Advances in the geotechnical analysis of energy piles

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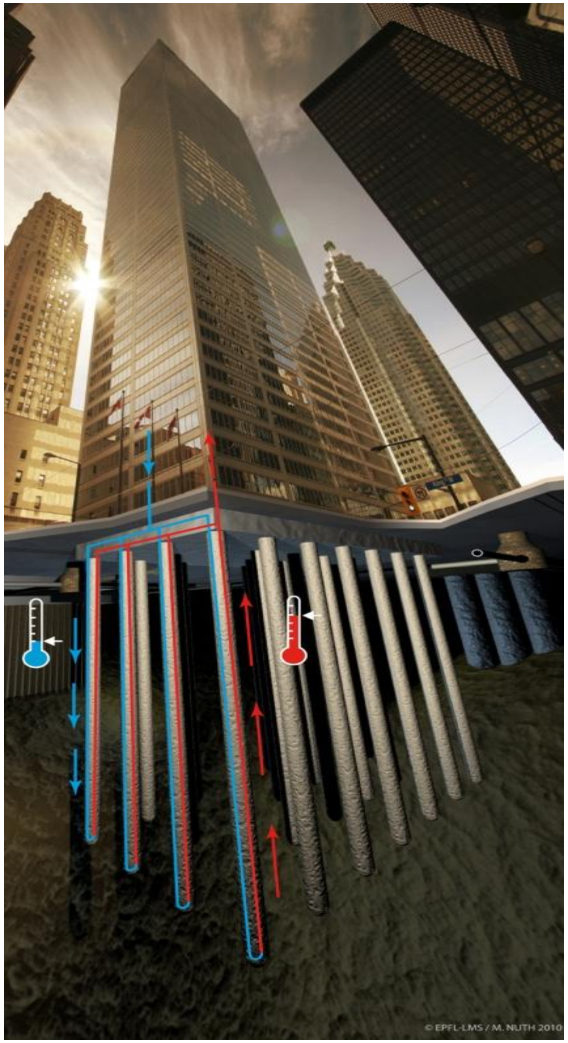
Outline

- Energy piles: an innovative technology
  - Principle, technology and application
- Energy piles thermo-mechanical behaviour
  - Response of energy piles under mechanical thermal actions
  - Geotechnical and structural challenges
- Thermo-Pile: a design check tool for energy piles
  - Background and extension
  - Hypotheses and methodology
  - Software validation and applications
- Conclusions and perspectives



The technology

Concept

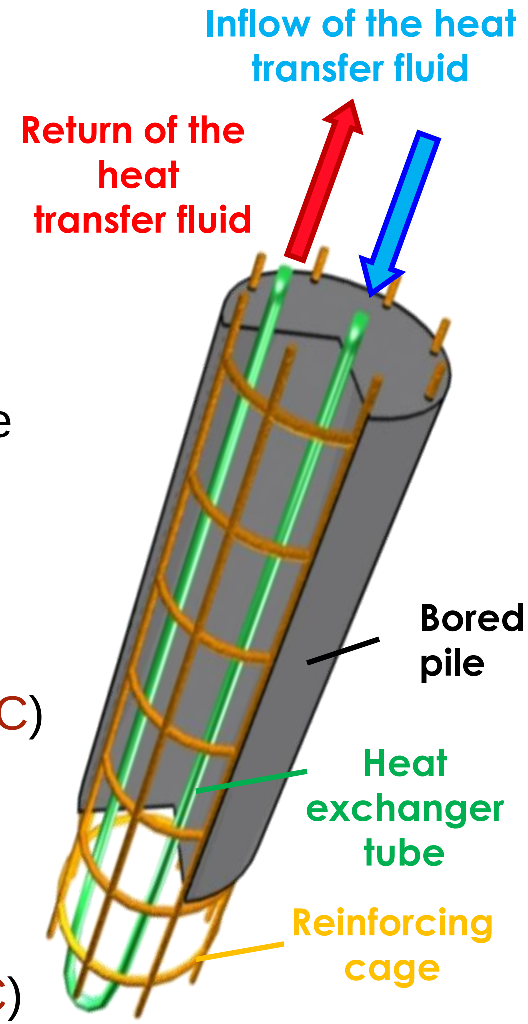
- Use the ground as energy source
- Couple the structural role of foundation piles with the one of geothermal cooling/heating elements

Technology

- Inflow and return tubes mounted along the reinforcing cage
- Heat carrier fluid circulating inside the pipes

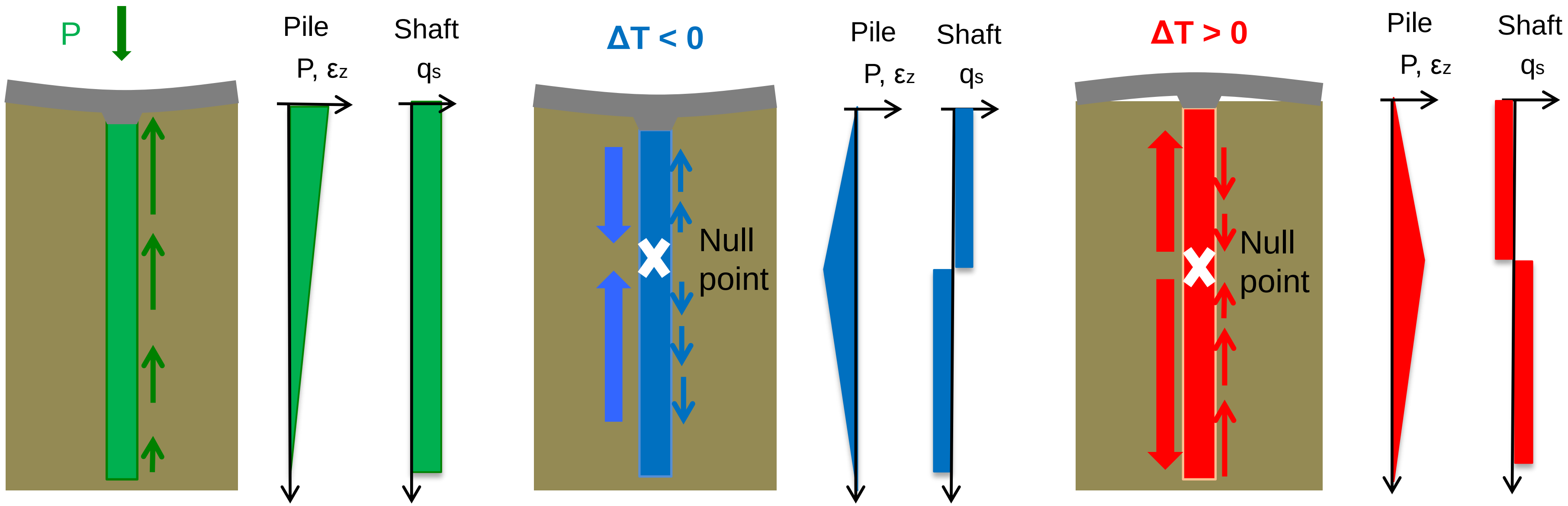
Possible applications

- 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)
  - Revered heat pump (50-100 W/m; T_{EP} = 25-35 ° C)
- Coupling with solar panels (100-150 W/m; T_{EP} = 35-50 ° C)



Thermo-mechanical behaviour of energy piles

Mechanical loading | **Pile cooled (building heated)** | **Pile heated (building cooled)**



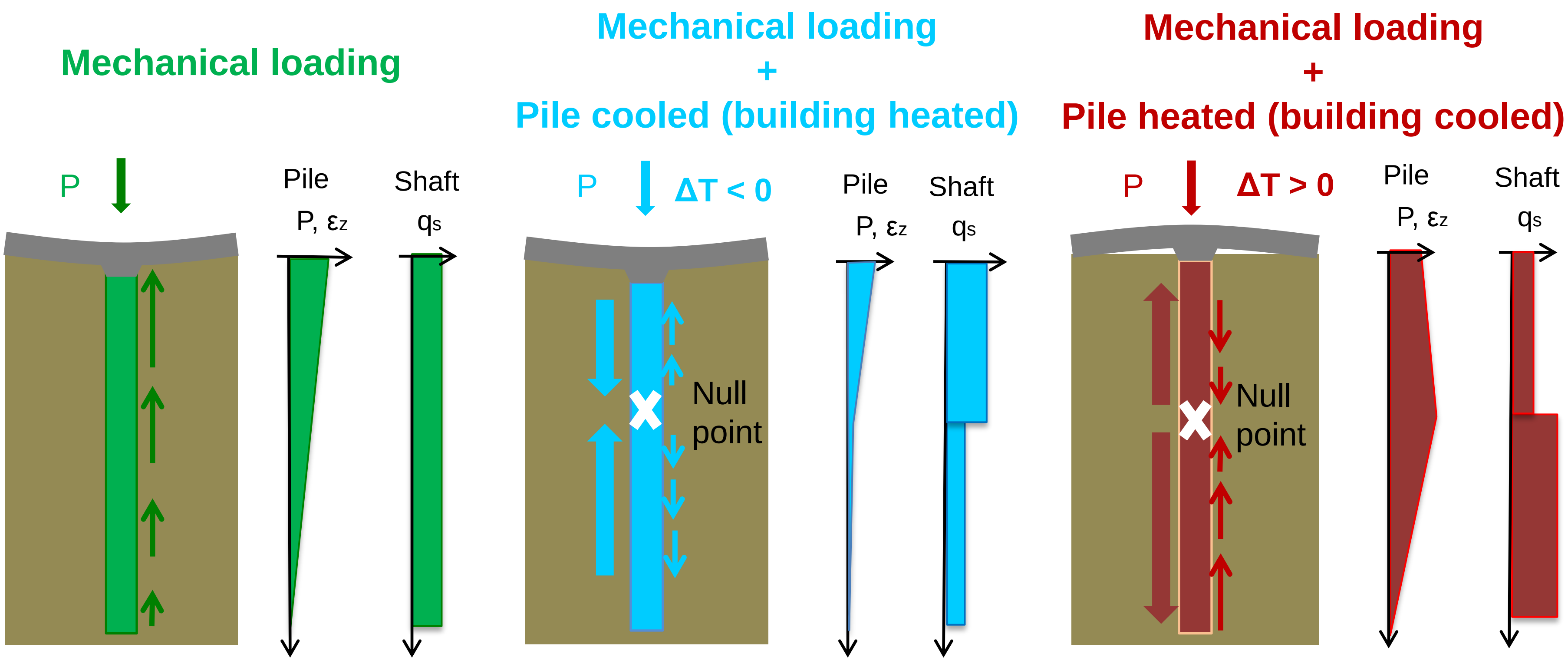
Pile shortening under mechanical load

Pile shortening around the null point

Pile lengthening around the null point

Null point: it represents the plane where any thermally induced displacements occur in the foundation (Laloui *et al*., 2003)

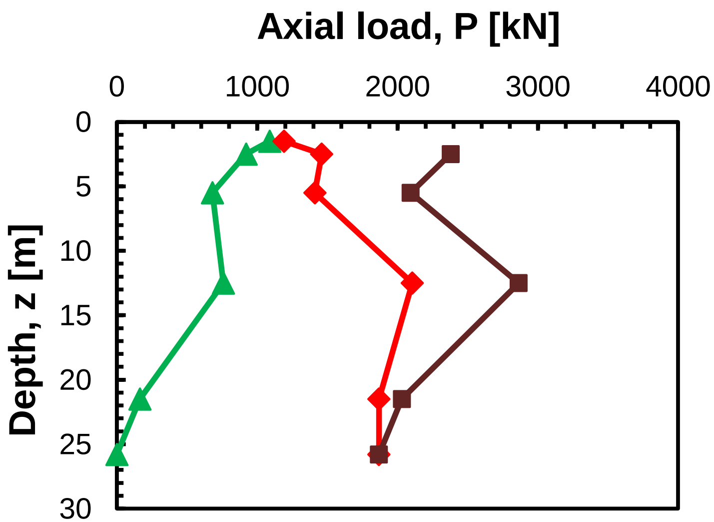
Thermo-mechanical behaviour of energy piles

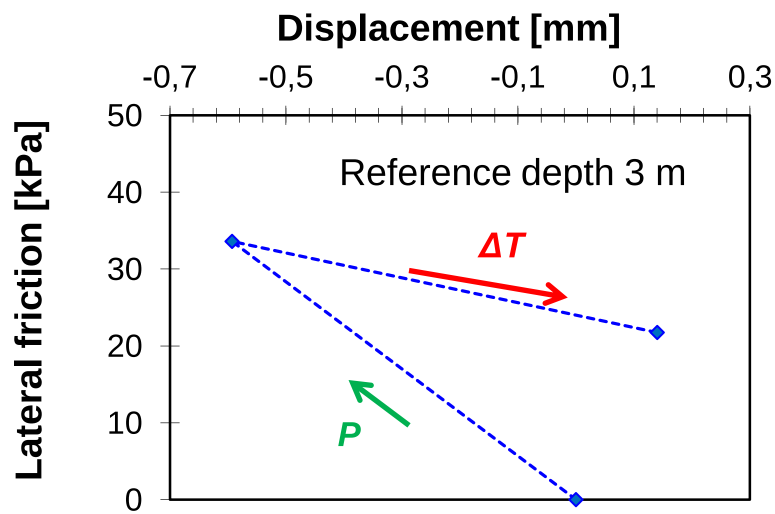


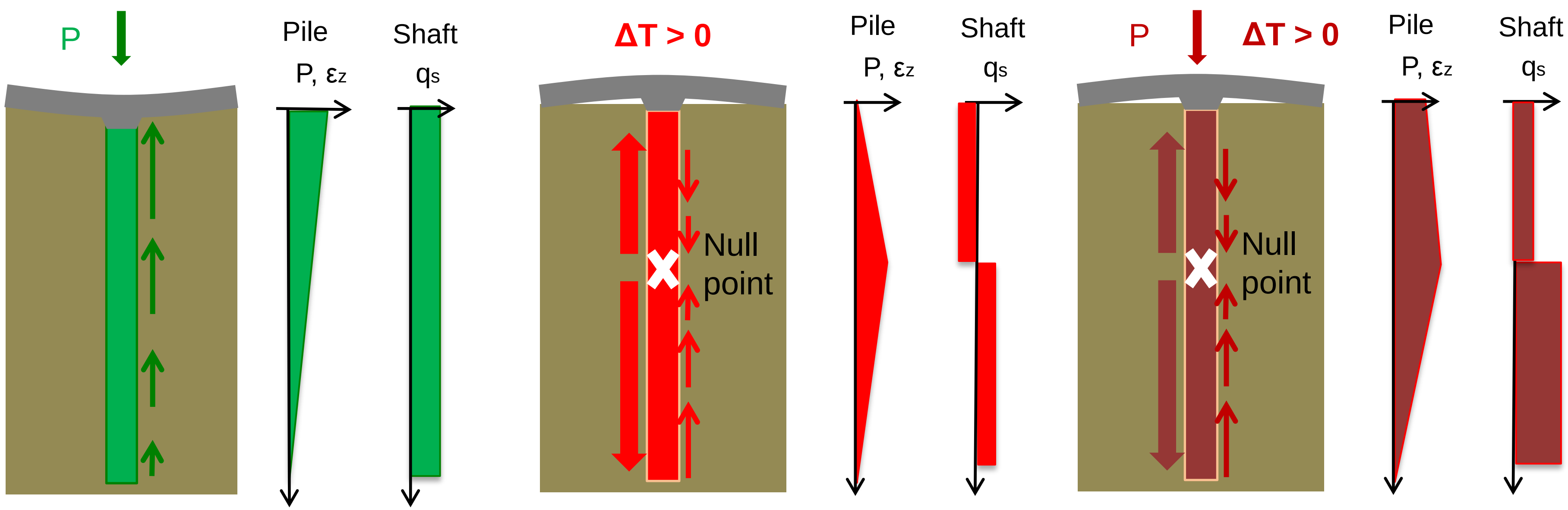
Fundamental hypothesis: the behaviour of the system remains in elastic conditions

- The higher the heating loads, the higher the induced thermal stresses into the piles
- The higher the cooling loads, the higher the foundation induced settlements
- The higher the mechanical load, the more pronounced these phenomena

Experimental evidence (Laloui *et al.*, 2003)







Geotechnical and structural challenges for the design of energy piles

- Quantify thermally induced stresses due to heating and cooling loads in the energy pile
  - Higher compressive stresses due to heating expected when dealing with high mech. loads
  - Potential tensile stresses experienced due to cooling when dealing with low mech. loads

- Define the related displacements of the foundation in short and long term periods
  - Usually more pronounced throughout the cooling phase

- Perform geotechnical and structural checks based on the obtained results, both in ULS and SLS conditions

Thermo-Pile

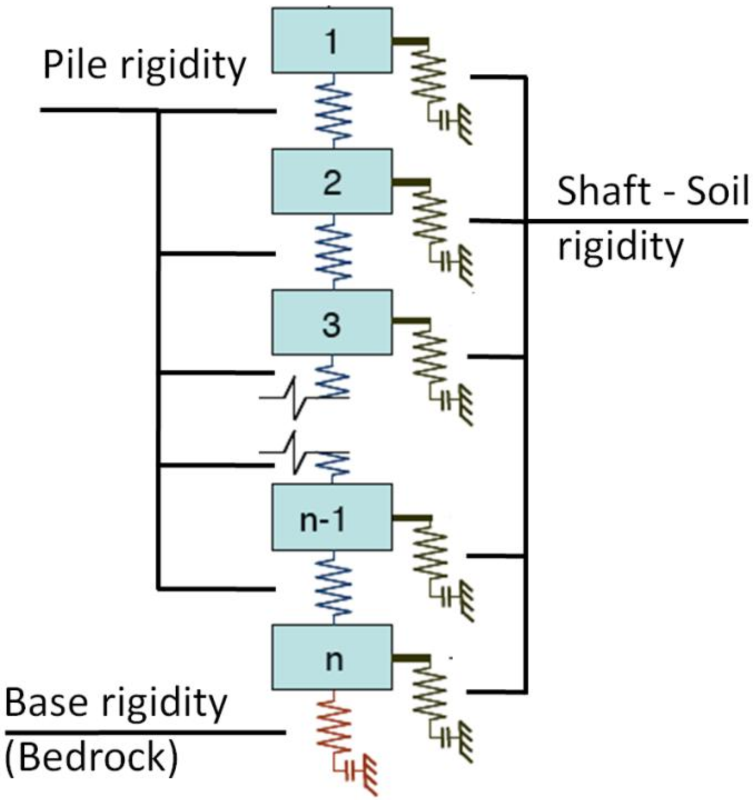
A suitable tool to check the geotechnical stability and structural integrity of energy piles

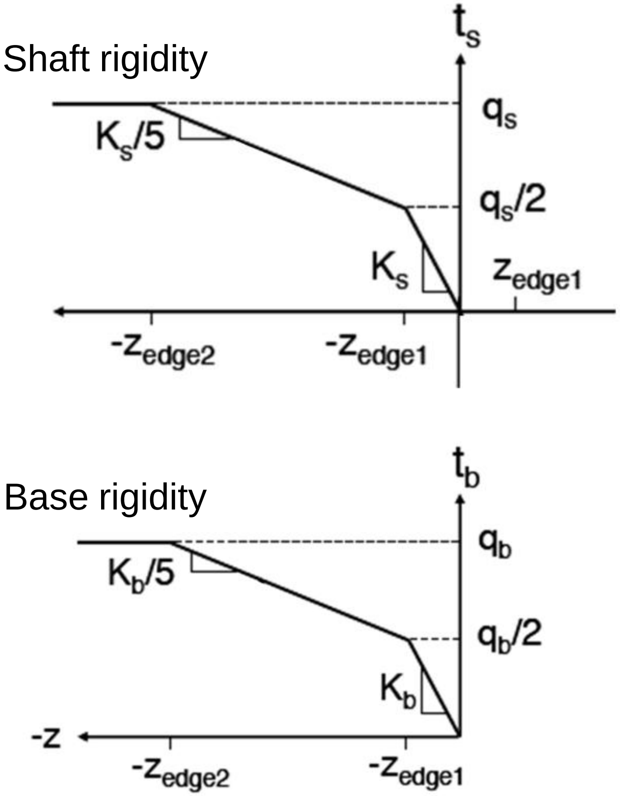
Currently employed worldwide by Companies and Universities

- Geotechnical Laboratory CEDEX, Spain
- Geotechnical Engineering Laboratory, Yonsei Univeresity, Republic of Korea
- Institute of Geotechnics and Hydrotechnology, Wroclaw University of Technology, Poland
- Glenn Department of Civil Engineering, Clemson University, USA
- Laboratoire de GéoMécanique, Université Libre de Bruxelles, Belgique
- ECOME Entreprendre s.à.r.l., France
- SAS Priser Forages Fondations de l’Ouest, France
- …

THERMO-PILE
A software for Geotechnical Design of Energy Piles

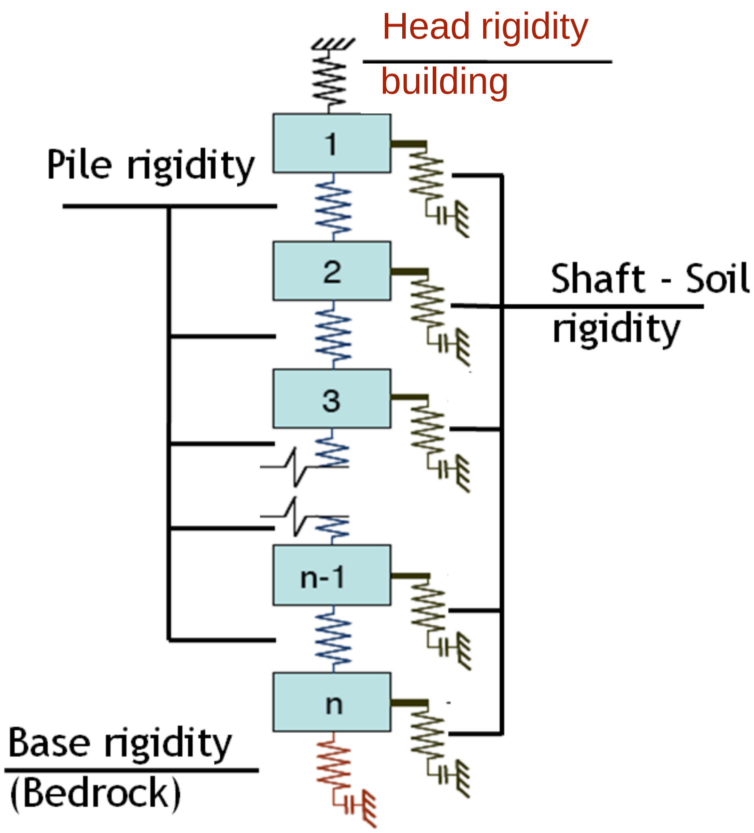
Background

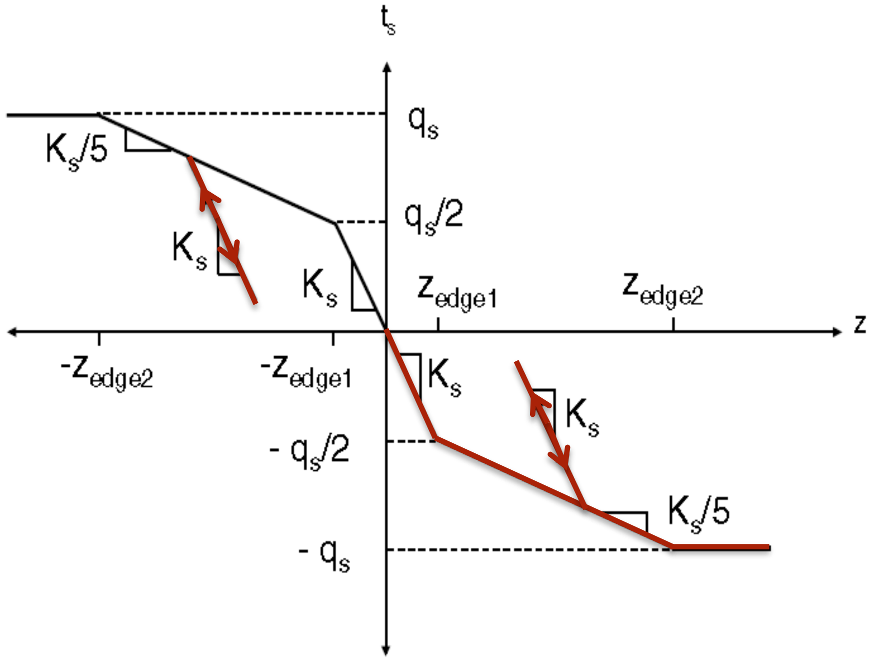




- Finite difference scheme for settlement evaluation based on the work developed by Coyle and Reese (1963)
- Shaft and base resistance load-transfer (t-z) diagrams based on those proposed by Frank and Zhao (1982)

Extension





- Head rigidity of the building

- Shaft resistance load-transfer (t-z) diagram extended to take into account thermlly induced foundation movements

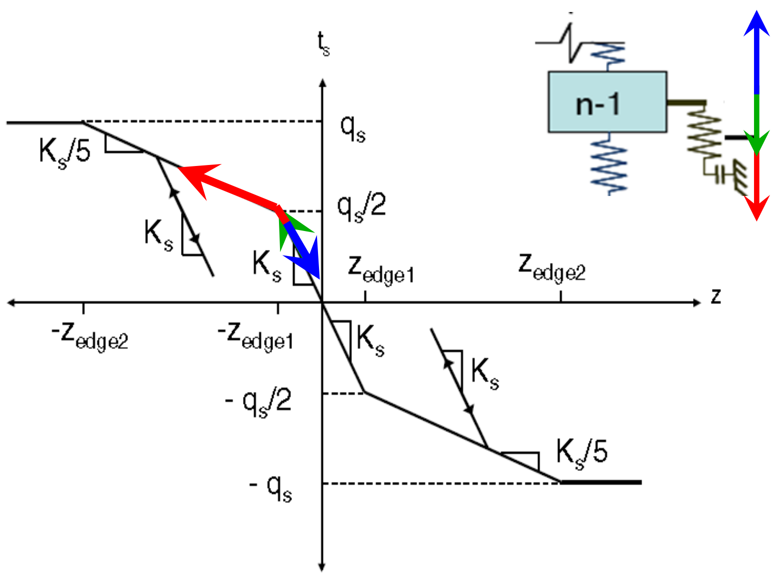
Hypotheses and methodology

Hypotheses

- The discretization of the pile in a number of segments enables to consider various soil layers with distinct properties
- The pile properties (φ, E, α) remain constant with temperature but can be imposed to vary with depth
- The 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)
- Radial strains of the foundation are neglected

Methodology

- 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



Problem resolution

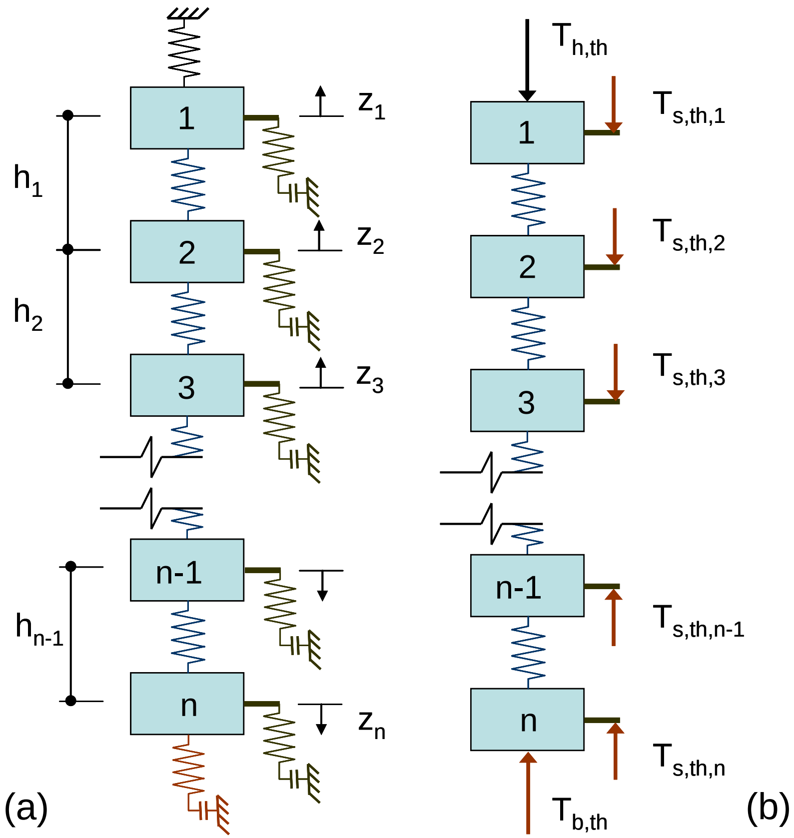
When a pile is heated or cooled, it expands or contracts around the null point.

Therefore, the null point will be located at a depth where:

$$\sum T_{th,NP} = T_{h,th} + \sum_{i=1}^{NP} T_{s,th,i} + T_{b,th} + \sum_{i=NP+1}^{n} T_{s,h,i} = 0$$

- The calculation adopts an iterative process to satisfy the aforementioned equation
- All the steps are done for every element as temporary null point
- The final null point is the one with the best equilibrium of resistances

Problem resolution



(a) model for thermal loading (z_i: displacement of pile segment i); (b) external forces $T_{h,th}$, $T_{s,th,i}$ and $T_{b,th}$ mobilized by thermal loading

1. Choice of a temporary null point
2. Calculation of free thermal strain for element i

$$\varepsilon_{th,i} = \varepsilon_{th,f} = \alpha \cdot \Delta T$$

3. Stress-Strain calculation

$$z_{th,NP} = 0 \qquad z_{th,i} = z_{th,i+1} \pm h_i \cdot \varepsilon_{th,i}$$

$$\sigma_{th,i} = \left(T_{th,b} + \sum_{j=n}^{i} T_{th,s,j} \right) \cdot \frac{1}{A}$$

4. Blocked thermal strain

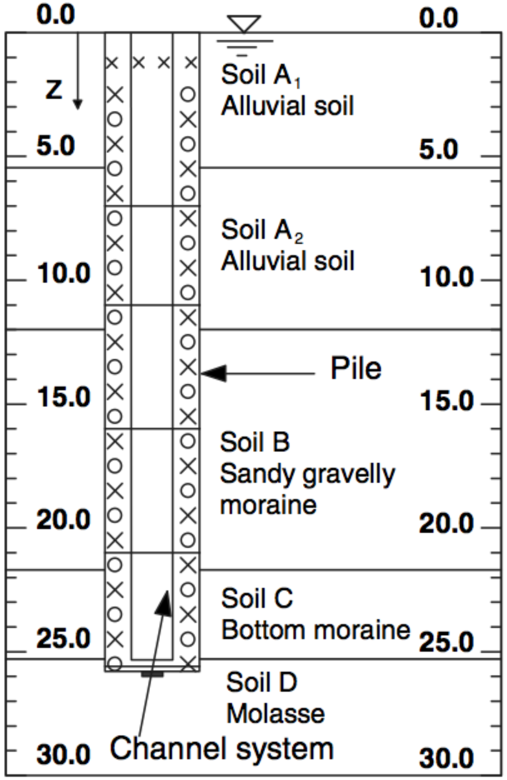
$$\varepsilon_{th,b} = \frac{\sigma_{th}}{E} \leq \varepsilon_{th,f}$$

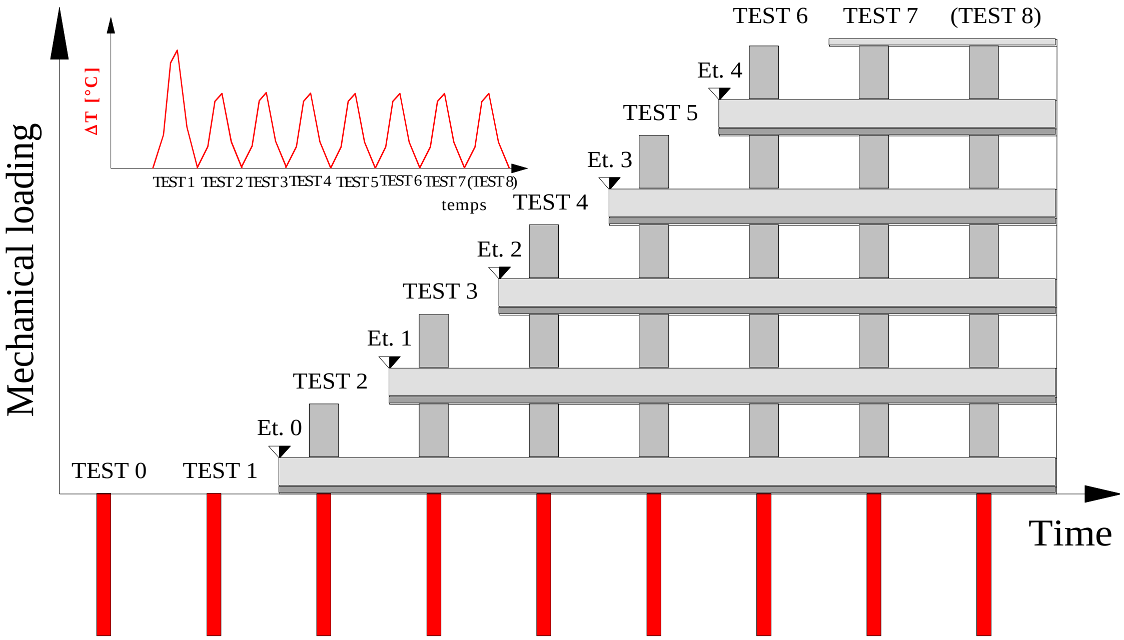
Steps 2-4 repeated until

5. Observed thermal strain

$$\varepsilon_{th,i} = \varepsilon_{th,o} = \varepsilon_{th,f} - \varepsilon_{th,b}$$

Validation of the method: the EPFL tests

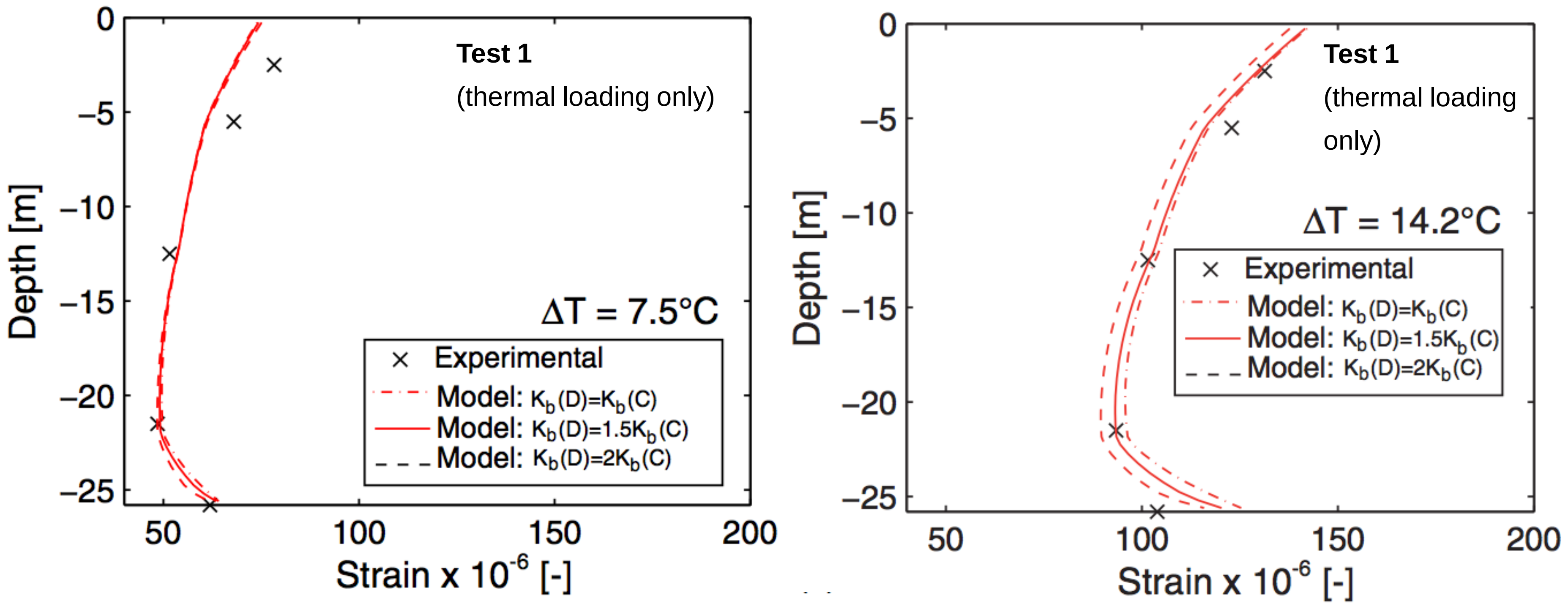




Laloui, L., Moreni, M., and Vulliet, L. (2003). "Comportement d'un pieu bi-fonction, fondation et échangeur de chaleur." Can. Geotech. J., 40(2), 388–402

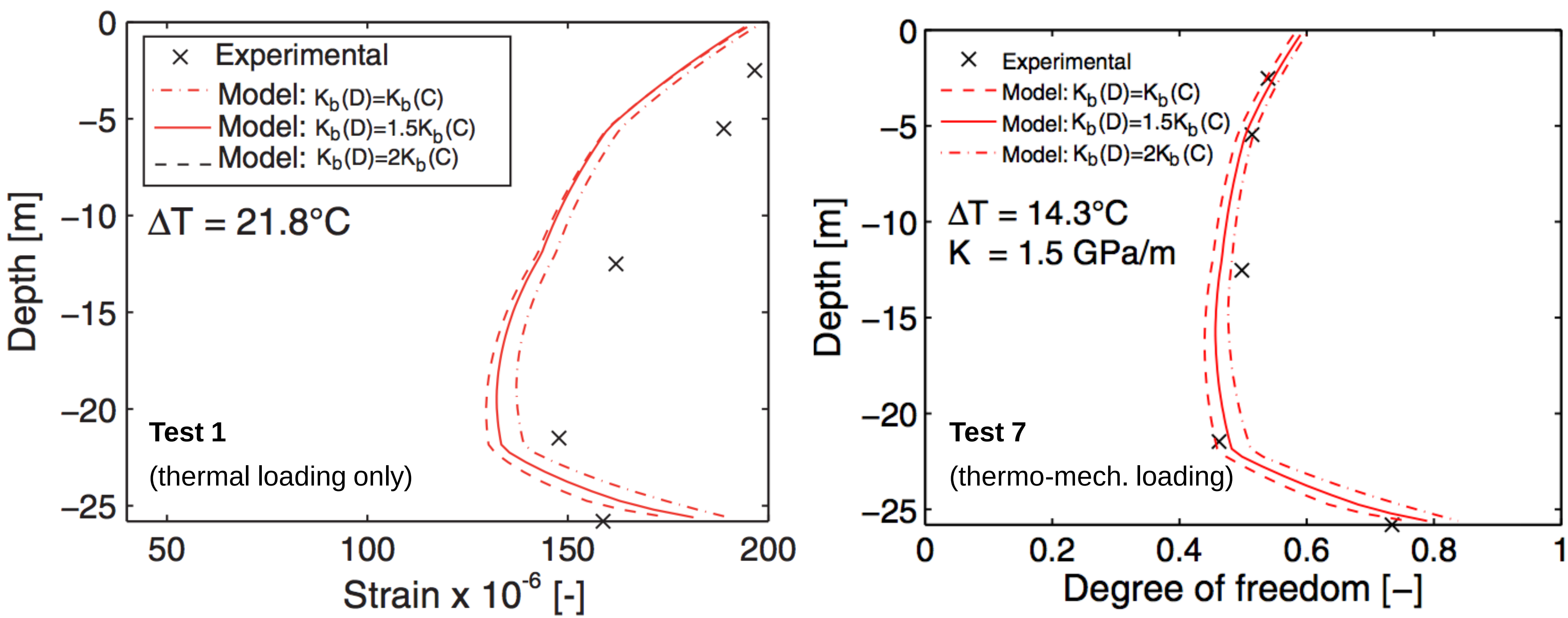
- 2 Thermal tests performed on the energy pile free at the top
- 7 Thermal tests on the pile subjected to increasing mechanical loads

Validation of the method: the EPFL tests



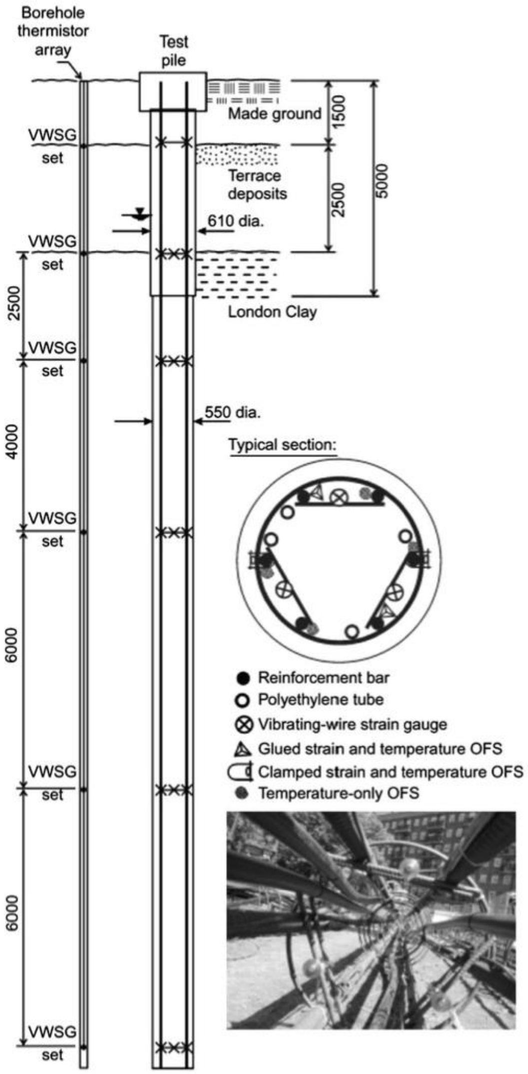
- The proposed approach is able to reproduce the observed energy pile behaviour under increasing thermal loads

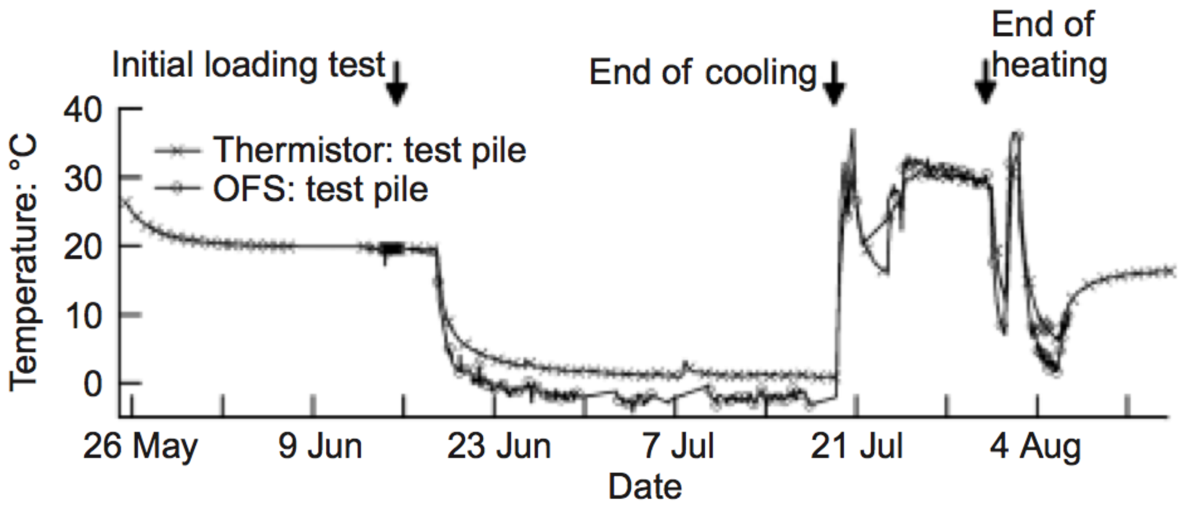
Validation of the method: the EPFL tests



- The proposed approach is able to reproduce the observed behaviour either in the case of thermal loading alone or in the case of both thermal and mechanical loading

Validation of the method: the Lambeth College tests

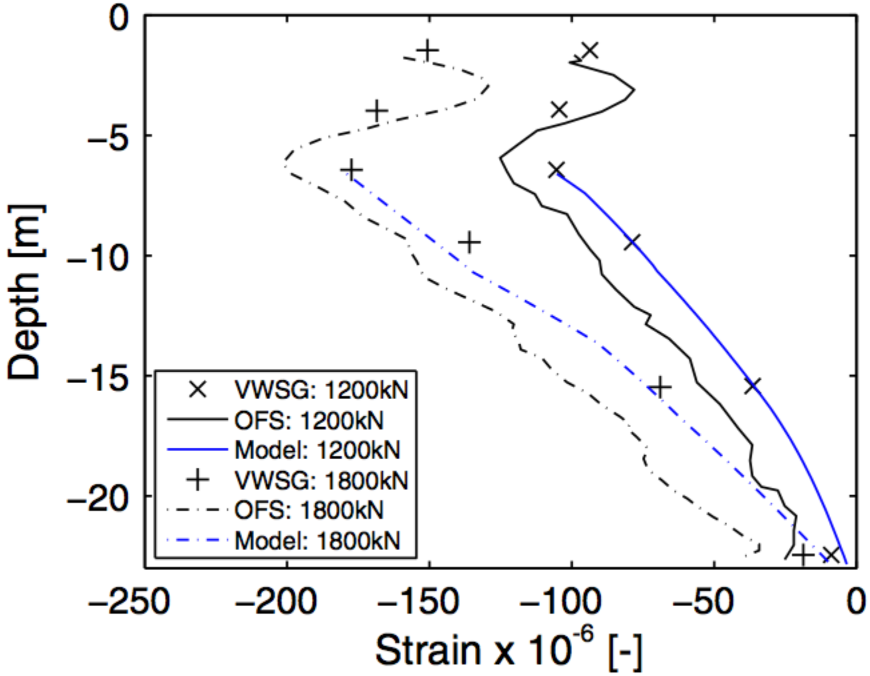


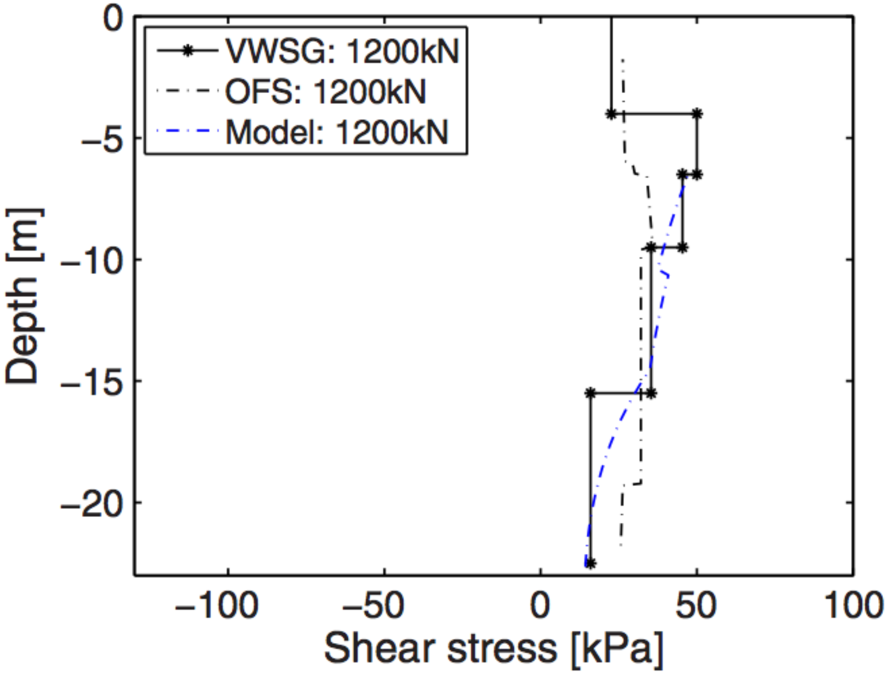


Bourne-Webb, P.J., Amatya, B., Soga, K., Amis, T., Davidson, C. and Payne, P. (2009) “Energy Pile Test at Lambeth College, London: Geotechnical and Thermodynamic Aspects of Pile Response to Heat Cycles.” Geotechnique, 59(3), 237–248.

- 2 Mechanical tests
- 1 Thermal cyclic test

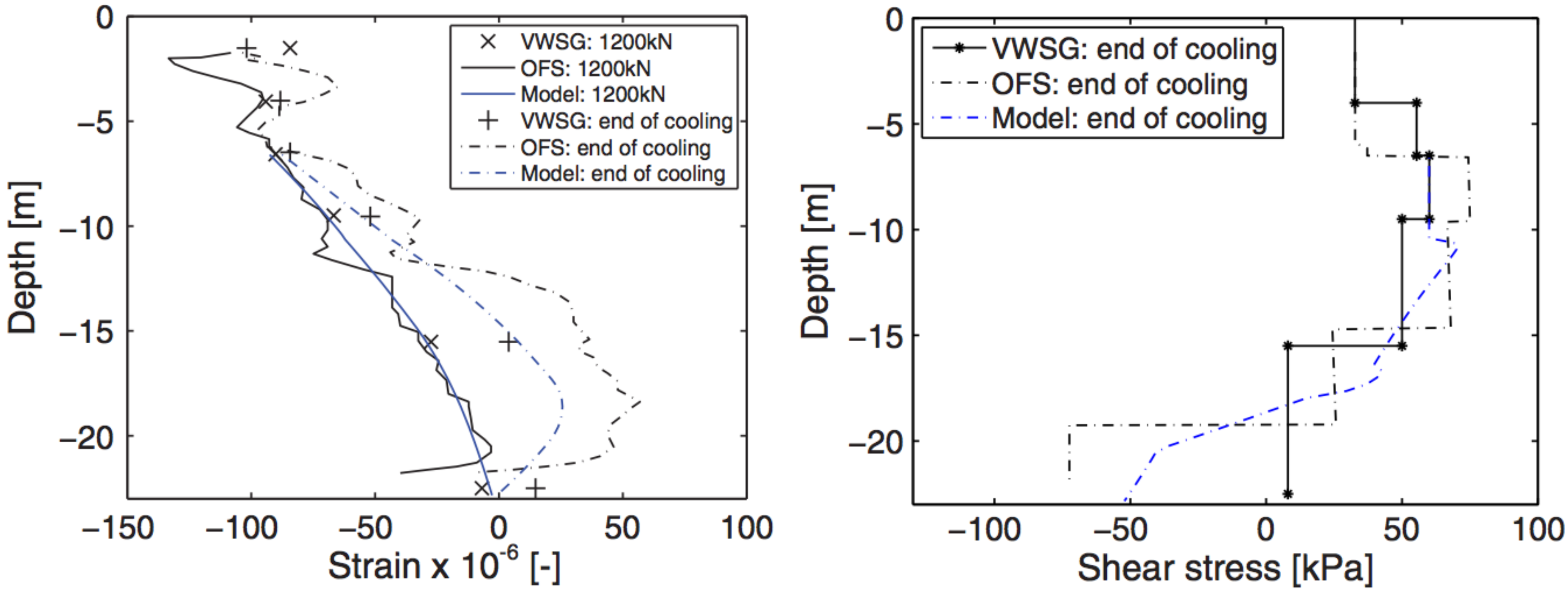
Validation of the method: the Lambeth College tests





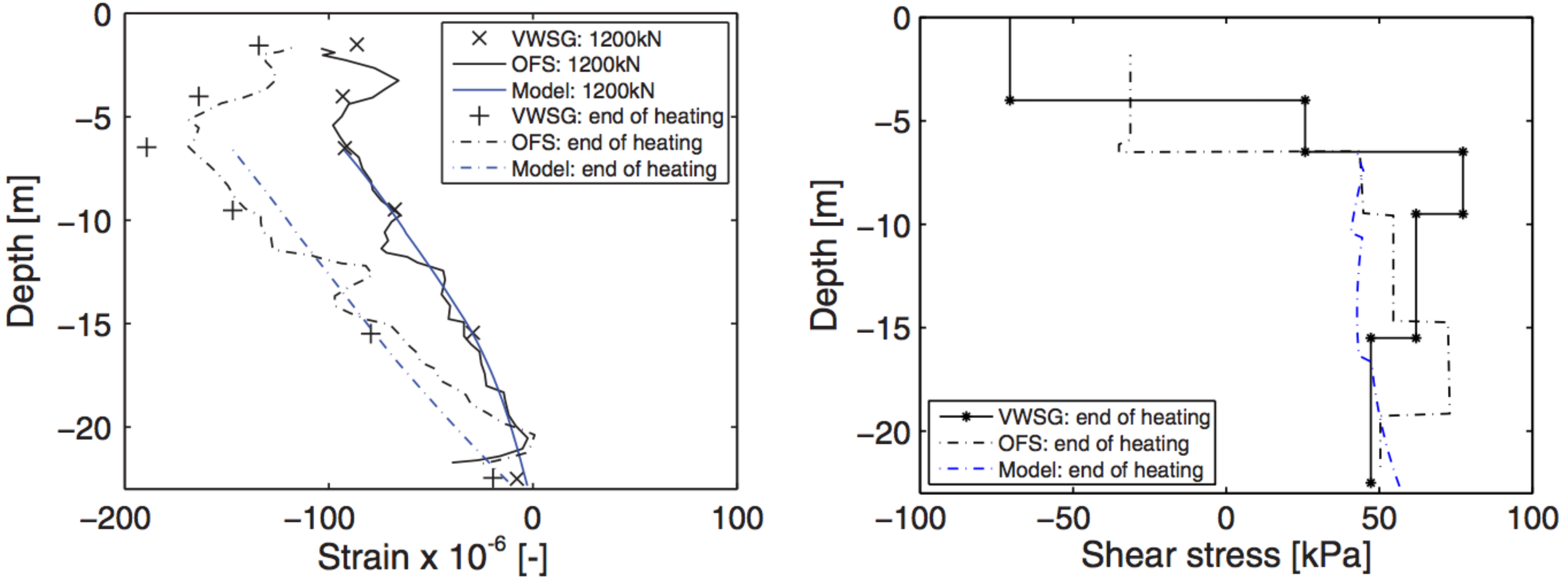
- The initial mechanical loading test (loading/unloading to 1,200 kN and 1,800 kN) is reproduced
- After discharging the pile from mechanical loading, residual strain is observed

Validation of the method: the Lambeth College tests



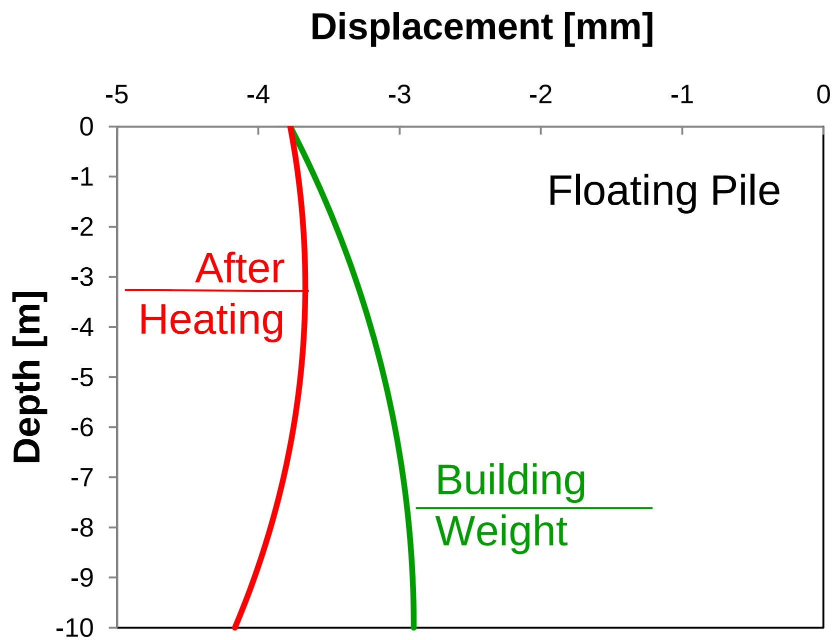
- The occurrence of tensile axial strain during the cooling phase in the bottom part of the pile is well predicted

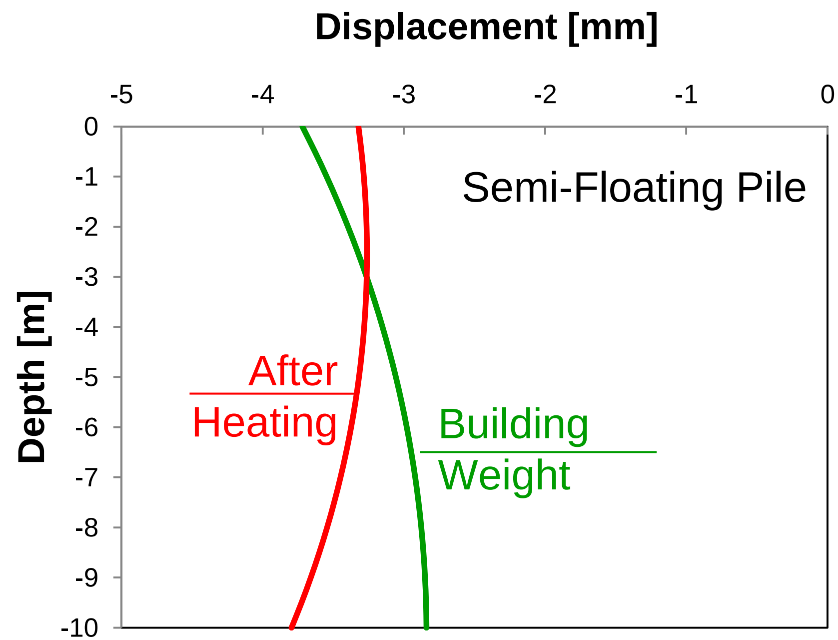
Validation of the method: the Lambeth College tests



- The noticeable increase in additional compressive axial strain observed within the whole pile during the heating phase is well assessed

Analysis of representative examples

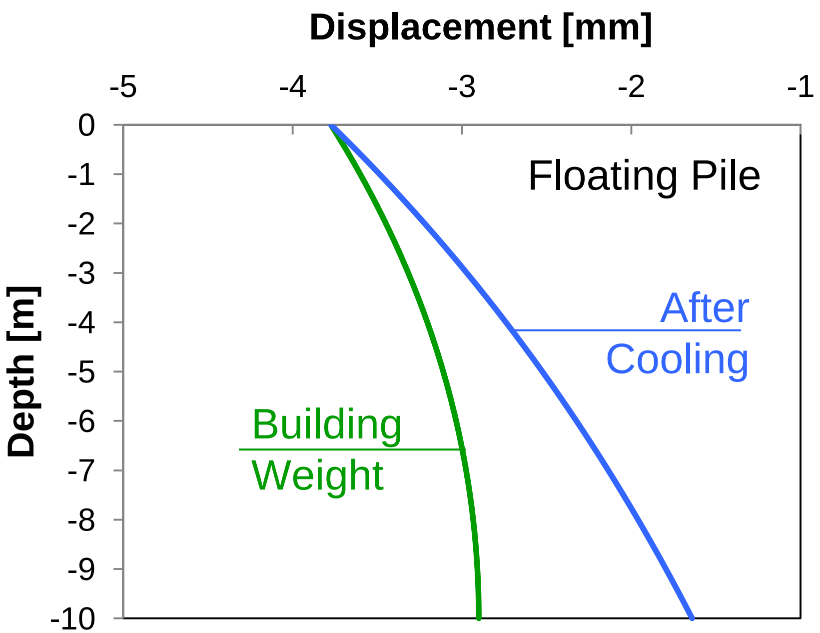


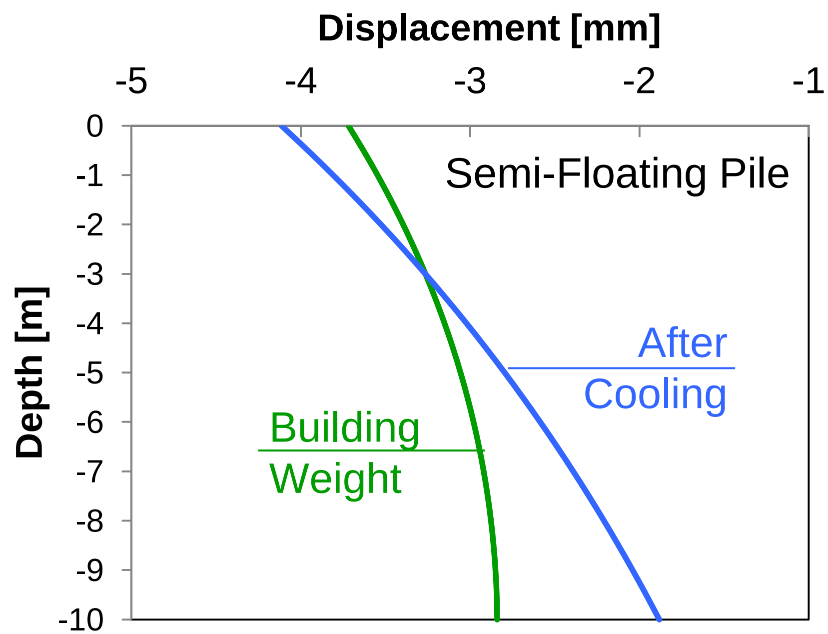


- Null point at the head of the pile
- Null point at 3 m depth

q_s(kPa)	50	E_M (MPa)	20
q_b (MPa)	0	K_h (GPa/m)	10
P (kN)	650	ΔT (℃)	+15

Analysis of representative examples

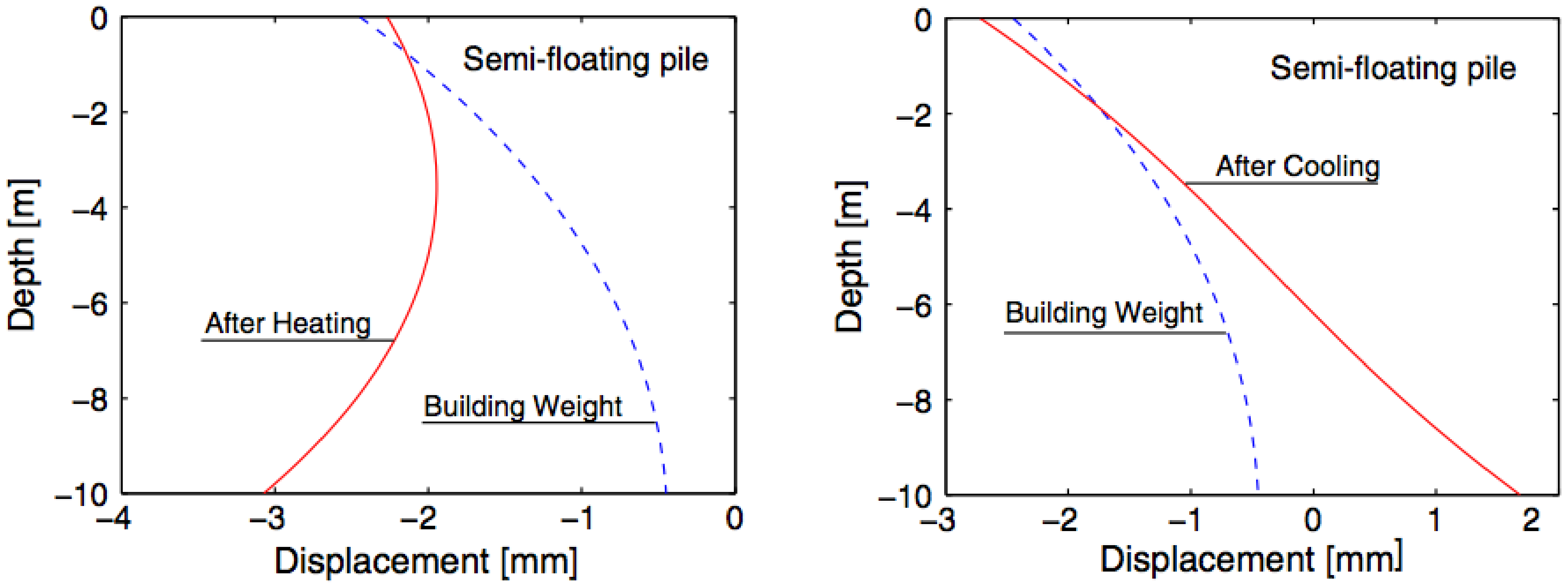




- Null point at the head of the pile
- Null point at 3 m depth

q_s(kPa)	50	E_M (MPa)	20
q_b (MPa)	0	K_h (GPa/m)	10
P (kN)	650	ΔT (℃)	- 15

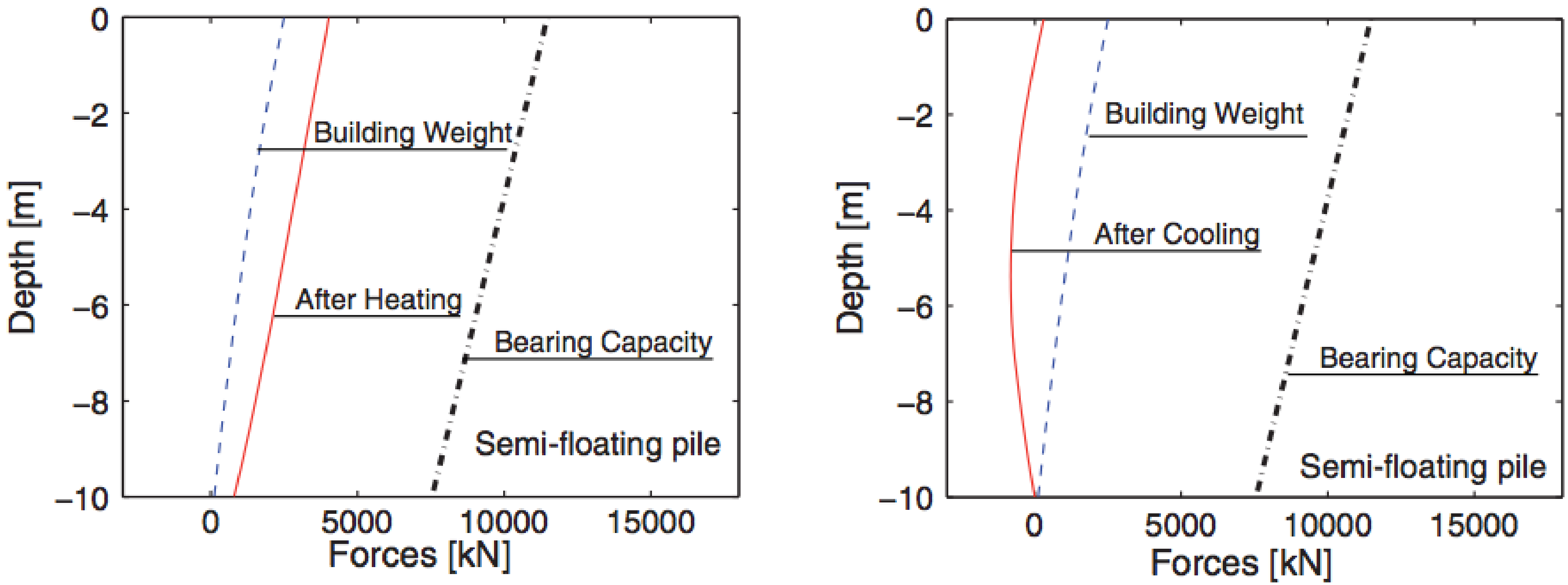
Analysis of extreme examples



- Null point at 1.5 m depth

q_s(kPa)	250	E_M (MPa)	60
q_b (MPa)	38.2	K_h (GPa/m)	45
P (kN)	2500	ΔT (℃)	$\pm$50

Analysis of extreme examples



- Null point at 1.5 m depth

q_s(kPa)	250	E_M (MPa)	60
q_b (MPa)	38.2	K_h (GPa/m)	45
P (kN)	2500	ΔT (℃)	±50

Concluding remarks and perspectives

- The available experimental evidences and numerical simulations show that energy piles function favorably from an energy, geotechnical and structural point of view even under the highest applied thermo-mechanical loads

- Geotechnical and structural checks are in any case needed to ensure the aimed performances of the system (e.g. geotechnical, structural)

- Further researches are needed to assess better the long-term behaviour of such foundations

- The behaviour of complex energy pile foundations needs also to be further investigated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Thank you very much