Thermal potential of sites and design parameters

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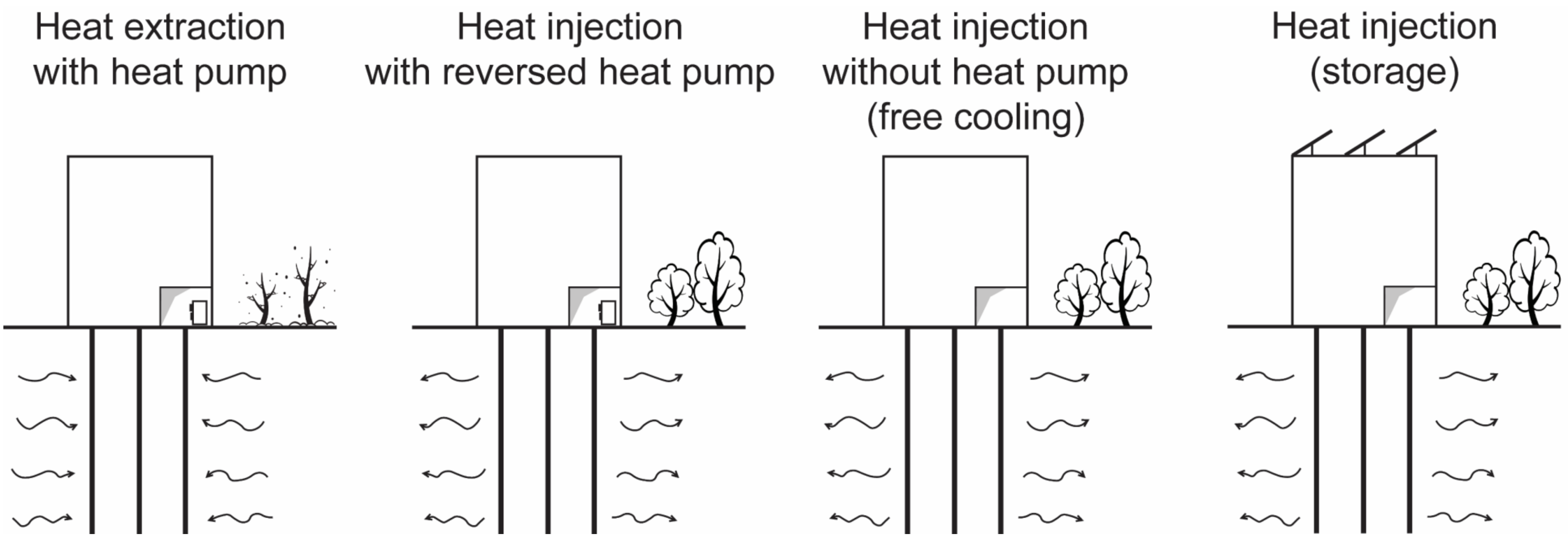
Outline

- Design considerations
- Laboratory testing
  - *Divided bar method*
  - *Thermal needle probe method*
- *In situ* testing
  - *Thermal Response test*
- Optimization

Design considerations

Aspects to consider

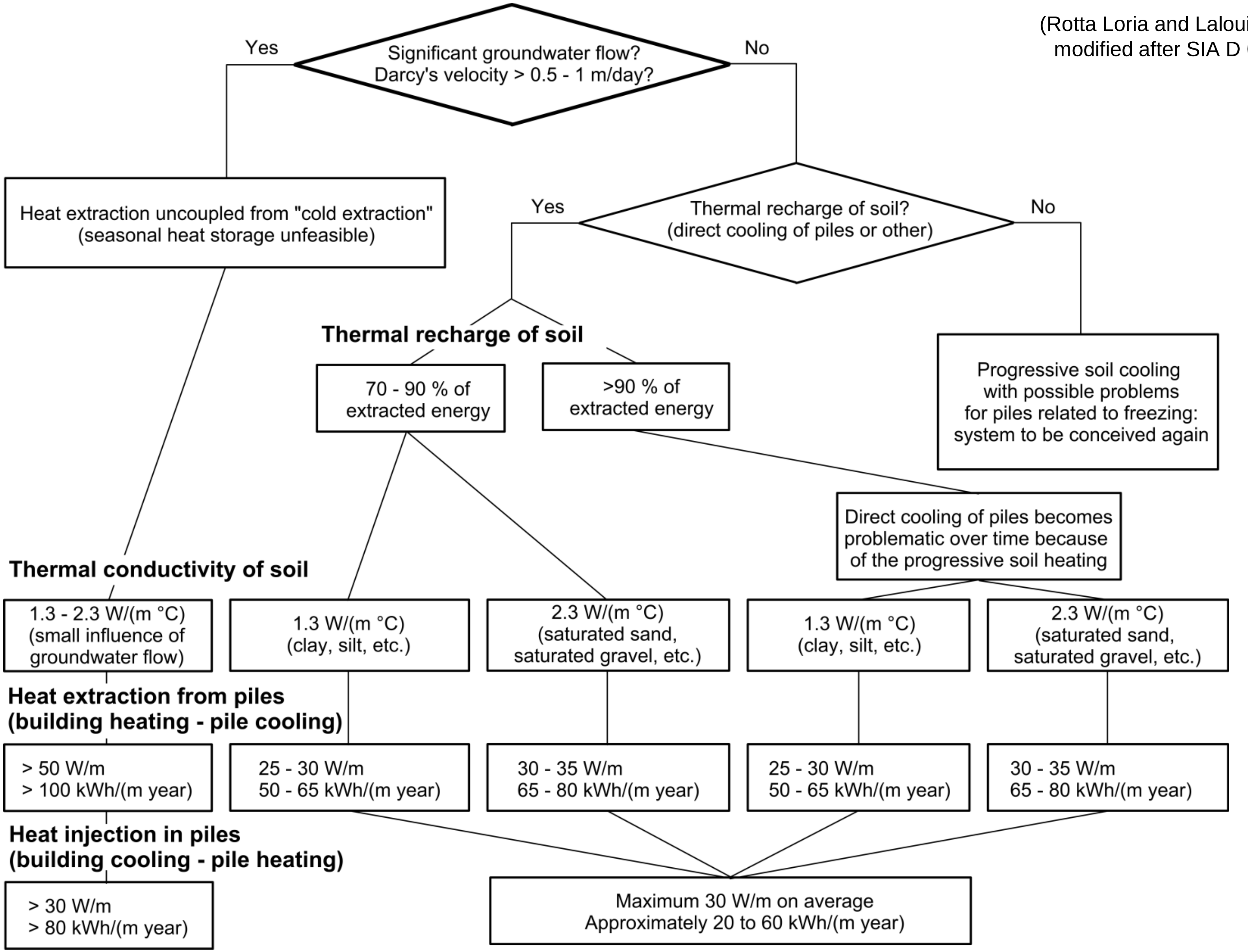


(Rotta Loria and Laloui, 2019)

- The operation of such systems depends on:
  - Superstructure energy needs
  - Ground thermal properties (thermal conductivity and diffusivity)
  - Significance of groundwater flow (Darcy's velocity)

Aspects to consider

(Rotta Loria and Laloui, 2019, modified after SIA D 0190)



Thermal potential and effective usable power

- Estimating the thermal potential of sites allows assessing the feasibility of energy geostructure applications
- There is a crucial difference between the estimation of the thermal potential and the actual performance of energy geostructures
- The actual performance of energy geostructures crucially depends on the design solutions and optimisation employed

Thermal (and hydraulic) properties of interest

- Initial temperature, T_0
- Thermal conductivity, λ
- Volumetric heat capacity, ρc_p
- Thermal diffusivity, $\alpha_d = \lambda/(\rho c_p)$
- Darcy's velocity, $\bar{v}_{rf,i}$

$$\lambda \nabla^2 T + \dot{q}_v = \rho c_p \frac{\partial T}{\partial t} + \rho_f c_{p,f} \bar{v}_{rf,i} \nabla T$$

Approaches to determine thermal properties

Laboratory tests:

- *Advantages*:
  - Can be repeated easily and performed for each soil layer
- *Disadvantages*:
  - Representativeness of soil samples can be questionable

In situ tests:

- *Advantages*:
  - Include the natural state of soil deposits
- *Disadvantages*:
  - Cannot be repeated easily

Laboratory Testing

Methods

(modified after Vulliet et al., 2016)

Method	Thermal Properties		Remarks
	Thermal conductivity λ [W/(m °C)]	Thermal diffusivity α_d [m^2/s]	
Divided bar method	✓	X	Measurement under steady conditions Applicable to soils and rocks
Thermal needle probe method (Single probe method)	✓	✓	Measurement in transient state Applicable to soils and rocks
Multiple probe method	✓	✓	Measurement in transient state Applicable to soils and rocks
Transient hot strip method	✓	✓	Measurement in transient state Applicable more to rocks than soils

In situ testing

The Thermal Response Test (TRT)

- Theory established by Mogensen (1983) for a system with a chilled heat carrier fluid

- First independent developments were carried out at

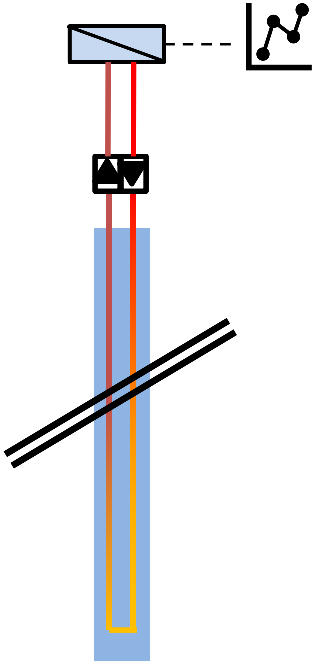
  - Luleå Technical University (Eklöf and Gehlin, 1996; Gehlin and Nordell, 1997)
  - Oklahoma State University (Austin, 1998; Austin et al., 2000)

- The LMS-EPFL developed its first equipment (Laloui and Steinmann, 2002) which is the preceding version to the compact equipment developed later on (Mattson et al., 2008)

Principle and objectives

- In-situ test to evaluate the thermal characteristics of the soil
- Test originally developed for borehole heat exchangers
- The test includes site specific conditions and external effects

- The following design parameters can be defined
  - T_0 : undisturbed ground temperature
  - λ: effective thermal conductivity of the ground
  - R'_{ghe}: thermal resistance between the heat carrier fluid and the ground heat exchanger wall



Equipment

Heating module developed by LMS-EPFL

Mini-module developed by LMS-EPFL

Available standards on TRT

- Test originally developed for borehole heat exchangers

- Four available guidelines for the TRT, providing suggestions for test duration, fluid flow rate, power level, acceptable power fluctuations, insulation requirements for the surface equipment:

  - ASHRAE (2002) guideline

  - From the working group of the Implementing Agreement on Energy Conservation through Energy Storage of the International Energy Agency (IEA) (Sanner et al, 2005)

  - Ground Source Heat Pump Association (2011)

  - ISO 17628:2015

Optimal test features

Optimum power:

- Should be between 30 and 50 W/m (at maximum of 80 W/m)

$$\dot{Q} = \dot{q}_l L$$

Flow rate:

- The inlet-outlet temperature difference should preferably be 3-5 °C
- Temperature variations of 2 °C ensure effective applications
- The flow rate should be determined as

$$\dot{m} = \frac{\dot{q}_l}{c_{p,f}\Delta T}$$

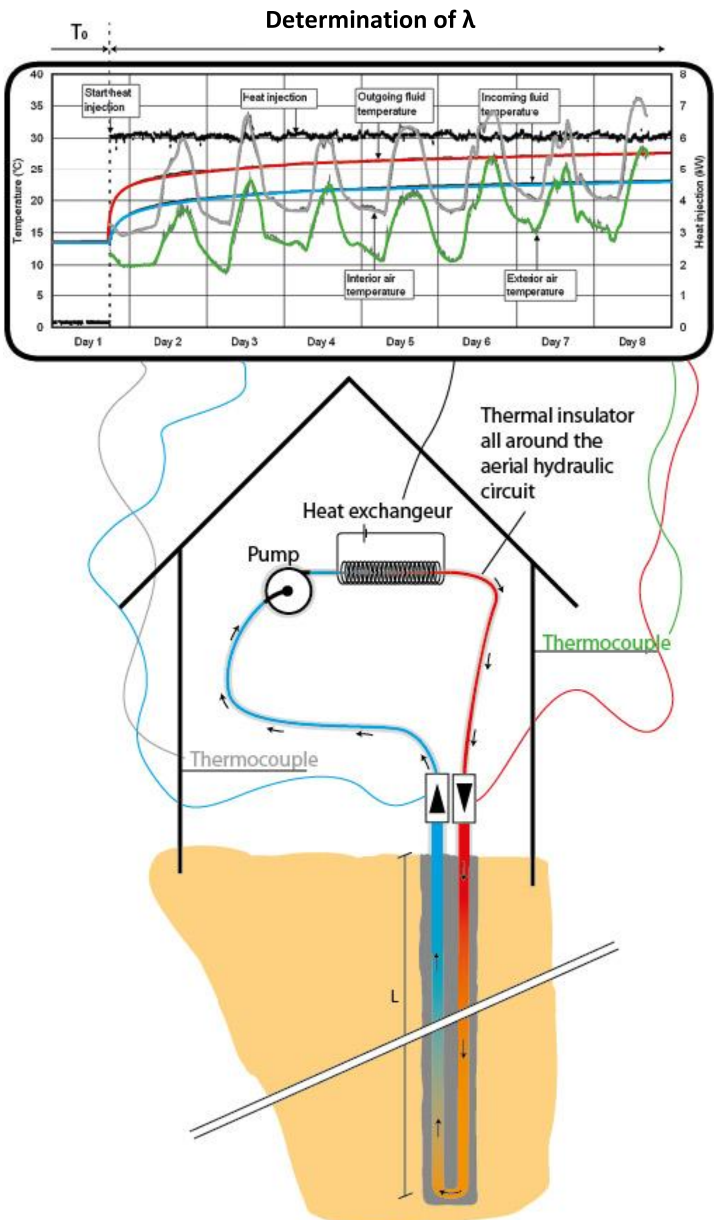
Procedure

1. Installation of ground heat exchanger and grouting
2. Setting up equipment, calibration and testing of components
3. Setting the levels for flow rate and heat power
4. Activating data logger and remote data transmission system
5. Insulating tubes between equipment and heat exchanger
6. Determination of the undisturbed ground temperature
7. Switching on heating and monitoring (constant power)
8. Switching off, dismantling and cleaning of test equipment

Measured data

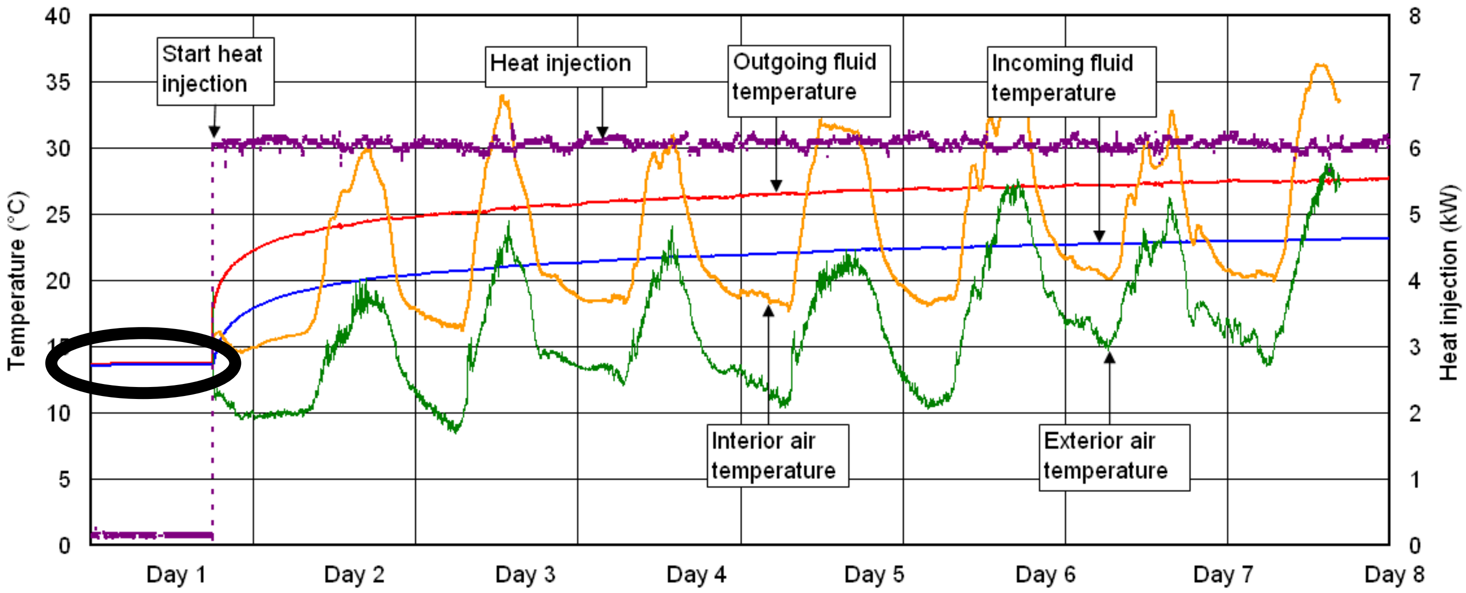
(Vulliet et al., 2016)

- Temperatures:
  - Inlet fluid temperature
  - Outlet fluid temperature
  - Temperature inside the module
  - Temperature outside the module
- Fluid pressure:
  - Inlet fluid pressure
  - Outlet fluid pressure
- Flow rate
- Power consumption



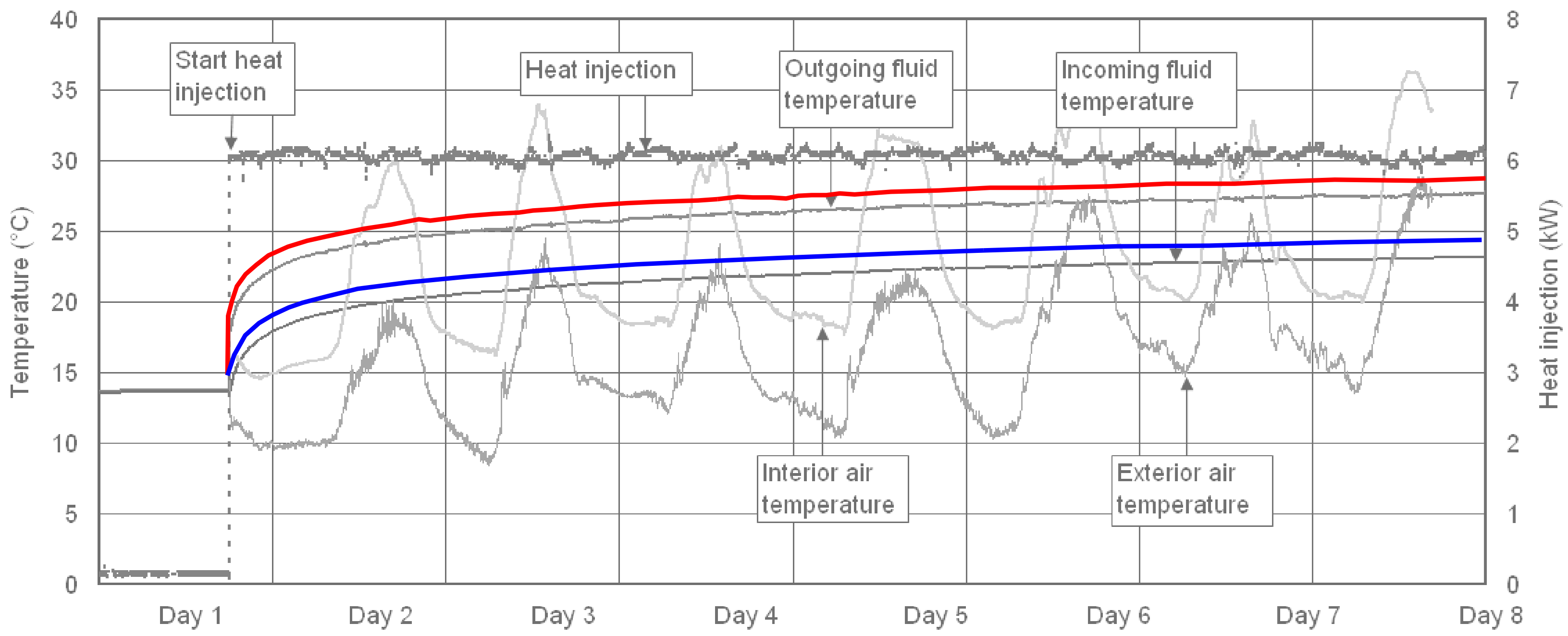
Undisturbed ground temperature

- Heat carrier fluid is circulated with the heater turned off
- Heating of the circulation pump is estimated and subtracted
- Duration depends on the difference between the initial temperature of the fluid and the in situ temperature of the ground
- Minimum recommended test duration of 12 hours



Effective thermal conductivity of the ground

- Heat carrier fluid is circulated with the heater turned on
- A constant heat power is injected
- Ground thermal conductivity is determined from the measurements of the inlet and outlet temperatures
- Minimum recommended test duration of 3 days (may be 6-7 days)



Effective thermal conductivity of the ground

- Infinite line source is typically used to describe heat transfer for

$$t_{ghe} > 5\frac{R^2}{\alpha_{d,ghe}}$$

- Under these conditions

$$T(t,R) - T_0 = \dot{q}_l G_f(t,R) = \dot{q}_l \frac{1}{4\pi\lambda}\left(\ln\frac{4\alpha_d t}{R^2} - \gamma_E\right)$$

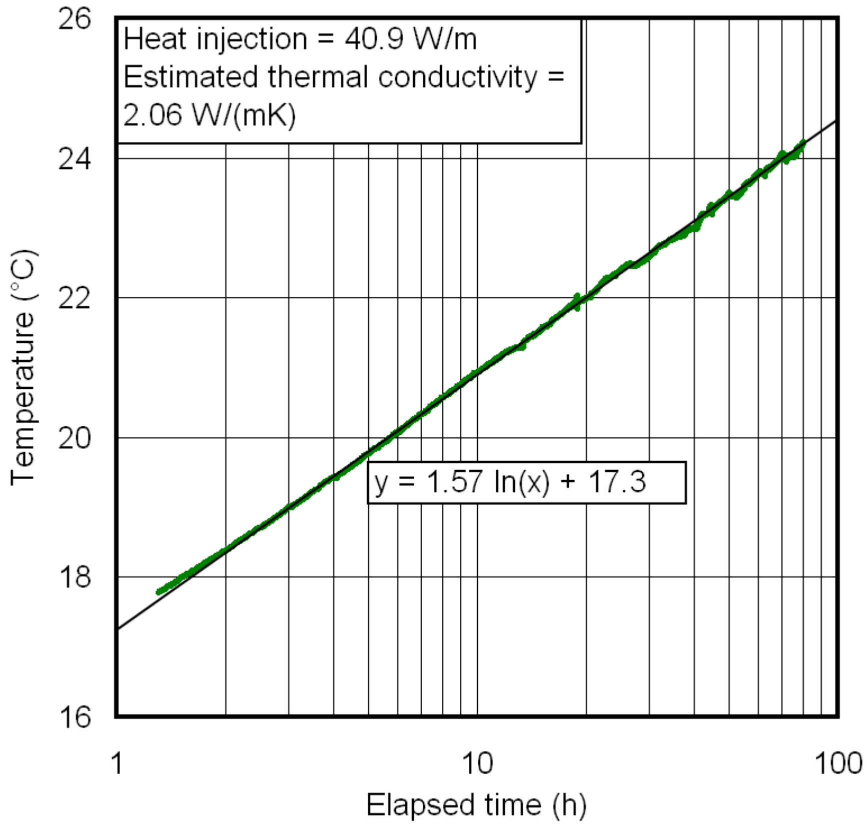
$$G_f(t,R) = \frac{1}{4\pi\lambda}E_1\left(\frac{r^2}{4\alpha_d t}\right) = \frac{1}{4\pi\lambda}\left(\ln\frac{4\alpha_d t}{r^2} - \gamma_E\right)$$

- At $t_{ghe} = 5\frac{R^2}{\alpha_{d,ghe}}$ the typical error is 10% while at $t_{ghe} = 20\frac{R^2}{\alpha_{d,ghe}}$ the typical error is 2.5%

(Li and Lai, 2015)

Effective thermal conductivity of the ground

- The thermal conductivity is estimated by plotting the mean fluid temperature against time in logarithmic scale



$$T(t) = k_{sl} \ln t + m$$

$$\lambda = \frac{\dot{q}_l}{4\pi k_{sl}}$$

$$k_{sl} = 1.57$$

$$\dot{q}_l = 40.9 \text{ W/m}$$

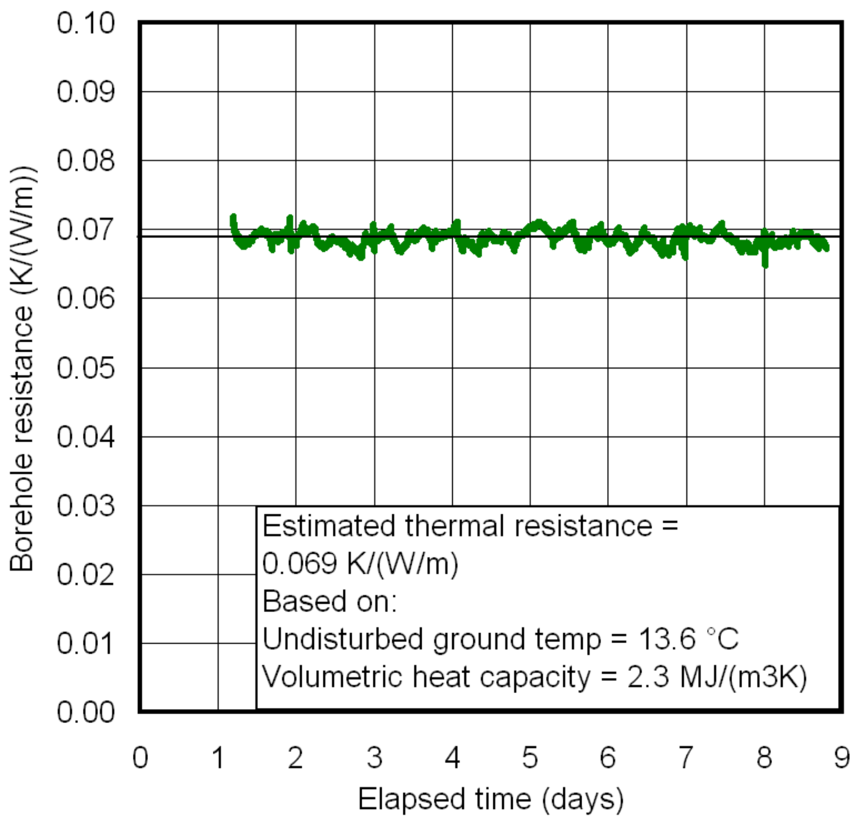
$$\lambda = \frac{40.9}{4\pi 1.57} = 2.06 \text{ W/(m °C)}$$

Ground heat exchanger thermal resistance

- The time-independent thermal resistance of the ground heat exchanger is calculated from the measurements recorded during TRT by knowing:
  - Undisturbed temperature of the ground (T_0)
  - Ground thermal conductivity (λ)
  - Ground volumetric heat capacity (typically defined through laboratory tests)

$$\Delta T = \dot{q}_l \left[R'_{ghe} + G_f(t, R) \right]$$

Ground heat exchanger thermal resistance

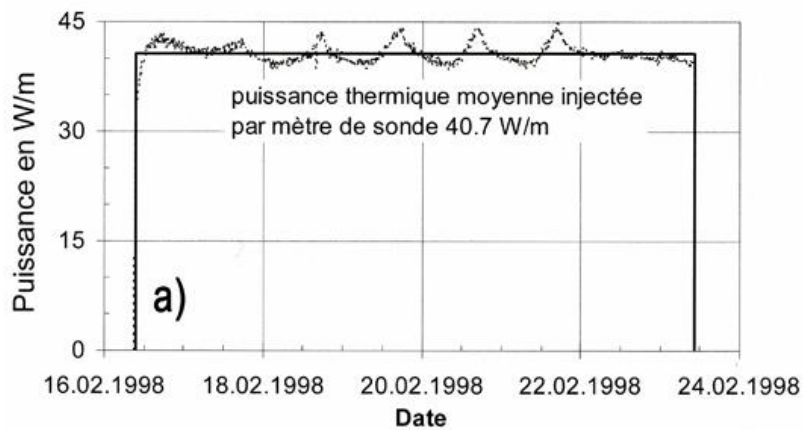


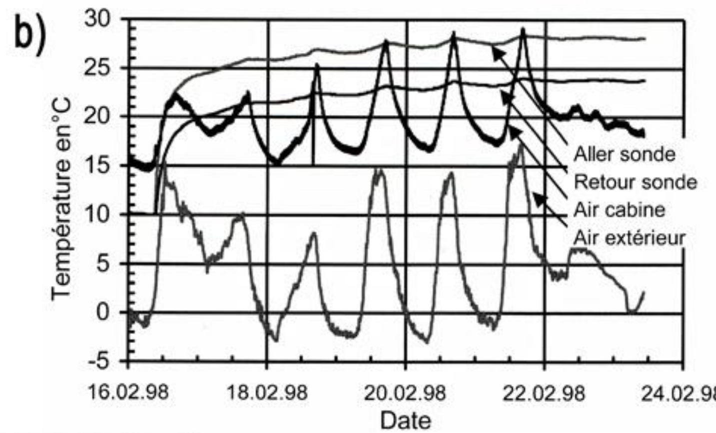
$$R'_{ghe} = 0.069\ °\mathrm{C}/(\mathrm{W}/\mathrm{m})$$

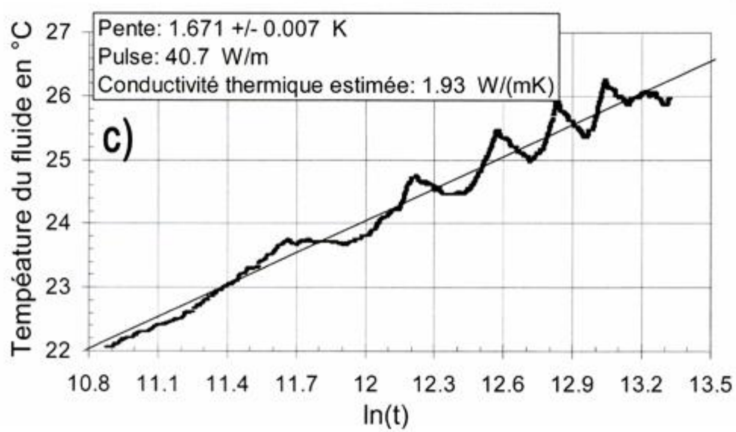
$$\Delta T = \dot{q}_l \left[R'_{ghe} + \frac{1}{4\pi\lambda}\left(\ln\frac{4\alpha_d t}{r^2} - \gamma_E \right) \right]$$

Data disturbance during TRT

- Insulation of the pipes in the open air is crucial for obtaining undisturbed data
- Fluctuations in the outside temperature induce strong disturbances in the net heat power injected into the pipes







(SIA D 0190)

Limits of TRT applied to energy piles

- Several thermal response tests have been applied to energy piles (Lennon et al., 2009; Wood et al., 2010; Brettmann et al., 2010)
- Method originally developed for geothermal boreholes
- The energy piles are shorter than the boreholes, between 20 and 50 m compared to 100 m to +200 m for the borehole.
- The thermal response of the ground around an energy pile lies between the infinite line source model and infinite cylindrical-surface source model (Loveridge, 2012)
- The energy piles only partially correspond to the basic assumptions of the analytical model used for the calculation of thermal conductivity and thermal resistance.

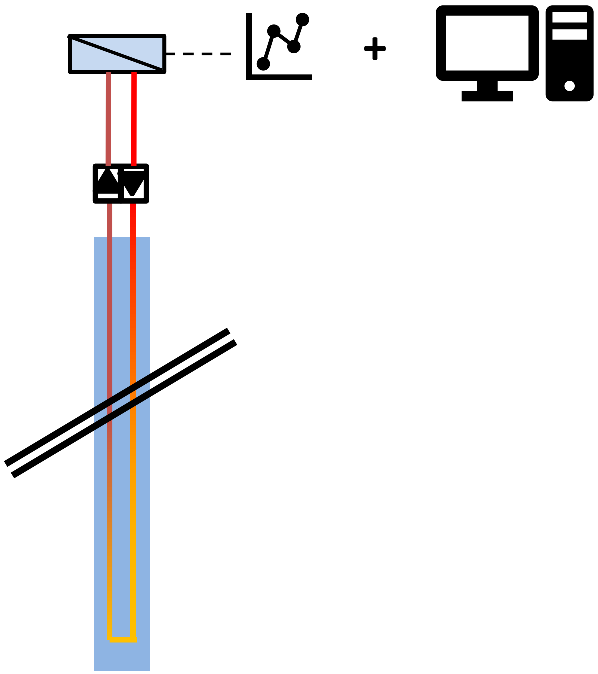
Thermal performance tests

Principle and objectives

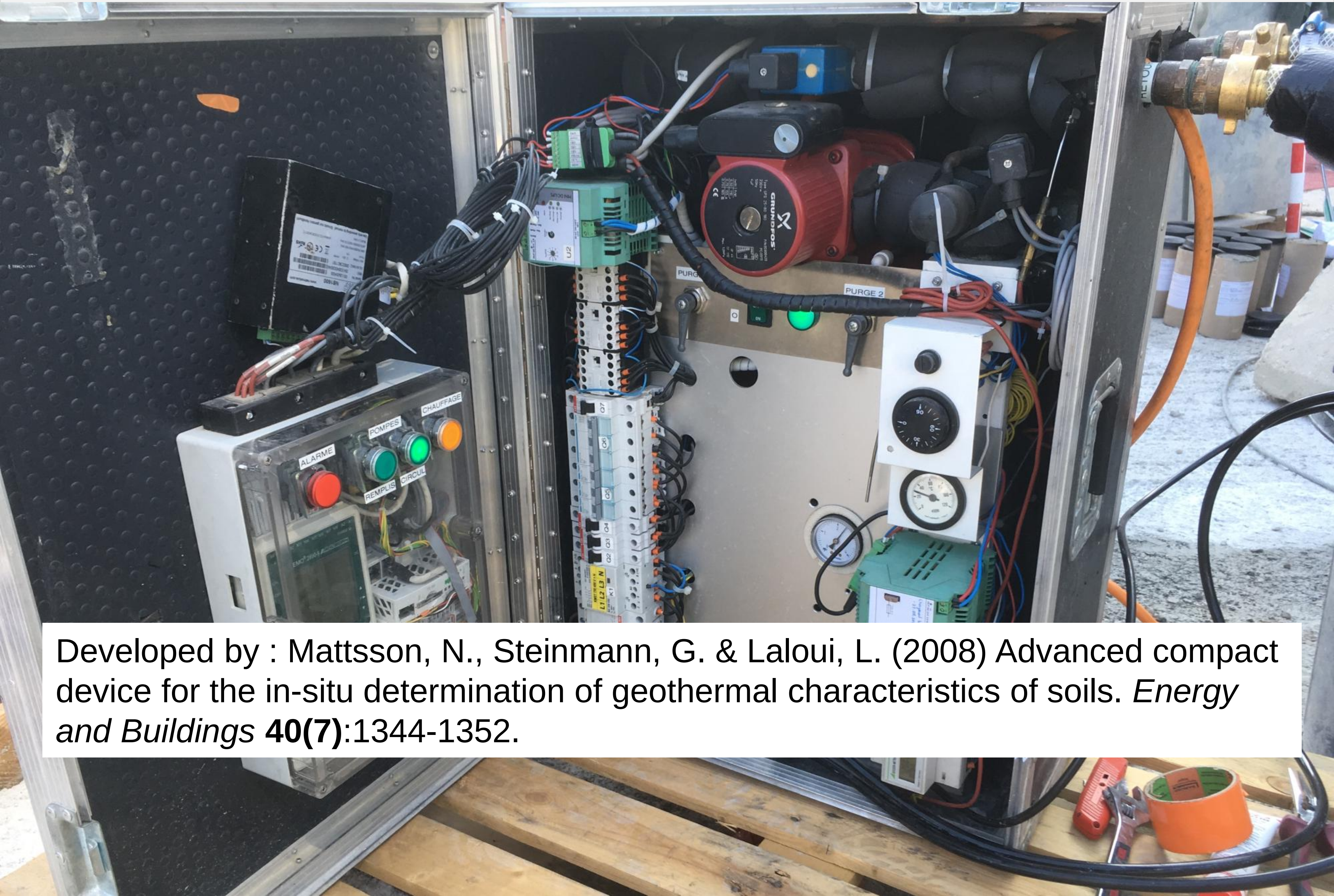
- Thermal performance testing combines in-situ testing (TRT) and numerical modelling
- The principle consists in using the experimental data obtained from a TRT on energy geostructures to calibrate a numerical model.

This method has the advantage of:

- **simulating the real performance** of an energy pile on the basis of experimental data
- allows the **thermal performance** of **other types of energy geostructures** to be interpreted
- **Optimise dimensioning parameters** (e.g. tube configuration)



Equipement



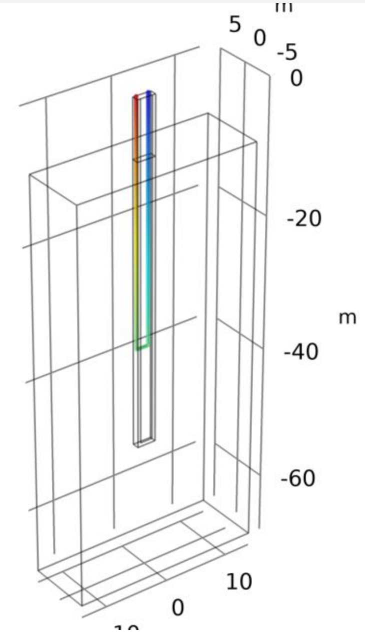
Developed by : Mattsson, N., Steinmann, G. & Laloui, L. (2008) Advanced compact device for the in-situ determination of geothermal characteristics of soils. *Energy and Buildings* **40(7)**:1344-1352.

Methodology

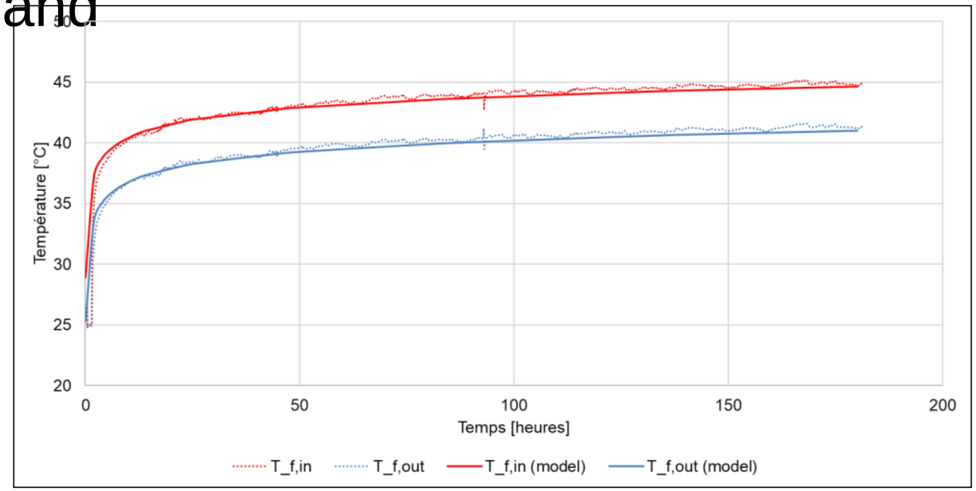
1. Carrying out the in-situ test

2. Numerical modelling of the test

3. Calibration of the parameters of the numerical model with the experimental results.



4. Interpretation, calculations, and optimisation



Summary and concluding remarks

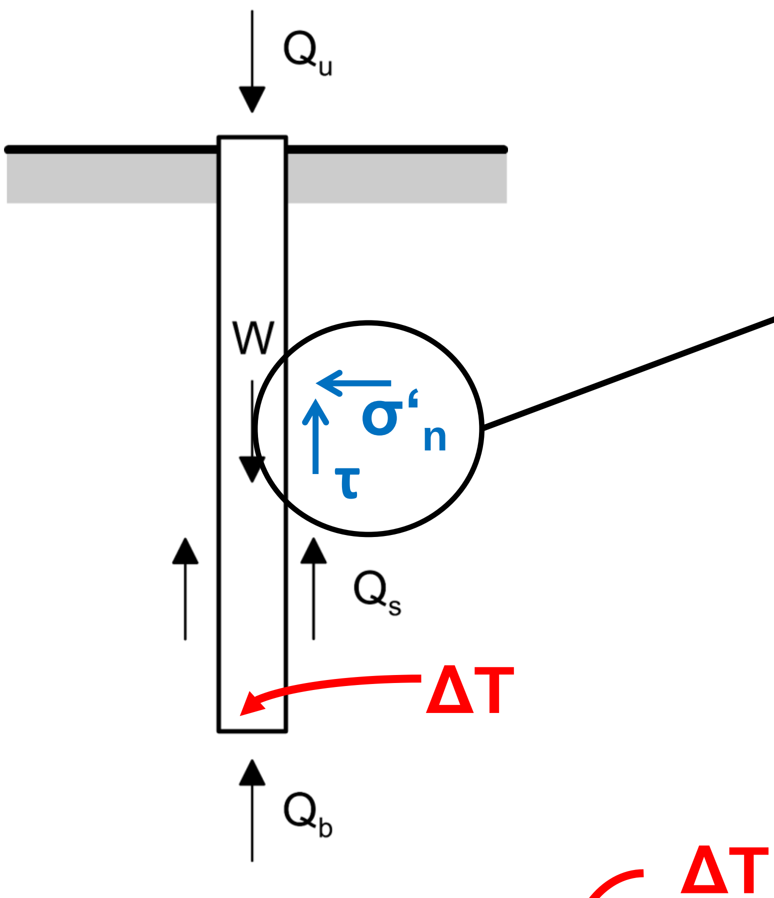
Concluding remarks

- Effective methods for defining the thermal properties of soils do exist
- The estimation of these properties characterises the energy design
- In addition to the determination of thermal properties, knowledge of the significance of groundwater flow is essential
- The extraction and storage potential of energy geostructures depends on the previous aspects
- A key design stage is represented by the optimisation of energy geostructures

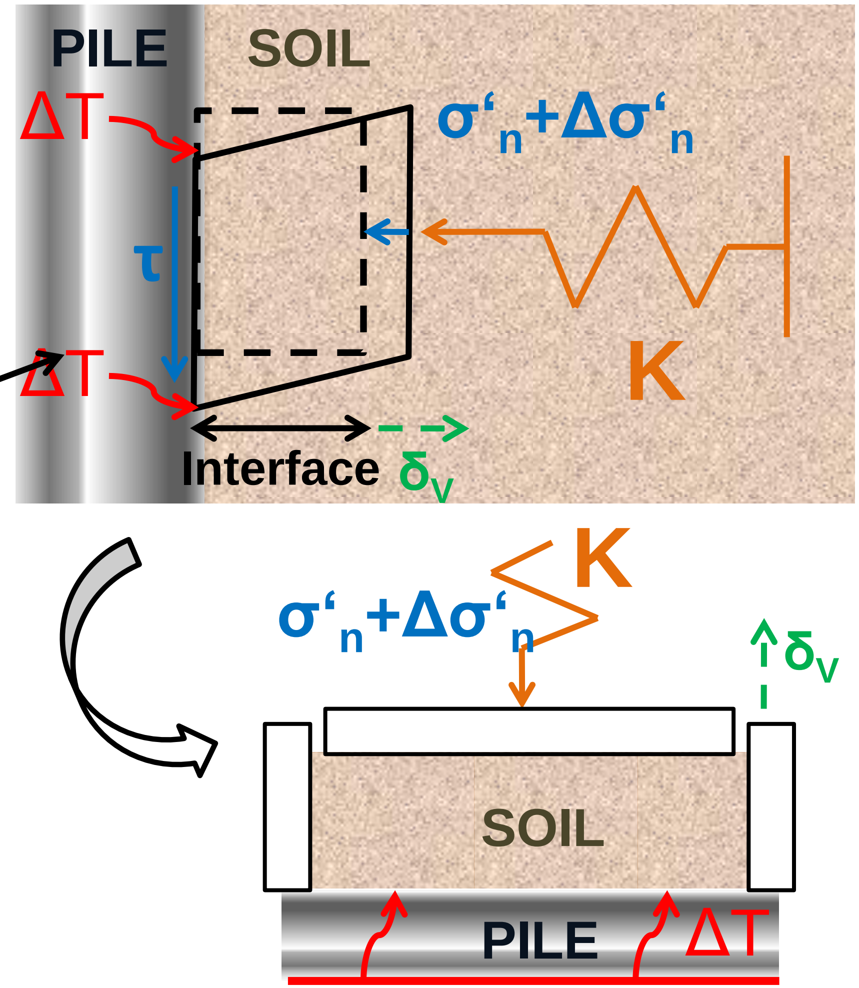
Thermo-mechanical behaviour of soil-concrete interfaces

Effect of temperature and soil consolidation

IN-SITU CONDITIONS



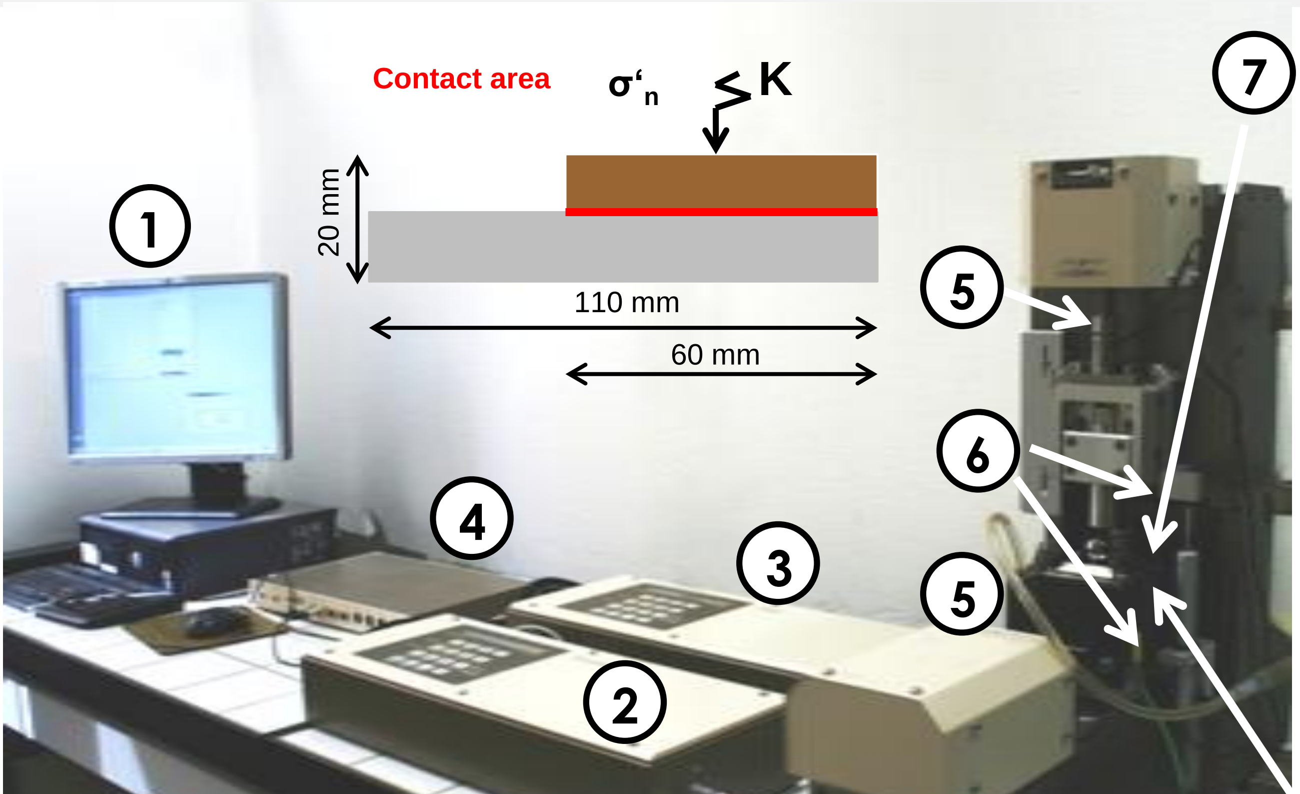
$$Q_S = A_s K \sigma_n^{'} \tan \varphi$$

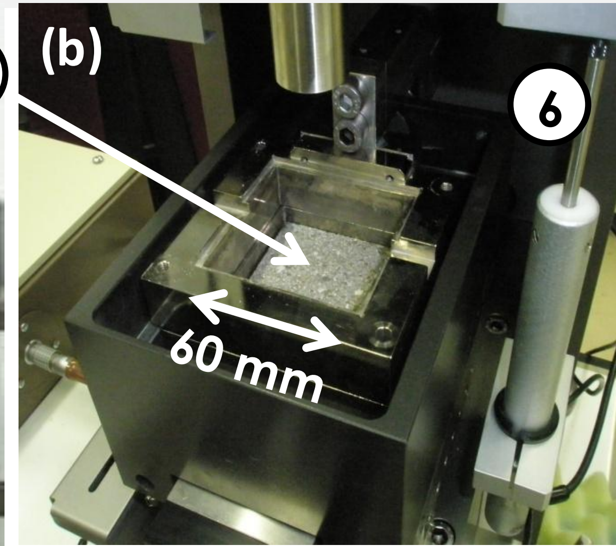


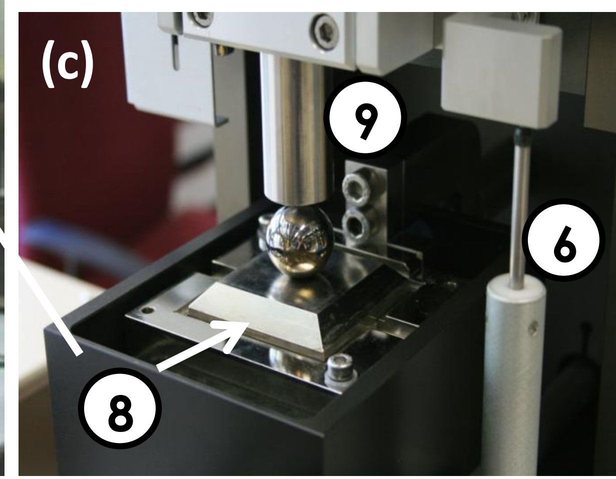
LABORATORY CONDITIONS

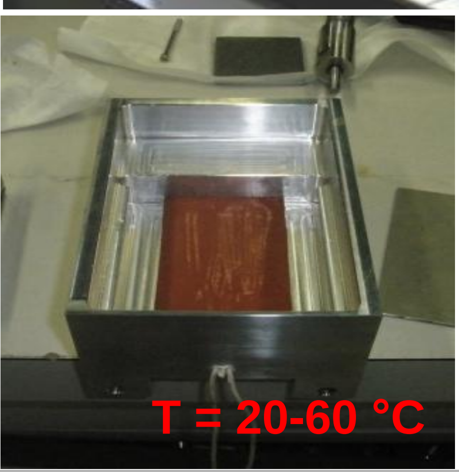
(Di Donna, 2015)

Experimental method: interface shear testing

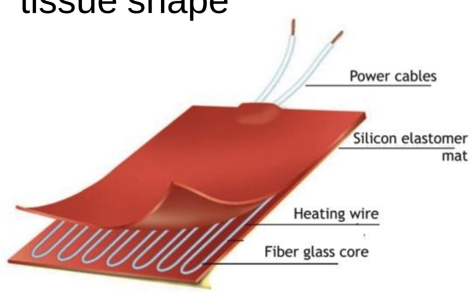








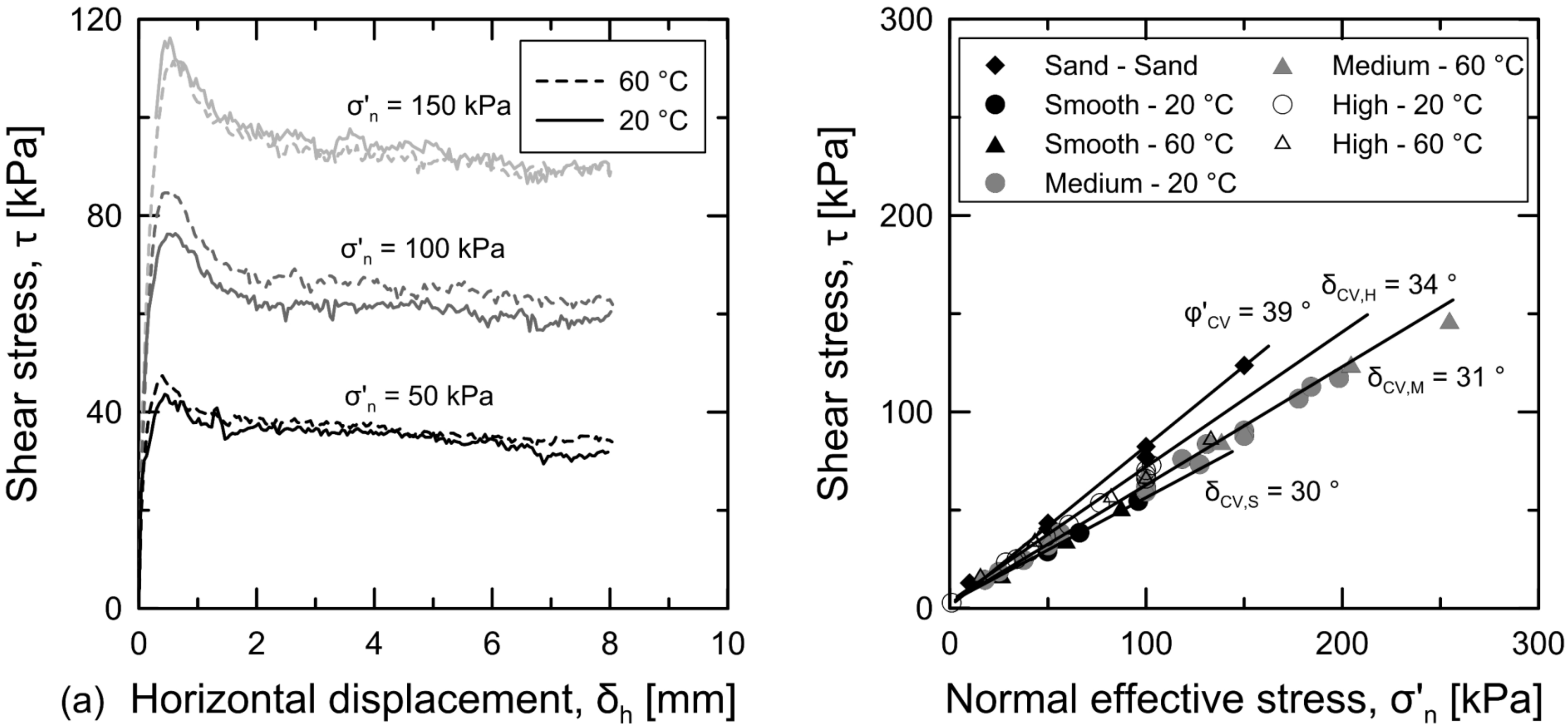
Heating system based on an **electrical resistance** in a tissue shape



Original version of the GDS direct shear device: (a) global view, (b) detail of the open shear box, (c) detail of the closed shear box (1:GDSLAB software control, 2: normal actuator, 3: horizontal actuator, 4: LVDTs acquisition pad, 5: Load cells, 6: LVDTs, 7: specimen placement, 8: top cap, 9: axial piston).

Sand-concrete interface behaviour

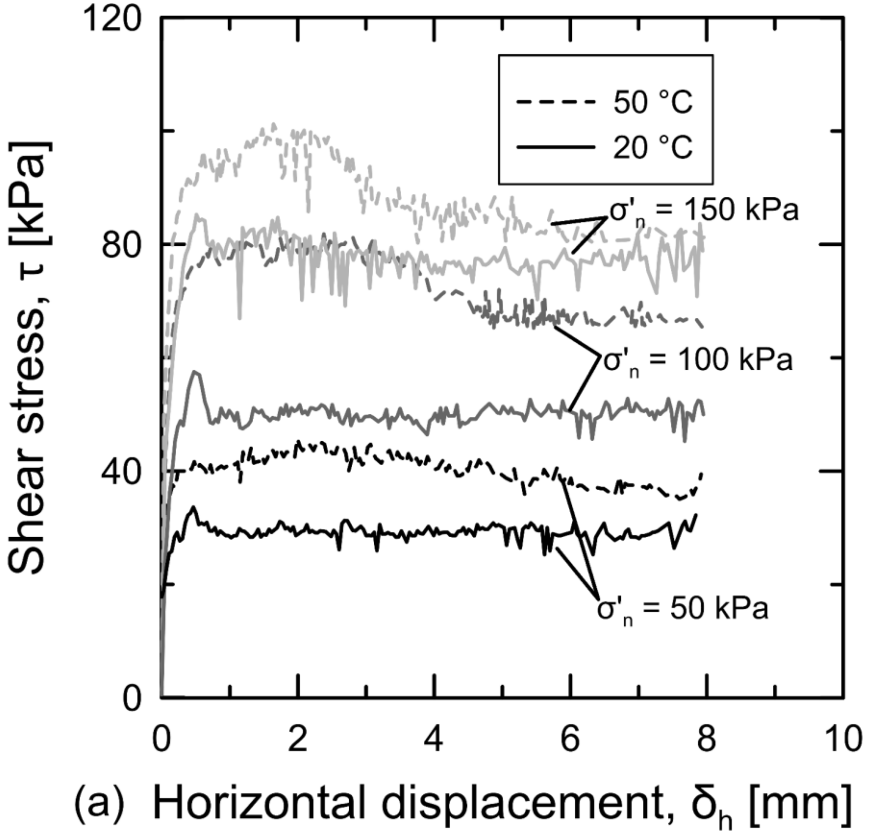
- No thermally induced effect characterises the sand-concrete interface shear response

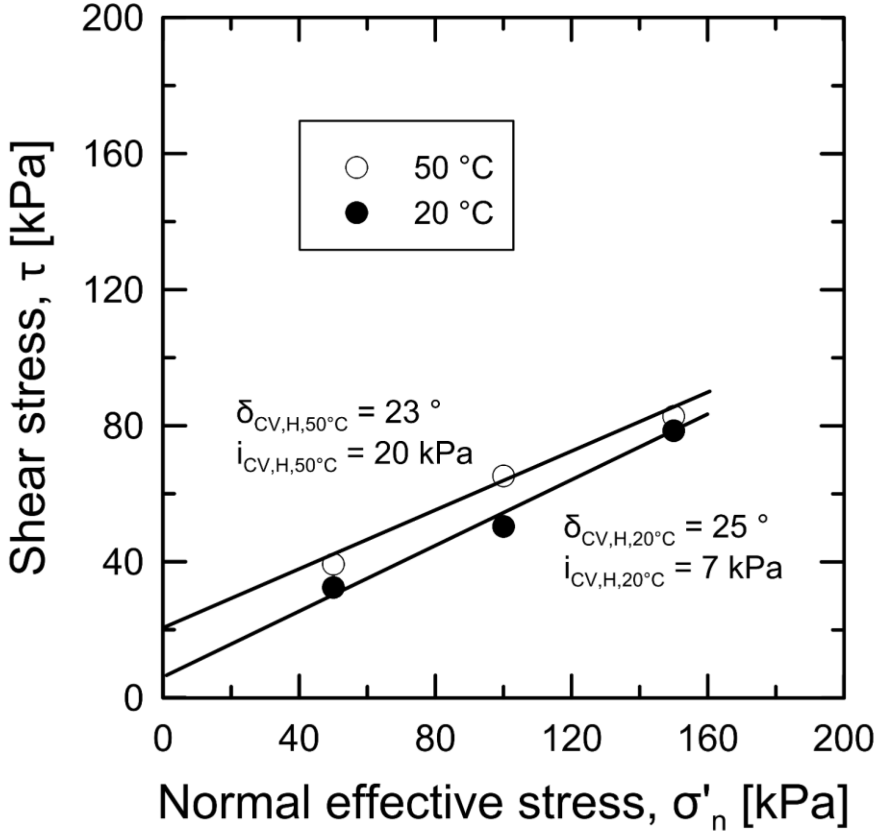


(redrawn after Di Donna et al., 2016)

Clay-concrete interface behaviour

- A thermally induced effect characterises the clay-concrete interface shear response

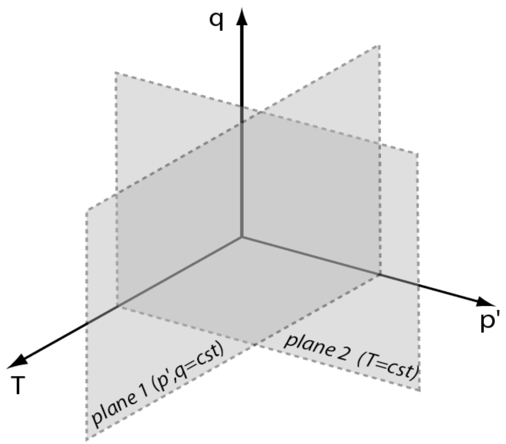




(redrawn after Di Donna et al., 2016)

Thermo-mechanical behaviour of soils

Loading types



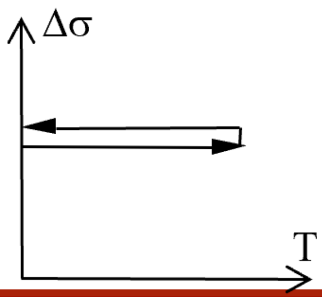
Plane 1:

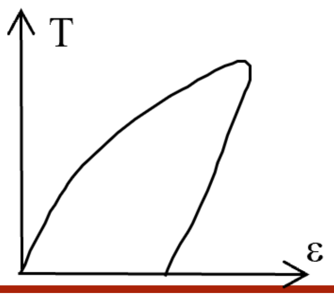
Thermal paths at constant mechanical stresses

Plane 2:

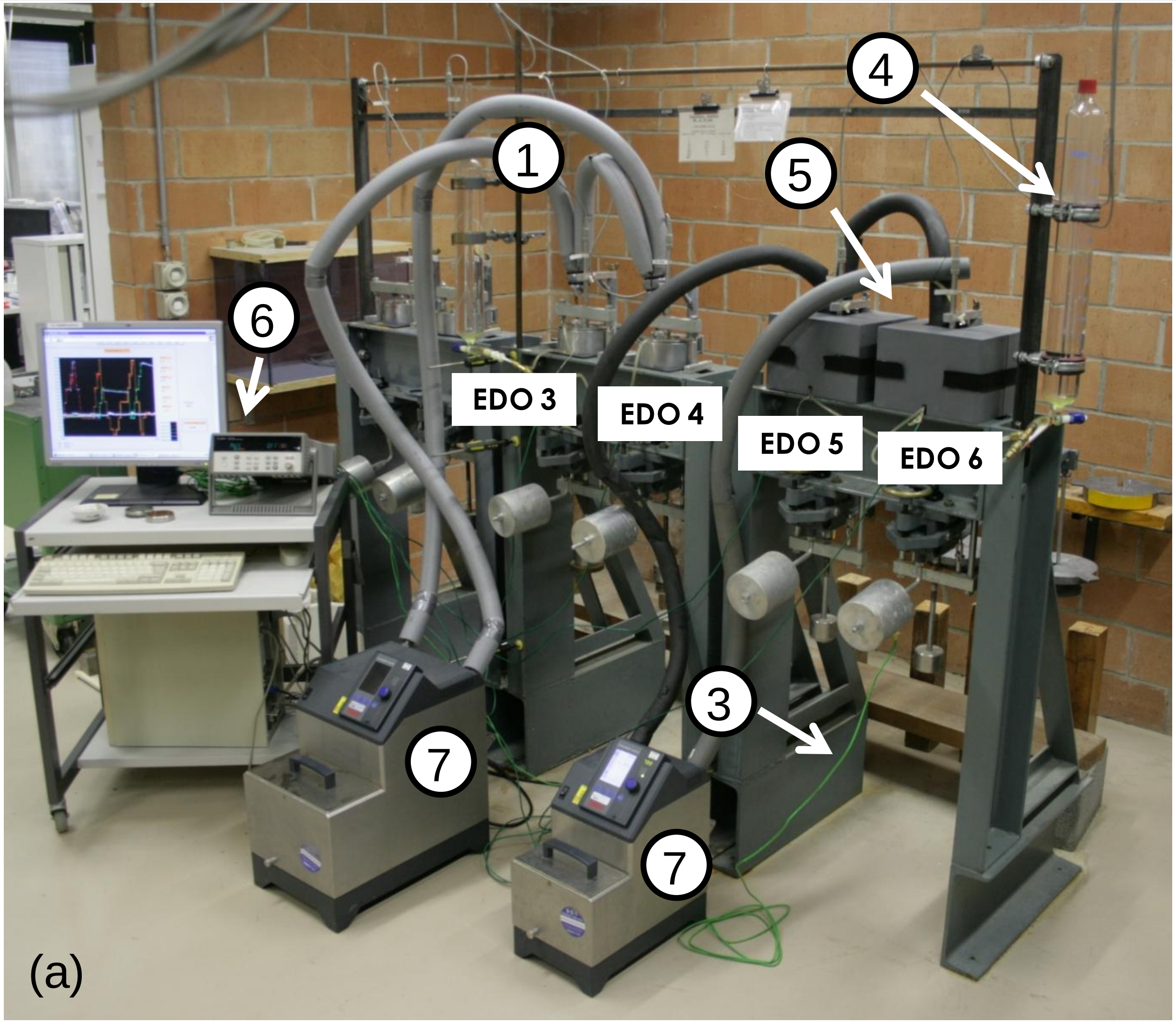
Mechanical paths at different constant temperatures

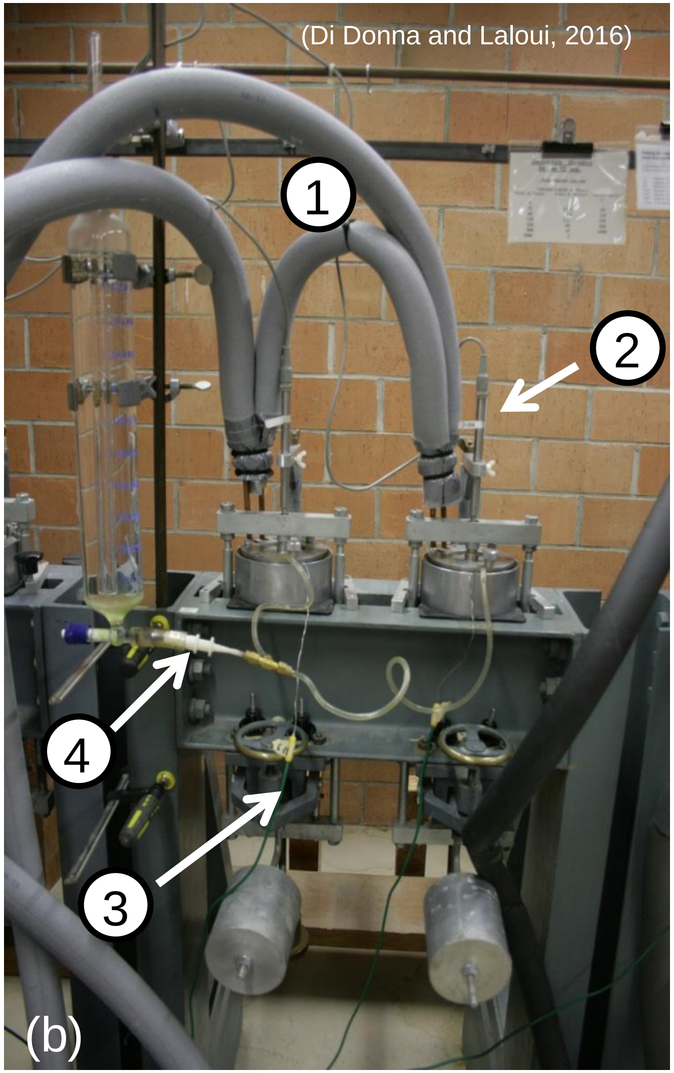
Thermal loading





Experimental method: thermal oedometric testing

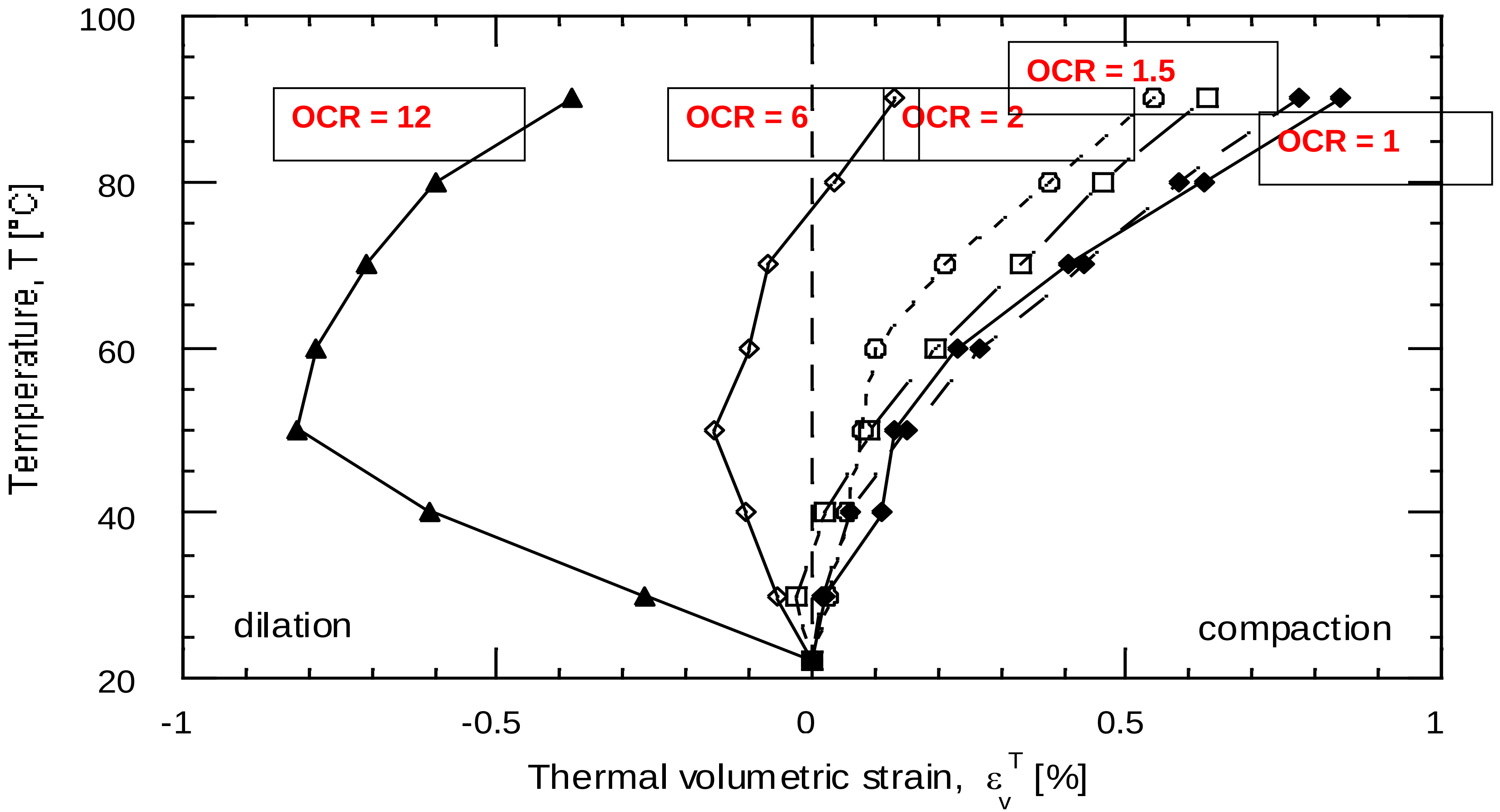




Experimental setup available at the LMS-EPFL: (a) global view of thermal oedometric apparatus and (b) detail (1: tubes with circulating water at the desired temperature, 2: LVDTs, 3: thermocouples, 4: water supplier, 5: insulation, 6: acquisition system, 7: heaters).

Influence of OCR on thermally induced strain

(Cekerevac and Laloui, 2004)



Temperature effect on Kaolin under constant isotropic compression

Temperature sensitivity of soil

- The response of soil to temperature changes can be more or less sensitive depending on the design situation

- Apects such as (i) overconsolidation ratio, (ii) intrinsic soil properties (e.g., mineralogy, plasticity index, etc.) and (iii) loading conditions play a major role for the soil response (e.g., drained or undrained loading)

- *Def.* Overconsolidation ratio definition, OCR:

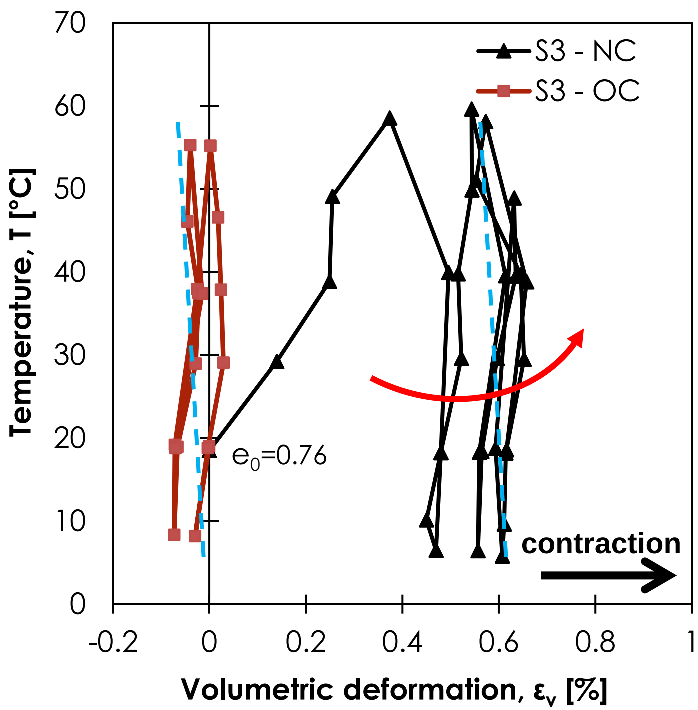
$$OCR = \frac{\sigma'_p}{\sigma'_v}$$

  - σ'_p = preconsolidation pressure
  - σ'_v = vertical effective stress

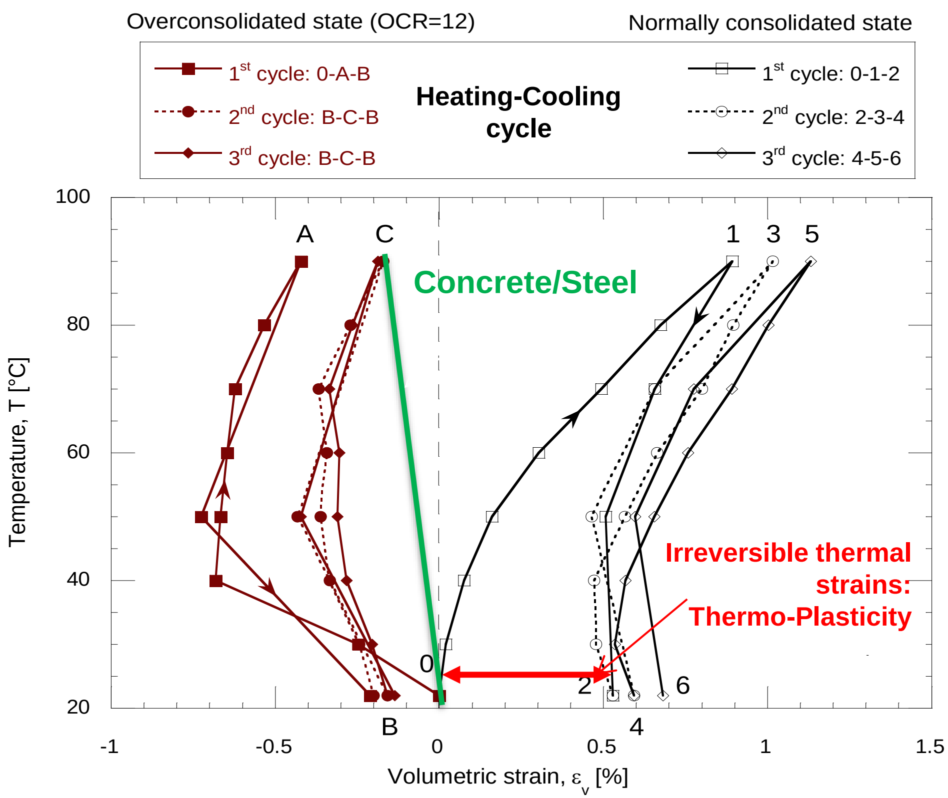
- *Rmk.*: Thermal loading is usually associated with drained conditions

Effect of temperature on volumetric behaviour of soils

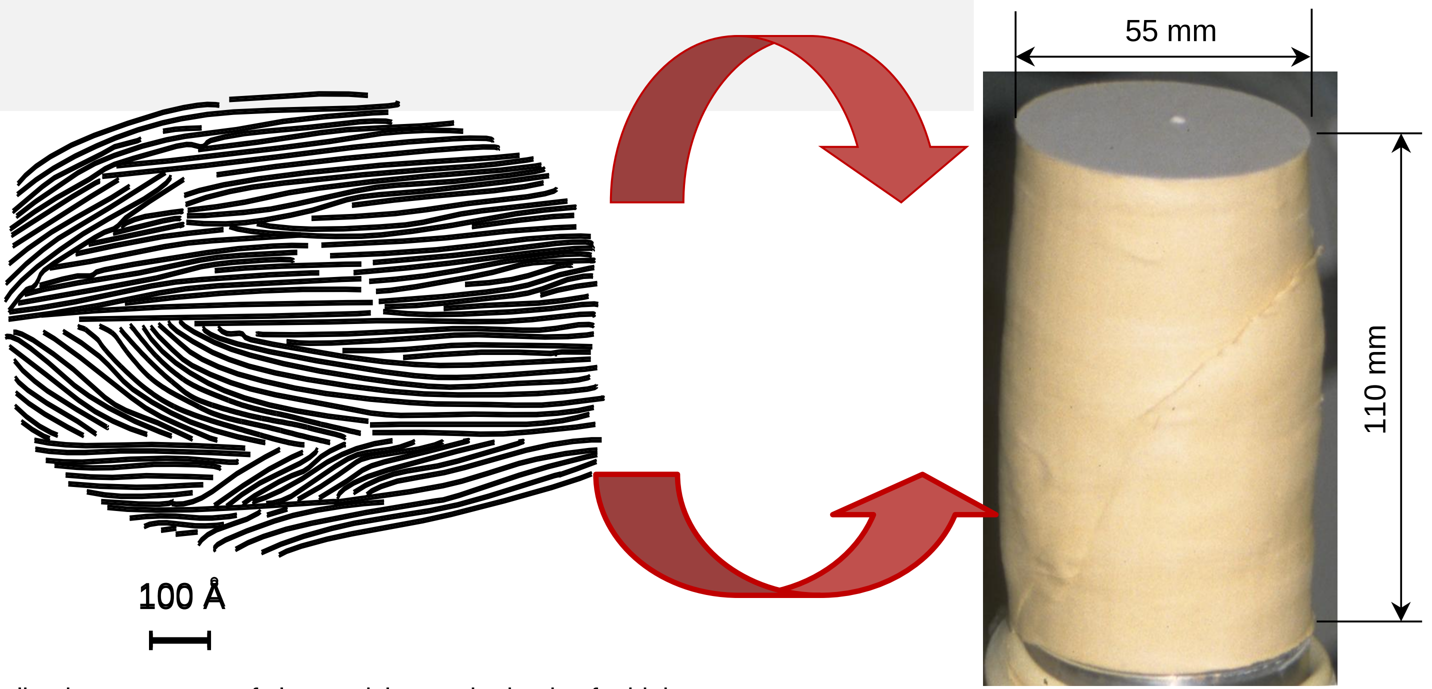
(Di Donna and Laloui, 2015)



(Laloui and Cekerevac, 2008)



- **OC clay** shows **thermo-elastic** response
- **NC clay** shows accumulation of irreversible deformation (**thermo-plastic** response)
- Phenomenon of thermal **accommodation**



Idealised arrangement of clay particles on the basis of a high-resolution transmission electron microscope computer image (after Veblen et al. 1990).

Sample of soil tested in a triaxial cell.

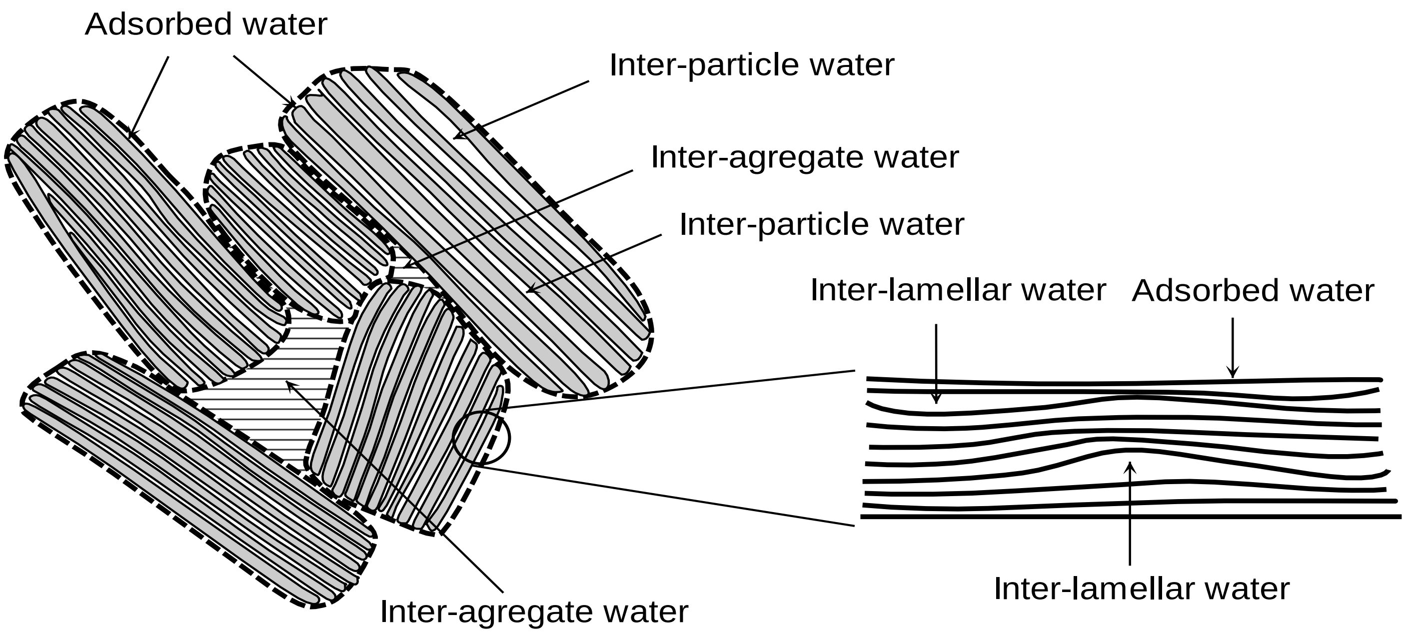
Micro-scale

Macro-scale (continuum)

The thermo-mechanical phenomena observed at the macro-scale are a consequence of the micro-structural changes

The understanding of micro-structural behaviour is required

Clay-water mineral systems



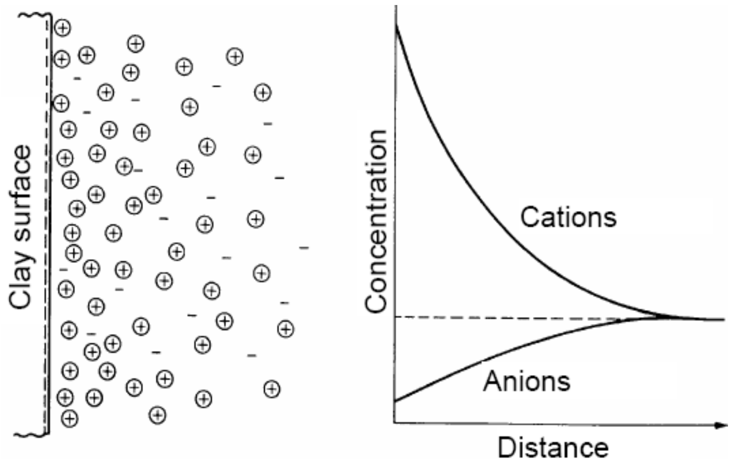
Schematic illustration of the two main types of water in saturated soils: i) free water, mainly in the inter-aggregate space and ii) adsorbed water located in the inter-particle and inter-lamellar spaces.

From soil constitutive point of view:

- Adsorbed water is considered as a part of the solid constituent
- Free water is taken into account only through the THM coupling

Diffuse double layer theory

Clay particle : Surface negative charge ↔ Water : Anions + Cations



Clay-water system (Mitchell, 1976)

Effect of the electrical potential on water

Closer to the particle is the water, higher is his attraction to the particle and lower is his mobility (adsorbed water)

Effect of the electrical potential on the particles interaction

Closer are the particles, greater is the repulsive forces acting between them (overlapping of the double layer)

Temperature effects - Dilation of clay minerals

- **Modification of the equilibrium between attractive and repulsive forces**
- **Failure of some interparticle ties**
- **Facilitation of particles rearrangement**

Unified soil classification system

Soils having more than 50% by weight passing the N°200 sieve (grain size of 0.06 mm)

Sand

Granular materials

Silt | Sand/clay mix | Clay

Low plasticity | High plasticity

Fine grained materials

Cohesive soils

Adsorbed water (solid/fluid interface) plays a major role

Micro-structural forces

- Surface electrical charges:

  •Proportional to the surface areas of the grains (diminish with the square of the particle diameter)

  Dominant for **cohesive soils**

- Self weight of the grains:

  •Proportional to the volumes of the grains (diminish with the cube of the particule diameter)

  Dominant in granular soils

Temperature influence is mainly on surface charges

Consolidation state and soil volumetric behaviour

- Soils in NC conditions contract upon heating and cooling irreversibly
- Soils in highly OC conditions dilate during heating and contract during cooling reversibly
- Soils in slightly OC conditions dilate for limited heating, contract for remarkable heating, and contract during cooling irreversibly

- Hence, for the temperature levels characterising energy geostructure applications, i.e., between 2 and 45 °C,

  1. Soils in NC conditions show a thermo-plastic behaviour upon a heating-cooling cycle
  2. Soils in highly OC conditions show a thermo-elastic behaviour upon a heating-cooling cycle
  3. Soils in slightly OC conditions show an intermediate behaviour between 1 and 2