Aalto University
School of Engineering

THEBES project meeting seminar

Espoo, 21 June 2018

Measurement of soil suction
and
Determination of the AEV of soils from pore size distribution

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Northumbria University
NEWCASTLE

Summary

Introduction to soil suction

Measurement of soil suction

Indirect and Direct methods

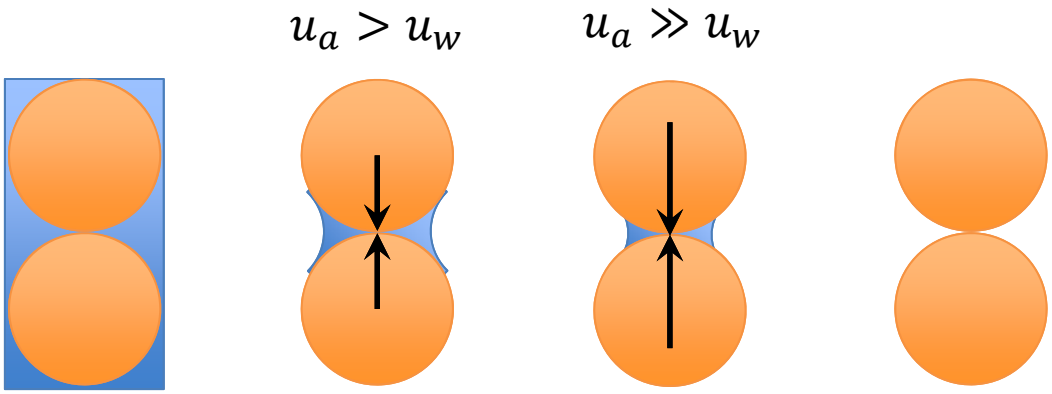
Determination of Air Entry Value (AEV) in soils

Mercury intrusion porosimetry (MIP)
Nitrogen adsorption porosimetry (NA)

Non-swelling soils
Swelling soils

Introduction

Introduction



Soil suction:

attraction that the soil exerts on water

Negative hydraulic tensile stress

Introduction

$$\Psi = (u_a - u_w) + \pi$$

Total Suction

Matric Suction

Osmotic Suction

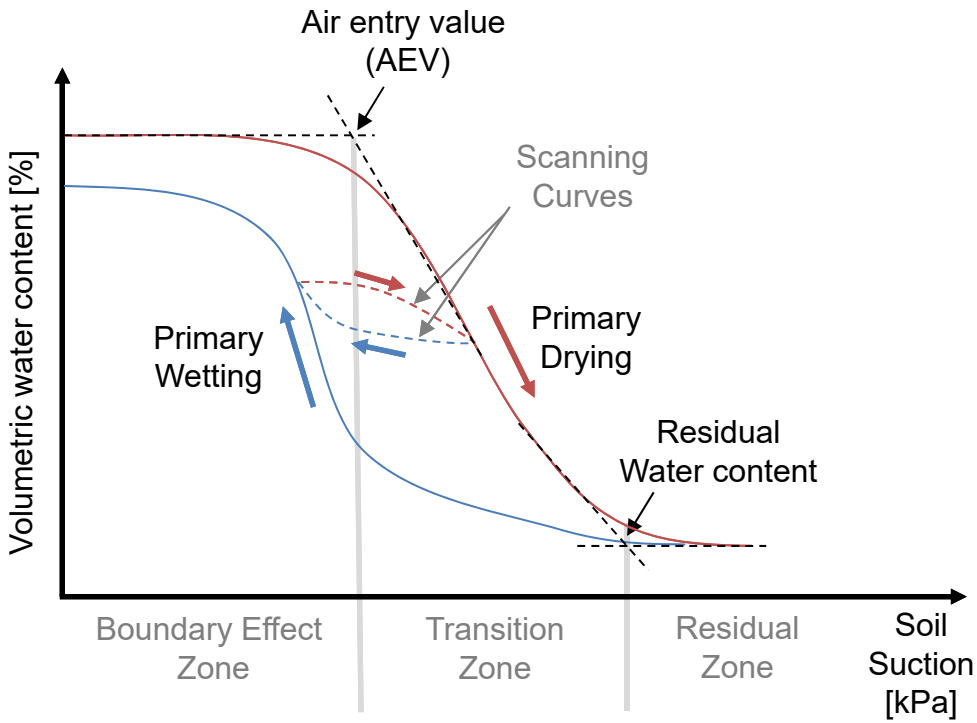
Matric suction : related to the capillary phenomenon associated to surface tension between water and air within soil pores

$$u_a - u_w = h_c = \frac{2\gamma \cos\theta}{\rho_w g r}$$

Osmotic suction : related to the salt concentration in pore water

Soil water retention curve / Soil water characteristic curve SWRC/SWCC

By measuring suction
Monitoring mass and volume



The shape of SWRCs depend on:

Soil type
(Sand, Silt and Clay)

Soil structure
(aggregate size, shape and stability)

Mineralogy

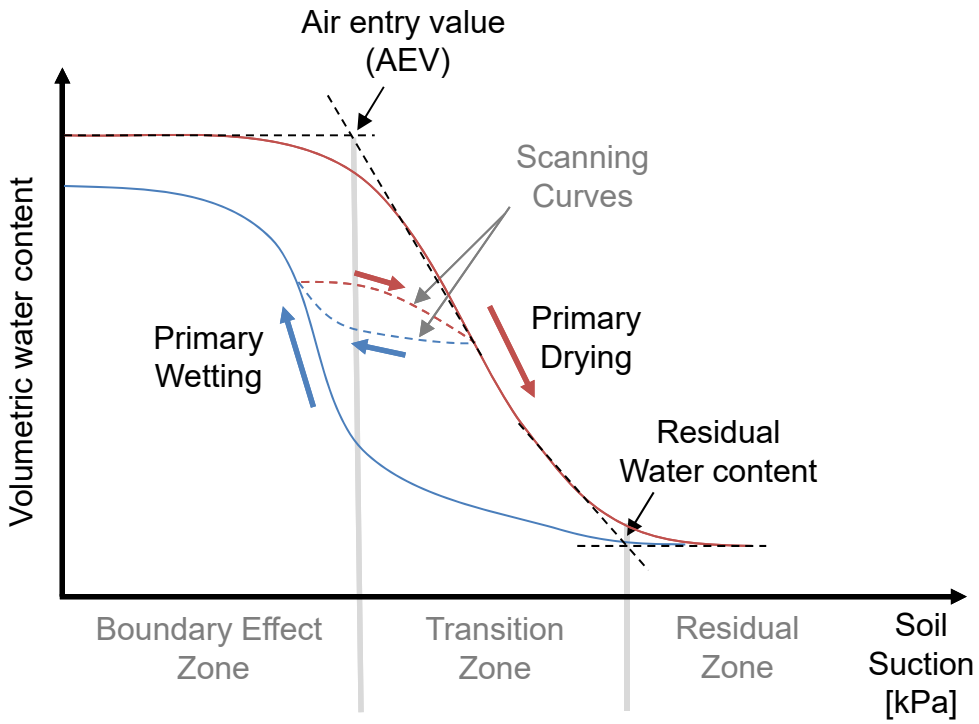
Initial conditions
(void ratio, water content and stress state)

Testing conditions
(temperature and confinement)

History
(wetting and drying cycles)

Soil water retention curve / Soil water characteristic curve SWRC/SWCC

By measuring suction
Monitoring mass and volume



The shape of SWRCs depend on:

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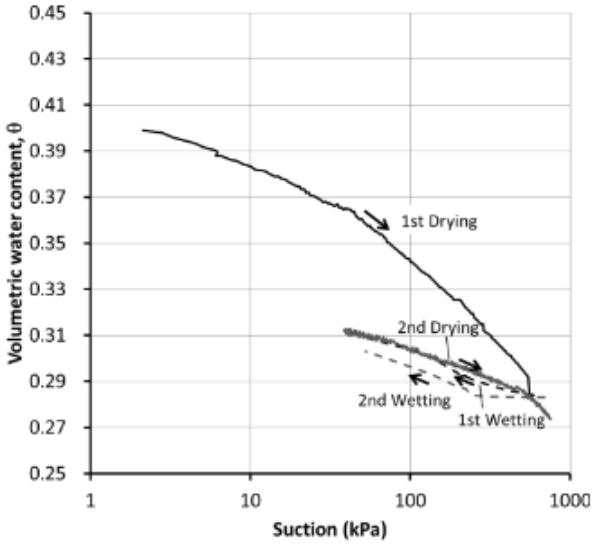

(Toll et al., 2016)

Method	Suction component	Suction Range [kPa]	Equilibration Time	Measurement Principle
Thermocouple Psychrometer	Total	300-7000	Hour	Relative Humidity
Transistor Psychrometer	Total	100-10000	Hour	
Chilled-Mirror Psychrometer	Total	100-30000	Minutes	
Filter Paper (non contact)	Total	50-30000	5-14 days	Moisture Equilibrium
Filter Paper (in contact)	Matric	50-30000	5-14 days	
Thermal Conductivity Sensor	Matric	1-1500	Hours to Days	
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Squeezing Technique	Osmotic	0-100000	Minutes	Electrical Conductivity

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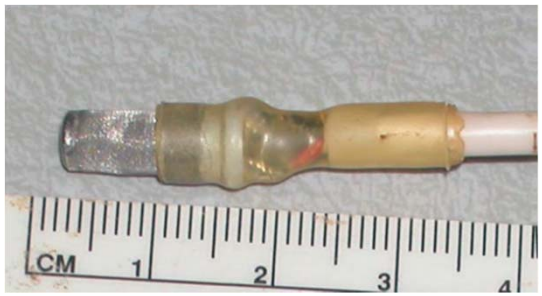
Total suction measurement

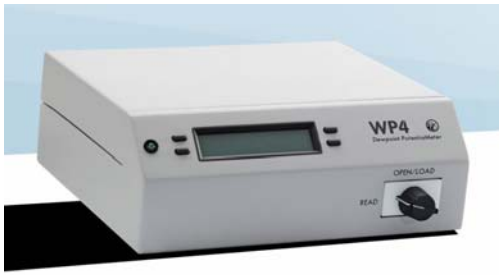
$$\psi = -\frac{RT}{v_{w0}\omega_v}\ln\left(\frac{\bar{u}_v}{\bar{u}_{v0}}\right)$$

Thermocouple Psychrometer



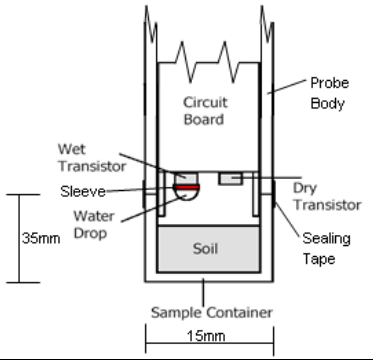
(Bulut and Leong, 2005)

Chilled-Mirror Psychrometer

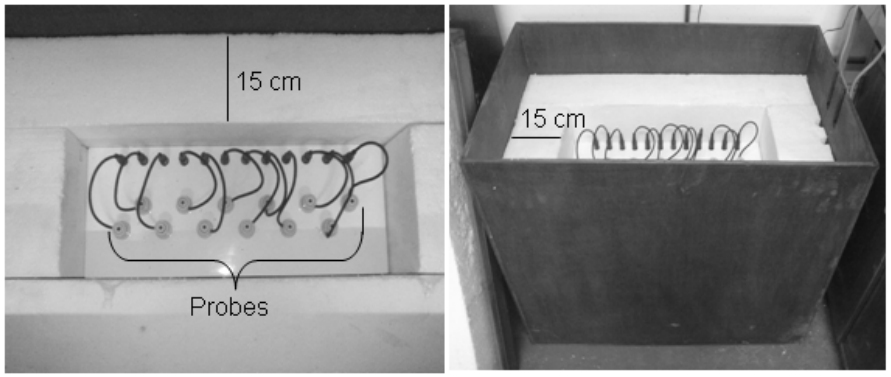


(Meter Group, 2018)

Transistor Psychrometer



(Bulut and Leong, 2005)



(Mendes, 2011)

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Total suction measurement

$$\psi = -\frac{RT}{v_{w0}\omega_v}\ln\left(\frac{\bar{u}_v}{\bar{u}_{v0}}\right)$$

Relative humidity – indirect measurement

Temperature sensitive – lab based technique

Chilled-mirror and Transistor psychrometer:

- Point measurement
- Small sample size
- Difficult to replicate samples
- Not suitable for small suctions

Method	Suction component	Suction Range [kPa]	Equilibration Time	Measurement Principle
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Total suction and Matric suction measurement

Moisture equilibrium between a known porous medium and the soil

Non-contact filter paper
Total suction

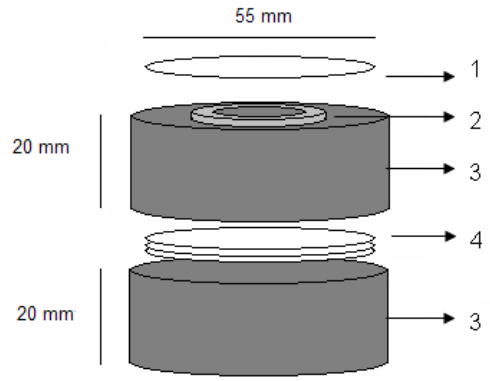
In-contact filter paper
Matric suction

Moisture equilibrium of filter paper in relation to value of suction

Calibration

Total suction
Salt solutions

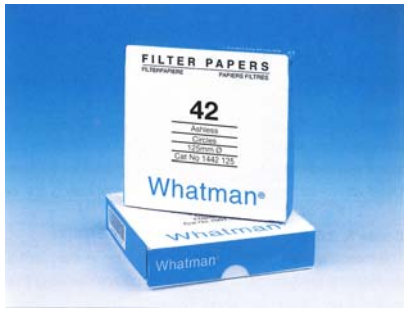
Matric suction
Pressure plate



1 - Non-contact filter paper for total suction measurement
2 - PCV ring to avoid contact between non-contact filter paper and sample
3 - Soil sample
4 - In-contact filter paper for matric suction measurement (one filter paper in between two protective filter papers)

(Noguchi et al., 2011)

Whatman No. 42



Schleicher & Schuell No. 589-WH

Total suction and Matric suction measurement

Moisture equilibrium between a known porous medium and the soil

Calibration curves for Whatman 42
van Genuchten (1980):

Matric suction

$$\Psi = 0.051\left[\left(\frac{248}{w_f}\right)^{9.615} - 1\right]^{0.473}$$

Total suction

$$\Psi = 56180\left[\left(\frac{37}{w_f}\right)^{0.44} - 1\right]^{2.361}$$

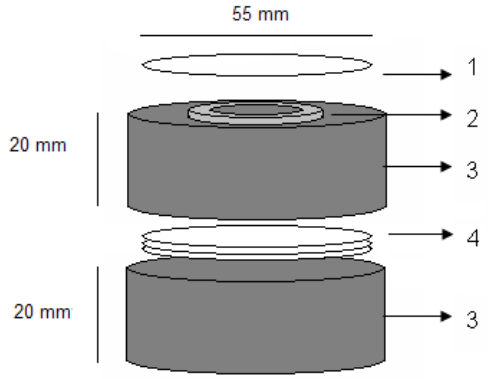
Hamblin (1981):

$$\log \Psi = 8.022 - 3.683 \log w_f$$

Leong et al (2002):

$$\log \Psi = 2.909 - 0.0229 w_f \qquad w_f \geq 47$$

$$\log \Psi = 4.945 - 0.0673 w_f \qquad w_f < 47$$



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(Noguchi et al., 2011)

Indirect measurement

Advantages:
Easy to implement
Good range
Low cost

Disadvantages:
Lab based
Temperature sensitive
Point measurement
Long equilibrium time
Requires experience

Method	Suction component	Suction Range [kPa]	Equilibration Time	Measurement Principle
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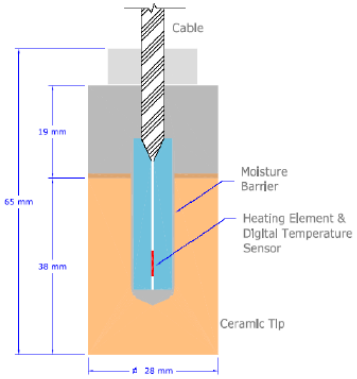
Matric suction measurement

Moisture equilibrium between a known porous medium and the soil

Thermal Conductivity



(GTCS, 2018)

Electrical Conductivity

(IRROMETER, 2018)

Dielectric Permittivity

Matric suction measurement

Moisture equilibrium between a known porous medium and the soil

Indirect measurement
Lab and field based techniques

Thermal Conductivity:
Temperature change is related to thermal conductivity of the porous block and its moisture content
Long equilibration time

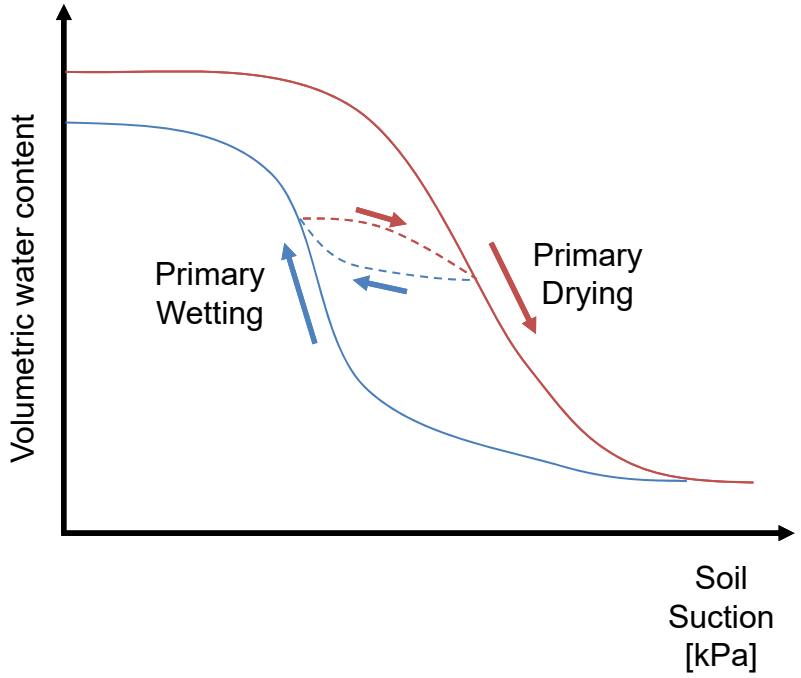
Electrical Conductivity:
Electrical conductivity is related to the moisture in the porous block
Long equilibration time

Dielectric Permittivity:
Dielectric permittivity is related to the moisture in the porous block

Matric suction measurement

Moisture equilibrium between a known porous medium and the soil

Indirect measurement
Lab and field based techniques



Special care when calibrating these type of devices

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Controlling Matric suction
Axis translation technique

Suction is imposed to the soil samples

$$u_a - u_w$$

u_a - increased to value above 0

u_w - maintained at value close to 0 or controlled

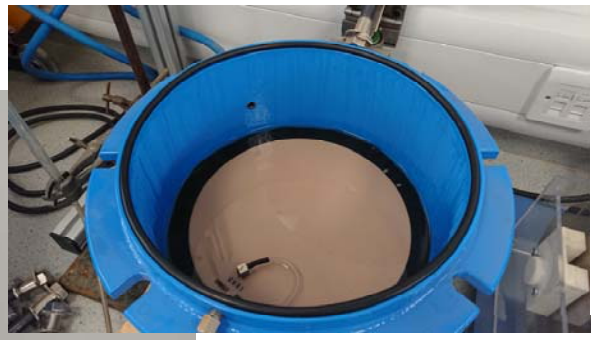
Versatile technique that can be applied to various testing devices.
Indirect suction measurement techniques for matric suction are calibrated with these type of devices

Controlling Matric suction
Axis translation technique

Suction is imposed to the soil samples

Disadvantages:
Soil samples are not tested in *in-situ* conditions
Cavitation in the soil is prevented

Complicated
Expensive
Long equilibrium time



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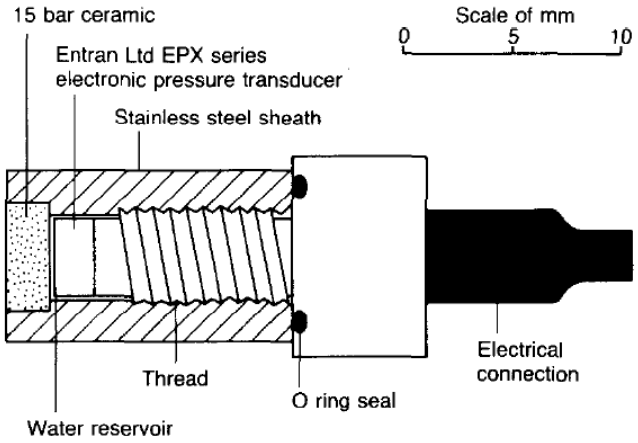
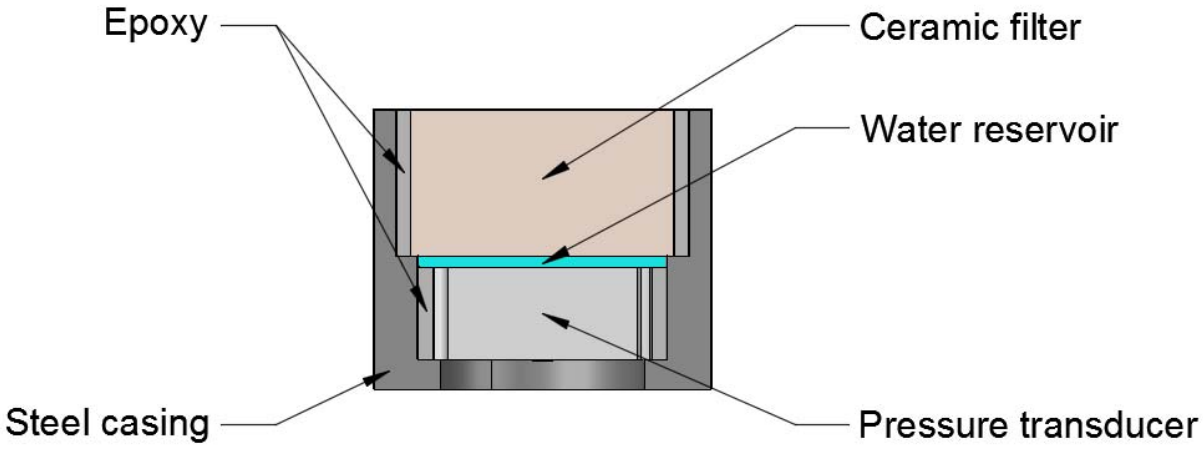
High Capacity Tensiometer



After Ridley and Burland (1993)

$$u_a - u_w = h_c = \frac{2\gamma \cos\theta}{\rho_w g r}$$



Key components:

Pressure transducer
Water reservoir
Ceramic filter

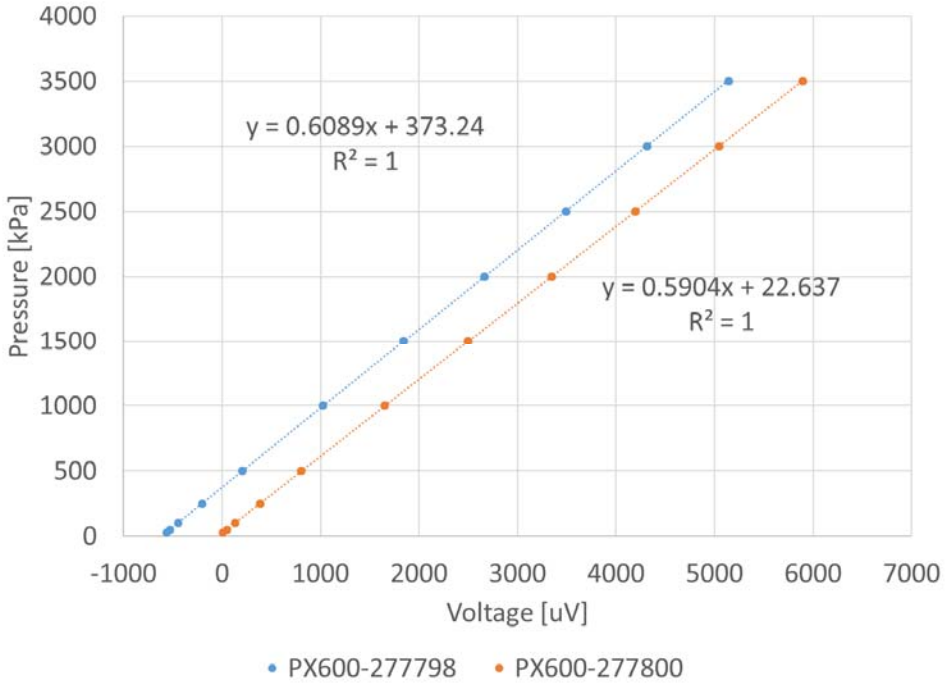
High Capacity Tensiometer

CALIBRATION

Cycling pressure in the positive range

Calibrations must be perfectly linear in both increasing and decreasing in pressure

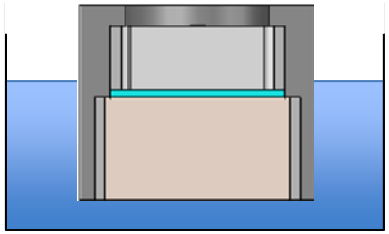
Calibrations can be extrapolated to the negative range **IF** the pressure transducers are built symmetrically



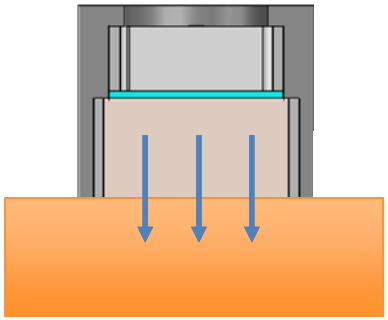
High Capacity Tensiometer

MEASUREMENT OF SOIL SUCTION WITH HCT

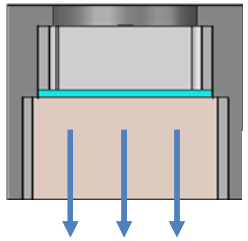
$P_{HCT} = P_{water}$

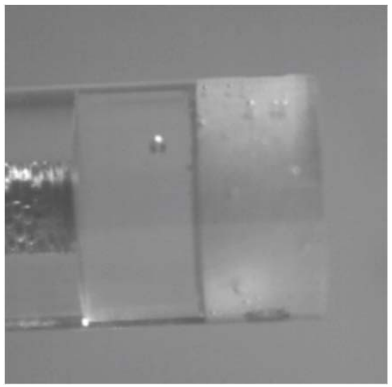


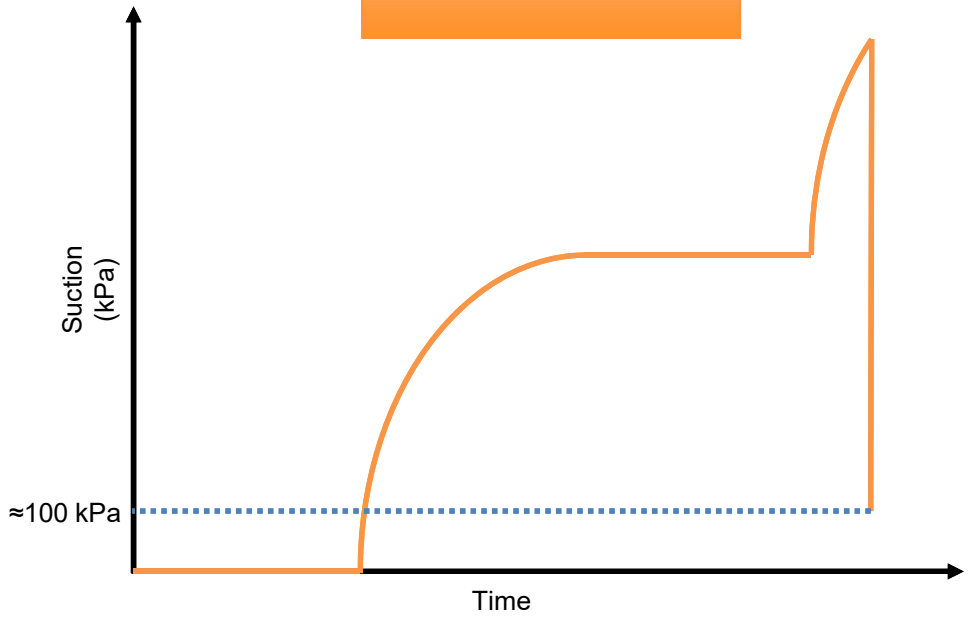
$P_{HCT} \geq Pwp_{soil}$

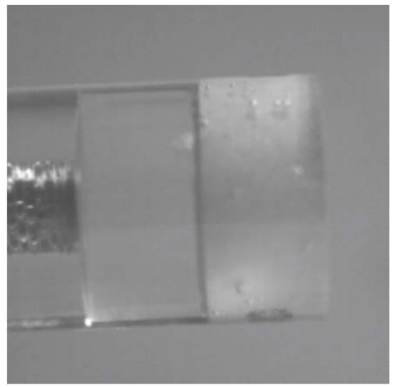


$P_{HCT} \geq AEV_{air}$









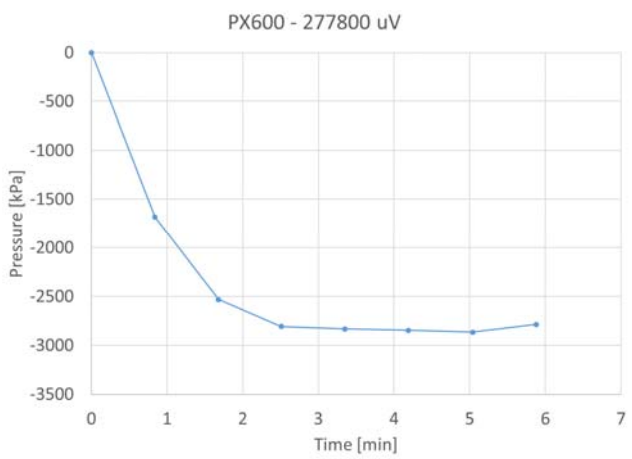
High Capacity Tensiometer

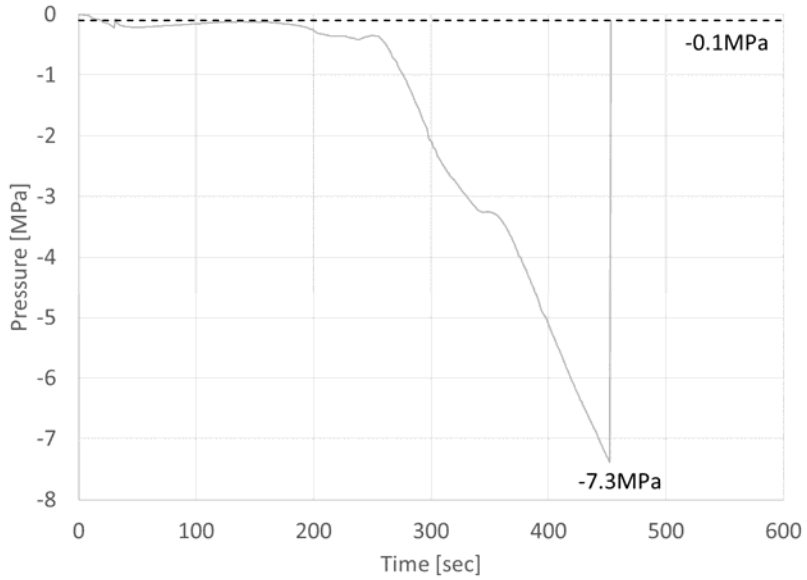
Direct measurement
Lab and field based techniques

Advantages:
Fast measurement
Direct measurement
Point and/or continuous measurement

Disadvantages:
Cavitation limits range
Expensive
Requires experience

$$u_a - u_w = h_c = \frac{2\gamma \cos\theta}{\rho_w g r}$$





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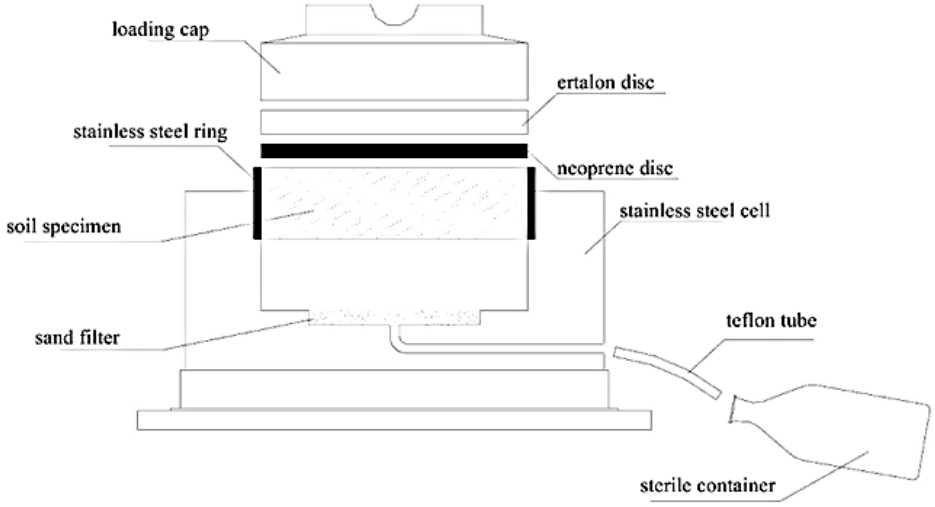
Squeezing Technique	**Osmotic**	**0-100000**	**Minutes**	**Electrical Conductivity**

Osmotic suction

Related to the salt concentration in pore water

Pore water is squeezed out of the sample
Osmotic suction is related to electrical conductivity of the pore water



(Peroni, 2002)

$\pi = 0.0191EC^{1.074}$ $(U.S.D.A., 1950)$
$\pi = 0.0240EC^{1.065}$ $(Romero, 1999)$

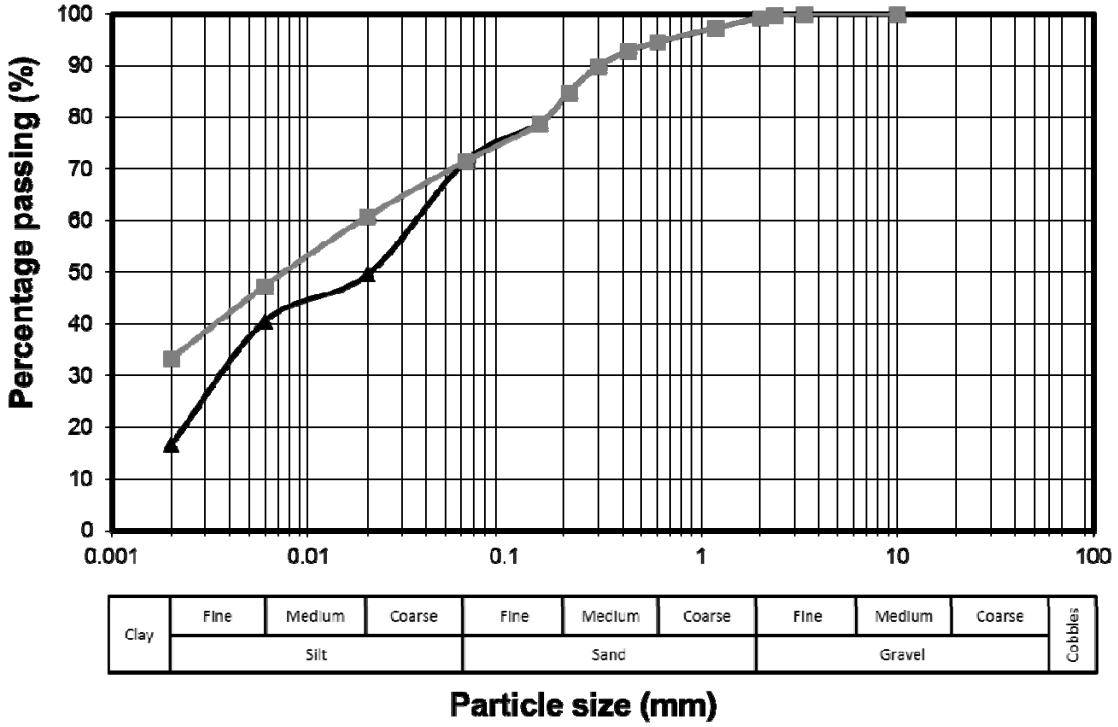
Measurement comparison 1

Total suction: Filter paper / Psychrometer / Chilled mirror
Matric suction: Filter paper / Axis translation / High capacity tensiometer

Sand clay soil

Measurement comparison 1

Total suction: Filter paper / Psychrometer / Chilled mirror
Matric suction: Filter paper / Axis translation / High capacity tensiometer



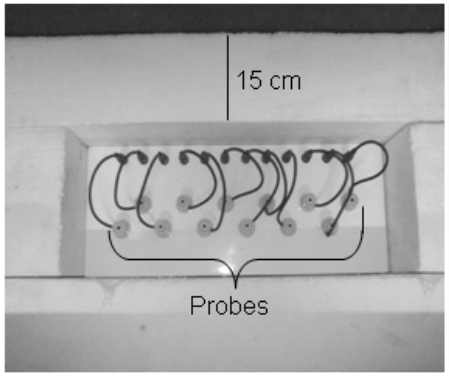
Sand clay soil

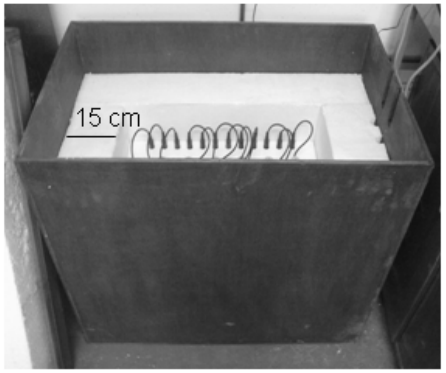
Samples were prepared at a similar water content of 25%

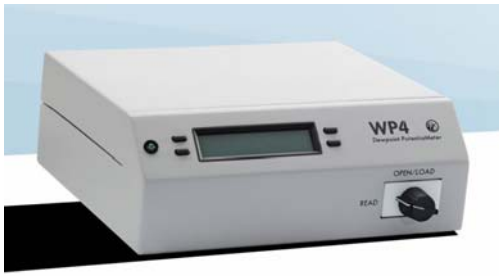
Compacted using the proctor hammer

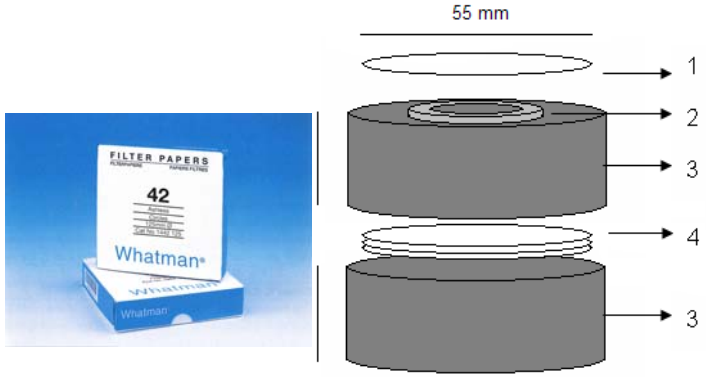
Stage and continuous dried

Transistor psychrometer vs Filter paper vs Chilled mirror



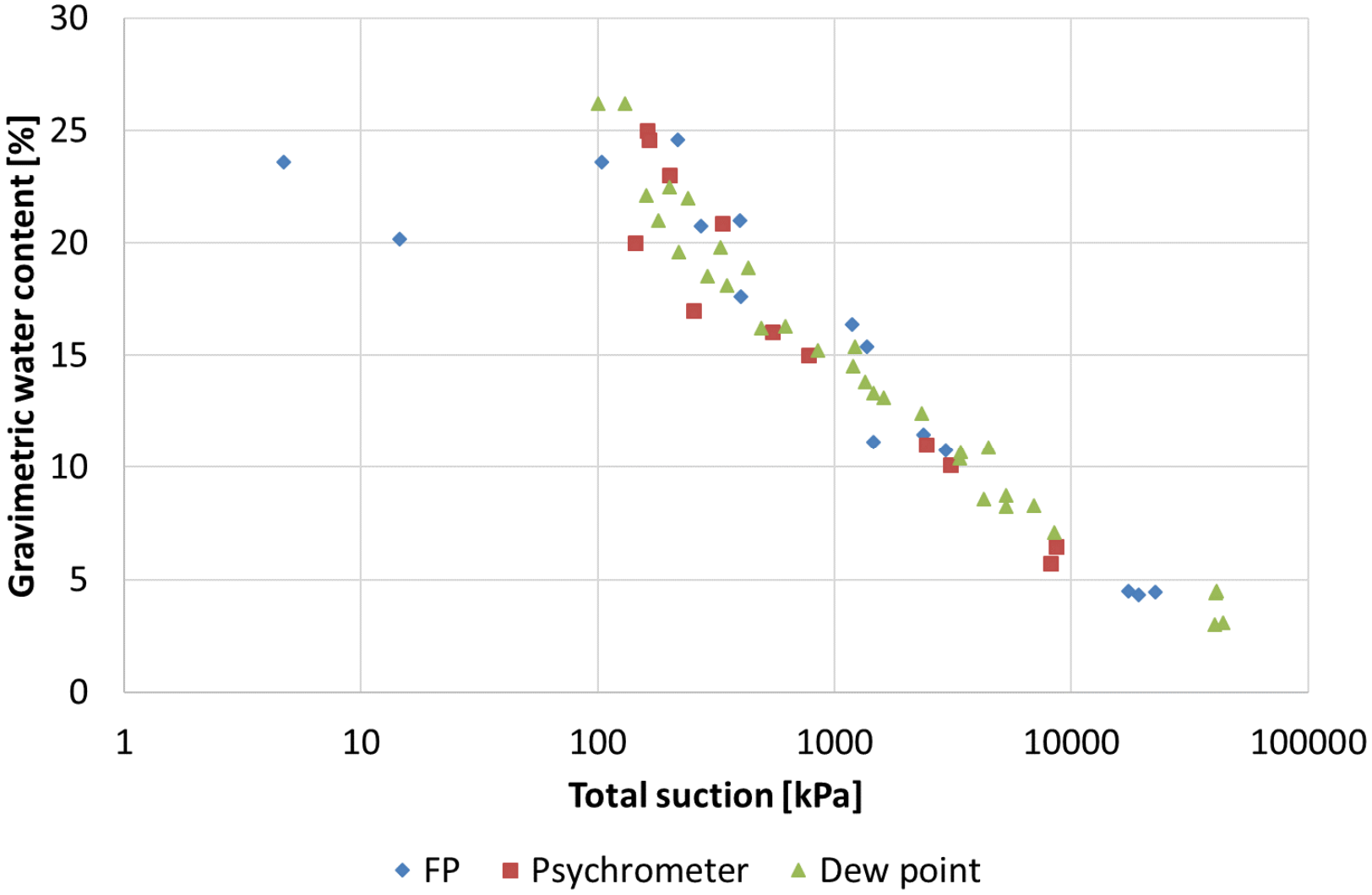




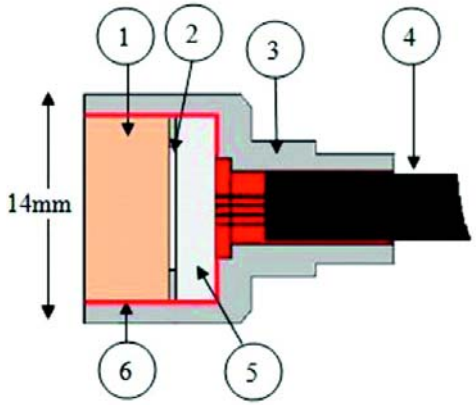


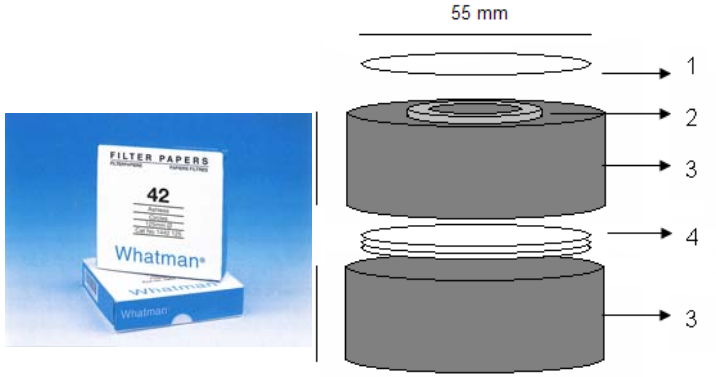
van Genuchten (1980)

Transistor psychrometer vs Filter paper vs Chilled mirror

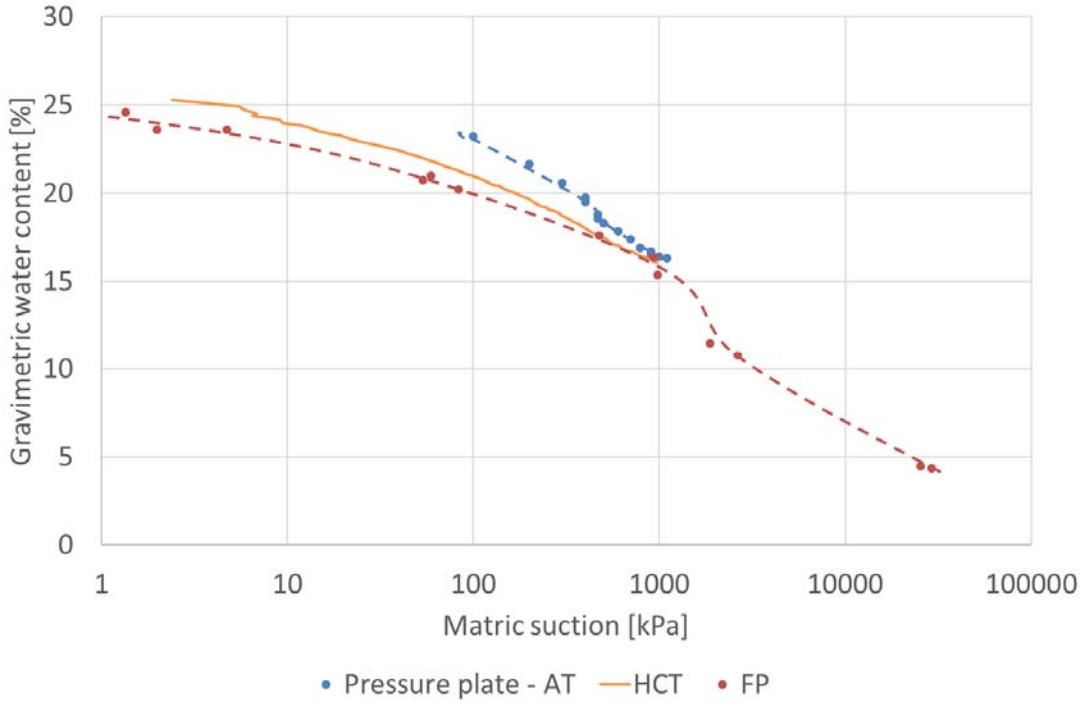


High Capacity Tensiometer vs Filter paper vs Axis translation

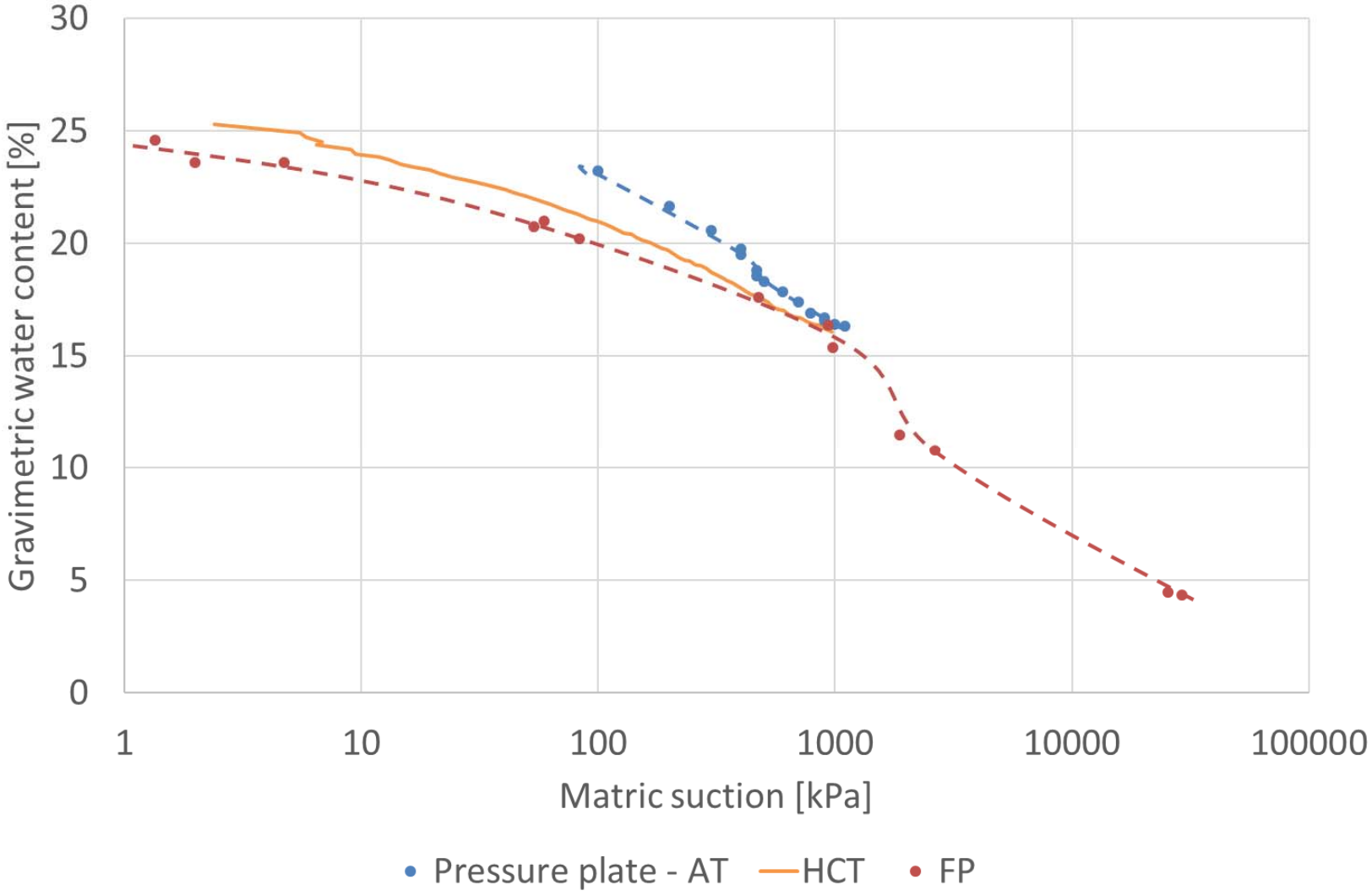




van Genuchten (1980)

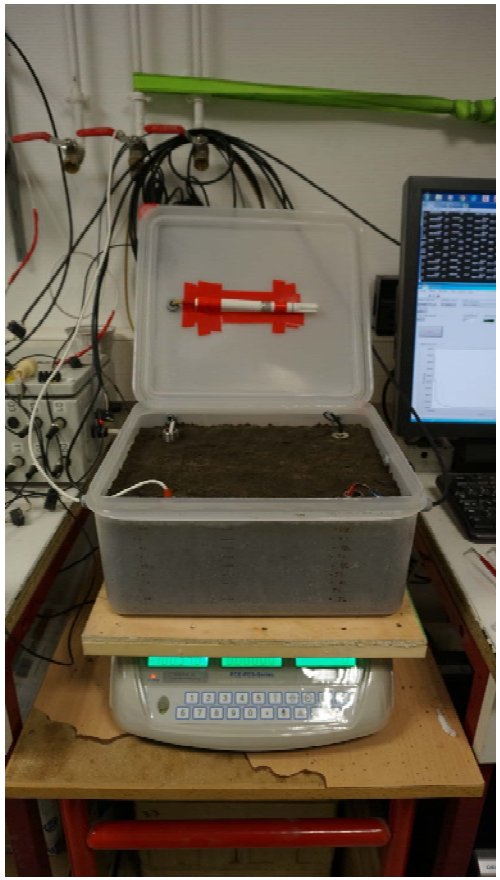


High Capacity Tensiometer vs Filter paper vs Axis translation



Measurement comparison 2

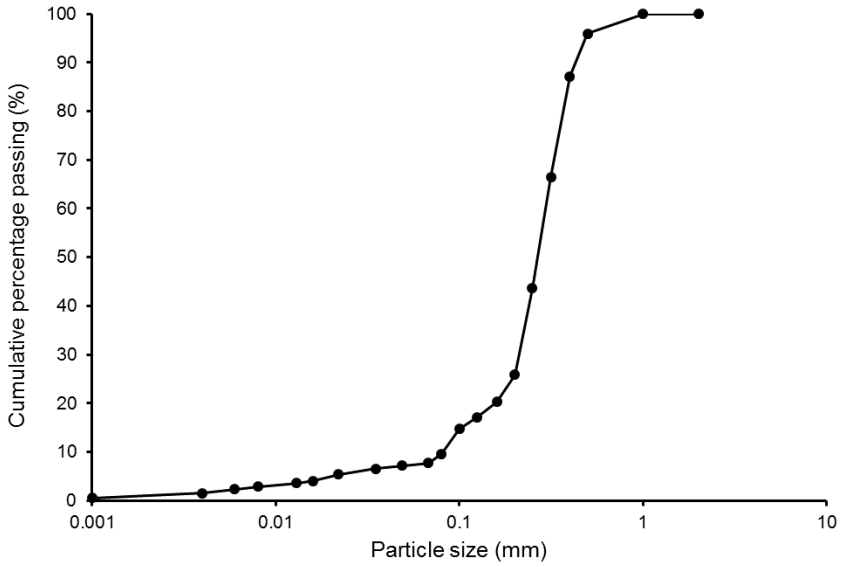
Matric suction: Dielectric Permittivity / High capacity tensiometer



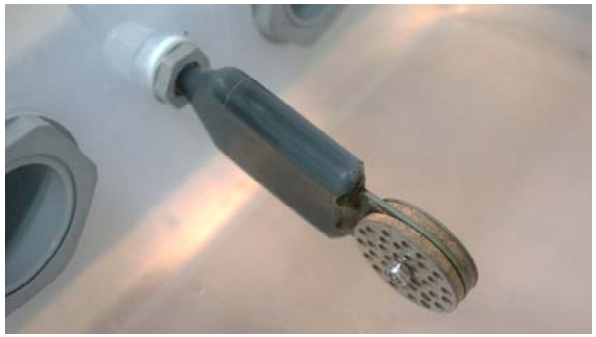
Sandy soil

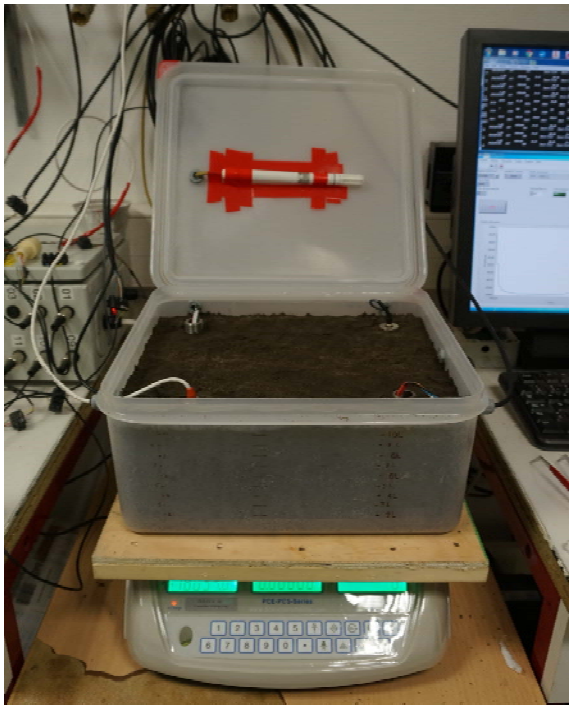
Initial water content = natural water content

Continuous dried

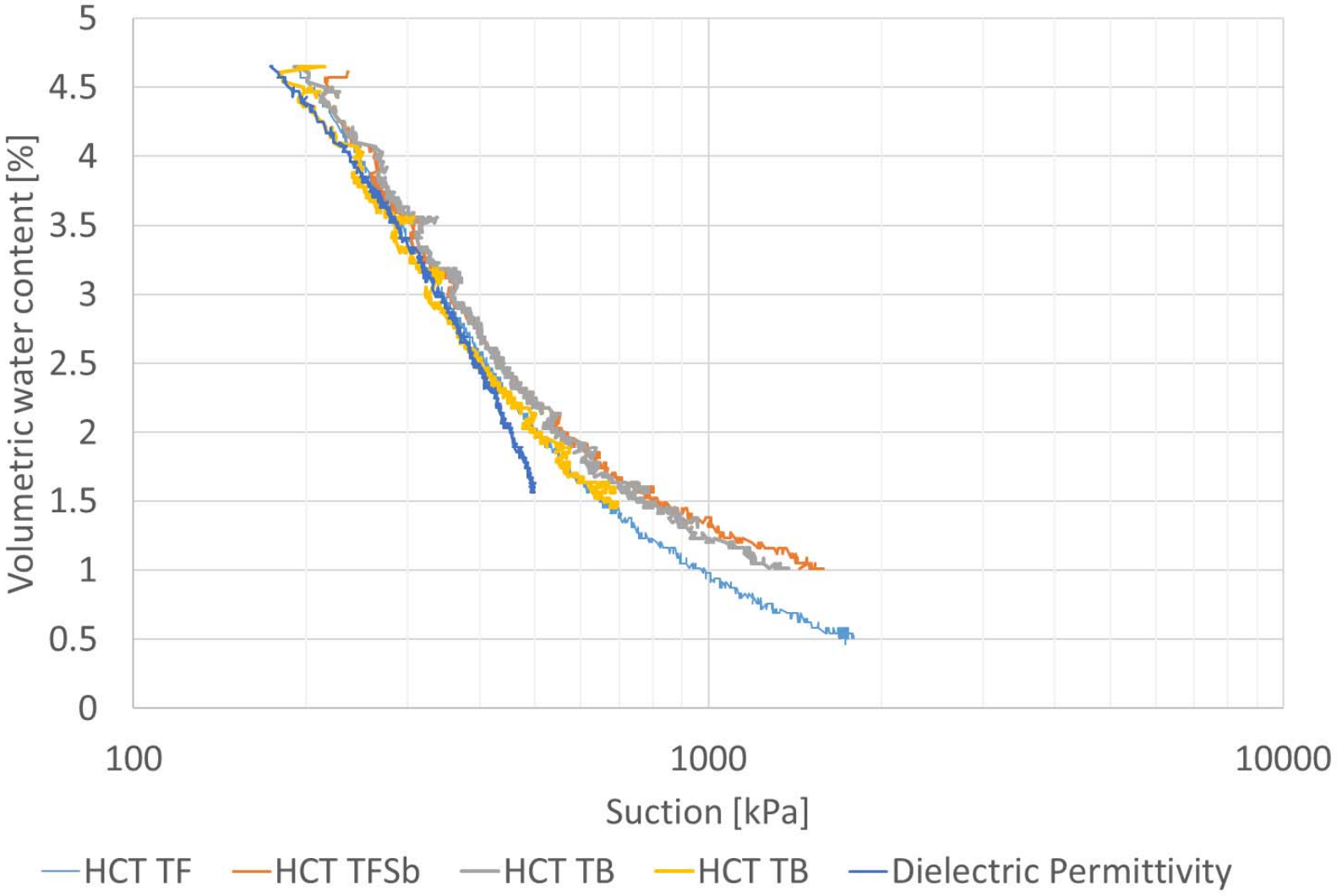


High Capacity Tensiometer vs Dielectric Permittivity





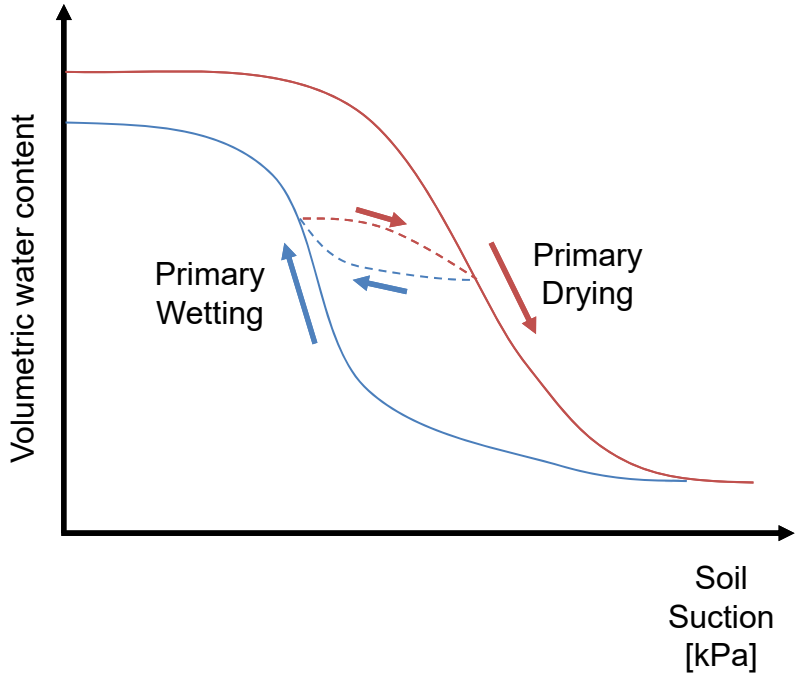
High Capacity Tensiometer vs Dielectric Permittivity



Matric suction measurement

Moisture equilibrium between a known porous medium and the soil

Indirect measurement
Lab and field based techniques



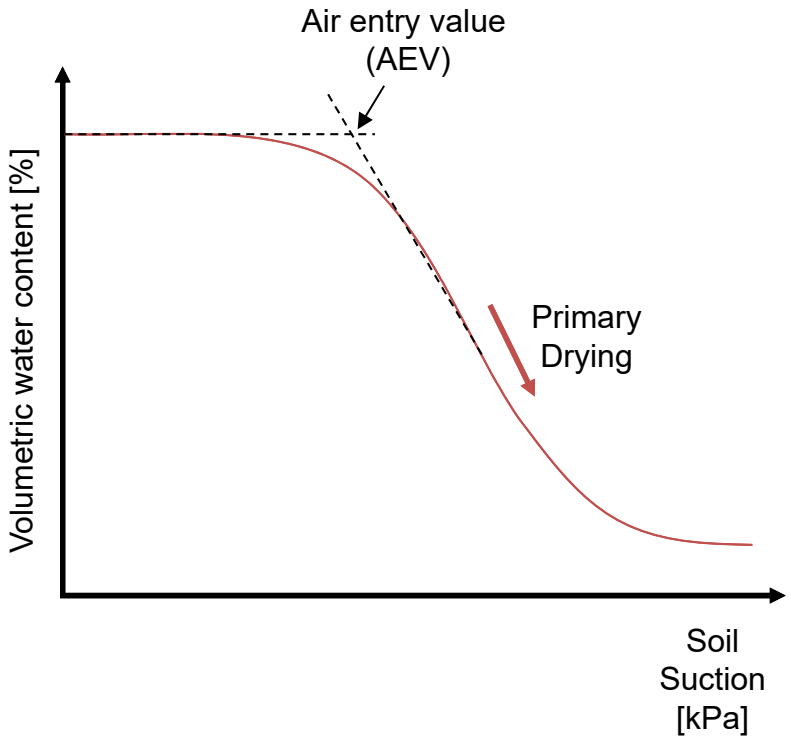
Special care when calibrating these type of devices

Suction measurement

Independently of the measuring technique, the measurement quality is highly dependent on the adopted testing protocol.

It is important to understand the limitations and their implications in order to obtain reliable data.

Determining the air entry value from pore size distribution



Determining the air entry value from pore size distribution

Air entry value is a soil property/characteristic* that is defined as the value of suction at which air recedes into the pores.

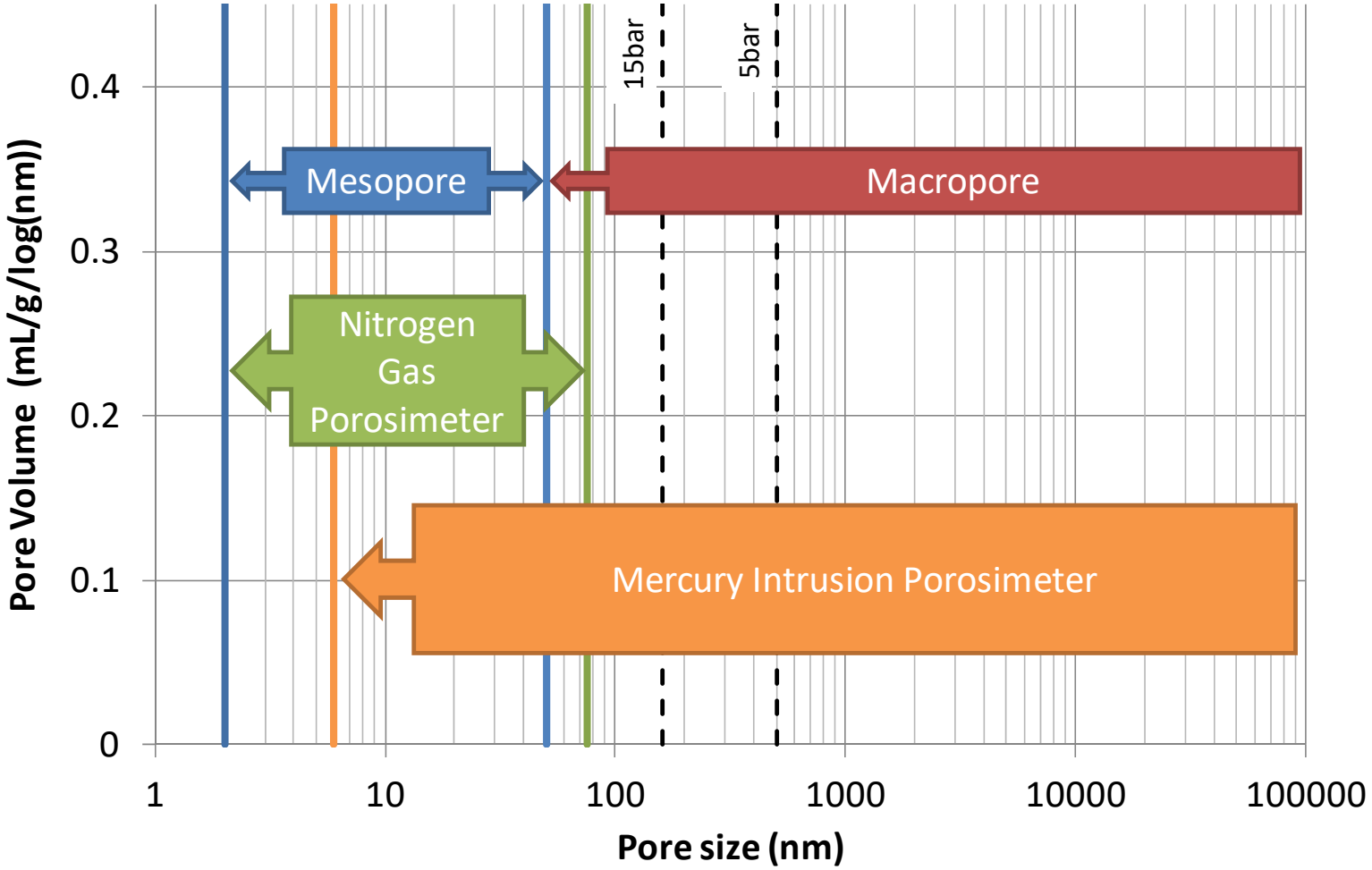
The soil* starts to desaturate – Sr <100%

The AEV is a key parameter used to estimate unsaturated soil properties

Shear Strength
Permeability

* - depends on the initial soil state and history

Determining the air entry value from pore size distribution



Pore size distribution in a porous media

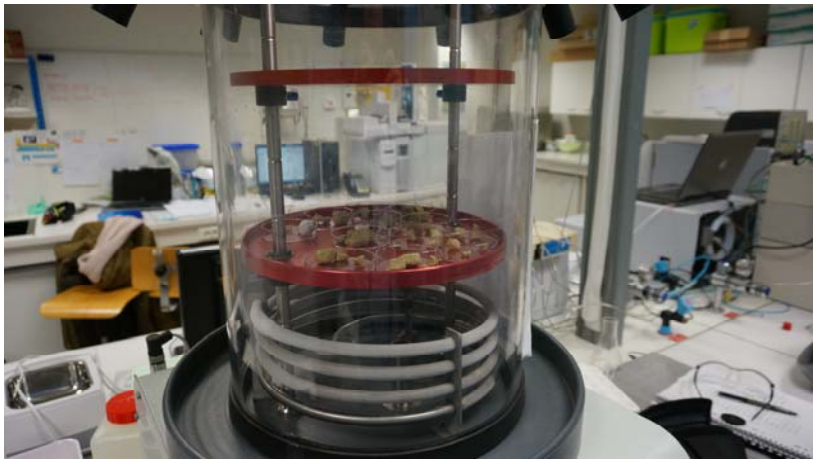
Preparation work

For **soil** samples it is important to keep the microstructure

Freeze-drying

Dip samples in liquid nitrogen

Vacuum at low temperature



Temperature shock can result in micro-fractures

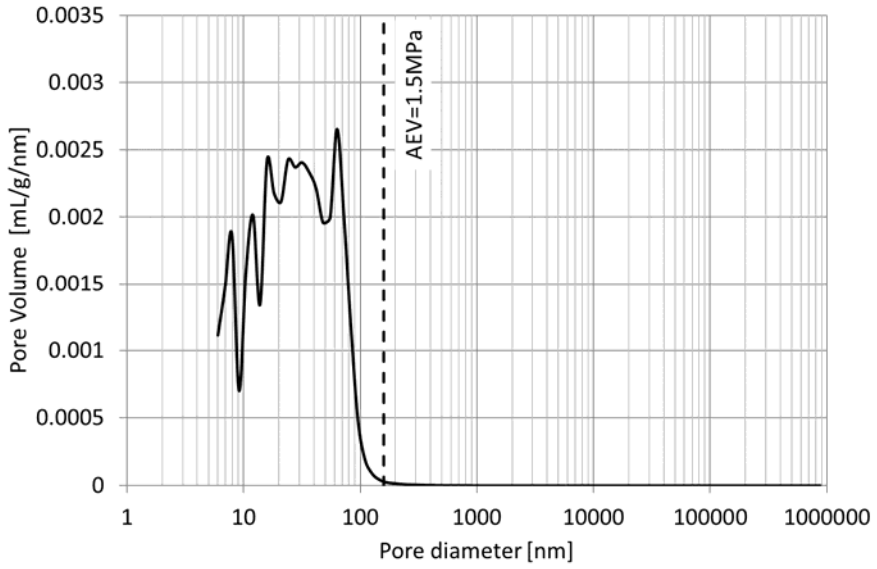
Pore size distribution in a porous media

Mercury intrusion porosimetry (MIP)
Measurement range: 6nm – 1mm

Young-Laplace equation for capillary pressure (P_c)

$$P_c = \frac{-4\gamma \cos\theta}{d} \Leftrightarrow d = \frac{-4\gamma \cos\theta}{P_c}$$

θ – mercury contact angle
γ – surface tension of mercury
d – pore diameter



Pores shape is not considered and can affect results

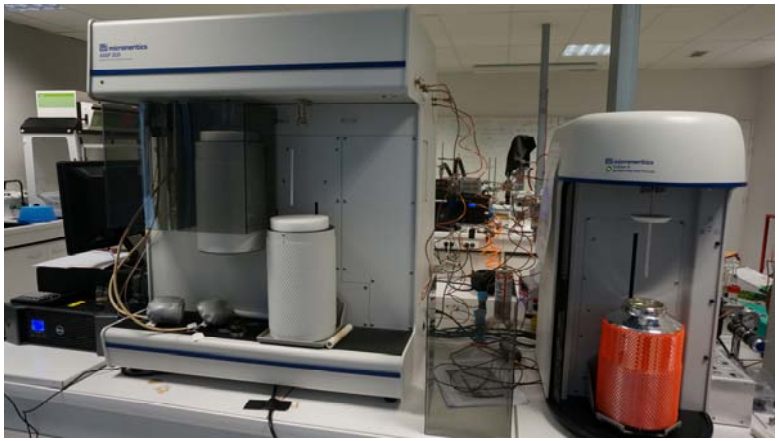
Northumbria University NEWCASTLE

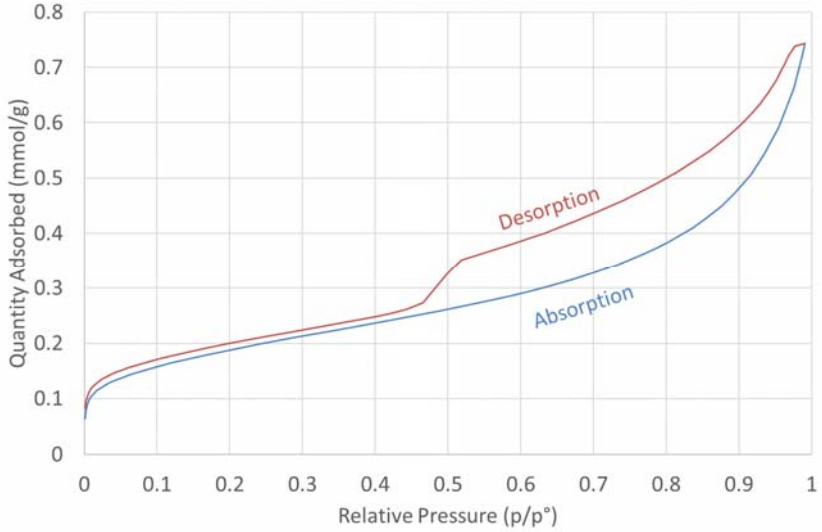
Pore size distribution in a porous media

Gas porosimetry (Nitrogen)
Measurement range: 2nm – 60nm

Barrett-Joyner-Halenda (BJH) (1950)

Adsorption – gas condensates and fills the pores with increase pressure
Desorption – evaporation of condensate gas with decrease pressure





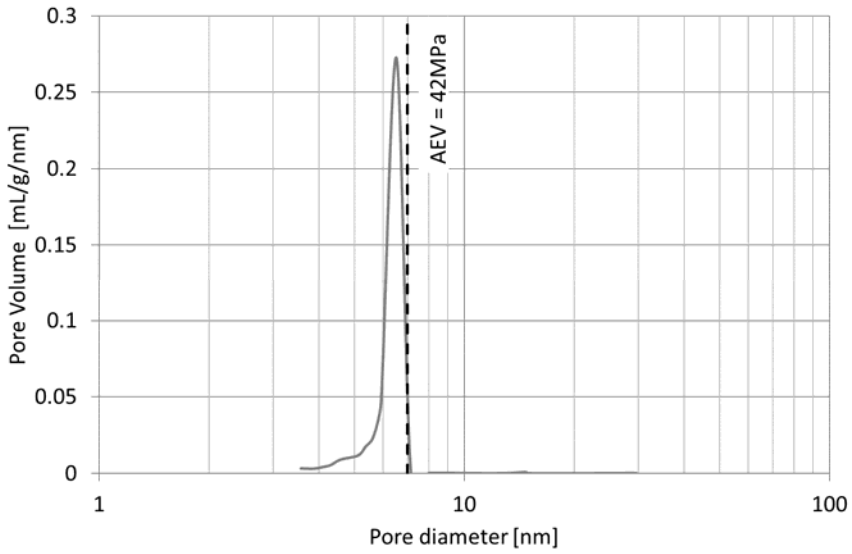
Pore size distribution in a porous media

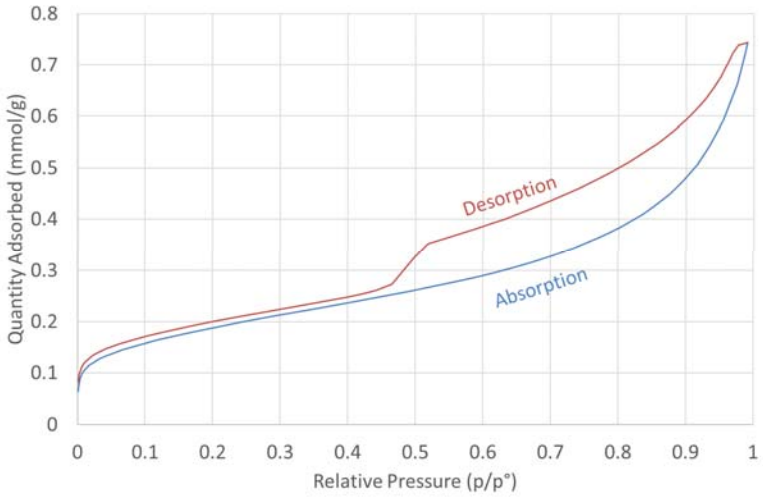
Gas porosimetry (Nitrogen)
Measurement range: 2nm – 60nm

Desorption branch of isotherm in the absolute pressure range

$$0.4\ to\ 0.967\ of\ \frac{p}{p_0}$$

$\frac{p}{p_0}$ - ratio of partial pressure of the absorbed substance to saturated vapour pressures of the absorbed gas





Using Kelvin equation

$$\ln\left(\frac{p}{p_0}\right) = \frac{4\gamma V}{RTd}$$

V – molar volume of nitrogen
γ – surface tension of nitrogen
R – universal gas constant
T – temperature
d – pore diameter

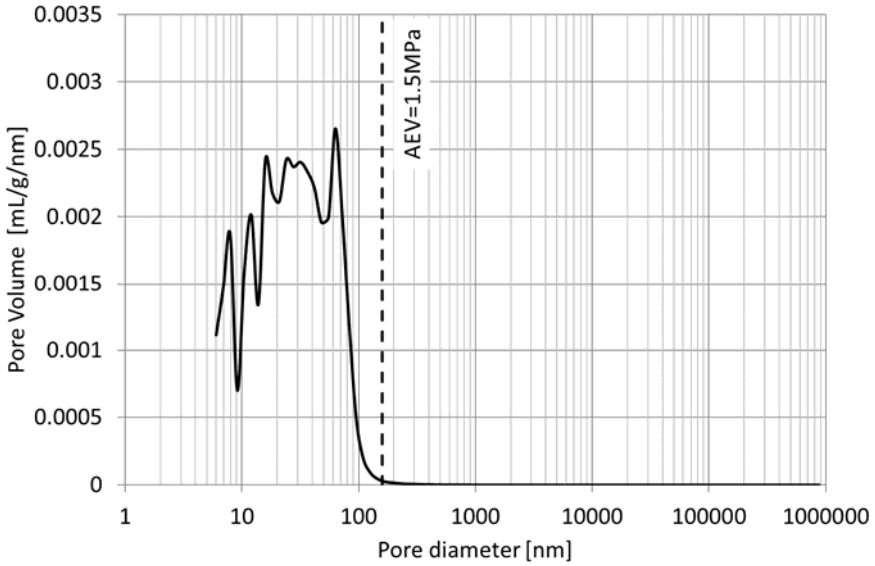
Pores shape is not considered and can affect results

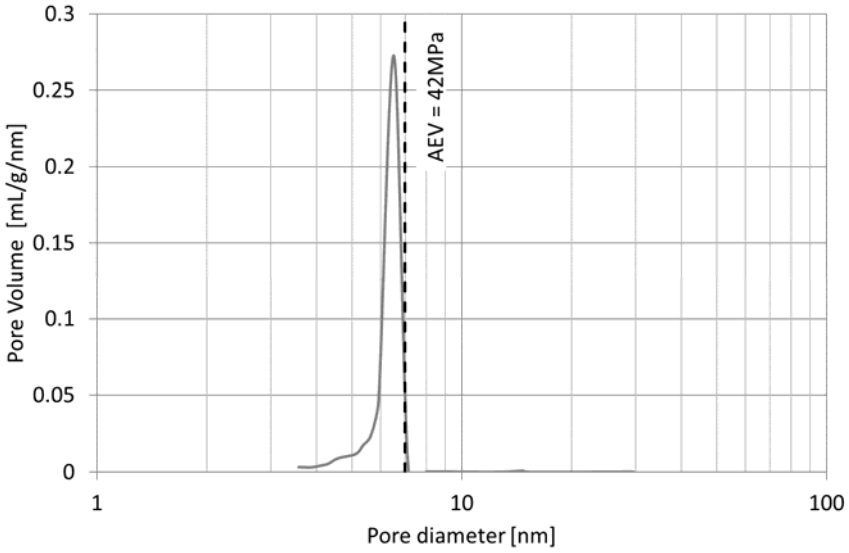
Determining the air entry value from pore size distribution

For non-swelling soils

AEV can be estimated from the largest pore size within the soil

No changes in void ratio are expected to occur





Determining the air entry value from pore size distribution

For non-swelling soils

AEV can be estimated from the largest pore size within the soil

No changes in void ratio are expected to occur

Mechanical compression

Decrease macropores size

Close macropores

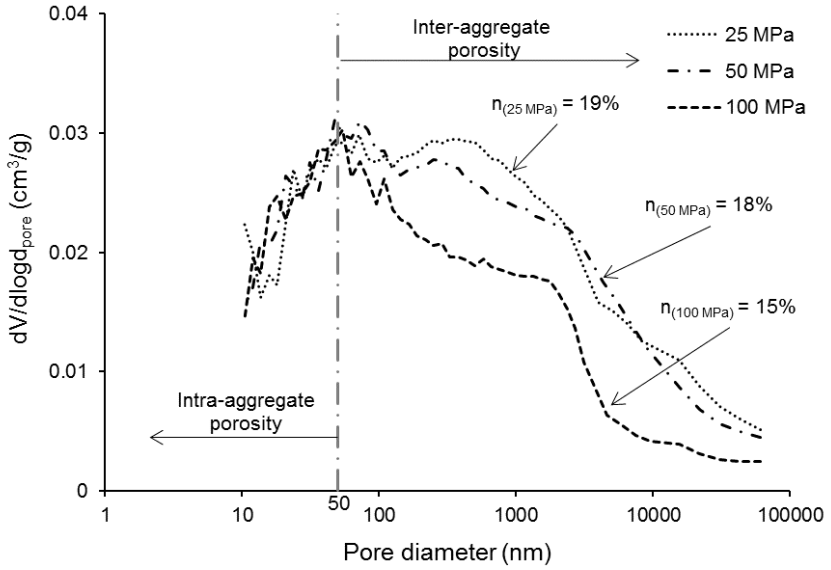
Reduce the number of intra-aggregate pores

Chemical activity

Constrict or obstruct pores (precipitation)

Enlarge pore size (dissolution)

Increase or decrease interparticle cohesion



Determining the air entry value from pore size distribution

For swelling/reactive soils

the estimation of AEV becomes more complicated.

Mechanical compression

Decrease macropores size
Close macropores
Reduce the number of intra-aggregate pores

Chemical activity

Constrict or obstruct pores (precipitation)
Enlarge pore size (dissolution)
Increase or decrease interparticle cohesion

Shrinkage

Decrease macropores size
Close macropores
Intra-aggregate pores to increase in size

Swelling

Enlarge macropores size
New macropores
Intra-aggregate pores to reduce in size

Determining the air entry value from pore size distribution

For swelling/reactive soils

the estimation of AEV becomes more complicated.

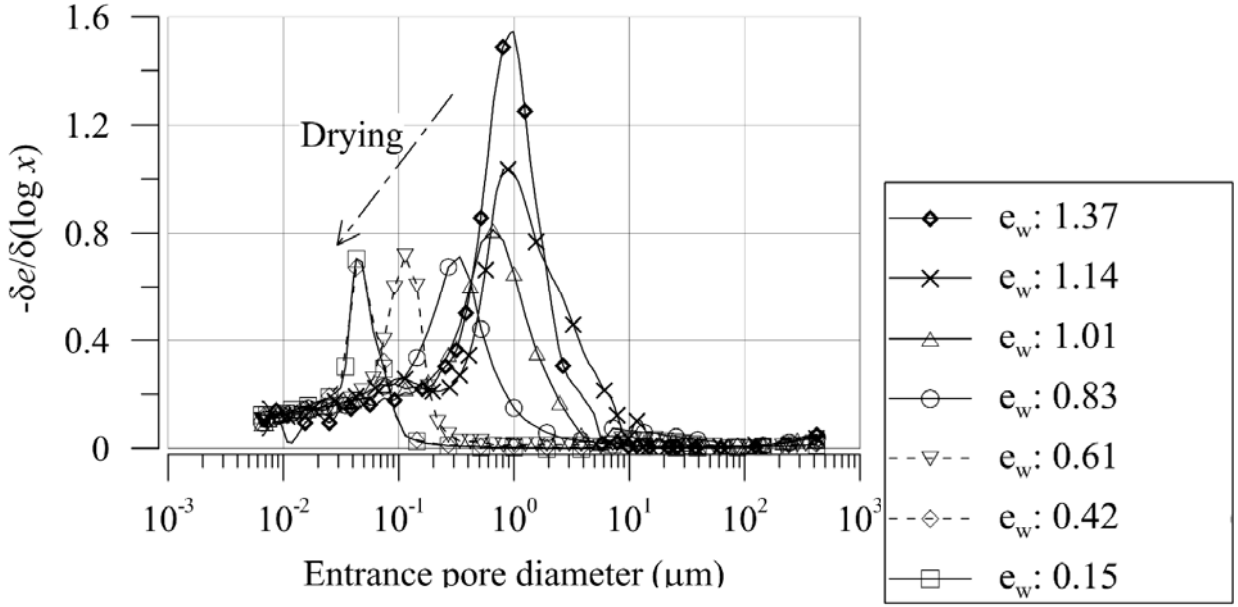
Shrinkage

Decrease macropores size

Close macropores

Intra-aggregate pores to increase in size

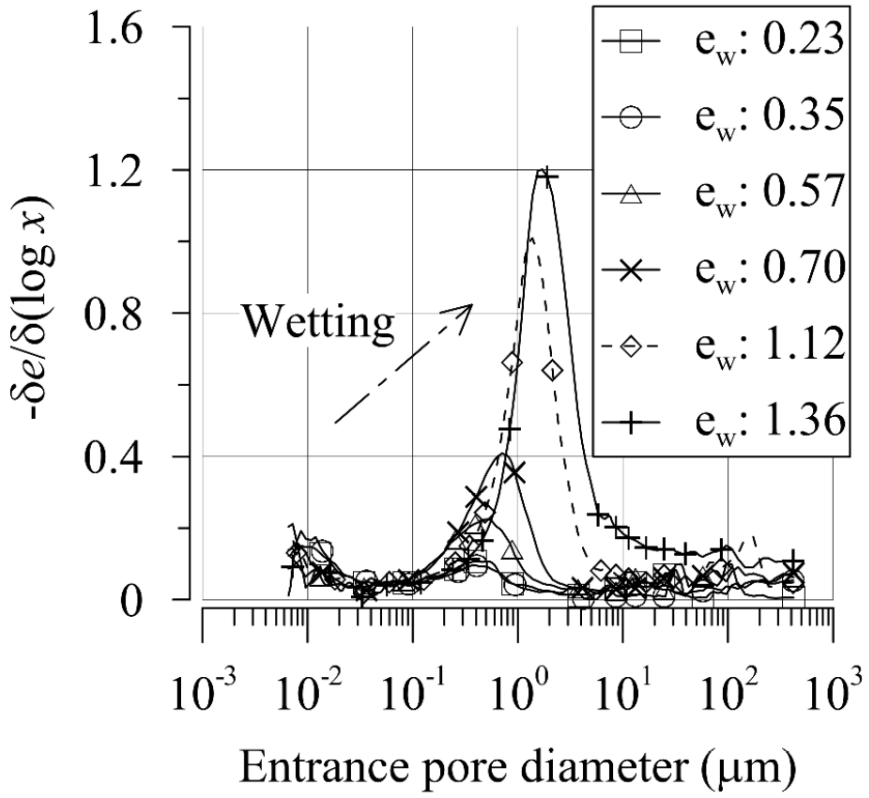
Low percentage of smectite (10%)



Determining the air entry value from pore size distribution

For swelling/reactive soils

the estimation of AEV becomes more complicated.



Swelling

Enlarge macropores size

New macropores

Intra-aggregate pores to reduce in size

High percentage of smectite (>40%)

Determining the air entry value from pore size distribution

For swelling/reactive soils, the estimation of AEV becomes more complicated.

Shrinkage

Decrease macropores size
Close macropores
Intra-aggregate pores to increase in size

Swelling

Enlarge macropores size
New macropores
Intra-aggregate pores to reduce in size

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Thank You