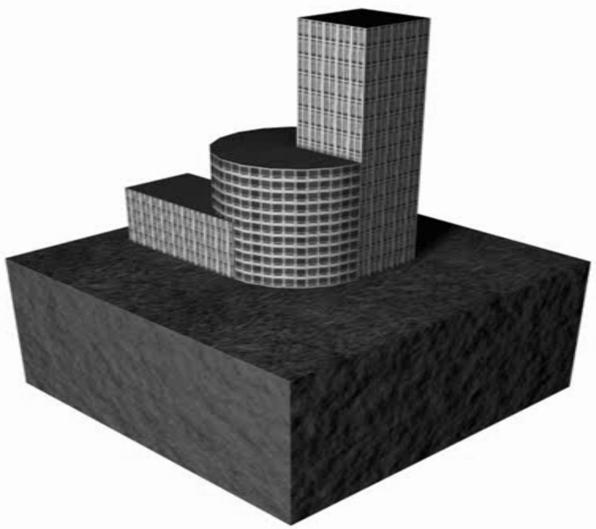
« Heat exchanger geostructures »

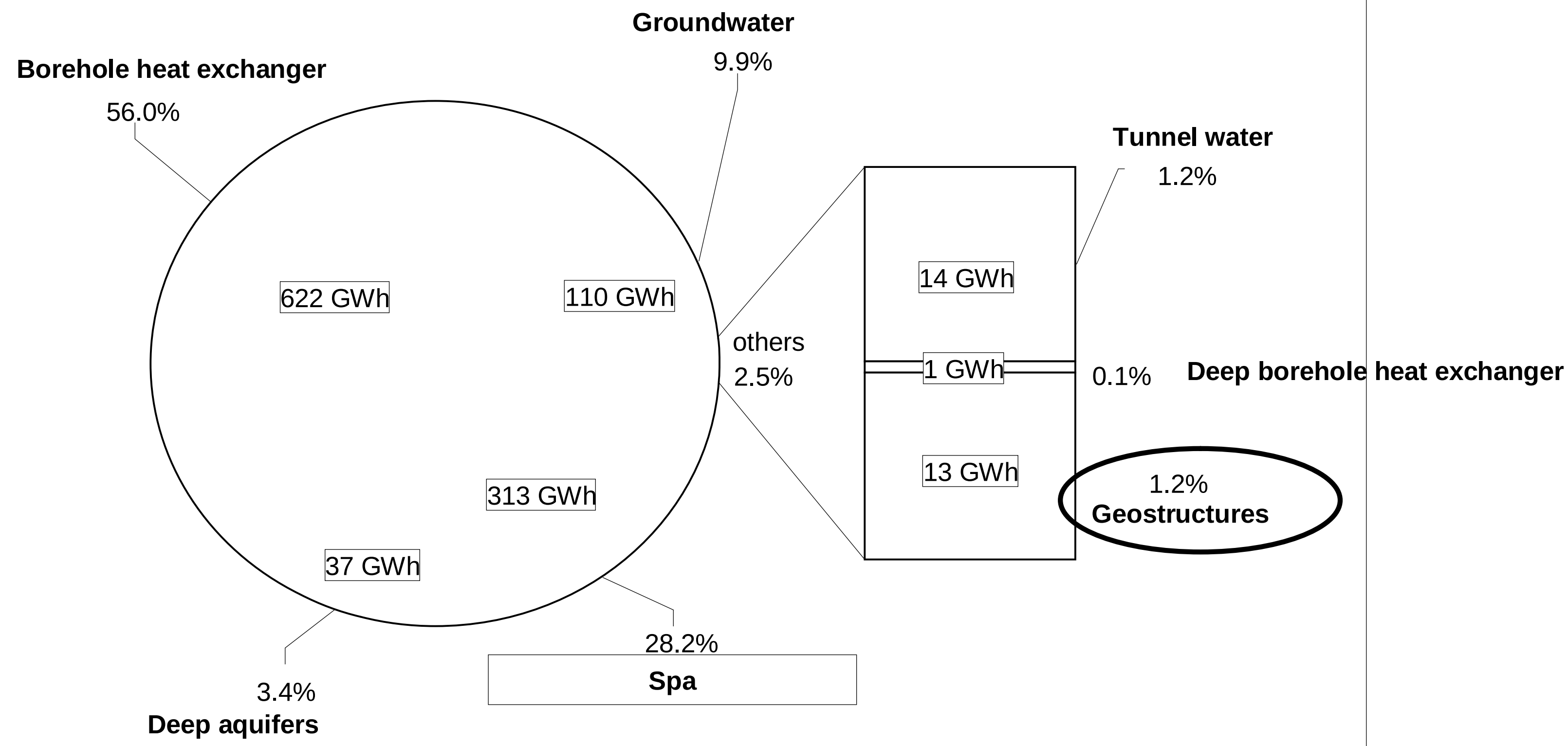
Static behaviour under temperature variations

Prof. L. Laloui



Development of the use of geothermal energy in Switzerland

ø e.g. 2003: produced heat energy 1110 GWh



Source: Geowatt AG

Heat exchanger piles

Constructions using thermal piles (more than 300 in Europe):

- The new Main Tower for Helicon (Frankfurt am Main)

112 bored piles with diameter of 150 cm, 30 m in depth

- Reha-Zentrum Bad Schallerbach (Austria)

175 bored piles with diameter of 120 cm

- In Switzerland:
  - Finkernweg (75 thermal piles)
  - Lidwil (120)
  - Pago (570)
  - Photocolor at Kreuzlinger (93)
  - Etc.

(Source: Lippuner & Partner AG, Grabs)

Outline

1. Heat exchanger geostructures

2. State of geotechnical knowledge

3. Experimental and modelling tools

4. Numerical simulations

5. Conclusion

Geothermal structures – Heat exchanger piles

• These structures permit the exchange of heat from the ground to satisfy the warming need in winter and the cooling need in summer. They have two main functions :

- Static: to transfer building loads into the ground;

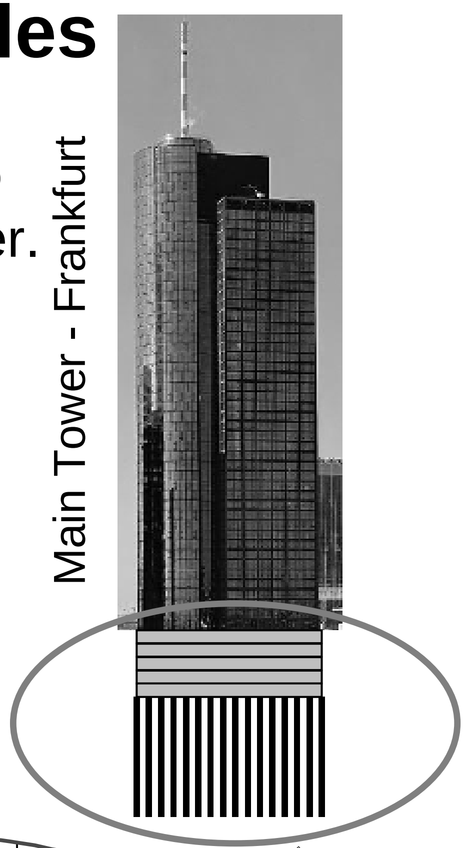
- Energetic: to serve as a heat exchanger with the ground (and usually linked to a heat pump); Production of recoverable energy.

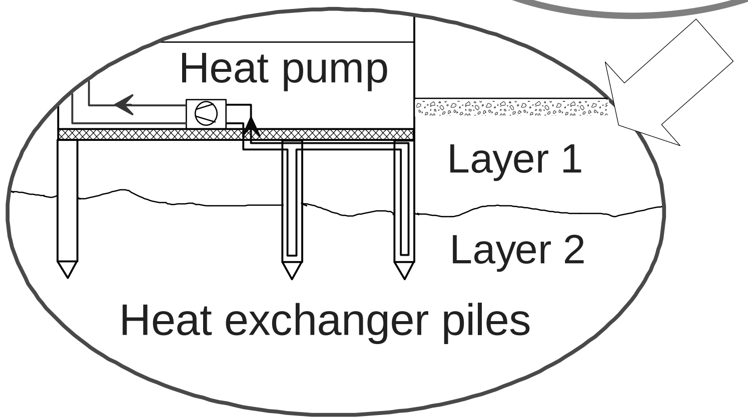
• Temperature up to about 70 °C (usually $0<\Delta T<30°C$)

• **How does temperature modify the behaviour of geostructures?**

• **Is it possible to predict such effect?**

Main Tower - Frankfurt





Heat exchanger piles

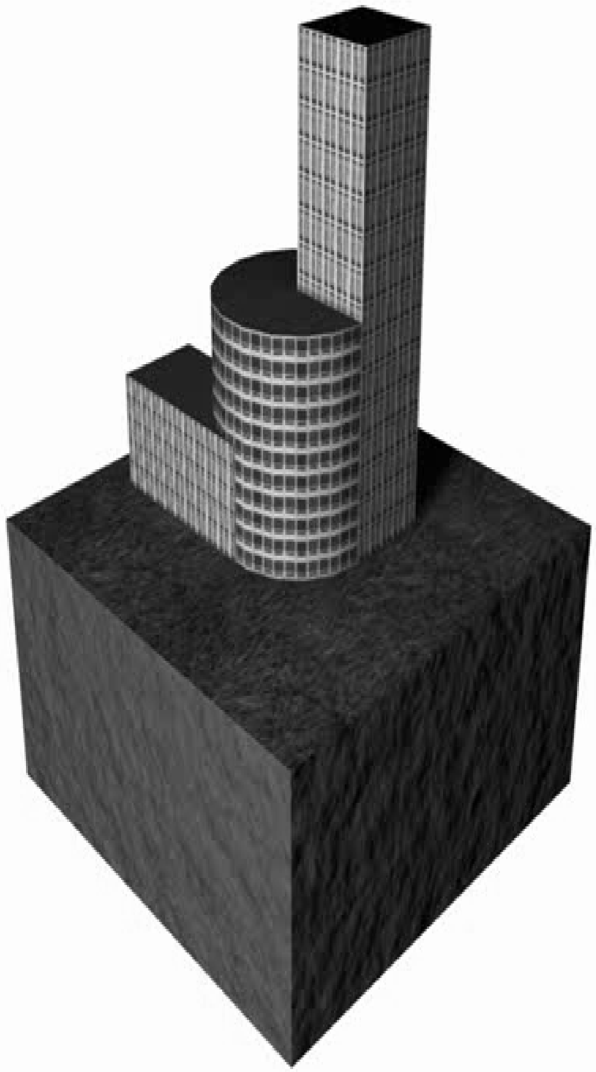
Heat exchanger piles may be driven or bored reinforced concrete piles.

Plastic tubes are embedded in the pile in which the heat exchanger fluid is flowing.

The inflow and return tubes are mounted along the reinforcing cage.

Usual characteristics:

- diameter: 30 to 150 cm
- active length: 10 to 30 m
- spacing: 3 to 10 m



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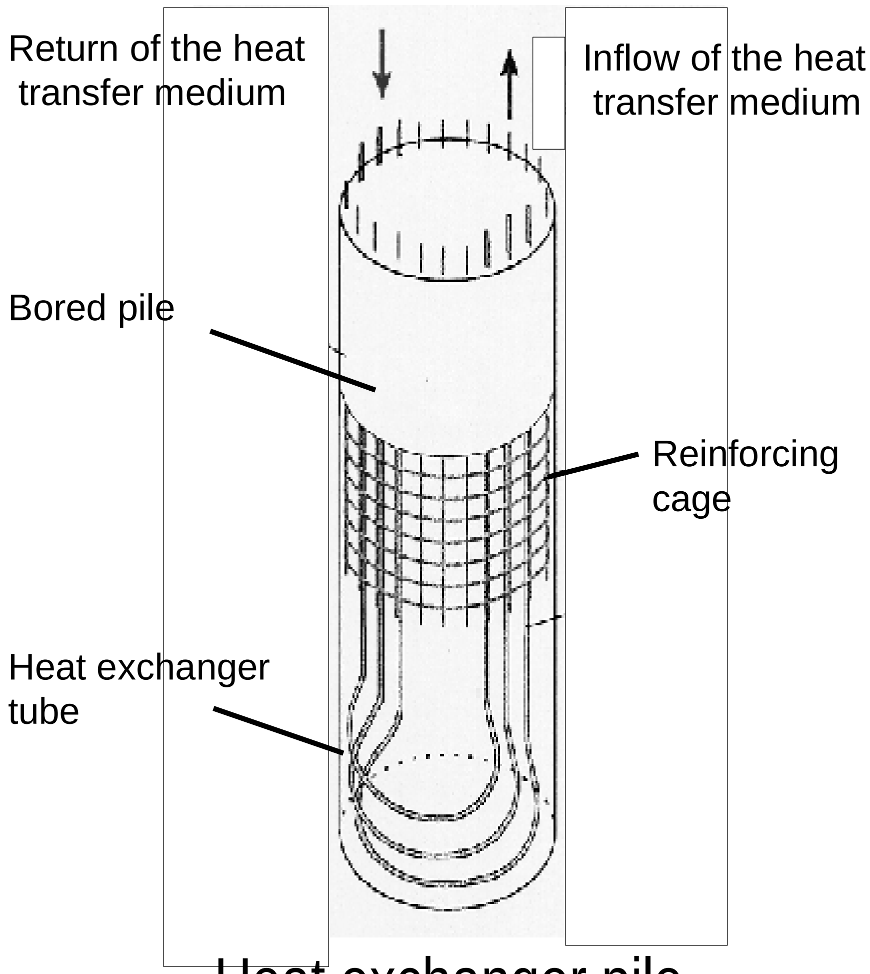

Heat exchanger pile

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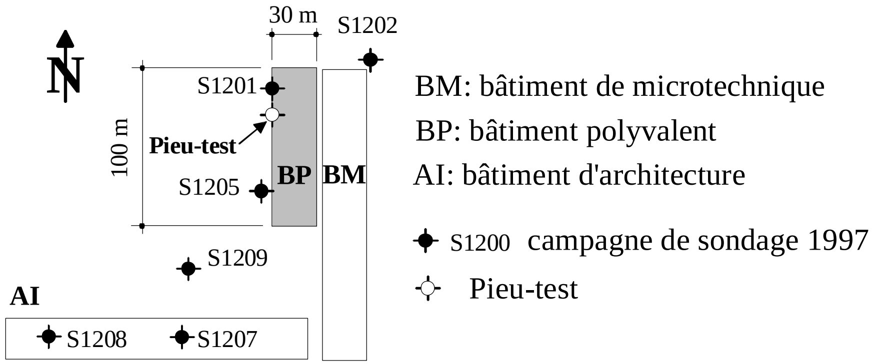
State of geotechnical knowledge

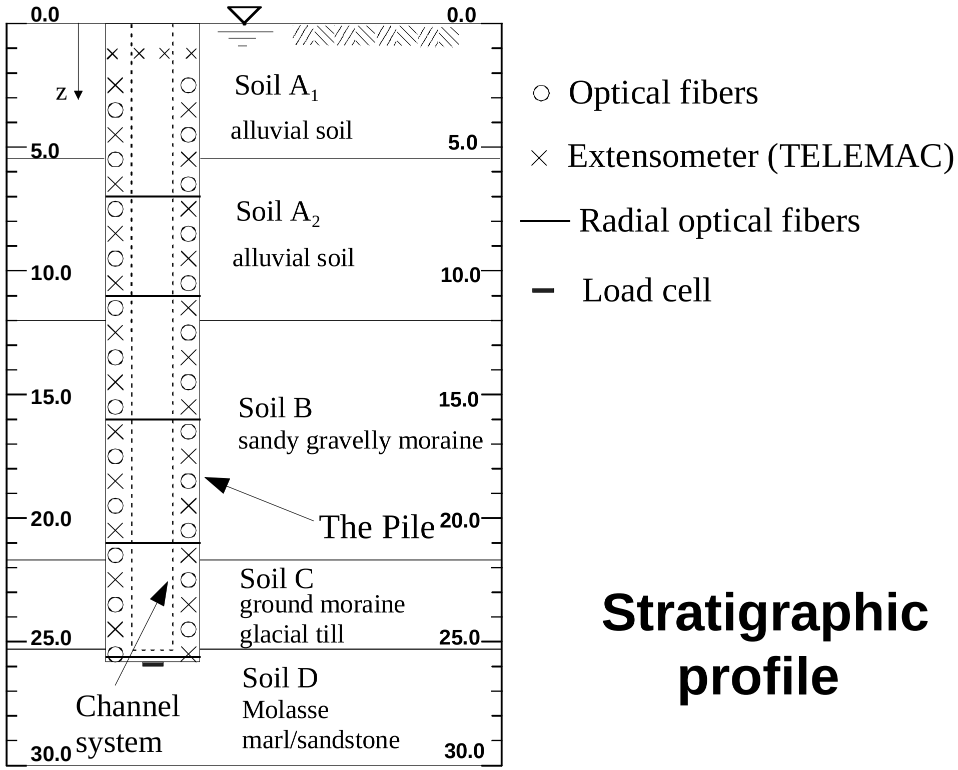
- What are the thermal fluctuations (ΔT = 30°C) long term effects on the bearing capacity of the foundation soil?
- What are the limit temperatures in the piles from which bearing capacity of friction piles starts to decrease? Is there a long term fatigue effect ?
- Can a -3°C fluid temperature inside the pile have a long term effect on the concrete resistance if the latter has no sufficient porosity due to special design mixture formula ?

In-situ load test: Experimental setup



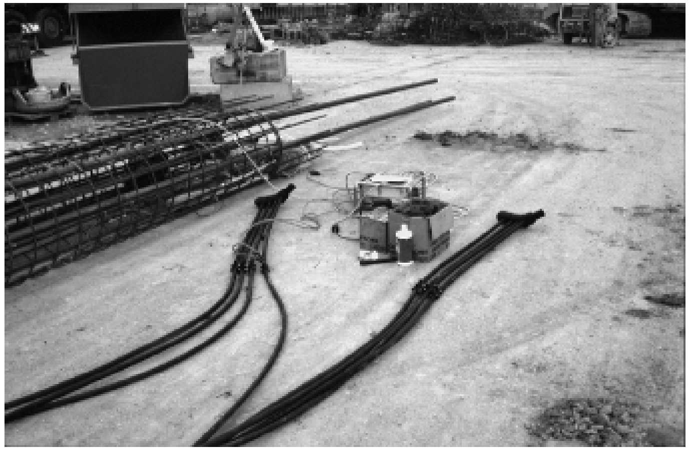
Pile of a building at the EPFL has been tested
Diameter 88 cm - length 26 m

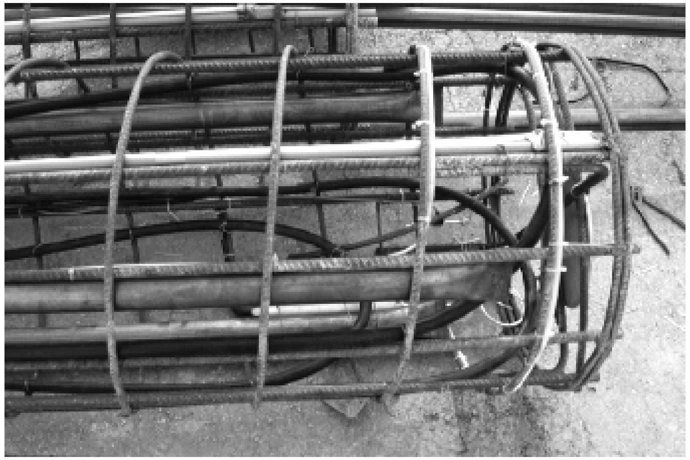
- **The pile is equipped with a pipe system and:**
  - **28 vibrating-wire extensometers and temperature-gages**
  - **29 fiber-optic extensometers**
  - **1 load cell (HCV-TELEMAC)**

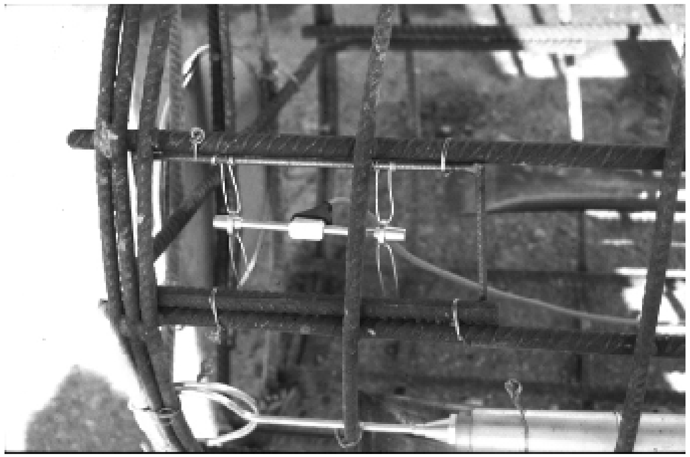


Stratigraphic profile

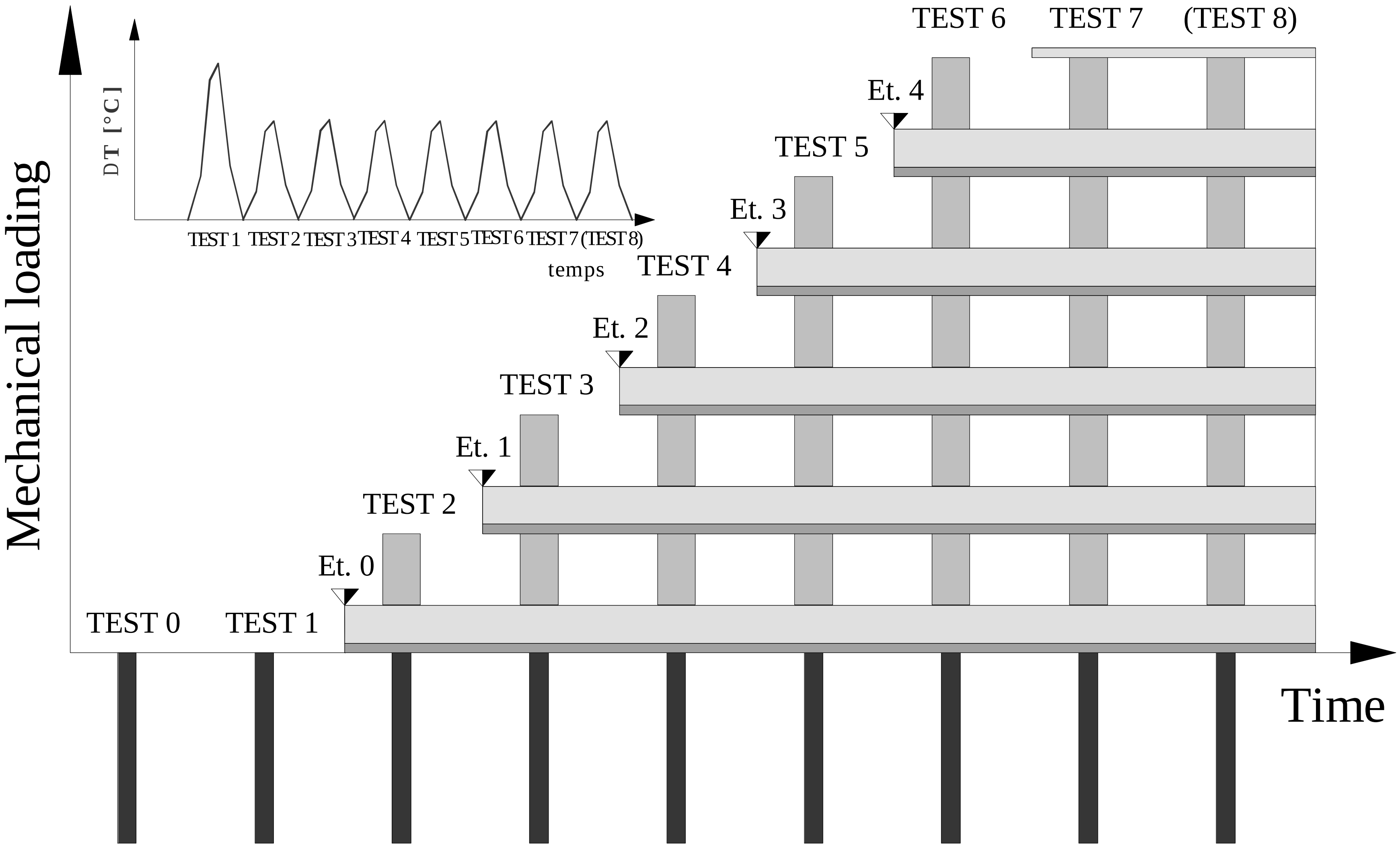
IN-SITU LOAD TEST







IN-SITU LOAD TEST : Thermo-mechanical loading



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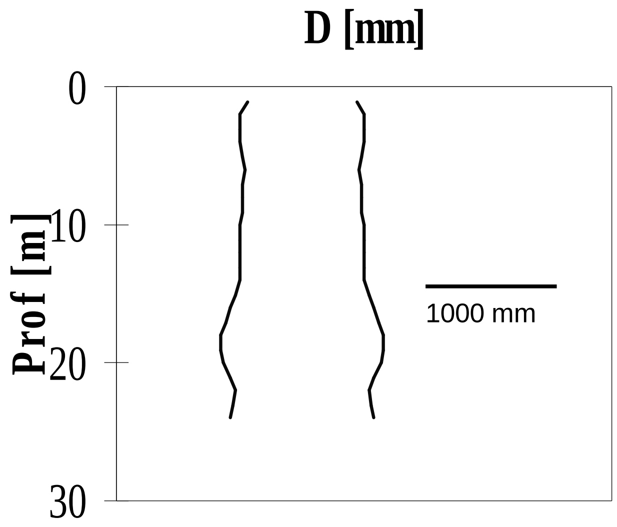
IN-SITU LOAD TEST : Initial results

- Integrity test (PIT)

  Section of the pile

  A = 7200 to 10800 cm^2

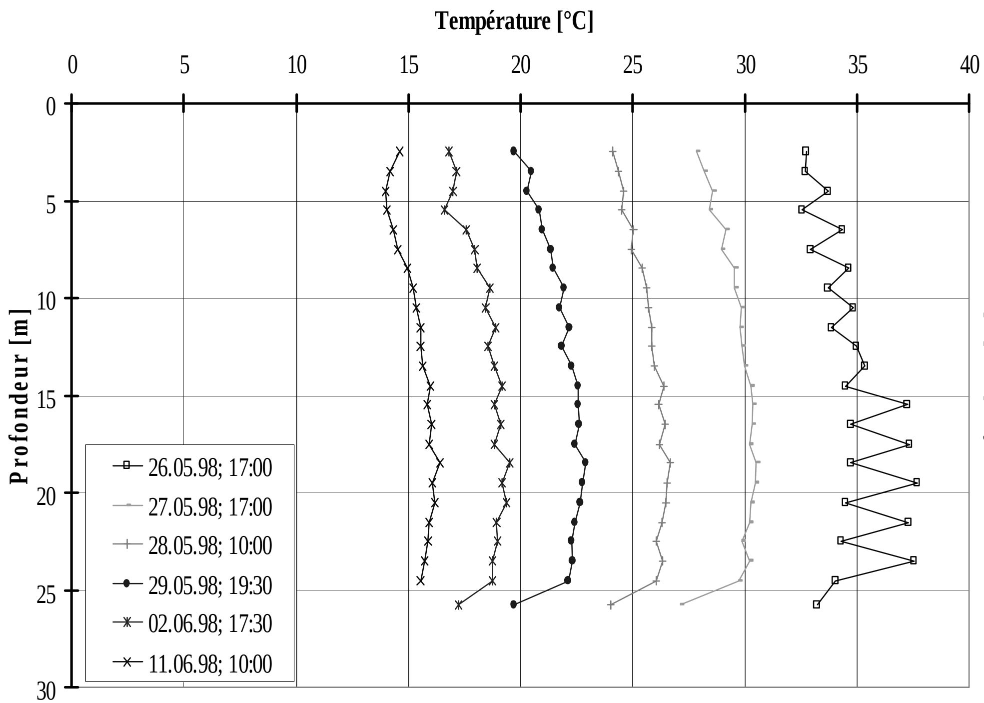


- Cross-hole ultrasonic transmission (three 2” steel tubes)

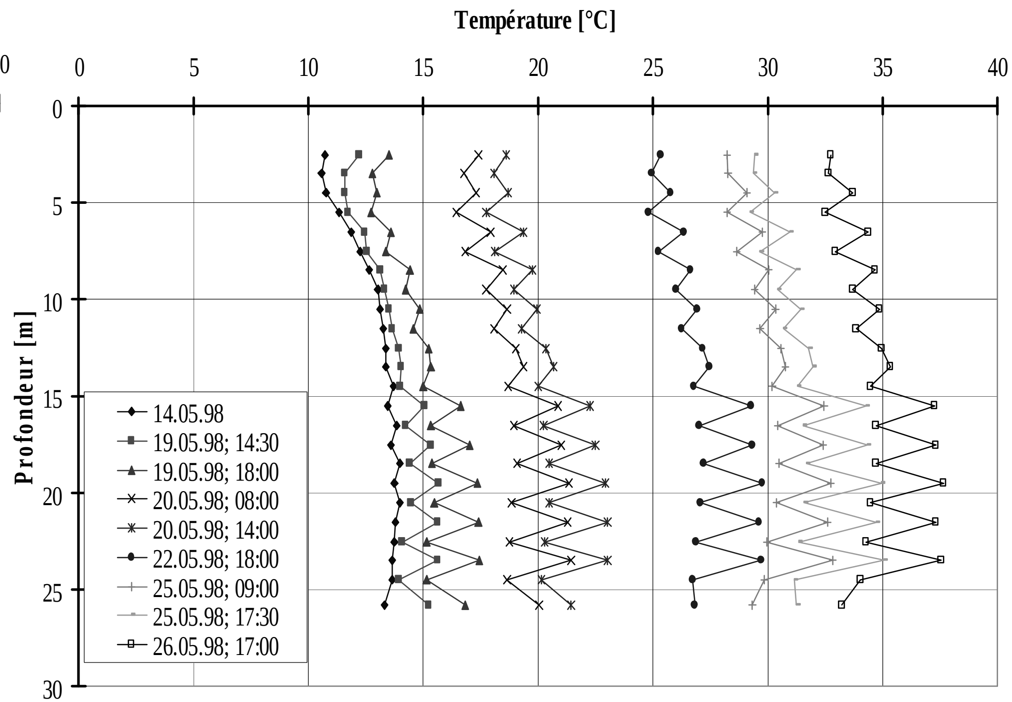
  E_c = 23000 MPa ---> E_{pile} = 23900 MPa. (at T=11°C)

Date	Température moyenne dans le pieu [°C]	$E_{béton}$ [MPa] (n = 0)	$E_{béton}$ [MPa] (n = 0.16)
24/02/98	23	28068	26357
25/05/98	35	27206	25547
03/06/98	24	31097	29201
25/05/99	19	31948	30000

Thermal behaviour of the heat exchanger pile



Heating phase



Cooling phase

ΔT ~ 30°C

In-situ measured temperatures – EPF Lausanne

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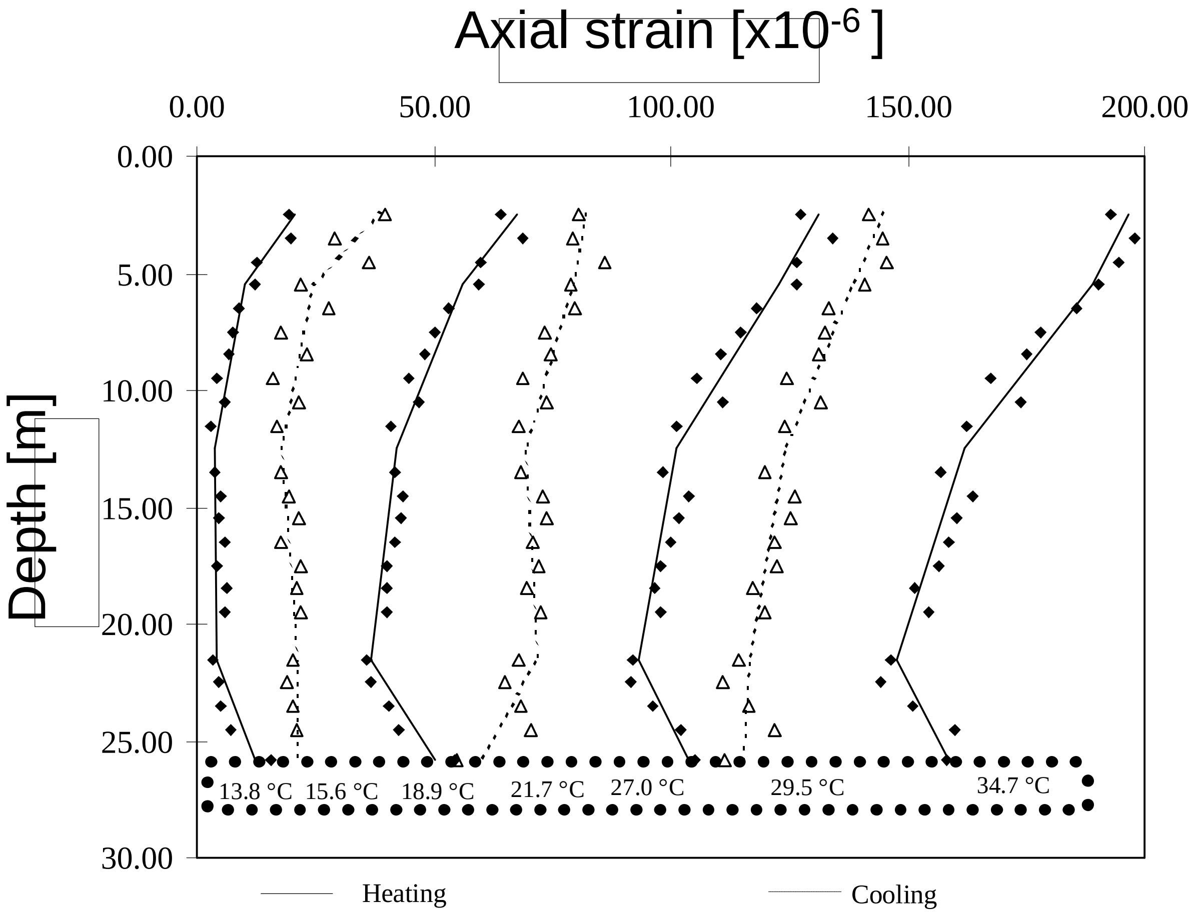
FÉDÉRALE DE LAUSANNE

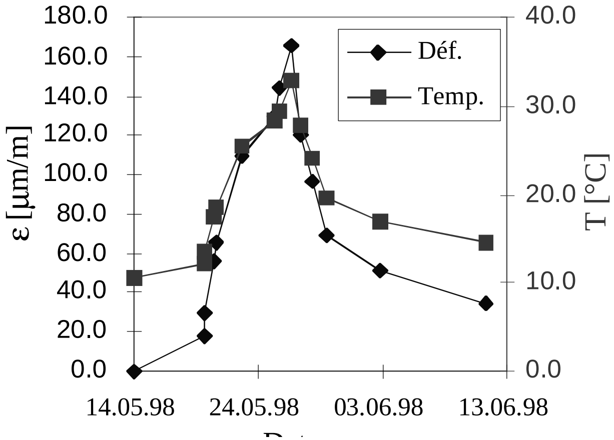
In-situ measured strains and temperatures



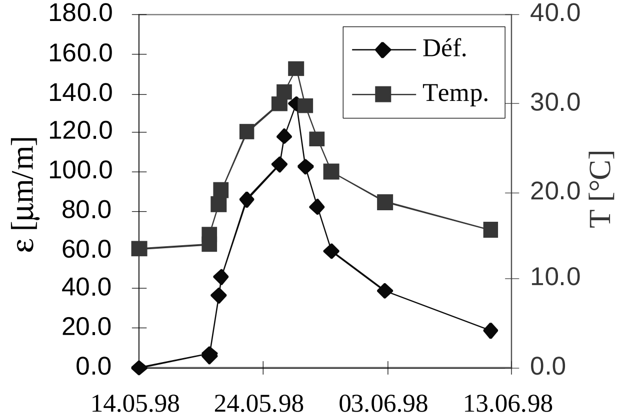
- Strains are not uniform and depend on the friction at the soil-pile interface
- Thermo-reversible linear behaviour

TEST RESULTS : Thermo-elastic behaviour of the pile

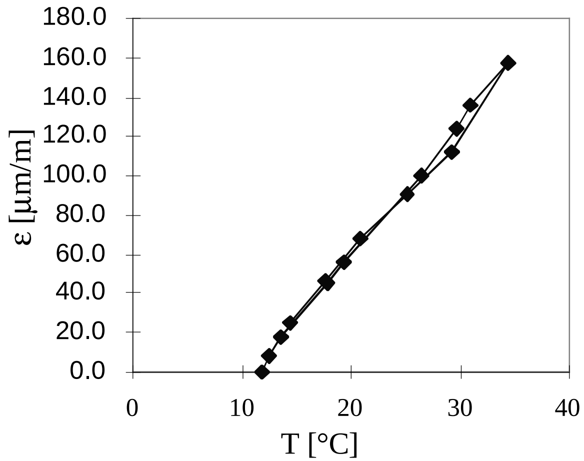
Test 1, T 33052, 2.5 m



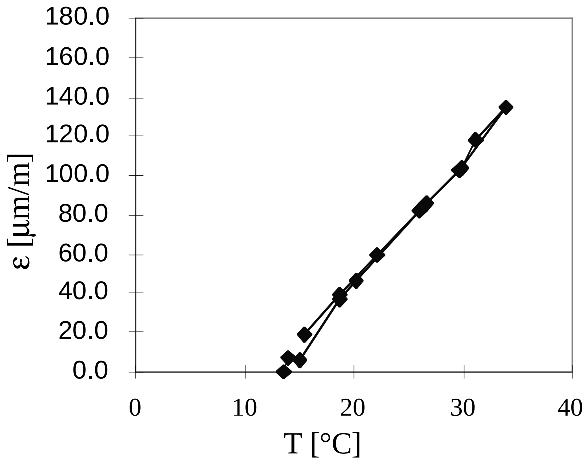
Test 1, T 33030, 24.5 m



Test 1, T 33048, 6.5 m

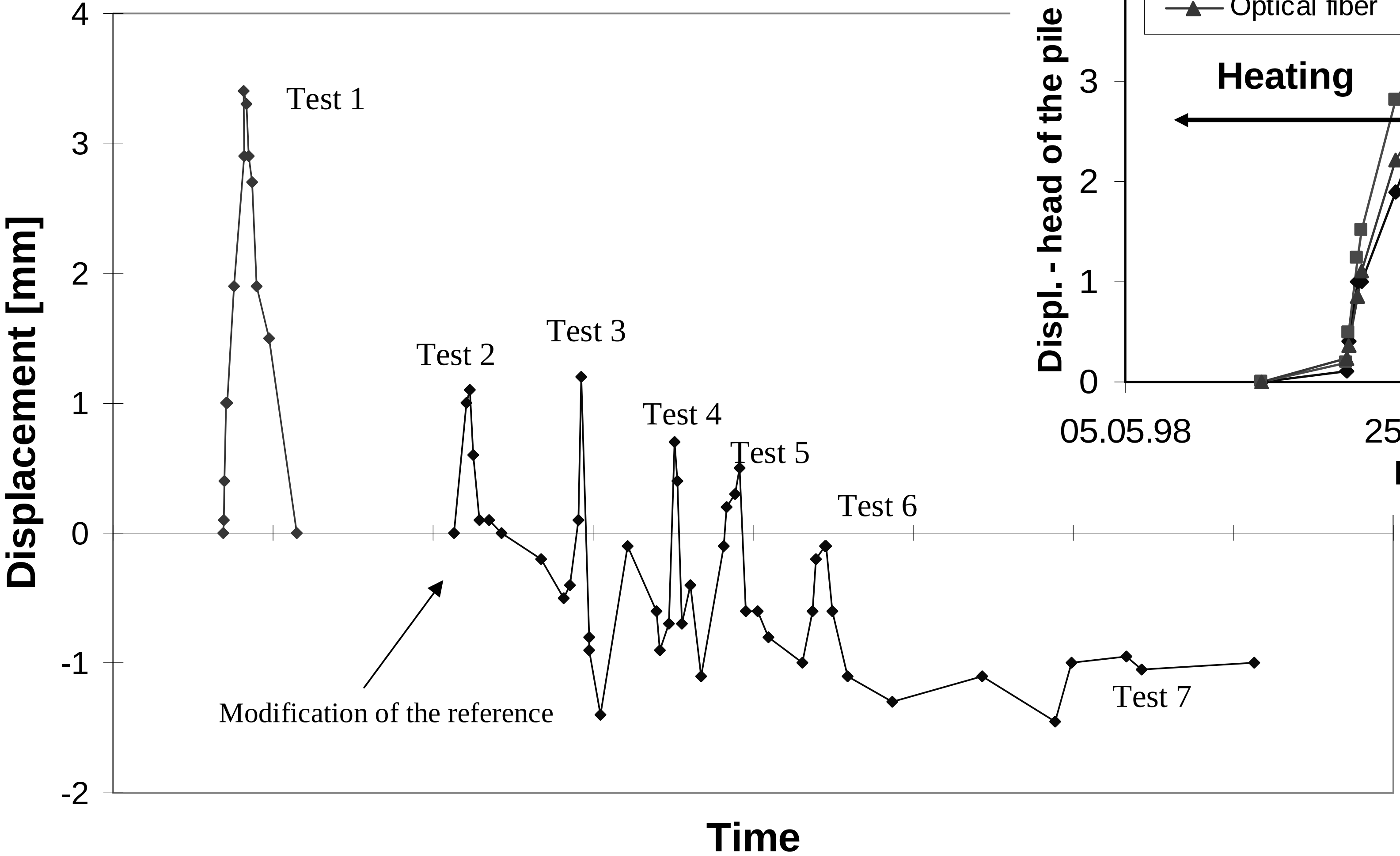


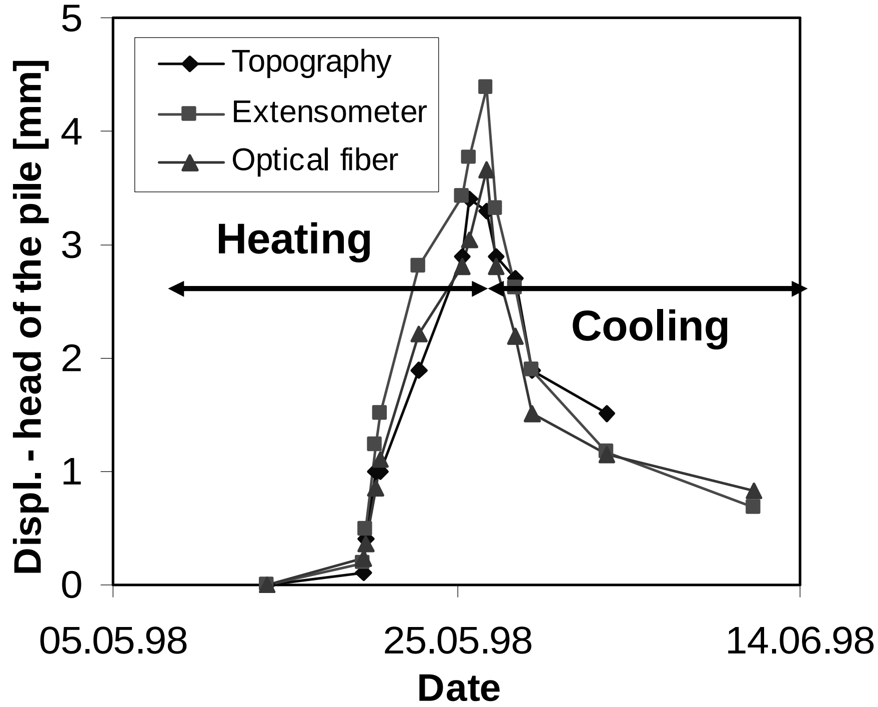
Test 1, T 33030, 24.5 m



Strains were not uniform and depended on the friction at the soil-pile interface

Heat exchanger pile uplift





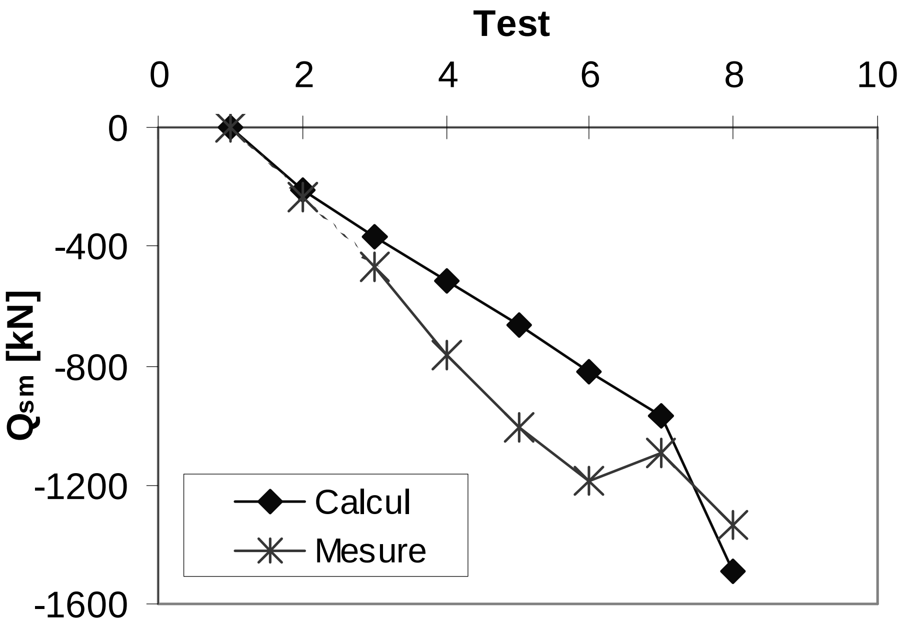
TEST RESULTS : Mechanical load

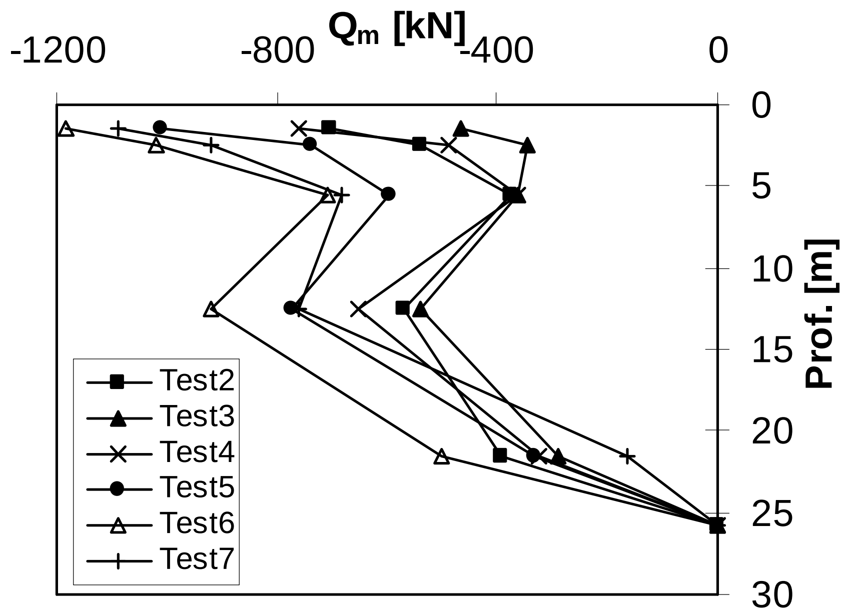
• The static load is imposed by the dead weight of the building under construction

• Q_{sm} is the static load deduced from measurement at the top of the pile

• Q_m is the load repartition versus depth

$$Q_m(z) = e_g(z) \cdot A(z) \cdot E_{pile}$$





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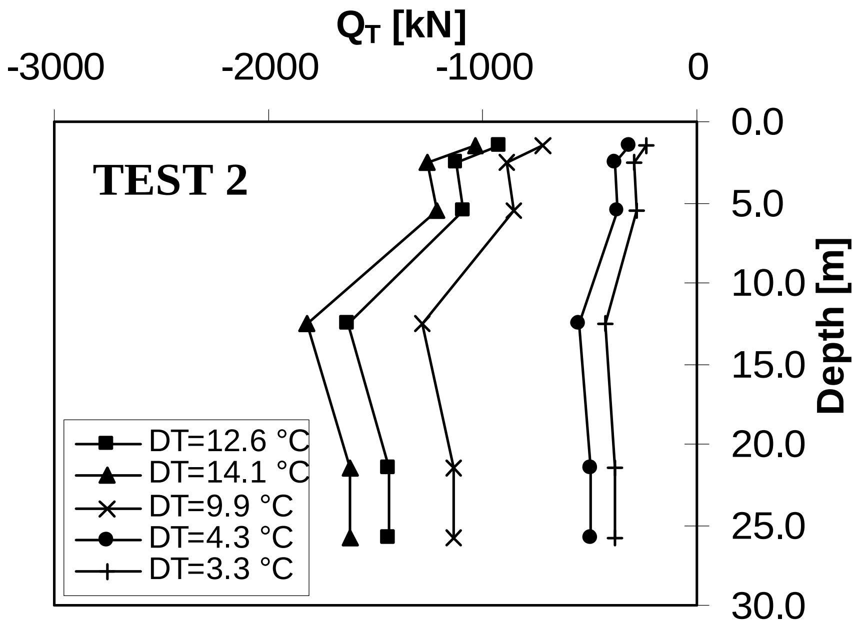
In-situ test: thermally induced load in the pile

• The added load in the pile due to thermal solicitations is

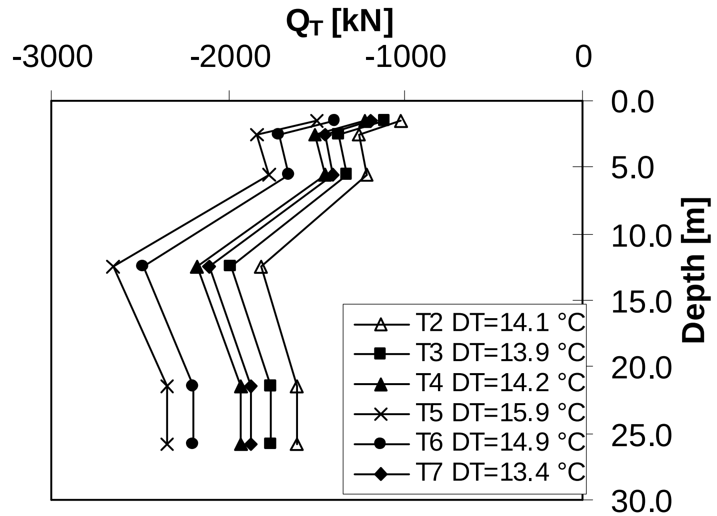
$$Q_T(z) = E_{pile} \cdot (n-1) \cdot b \cdot \Delta T \cdot A(z)$$

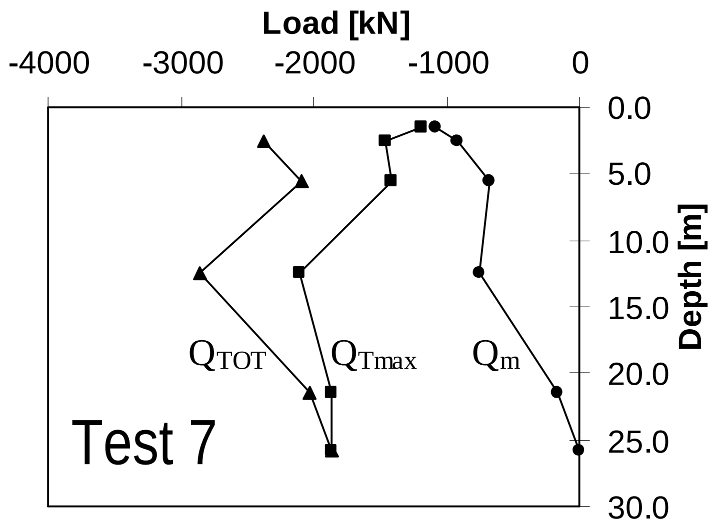


• It is well-known that the induced mechanical load is important at the top and diminishes with depth

• The thermally induced load is more uniform. It strongly solicits the toe.

TEST RESULTS : Induced loads



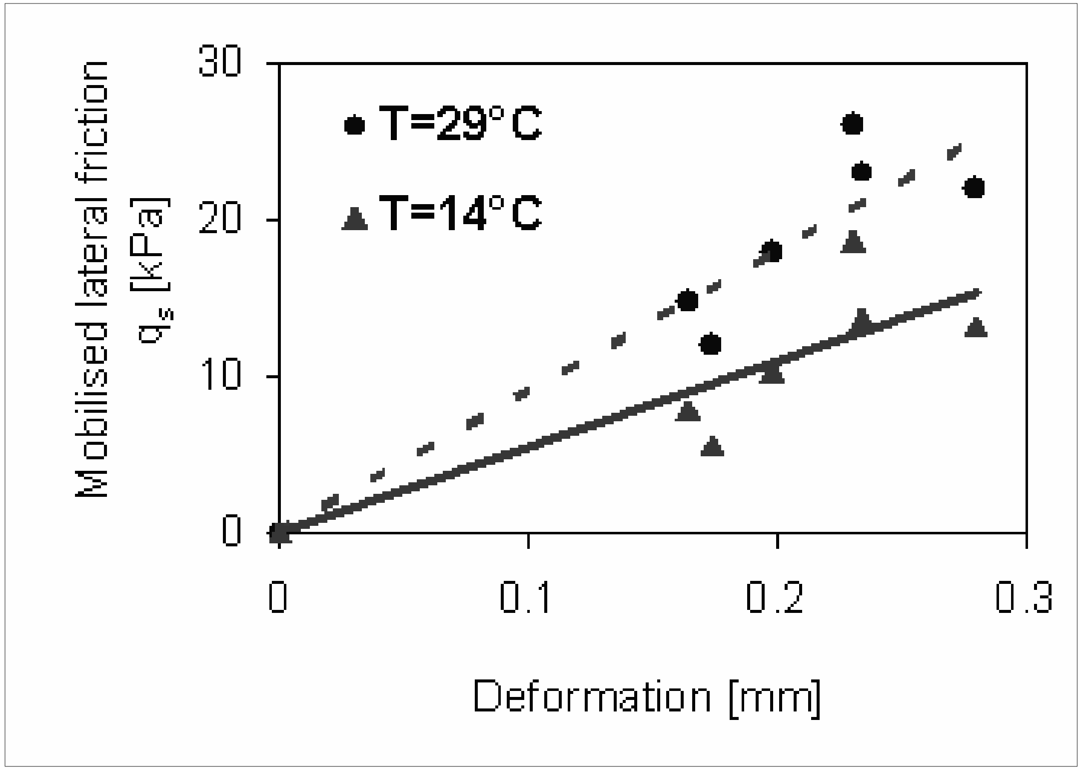


Maximum thermal loads

Load caused by the building weight, the maximum thermal surcharge (ΔT= 13.4 °C) and the total load thus obtained

In-situ test: mobilisation of the lateral friction

$$q_s(z) = \frac{A(z) \cdot E_{pile}}{p \cdot D(z)} \cdot \frac{\Delta e(z)}{dz_i}$$



Heating has a strong influence of the lateral friction mobilisation

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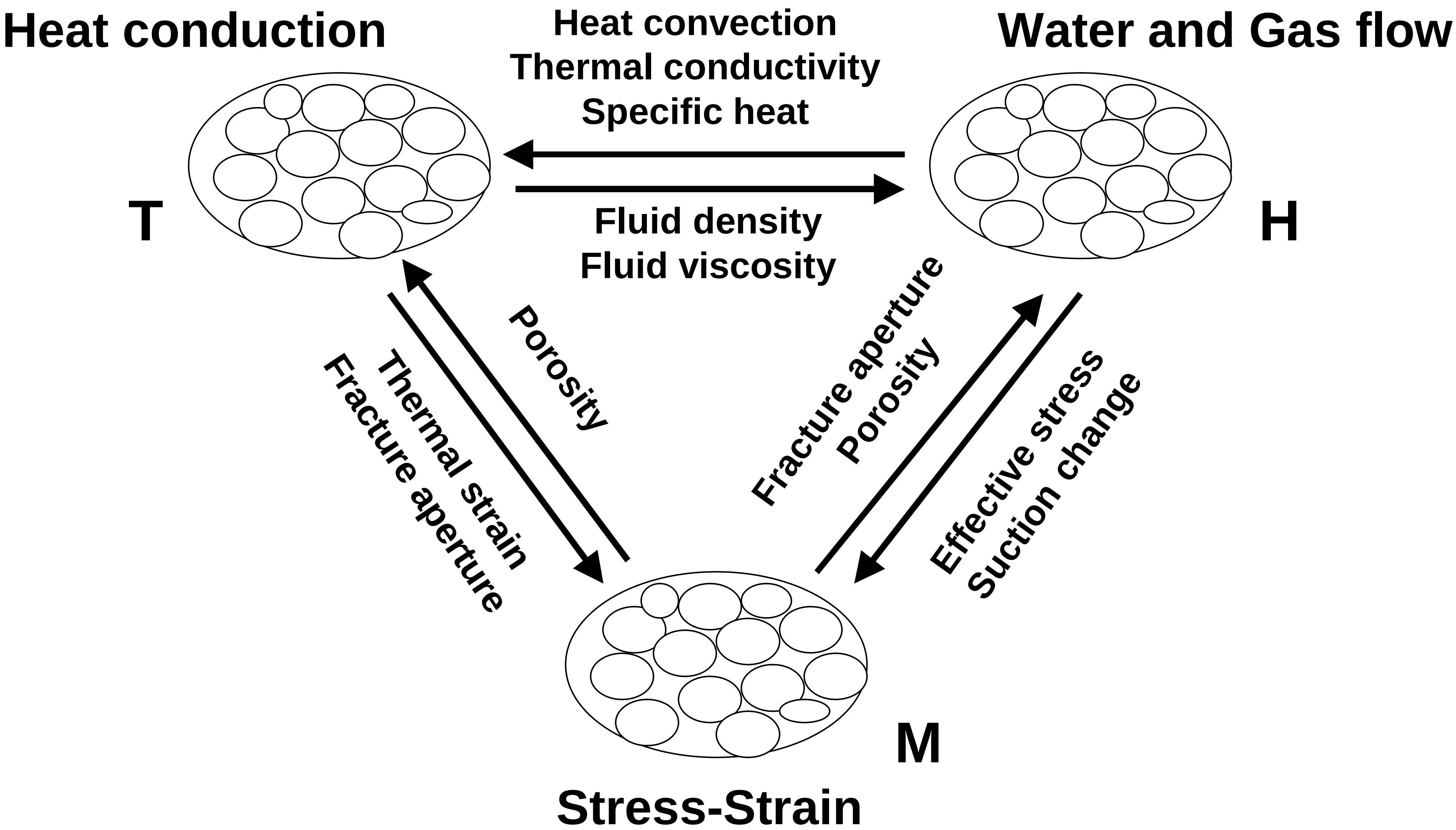
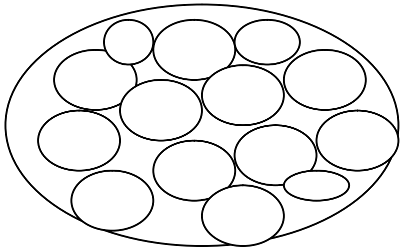
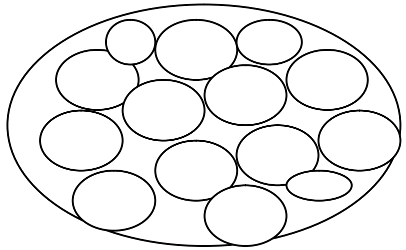
Thermo-Hydro-Mechanical coupled approach



Constitutive laws

Fourier's law **Darcy's law**

T 

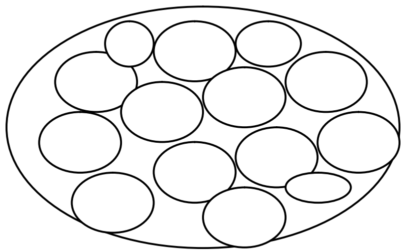
 H

- Thermal conductivity
- Heat capacity

- Permeability (T)
- Storage coefficient (T)

- Elastic parameters (Young modulus)
- Hardening parameters (preconsolidation pressure) (T)
- Plastic parameters (friction angle)
- Thermo-elastoplastic parameters (T)

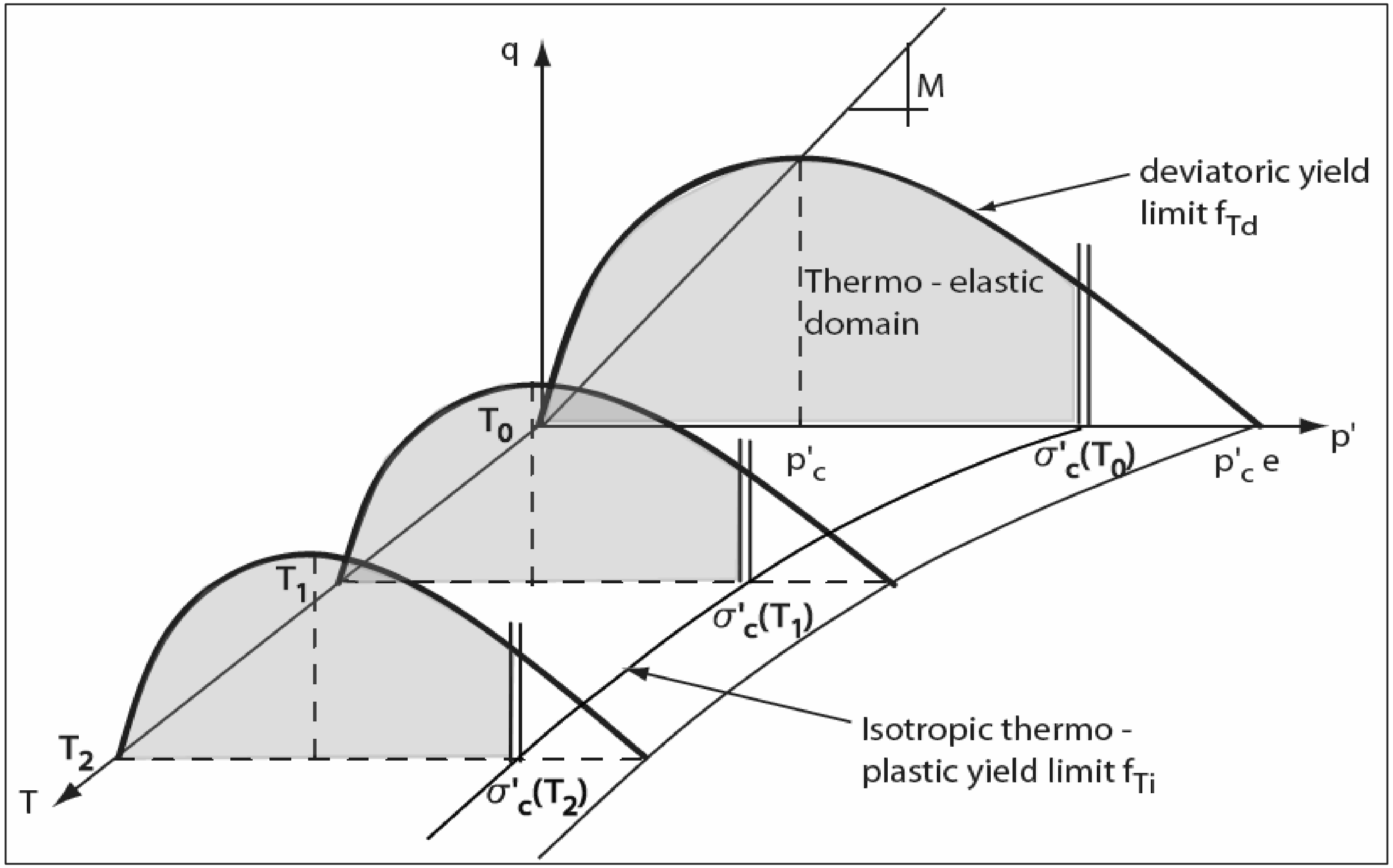
Thermo-mechanical triaxial system

 M

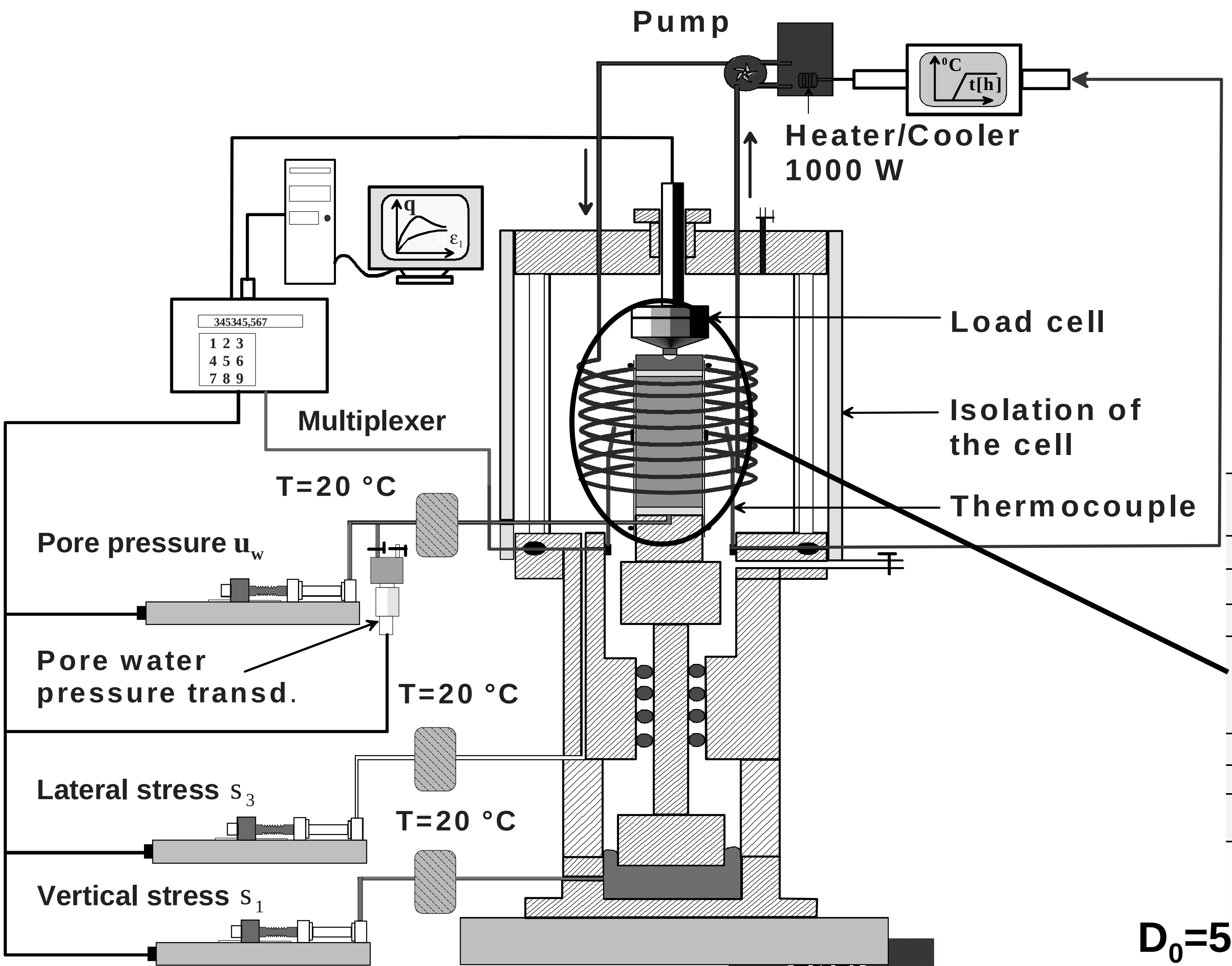
Thermo-(visco)plastic law

Advanced Constitutive Model for Environmental Geomechanics – Temperature (ACMEG – T Model)

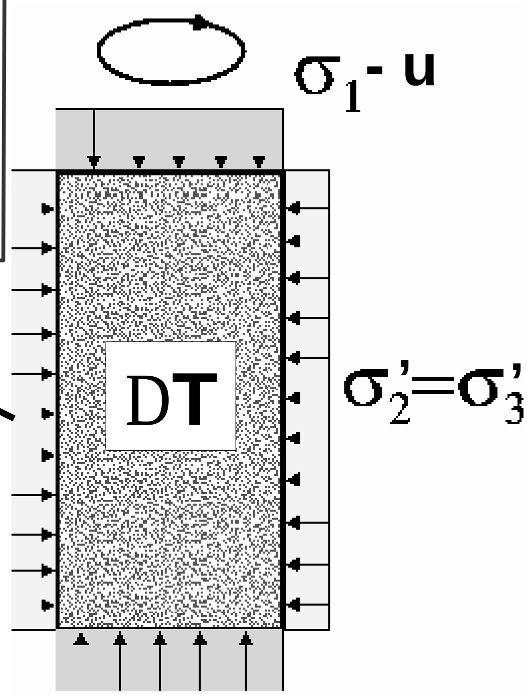
(Laloui et al., 2005)



Thermo-mechanical triaxial system

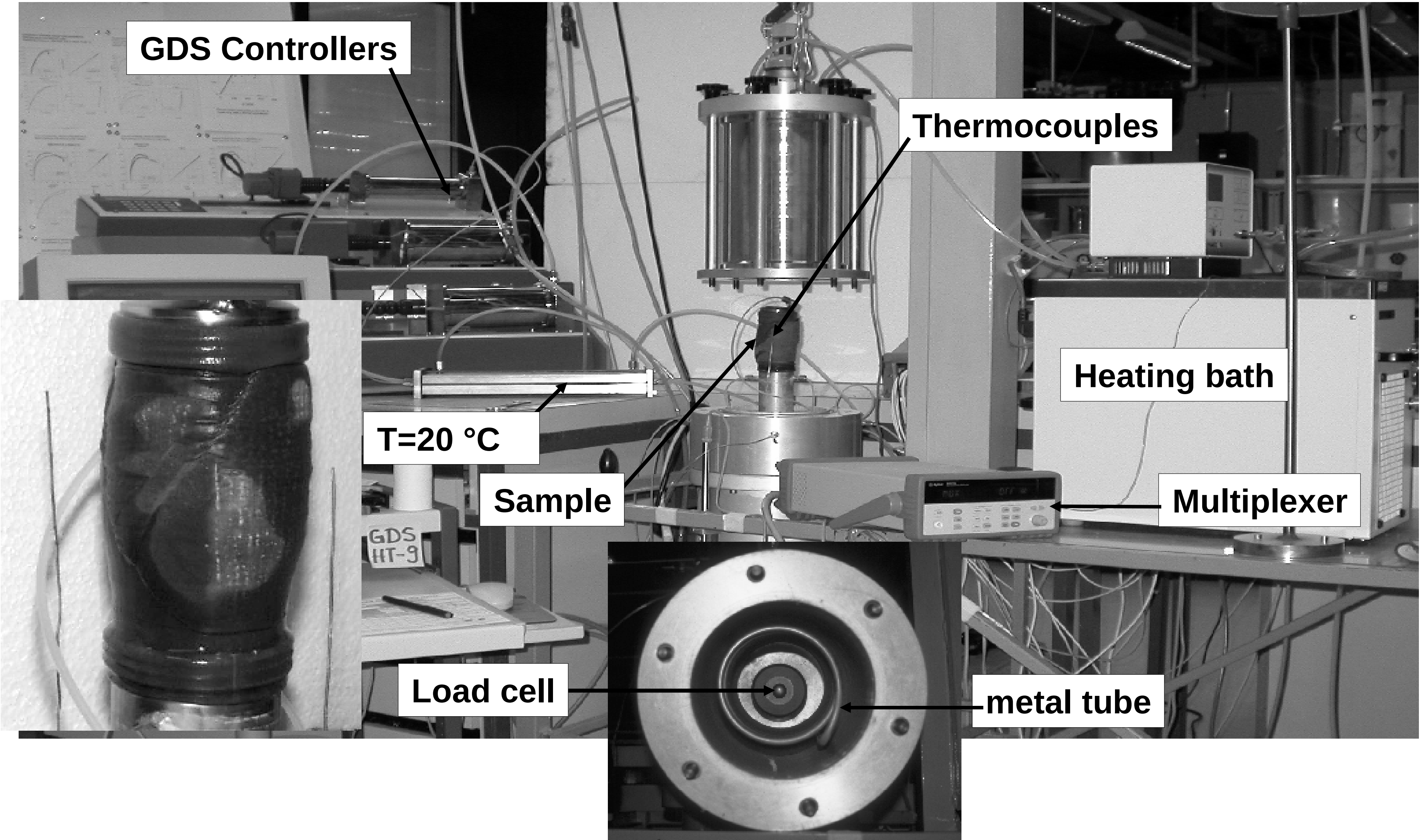


Thermo-mechanical loading conditions



D_0=5.5 cm H_0=11 cm

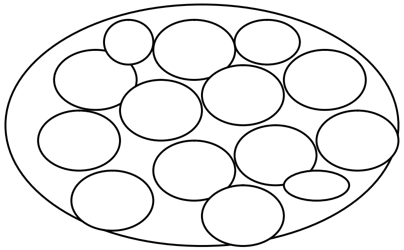
"A novel triaxial apparatus for thermo-mechanical testing of soils". Geotechnical Testing Journal, Vol. 28, issue 2, 2005



Constitutive laws

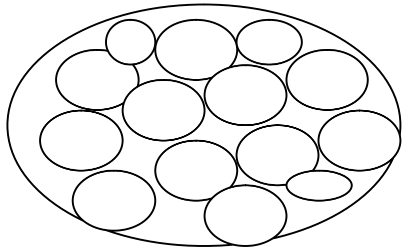
Fourier's law

T



- Thermal conductivity
- Heat capacity

Darcy's law

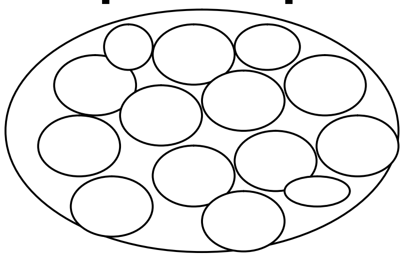


H

- Permeability (T)
- Storage coefficient (T)

- Elastic parameters (Young modulus)
- Hardening parameters (preconsolidation pressure) (T)
- Plastic parameters (friction angle)
- Thermo-elastoplastic parameters (T)

In-situ thermal response test



M

Thermo-(visco)plastic law

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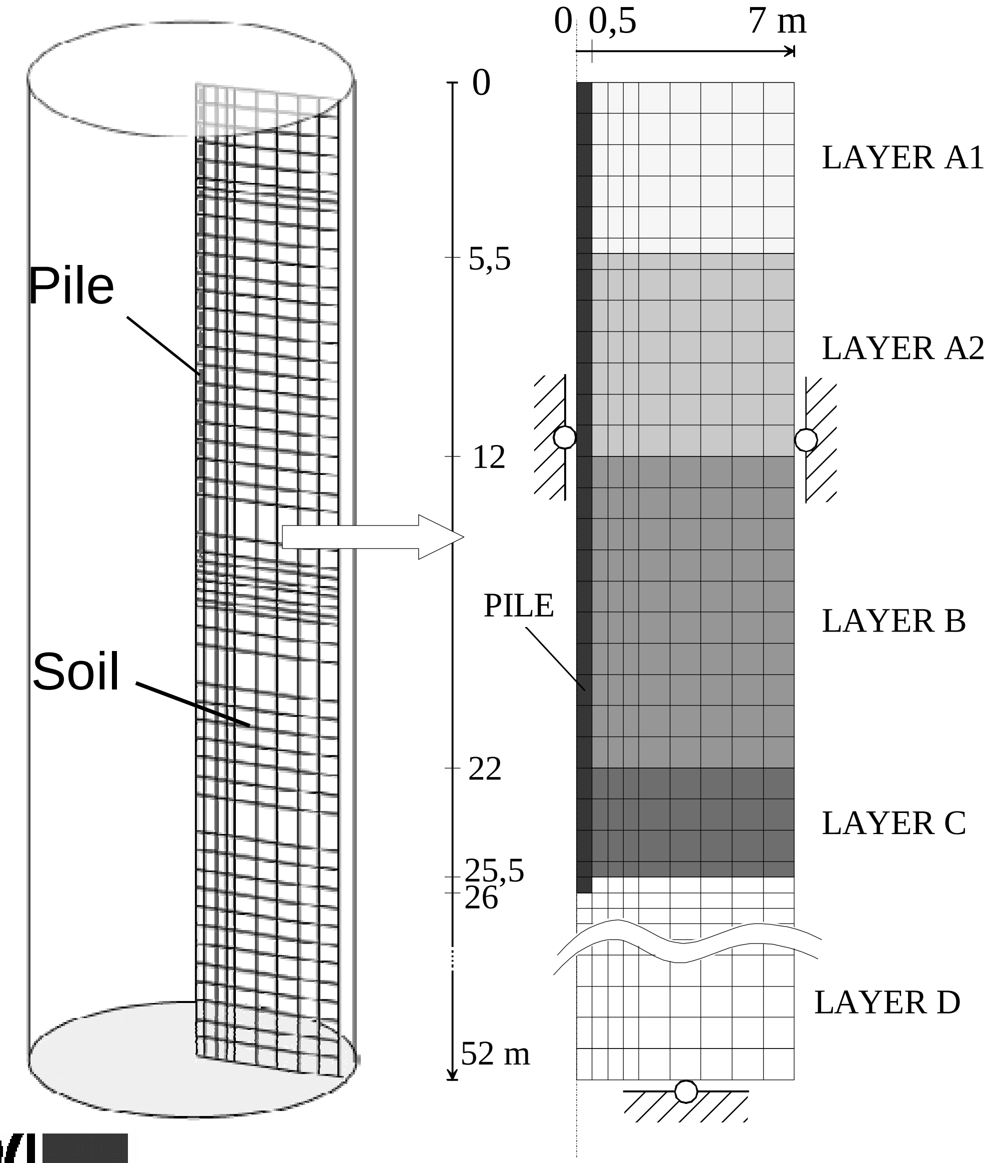
Numerical modeling

- **Assumptions:**
  - A single pile is modeled
  - Pile diameter 1 m ; length 26 m
  - Five soil layers/Drucker-Prager thermo-elastoplastic law
  - Concrete: impervious and thermo-elastic behaviour
  - Fully saturated ground

Simulation tools:
- Coupled THM model
- GEFDYN FE code



Numerical modeling

Material Parameters

- Mechanical parameters (K,G, Φ ,c) determined from triaxial tests run on samples from the A, B and C soil layers (3 confining pressures for each layer)

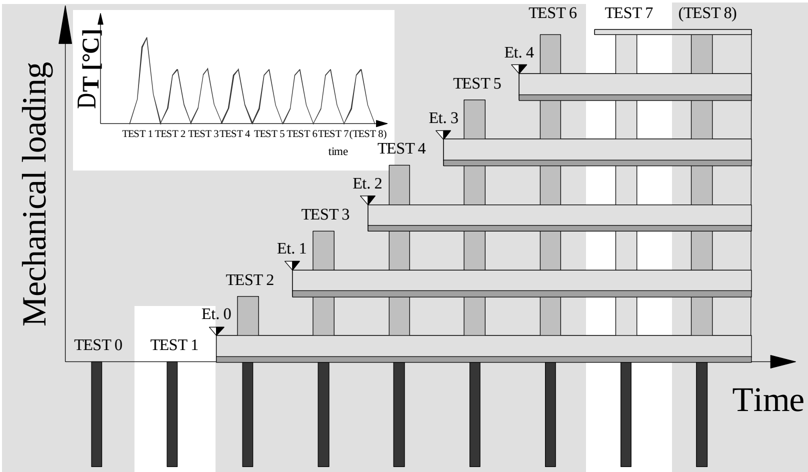
- Thermal parameters (Λ, ρc, β_s') estimated on the basis of geotechnical characteristics

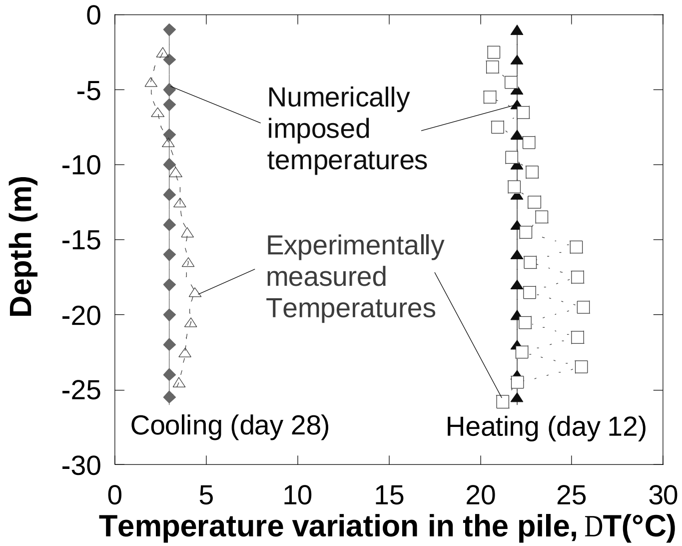
- Horizontal permeabilities measured in situ via geotechnical investigations (De Cérenville 1997). Assumption of isotropic permeability

	Parameter	Range	Material
Mechanical	K [MPa]	122	layer A1
		17381	concrete
	G [MPa]	113	layer A1
		14313	concrete
	Φ [°]	23	layer B
		30	layer A1
	c [KPa]	3	layer A2
		20	layer C
Thermal	Λ [W/m/°C]	1.1	layer D
		2.1	concrete
	ρc [J/m^3.°C]	2.0 10^6	layer D
		2.4 10^6	layerA1
	β_s' [°C^{-1}]	10^{-6}	layer D
		10^{-4}	layer B
	K* [m/s]	7 10^{-7}	layer A2
		2 10^{-6}	layer A1

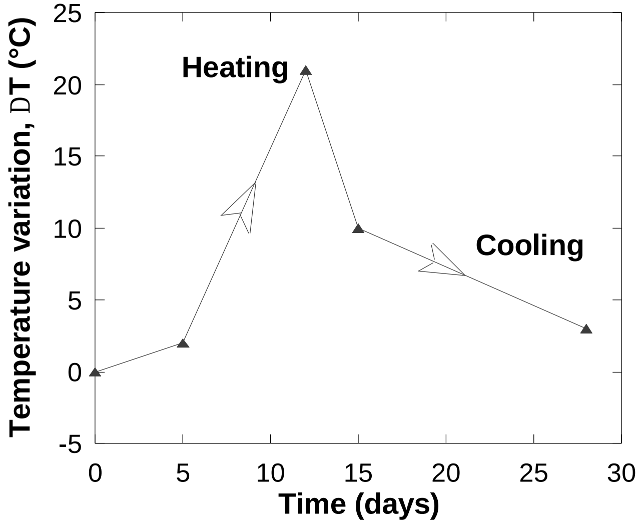
Numerical modeling

Test 1 (thermal load only) and test 7 (thermo-mechanical loading) are simulated:





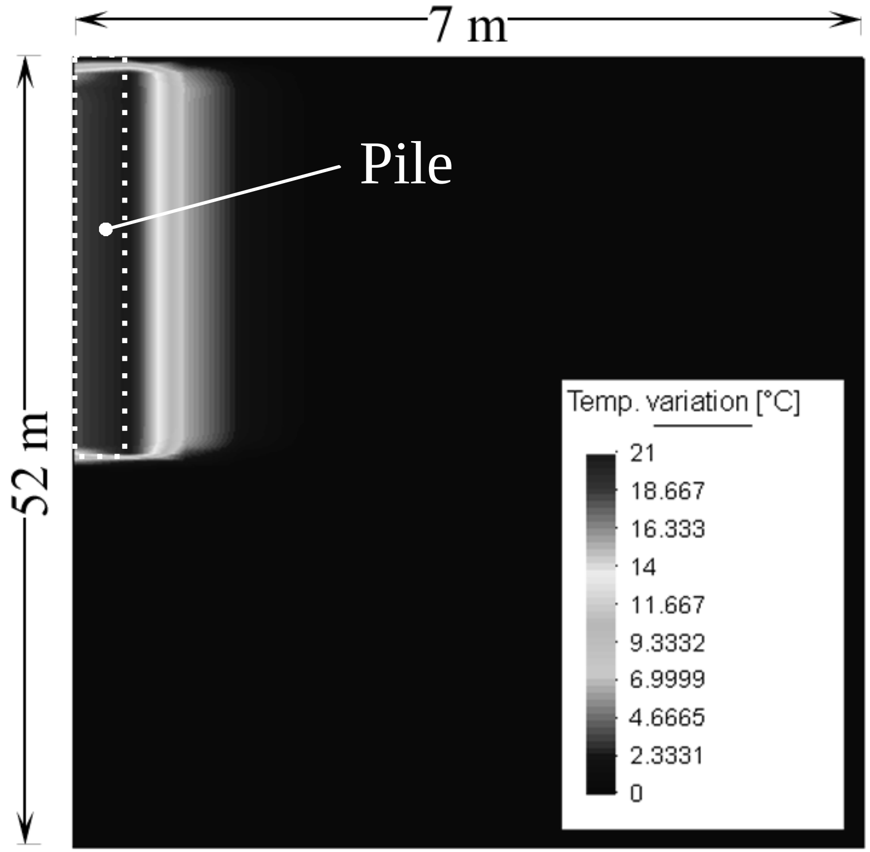
- **Imposing temperature variation in the pile (heating cooling cycle, DTmax = 21°C, 12 days of heating followed by 16 days of cooling)**



Numerical modeling

Thermal fields

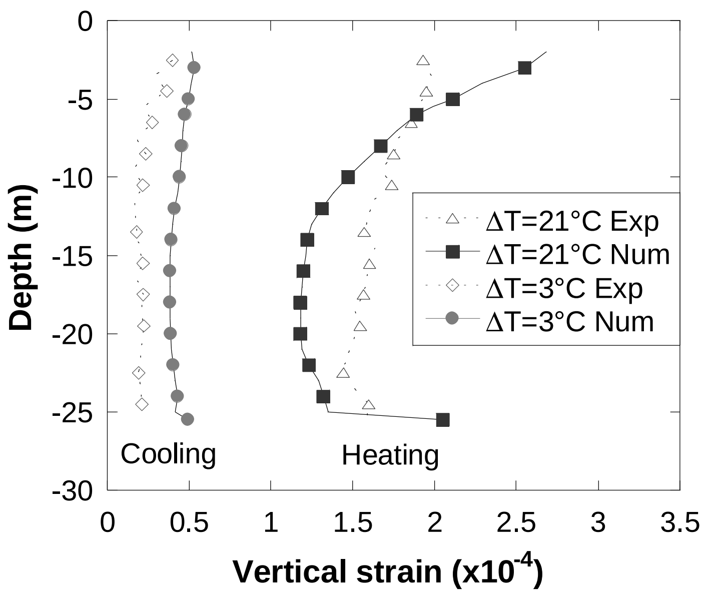
- **Constant temperature at the top surface**
- **Imposed incremental temperatures in the concrete pile**
- **Heat flux is supposed null along the axis of symmetry**

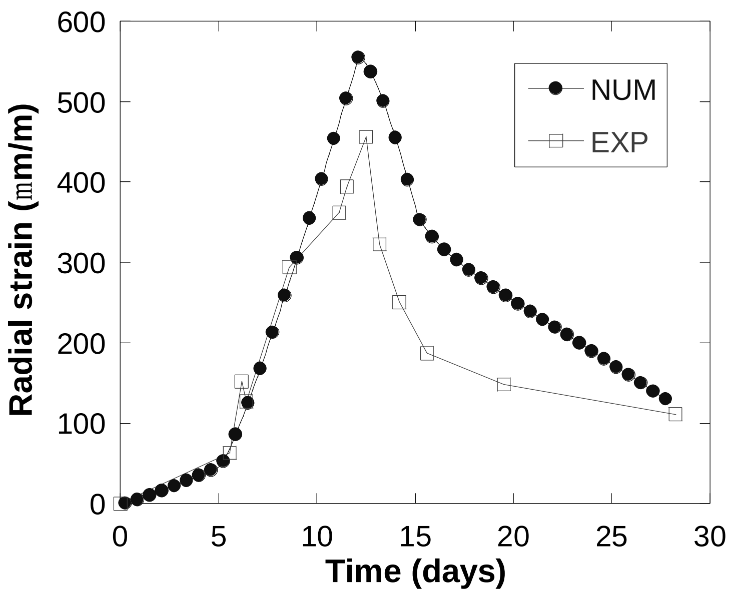


Normalised mesh : isothermal values at the end of the heating period (day 12)

Numerical modeling

Thermal effect on the mechanical behaviour of the pile (Test 1)

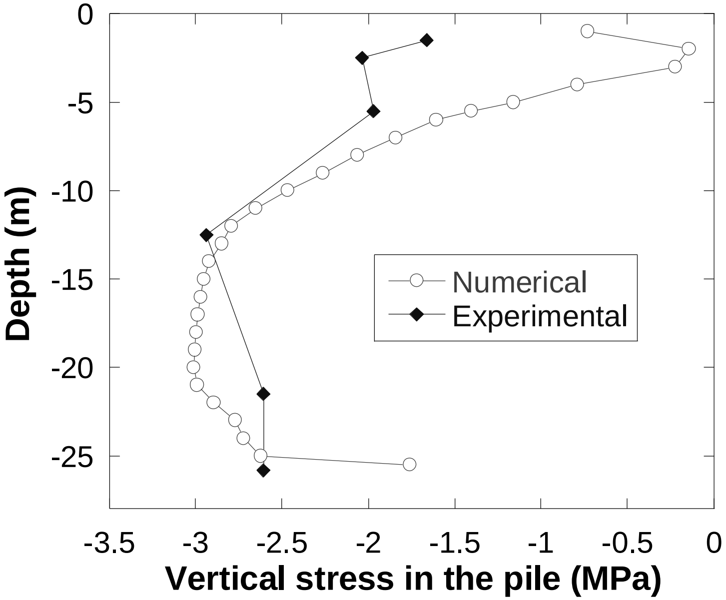




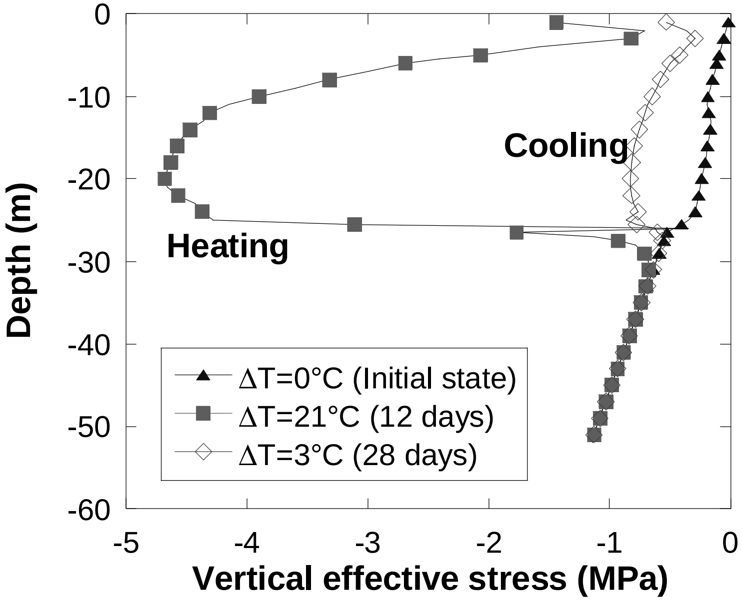
(Depth 16 m)

Numerical modeling

Thermal effect on the mechanical behaviour of the pile (Test 1)



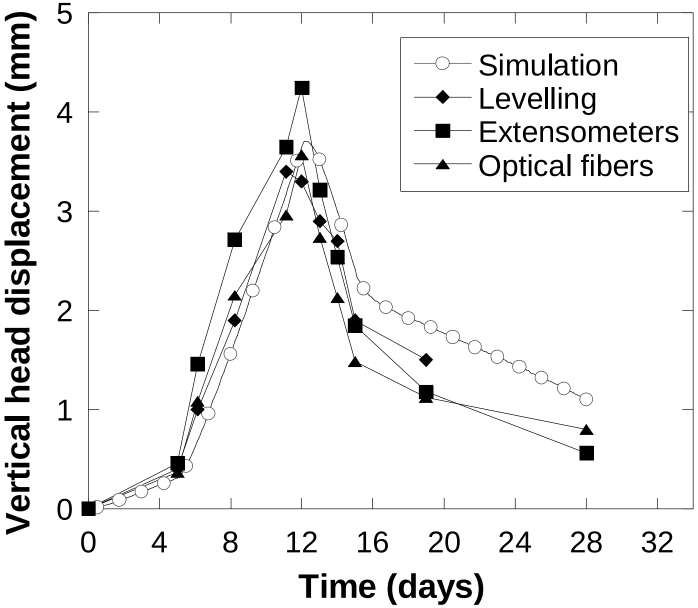
Vertical stresses in pile, ΔT=13.4°C



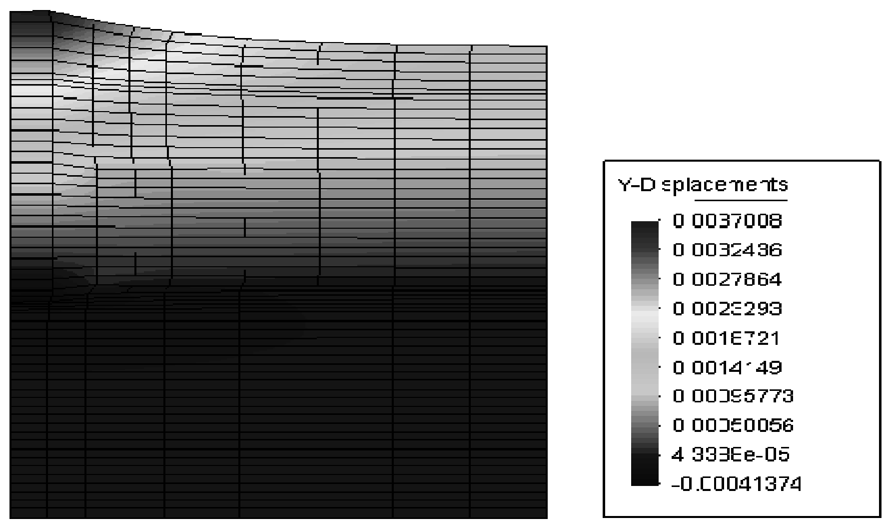
Vertical stresses induced by heating cooling cycle

Numerical modeling

Thermal effect on the mechanical behaviour of the pile (Test 1)



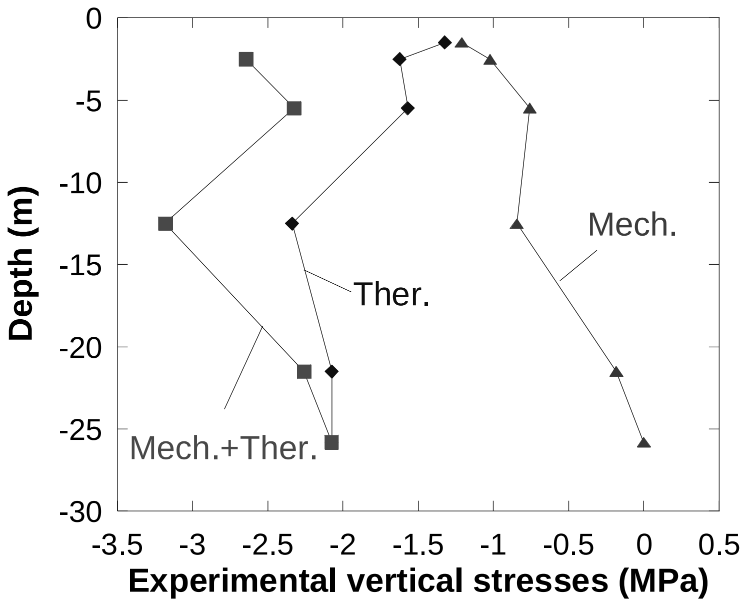
Vertical displacements

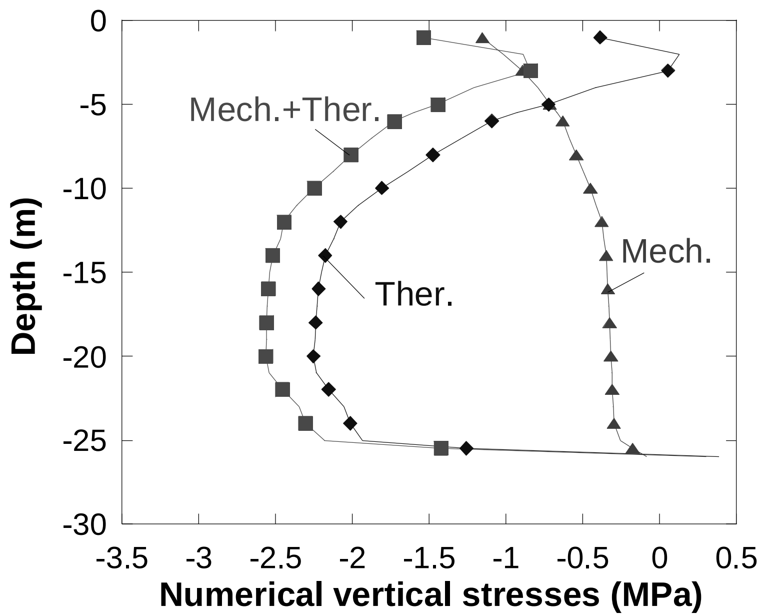


Normalized mesh

Numerical modeling

Thermo-mechanical behaviour of the pile
(Test 7 = Test 1+ dead weight of building on pile head)





Conclusions

The heating-cooling process of the building foundations induces significant modifications in the soil-structure interactions behaviour:

- **Additional stresses in the piles**
- **Decrease of the lateral friction**
- **Creation of gap between the pile (thermo-elastic) and the soil (thermo-plastic), …**

To improve the industrial-oriented development of this new technology, we developed several design tools:

- **Advanced THM simulation codes including dynamical behaviour (earthquake aspect)**
- **Advanced experimental equipments (thermo-mechanical triaxial test, TRT, …).**

References and contact

• Laloui L. et al. *“Experimental and numerical investigations of the behaviour of a heat exchanger pile”*. International Journal of Numerical and Analytical Methods in Geomechanics, vol. 30, pp. 763-781, 2006.

• http://lms.epfl.ch/en/page55176.html

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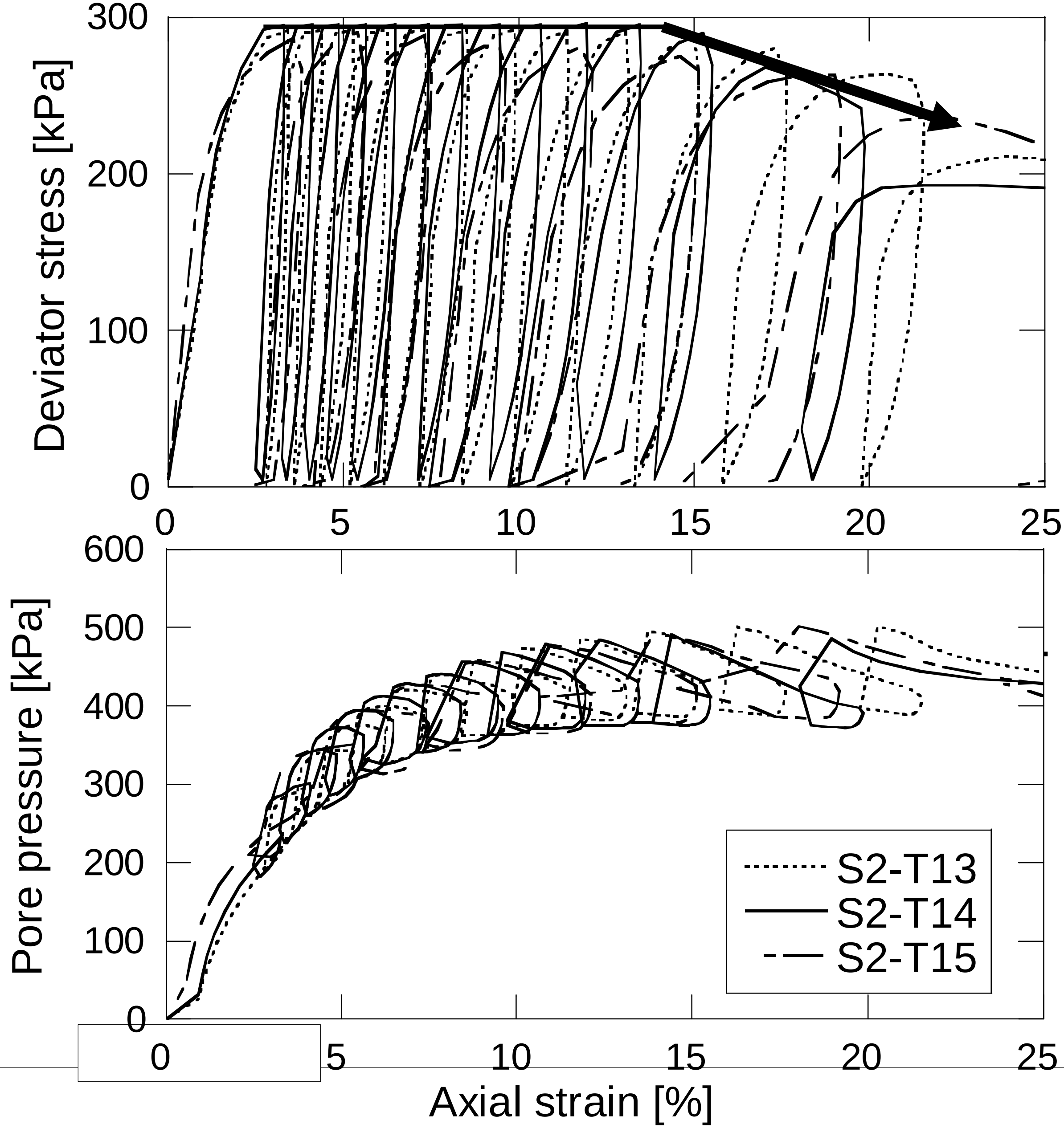
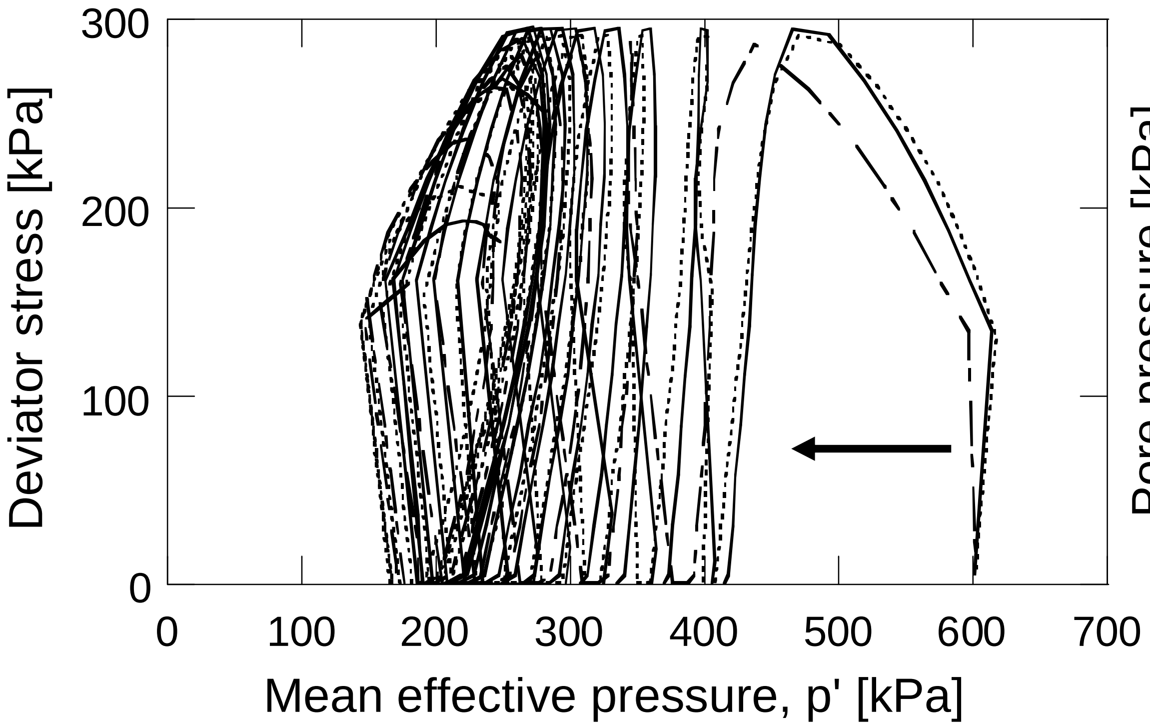
Cyclic stress-strain behaviour at 22 °C

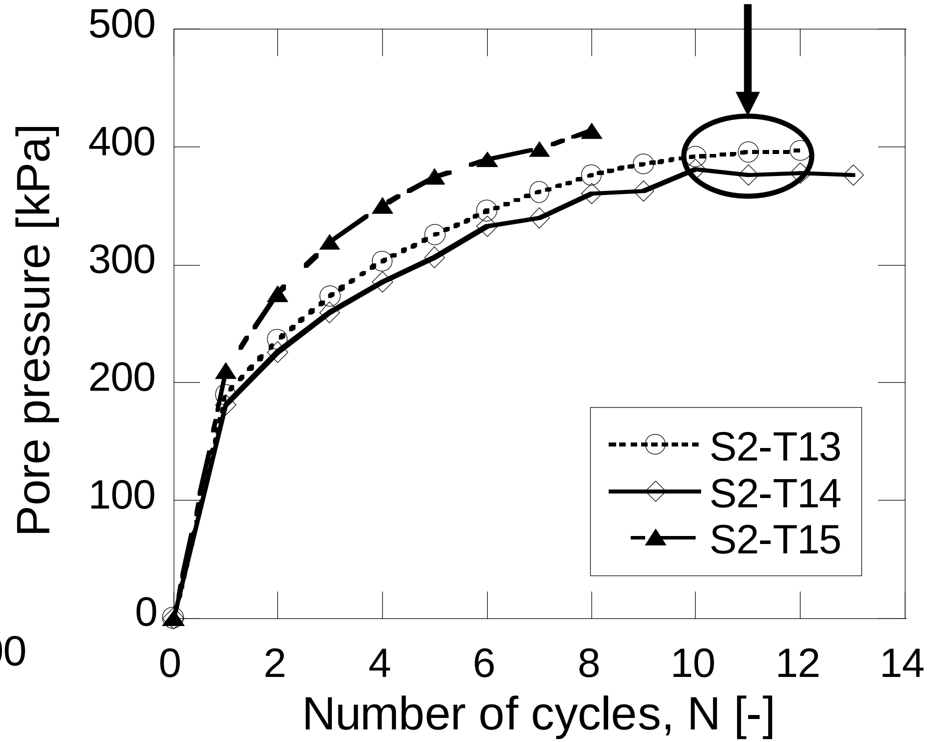
Undrained cyclic shear tests

- **During the first cycle, significant plastic strain was created.**
- **The subsequent cycles retained practically the same shape.**
- **Good reproducibility of the results.**
- **Cyclic mobility is reached at about 15%.**



Cyclic stress-strain behaviour at 22 °C



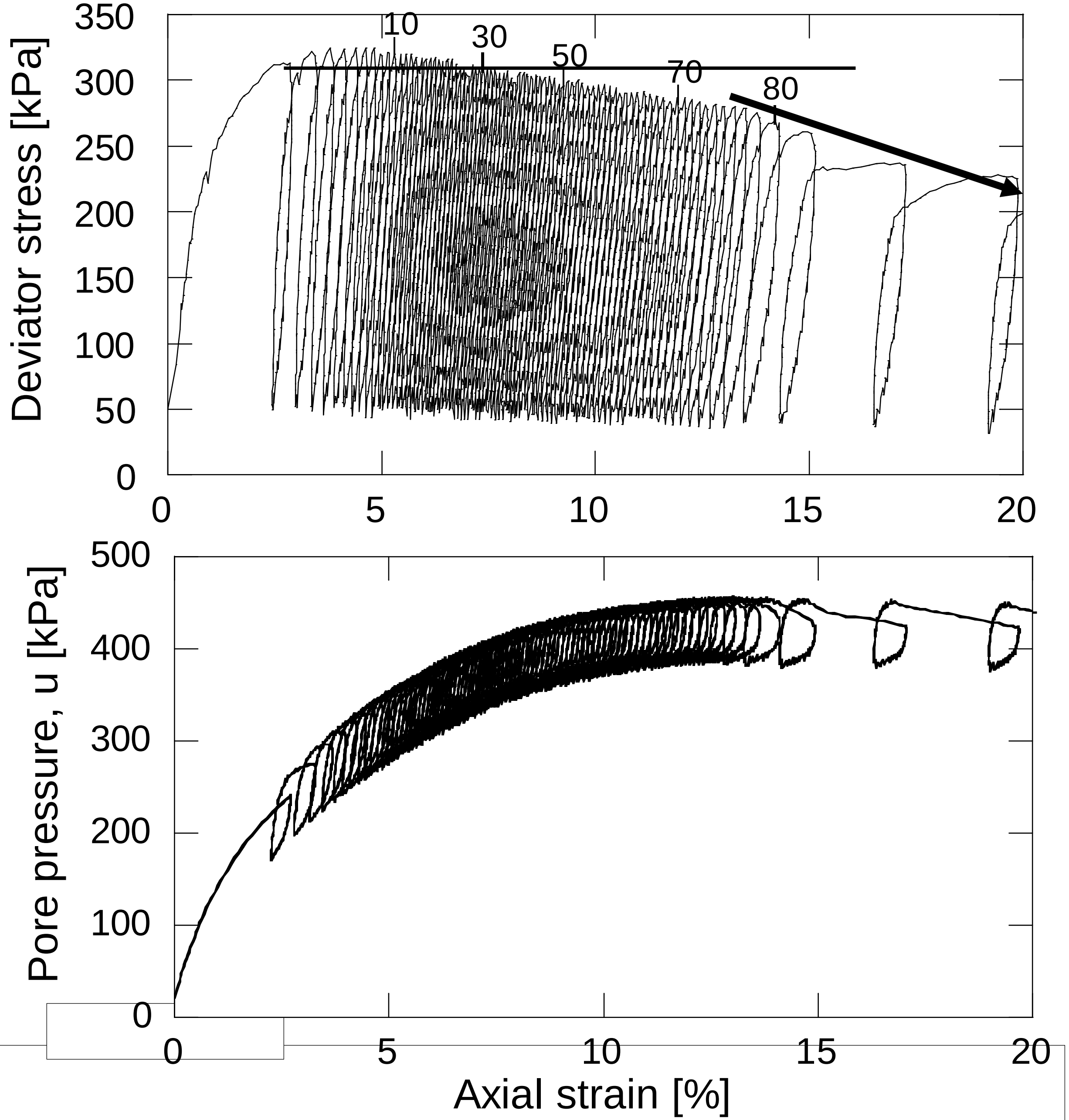


- An increase in pore pressure until the stress cycle almost met the line of perfect plasticity
- Material failure occurred after about 8-12 cycles

Cyclic stress-strain behaviour at 90 °C

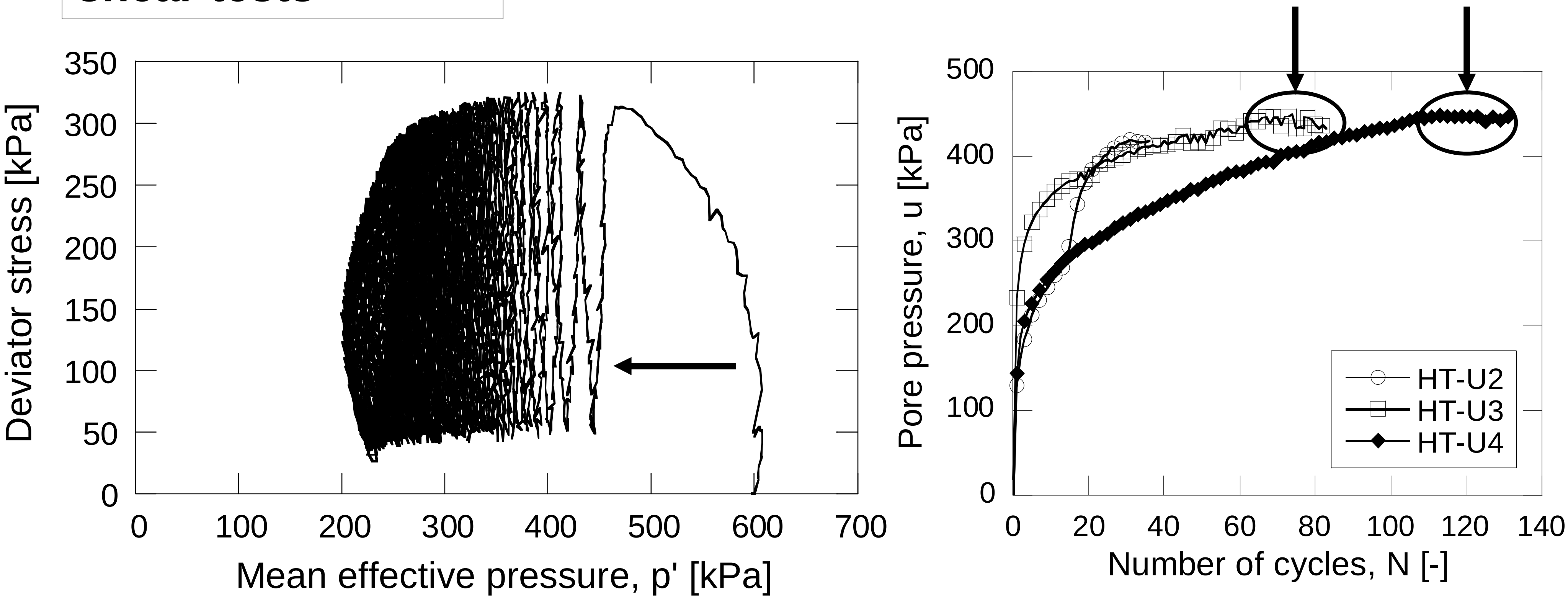
Undrained cyclic shear tests

- **During the first cycle, significant plastic strain was created.**
- **The following cycles were much more steeper.**
- **Failure of the sample was observed after about 60-70 cycles at axial strain of 12%.**



Cyclic stress-strain behaviour at 90 °C

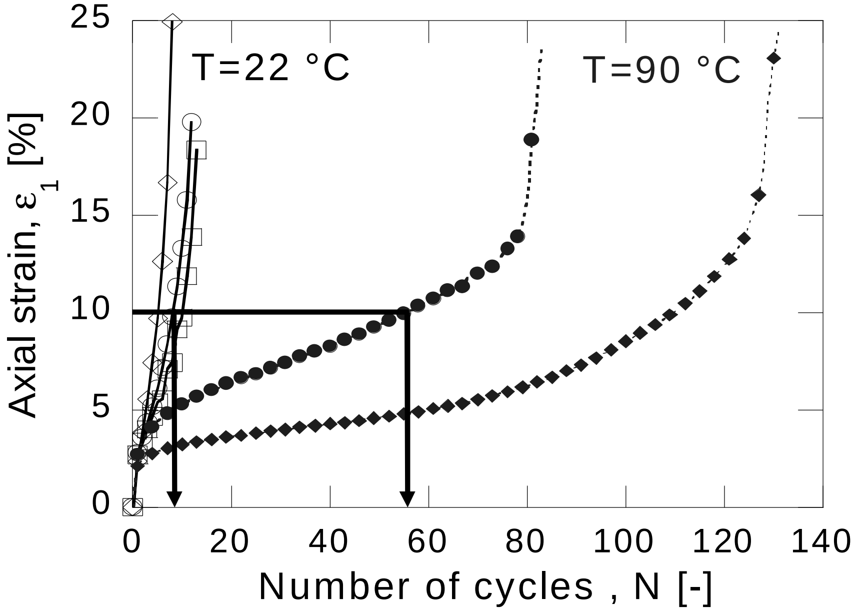
3 Undrained cyclic shear tests



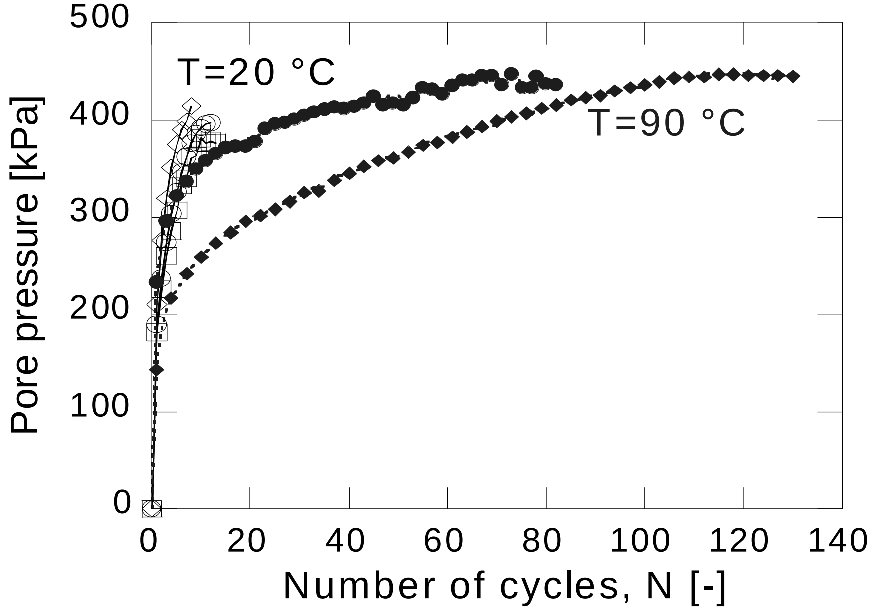
Cyclic mobility occurs after about 70-120 cycles at axial strain of about 12-15 %.

Comparison of cyclic shear tests at 22 °C and 90 °C

- **Axial strain**



- **Pore pressure**



- **The material exhibits a substantially increased resilience to cyclic loading after the heating**
- **Clearly, the pore pressure developed per single cycle is much smaller**
- **Number of cycles to failure increases from nearly 10 at 22 °C to 100 at 90 °C**
- **In both cases, failure occurred at an axial strain of about 15 %**