Thermo-mechanical behaviour of energy pile groups

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Outline

- Interactions and group effects in energy pile groups
- Observed response of energy pile groups
- Axial capacity of energy pile groups
- Thermo-mechanical modelling of energy pile groups:
  - Interaction factor method
  - Equivalent pier method
  - Load transfer method

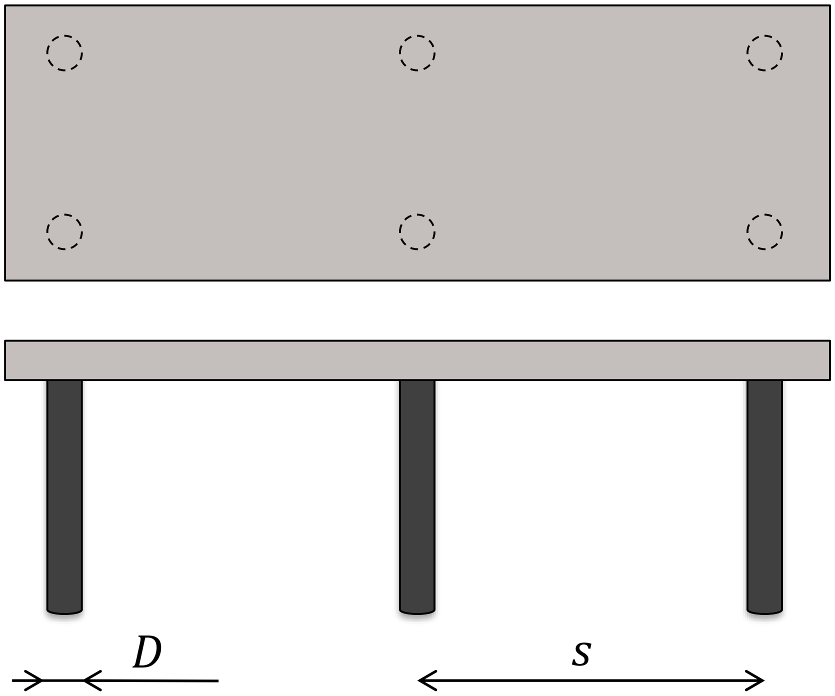
Interactions and group effects in energy pile groups

Context: pile group situation and group effects

Widely spaced piles

- Response of individual piles essentially independent from each of the others:

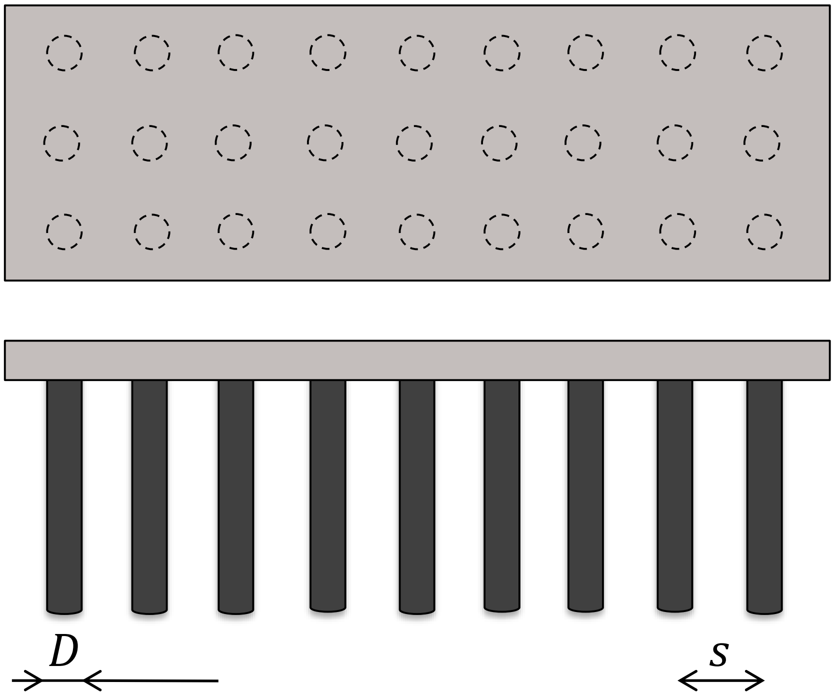
$$\frac{s}{D} > 8$$



Closely spaced piles

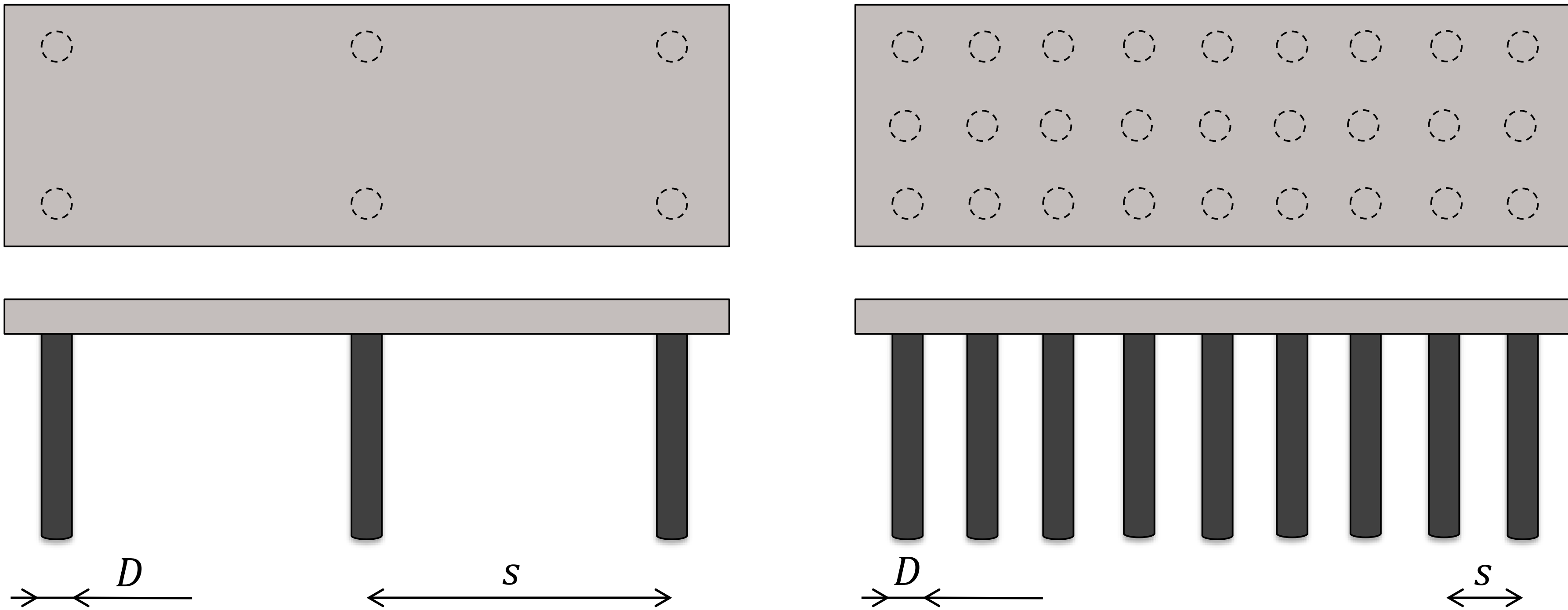
- Response of individual piles dependent on *presence* of and *loadings* on neighboring piles:

$$\frac{s}{D} \leq 8$$



Context: pile group situation and group effects

Group effects, caused by interactions in energy pile groups, involve a different behaviour of the piles in the group compared to that of the same piles in an isolated case



Causes and types of interaction

- Mechanical and thermal loads applied to energy piles cause interactions

- There exist *two types of interactions in energy pile groups*:

  - Mechanically induced interactions: mechanical interactions caused by the application of mechanical loads

    - Associated with variations in deformation and stress

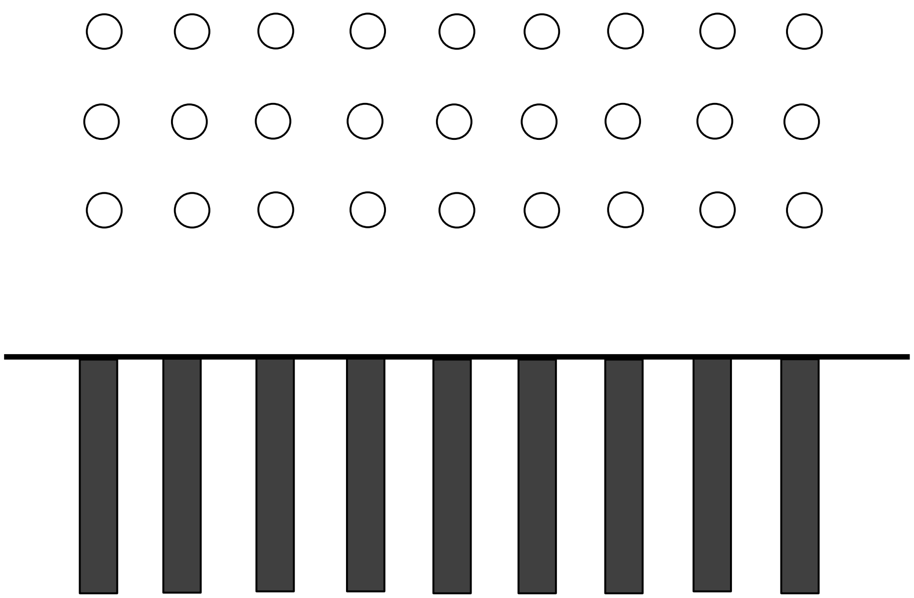
  - Thermally induced interactions: mechanical and thermal interactions caused by the application of thermal loads

    - Associated with variations in temperature

Objects of interaction

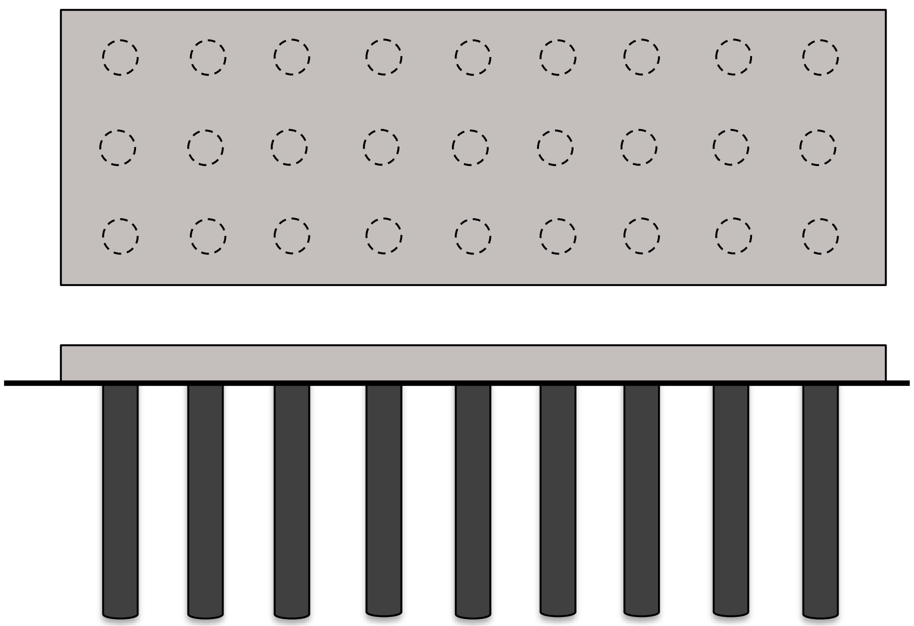
Pile-soil-pile interaction

- Less usual in practical applications but more used for analytical expressions



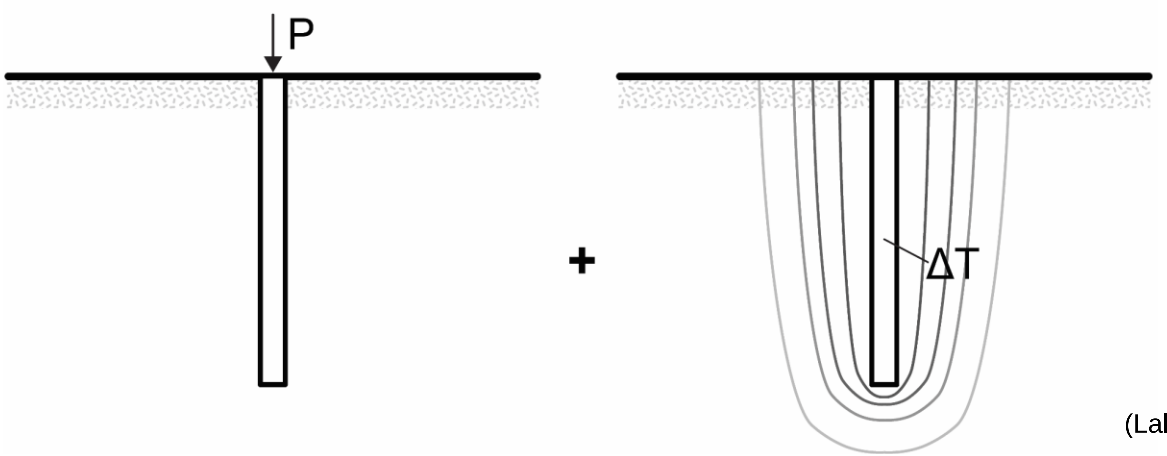
Pile-soil-slab-pile interaction

- More usual in practical applications but less used for analytical expressions



Aspects governing interaction

- Magnitude of applied mechanical and thermal loads to energy piles (i.e., elastic or plastic soil response)
- In the case of elasto-plastic soil behaviour, sequence of loading (i.e., prior mechanical and then thermal loading or the opposite)
- Rate of heat diffusion in the soil (higher rates correspond to more significant and faster thermal interactions for the same pile spacing)



(Laloui and Rotta Loria, 2019)

Observed response of energy pile groups

Observed response of a group of energy pile

Full-scale in situ testing of a group of energy pile

Under the **Swiss Tech Convention Center**

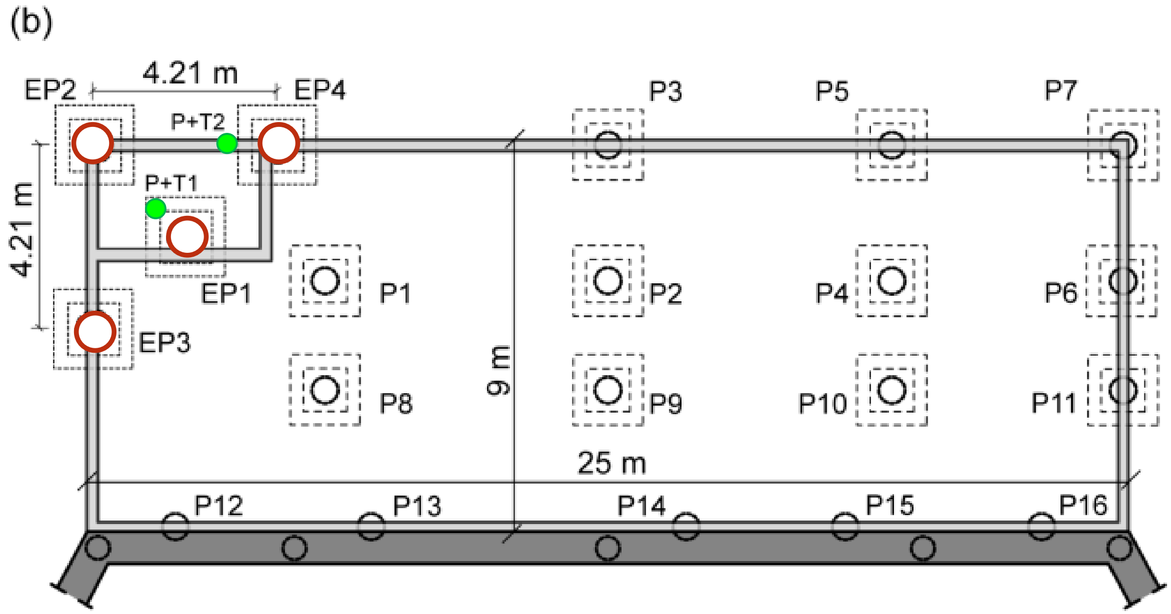
4 energy test piles among 20 piles

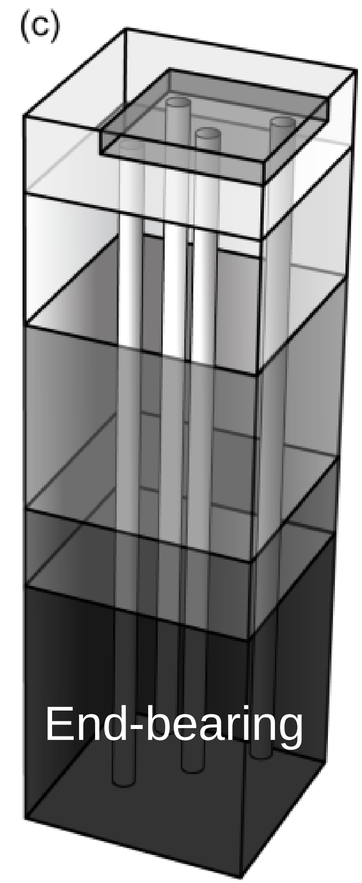
Test pile: **90 cm in diameter and 28 m in length**

Polyethylene U-tube attached on the reinforcing cage

Full-scale *in situ* testing of a group of energy piles

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

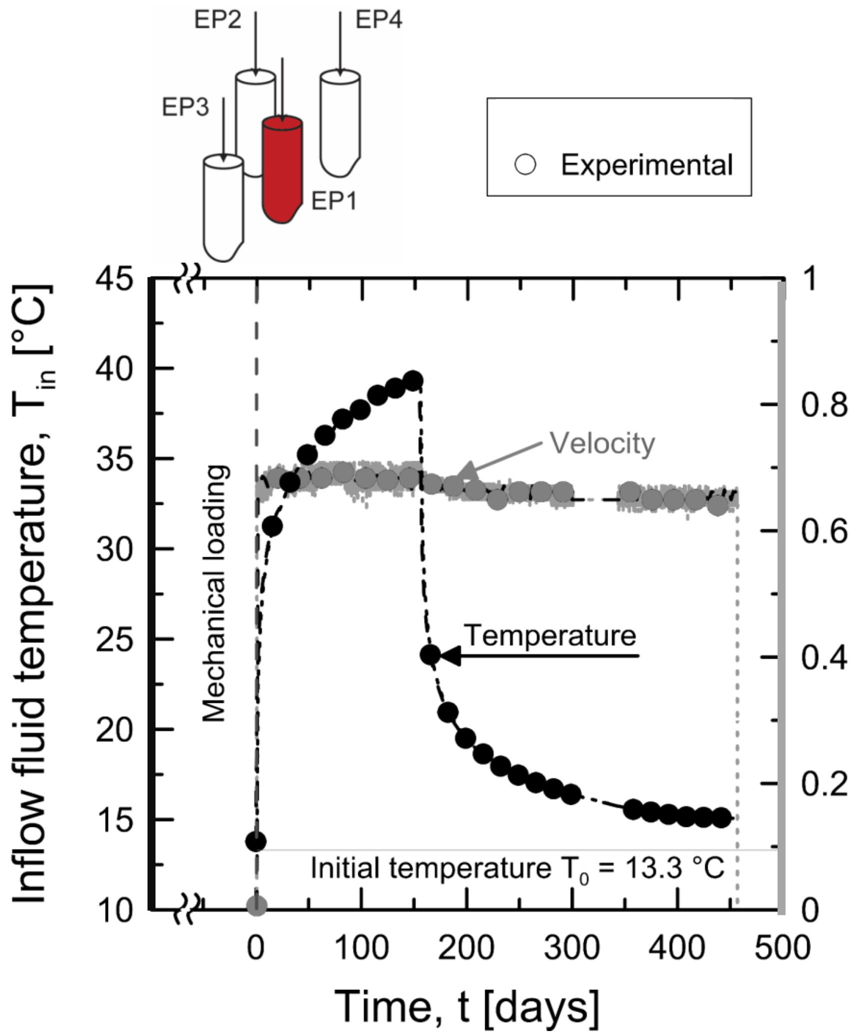


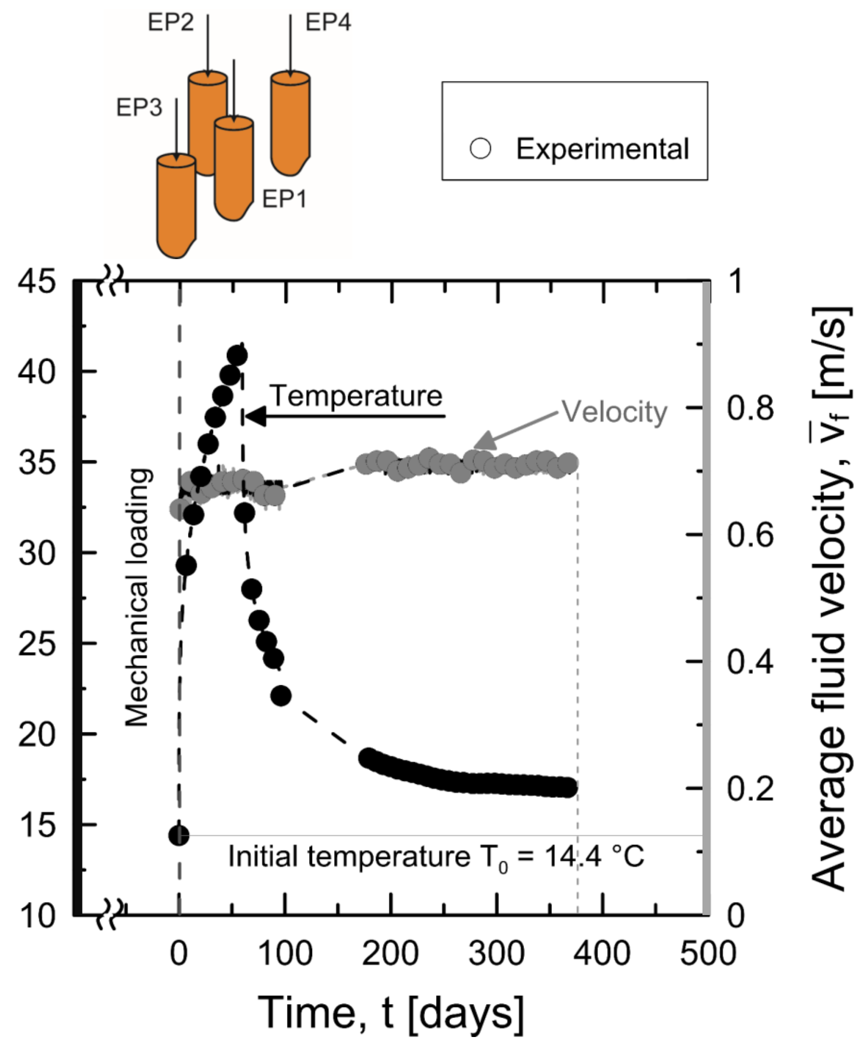


Alluvial soil - A1 - 3.1 m | Alluvial soil - A2 - 5.5 m | Sandy-gravelly moraine - B - 8.0 m | Bottom moraine - C - 3.5 m | Molasse - D

Mimouni T., L. Laloui "Behaviour of a group of energy piles". The **2016 RM Quigley Award Winner** for the best paper published in the Canadian Geotechnical Journal in 2015.

Tests performed



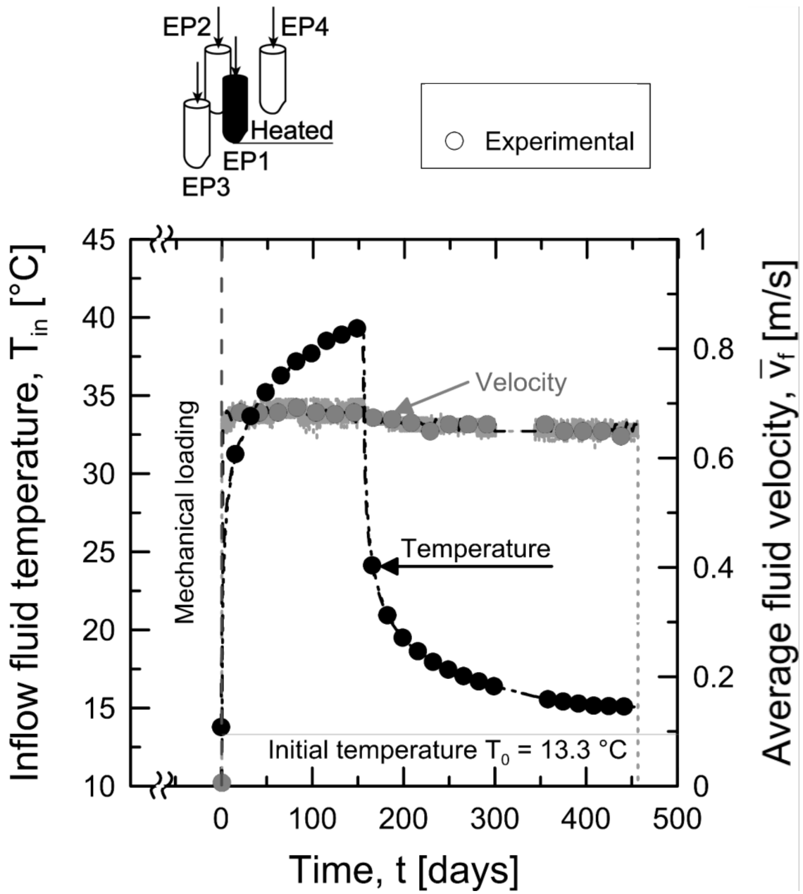


(Rotta Loria and Laloui, 2017, 2018)

Test 20EP1 – features and goal

- 1 thermally active energy pile in a group of 4 energy piles

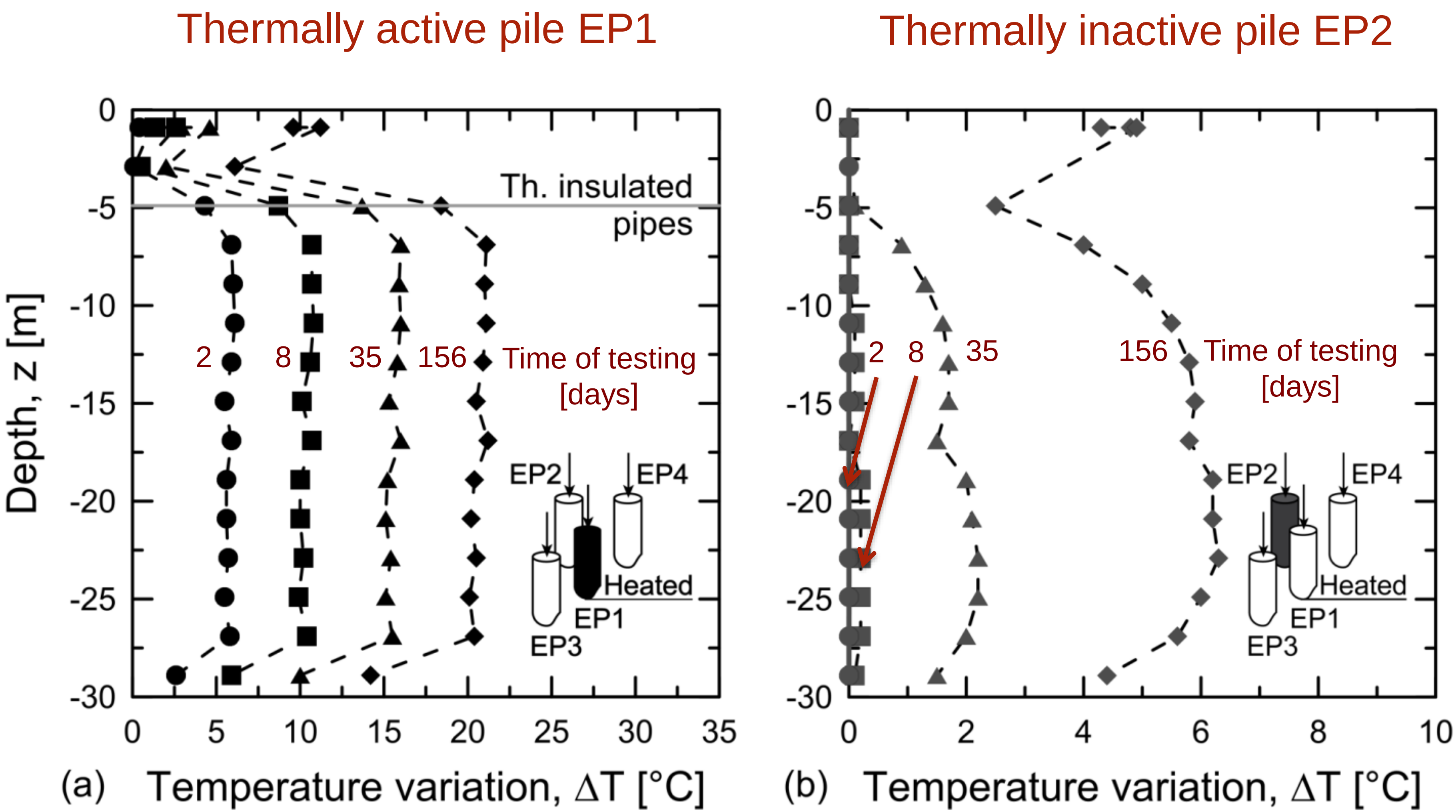
- Heating-passive cooling cycle of 5 months and 10 months, respectively



Investigate the thermally induced group effects among groups of piles partly operating as heat exchangers over typical time-scales of practical geothermal applications

(Rotta Loria and Laloui, 2017)

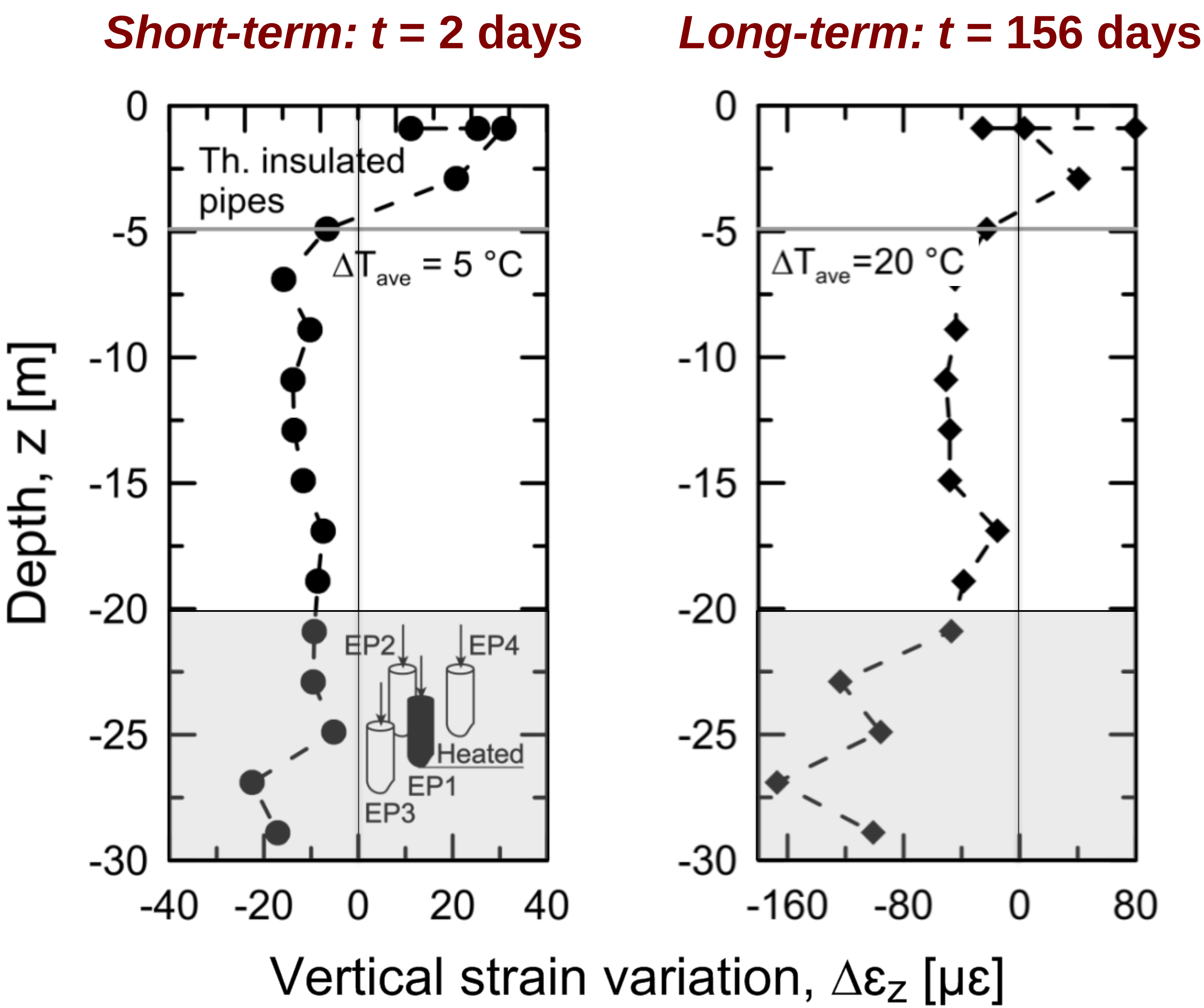
Temperature variations in EP1-2



Thermal interactions arise at successive stages of geothermal operations

(Rotta Loria and Laloui, 2017)

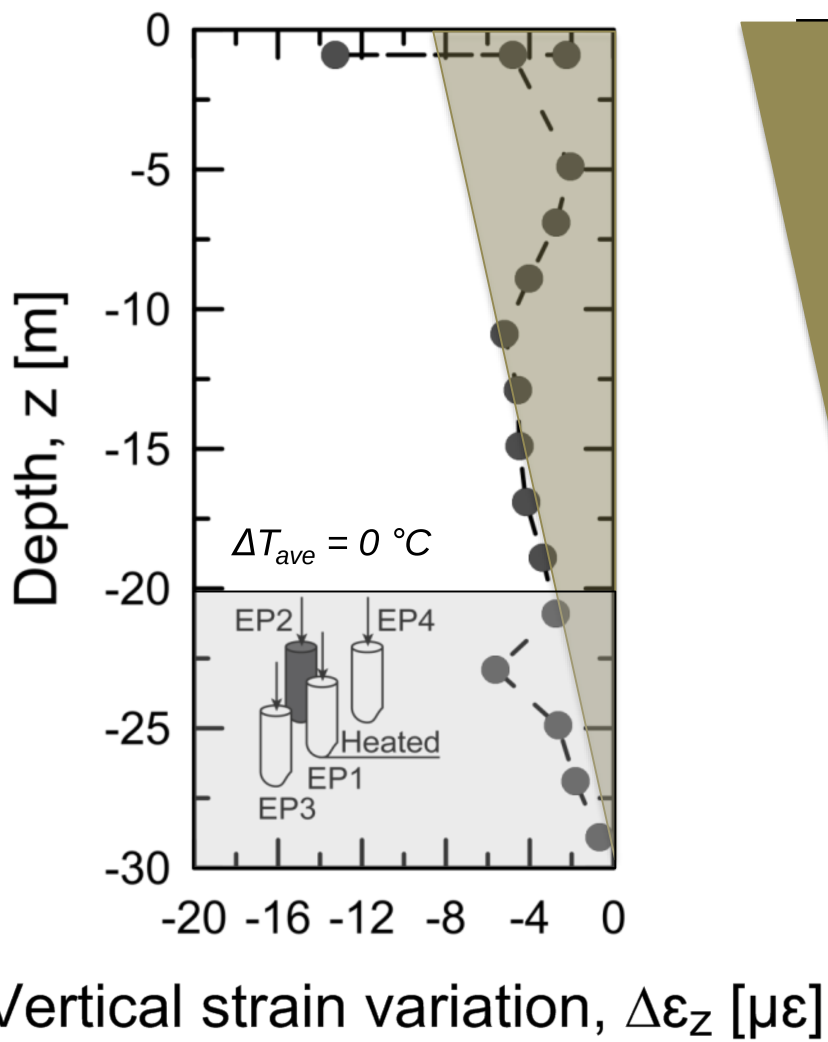
Thermally induced strain variations in EP1

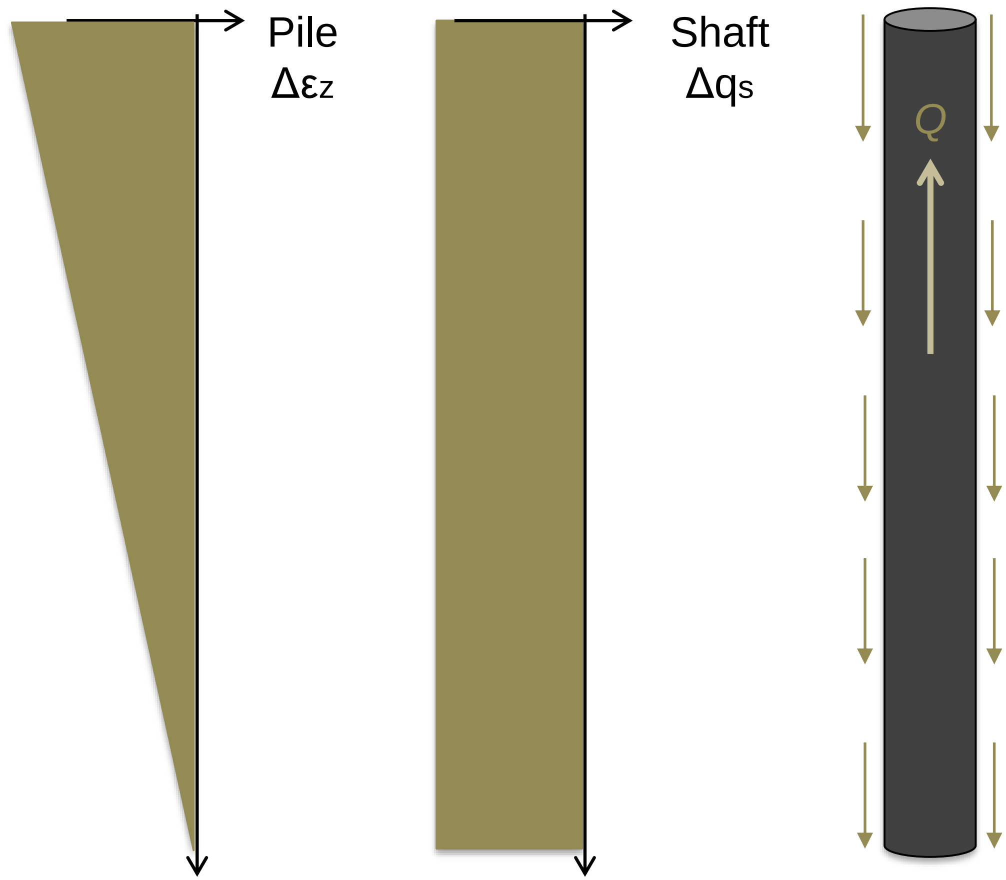


(Rotta Loria and Laloui, 2017)

Thermally induced strain variations in EP2

***Short-term: t* = 2 days**

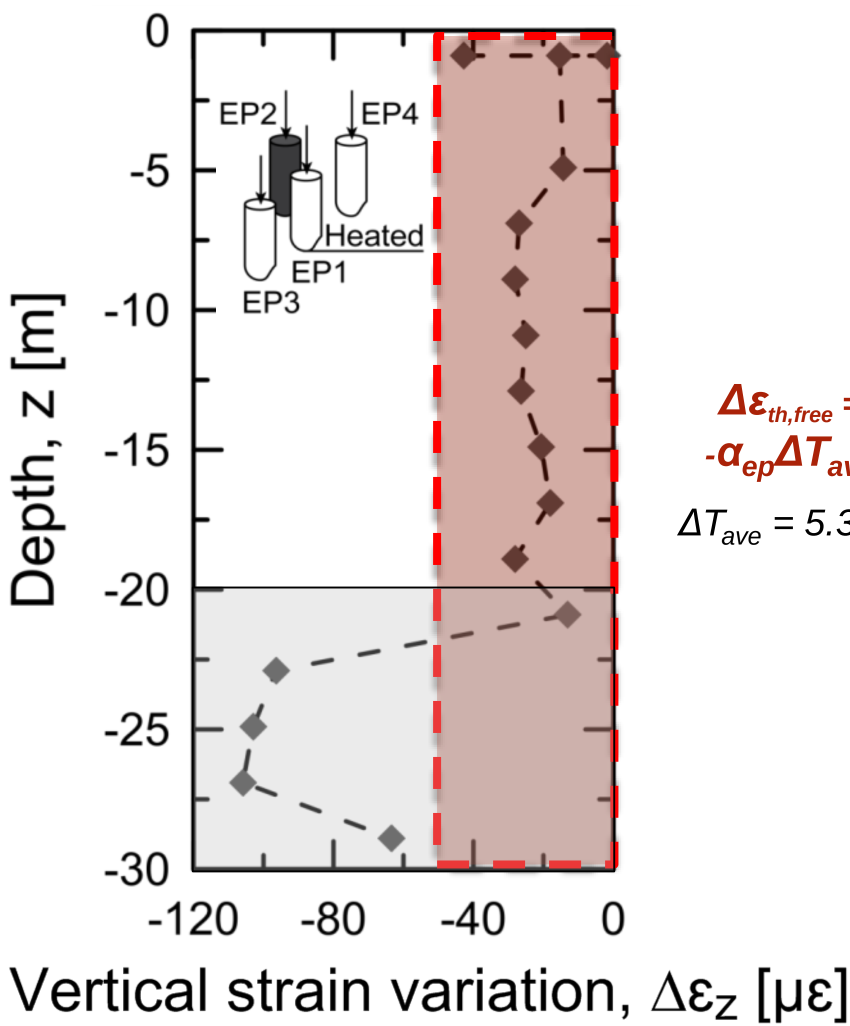




(Rotta Loria and Laloui, 2017)

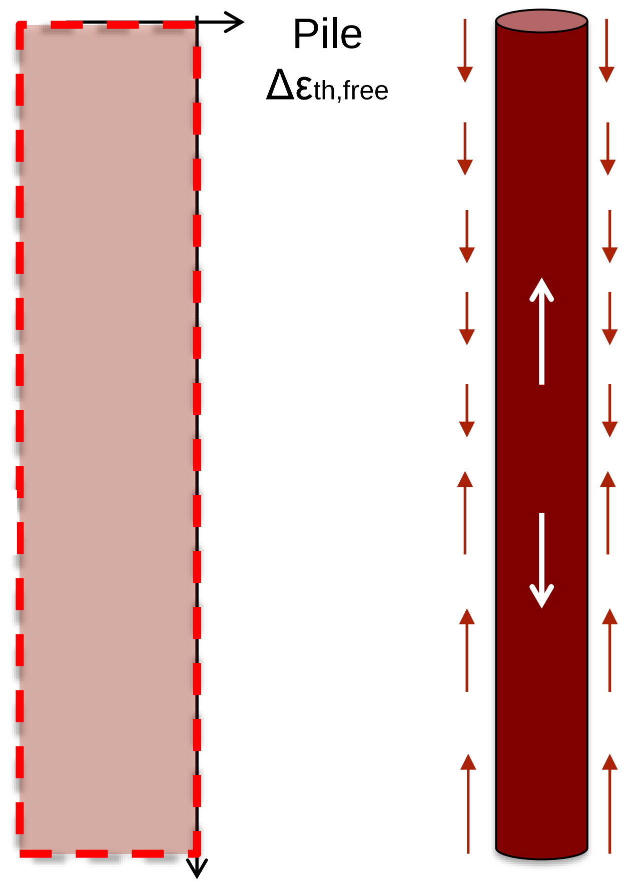
Thermally induced strain variations in EP2

Long-term: t = 156 days



$\Delta\varepsilon_{th,free} = -\alpha_{ep}\Delta T_{ave}$

$\Delta T_{ave} = 5.3$ °C



$\alpha_{ep} = 1*10^{-5}$ 1/°C
$\alpha_{molasse} = 2.3*10^{-5}$ 1/°C

(Rotta Loria and Laloui, 2017)

Comments

- Pile-soil-slab-pile interaction, as a consequence of the application of a thermal load to an active energy pile in the group, can cause

    - In the short-term, a strain variation in inactive energy piles comparable to that induced by a mechanical load applied at the pile head

    - In the long-term, a strain variation in the inactive energy piles that is greater than that associated to free thermal expansion conditions (referring to the pile thermal expansion coefficient)

Comments

- In summary, where $X = \frac{\alpha_{soil}}{\alpha_{EP}} > 1$, at successive stages of geothermal operations it can happen that

$$\varepsilon_o^{th} > \varepsilon_f^{th} = -\alpha_{EP}\Delta T$$

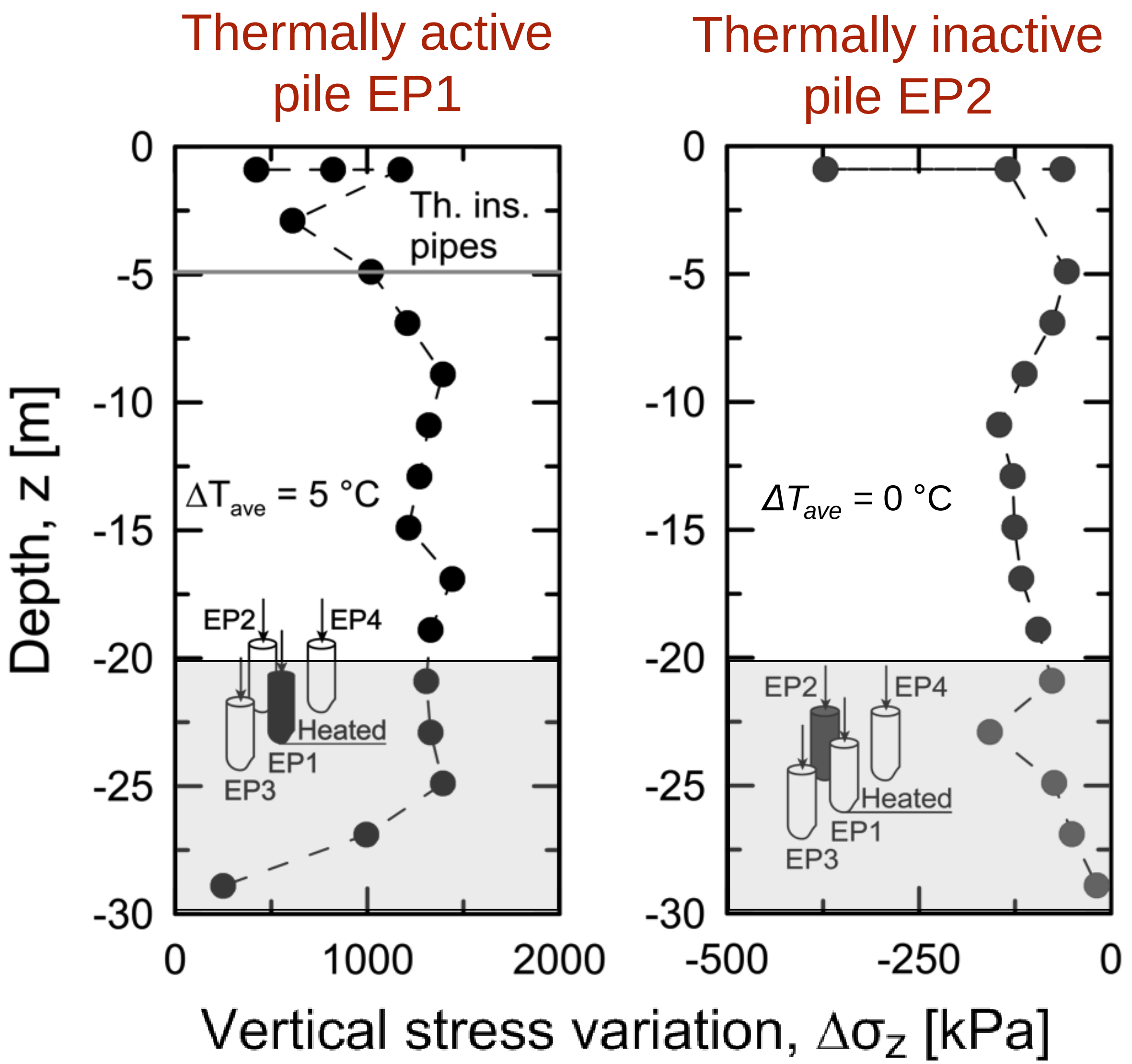
- The reason for this is that the thermally induced deformation of the energy pile is governed by that of the soil

- The above implies that, for energy piles subjected to heating thermal loads, the thermally induced stress can be tensile:

$$\sigma_o^{th} = E(\varepsilon_o^{th} + \alpha_{EP}\Delta T) < 0$$

- The opposite is true for cooling thermal loads

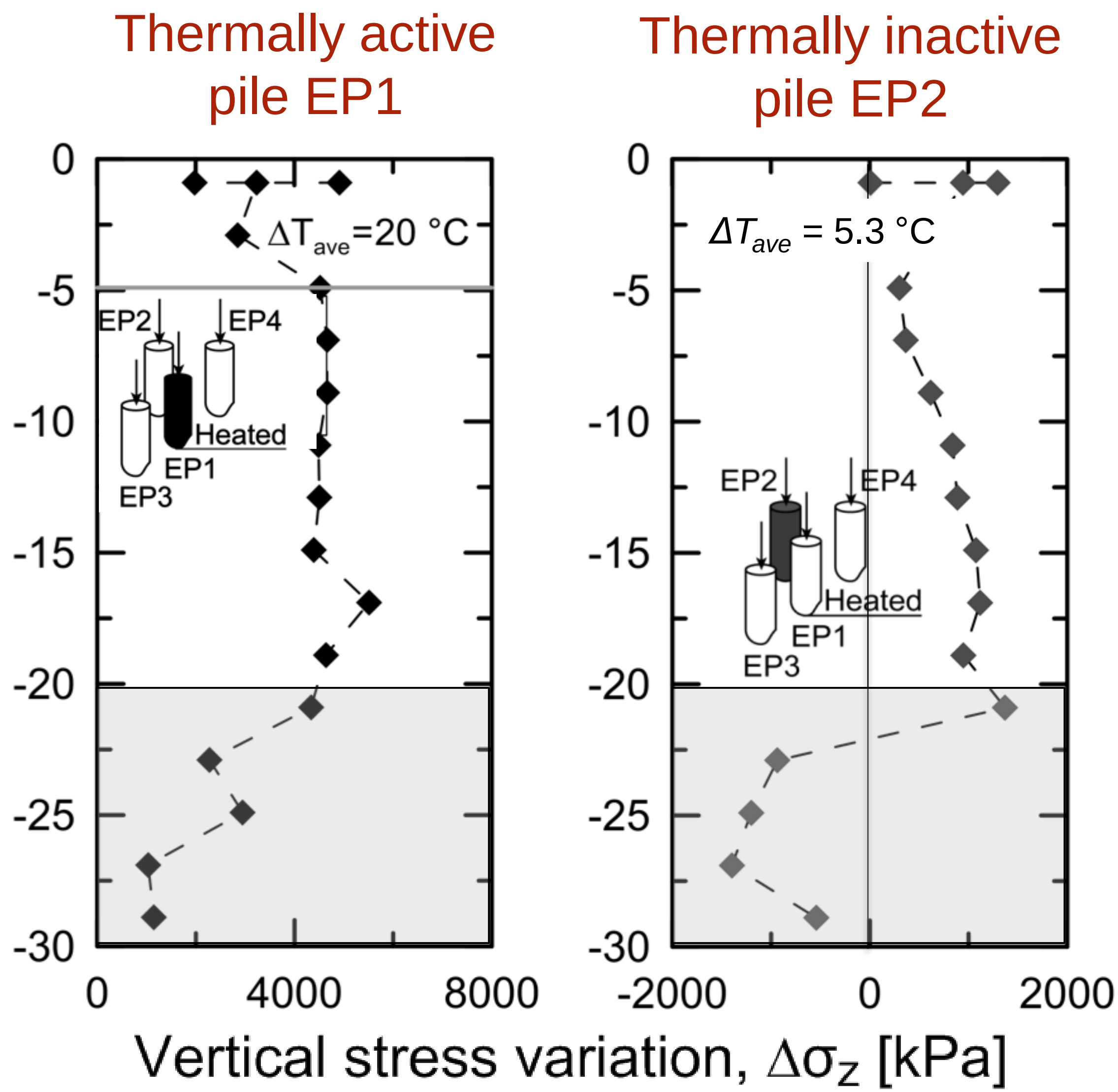
Thermally induced stress variations in EP1-2



Short-term: t = 2 days

(Rotta Loria and Laloui, 2017)

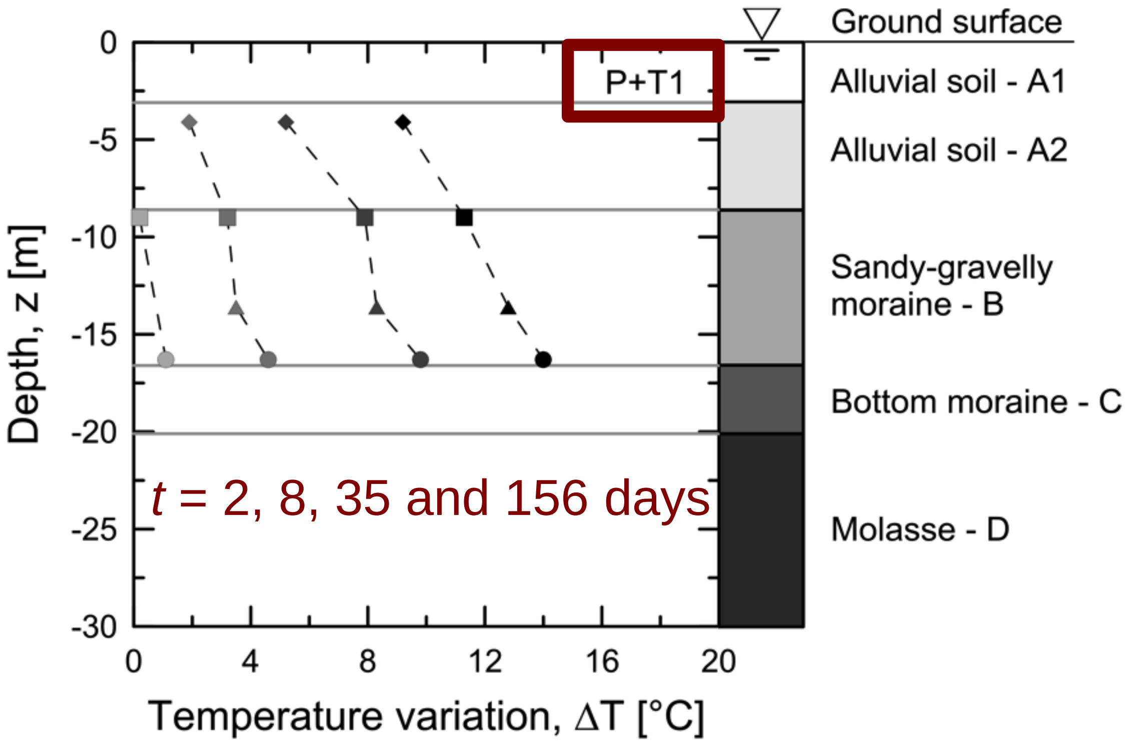
Thermally induced stress variations in EP1-2

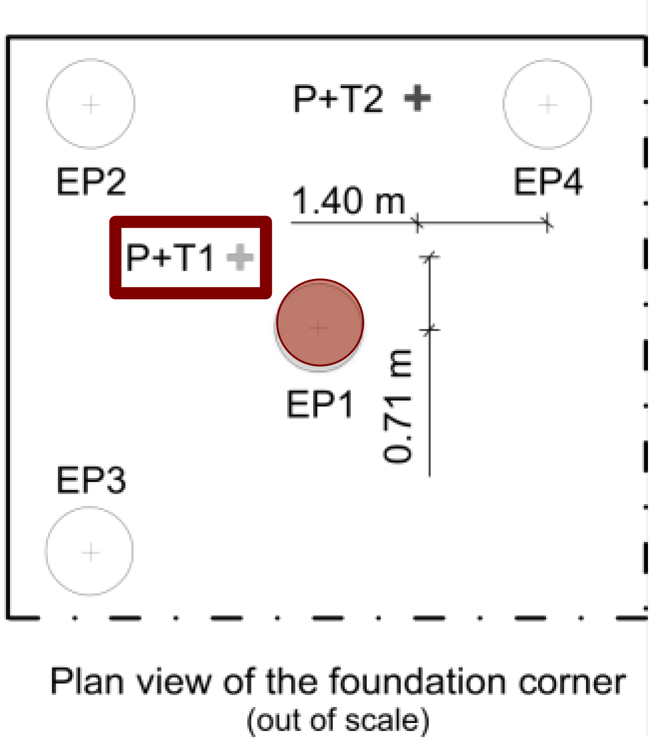


Long-term: t = 156 days

(Rotta Loria and Laloui, 2017)

Temperature variations in the soil

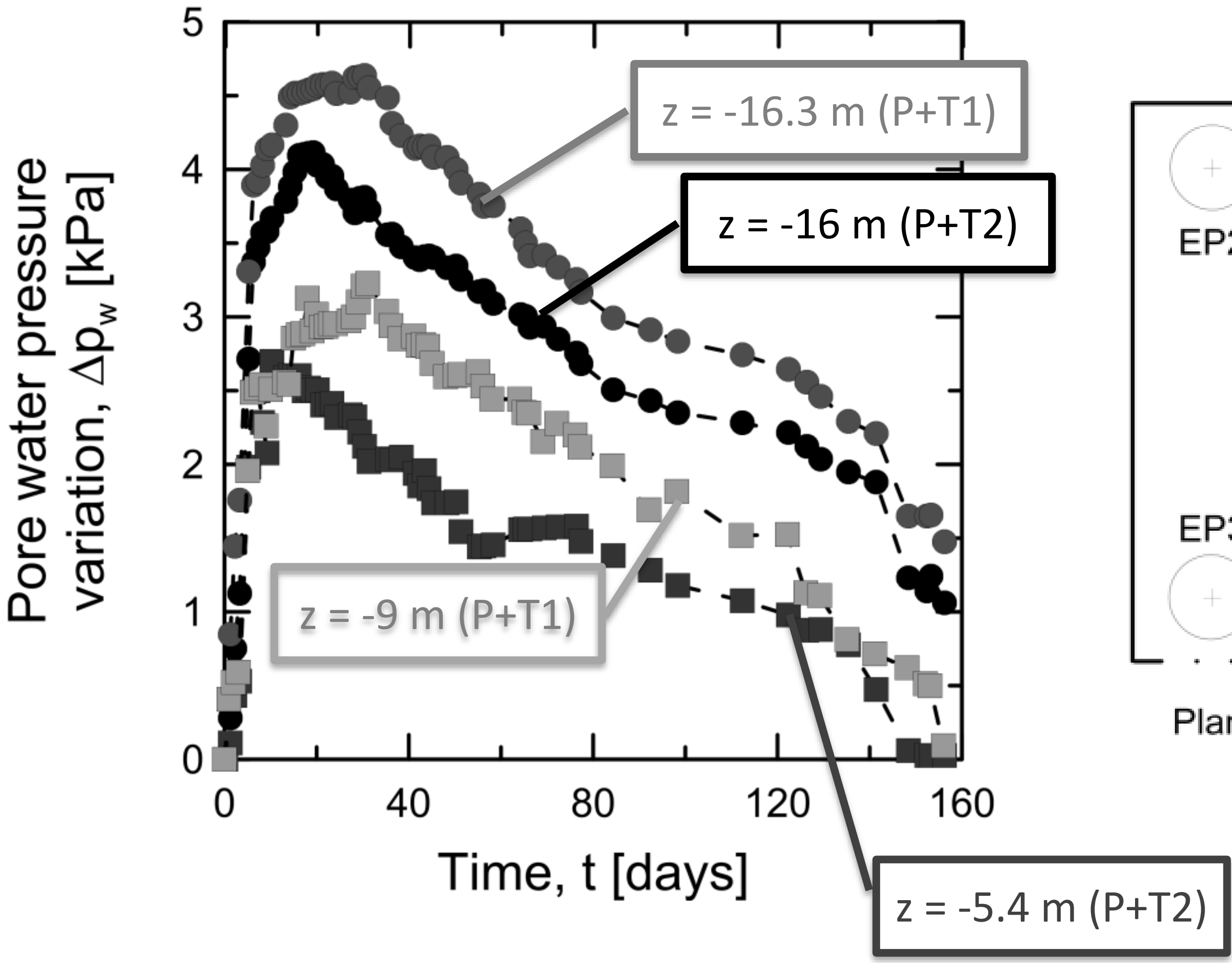


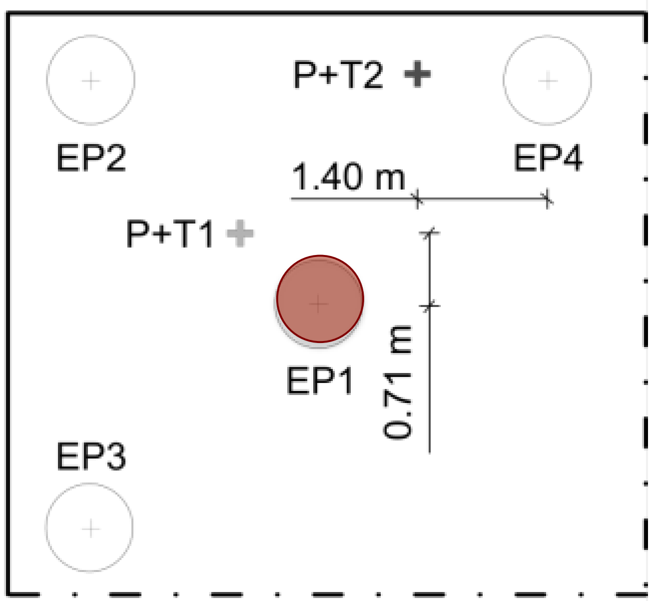


Maximum ΔT = 20 °C in pile induces
ΔT = 15 °C in soil at radial distance of 1 m after 156 days

(Rotta Loria and Laloui, 2017)

Pore water pressure variations in the soil



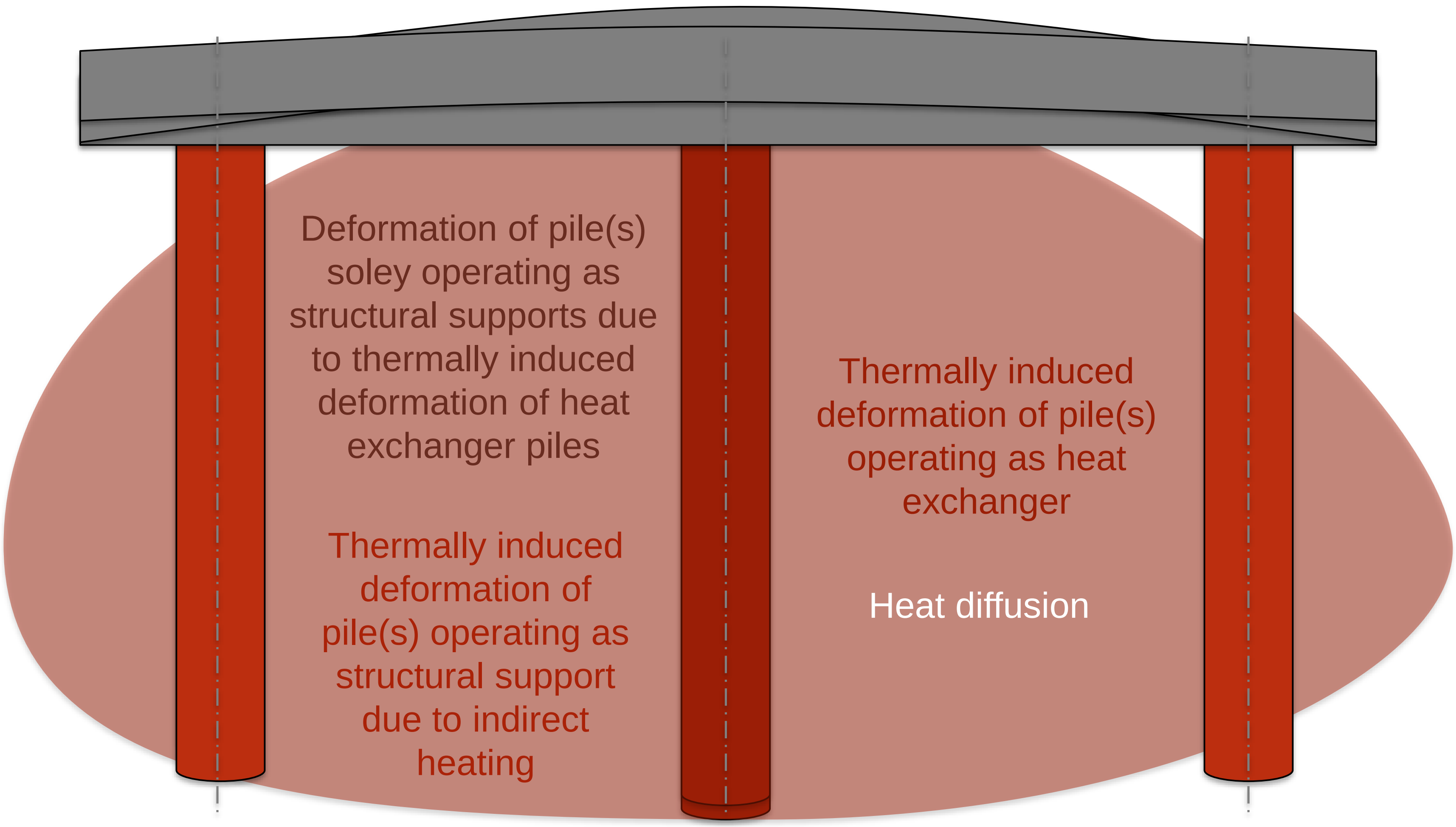


Plan view of the foundation corner
(out of scale)

Drained conditions are preserved during heating

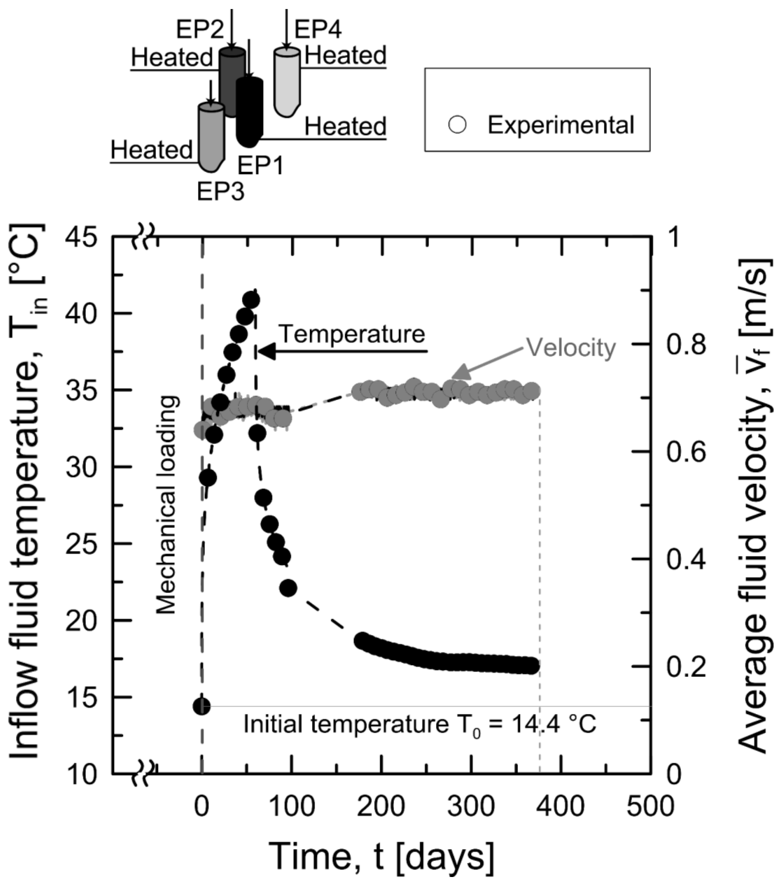
(Rotta Loria and Laloui, 2017)

Summary: interactions caused by a single energy pile



Test 20EPall – features and goal

- 4 thermally active energy pile in a group of 4 energy piles
- Heating-passive cooling cycle of 3 months and 10 months, respectively



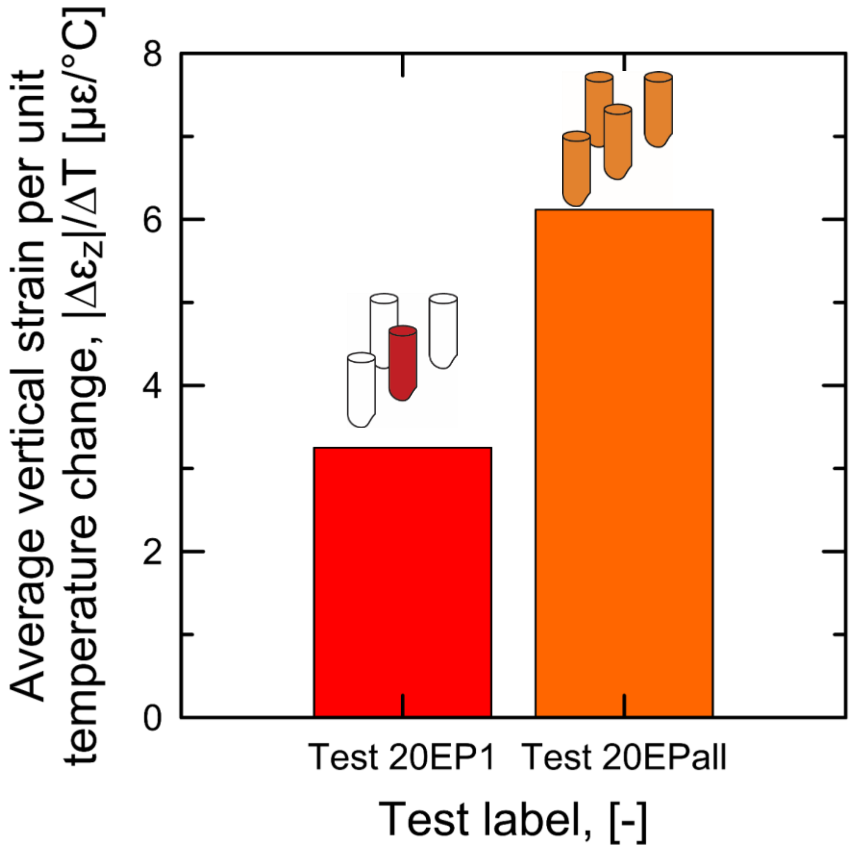
Investigate the thermally induced group effects among groups of piles partly operating as heat exchangers over typical time-scales of practical geothermal applications

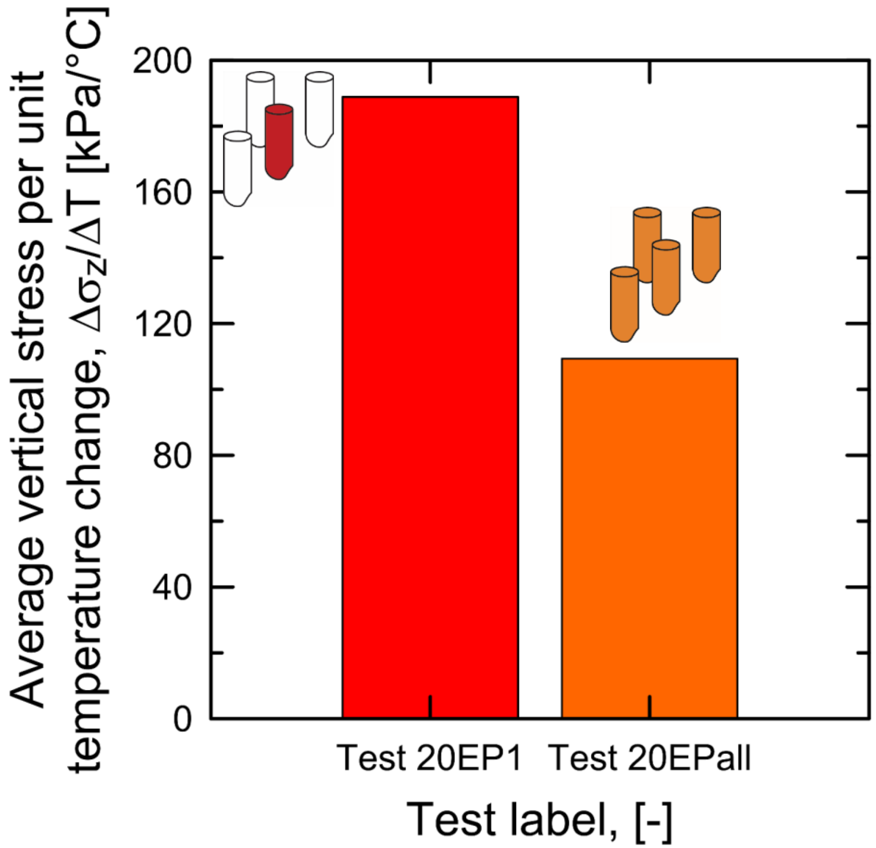
(Rotta Loria and Laloui, 2018)

Effect of thermally active energy piles

$$\Delta\varepsilon_z = \Delta\varepsilon_o^{th} = \Delta\varepsilon_b^{th} + \Delta\varepsilon_f^{th} = \Delta\varepsilon_b^{th} - \alpha\Delta T$$

$$\Delta\sigma_z = \Delta\sigma_o^{th} = E\Delta\varepsilon_b^{th} = E(\Delta\varepsilon_o^{th} - \Delta\varepsilon_f^{th}) = E(\Delta\varepsilon_o^{th} + \alpha\Delta T)$$





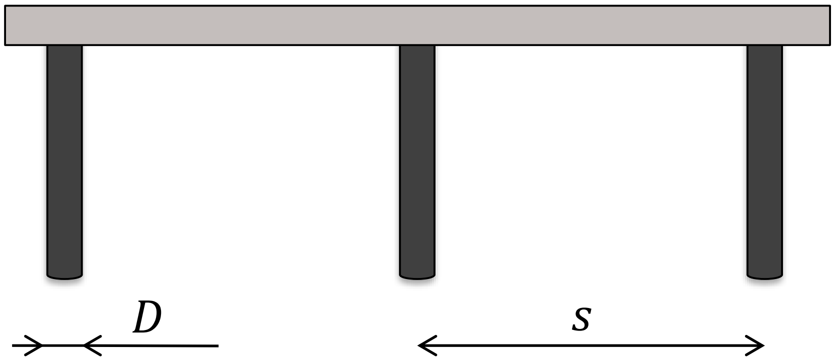
(Rotta Loria and Laloui, 2018)

Axial capacity of energy pile groups

Considerations

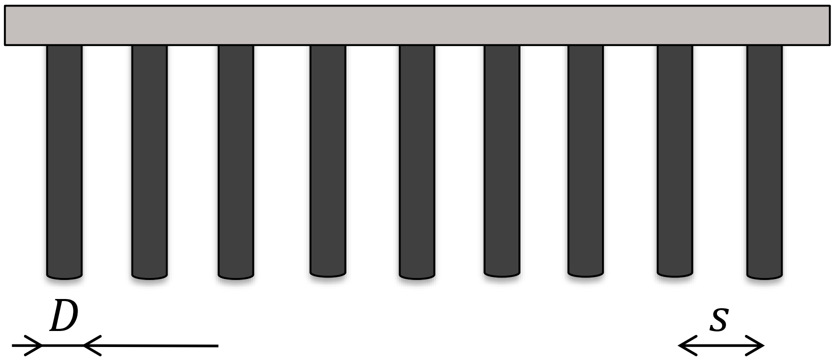
- Piles may fail as if they were single isolated elements
- Group capacity is equal to sum of individual pile capacities
- Block failure is unlikely to occur

$$\frac{s}{D} > 8$$



- Piles may fail as a block
- Group capacity is different than sum of individual pile capacities
- Both block and group capacities need to be assessed

$$\frac{s}{D} \leq 8$$



Block capacity formulation

- Critical for $s/D < 3$

$$Q_{u,b} = q_{s,g}A_{g,s} + q_{b,g}A_g - W_g$$

- where:
  - $q_{s,g}$ = shaft resistance for block failure of the pile group
  - $A_{g,s}$ = area of the block shaft
  - $q_{b,g}$ = base resistance for block failure of the pile group
  - A_g = plan area of the block (area of soil and piles delimited by the simplest polygon that best reproduces the group shape)
  - W_g = weight of the pile group

Block capacity formulation

$$Q_{u,b} = q_{s,g}A_{g,s} + q_{b,g}A_g - W_g = \overline{\sigma'}_v K_0 \tan\varphi' \, A_{g,s} + (\sigma'_{vb} N_q + \frac{1}{2}\gamma' L_g N_\gamma) A_g - W_g$$

- where:
  - $\overline{\sigma'}_v$ = average value of the effective vertical stress with depth
  - K_0 = coefficient of earth pressure at rest
  - φ' = soil angle of shear strength
  - σ'_{vb} = vertical effective stress at the level of the pile base
  - γ' = buoyant unit weight
  - L_g = width of the pile group in plan view
  - N_q and N_γ are bearing capacity factors

Likelihood of block failure

(Fleming et al., 2008)

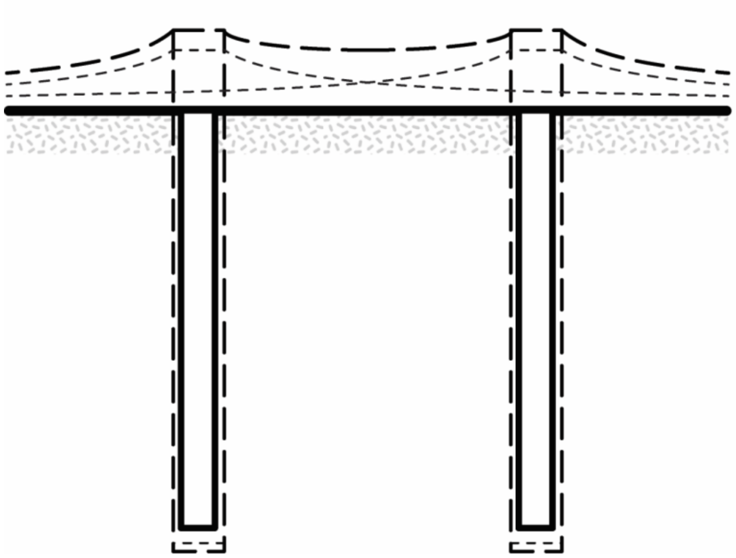
- The settlement needed to mobilise the base capacity of the block is usually very large (e.g., 5 to 10% of the width of the group).
- Block failure is more likely to occur for groups of long slender piles at a particular spacing than for groups consisting of a few short stubby piles at the same spacing
- Group failure is less likely for piles in sand (where $q_{b,g}/q_{s,g}$ usually varies from 50 to 200) than for piles in clay (where $q_{b,g}/q_{s,g}$ usually varies from 10 to 20)

Thermo-mechanical modelling of energy pile groups

Effects produced by mechanical interactions

- Interaction between the displacement fields of piles implies an increased displacement of each pile compared to an isolated case

- In other words, interaction implies an increased group deformation

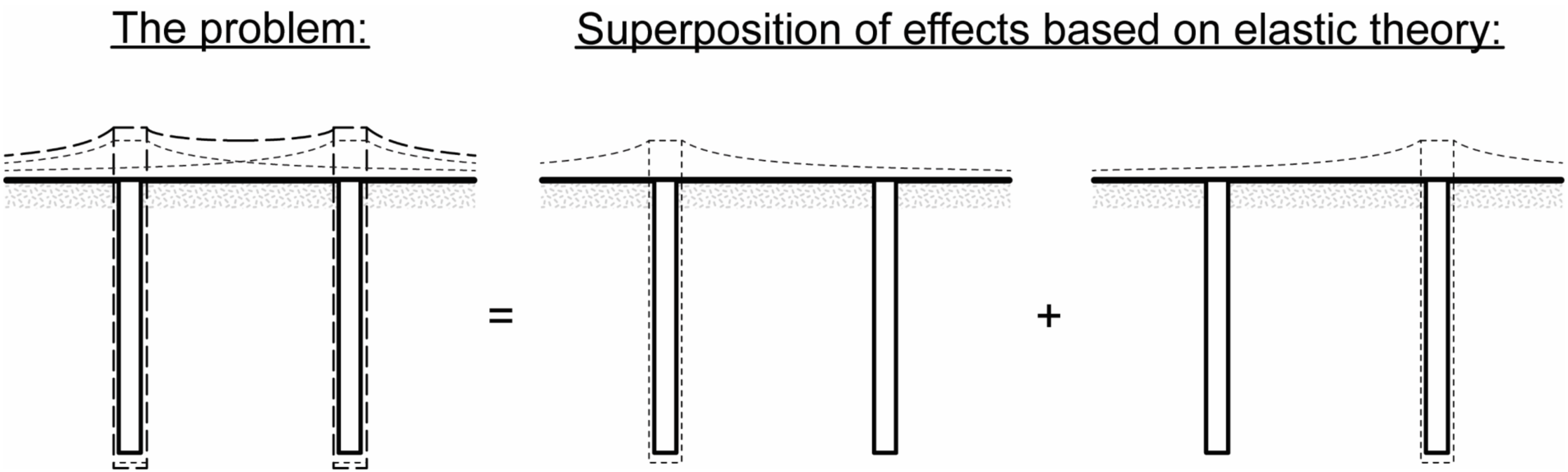


- Because under the same average load a greater strain is developed, lower stress characterises piles for greater number of loaded piles

(Rotta Loria and Laloui, 2017)

Interaction factor method

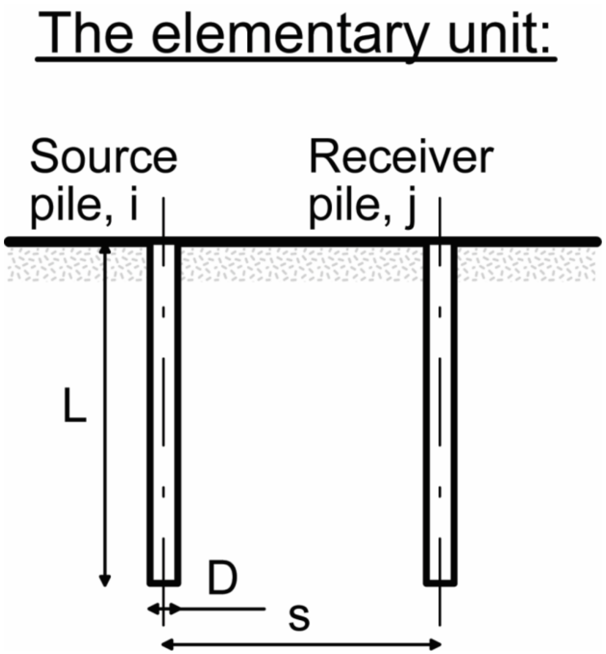
The problem, hypotheses and approach of solution



- Analysis of pile groups based on consideration of two identical piles in a deep, uniform, isotropic and homogeneous soil mass
- No slip between pile and soil considered
- Thermo-elastic conditions
- Infinitely flexible slab considered

(Poulos, 1968)
(Randolph and Wroth, 1979)
(Mylonakis and Gazetas, 1998)
(Rotta Loria and Laloui, 2016)

Displacement interaction factor for energy piles



$$\Omega = \frac{\text{additional displacement due to adjacent pile}}{\text{displacement of single pile alone}} = \frac{w_j}{w_i}$$

(Rotta Loria and Laloui, 2016)

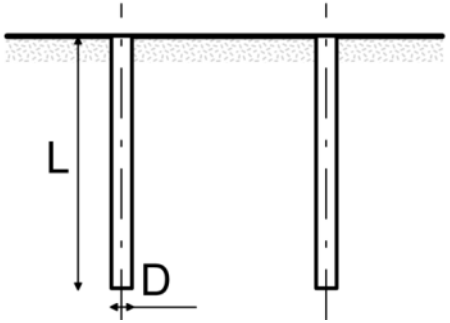
Application of the interaction factor method

1. Analysis of single isolated pile

$$w_1$$

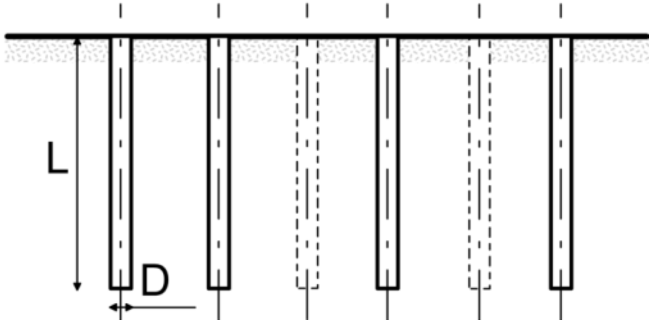
2. Definition of interaction factor for a pair of piles

$$\Omega$$



3. Analytical analysis of general pile groups

$$w_k = w_1 \sum_{i=1}^{i=n_{EP}} \Delta T_i \ \Omega_{ik}$$



(Rotta Loria and Laloui, 2016)

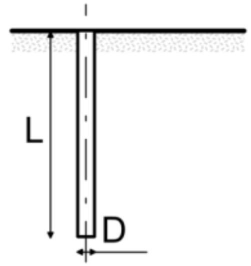
Methods to define the interaction factor:

analytical models

Procedure

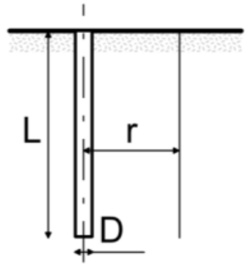
1. Analysis of single isolated pile

$$w_i(z), \tau(z)$$



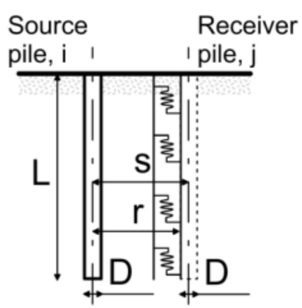
2. Definition of vertical displacement of soil and approximate interaction factor

$$w(r, z) \quad \tilde{\Omega}(r, z) = \frac{w(r, z)}{w_i(z)}$$



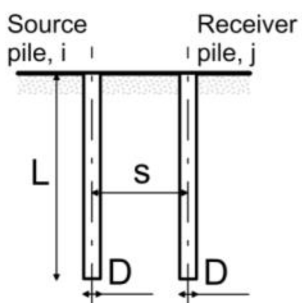
3. Analysis of vertical displacement of receiver pile

$$w_j(s, z)$$



4. Definition of corrected interaction factor

$$\Omega(s, z) = \frac{w_j(s, z)}{w_i(z)}$$

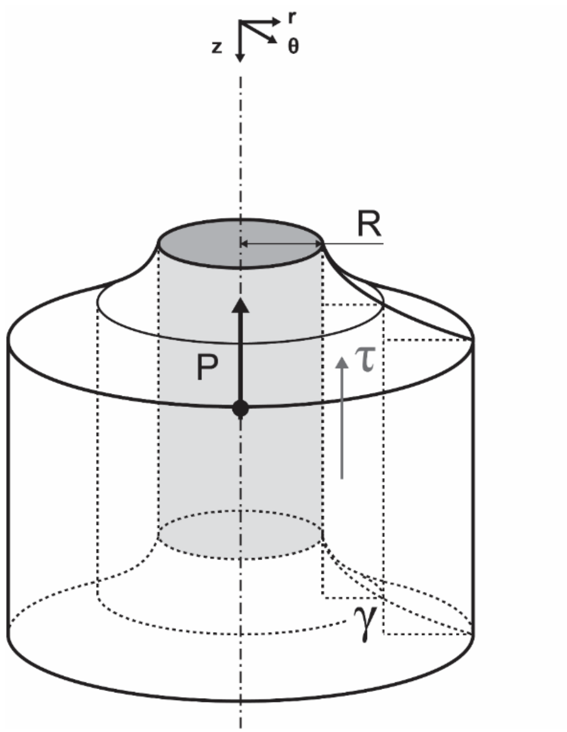


(Rotta Loria and Laloui, 2016)

Analytical models

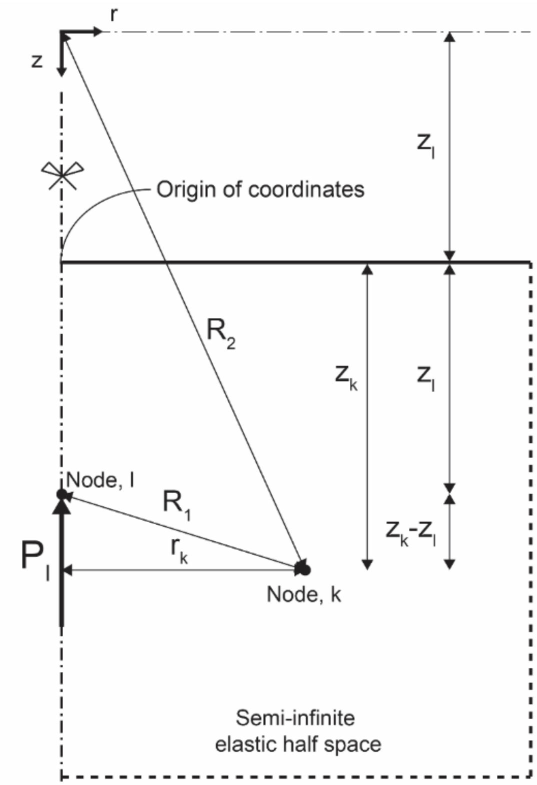
(Randolph and Wroth, 1979; Rotta Loria and Laloui, 2018)

1 Layer model:



$$w(r,z) = w_i(z) - \frac{\tau_i(z)R}{G_{soil}} \ln\left(\frac{r}{R}\right)$$

2 Continuous model:



$$w(r,z) = \sum_{l=1}^{m} \frac{P_l}{16\pi G_{soil}(1-\nu_{soil})} f(\nu_{soil}, R_1, R_2)$$

Layer model and approximate pile-soil interaction factor

The soil around the shaft of piles consists of concentric cylindrical elements, with shear stresses distributed on their surface

The vertical equilibrium equation for a pile is

$$\frac{\partial \tau}{\partial r} + \frac{\tau}{r} = 0$$

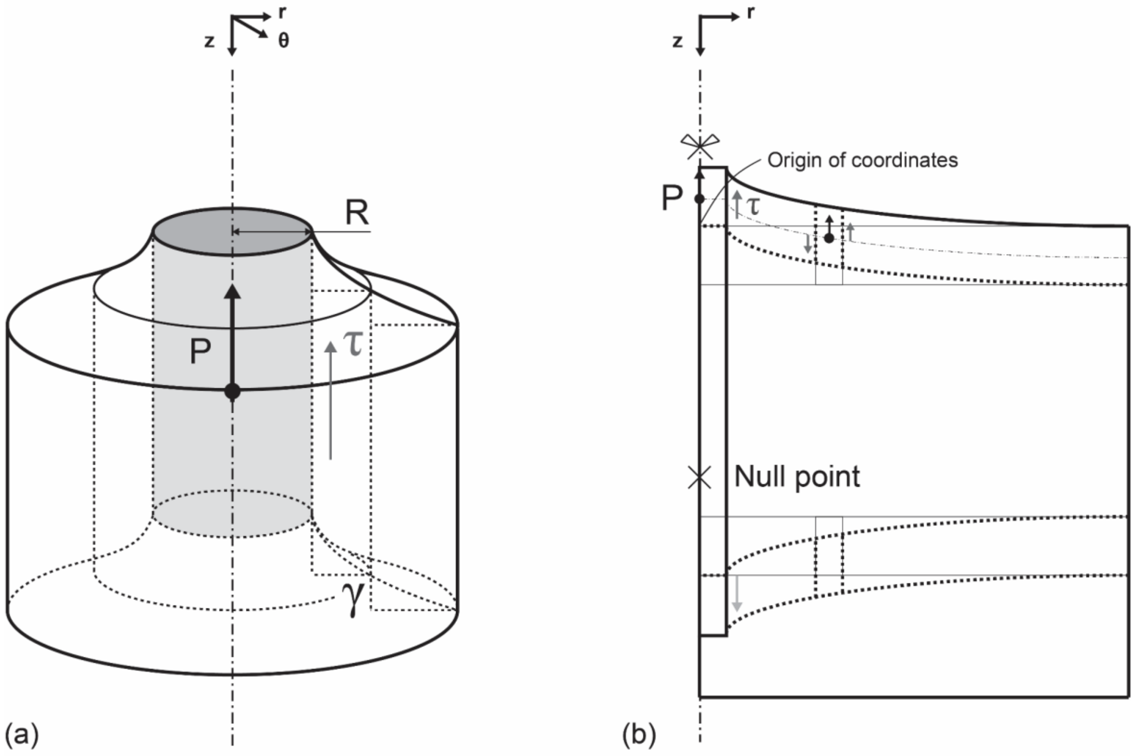
The shear stress is

$$\tau(r,z) = \frac{\tau_i(z)R}{r}$$

The shear strain is

$$\gamma = \frac{\partial w}{\partial r} + \frac{\partial u}{\partial z} = -\frac{\tau}{G_{soil}}$$

So $$\frac{\partial w}{\partial r} = -\frac{\tau_i(z)R}{rG_{soil}}$$

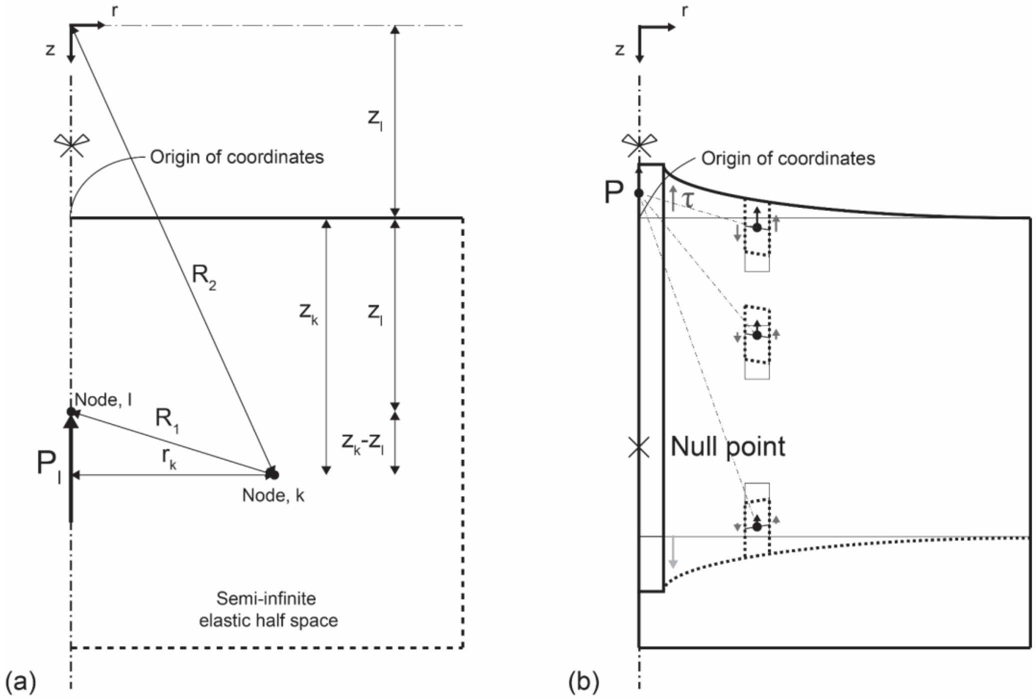


$$w(r,z) = w_i(z) - \frac{\tau_i(z)R}{G_{soil}} \ln\left(\frac{r}{R}\right)$$

(Randolph and Wroth, 1979; Rotta Loria and Laloui, 2017)

Continuous model and approximate pile-soil interaction factor

The distribution of the shear stresses at the pile shaft is approximated as a distribution of point loads described by Mindlin (1936)



(Rotta Loria and Laloui, 2017)

$$w(r,z) = \sum_{l=1}^{m} w_{kl}$$

$$= \sum_{l=1}^{m} \frac{P_l}{16\pi G_{soil}(1-\nu_{soil})}\left(\frac{3-4\nu_{soil}}{R_1} + \frac{8(1-\nu_{soil})^2-(3-4\nu_{soil})}{R_2} + \frac{(z_l-z_k)^2}{R_1^3} + \frac{(3-4\nu_{soil})(z_l+z_k)^2-2z_lz_k}{R_2^3} + \frac{6z_lz_k(z_l+z_k)^2}{R_2^5}\right)$$

Displacement of receiver pile

Knowledge of the displacement field in the soil allows the displacement of a receiver pile to be approximately determined

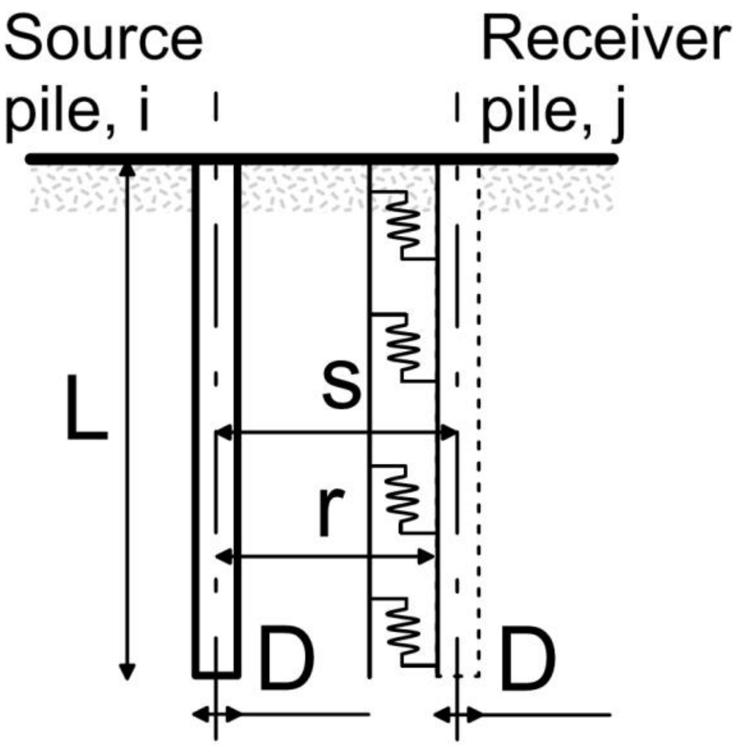
Equilibrium of a pile element gives

$$\frac{\partial^2 w_j}{\partial z^2} - \lambda_{lt}^2 \left(w(r,z) - w_j(s,z) \right) = 0$$

$$\lambda_{lt} = \sqrt{\frac{\pi D K_s}{A_{EP} E_{EP}}}$$

Boundary conditions

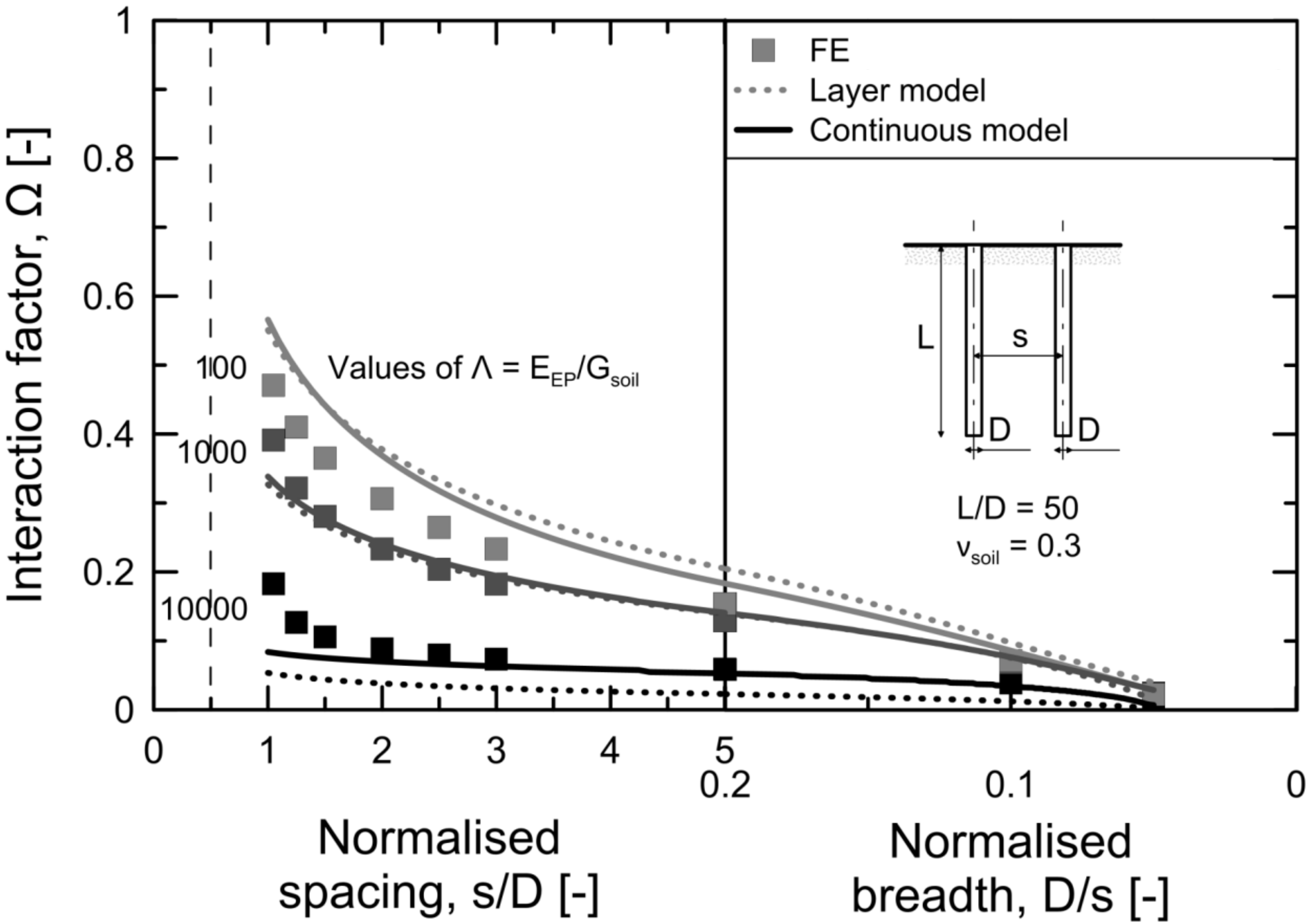
$$\left. \frac{\partial w_j}{\partial z} \right|_{z=0} = 0 \qquad w_j\left(s, z = z\big|_{\tau=0} \right) = w\left(r, z = z\big|_{\tau=0}\right)$$



(Mylonakis and Gazetas, 1998; Rotta Loria and Laloui, 2017)

Corrected pile-soil-pile interaction factor

(Rotta Loria and Laloui, 2017)

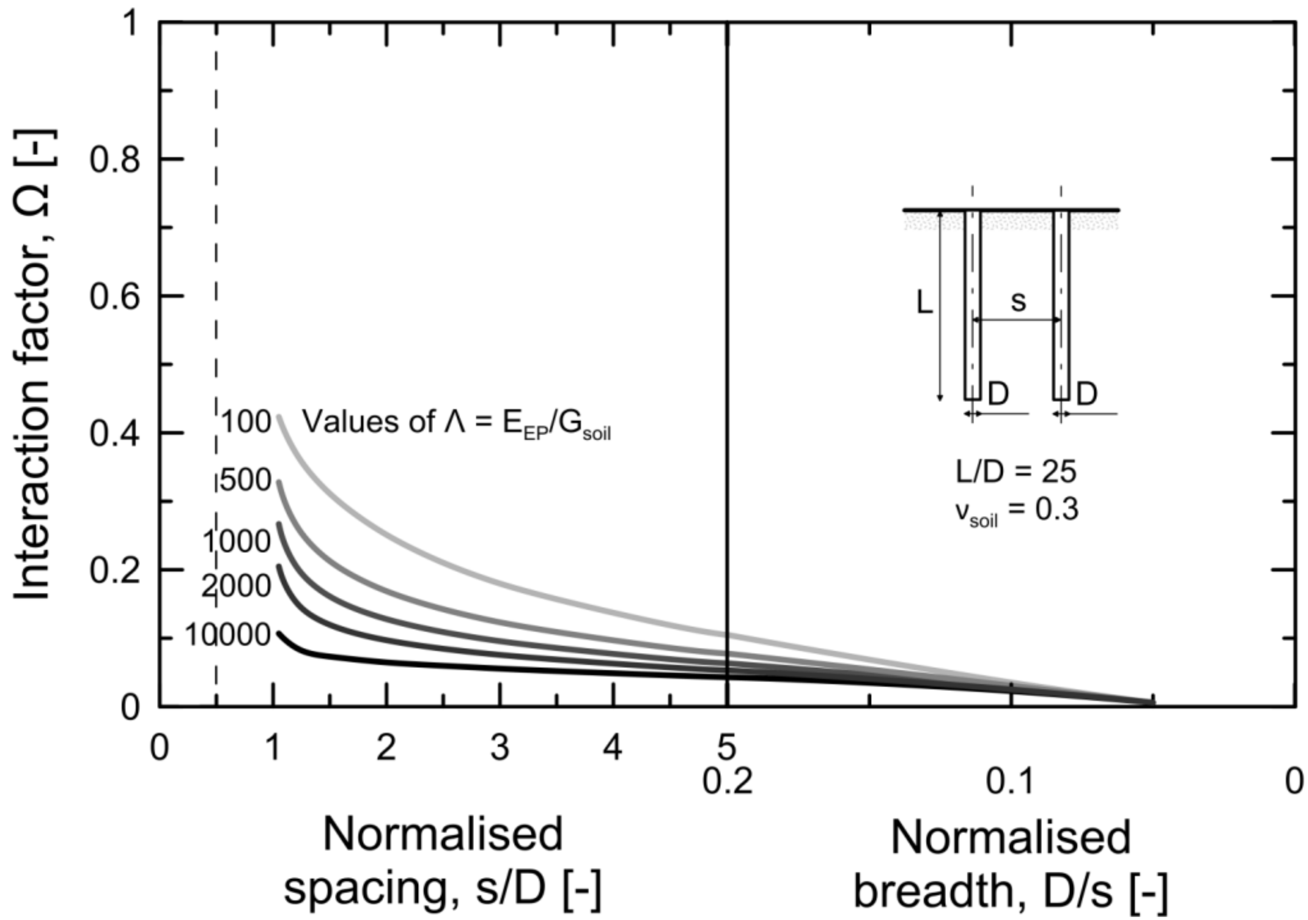


Methods to define the interaction factor:

design charts

Evolution of interaction factor with horizontal distance

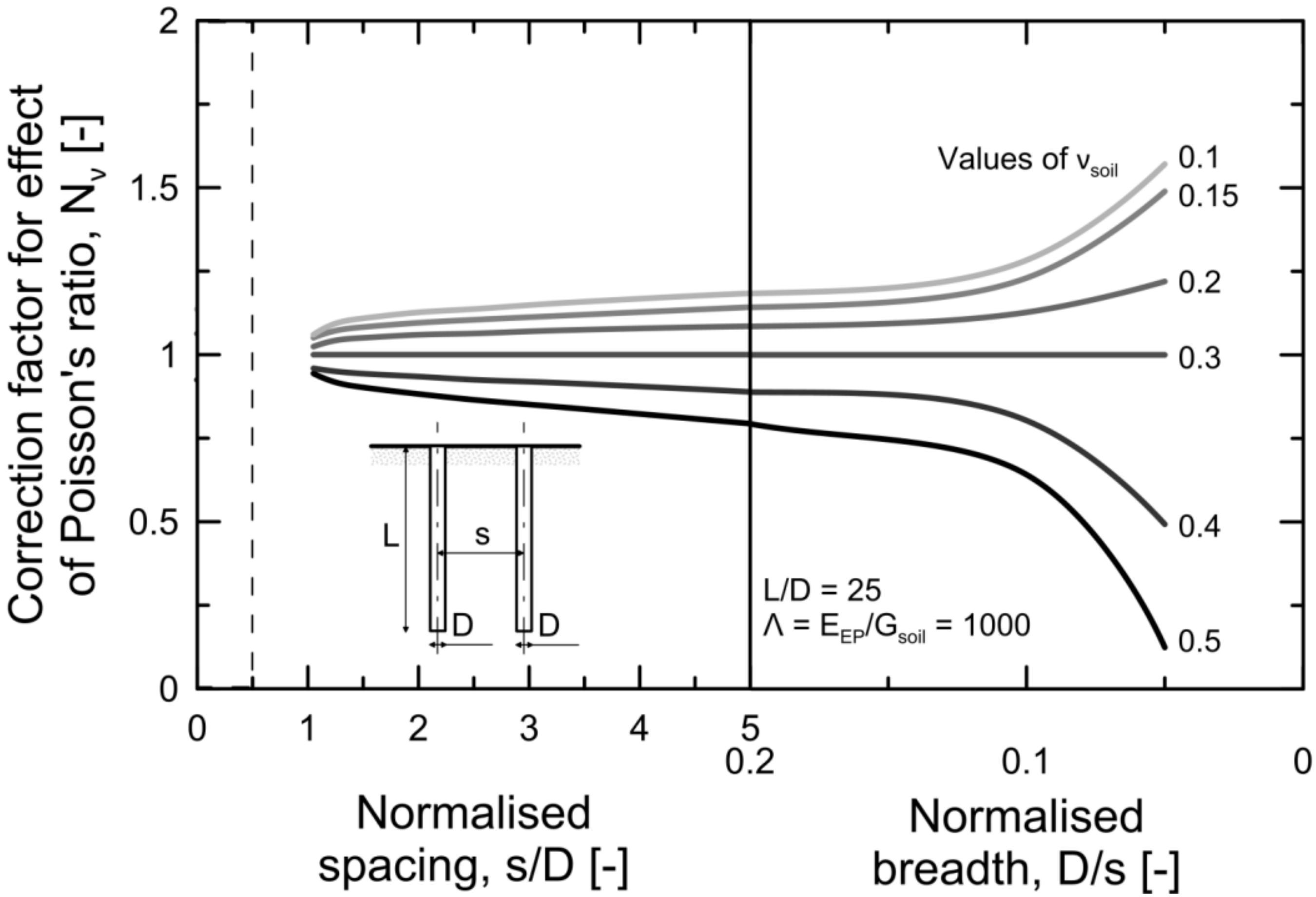
(Rotta Loria and Laloui, 2016)



- Increasing interaction with: decreasing *s*
  increasing L_{EP}/D_{EP}
  decreasing E_{EP}/G_{soil}

Effect of Poisson's ration of soil

(Rotta Loria and Laloui, 2016)

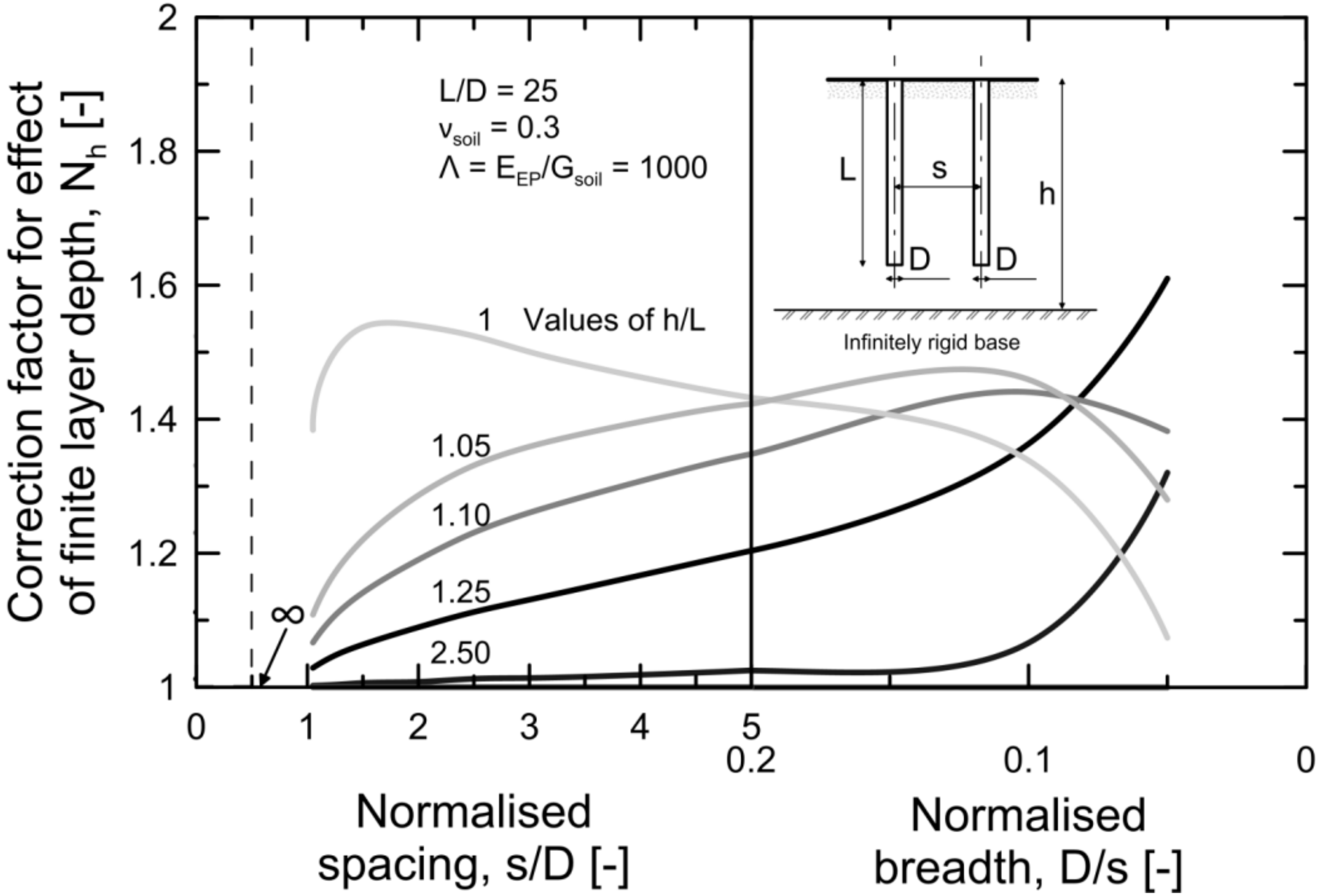


- Increasing interaction with decreasing ν_{soil}

$$\Omega = \Omega_{\nu=0.3} N_\nu$$

Effect of finite layer depth

(Rotta Loria and Laloui, 2016)

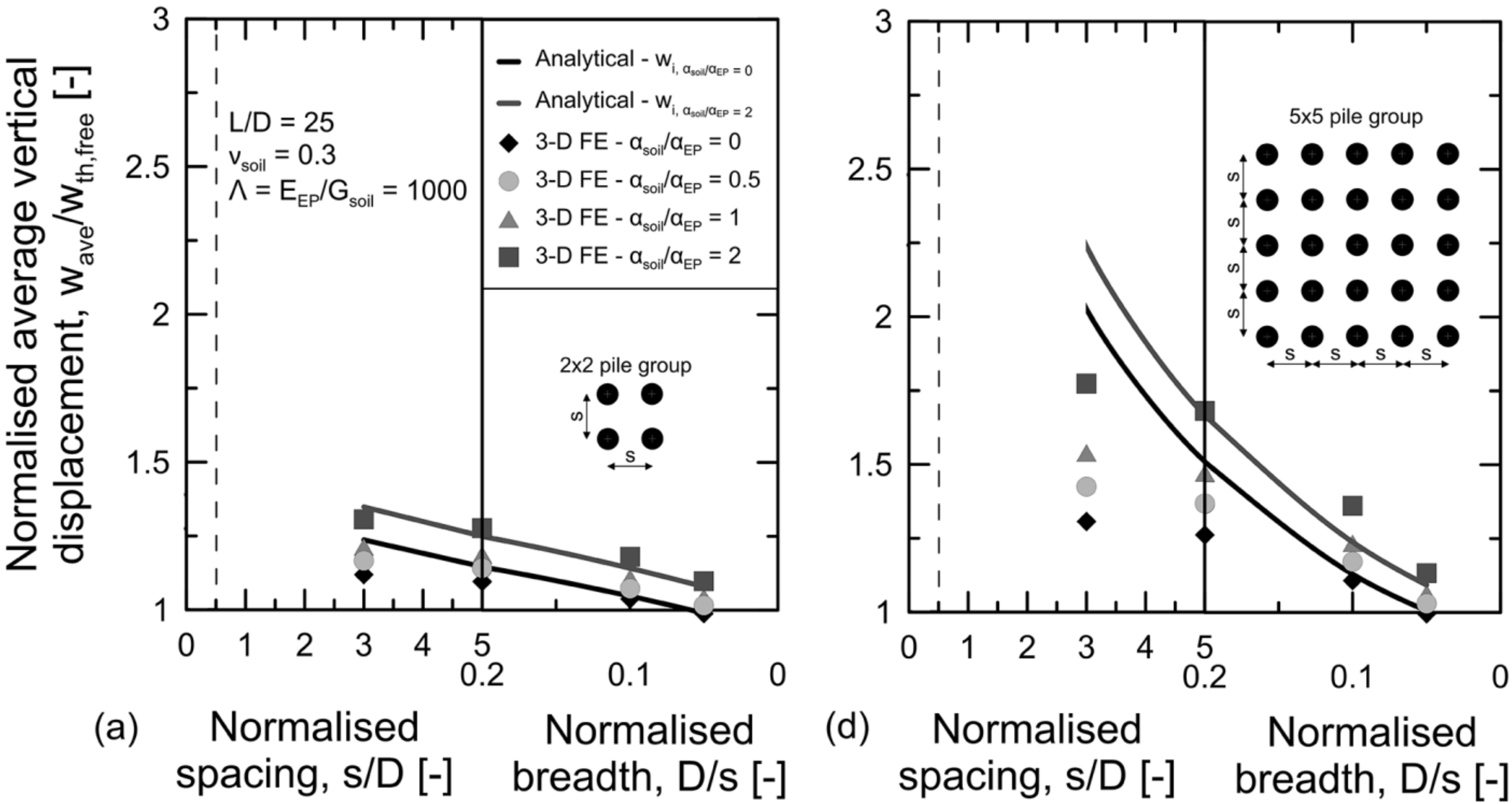


- Increasing interaction with decreasing h/L_{EP}

$$\Omega = \Omega_{h/L_{ep} \to \infty} N_h$$

Application and validation of the interaction factor method

(Rotta Loria and Laloui, 2016)

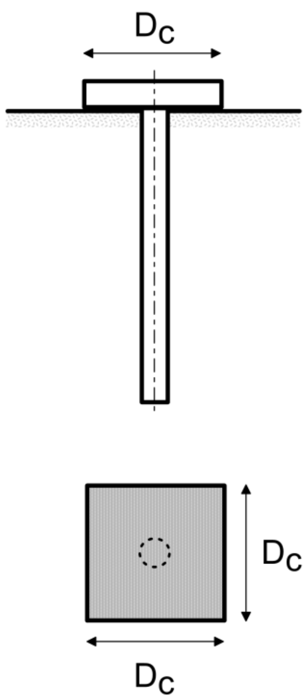


Method suggested for s/D ≥ 3 and certainly for s/D ≥ 5

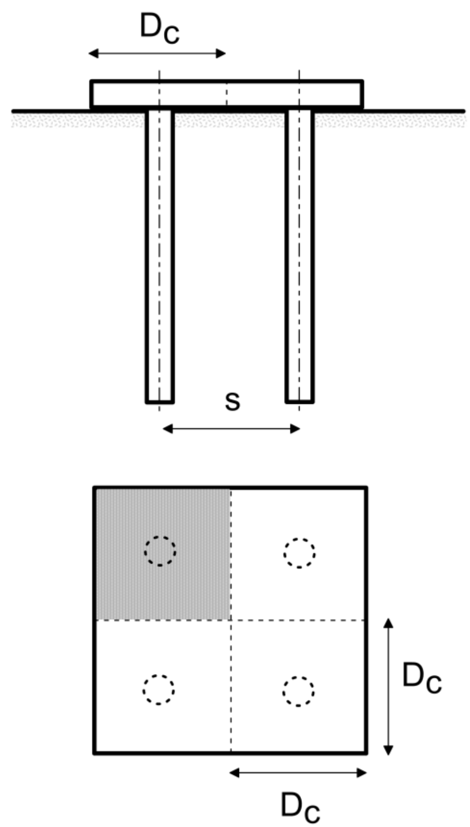
Interaction factor method for energy pile groups with slab

The problem, hypotheses and approach of solution

Pile-cap unit



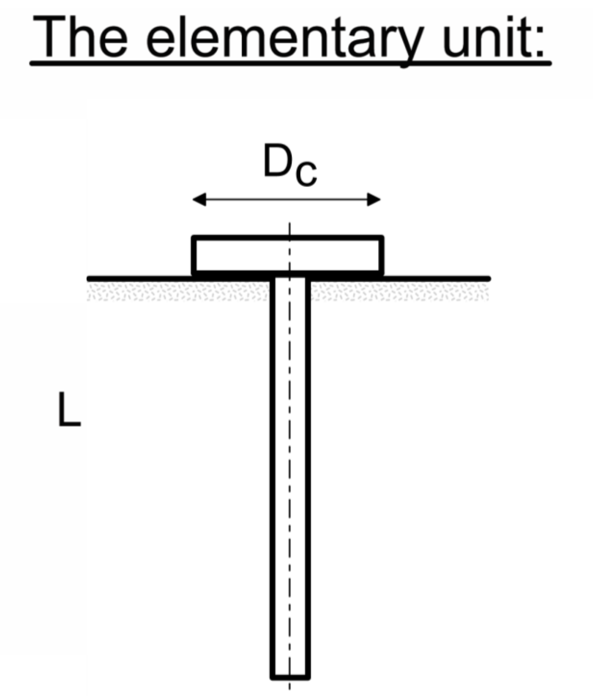
Analysis of general systems



- The pile-cap unit may be seen as the simplest system representing an energy pile group with slab.
- No slip between pile and soil considered
- Thermo-elastic conditions
- Influence of the slab

(Ravera et al., 2019)

Pile-cap Displacement ratio



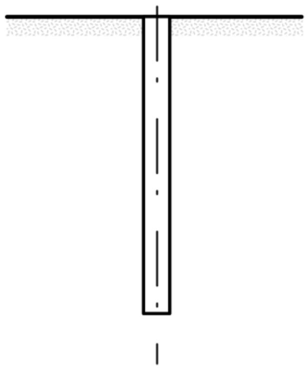
$$R_C = \frac{\text{displacement of pile with cap}}{\text{displacement of freestanding pile}}$$

(Ravera et al., 2019)

Application of the modified interaction factor method

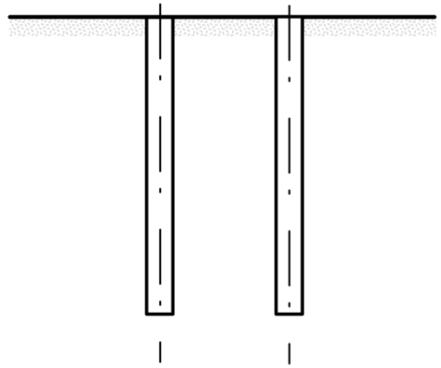
1. Analysis of single isolated pile

w_1



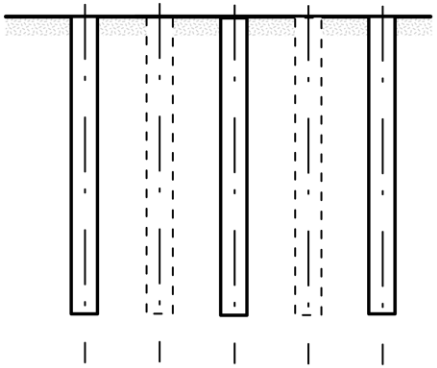
2. Definition of the interaction factor for a pair of piles

Ω



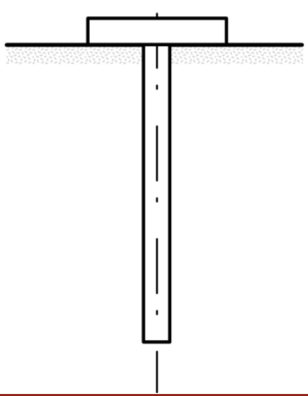
3. Analytical analysis of general pile groups

$$w_k = w_1 \sum_{i=1}^{i=n_{EP}} \Delta T_i \Omega_{ik}$$



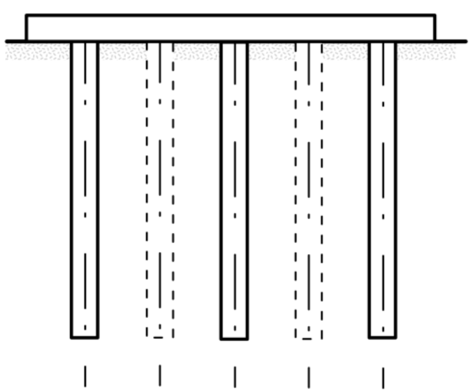
4. Definition of the pile-cap displacement ratio

R_c



5. Correction of the displacement in free-standing conditions considering a contacting slab

$$w_k = R_c \, w_1 \sum_{i=1}^{i=n_{EP}} \Delta T_i \Omega_{ik}$$

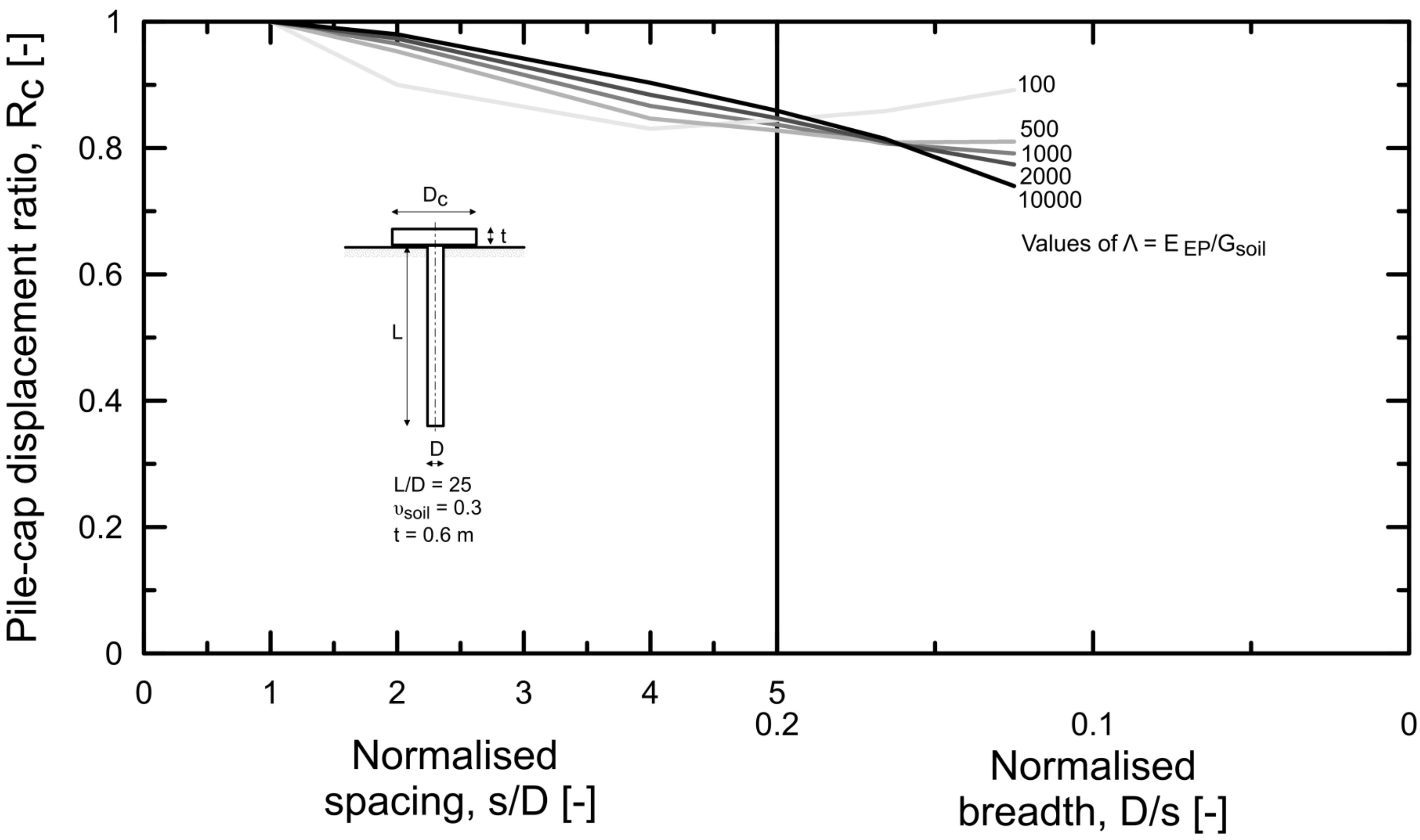


(Ravera et al., 2019)

Methods to define the pile-cap displacement ratio: design charts

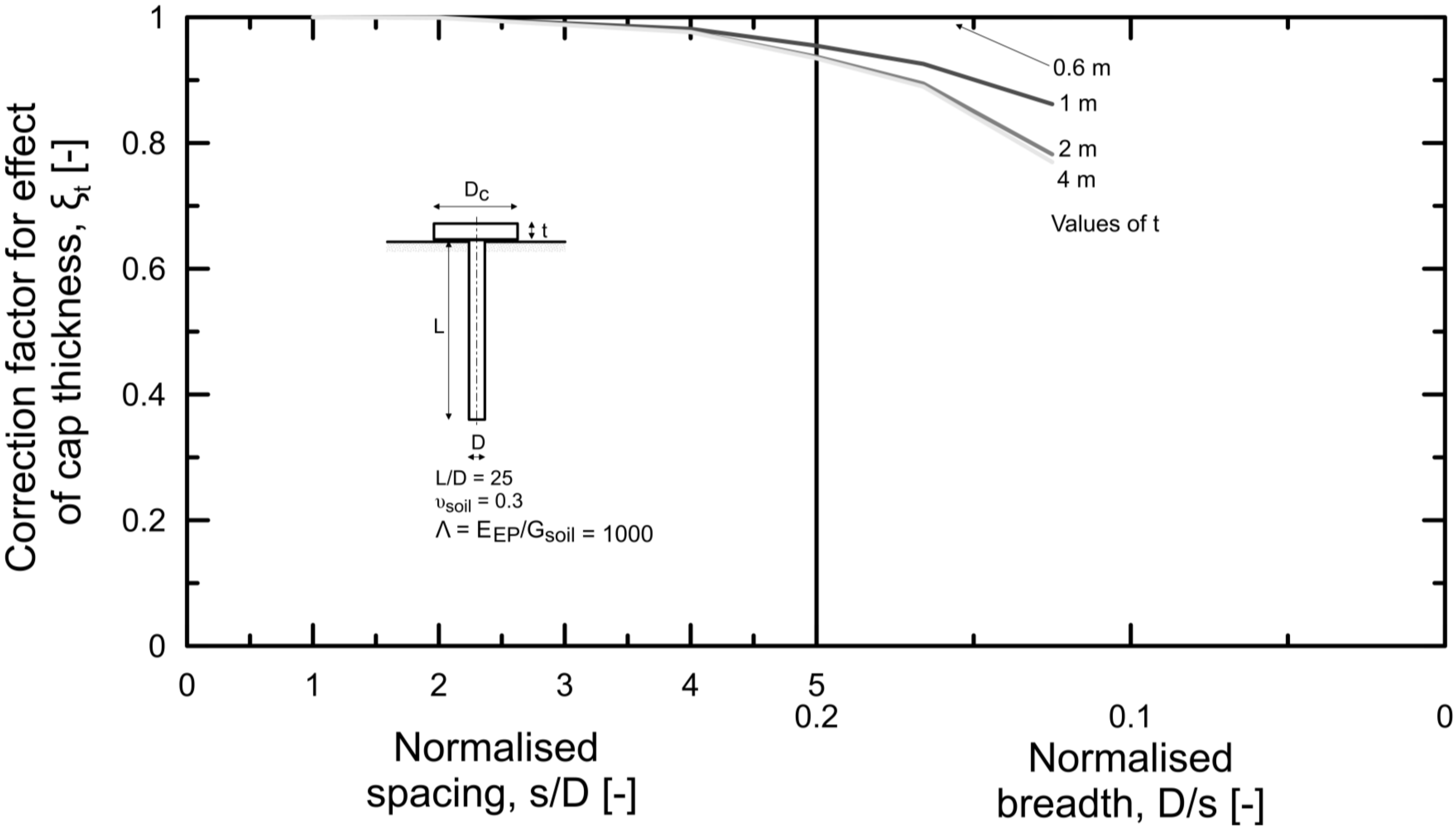
Evolution with horizontal distance

(Ravera et al., 2019)



Effect of cap thickness

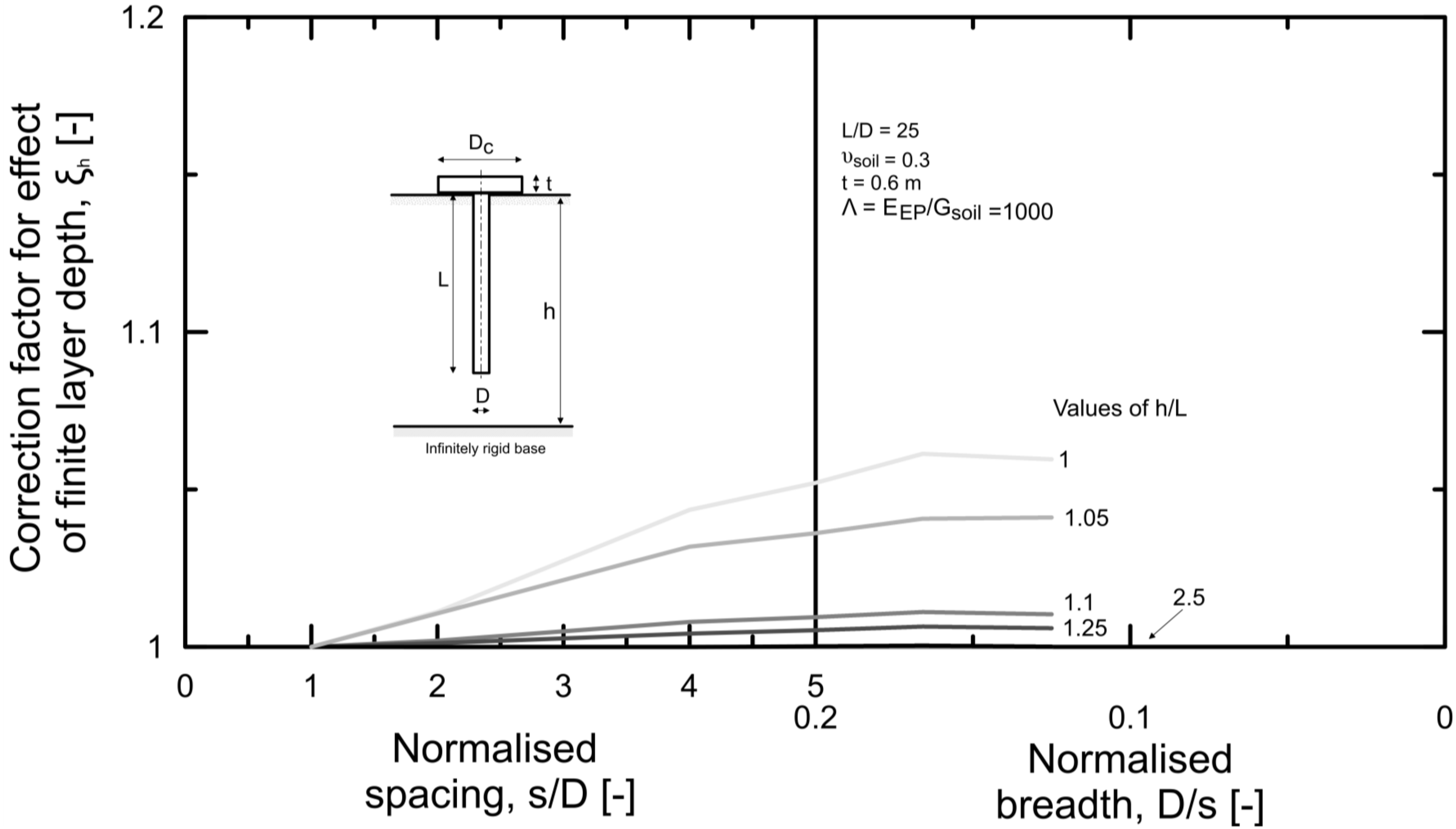
(Ravera et al., 2019)



$$R_C = \xi_t R_{C,\, t=0.6\ m}$$

Effect of finite layer depth

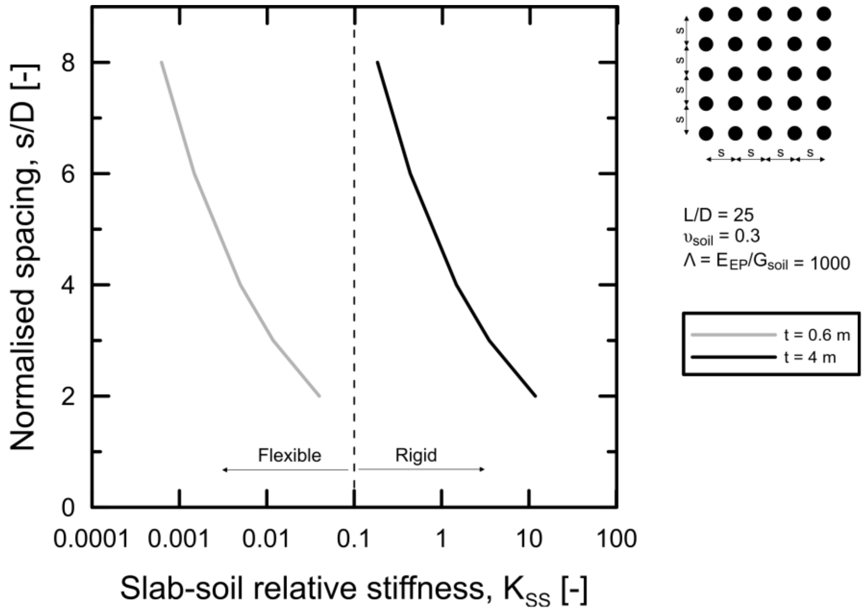
(Ravera et al., 2019)

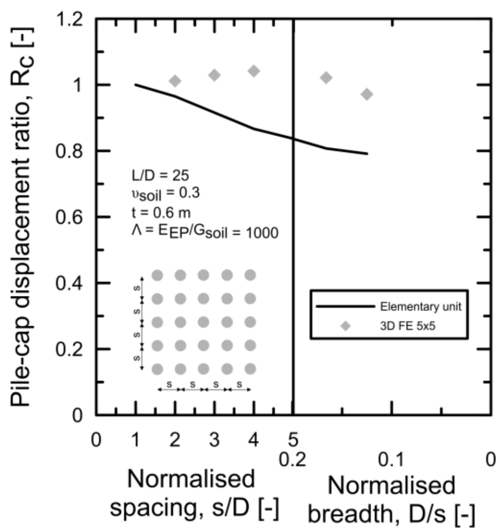


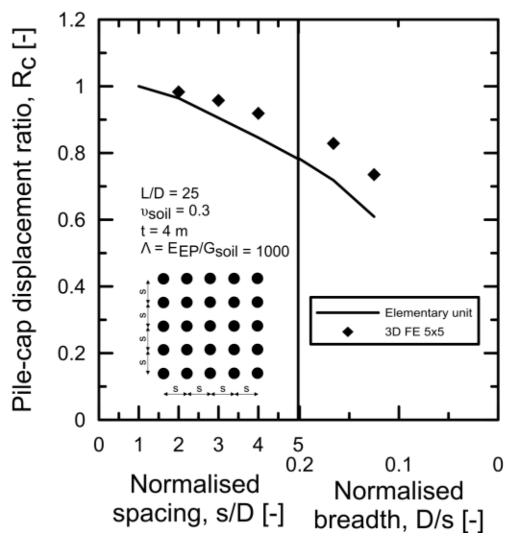
$$R_C = \xi_h R_{C,\, h/L \rightarrow \infty}$$

Application and validation of the interaction factor method

(Ravera et al., 2019)







Equivalent pier method

The problem, hypotheses and approach of solution

- The method consists in considering any pile group as a single equivalent pier (Poulos and Davis, 1980)

- The method aims at estimating the average displacement of any regular (e.g., square) pile group

- The method can be applied for aspect ratios of the group $AR < 4$ (Randolph, 1994) and for spacing between the piles $s/D \leq 5$ (Poulos, 2002)

- The load-displacement response of the equivalent pier is calculated using solutions for the response of a single pile, modified for considering the influence of group effects

Geometrical description of the equivalent pier

(Poulos, 1993)

$$D_{eq} = \frac{2}{\sqrt{\pi}}\sqrt{A_g} = 1.13\sqrt{A_g} \text{ (end-bearing piles)}$$

$$D_{eq} = 1.27\sqrt{A_g} \text{ (floating piles)}$$

$$A_g = A_{t,EP} + A_{soil}$$

$$A_{t,EP} = \pi \frac{D^2}{4} n_{EP}$$

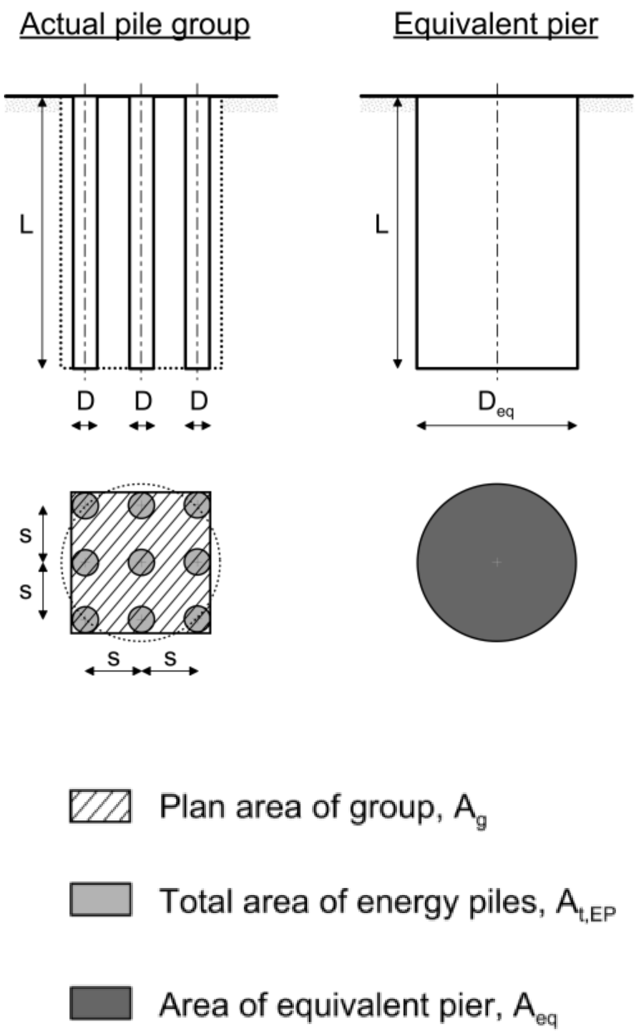
For a square group of energy piles

$$A_g = [(\sqrt{n_{EP}} - 1)s + D]^2$$

(Randolph and Clancy, 1993)

$$A_{eq} = \pi \frac{D_{eq}^{\ 2}}{4}$$

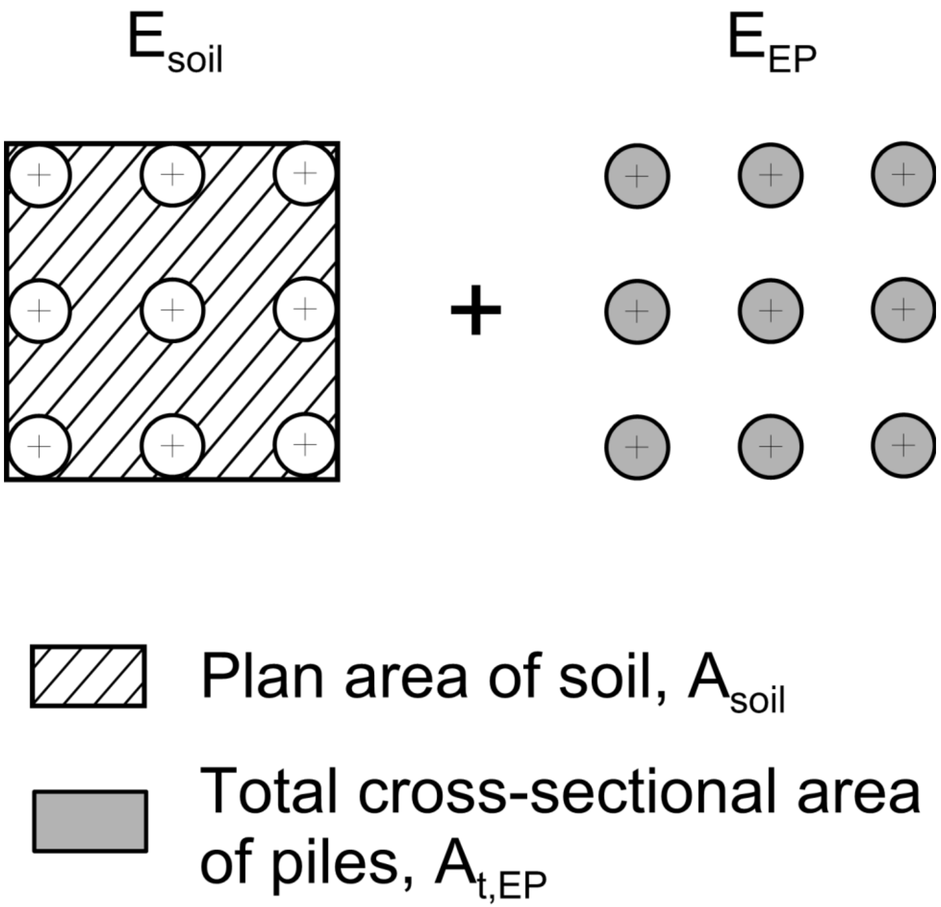
$$AR = \sqrt{\frac{n_{EP}\, s}{L}}$$



Homogenised Young's modulus of the equivalent pier

$$E_{eq} = \frac{A_{t,EP} E_{EP} + A_{soil} E_{soil}}{A_{t,EP} + A_{soil}} = E_{EP} \frac{A_{t,EP}}{A_g} + E_{soil} \left(1 - \frac{A_{t,EP}}{A_g}\right)$$

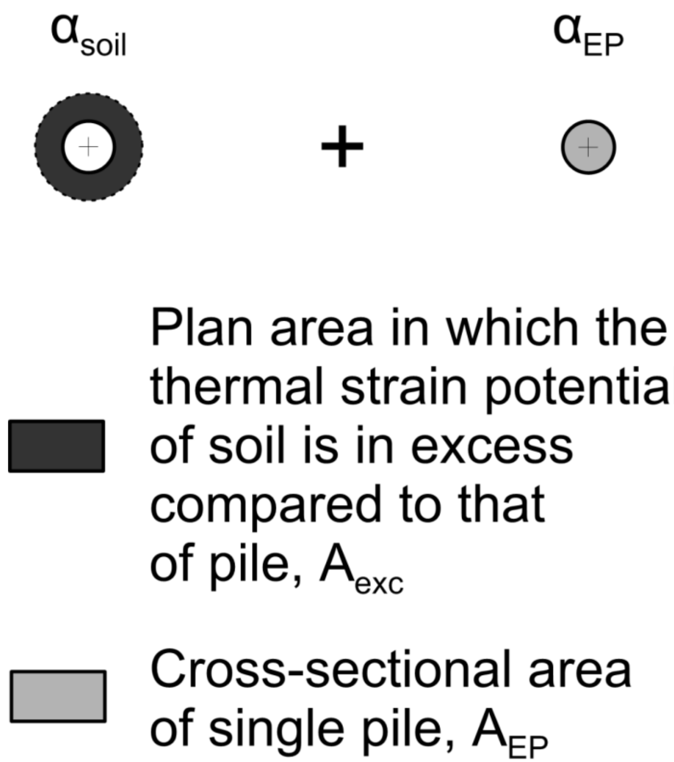
(Poulos, 1993)



Homogenised thermal expansion coefficient of the equivalent pier

$$\alpha_{eq} = \begin{cases} \alpha_{EP} & \text{for } X = \alpha_{soil} / \alpha_{EP} \leq 1 \\ \dfrac{A_{EP}\alpha_{EP} + A_{exc}\alpha_{soil} Y}{A_{EP} + A_{exc}} = \alpha_{EP} \dfrac{A_{EP} + A_{exc} XY}{A_{EP} + A_{exc}} & \text{for } X = \alpha_{soil} / \alpha_{EP} > 1 \end{cases}$$

(Rotta Loria and Laloui, 2017)



Load-displacement relationship

- The degree of interaction between the piles may be quantified by *L/s* (Randolph and Clancy, 1993)

- A stiffness factor to consider the effect of the interactions on the displacement behaviour of a characteristic pile in the group is defined as

$$\zeta = \frac{s}{L}$$

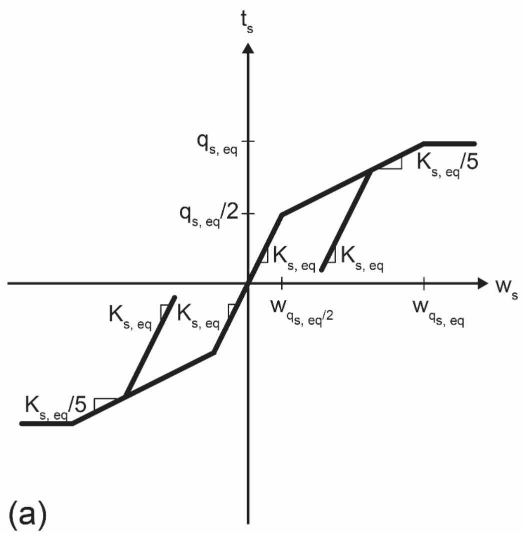
$$K_{s,eq} = \zeta K_s$$

$$K_{b,eq} = \zeta K_b$$

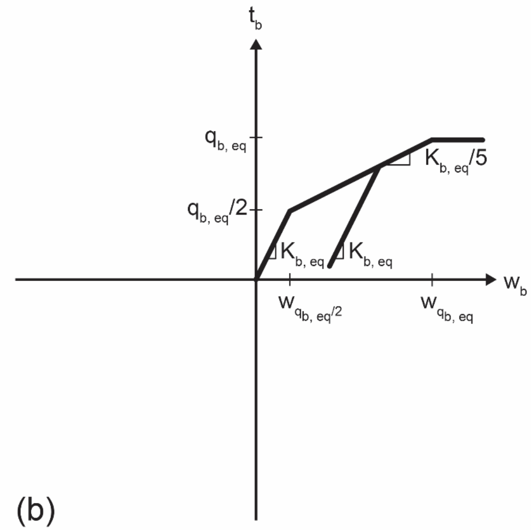
(Rotta Loria and Laloui, 2017)

Load-displacement relationship

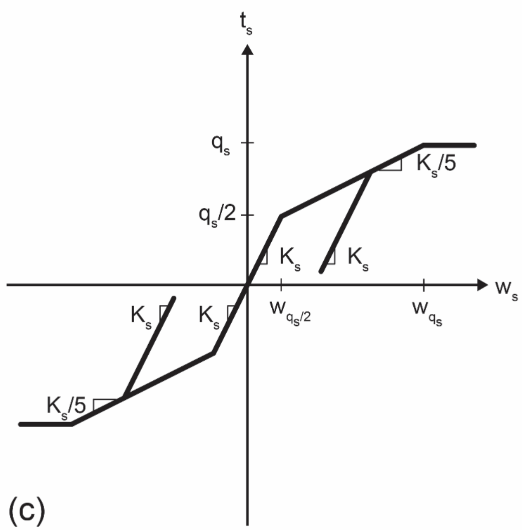
Load-transfer relationship for shaft of equivalent pier



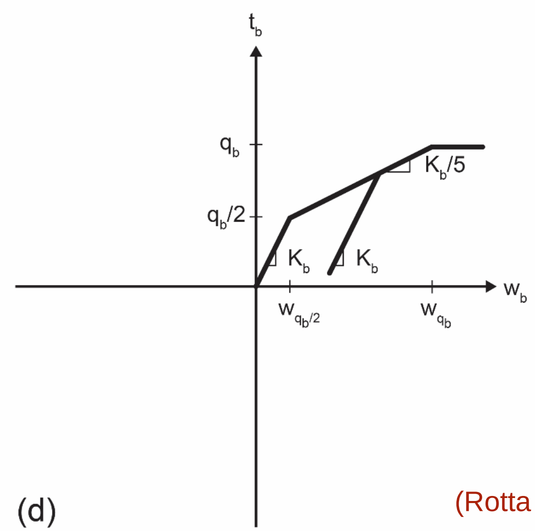
Load-transfer relationship for base of equivalent pier



Load-transfer relationship for shaft of single isolated pile

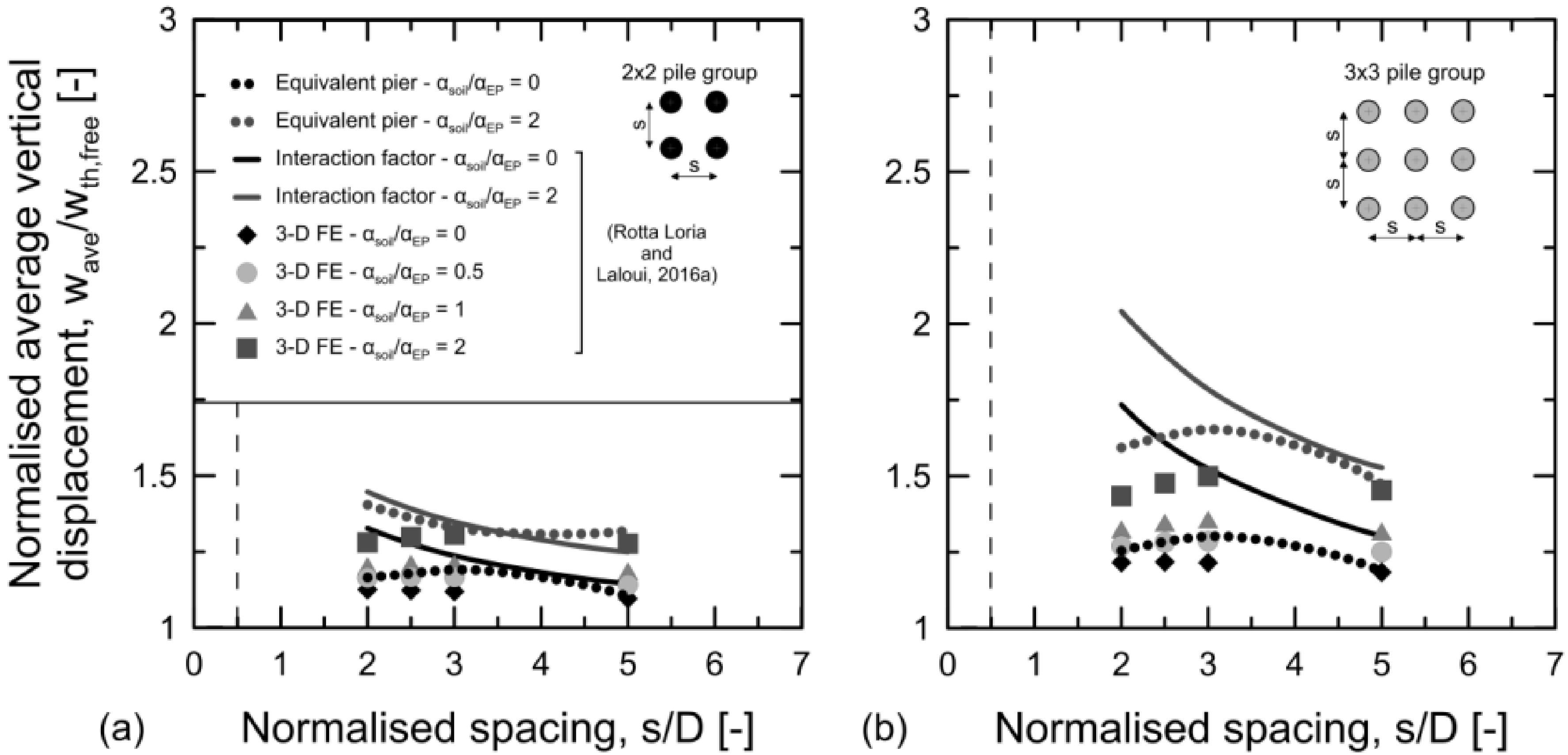


Load-transfer relationship for base of single isolated pile



(Rotta Loria and Laloui, 2017)

Application and validation of the equivalent pier method

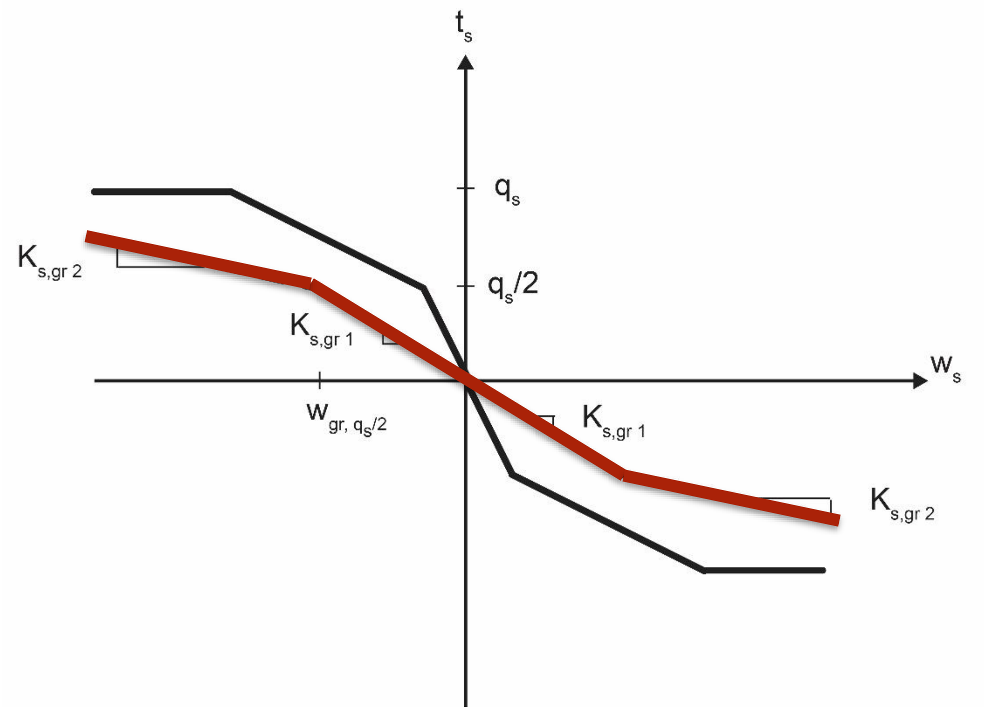


(Rotta Loria and Laloui, 2017)

Load transfer method

The problem, hypotheses and approach of solution

Load-transfer relationship for shaft of single energy pile in a group



$$w_{gr,q_s/2} = R_d \cdot w_{is,q_s/2}$$

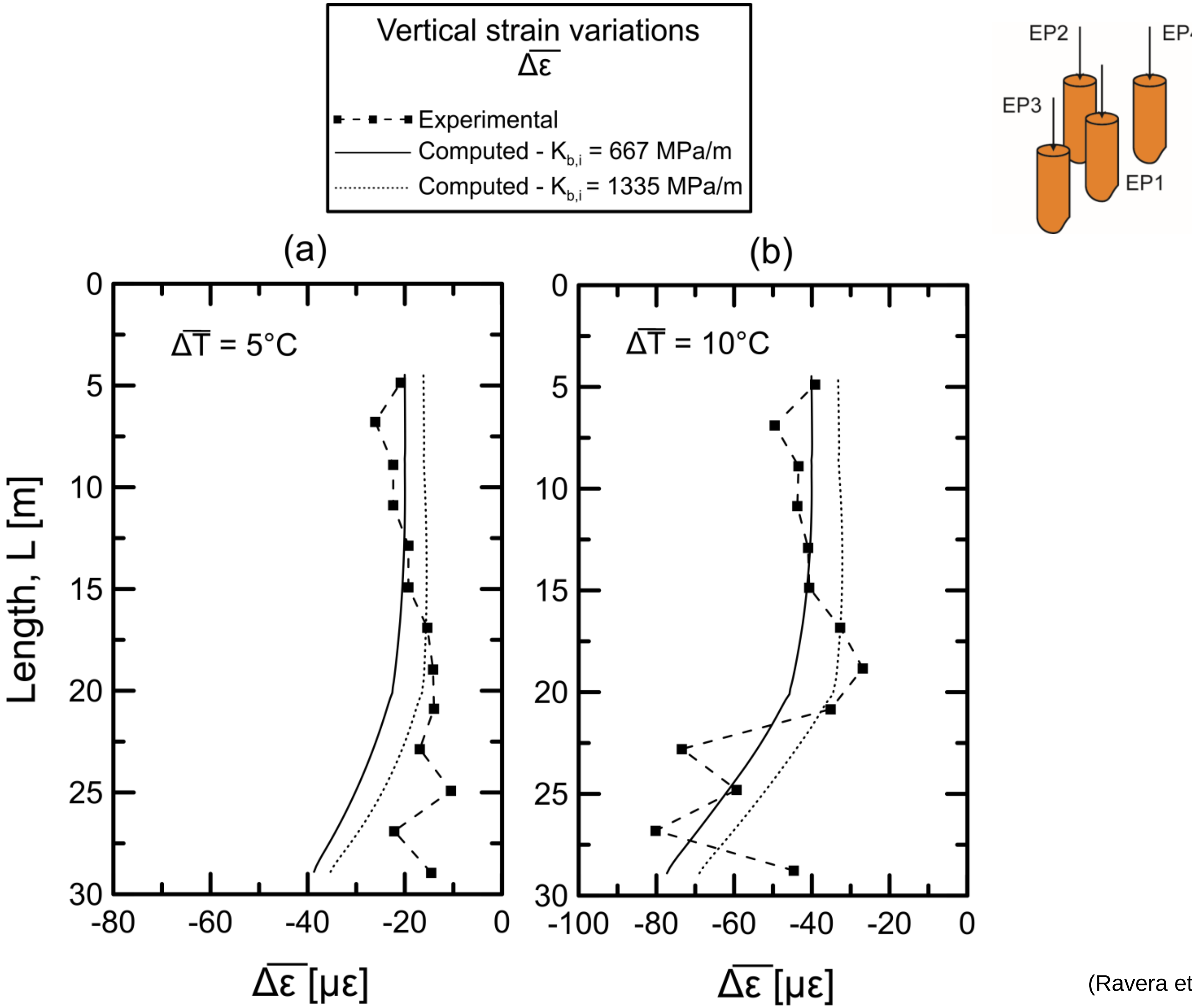
$$t_{s,gr\ 1} = t_{s,1} = \frac{q_s}{2}$$

$$\mathrm{R_d} = \frac{\text{average displacement of group}}{\text{displacement of single pile subjected to same average load}}$$

- Load transfer method to consider mechanical and thermal interactions of energy piles in groups
- Load displacement curve of an energy pile in a group is modified from that of the isolated pile through a displacement factor to account for group effects

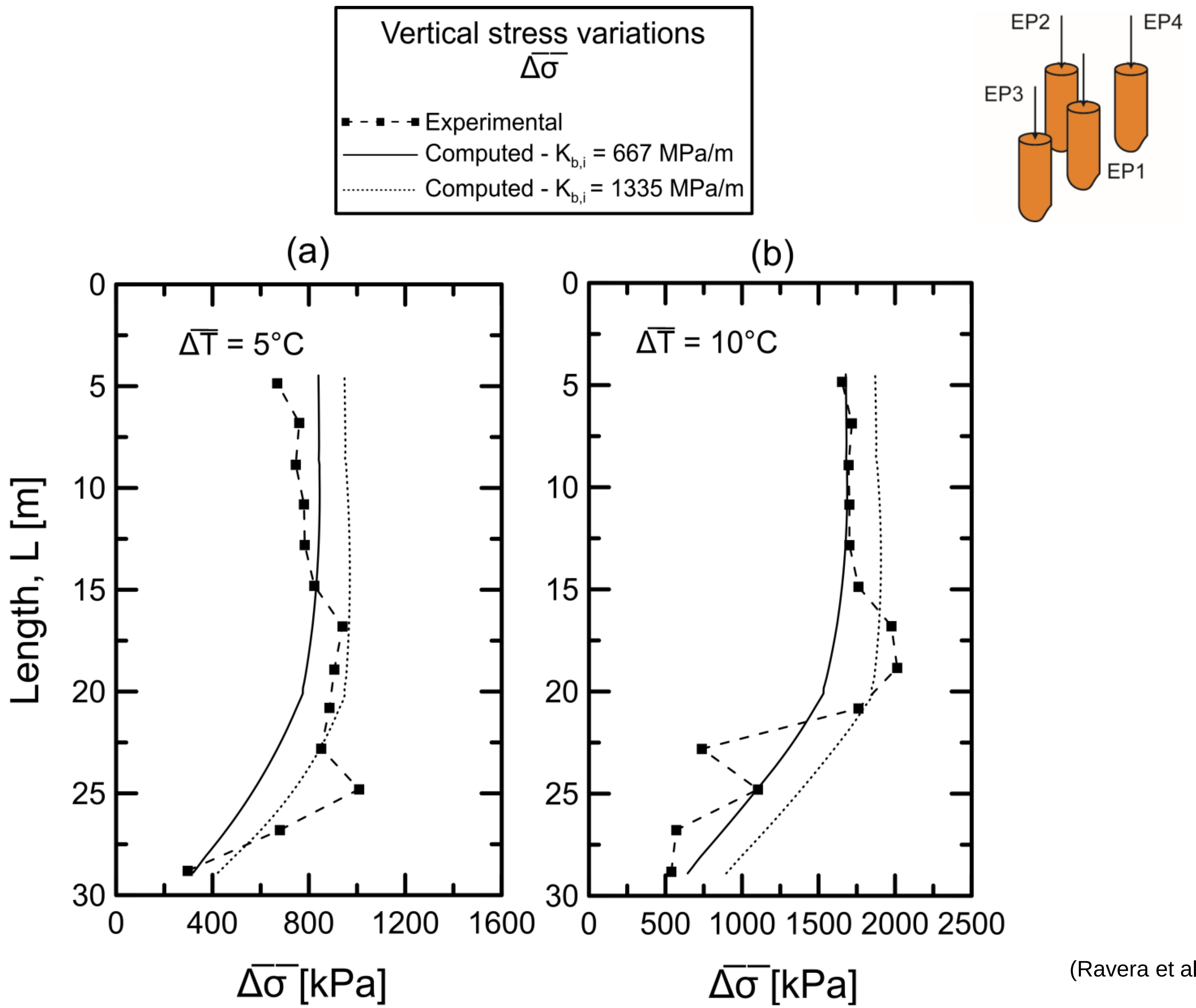
(Comodromos et al., 2016)
(Ravera et al., 2020)

Modelling of thermally induced strain variations



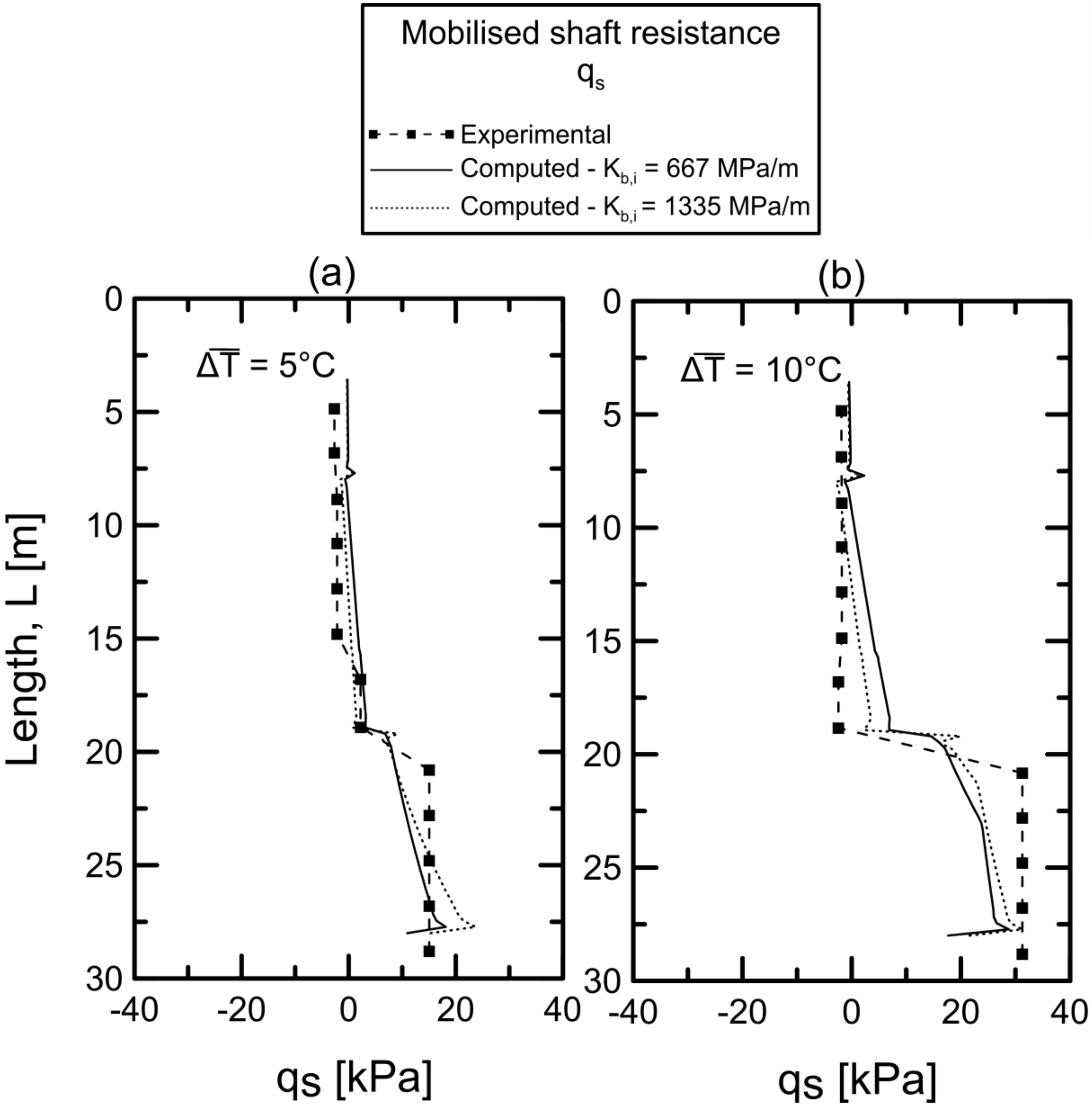
(Ravera et al., 2020)

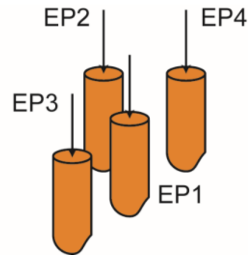
Modelling of thermally induced stress variations



(Ravera et al., 2020)

Modelling of mobilised shaft resistance





(Ravera et al., 2020)

Summary and concluding remarks

Concluding comments

- Interactions and group effects govern the performance of energy pile groups
- There exist different causes and types of interactions
- Mechanical interactions and group effects are associated with greater group deformation and lower average stress compared to those observed for the same average load applied to an energy pile in an isolated case
- Thermal interactions are associated with lower energy performance

Concluding comments

- The thermo-mechanical behaviour of energy pile groups is governed:
  - At initial stages of geothermal operations, by the thermally induced pile deformation, irrespective of whether $X \leq 1$ or $X > 1$
  - At successive stages of geothermal operations:
    - For $X \leq 1$, by the thermally induced pile deformation
    - For $X > 1$, by the thermally induced soil deformation

Considerations for analysis and design

- ✓ Three methods to expediently analyse mechanical interactions and group effects in general configurations of energy piles have been formulated
- ✓ These methods may be cost-effectively applied during design stages of the analysis and design of energy pile groups
- ✓ The methods may also be combined to analyse very large energy pile groups subjected to mechanical and thermal loads

Considerations for analysis and design

- An analysis of an energy pile considered as isolated gives a conservative estimate of the stress for the piles in a group

- However, this estimate is not conservative for the displacement, which must be addressed by a group analysis

- *No energy pile group design can be considered complete without assessing*:

  - The thermo-mechanical behaviour of each of the single piles of the group considered as isolated elements (e.g., the piles in the worst conditions)

  - The thermo-mechanical behaviour of the single piles in the group (e.g., the piles in the worst conditions)