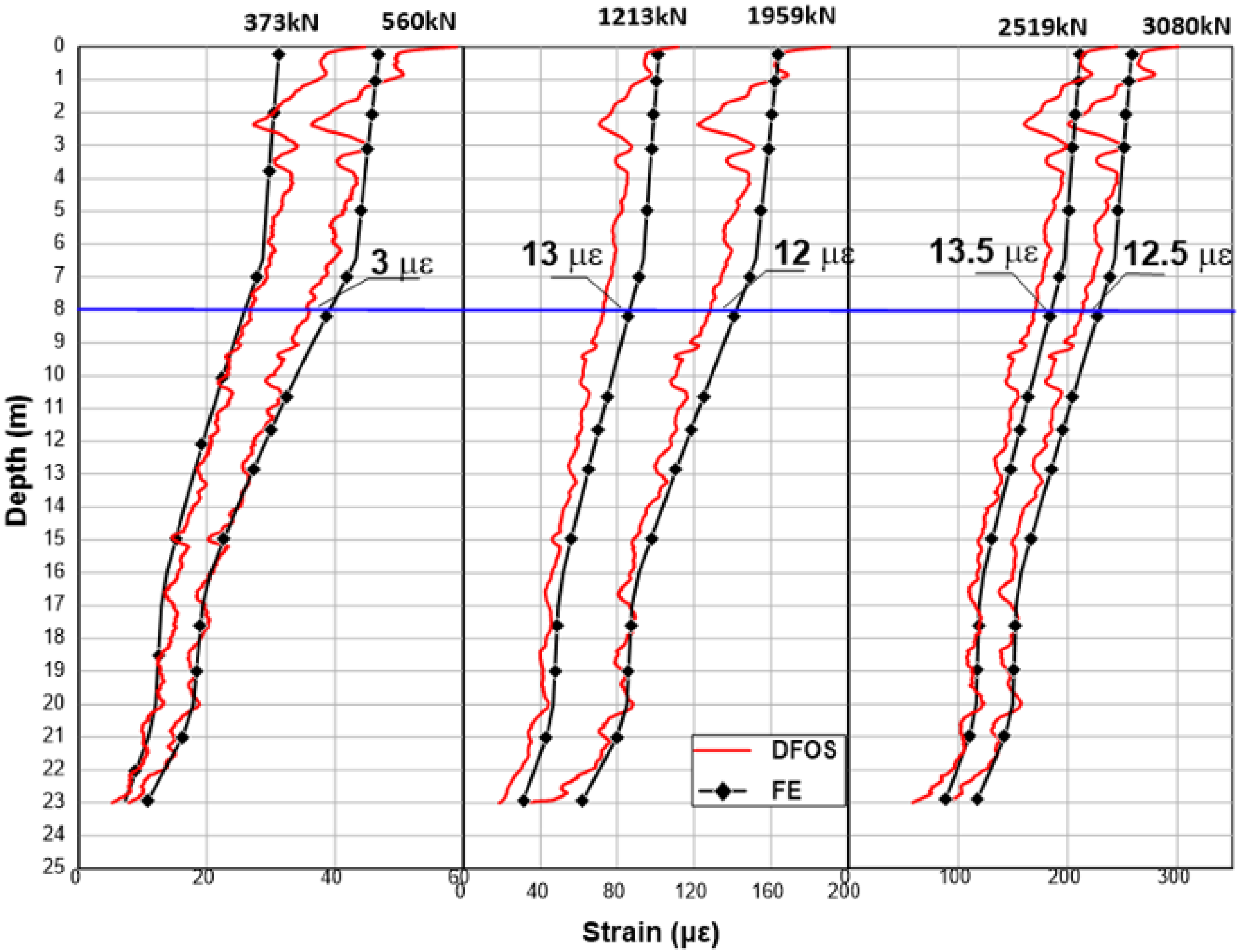


❑ Comparison between DFOS and FEM results

Settlements of the pile head



FE and DFOS strain profiles at different load steps



Strain measured with **DFOS** are helpful for obtaining the **actual load transfer curves** at soil-pile interface

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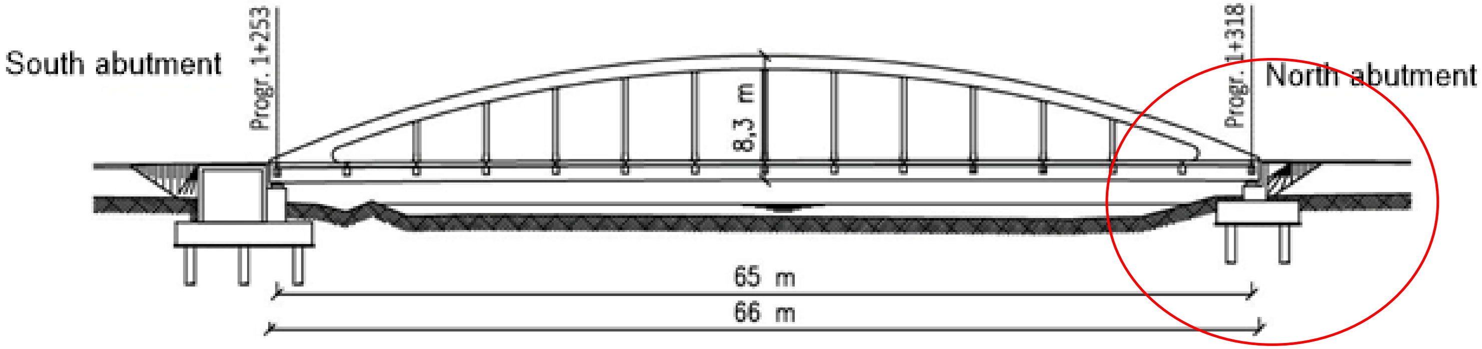
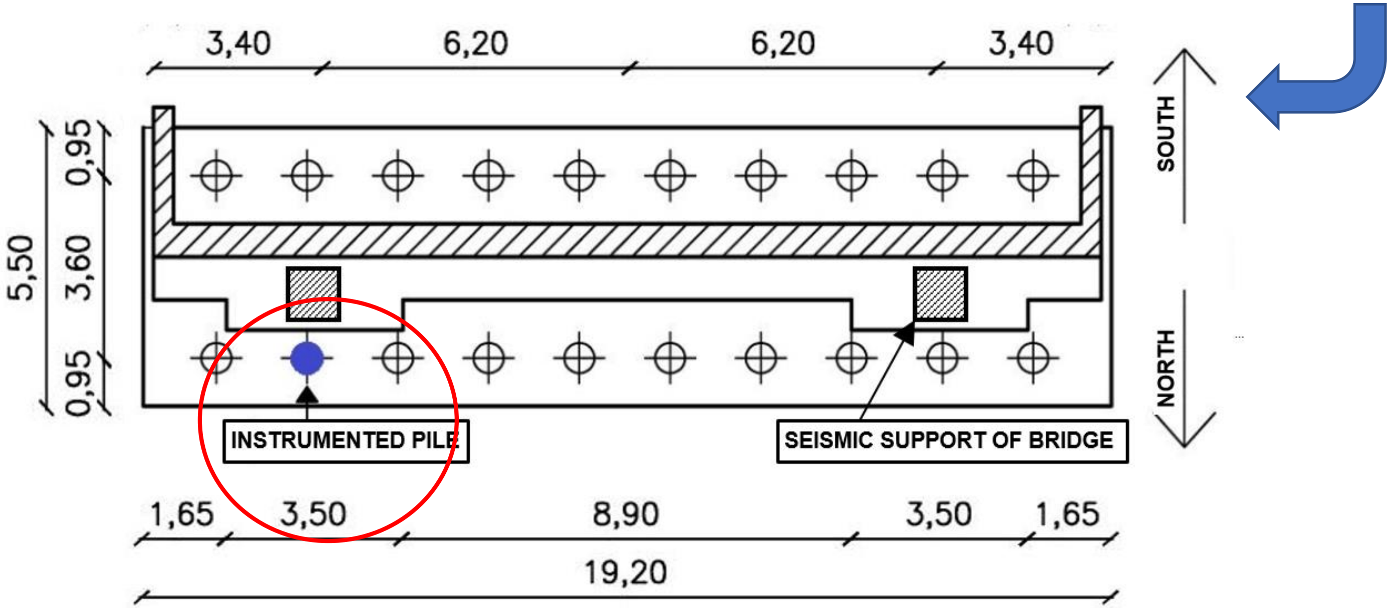
5. Final remarks

Monitoring of a foundation pile under serviceability loads

- Steel bridge founded on two piled rafts.
- In the North abutment: 20 CFA pile, L=22 m, D=64 cm





The monitoring system is composed by:

- 4 optical fiber sensors for strain
- 1 optical fiber sensor for temperature
- 6 temperature sensors (PT100) along the pile at various depths

DFOS Reading steps:

a) End of abutment construction (**21.10.2016, reference reading**)

b) Set up of the bridge steel structure (**30.01.2017**)

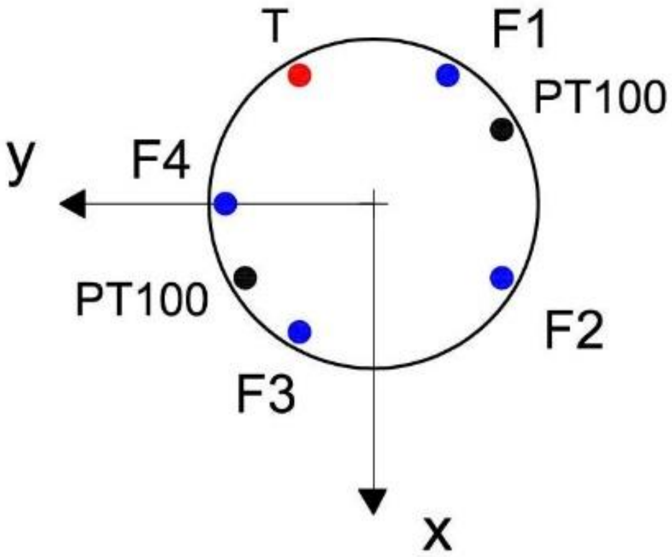
c) Bridge completion (08.03.2017) (*predalles* plates, concrete platform and earth embankment for the access ramp)

d) Before the acceptance load test (**10.05.2017**)

e) Half acceptance load test (**3 trucks**, Q=1200kN)

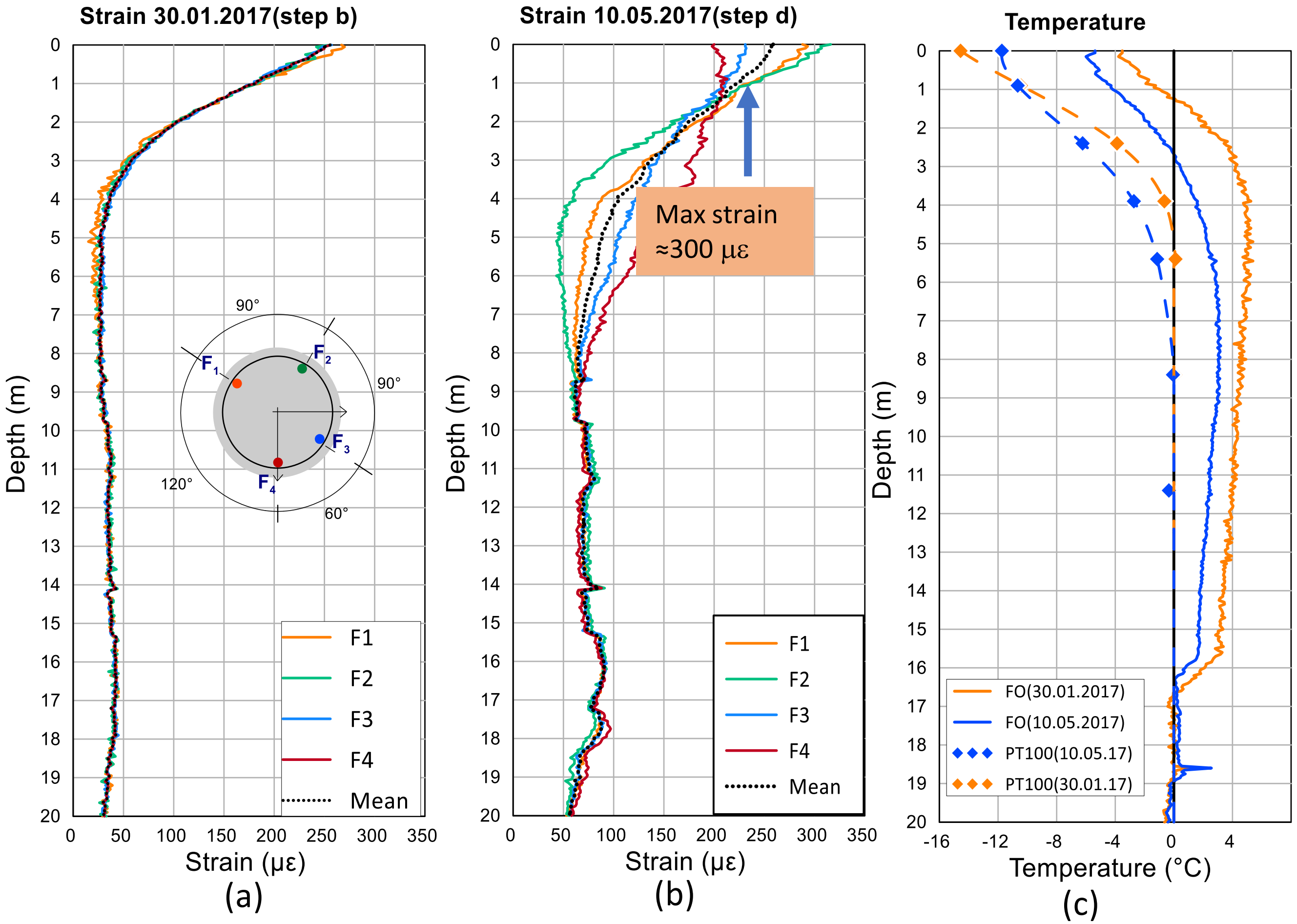
f) Maximum acceptance load (**6 trucks**, Q=2400kN)

g) Unloading phase

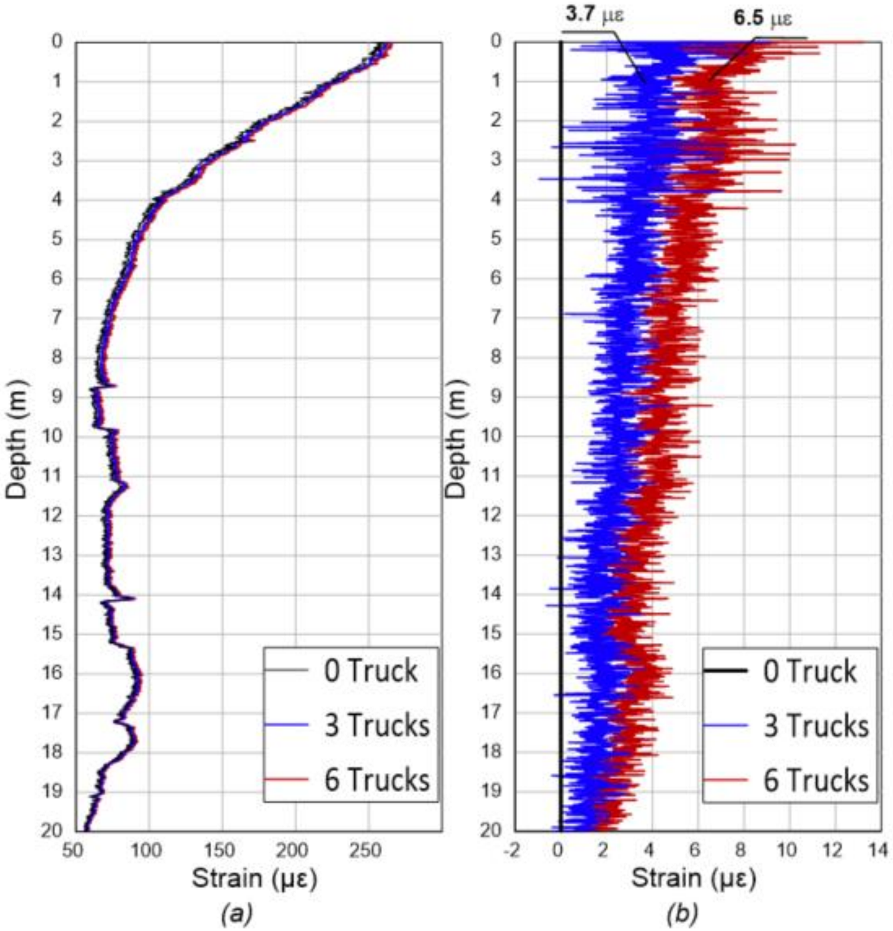


❑ DFOS measurement obtained during bridge construction

- **Max strain about 300 με similar to strain obtained during Pile load test with a load of 3000 kN**
- **Load on the instrumented pile is about $F_{pile,\ calc.}$ ≈91 kN**



(a) strain profiles on 30.01.17; (b) strain profiles on 10.05.17, and (c) Temperature profiles from FO cables and platinum temperature (PT100) sensors



(a) Average strain and (b) strain differences recorded during the bridge acceptance test on 10.05.2017

Different sources of the strain measured by DFOS

$$\varepsilon_{tot} = \varepsilon_{struct} + \varepsilon_T + \varepsilon_{creep} + \varepsilon_{sh} + \varepsilon_{other}$$

$$\varepsilon_{struct.}(y,z) = \varepsilon_{axial} + \varepsilon_{Moment}$$

$\varepsilon_T = C_{con} * \Delta T$ — **Concrete thermal volumetric coeff. C_{con} =1.2·10^{-5} °C^{-1}**

ε_{creep}; ε_{sh} — **CEB-FIP (2010), Eurocode2**

$$\varepsilon_{sh}(t,t_s) = \varepsilon_{cas}(t) + \varepsilon_{cds}(t,t_s)$$

$RH = 100\%$; therefore, there is **no drying shrinkage**

$$\varepsilon_{creep}(t,t_0) = \varepsilon_c(t_0) \cdot \Phi(t,t_0)$$

Where,

$$\varepsilon_c(t_0) = \frac{\sigma_c(t_0)}{E_c} = \frac{\Delta N}{EA}$$

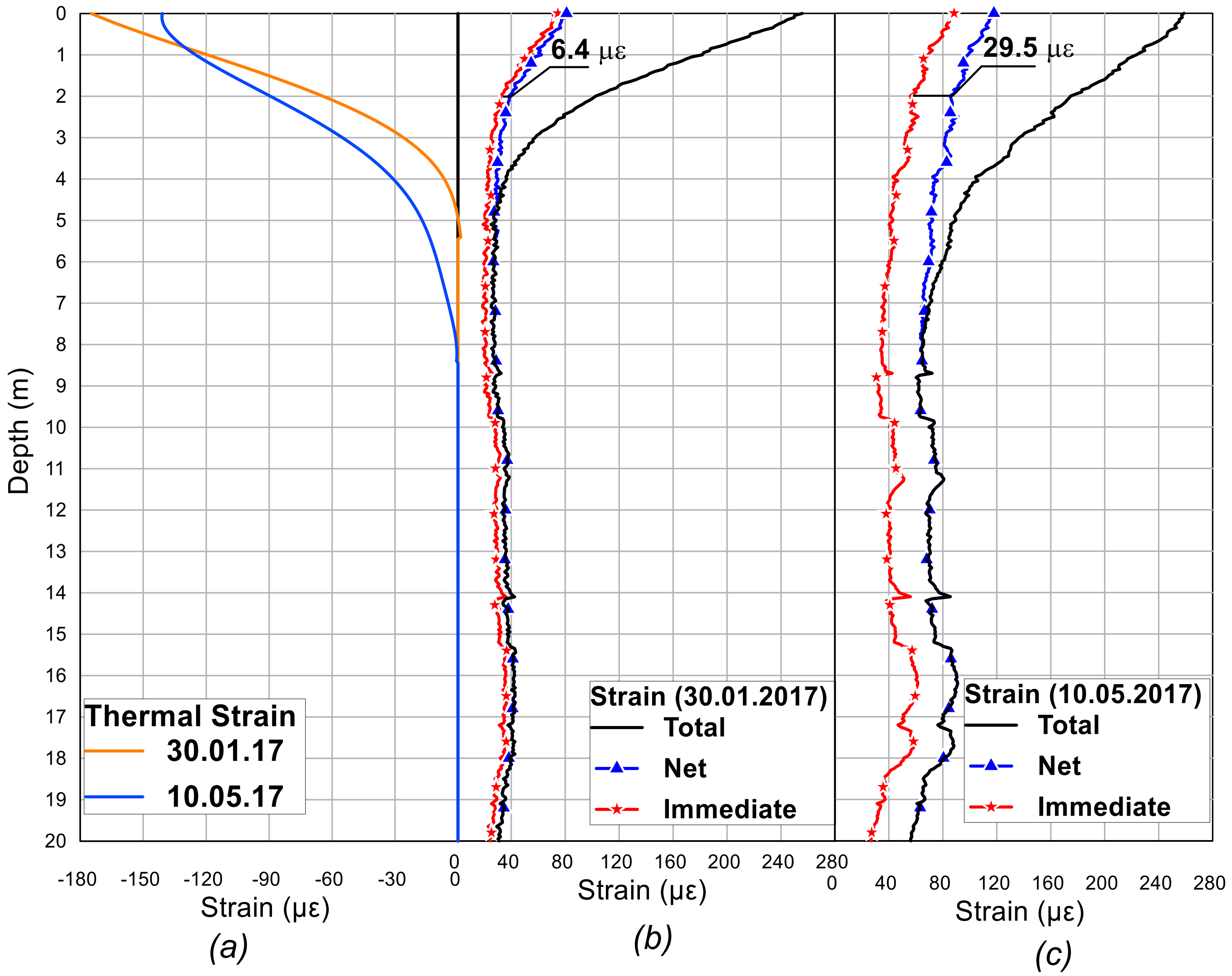
$$\varphi(t,t_0) = 1.37 * \left[\frac{(t-t_0)}{1500+(t-t_0)}\right]^{0.3}$$

- ε_{struct} Structural strain (short term)
- ε_T Thermal strain
- ε_{creep} Strain due to creep
- ε_{sh} Strain due to shrinkage
- ε_{other} Strain from others sources

Creep strain from 21/10/2016 (t_0=91days)

Measurement day	t(days)	ΔN [kN]	$\varepsilon_c(t_0)$ [$\mu\varepsilon$]	$\varphi(t-t_0)$	ε_{cc} [$\mu\varepsilon$]
30/01/2017	192	91.3	10.76	0.59	6.44
10/05/2017	292	346.7	40.9	0.72	29.51

❑ Different sources of strain measured by DFOS

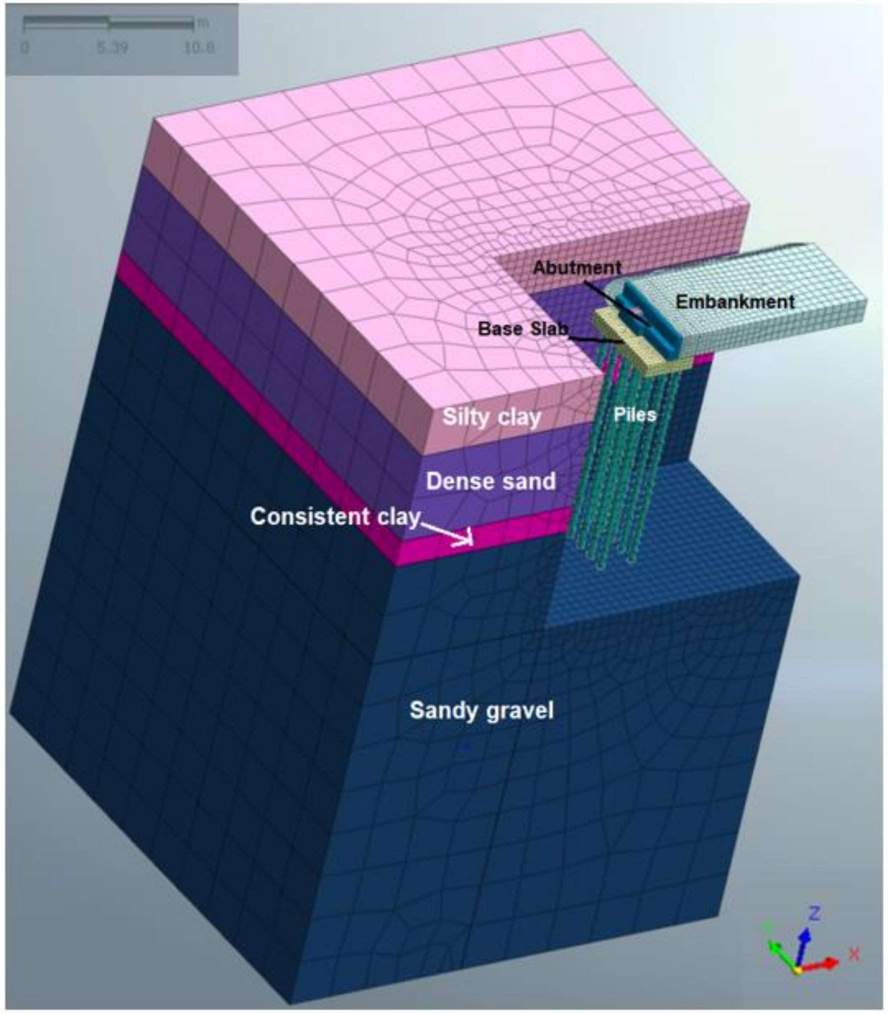


(a) Thermal strain derived from PT100 measurement during the bridge construction, Total average, net and immediate strain profiles on (b) 30.01.2017 and on (c) 10.05.2017.

- The net strain is the mechanical effect of the loads applied with the bridge construction. At pile head, it is about 80 με at step*(b)* and 120 με at step*(d)*

- The FO cables measurements could not be considered totally reliable in this case study

FE Model of the Bridge North Abutment

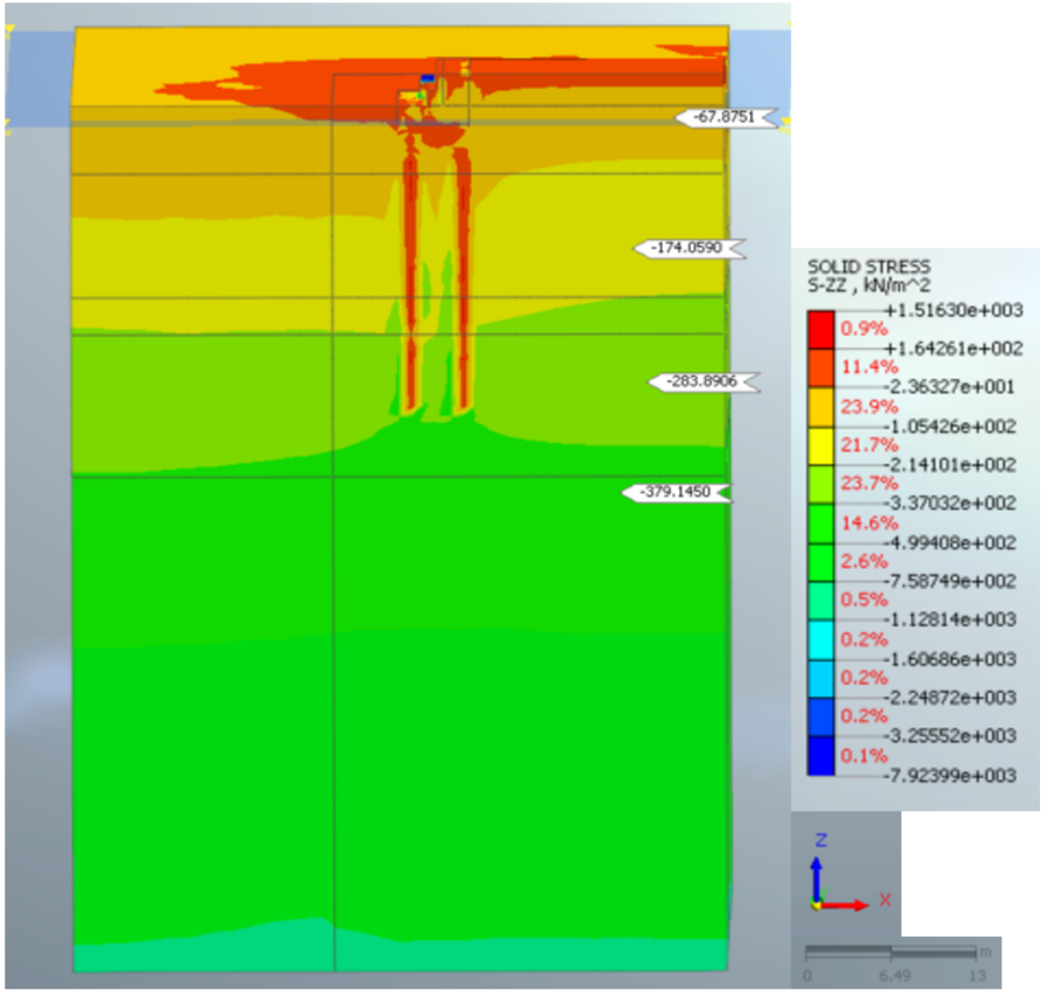


- Half bridge foundation is modelled thanks to the symmetry along the longitudinal part of the abutment foundation (Y-axis)
- Same properties for materials as in the case of the pile load test
- Interaction soil-pile is modelled with the calibrated transfer functions

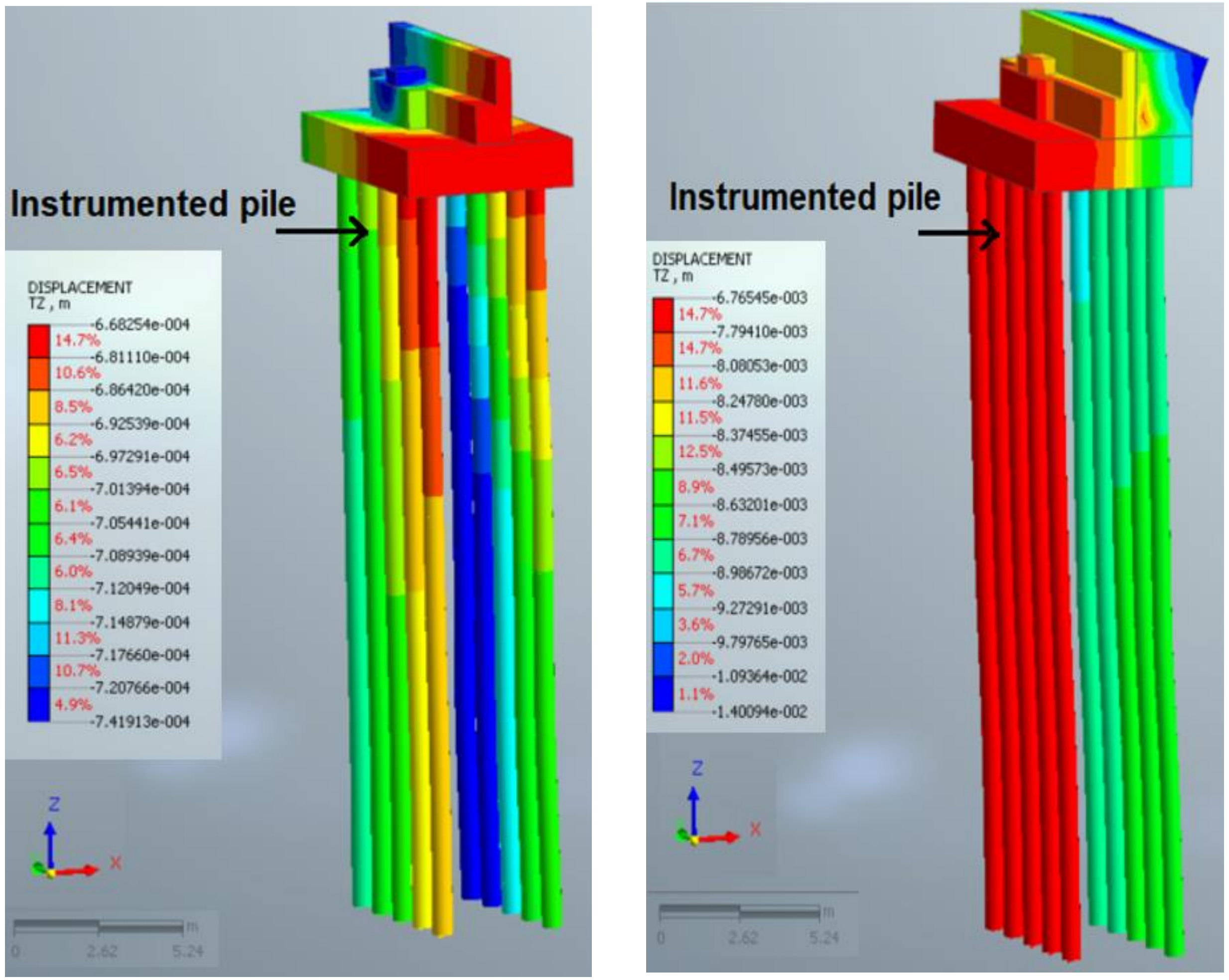
Material properties of slabs and embankment

Structural element	φ' [°]	C' [kPa]	E [MPa]	ν' [-]	γ (kN/m^3)
Abutment/Slab	-	-	35000	0.18	25
Embankment	30	10	40	0.3	20

❑ FE Model of the Bridge North Abutment



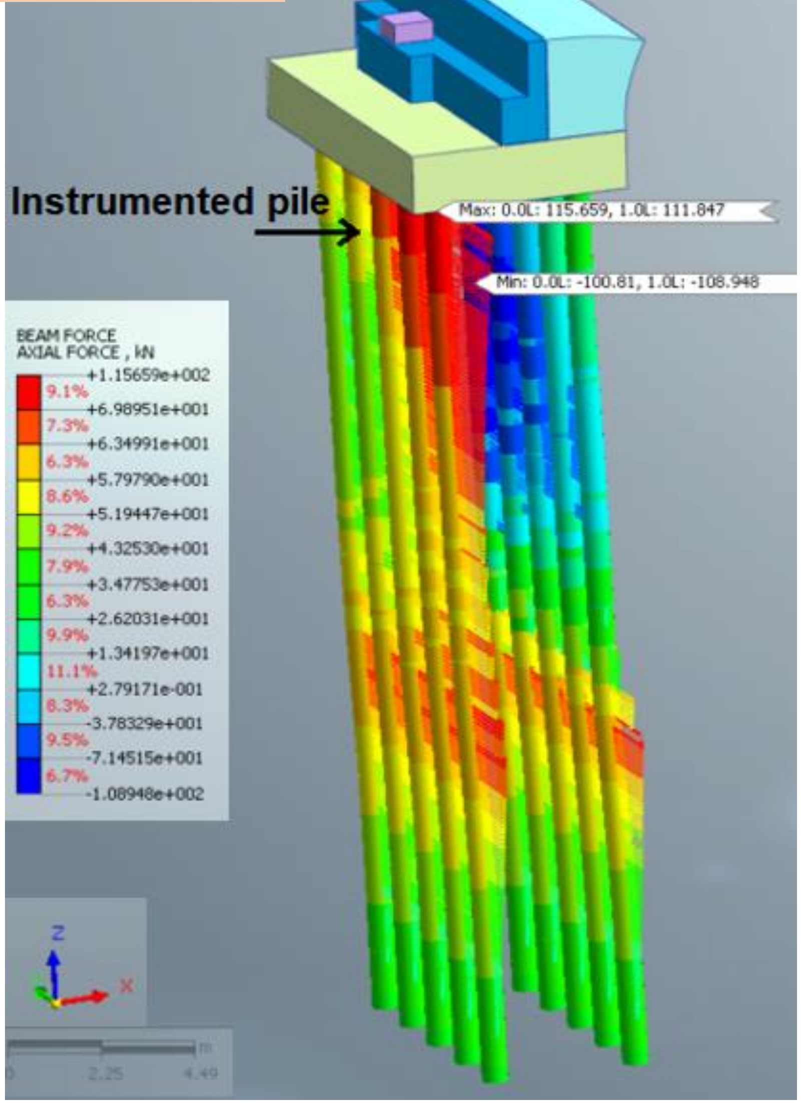
Effective soil stress state at the end of Bridge Construction (10.05.2017).



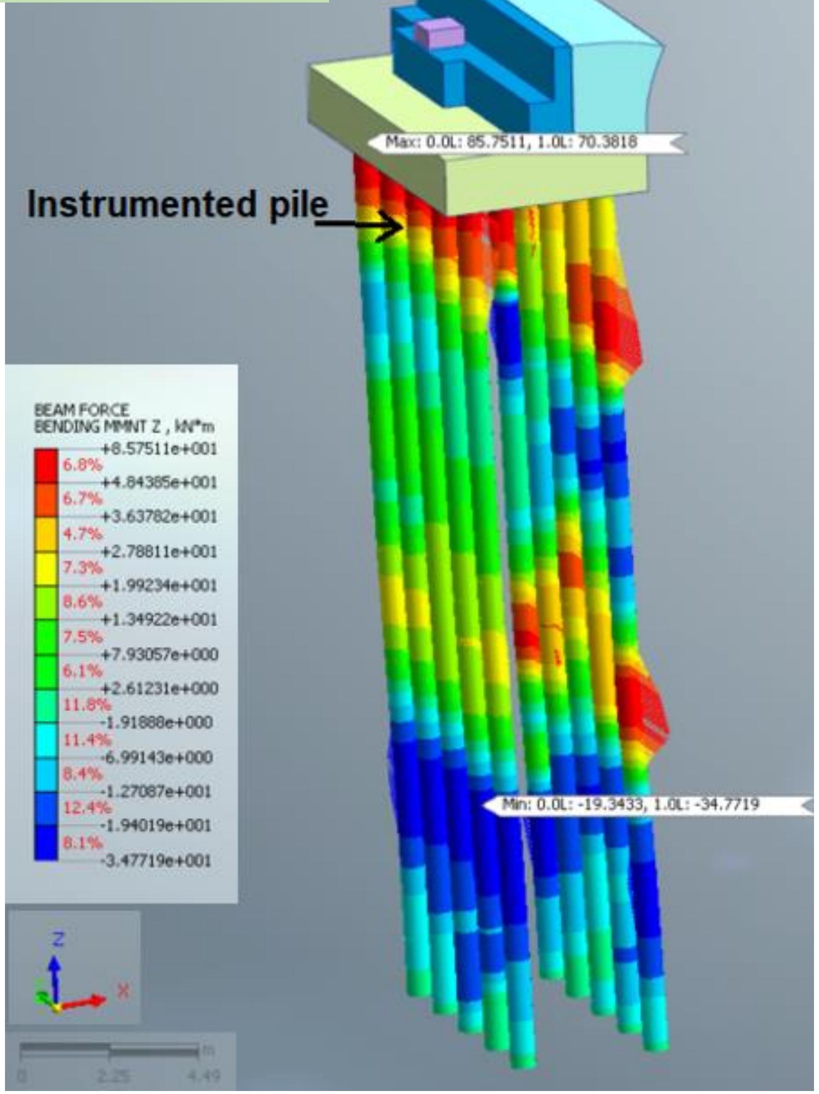
Vertical displacement: (a) at the end of abutment construction (30.01.2017) and (b) at the end of bridge construction (10.05.2017)

❑ FE Model of the Bridge North Abutment

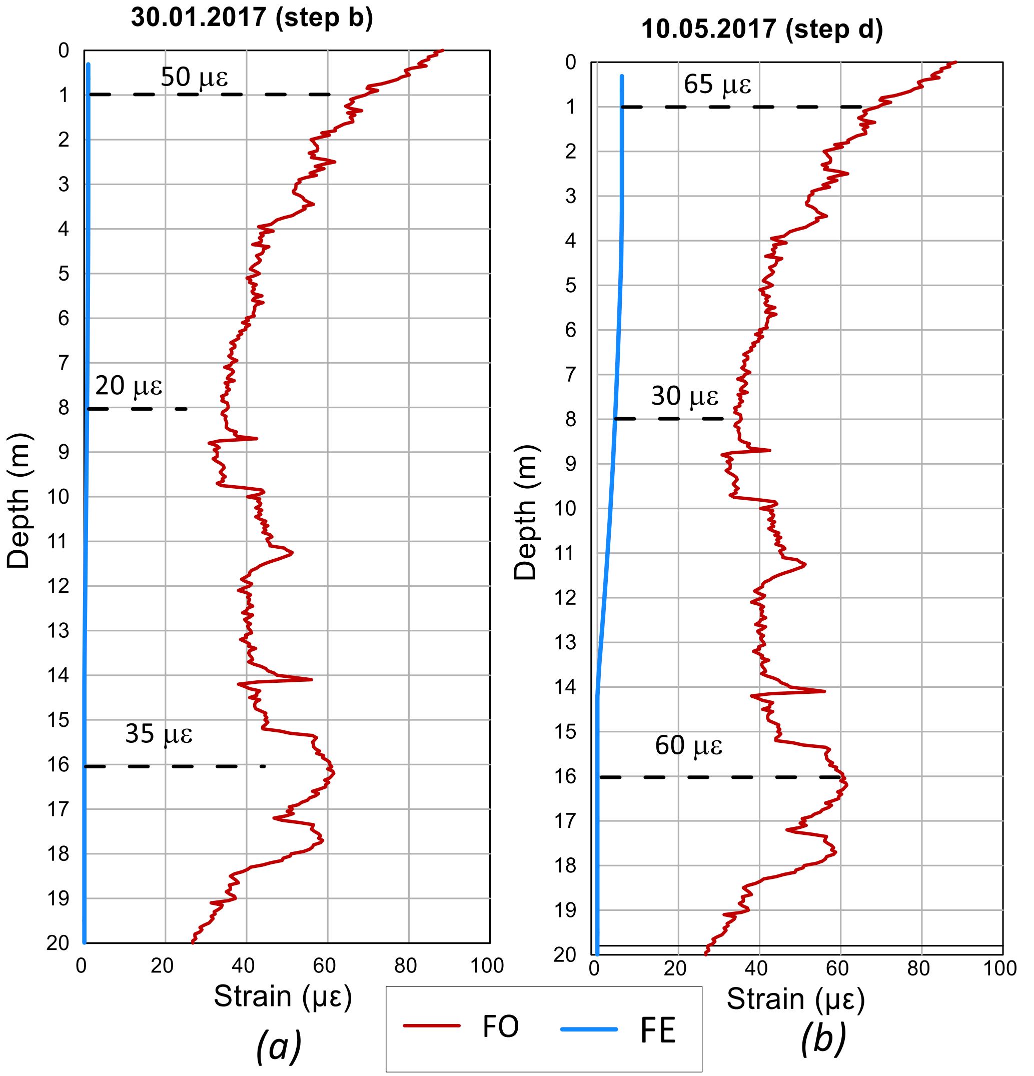
Pile axial Force profile



Pile bending moment Mz



❑Comparison between immediate strain from FO cable and FE model



- The net strain obtained with DFOS are larger than the FEM strain with a difference varying from 20 to 65 με.
- DFOS measurement are affected by other effects that are not correctly consider here.
- It is advised to combined them with traditional monitoring in case they break during installation.
- FEM calibrated with DFOS load transfer curves are more reliable for analyzing in detail the real pile behavior.

- ❖ DFOS offers a more detailed view of both the geometry and the response of the structure by highlighting unexpected anomalies observed during the monitoring.
- ❖ They have demonstrated to be **reliable** for collecting significant information and for **studying the real behavior** of geotechnical structures, however it is advised to combine them with **traditional monitoring** in case they **break** or **are affected by high strain** during installation.
- ❖ The load transfer curves obtained from DFOS strain measurements can be combined with theoretical load transfer functions for a better calibration of FE Model.

Some difficulties in field applications:

- DFOS state tension is not know while taking measurement and their installation inside the structure are still a challenge.
- Cross-sensitivity between temperature and strain in DFOS is a major obstacle for practical application.

Future Perspectives

- Some tests in laboratory or in situ of small piles instrumented with DFOS could be performed to measure better the effect of concrete shrinkage and temperature variation on DFOS measurement during and after concrete curing.

- Further studies should be done to evaluate the **effect of concrete shrinkage and creep** in geotechnical structures, because **their variation** along pile depth is affected by the soil stress state.

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