GSHPA Workshop
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Soil-structure interactions for thermal piles/walls; Fundamentals; Design considerations; Future research needs

Kenichi Soga
Professor of Civil Engineering
Department of Engineering

UNIVERSITY OF CAMBRIDGE

Acknowledgement

- Former and current researchers: Binod Amatya, Echo Ouyang, Ray Yi, Denis Garber, Yi Zhang, He Qi, Maria Canellas
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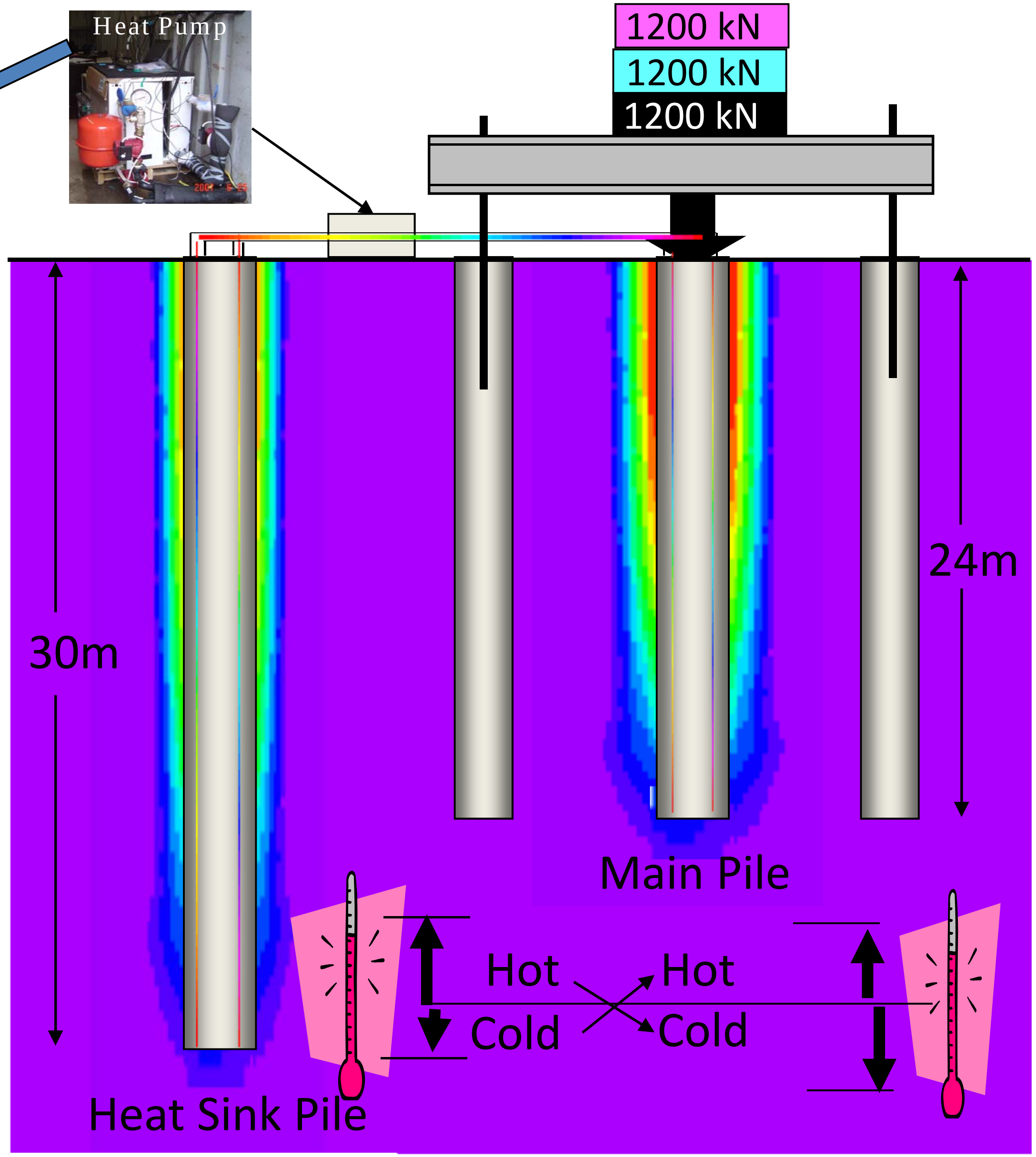
- Arup – Duncan Nicholson, Anton Pillai, Paul Bailie

Current research projects at Cambridge

- Field study on long-term behaviour of thermal piles
- A pile-raft-structure interaction code for thermal piles
- Thermo-Hydro-Mechanical finite element code for thermal piles/tunnels/walls
- Interaction modelling of building performance and GSHP (boreholes, thermal piles/tunnels/walls)
- Capacity of GSHP systems at city-scale
- Thermal response testing

Mechanical Load Tests coupled with thermal loading



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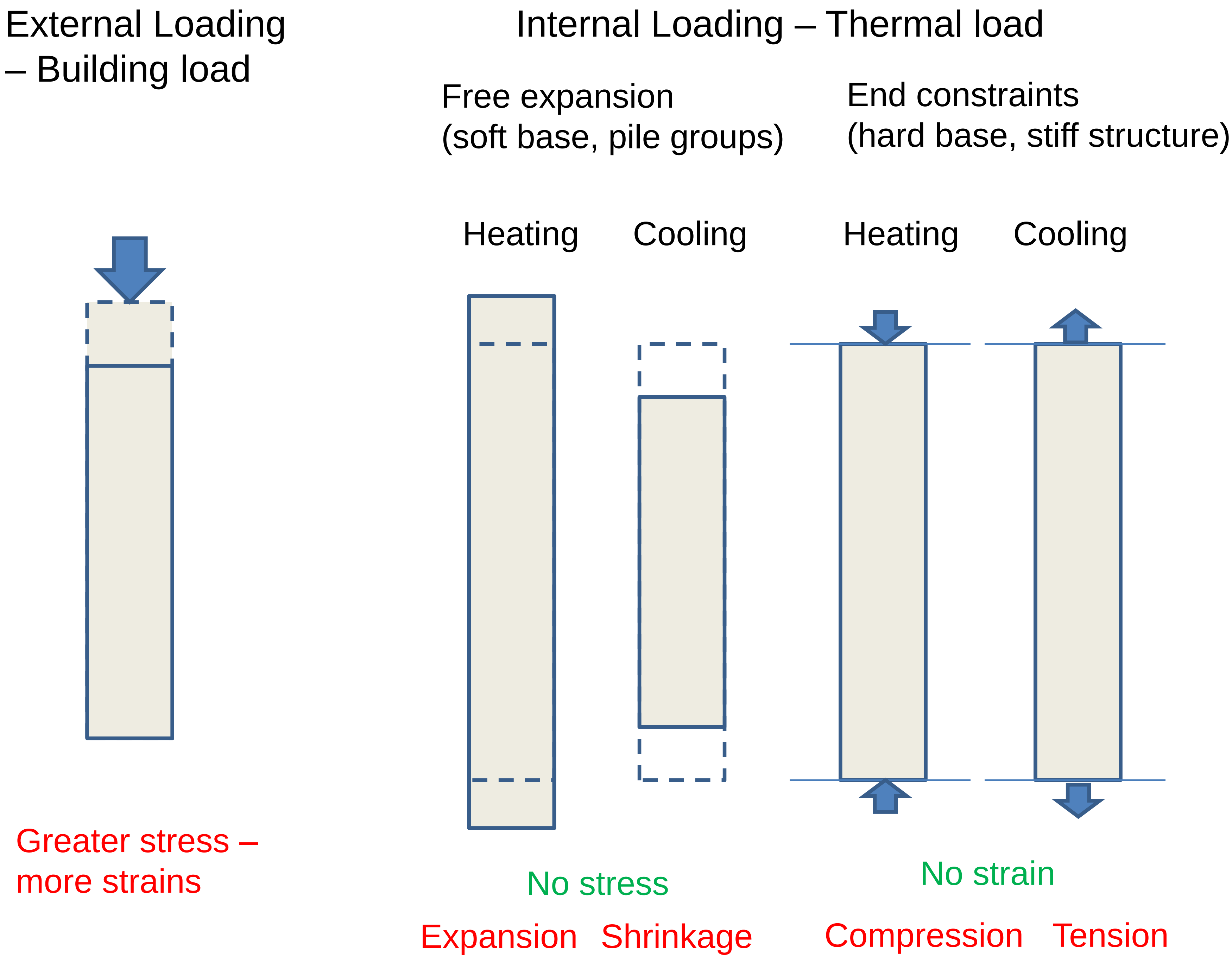
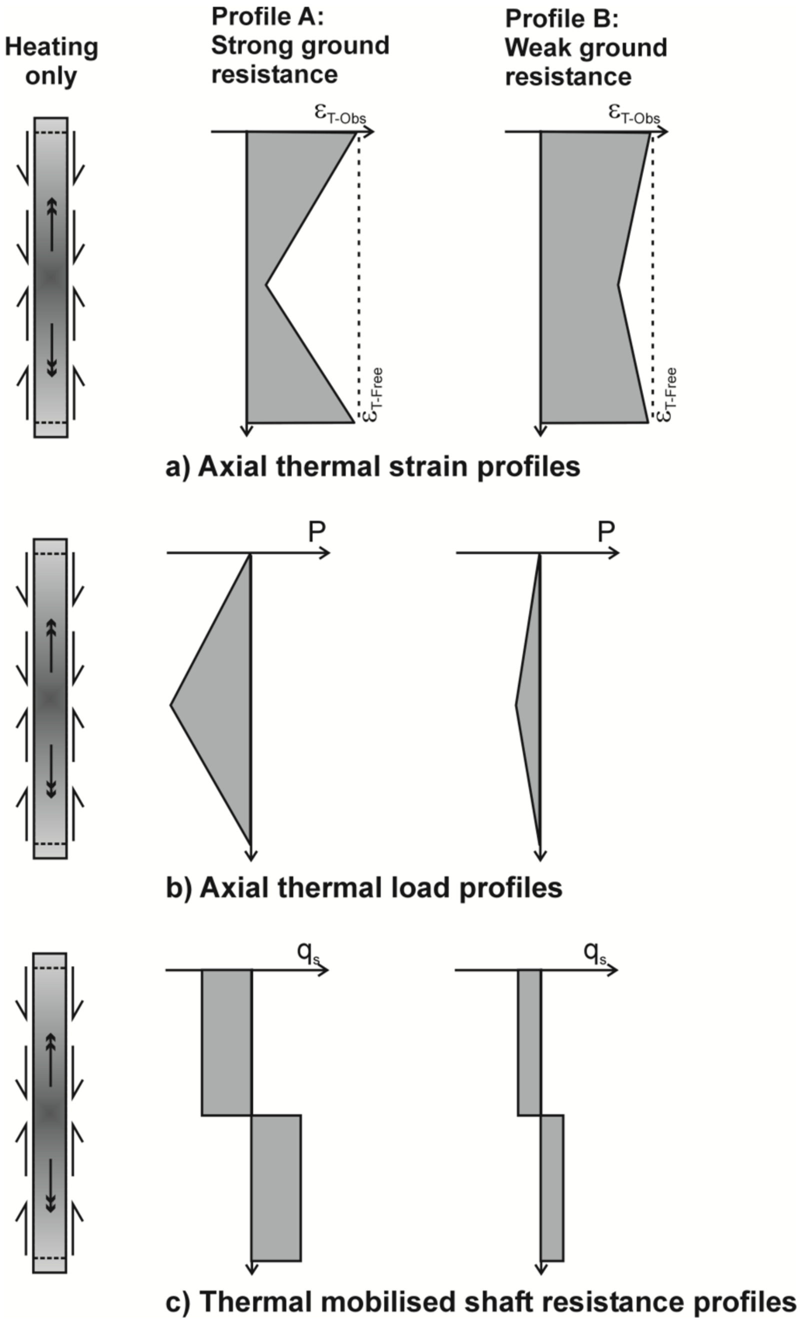
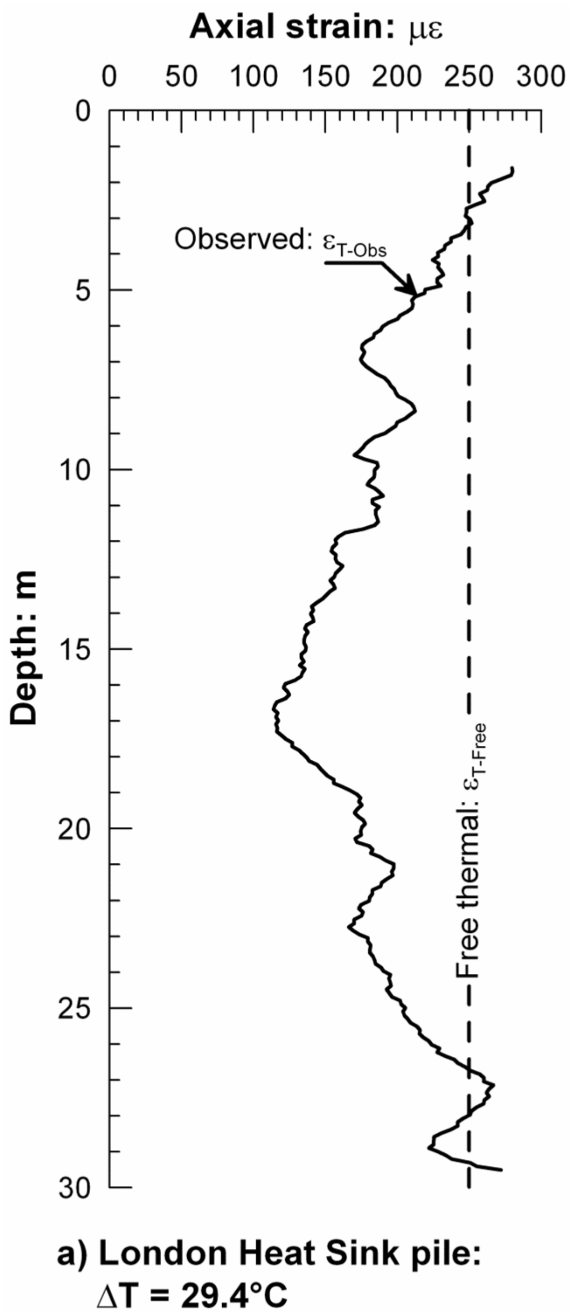
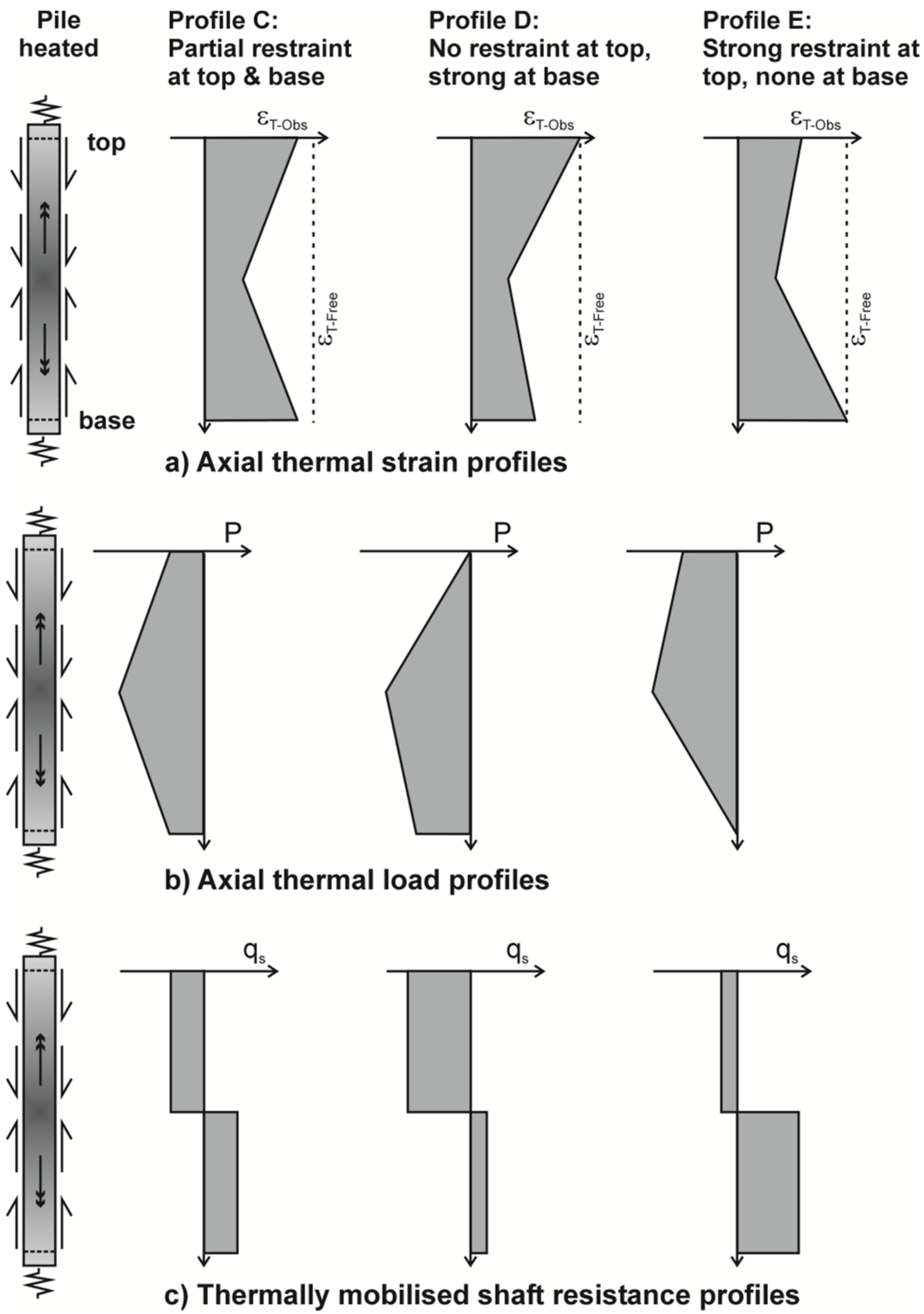

External Loading
– Building load
Internal Loading – Thermal load
Free expansion
(soft base, pile groups)
End constraints
(hard base, stiff structure)
Heating
Cooling
Heating
Cooling
Greater stress –
more strains
No stress
No strain
Expansion
Shrinkage
Compression
Tension

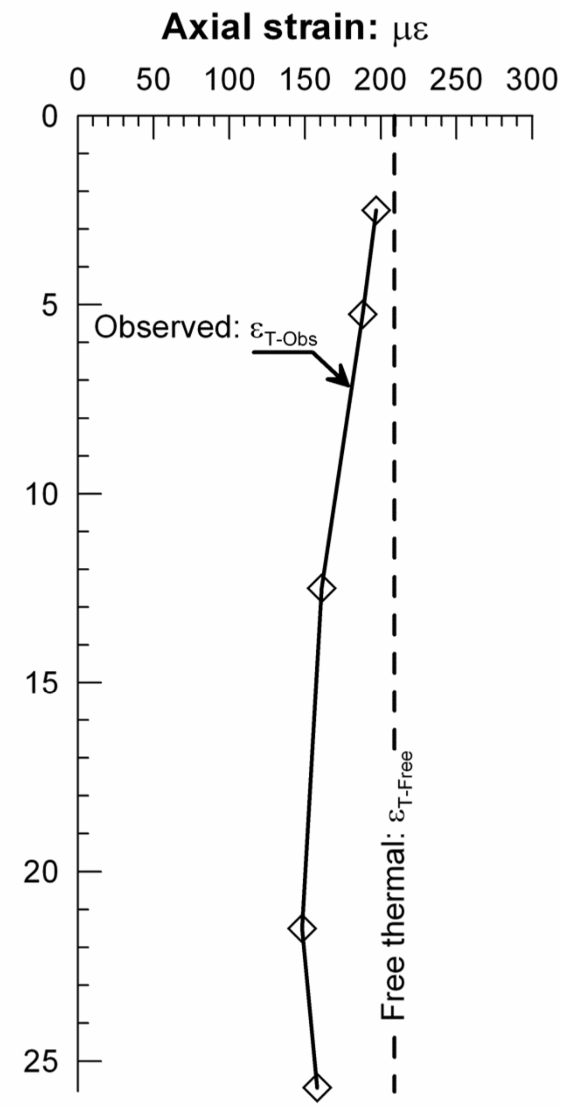


Heating only
Profile A: Strong ground resistance
Profile B: Weak ground resistance
ε_{T-Obs}
ε_{T-Free}
a) Axial thermal strain profiles
P
b) Axial thermal load profiles
q_s
c) Thermal mobilised shaft resistance profiles



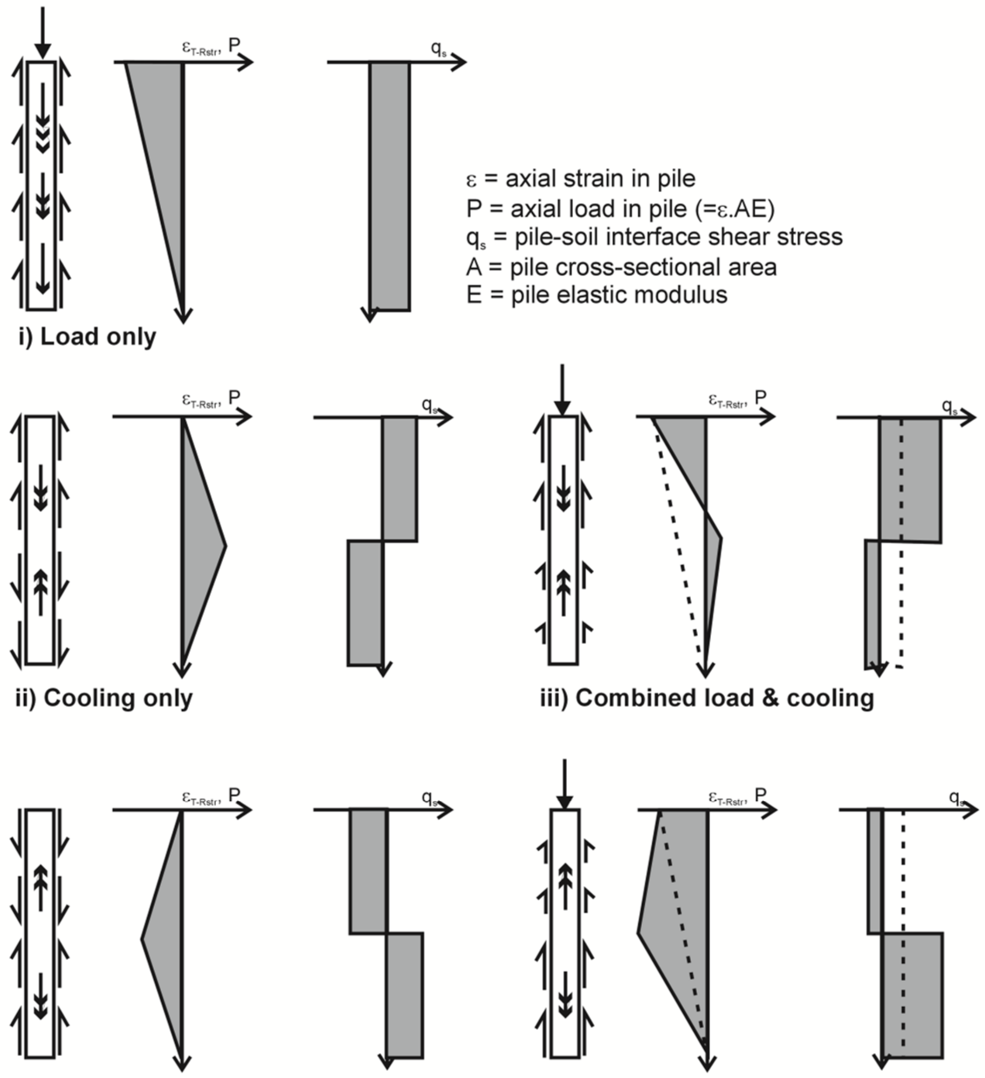
Axial strain: $\mu\varepsilon$
0
50
100
150
200
250
300
Depth: m
0
5
10
15
20
25
30
Observed: ε_{T-Obs}
Free thermal: ε_{T-Free}
a) London Heat Sink pile:
ΔT = 29.4°C

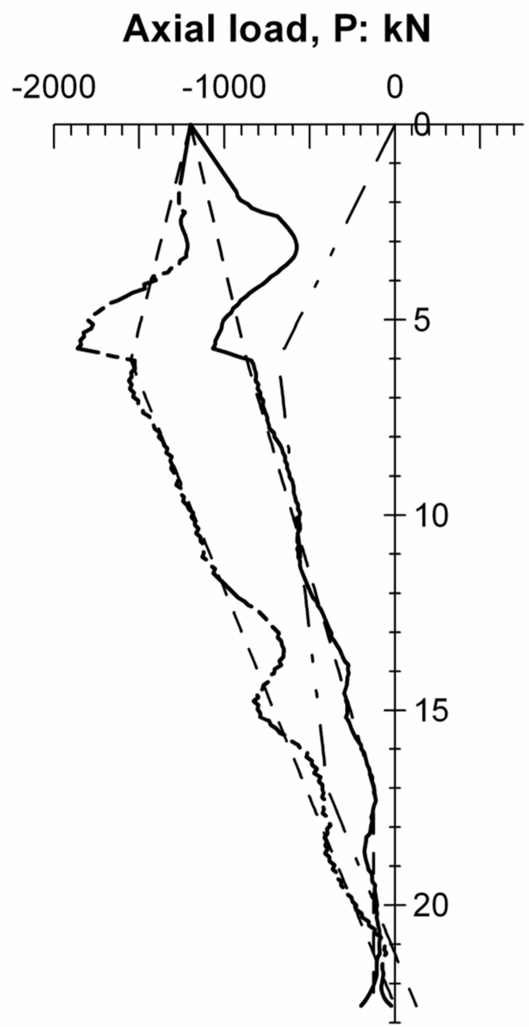




b) Lausanne T-1 test:
$\Delta T = 20.9°C$

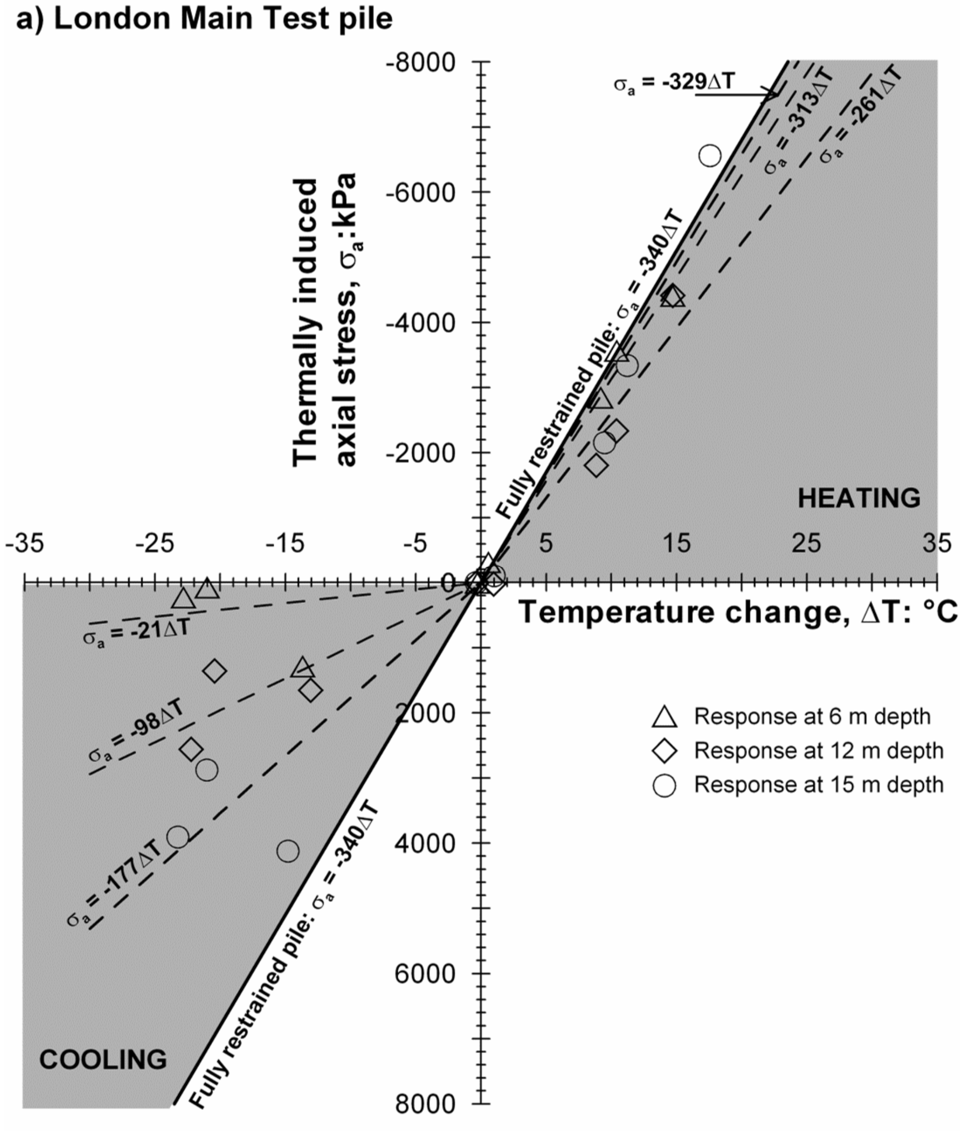
a) Heating & cooling with no end restraint, after Bourne-Webb et al (2009, in print)





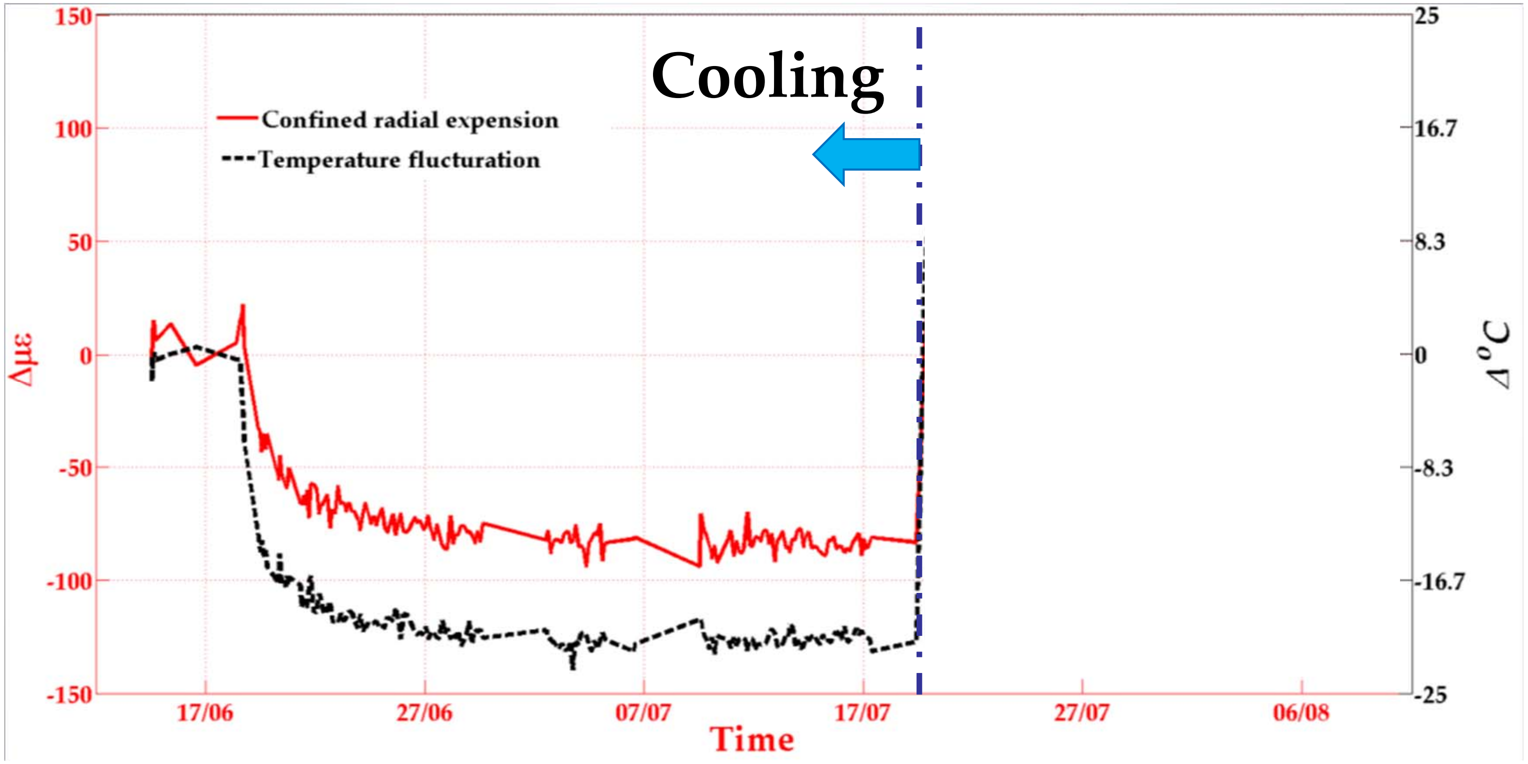
(ii) Heating, ΔT = +10°C

Check 1: Is the stress in the concrete smaller than the strength?



Thermal stress in heating > Thermal stress in cooling. Why?

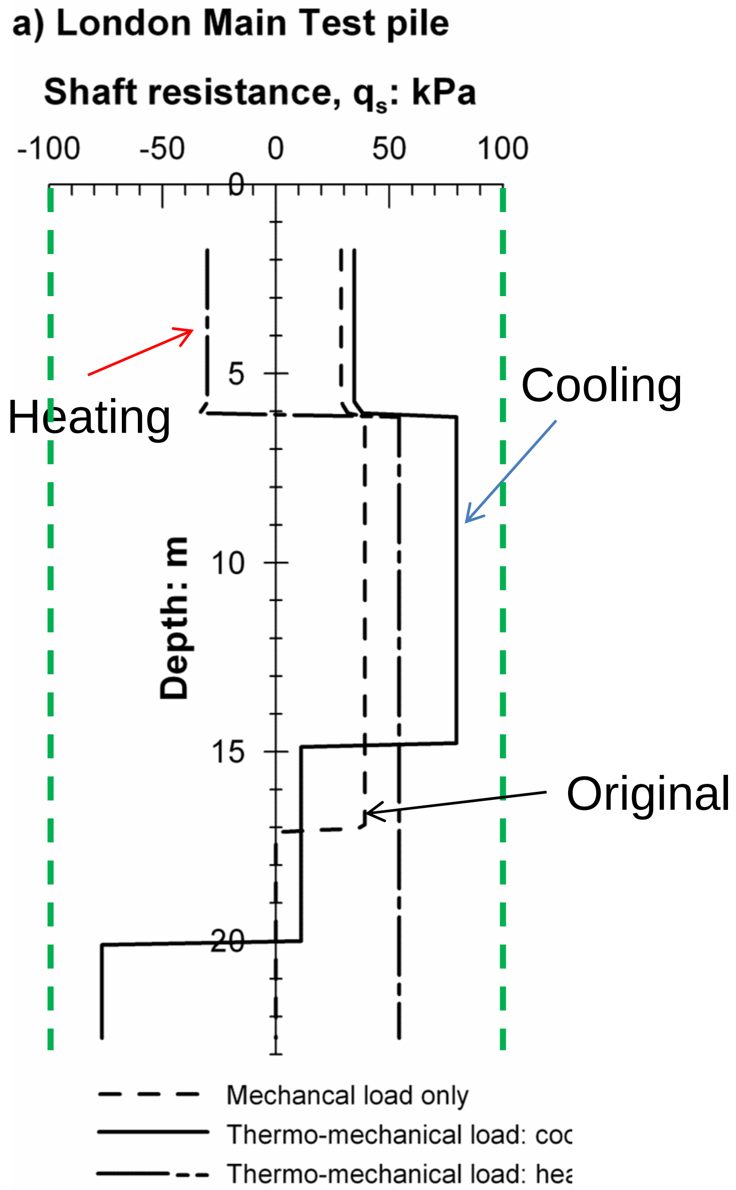
Measurement of radial strain



A bigger diameter pile will have more radial displacement

What is the effect on heat transfer and shaft resistance?

Check 2&3: Are the mobilised shaft friction and the end bearing pressure smaller than the design limits?



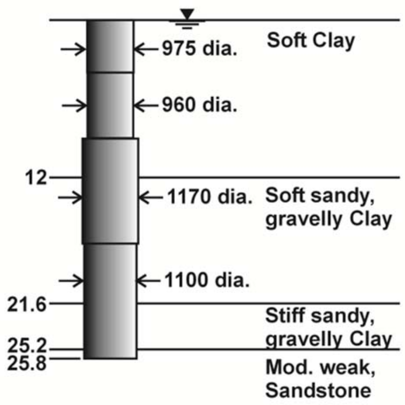
But….

No change in ultimate strength?

Cyclic heating and cooling will damage the clay?

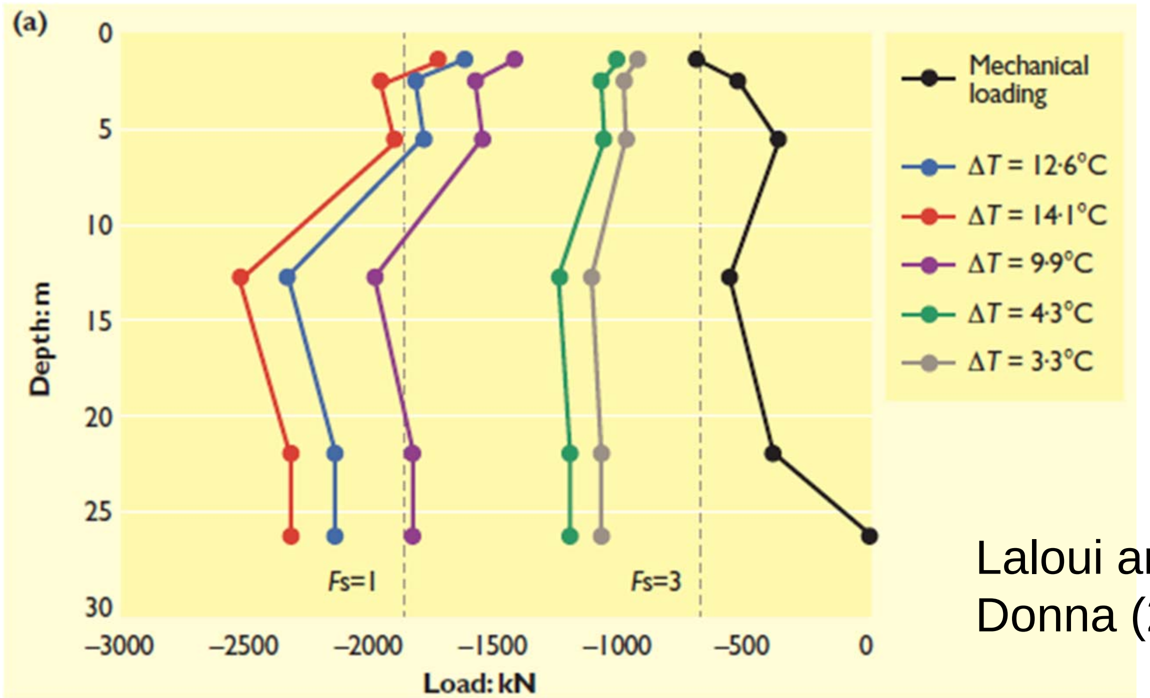
Short term test (with excess pore pressure) versus long-term performance (excess pore pressure dissipation)

b) Lausanne



Typical soil properties

Soft Clay	γ = 19.6 kN/m^3 c_u = 15 - 20 kPa
Soft sandy, gravelly Clay	γ = 19.1 kN/m^3 c_u = 20 - 30 kPa
Stiff, sandy gravelly Clay	γ = 21.6 kN/m^3 c_u = 70 - 150 kPa
Mod. weak Sandstone	γ = 25 kN/m^3 UCS = 12 MPa

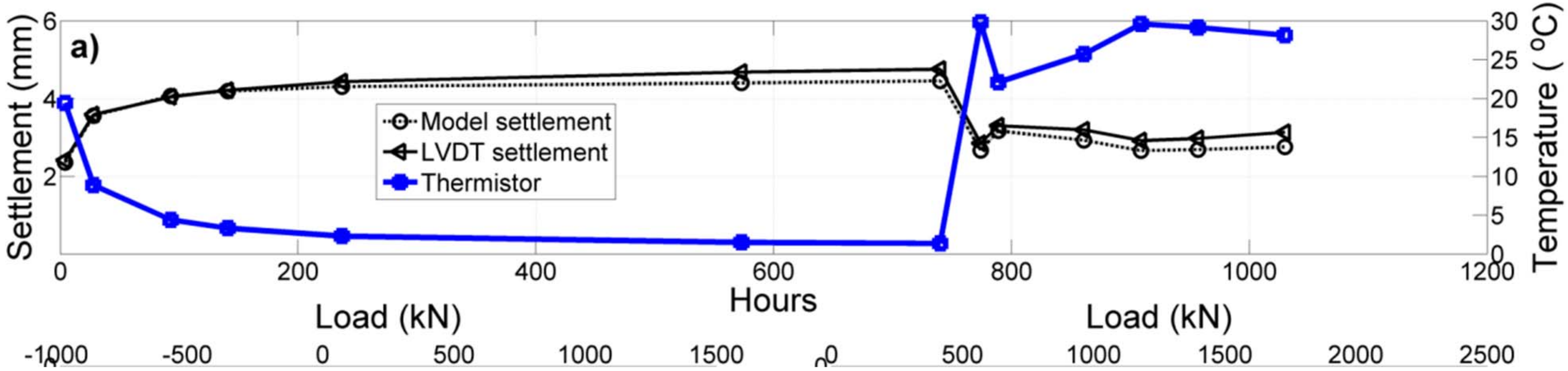


Laloui and Donna (2011)

2400 kN load at the base is about 3 MPa

Check 4: Is the pile movement acceptable?

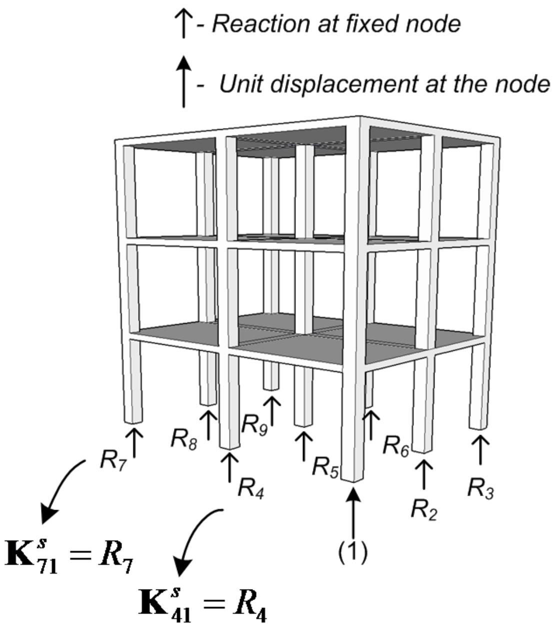
Lambeth College

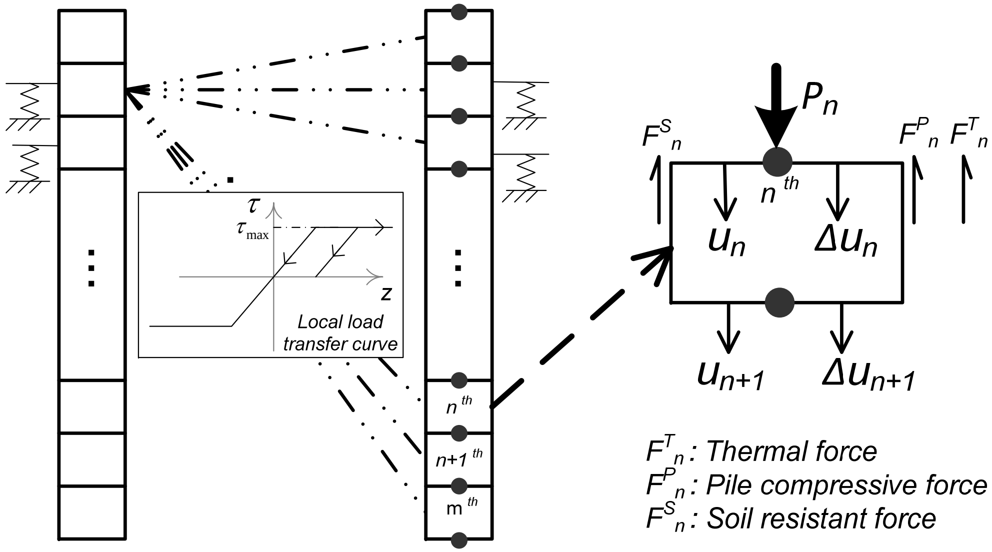


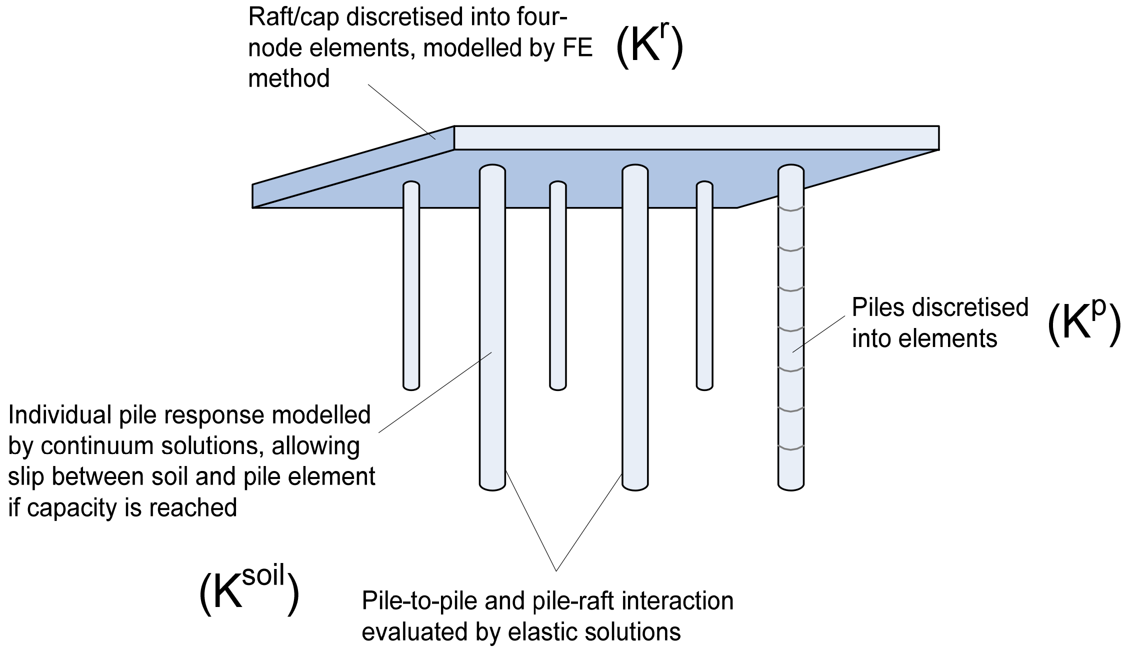
EPFL Lausanne

Laloui and Donna (2011)

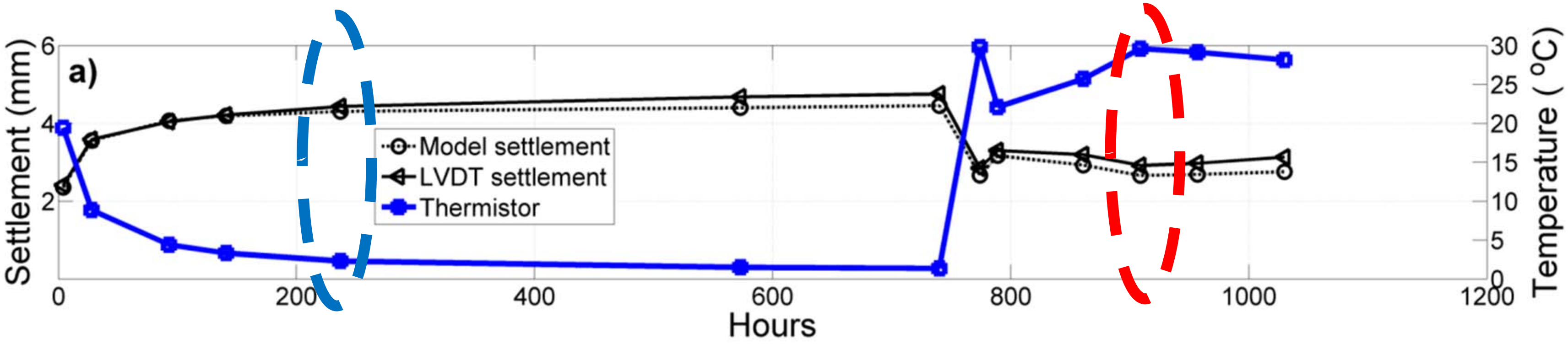
Thermal pile design software

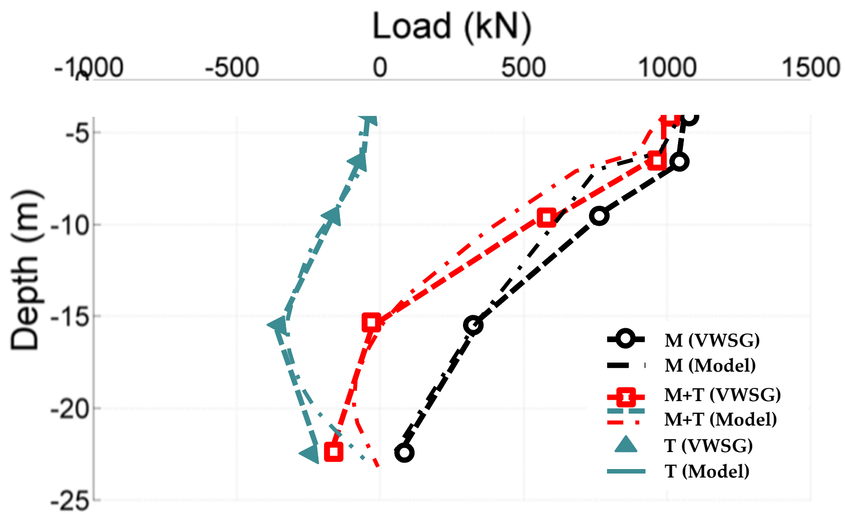


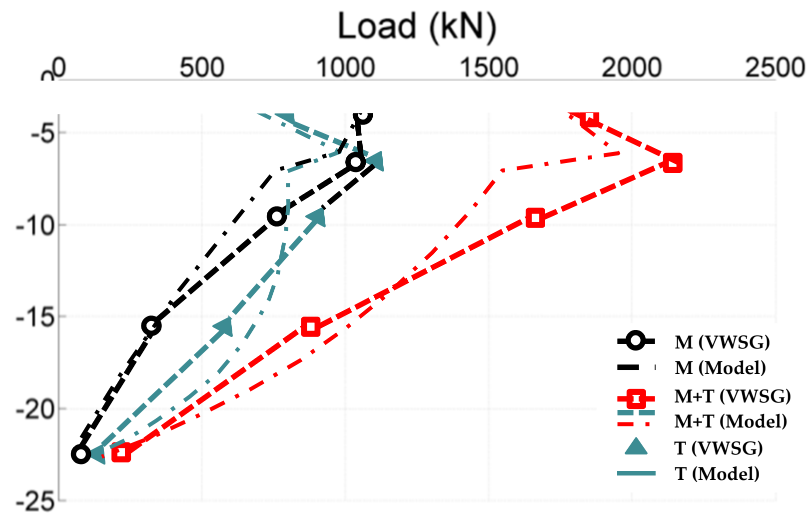




Results

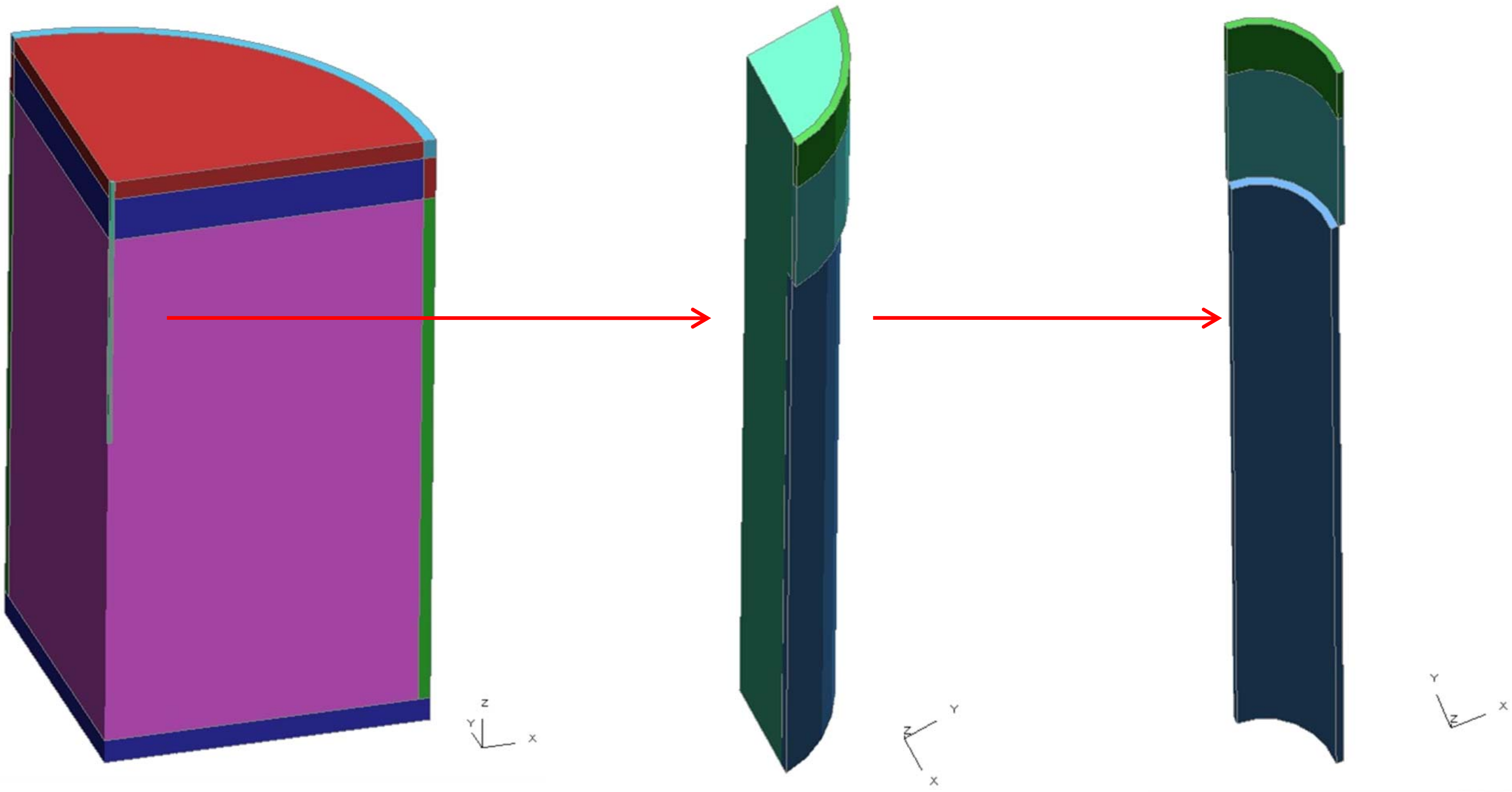






Cooling: Es = 450 * Cu; **Heating: Es = 600 * Cu**

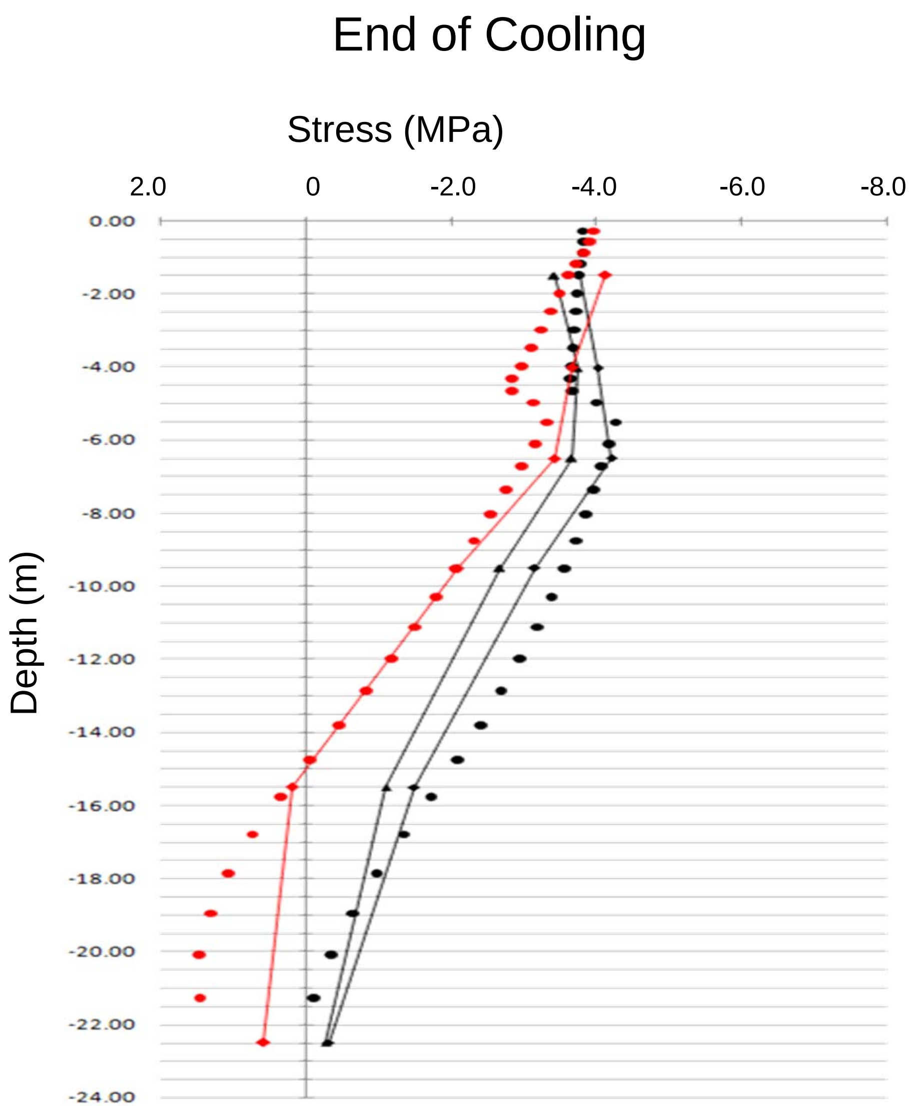
Finite Element Analysis of Thermal Pile

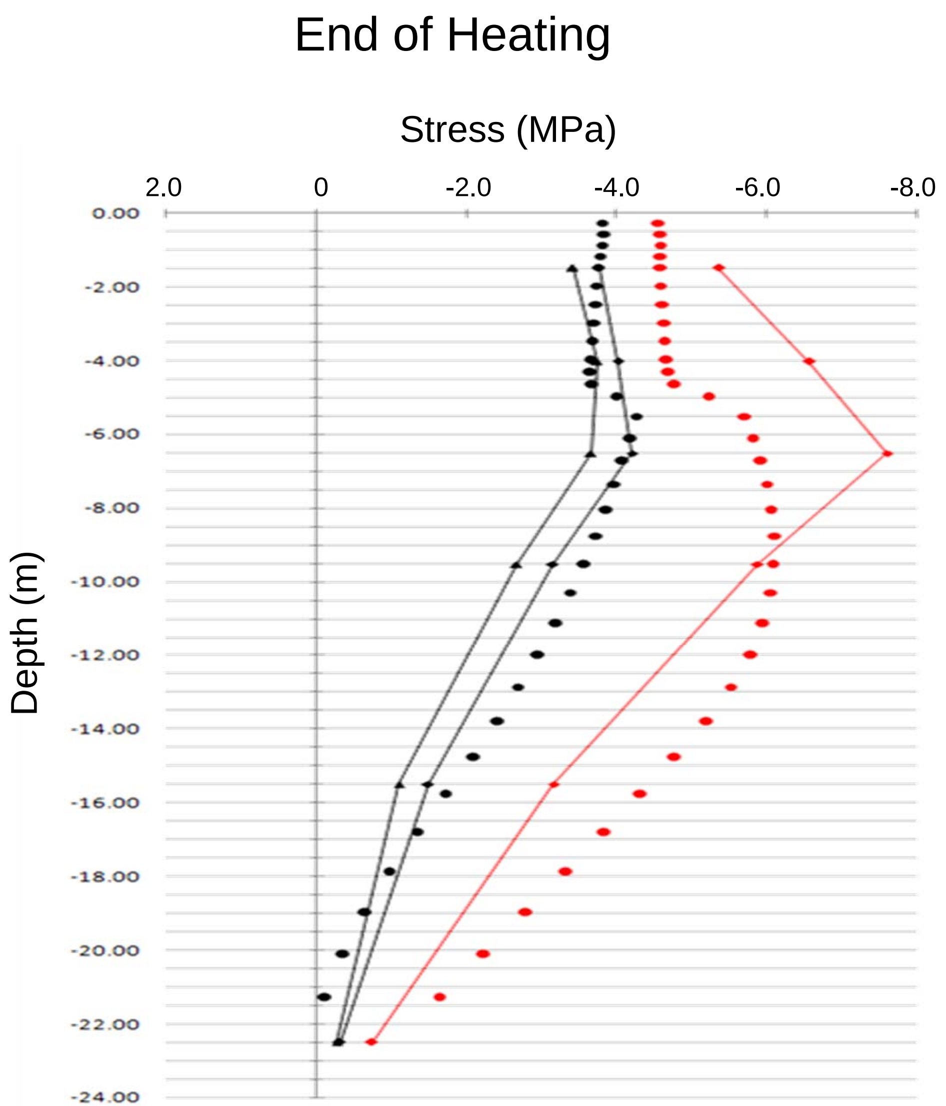


Pile & Soil

Pile

Interface

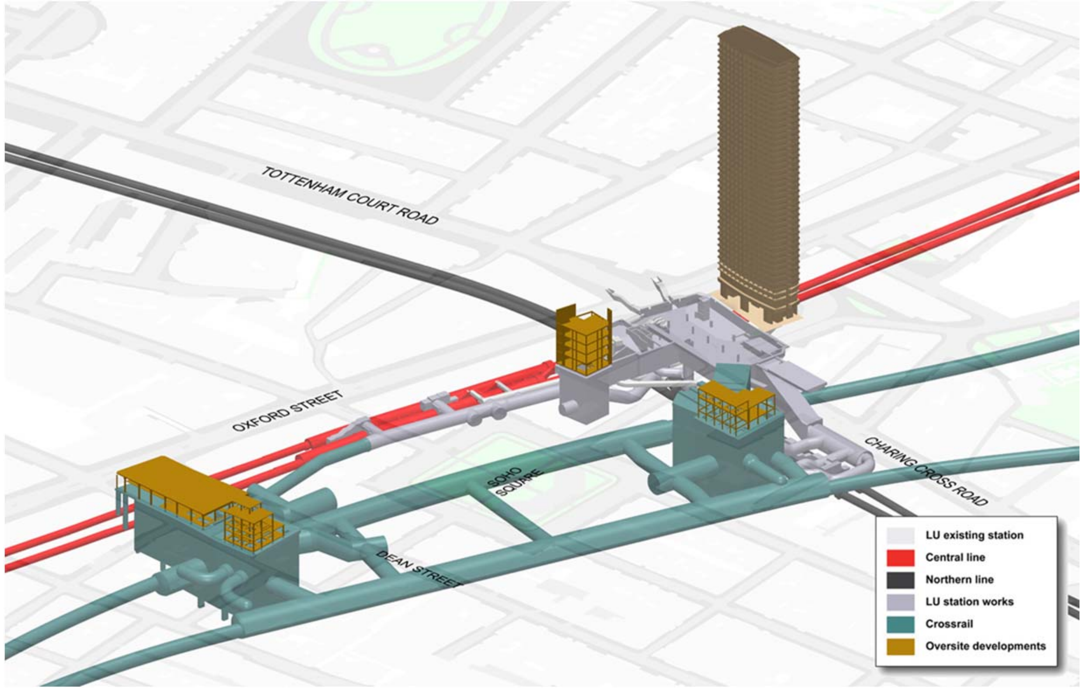

End of Cooling
Stress (MPa)
2.0
0
-2.0
-4.0
-6.0
-8.0
Depth (m)
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
-18.00
-20.00
-22.00
-24.00


End of Heating
Stress (MPa)
2.0
0
-2.0
-4.0
-6.0
-8.0
Depth (m)
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
-18.00
-20.00
-22.00
-24.00

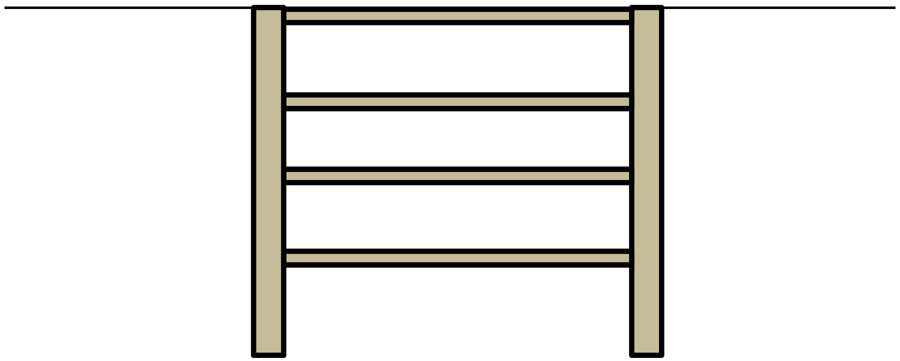
Summary for Thermal Piles

- **Check 1: Stress in the concrete is less than the allowable limit.**
  - Extreme – assume that the pile is fully restrained.
- **Check 2: Mobilised shaft friction is less than the design limit.**
  - Assume that the pile can fully expand at both ends but no movement at somewhere in the middle?
- **Check 3: End bearing pressure is less than the design limit.**
  - Extreme – assume that the pile is fully restrained. But end movement will reduce the thermally applied load.
- **Check 4: Pile movement is less than what the superstructure can tolerate.**
  - Need to do pile-soil interaction analysis

Thermal Walls – extracting heat from "hot" station



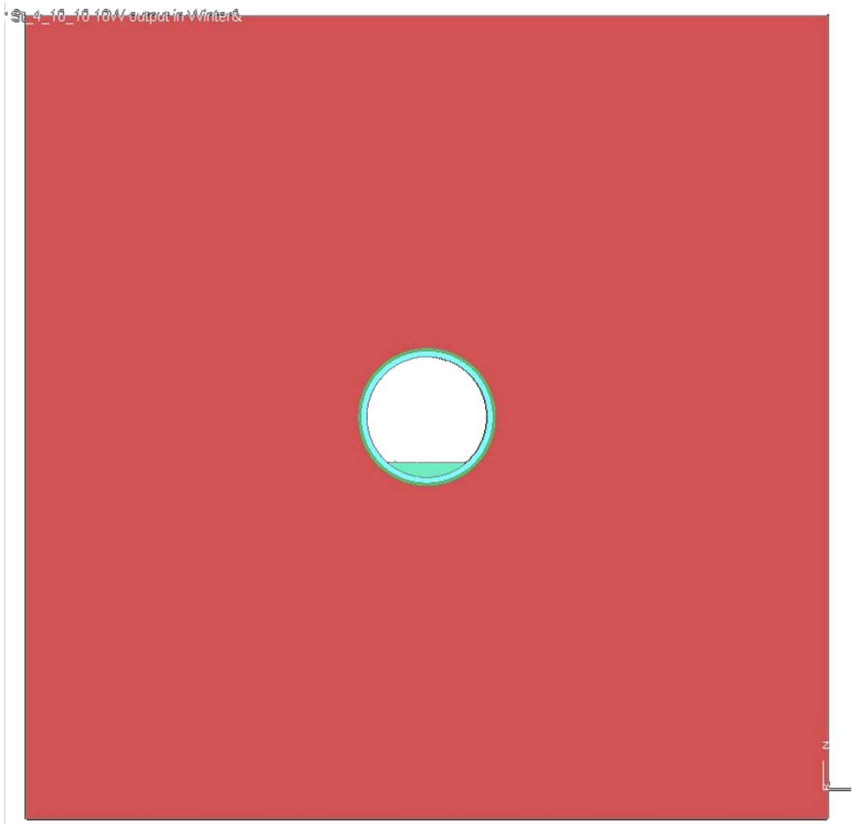
Tottenham Court Station



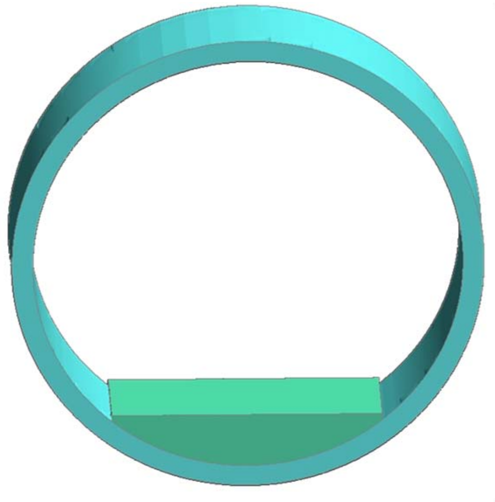
Wall bending?

Soil expansion – increase in earth pressure? Strut loads?

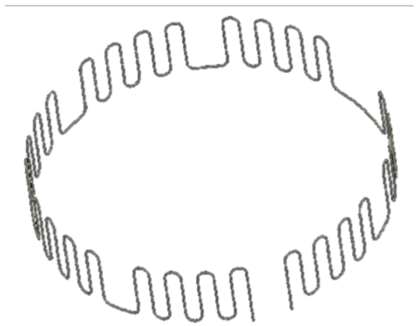
Thermal Tunnels – extracting heat from ‘hot’ tunnels



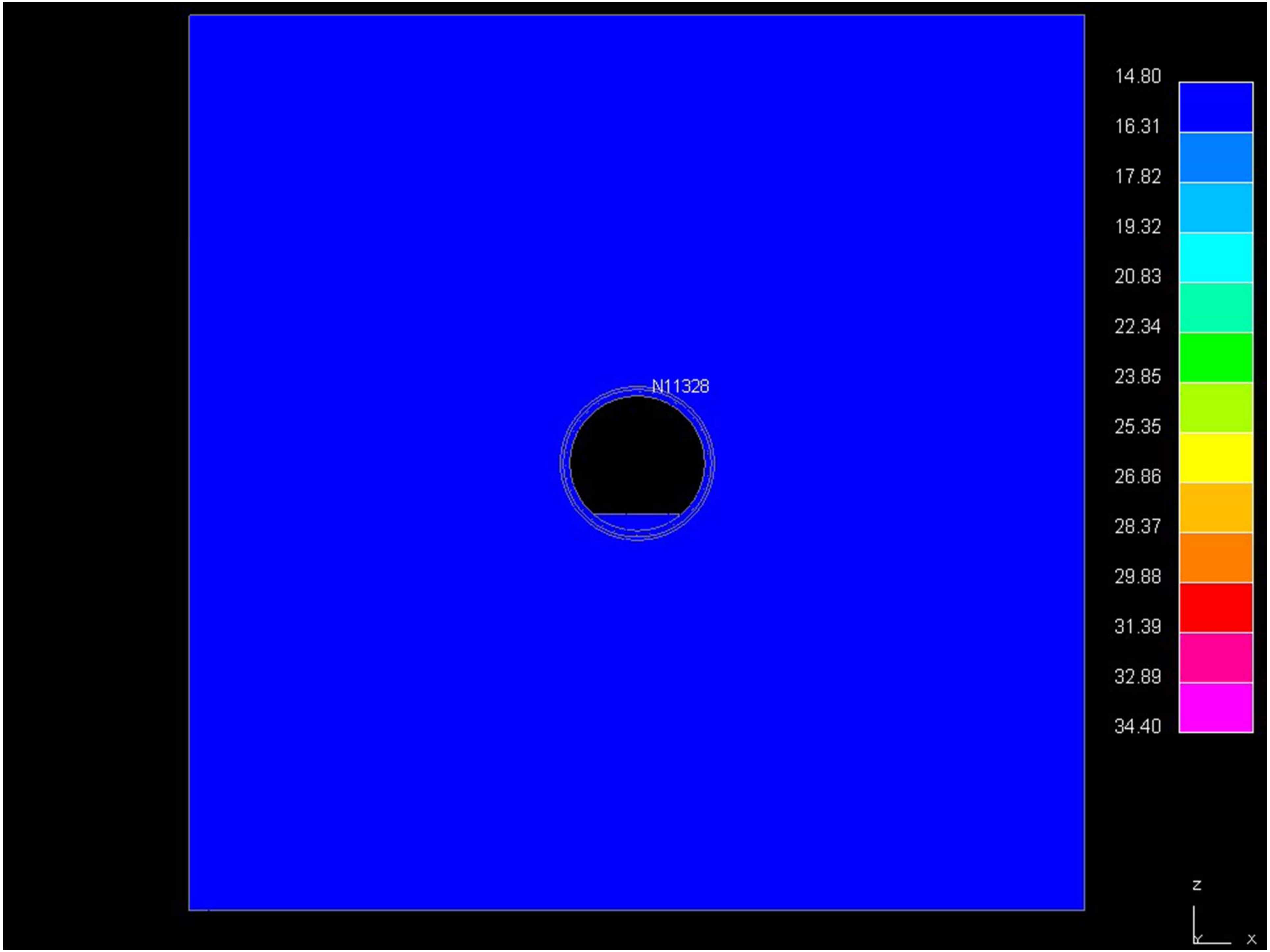
Whole Model



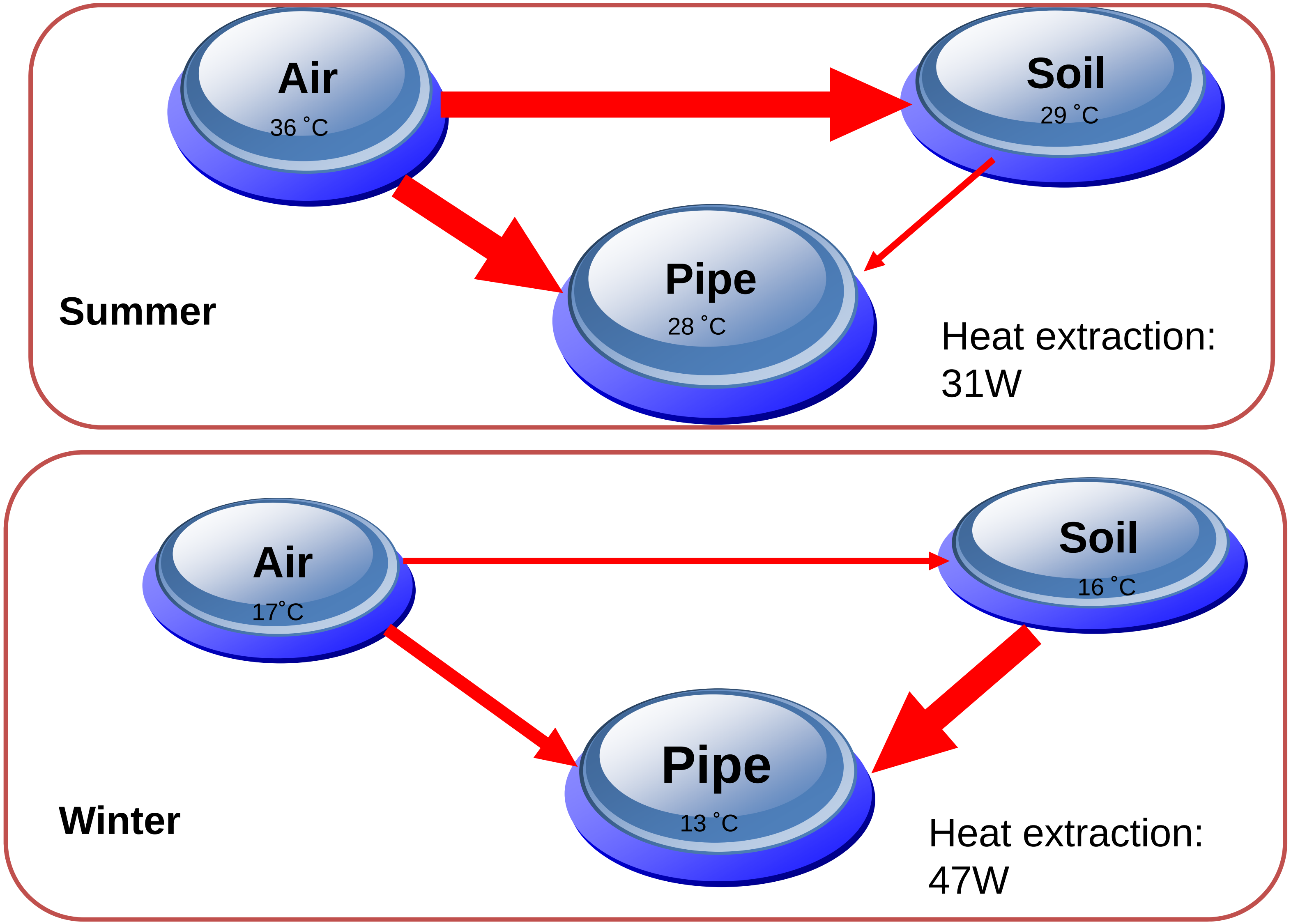
Tunnel Segment



Pipe

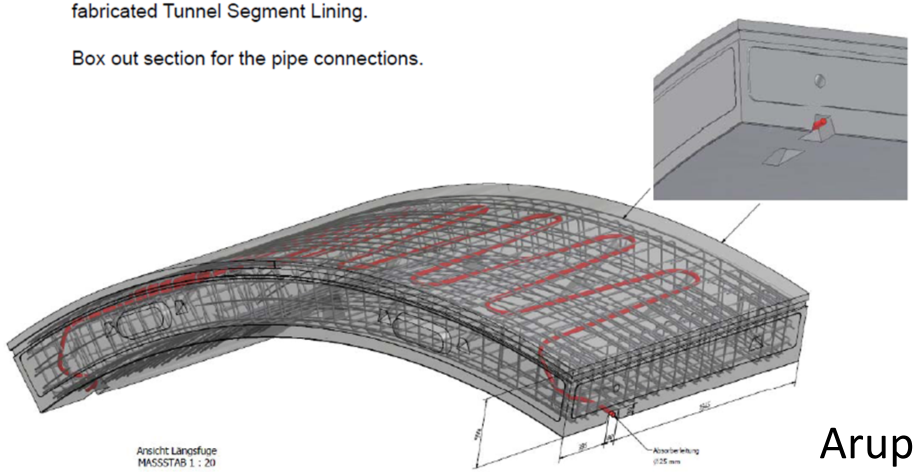


N11328
14.80
16.31
17.82
19.32
20.83
22.34
23.85
25.35
26.86
28.37
29.88
31.39
32.89
34.40
Z
X

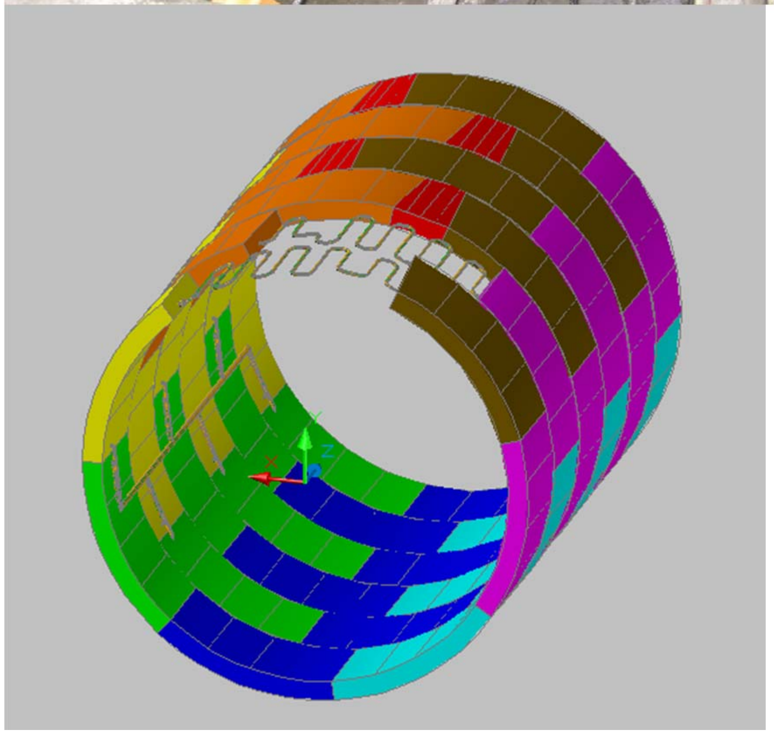

Air
36 ˚C
Soil
29 ˚C
Pipe
28 ˚C
Summer
Heat extraction:
31W
Air
17˚C
Soil
16 ˚C
Pipe
13 ˚C
Winter
Heat extraction:
47W

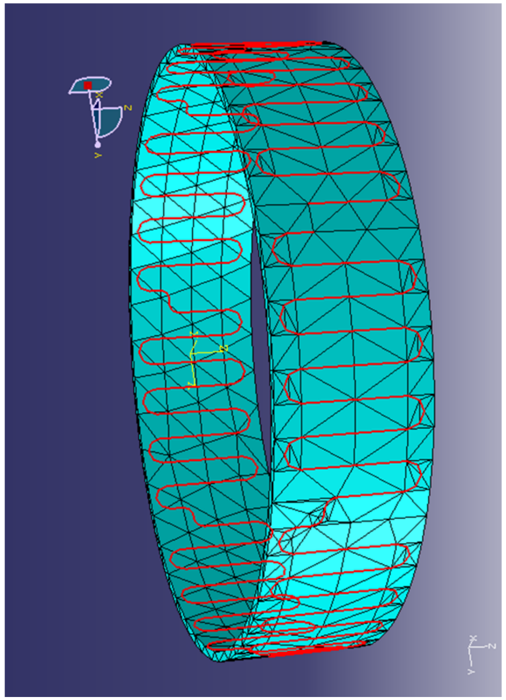
Positioning of the absorber pipe inside the pre-fabricated Tunnel Segment Lining.

Box out section for the pipe connections.



Arup





Lining stresses?

Final remarks

- Appreciation of the difference between “External” loading versus “Internally” generated thermal loading.

- We now know better, but more questions to be answered because of this.

- Opportunities and Challenges in thermal walls and thermal tunnels.

Thank you.