Assessing the performance of thermo-active geotechnical structures

David M G Taborda
Imperial College London

GSHPA Technical Seminar
University of Leeds, 24th May 2018

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Energy Geotechnics

- Combines all geotechnical issues of energy provision:
  i) gas hydrate sediments,
  ii) unconventional hydrocarbons and hydraulic fracturing
  iii) energy geostructures
  iv) energy geostorage
  v) high-level radioactive waste disposal
  vi) CO2 storage

- At Imperial College, the focus has been on **energy geostructures**, **energy geostorage** and **nuclear waste disposal**

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Energy Geotechnics

Energy geostorage

- *BHEs*
- *Horizontal loops*
- *Open loops*

Energy structures

- *Piles*
- *Retaining walls*
- *Tunnel linings*

Nuclear waste disposal

- *Geological disposal*
- *£20-£30 billion*
- *10 000 years design*

Energy Geotechnics

Energy structures

- Piles
- Retaining walls
- Tunnel linings

What are we asking?

- Thermal performance?
- Additional structural forces?
- Additional ground movements?
- Impact on adjacent structures?

Which do we need to know?

- Thermal properties
- Thermal loads
- Thermo-hydro-mechanical properties of soil

How do we find out?

- Specialist temperature-controlled lab equipment
- Advanced numerical methods
- Field data for validation

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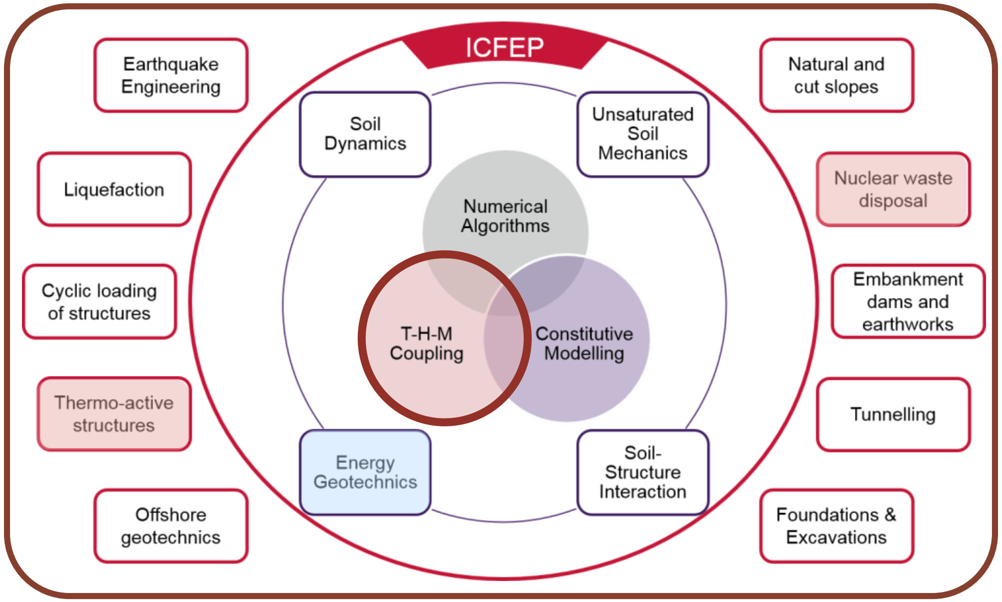
Energy Geotechnics



How do we find out?

- *Specialist temperature-controlled lab equipment*
- *Advanced numerical methods*
- *Field data for validation*

- *Temperature-controlled triaxial equipment*
- *Temperature-controlled oedometers*
- *Strength & stiffness under temperature changes*
- *Thermal expansion*
- *Thermal pressurisation of pore water*

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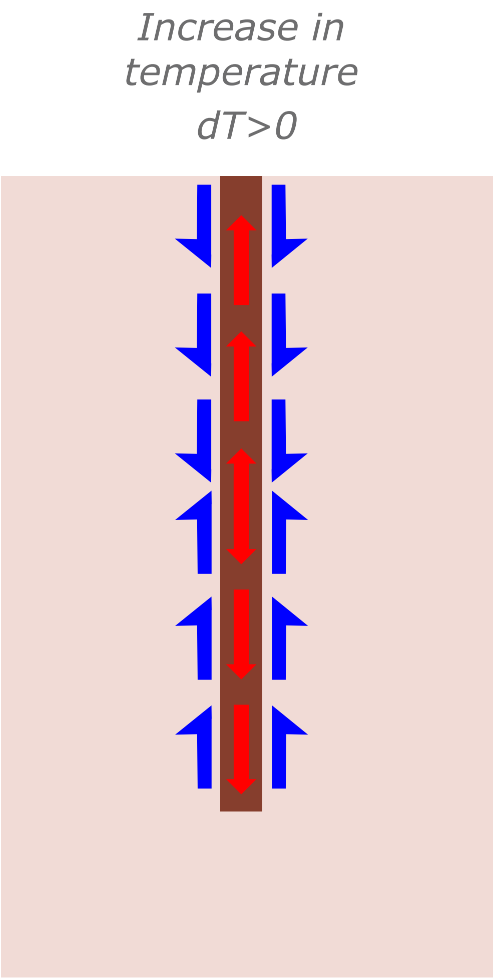
Behaviour of a single thermo-active pile



- *Pile expands when heated*
- *Soil restrains the deformation*
- *Additional axial forces are generated*
- *The more the soil effectively restrains the pile the larger the axial force increase*
- *The opposite is expected when cooling (i.e. reduction in axial force)*

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Numerical modelling of thermo-active piles

Initial conditions	*Material behaviour*
Numerical algorithms	*Coupled phenomena*

Numerical modelling of thermo-active piles

Initial conditions

- *Stress state*
- *Pore water pressure profile*
- *Temperature field*

Material behaviour

- *Mechanical response*
- *Hydraulic properties*
- *Thermal properties (thermal conductivity, specific heat capacity)*

Numerical modelling

- *Transient seepage*
- *Hydraulic boundary conditions*
- *Transient heat flux (advection-diffusion)*
- *Thermal BC & modelling of pipes*

Coupled phenomena

- *Consolidation (HM)*
- *Thermal expansion (TM)*
- *Advection (TH)*
- *Temperature-induced pore water pressure (THM)*

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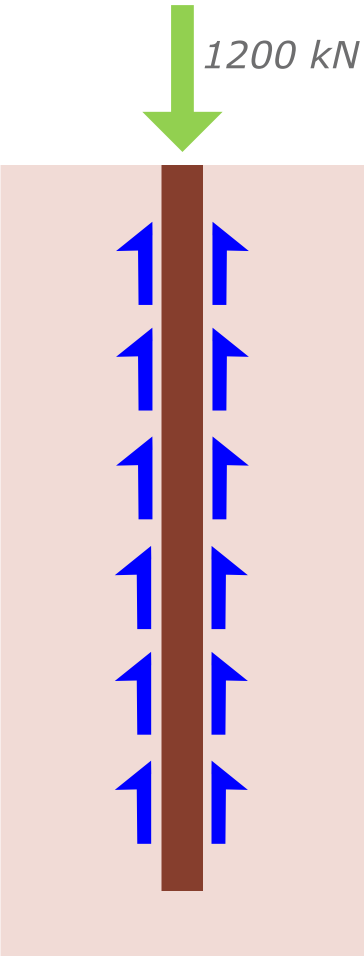
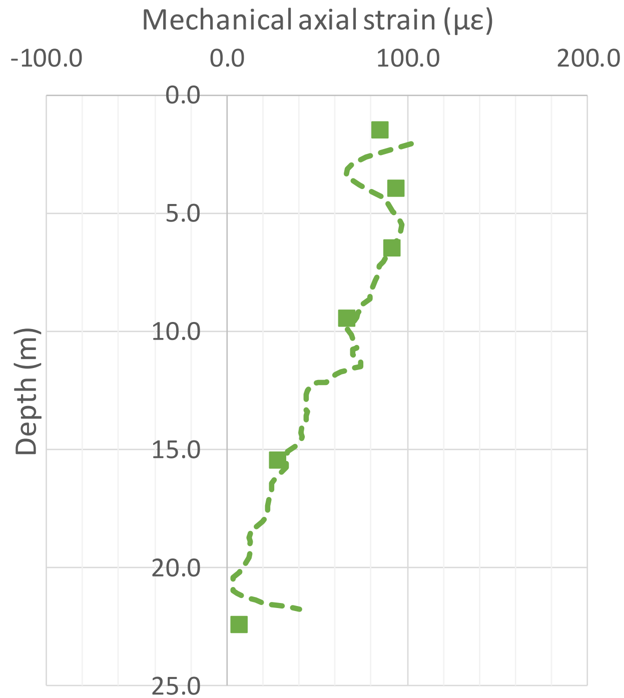
Reproduction of a field test

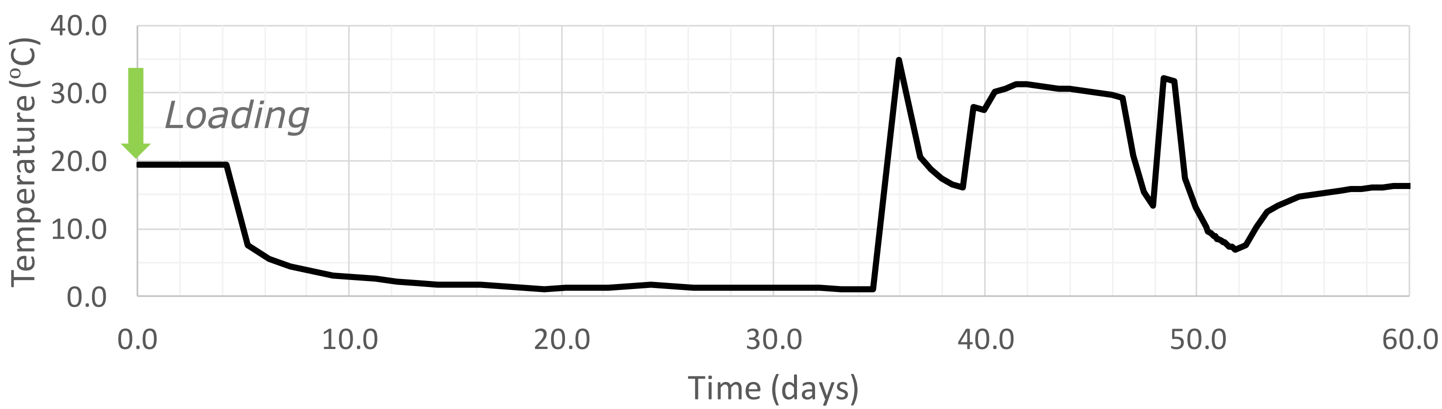
Lambeth College main test pile (Bourne-Webb et al., 2009)

- 23 m long pile (19 m in London Clay)
- 550 mm diameter
- Loaded mechanically to 1200 kN (FoS = 2.5)
- Pile temperatures ranged from 0 °C to 35 °C
- Heavily instrumented pile (including OFS & VWSG)
- $E = 40\ GPa$, $\alpha_{concrete} = 8.5 \times 10^{-6} m/(mK)$
- Coupled THM modelling assuming non-linear elasticity below yield, properties obtained from literature on London Clay

Reproduction of a field test







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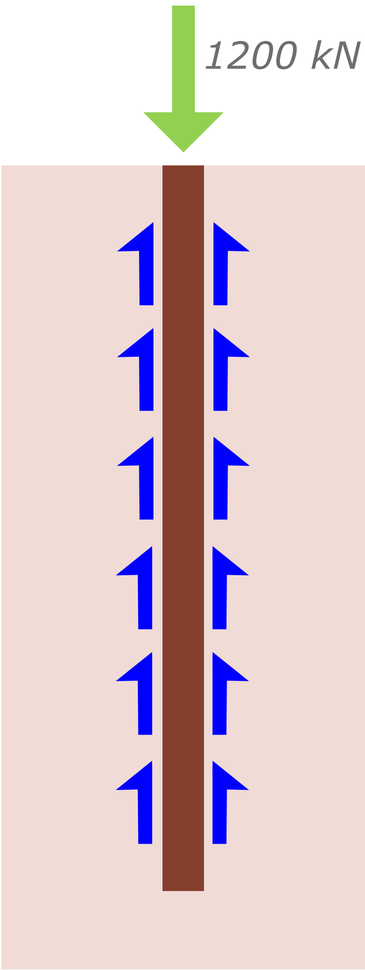

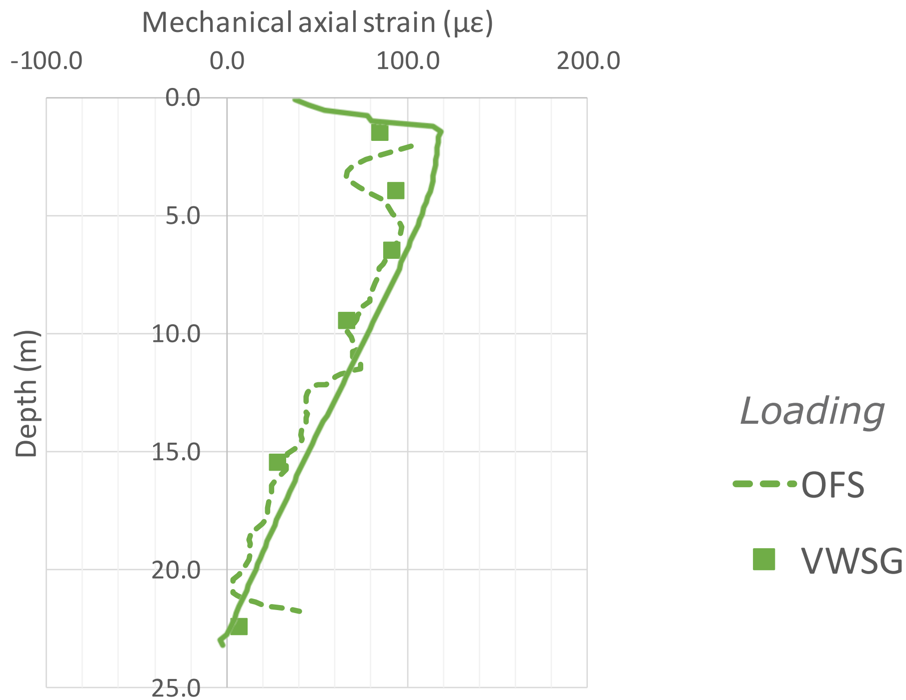

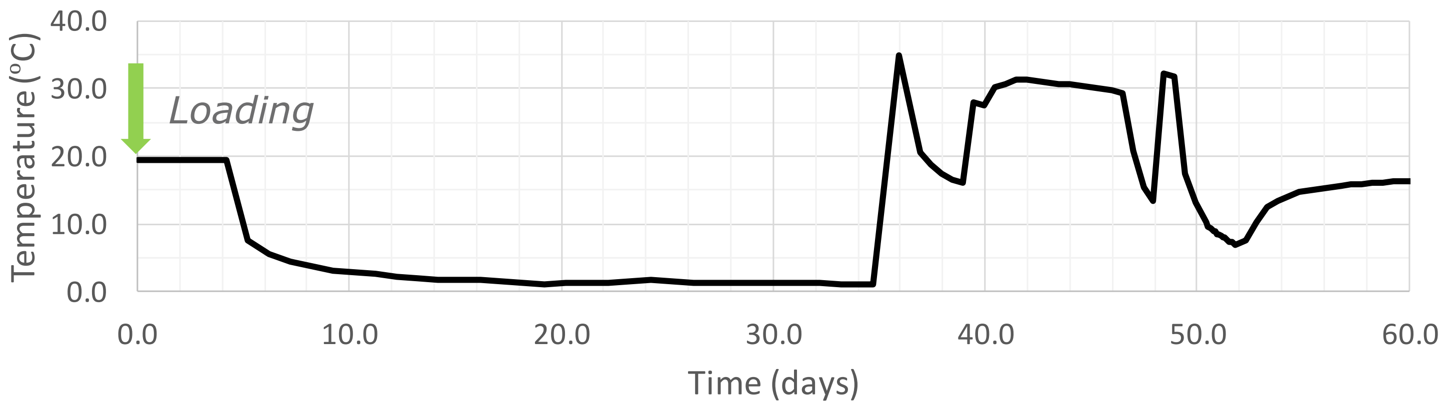

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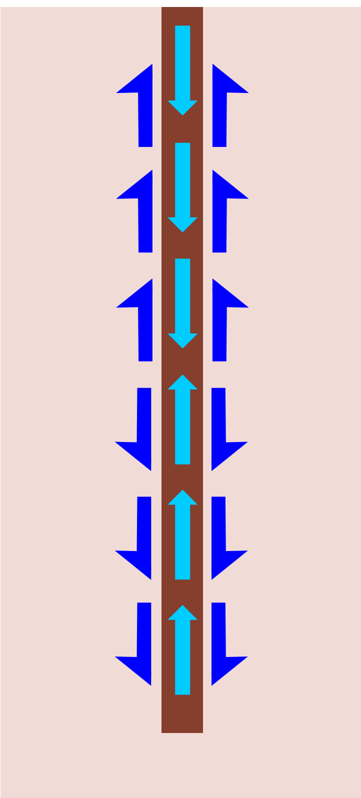

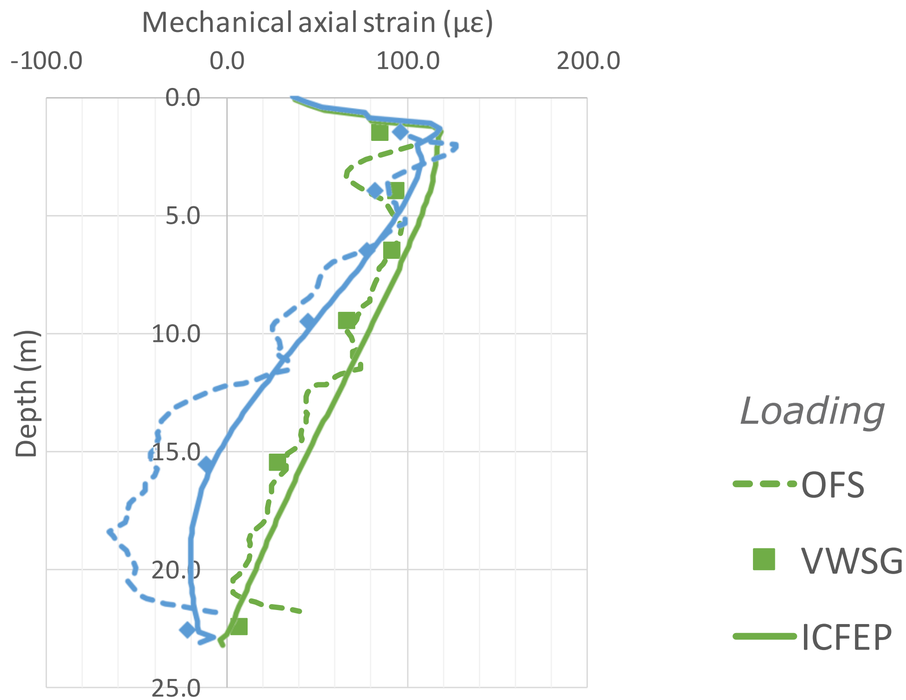

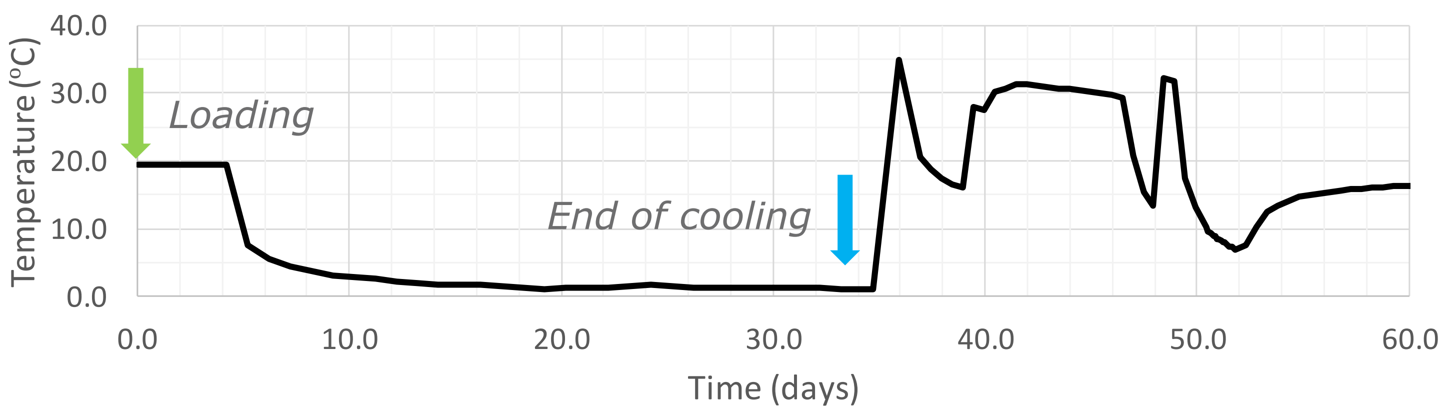

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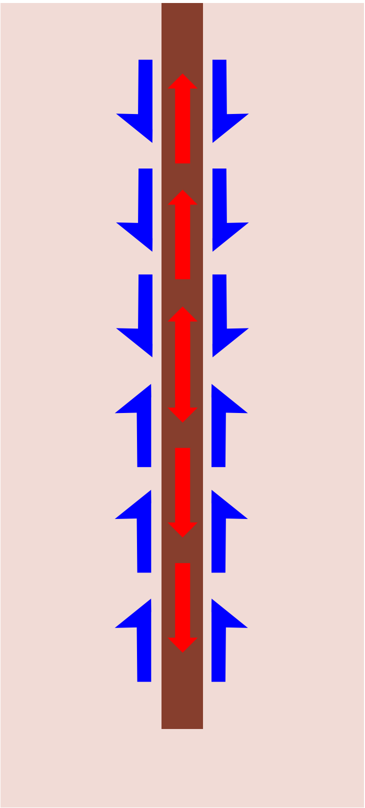

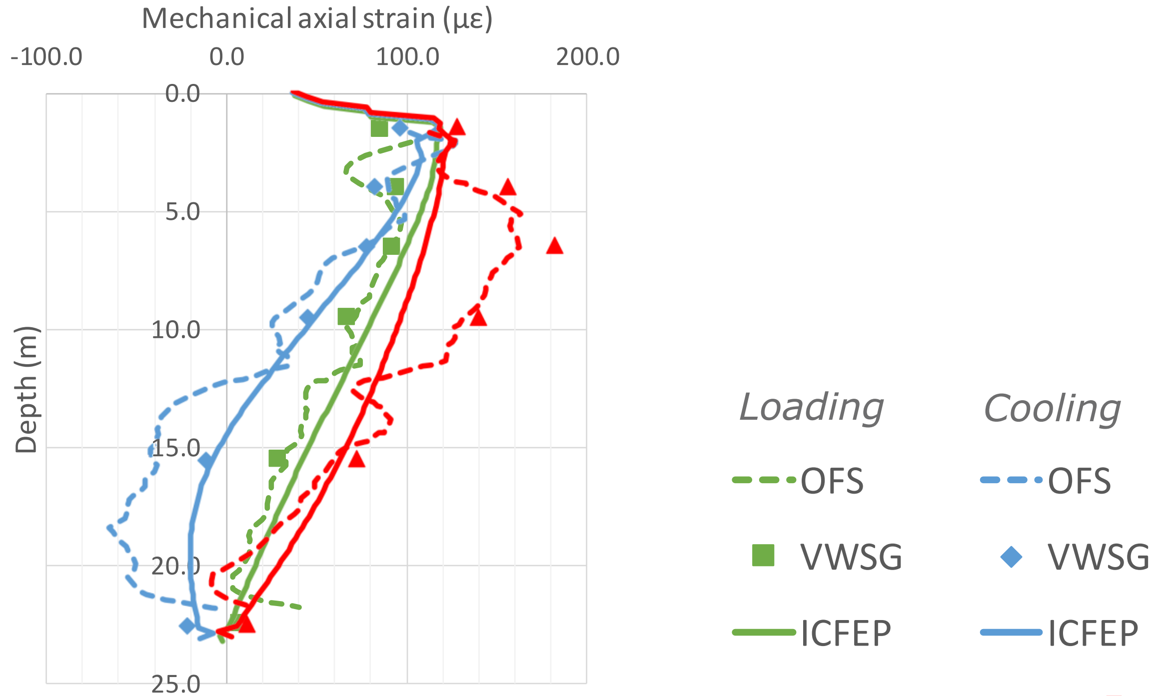

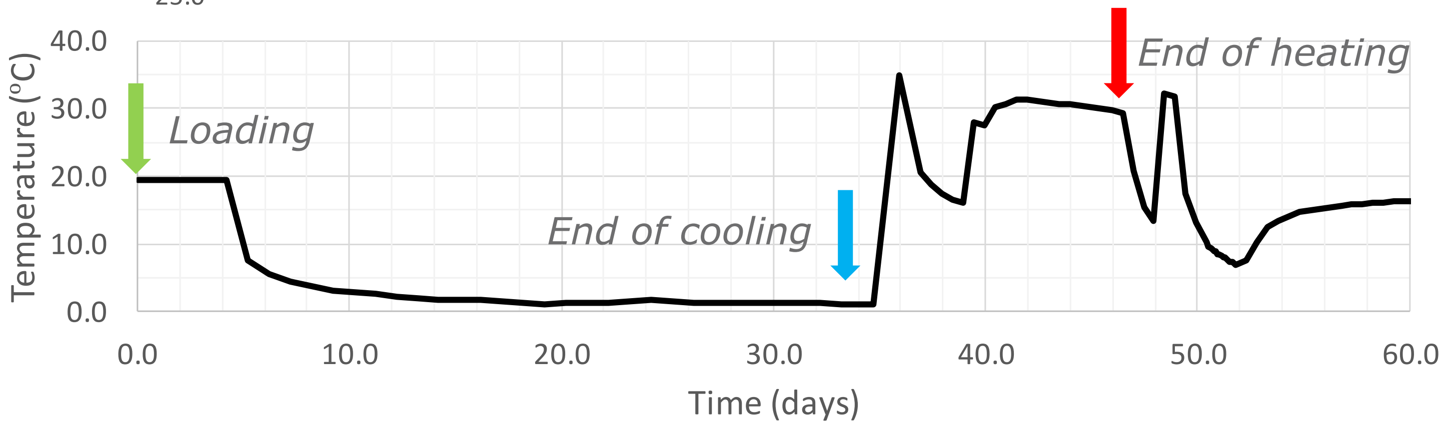

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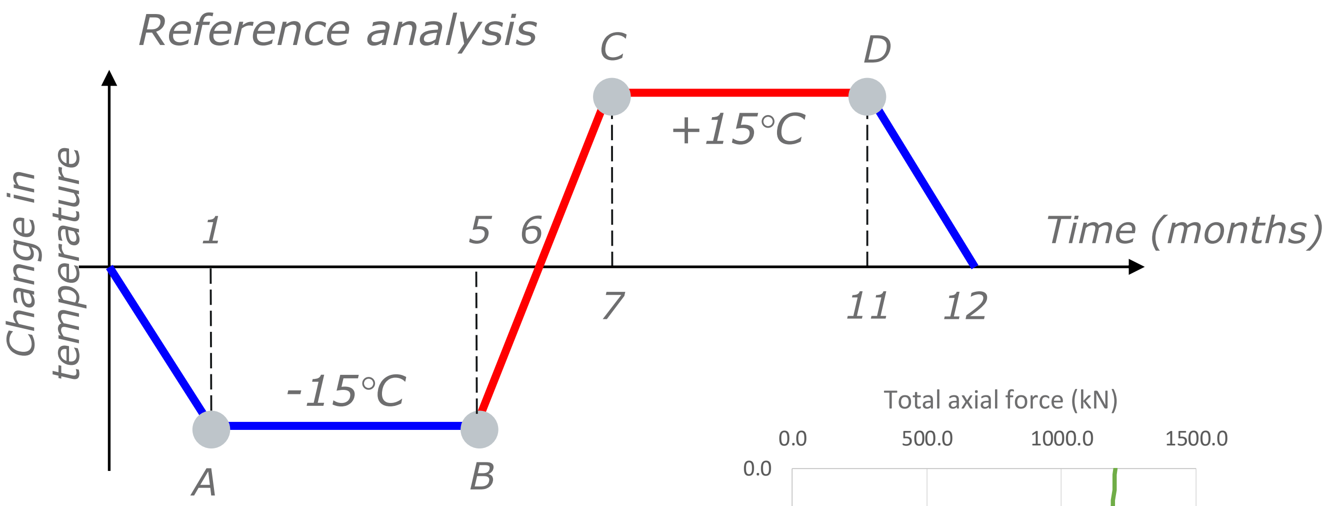
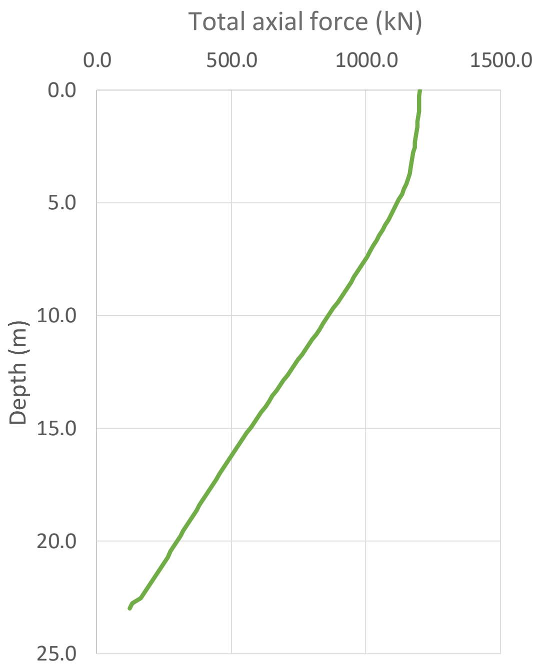
Exploratory studies

- Based on the validated numerical model
- Investigate the effect of:
  - Transient phenomena
  - Thermo-mechanical response of soil (linear)
  - Thermo-mechanical response of soil (thermo-plastic)
  - Adopted boundary conditions within pile (temperature / heat flux / modelled pipe)
  - Thermal conductivity of soil
  - Permeability
  - Thermo-induced pore water pressures
- Reported in Gawecka et al. (2017) (ICE Proceedings) and in Gawecka (2017)

Exploratory studies





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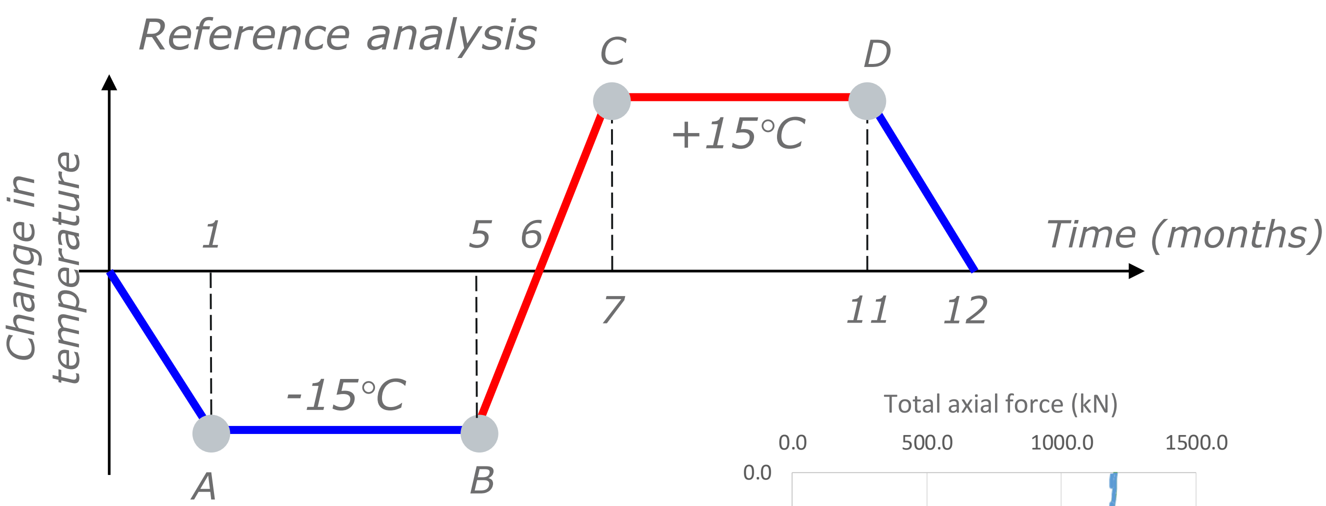
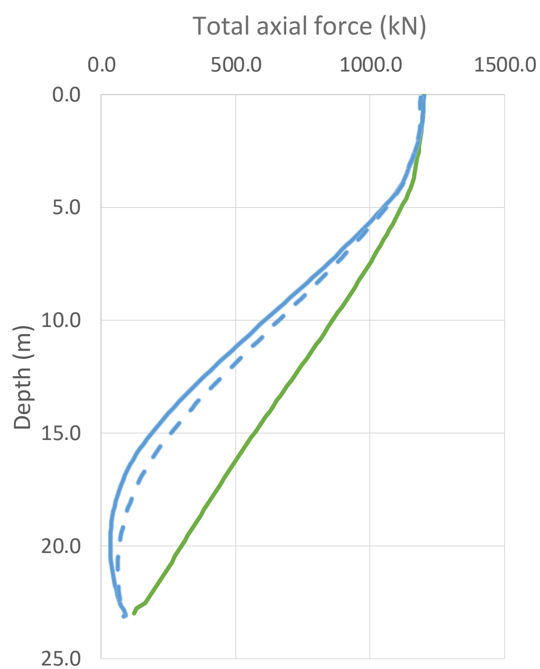
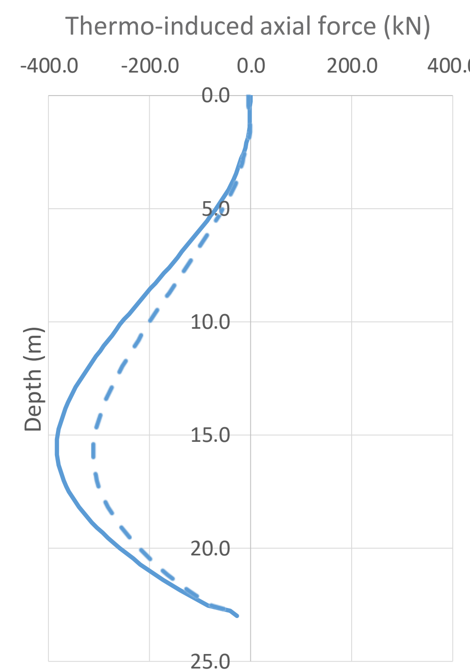
Exploratory studies



Mechanical loading





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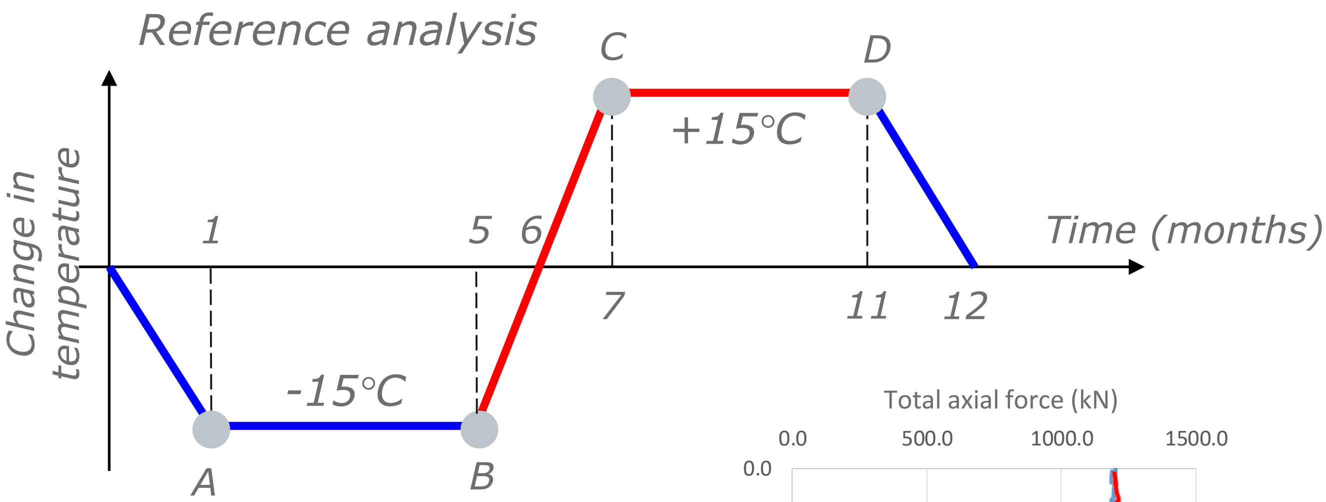
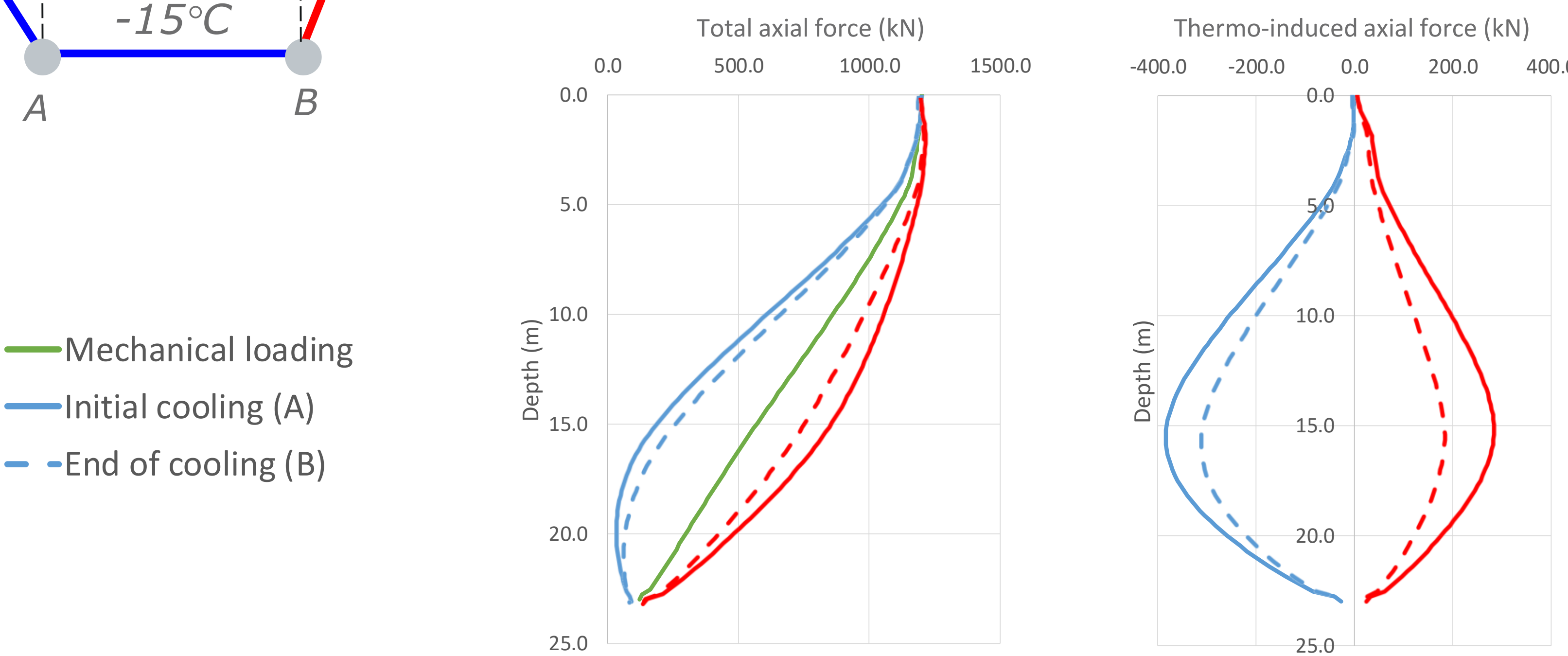
Exploratory studies





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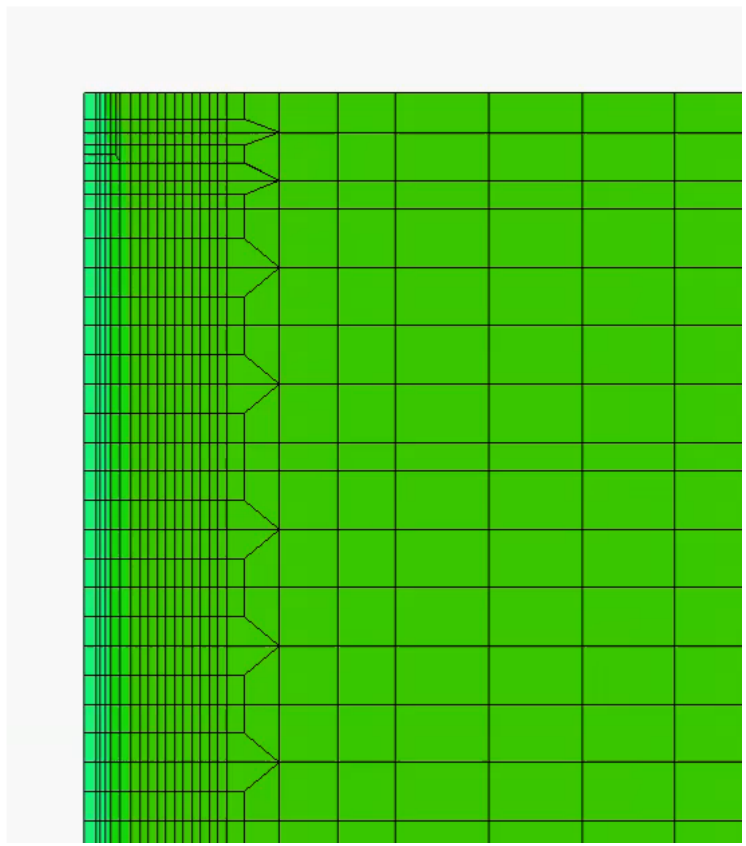
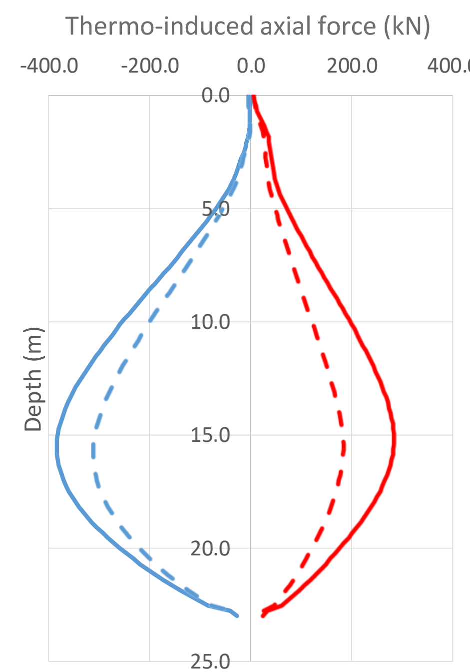
Exploratory studies

Reference analysis

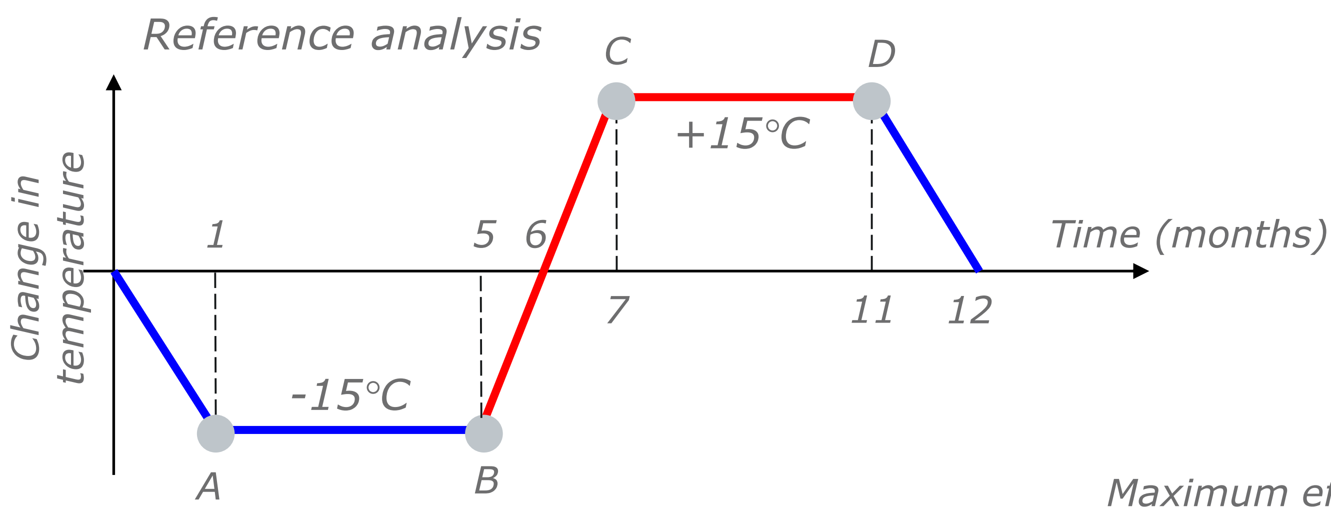
Mechanical loading
Initial cooling (A)
End of cooling (B)
Initial heating (C)
End of heating (D)

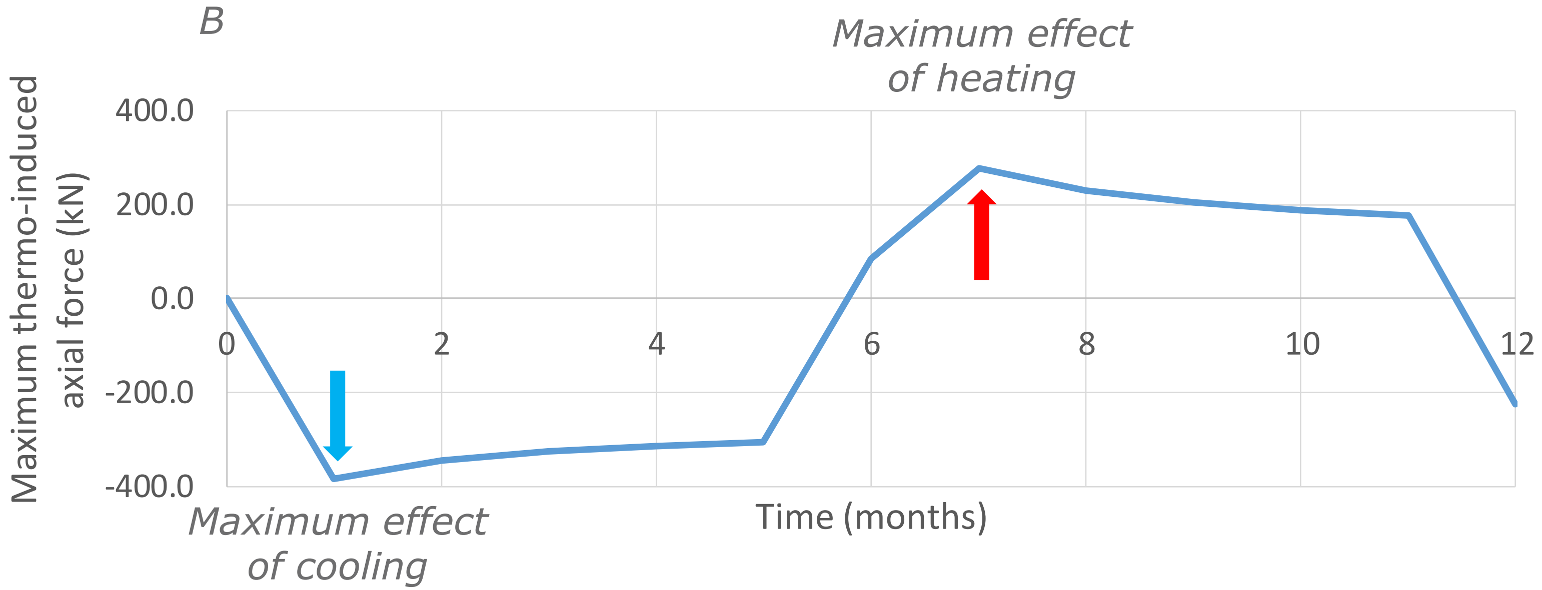


Animation of pile behaviour under temperature changes



Exploratory studies





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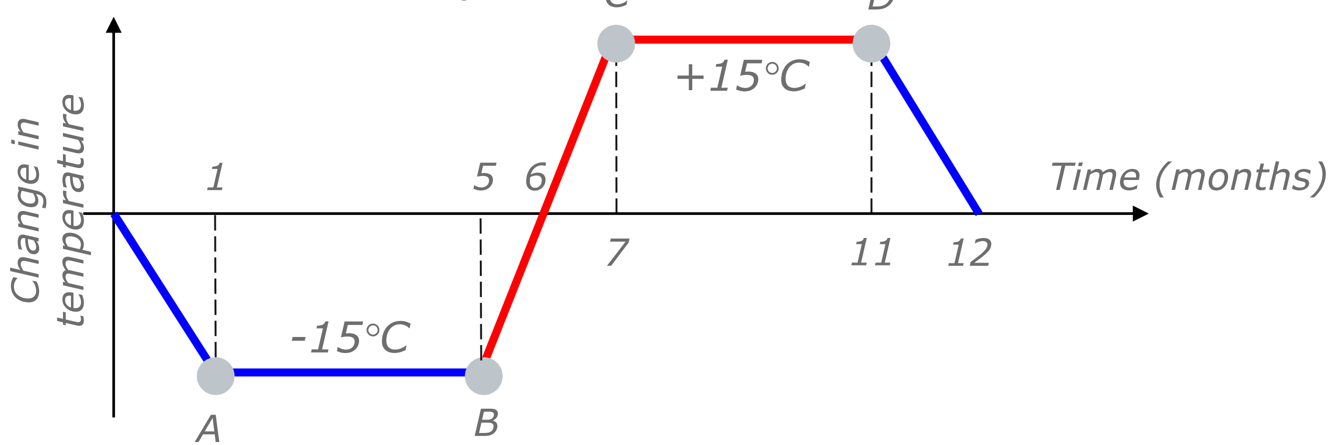
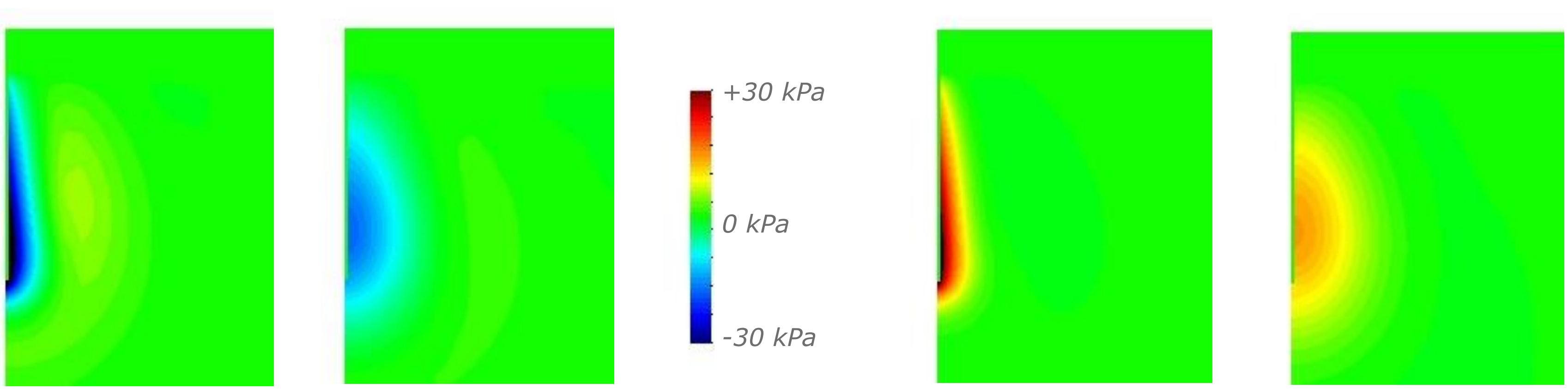
Exploratory studies

Reference analysis



Excess pore water pressures



Initial cooling (A) End of cooling (B) Initial heating (C) End of heating (D)

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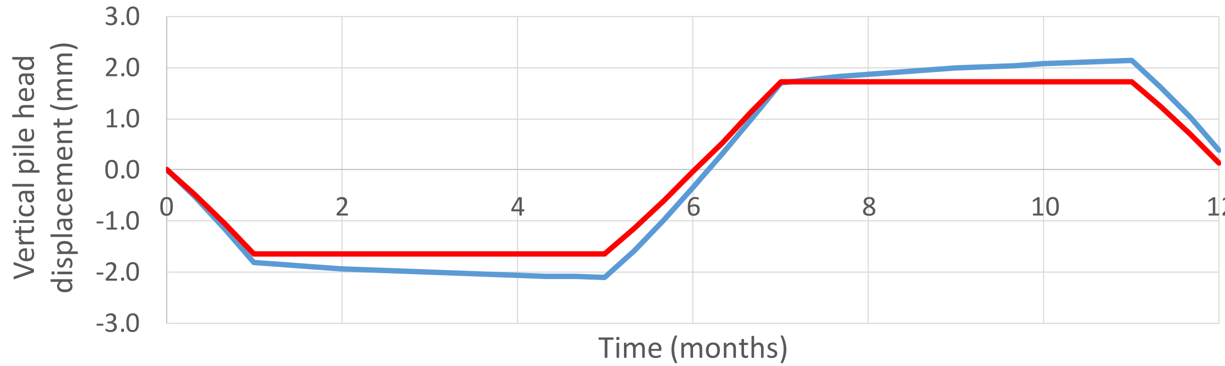
Exploratory studies

Effect of transient phenomena

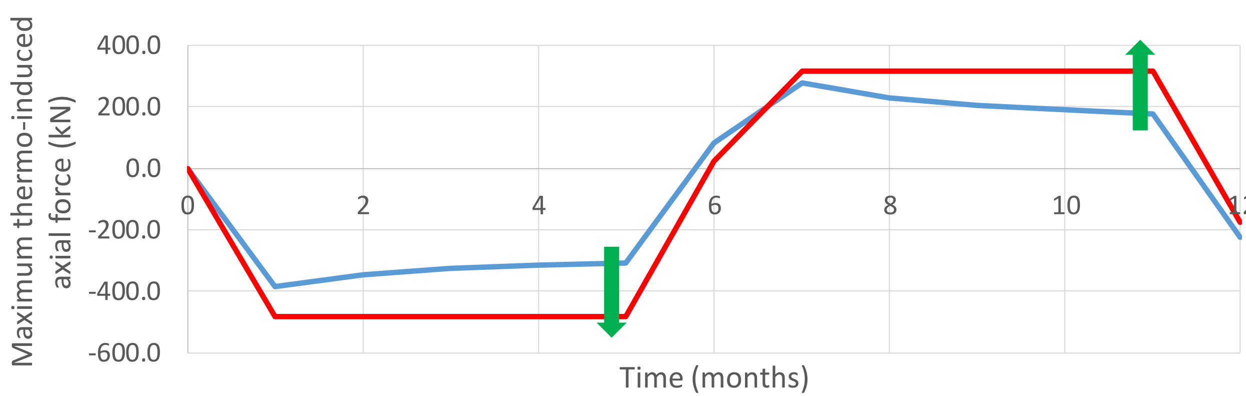
- *Analysis without pwp or temperature degrees of freedom*
- *No transient seepage or heat flux*

Full THM analysis

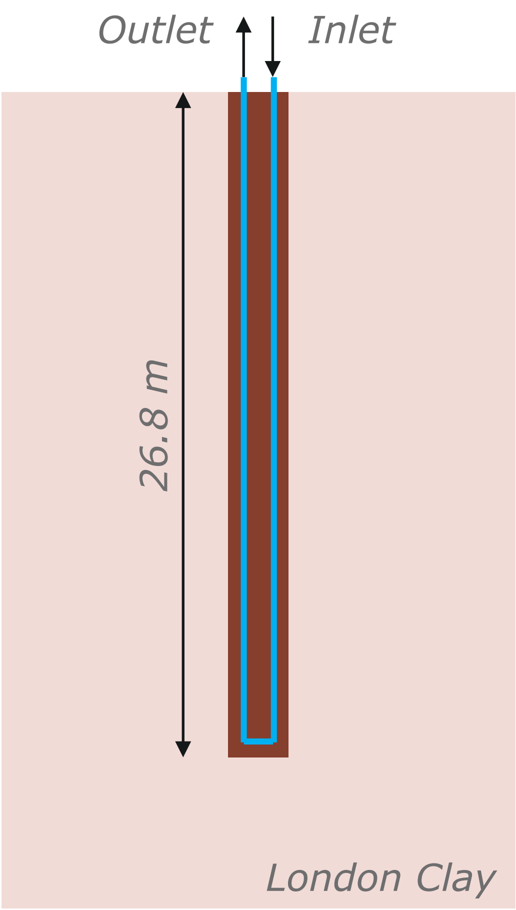
Non-transient analysis



Further reduction in forces can be observed when enhancing transient effects (e.g. higher thermal conductivity)

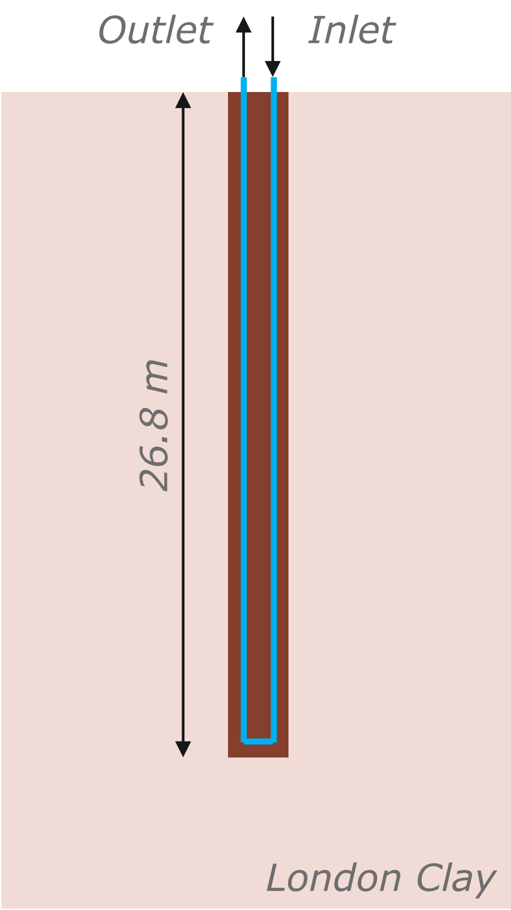


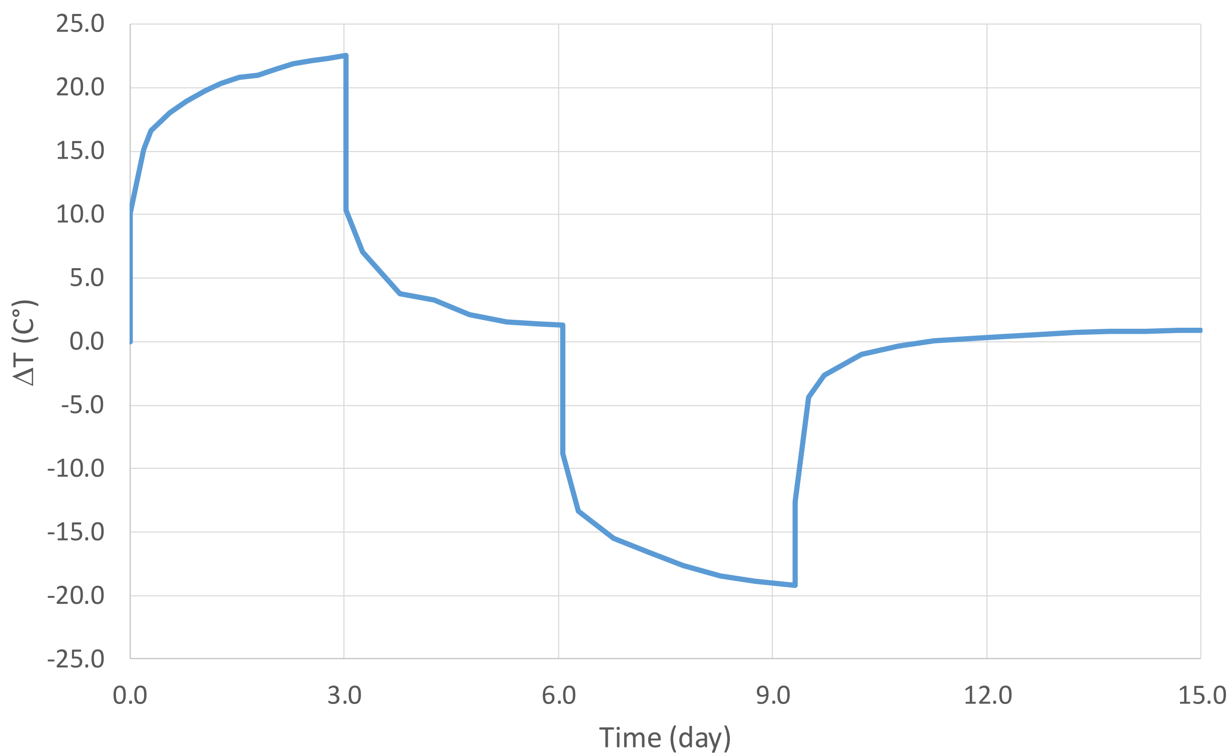
Modelling pipe-pile-soil interaction



- *Thermal response test reported by Loveridge et al. (2014)*
- *300 mm diameter pile with a length of 26.8 m*
- *Single U-loop installed with spacing between pipes of 135 mm*
- *Pile entirely within London Clay*
- *Pipe discretised using linear elements:*
    - *If elements are* $1\,m$ *long:* $P_e = 1.33 \times 10^6$
    - *To satisfy* $P_e \leq 1$*, size should be* $7.5 \times 10^{-7} m$
    - *Alternatively, use Petrov-Galerkin FE*

Modelling pipe-pile-soil interaction





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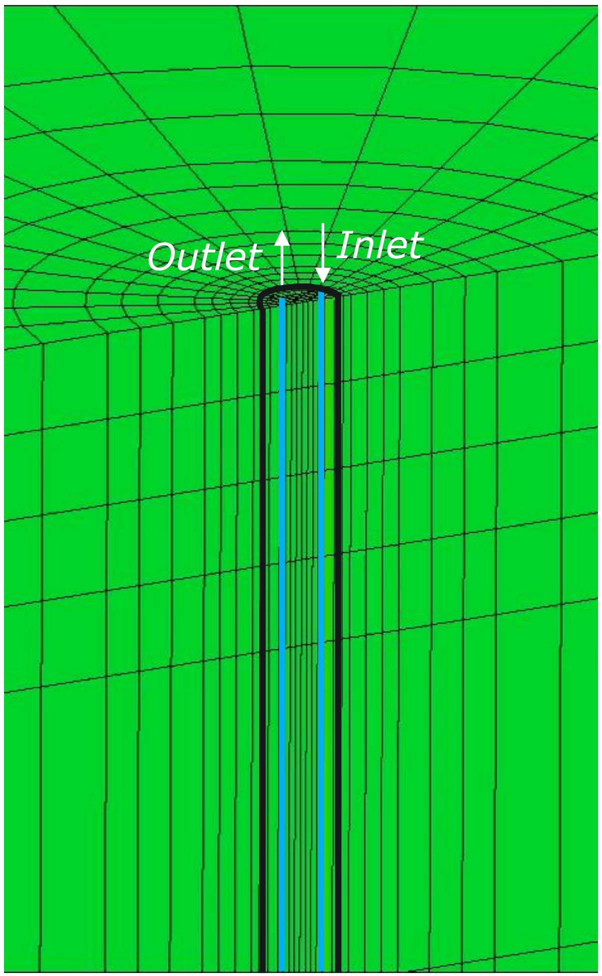
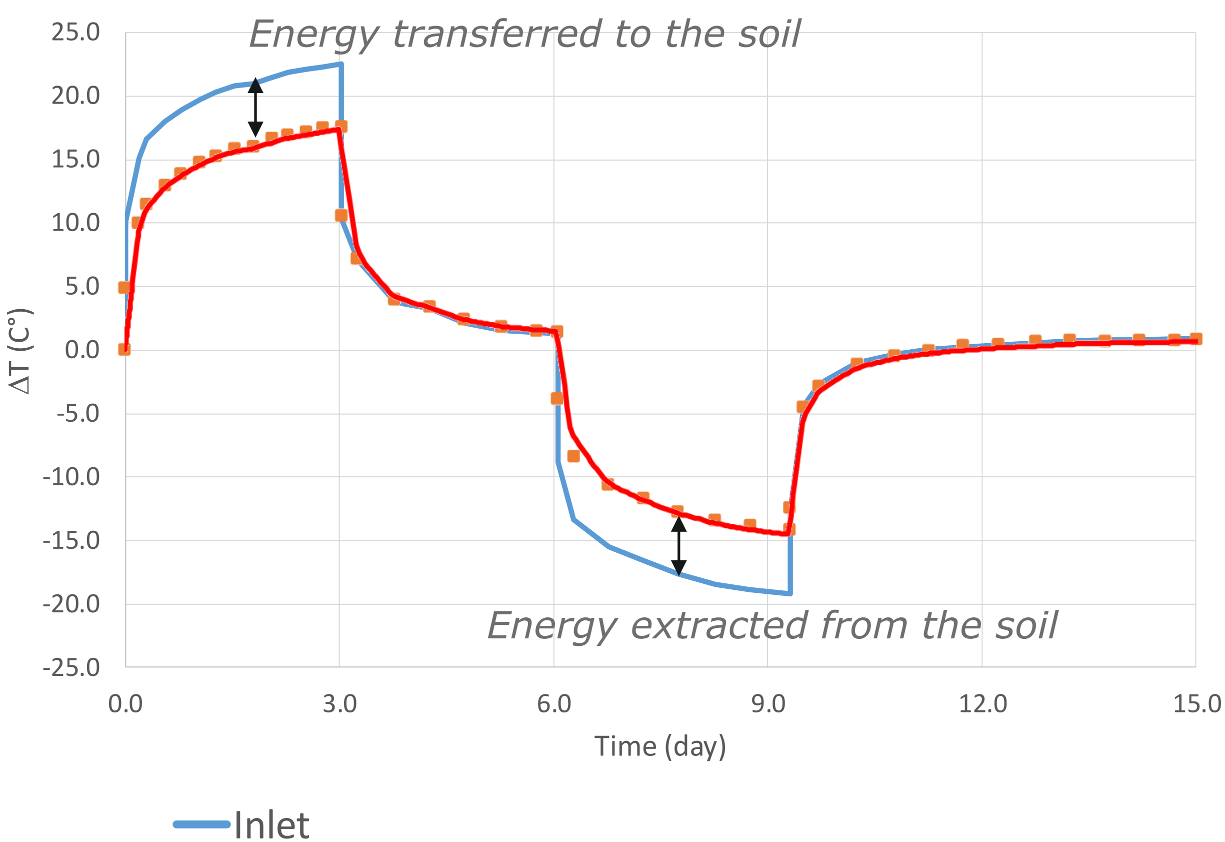
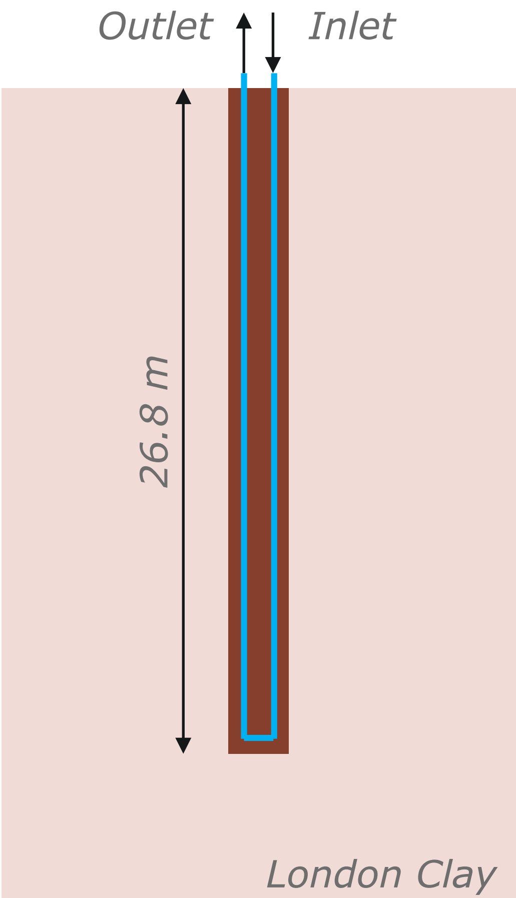
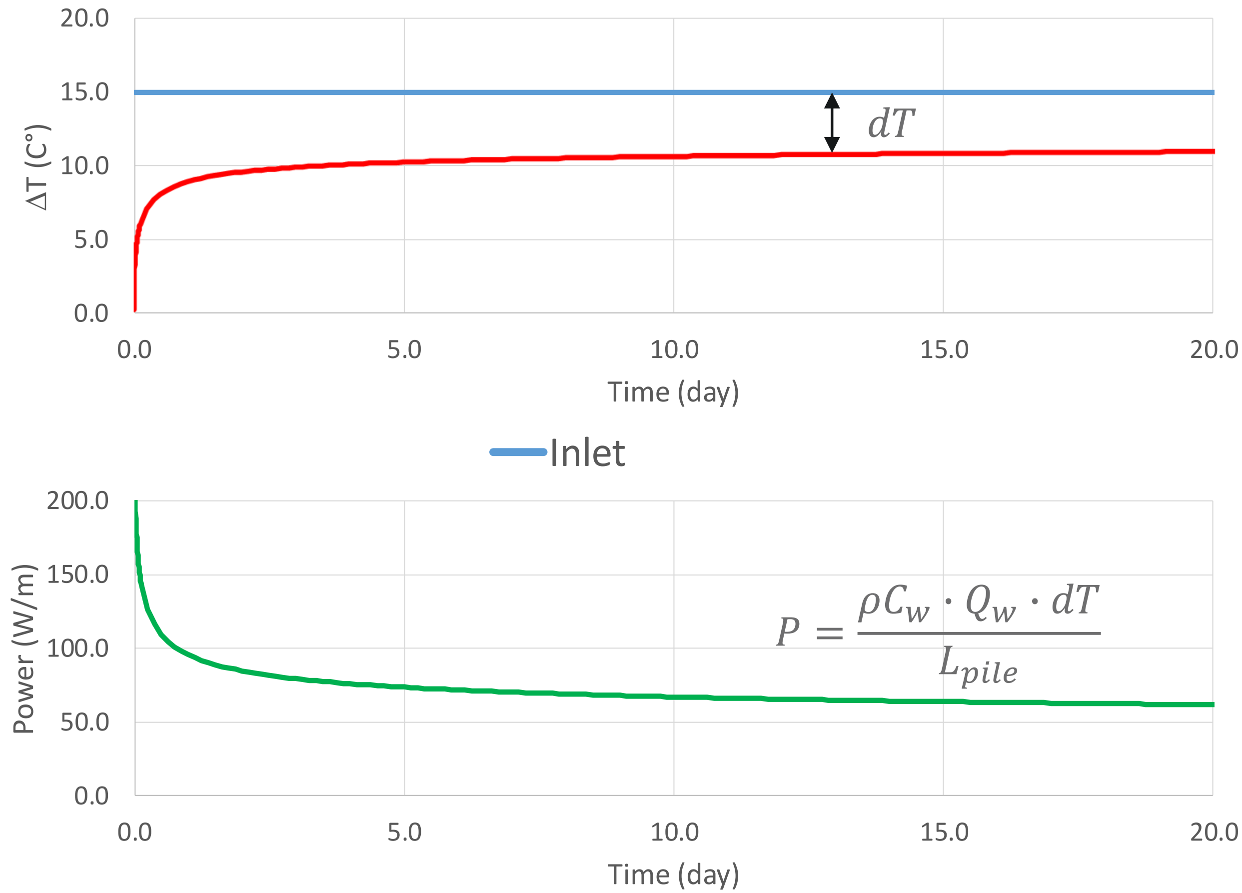


Animation of heat propagation from pipes to the pile



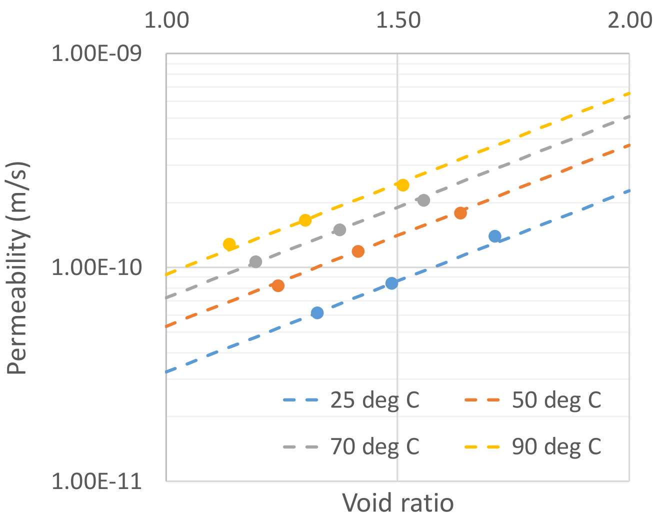
Modelling pipe-pile-soil interaction



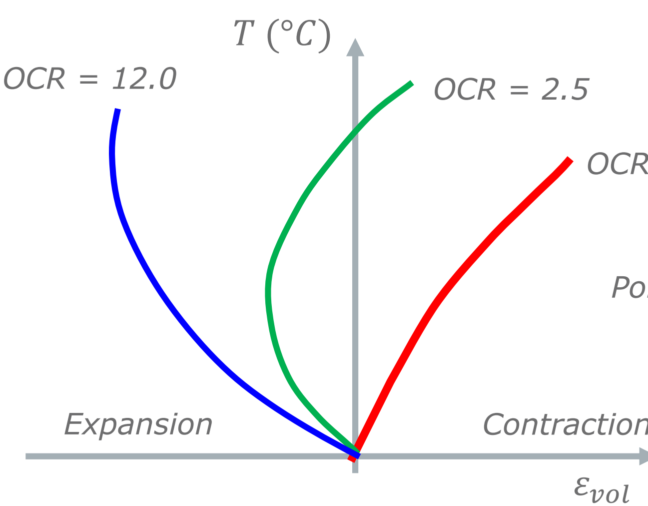


Temperature-dependent soil-fluid behaviour

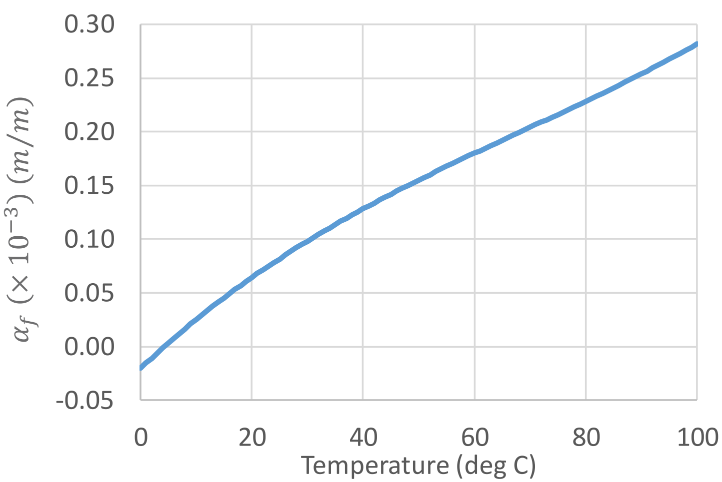
Soil permeability



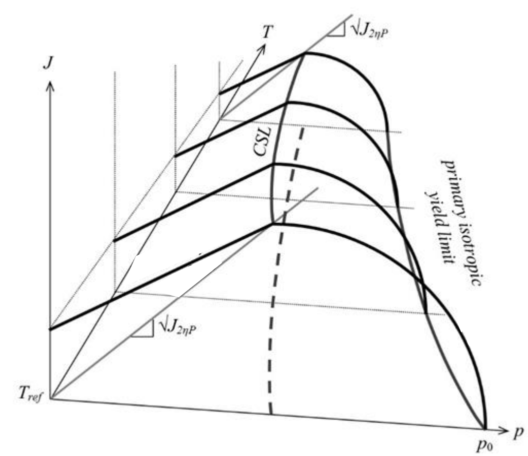
Thermo-plasticity



Thermal expansion of fluid



IC Thermal Model



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Conclusions

- Thermo-active structures need to be assessed during design considering issues of **stability** (forces), **serviceability** (deformations) and **impact on neighbouring structures**
- These require **new aspects of numerical analysis** to be developed
- New components of analysis require more information from **experimental investigation** (calibration) and from **field testing** (validation)
- There are **substantial transient effects** when modelling thermo-active piles – ignoring these will lead to overestimation of pile axial forces
- Modelling the **full pipe-pile-soil interaction** provides new insight into the pile response and its thermal performance
- Detailed modelling can be used to **reduce uncertainties**, **remove excessive conservatism** and enables the **assessment of more complex systems**