“Theoretical and experimental aspects of two phase flow and transport in unsaturated soils and aquifer systems”

Timetable is as follows:

- 27 June 14.00-19.00:

a) Monitoring of transport processes and estimation of hydro mechanical parameters by means of electrical resistivity tomography (Musso, Cosentini);
b) Transport of colloids and nanoparticles in saturated porous media for environmental remediation (Sethi, Tosco)

“Theoretical and experimental aspects of two phase flow and transport in unsaturated soils and aquifer systems”

Timetable is as follows:

- 29 June 8.30 A.M.: EXTENDED DARCY LECTURES 2012 - Prof. Majid Hassanizadeh (http://www.soilmech.polito.it/news/2012_darcy_lectures ; http://areeweb.polito.it/ricerca/groundwater/corsi/hassanizadeh.html)

a) Transport of viruses in partially saturated soils and groundwater (Hassanizadeh)

b) Capillarity in porous media, on micro and macroscale, revisited (Hassanizadeh)

Venerdì 29 giugno Ore 15.00 Aula Albenga – DISEG

Prof. Michele Maugeri
Università degli Studi di Catania

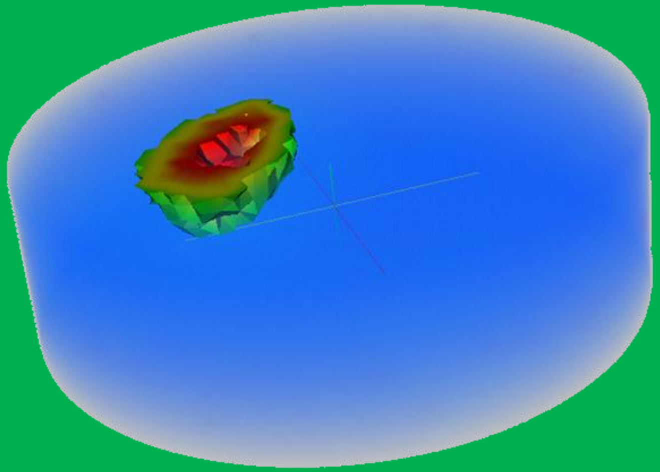
EFFECTS OF HEAVY RAINFALLS ON SLOPE BEHAVIOR: THE OCTOBER 1, 2009 DISASTER OF MESSINA

ANALISI E MITIGAZIONE DEL PERICOLO DI FRANE CAUSATE DA PIOGGE

La S.V. è cordialmente invitata

Politecnico di Torino – SCUDO Scuola di Dottorato – DISEG

"Monitoring transport processes and estimation of hydro mechanical parameters in soil samples by means of electrical resistivity tomography"



Guido Musso e Renato Cosentini

POLITECNICO DI TORINO

Dipartimento di Ingegneria Strutturale, Edile e Geotecnica

Sebastiano Foti — Politecnico di Torino

Cesare Comina — Università degli studi di Torino

Gabriele Della Vecchia — Politecnico di Milano

Claudia Festa — ex Politecnico di Torino

Enrique Romero Morales — UPC (Barcelona, Spain)

Outline

- Electrical conductivity of soils
- Applications
- EIT-oedometer: 3D tomography in the lab
- Validation
- ERT as a tool for monitoring transient phenomena in soil samples
  - Mechanical Consolidation
  - Chemical Diffusion
  - Saturation/Desaturation
- Use of the results for evaluation of soil model parameters for transport phenomena:
  - Diffusion
  - Saturation

Review of some general aspects of mass, electrical charge and heat transport in soils

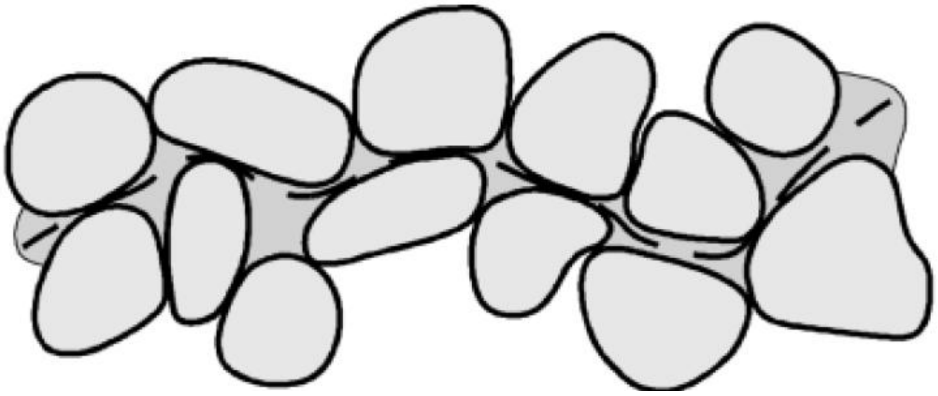
Soils are **multiphase materials** which are the seat of multi-physical problems, whose onset is conditioned by **microstructure**

Even in traditional soil mechanics

microstructural information is claimed to conceptually understand and reproduce the mechnical behavior of the soil

$$\sigma' = \sigma - u_w$$

(e.g. explanation of effective stress by Lambe & Whitman, 1979)



σ'	effective stress
σ	total stress
u_w	water pressure

Review of some general aspects of mass, electrical charge and heat transport in soils

Soils are **multiphase materials** which are the seat of **multi-physical problems**, whose onset is conditioned by microstructure

Even in traditional soil mechanics several problems are of coupled (multi physics) nature:

For instance, 3D consolidation equation (Biot, 1943)

COUPLING BETWEEN MECHANICAL AND HYDRAULIC PHENOMENA

$$\frac{\kappa}{\gamma_w m}\nabla^2 u_w = \frac{\kappa}{\gamma_w m}\left(\frac{\partial^2 u_w}{\partial x^2}+\frac{\partial^2 u_w}{\partial y^2}+\frac{\partial^2 u_w}{\partial z^2}\right)$$

$$= \frac{\partial u_w}{\partial t} - \frac{1}{3}\frac{\partial p_t}{\partial t}$$

Review of some general aspects of mass, electrical charge and heat transport in soils

COUPLING BETWEEN MECHANICAL AND HYDRAULIC PHENOMENA

$$\frac{\kappa}{\gamma_w m}\nabla^2 u_w = \frac{\kappa}{\gamma_w m}\left(\frac{\partial^2 u_w}{\partial x^2}+\frac{\partial^2 u_w}{\partial y^2}+\frac{\partial^2 u_w}{\partial z^2}\right)$$

$$= \frac{\partial u_w}{\partial t} - \frac{1}{3}\frac{\partial p_t}{\partial t}$$

κ	*- hydraulic permeability*
γ_w	*- unit weight of water*
1/3 p_t	*- mean total stress*
$m = 1/K$	*inverse of the bulk modulus*

Review of some general aspects of mass, electrical charge and heat transport in soils

COUPLING BETWEEN MECHANICAL AND HYDRAULIC PHENOMENA

Ingredients of the 3D consolidation equation:

3 balance equations + 2 constitutive laws

$$\frac{\partial \rho_s (1-n)}{\partial t} + \nabla \cdot \left[(1-n) \rho_s \cdot \dot{\mathbf{u}} \right] = 0$$

Mass balance of the solid phase

$$\frac{\partial \rho_w n}{\partial t} + \nabla \cdot \mathbf{j_w} = 0$$

Mass balance of the water phase

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = 0$$

Momentum balance of the mixture *(equilibrium)*

ρ_s density of the solid phase

ρ_w density of the water phase

n porosity

$\mathbf{j_w}$ water total flux

$\mathbf{u}$ displacement field

$\mathbf{b}$ body force

Review of some general aspects of mass, electrical charge and heat transport in soils

COUPLING BETWEEN MECHANICAL AND HYDRAULIC PHENOMENA

3 balance equations **+ 2 constitutive laws**

Darcy's law

$$\mathbf{q_w} = -\kappa\nabla\left(\frac{u_w}{\gamma_w} + z\right)$$

Isotropic linear elasticity

$$d\varepsilon_v = m dp' = \frac{dp'}{K}$$

$\mathbf{q_w}$ Water flow

ε_v Volumetric strain

Review of some general aspects of mass, electrical charge and heat transport in soils

Soils are the seat of a number of transport and mechanical phenomena:

Fluxes

TRANSPORT OF HEAT

MASS TRANSPORT: fluid phases (water, air, hydrocarbons);

MASS TRANSPORT: species in solution;

TRANSPORT OF ELECTRICAL CHARGE

Each **flux requires** its own **constitutive law**

Each **extensive property** requires its own **balance equation**

As in the consolidation problem, changes can occur simultaneuosly:

COUPLED PROBLEMS

Review of some general aspects of mass, electrical charge and heat transport in soils

Intensive property

physical quantity whose value does not depend on the amount of the substance for which it is measured. For example:

- **Temperature**
- **Pressure**
- **Concentration**
- **Electrical potential**

Extensive property

physical quantity whose value does depend on the amount of the substance for which it is measured. For example:

- **Heat**
- **Mass (phase)**
- **Mass (species)**
- **Electrical charge**

It is quite intuitive to relate the flux of the extensive property to the gradient of the related intensive property (same color)

Review of some general aspects of mass, electrical charge and heat transport in soils

Heat	$\mathbf{q}_t = -\boldsymbol{\kappa}_\mathbf{t} \nabla T$	Fourier's law
Mass (phase)	$\mathbf{q}_\mathbf{w} = -\boldsymbol{\kappa} \nabla \left(\dfrac{u_w}{\gamma_w} + z \right)$	**Darcy's law**
Mass (chemical)	$\mathbf{j}_\mathbf{D} = -\mathbf{D} \nabla c$	**Fick's law**
Electrical flow	$\mathbf{i} = -\boldsymbol{\chi} \nabla \phi$	**Ohm's law**

κ_T**:** thermal conductivity; **D:** effective diffusion; χ**:** electric conductivity

T**:** temperature; c**:** concentration; ϕ**:** electric potential

Review of some general aspects of mass, electrical charge and heat transport in soils

$$\begin{bmatrix} \mathbf{q_w} \\ \mathbf{i} \\ \mathbf{j_c} \\ \mathbf{j_a} \end{bmatrix} = -\begin{bmatrix} L_{ww} & L_{we} & L_{wc} & L_{wa} \\ L_{ew} & L_{ee} & L_{ec} & L_{ea} \\ L_{cw} & L_{ce} & L_{cc} & L_{ca} \\ L_{aw} & L_{ae} & L_{ac} & L_{aa} \end{bmatrix} \begin{bmatrix} \nabla h \\ \nabla \phi \\ \nabla c_c \\ \nabla c_a \end{bmatrix}$$

j_c diffusion flow rate of cation species (e.g. H^+, Na^+, Ca^{2+}, …)

j_a diffusion flow rate of anion species (e.g. OH^-, Cl^-, SO_4^{2-}, …)

Review of some general aspects of mass, electrical charge and heat transport in soils

$$\begin{bmatrix} \mathbf{q_w} \\ \mathbf{i} \\ \mathbf{j_c} \\ \mathbf{j_a} \end{bmatrix} = - \begin{bmatrix} L_{ww} & L_{we} & L_{wc} & L_{wa} \\ L_{ew} & L_{ee} & L_{ec} & L_{ea} \\ L_{cw} & L_{ce} & L_{cc} & L_{ca} \\ L_{aw} & L_{ae} & L_{ac} & L_{aa} \end{bmatrix} \begin{bmatrix} \nabla h \\ \nabla \phi \\ \nabla c_c \\ \nabla c_a \end{bmatrix}$$

Direct fluxes

Coupled fluxes

Review of some general aspects of mass, electrical charge and heat transport in soils

$$\begin{bmatrix} \mathbf{q_w} \\ \mathbf{i} \\ \mathbf{j_c} \\ \mathbf{j_a} \end{bmatrix} = -\begin{bmatrix} L_{ww} & L_{we} & L_{wc} & L_{wa} \\ L_{ew} & L_{ee} & L_{ec} & L_{ea} \\ L_{cw} & L_{ce} & L_{cc} & L_{ca} \\ L_{aw} & L_{ae} & L_{ac} & L_{aa} \end{bmatrix} \begin{bmatrix} \nabla h \\ \nabla \phi \\ \nabla c_c \\ \nabla c_a \end{bmatrix}$$

Taking water flow as an example:

$\mathbf{q_w}$ = **Darcian flow** + **Electroosmosis** + **Osmosis**

Review of some general aspects of mass, electrical charge and heat transport in soils

$$
\begin{matrix} \mathbf{q_w} \\ \mathbf{i} \\ \mathbf{j_c} \\ \mathbf{j_a} \end{matrix} = - \begin{bmatrix} L_{ww} & L_{we} & L_{wc} & L_{wa} \\ L_{ew} & L_{ee} & L_{ec} & L_{ea} \\ L_{cw} & L_{ce} & L_{cc} & L_{ca} \\ L_{aw} & L_{ae} & L_{ac} & L_{aa} \end{bmatrix} \begin{bmatrix} \nabla h \\ \nabla \phi \\ \nabla c_c \\ \nabla c_a \end{bmatrix}
$$

Through Thermodynamics of Irreversible processes, it can be proved that the matrix of transport coefficient is symmetric:

$$L_{ij} = L_{ji}$$

(Onsager Reciprocity Theorem)

Review of some general aspects of mass, electrical charge and heat transport in soils

$$L_{ij} = L_{ji}$$

(Onsager Reciprocity Theorem)

e.g.: when no chemical gradients are acting

$$\begin{matrix} \mathbf{q_w} \\ \mathbf{i} \end{matrix} = -\begin{bmatrix} L_{ww} & L_{we} \\ L_{ew} & L_{ee} \end{bmatrix} \cdot \begin{bmatrix} \nabla h \\ \nabla \phi \end{bmatrix}$$

$$\boldsymbol{L_{ew} = L_{we}}$$

flow of water under unit electrical field

flow of electrical charges under unit hydraulic field

Review of some general aspects of mass, electrical charge and heat transport in soils

Some conclusions (partial, 1/2):

1) Soil behaviour is ruled by a number of phenomena, not simply mechanical;

2) Each additional extensive property introduced (e.g. heat, mass of chemical, mass of air, electrical charge) requires:

-a further intensive property (temperature, concentration, air pressure, electric potential);

- a further constitutive law (e.g. Fourier’s law, Fick’s law, Ohm’s law);

- a further balance equation

Review of some general aspects of mass, electrical charge and heat transport in soils

Some conclusions (partial 2/2):

3) Beside **direct fluxes** (which are “intuitive”), **coupled fluxes** also occur;

4) Conduction coefficients can be related to **microstructural characteristics**;

5) Simmetry also suggests that one phenomenon can be used for indirect investigation of other processes;

What kind of information can we obtain from electrical measurements? How can we interpret them?

Some simple underlying physics when no other thermodynamic gradients are acting:

Ohm's law $\boldsymbol{i} = - \chi \nabla \phi$

$\boldsymbol{i}$: current density χ: soil electrical conductivity ϕ: electric potential

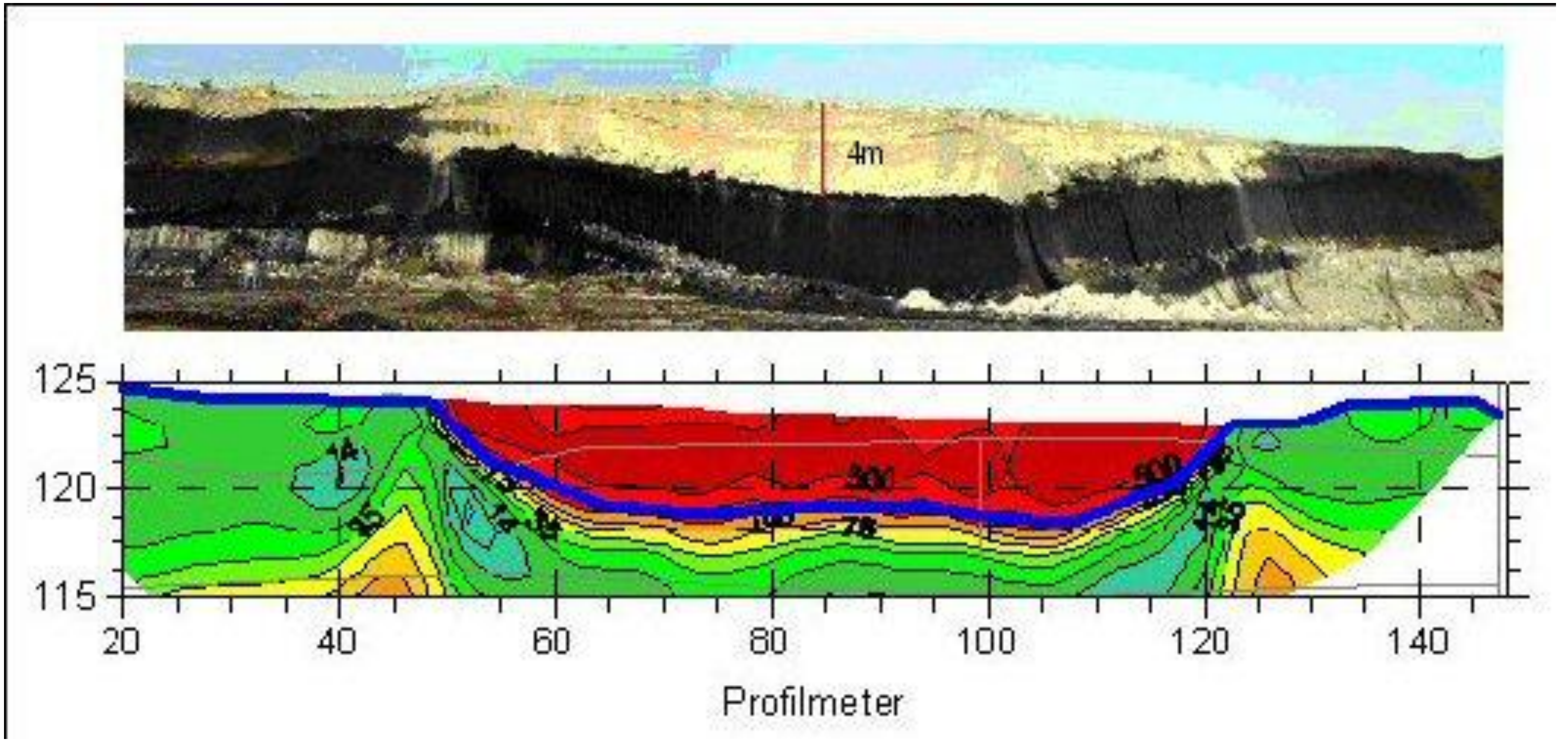
Electrical conductivity of soils

Trasport parameter related to:

- fluid properties (concentration of ionic species and diffusion coefficients);
- porosity;
- fabric;
- mineralogy and specific surface of the soil;
- degree of saturation

Traditional and most extensive use of electrical characterization:

In situ **geophysical characterization** several different techniques (from electrical logging to electrical arrays to tomography…) to identify soil stratigraphy and horizons (both geologic or hydraulic)



GGL : Geophysics und Geotechnik Leipzig Gmbh **Case study 2: Investigation of coal diapirs and gravel banks**

http://www.ggl-gmbh.de/index_eng.01.html

First type of in situ application

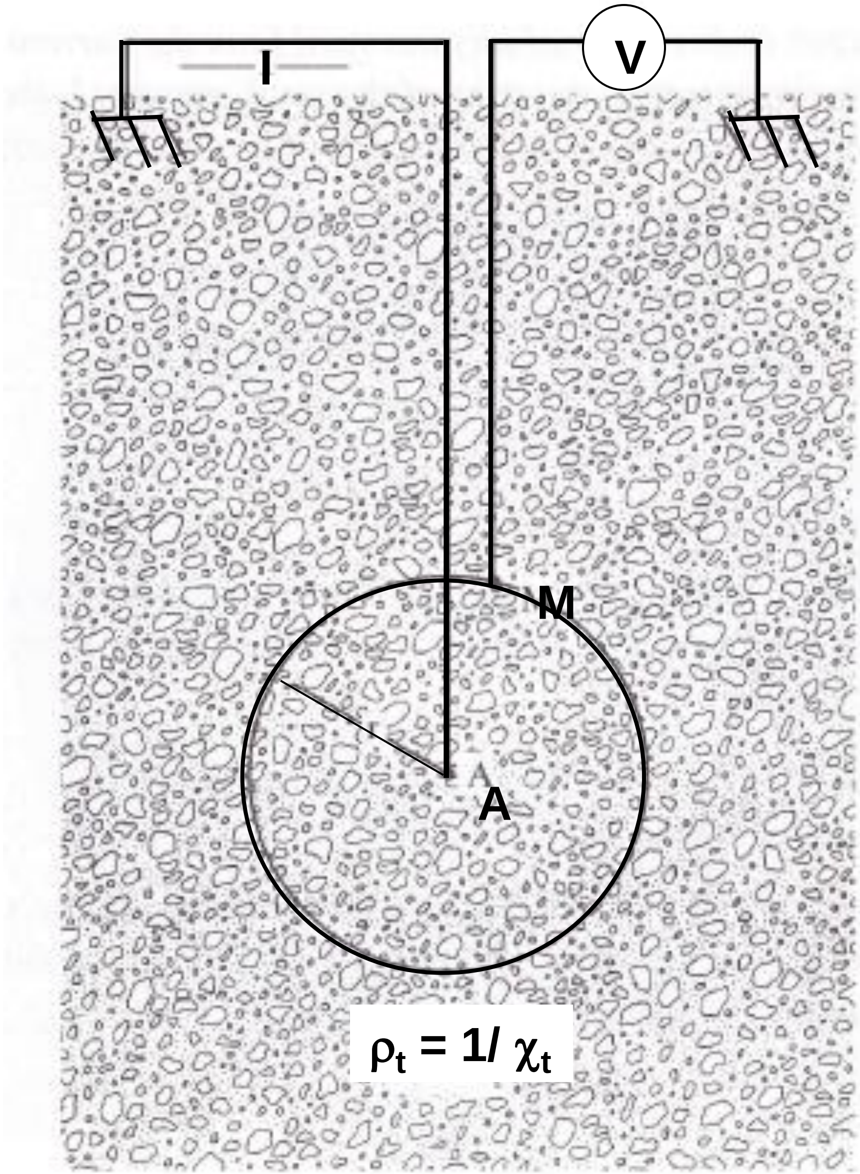
Archie, G.E. (1942)
The electrical resistivity log as an aid to determining some reservoir characteristics. *Trans AIME* 146, 54-63

Reservoir characteristics:

- Saturation degree: and then mass of hydrocarbon in the reservoir rock;

- Porosity;

- Fractures / failure zones around hydrocarbon wells.



(Ellis Singer, 2007: original concept of resisivity logging)

Pioneering work in terms of interpretation:

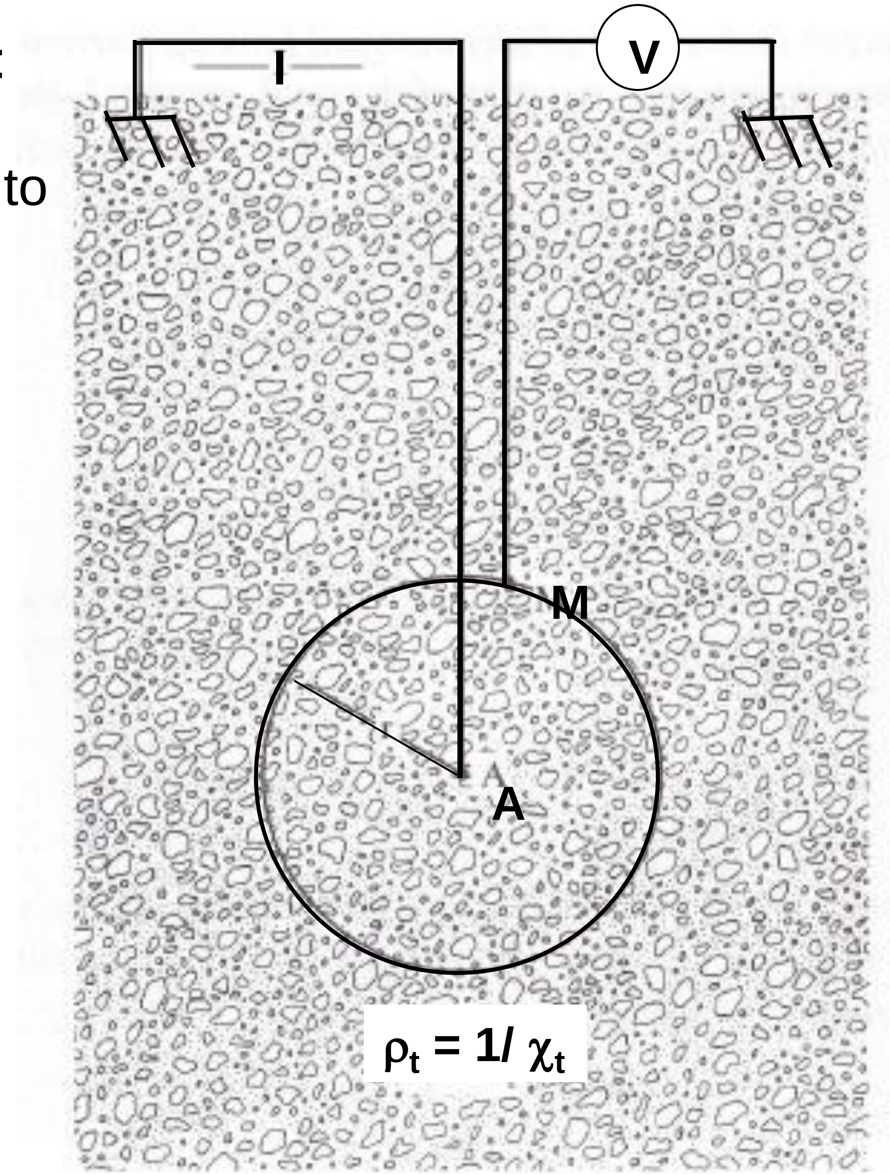
Electrostatics relationships were used to relate potential M to the current I:

$$\phi(r) = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

$$\mathbf{i} = \chi_t \mathbf{E} = -\chi_t \frac{\partial \phi(r)}{\partial r}$$

$$\rho_t = 4\pi r \frac{\phi}{I} = k\frac{\phi}{I}$$

$$\chi_t = \frac{1}{\rho_t} = \frac{I}{k\phi}$$



(Ellis Singer, 2007: original concept of resisivity logging)

Theoretical and empirical 'laws' relating the electrical conductivity of a soil to its structure and to the properties of its constituents

Archie's law

$$\chi_t = \chi_w \, n^m \, S_r^p$$

χ_w Electrical conductivity of the pore water

n Porosity

S_r Degree of (water) saturation

n^{-m} **: formation factor: ratio of the resistivity of the rock formation to the resistivity of the pore water in saturated conditions**

Values of exponents: loose sand $1.3 < m < 2$ cemented sandstones

Mitchell and Soga (2005) $1.4 < p < 4.6$

Other empirical or theoretical laws for electrical conductivity of soils

Clean formations (no clays or shales)

Bruggeman $\chi_t = \chi_w\, n^{3/2}$ $m = 3/2$: from inclusion theory

Clayey formations:

Waxman & Smits $\chi_t = \Gamma\,(\chi_w + \chi_s)$ σ_s : surface conductivity

Santamarina & Klein $$\chi_t = n\chi_w + (1-n)\left(\lambda_{ddl}\frac{G_s\gamma_w}{g}\right)S_a$$

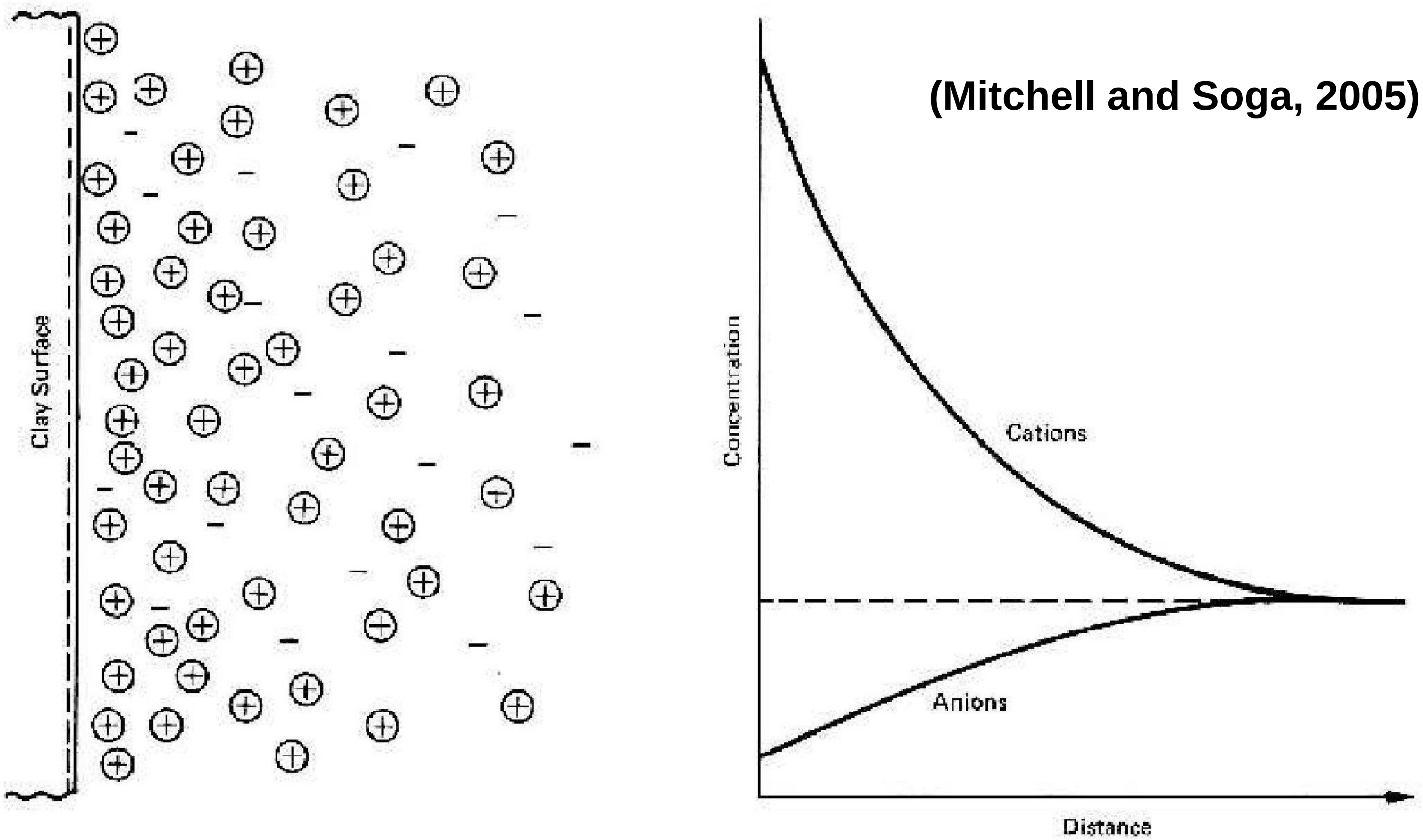
λ_{ddl} : double layer excess conduction

S_a: specific surface

Surface conductivity occurs at the interface between solid particles and pore water

Surface conductivity in clays or shales

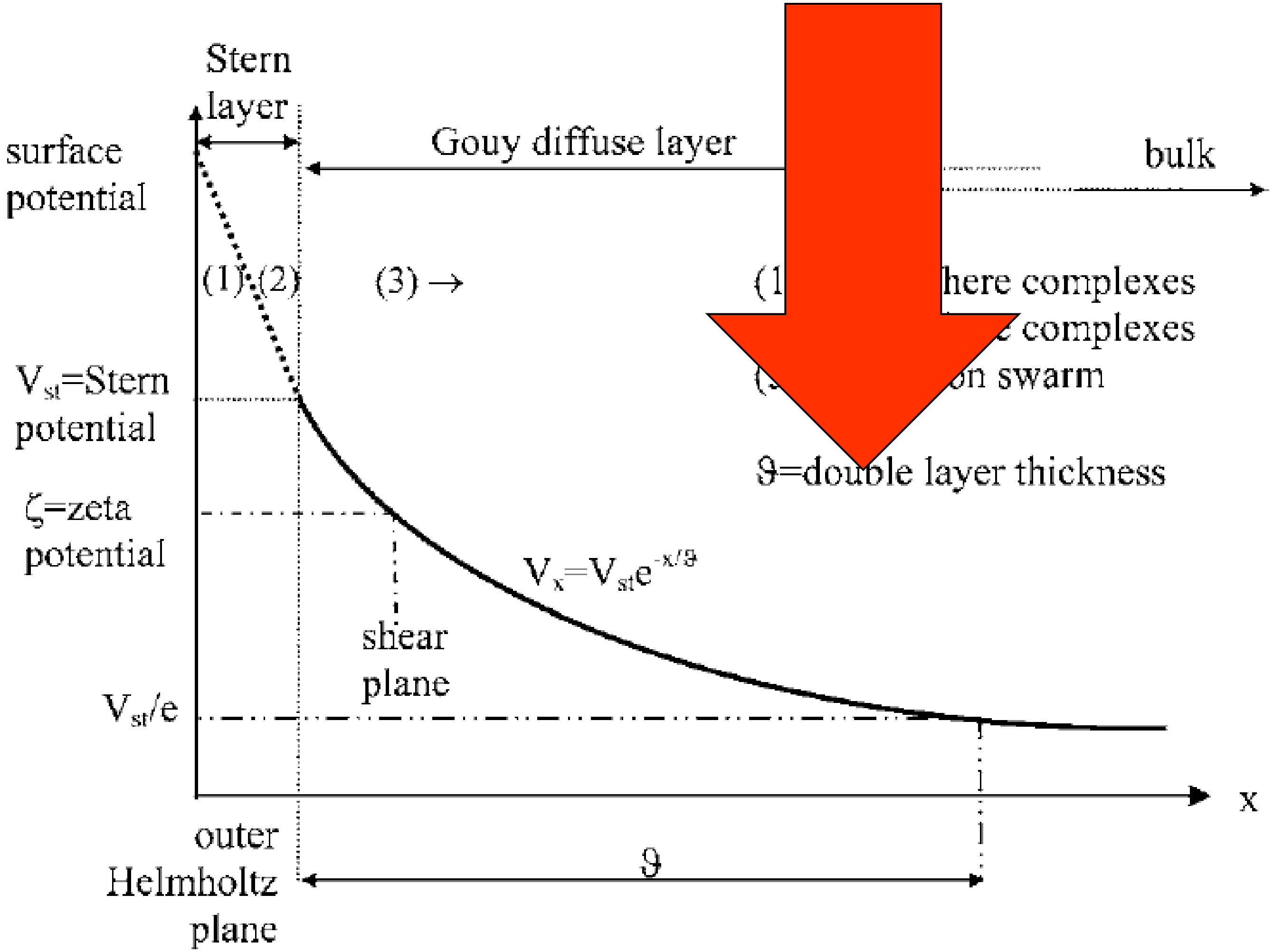
Double layer: the negatively charged surface of clay minerals attracts positive charges (cations) to balance electrical charge



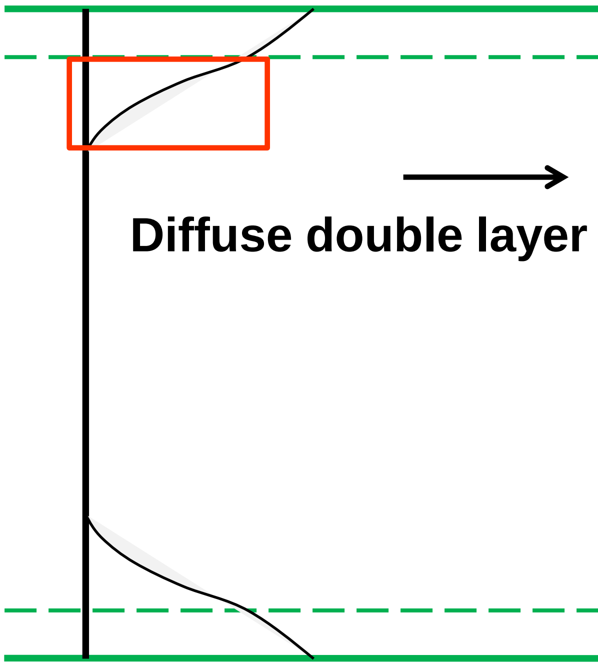
(Mitchell and Soga, 2005)

Surface conductivity in clays or shales

Cations in the diffuse layer can move (in the Stern layer are ‘blocked’) increasing overall conductivity

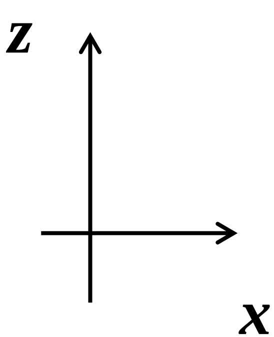


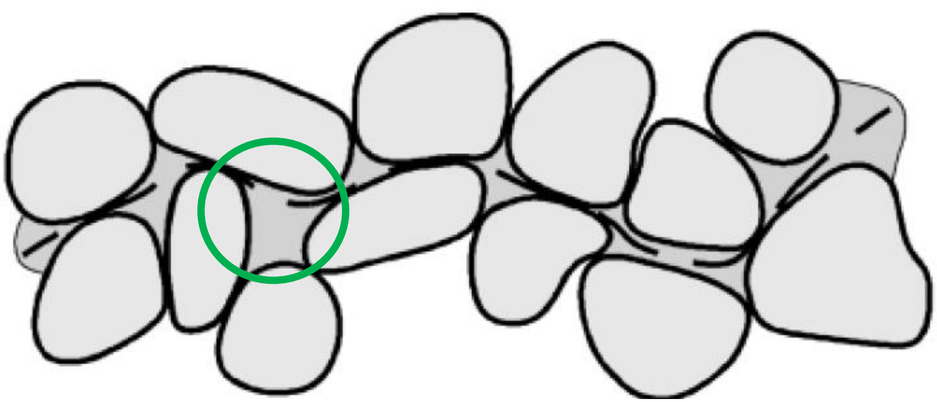
Surface conductivity in clays or shales



$$E = -\frac{\partial \phi}{\partial x}$$

Presence of diffuse double layer increases the conductivity of the soil, under equal conductivity of the bulk pore fluid





Bulk water conductivity

Archie's law

$$\chi_t = \chi_w\, n^m\, S_r^{\,p}$$

Water is an electrolyte:

- Electrical current is associated to the movement of ions
- Ions are molecules that have lost / accepted one or more electrons

Cations: positively charged ions: H^+, Na^+, Ca^{2+}, Al^{3+}….

Anions: negatively charged ions: OH^-, Cl^-, SO_4^{2-}, …

Bulk water conductivity χ_w

Concept of mobility

'u': velocity of a ion under the effect of a unit electrical field

Mobility *u* is related to diffusivity *D*

$$u_i = \frac{D_i z_i F}{RT}$$

F : Faraday's constant: F=96485 C/gram equivalents

z_i : ionic valence

D_i : diffusion coefficient [m/s]

R: universal gas constant

T: temperature [K]

Some diffusion coefficients / mobilities (Acar Alshawabkkeh, 1993)

Species	**D_a x 10 ^{6} cm^2 s^{-1}**	**u_a x 10 ^{6} cm^2 V^{-1} s^{-1}**
H^+	93	3625
Na^+	13	519
Ca^{2+}	8	617
Cd^{2+}	9	736
Pb^{2+}	7	560
Cr^{3+}	6	694
OH^-	53	2058
NO^{3-}	19	740
CO_3^{2-}	10	746
SO_4^{2-}	11	413
PO_4^{3-}	6	715

Bulk water conductivity χ_w

From mobility (velocity of ion) to contribution of that ion to electrical flow

u u ·c · z· F ·

concentration **valence** **Faraday's constant**

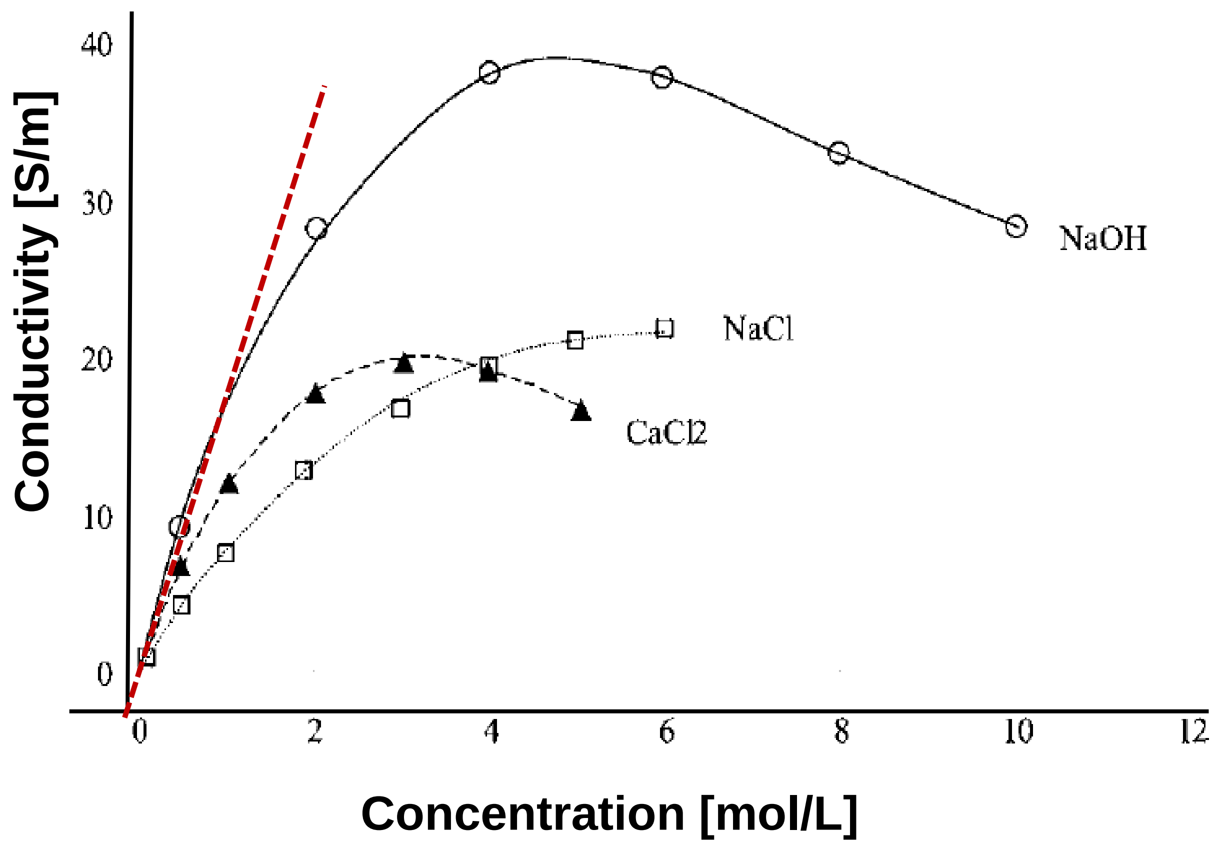
So in **dilute solutions** electrical conductivity is linearly related to type of ions dissolved in solution and to their concentration

Nernst Einstein relation :
(dilute solutions)

$$\chi_w = F\left(\sum_{i=1}^{n} c_i z_i u_i\right) = F^2\left(\sum_{\alpha=1}^{n} \frac{c_i z_i^2 D_i}{RT}\right)$$

Bulk water conductivity χ_w

----- Relationship conductivity – concentration deviates from linearity at higher concentrations (mobility is decreased)



Klein & Santamarina, 2003

Some partial conclusion:

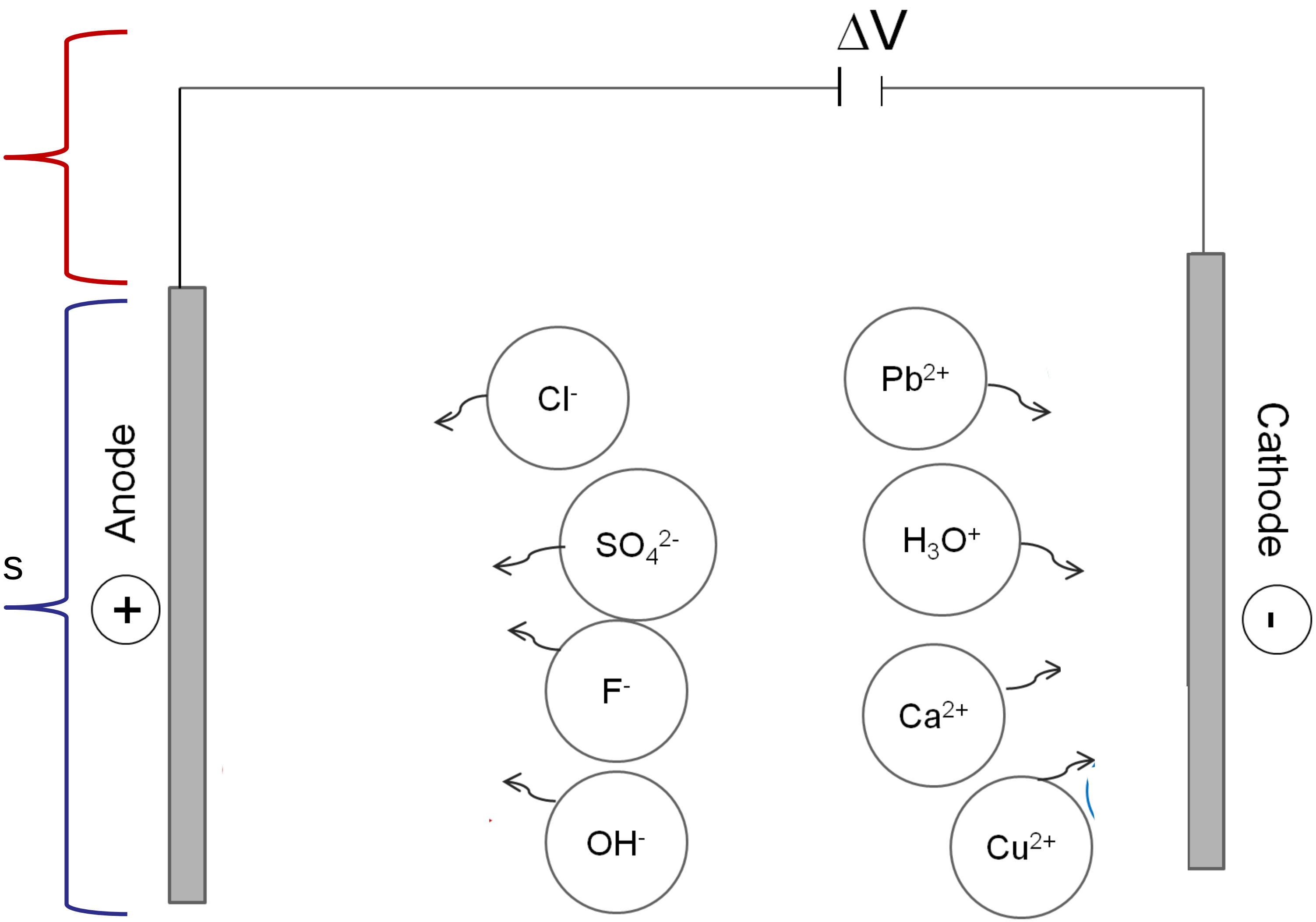
1 – Soil electrical conductivity depends on
porosity,
degree of saturation,
type and content of clay,
electrical conductivity of water

2 – Water electrical conductivity depends on
type of ion in solution (diffusion constant),
concentration

Boundary phenomena related to the injection of an electrical current in an electrolyte:

Charges are carried by electrons (metal)

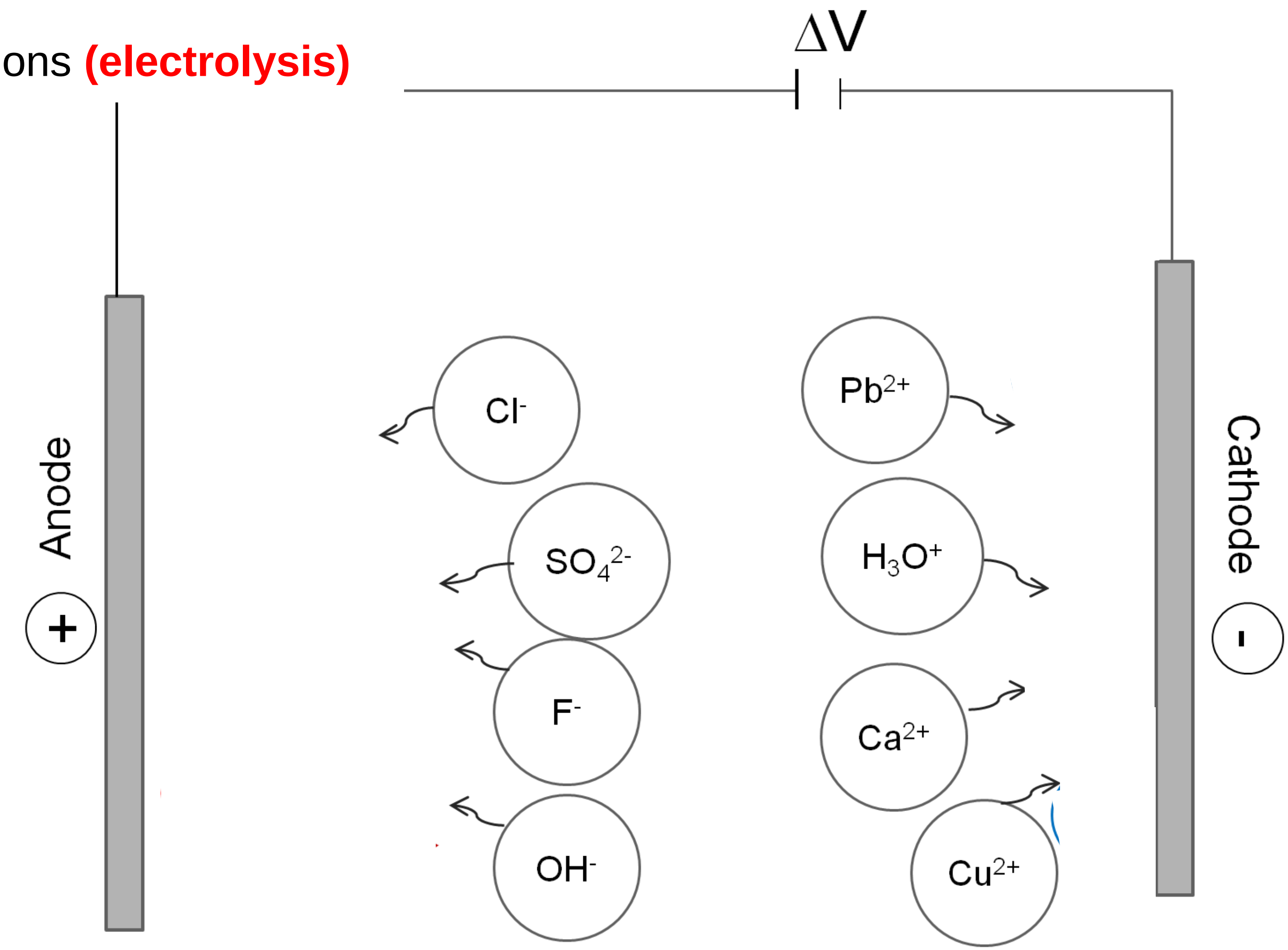
Charges are carried by ions (electrolyte)



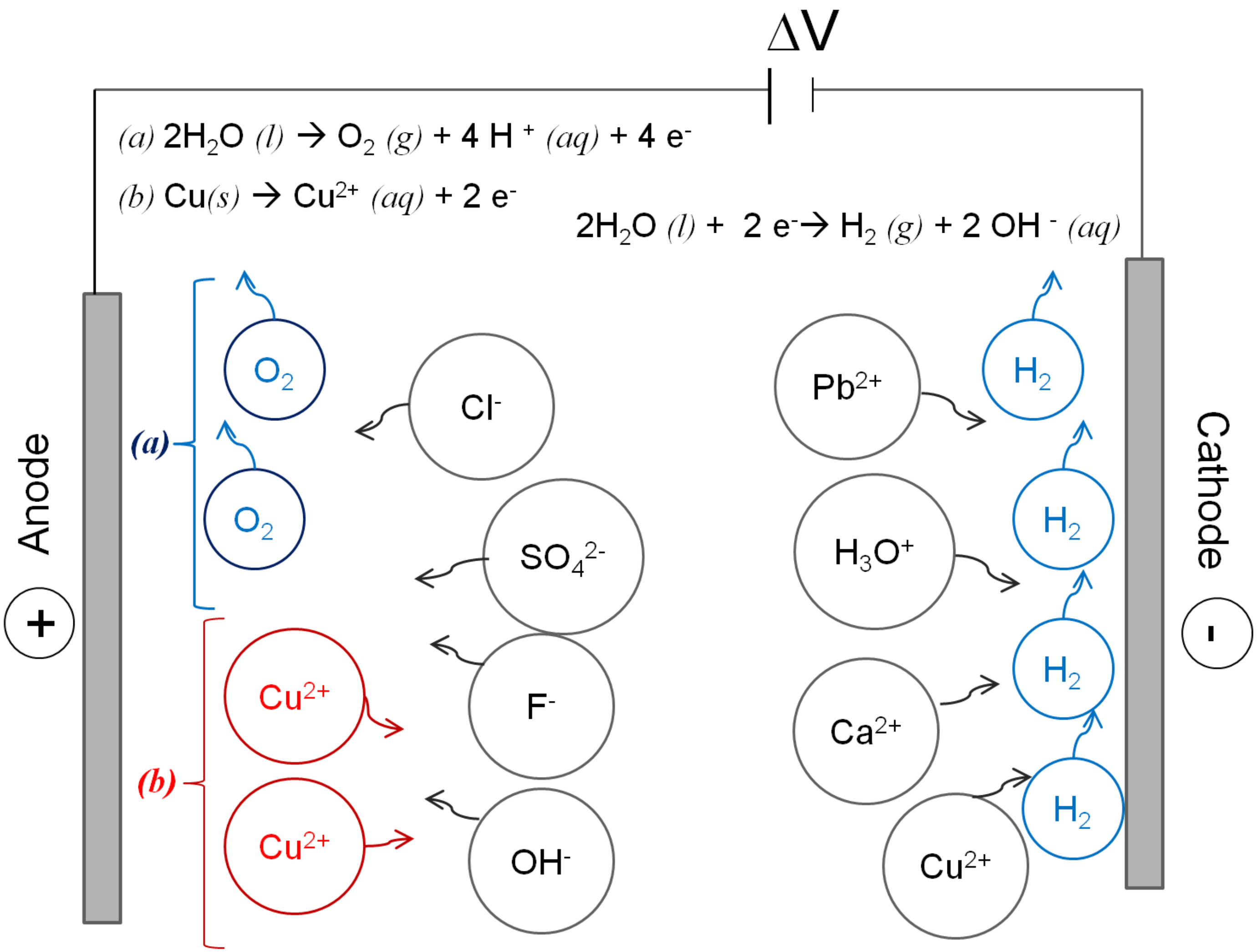
Boundary phenomena related to the injection of an electrical current in an electrolyte:

Charges must be exchanged at the electrodes between solid and electrolyte

Electrode reactions **(electrolysis)**



Electrolysis reactions driven by a DC current can alter composition of the pore water.



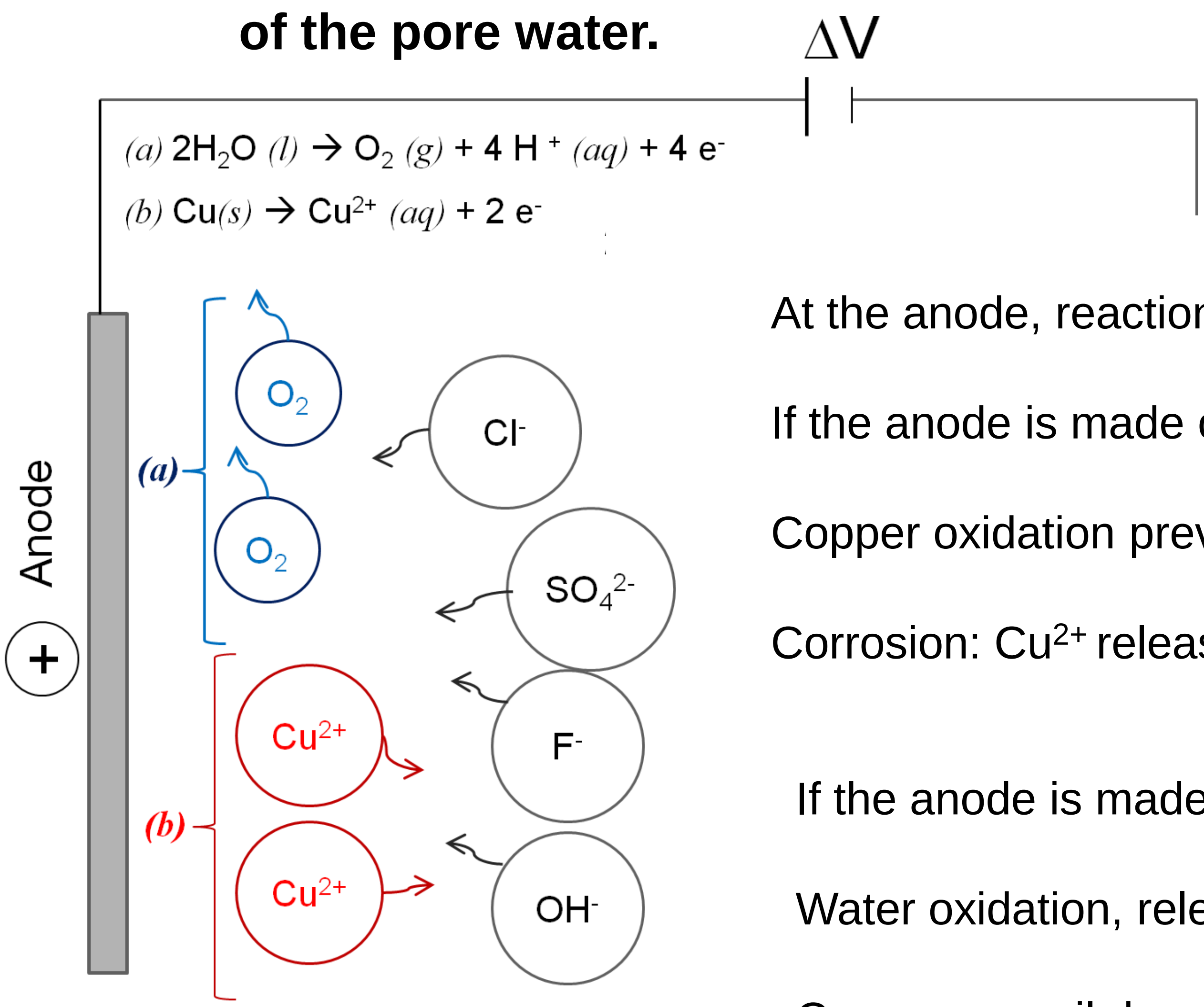
Type of reaction taking place depends on electrical potential of the species and of the electrodes.

Electrolysis reactions driven by a DC current can alter composition of the pore water.

Reaction	**Standard Electrode Potential E^0 (V)**
$Al^{3+} + 3e^- \leftrightarrows Al(s)$	−1.66
$Zn^{2+} + 2e^- \leftrightarrows Zn(s)$	−0.7618
$Fe^{2+} + 2e^- \leftrightarrows Fe(s)$	−0.44
$Cu^{2+} + 2e^- \leftrightarrows Cu(s)$	+0.340
$2H_2O\ (l) \leftrightarrows O_2(g) + 4H^+(aq) + 4e^-$	+1.23 (E = +0.82V if pH = 7)
$Hg^{2+}\ \ 2e^- \leftrightarrows Hg(l)$	+0.85
$Pt^{2+} + 2e^- \leftrightarrows Pt(s)$	+1.188
$Au^+ + e^- \leftrightarrows Au(s)$	+1.69

Reaction taking place depends on electrical potential of the species and of the electrodes.

Electrolysis reactions driven by a DC current can alter composition of the pore water.



At the anode, reaction with the lower potential

If the anode is made of copper:

Copper oxidation prevails over water oxidation

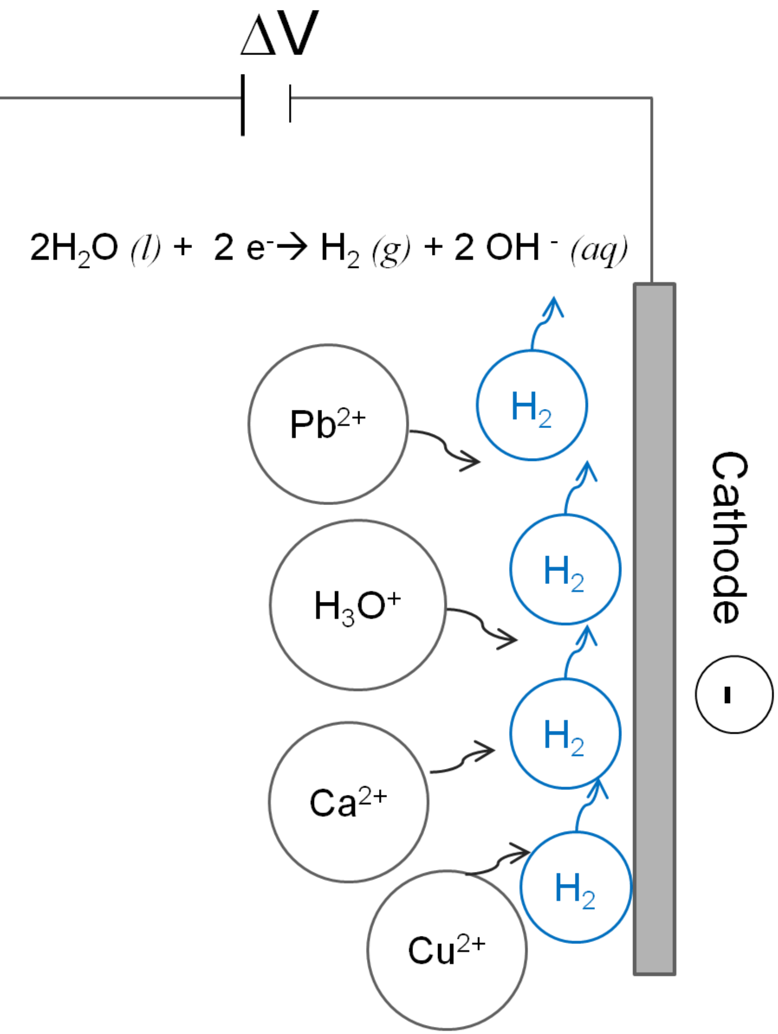
Corrosion: Cu^{2+} released in solution

If the anode is made a noble metal:

Water oxidation, release of O2 in gasous form

Can cause soil desaturation

Electrolysis reactions driven by a DC current can alter composition of the pore water.



At the cathode, reaction with the higher potential

Normally water reduction prevails

Release of H_2 (gas): can desaturate the soil

Electrolysis reactions driven by a DC current can alter composition of the pore water.

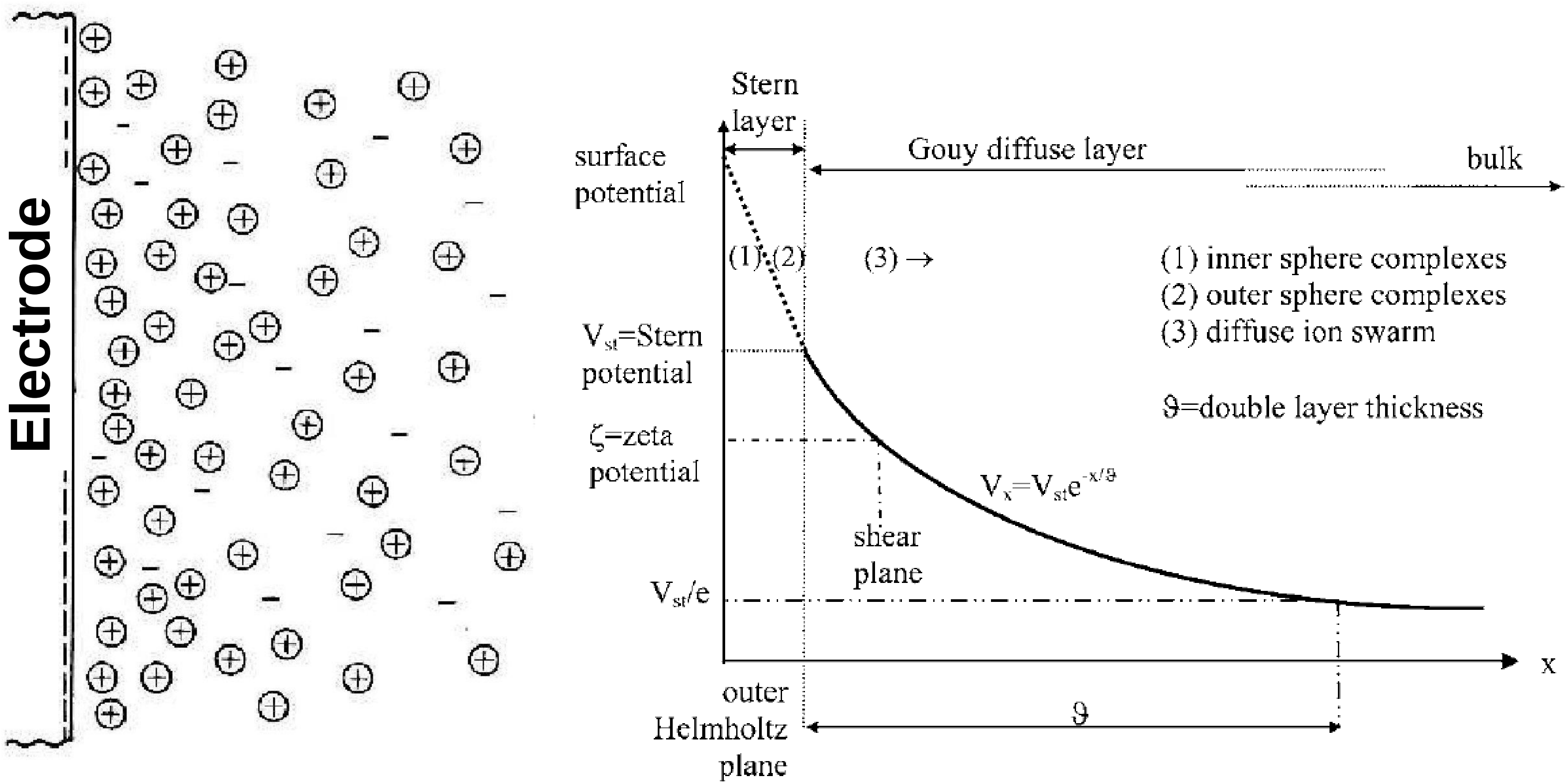
Practical implications:

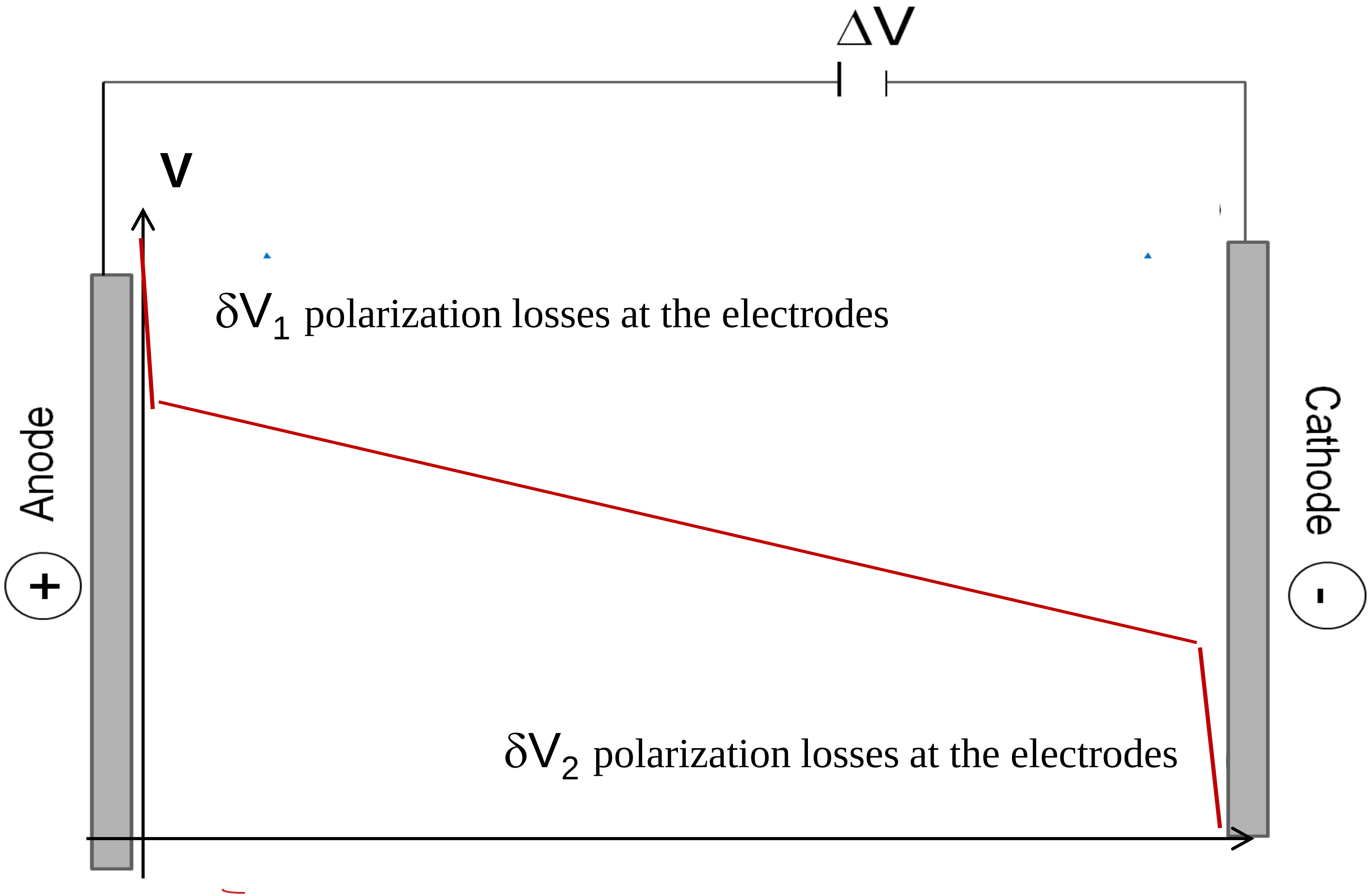
1 – choice of the proper type of electrode conditions chemical changes that take place in the soil

2 – DC electrical current cannot be applied for long periods (corrosion, important changes of chemistry / soil property)

3 – DC electrical current produces an electrical double layer at the electrode – electrolyte interface

In proximity of the eletrode the electric field is influenced by the double layer (electrode polarization)

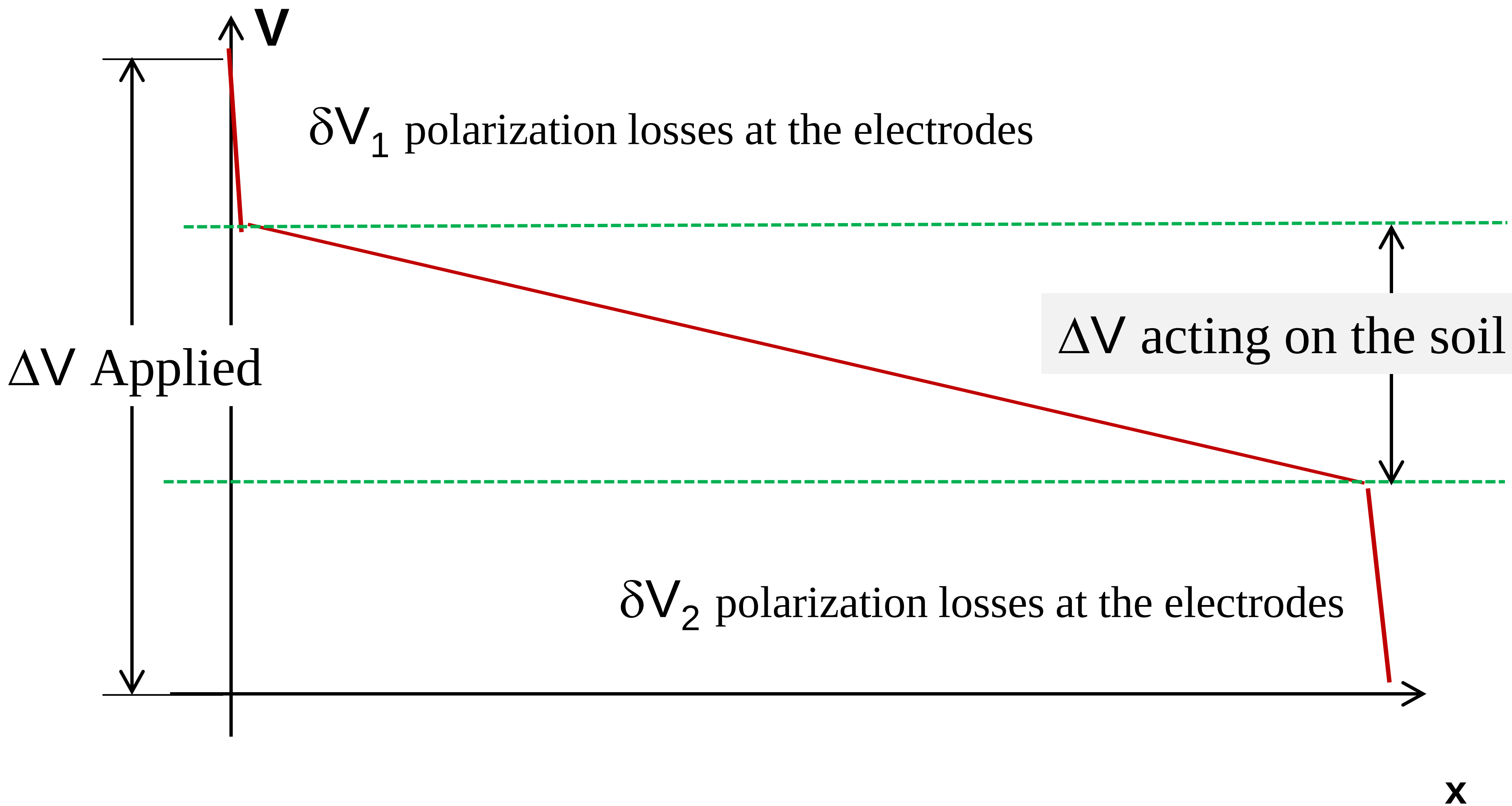



ΔV
V
δV1 polarization losses at the electrodes
Anode
+
Cathode
-
δV2 polarization losses at the electrodes

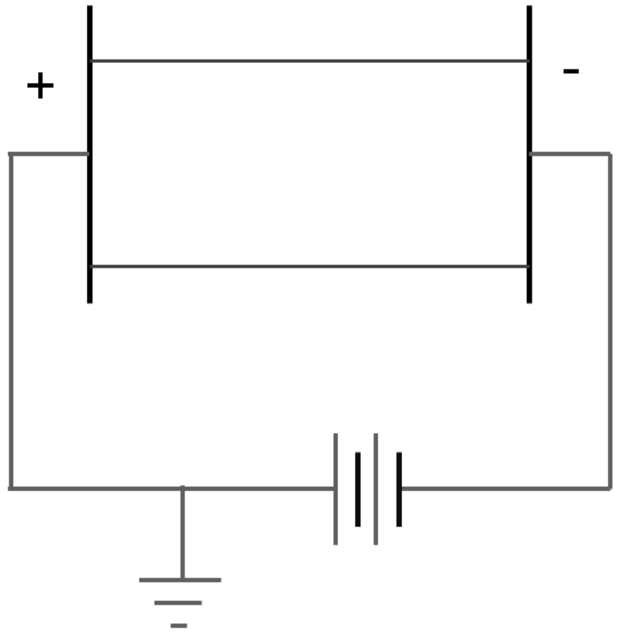
In DC conditions, not all the ΔV applied goes to the electrolyte (soil)

Polarization losses are difficult to evaluate →

Soil electrical Conductivity is difficult to evaluate



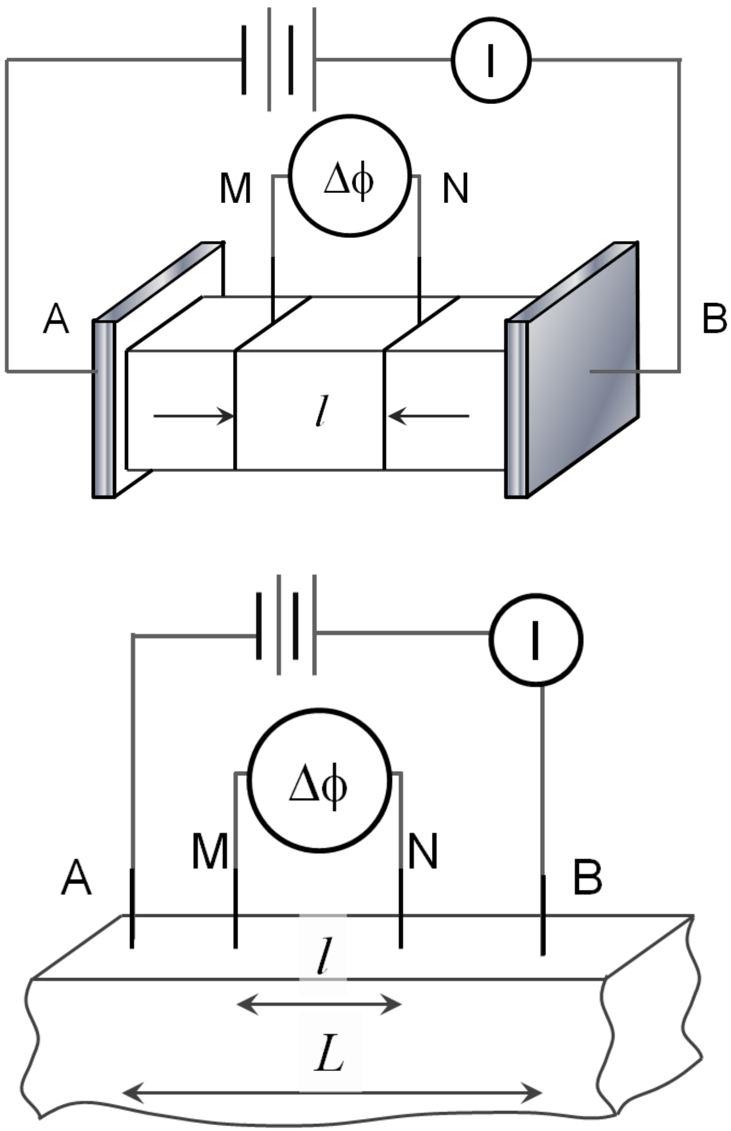
Traditional measuring strategies and arrangements:



Two electrodes terminal system:

- The anode and the cathode work both to inject current and to measure potential drop

- Electrode polarization effects are reduced by working at (relatively) high frequencies



Four electrodes terminal system:

- The anode and the cathode (A and B) inject current , two electrodes (M and N) measure the potential difference among them

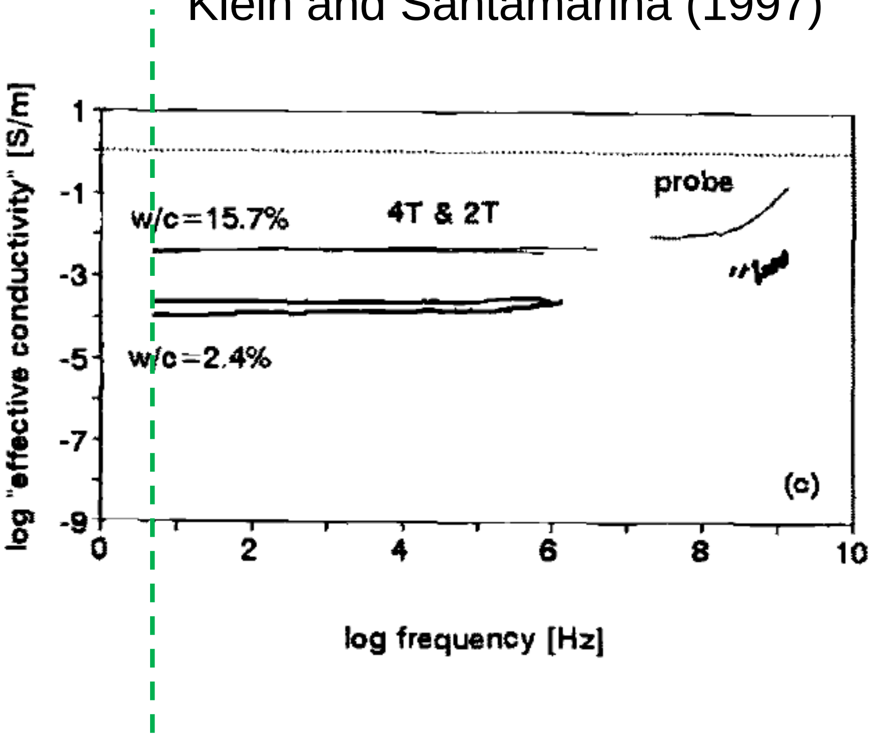
- Polarization effects do not occur on electrodes M and N: can operate at low frequencies

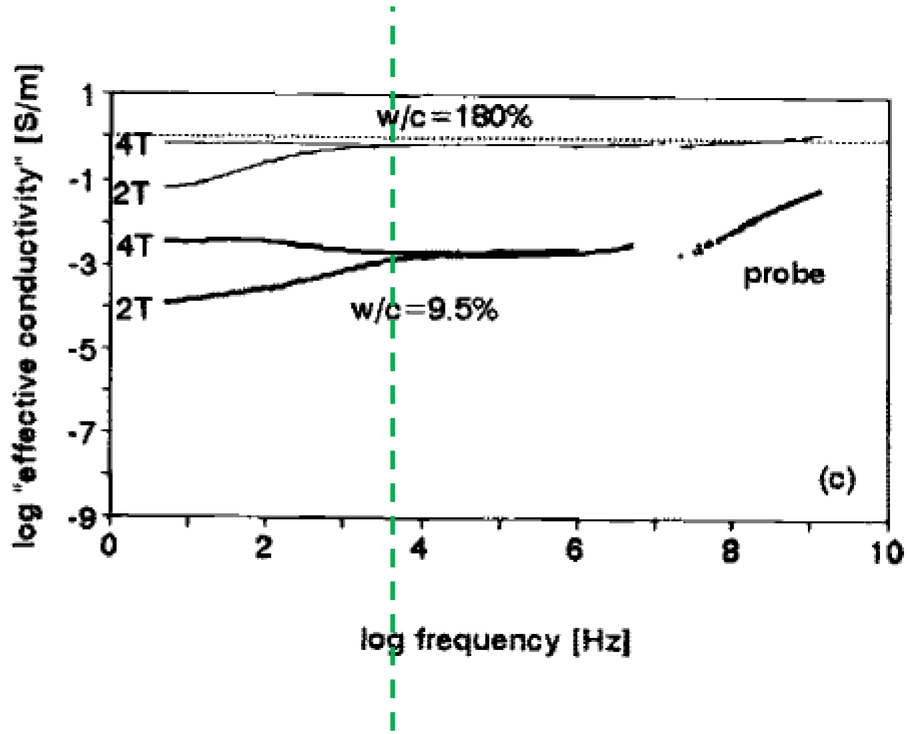
- Different geometrical arrangements are possible, with different shape factors *k*

$$\chi_t = \frac{1}{\rho_t} = \frac{I}{k\Delta\phi}$$

Comparison between lab results of 2T and 4T systems:

Klein and Santamarina (1997)





Sand sample

Clay sample (bentonite)

Above a certain limiting frequency , 2T and 4T systems provide same results

Limiting frequency depends on the material and water content

Review of selected 2T systems lab studies:

Study	Geometry	Mechanical	Hydr / Chem	Objective / Results
Fukue et al. (1999)	Stainless steel mesh 1D vertical meas.	Oedometer	-	**Microstructure** of clay upon loading
McCarter et al. (2005)	Stainless steel. 1D horizontal and vertical measurements	Oedometer	-	**Anisotropy** upon loading
Lee et al. (2008)	Stainless steel. Quasi spherical (Needle probe)	Oedometer	-	**Resistance** upon loading: evidences of anisotropy and load history effects
Fukue et al. (2001)	Stainless steel mesh 1D vertical meas.	Oedometer	Imposed saturation water salinity	**Soil electrical behavior** for in situ investigation

Review of selected 2T systems lab studies:

Study	**Geometry**	**Mechanical**	**Hydr / Chem**	**Objective / Results**
Blewett et al. (2003)	1D **radial** and **vertical** measurements	-	1 D **diffusion** column and oedometer	**Diffusion parameter** of NaCl in kaolin specimens
Attia et al. (2007)	1D **vertical** measurements	-	**Evaporation**	**water retention** and **electrical conductivity** in the unsaturated range
Cho and Santamarina (2004)	Quasi spherical (Needle probe)	-	-	**specimen heterogeneity** through electrical resistance **profiles**
Musso et al. (2009)	Stainless steel. Quasi spherical (Needle probe)	-	**Evaporation**	**Degree** of **saturation** through electrical resistance **profiles**

Observations on literature studies:

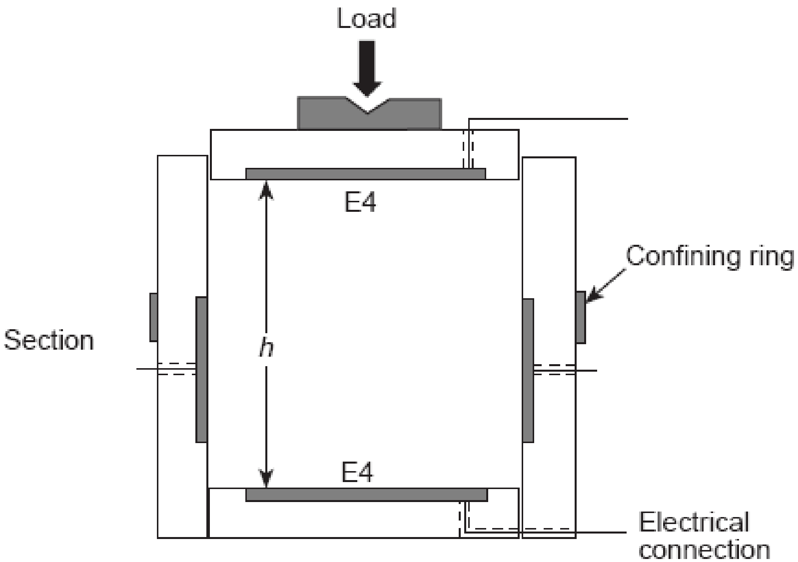
1 – both mechanical and hydro-chemical studies have been published

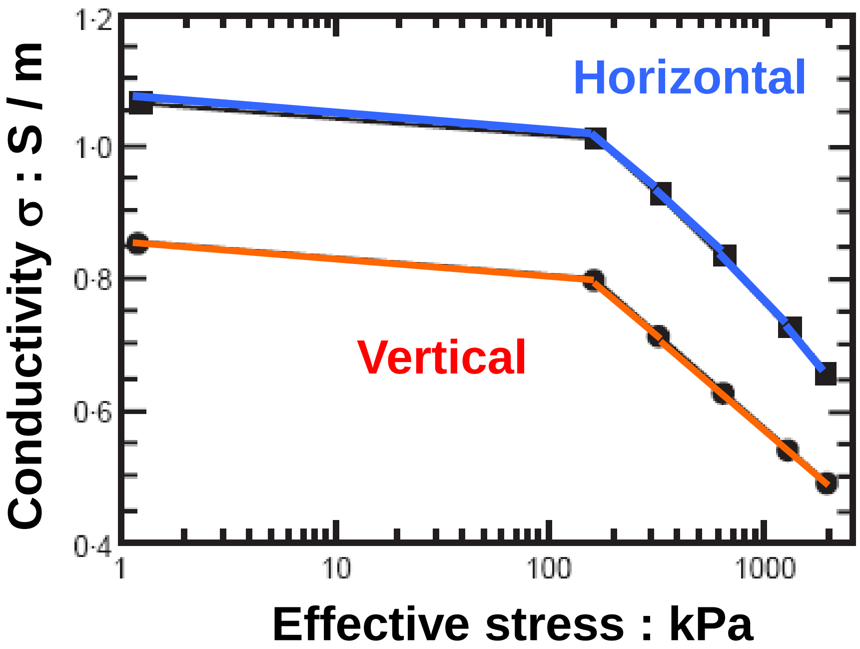
2 – electrical measurements particularly used for anisotropy evaluation (can be correlated with hydraulic transverse isotropy ane mechanical effects as well)

3 – diffusion and transport studies are limited (difficulties in following transient conditions and ‘heterogenities’ at the same time)

Electrical measurements in geotechnical laboratory testing (not ERT):

- anisotropy of clays (McCarter and Desmazes, Géotechnique, 1997)

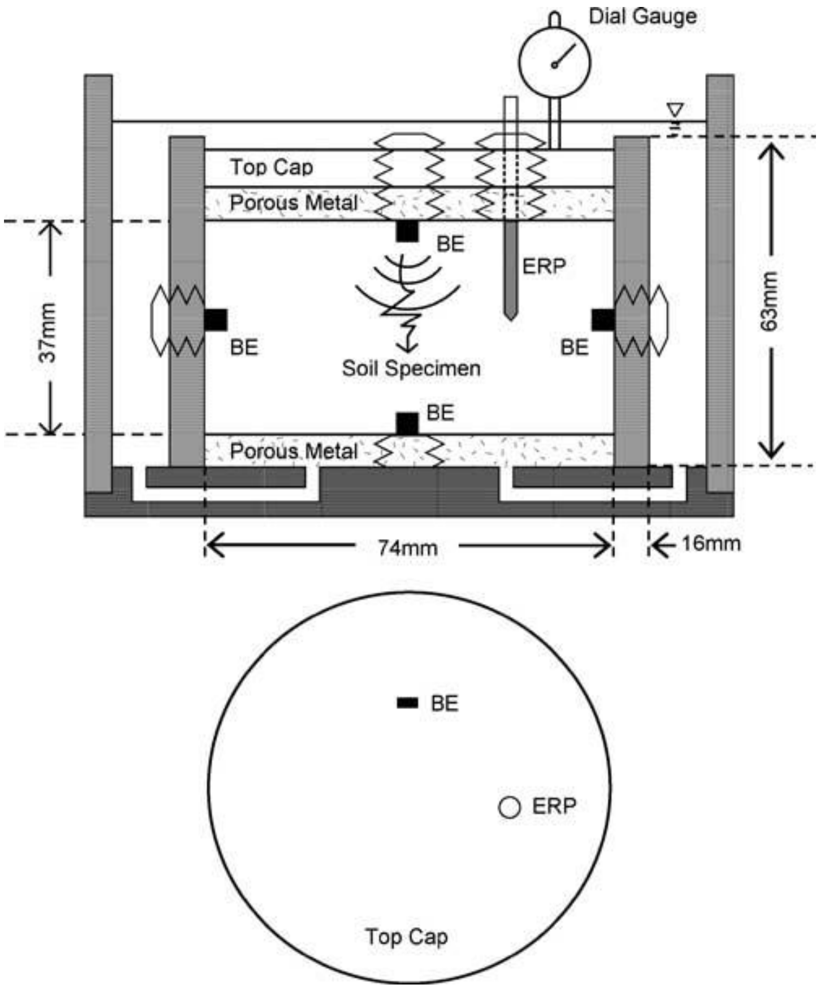


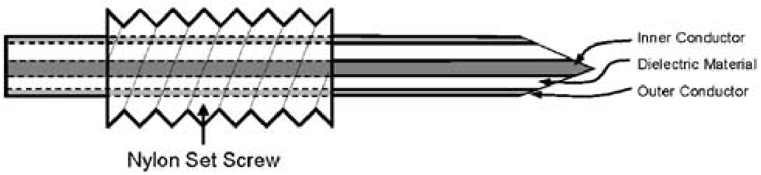


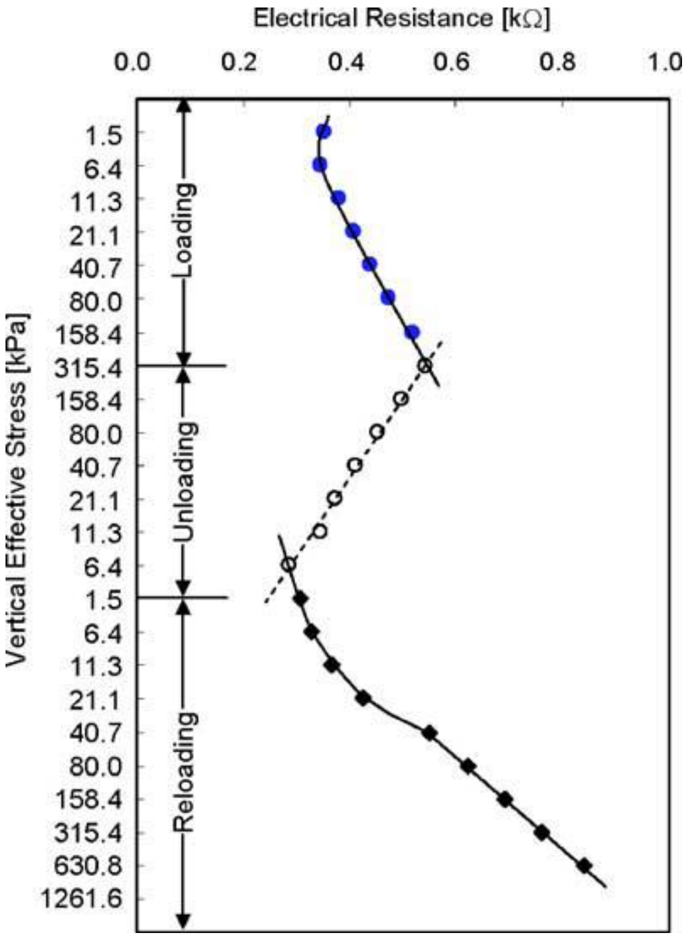
All measurements taken at the end of consolidation process

Electrical measurements in geotechnical laboratory testing (not ERT):

- consolidation processes (Lee et al., GTJ, 2008)



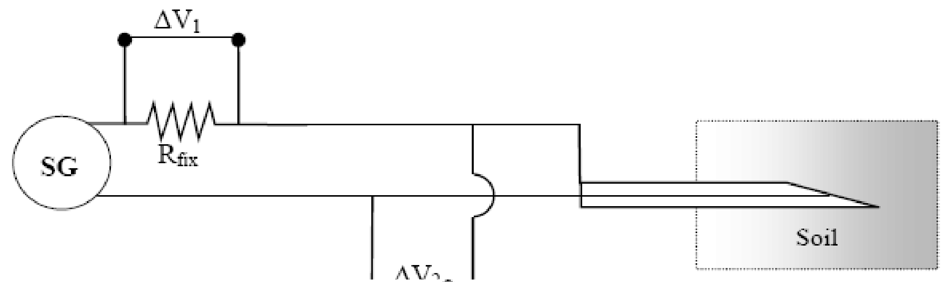


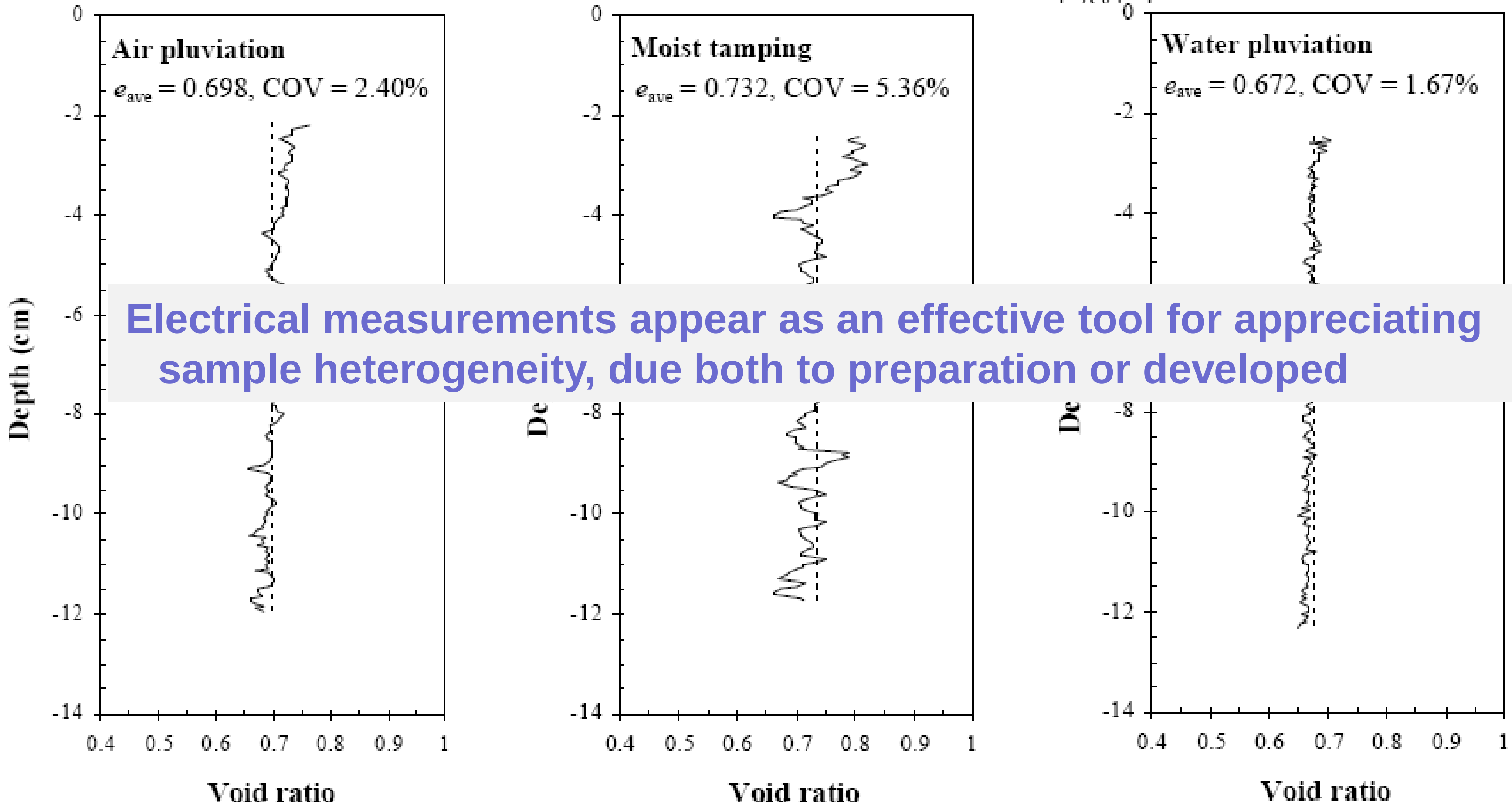


Electrical measurements in geotechnical laboratory testing (not ERT):

- specimen heterogeneity

(Cho and Santamarina, J.G.G.E., 2004)

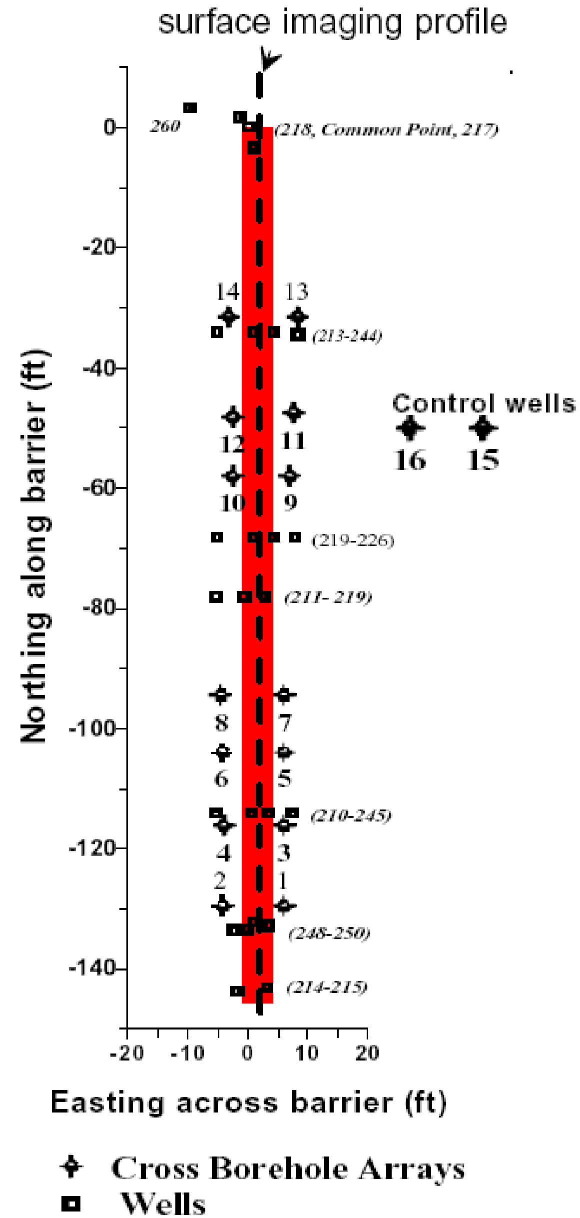




Electrical measurements appear as an effective tool for appreciating sample heterogeneity, due both to preparation or developed

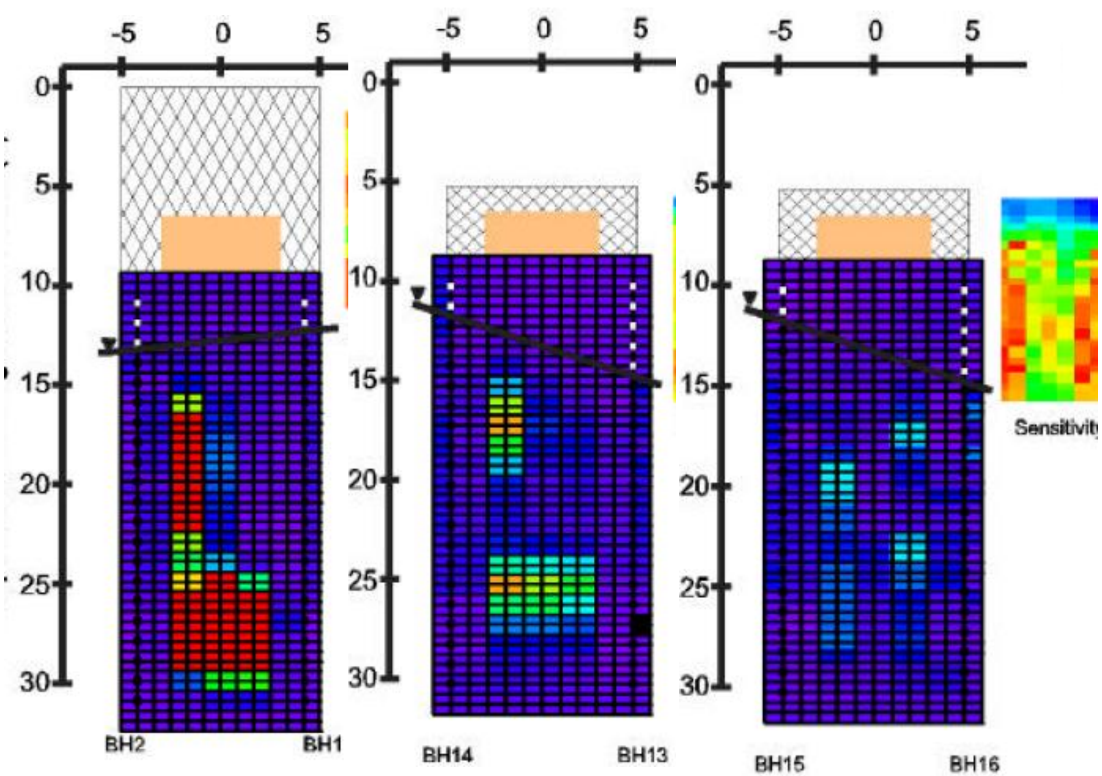
Electrical Resistivity Tomography (ERT)

- developed for in situ investigations, where it showed good result
chemical' variables



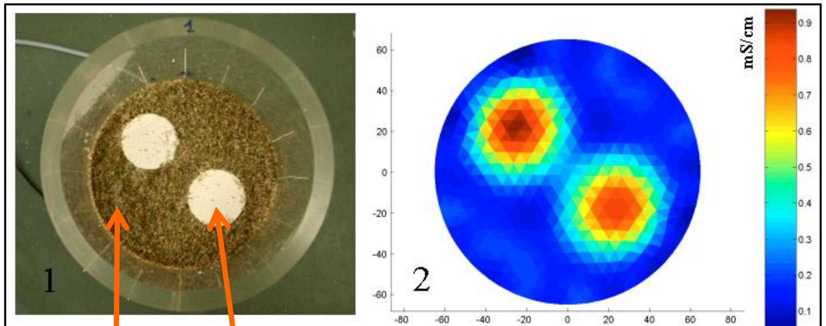
Some studies at 'our beginning'

Monitoring of leaks from underground storage structures (Ramirez et
Imaging hydraulic barriers (Daily and Ramirez, 2000),
Evaluation of permeable reactive barrier (PRB) integrity using electri
methods (Slater and Binley, 2003)



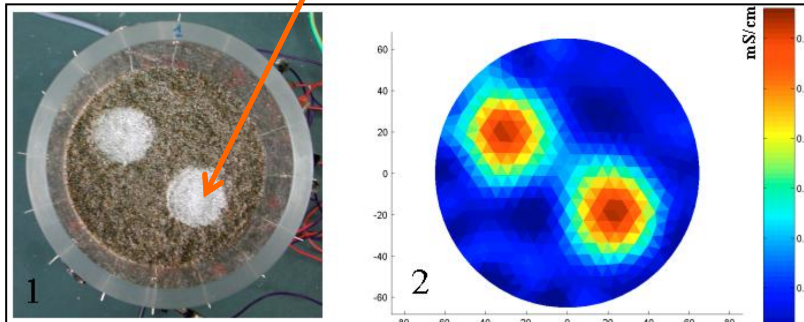
Electrical Resistivity Tomography : a full field technique, aiming at the reconstruction of the distribution of the electrical conductivity within a body, used for instance to detect heterogeneities

90% Sand 10% Kaolin



1. Inclusions of Kaolin (D = 38 mm) within a Ticino sand matrix

2. Tomographic reconstruction

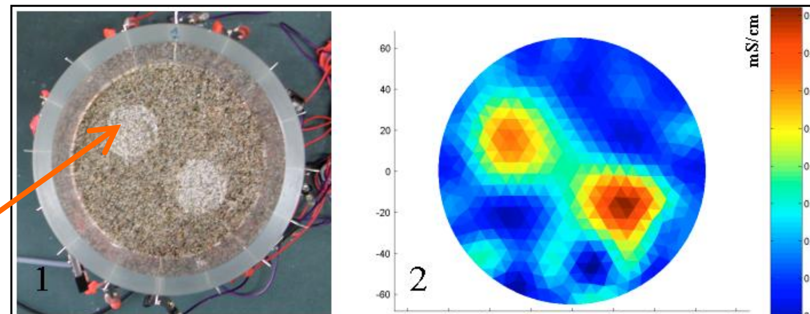


1. Inclusions of Ticino sand mixed with 10% of Kaolin (D = 38 mm) within a Ticino sand matrix

2. Tomographic reconstruction

Sand 100% Kaolin

95% Sand
5% Kaolin

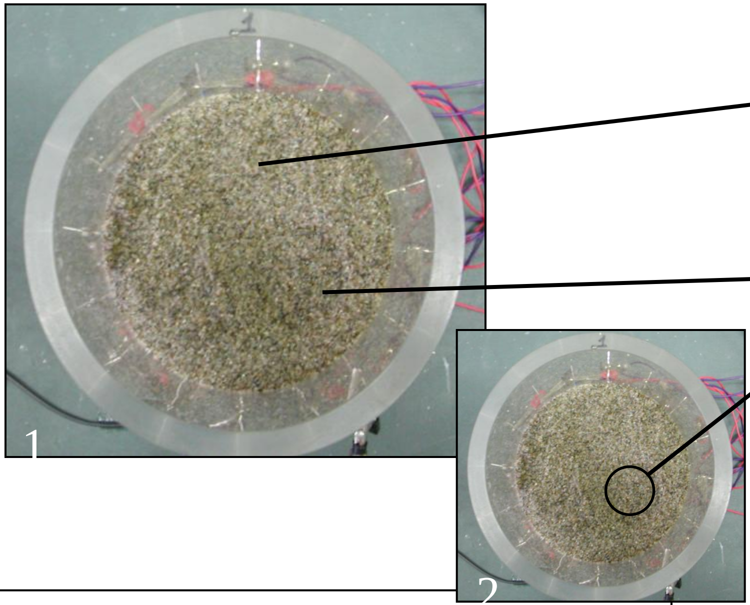


1. Inclusions of Ticino sand mixed with 5% of Kaolin (D = 38 mm) within a Ticino sand matrix

2. Tomographic reconstruction

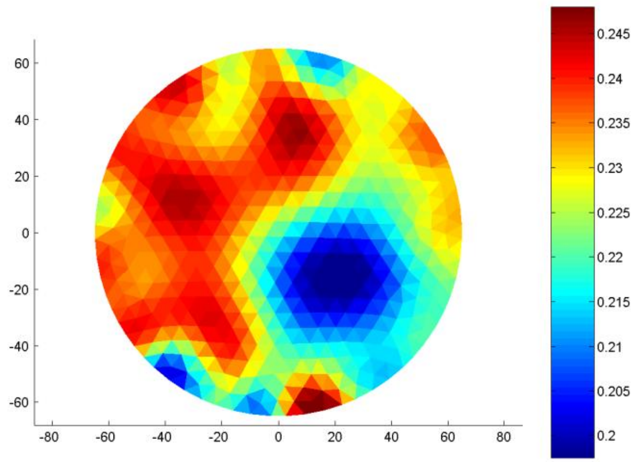
Polito – 2D ERT (Borsic et al., 2005)

Polito – 2D ERT (Borsic et al., 2005)



Coarse Matrix
n ≈ **0.48**

Dense Inclusion
n ≈ **0.43**



3. Tomographic reconstruction

$$n = \frac{\sigma_1 - \sigma_D^*}{\sigma_1 - \sigma_2} \cdot \left(\frac{\sigma_2}{\sigma_D^*} \right)^{1/3}$$

Bruggeman, 1935

Estimated values of

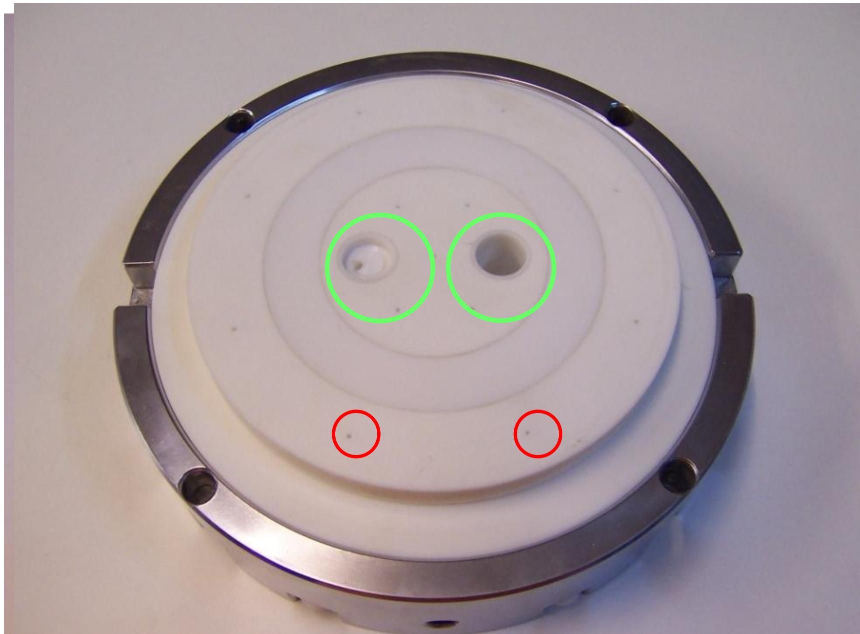
Matrix n ≈ **0.46** Inclusion n ≈ **0.42**

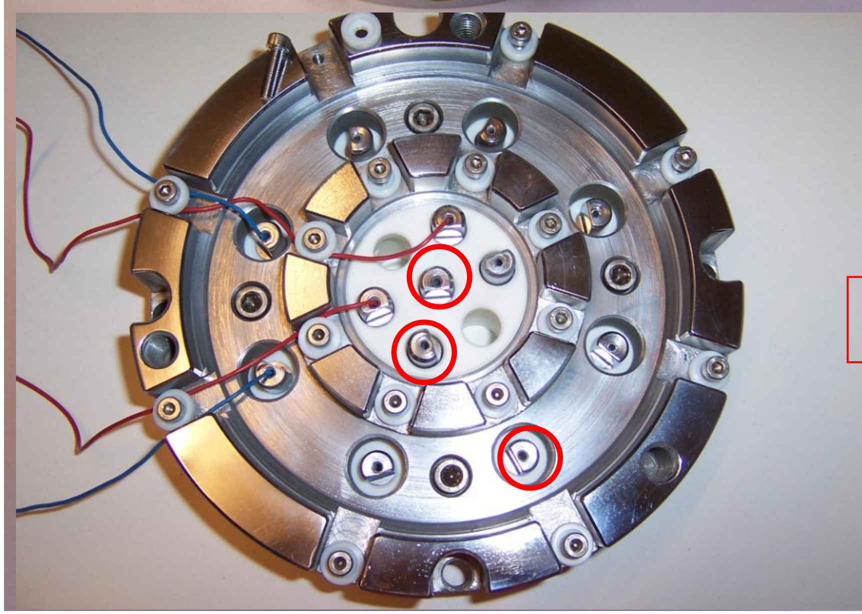
On basis of literature studies: what about following transient processes in the laboratory using ERT (3D) and controlled hydro-mechanical conditions?

1 – experimental aspects

2 – electrical inversion (tomography) aspects

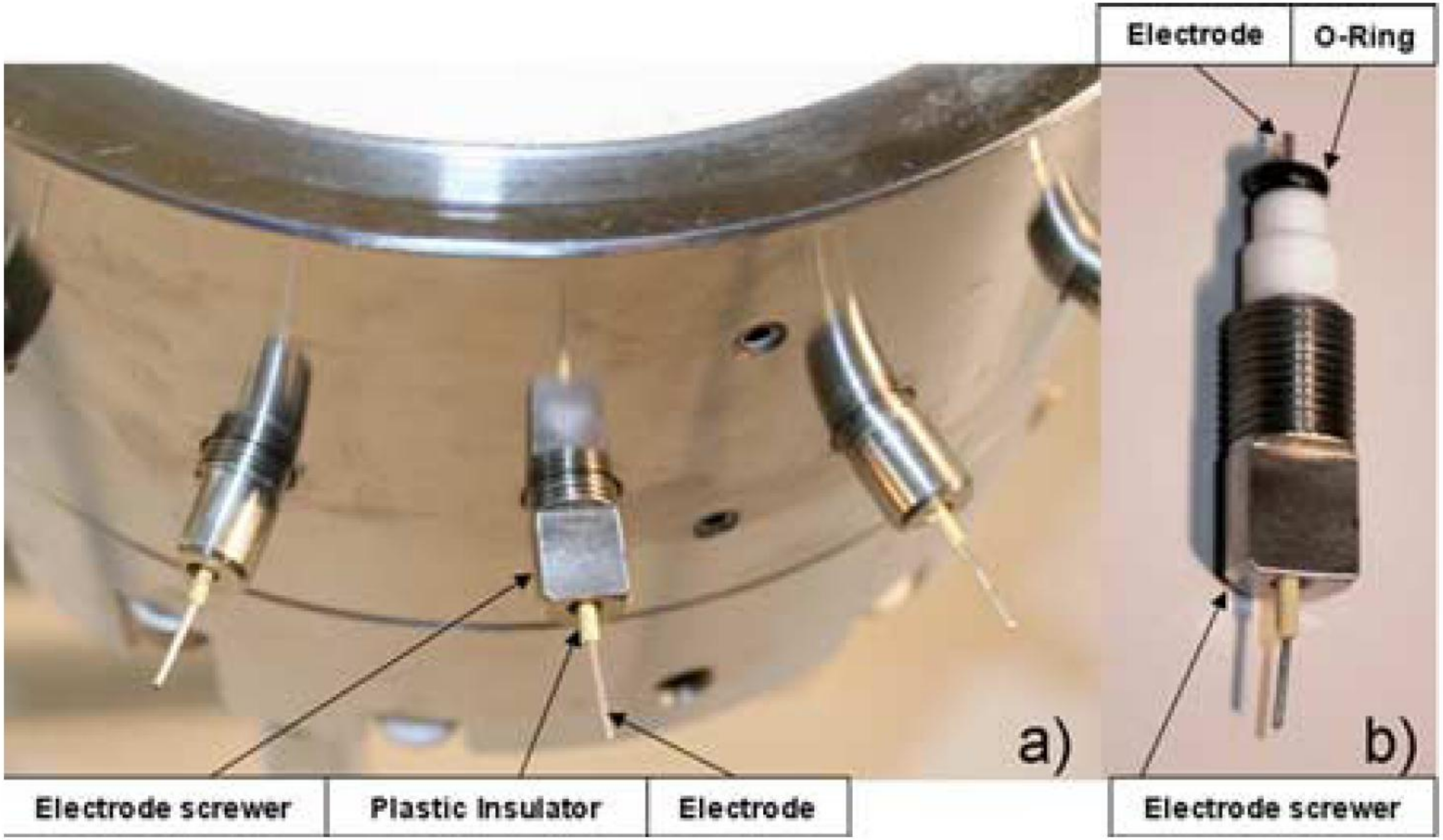
3 – modelling aspects





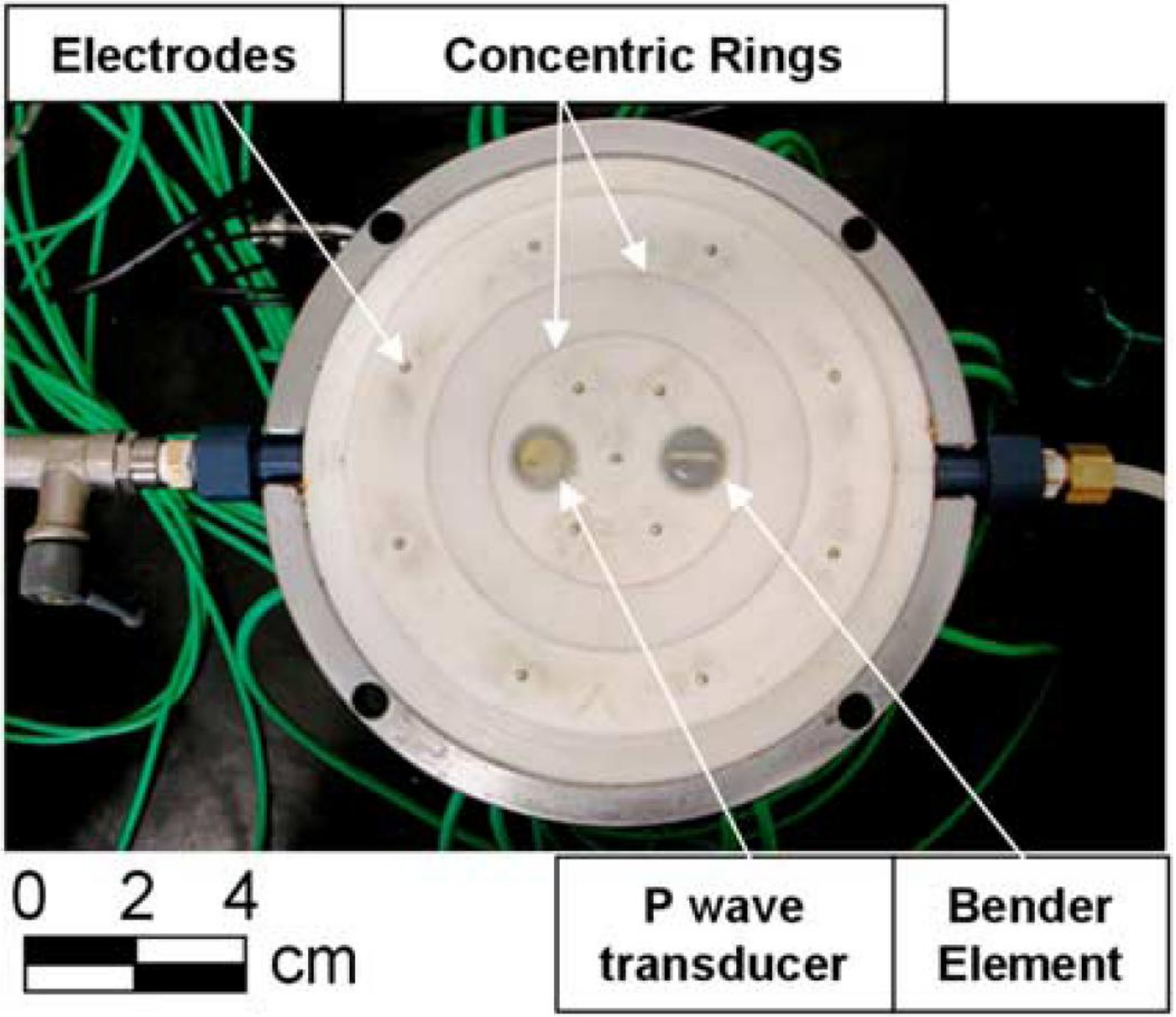
(Comina et al., Geot. Test. J.(2008) **31**, 5)

Electrical isolation



(Comina et al., 2008)

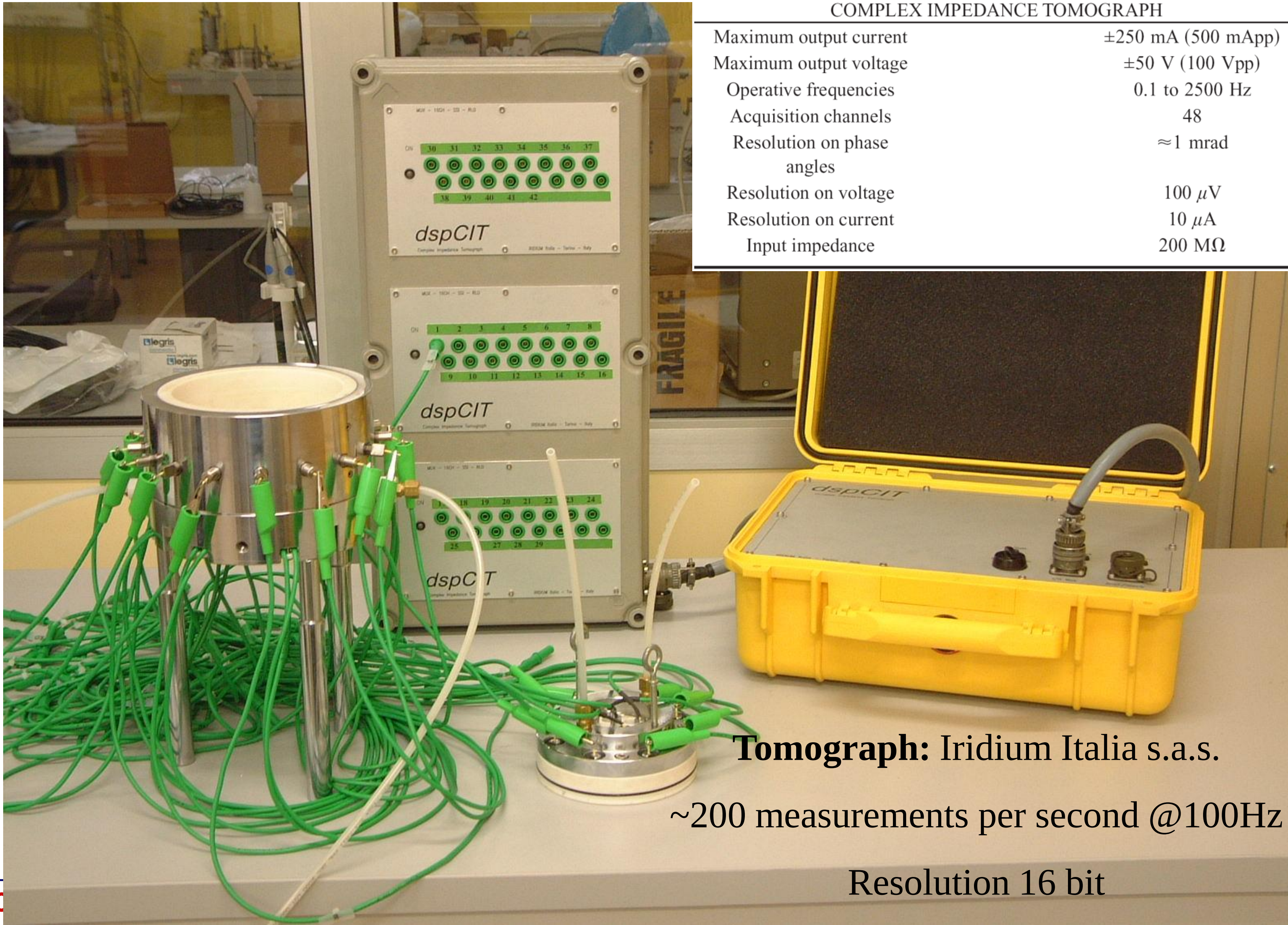
Seismic – electrical caps



(Comina et al., 2008)

ERT monitoring of hydro–chemo–mechanical processes in soil samples

COMPLEX IMPEDANCE TOMOGRAPH	
Maximum output current	±250 mA (500 mApp)
Maximum output voltage	±50 V (100 Vpp)
Operative frequencies	0.1 to 2500 Hz
Acquisition channels	48
Resolution on phase angles	≈1 mrad
Resolution on voltage	100 μV
Resolution on current	10 μA
Input impedance	200 MΩ

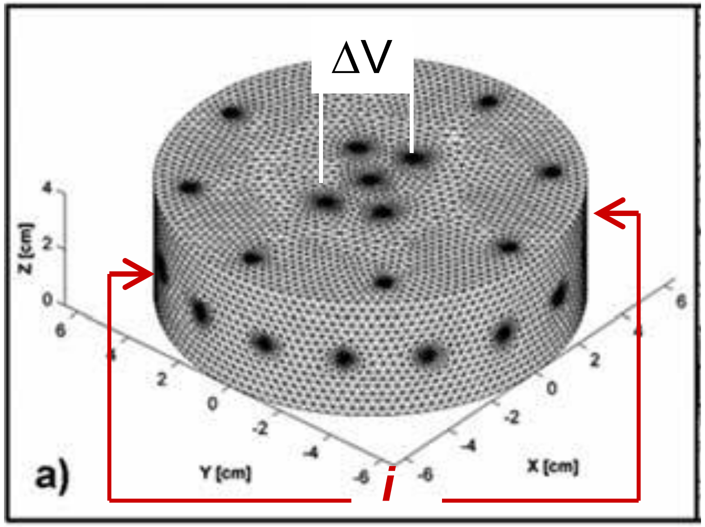


Tomograph: Iridium Italia s.a.s.

~200 measurements per second @100Hz

Resolution 16 bit

Acquisition protocol



(Comina et al., 2008)

Independent measurement (n=42 electrodes): N= $n(n-1)/2$=861

Protocol for the present study: 788 measurement

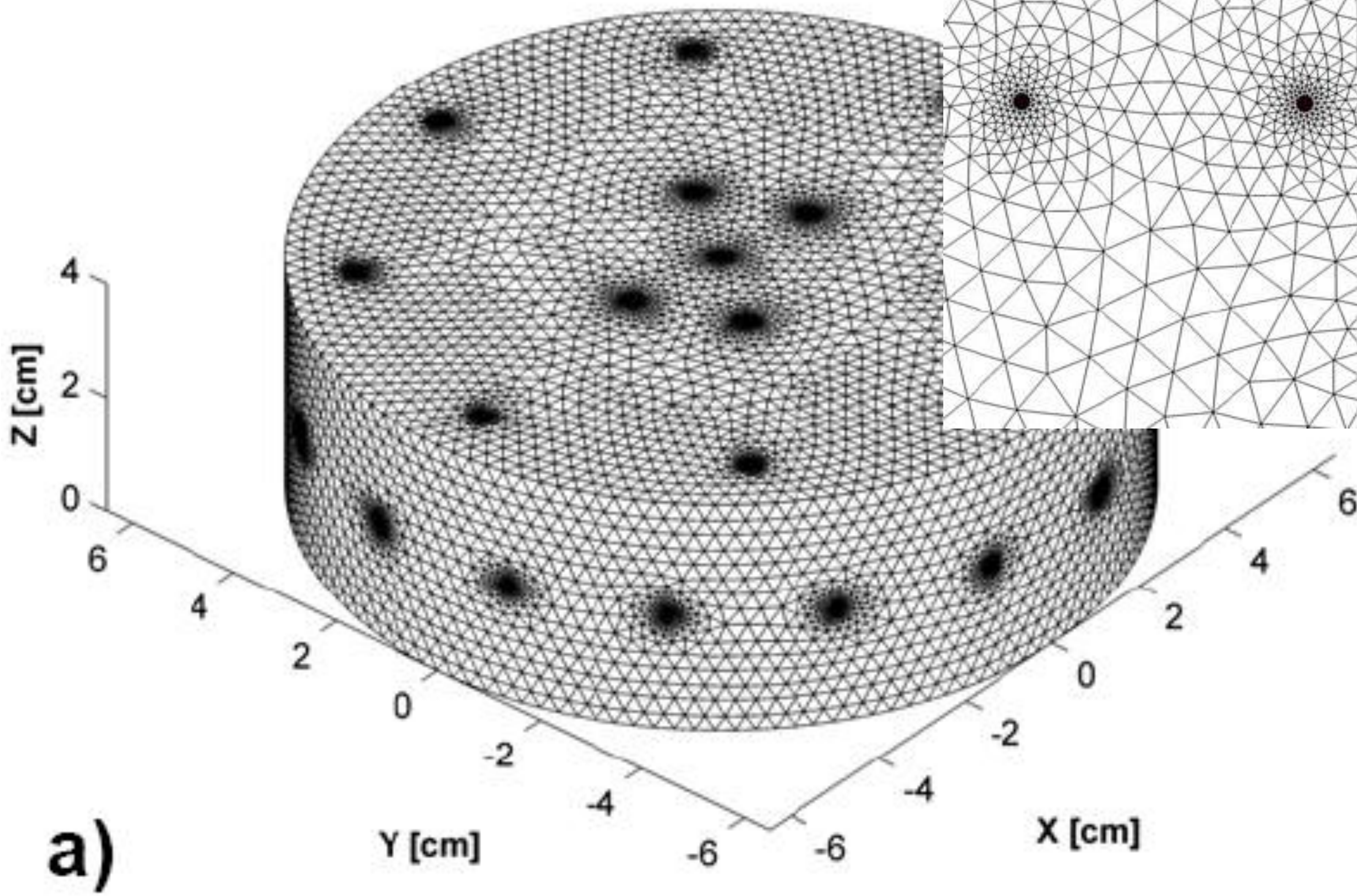
Forward model: FEM discretization of Maxwell Equation: $\nabla \cdot (\chi_t \nabla \phi) = 0$

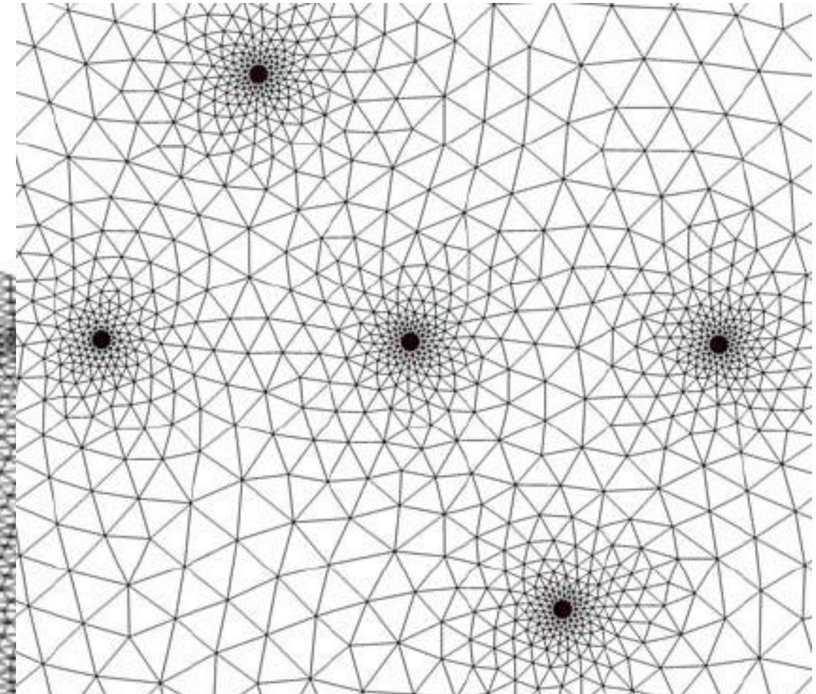
contact impedance soil-electrodes → need for modelling electrodes with their dimensions

Inversion: Least square algorithm with regularization

FEM Mesh

REFINED MESH FOR FORWARD PROBLEM SOLUTION





Reconstruction of the electrical conductivity: FEM and optimisation

Forward Problem:

Stationary form of Maxwell's equations:

$$\nabla \cdot (\chi \nabla \phi) = 0$$

Boundary conditions:

Measuring electrodes:

$$V_l = \phi + z_l \sigma \frac{\partial u}{\partial \vec{n}} \quad on \quad \partial\Omega_l, \quad l = 1,..,L$$

Injecting electrodes:

$$\int \sigma \frac{\partial \phi}{\partial \vec{n}} d\Omega = I_l$$

Cell walls:

$$\int \sigma \frac{\partial \phi}{\partial \vec{n}} d\Omega = 0$$

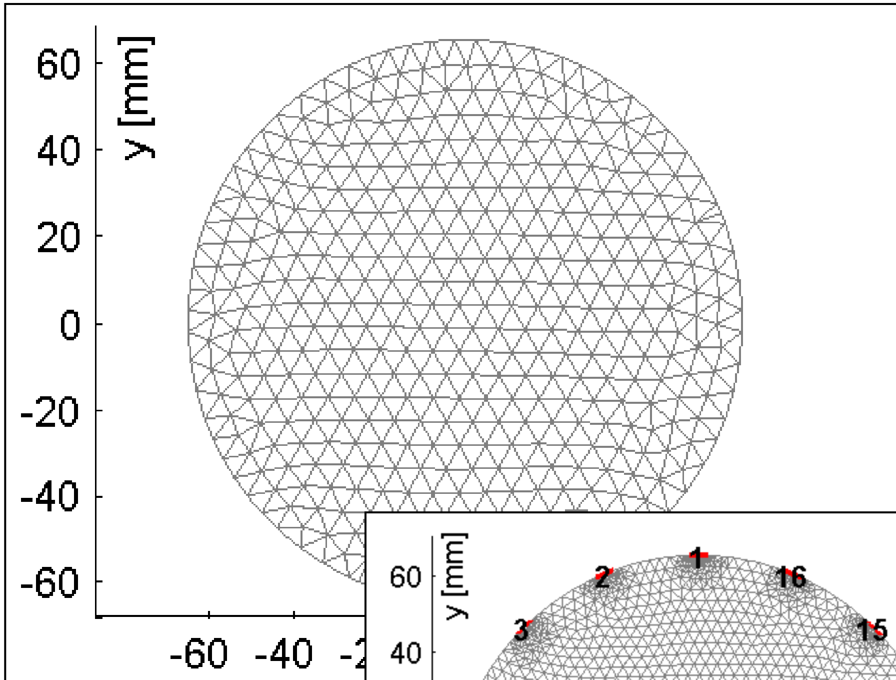
Inverse Problem:

$$\mathbf{s}_{rec} = \arg\min \left\{ \left\| h(\mathbf{s}) - z \right\|^2 + \alpha \left\| L\mathbf{s} \right\|^2 \right\}$$

- Synthetic data: $h(\mathbf{s})$
- Measured data: z
- Regularization Matrix discrete representation of the Laplacian: L
- Tikhonov factor: α

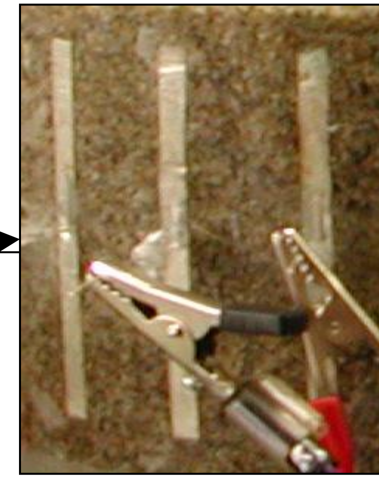
Borsic, 2002

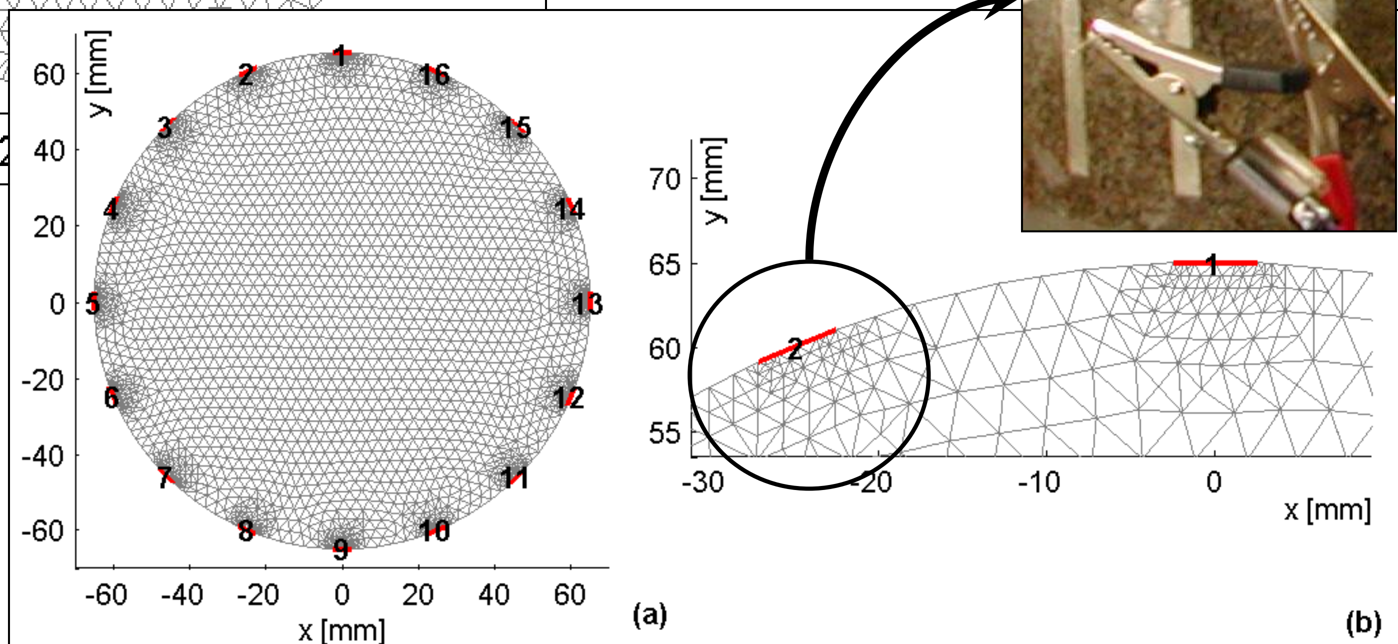
2D Mesh



COARSE MESH

REFINED MESH

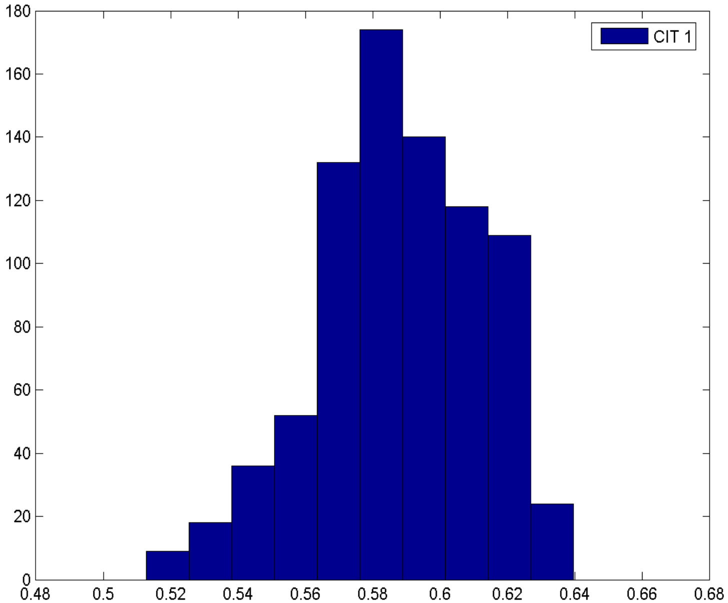




Reconstruction of the electrical conductivity: verification problems

Homogeneous sample

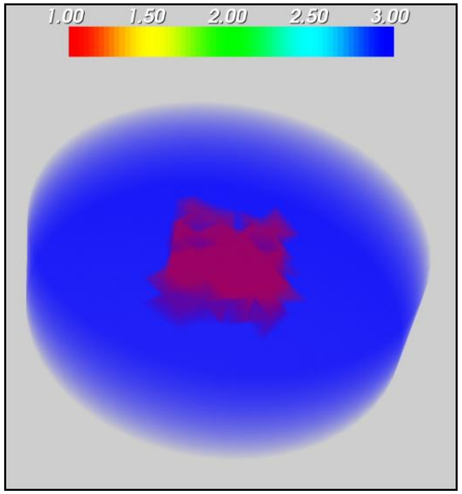
σ_{exact} = 0.580 mS/cm

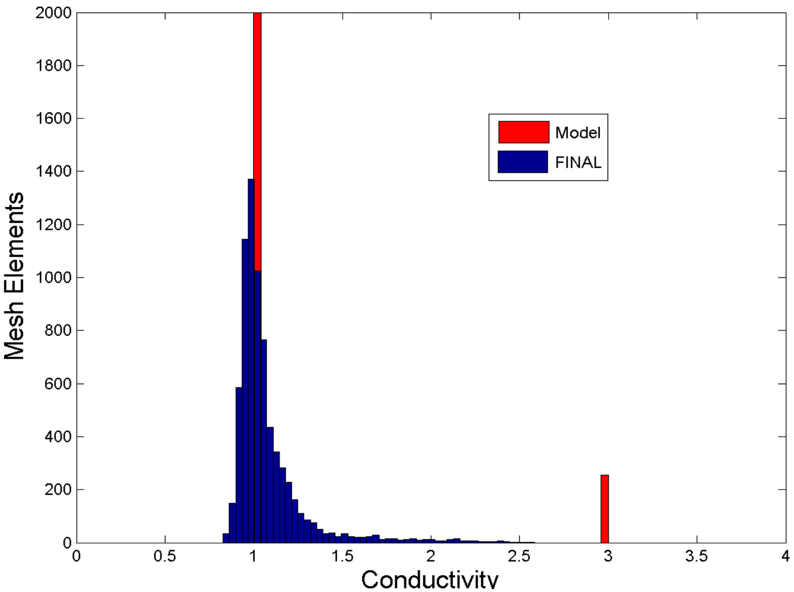


0.52 **0.64**

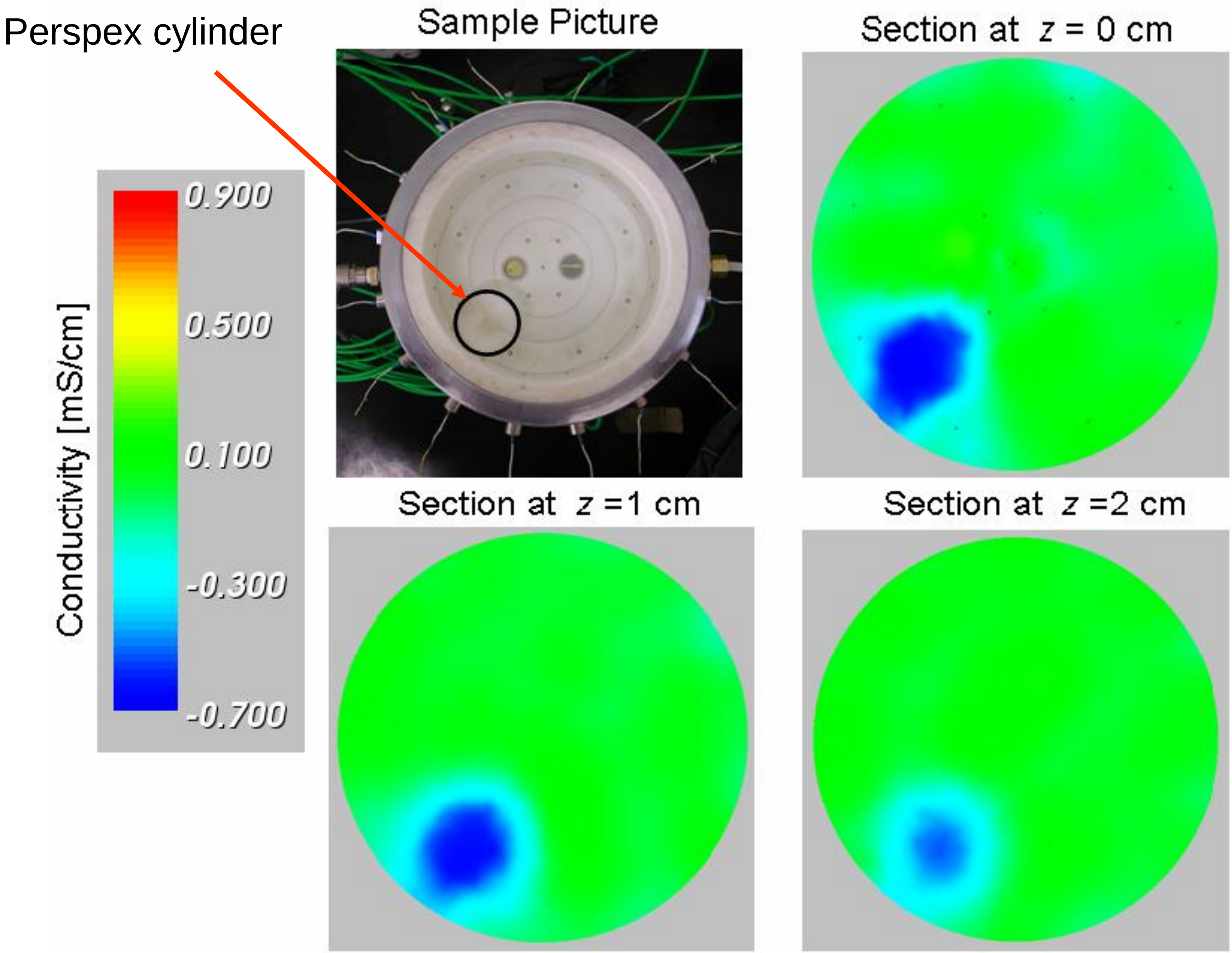
Average σ = 0.588 mS/cm

Sample with inclusion



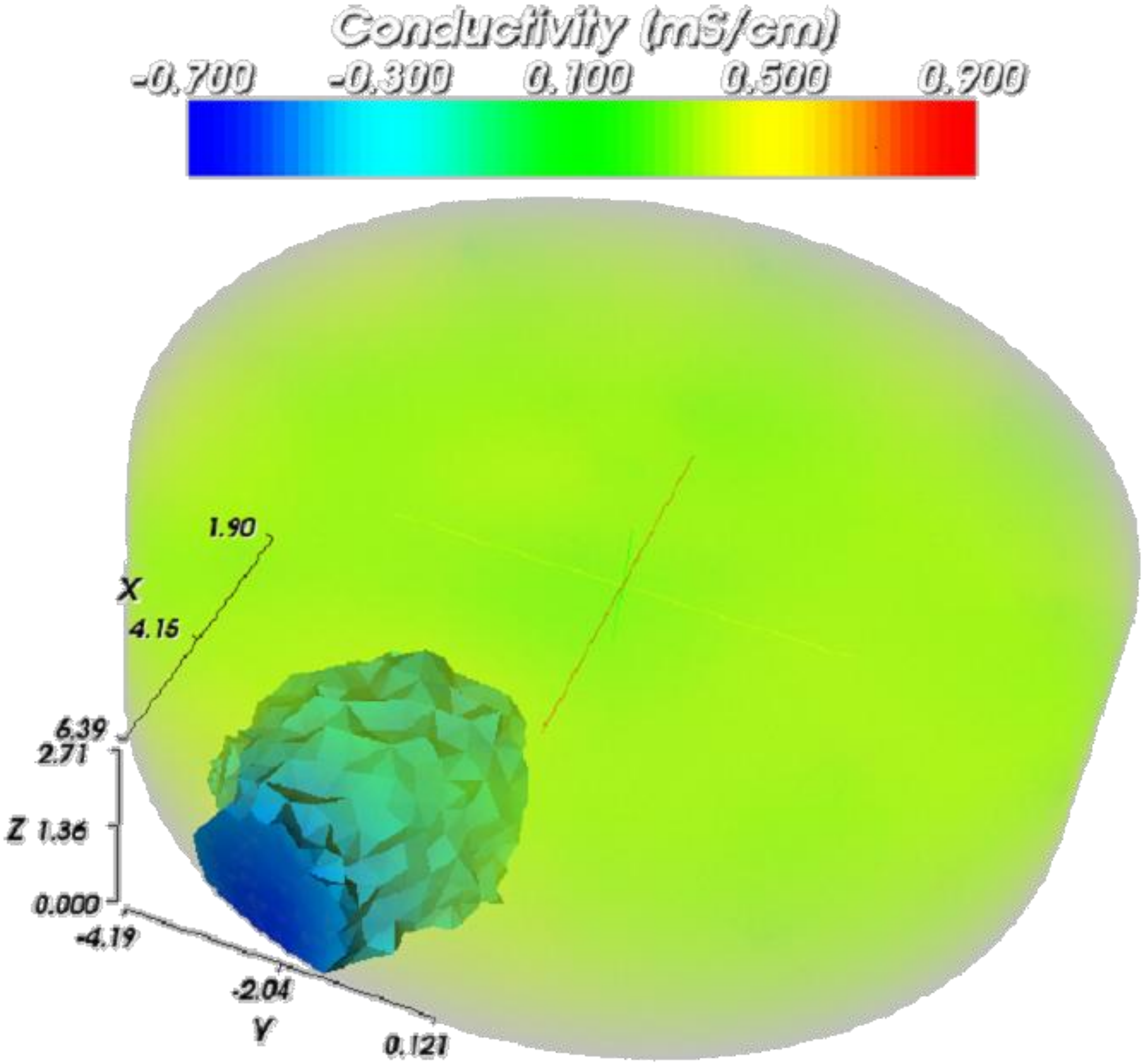


Benchmark test in water: Resistive inclusion

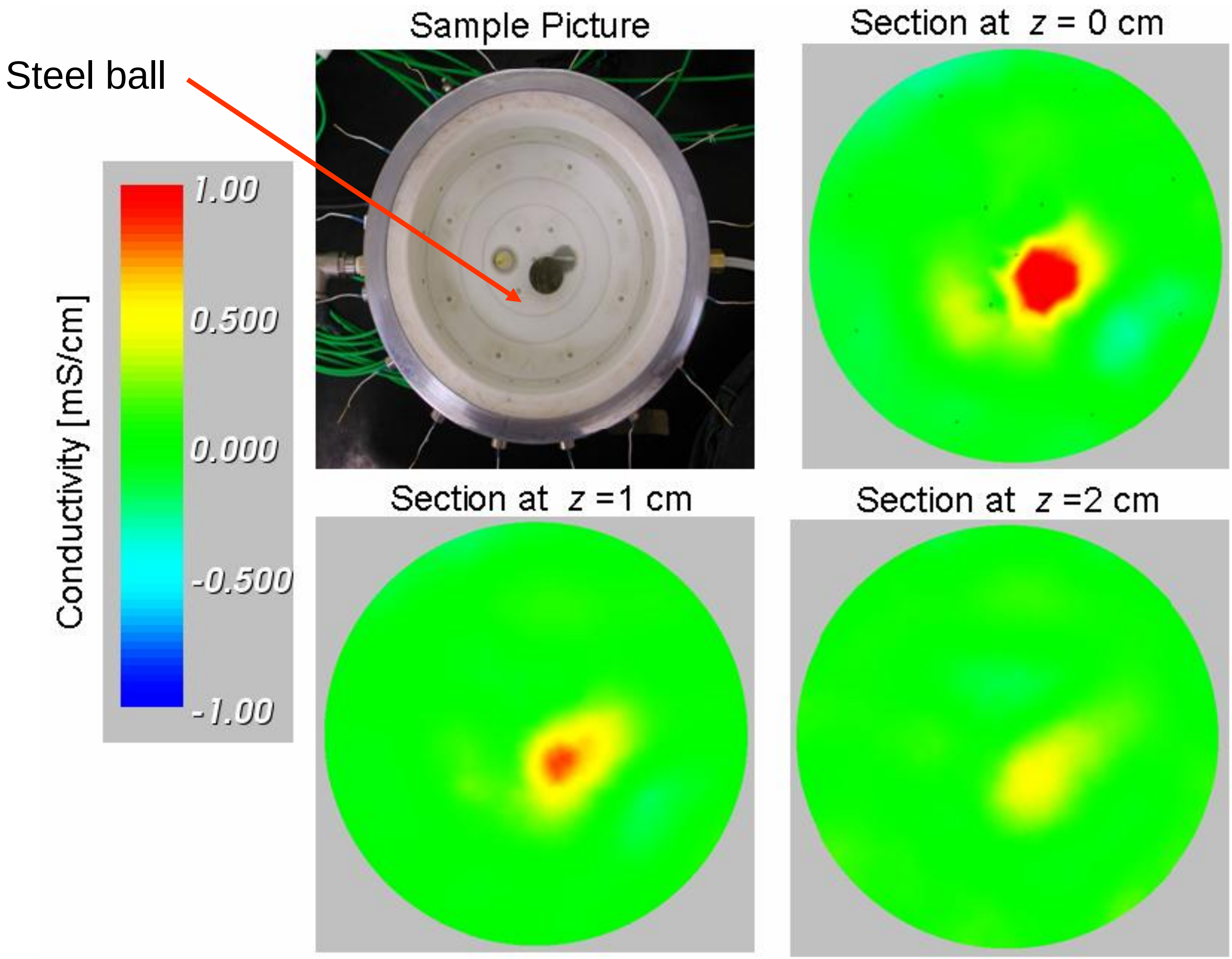


(Comina et al., 2008)

Benchmark test in water: Resistive inclusion



Benchmark test in water: Conductive inclusion

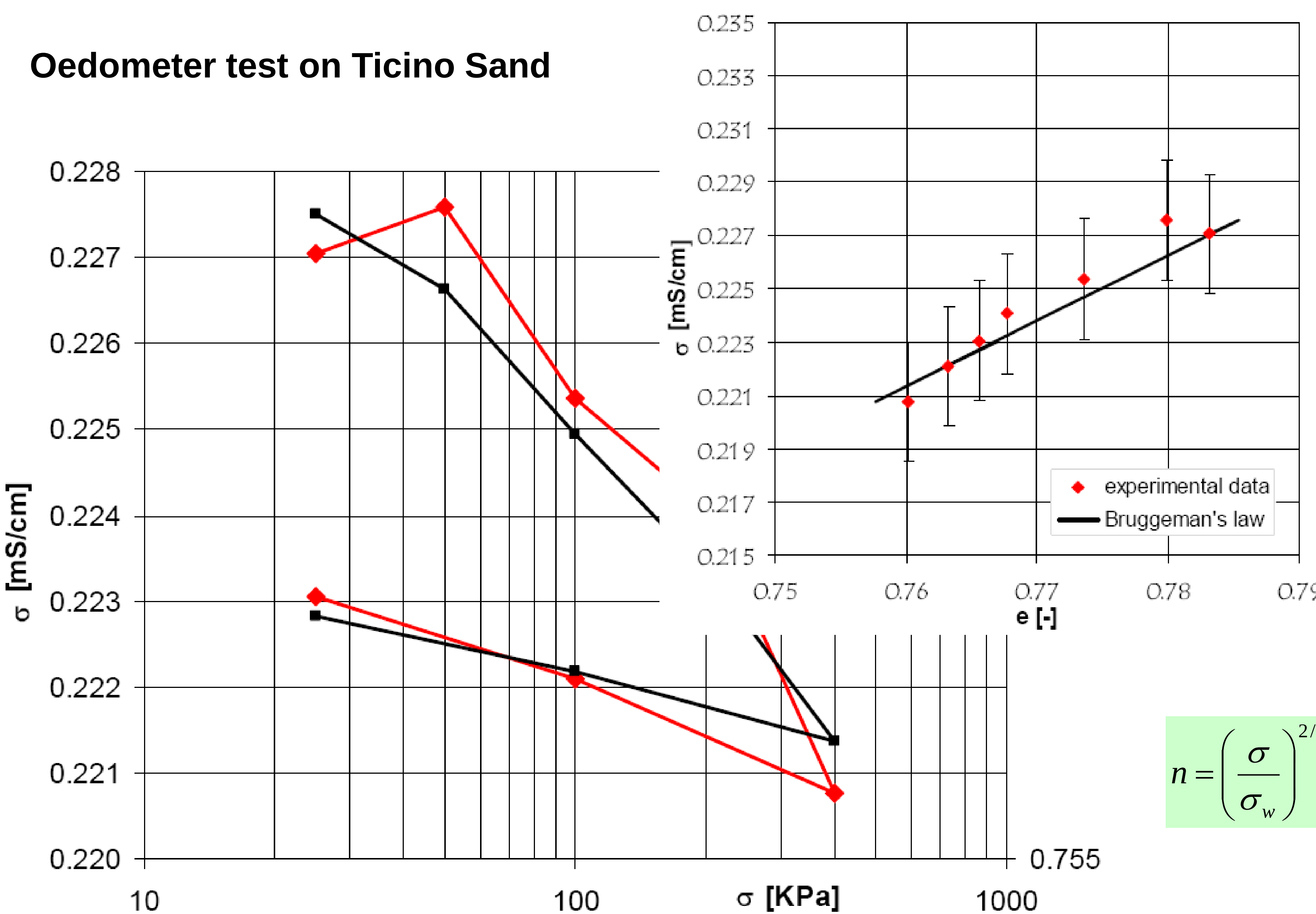


(Comina et al., 2008)

Outline

- Electrical conductivity of soils and literature applications
- EIT-oedometer: 3D tomography in the lab
- ERT as a tool for monitoring transient phenomena in soil samples
  - Mechanical Consolidation
  - Chemical Diffusion
  - Saturation/Desaturation
- Evaluation of soil model parameters for transport phenomena:
  - Diffusion
  - Saturation

Oedometer test on Ticino Sand

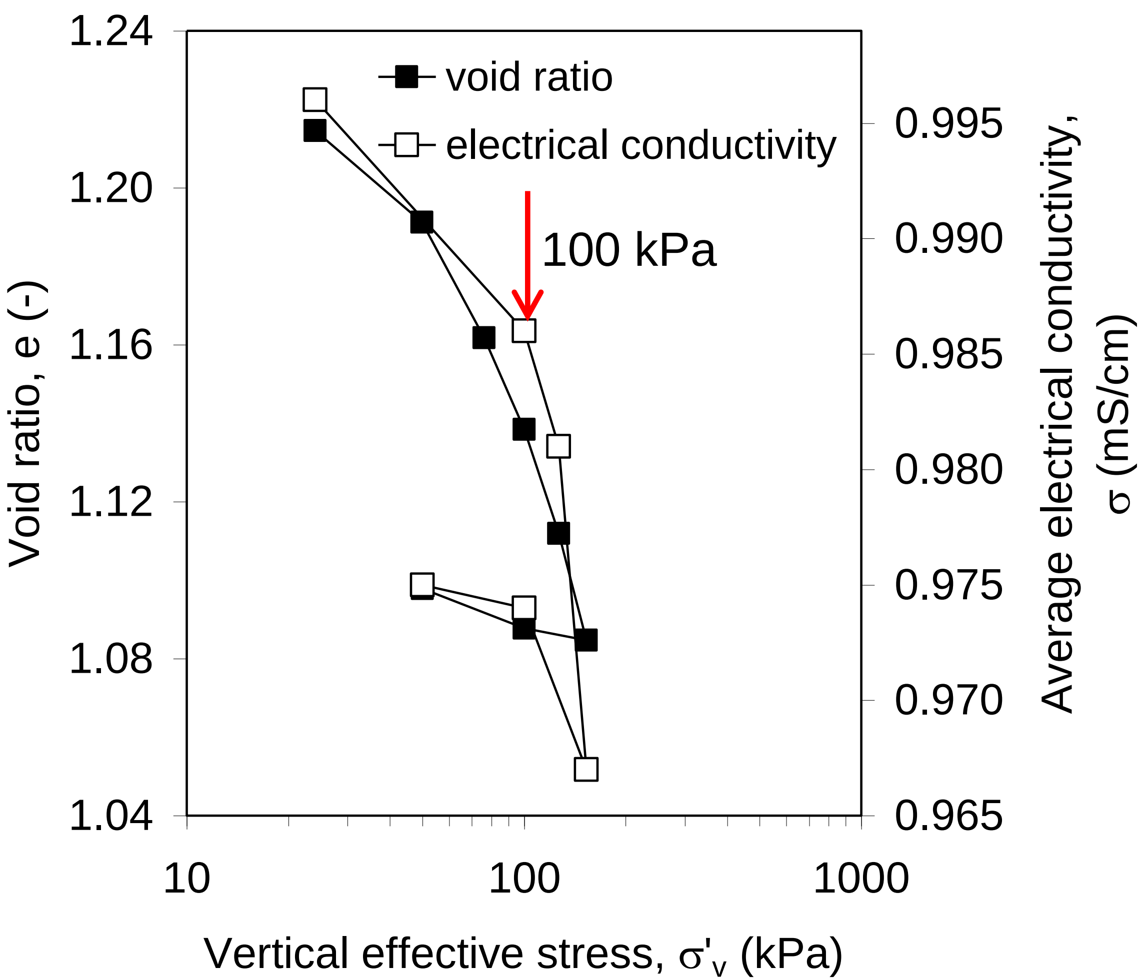


$$n = \left(\frac{\sigma}{\sigma_w} \right)^{2/3}$$

Oedometer test on Kaolinite (previously consolidated at 100 kPa)

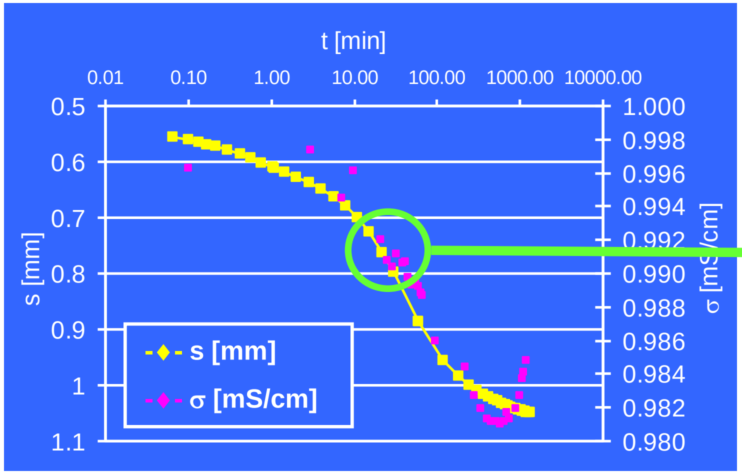
Oedometer curve

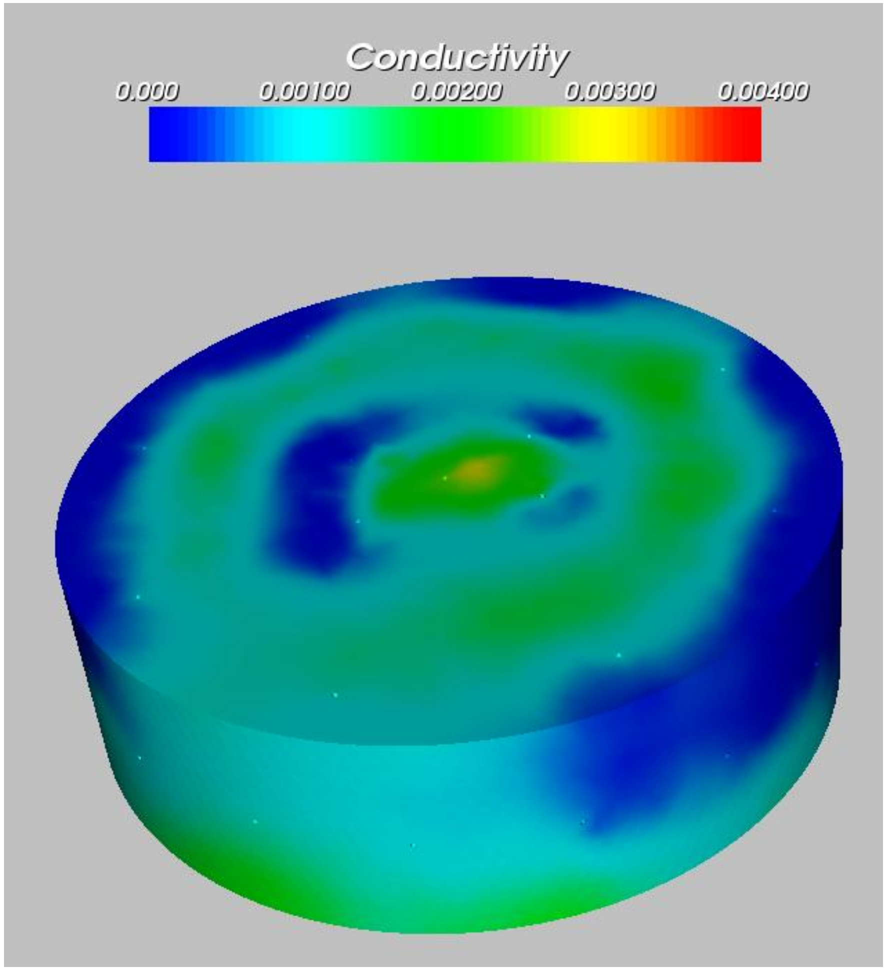
History effects seem to be more evident from electrical data than from displacement measurements



Oedometer test on Kaolin at 10 min

$$\Delta\sigma = \sigma_{t0} - \sigma_{t50}$$

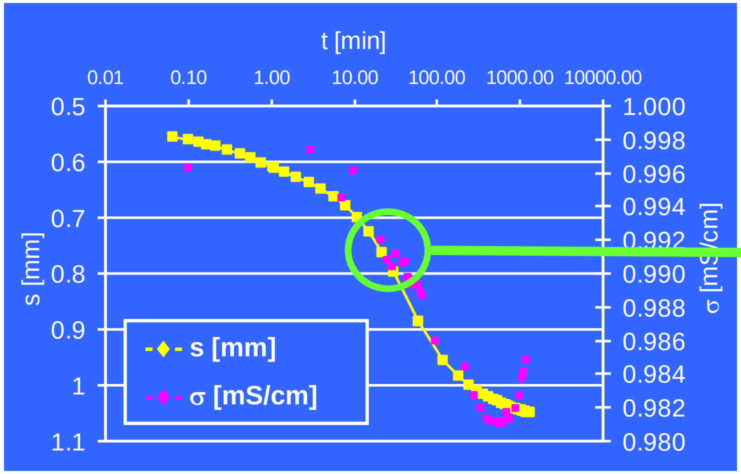


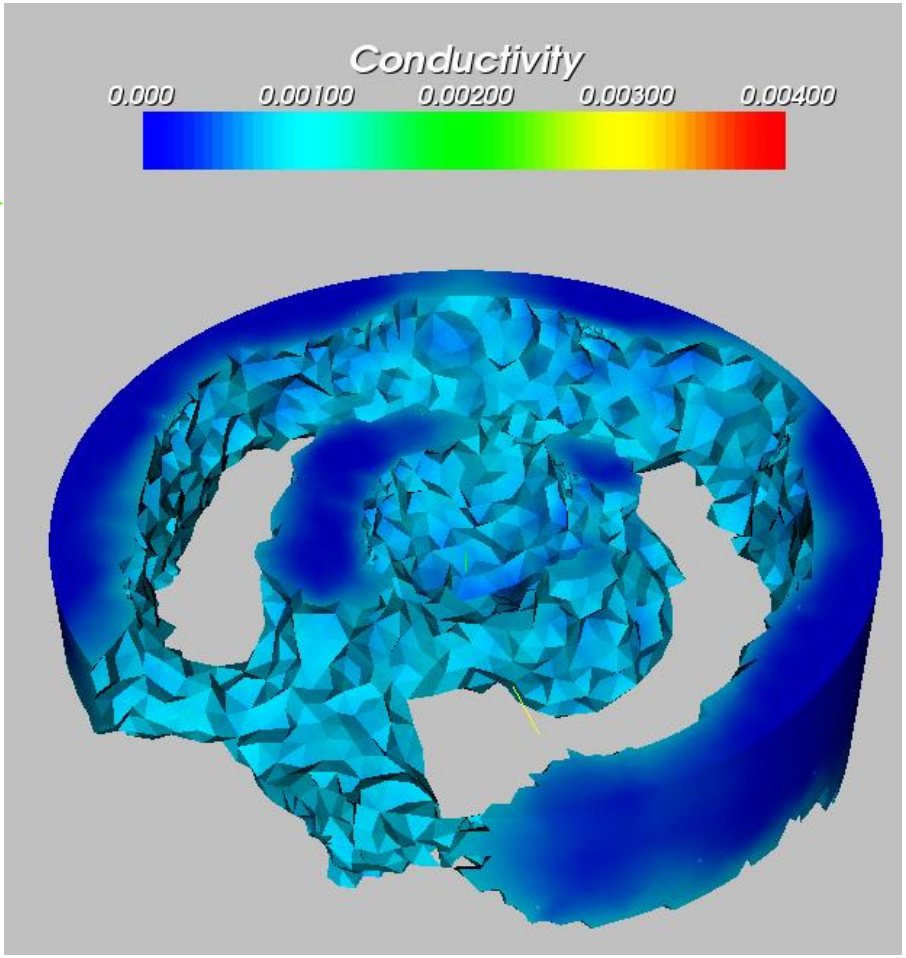


Lower conductivity areas located on the top cap (drainage allowed) represent lower porosity and thus consolidation

Oedometer test on Kaolin at 10 min

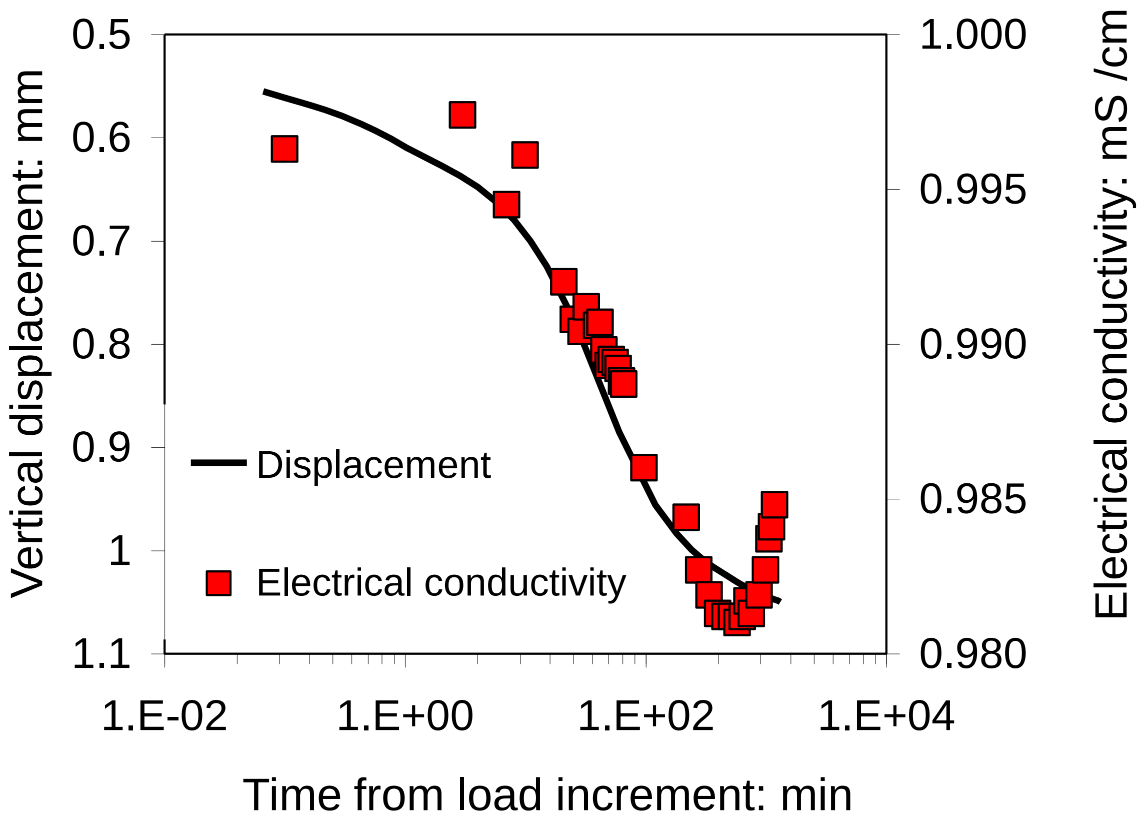
$$\Delta\sigma = \sigma_{t0} - \sigma_{t50}$$





Selected conductivity range (below 0.0015 mS/cm)
Represent areas of delayed consolidation inside the sample.

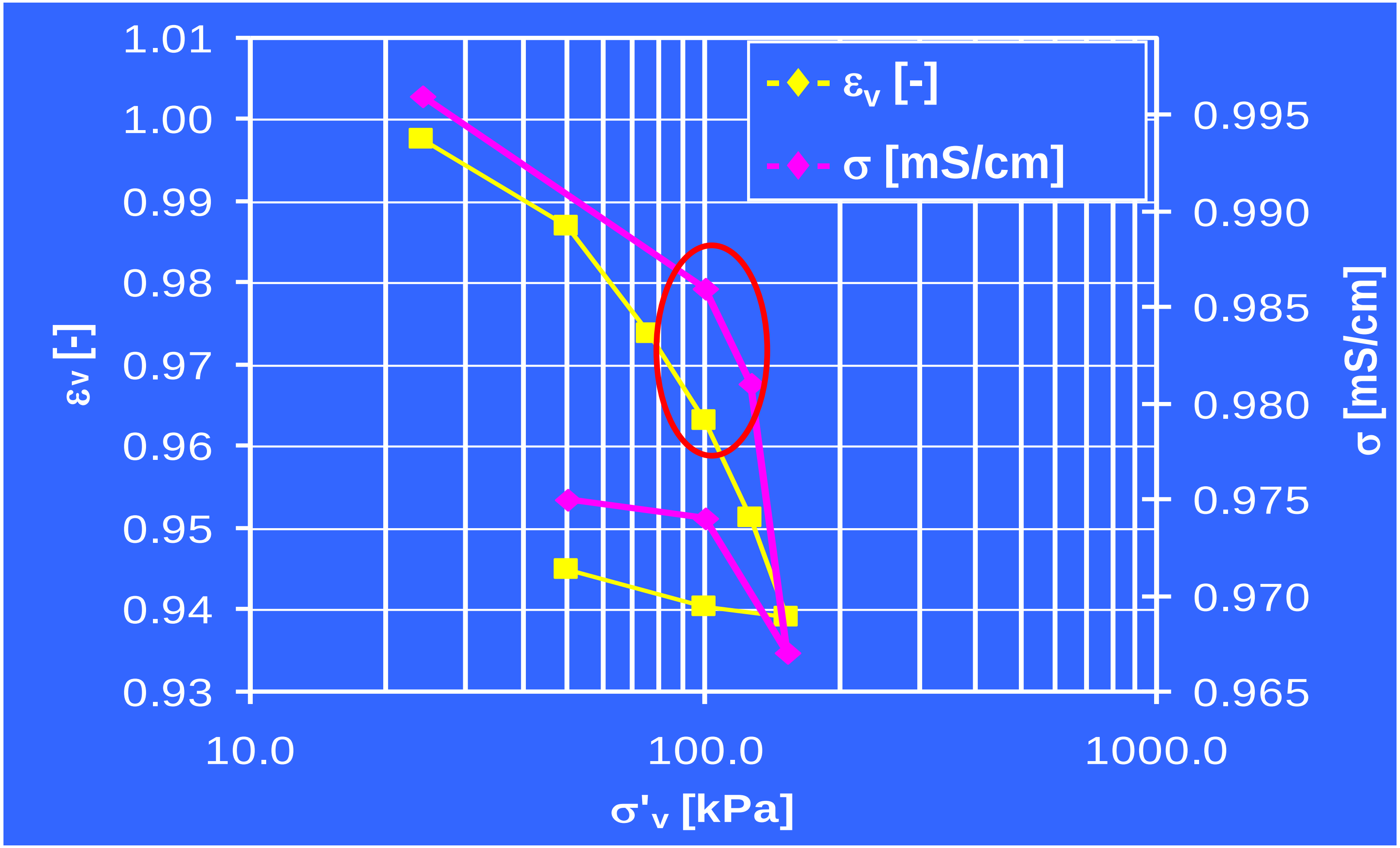
Oedometer test on Kaolin sample: load step



Time evolution of electrical conductivity in line with vertical displacements

The average electrical conductivity recovers slightly during secondary compression

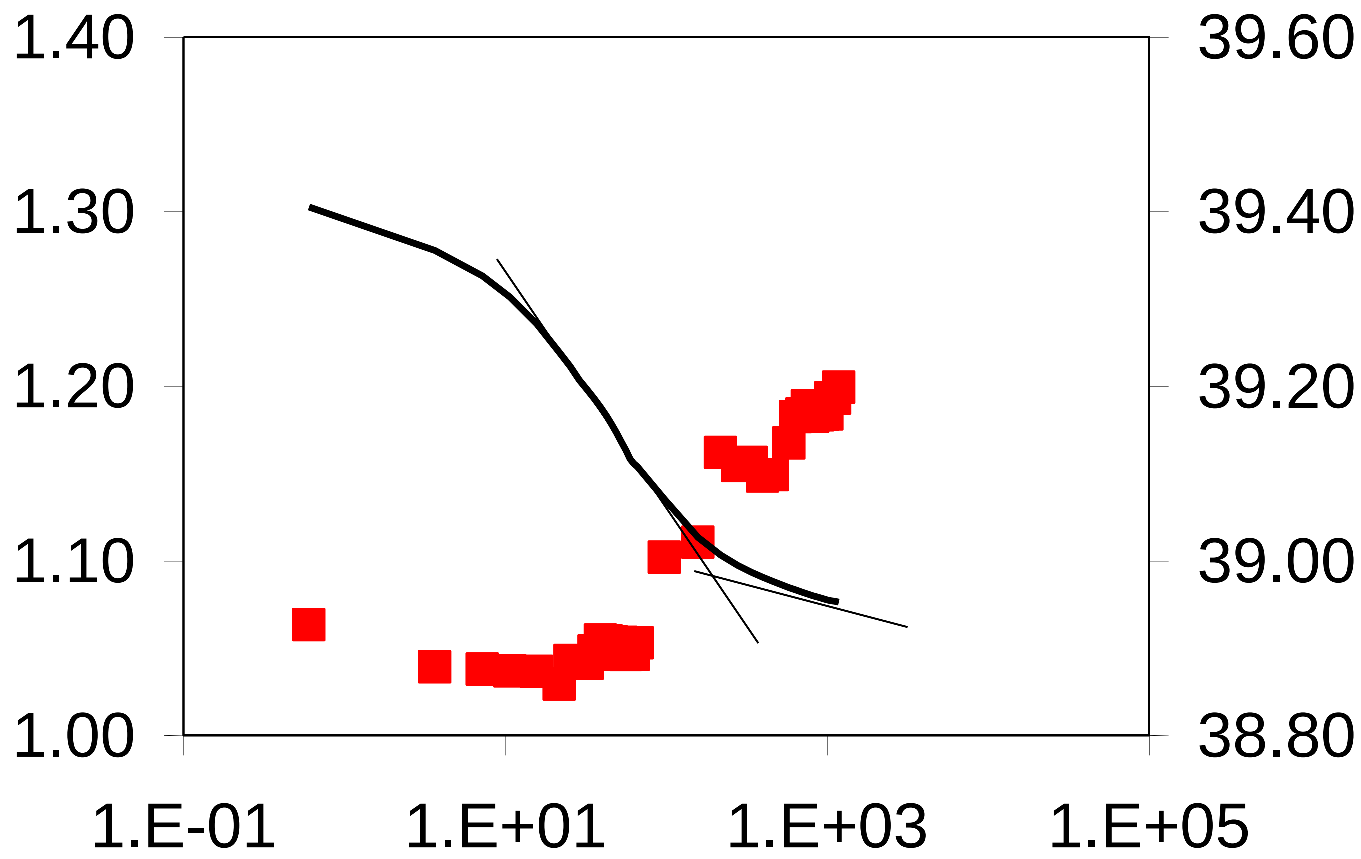
Oedometer test on Kaolin sample (preconsolidated 100 KPa)



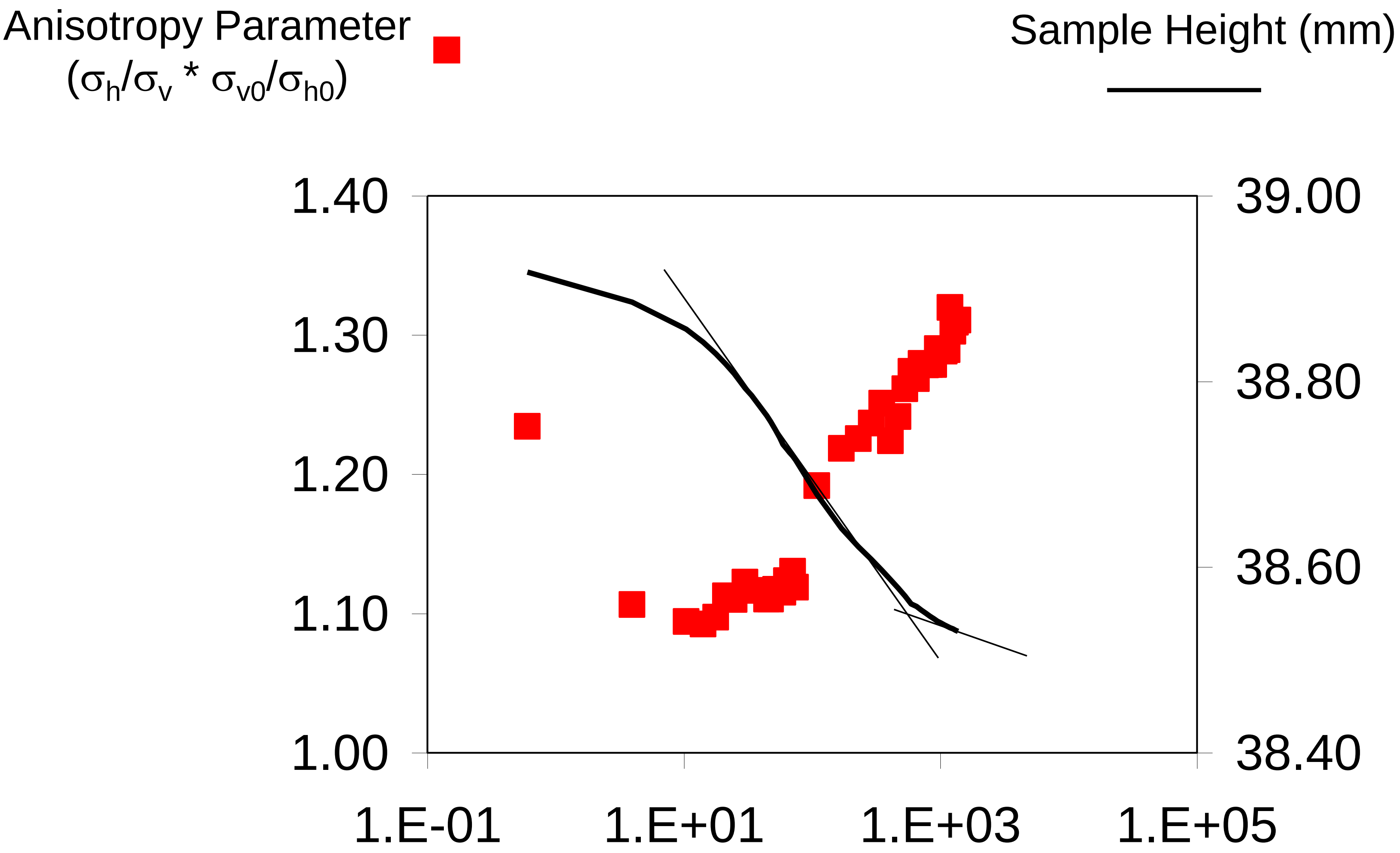
Interpretation of the load steps 50 – 75 kPa

Anisotropy Parameter ($\sigma_h/\sigma_v * \sigma_{v0}/\sigma_{h0}$)

Sample Height (mm)



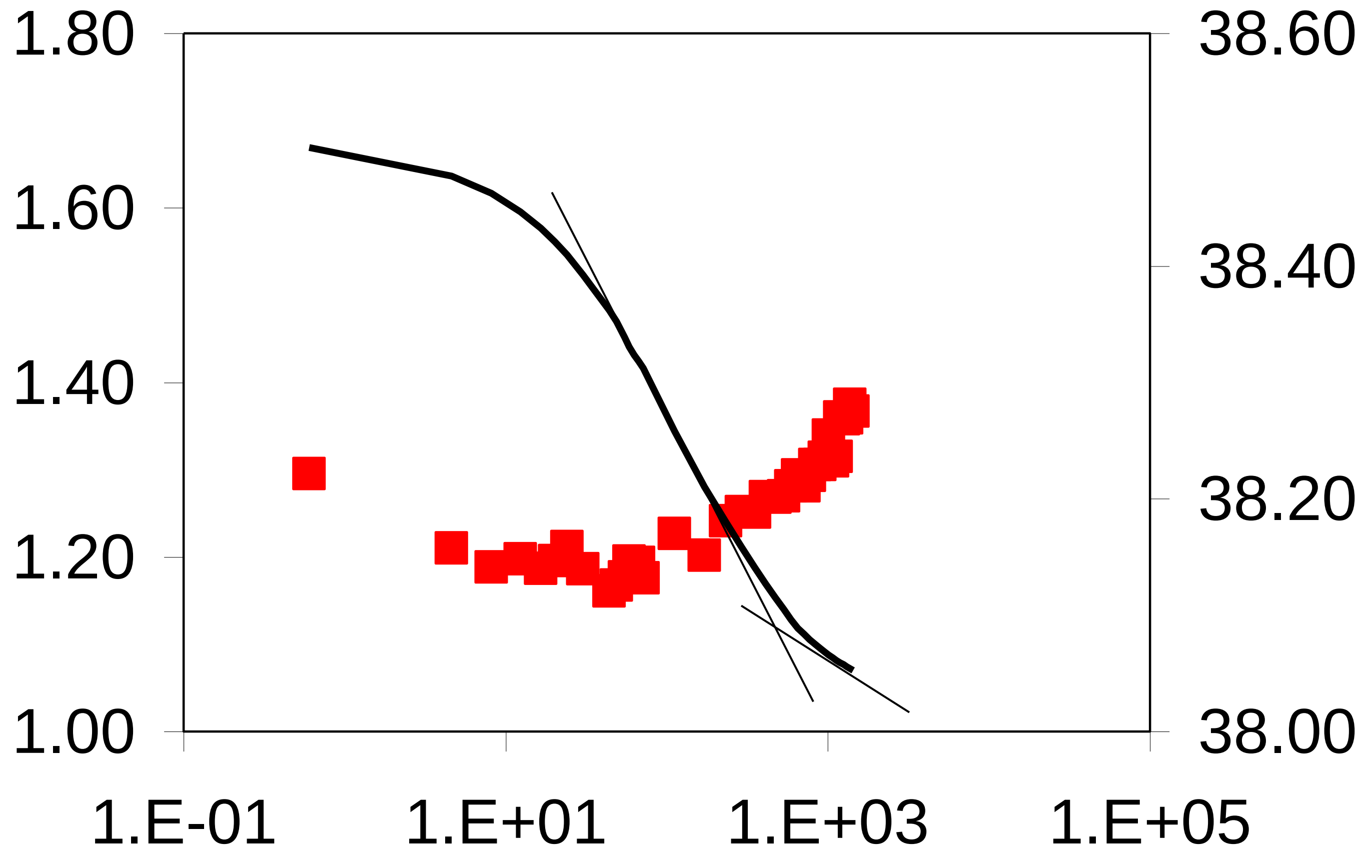
Interpretation of the load steps 75 – 100 kPa



Interpretation of the load steps 100 – 125 kPa

Anisotropy Parameter ($\sigma_h/\sigma_v * \sigma_{v0}/\sigma_{h0}$)

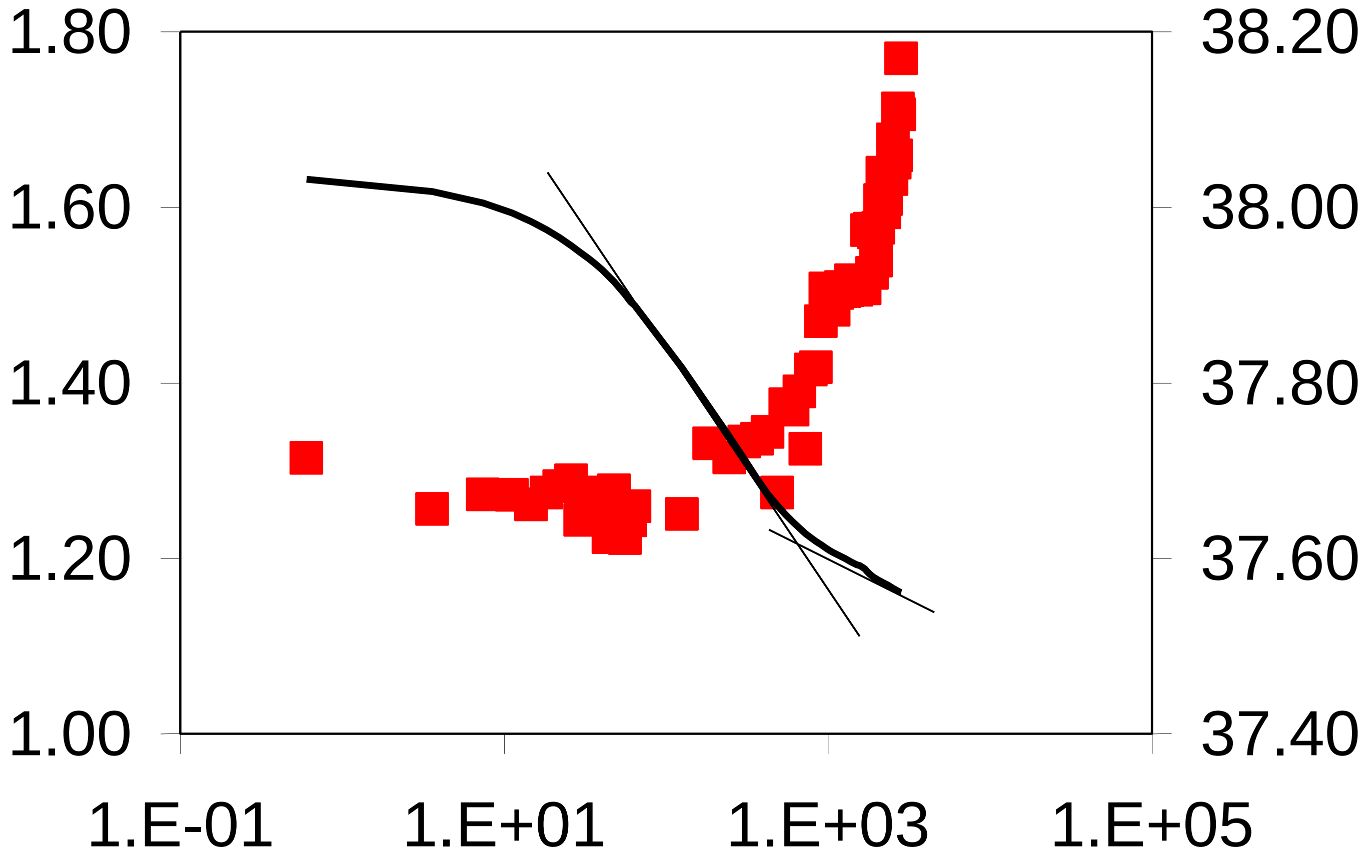
Sample Height (mm)



Interpretation of the load steps 125 – 150 kPa

Anisotropy Parameter ($\sigma_h/\sigma_v * \sigma_{v0}/\sigma_{h0}$)

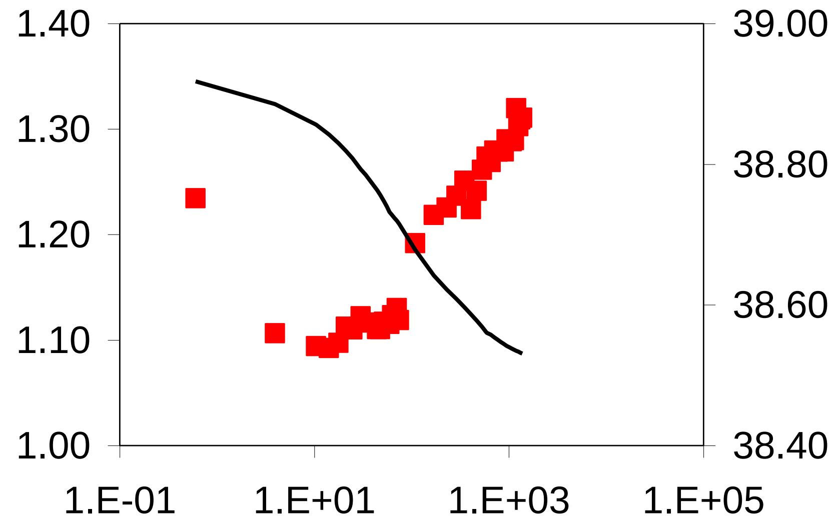
Sample Height (mm)

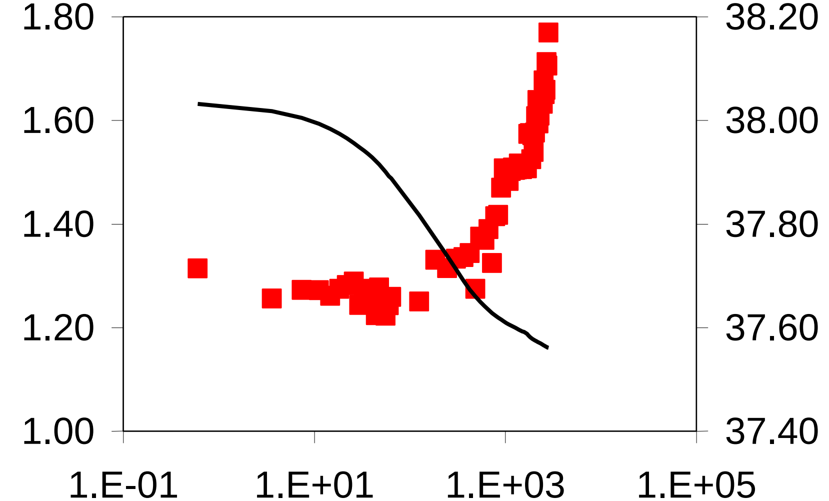


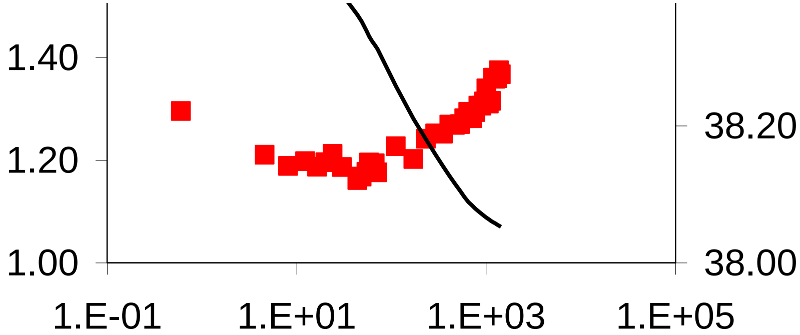
Interpretation of the load steps

Electrical anisotropy appears to **decrease first** and **increase afterwards** (mainly during secondary compression)

Results would suggest that in latter phases of consolidation clay particles tend to align more hortogonally to the direction of load







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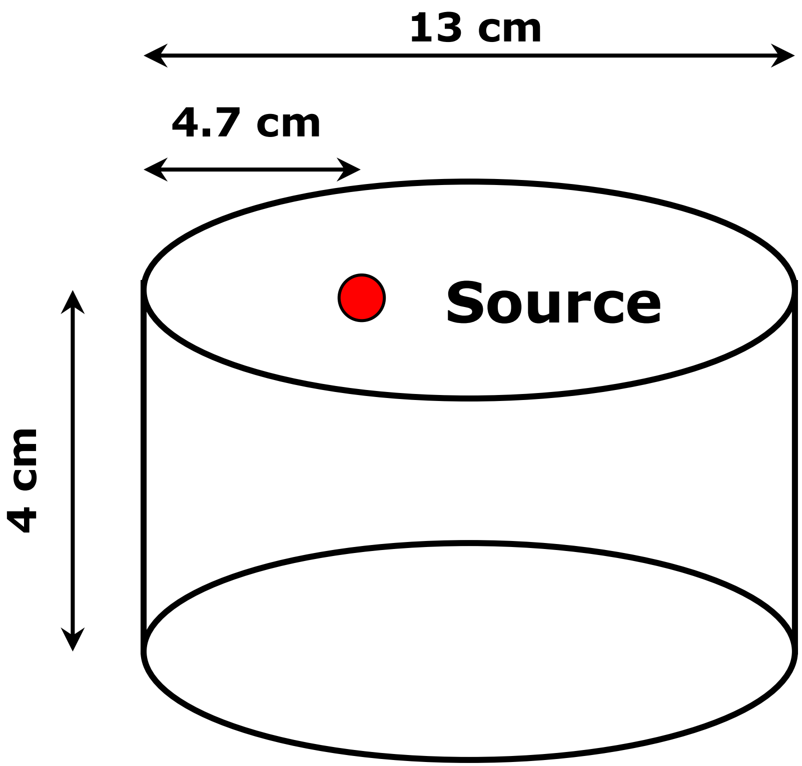
  - Chemical Diffusion
  - Saturation/Desaturation
- Use of the results for evaluation of soil model parameters for transport phenomena:
  - Diffusion
  - Saturation

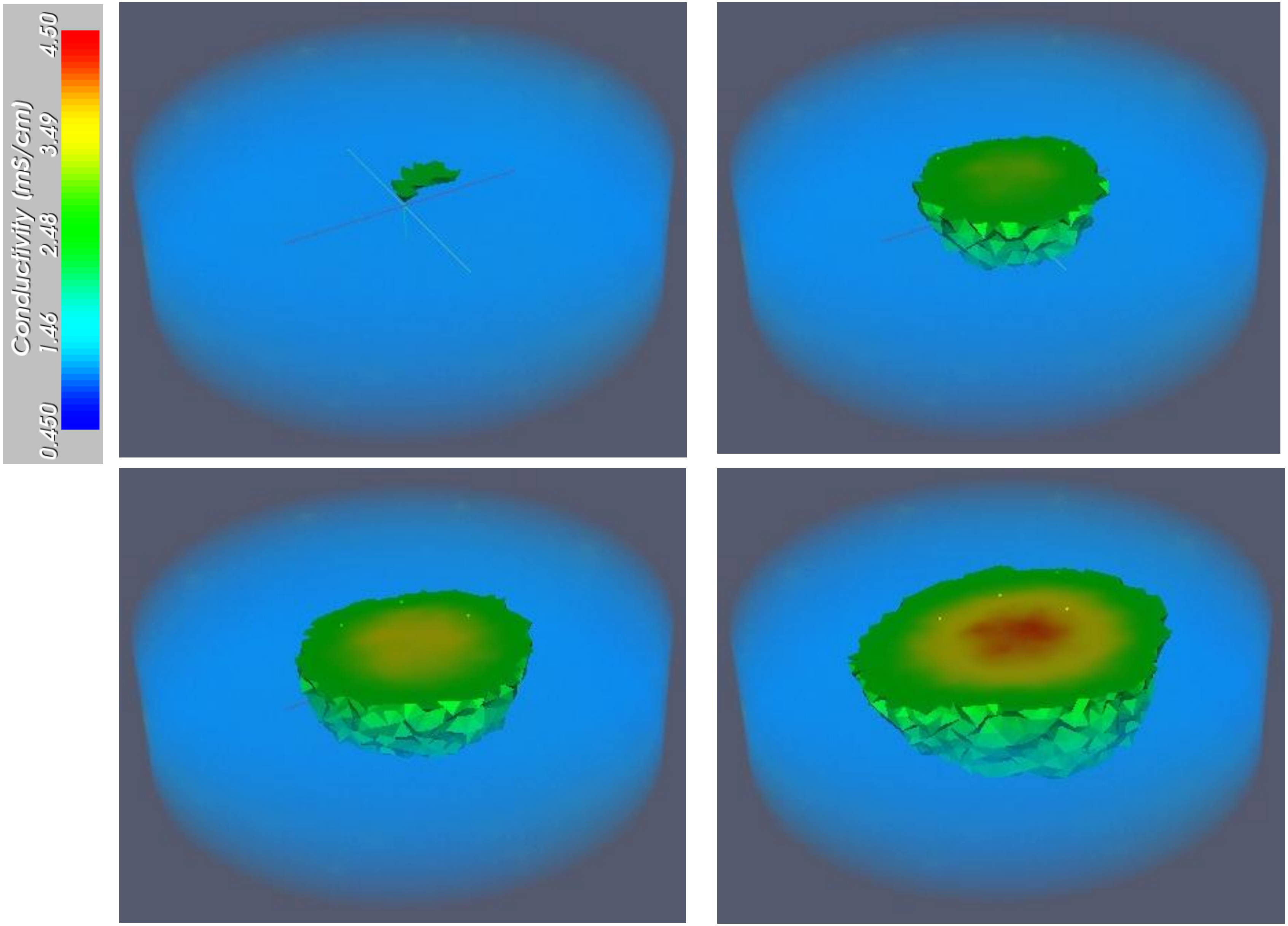
Diffusion in Uniform Ticino Sand Sample

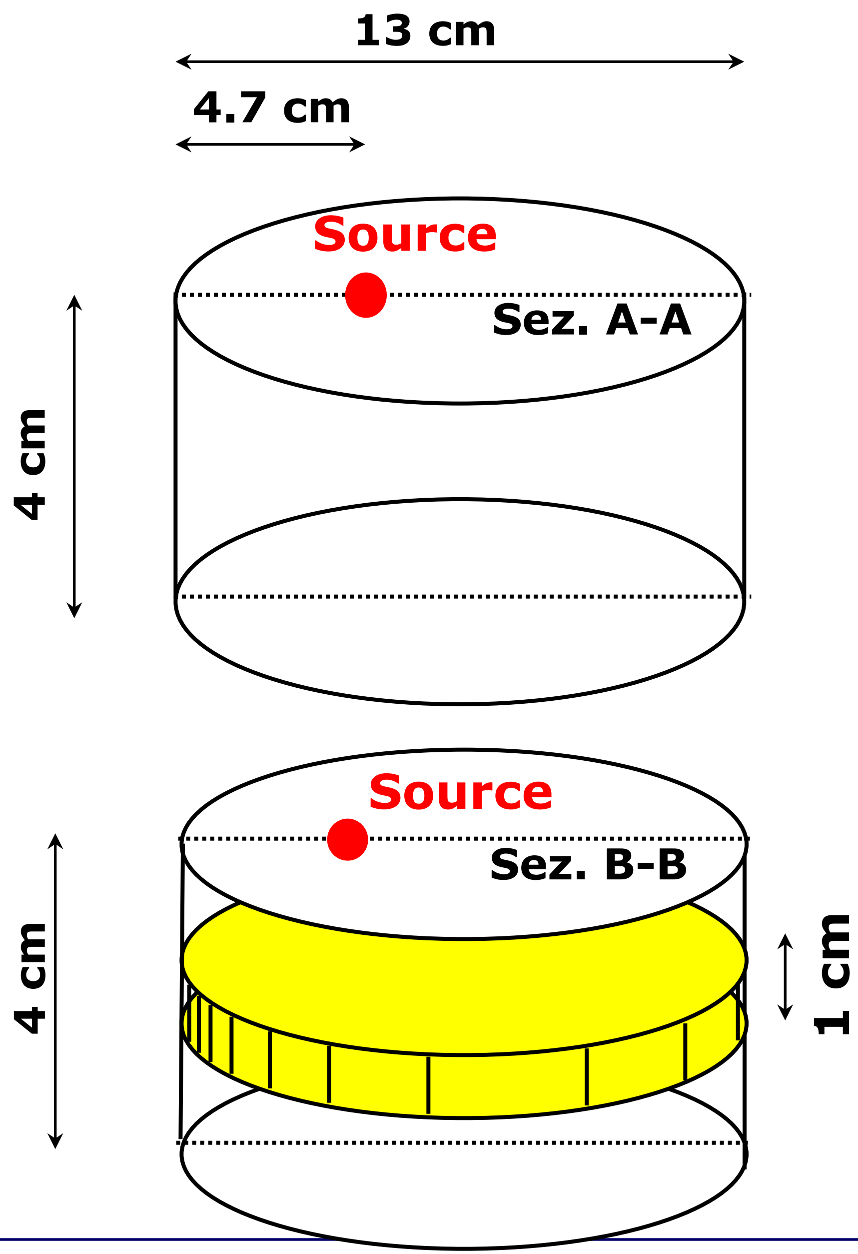


Sample
Ticino Sand
compacted at about
80% Relative Density
(n=0.4)

Source
Pure NaCl (molecular mass 58.443 kg/kmol)
Solution Saturation limit ~ 6M
kept constant during the whole test

Diffusion in Uniform Ticino Sand Sample



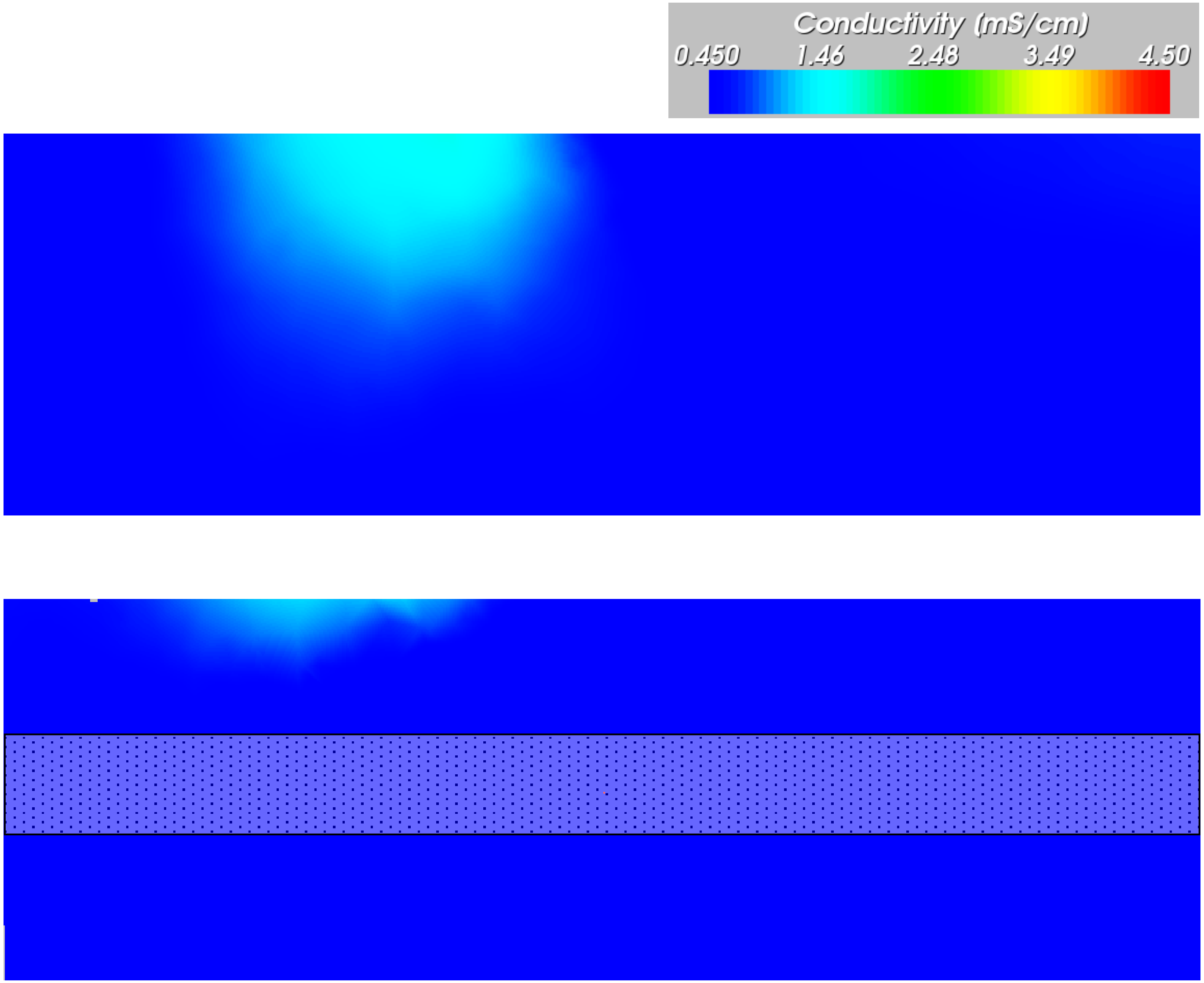


Ticino Sand n = 0.40

Kaolin n = 0.50

Grains of NaCl→ c = 350 g/l [6 M]

20’



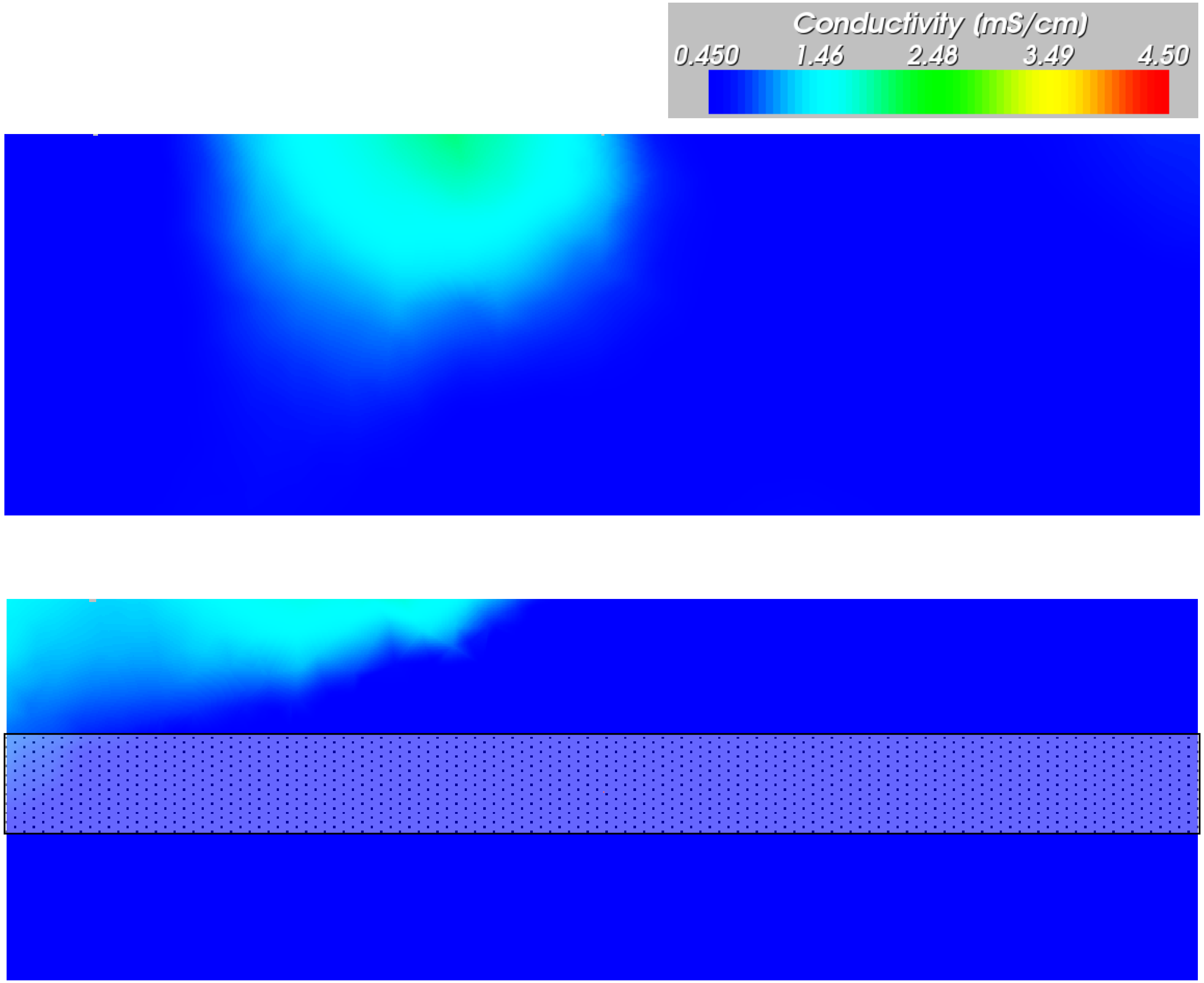
HOMOGENEOUS

HETEROGENEOUS

30'

HOMOGENEOUS

HETEROGENEOUS



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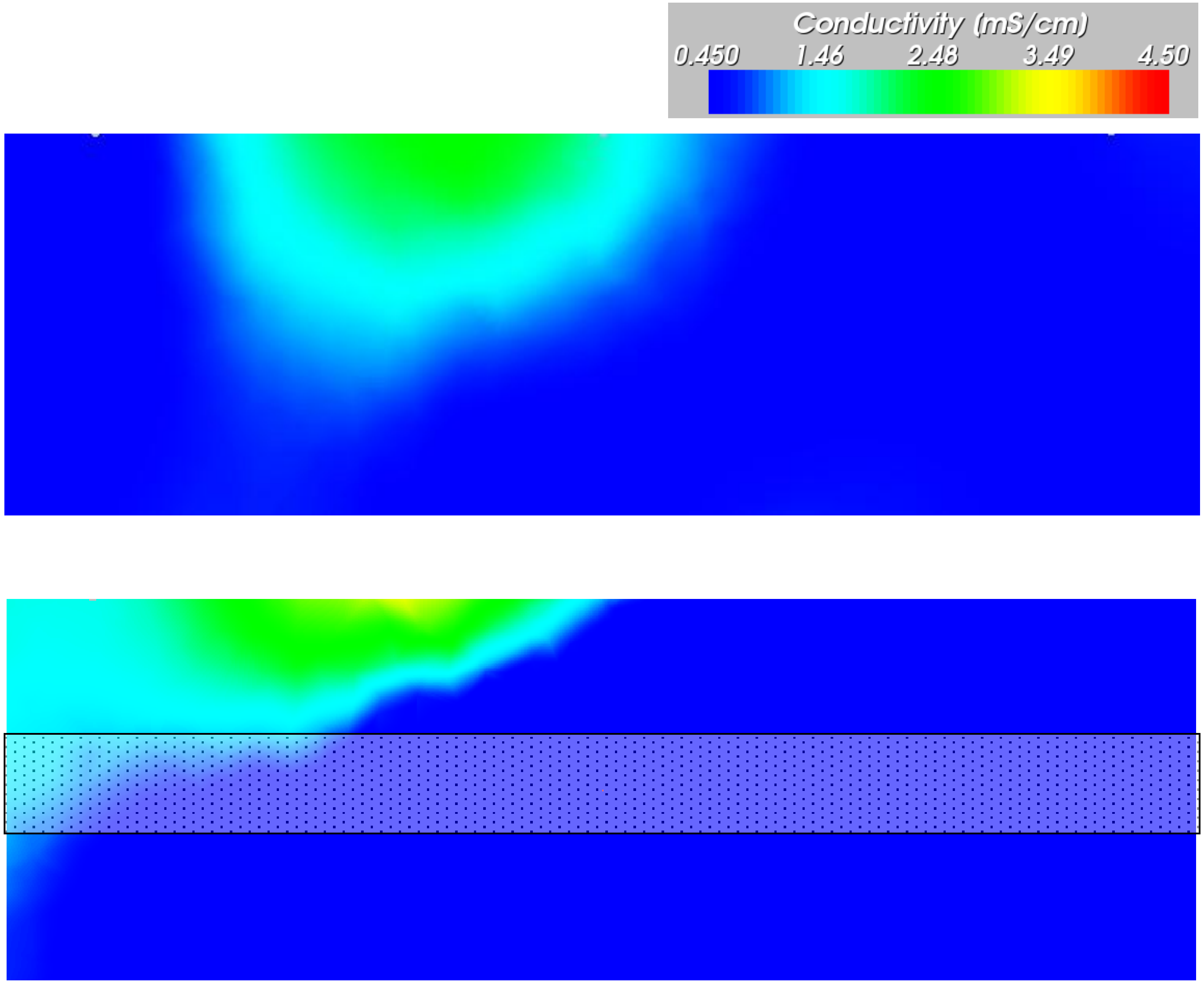

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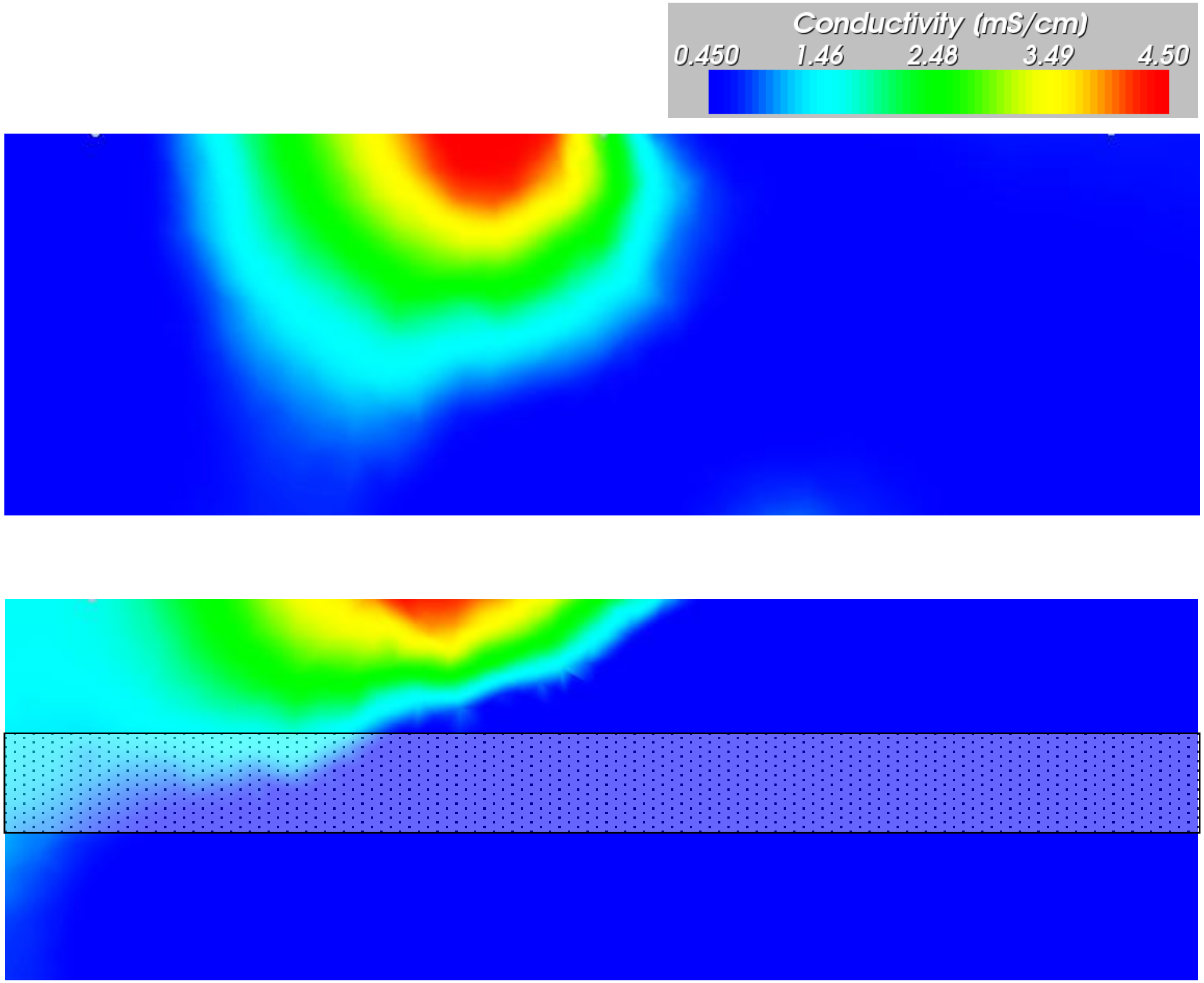
HETEROGENOUS

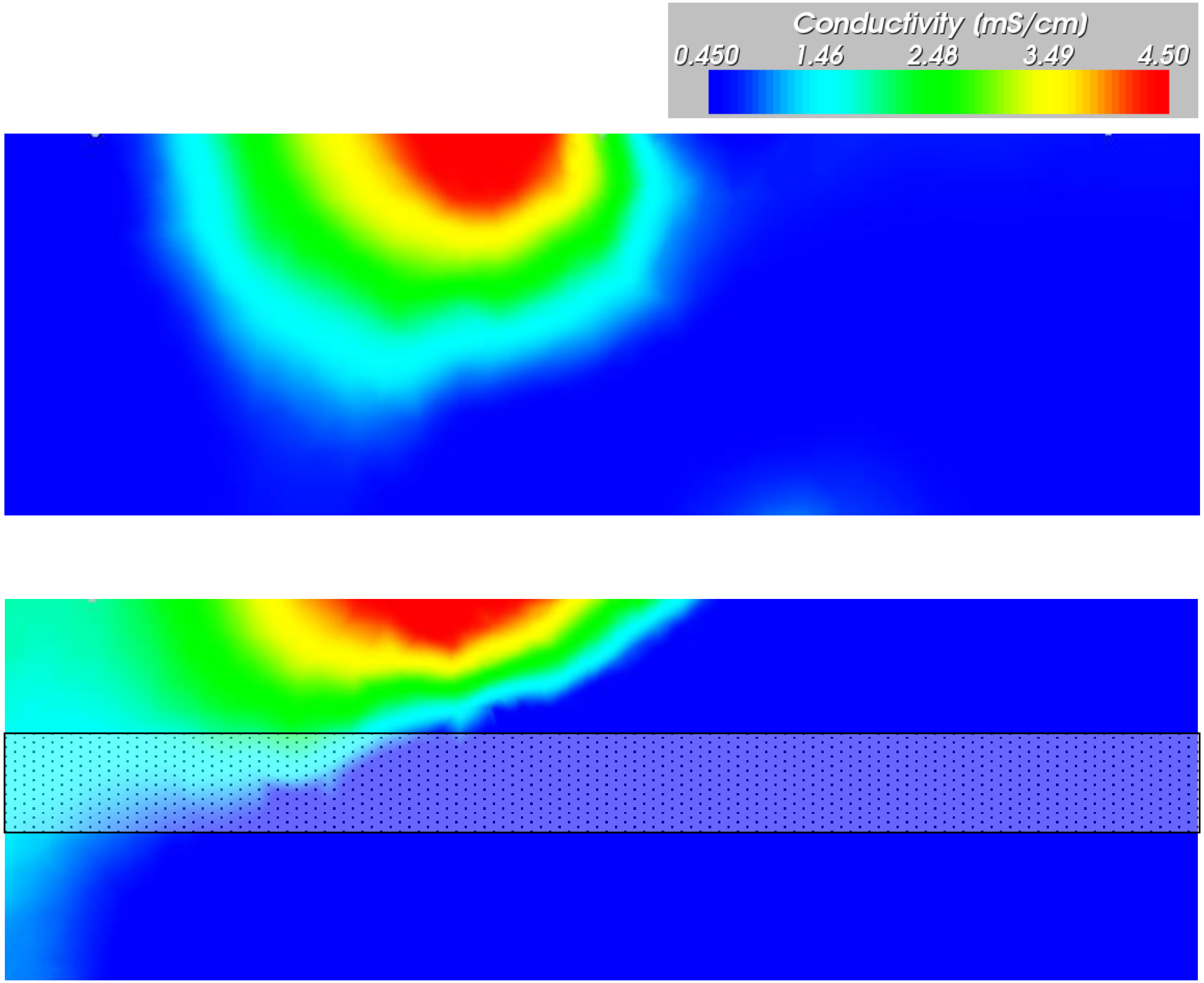
64’

HOMOGENEOUS

HETEROGENEOUS



82'



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90’

HOMOGENEOUS

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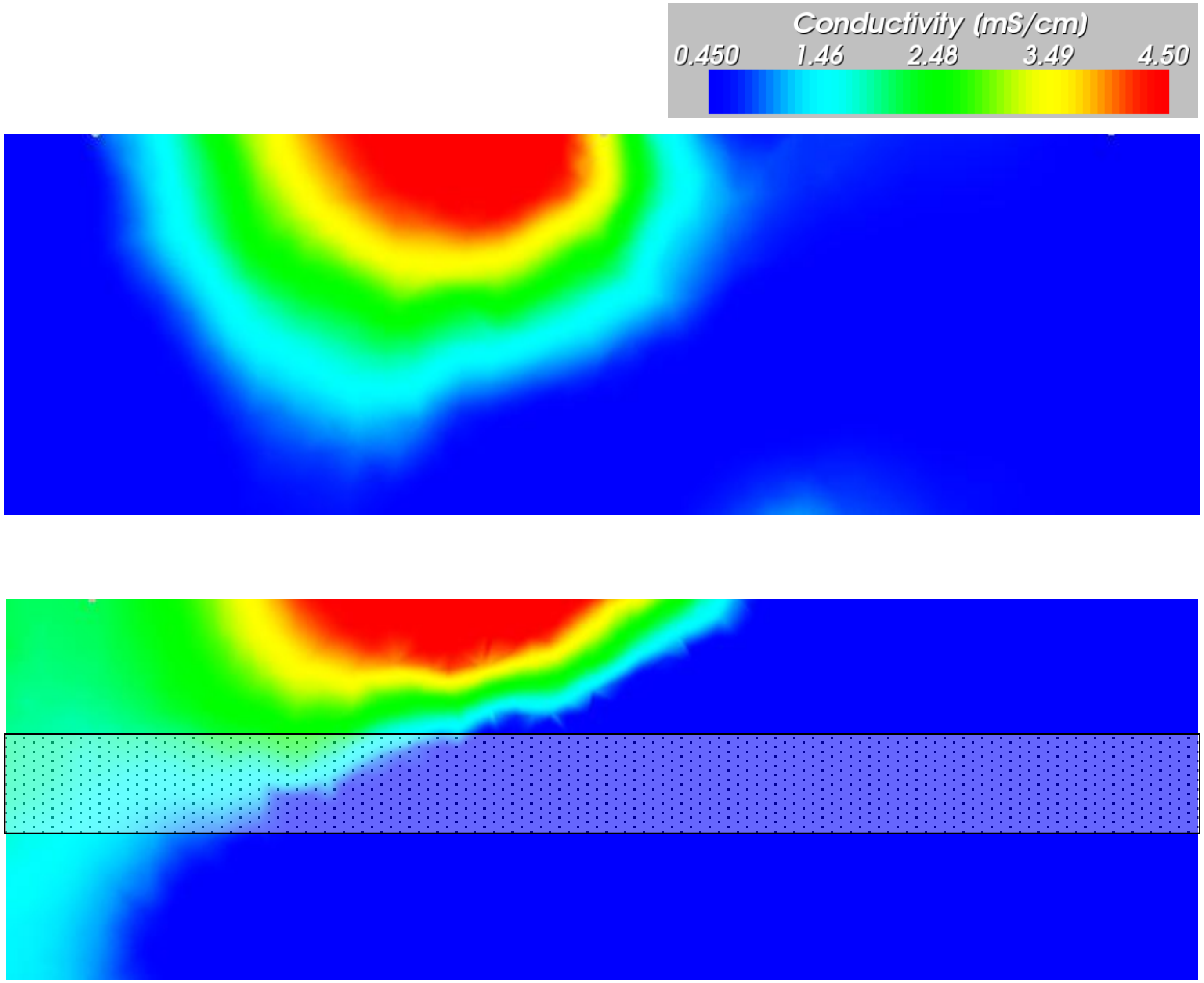
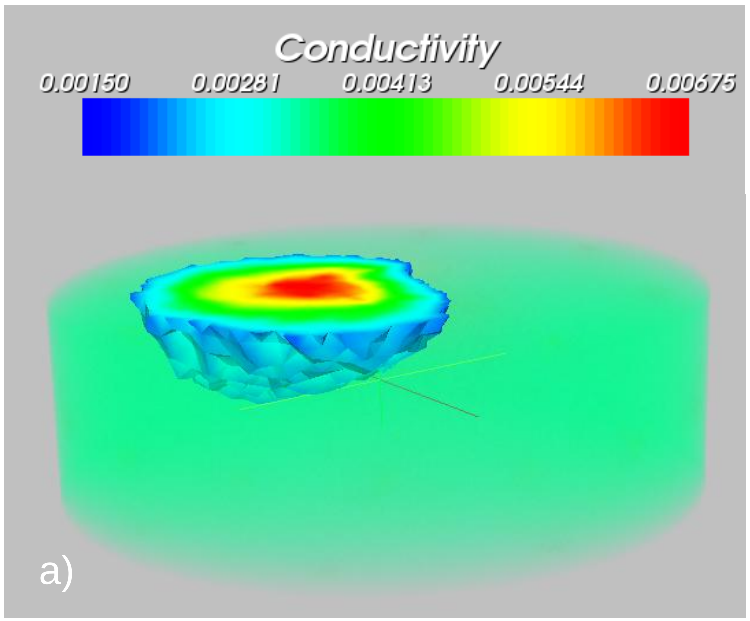
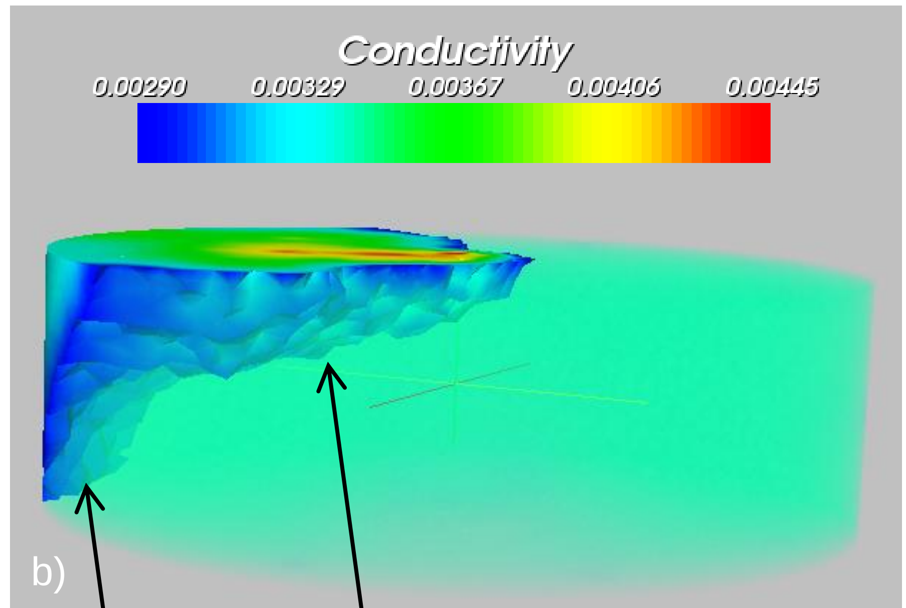


3D visualization of the diffusion process

Homogeneous sample



Heterogeneous sample

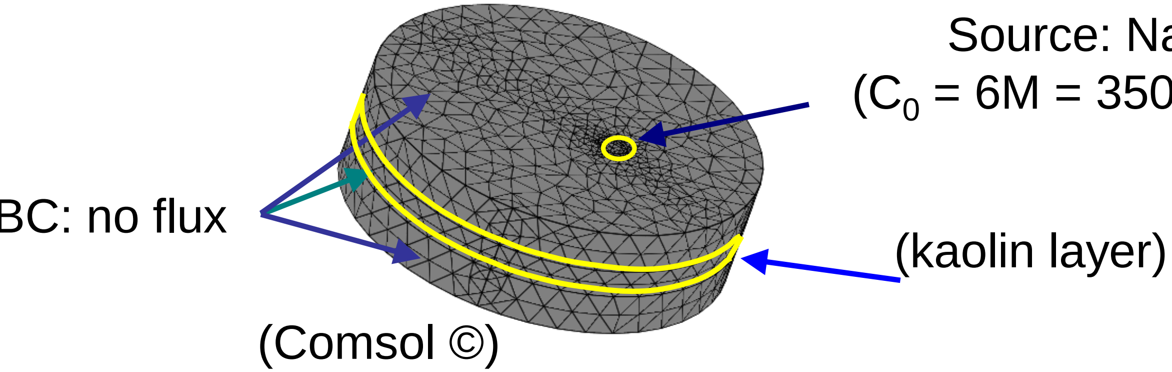


Effect of the Kaolin layer

Preferential path on the side

Table of contents

Numerical simulations of the diffusion process (FEM)



Water Phase Mass Balance

$$S_s \frac{\partial h_0}{\partial t} + \phi \frac{a}{\rho_0} \frac{\partial c}{\partial t} + \nabla \cdot (\mathbf{q}) = 0$$

Salt Mass Balance (diffusion and adsorption)

Rd retardation factor

$$nR_d \frac{\partial c}{\partial t} + c\nabla \cdot \mathbf{q} + \mathbf{q} \cdot \nabla c - D^* \nabla^2 c = 0$$

Specific discharge

(accounting for density effects)

$$\mathbf{q} = -K\left(\nabla h_0 + \left(\frac{\rho - \rho_0}{\rho_0}\right)\nabla z\right)$$

$$h_0 = z + \frac{p}{\rho_0 g} \qquad \rho = \rho_0 + ac$$

Transport process has been simulated with Comsol.

Concentration has been ‘translated’ into water electrical conductivity χ_w

Water electrical conductivity χ_w has been converted into soil electrical conductivity χ_s

$$\chi_s = n^m \chi_W$$

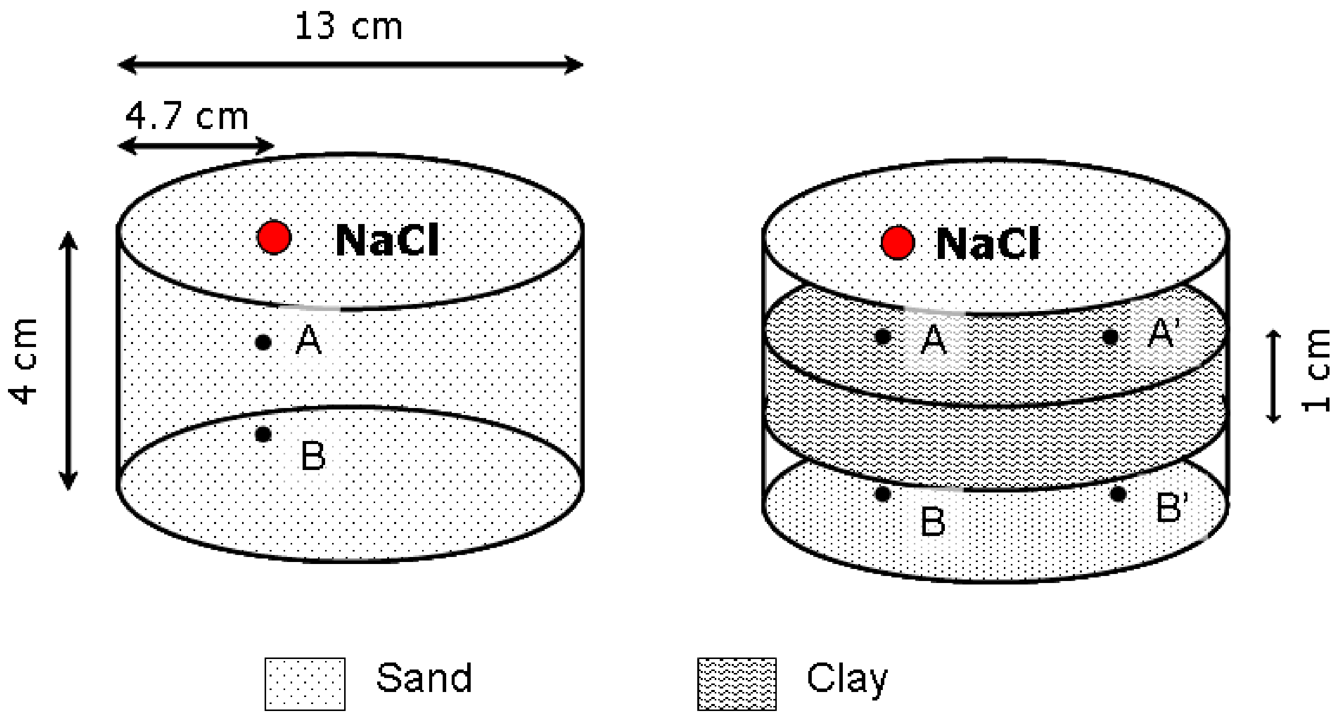
Based on previous measurements:

m = 1.76 for the sand

m = *2.0* for the clay

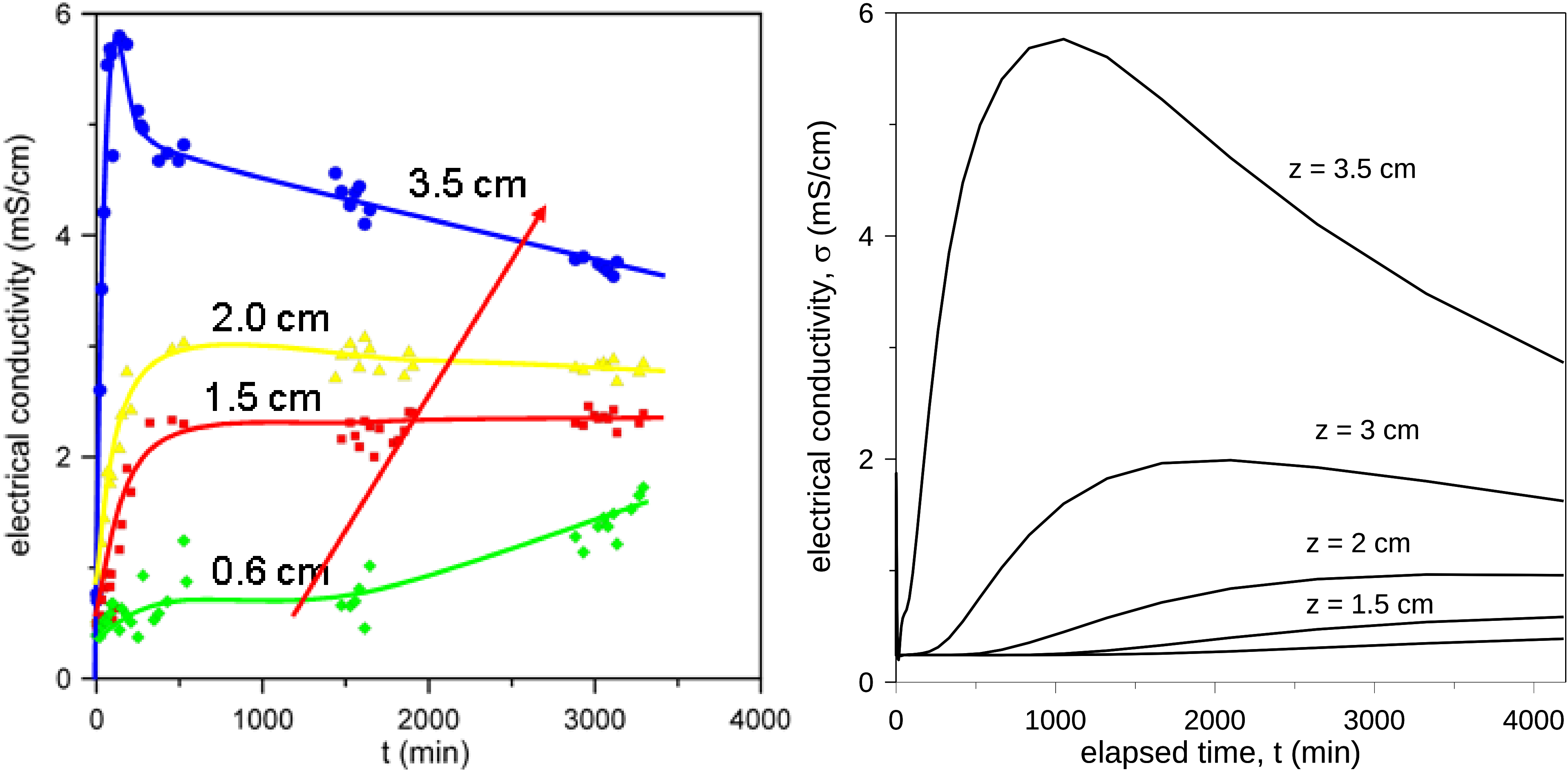
Numerical simulation of the transport process: parameters

Sand				Clay					
ϕ (-)	K (m/s)	D/Rd (m²/s)	m (-)	ϕ (-)	K (m/s)	D/Rd (m²/s)	m (-)	ρ_0 (kg/m3)	a (-)
0.4	$1\cdot10^{-6}$	$3\cdot10^{-10}$	1.8	0.5	$1\cdot10^{-9}$	$6\cdot10^{-11}$	2.0	$9.96\cdot10^{2}$	0.820



ERT inversion vs simulation: results

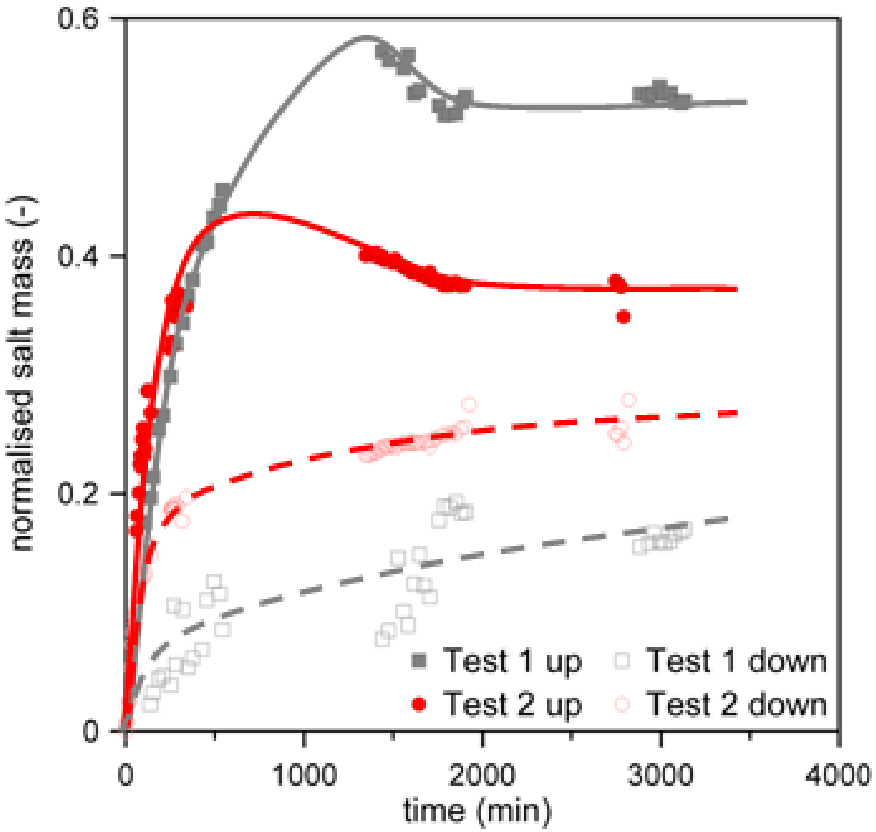
Electrical breakthrough at different heights below saline source



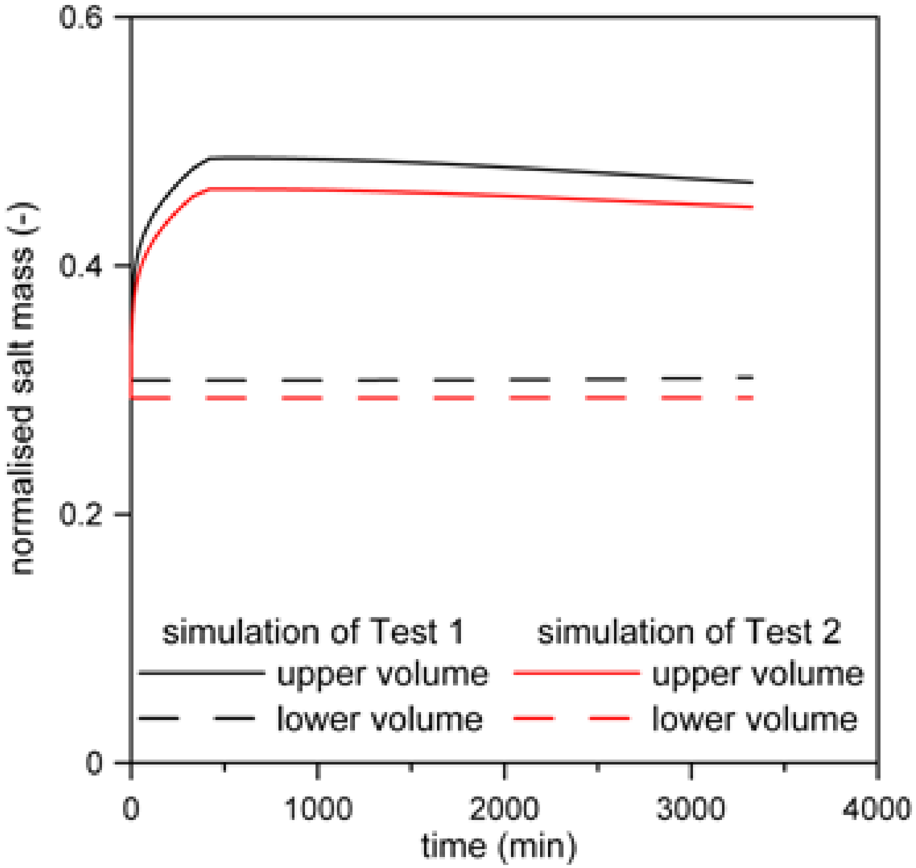
ERT inversion **simulation**

ERT inversion vs simulation: results

Estimated mass of salt within the higher and lower portion of sample



ERT inversion

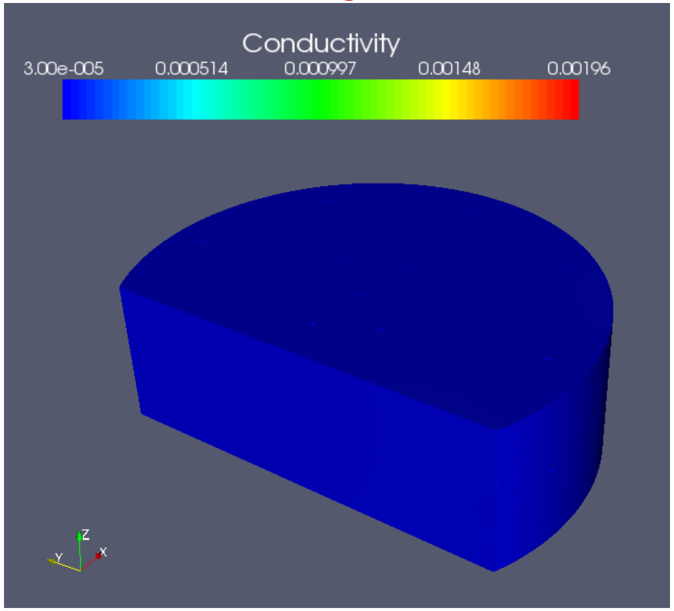


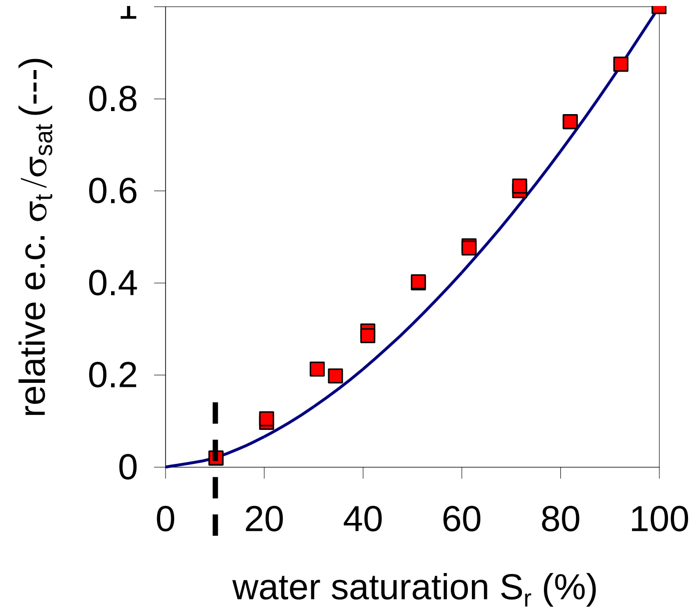
simulation

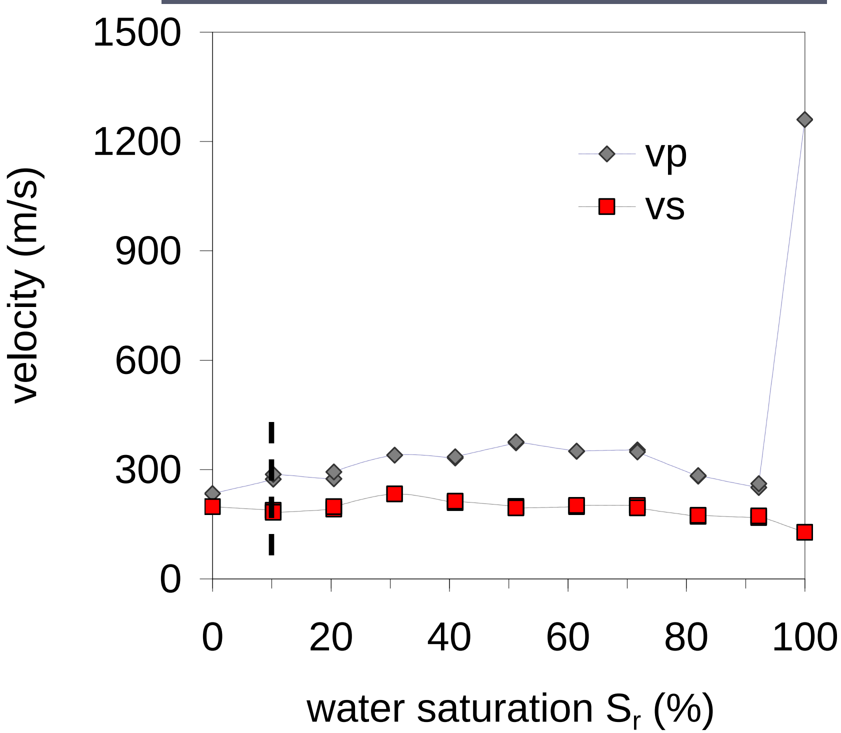
Outline

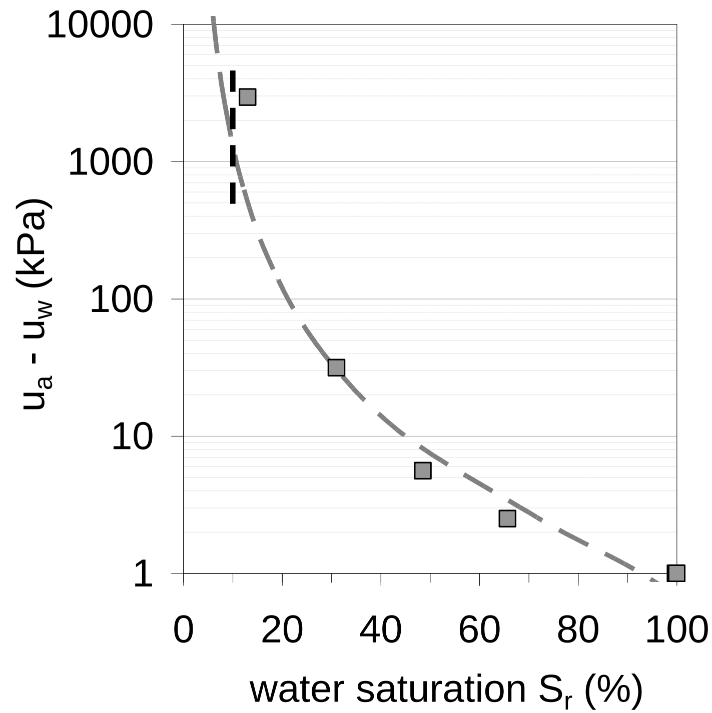
- Electrical conductivity of soils and literature applications
- EIT-oedometer: 3D tomography in the lab
- ERT as a tool for monitoring transient phenomena in soil samples
  - Mechanical Consolidation
  - Chemical Diffusion
  - Saturation/Desaturation
- Evaluation of soil model parameters for transport phenomena:
  - Diffusion
  - Saturation

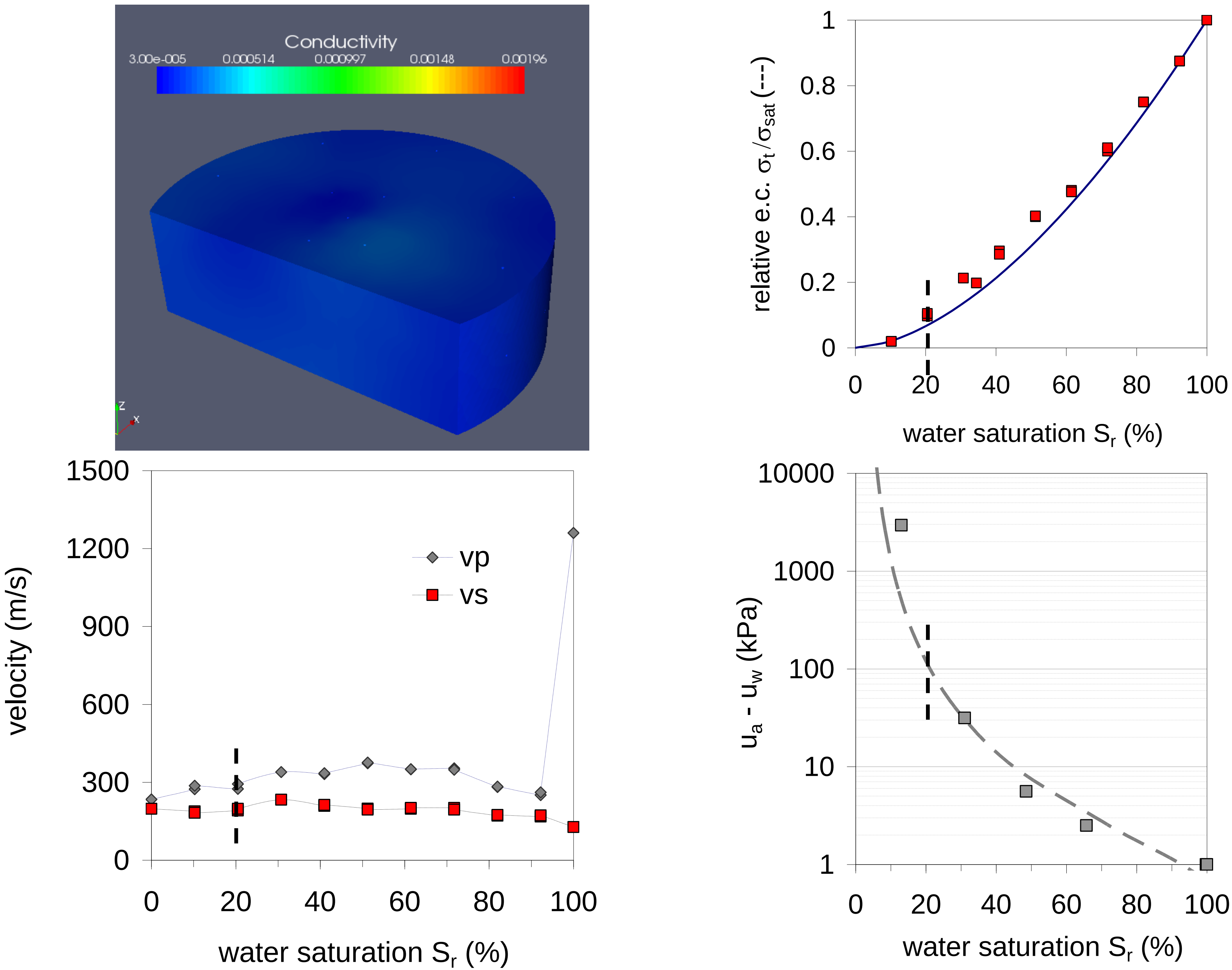
Conductivity calibration procedure for unsat soils

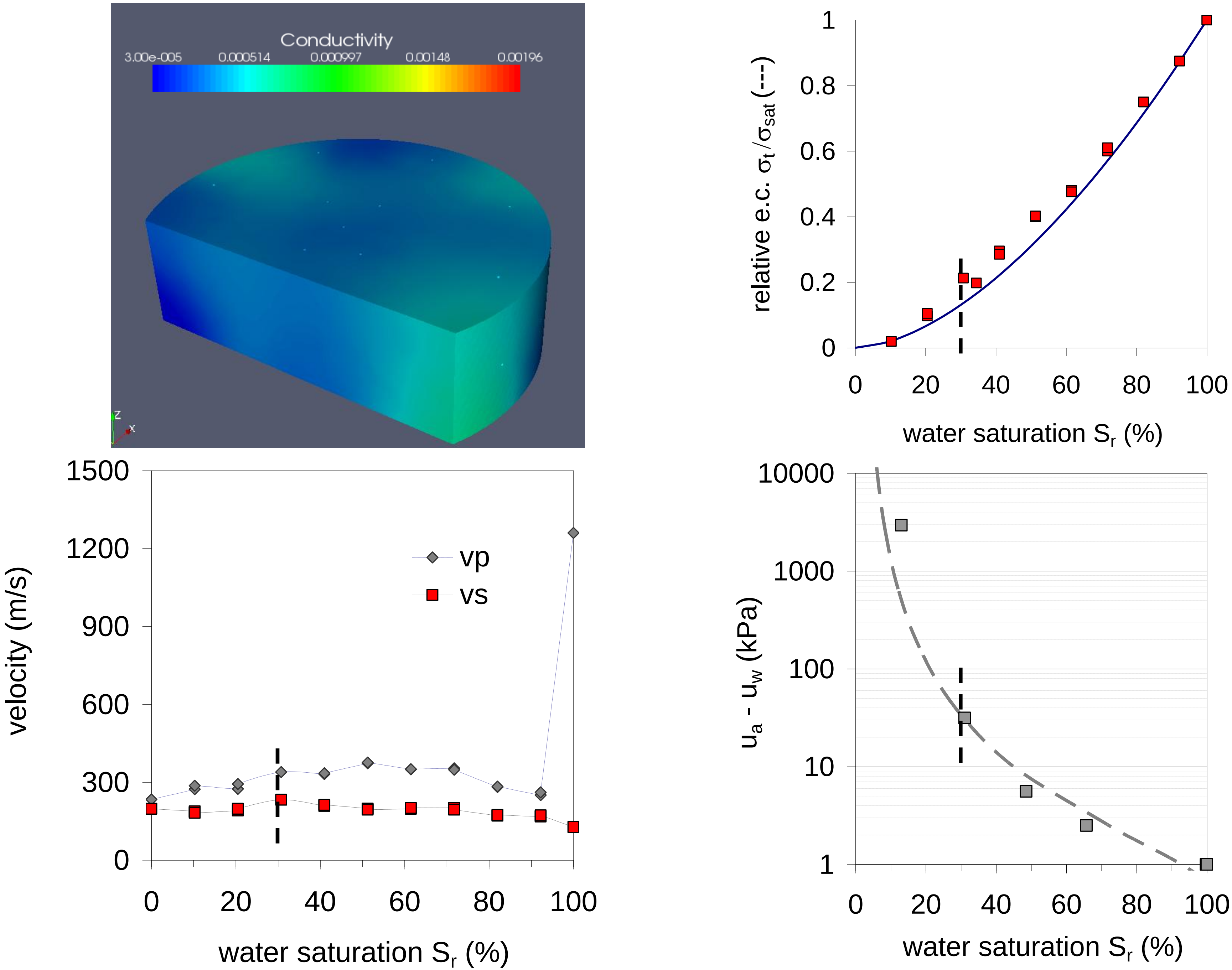









Conductivity
3.00e-005
0.000514
0.000997
0.00148
0.00196
Z
X
1
0.8
0.6
0.4
0.2
0
relative e.c. σ_t/σ_{sat} (---)
0
20
40
60
80
100
water saturation S_r (%)
1500
1200
900
600
300
0
velocity (m/s)
vp
vs
0
20
40
60
80
100
water saturation S_r (%)
10000
1000
100
10
1
u_a - u_w (kPa)
0
20
40
60
80
100
water saturation S_r (%)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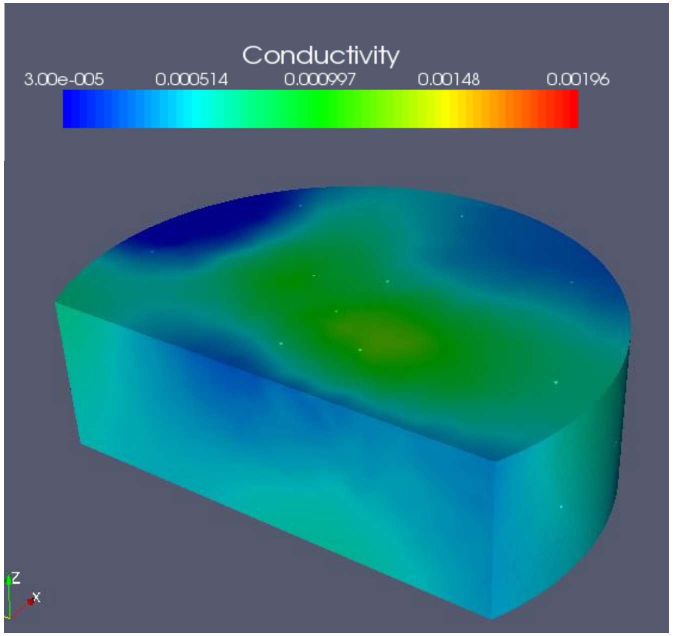
relative e.c. σt/σsat (---)
water saturation Sr (%)
velocity (m/s)
vp
vs
water saturation Sr (%)
ua - uw (kPa)
water saturation Sr (%)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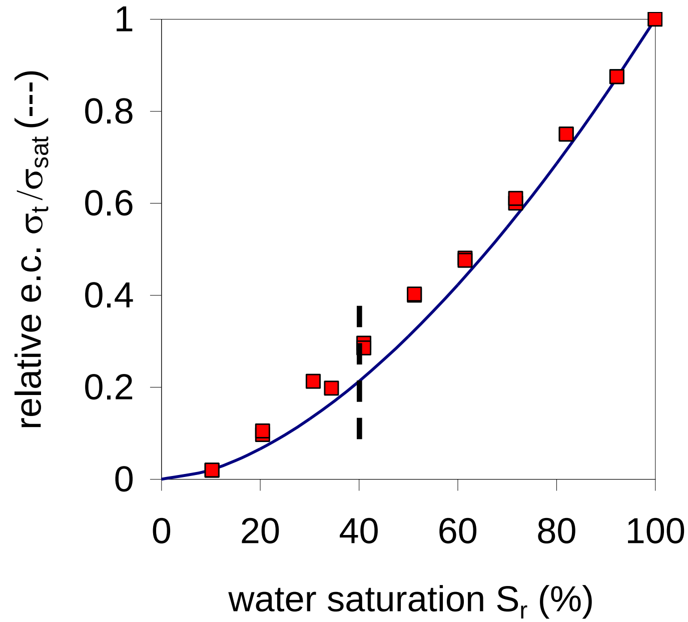
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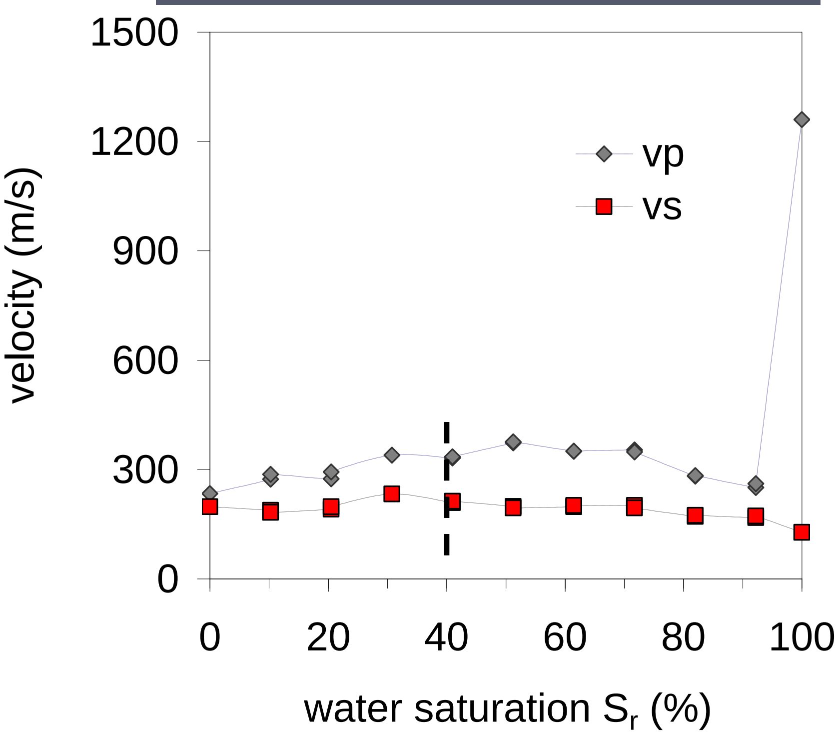
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1200
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vp
vs
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80
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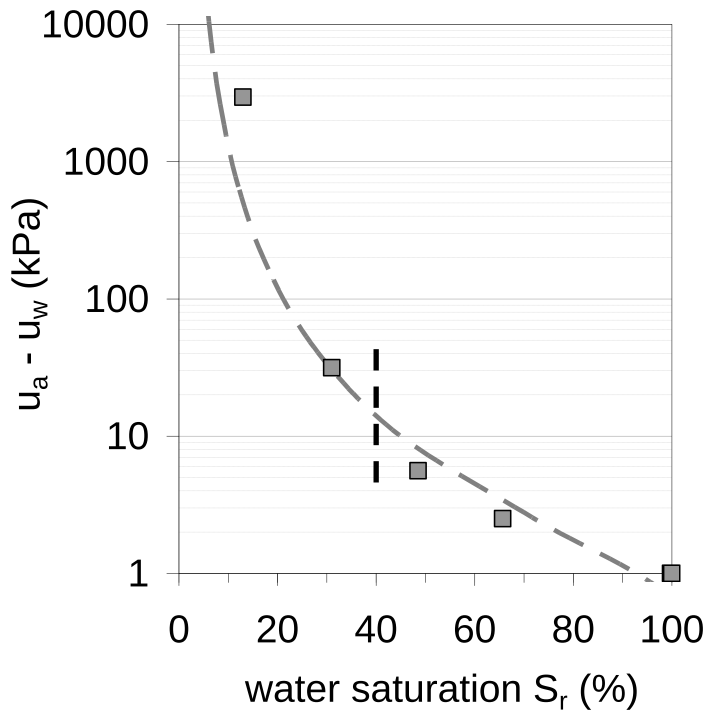
water saturation S_r (%)


u_a - u_w (kPa)
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1000
100
10
1
0
20
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80
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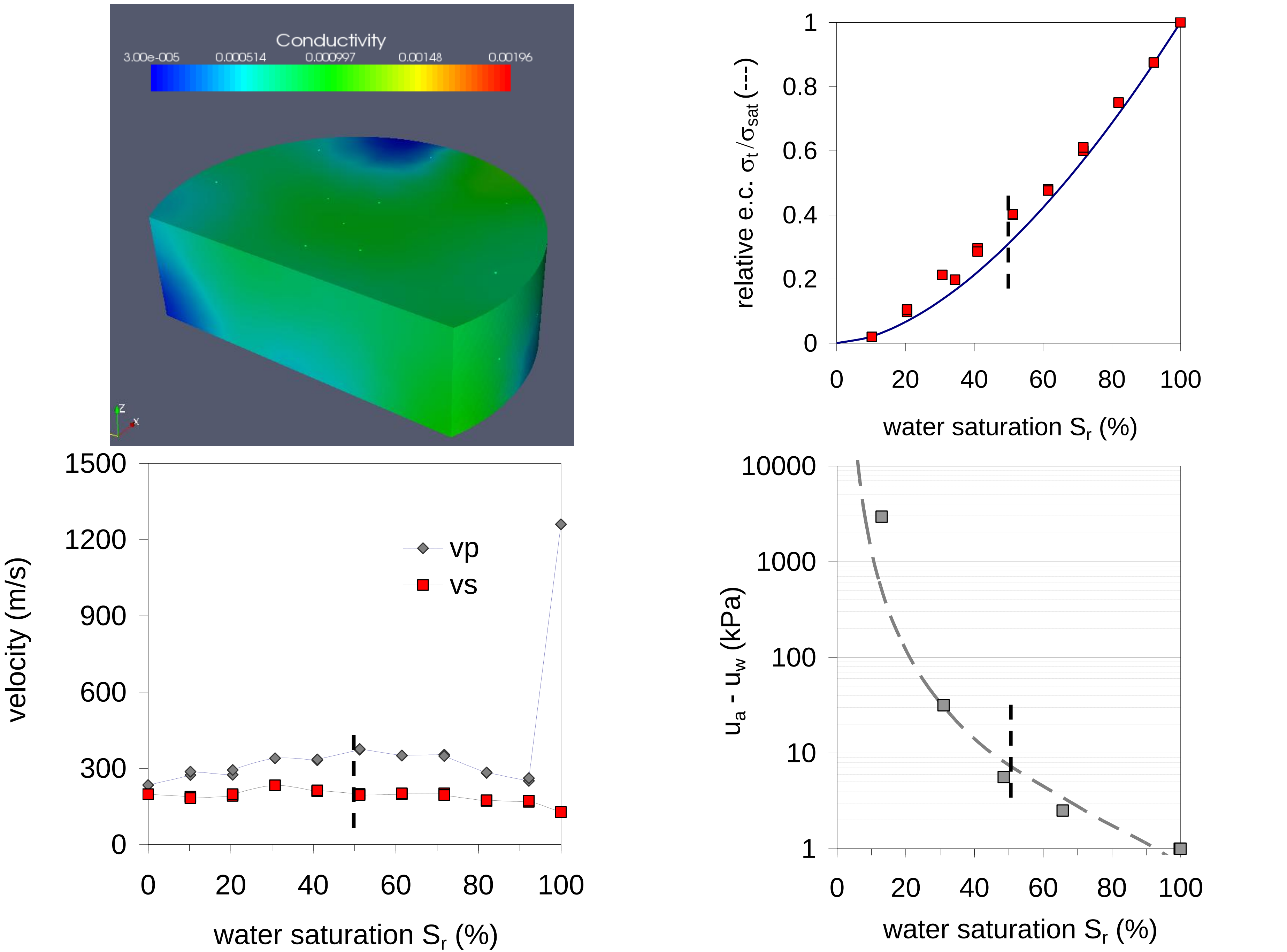
water saturation S_r (%)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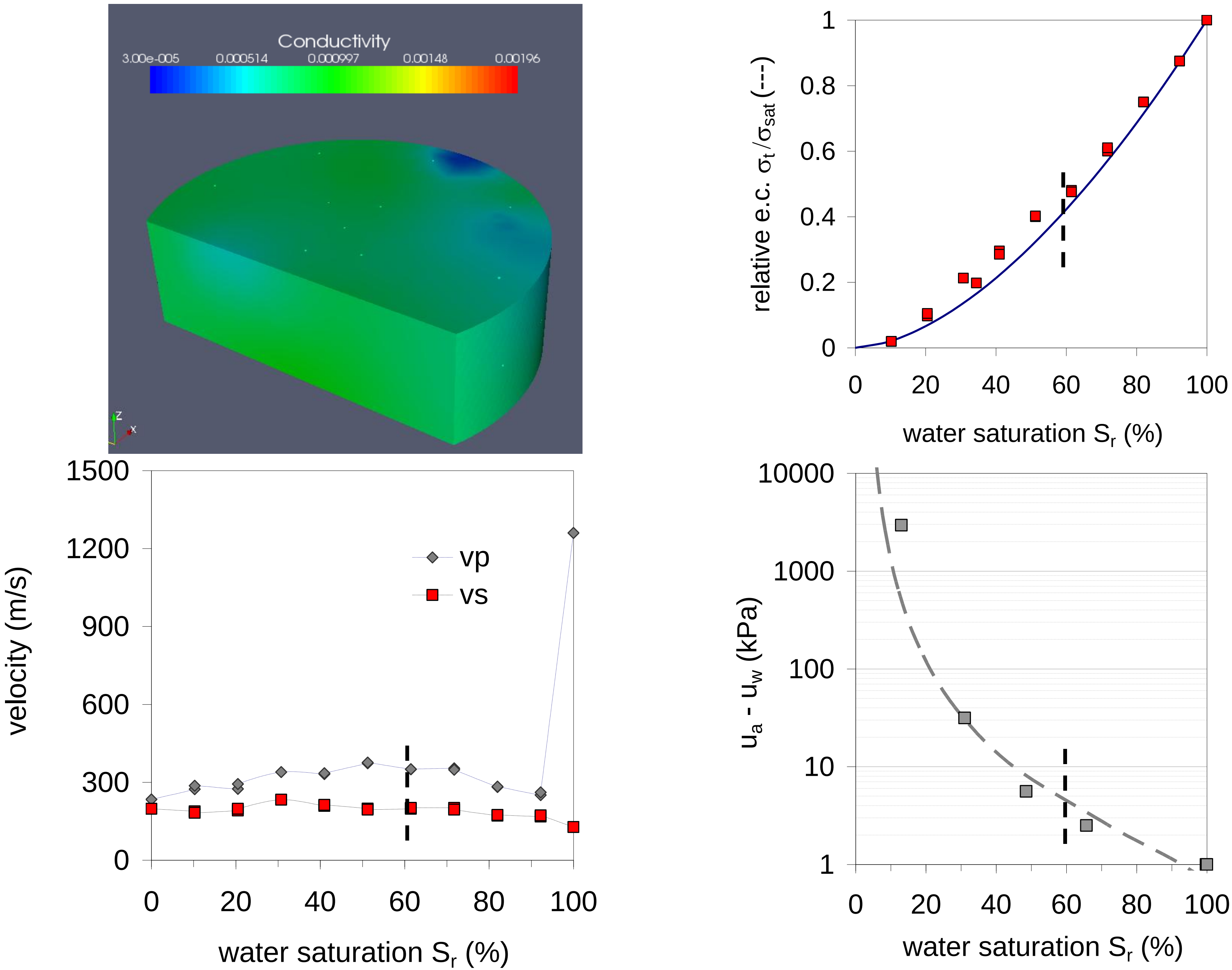

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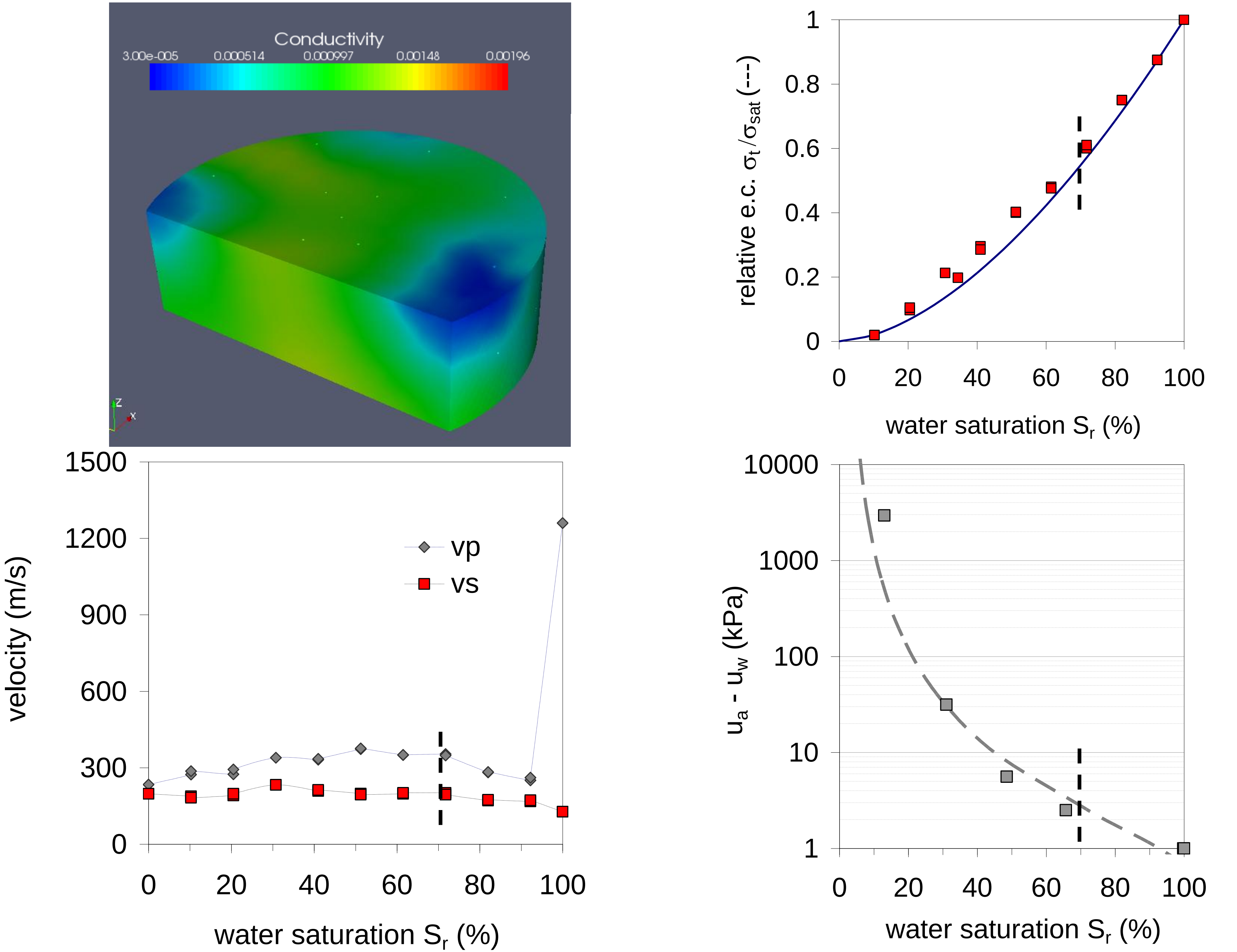

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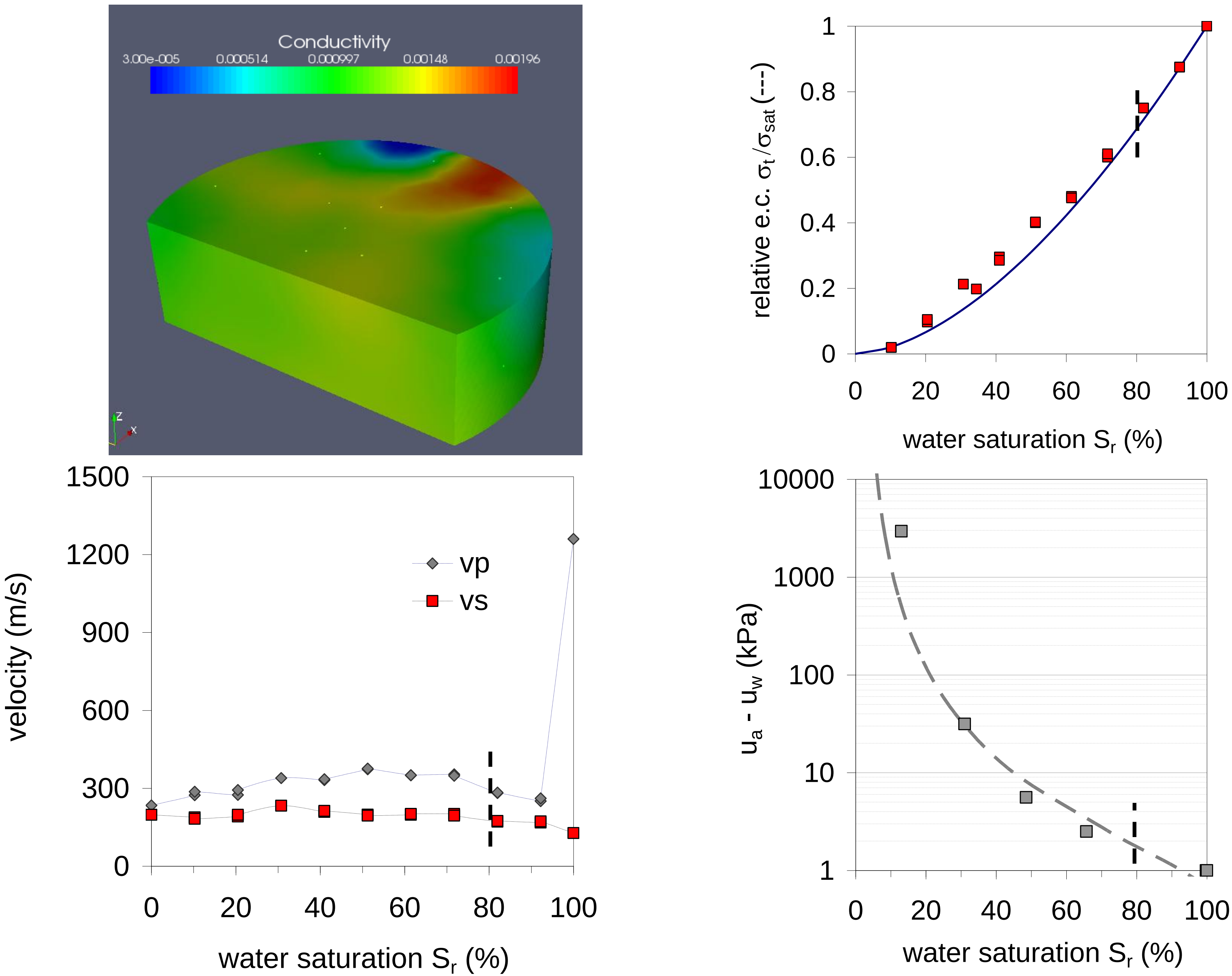

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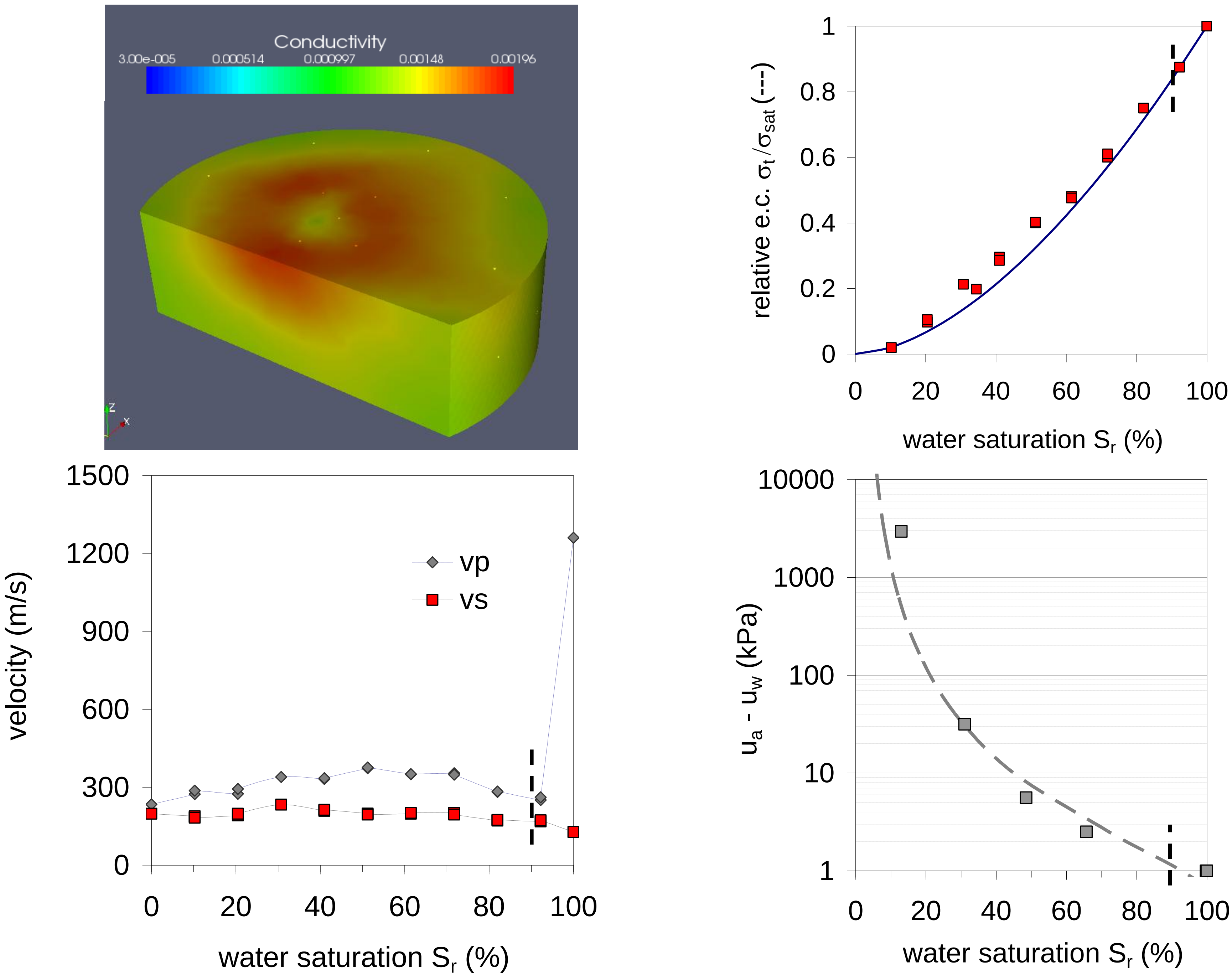
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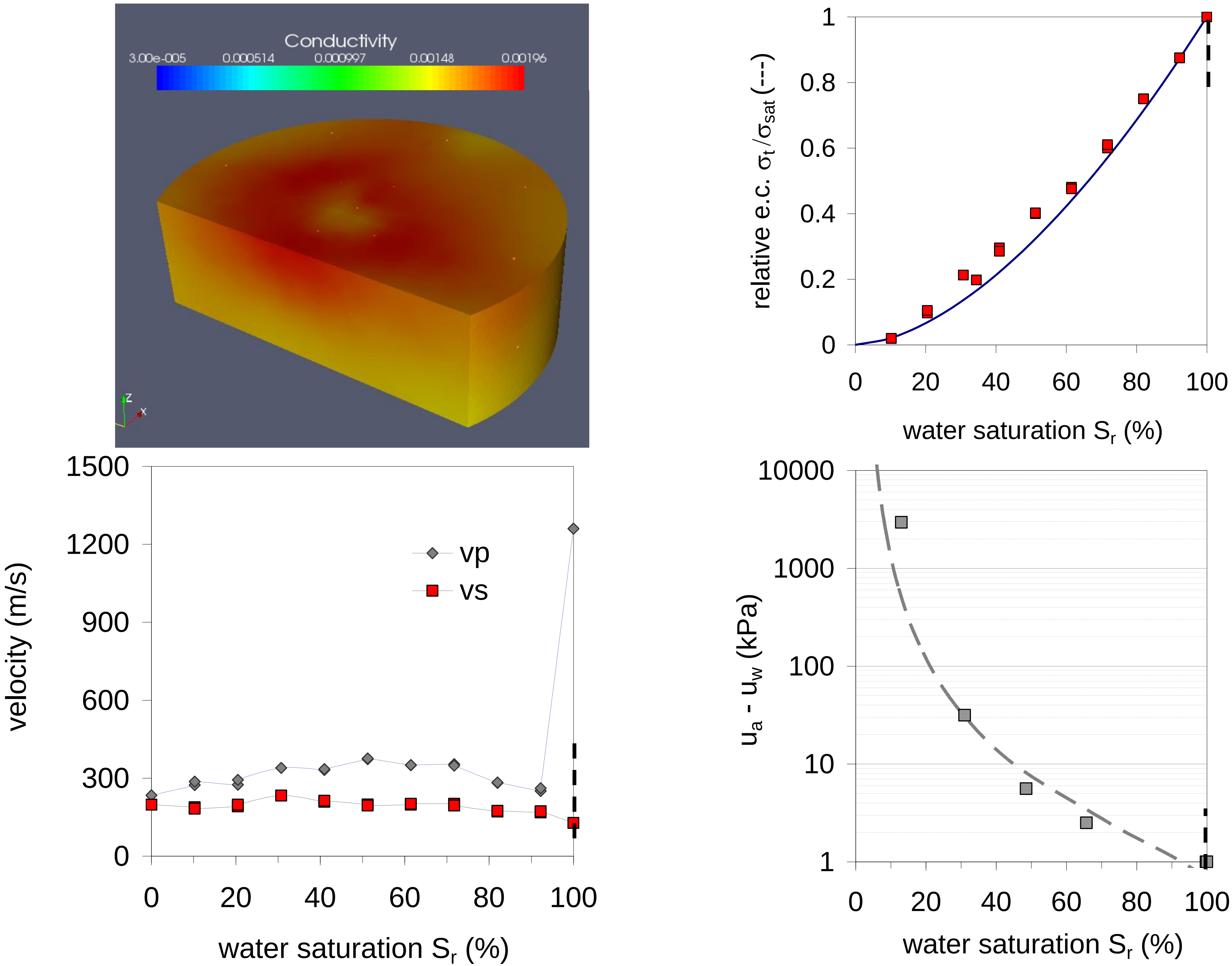

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water saturation Sr (%)
velocity (m/s)
vp
vs
water saturation Sr (%)
ua - uw (kPa)
water saturation Sr (%)

Trecate Sand (testing site for SOILCAM project (EU 7° FP)

→ Depth: 2 m from the ground surface

→ Predominant sand fraction (Type A)

→ Intercalations of finer material (Type B)

Characterization of the soil used in the investigation

Coarse fraction (A): silty sand

→Granulometric distribution: 9.1% Gravel, 78.2% Sand, 12.7% Silt

→Specific density of solid particles G_s= 2.71

→Saturated hydraulic conductivity $k_w = 1 \cdot 10^{-5}$ m/s

Finer fraction (B): sandy silt

→Granulometric distribution: 0.6% Gravel, 13.8% Sand, 85.8% Silt

→Specific density of solid particles G_s= 2.73

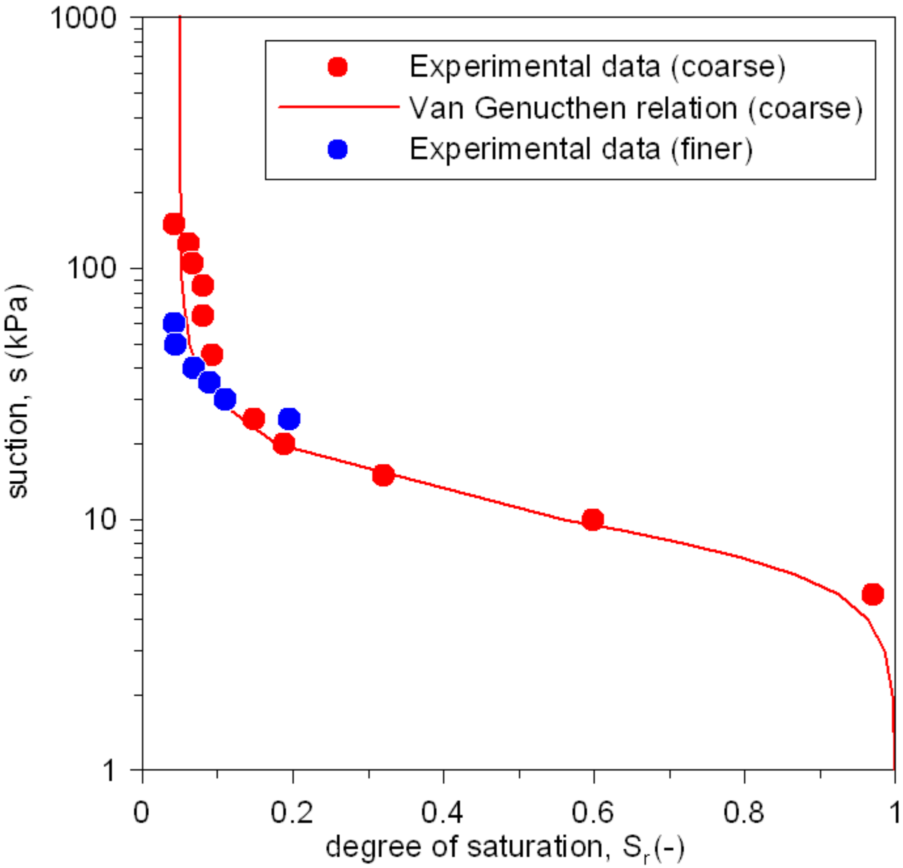
→Saturated hydraulic conductivity $k_w = 1.8 \cdot 10^{-6}$ m/s

Hydraulic characterization: Soil Water Retention Curve

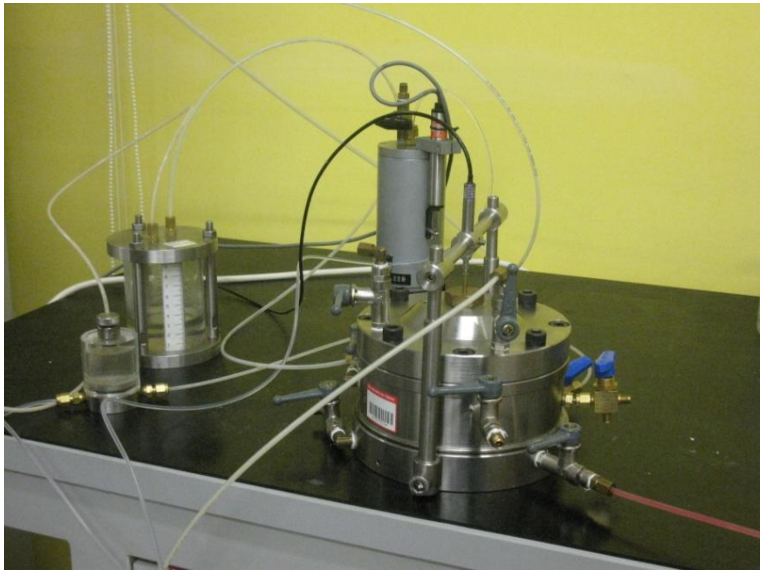
→ Determined with a suction controlled oedometer cell applying the axis translation technique

→ Constant porosity, n=0.45

→ Modelled with Van Genuchten relation (3 parameters)



$$S_e = \frac{S_r - S_r^{res}}{1 - S_r^{res}} = \left(\frac{1}{1 + (\alpha s)^n} \right)^m$$



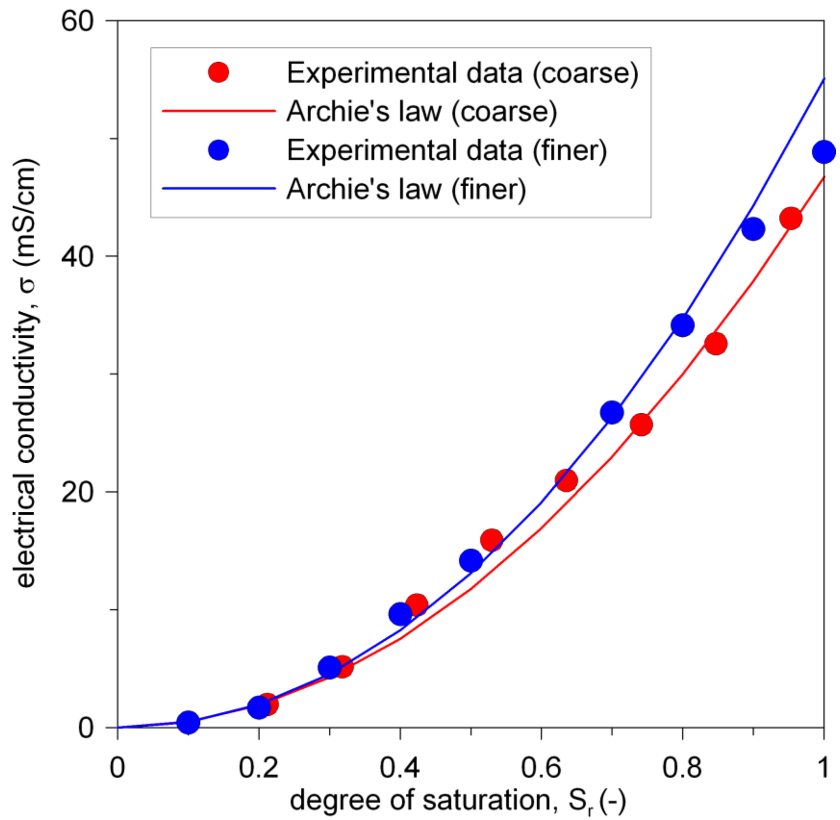
Electrical characterization: evolution of electric conductivity with the degree of saturation

→ Determined in the ERT oedometer by preparing homogeneous samples at increasing water contents

→ Constant porosity and water salinity

→ Modelled with Archie's law (1 parameter)

$$\frac{\chi}{\chi_{sat}} = S_r^{\,p}$$



$p_A = 2.0$

$p_B = 2.1$

Similar geometry of the interconnected porosity

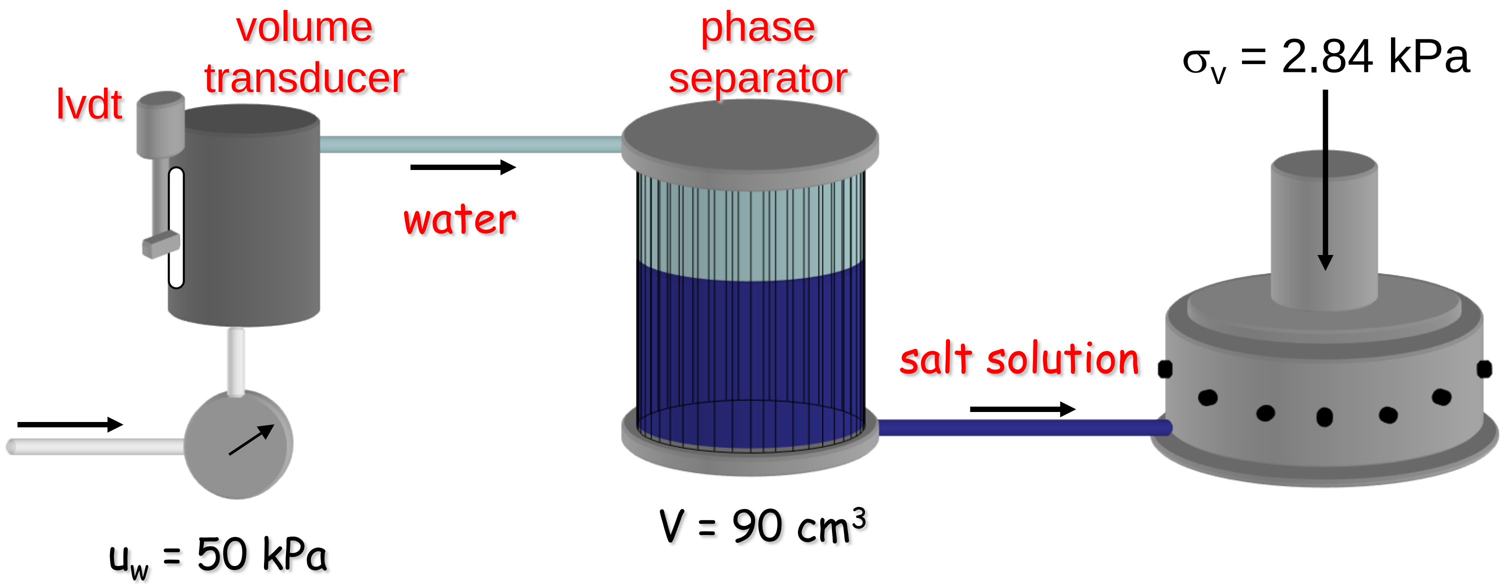
Wetting test procedure

→ Samples prepared by dynamic compaction at S_r=0.2 and *n*=0.45.

→ Homogenization stage of 12 hours after preparation.

→ Wetting performed imposing inflow of water from the drainage at the base of the cell.

→ Measured displacement of the top of the sample by an LVDT, in order to evaluate the volumetric deformation.



Experimental test procedure: wetting test on type A material

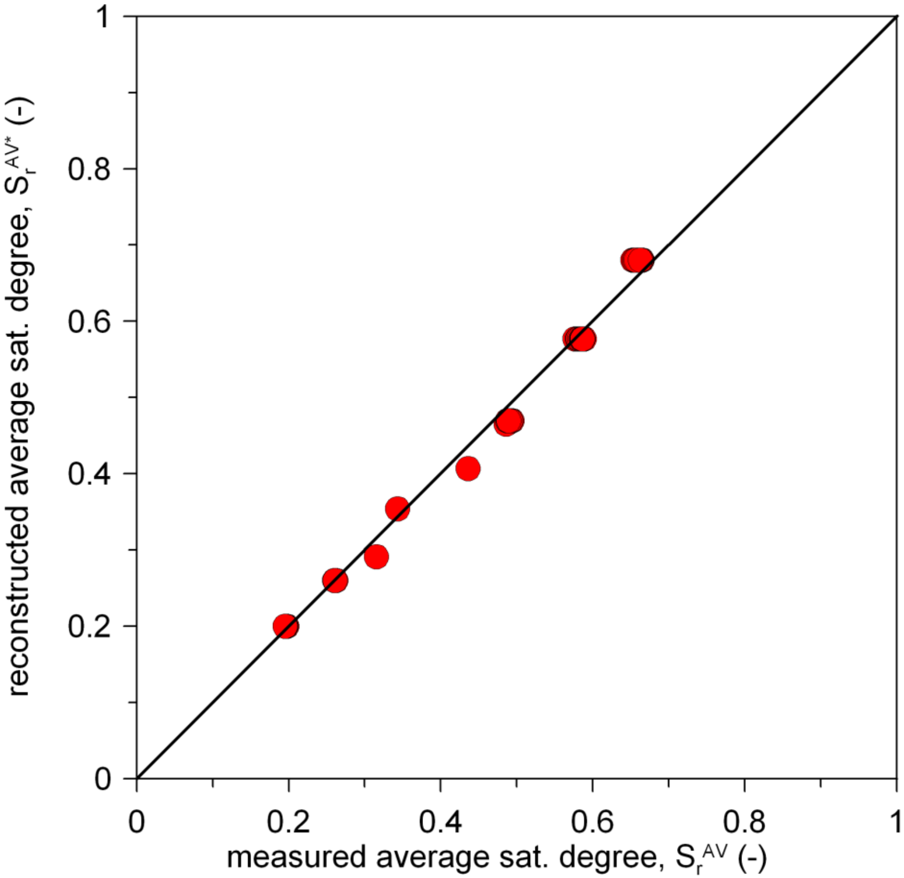
Test	Imposed External Water Pressure (kPa)	Volume inflow (ml)	Time of flow of the infiltration stage (min)	Total time of ERT monitoring (min)
1	50	90	0.67	3000
2	5	50	115	115

Electrical measurements → electrical conductivity data in space and time by inversion algorithm → estimation of the local degree of saturation inside the sample by means of Archie's law.

Test 1: electrical measurements performed at constant global water content of the sample → monitoring of the local redistribution of water content (homogenization).

Test 2: electrical measurements performed during the whole wetting process → monitoring of the saturation process under the imposed flow condition.

Consistency check between imposed and reconstructed averaged water content ("mass balance")



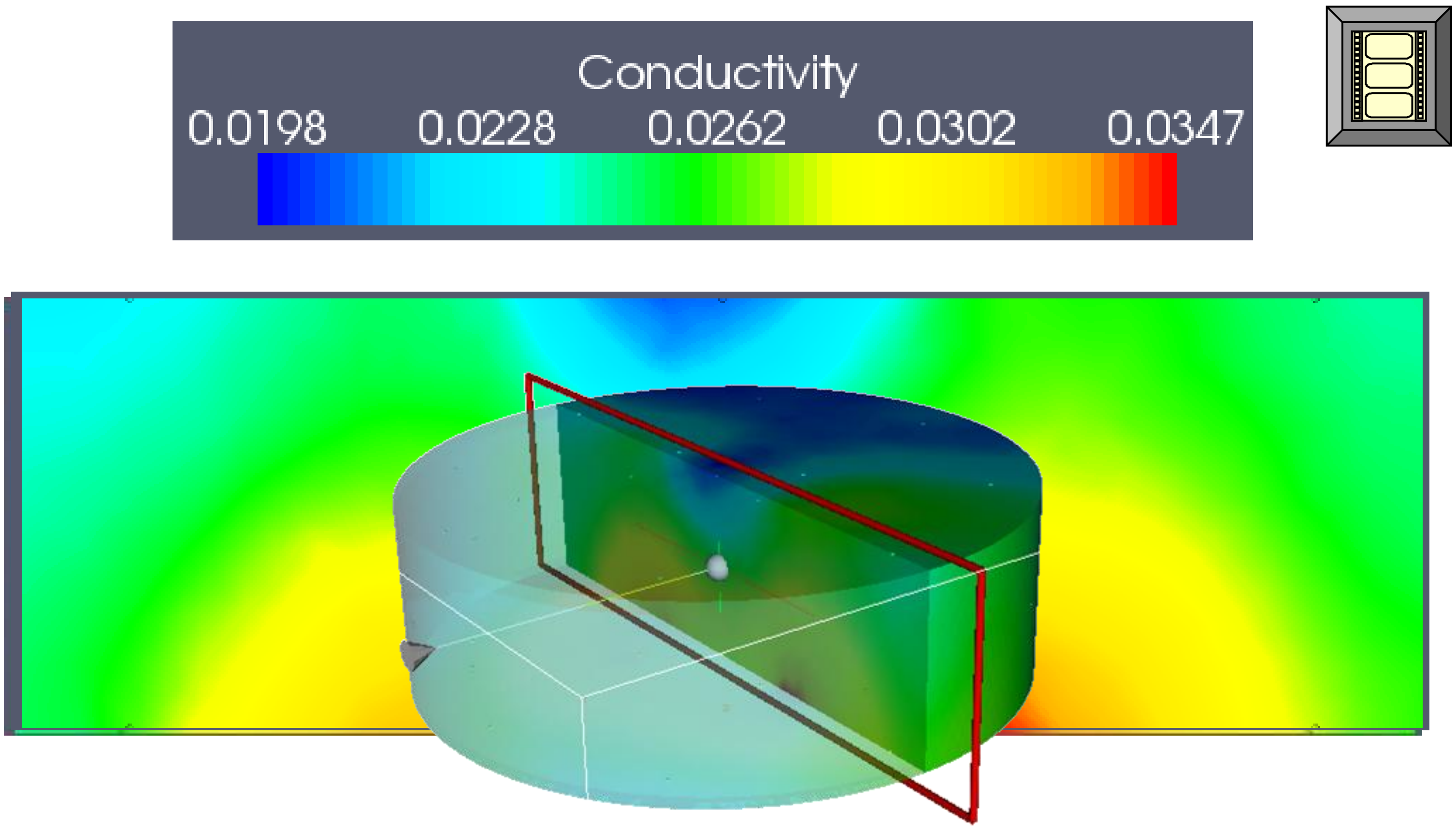
Measured data

$$S_r^{AV} = \frac{V_w}{V_{sample}}$$

Reconstructed data

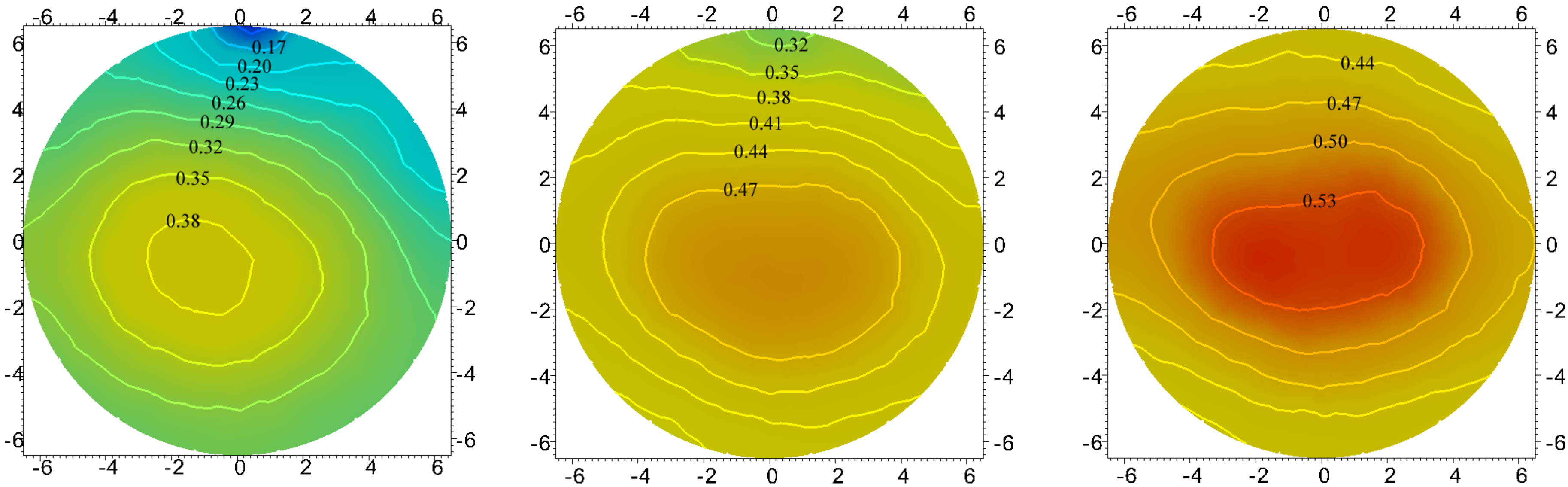
$$\sigma^{AV*} = \frac{1}{V_{sample}} \int_{V_{sample}} \sigma dV \approx \frac{1}{V_{sample}} \sum_{e=1}^{N_e} \sigma_e \Delta V_e$$

Test 1. Experimental results: evolution of conductivity along a longitudinal section during homogenization



Test 2. Experimental results: transversal section during infiltration

Isosaturation lines at the middle height of the sample, z=2 cm



t=15 min

t=54 min

t=115 min

Infiltration stage: increasing electrical conductivity (degree of saturation) for increasing time

Table of contents

- Electrical conductivity of soils
- Applications
- EIT-oedometer: 3D tomography in the lab
- Validation
- ERT as a tool for monitoring transient phenomena in soil samples
  - Mechanical Consolidation
  - Chemical Diffusion
  - Saturation/Desaturation
- Use of the results for evaluation of soil model parameters for transport phenomena:
  - Diffusion
  - Saturation

Model equations:

$$\frac{\partial(\rho_w n S_r)}{\partial t} + \nabla\cdot(\rho_w \mathbf{q}_w) = 0$$

$$\frac{\partial(\rho_a n (1-S_r))}{\partial t} + \nabla\cdot(\rho_a \mathbf{q}_a) = 0$$

Mass balance for water and air

$$\mathbf{q}_w = -\mathbf{k}_w(S_r)\nabla\left(z + \frac{u_w}{\rho_w g}\right)$$

$$\mathbf{q}_a = -\mathbf{k}_a(S_r)\nabla\left(z + \frac{u_a}{\rho_a g}\right)$$

Flow equations for water and air: extended Darcy's law

$$S_e = \frac{S_r - S_r^{res}}{1 - S_r^{res}} = \left(\frac{1}{1+(\alpha s)^n}\right)^{1-1/n}$$

Retention curve

$$k_w(S_r) = k_w^{sat} S_r^{\beta}$$

$$k_a(S_r) = k_a^{dry}(1-S_r^2)(1-S_r)^2$$

Unsaturated permability functions

Description of the unsaturated behaviour:

$$S_e = \frac{S_r - S_r^{res}}{1 - S_r^{res}} = \left(\frac{1}{1 + (\alpha s)^n} \right)^m$$

$$k_w(S_r) = k_w^{sat} S_r^{\beta}$$

$$k_a(S_r) = k_a^{dry} \left(1 - S_r^2\right)\left(1 - S_r\right)^2$$

Retention curve: m, n, α
for each branch

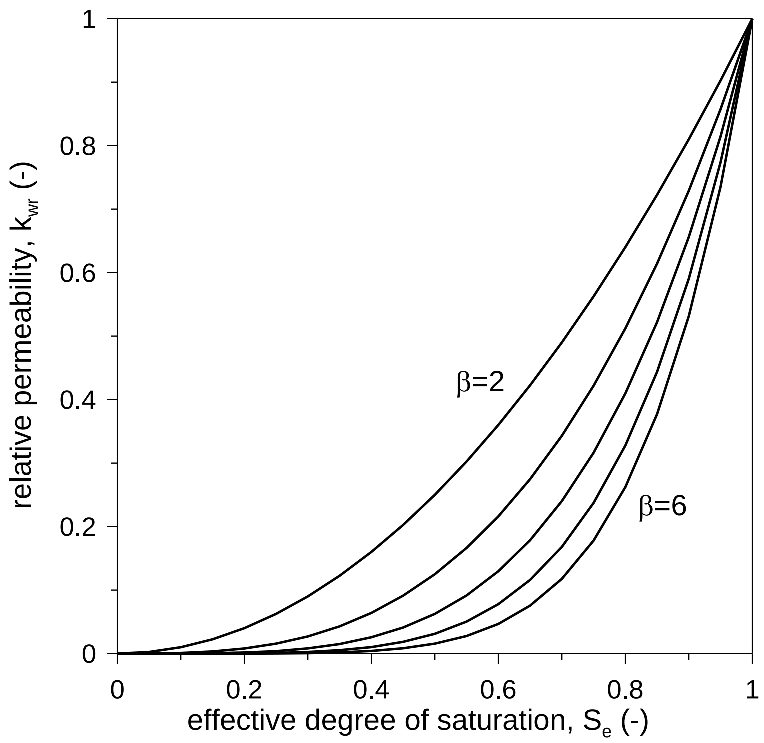
Relative permeability: β

Estimate parameters α, m ,n and β

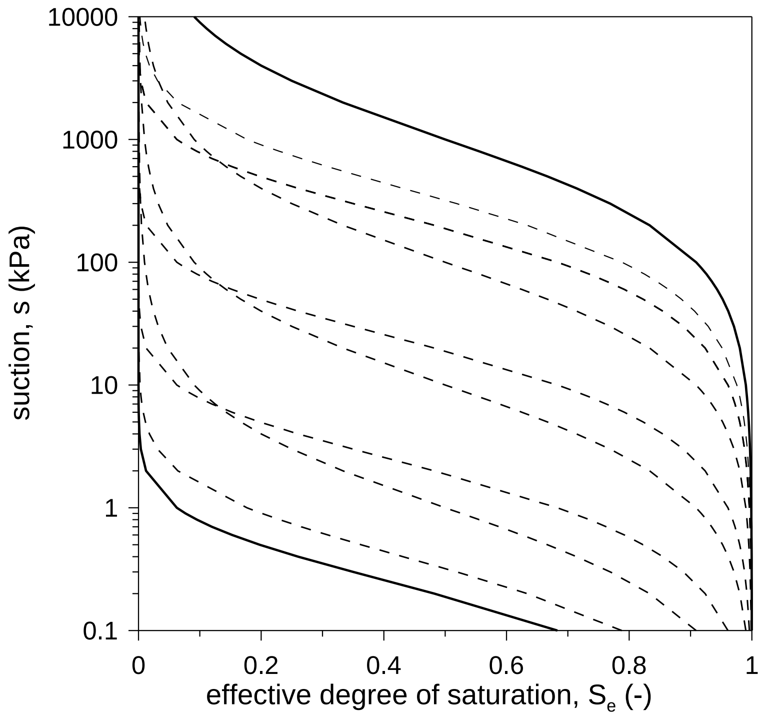
Estimated ranges for soil parameters: α, n and β

$$\alpha \in 10^{-3} \div 10^{-6}$$
$$n \in 2 \div 5$$
$$\beta \in 2 \div 6$$

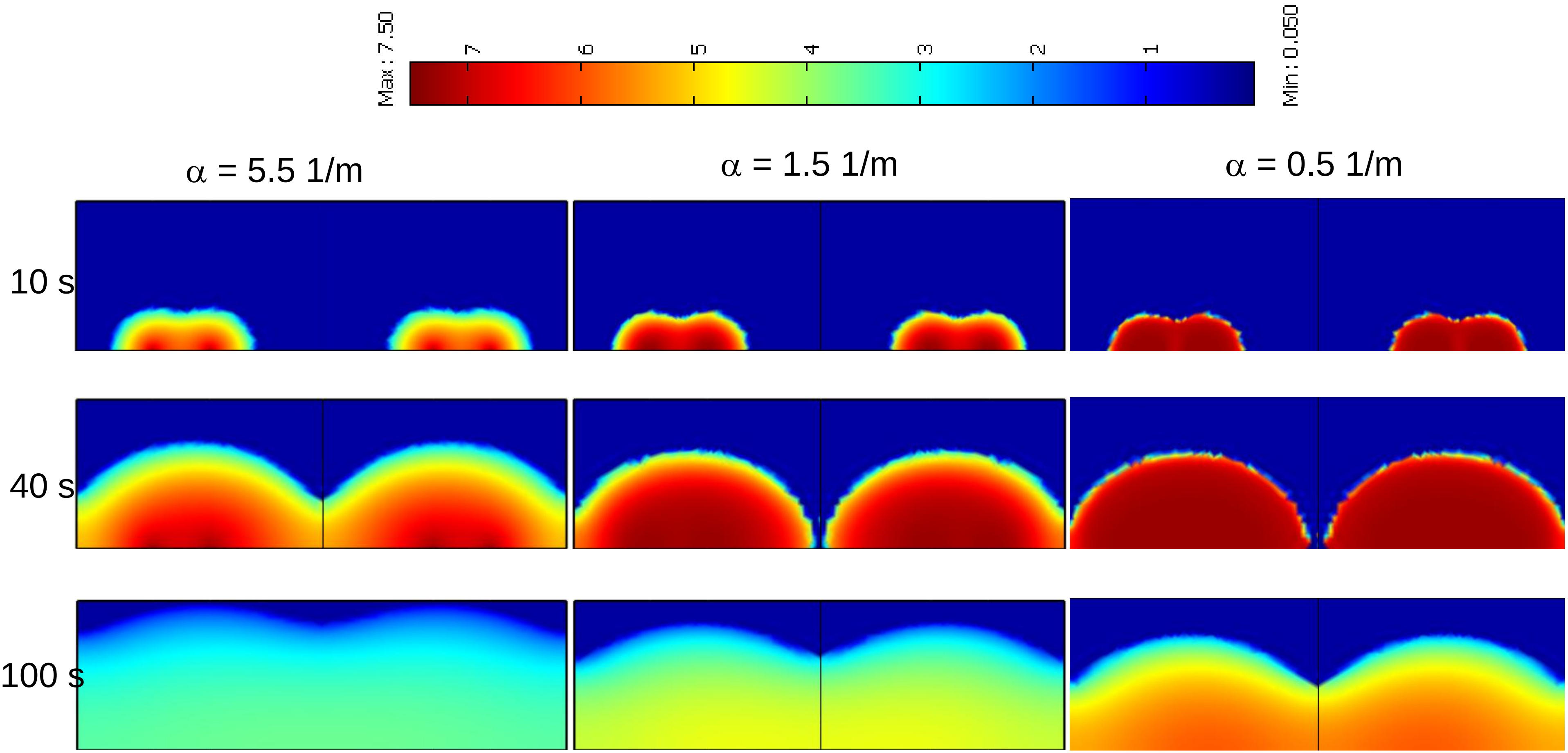
Relative permeability



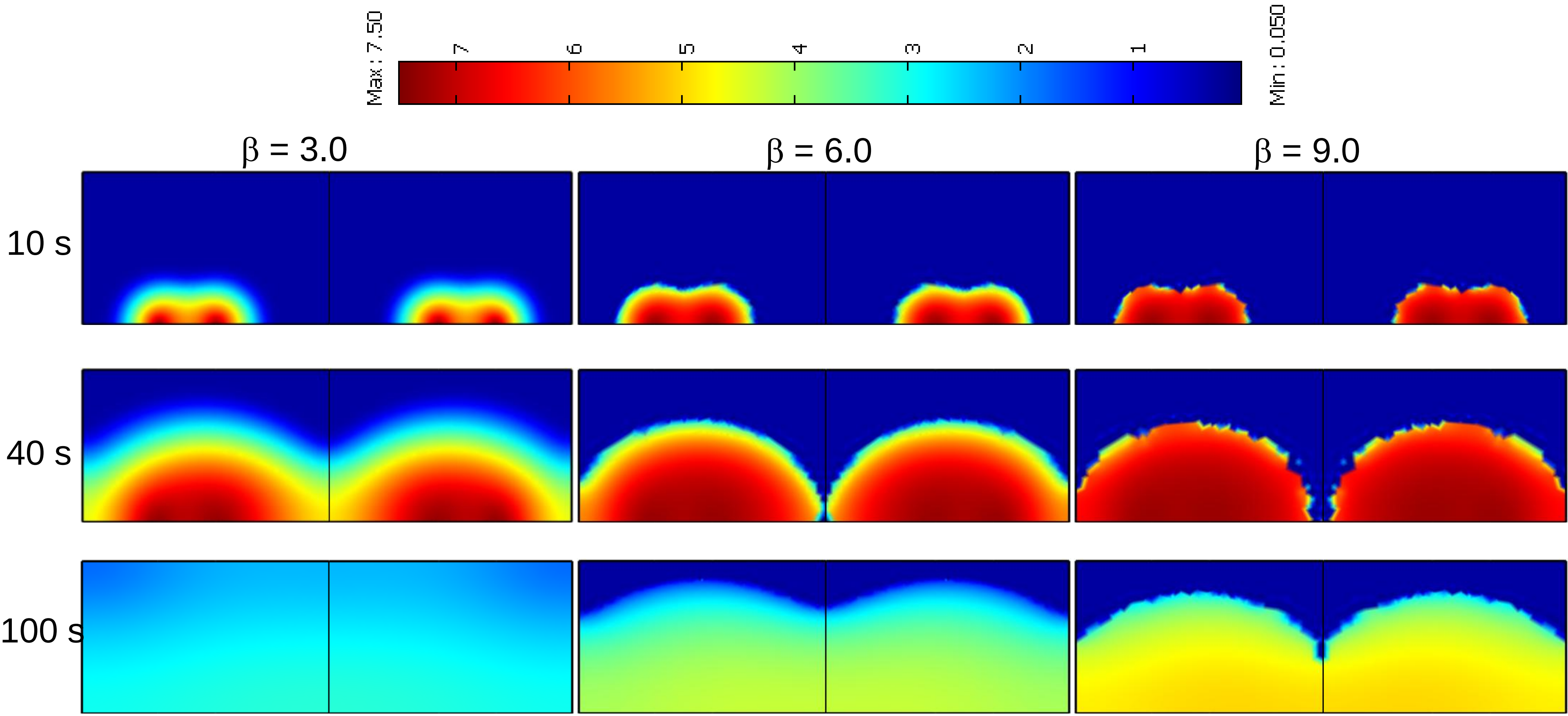
Retention curve (wetting branch)



Effect of parameters change on the numerical solution: evolution of electrical conductivity during test 1



Effect of parameters change on the numerical solution: evolution of electrical conductivity during test 1

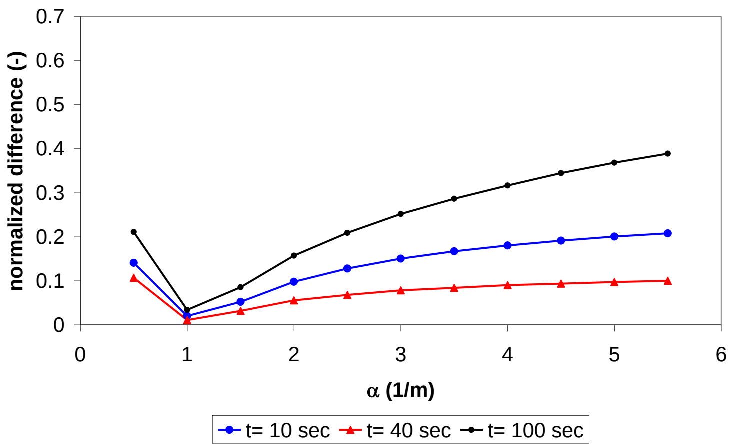


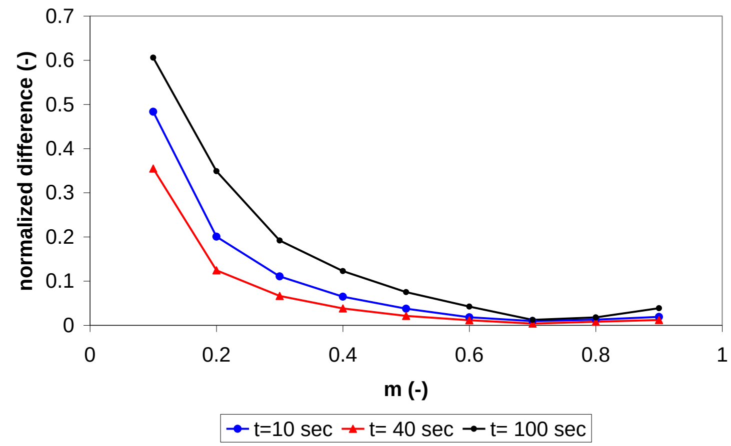
Effect of parameters change on the numerical solution: evolution of electrical conductivity during test 1

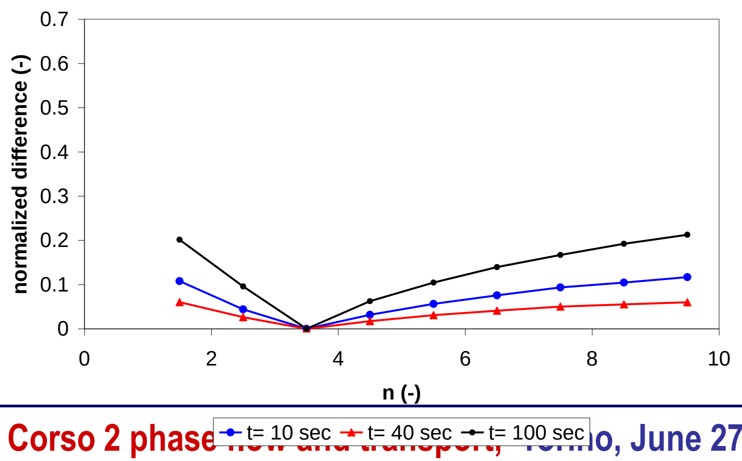
$$\text{norm.diff} = \frac{\left\|\sigma - \sigma_{ok}\right\|_2}{\left\|\sigma_{ok}\right\|_2}$$

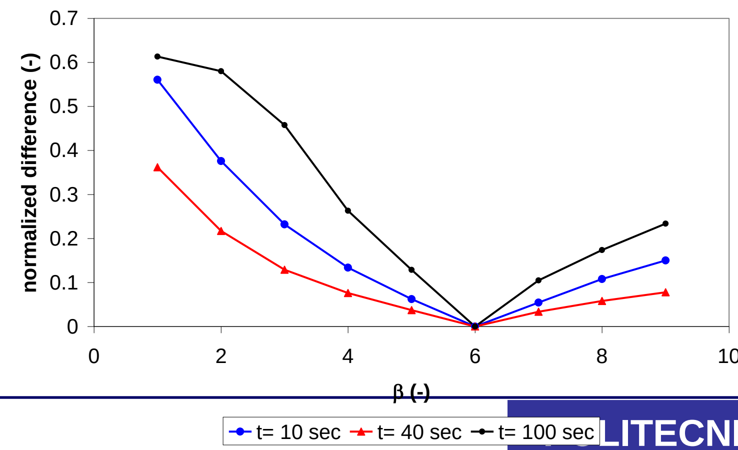
with

$$\left\|\sigma_{ok}\right\|_2 = \left[\sum_{i=1}^{n}\left(\sigma_{ok}^{i}\right)^2\right]^{1/2} \qquad \left\|\sigma - \sigma_{ok}\right\|_2 = \left[\sum_{i=1}^{n}\left(\sigma^{i} - \sigma_{ok}^{i}\right)^2\right]^{1/2}$$



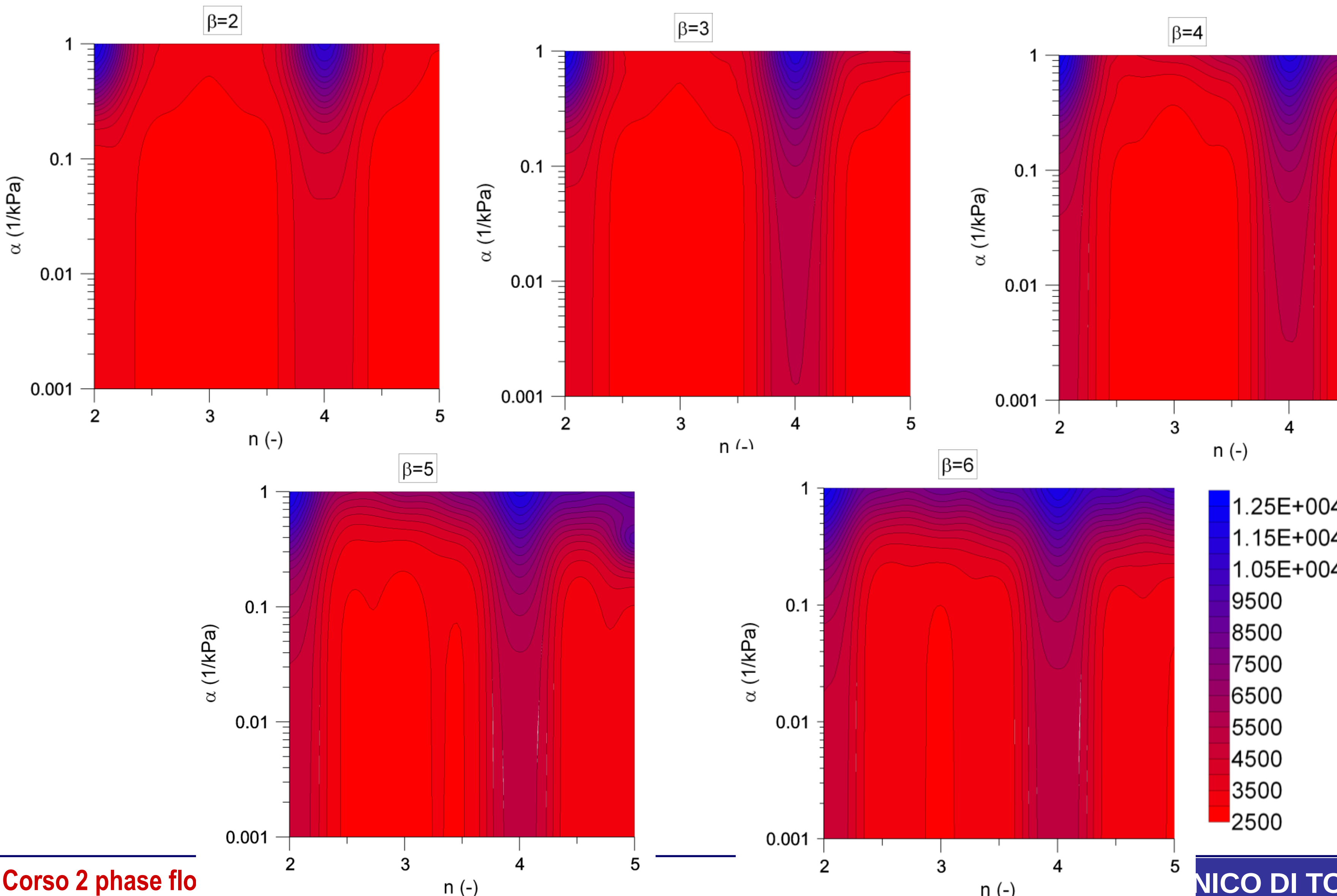






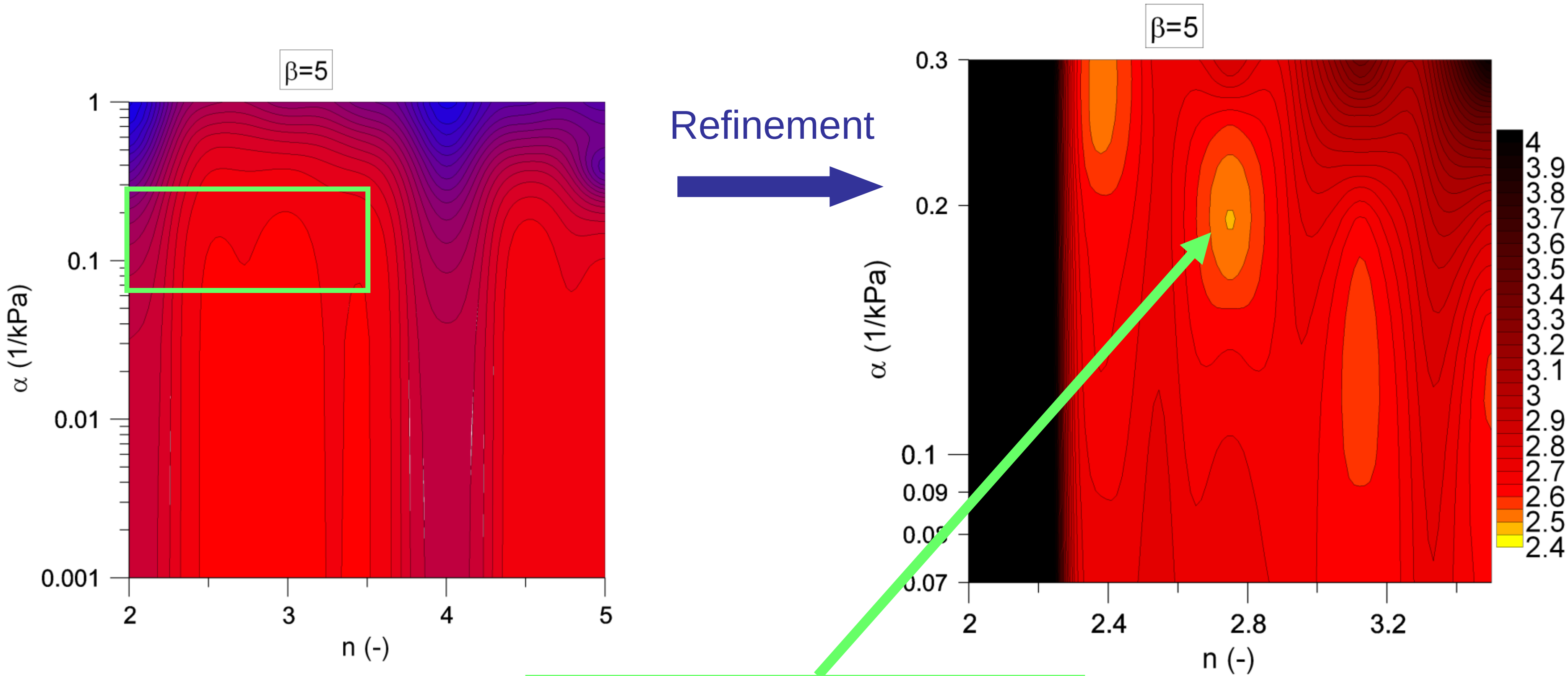
Evaluation of the error on a regular spatial grid

$$\|\sigma - \sigma_{ok}\|_{L1} = \sum_{i=1}^{n} \left|\sigma^i - \sigma^i_{exp}\right|$$



Trial and error technique

$$\left\| \sigma - \sigma_{ok} \right\|_{L1} = \sum_{i=1}^{n} \left| \sigma^{i} - \sigma^{i}_{exp} \right| = \min$$



$\beta=5$

$\alpha=1.85e^{-4}\ Pa^{-1}$

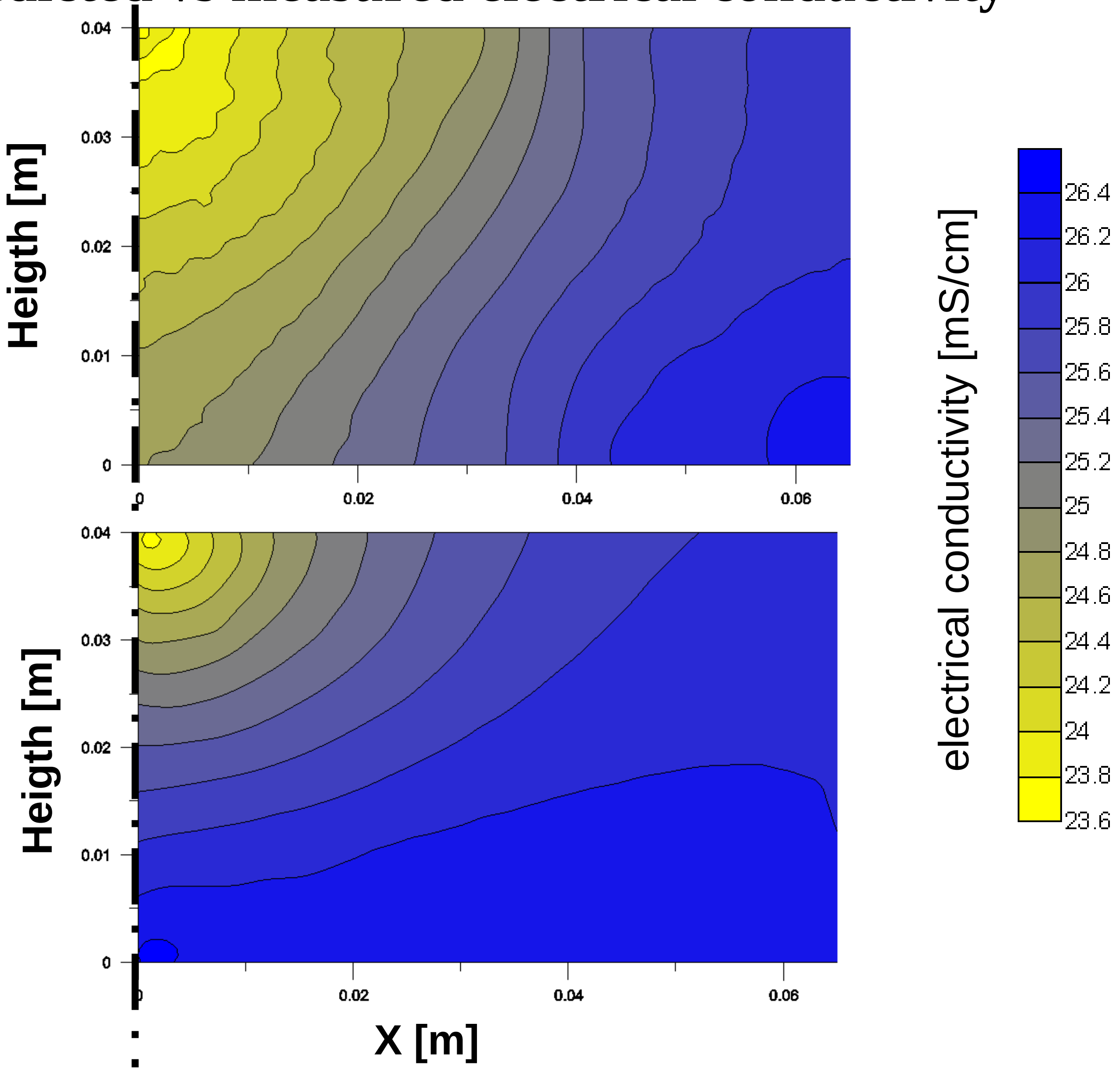
$n=2.75$

Comparison of predicted vs measured electrical conductivity

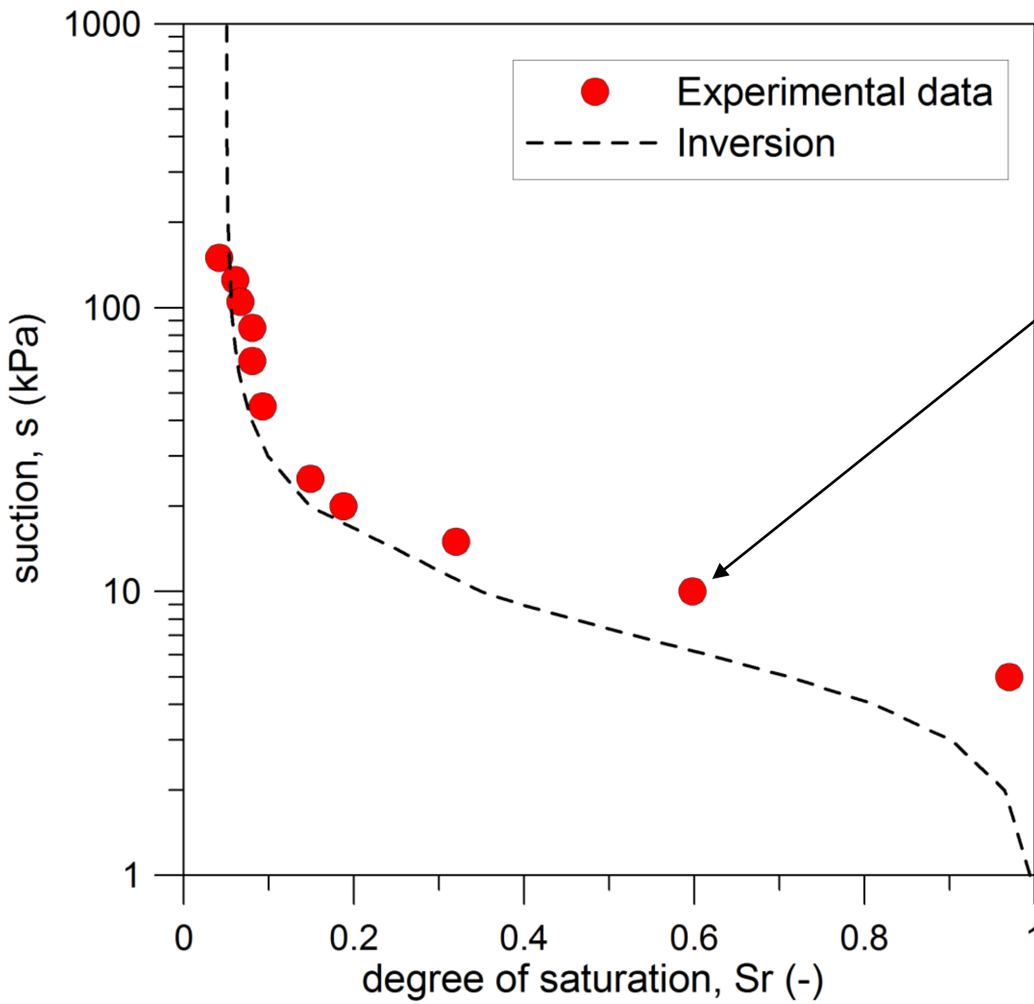
Best fitting FEM Model

β=5
α=1.85e^{-4} Pa^{-1}
n=2.75

Electrical tomography



Predicted retention curve vs. experimental data



Independent evaluation with conventional technique

β=5

α=1.85e^{-4} Pa^{-1}

n=2.75

Advantages: testing times
possible applications on site

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Tomàs Pérez (UPC, Barcelona) for the design of the cell

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References

Cosentini R.M., Della Vecchia G., Foti S., Musso G. (2012) *Estimation of the hydraulic parameters of unsaturated samples by electrical resistivity tomography* – Géotechnique - vol. 62 n. 7, pp. 583-594

Comina C., Cosentini R.M. , Della Vecchia G., Foti S., Musso G. (2011) *3-D electrical resistivity tomography monitoring of salt transport in homogeneous and layered soil samples*. Acta Geotechnica, vol. 6 n. 4, pp. 195-203

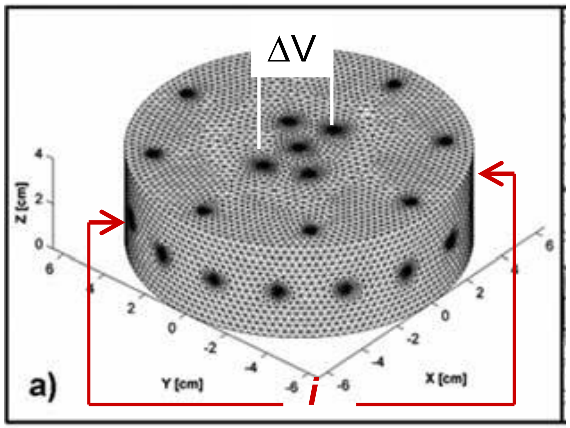
Comina C., Foti S., Musso G., Romero E. (2008) - *EIT oedometer - an advanced cell to monitor spatial and time variability in soil* – Geotechnical Testing Journal, **31** – 5

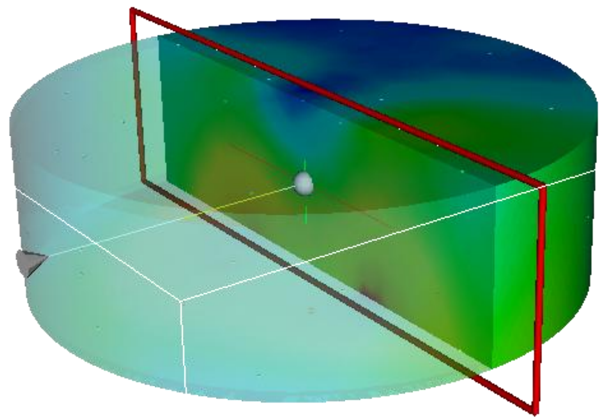
Borsic A., Comina C., Foti S., Lancellotta R., Musso G. (2005) - *Imaging heterogeneities in sand samples with EIT: laboratory results* – Geotechnique, **55** (7), 539-547

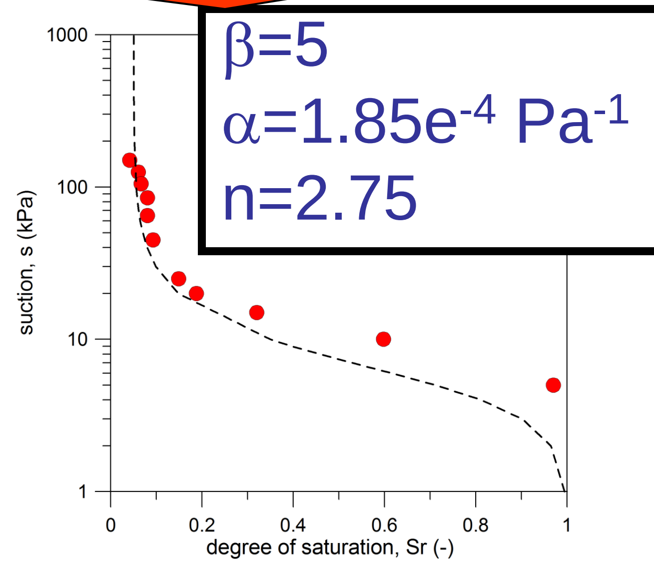
Further developments:

- Rigorous solution of the inverse problem
- Possibility to avoid an intermediate step (the same 3D model can be used to simulate transport phenomena and electrical conductivity measurements)
- Site applications

Inverse problem
(misfit on ΔV)







measurements

conductivity

Model parameters

Tomographic reconstruction

Inverse problem
(misfit on conductivity)

References

Comina C., Foti S., Musso G., Romero E. (2008) - *EIT oedometer - an advanced cell to monitor spatial and time variability in soil* – Geotechnical Testing Journal, **31** - 5

Comina C., Festa C., Foti S., Musso G. (2008) - *Monitoring 3D diffusion processes with high-speed electric tomography* – The Leading Edge, **27**, 4, 468 – 471

Borsic A., Comina C., Foti S., Lancellotta R., Musso G. (2005) - *Imaging heterogeneities in sand samples with EIT: laboratory results* – Geotechnique, **55** (7), 539-547