Energy and geotechnical performance of energy piles for different design solutions

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Outline

- Concept, technology and challenges
- Energy and geotechnical performance of energy piles
- Concluding remarks

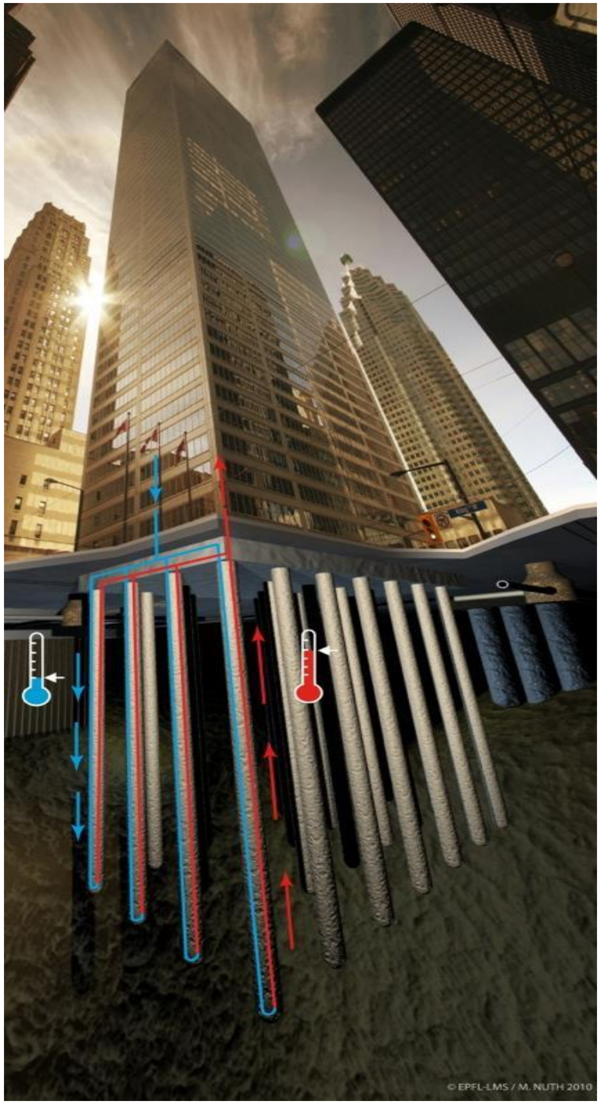
Energy geostructures: an innovative technology

Environmentally friendly technology

- A solution for the heating and cooling of buildings
- An innovative technology for the environment protection (reduction of CO2 emissions)
- A local source of renewable energy (heat naturally present in the ground)

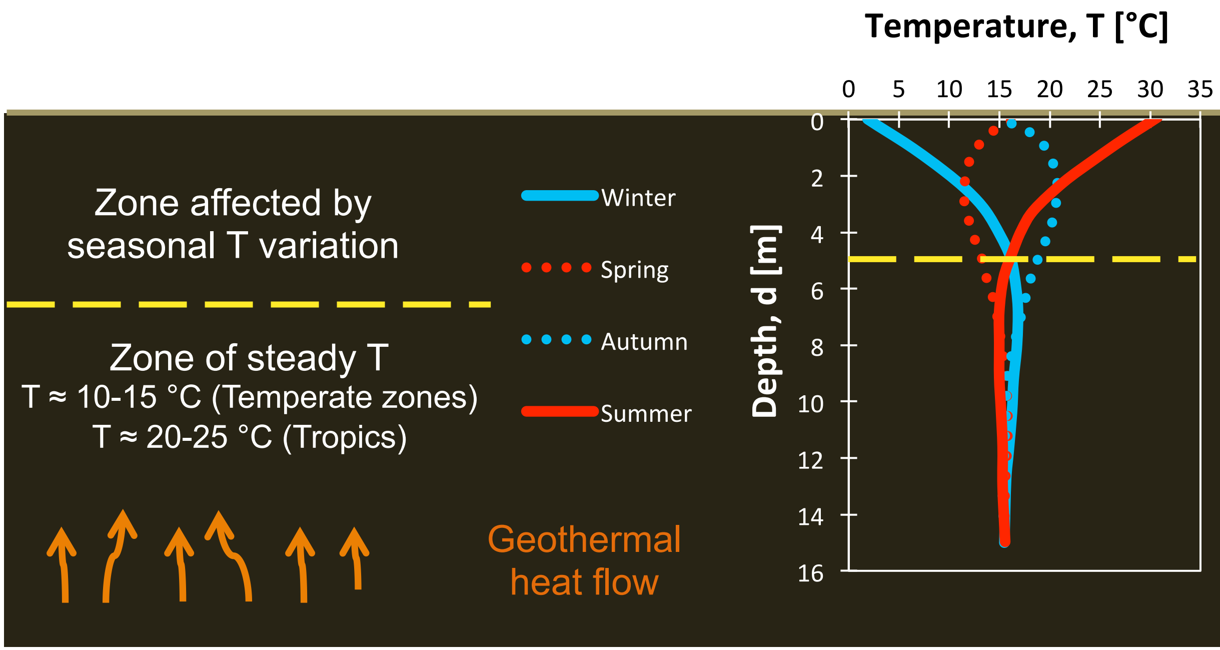
Cost effective technology

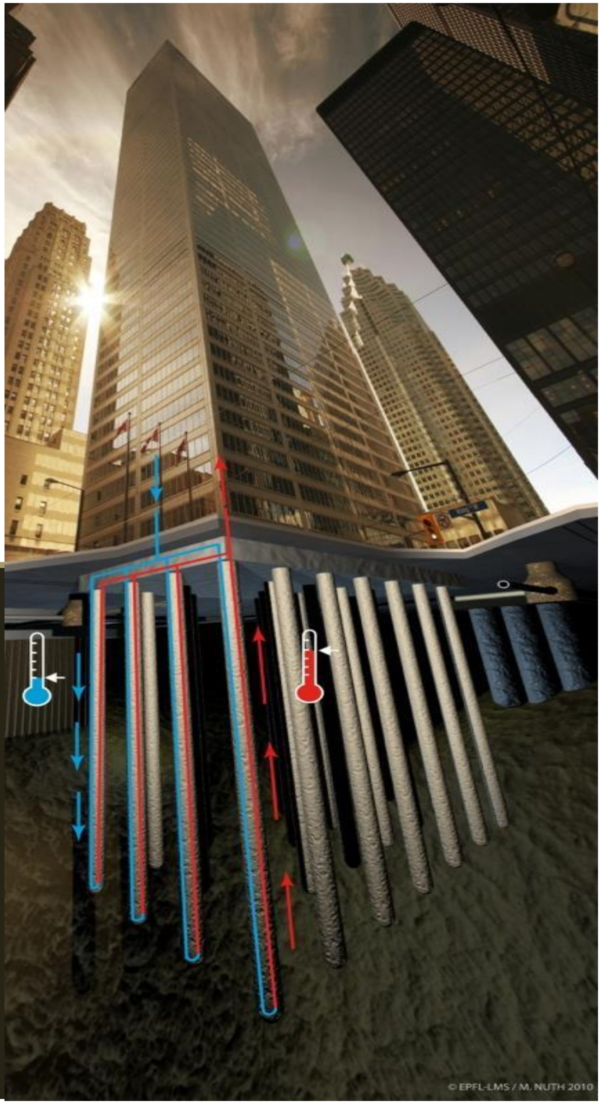
- Minor additional energy supply
- Minor modifications in the foundation design
- Minor additional installation costs



Principle of energy geostructures

Geothermal energy
at shallow depth (< 100 m)





Energy piles: the technology

Concept

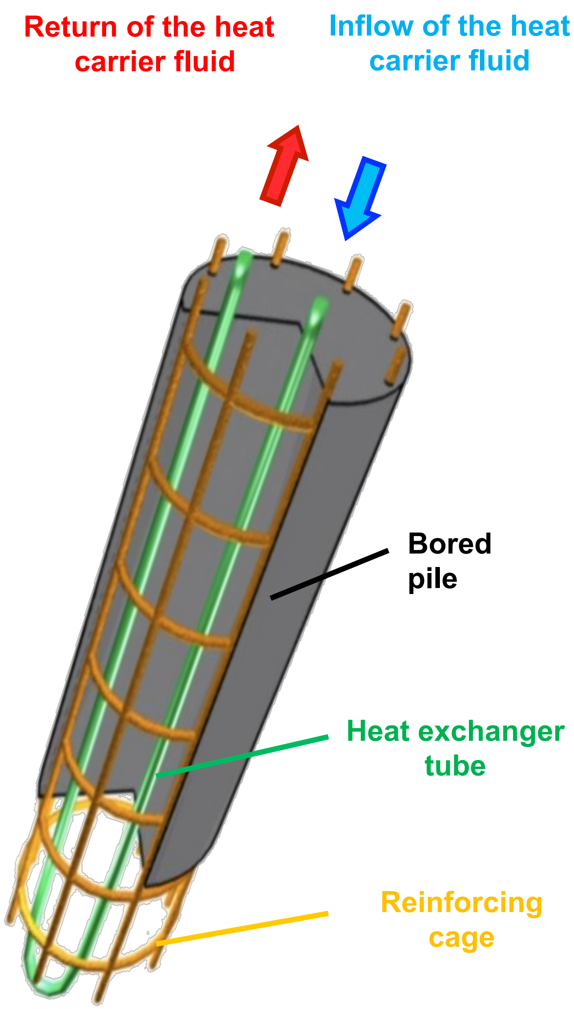
- Use the ground as heat exchanger and storage medium
- Couple the structural role of foundation piles with the one of geothermal cooling/heating elements

Technology

- Pipes mounted along the reinforcing cage
- Heat carrier fluid circulating inside the pipes

Possible applications

- Only heat extraction with heat pump (40-60 W/m; T_{EP} = 2-15 °C)
- Heat extraction and injection
  - Free cooling (20-40 W/m; T_{EP} = 10-16 °C)
  - Reversed heat pump (50-100 W/m; T_{EP} = 25-35 °C)
- Coupling with solar panels (100-150 W/m; T_{EP} = 35-50 °C)



Energy piles: the technology

Construction of energy piles at the EPFL, 2011

Development

UK – London – The One New Change

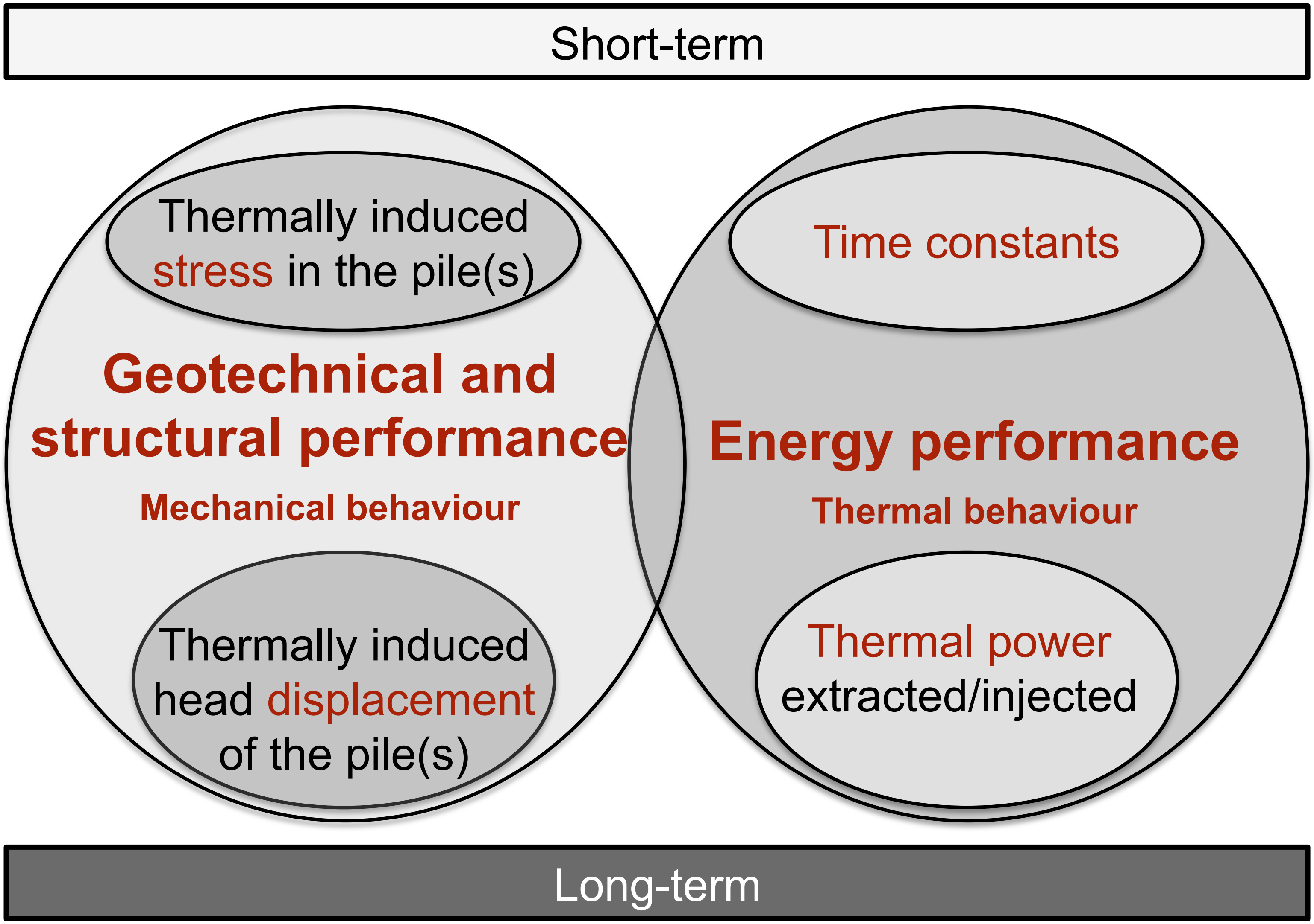
Switzerland – Zürich
The Dock Mielfield Zürich Airport

Austria - Vienna – The UNIQUA Tower

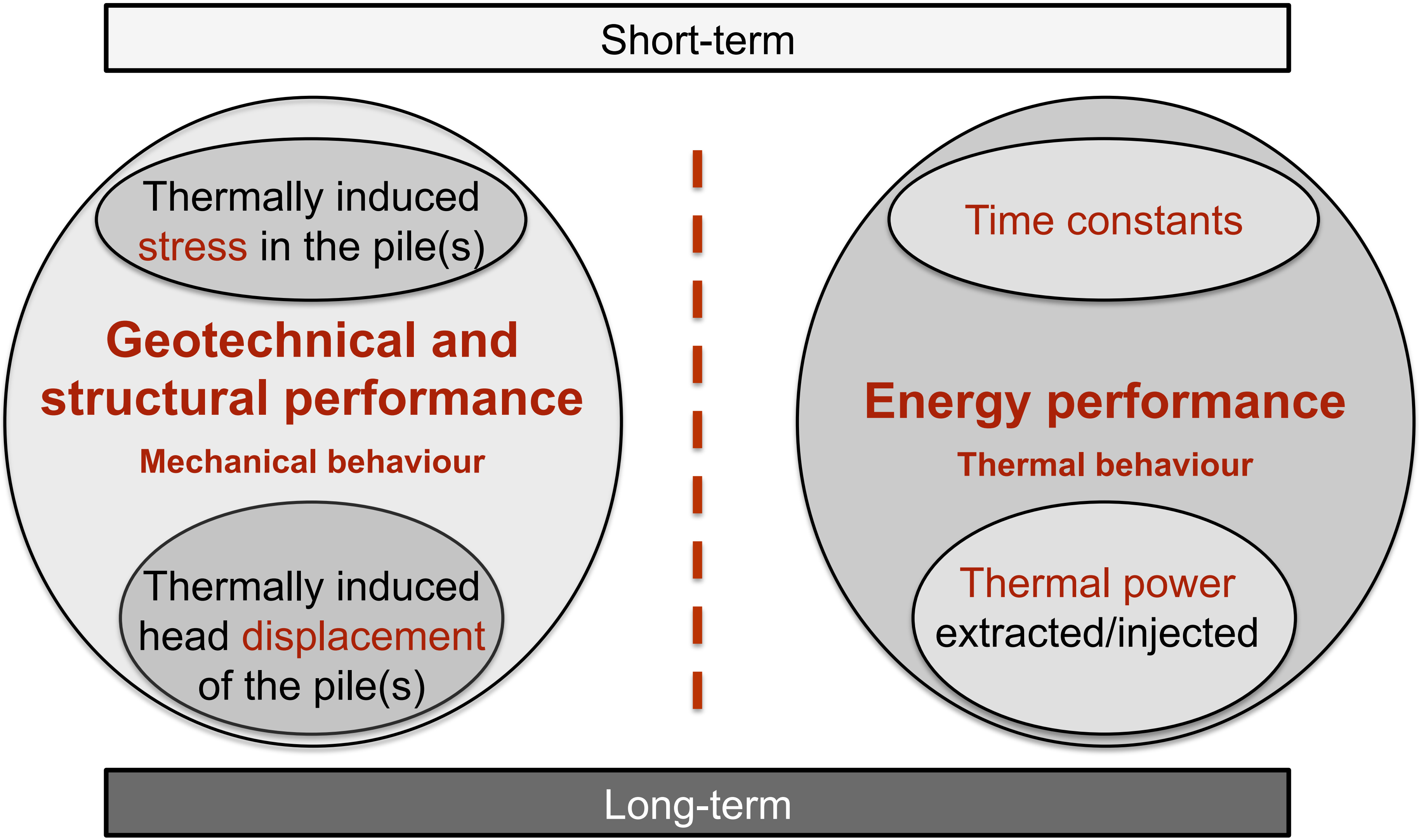
China – Shanghai – The Shanghai World Financial Center

Germany – Frankfurt - The Main Tower

Design considerations



Approach of analysis often observed



Approach of analysis often observed

Short-term

Modelling of mechanical behaviour of *pile-soil system*

Modelling of thermal behaviour of *pipe-pile-soil system*

Long-term

Approach of analysis of this study

Short-term

Modelling of mechanical behaviour of *pile-soil system*

Modelling of thermal behaviour of *pipe-pile-soil system*

Long-term

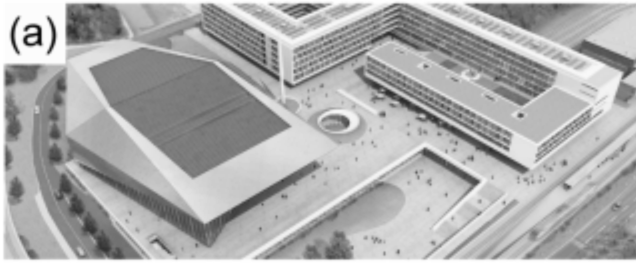
Goal of this study

Investigate the energy and geotechnical performance of energy piles for different design solutions, including

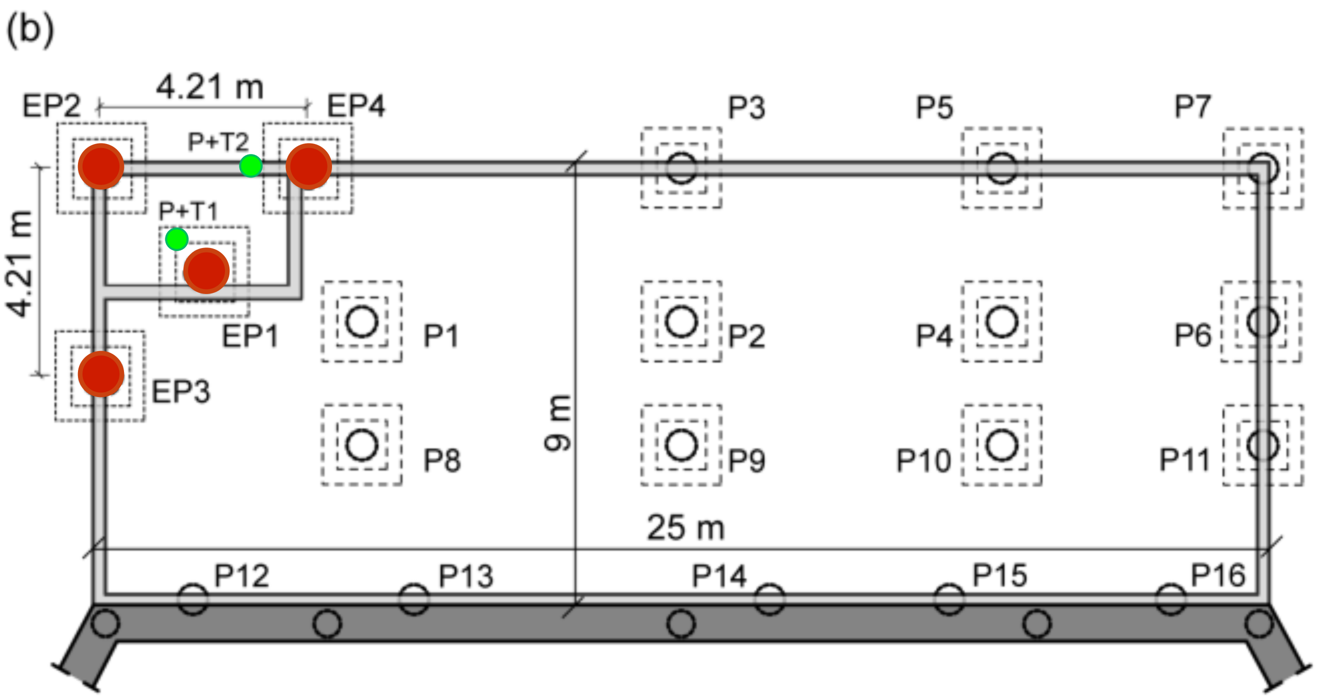
- pipe configurations
- pile aspect ratios
- mass flow rates of fluid circulating in the pipes
- fluid mixture compositions

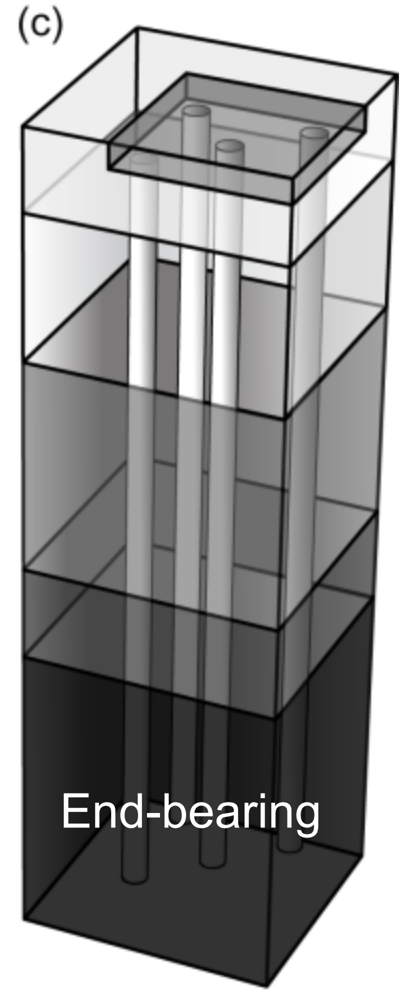
Reference made to a real-scale energy pile at the EPFL

The Swiss Tech Convention Centre energy foundation



- Strain gauges, optical fibers, thermocouples and pressure cells in the energy piles
- Piezometers and thermistors installed in the soil





Alluvial soil - A1 - 3.1 m
Alluvial soil - A2 - 5.5 m
Sandy-gravelly moraine - B - 8.0 m
Bottom moraine - C - 3.5 m
Molasse - D

3-D thermo-mechanical finite element modelling

(Batini et al., 2015)

Boundary conditions

Pinned boundary

Roller boundary

Temperature constraint T_{soil}=13.2°C

Water inflow T_{in}=5°C

Water outflow

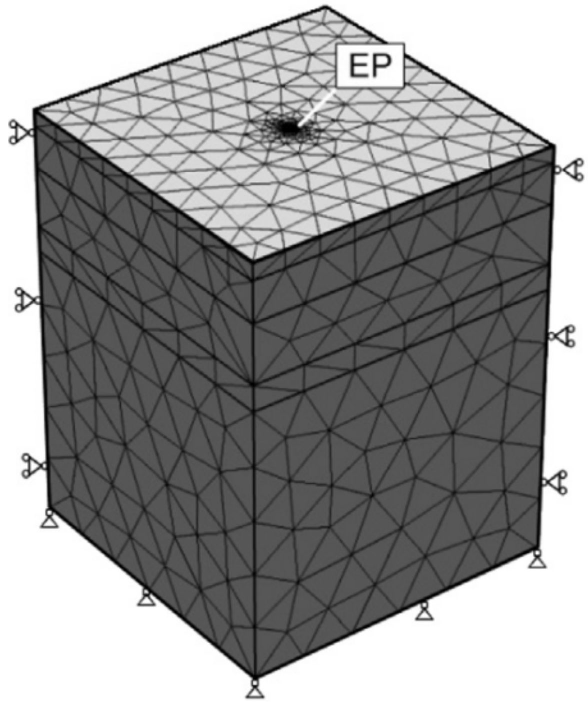
Adiabatic boundary

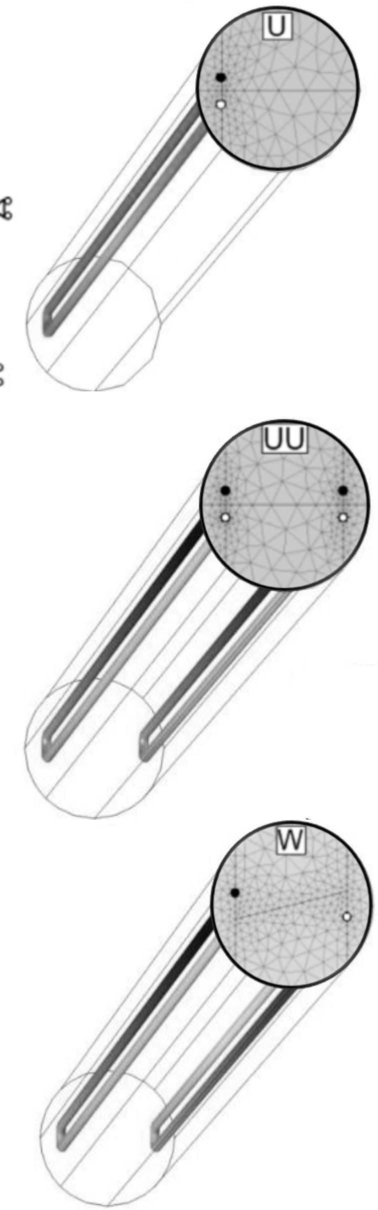
Base case properties

D_{EP} = 0.9 m, H_{EP} = 28 m
Fluid velocity u_f = 0.2 m/s
Pipe diameter ϕ = 32 mm

Heating operation mode (15 days)

Linear thermo-elastic behaviour of pile and soil





- Equilibrium equation and stress-strain relation:

$$\nabla \cdot \sigma_{ij} + \rho g_i = 0 \qquad d\sigma_{ij} = C_{ijkl}\left(d\varepsilon_{kl} + \beta_{s,kl} dT\right)$$

- Energy conservation equations:

$$\rho c \partial_t T - \lambda \nabla^2 T = 0 \qquad \rho_f c_f A_p \partial_t T_{bulk,f} + \rho_f c_f A_p u_{f,i} \nabla \cdot \left(T_{bulk,f}\right) = \nabla \cdot [A_p \lambda_f \nabla\left(T_{bulk,f}\right)] + \dot{q}_p$$

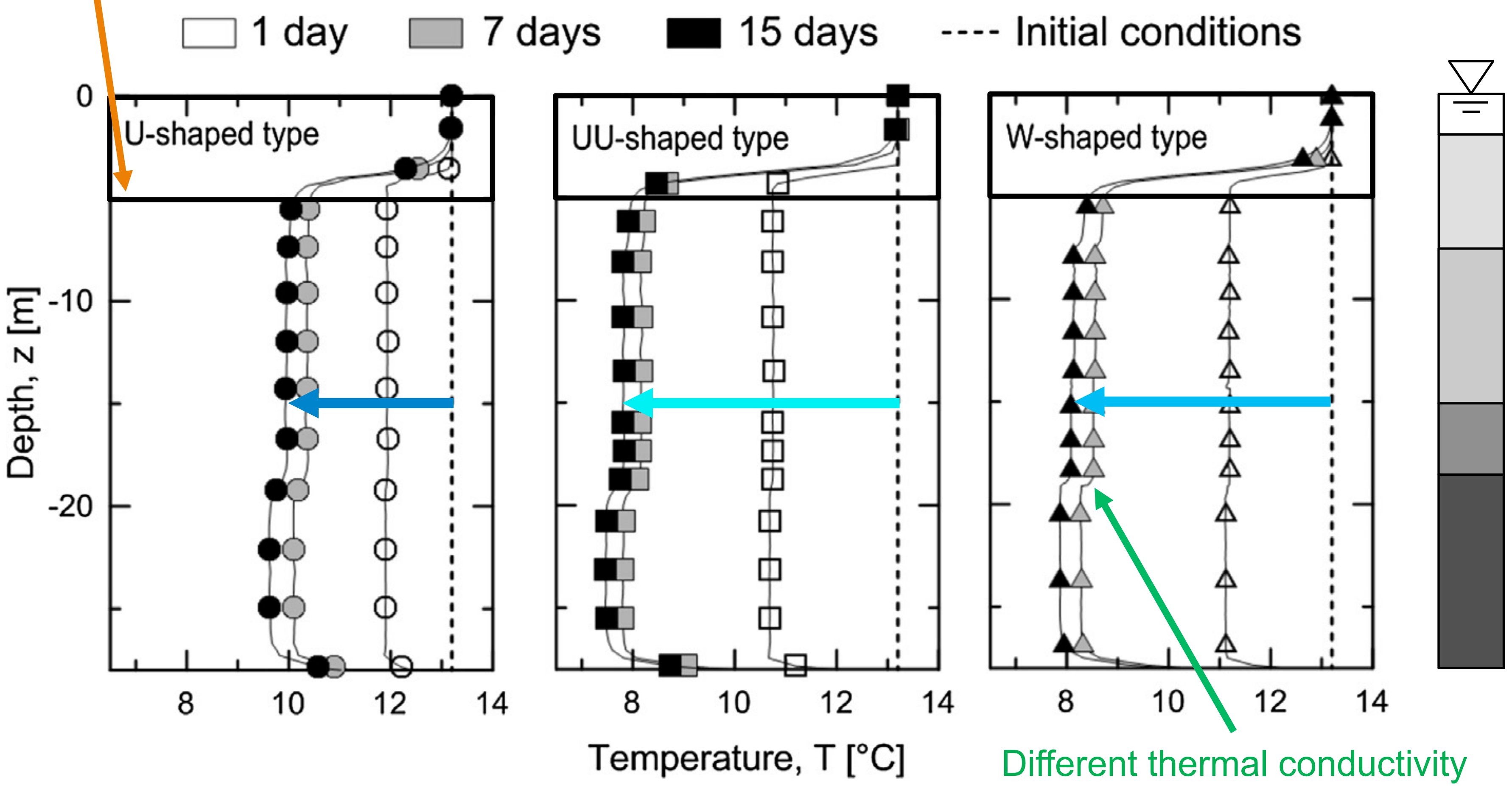
Influence of pipe layout

- U-shaped pipe configuration
- UU-shaped pipe configuration
- W-shaped pipe configuration

Influence of *pipe layout* on temperature variation

Zone of thermal insulation of pipes

(Batini et al., 2015)



Different thermal conductivity of Molasse

ΔT_{max} = -3.5 °C

ΔT_{max} = -5.5 °C

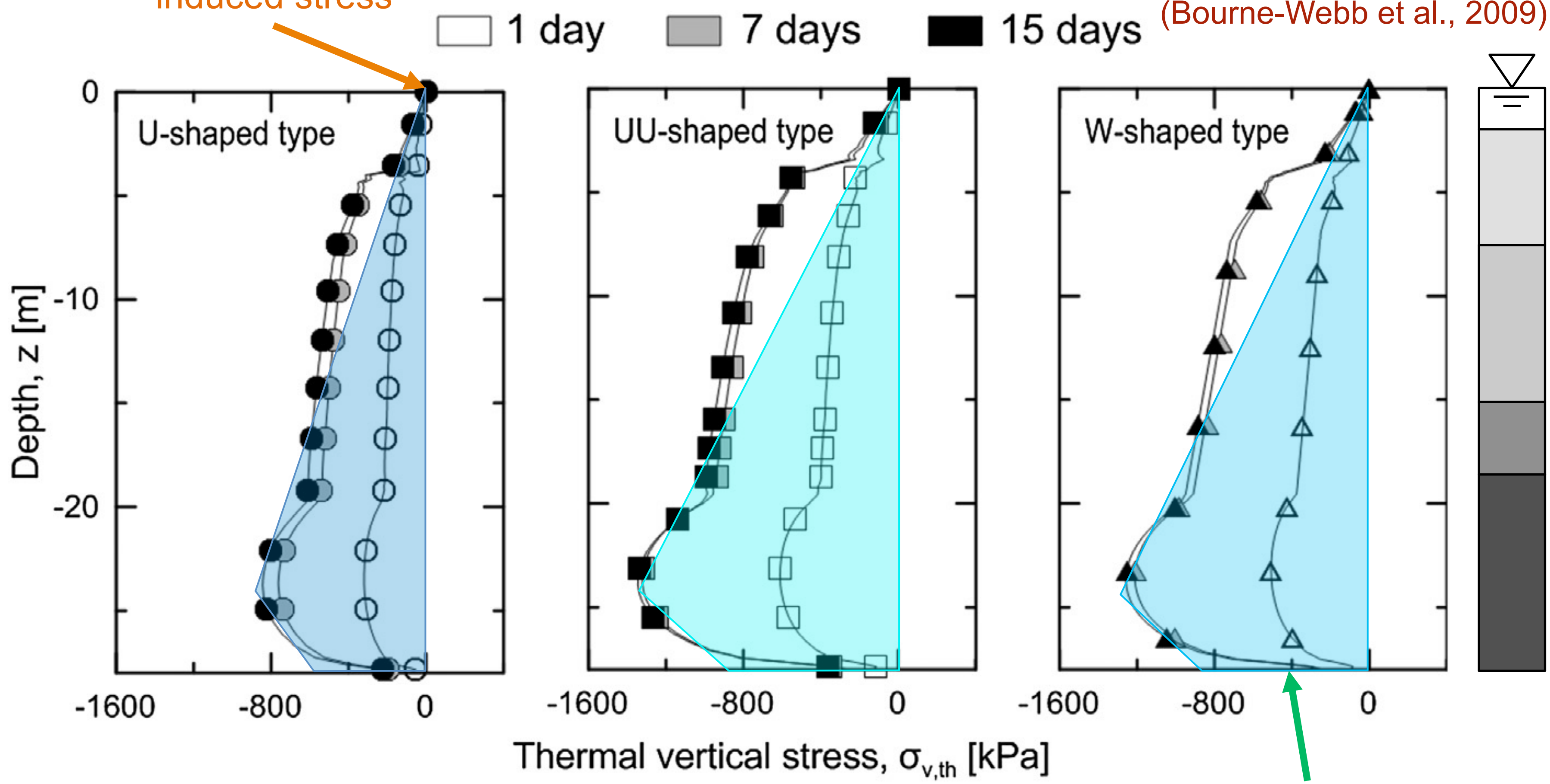
ΔT_{max} = -5.0 °C

Influence of *pipe layout* on stress variation

Null head-restraint so zero thermally induced stress

(Batini et al., 2015)

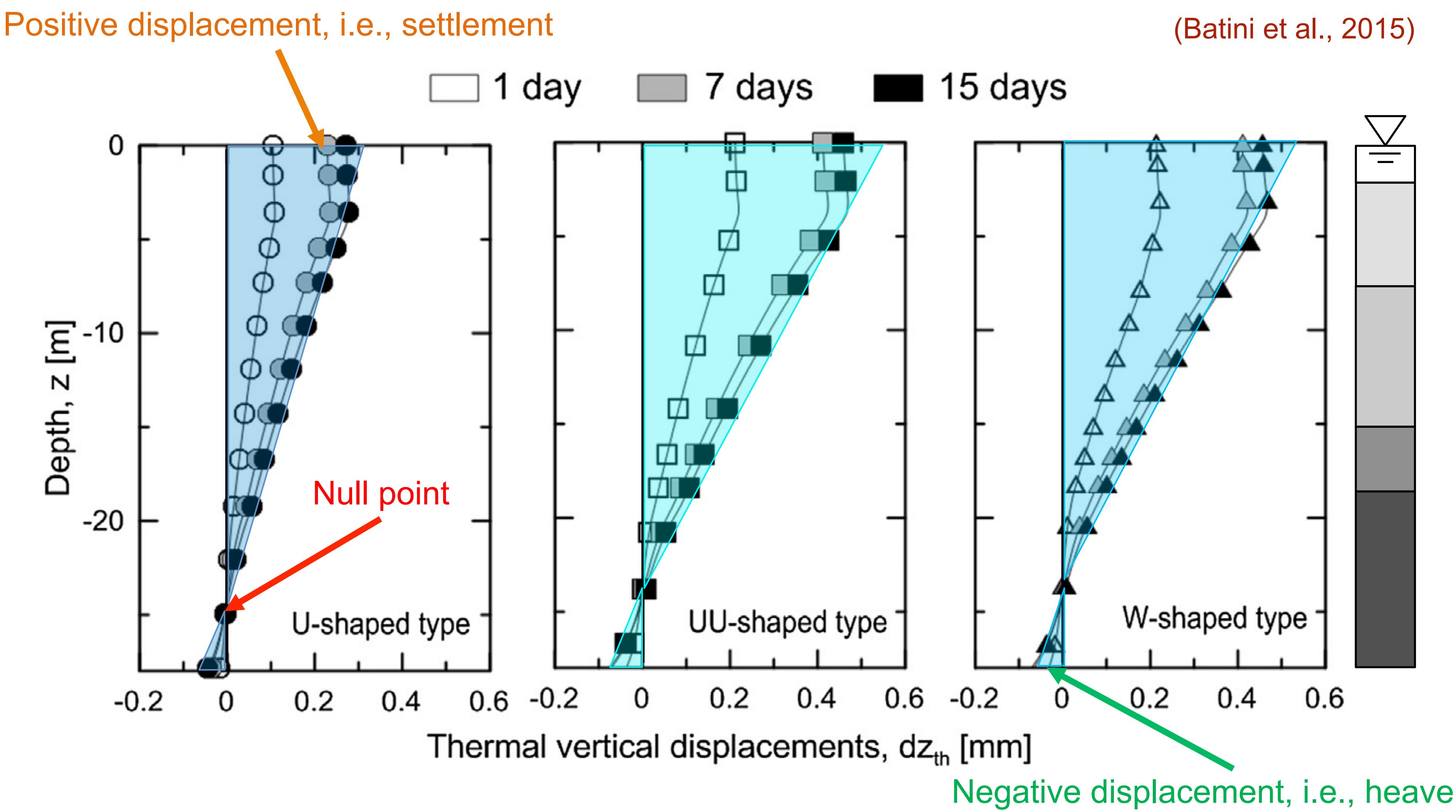
(Bourne-Webb et al., 2009)



High restraint provided by Molasse

$\Delta\sigma_{th,\ max}$ = -800 kPa $\Delta\sigma_{th,\ max}$ = -1400 kPa $\Delta\sigma_{th,\ max}$ = -1300 kPa

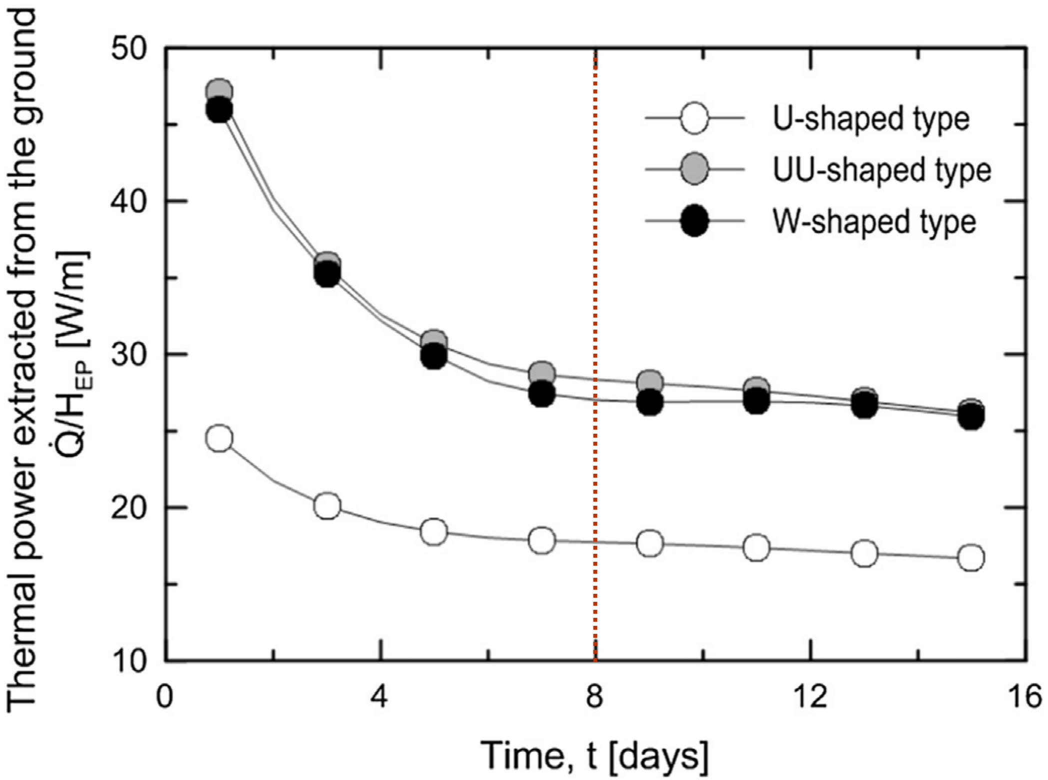
Influence of *pipe layout* on displacement variation



$\Delta z_{th,\,max}$ = 0.28 mm $\Delta z_{th,\,max}$ = 0.47 mm $\Delta z_{th,\,max}$ = 0.46 mm

Influence of *pipe layout* on extracted thermal power

(Batini et al., 2015)



- Steady-state thermal conditions reached after almost 7 days
- After 15 days the UU-shaped geometry involves:
  - a 57% higher heat transfer rate than the U-shaped pipe configuration
  - a 2% higher heat transfer rate than the W-shaped pipe configuration

Comments on *pipe layout*

(Batini et al., 2015)

- The W-shaped pipe configuration is the best trade-off among the analysed design solutions, owing to
  - a significantly higher energy extraction compared to the U-shaped configuration
  - a comparable energy extraction compared to the UU-shaped configuration

- The pipe configuration strongly influences both the energy and geotechnical performance of energy piles

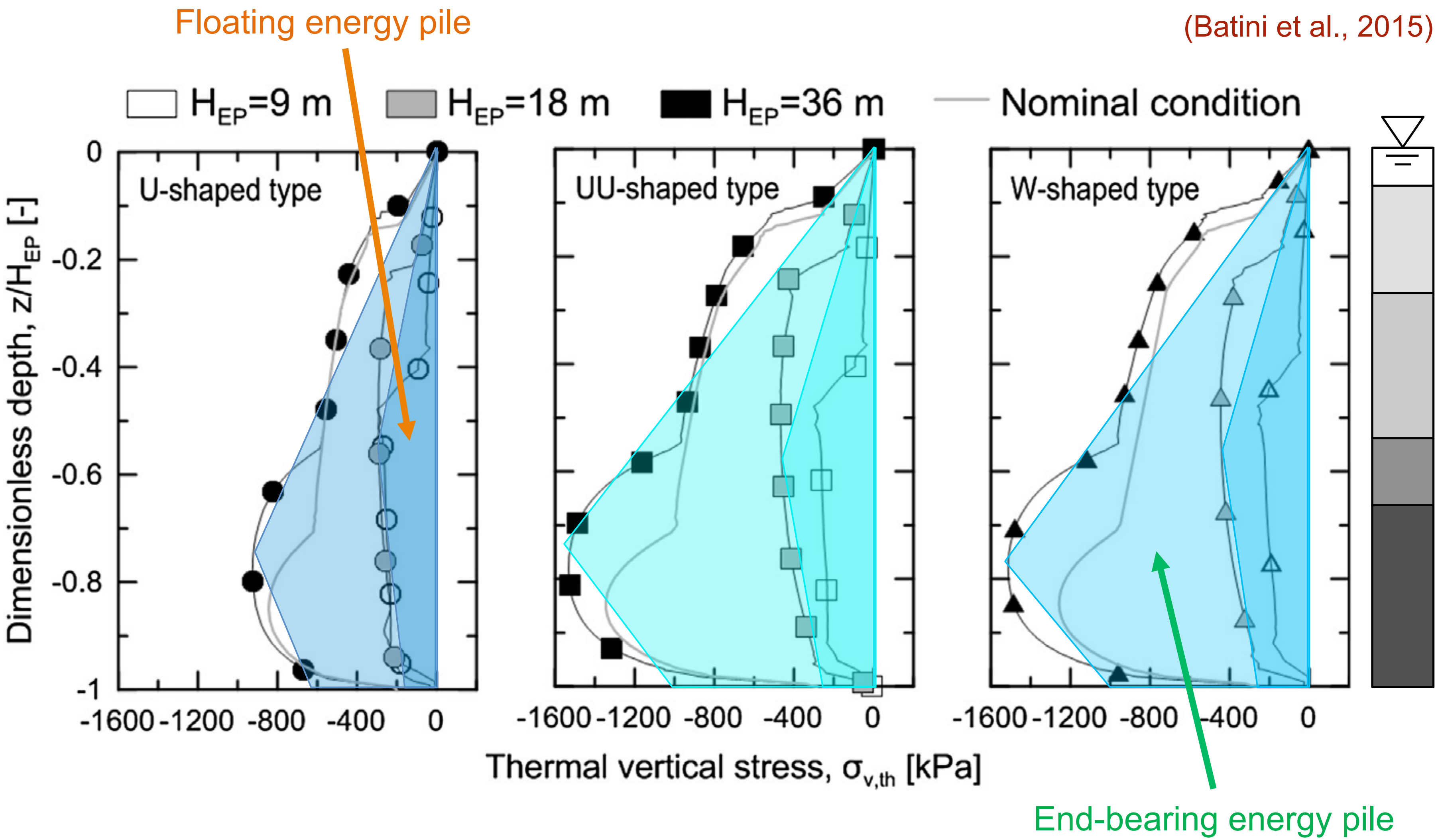
Influence of pile aspect ratio

- H_{EP} = 9 m
- H_{EP} = 18 m
- H_{EP} = 28 m (nominal condition)
- H_{EP} = 36 m

D_{EP} = 0.9 m

Influence of *aspect ratio* on stress variation

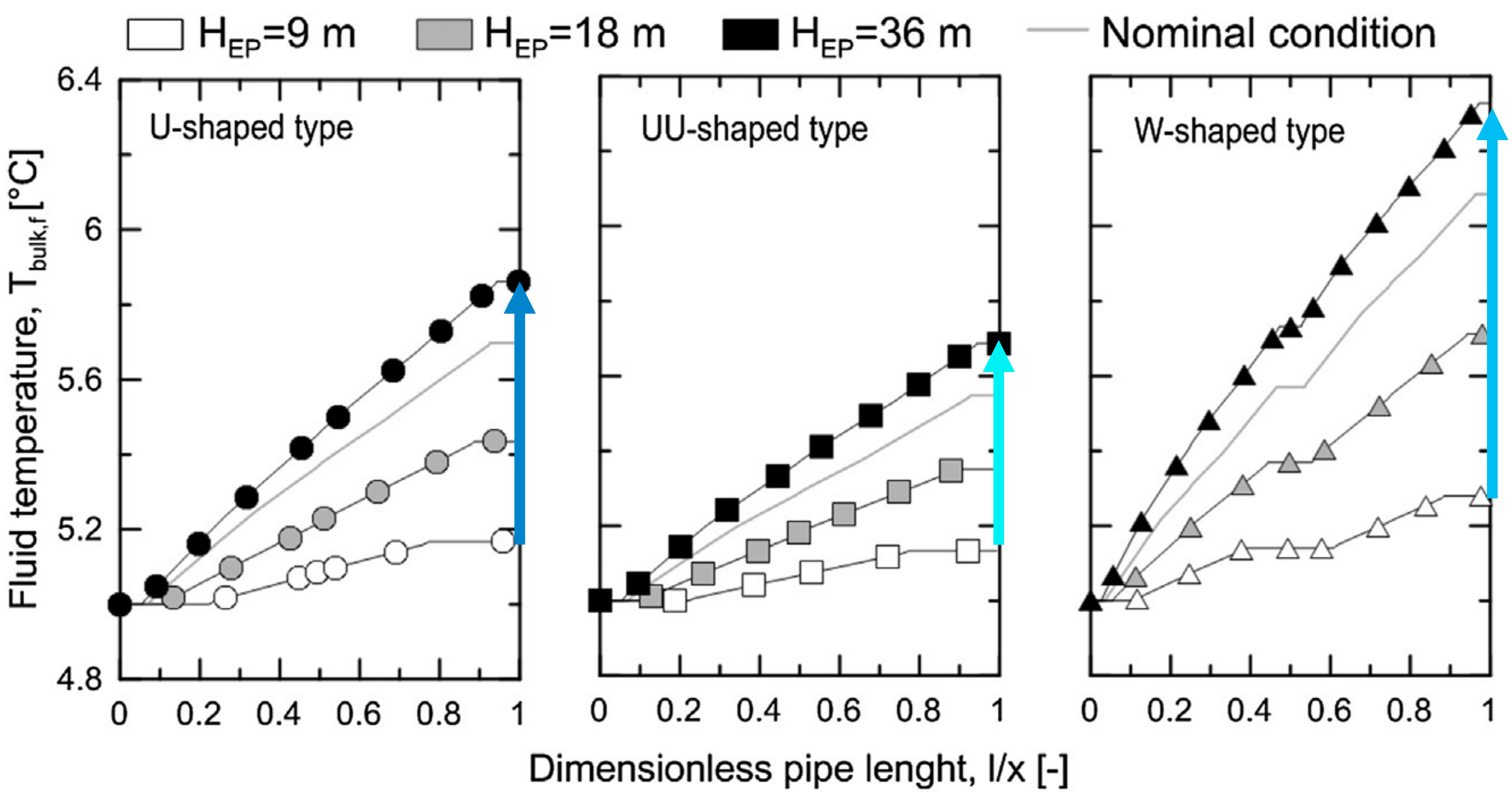
(Batini et al., 2015)



$\Delta\sigma_{th,\,max}$ = -926 kPa $\Delta\sigma_{th,\,max}$ = -1531 kPa $\Delta\sigma_{th,\,max}$ = -1513 kPa

Influence of *aspect ratio* on operative fluid temperature

(Batini et al., 2015)



The operative fluid temperature increases approximately linearly with the pile aspect ratio due to the increase in the heat transfer surface

Comments on *aspect ratio*

(Batini et al., 2015)

- Doubling the foundation aspect ratio:
  - from 10 to 20 => increase of thermal power extraction between 152 and 170%
  - from 20 to 40 => increase between 87 and 100%
- Attention has to be paid to the tendency of the heat exchanger to become saturated with increasing heat transfer surface
- The foundation aspect ratio is crucial for both the energy and geotechnical performance of energy piles

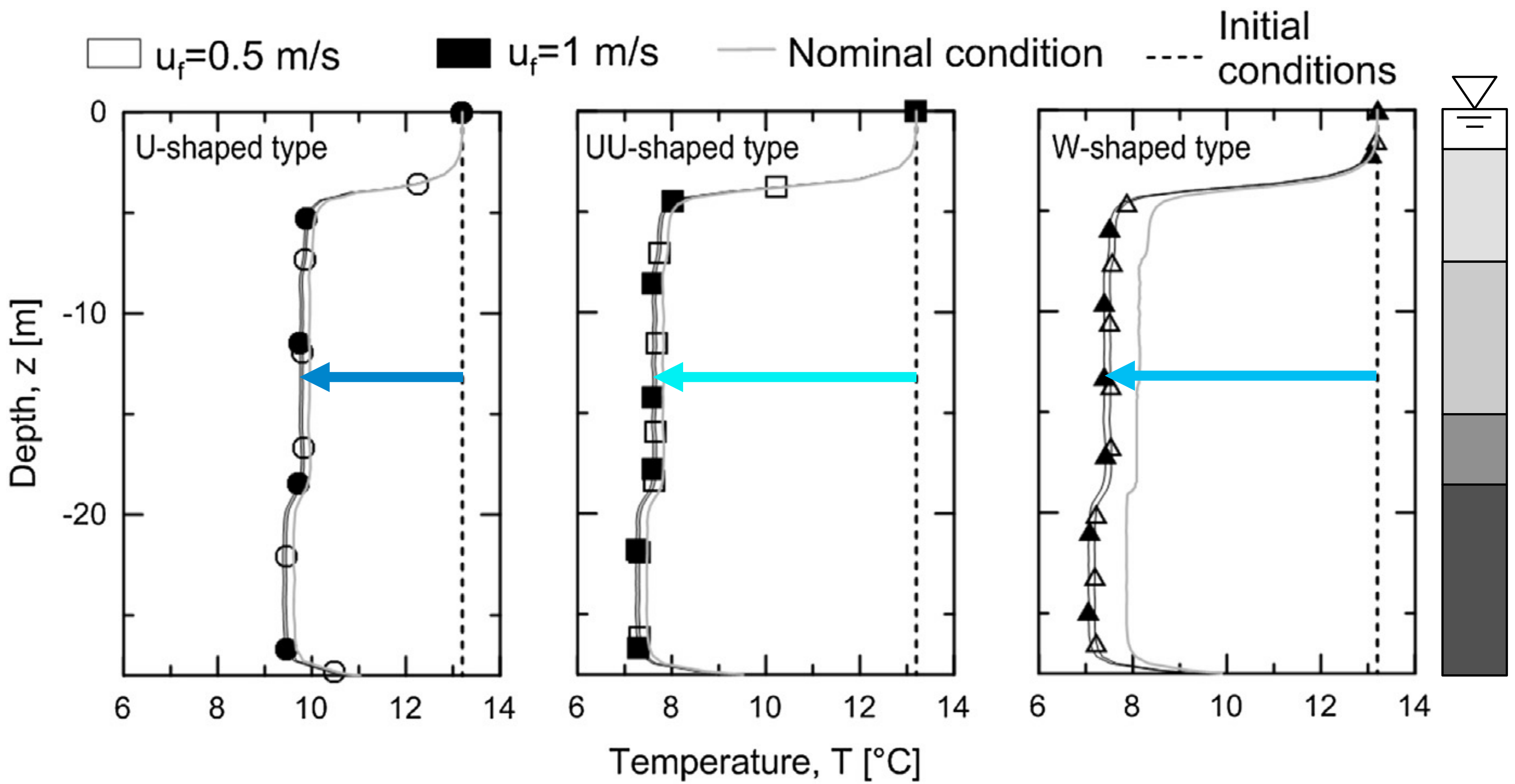
Influence of mass flow rate of fluid circulating in the pipes

- u_f = 0.2 m/s (nom. condition)
- u_f = 0.5 m/s
- u_f = 1 m/s

- Φ = 25 mm
- Φ = 32 mm (nom. condition)
- Φ = 40 mm

Influence of *fluid flow rate* on temperature variation

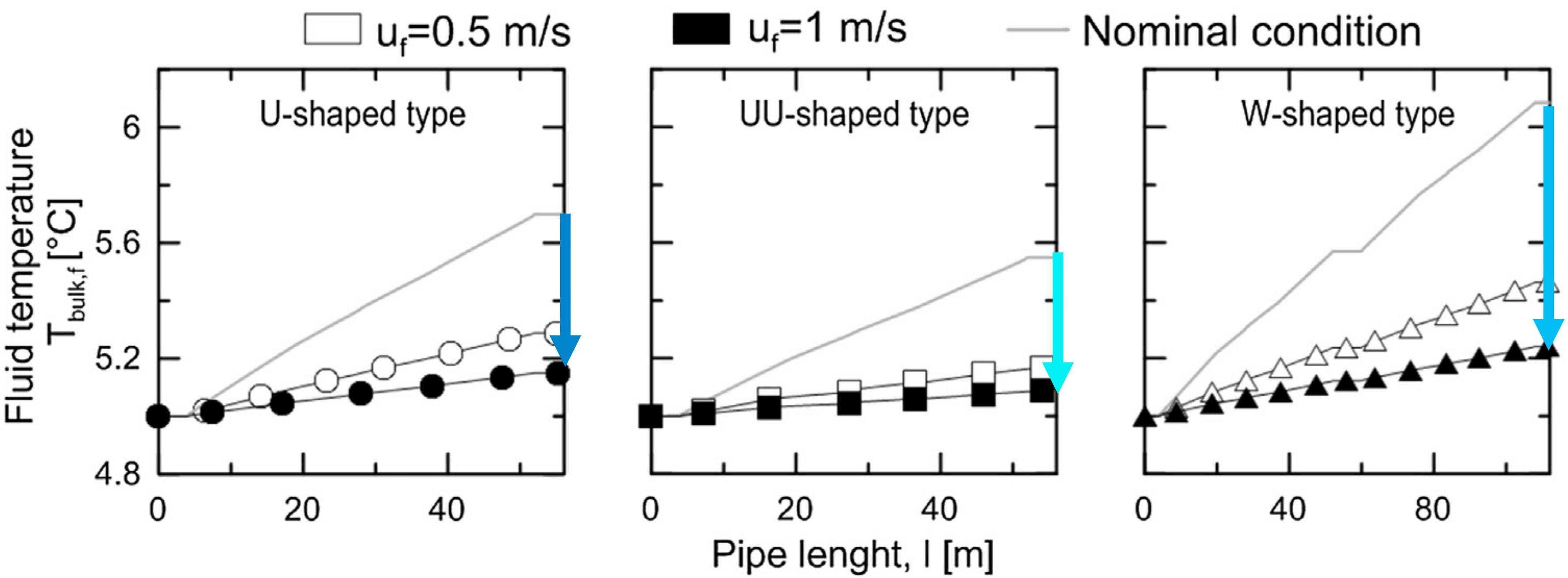
(Batini et al., 2015)



Negligible influence of fluid flow rate on temperature variation in the energy pile and thus on stress and displacement variations

Influence of *fluid flow rate* on extracted thermal power

(Batini et al., 2015)



- Notable growth of heat transfer efficiency when fluid flow rate increases
- An increase of fluid velocity from 0.2 to 1 m/s leads an increase in heat transfer rate of 11% (W-shaped configuration)

Comments on *fluid flow rate*

(Batini et al., 2015)

- Varying the fluid velocity appears a more effective solution than varying the pipe diameter for changing the flow rate

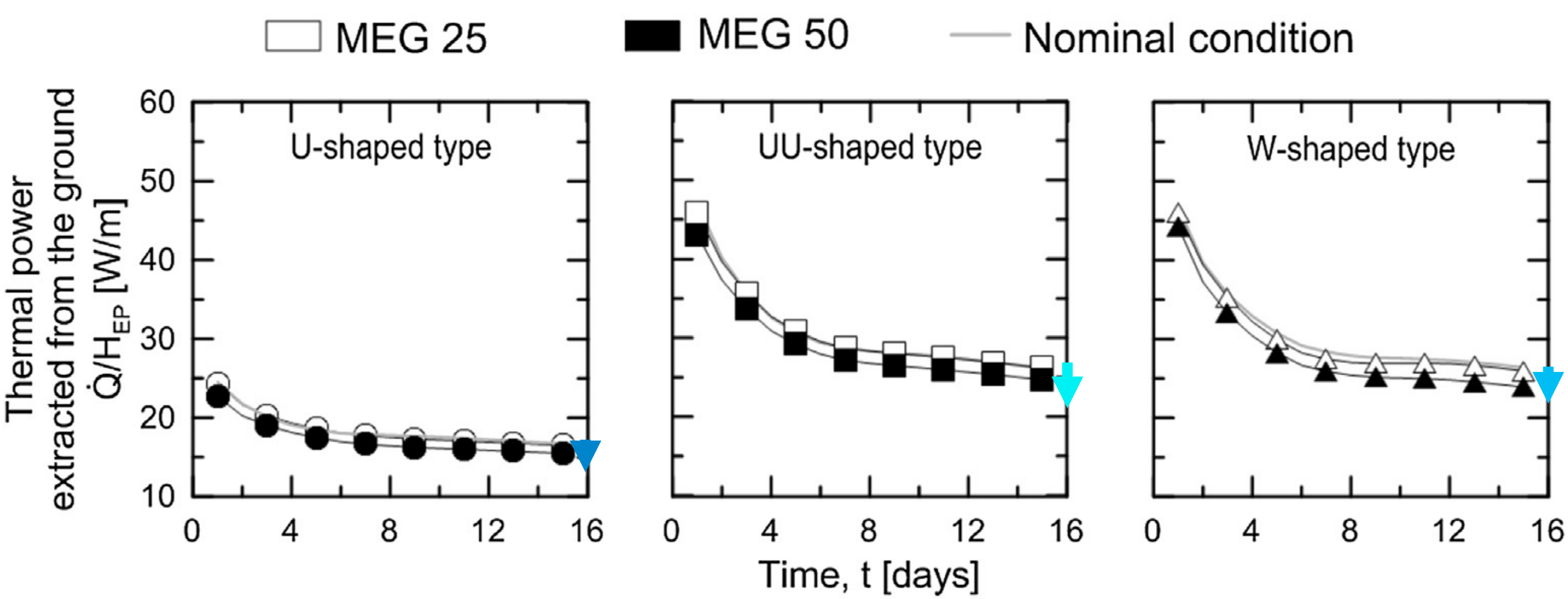
- The mass flow rate of the fluid circulating in the pipes notably characterises only the energy performance of energy piles

Influence of mixture composition of fluid circulating in the pipes

- water (nominal condition)
- MEG 25 = mixture of 25% mono-ethylene glycol+water
- MEG 50 = mixture of 50% mono-ethylene glycol+water

Influence of *fluid composition* on extracted thermal power

(Batini et al., 2015)



- Slight differences in the results for the different pipe configurations
- MEG 50 induces a decrease of extracted thermal power up to 11% compared to the nominal conditions with pure water

Comments on *fluid composition*

(Batini et al., 2015)

- Usual mixtures of water-antifreeze liquid do not markedly affect the energy performance of energy piles
- Only high concentrations of antifreeze cause considerable decreases in the heat transfer rates
- Usual mixtures of water-antifreeze do not influence the geotechnical performance of energy piles

Concluding remarks

Concluding remarks

(Batini et al., 2015)

- The pipe configuration majorly characterises both the energy and the geotechnical performance of energy piles
- The foundation aspect ratio is also crucial for both the energy and the geotechnical performance of energy piles
- The mass flow rate of the fluid circulating in the pipes markedly influences only the energy performance
- Usual mixtures of a water-antifreeze liquid circulating in the pipes do not markedly affect neither the energy nor the geotechnical performance of energy piles

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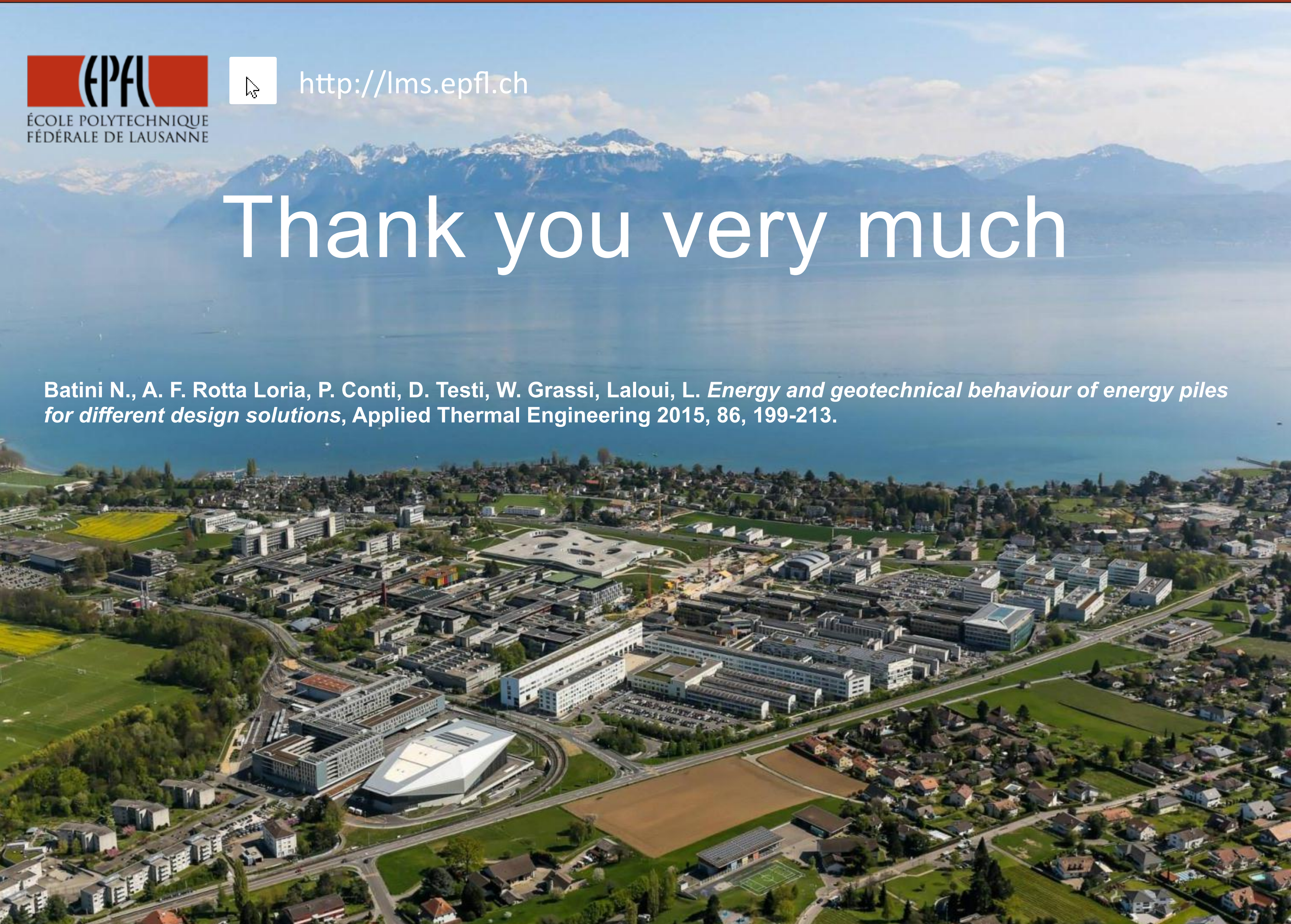
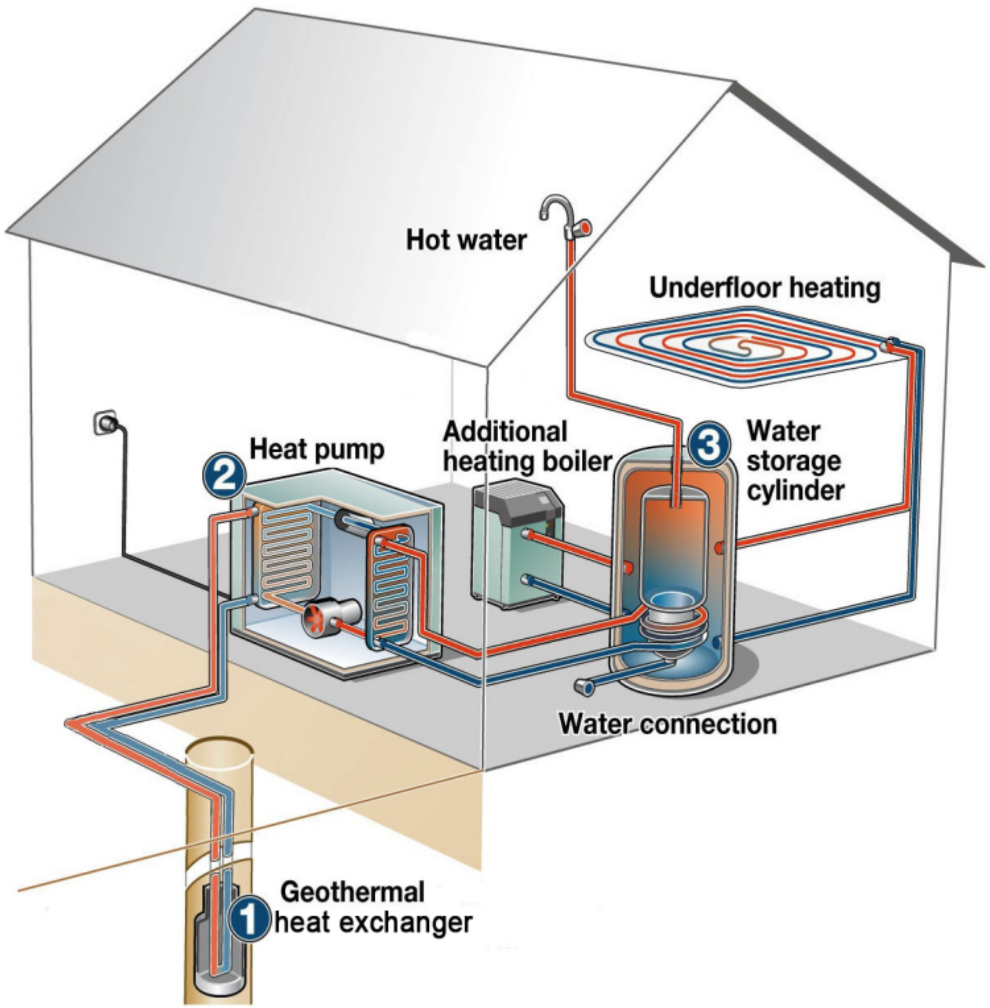


Thank you very much

Batini N., A. F. Rotta Loria, P. Conti, D. Testi, W. Grassi, Laloui, L. *Energy and geotechnical behaviour of energy piles for different design solutions*, Applied Thermal Engineering 2015, 86, 199-213.

The Ground Source Heat Pump System - GSHP



Modified after Renewable Energy Agency (2013)