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UNIVERSITÉ LIBRE DE BRUXELLES, UNIVERSITÉ D'EUROPE

Study of the thermal conductivity of fine-grained soils

Effect of density, water content and microstructure

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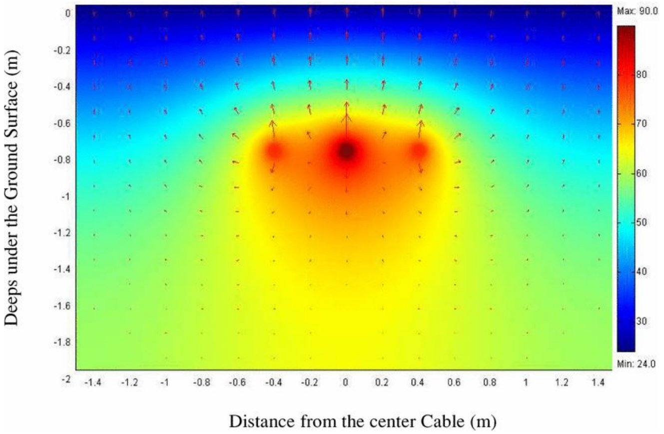
07/11/2013

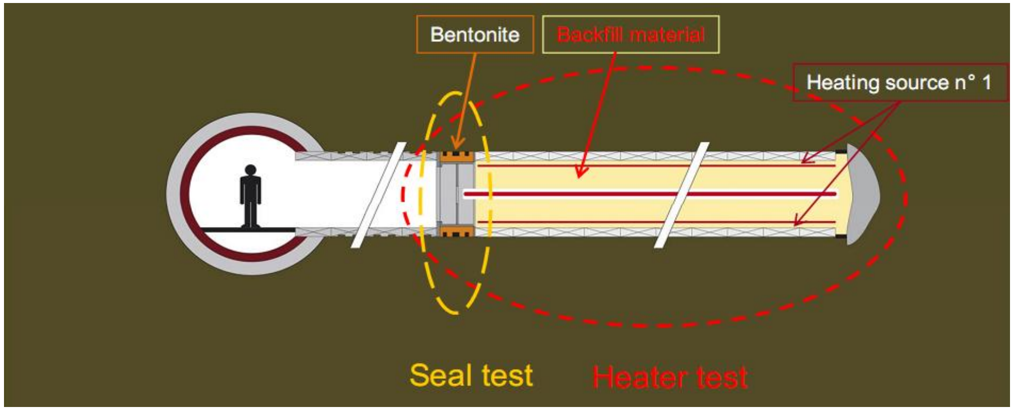
Introduction

The knowledge of the thermal conductivity of soils required in various applications:

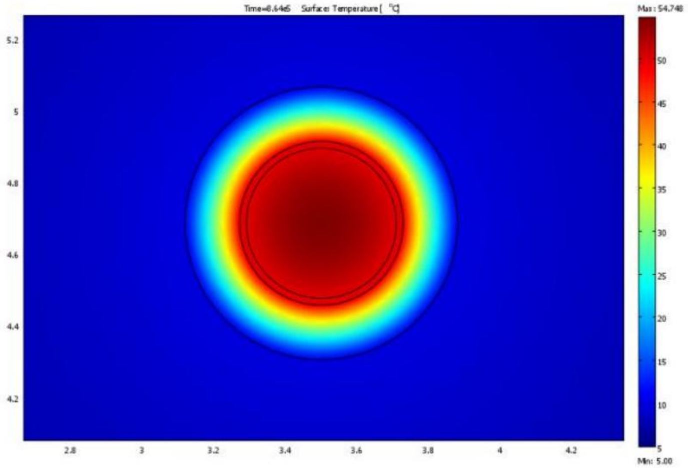
- Nuclear waste disposals
- Buried cables and pipelines
- Geothermal applications



(Source: IEEE, 2011)



(Source: EIG Euridice, 2011)



(Source: COMSOL, 2010)

Objectives

- Initial objective:
  - ➔ Measure thermal conductivity of a fine-grained soil and assess structural aspects in compacted state
- Discuss the applicability of the measurement method on soils in laboratory conditions
- Compare the obtained results with existing models for soil thermal conductivity prediction

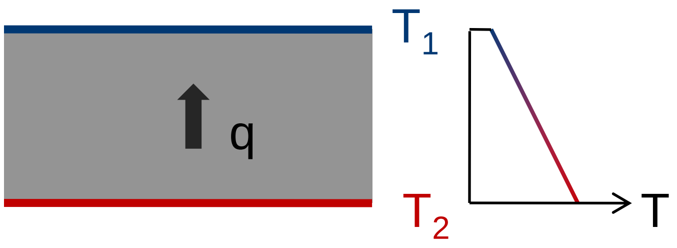
Plan

1. Theoretical aspects
    A. Thermal transfer in soil materials
    B. Thermal conductivity models for soils
2. Measuring soil thermal conductivity
    A. Thermal conductivity measurement methods
    B. Experimental set-up
    C. Calibration
    D. Studied soils & Scope of tests
3. Results and discussion
    A. Results
    B. Error analysis
4. Conclusion

Thermal transfer: Fourier’s Law

$$\vec{q} = -\lambda \vec{\nabla} T$$

Proportionality factor =
thermal conductivity [W/mK]



In conventional materials λ is <u>constant</u> for a given material at a given temperature

In soils λ may vary with a change of the soil state (amount of water, degree of compaction, structure,...)

Thermal transfer in soils

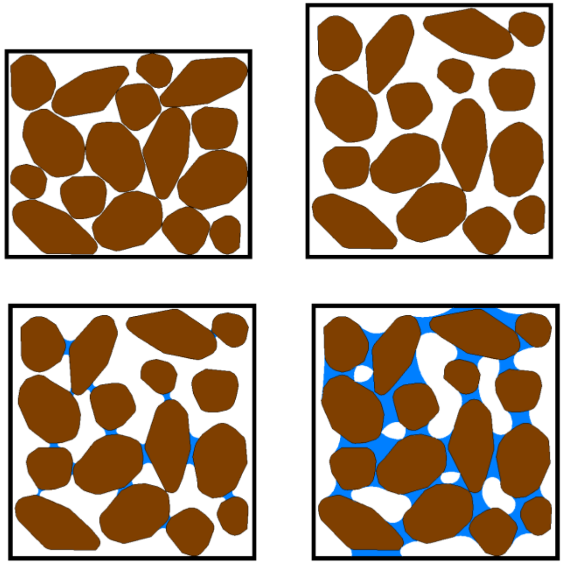
- Soil is a 3-phase material:
  - ➔ λ_{soil} depends on the conductivity of each phase and on their proportions

$$\lambda_{solid} \approx 10\ \lambda_{water} \approx 200\ \lambda_{air}$$

- 3 main factors have an influence on λ in soils:
  1. Proportion of voids and their spatial distribution (n or γ_d)
  2. Proportion of water that fills the voids (S$_r$ or w)
  3. Mineral composition of the solid phase

     mica → 2-3 W/mK

     quartz → 7-8 W/mK



Influence of the structure (1/2)

- Two extreme configurations: parallel/series model

- 2 observations

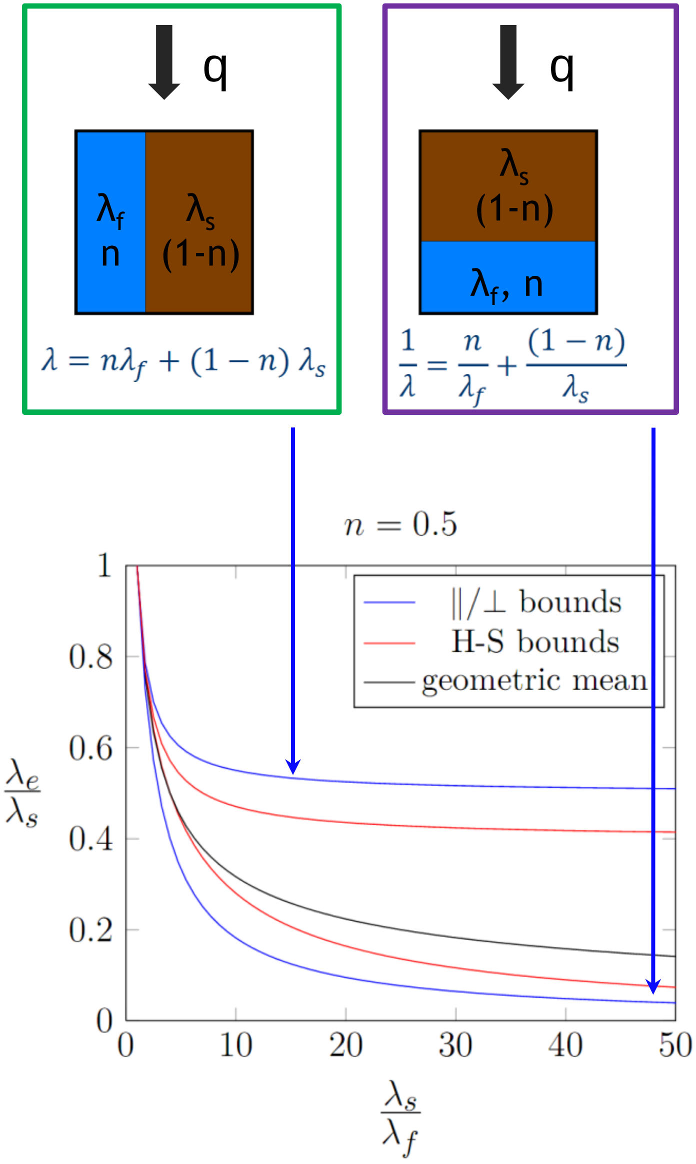
  $\lambda_s / \lambda_f \gtrsim 10$

  ➔ high sensitivity of λ to the microstructure

  $\lambda_s / \lambda_f \lesssim 10$

  ➔ low dependence on the spatial arrangement

  ➔ high sensitivity of λ to a variation in λ_s or λ_f



$$\lambda = n\lambda_f + (1-n)\,\lambda_s$$

$$\frac{1}{\lambda} = \frac{n}{\lambda_f} + \frac{(1-n)}{\lambda_s}$$

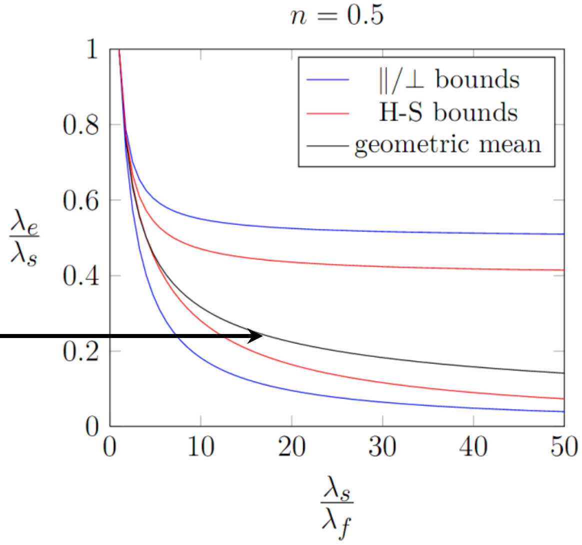
Influence of the structure (2/2)

In practice:

- In dry soils λ_s/λ_f is important (>100)
  - ➔ very high sensitivity to the particle spatial distribution
- In saturated soils λ_s/λ_f is moderate (<13)
  - ➔ The thermal conductivity can be approximated by the geometric mean equation:

$$\lambda = \lambda_s^{1-n}\ \lambda_f^{n}$$

always contained between the upper and lower bounds

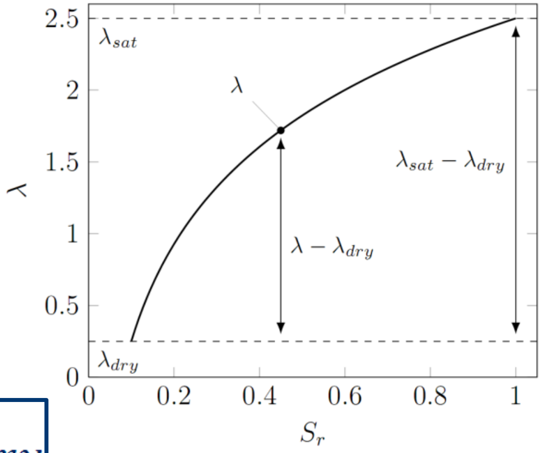


Models for soil thermal conductivity

2 well-known models for thermal conductivity prediction:

- Kersten's model $\lambda = A(a\log w + b)10^{B\gamma_d}$
- Johansen's model

➔ based on an interpolation at a given porosity between the conductivity in the dry state and in the saturated state:



Normalized thermal conductivity: $Ke = \dfrac{\lambda - \lambda_{dry}}{\lambda_{sat} - \lambda_{dry}}$

$$\boxed{\lambda = Ke\left(\lambda_{sat} - \lambda_{dry}\right) + \lambda_{dry}}$$

Empirical function of S_r
Does not depend on n
Depends on type of soil

$$Ke = a\log S_r + b$$

Geometric mean

$$\lambda_{sat} = \lambda_s^{1-n}\,\lambda_w^n$$

$$\lambda_s = \lambda_o^{1-q}\,\lambda_q^q$$

other minerals ← λ_o; λ_q → quartz

Empirical function of n
(linear, exponential,...)

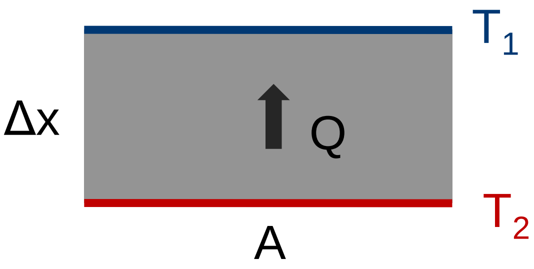
$$\lambda_{dry} = f(n)$$

➔ Require good knowledge of soil parameters: n, S_r, q

Thermal conductivity measurement

- Steady-state methods
  - Guarded hot plate
  - Heat-flow meter

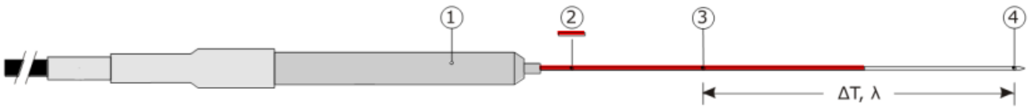
$$\left.\begin{array}{l}\text{Guarded hot plate}\\ \text{Heat-flow meter}\end{array}\right\} \Rightarrow \lambda = \frac{Q}{A}\frac{\Delta x}{\Delta T}$$



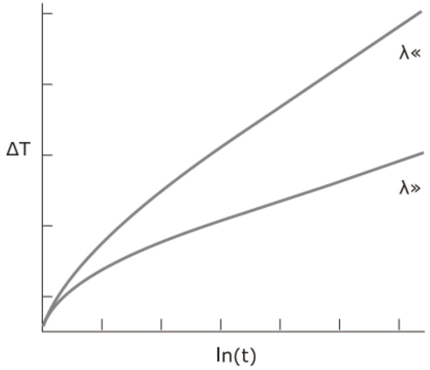
- Transient methods

➔ infinite line source theory

– Thermal needle probe



$$\boxed{\lambda = \frac{q}{4\pi}\frac{\Delta \ln t}{\Delta T}}$$



(Hukseflux, 2003)

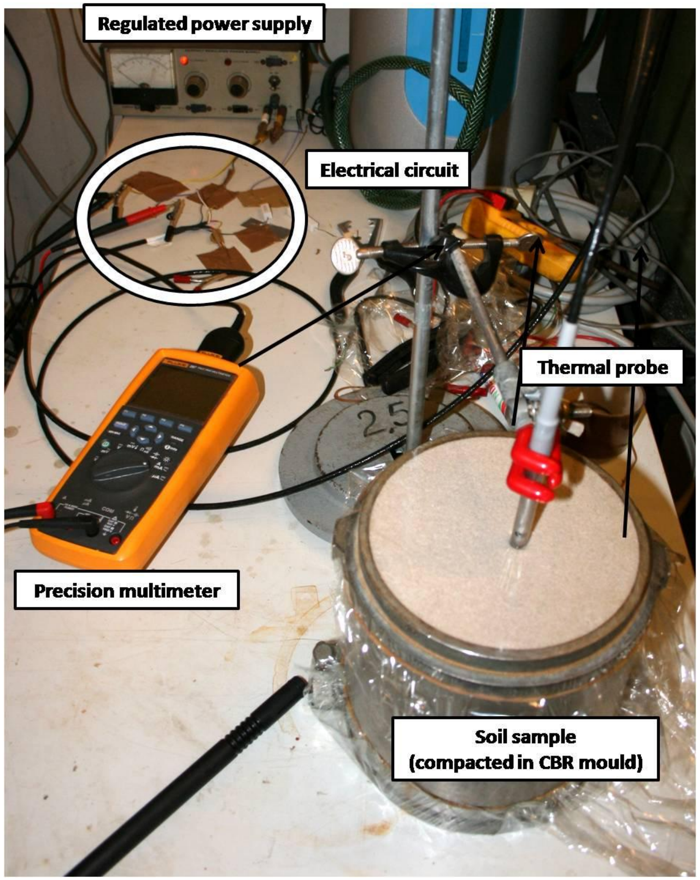
Experimental set-up

- Thermal probe
  - Length: 15 cm
  - heating wire resistance R_h [Ω/m]
  - thermocouple junction
  - Specified accuracy: ± (3% + 0,02) W/mK (homogeneous material and good contact)
- Constant current source

$$I \Rightarrow q = R_h I^2$$

- Precision multimetre to record output signal [mV]
- Shunt resistance R_c to measure input current accurately at the end of the test

$$I = V_c / R_c$$



Calibration (1/2)

- The probe was calibrated on agar gel reference material:

  $\lambda_{\text{tabulated}} = 0.61$ W/mK $\lambda_{\text{measured}} = 0.57 - 0.65$ W/mK

- Check influence of
  - Measurement time
    1. First non-linear transient part
    2. Then linear portion ➔ λ
    3. Border effects

    Transient time over after 25 seconds
  - Sample size

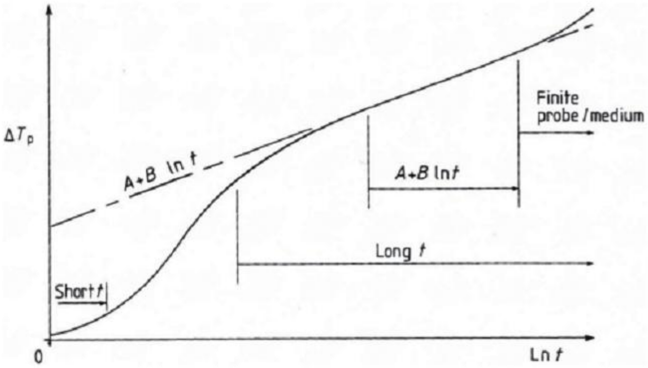
    Height: 20 cm, Diameter: 10 cm

    No border effects were observed for measurements as long as 10 minutes
  - Input power

    Should large enough to generate measurable temperature increases

    Limited to 6 W/m (0.3 A)

    Appropriate: 4 W/m K



(Jones, 1988)

Calibration (2/2)

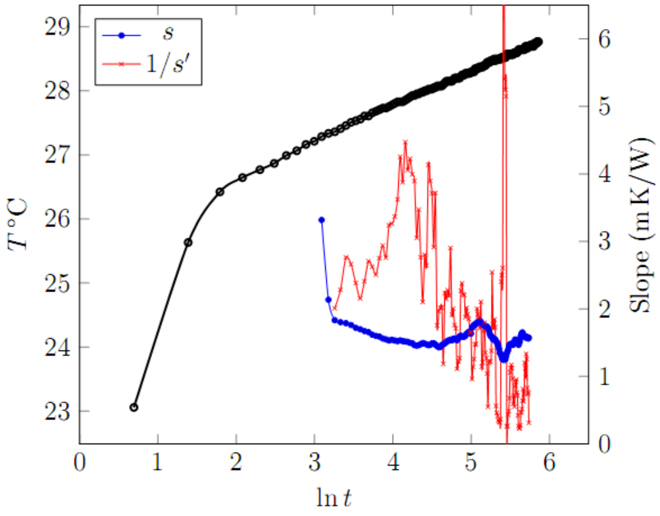
- Develop a systematic method to detect the linear part in the *ln(t) – T* graph

➔ Based on method used at ULg

1. Plot *ln(t) – T* graph
2. Compute first derivative s based on several measurement points by least square method
3. Compute second derivative *s'*

➔ The most linear part corresponds to the peak value in 1/s'

If several peaks, observe s to check coherence



Studied soils & Scope of tests

- <u>Fine-grained: MLD silt</u>

  Compacted (Proctor) at various stages to assess different effects:

  1 – 4: dry density/porosity

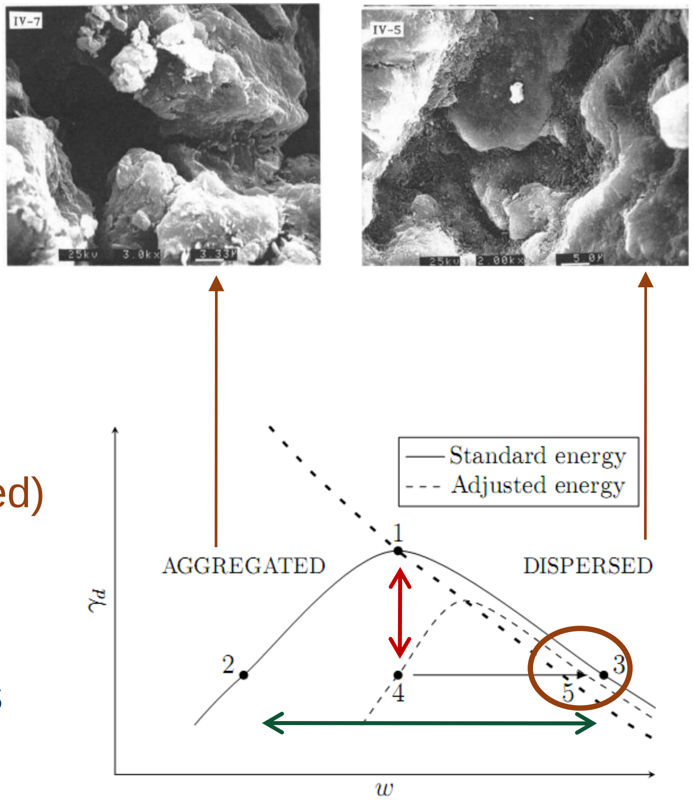
  2 – 4 – 5: water content/degree of saturation

  3 – 5: effect of structure (dispersed or aggregated)

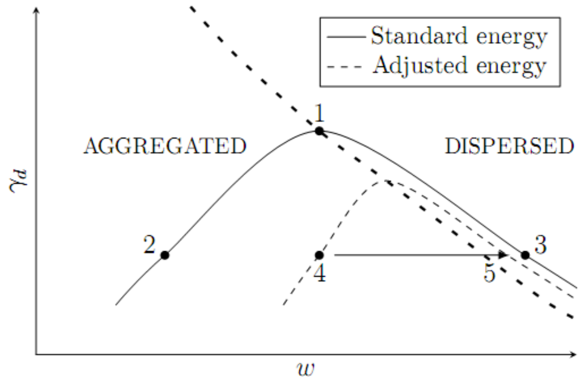
- <u>Coarse-grained: MOL fine sand</u>

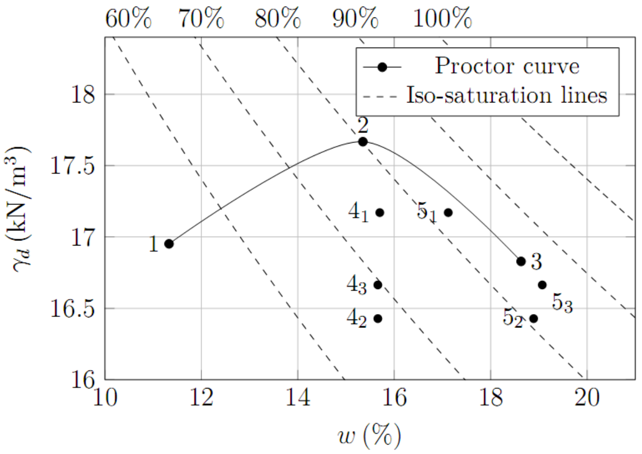
  Dense and loose at various water contents

(Delage, 1996)



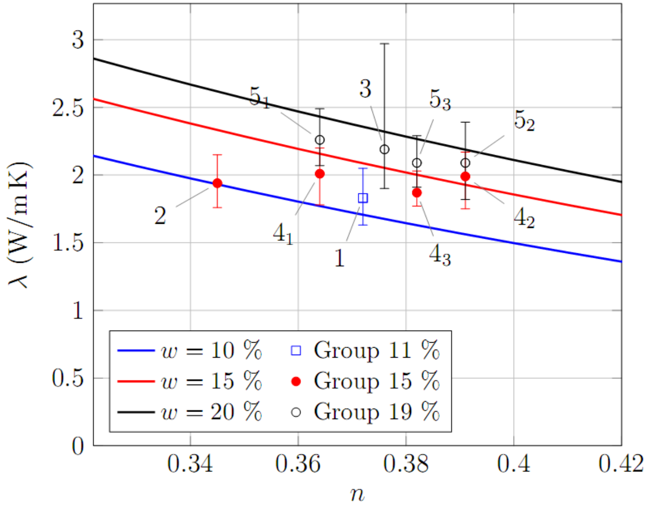
Results: silt (1/2)

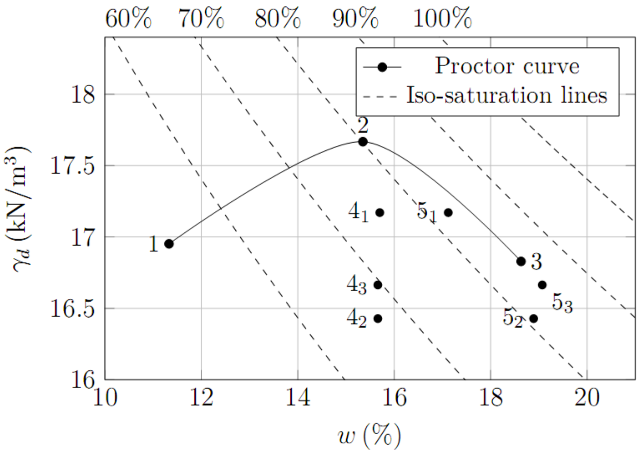




- Difficult to reach desired density
- Wetting of samples 4 → 5
  - ➔ Vertical moisture gradient due to low permeability
  - ➔ Solution: wet sample from top & bottom side
- Hard to insert probe in compacted silt, even with pre-hole

Results: silt (2/2)

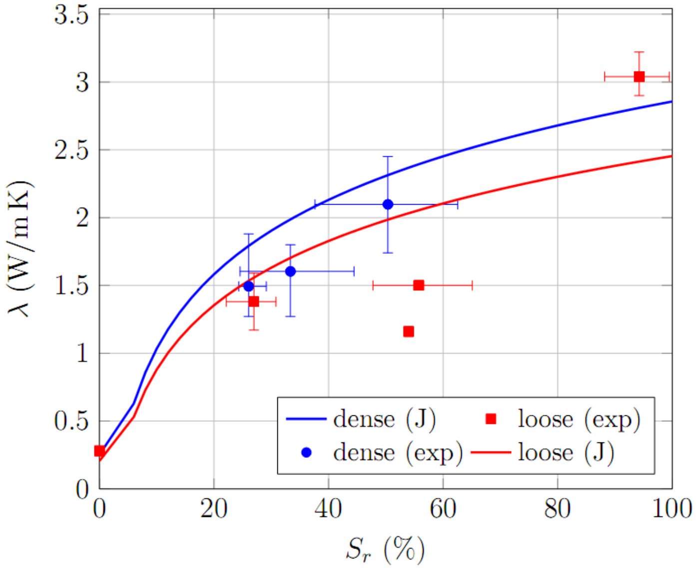




- Values fit with Johansen’s model: ± 10 % difference (except point 2)
- Results are globally coherent
  - ➔ Clear influence of w
- But large dispersion: ± 10 %
  - ➔ Higher dispersion than for the reference material

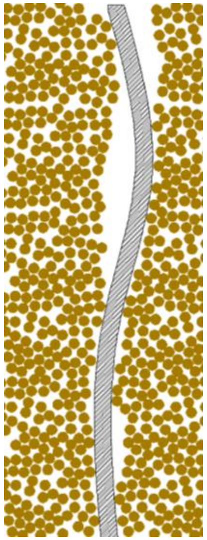
Results: sand

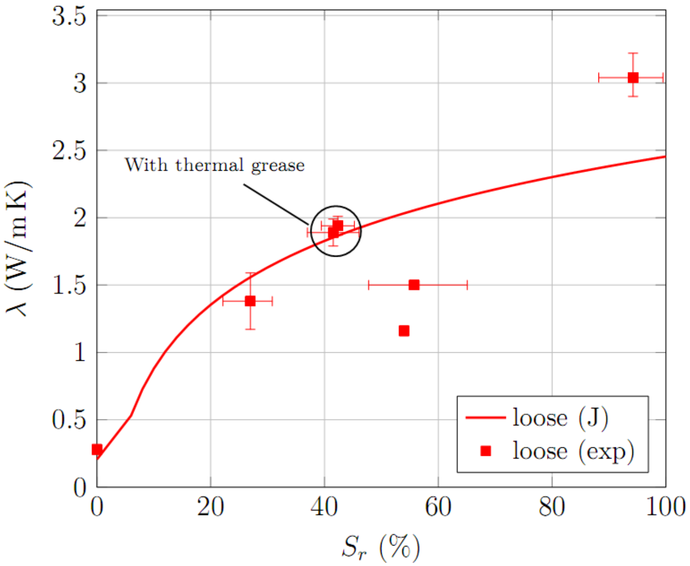
- Agreement with model
  - Good agreement for dry state
  - Over-prediction of saturated state
  - Incoherence of intermediate values and <u>under-prediction</u> with respect to the model
- Significant dispersion on the thermal conductivity: ± 15 %
- Significant vertical moisture gradient in both dense and loose state due to gravity



Error analysis (1/2)

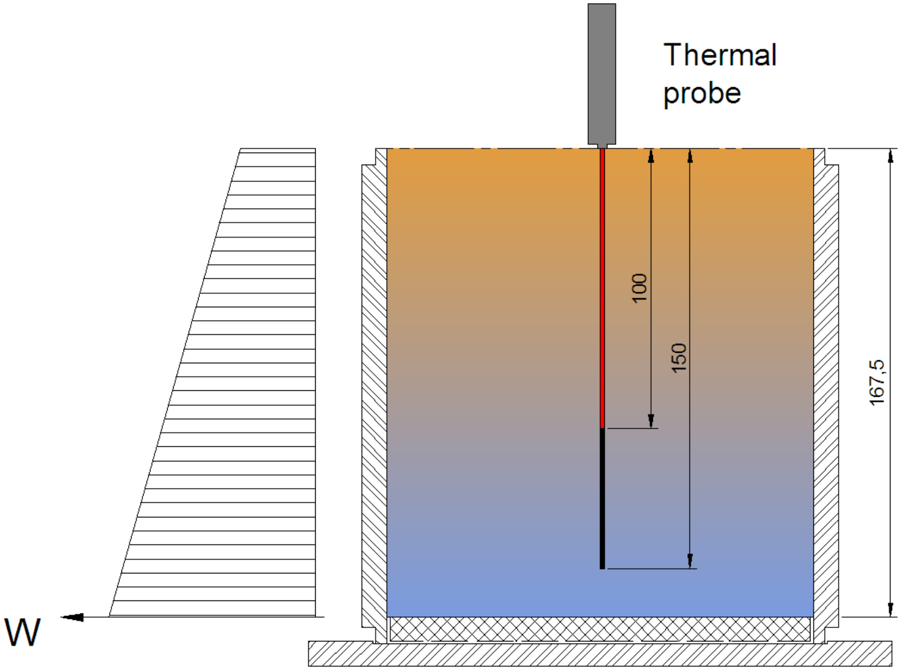
- Errors due to measurement method
  - Probe-to-sample contact resistance
    - ➔ May lead to an excessive transient time
    - ➔ Values improved by spreading high thermal conductivity grease on the needle
    - ➔ Under-prediction caused by bended needle and soil cohesion
  - Errors due to a variation of input current





Error analysis (2/2)

- Errors due to sample heterogeneities
  - ➔ Mainly caused by vertical moisture gradient
    - Uncertainty about the moisture content value associated to the measurement
    - Effect of vertical thermal conductivity gradient on measured values unclear



Improvements & Recommendations

- Apply thermal grease on probe in soils that present cohesion
- Sample dimensions as small as possible
- Determine moisture content at least at 3 levels in the sample
- Use constant current source
  - ➔ If possible monitor value during measurement to check stability (3 digits)

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Conclusion

- Better understanding of parameters that influence soil thermal conductivity
- In soils → decreased accuracy
- Large samples required

Thermal probe not ideal for precise laboratory study involving structural aspects

- Appropriate for in-situ and undisturbed soil sample measurements
- Models are useful and precise, provided good knowledge of soils characteristics (S_r, n, quartz content)