Using piled foundations as ground heat exchnagers

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Acknowledgements

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Using piled foundations as ground heat exchnagers

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- What is an energy pile?
- Construction of energy piles
- Design of energy piles
- Thermal response testing
- Case studies
    - The Crystal building (London, UK)
    - Rosborg Gymnasium (Vejle, Denmark)

What is an energy pile?

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- A pile is a relatively long and slender structural member used to transmit foundation loads to the ground
  - End bearing piles
  - Friction piles
  - Laterally loaded piles
- Contain steel reinforcement to carry bending moments and shear forces
- Can be equipped with heat transfer pipes for integration into GSHP system

Types of pile construction

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Depends on geology and site access:

- Rotary bored
- Continuous flight auger (CFA)
- Driven piles
  - Steel – H section; hollow cylinder
  - Precast concrete
- Screw piles

Above images courtesy of Cementation Skanska

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Image courtesy of Geologic Foundations

Images courtesy of Maria Alberdi

Construction challenges I

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- Pre-fabrication vs on site installation of loops
- Prevention of damage:
  - Concreting >> use of tremmie
  - Pile break out
  - Protection by foam
  - Groundworks
- Pressure testing at handover

Construction challenges II

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- Coordination and contractual arrangements
- Construction Interfaces:
  - Piling
  - Groundworks
  - M & E
  - Control systems
- Redundancy (design vs construction)

How much energy is obtainable?

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- Rules of thumb: 20 – 75 W/m (CIBSE, 2013)
- Borehole rules of thumb: 20 – 55 W/m (CIBSE, 2013)

Reference	Pile Type	Pile Dia (mm)	Monitoring Period	COP / SPF*	Heat Transfer Rate (W/m)
Henderson et al., 1998	Steel tubes with concrete infill	200	12 months		16.4 extraction 18.3 injection
Wood et al., 2010a, b	Bored cast in situ	300	7 months		26
Murphy et al., 2015	Bored cast in situ	910	22 months		91, 95
Pahud & Hubbach, 2007	Bored cast in situ	900 - 1500	24 months	2.7 to 3.9 (SPF)	15 extraction 16 rejection
Sekine et al., 2007	Bored cast in situ	1500	15 months	3.2 extraction (COP) 3.7 injection (COP)	120 extraction 100 – 220 rejection
Kipry et al., 2009	Various schemes			3 to 6.5 (SPF)	<30 extraction <35 injection

Design Issues

Differences to classical borehole schemes:

- Length constrained by structural design
- Plan arrangements likely to be irregular
  - Several closely spaced piles under structural columns
  - Wider spacing in between
- Much shorter aspect ratio
  - Larger diameter (short term issues)
  - Shorter length (long term issues)

Design considerations: short term

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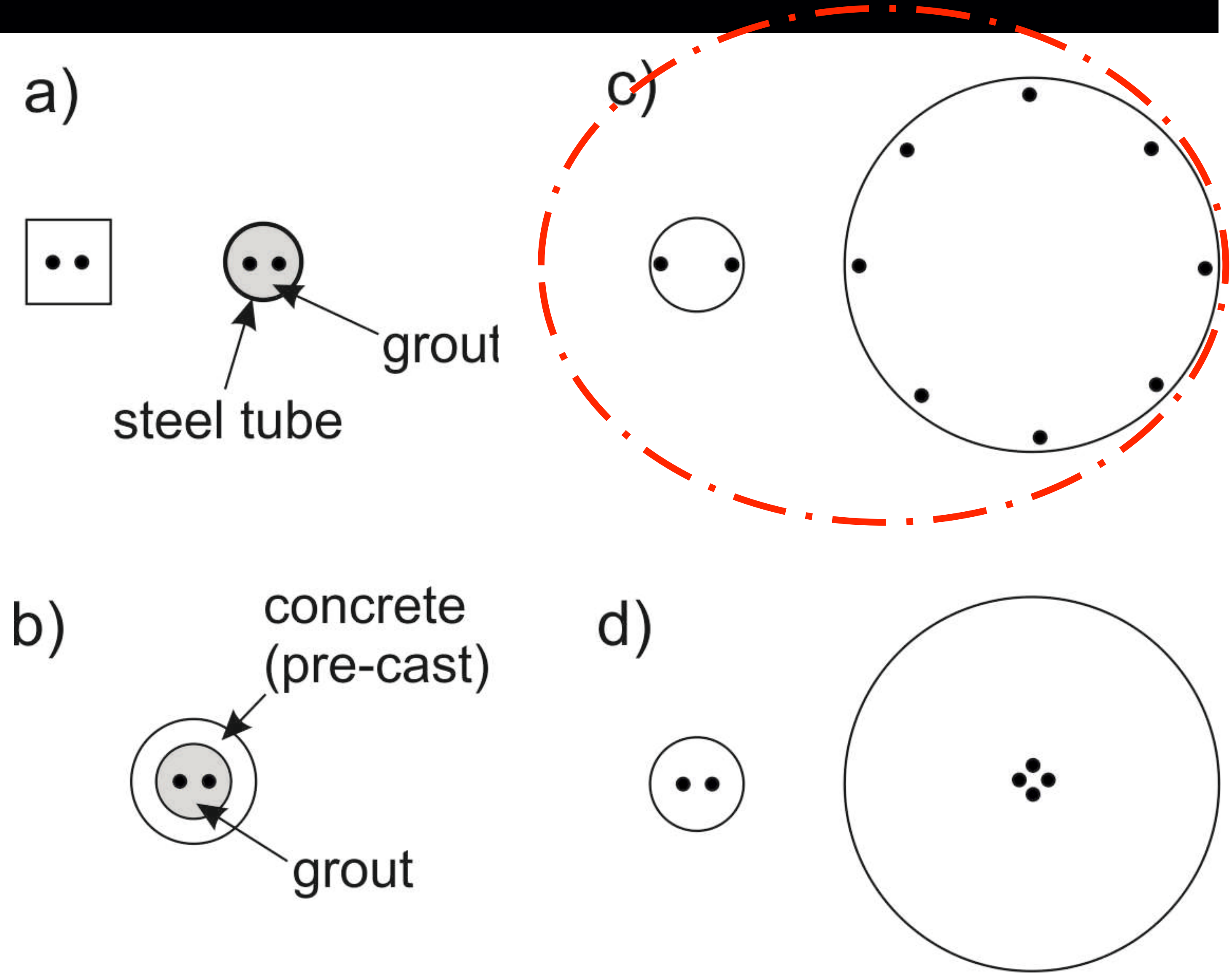
a) 300mm driven

b) 450mm driven

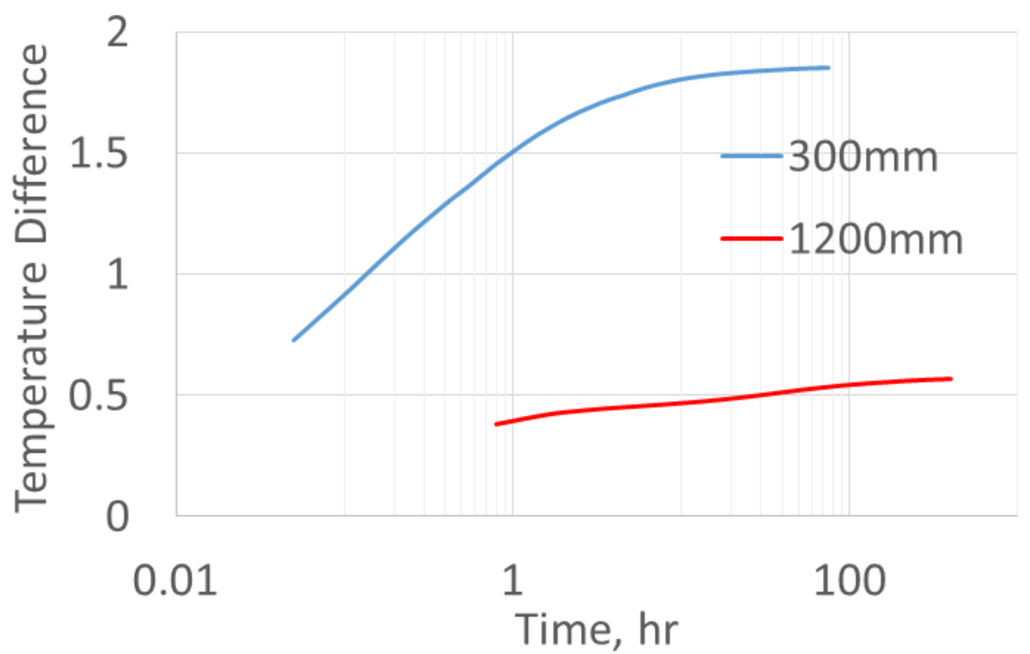
c) 300mm or 1200mm rotary bored

d) 300mm or 1200mm bored CFA



Example temperature changes

- Temperature difference between pipes and pile edge as measure of thermal behaviour
- For given 20 W/m constant heat input at $\lambda_c = \lambda_g = 2$ W/mK
- Smaller pile >>
  - bigger temperature difference (fewer pipes)
  - Temperature difference appears to stabilise sooner
- Convert to thermal resistance



Pile thermal resistance (circular cross section, rotary bored)

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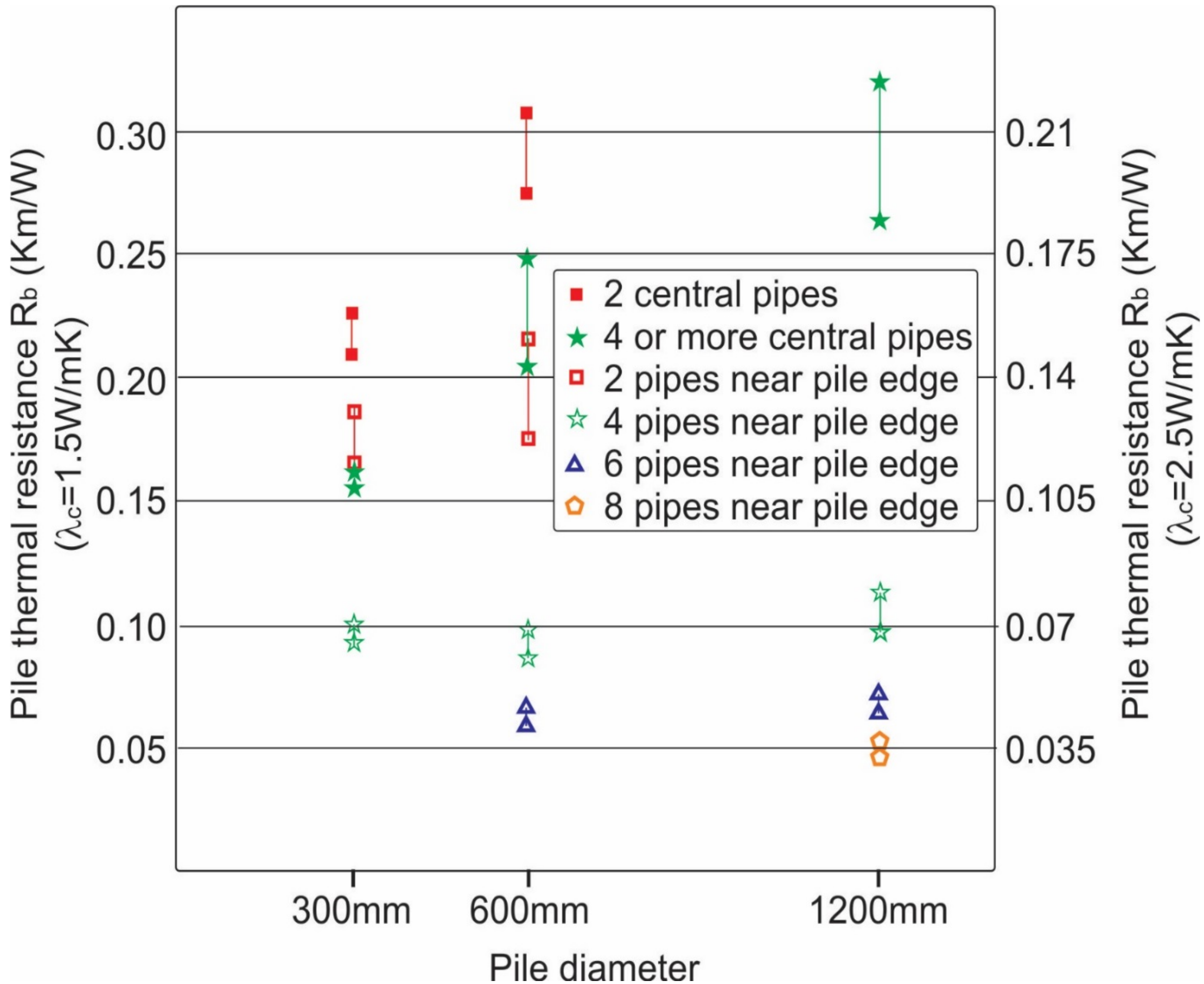

Loveridge, F., Smith, P. & Powrie, W. (2013) A review of design and construction aspects for bored thermal piles, Ground Engineering, March 2013.

Time for pile to reach steady state

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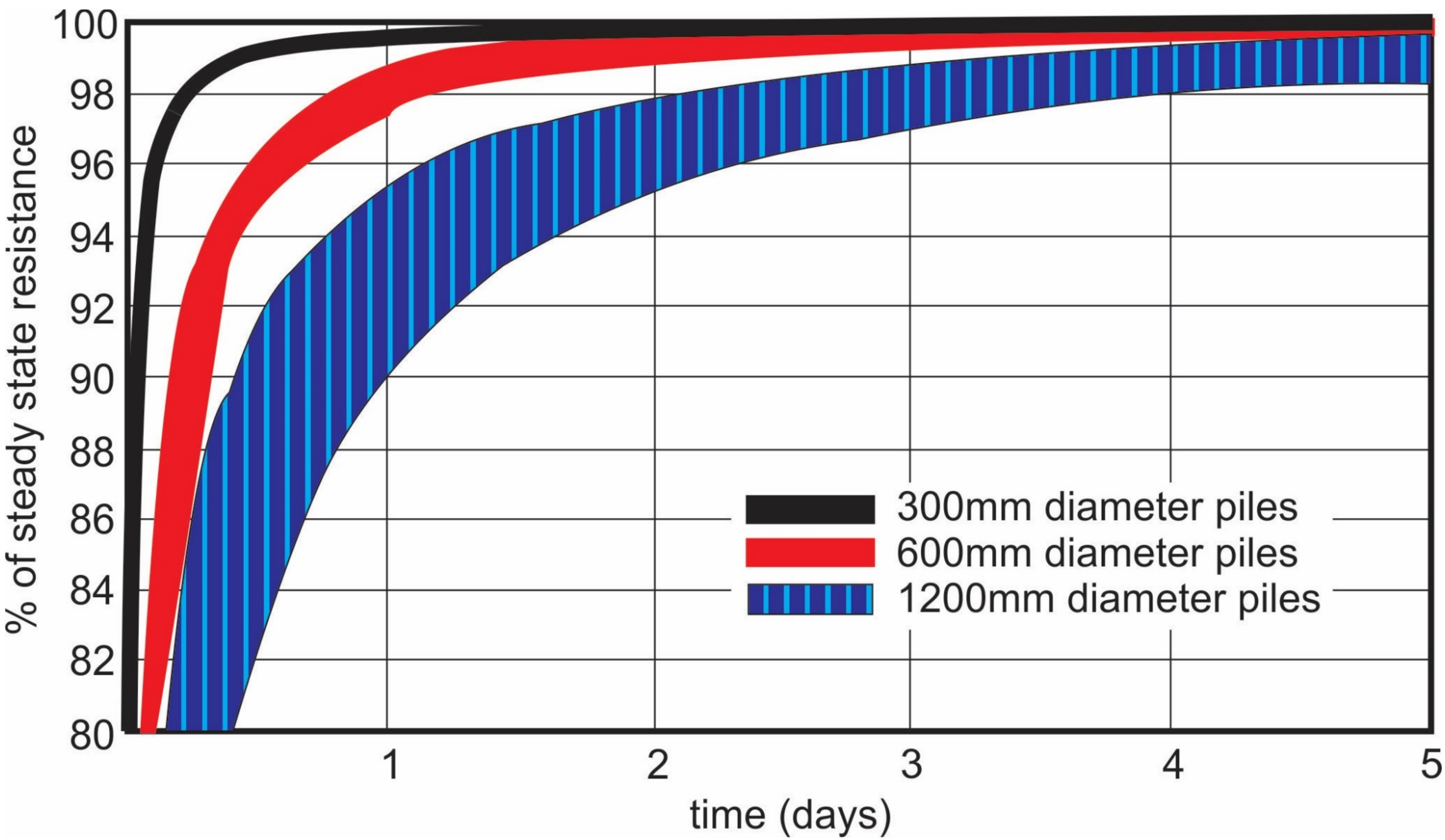
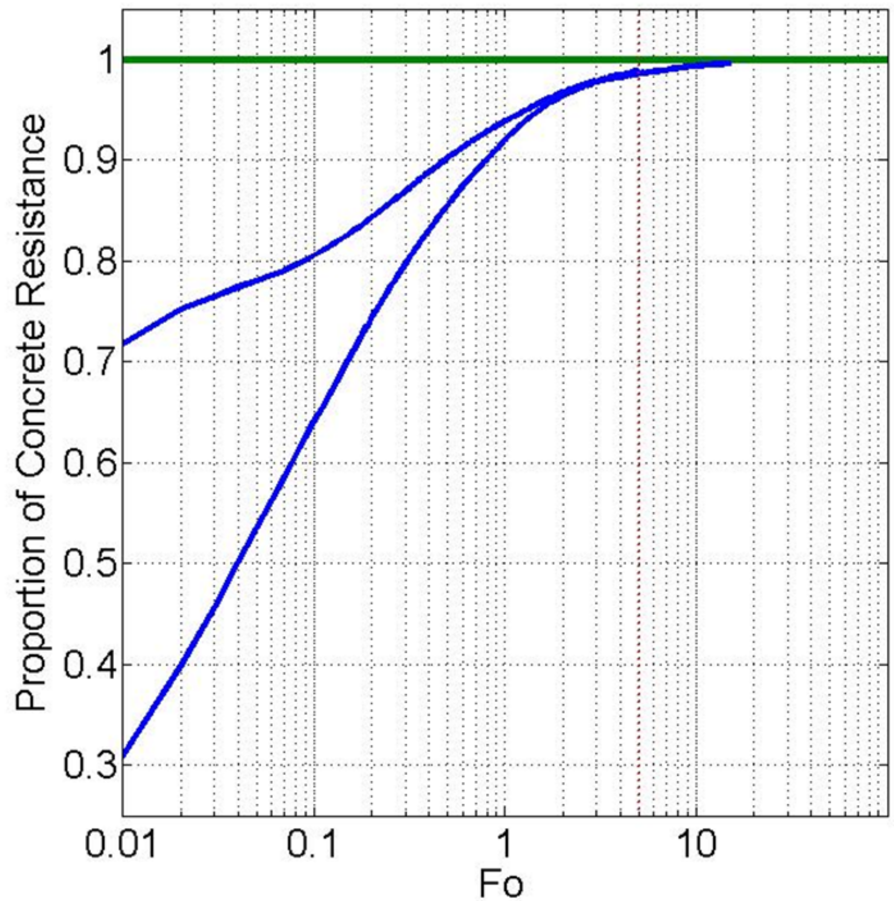


Loveridge, F., Smith, P. & Powrie, W. (2013) A review of design and construction aspects for bored thermal piles, Ground Engineering, March 2013.

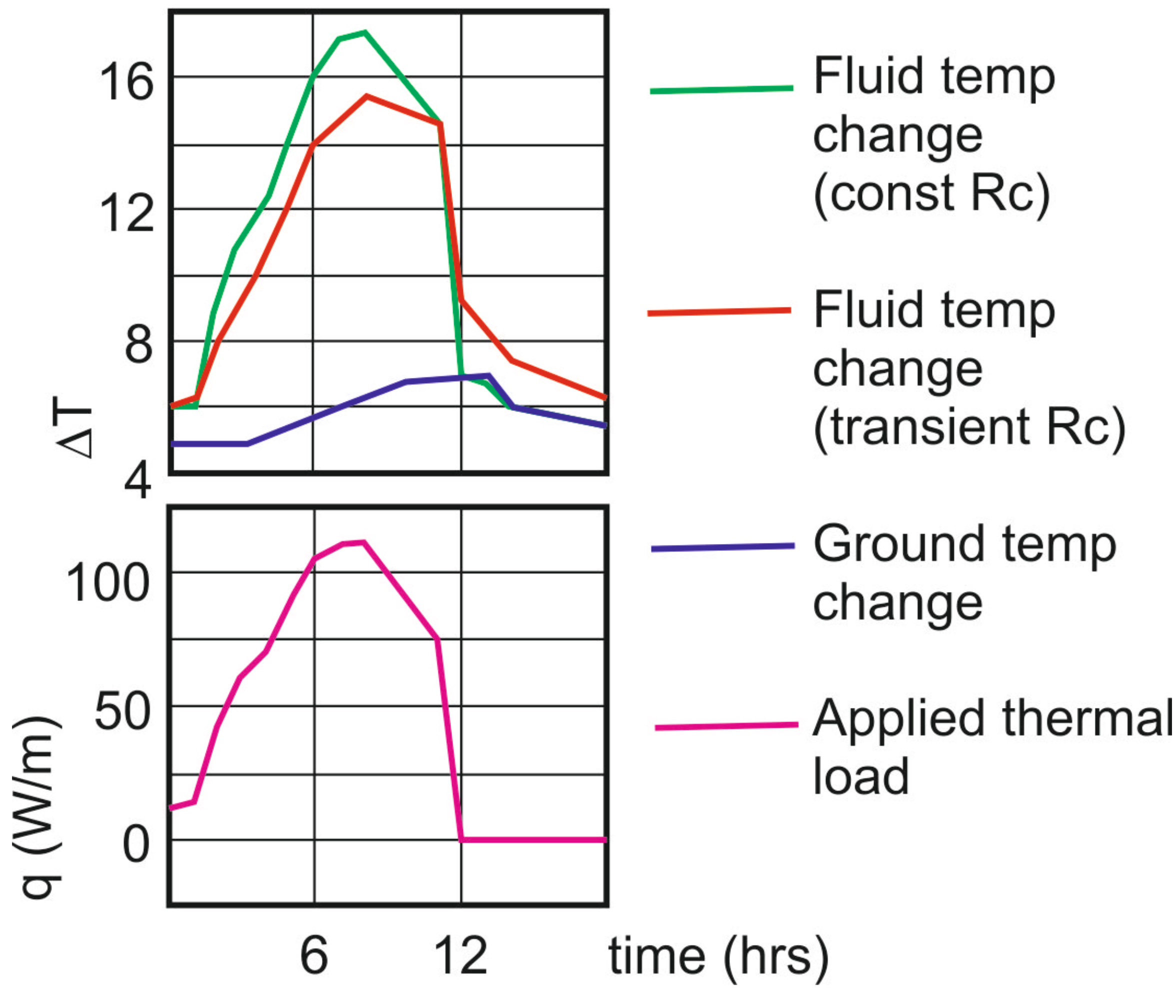
Transient approach to resistance

- It may take several days for a pile to reach steady state
- Operational conditions are rarely steady
- Must have transient short time step analysis
  - Combined pile and concrete G-function (no pile resistance term)
  - Transient function for pile resistance



Analytical Example

- 600mm dia pile, 20m long
- Hourly time steps
- Analytical temperature response functions (G-functions)
- Potentially 20% underestimate of energy for steady analysis



Design considerations: long term

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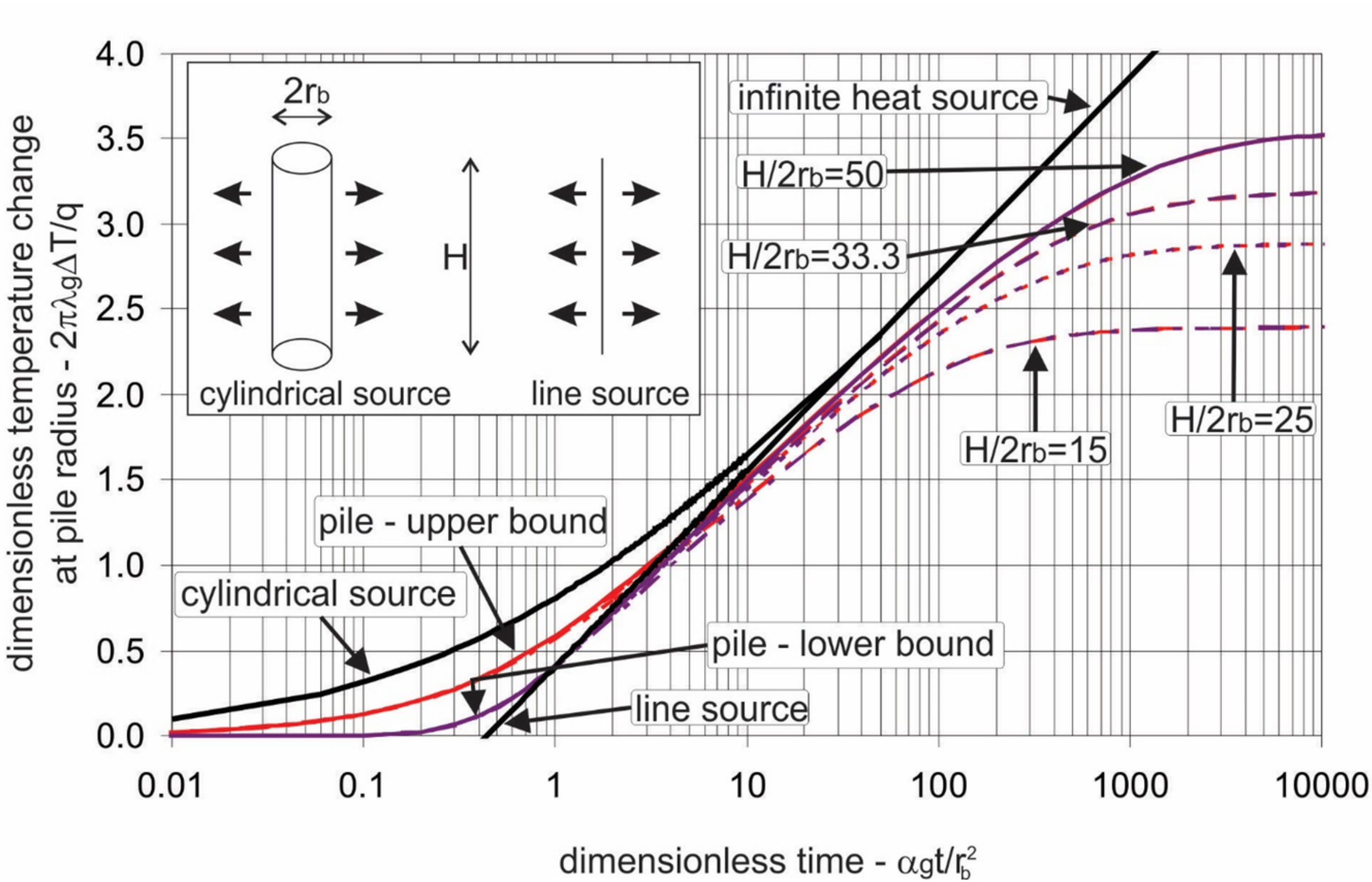
- Important to agree temperature limits with geotechnical & heat pump design teams
- Piles have short aspect ratio (AR) – making boundary conditions more important
- Classic borehole design assumes constant surface temperature >> Low AR >> reach steady state sooner
- Analysis has shown that for short heat exchangers this underestimates the benefit of surface thermal recharge
- But for piles beneath a building an insulated or net heat flux boundary condition may be more appropriate

Design considerations: long term



Design considerations: long term

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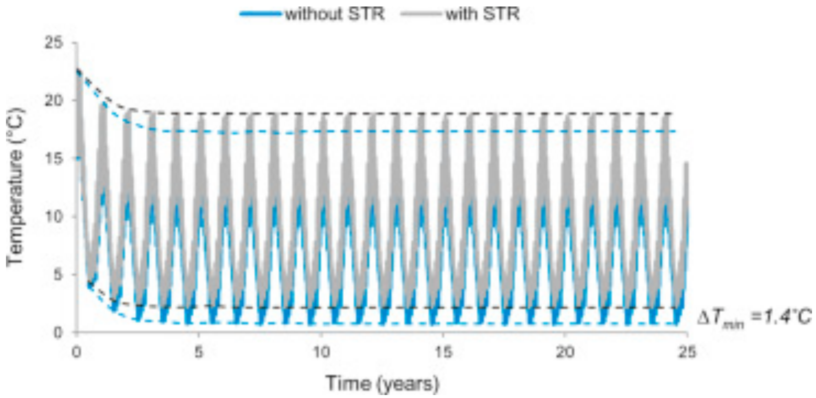
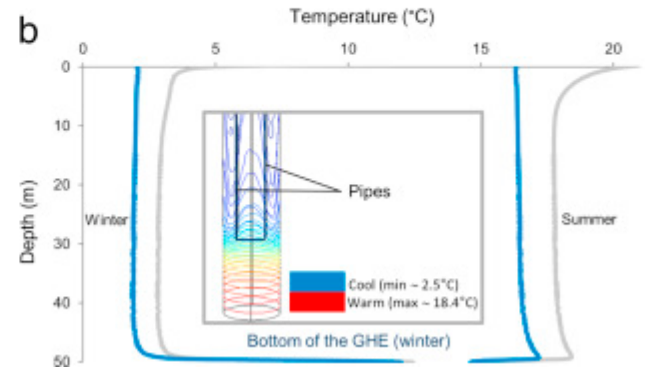
Bidarmaghz et al 2016:

- 4 no 30m deep ground heat exchangers
- Surface thermal recharge can cause reduced ground temperature change
- Effect 40% bigger compared to 50m deep installations





Bidarmaghz et al (2016), The importance of surface air temperature fluctuations on long-term performance of vertical ground heat exchangers, Geomechanics for Energy and the Environment, 6, 35-44.

Design considerations: long term

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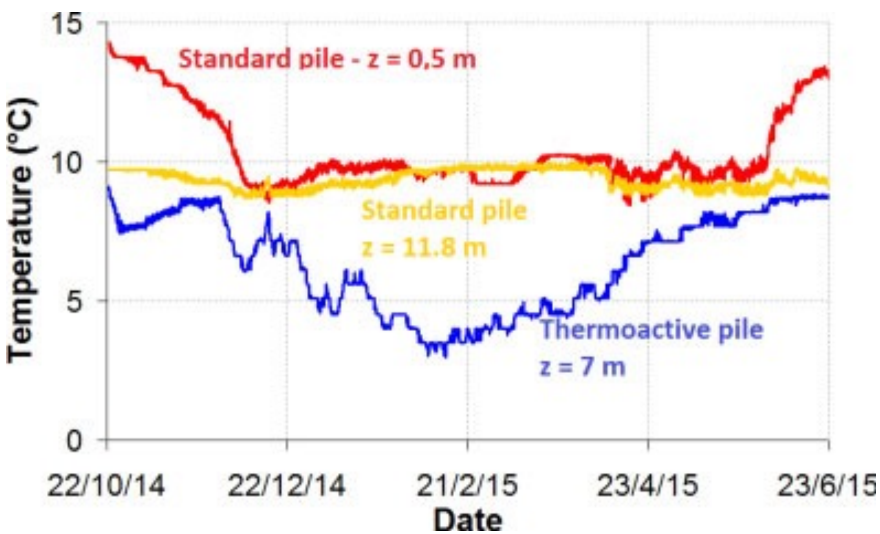
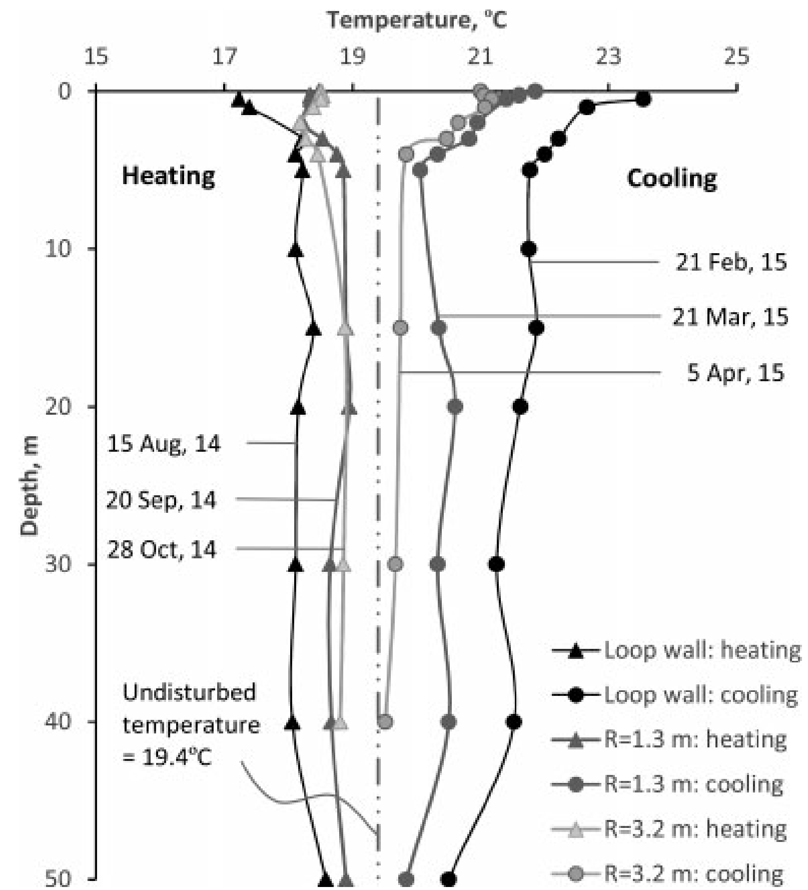
Monitoring data from active systems beneath buildings:

- Mikhaylova et al (2016) & Habert et al (2016) show some fluctuations at the pile head.





Above: Mikhaylova et al (2016) Ground thermal response to borehole ground heat exchangers, Proc ICEG
Left: Habert et al (2016) Lessons learnt from mechanical monitoring of thermoactive pile, Proc ICEG

Thermal response testing for piles

Size restrictions for TRT

- IGSHPA >> 152 mm
- GSHPA >> 200 mm

Why?

- Exponential Integral in line source model
- Heat capacity of grout / concrete

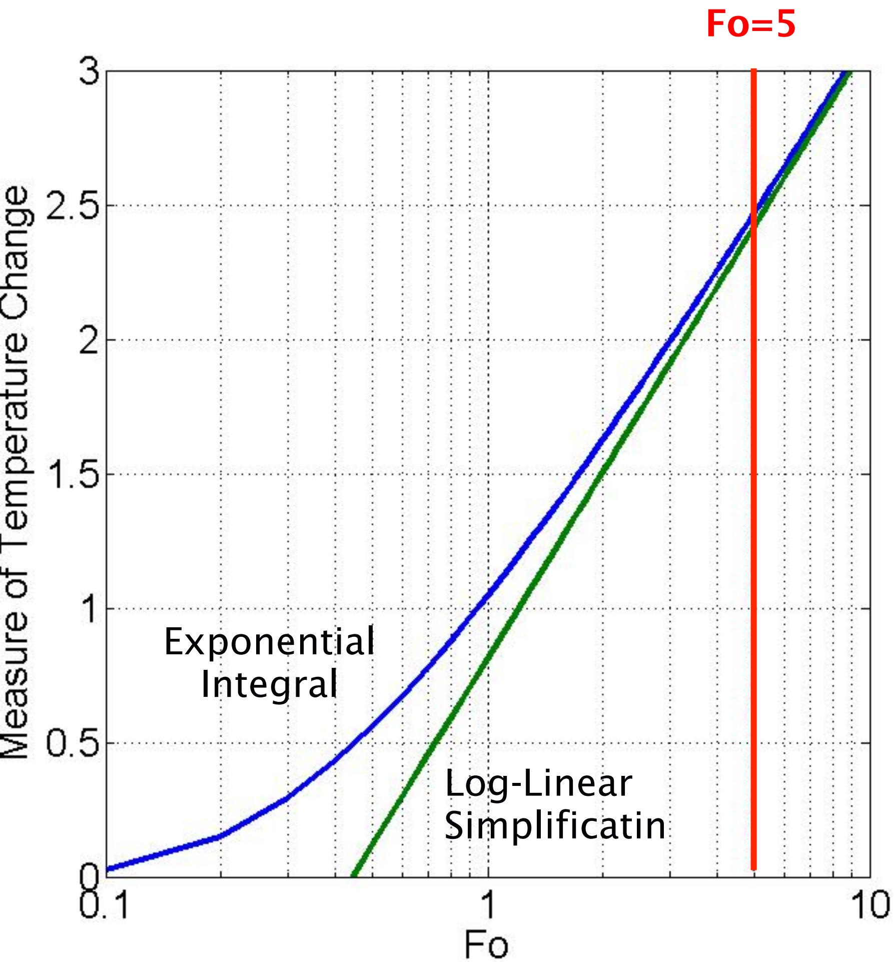
For piles larger r >> larger minimum time

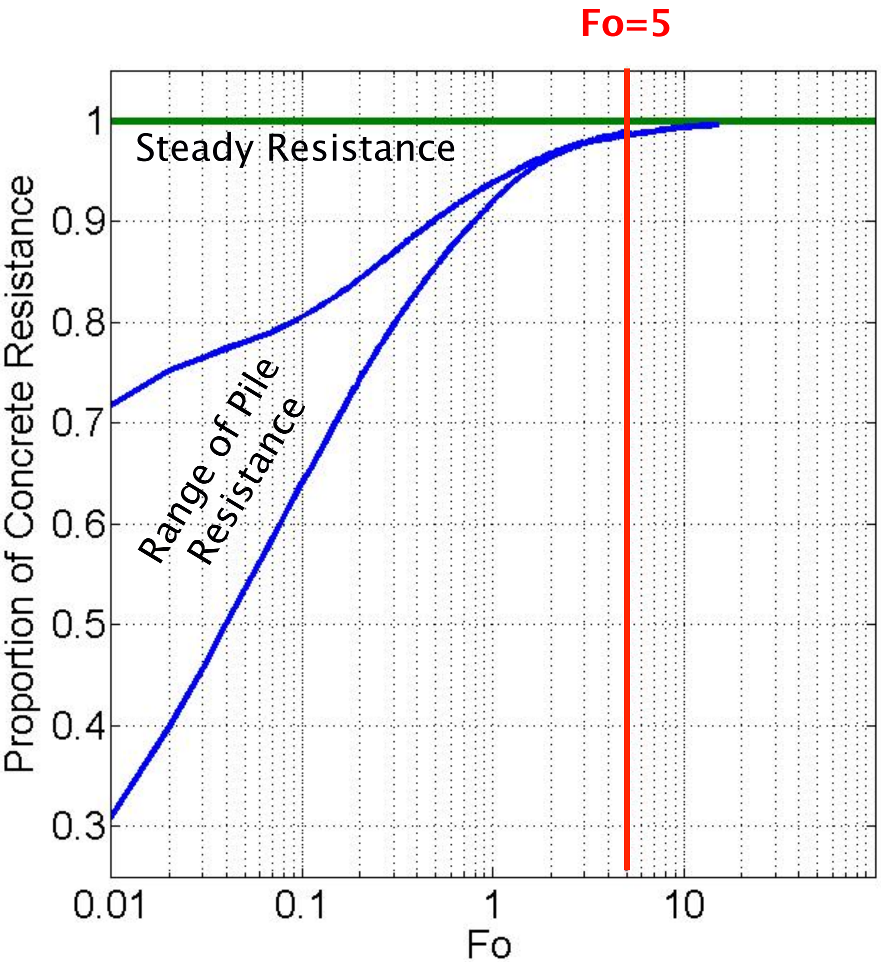
$$\Delta T = qR_b + \frac{q}{4\pi\lambda}\left\{ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right\}$$

$$\Delta T = qR_b + \frac{q}{4\pi\lambda}\left\{Ei\left(\frac{r^2}{4\alpha t}\right)\right\}$$

$$Fo = \frac{4\alpha t}{r^2} \qquad Fo > 5$$

Quantification of Model Errors





Axial Effects in TRT ?

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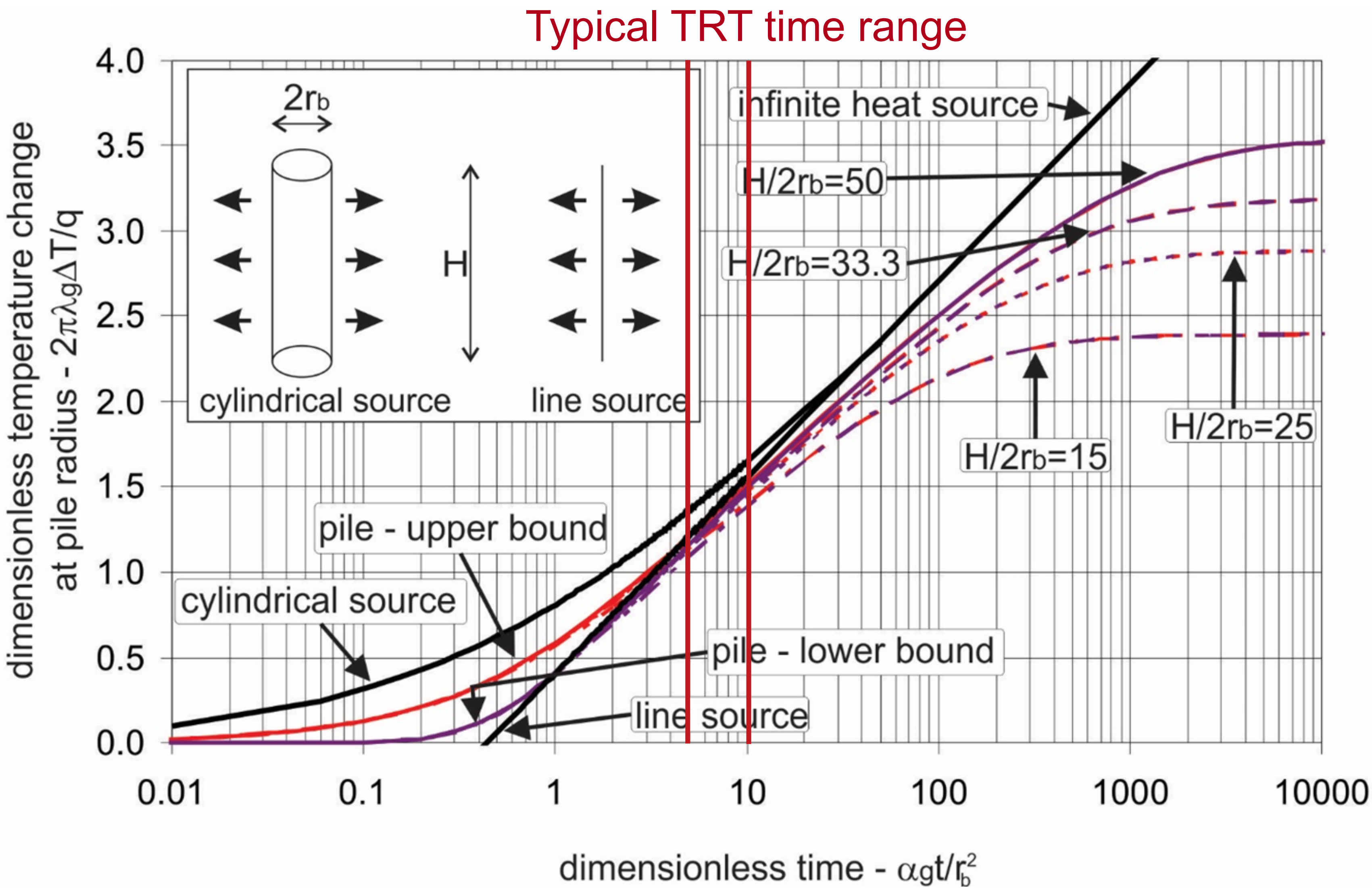

Field to lab thermal conductivity for energy piles

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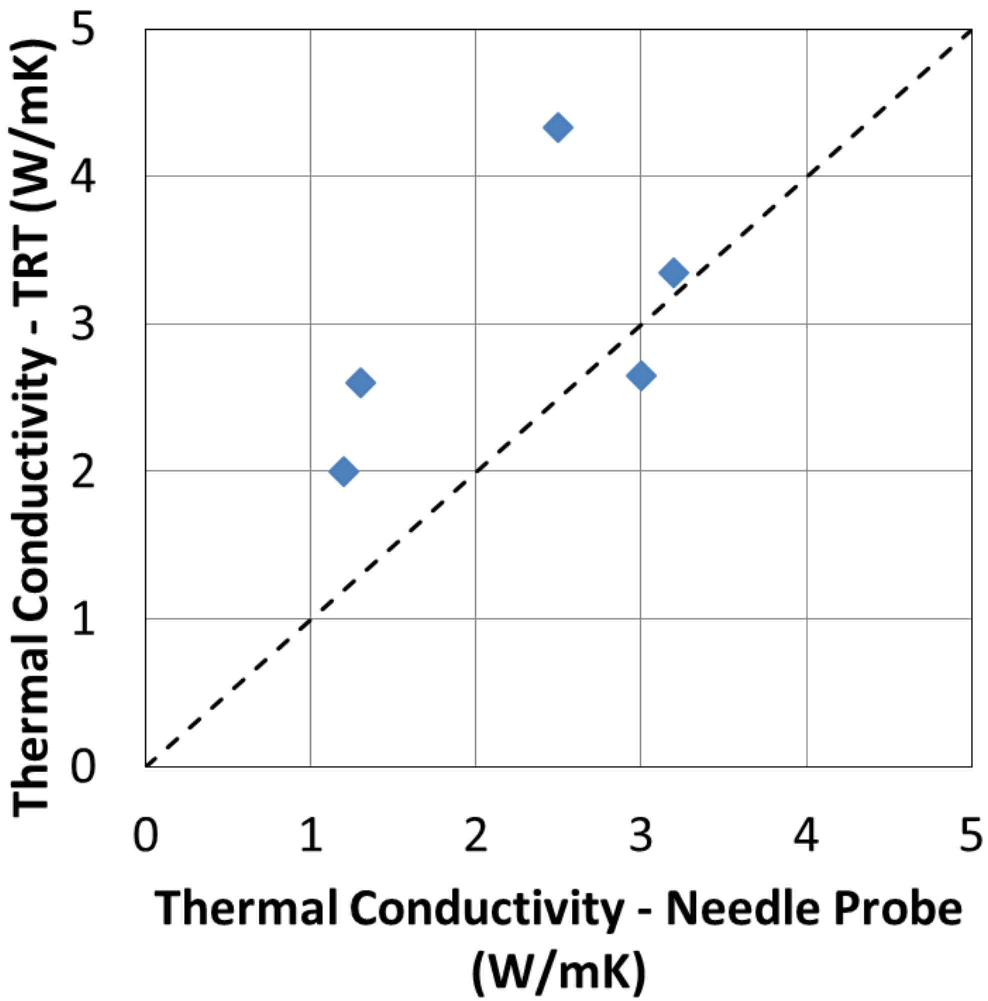

TRT Recommendations

- If you must do a pile TRT:
  - Give due regard to diameter when determining test length
  - Don’t just use the line source to interpret the results; use a transient model or numerical simulation (ideally 3D) with parameter estimation
  - Remember it likely has reduced accuracy
- Consider testing a borehole at site investigation stage:
  - More accurate; easier to interpret
  - Fewer programme issues (heat of hydration, critical path)
  - Pile length may not yet be known (less issue for end bearing driven?)
  - No concrete resistance / thermal properties information

Case study: The Crystal

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- Siemens landmark new building in East London
- All electric building
- 160 energy piles (600mm to 1200mm diameter; 21m deep)
- 36 closed loop boreholes (137.5 mm diameter; 150m deep) into the Chalk

Construction

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Construction

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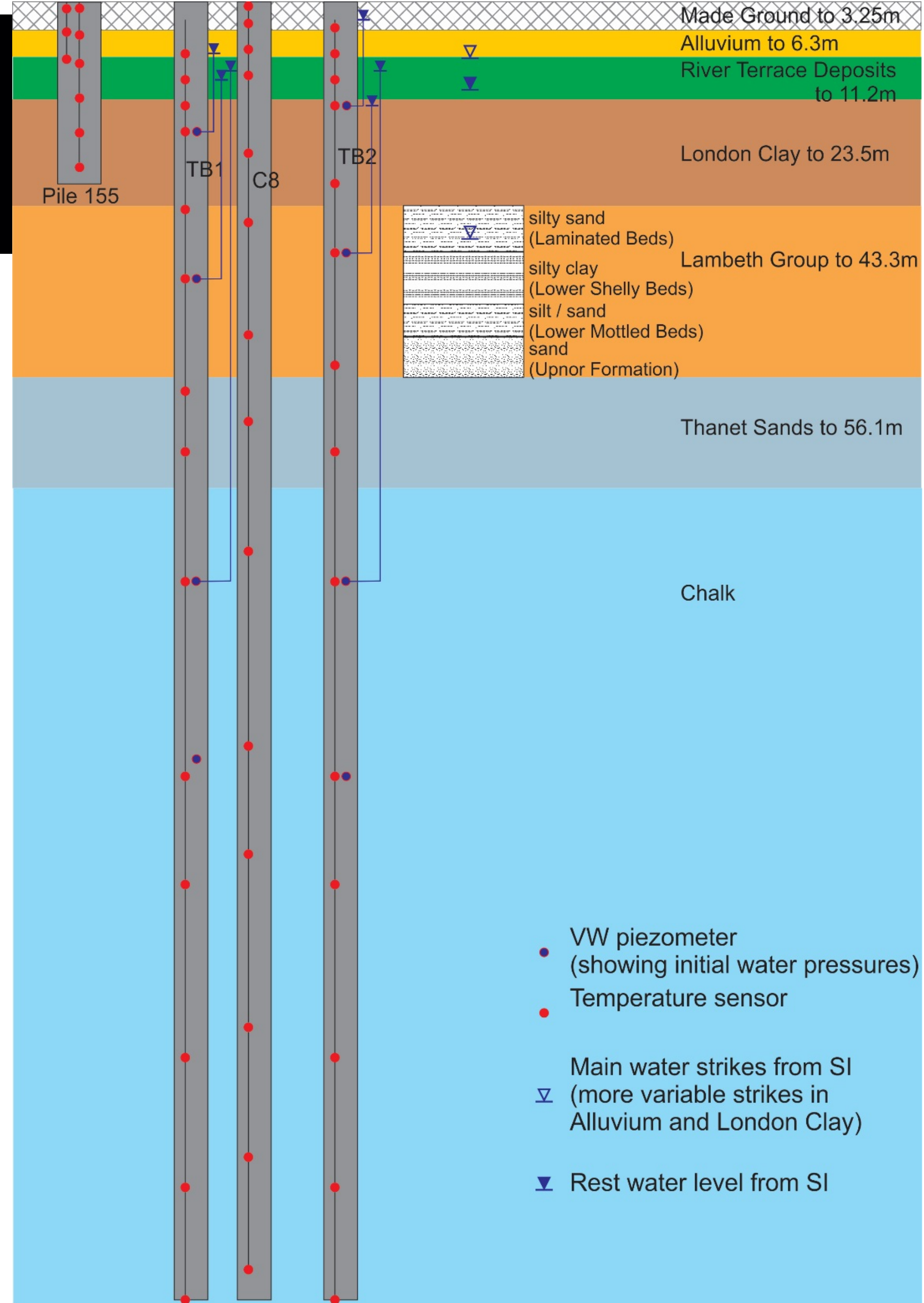
Geology

- Piles
  - Made ground, alluvium, river gravels & London Clay
- Boreholes
  - Full London basin sequence, including Thanet Sands and Chalk aquifer
- High groundwater table



Heat pump arrangement

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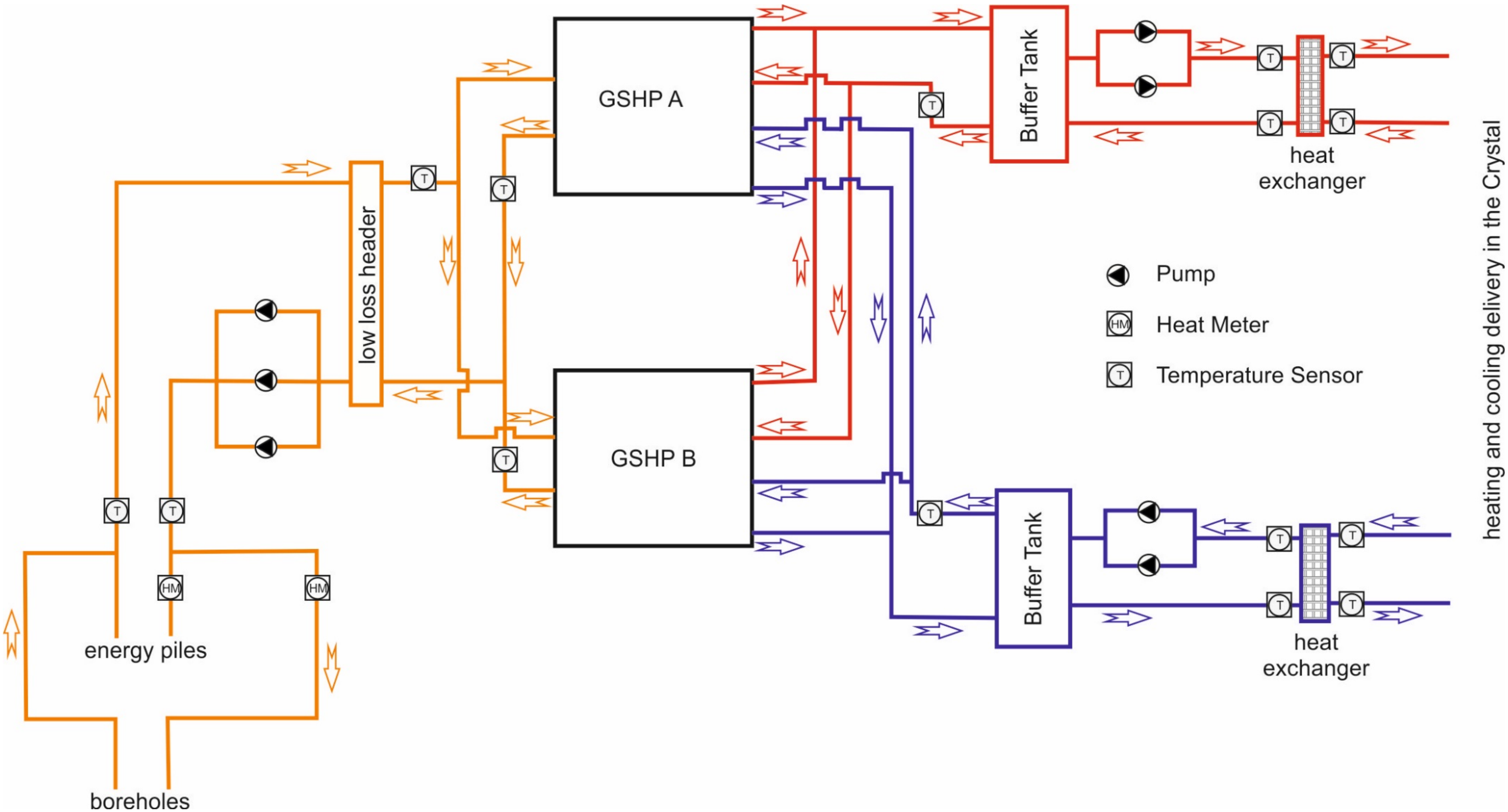
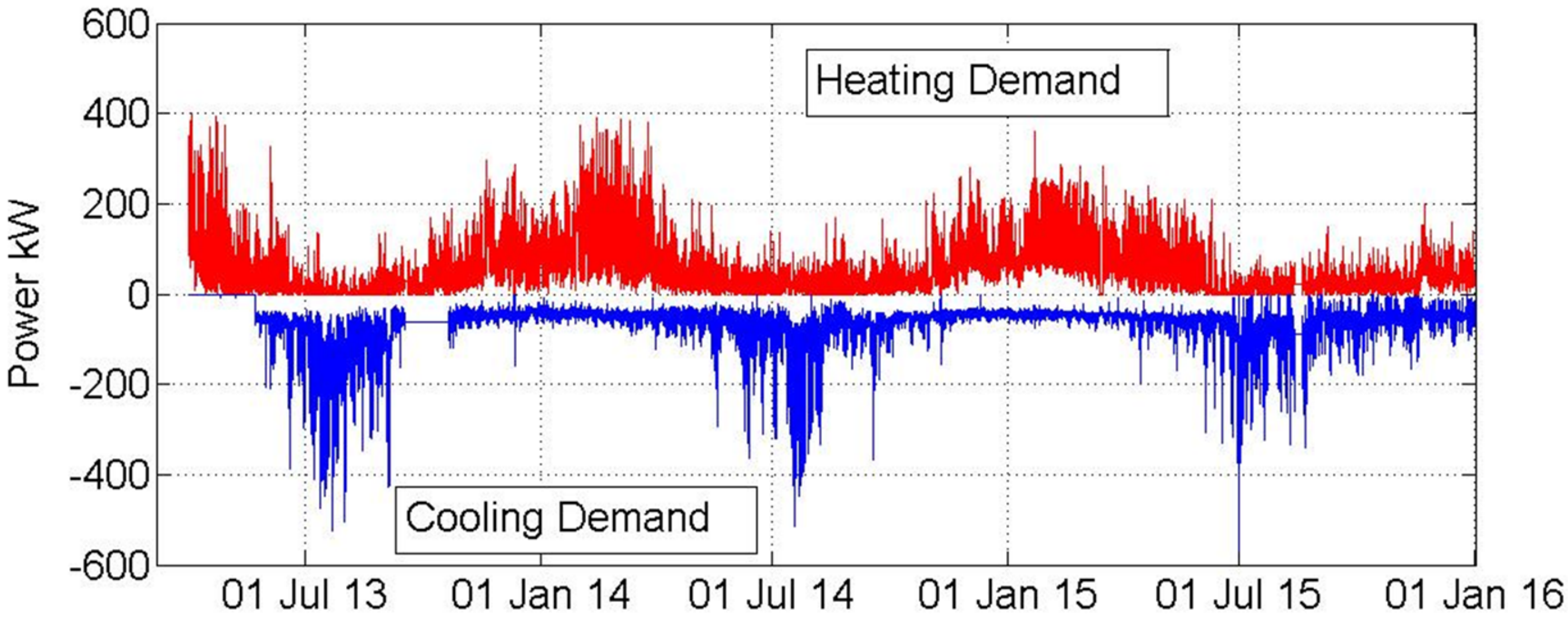


Thermal Demand

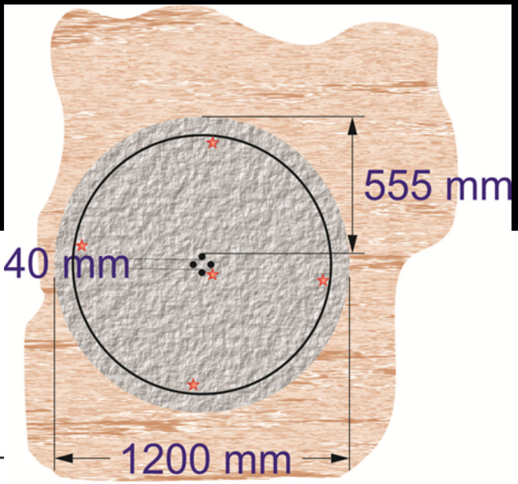
Predicted demand: Heating 307 MWh/yr; Cooling 173 MWh/yr

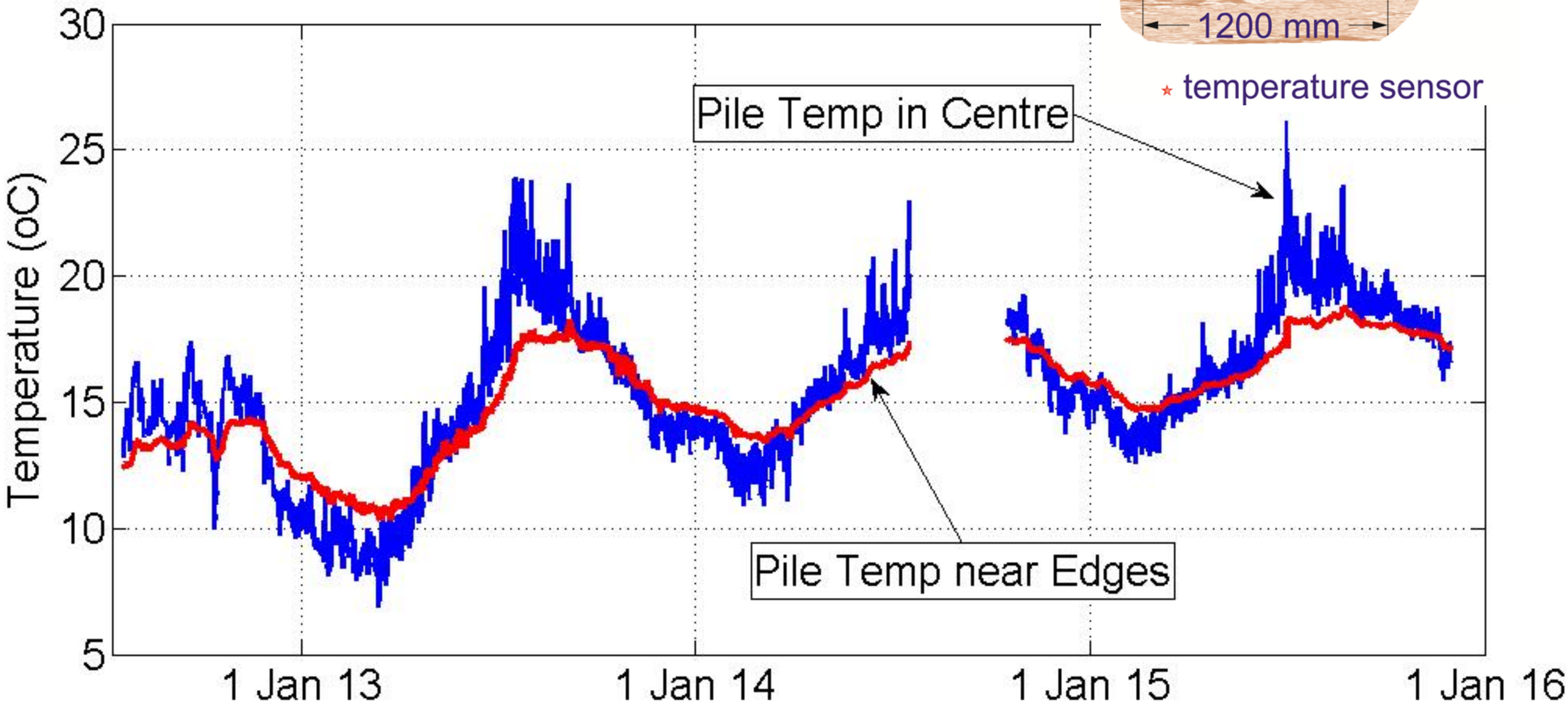
Actual usage: Heating ~ 550 MWh/yr; Cooling ~ 550 MWh/yr

Nominal 600kW systems: actual 399 kW H & 572 kW C



Pile monitoring





Loveridge et al. (2016) Long term monitoring of CFA energy pile schemes in the UK. Proc. ICEGT 2016.

Pile behaviour

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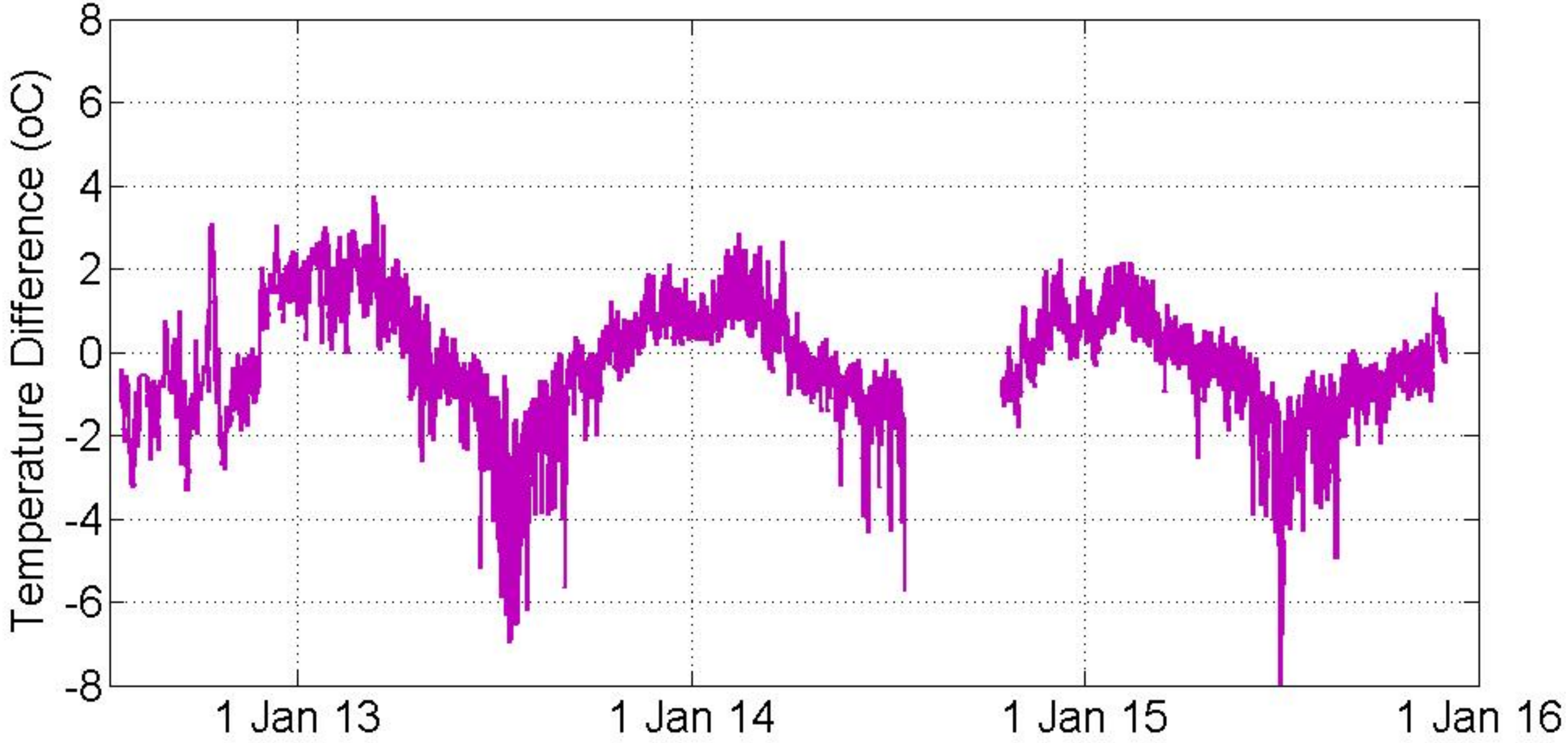

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Apparent thermal resistance

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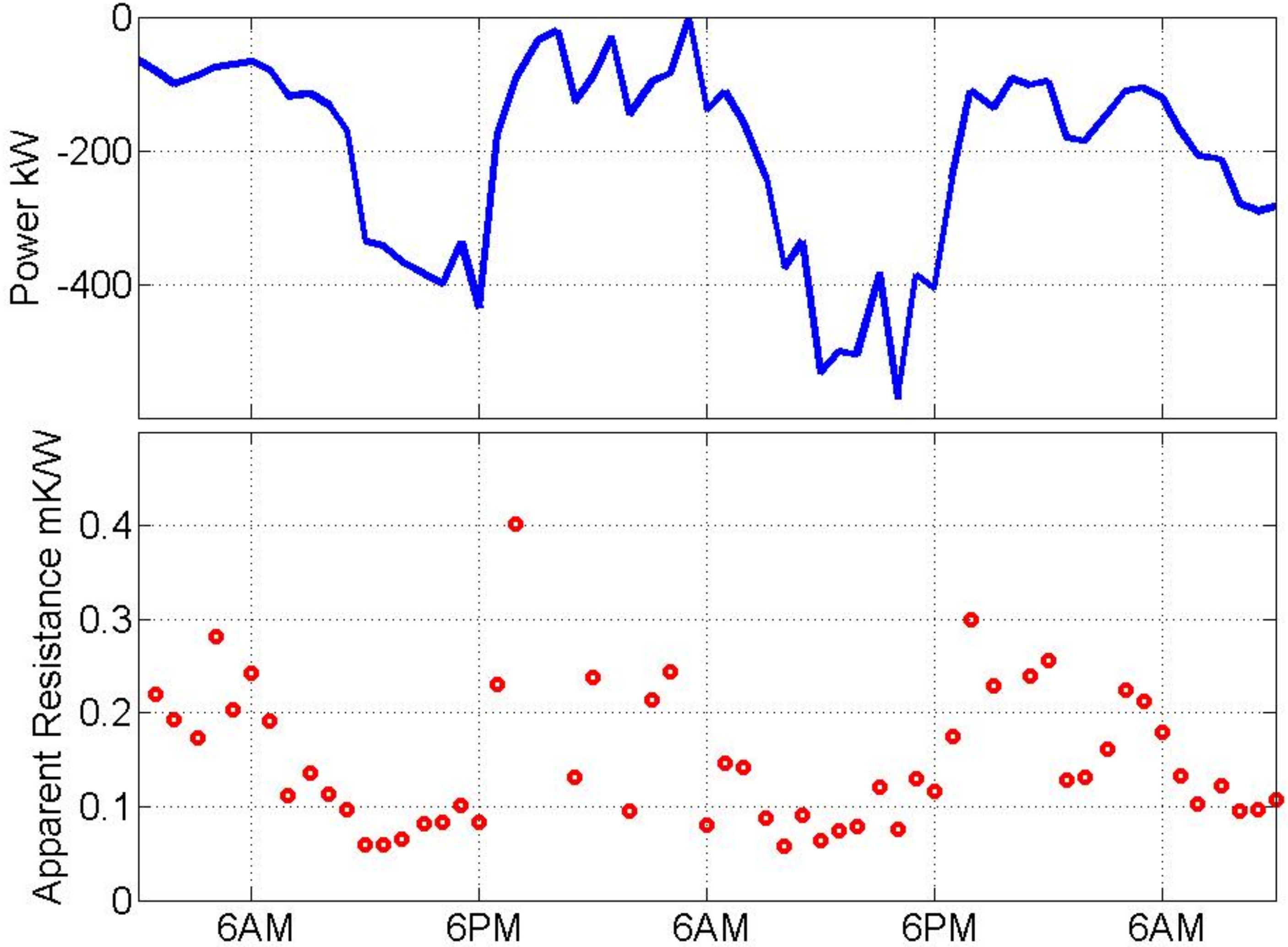

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Heat transferred to the ground

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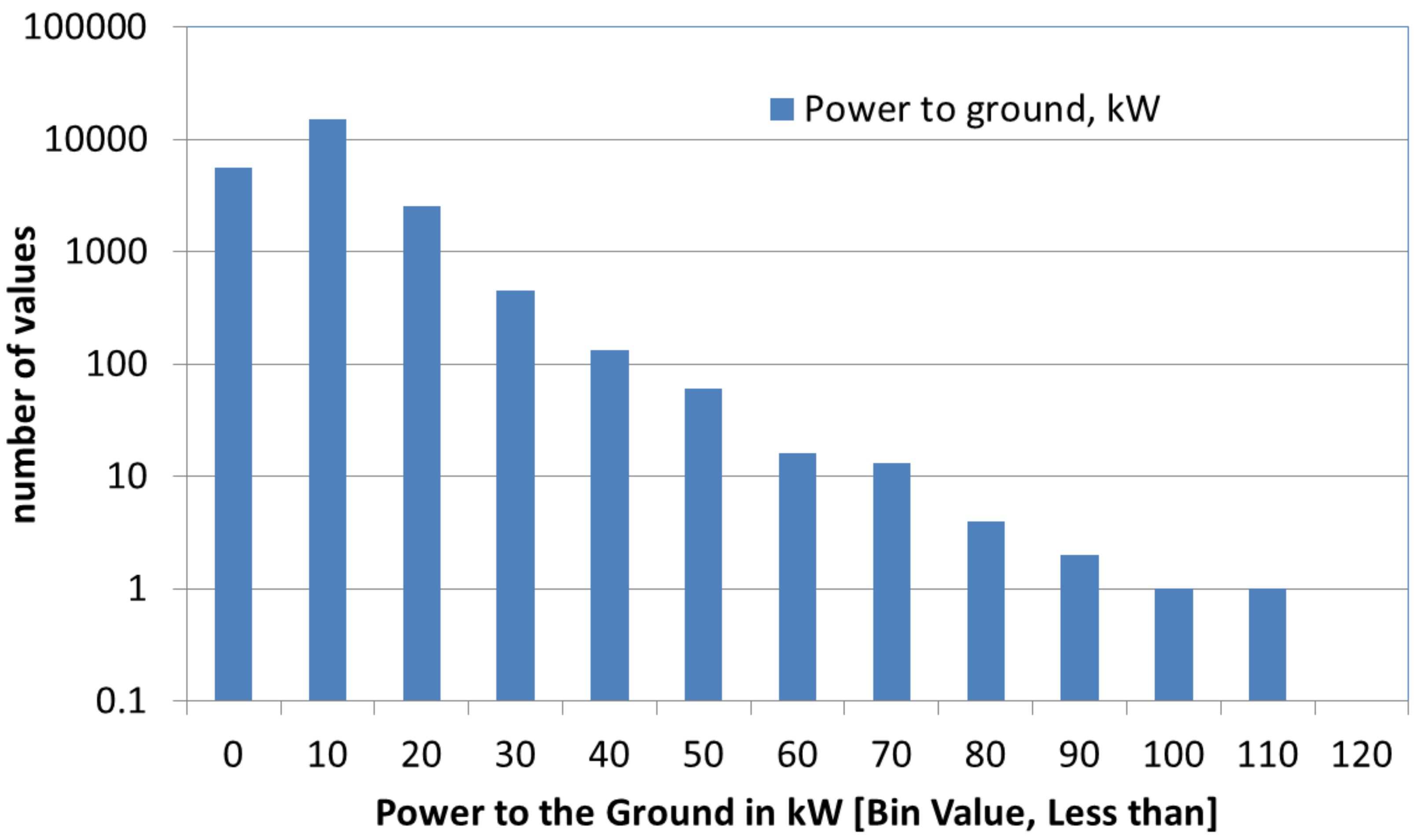

Seasonal Performance Factor

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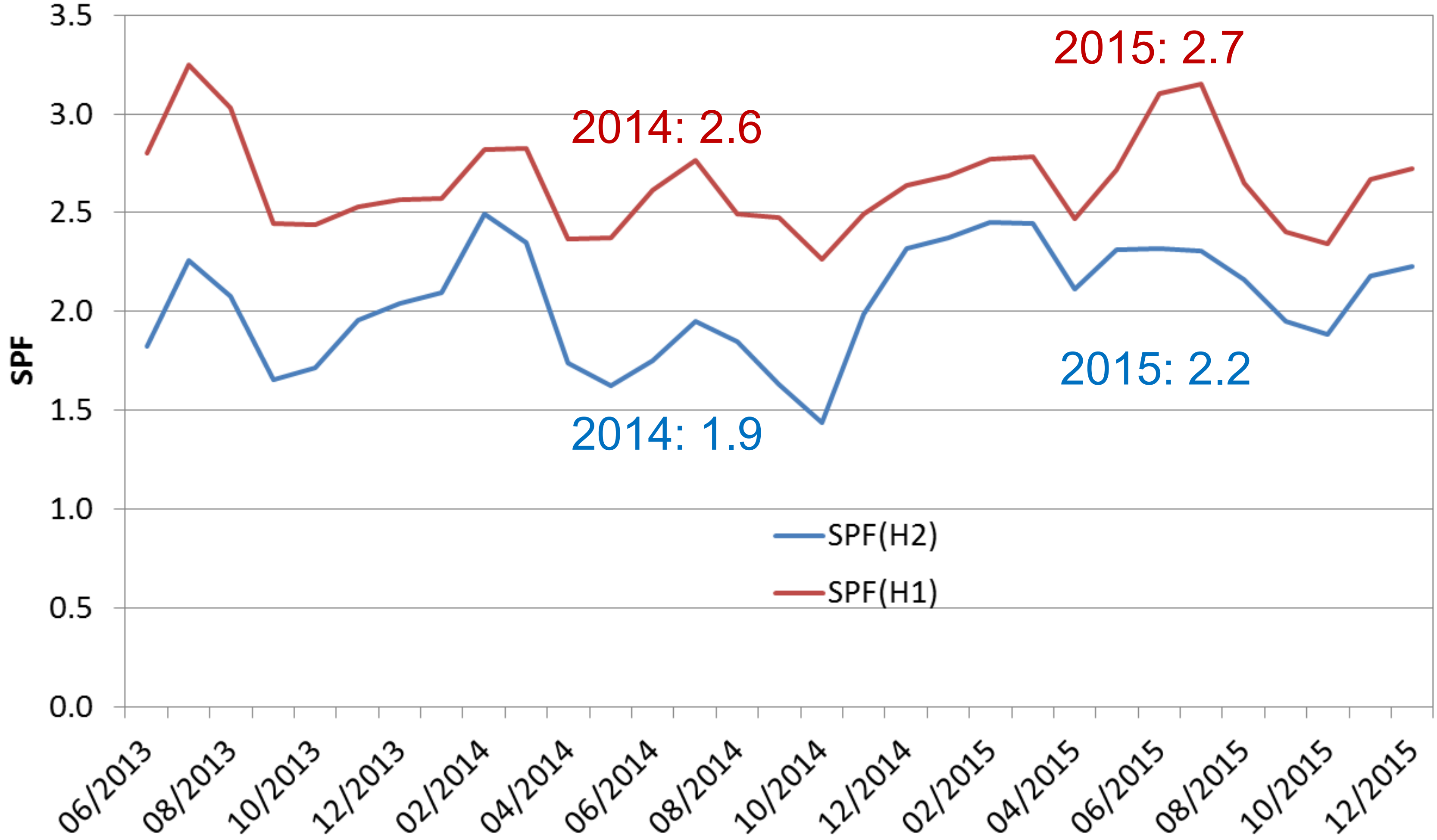

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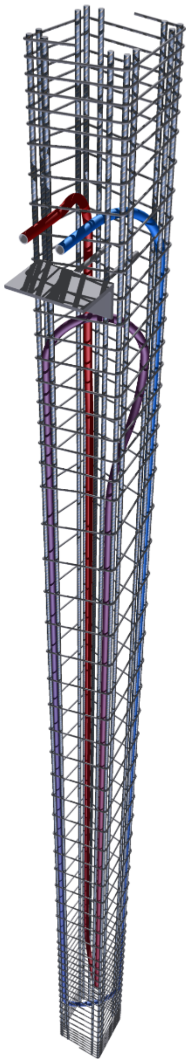
Case study: Rosborg Gymnasium

- 2011 extension founded on 200 energy piles
- 2 story building
- 0.3m square 15m long driven precast concrete piles
- Each with "W" pipe loop
- 16 piles grouped in series
- Glacial sediments; high natural groundwater is artificially drained

Construction



Images courtesy of Maria Alberdi

Heat pump arrangement

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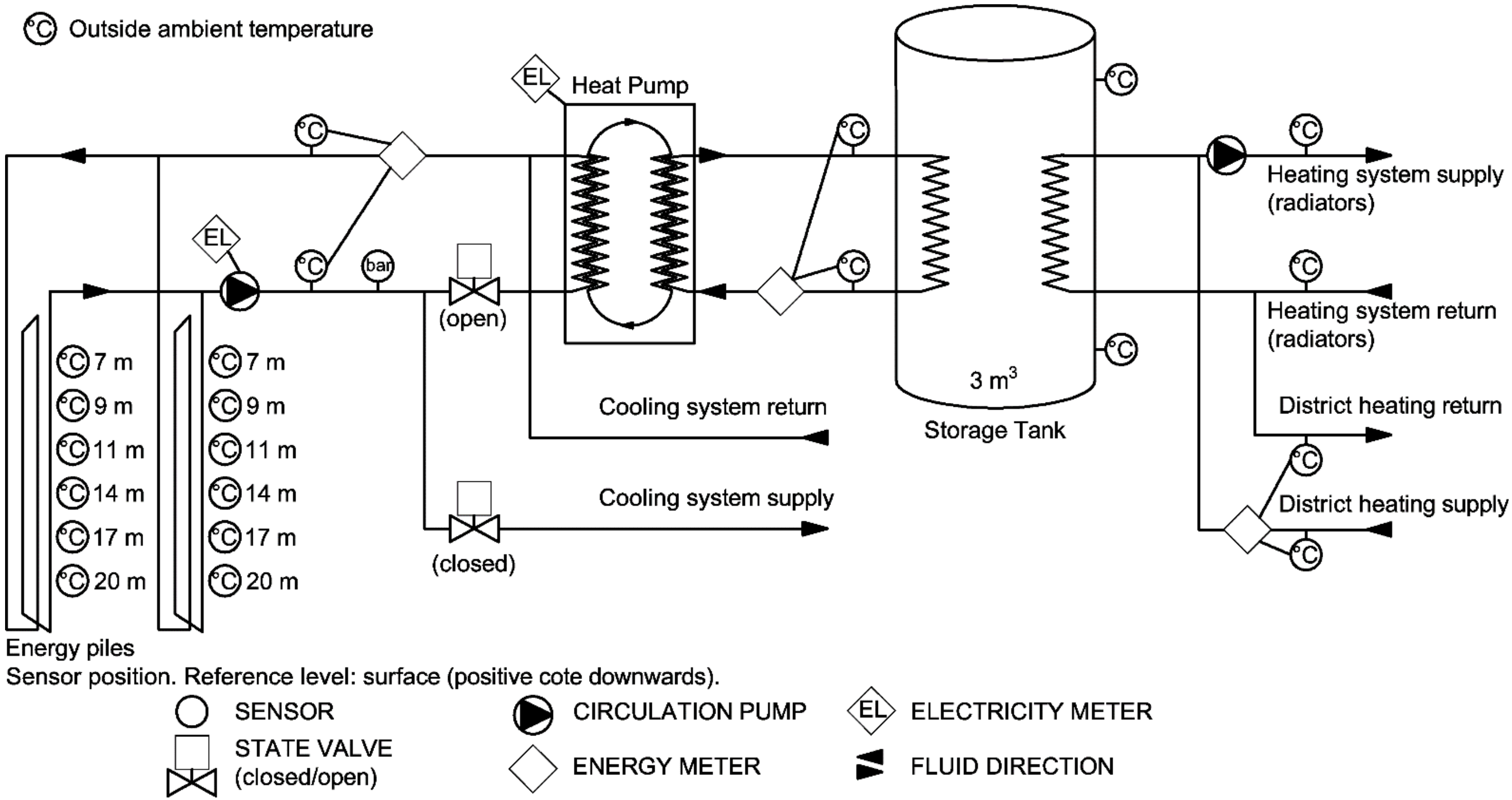
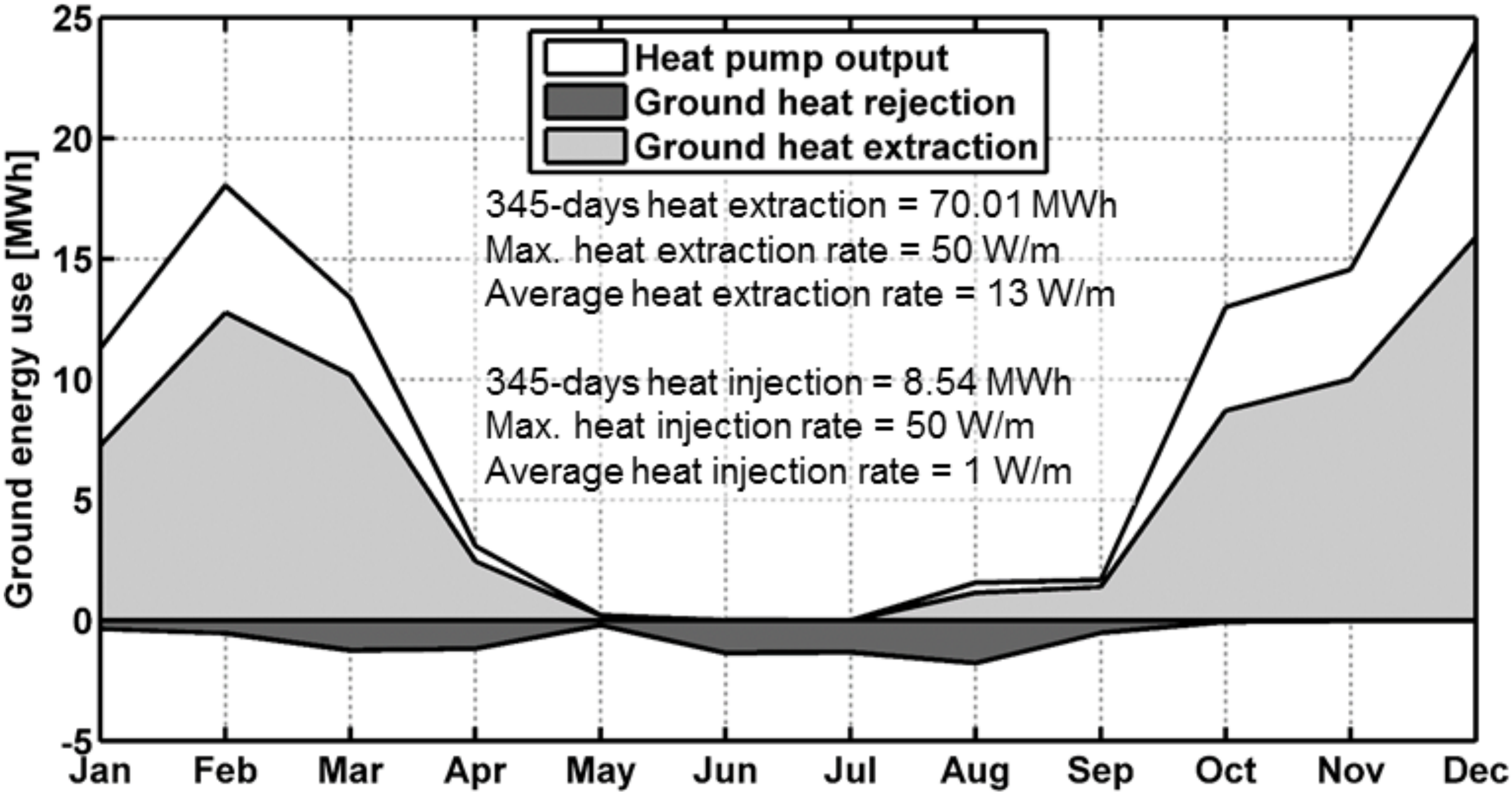


Alberdi et al (2016) A performance case study of energy pile foundation at Rosborg Gymnasium (Denmark). Proc 12th REHVA World Congress.



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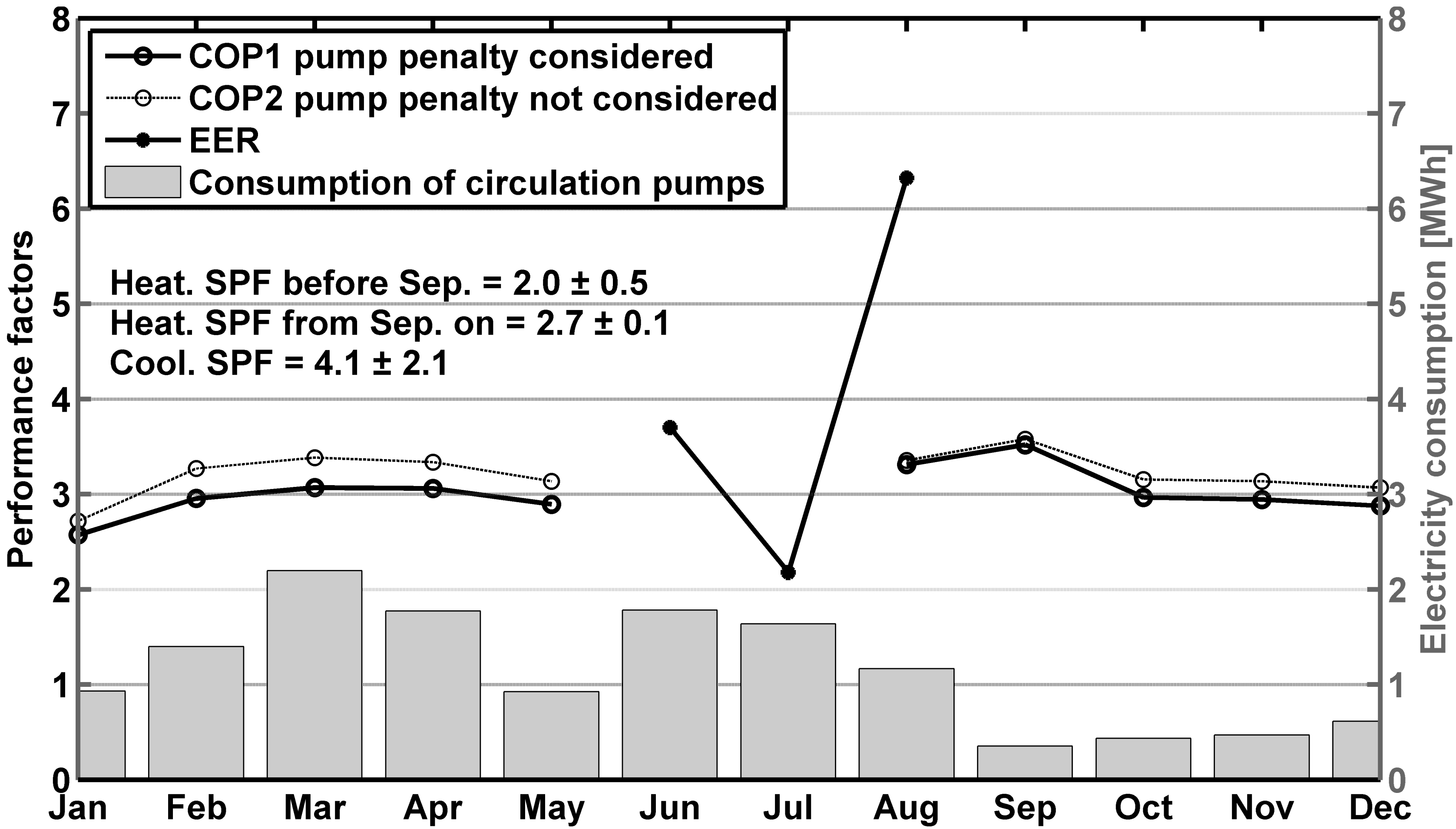

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Concluding remarks

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- Piles can potentially offer cost & carbon savings compared to boreholes; may be more efficient per linear metre.
  - But still require same care and attention in terms of system design
- Need to consider thermal storage in pile for design & TRT.
- Need to consider short length and potential for revised boundary condition in long term.
- Must liaise with geotechnical designers about temperature changes/limits.
- Must consider construction interfaces and damage avoidance; site coordination essential