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

Task Force 3 Position Paper
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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?
Experimental Studies - Piles

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

- **EPFL Test, Switzerland**
  - Lalouï 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
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)
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°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
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
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
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