Thermo-hydro-mechanical behavior of single energy piles

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Outline

- Thermo-mechanical testing
- Axial capacity and deformation
- Thermo-mechanical schemes
- Thermo-Pile

Thermo-mechanical testing of single energy piles

Sign convention:

- Compressive stresses and contractive strains considered positive
- Downward displacements (i.e., settlements) considered positive

Observed response of a single energy pile

Full-scale in situ testing of a single energy pile

Under a 4-storey building at **EPFL campus** (Bâtiment Polyvalent)

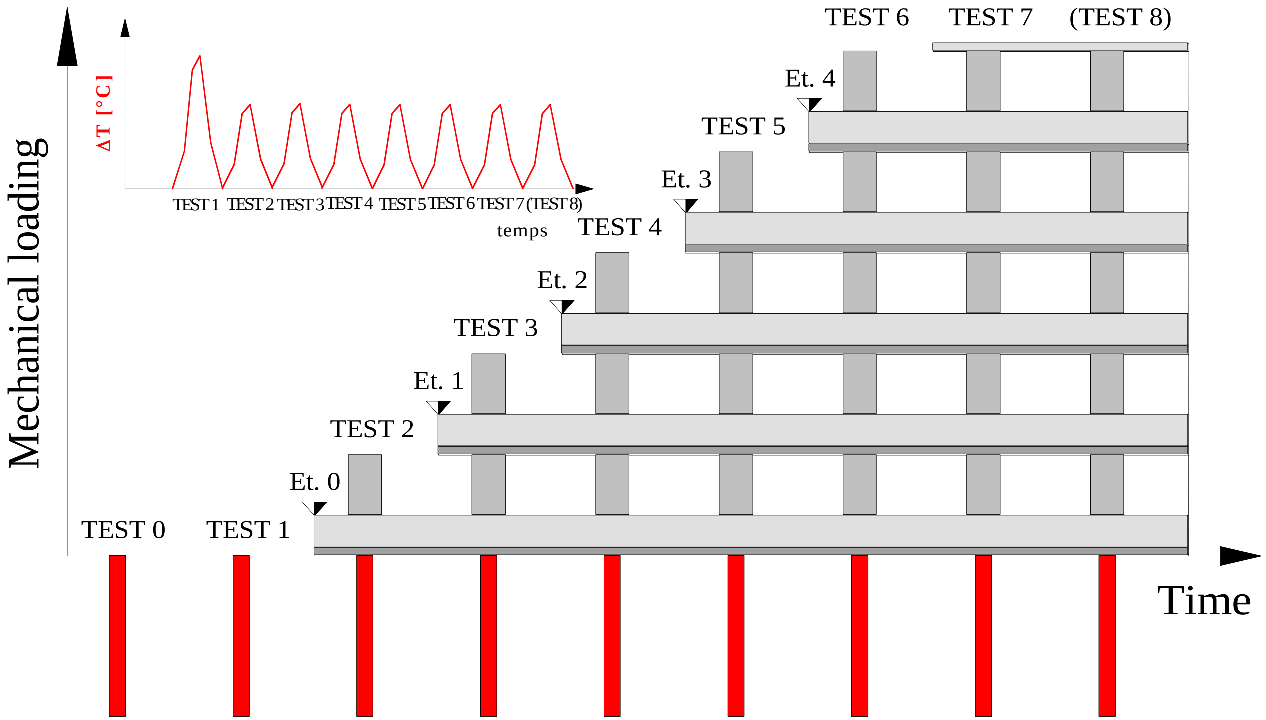
Founded on **97 piles**

Test pile: **88 cm in diameter and 25.8 m in length**

Polyethylene U-tube attached on the reinforcing cage

Features of the test

1. The BP Building

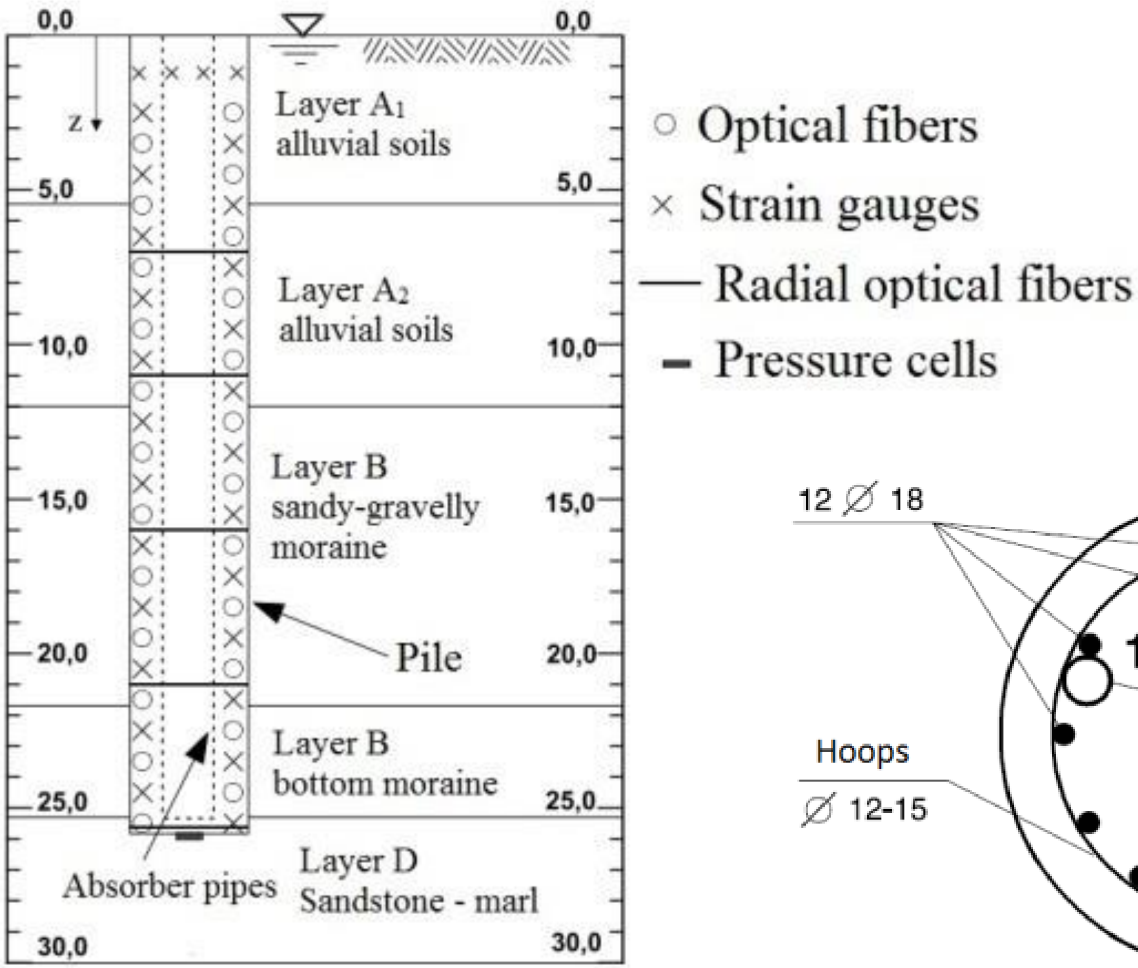


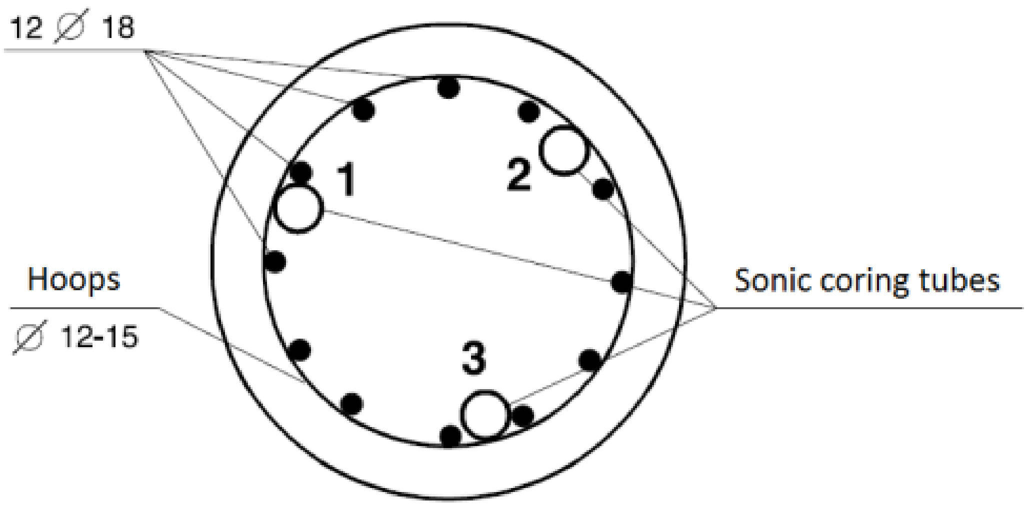
Goal of the field test

- Analyse the thermo-mechanical behaviour of a single energy pile subjected to heating loads

(Laloui et al., 2003)

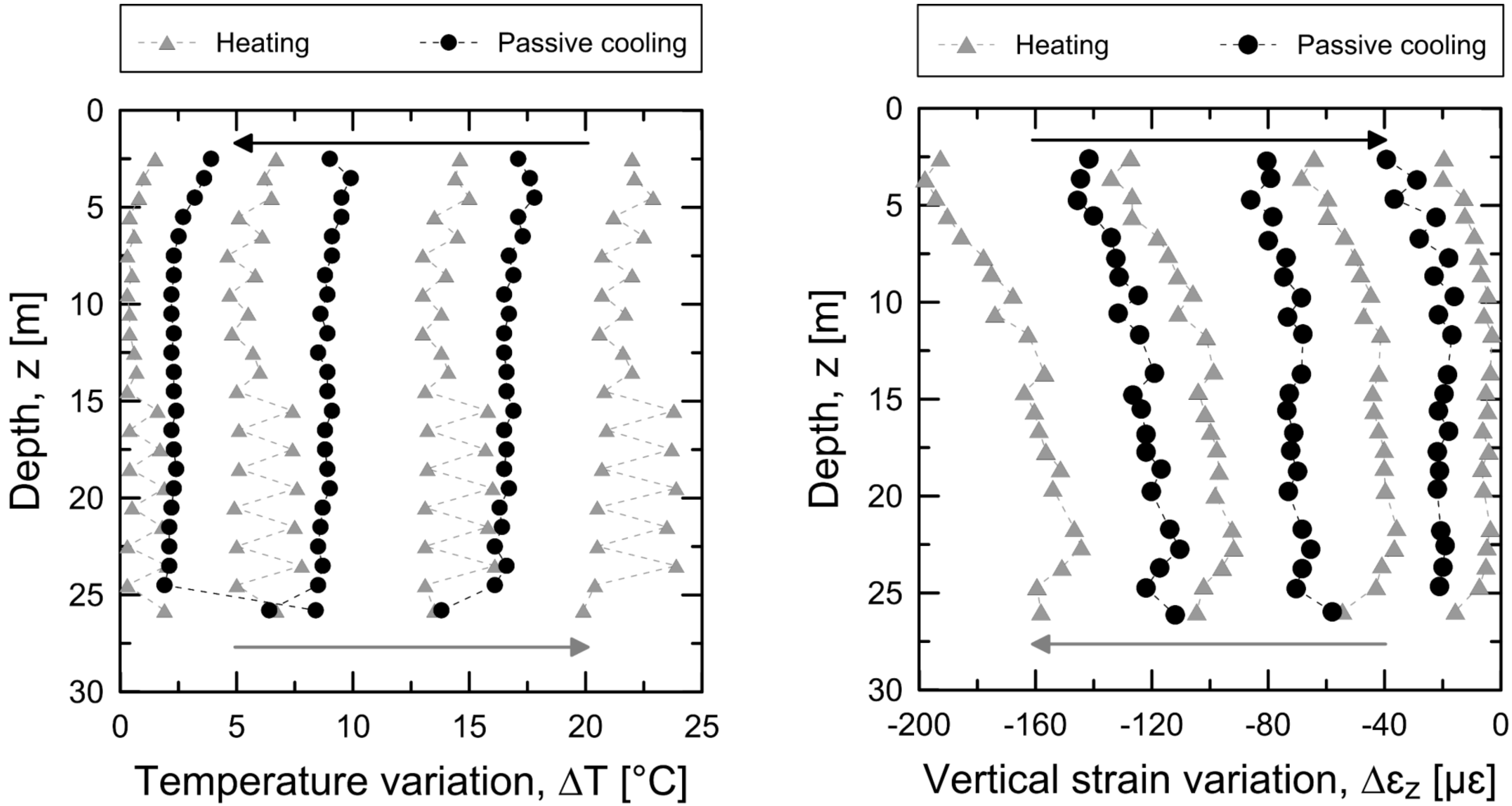
End-bearing energy pile





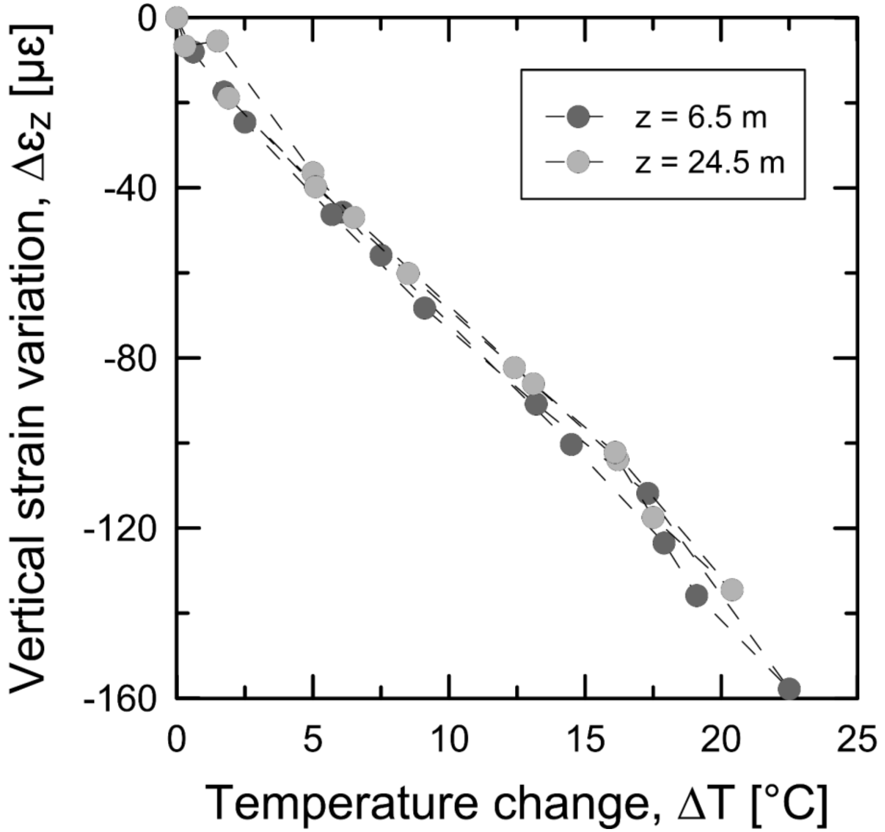
(Laloui et al., 2003)

Temperature and vertical strain variation – Test 1



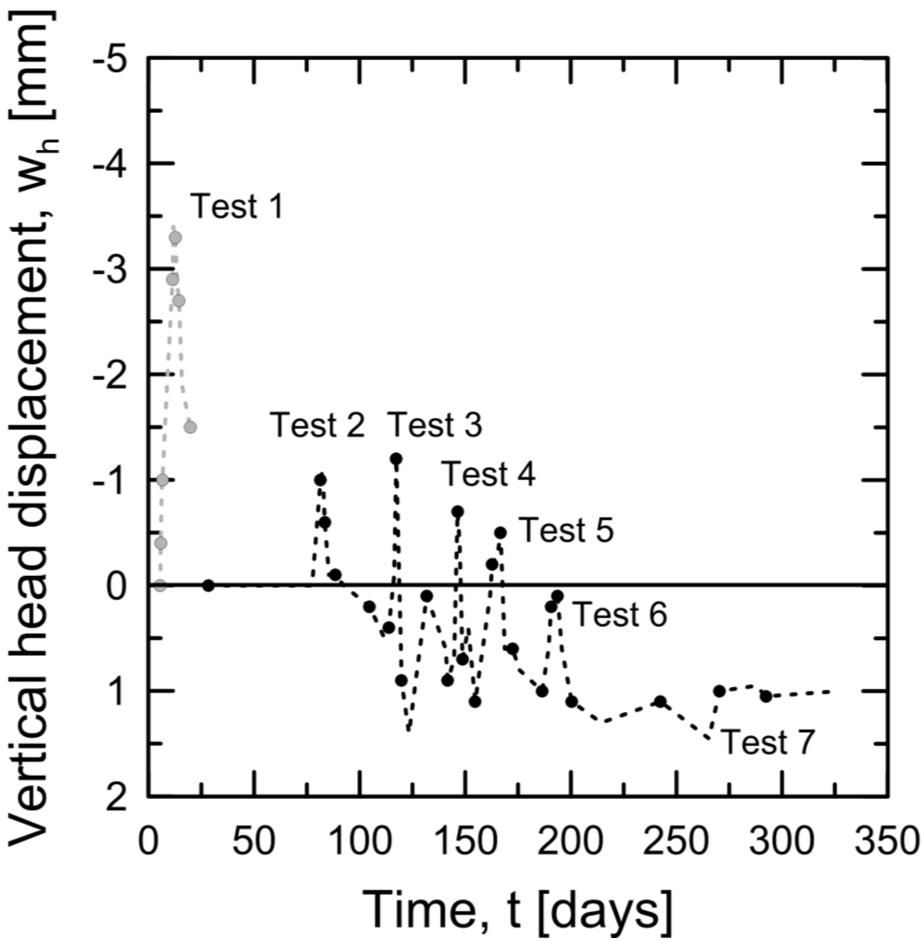
(Laloui et al., 2003)

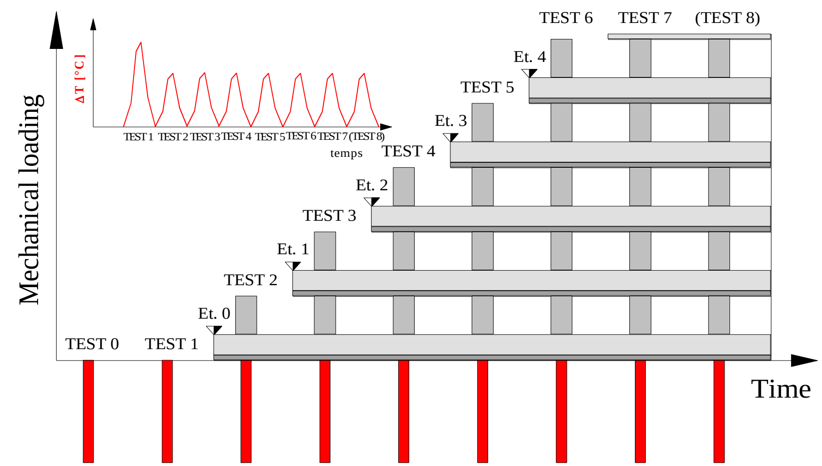
Vertical strain reversibility – Test 1



(Laloui et al., 2003)

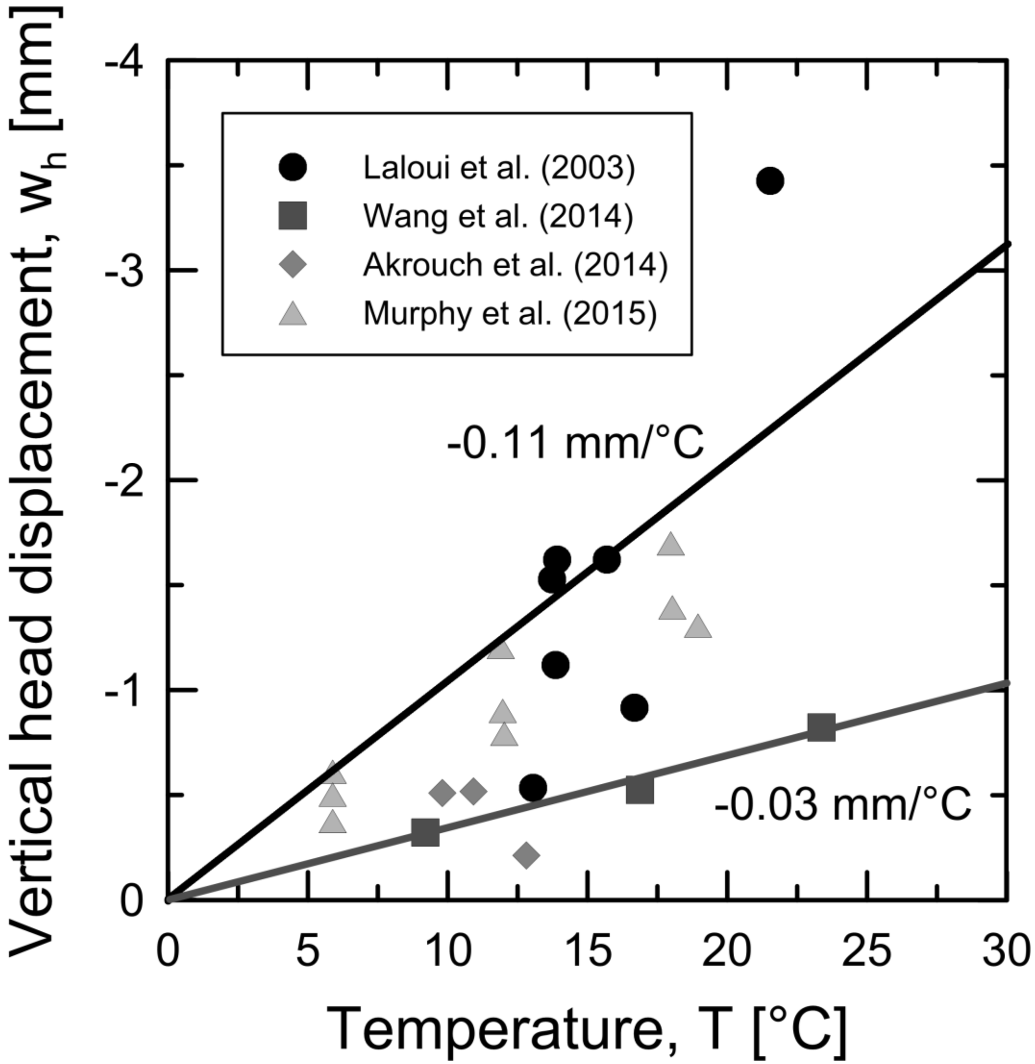
Vertical head displacement history





(Laloui et al., 2003)

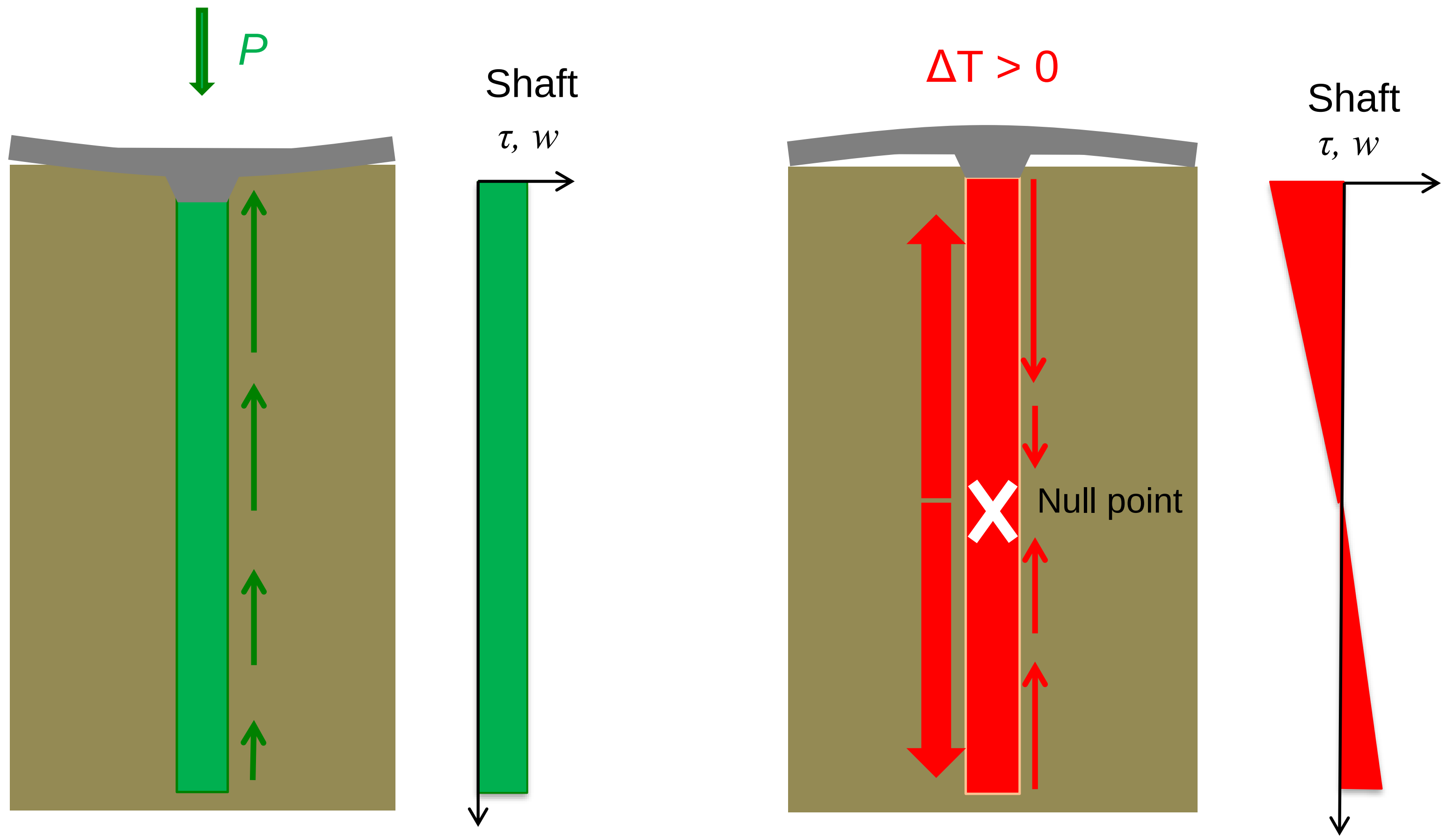
Vertical head displacement



(Laloui and Rotta Loria 2019)

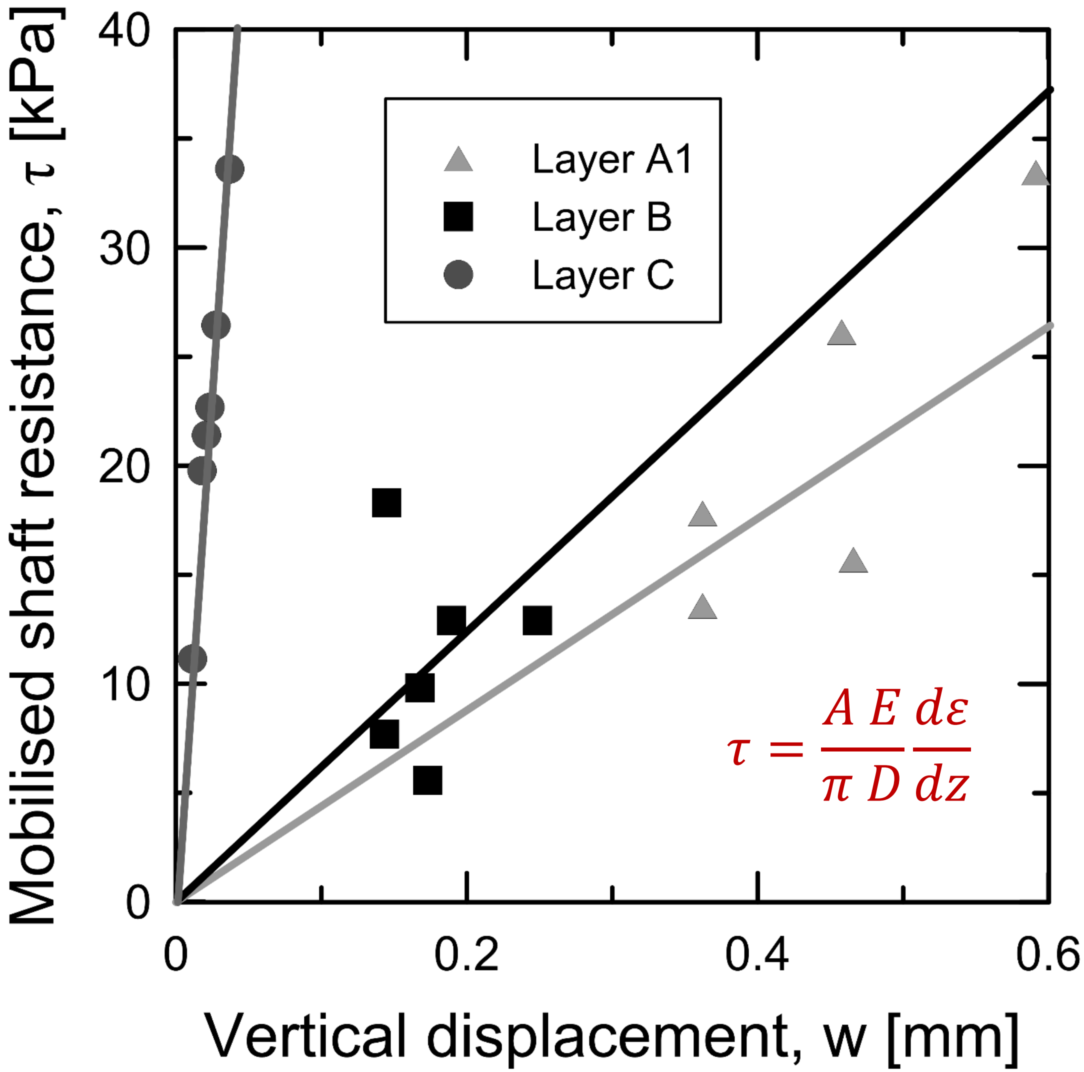
Null point of vertical displacement

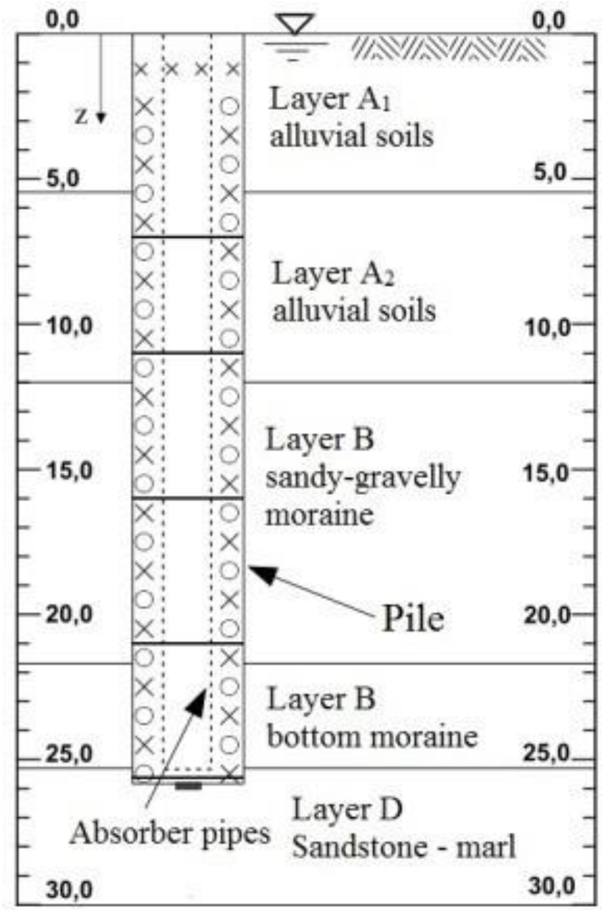
It represents the plane where no thermally induced displacement occur in the pile



(Laloui et al., 2003)

Mobilised shaft resistance (mechanical loading)

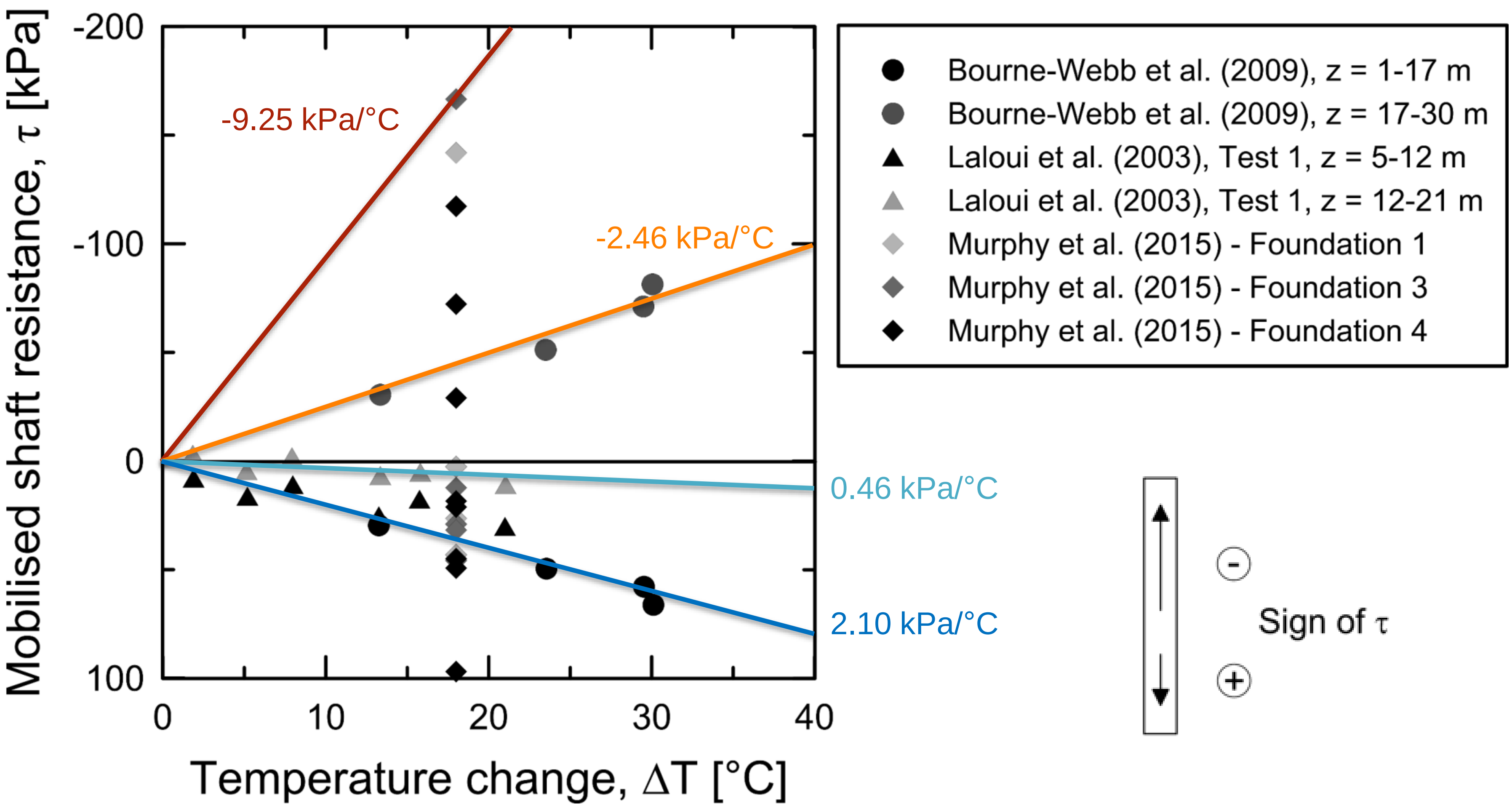




(Laloui et al., 2003)

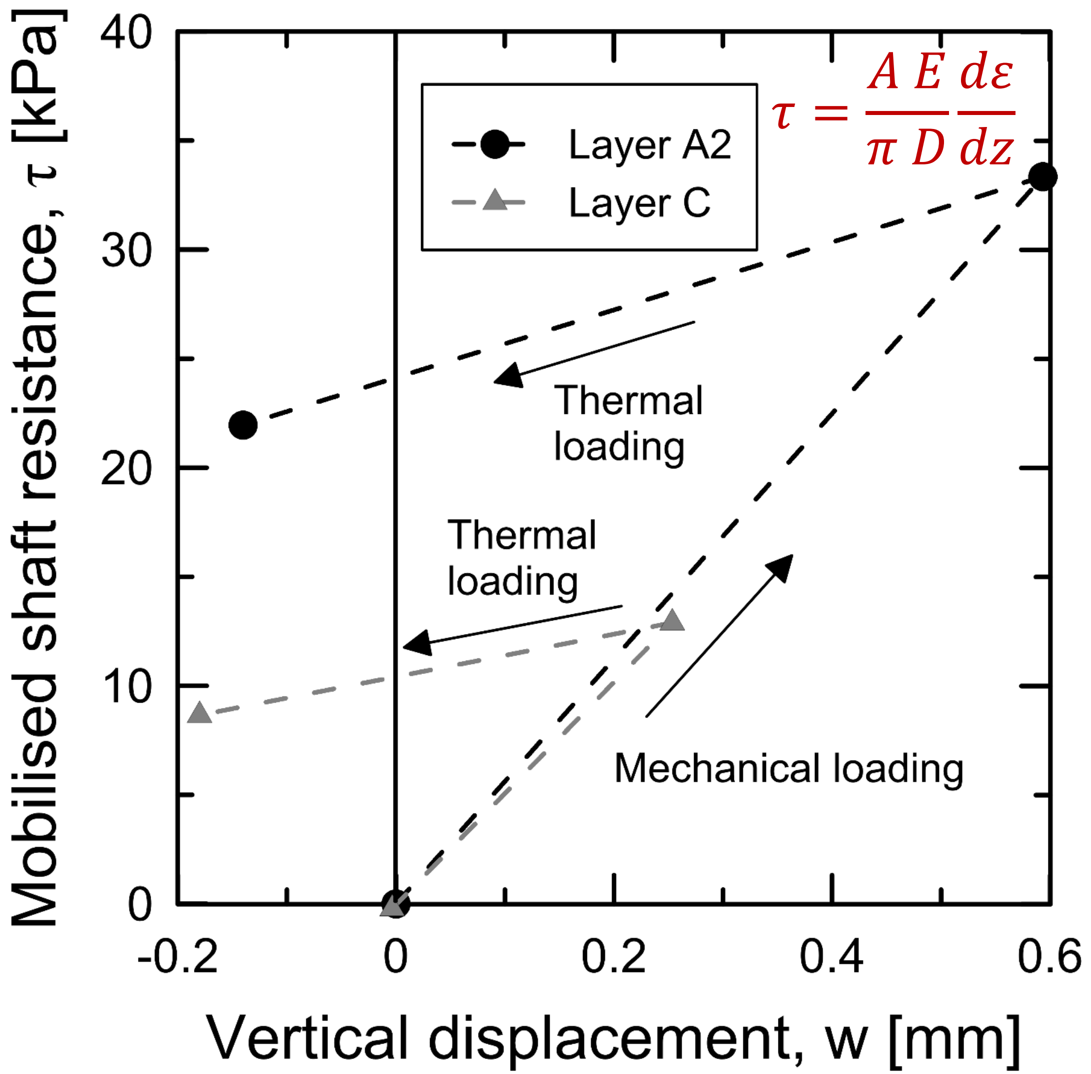
Observed thermally induced shaft resistance variations

(Laloui and Rotta Loria, 2019)



Mobilised shaft resistance (thermo-mechanical loading)

(Laloui et al., 2003)



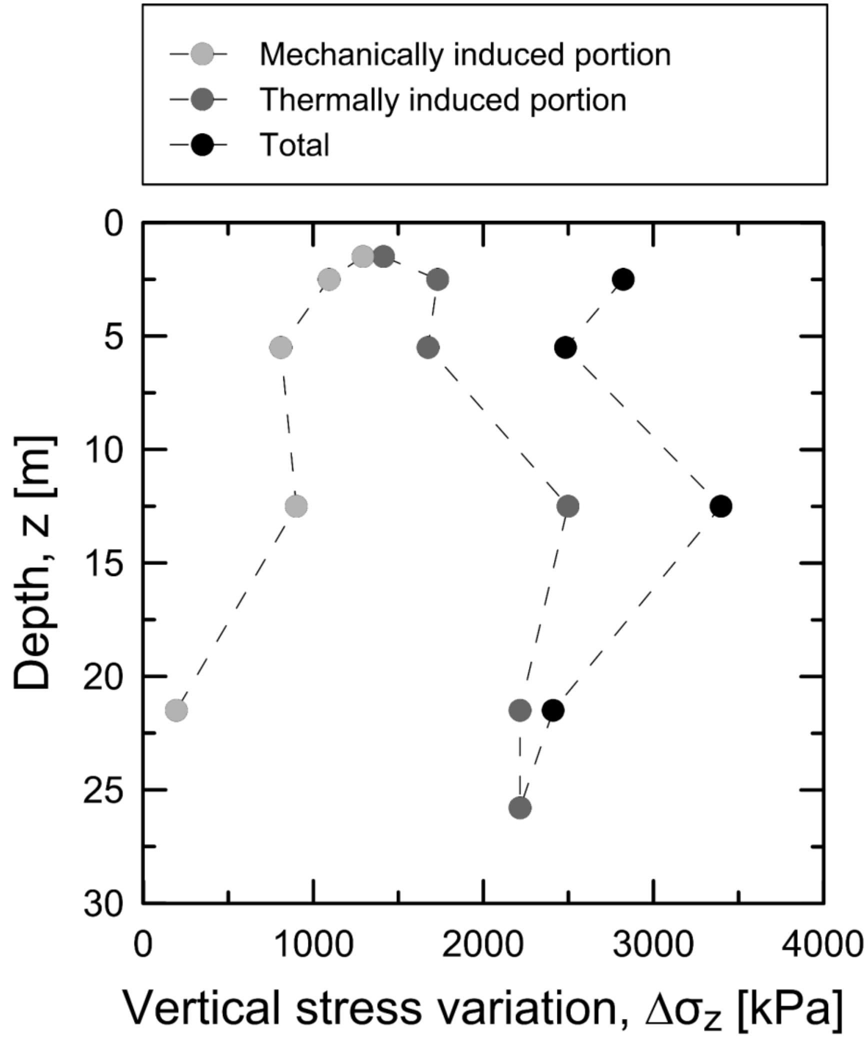
$$\tau = \frac{A\,E}{\pi\,D}\frac{d\varepsilon}{dz}$$

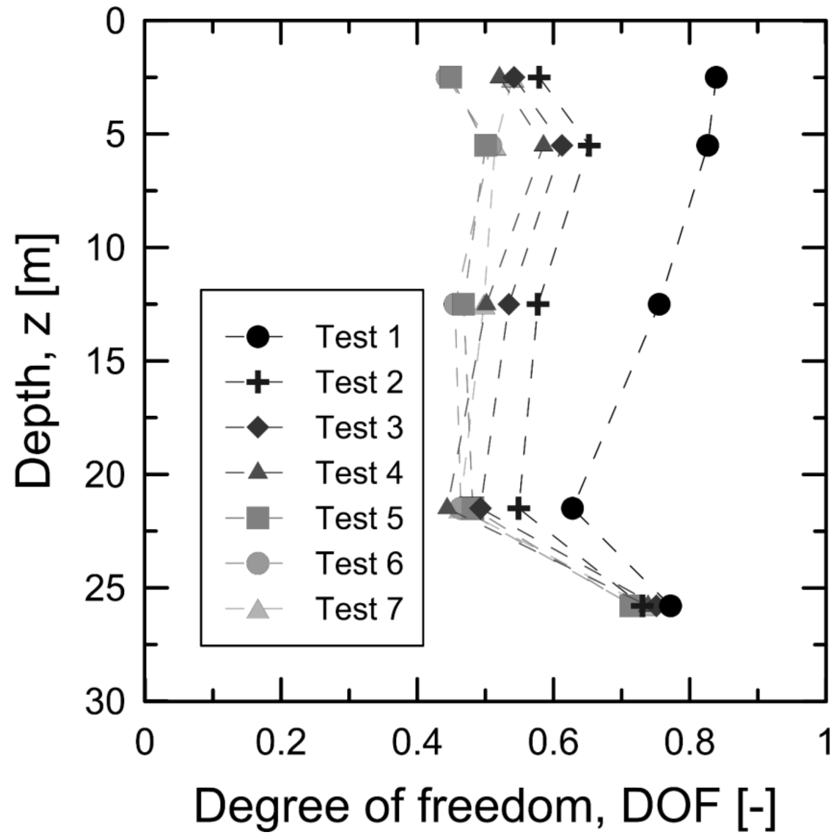
Linear decrease of 2.1 kPa/°C for shaft resistance above null point

Vertical stress variation and degree of freedom

150 kPa/°C at the pile head

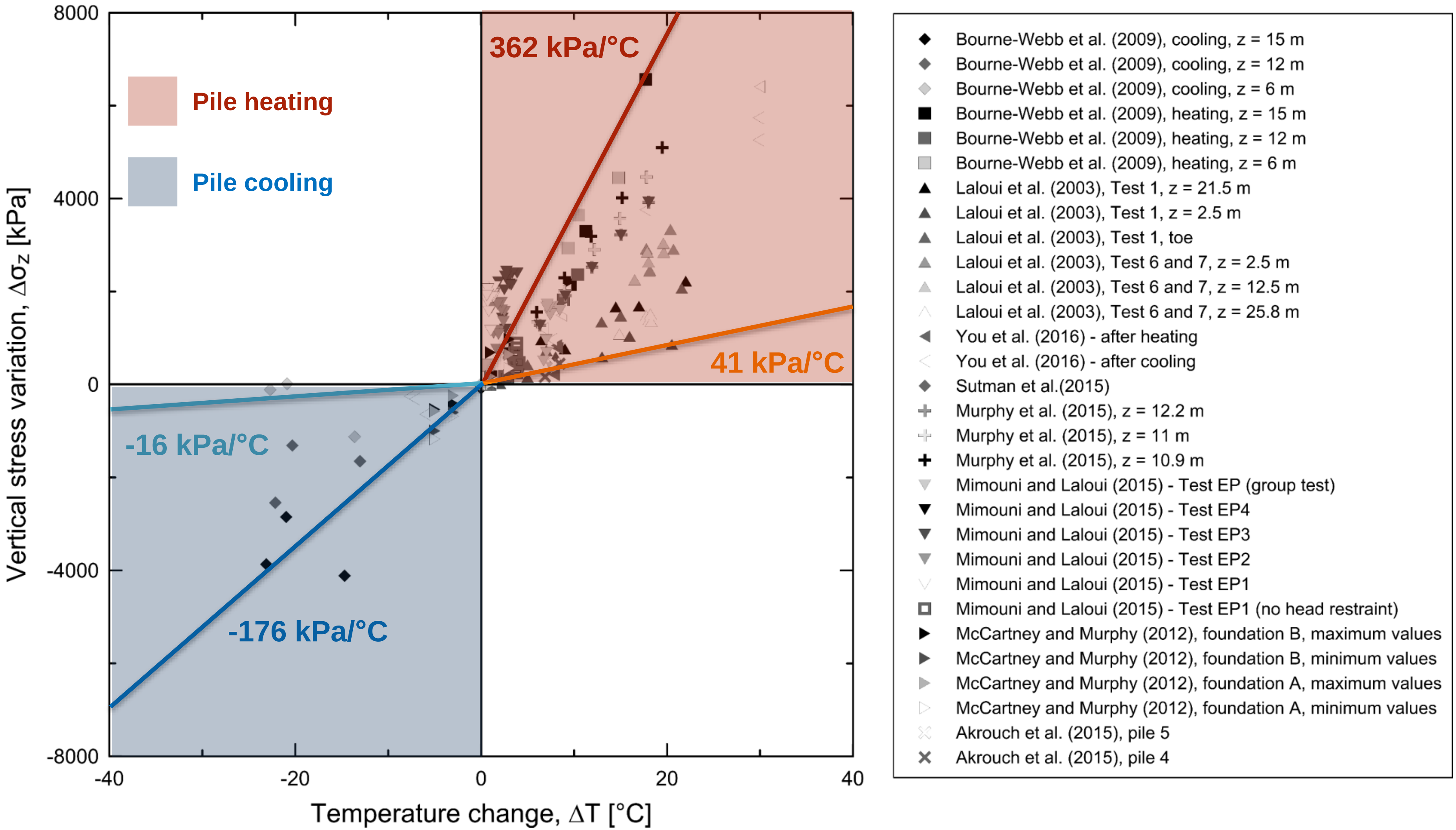
(Laloui et al., 2003)



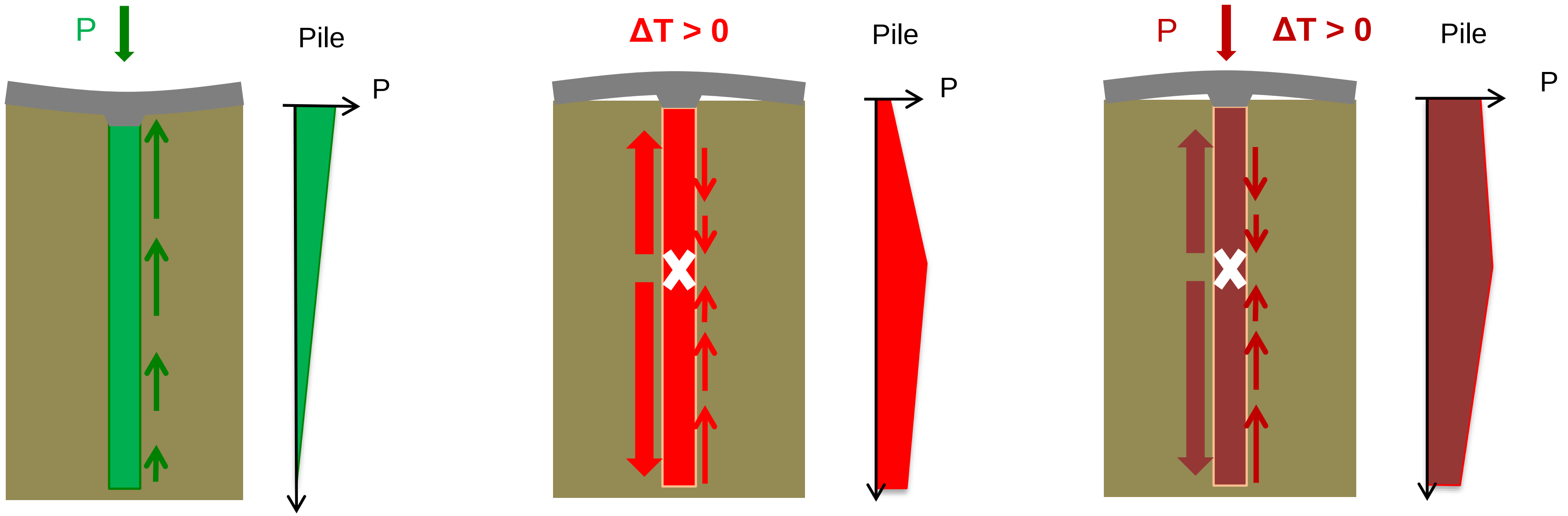


Observed thermally induced vertical stress variations

(Laloui and Rotta Loria, 2019)



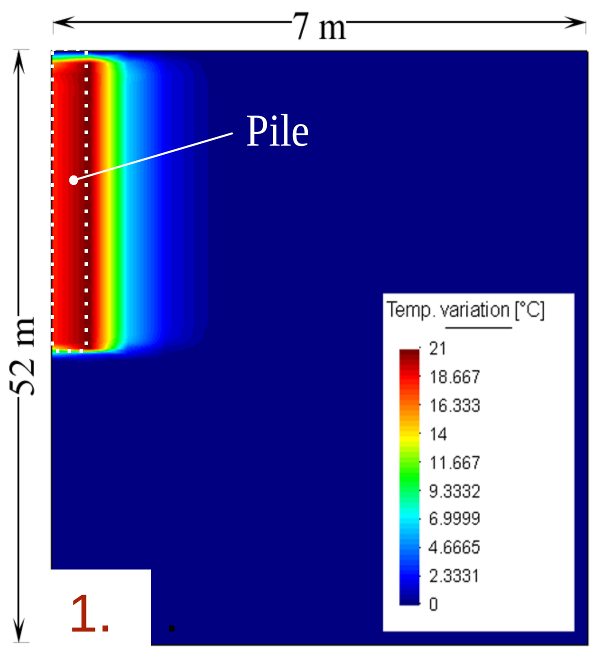
Application of principle of superposition



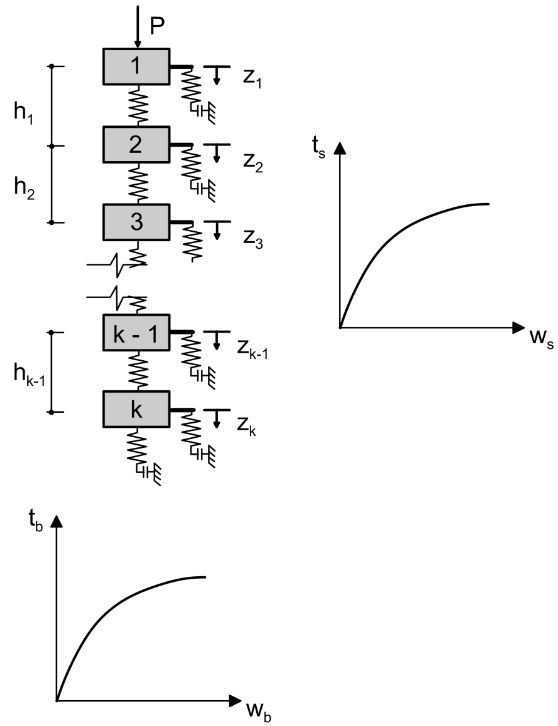
Axial capacity and deformation of single energy piles

Modelling approaches

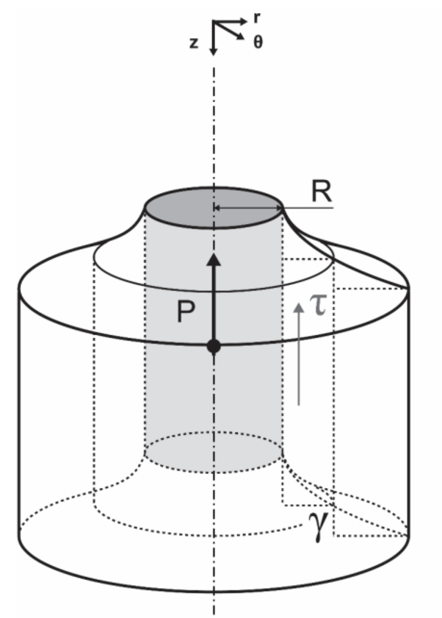
1. Numerical methods (FE, DE)
2. Load-transfer methods (t-z)
3. Analytical solutions (closed-form expressions)



1.

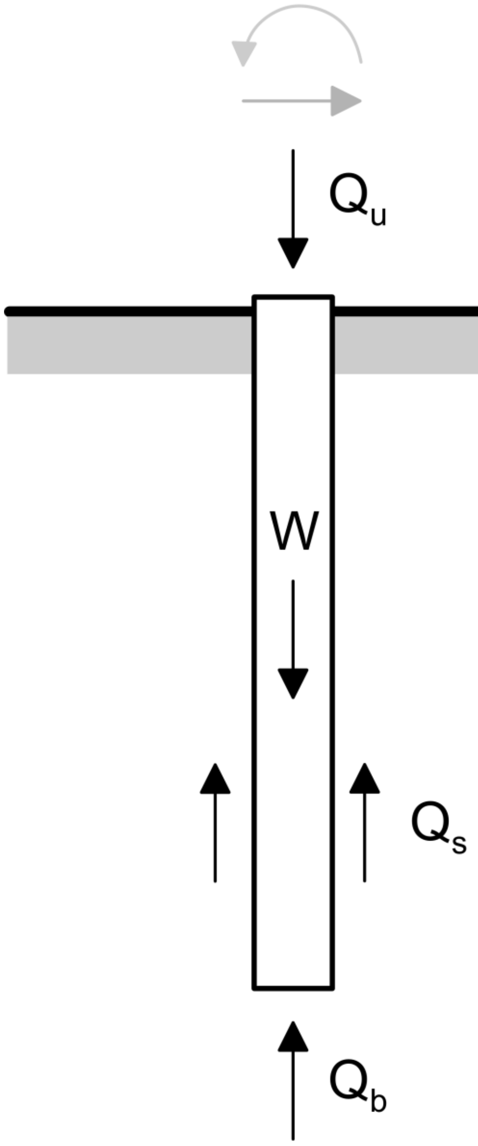


2.



3.

The problem



(Laloui and Rotta Loria, 2019)

General methods of pile installation

- Pile driving: Installation of piles by driving them into the ground (i.e., *displacement piles*)

  - During installation, the soil is displaced mainly radially, so

    - Non-cohesive (e.g., coarse-grained) soils are compacted
    - Cohesive (e.g., fine-grained) soils tend to suffer heave

- Pile boring: Installation of piles by excavating the ground and filling with concrete (i.e., *non-displacement piles*)

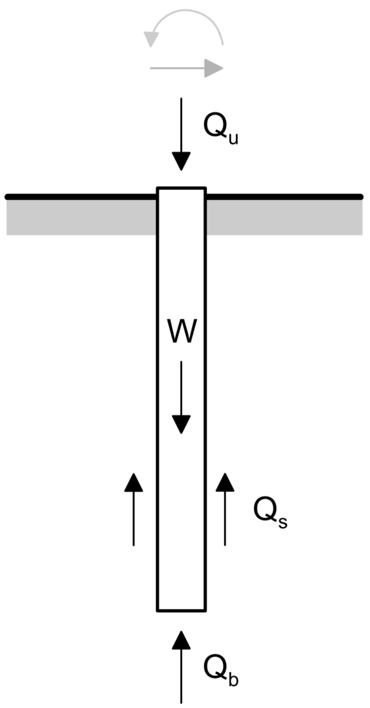
  - During installation lateral stresses in the ground are reduced, so

    - Fine-grained soils tend to suffer swelling and softening, and the initial condition are only partly restored upon concreting

Generalised formulation of bearing capacity

- The net ultimate load capacity, Q_u, of a single pile is equal to the sum of the shaft capacity, Q_s, and base capacity, Q_b, less than the weight of the pile, W:

$$Q_u = Q_s + Q_b - W$$



- In the design practice, the shaft and base capacities are computed independently from each other, even if they are not necessarily mobilised at the same time:
  - Pile shaft: 0.5 to 2% of the pile diameter, i.e., displacements usually in the range of 5 to 15 mm
  - Pile base: 5 to 10% of the pile base diameter

Types of piles

- End-bearing piles: piles that penetrate a relatively soft layer of soil to found on a firmer stratum and derive most of their capacity from the base capacity, Q_b
- Floating piles: piles that do not found on a particularly firm stratum and derive most of their capacity from the shaft capacity, Q_s

- In cohesive soil, the shaft capacity of piles is generally paramount
- In non-cohesive soil the overall capacity is more evenly divided between shaft and base

Methods to estimate the bearing capacity

- Two main different ways to estimate the axial capacity of piles:
  - Experimental estimation, e.g., use of *load-settlement curves*
  - Analytical estimation, e.g., use of *bearing capacity theory*

- The bearing capacity of a pile is considered as:
  - load for which a further increase in settlement does not induce an increase in load
  - load causing a settlement of 10% of the pile base diameter, D

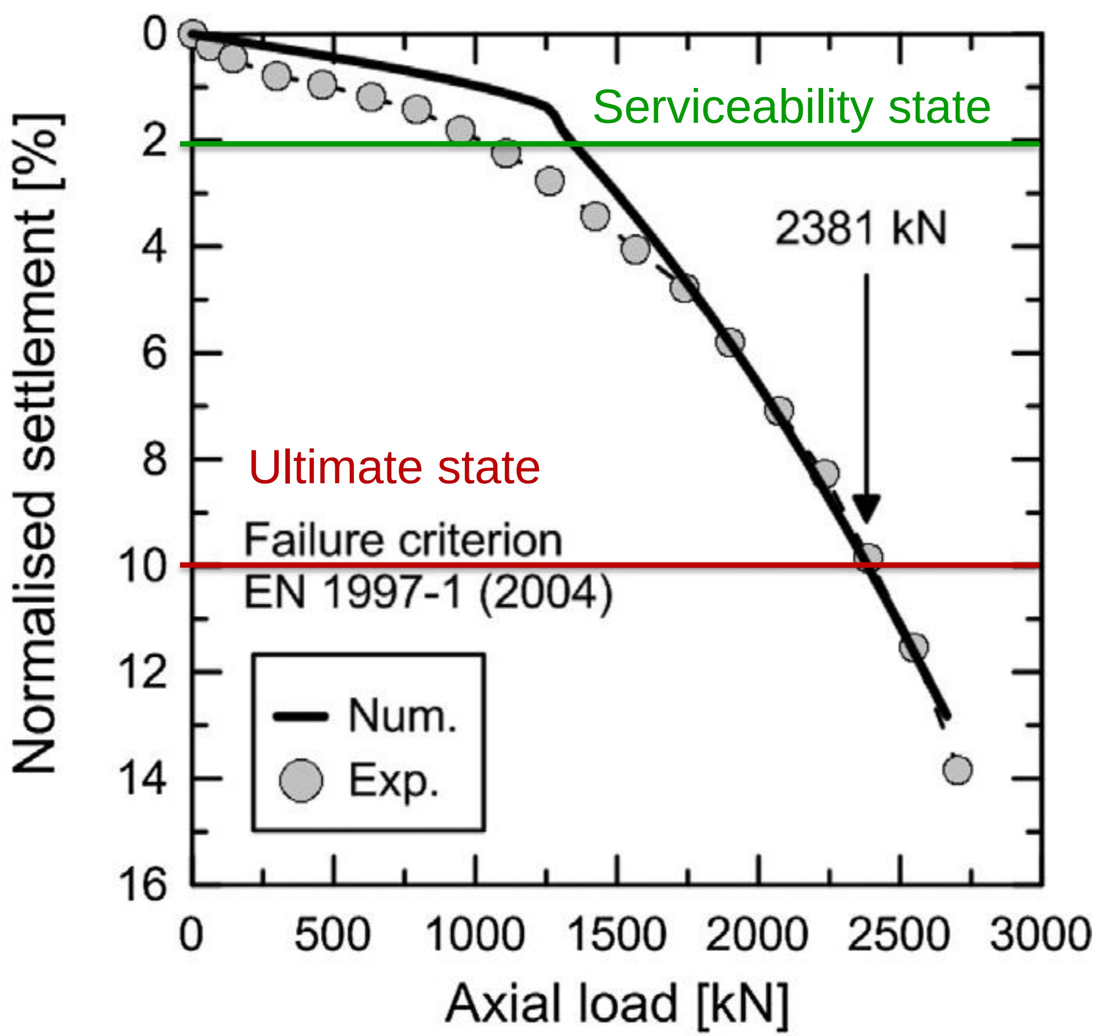
Experimental estimation of bearing capacity

Two typical branches of load-settlement curves:

- A first elastic branch where the settlements are less than 1%*D*

- A second non-linear branch for higher settlements governed by plastic mechanisms at pile-soil interface and eventually at pile base

(Rotta Loria et al., 2016)



Analytical estimation of bearing capacity

- The shaft capacity can be estimated by integrating along the pile shaft the pile-soil interface shear strength
- The base capacity can be evaluated from bearing capacity theory

$$Q_u = q_s A_s + q_b A_b - W$$
$$= (\bar{c}_a + \bar{\sigma}_v \bar{K} \tan\delta) A_s + \left(c N_c + \sigma_{vb} N_q + \frac{1}{2} \gamma D N_\gamma \right) A_b - W$$

- q_s: average shear strength down the pile shaft
- $A_s = 2\pi R L$: external surface of the pile shaft (R = pile radius; L = pile length)
- q_b: base resistance
- $A_b = \pi R^2$ pile cross-sectional area
- $\bar{c}_a$: average pile-soil interface adhesion
- $\bar{\sigma}_v$: some average vertical stress
- $\bar{K}$: some average coefficient of lateral pressure
- δ: some angle of pile-soil interface shear strength
- c: soil cohesion
- N_c, N_q and N_γ: bearing capacity factors
- σ_{vb}: some vertical stress at pile base
- γ: some unit weight of the soil

Effective stress analysis

- When drained conditions may be assumed upon loading an effective stress analysis approach can be considered

- Assuming equal to zero the cohesive components and neglecting the term $\frac{1}{2}\gamma' D N_\gamma$ because small in relation to the term involving N_q, the generalised formulation of the ultimate load capacity becomes

$$Q_u = q_s A_s + q_b A_b - W = \overline{\sigma'}_v \bar{K} \tan\delta\, A_s + \sigma'_{vb} N_q A_b - W$$

Effective stress analysis - shaft capacity

- The shaft resistance is often expressed as $\overline{\sigma'}_v \bar{K} \tan\delta = \overline{\sigma'}_v \beta$

- $\beta = \bar{K} \tan\delta$ must be defined considering $\bar{K}$ and $\tan\delta$

- $\bar{K}$ relates the normal stress acting on the pile-soil interface after pile installation, $\overline{\sigma}'_n$, to the *in situ* vertical effective stress, $\overline{\sigma}'_v$

- For displacement piles: $\bar{K} = K_0 = 1 - \sin\varphi_{cv}$, $\delta = \varphi'_{cv}$

- For non-displacement piles: $\bar{K} = 0.7K_0 = 0.7(1 - \sin\varphi_{cv})$, $\delta = \varphi'_{cv}$

- The approach of considering $\delta' = \varphi'_{cv}$ may be justified on the basis that no dilation is expected between the soil and the shaft at failure

Effective stress analysis – base capacity

- Instead of the simple product $\sigma'_{vb} N_q$ the base resistance is often expressed as

$$q_b = \sigma'_{vb} N_q s_q d_q$$

- According to Hansen (1970):

$$N_q s_q d_q = K_p\, e^{\pi \tan \varphi^*}\, d_q\, s_q$$
$$= \left(K_p e^{\pi \tan \varphi^*}\right)\left(1 + 2 \tan \varphi^* \,(1 - \sin \varphi^*)^2 k\right)\left(1 + 0.1 K_p\right)$$
$$= \left(\frac{1 + \sin \varphi^*}{1 - \sin \varphi^*} e^{\pi \tan \varphi^*}\right)\left(1 + 2 \tan \varphi^* \,(1 - \sin \varphi^*)^2 \tan^{-1}\left(\frac{L}{D}\right)\right)(1 + 0.1 K_p)$$

- In the previous formula, it is often considered $s_q = 1$ and φ^* represents an appropriate value of angle of shear strength

Analysis of piles in rock

- When dealing with piles founded on rock, only the base capacity can be considered to contribute to the total pile capacity, hence

$$Q_u \cong Q_b$$

- According to Zhang and Einstein (1998):

$$Q_b = q_b A_b = 15\, p_a \sqrt{\frac{UCS}{p_a}} A_b$$

- UCS = unconfined compressive strength
- p_a = atmospheric pressure

Thermo-mechanical schemes for energy piles

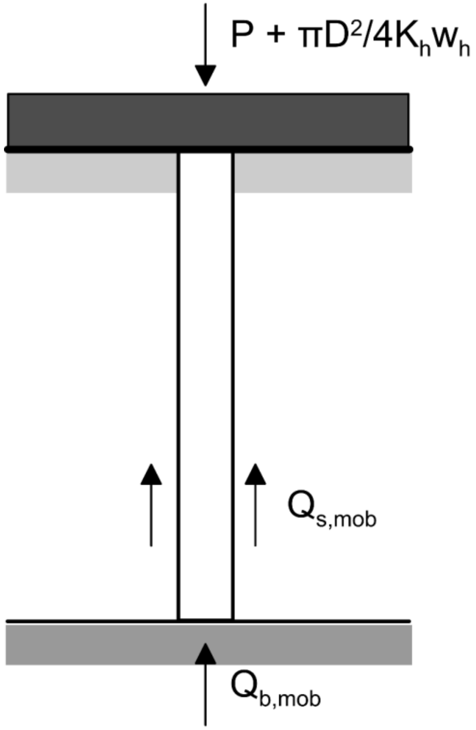
Fundamental hypothesis:

- Thermo-elastic behaviour of the energy pile-soil system

Mathematical formulation for axial equilibrium

$$P + \frac{\pi D^2}{4} K_h w(z=0) + W + Q_{s,mob} + Q_{b,mob} = 0$$

- P: applied load
- K_h: head stiffness
- w_h: vertical head displacement
- $Q_{s,mob}$: mobilised shaft capacity
- $Q_{b,mob}$: mobilised base capacity



Mathematical formulation for axial equilibrium

- Both $Q_{s,mob}$ and $Q_{b,mob}$ can be written in terms of a mechanical and a thermal portion as

$$Q_{s,mob} = Q_{s,mob}^{m} + Q_{s,mob}^{th}$$

$$Q_{b,mob} = Q_{b,mob}^{m} + Q_{b,mob}^{th}$$

(Mimouni and Laloui, 2014)

- where

$$Q_{s,mob}^{th} = Q_{s,mob,up} + Q_{s,mob,down}$$

$$Q_{s,mob,up} = \pi D \int_{0}^{z_{NP,\tau}} \tau \, dz$$

$$Q_{s,mob,down} = \pi D \int_{z_{NP,\tau}}^{L} \tau \, dz$$

$z_{NP,\tau}$: depth of null point of shear stress

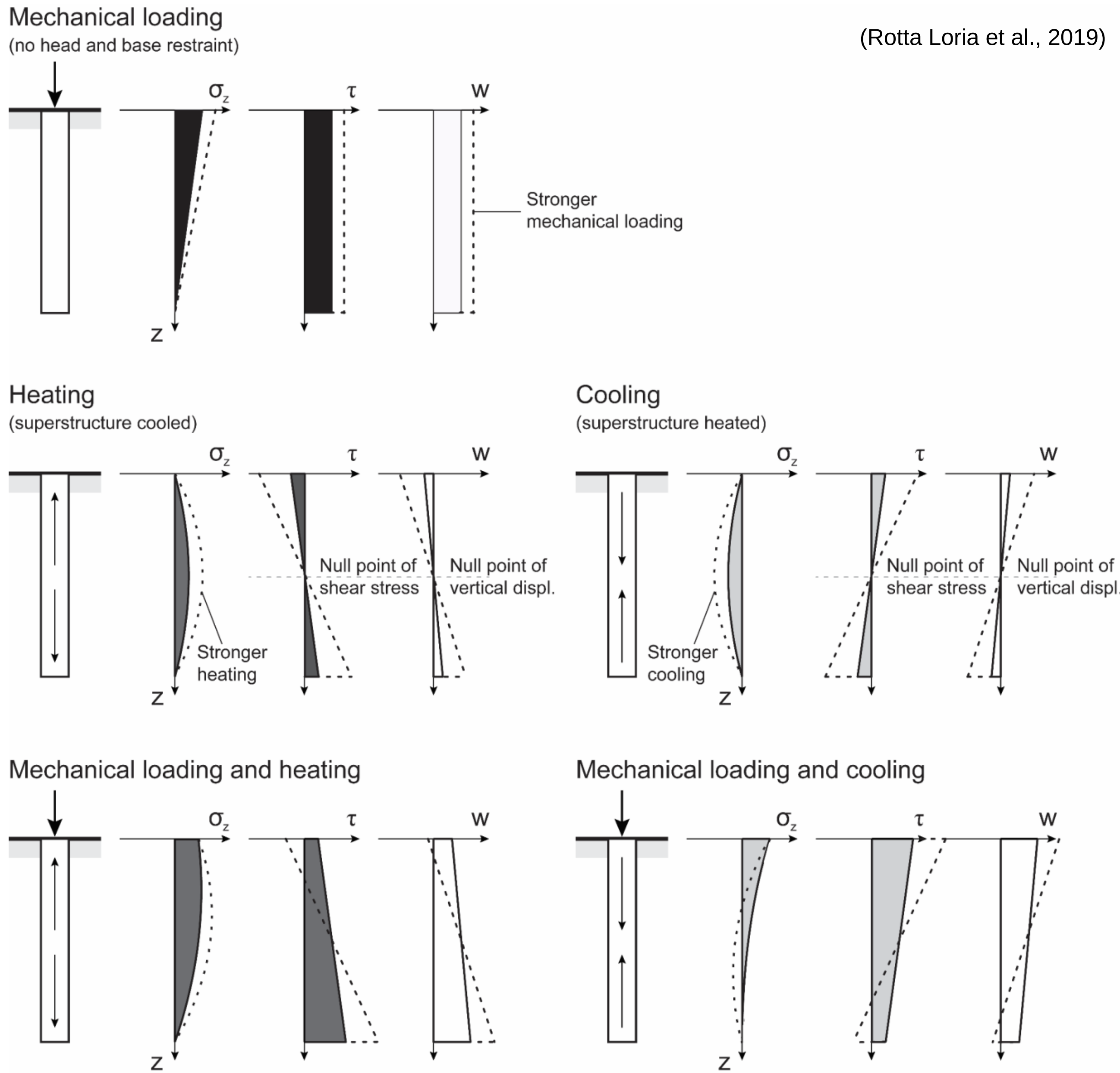
Energy pile with no head and base restraint

(Rotta Loria et al., 2019)

$$P + Q_{s,mob}^{m} = 0$$

$$Q_{s,mob}^{th} = Q_{s,mob,up} + Q_{s,mob,down} = 0$$

$$P + Q_{s,mob} = P + Q_{s,mob}^{m} + Q_{s,mob}^{th} = 0$$



Energy pile with head or base restraint

(Rotta Loria et al., 2019)

$$P + Q_{s,mob}^{m} + Q_{b,mob}^{m} = 0$$

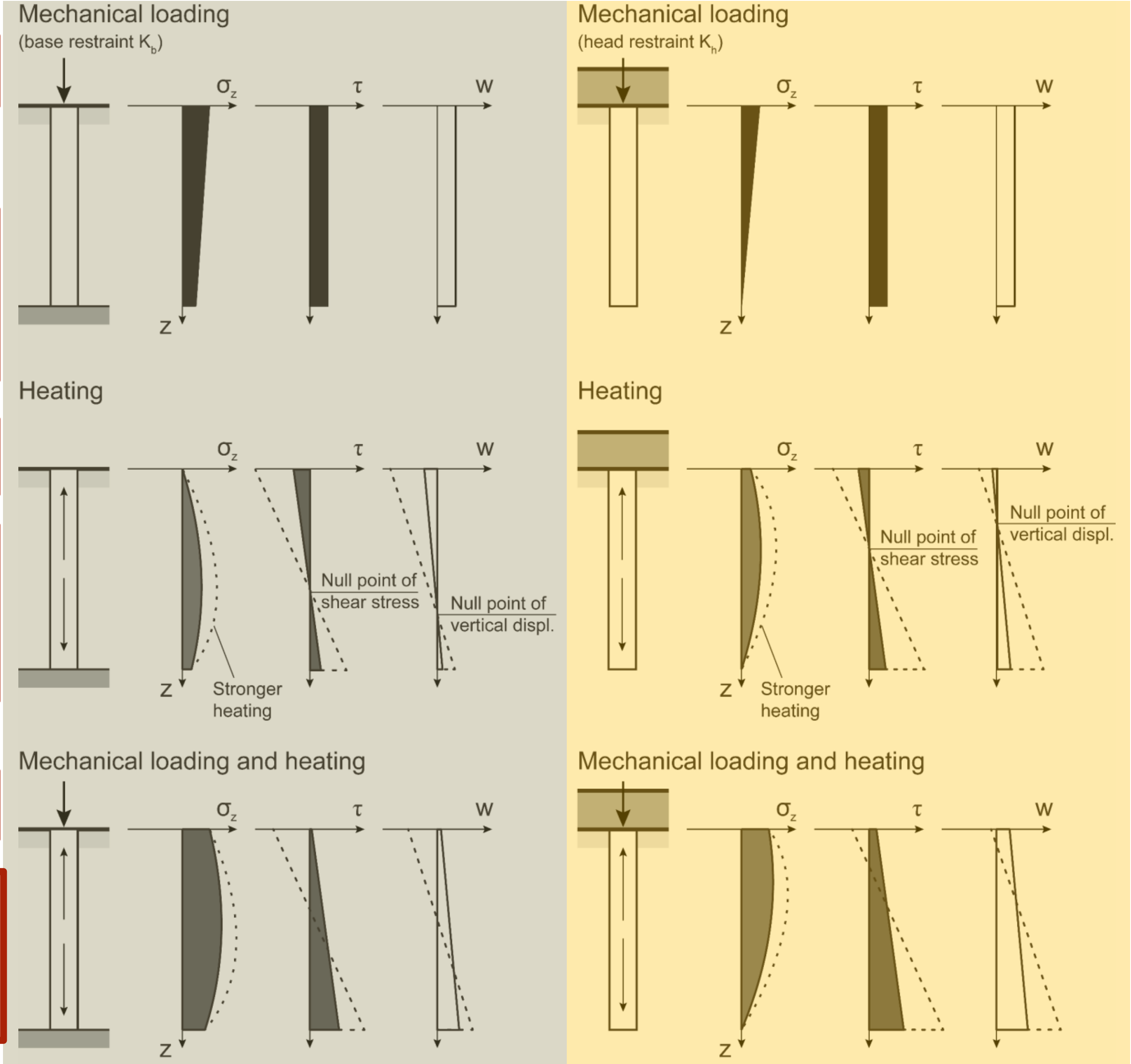
$$P + \pi \frac{D^2}{4} K_h w^m(z = 0) + Q_{s,mob}^{m} = 0$$

$$Q_{s,mob}^{th} + Q_{b,mob}^{th} = 0$$

$$\pi \frac{D^2}{4} K_h w^{th}(z = 0) + Q_{s,mob}^{th} = 0$$

$$P + Q_{s,mob} + Q_{b,mob} = 0$$

$$P + \pi \frac{D^2}{4} K_h w(z = 0) + Q_{s,mob} = 0$$



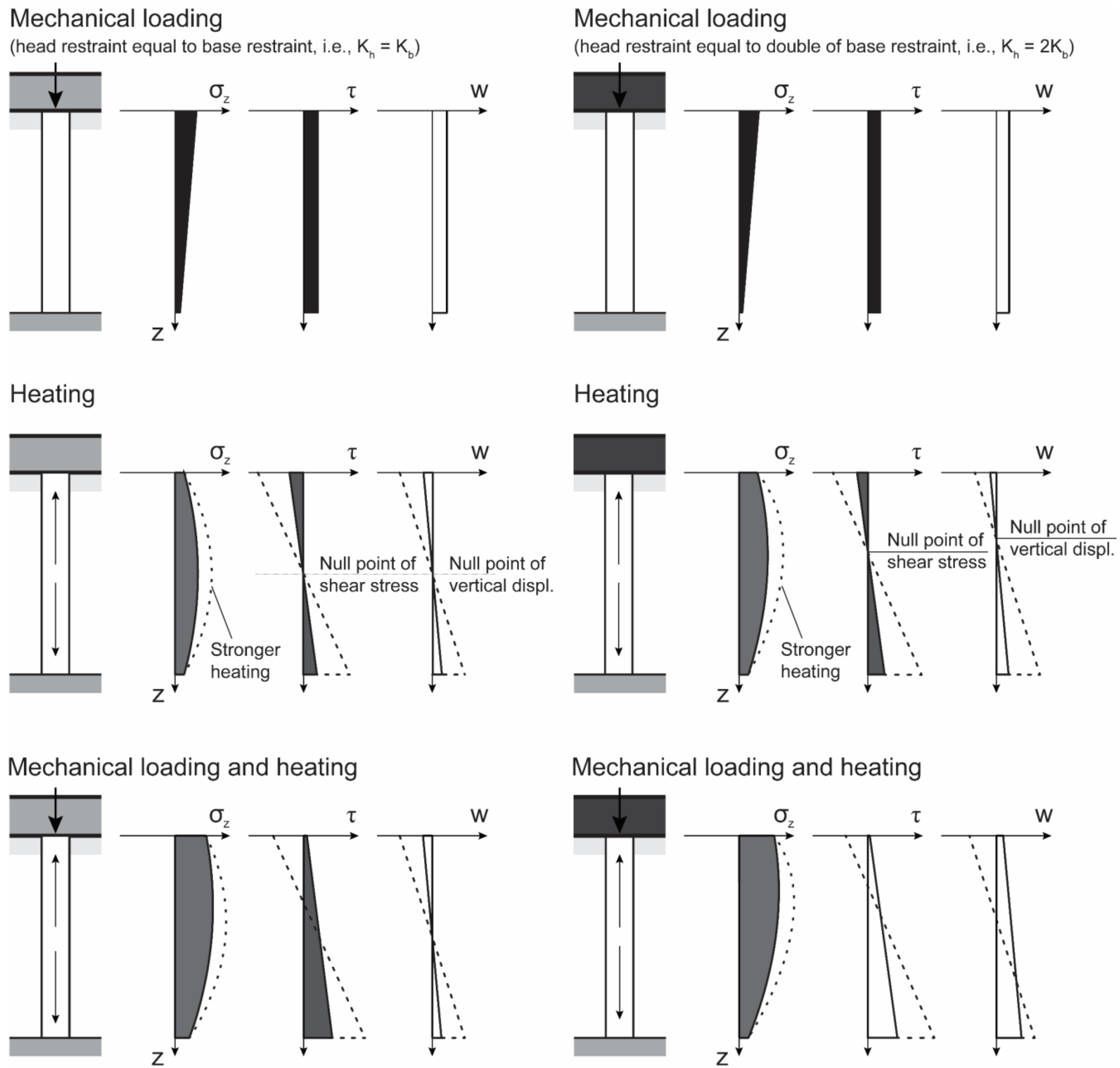
Energy pile with head and base restraint

(Rotta Loria et al., 2019)

$$P+\pi\frac{D^2}{4}K_h w^m(z=0) + Q^m_{s,mob} + Q^m_{b,mob} = 0$$

$$\pi\frac{D^2}{4}K_h w^{th}(z=0) + Q^{th}_{s,mob} + Q^{th}_{b,mob} = 0$$

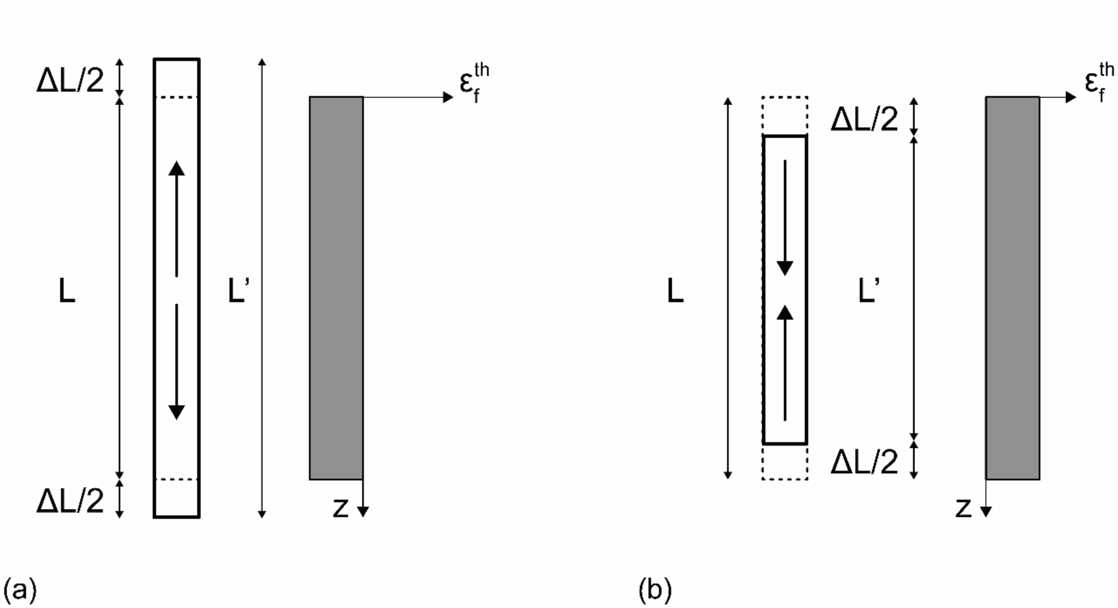
$$P + \pi\frac{D^2}{4}K_h\left(w_{h,m}+w_{h,th}\right) + Q_{s,mob} + Q_{b,mob} = 0$$



Thermally induced strain

- If a pile can deform freely, a temperature change results in a thermal deformation proportional to the coefficient of thermal expansion, α, and the temperature change ΔT:

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

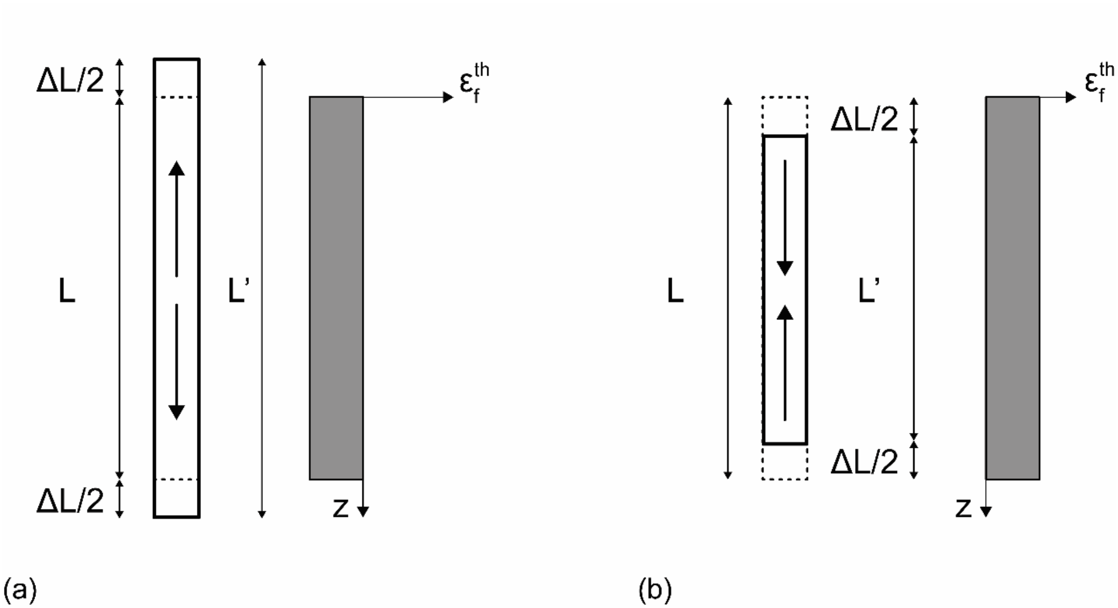


(Laloui et al., 2003; Rotta Loria, 2018)

Variation of body dimension

- This thermally induced strain leads to a change in length of

$$\Delta L = L' - L = -L\varepsilon_f^{th} = L\alpha_{EP}\Delta T$$



(Laloui et al., 2003;
Rotta Loria, 2018)

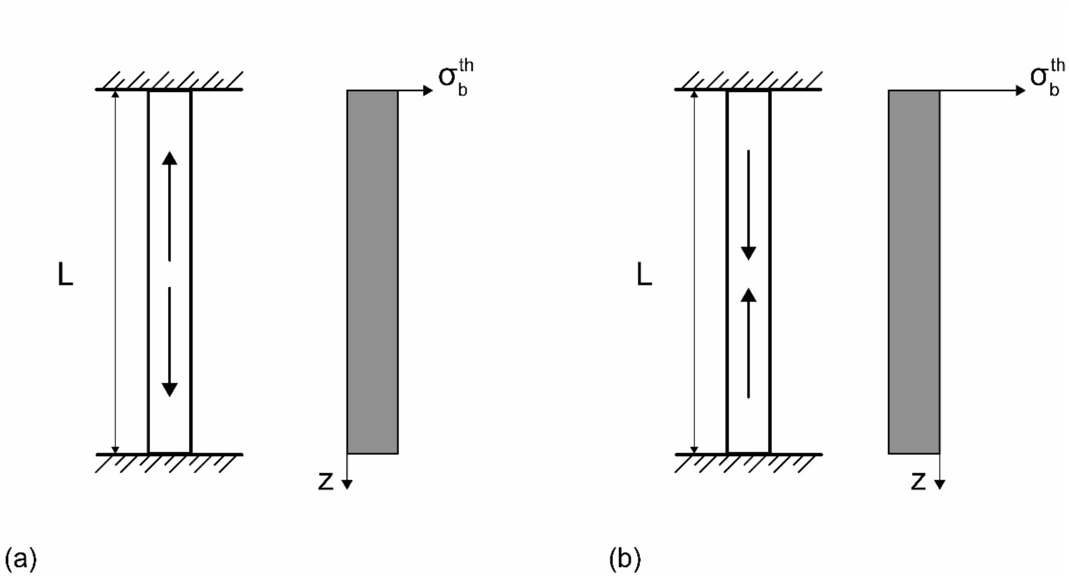
Thermally induced stress

- When the thermally induced deformation is completely blocked

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

- Therefore, a thermally induced stress arises

$$\sigma_b^{th} = E_{EP} \varepsilon_b^{th} = E_{EP} \alpha_{EP} \Delta T$$



(Laloui et al., 2003;
Rotta Loria, 2018)

Summary

- Energy piles will generally be subjected to an observed thermal strain when subjected to temperature changes of

$$\varepsilon_o^{th} \leq \varepsilon_f^{th}$$

- Hence, a portion of strain will be blocked

$$\varepsilon_b^{th} = \varepsilon_o^{th} - \varepsilon_f^{th}$$

and pile behaviour will be characterised by a degree of freedom:

$$DOF = \frac{\varepsilon_o^{th}}{\varepsilon_f^{th}} \quad \text{with} \quad 0 \leq DOF \leq 1$$

- The blocked thermal strain will induce a thermal stress in the pile:

$$\sigma_o^{th} = E_{EP}\varepsilon_b^{th} = E_{EP}\left(\varepsilon_o^{th} - \varepsilon_f^{th}\right) = E_{EP}\left(\varepsilon_o^{th} + \alpha_{EP}\Delta T\right)$$
$$= E_{EP}\alpha_{EP}\Delta T(1 - DOF)$$

(Laloui et al., 2003)

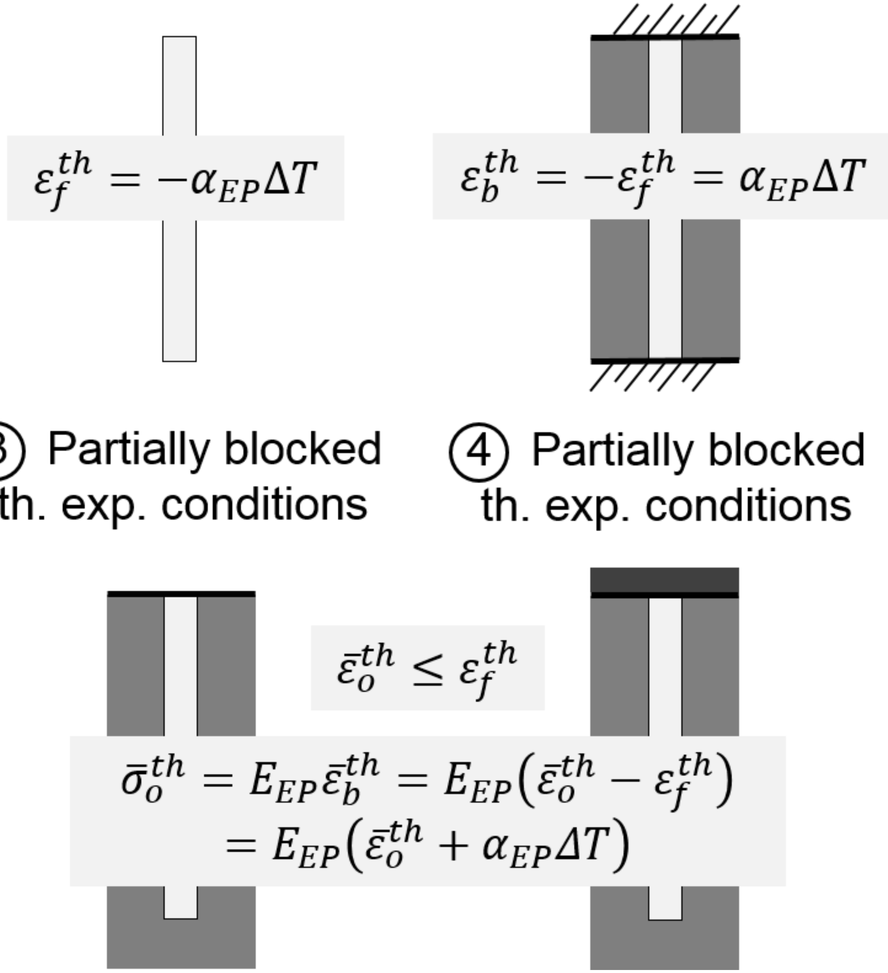
Summary

① Free thermal exp. conditions

② Fully blocked thermal exp. conditions

③ Partially blocked th. exp. conditions

④ Partially blocked th. exp. conditions

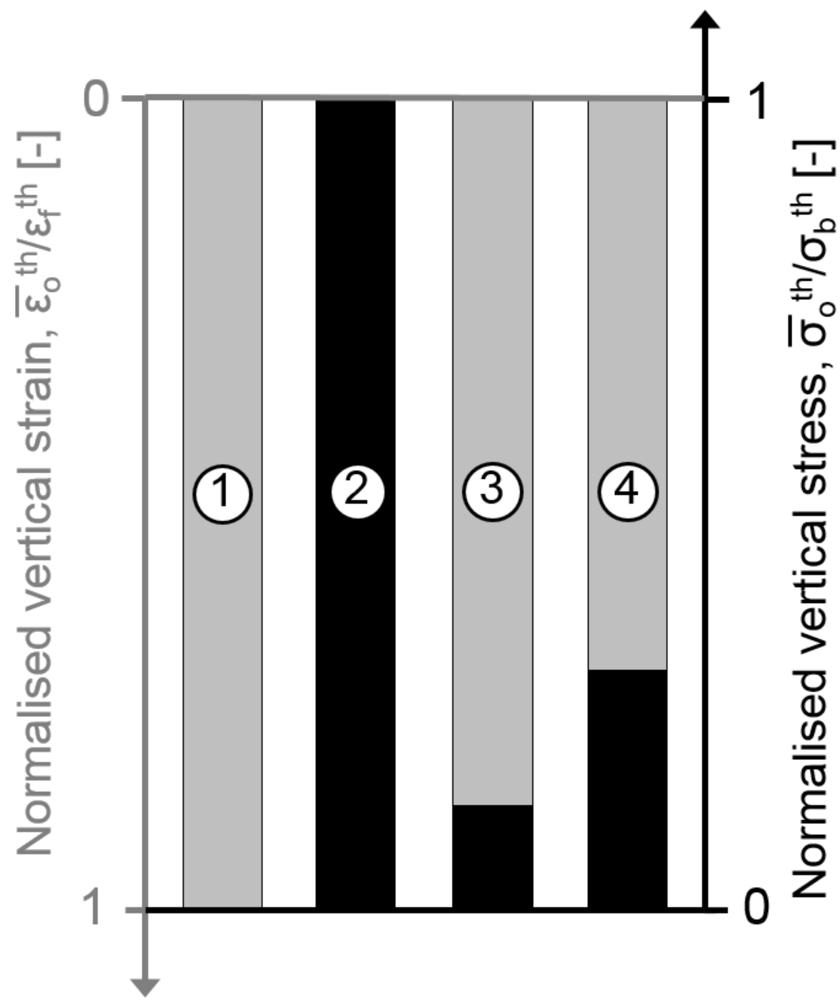


$$\varepsilon_f^{th} = -\alpha_{EP}\Delta T$$

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

$$\bar{\varepsilon}_o^{th} \leq \varepsilon_f^{th}$$

$$\bar{\sigma}_o^{th} = E_{EP}\bar{\varepsilon}_b^{th} = E_{EP}\left(\bar{\varepsilon}_o^{th} - \varepsilon_f^{th}\right) = E_{EP}\left(\bar{\varepsilon}_o^{th} + \alpha_{EP}\Delta T\right)$$



(Rotta Loria, 2018)

Thermo-Pile

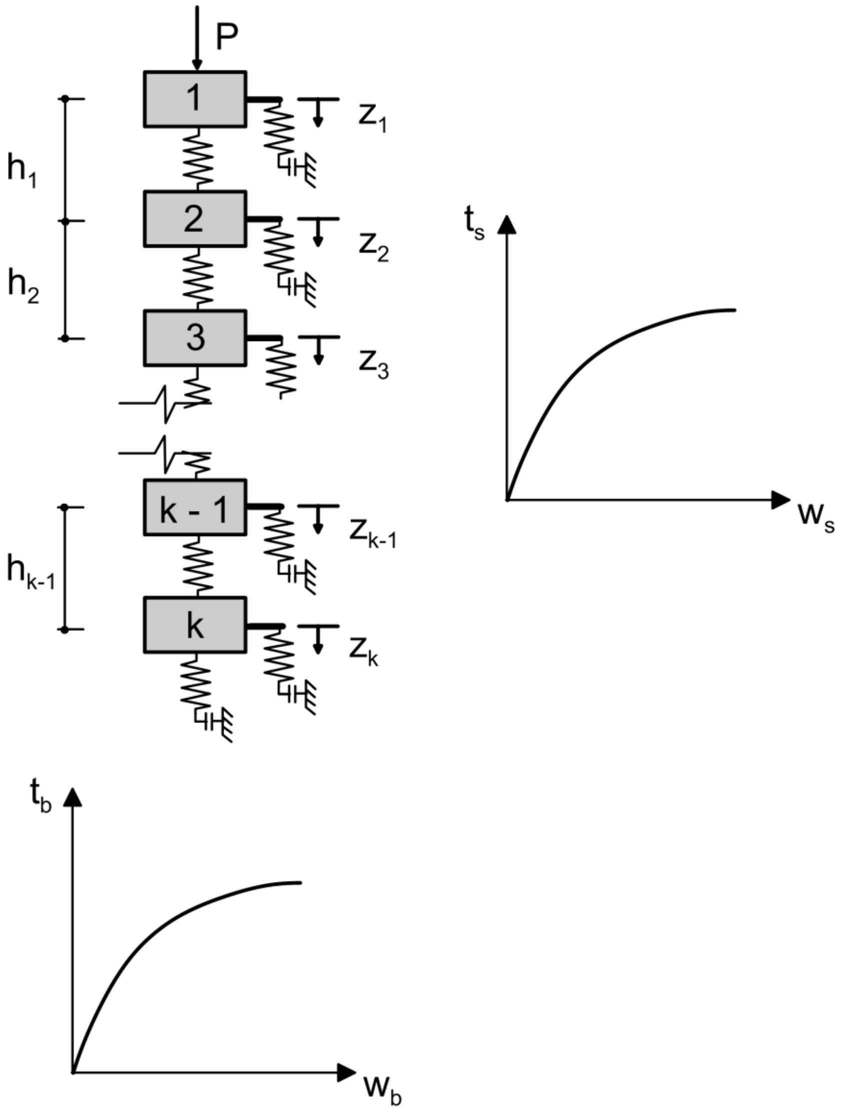
Fundamental hypothesis:

- Thermo-elastic behaviour of the energy pile-soil system

Load-transfer analysis approach

(Laloui and Rotta Loria, 2019; redrawn after Knellwolf et al., 2011)

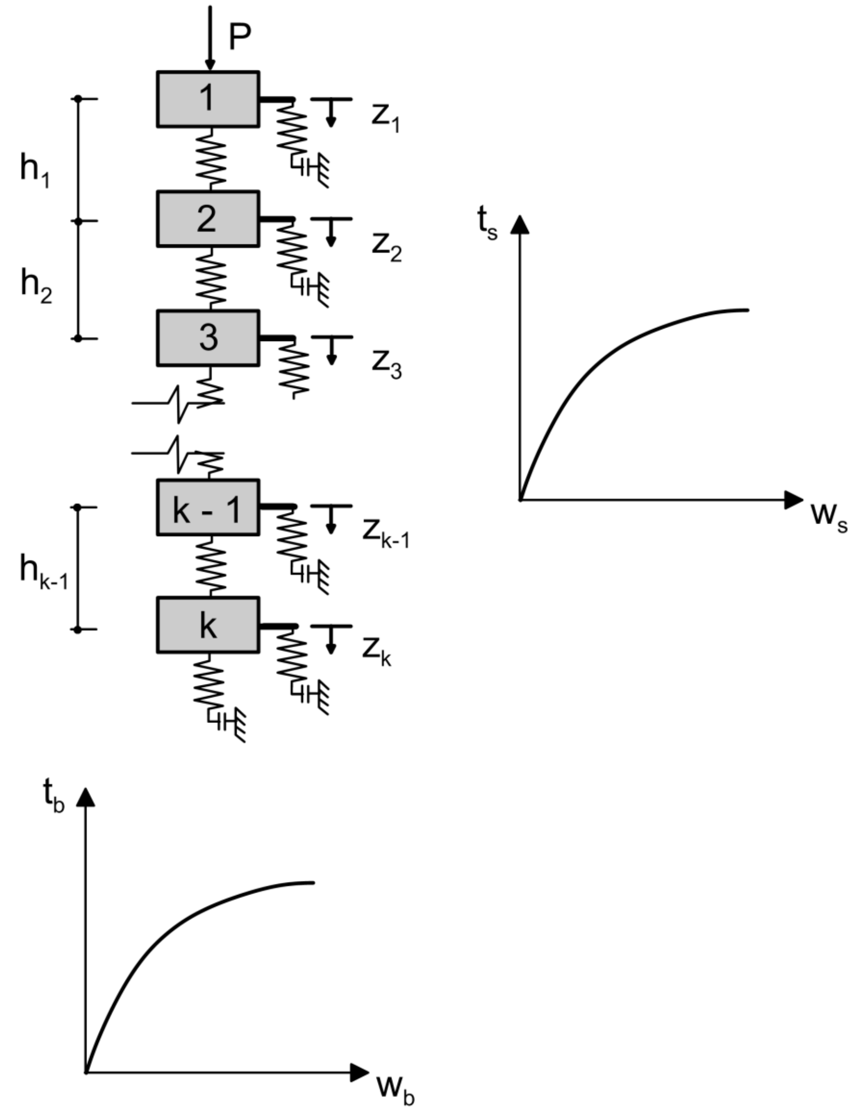
- Pile-soil interaction modelled through a load-transfer approach t-z
- The pile displacement calculation is based on a one dimensional finite difference scheme
- Standard calculation of pile bearing capacity



Load-transfer analysis approach

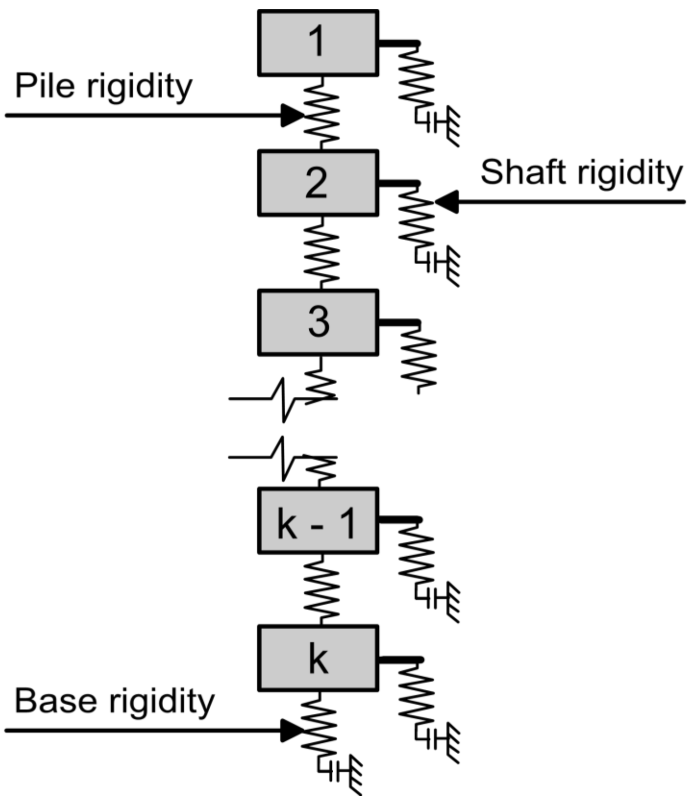
(Laloui and Rotta Loria, 2019; redrawn after Knellwolf et al., 2011)

- First introduced by Coyle and Reese (1966)
- Pile discretised into k elements of length h_i
- Springs between two adjacent elements represent pile rigidity
- Interaction between soil and pile along the lateral surface and at tip is described by load transfer curves

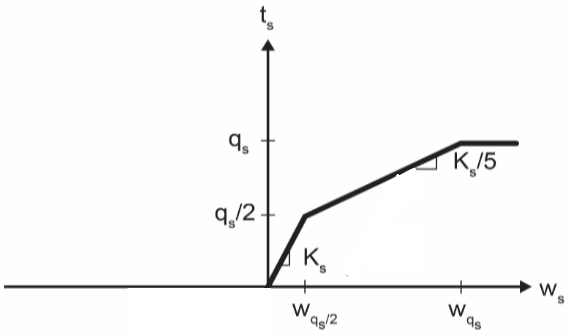


Background

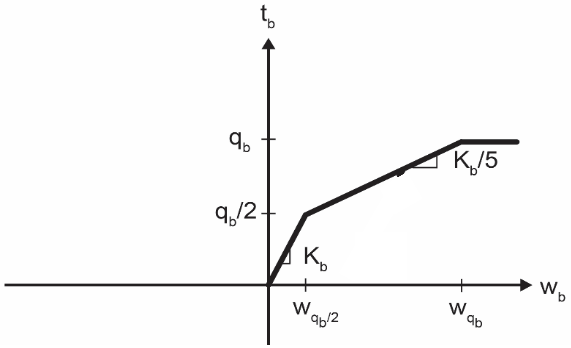
(Laloui and Rotta Loria, 2019;
redrawn after Knellwolf et al., 2011)



Load-transfer relationship for shaft of single isolated pile



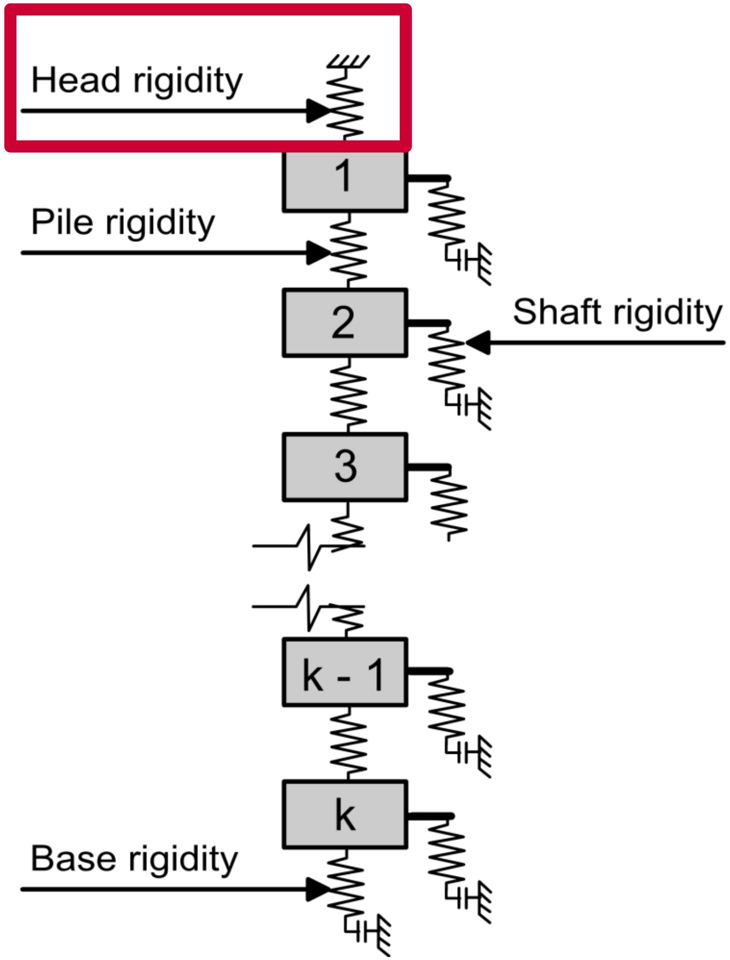
Load-transfer relationship for base of single isolated pile

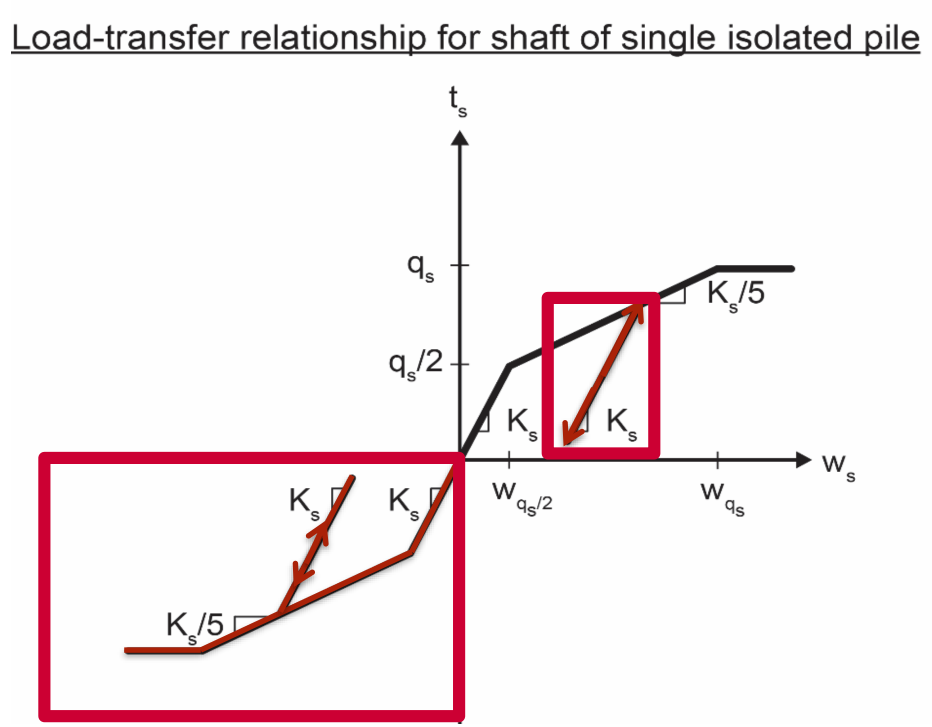


- Finite difference scheme for settlement evaluation based on the work of Coyle and Reese (1963)
- Shaft and base resistance load-transfer (t-z) diagrams based on those proposed by Frank and Zhao (1982)

Extension

(Knellwolf et al., 2011)

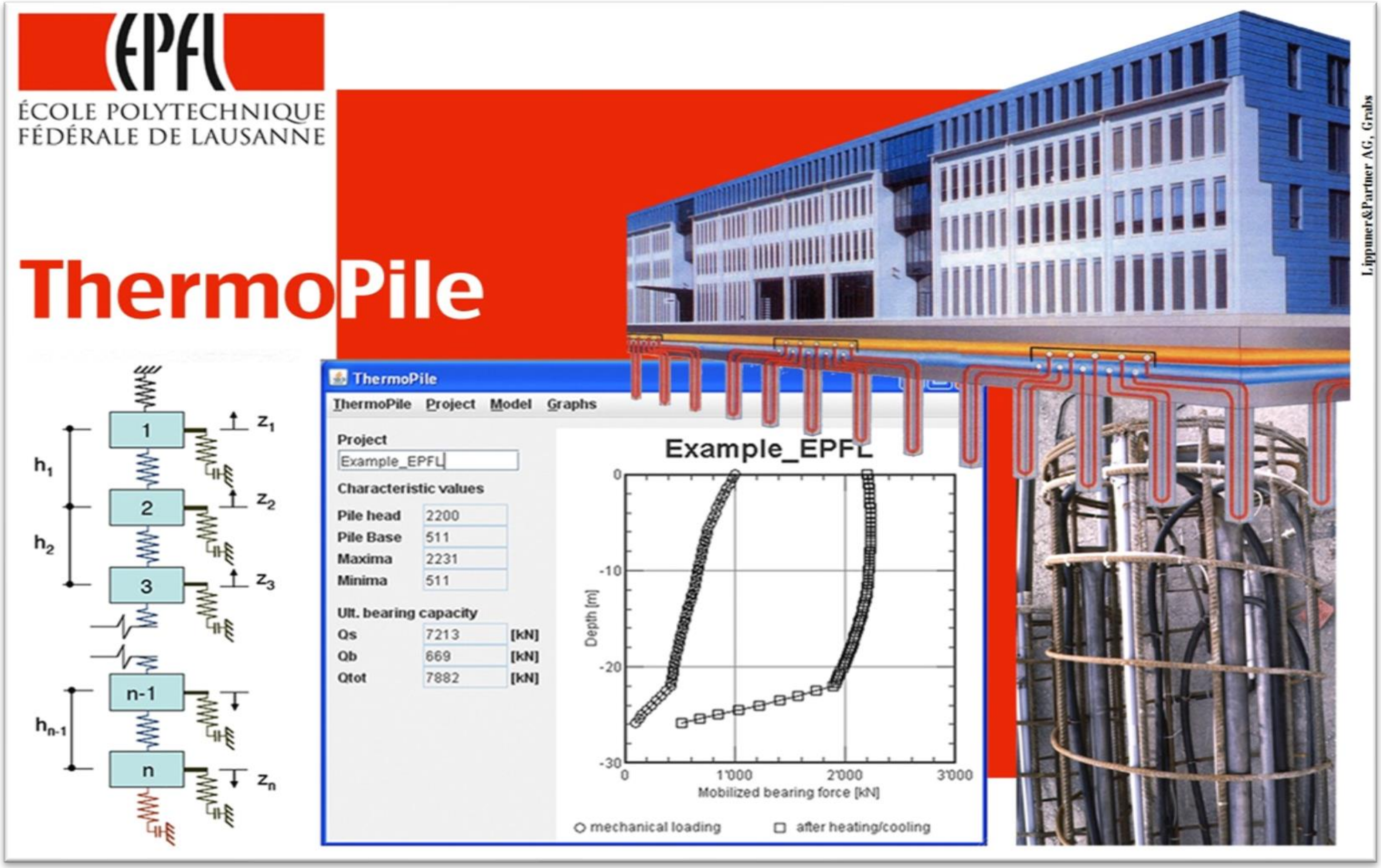




- Head stiffness of the building
- Shaft resistance t-z diagram extended to consider thermlly induced displacements

(Knellwolf et al., 2011)

A suitable tool to perform the geotechnical and structural design of energy piles



Hypotheses

- Discretization of the pile in a number of segments to consider soil layers with different properties
- Soil and pile properties (φ, E, α) remain constant with temperature (can be imposed to vary with depth)
- Soil and pile-soil interaction properties do not change with temperature
- The relationships between the shaft friction-shaft displacement, head stress-head displacement and base stress-base displacement are known (Load-transfer curves)
- Pile radial strains neglected

Key parameters

(Laloui and Rotta Loria, 2019;
redrawn after Knellwolf et al., 2011)

- The load-transfer curves vary for different soil types depending on the values of q_s, q_b, K_s and K_b

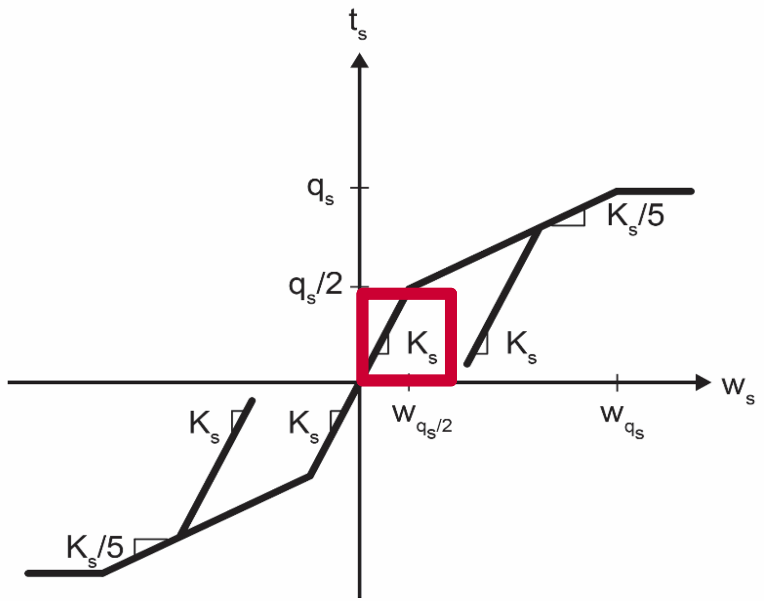
- According to Frank et al (1991)

$$K_s = c_1 \frac{E_M}{D}$$

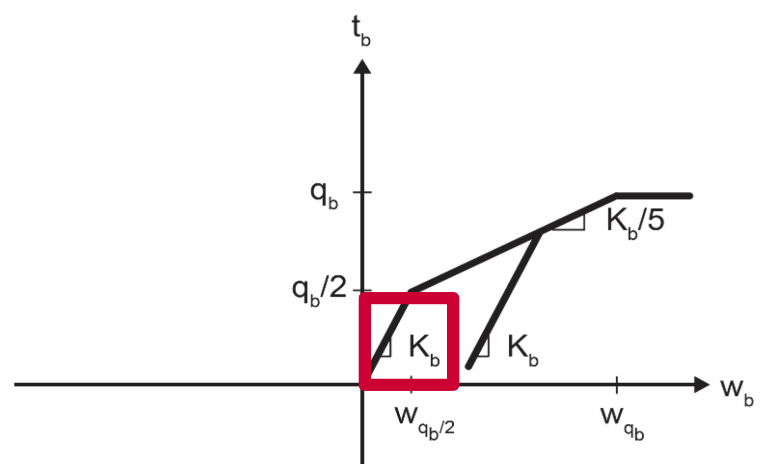
$$K_b = c_2 \frac{E_M}{D}$$

- c_1, c_2: empirical coefficients
- E_M: Menard pressurementer modulus
- D: pile diameter

Load-transfer relationship for shaft of single isolated pile



Load-transfer relationship for base of single isolated pile



Key parameters

(Knellwolf et al., 2011)

- For coarse-grained soils (Frank et al 1991)
  - $c_1 = 0.8$ and $c_2 = 4.8$
- For fine-grained soils (Frank et al 1991)
  - $c_1 = 2$ and $c_2 = 11$

- The Menard pressurementer modulus can be related to the soil Young's modulus E_{soil} through the oedometric modulus as

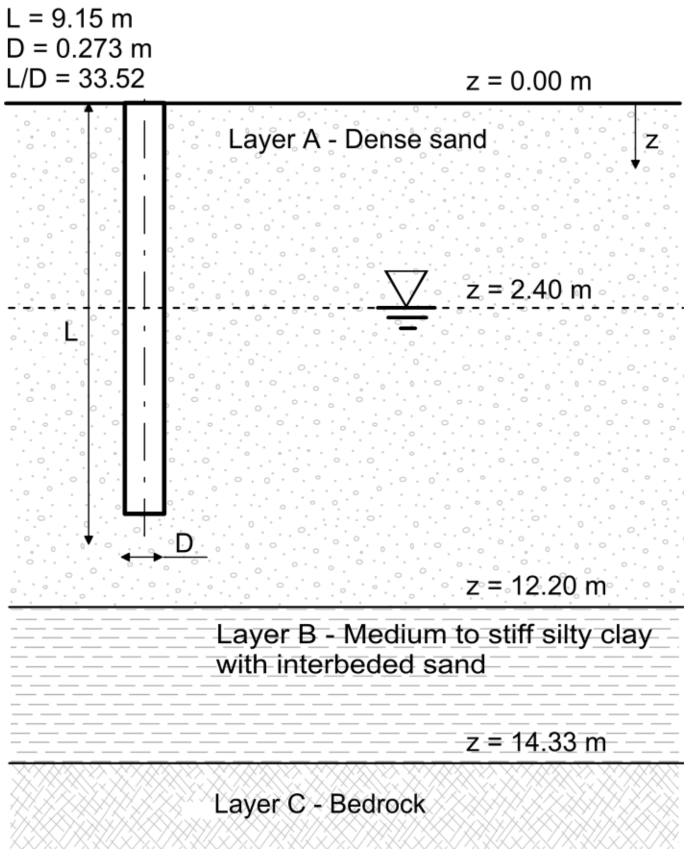
$$E_M = E_{oed}\alpha_r = \frac{E_{soil}(1 - v_{soil})}{(1 + v_{soil})(1 - 2v_{soil})}\alpha_r$$

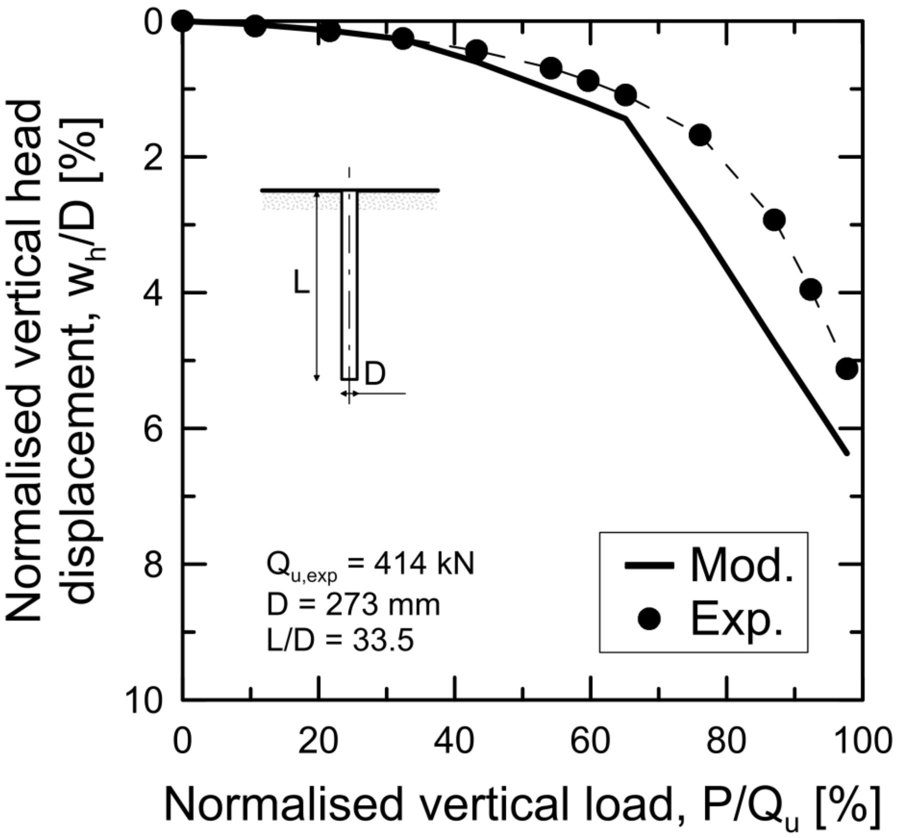
- α_r is a rheological coefficient typically equal to 1/3 for coarse-grained soils and equal to 1 for fine-grained soils

Modelled and observed responses

Modelling of piles in sand (tests by Briaud et al. (1989))

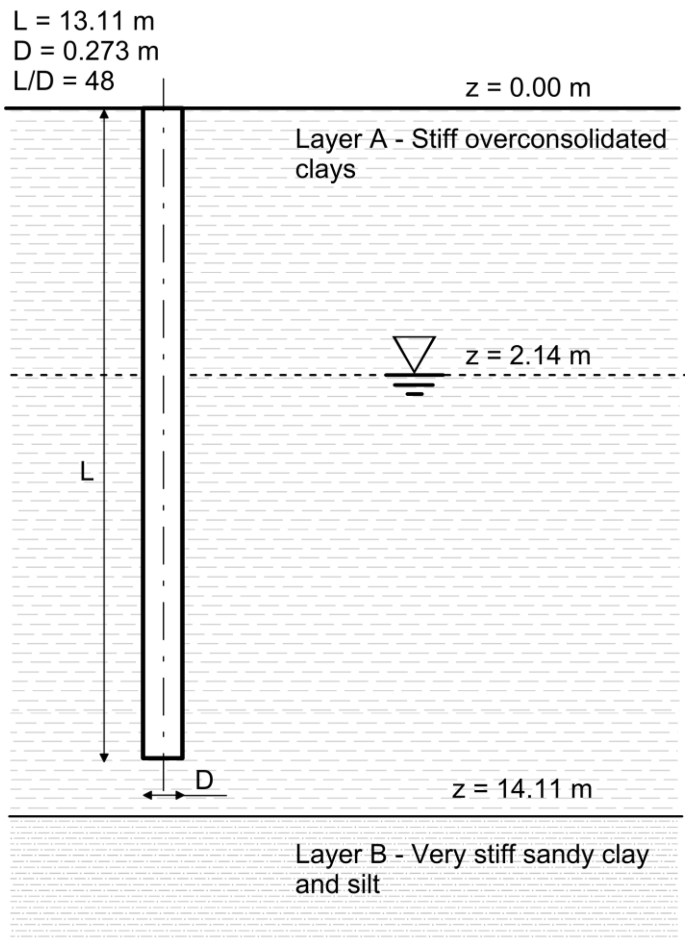
(Rotta Loria et al., 2020)

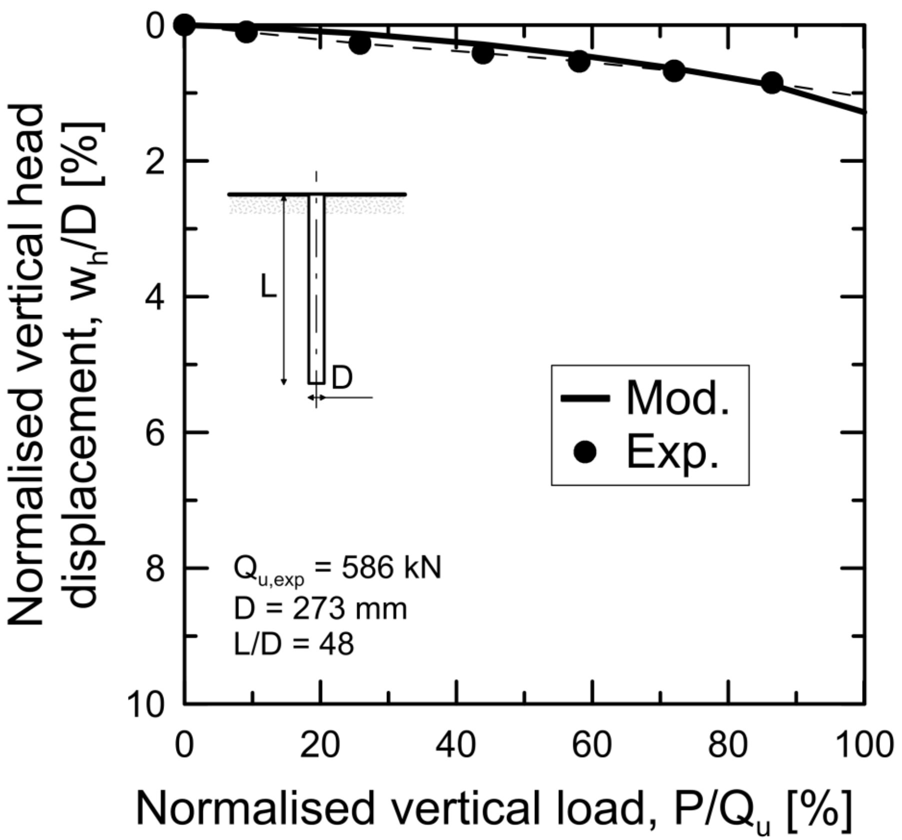




Modelling of piles in clay (tests by O'Neill et al. (1981))

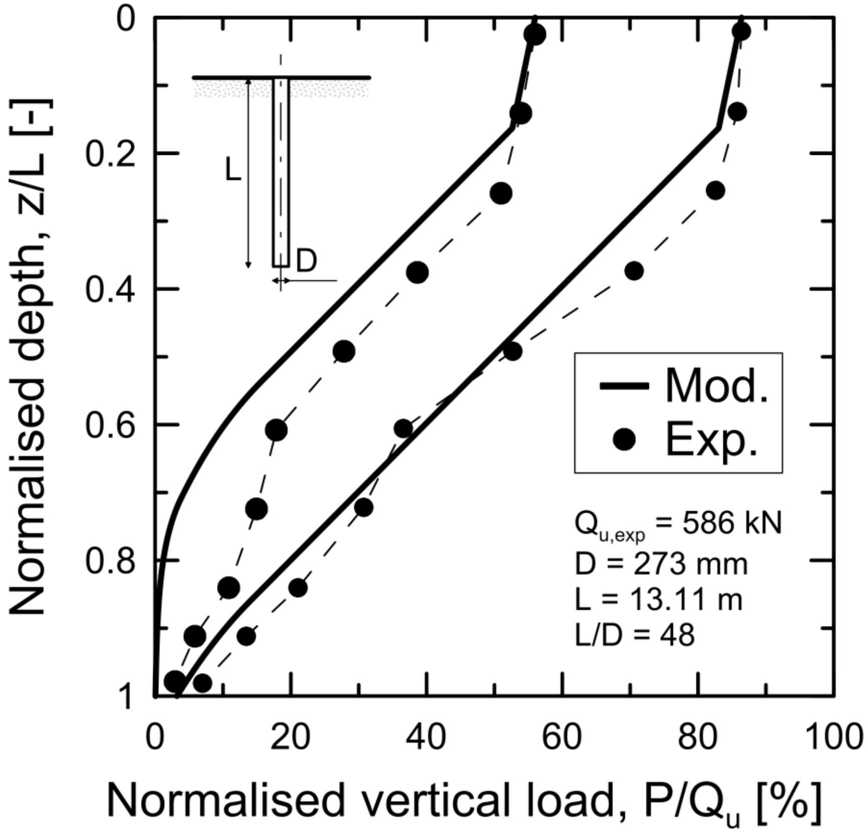
(Rotta Loria et al., 2020)





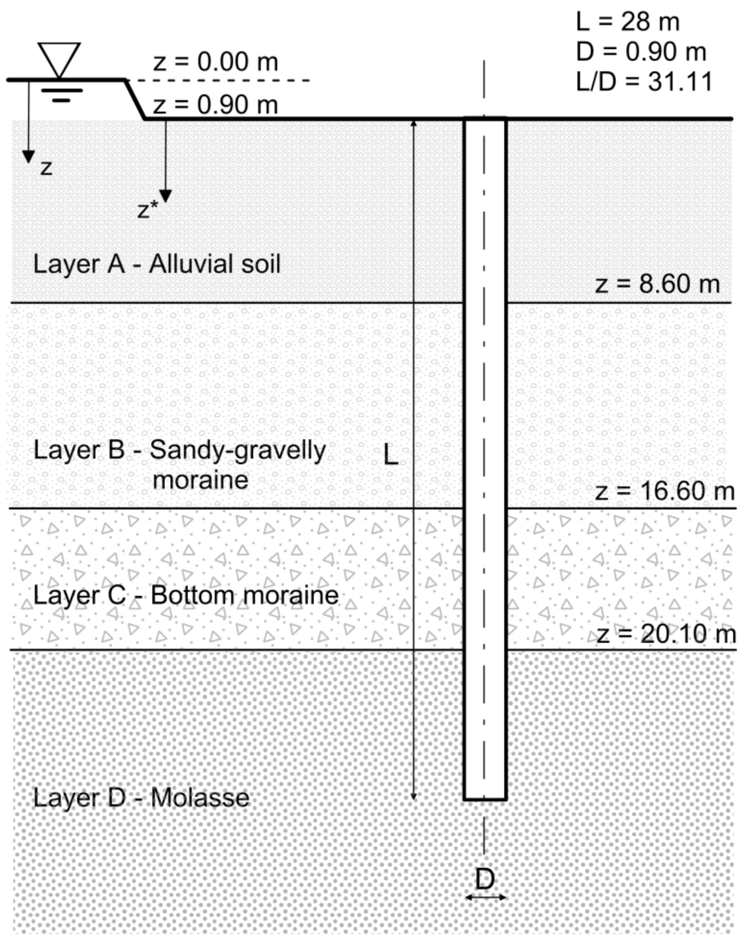
Modelling of piles in clay (tests by O'Neill et al. (1981))

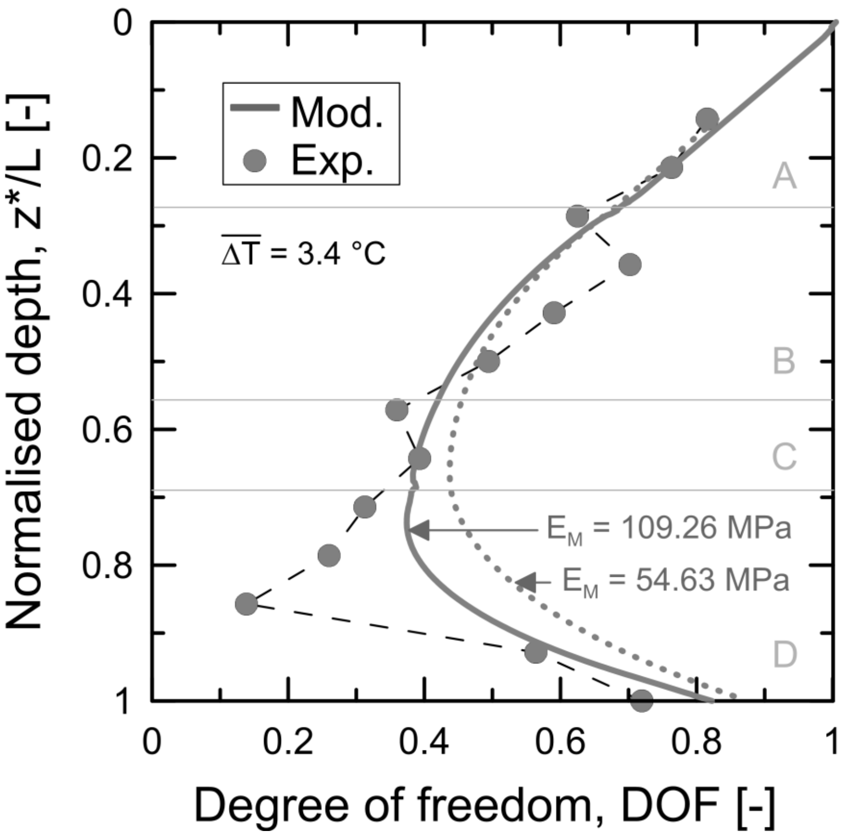
(Rotta Loria et al., 2020)



Modelling of piles in stratified soil (tests by Mimouni and Laloui (2015))

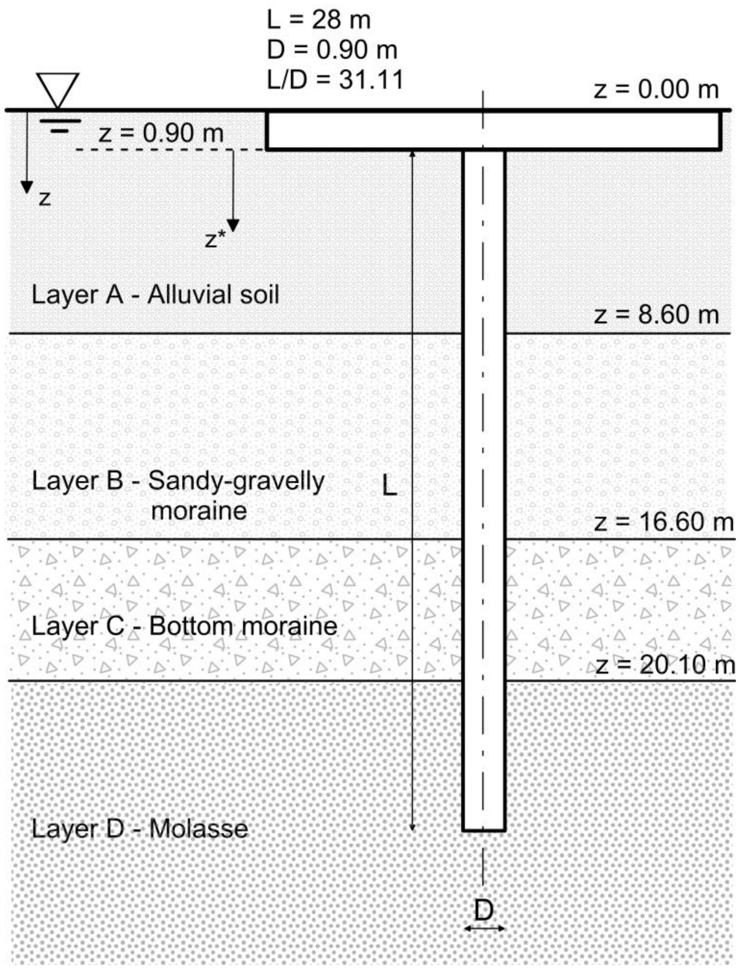
(Rotta Loria et al., 2020)

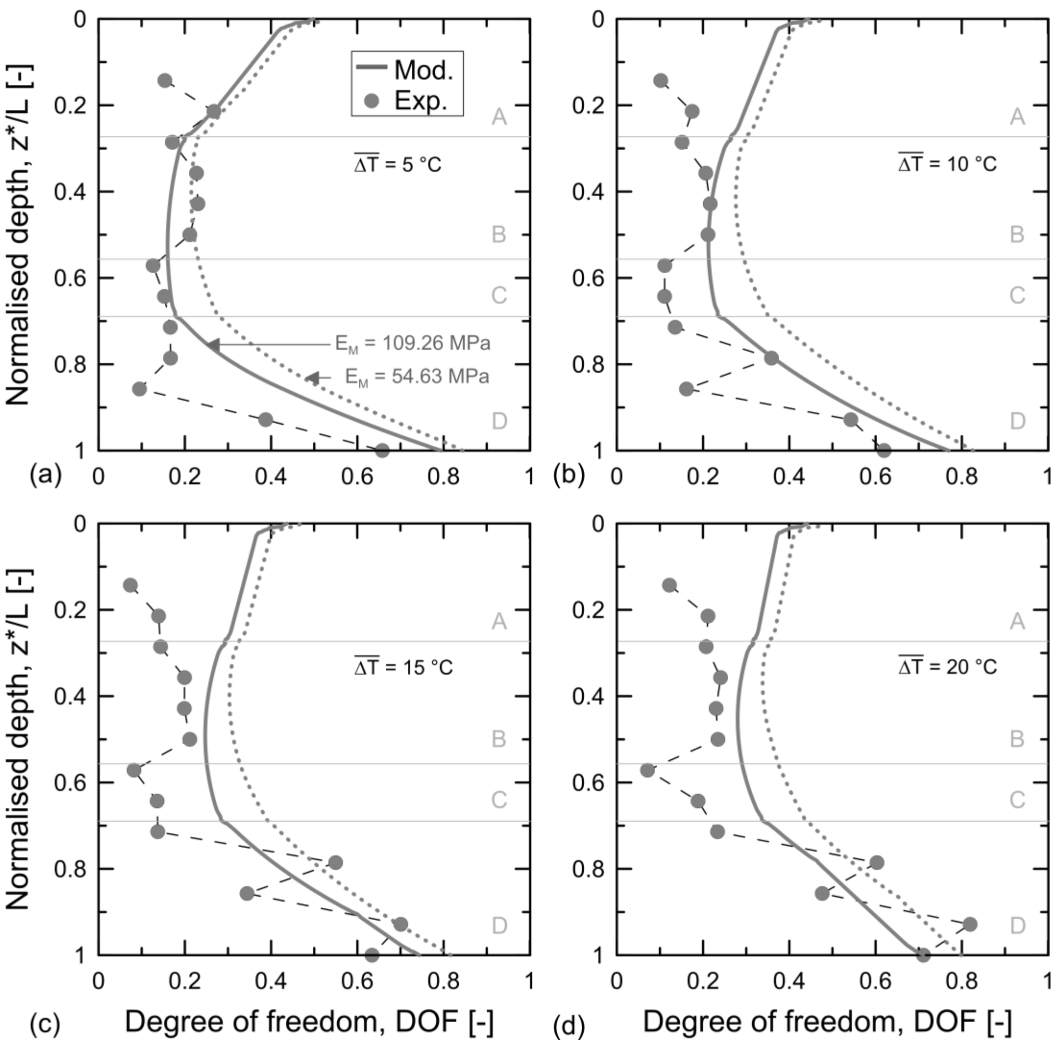




Modelling of piles in stratified soil (tests by Rotta Loria and Laloui (2017))

(Rotta Loria et al., 2020)





Concluding remarks

Geotechnical and structural challenges

- Quantify thermally induced stresses due to heating/cooling loads
  - Potential tensile stresses experienced due to cooling when dealing with low mechanical loads

- Define the related displacements in the short- and long-term
  - Settlements expected throughout the cooling phase, while heaves expected throughout the heating phase