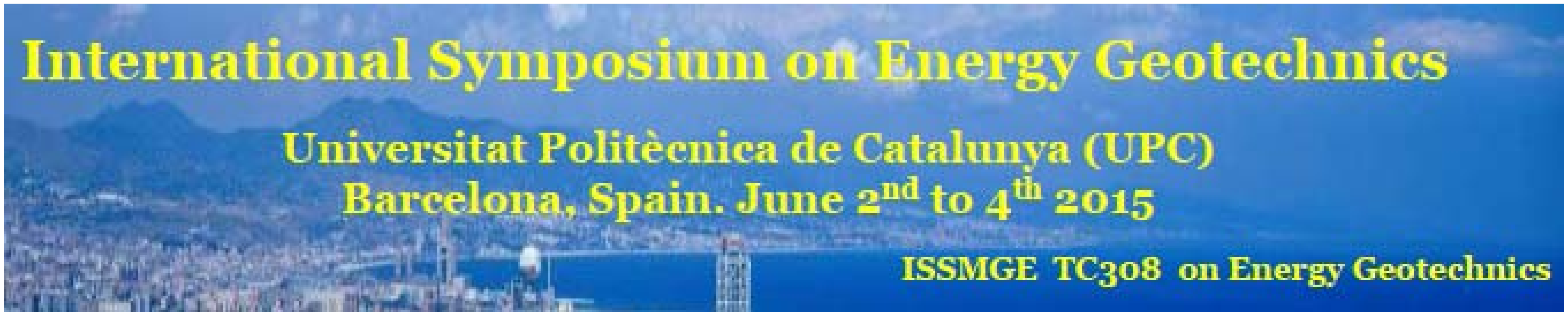
Energy Geo-Structures and Storage of Thermal Energy in the Ground

Task Force 3 Position Paper

Guney Olgun & Fleur Loveridge



Energy Geo-Structures and Thermal Energy Storage

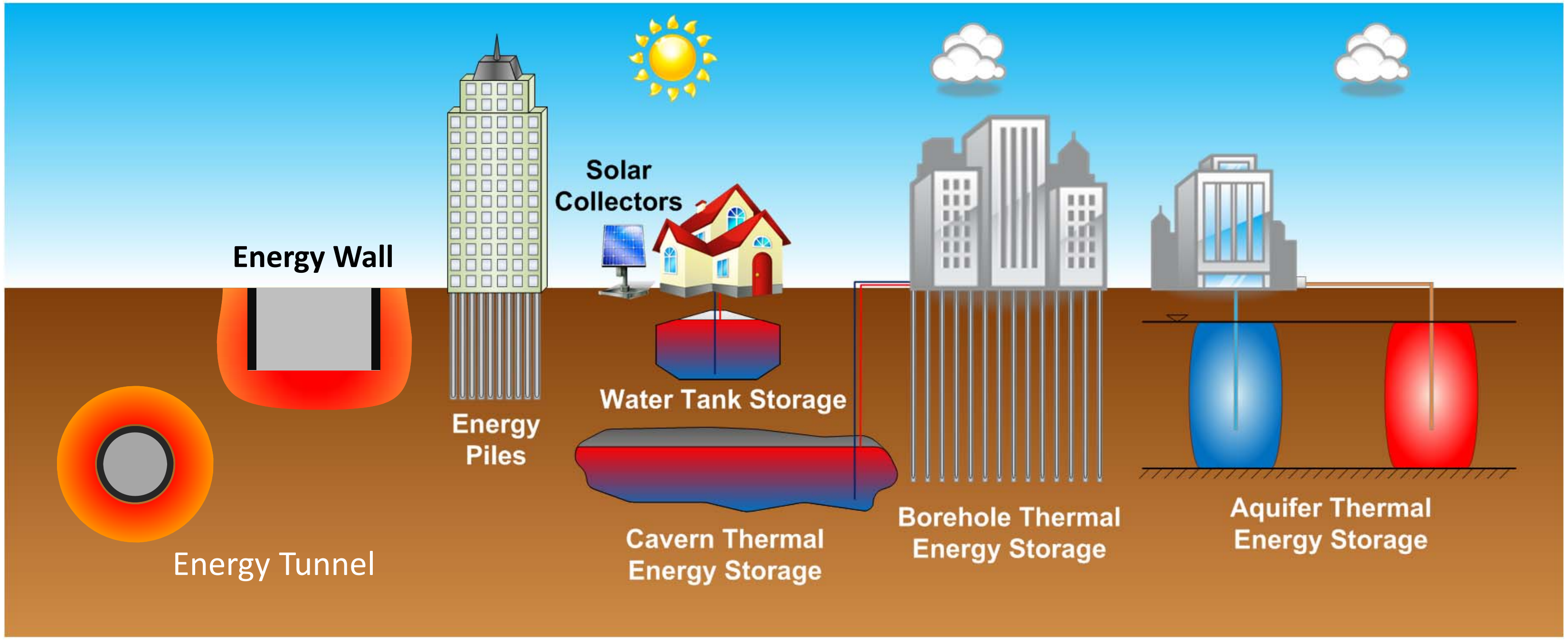


figure courtesy of Tolga Ozudogru

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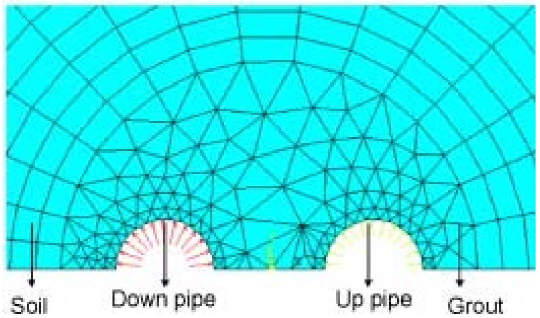

Introduction

- Shallow storage of thermal energy in the ground
- With (or without) a heat pump
- Available energy:
  - How much?
  - What are the related temperature changes?
- Impact on geo-structure:
  - Stress changes?
  - Deformations?
  - Changes in available load capacity?

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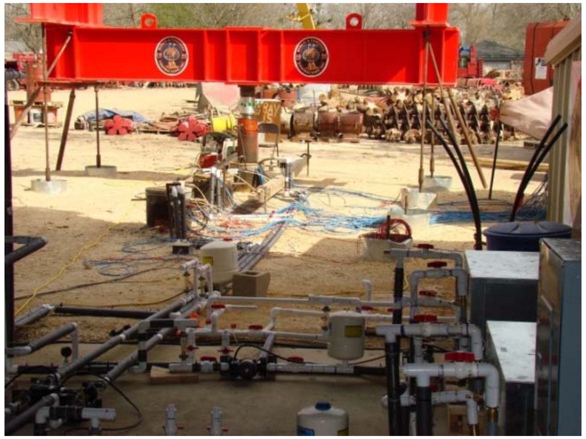
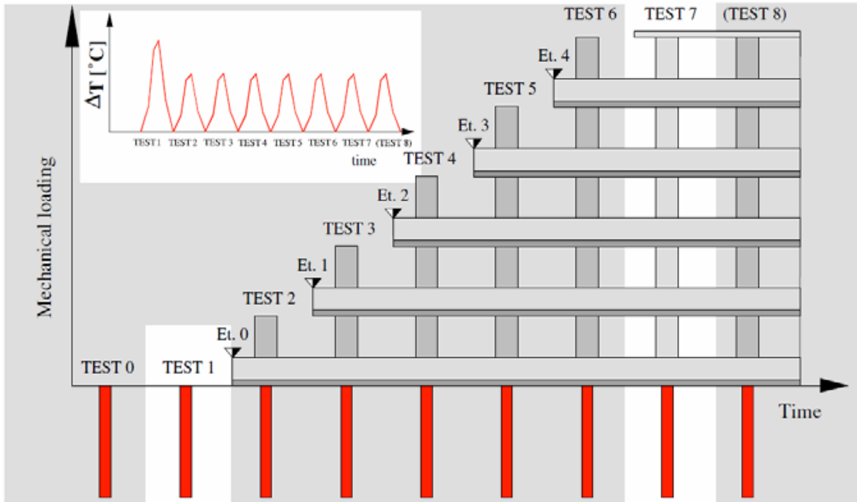
Experimental Studies - Piles

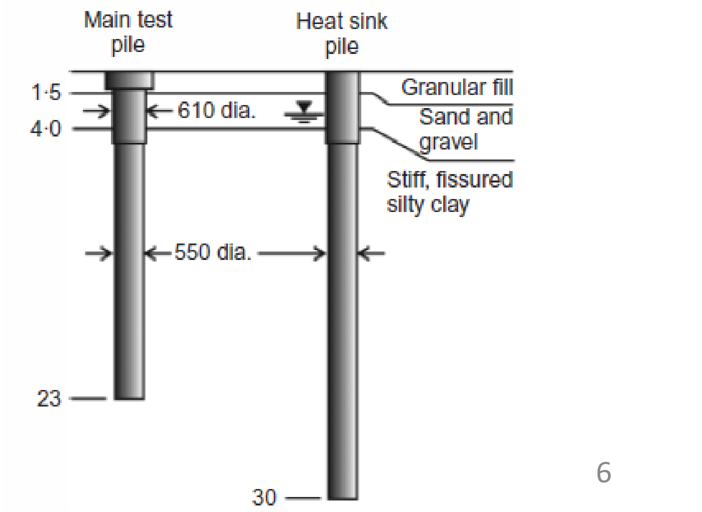
- Thermo-Mechanical Tests
  - Full-Scale Field Tests
  - Model Tests
- Thermal Response Tests



Full-Scale Field Tests

- EPFL Test, Switzerland
  - Laloui et al., 2006
  - Under building load
  - Thermal cycles after each floor completion
  - Restrained at pile toe due to sandstone
- Lambeth College, UK
  - Bourne-Webb et al., 2009
  - London Clay, semi-floating
  - Test Pile: Thermal cycles with load on top
  - Heat Sink Pile: No structural load on top



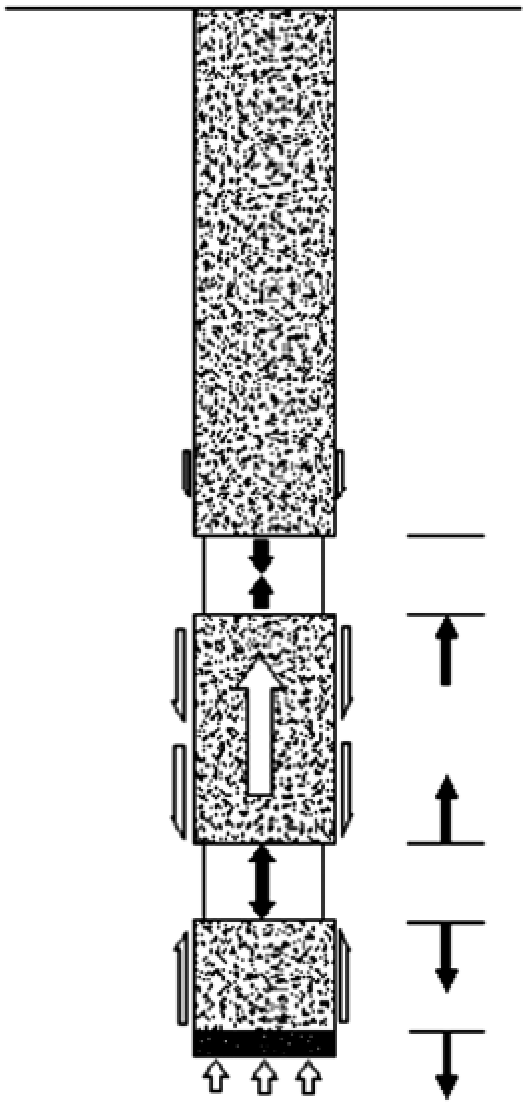


Full-Scale Field Tests

- Virginia Tech, Blacksburg, VA, U.S.
  - Olgun et al., 2012
  - Temperature cycles on end-bearing energy pile
- University of Colorado Boulder, U.S.
  - McCartney and Murphy, 2012
  - Long-term monitoring of energy piles (Denver, Colorado)
- Texas A&M University, U.S.
  - Akrouch et al., 2014
  - Effect of temperature on the creep rate of energy piles

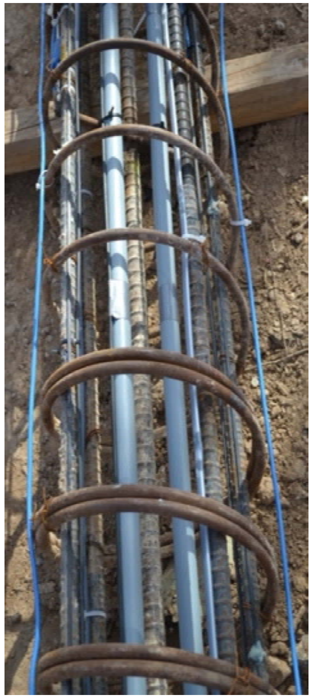
Full-Scale Field Tests

- University of Melbourne, Australia
  - Colls, 2013
  - Factors affecting energy pile efficiency
- Monash University, Australia
  - Wang et al., 2015
  - Impact of thermo-mechanical loads on the shaft capacity
  - Load cycles with Osterberg-Cell

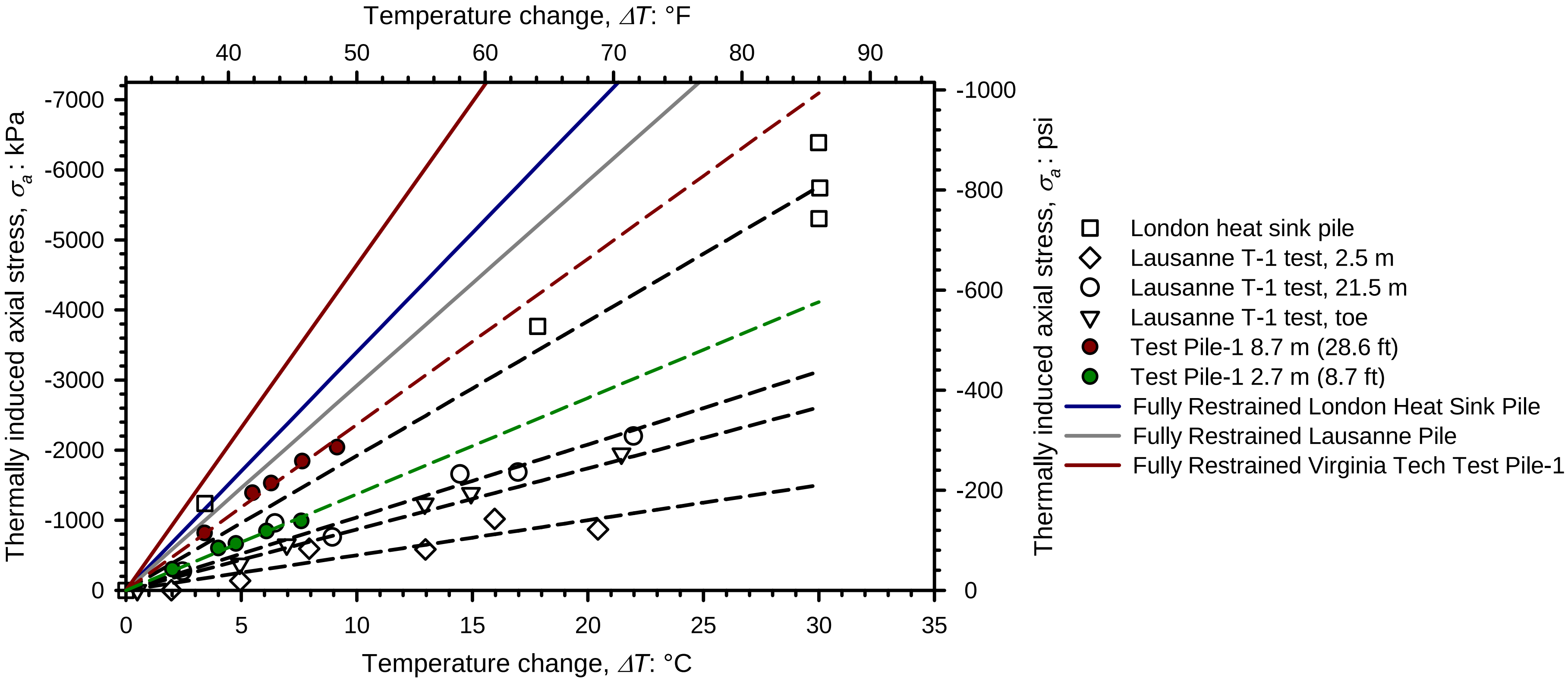


Full-Scale Field Tests

- Virginia Tech/EPFL/Cambridge – Houston, TX, U.S.
  - Sutman et al., 2014
  - Effect of end-restraint conditions on energy pile behaviour
  - 2 test piles with end-bearing in dense sand layer
  - 1 test pile semi-floating in clay layer
  - Thermal cycles applied with/without mechanical load on top



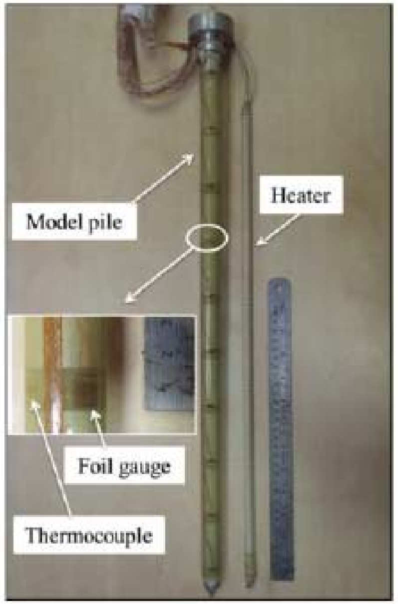
Full-Scale Field Tests



Redrawn after Amatya et al., 2012, field test results from Sutman et al., 2014 are added.

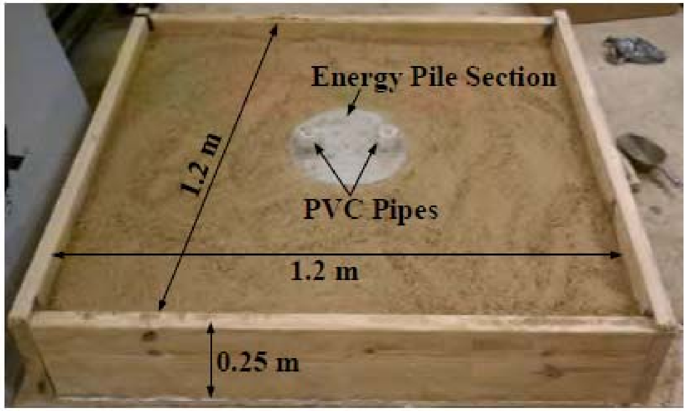
Model Tests

- University of Colorado, Boulder, U.S.
  - McCartney and Rosenberg, 2011
  - Centrifuge testing on scale-model energy piles
- Hong Kong University
  - Ng et al., 2014
  - Centrifuge tests on energy piles in sand and clay
- Ecole des Ponts ParisTech, France
  - Kalantidou et al., 2012
  - Temperature cycles on model-scale piles

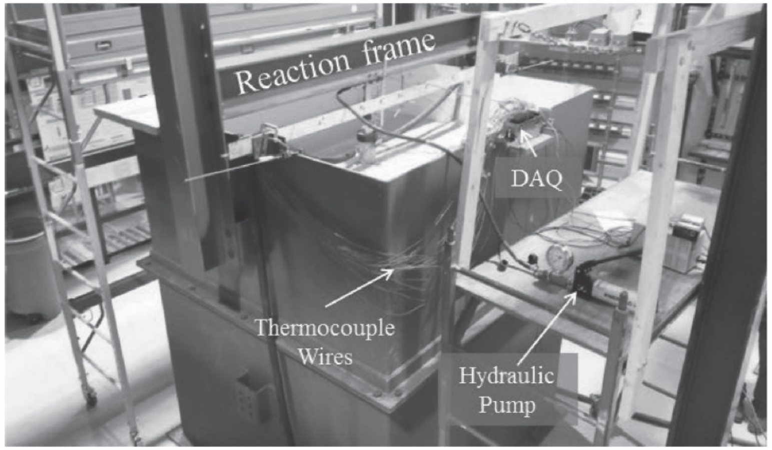


Model Tests

- Texas A&M University, U.S.
  - Akrouch et al., 2015
  - Effect of unsaturated soil conditions on energy pile efficiency



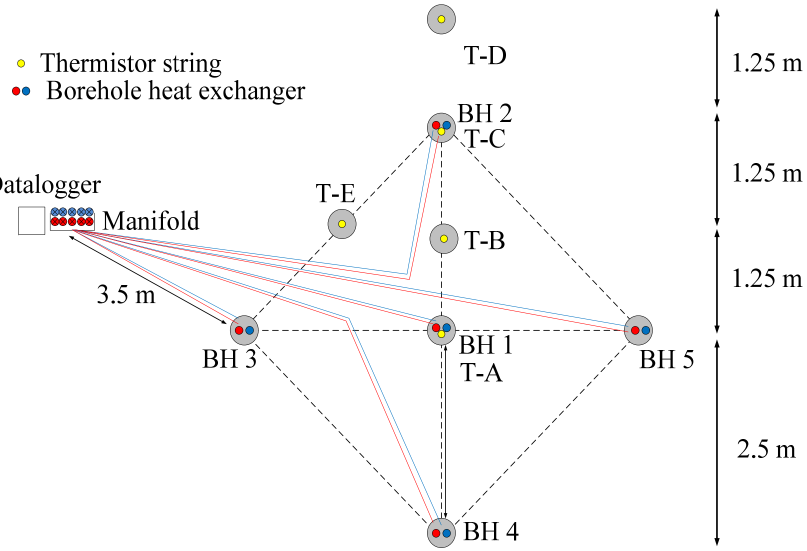
- Pennsylvania State University, U.S.
  - Kramer and Basu, 2014
  - Model pile in sand bed subject to thermal cycles and mechanical loading



Thermal Response Tests

- Oklahoma State University, U.S.
  - Beier et al., 2011
  - Laboratory thermal response tests on boreholes
- Berkel, Houston, U.S.
  - Brettmann and Amis, 2011
  - Thermal conductivity tests on 3 CFA piles
- Virginia Tech, Blacksburg, VA, U.S.
  - Olgun et al., 2012
  - Thermal conductivity test on energy piles

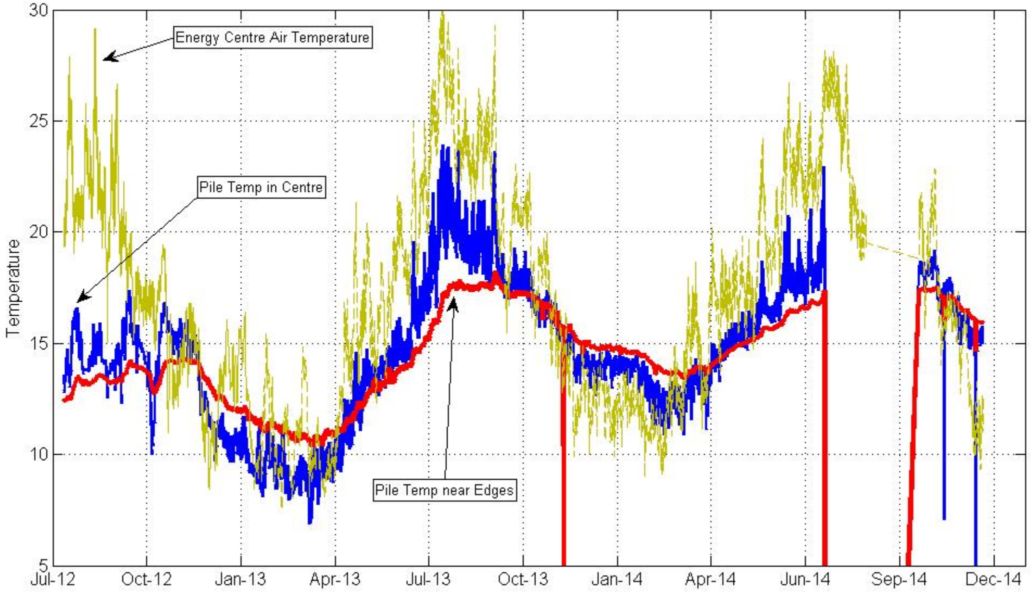
Thermal Response Tests



- KAIST, South Korea
  - Park et al., 2012
  - Indoor thermal response tests on piles in dry sand
- University of Colorado, Boulder, U.S.
  - Baser and McCartney, 2015
  - Soil-borehole thermal energy storage system
  - Long-term thermal response test on the system

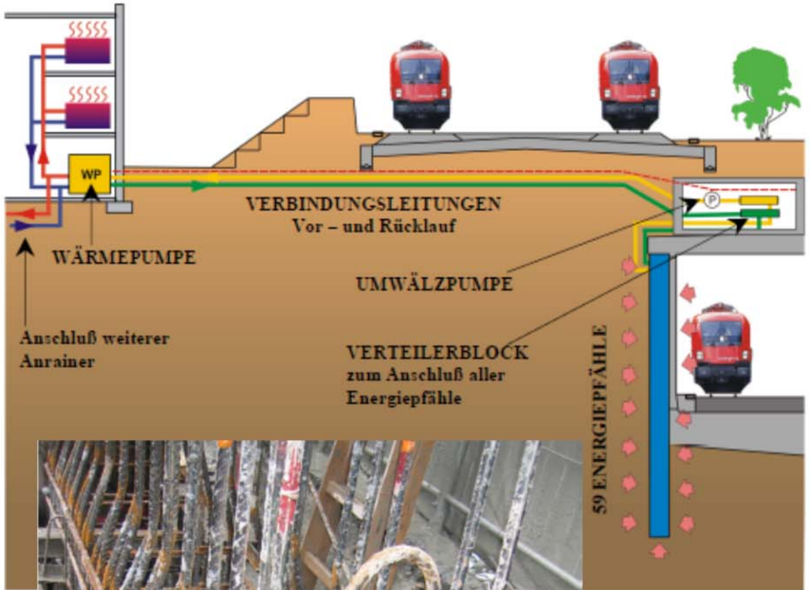
Thermal Response Tests

- University of Southampton, UK
  - Loveridge et al., 2014 (Thermal response test on small diameter piles)
  - Loveridge and Powrie, 2013 (Long-term in-situ monitoring of pile heat exchangers)



Experimental Studies - Walls

- Lainzer Tunnel (Markiewicz, 2004) bored pile wall
  - Monitoring temperature and stress-strain response
  - Viable for heating adjoining school
- U2 metro line D-walls (Markiewicz, 2004)
  - Monitoring installed, but outcomes not widely available

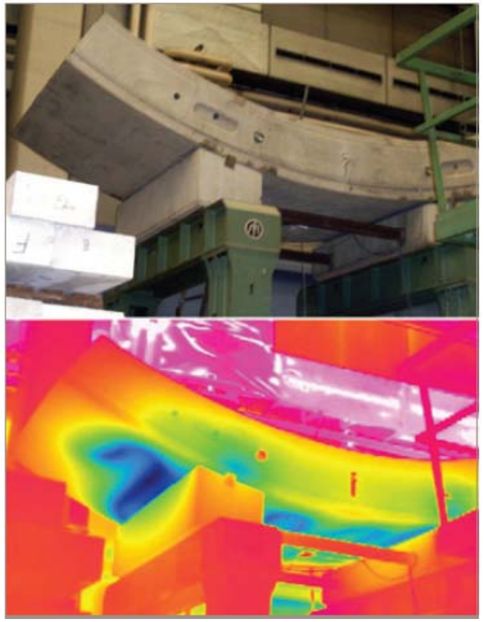


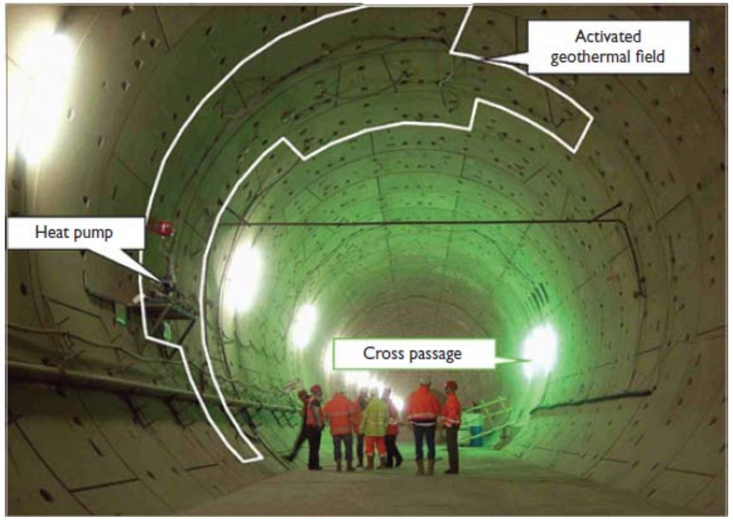
Experimental Studies - Tunnels

- Katzenbergtunnel High-Speed Rail Tunnel, Germany

4-Phase Field Test:

- Background temperature reading
- Thermal response test (heat charged into the ground through constant heat flux)
- Thermal relaxation of system (no heat flux imposed
- Operation of heat pump (heat extracted from the ground)





Thermal Analysis Approaches – Piles

- Thermal analysis approach:
  - Ground temperature response: at pile edge
  - Temperature change across pile: assumed steady
- Thermal analysis considerations
  - Heat transfer mechanisms: conduction & convection
  - Surface boundary condition
  - Infinite vs finite length
  - Interactions & superposition

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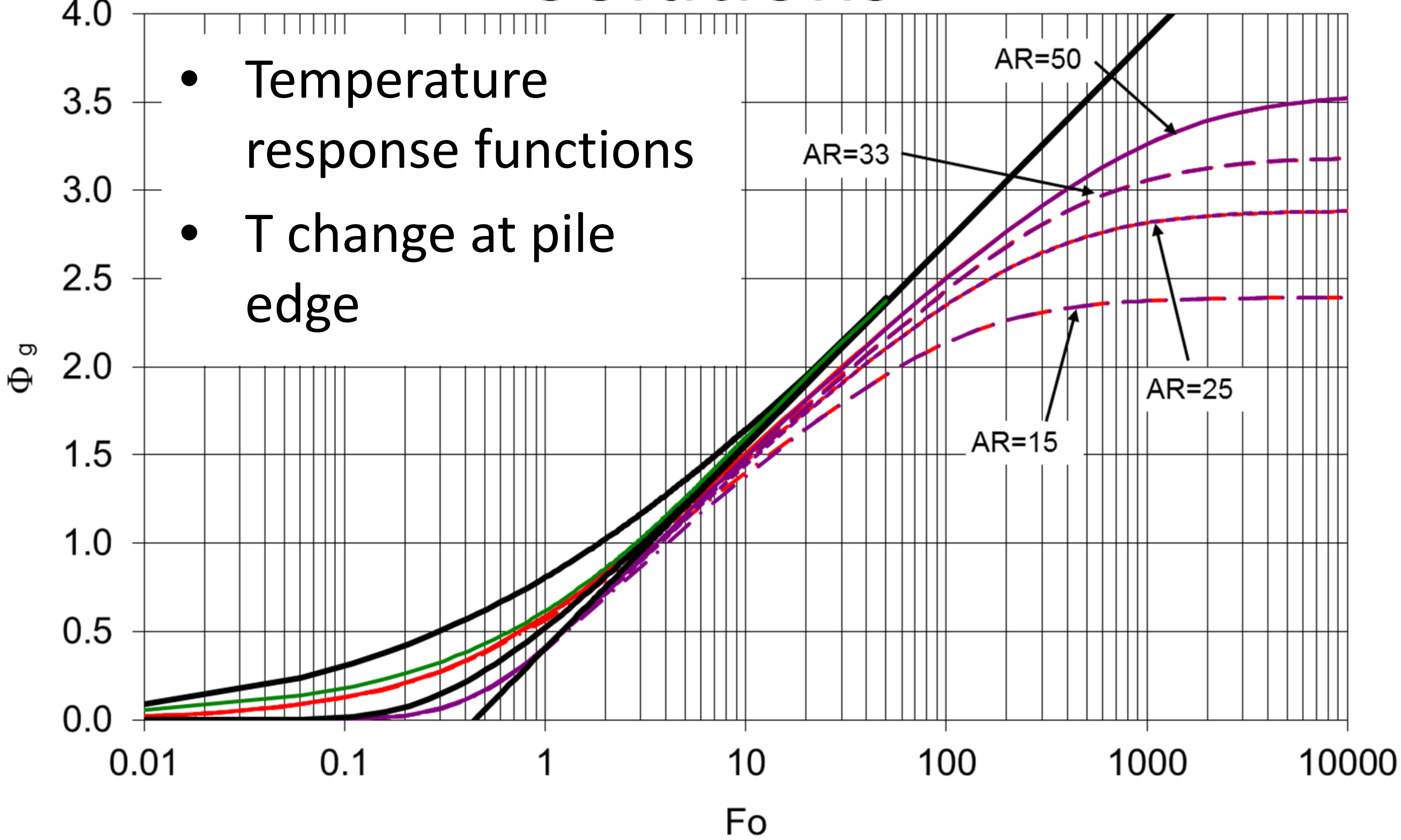
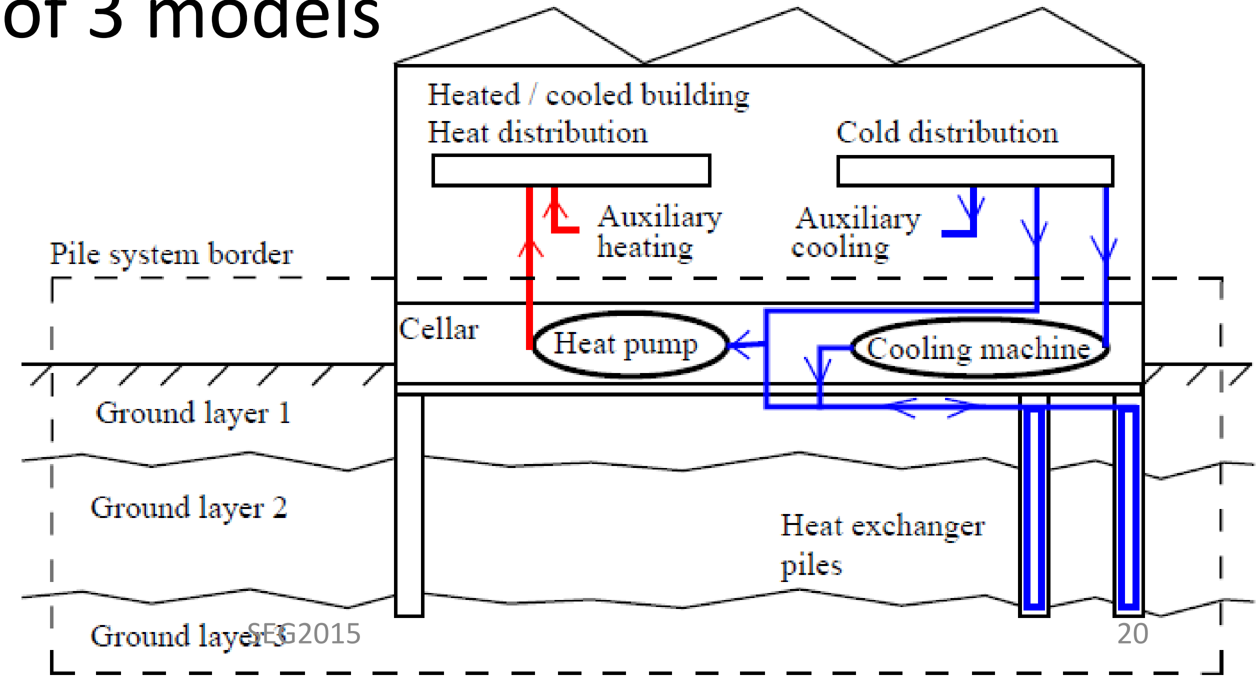
Classical Heat Source Analytical Solutions

- Temperature response functions
- T change at pile edge



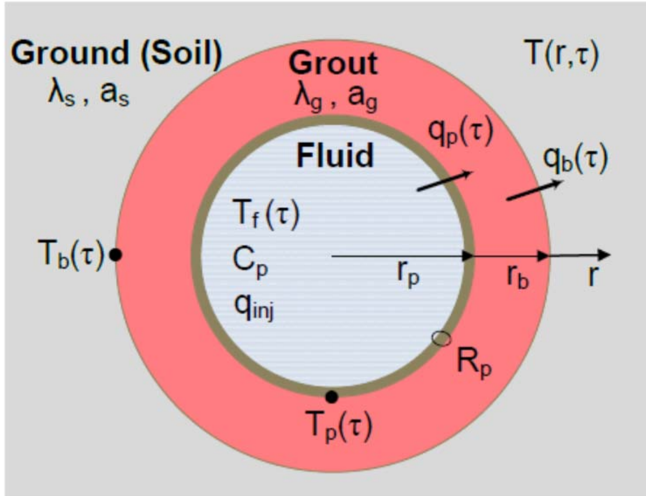
PILESIM (Pahud, 2007)

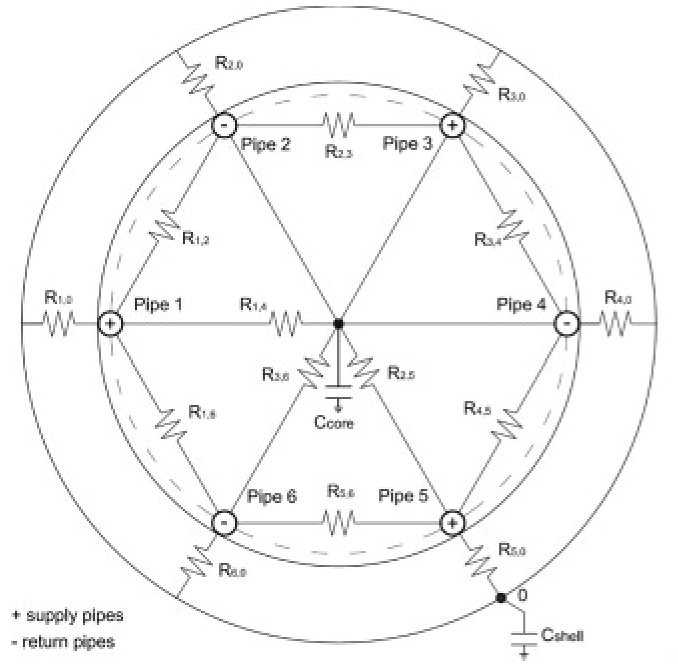
- System design tool, including heat pump
- Validated against data from Zurich Airport
- Superposition of 3 models
  - Transfer between storage and surrounding ground
  - Pile to storage volume transfer
  - Steady flux between fluid and pile edge



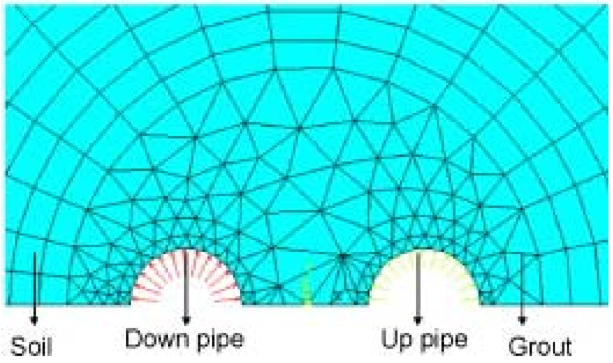
Alternatives to the Steady State Assumption

- Javed & Claesson (2011) analytical two material radial borehole model
- Composite medium line source theory (Li & Lai, 2011)
- CaRM electrical analogy model, with circuit of resistances and capacitances (Zarella et al., 2013)
- Transient temperature response functions (Loveridge & Powrie, 2014)

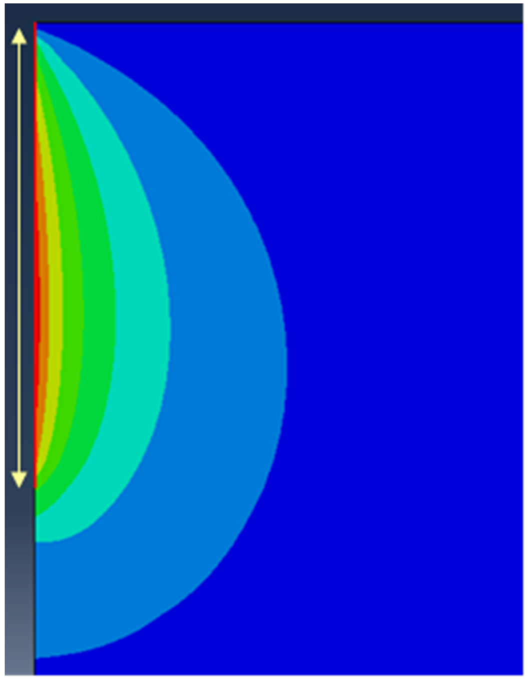




2D Numerical Simulation of Pile Thermal Behaviour



- 2D slice models
  - Loveridge & Powrie (2013)
  - Validated to ±6% in boreholes by Cui et al (2008)
- 2D radial symmetric models
  - Annular model of Ghasemi-Fare & Basu (2013)
  - Superposition Borehole Model (SBM) of Eskilson (1987) & similar approach of Loveridge & Powrie (2013)



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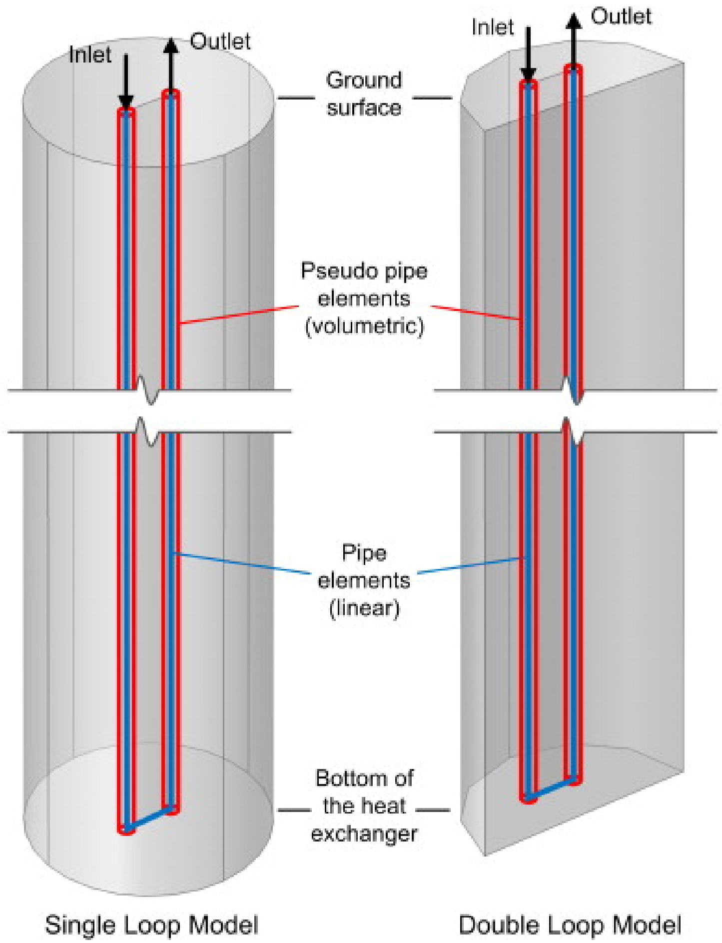
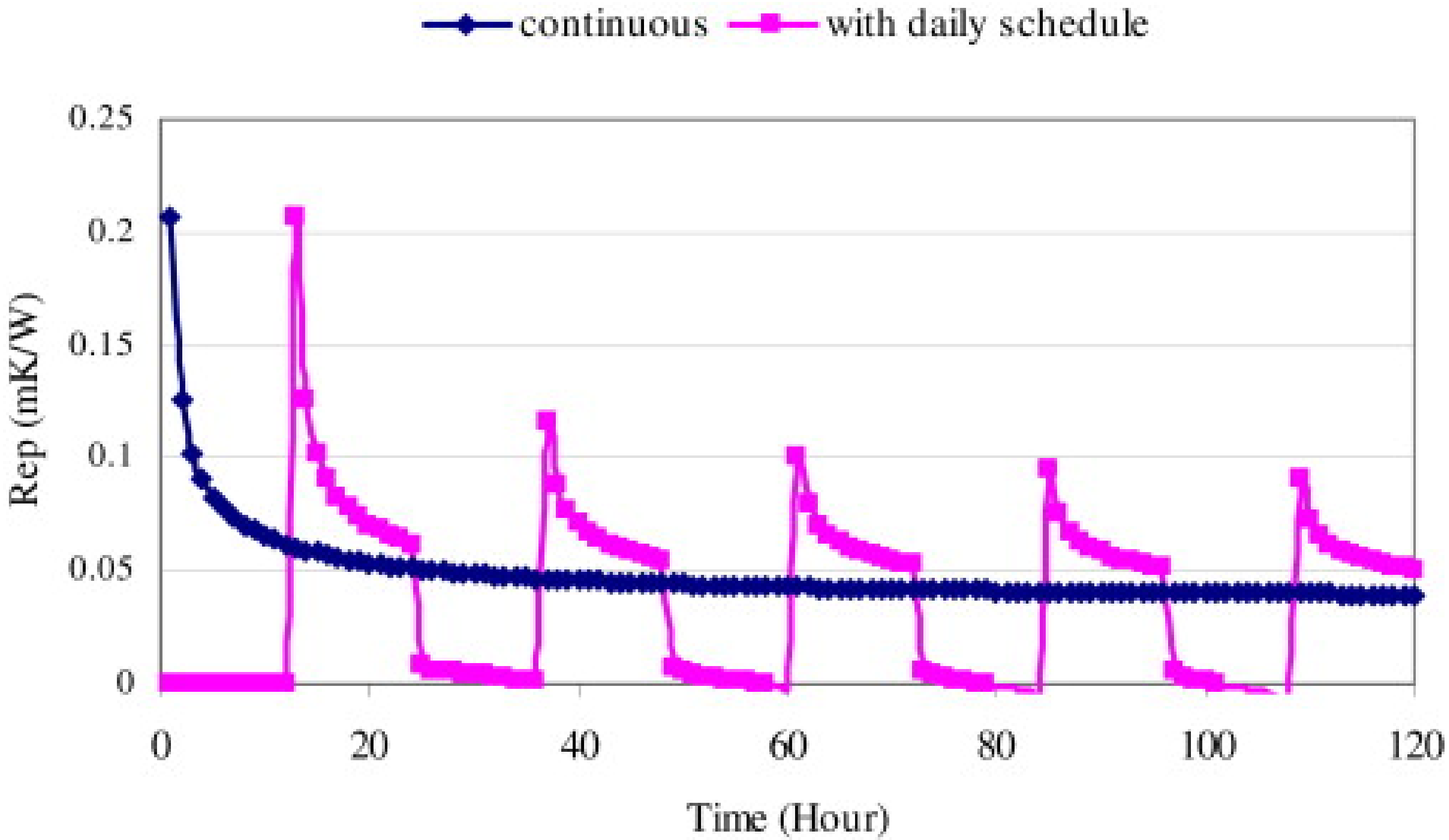
3D Numerical Simulation of Pile Thermal Behaviour

- Special pipe elements
  - Choi et al., 2011; Ozudogru et al., 2014; Cecinato & Loveridge, 2015
- Heat exchanger elements
  - Accurate to 1^{o}C, Al-Khoury & Bonnier, 2006
- Full numerical simulation
  - e.g in COMSOL, Bidarmaghz, 2014



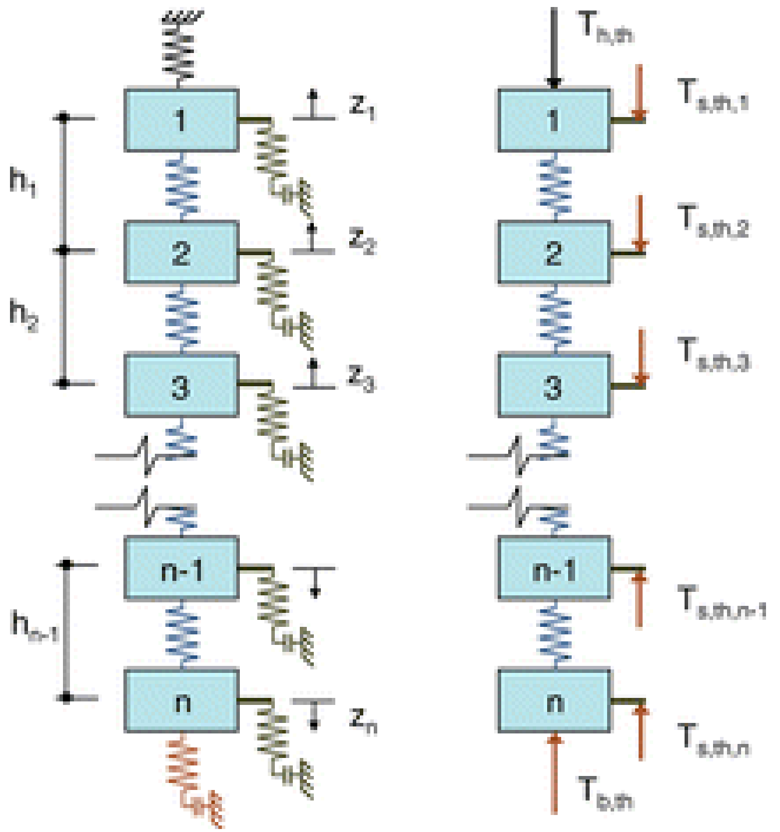
Example 3D Results



Transient nature of pile concrete, e.g., Lee & Lam, 2013

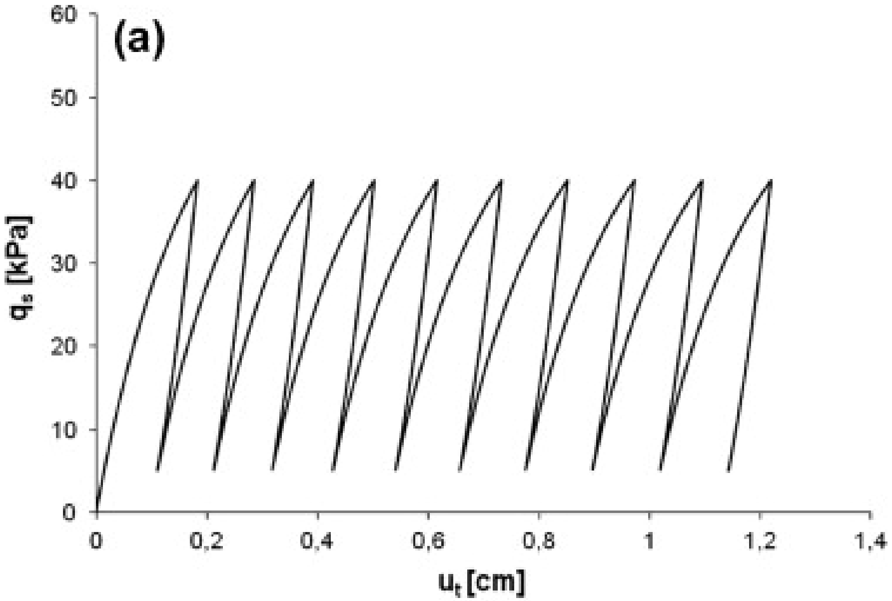
Load Transfer Methods for Thermo-Mechanical Response of Piles

- Based on adapting t-z curves to describe:
  - Mobilised shaft friction & base resistance
  - May include spring for building or ground restraint
- Knellwolf et al., 2011, calibrated against field tests
- McCartney & Rosenberg, 2011, against centrifuge



Load Transfer Methods for Thermo-Mechanical Response of Piles

- Suryatriyastuti et al., 2014, added cyclic degradation of pile interface
- But all assume:
  - Uniform pile temperature
  - Inert ground not changing volume



Example strain ratcheting

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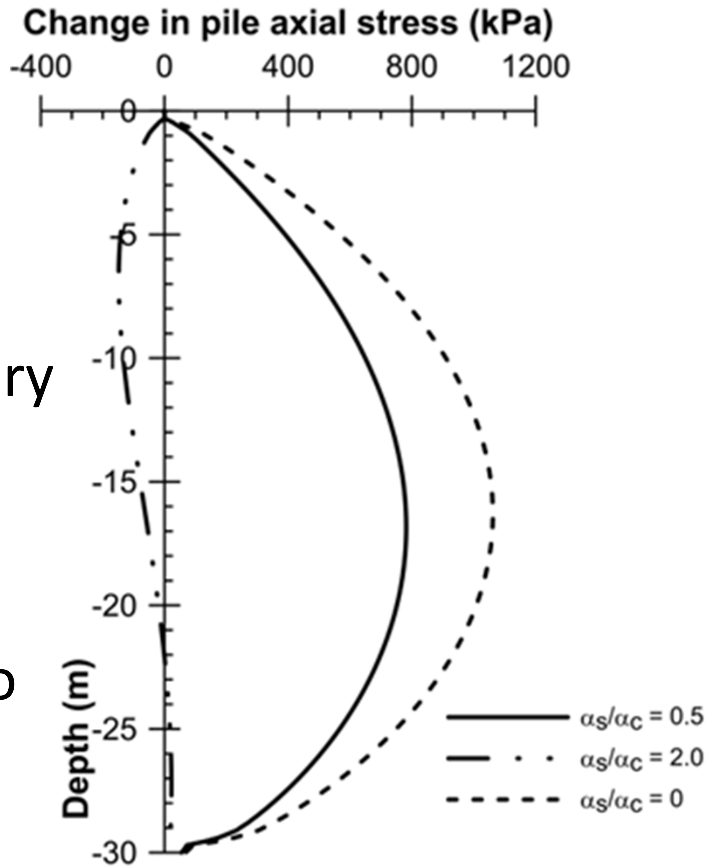
2D Pile Thermo-Mechanical Simulations

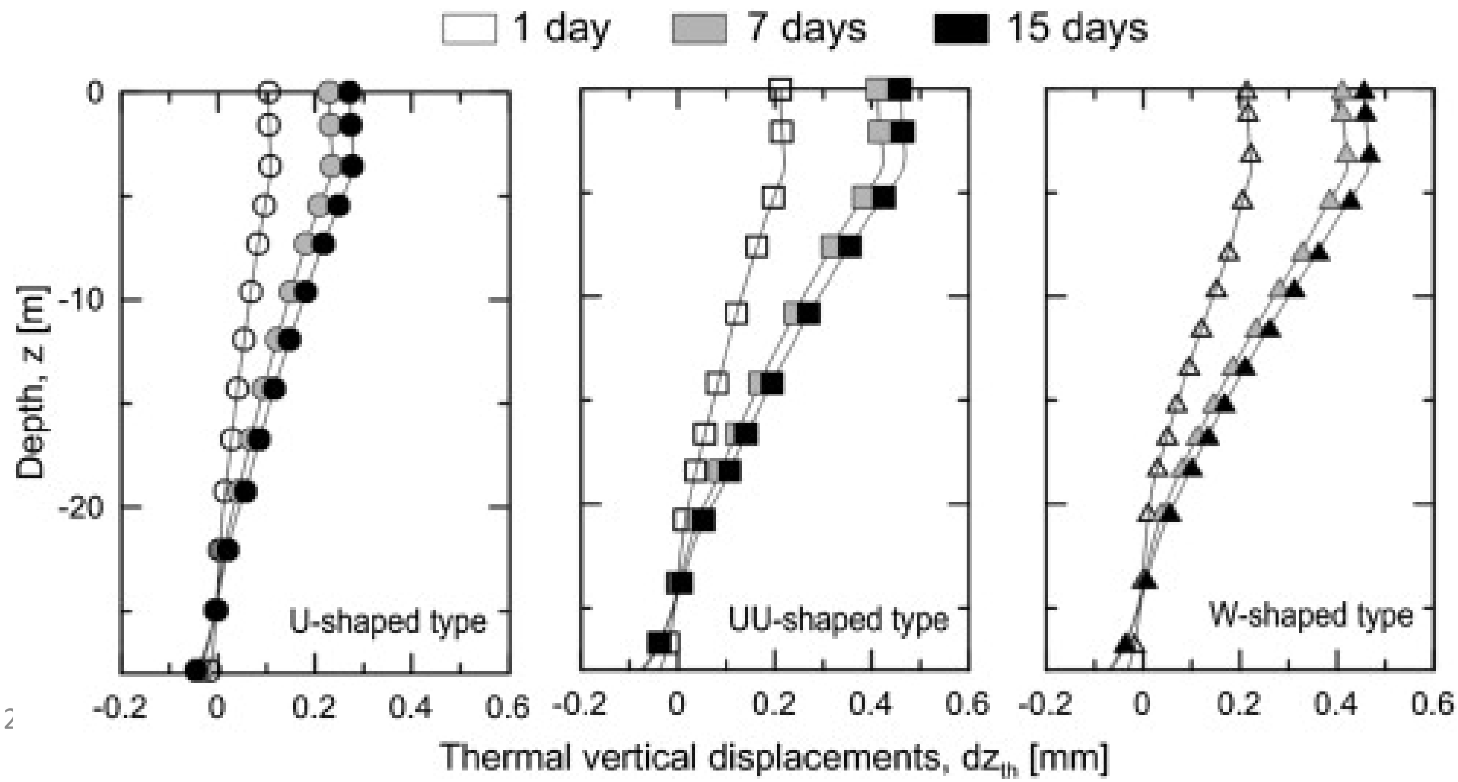
- 2D axisymmetric models:
  - Simplified pile temperature boundary
- Laloui et al., 2006 & Ma et al., 2011:
  - Thermo-elastic, qualitative match to field data
- Bodas-Freitas et al., 2013:
  - Examined ratio of CTE, with implications for load transfer method



In heating for different CTE ratios

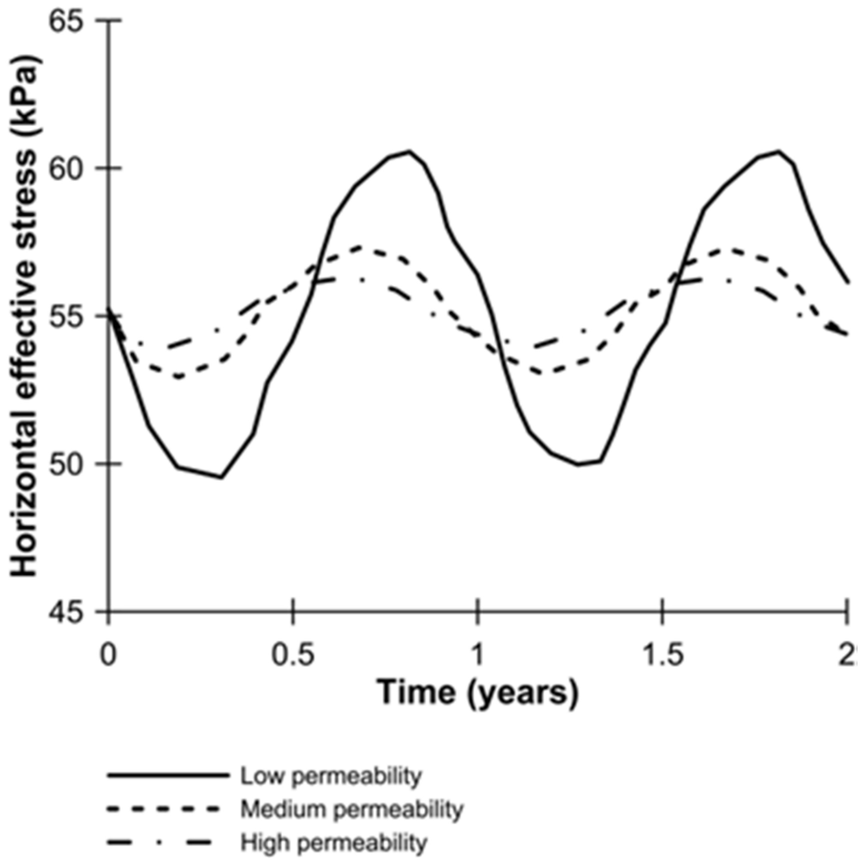
3D Pile Thermo-Mechanical Simulations

Batini et al., 2015 have begun to examine the effect of the thermal design on the thermo-mechanical response



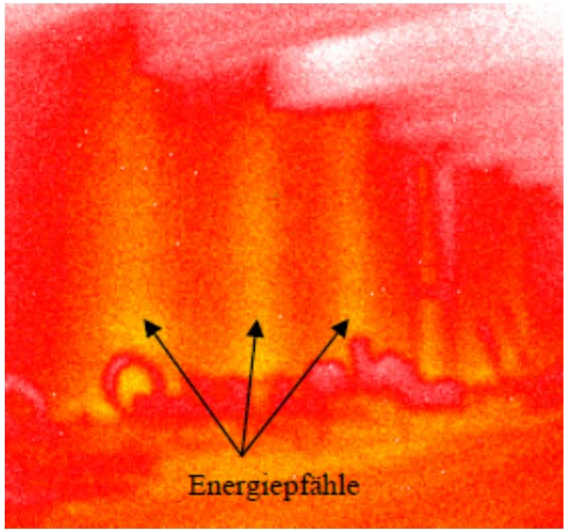
Pile Group Thermo-Mechanical Simulations

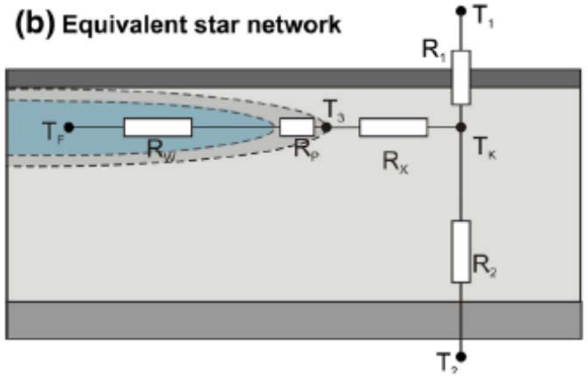
- 2D model of regular pile group (Dupray et al., 2014)
- Response depends on which piles are heated (non heated piles provide restraint)
- Changes in effective stress related to permeability



Thermally Active Retaining Walls

- 4 notable case studies:
  - Lainzer tunnel (Brandl, 2006)
  - Keble College (Suckling & Smith, 2002)
  - Vienna U2 Metro (Adam, 2008)
  - Bulgari Hotel, London (Amis et al., 2010)
- Recent resistance based thermal design methods by Sun et al. (2013) & Kurten et al. (2015)
  - verified against limited field data and full numerical simulation, respectively





Numerical Simulation of Walls

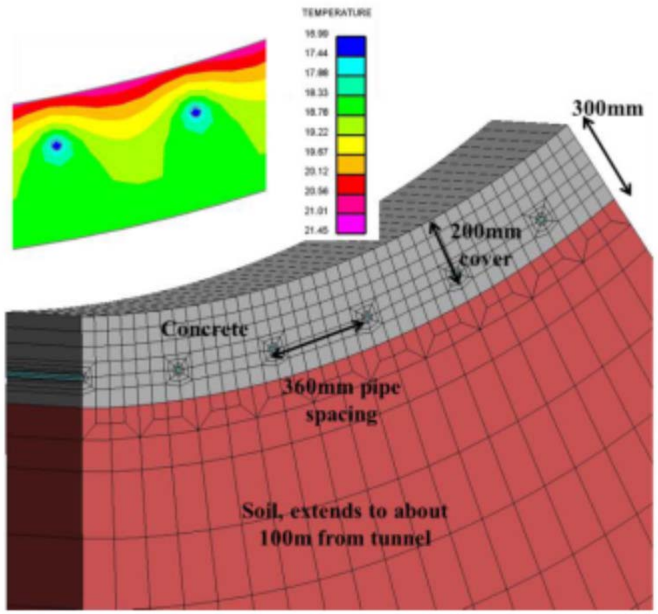
- Station box D walls: Soga et al. (2014):
  - 3D model for thermal analysis: heat mainly comes from inside the station box
  - 2D model for THM response: very small wall movements predicted
- 2D plane strains for shallow cut & cover structure: Bourne-Webb et al. (2015)
  - Tunnel side dominated heat flow >> boundary condition very important
  - Negligible impact of thermo-mechanical response

Geothermal Tunnels

- Notable trials in Austria:
  - Lainzer tunnel (Adam & Markiewicz, 2009)
  - Jenbach Tunnel (Franzius & Pralle, 2011)
- Operational case in U2 Vienna (Unterberger et al, 2014)
- Very limited use of analytical solutions, e.g. Schlosser et al., 2007 – thermal resistance model

Numerical Simulation of Tunnels

- Franzius & Pralle, 2011, used 1D axisymmetric model for thermal analysis
- Thermal & thermo-mechanical analysis was carried out by Arup (Nicholson et al., 2013)
  - 7% increase in hoop stress
- Key assumption is tunnel internal boundary conditions



Design Guidance

- VDI 4640
  - No detailed information for energy geo-structures
- SIA D0190
  - Guidance for thermal piles, especially thermal capacity and construction. No details for other structures
- GSHPA Thermal Pile Standard
  - A best practice guide, also considering construction processes. Design guidance limited.

Research Needs 1

- Consideration of laterally loaded piles & pile groups
- Analysis and design approaches for walls, tunnels and other structures
  - Internal boundary conditions
- Development and validation of design tools
  - Long term validation datasets
  - Integration with building physics software

Research Needs 2

- Investigation of cyclic effects
- Reducing capital costs and increasing energy efficiency
- Long term sustainability and potential for long term interactions in cities
- Guidance for analysis and design of all geo-structures

Acknowledgements

- Peter Bourne-Webb, Sebastien Burlon, Sylvia Kuerten, Saqib Javed
- Melis Sutman