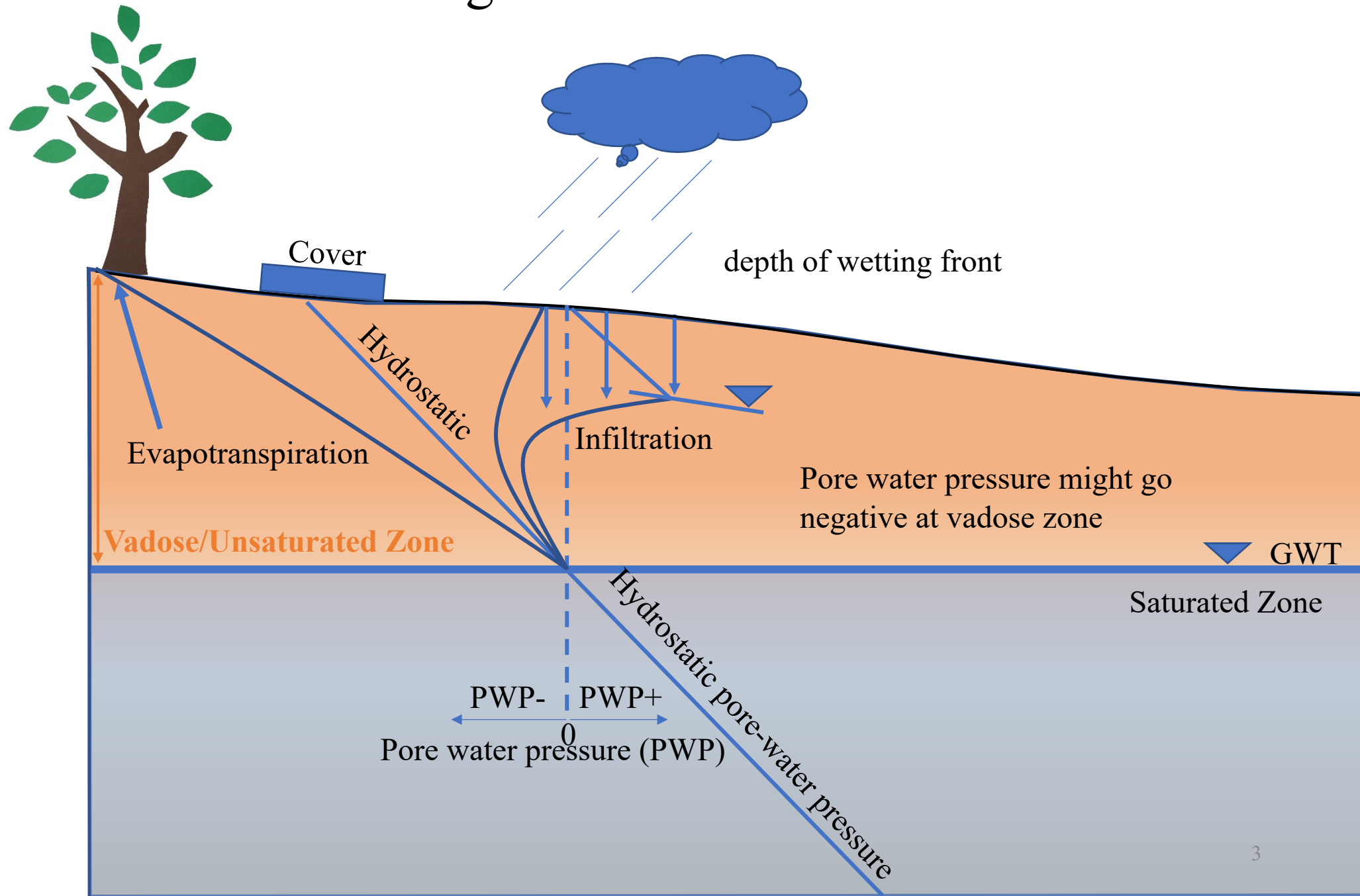


Introduction to Unsaturated Soil Mechanics

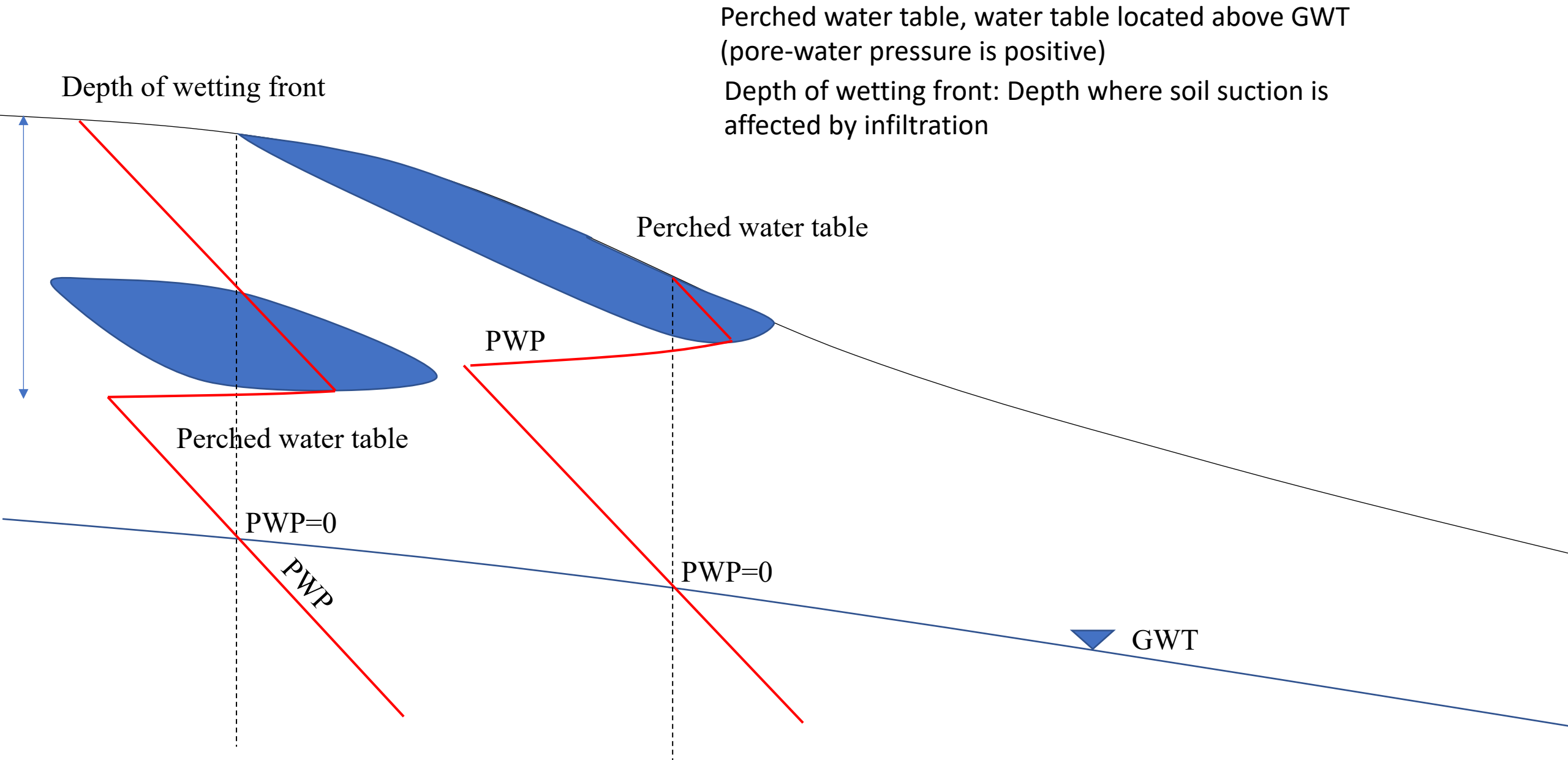
Ir. Abdul Halim Hamdany, S.T., M.Sc., Ph.D

Pore-Water Pressure Distribution in Unsaturated Zone/Vadose Zone

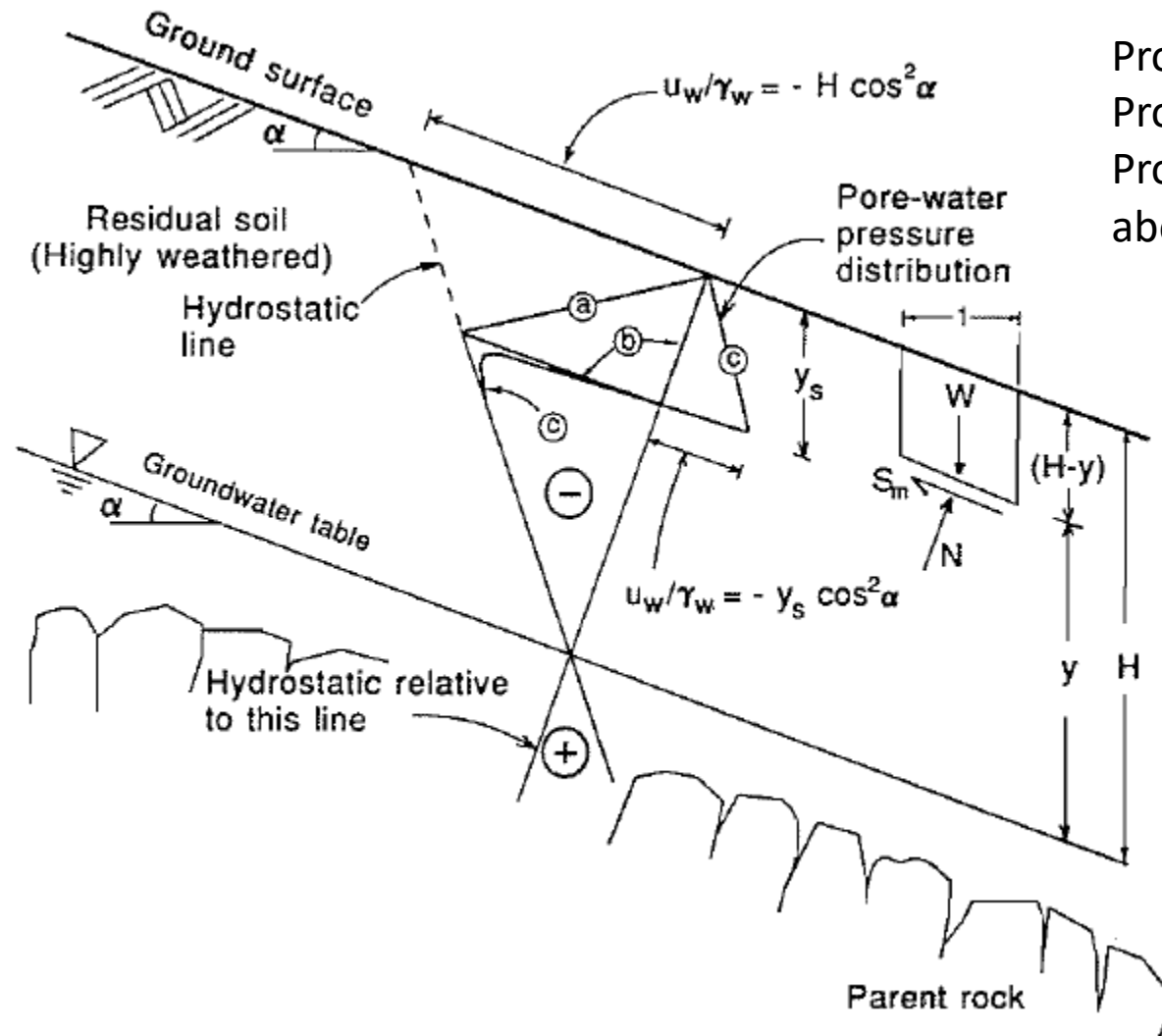
Unsaturated soils cover significant areas of the Earth's land surface



Perched water table and depth of wetting front



Pore water pressure distribution



Profile a: Homogeneous low permeability soil

Profile b: Homogeneous high permeability soil

Profile c: Layered soil (clay above unsaturated sand or sand above clay)

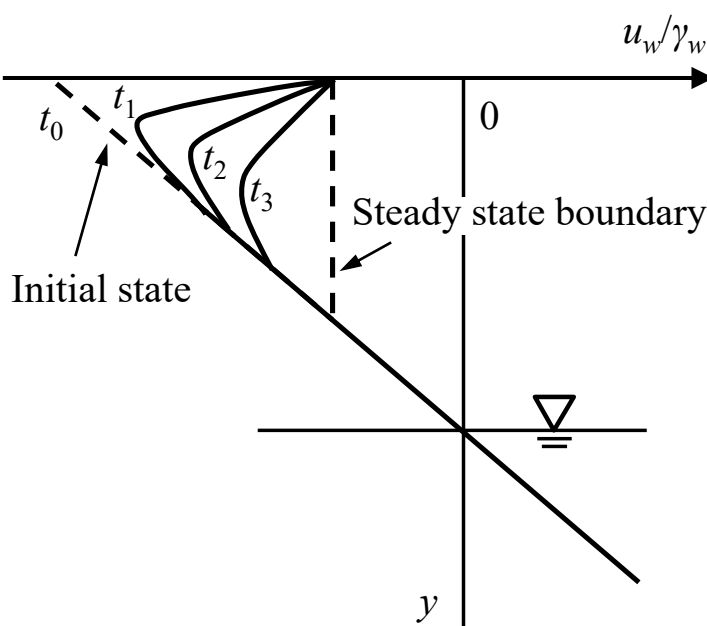
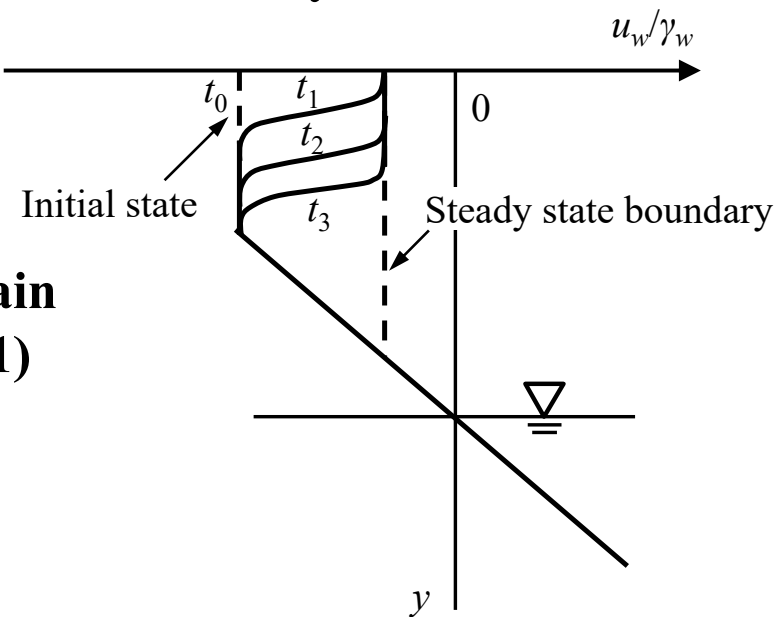
Unsaturated sand can be more impermeable than unsaturated clay!

Pore water pressure distribution in unsaturated soils

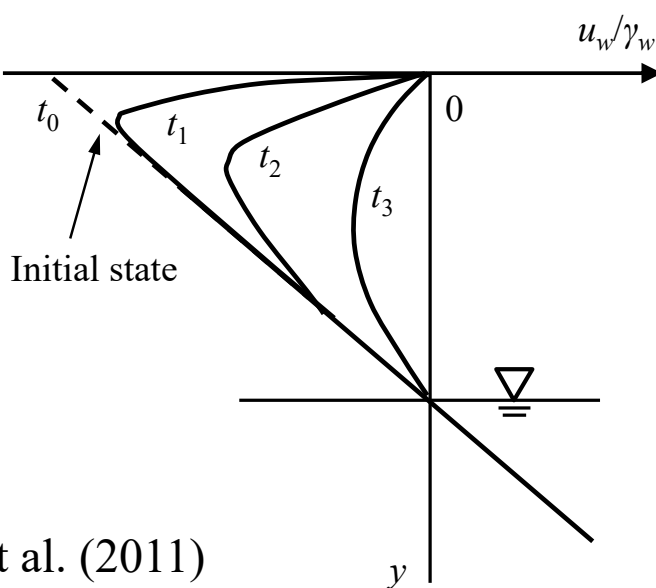
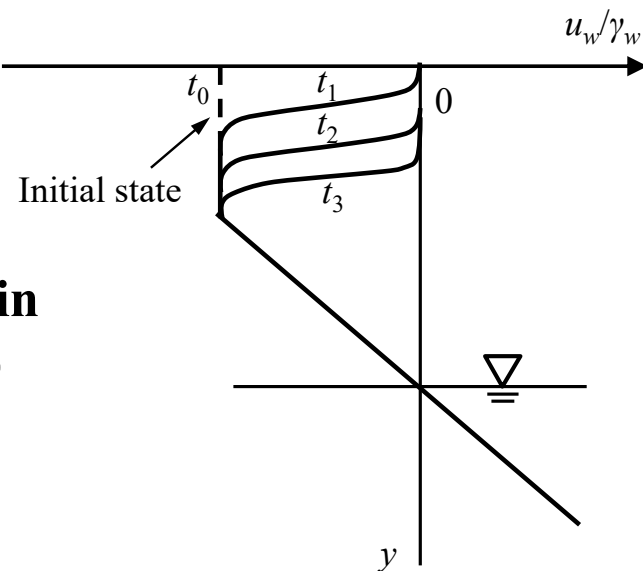
Sandy Soil

Clayey Soil

Light Rain
 $(I/k_s < 1)$



Heavy Rain
 $(I/k_s \geq 1)$

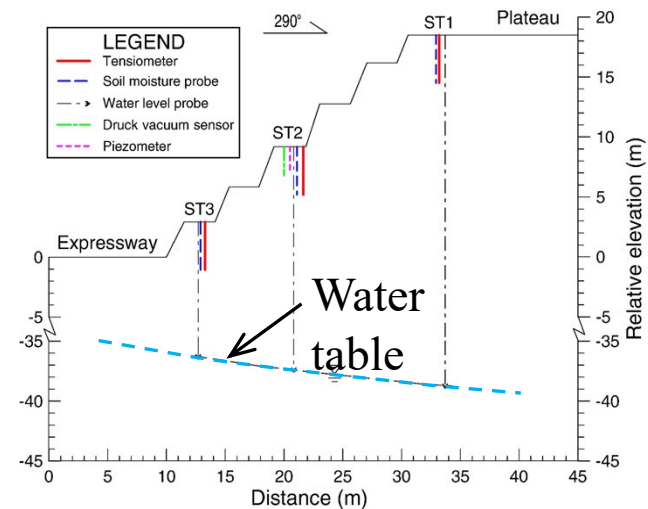


Matric Suction

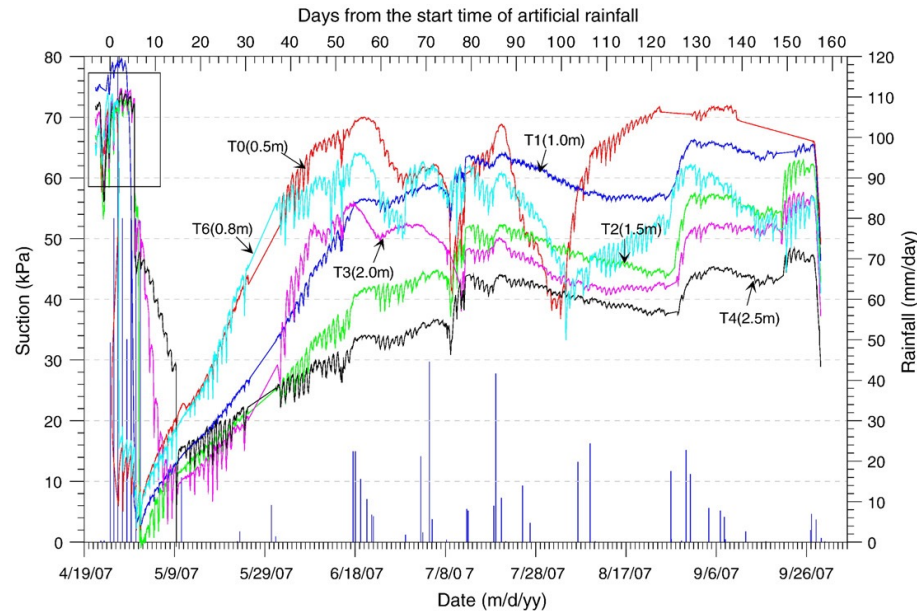
In Situ Monitoring of Soil Suctions



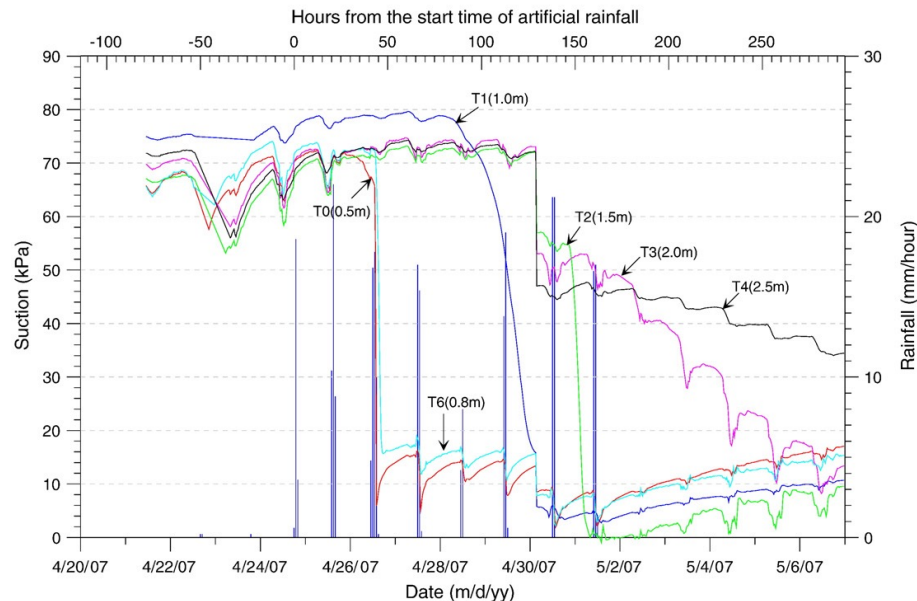
(a) Site photograph showing the monitoring locations on the slope



(b) Cross sectional view of the monitoring slope. The coordinate system is in the plane perpendicular to the expressway, with the origin at the centerline of the pavement.



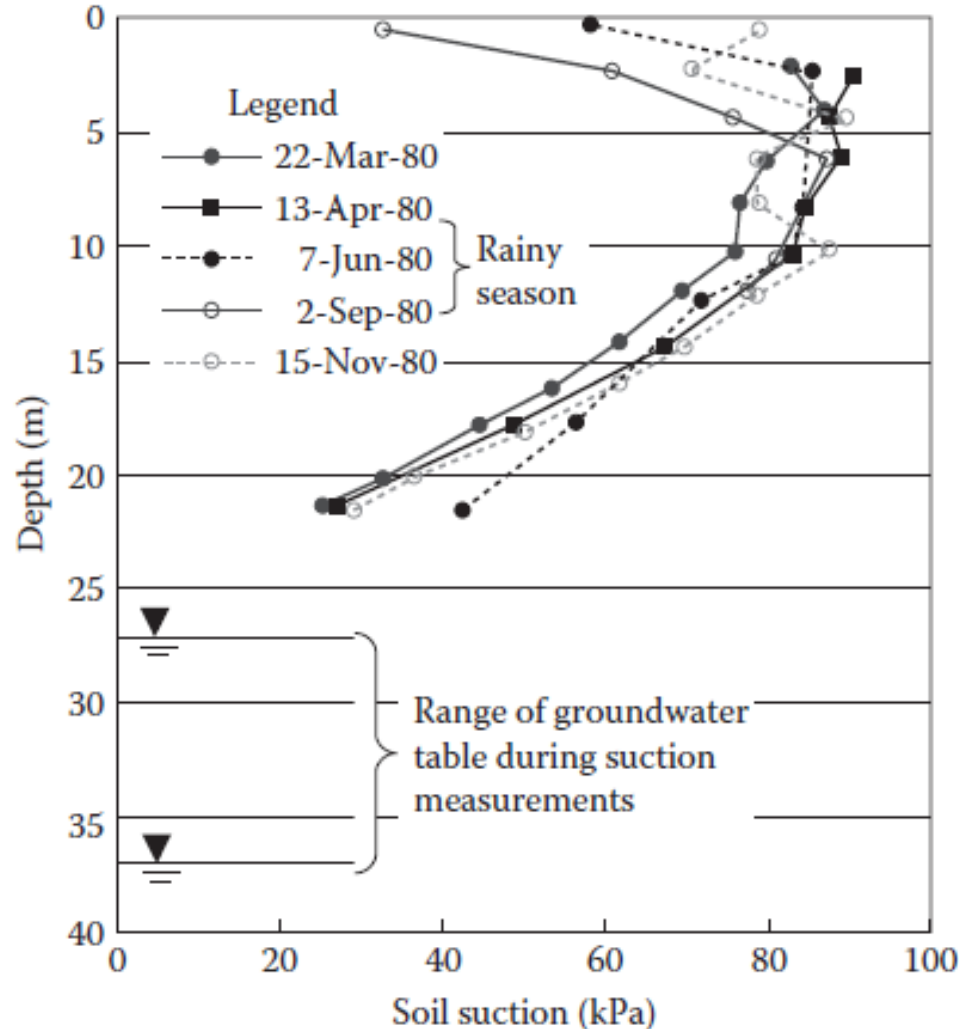
(a) Matrix suction during and after artificial rainfall



(b) Detailed study of matrix suction during artificial rainfall (21 April to 6 May 2007)

In situ suction measurements were made throughout the year 1980 in a 30 m high, completely weathered rhyolite slope instrumented with tensiometers in Hong Kong (Sweeney, 1982).

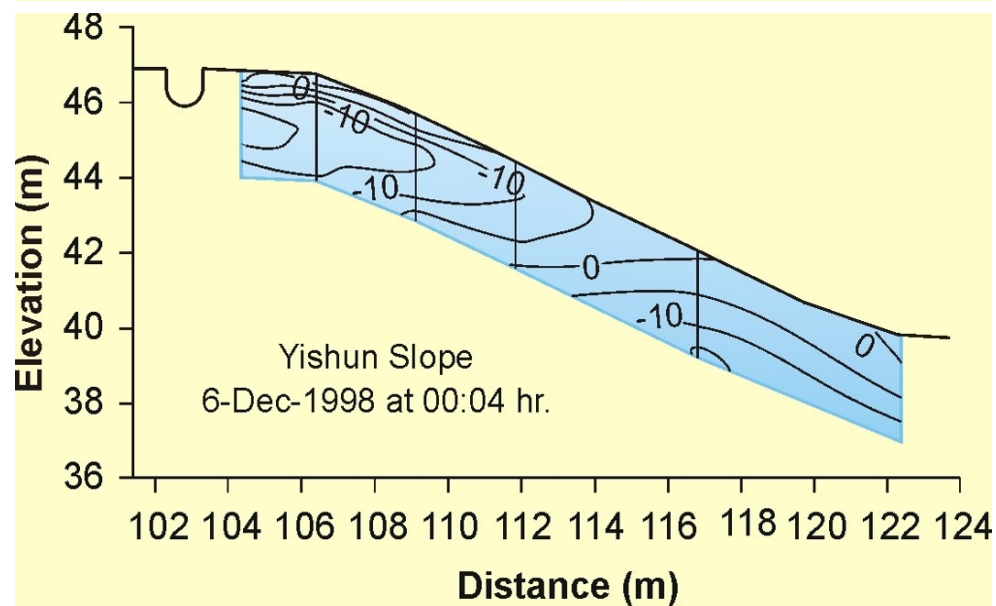
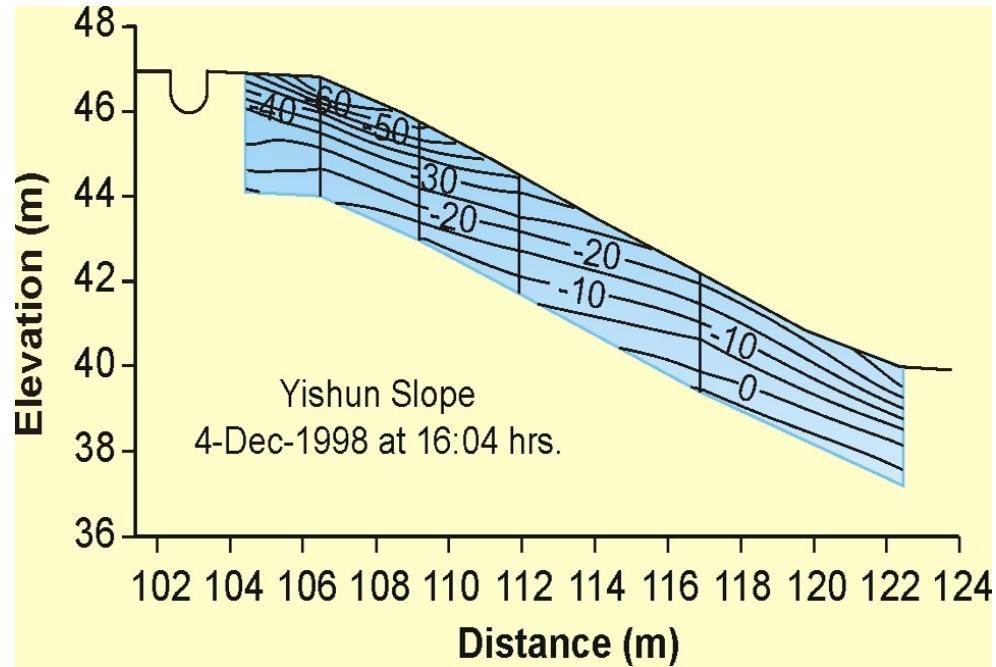
In Situ Monitoring of Soil Suctions



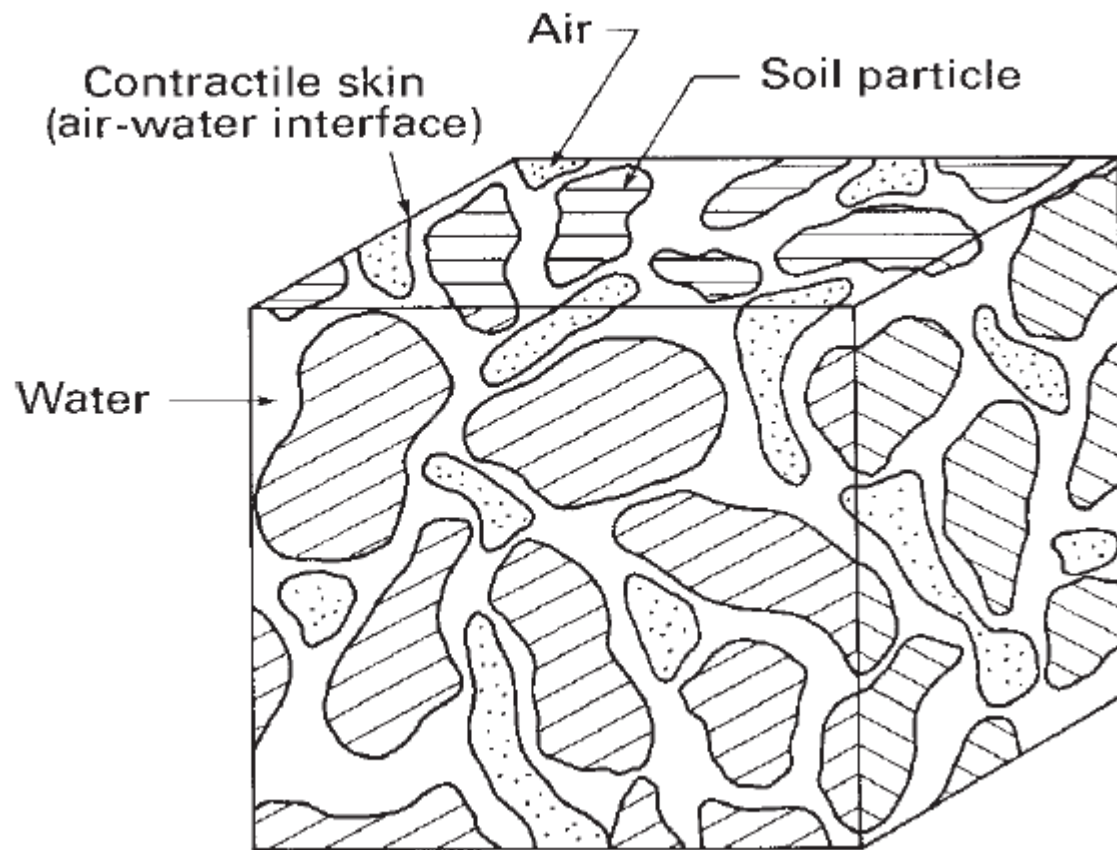
Suction measurements in a weathered rhyolite in Hong Kong (Sweeney, 1982).

Matrix suction at shallow depths showed a gradual reduction during the rainy season, but, at 5–17 m depths, the soil suction remained constant throughout the year. The pore water pressures remained negative, even during the rainy season

Pore-water Pressures within Residual Soil Slope from Bukit Timah Granite at Yishun (Rahardjo et al. 2001)



Element of unsaturated soil



Source: Fredlund et al. (2012)

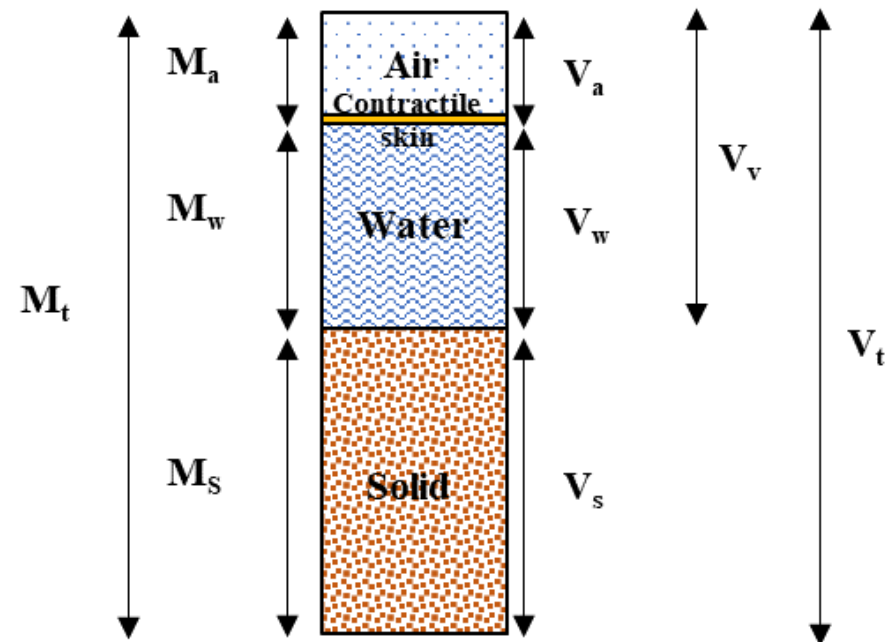
w = Gravimetric water content

θ = Volumetric water content

e_w = Moisture ratio

$$w = \frac{M_w}{M_s} \quad \theta = \frac{V_w}{V_t}$$

$$e_w = w.G_s = S_r e = \frac{V_w}{V_s}$$



Dimensionless and Normalized properties

Dimensionless volumetric water content

$$\Theta = \frac{\theta}{\theta_s}$$

Normalized gravimetric water content

$$\Theta_w = \frac{w - w_r}{w_s - w_r}$$

Normalized volumetric water content

$$\Theta_v = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

Effective degree of saturation

$$S_e = \frac{100 - S_r}{100 - S_{r,r}}$$

Θ = Dimensionless volumetric water content

Θ_w = Normalized gravimetric water content

Θ_v = Normalized volumetric water content

θ = Volumetric water content

θ_s = Saturated volumetric water content

θ_r = Residual volumetric water content

S_e = Effective degree of saturation

S_r = Degree of saturation

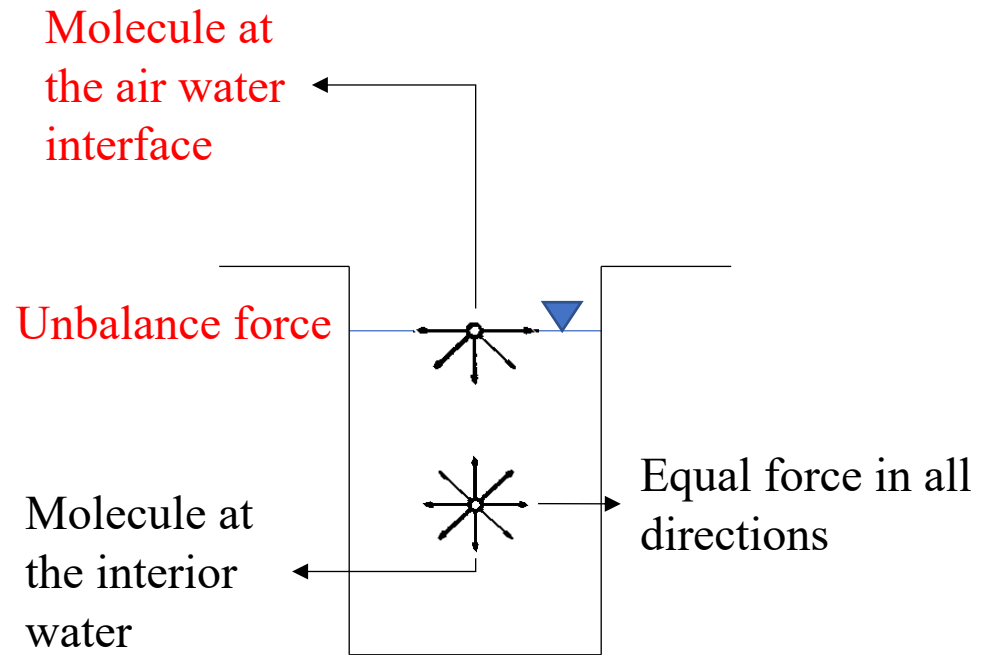
$S_{r,r}$ = Residual degree of saturation

w = Gravimetric water content

w_r = Residual gravimetric water content

w_s = Saturated gravimetric water content

Contractile skin, surface tension and matric suction

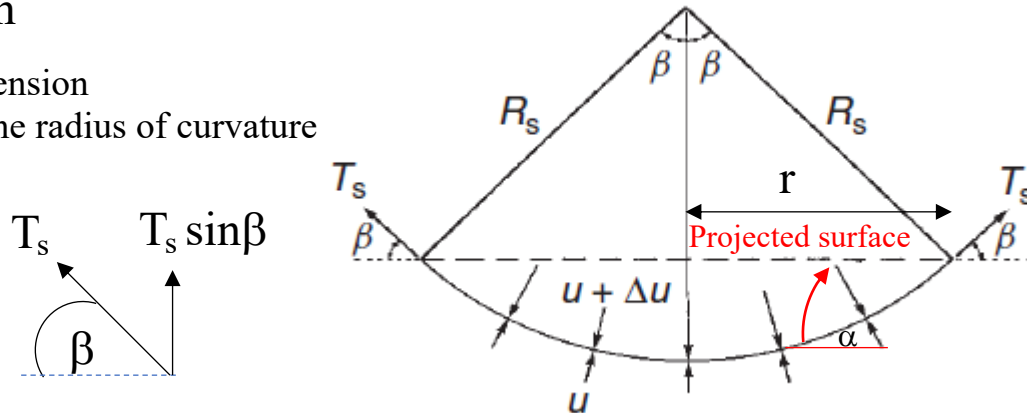


Thorp and O'Neill (2015)

Contractile skin, surface tension and matric suction

Tensile pull is generated along the contractile skin to be in equilibrium

T_s = surface tension
 R_s = membrane radius of curvature



Projection of surface tension around circumference in vertical direction:

$$F_{v,T_s} = 2\pi r T_s \sin \beta$$

Temperature (°C)	Surface Tension, T_s (mN/m)
0	75.7
10	74.2
20	72.75
30	71.2
40	69.6
60	66.2
80	62.6
100	58.8

Source: From Kaye and Laby, 1973.

Pressure acting on the contractile skin (u) are perpendicular towards the contractile skin.

Vertical force due to the pressure difference at contractile skin can be resolved by projecting the area of contractile skin to the horizontal axis:

$$\Delta u \cos \alpha \quad (\Delta u \cos \alpha)L = \Delta u (L \cos \alpha) \quad \sum_i^n L_i \cos \alpha_i = 2r$$

$$F_{v,\Delta u} = A_r \Delta u = \pi r^2 \Delta u$$

Projected surface

Based on force equilibrium:

$$F_{v,\Delta u} = F_{v,T_s}$$

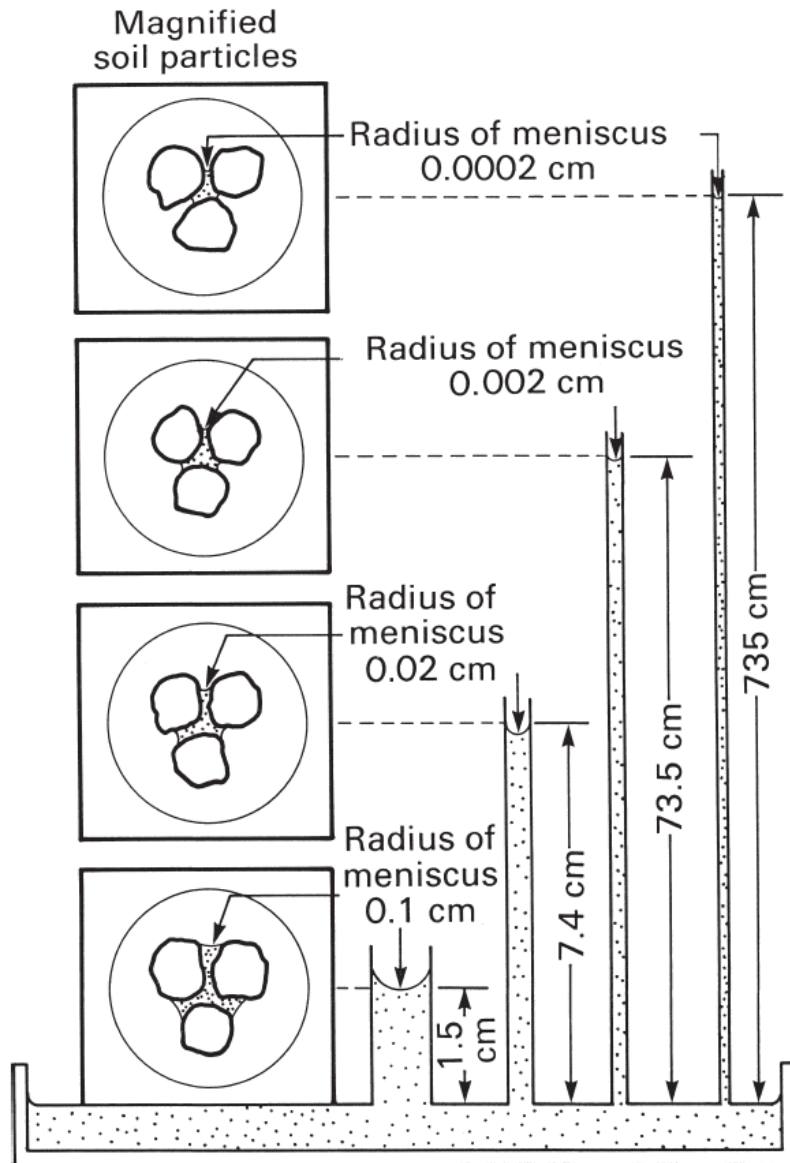
$$\pi r^2 \Delta u = 2\pi r T_s \sin \beta$$

$$\Delta u = \frac{2T_s}{r / \sin \beta}; R_s = r / \sin \beta$$

$$\Delta u = u_a - u_w = \frac{2T_s}{R_s}$$

$u_a - u_w$ is known as matric suction

Capillary tubes of different radii



$$H_E = 7.35\text{m} \quad H_P = -7.35\text{m}$$

$$H_T = H_E + H_P \quad u_w = H_P \gamma_w$$

1. Total head (H_T) of the entire capillary tubes are the same (no movement of water)
2. Pressure head (H_P) at the top of the capillary tubes equal to $-H_E$ (elevation head)

$$\Delta u = u_a - u_w = \frac{2T_s}{R_s} = \rho_w g h_c$$

$$R_s \approx r$$

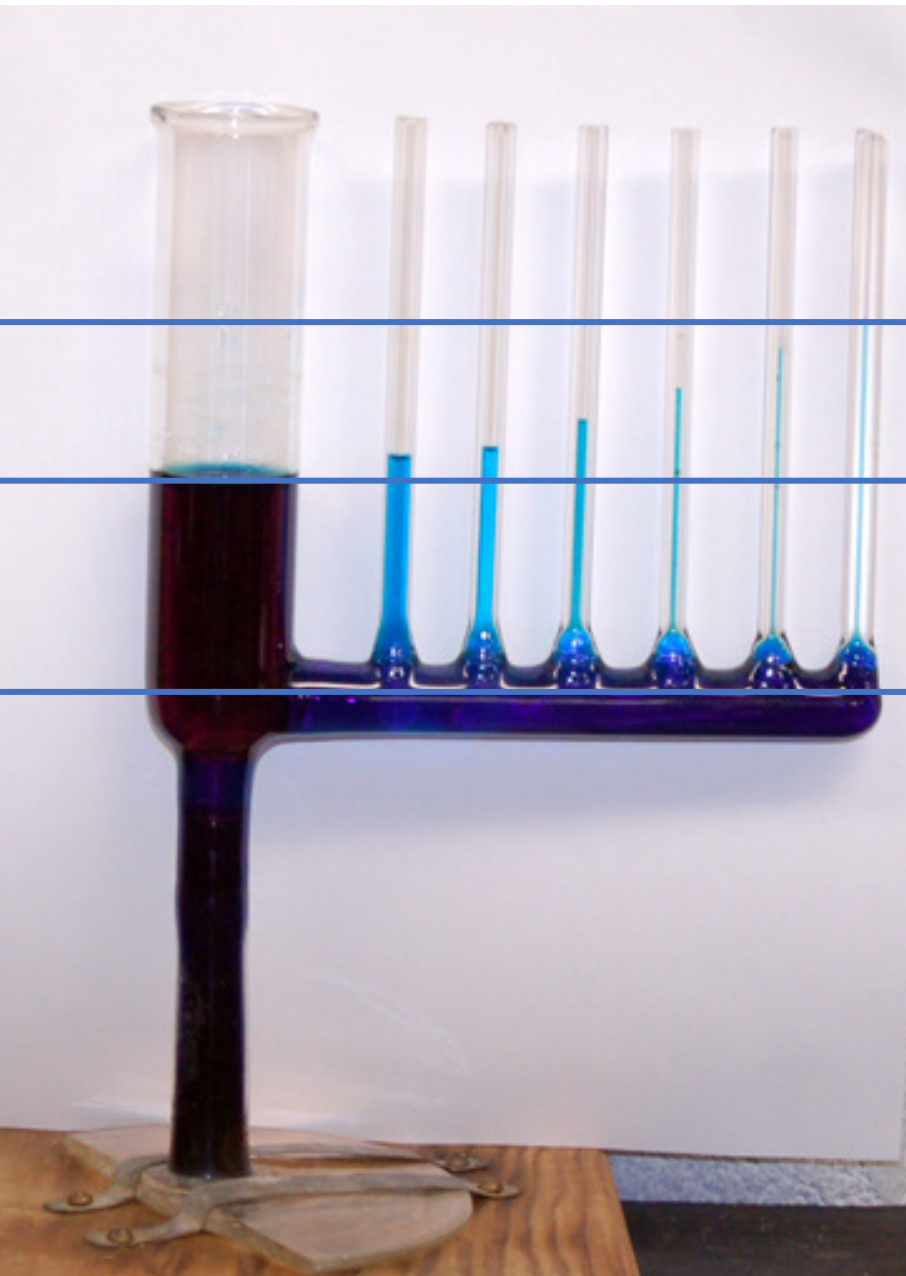
$$h_c = \frac{2T_s}{\rho_w g r}$$

h_c = Height of capillary rise
 r = radius of the tube

Capillary tubes showing air-water interfaces at varying heights for different radii of curvature (after Janssen and Dempsey, 1980).

Capillary tubes of different radii

$$H_T = H_E + H_P \quad h_c = \frac{2T_s}{\rho_w g r}$$



$$H_E = h_c; H_P = -h_c; H_T = 0$$

h_c

$$H_T = 0; H_E = 0; H_P = 0$$

h

$$H_E = -h; H_P = h; H_T = 0$$

Component of soil suction

- Soil suction (s) can be either:

1. Matric suction, $\psi = u_a - u_w$
2. Osmotic suction, π
3. Total suction, $\Psi = \psi + \pi$

Osmotic suction related to the salt content in the pore water and can be defined as:

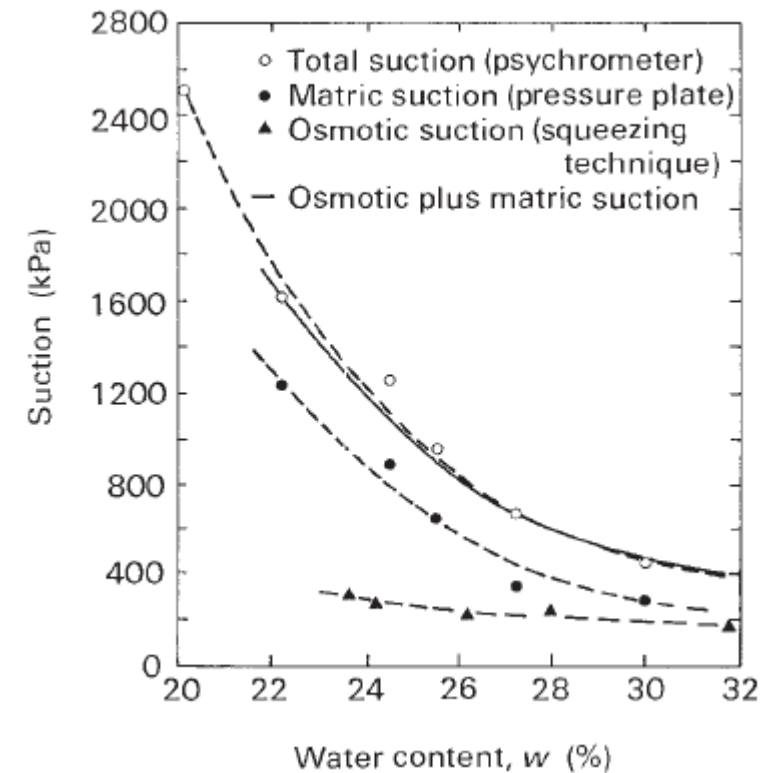
$$\pi = RTC$$

R = Universal gas constant = 8.314 J/(mol. K)

T = Absolute temperature (in Kelvin)

C = sum of molar concentration in solution (mol/L)

If there is no change in the salt solution, the influence of osmotic suction can be ignored.



Source: Krahn and Fredlund (1972)

Total suction based on thermodynamic relationship

Richard (1965) Equation based on thermodynamic:

$$\Psi = -\frac{RT}{v_{w0}\omega_v} \ln RH$$

$$RH = \frac{\overline{\rho_v}}{\rho_{v0}} = \frac{\overline{u_v}}{u_{v0}}$$

At temperature 20°C:

$$\Psi = -135022 \ln RH$$

Example:

$$RH = 0.9424; \Psi = 8010 \text{ kPa}$$

R = Universal gas constant = 8.314 J/(mol. K)

T = Absolute temperature (in Kelvin)

v_{w0} = Specific volume of water or the inverse of the density of water ($1/\rho_w$), m³/kg

ρ_w = density of water (i.e. 998 kg/m³ at temperature 20°C)

ω_v = molecular mass of water vapor (18016 kg/kmol)

RH = Relative humidity (in decimal)

$\overline{u_v}$ = Partial pressure of pore-water vapor (kPa)

u_{v0} = Saturation pressure of water vapor over a flat surface of pure water at the same temperature (kPa)

$\overline{\rho_v}$ = Absolute humidity in equilibrium with any solution

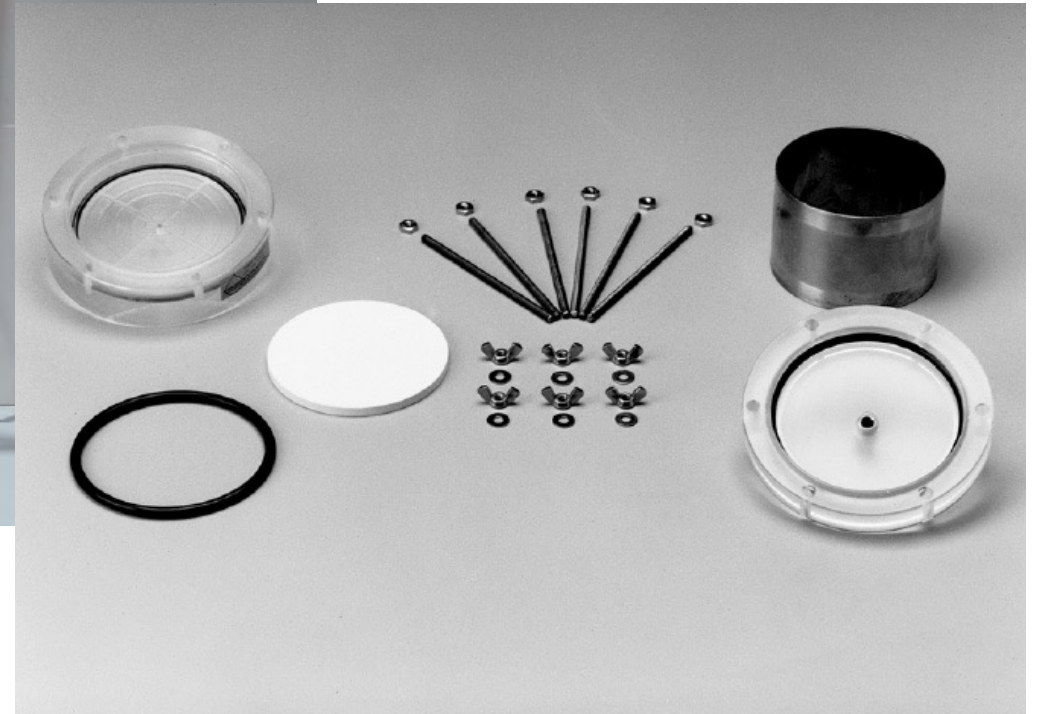
ρ_v = Absolute humidity in equilibrium with free water

Suction Measurement and Suction Control

Measurement of soil suction

- Direct measurement-directly measured pore-water pressure (matric suction)
 - Tensiometer
 - **Null-type Axis translation apparatus (i.e. pressure plate, tempe cell)**
 - High-capacity tensiometer (HCT)
 - Column test
- Indirect measurement-using secondary parameter to measure pore-water pressure (matric or total suction)
 - Filter paper
 - Thermal conductivity suction sensor
 - Thermocouple psychrometer
 - **Chilled mirror dew point psychrometer**

Axis Translation Apparatus-Tempe Cell



Disassembled components of a Tempe cell;
(Courtesy of Soil Moisture Equipment Corporation,
Santa Barbara, CA).

Axis Translation Apparatus-Pressure Plate



A 5-bar ceramic plate extractor (i.e., maximum applied matrix suction is 500 kPa).
(Courtesy of SoilMoisture Equipment Corporation, Santa Barbara, CA).

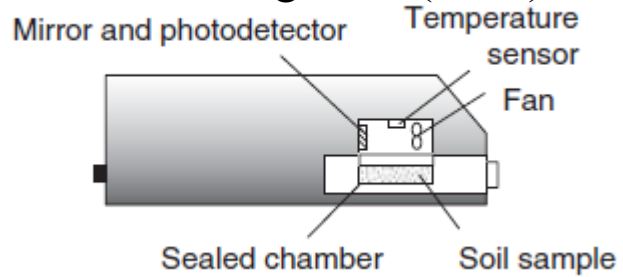
Chilled mirror psychrometer



WP4 chilled-mirror Water Potential Meter
(Courtesy of Decagon Devices, Pullman, WA).

Chilled Mirror (Dew point) Psychrometer

Source: Leong et al. (2003)



Principles:

1. Specimen (1 to 5 mm thick) placed 40 mm diameter plastic container
2. Moved the specimen into chamber tray
3. Specimen is thermodynamically equilibrated with the chamber environment.
4. Fan is used to accelerates the equilibration process.
5. Cooling system is used to reduce the temperature on the surface of the mirror to the dew point temperature
6. A beam of light from LED is directed to the mirror and reflected back to photodetector cell. When there is a condensation which signals dew point, light reflected from the mirror is scattered and intensity detected is reduced.
7. Dew point temperature (T_d) is maintained constant by a microprocessor circuit.
8. Resistance thermometer embedded in the mirror or thermocouple is used to detect the temperature of the mirror (T_d)
9. Infrared measured the temperature of the chamber which is assumed to be the temperature of specimen (T_s)
10. Vapor pressure and saturated vapor pressure at the same temperature are computed by using the dew point temperature (T_d) and specimen temperature (T_s) and psychrometer constant (γ_{psy})

$$\overline{u_v} = u_{v0} (T_d) - \gamma_{psy} (T_s - T_d)$$

11. Relative humidity is then calculated from vapor pressure and saturated vapor pressure

$$RH = \frac{u_v}{u_{v0}}$$

12. Richard's equation is used to calculate the total suction

Richard's equation

$$\Psi = -\frac{RT}{v_{w0}\omega_v} \ln RH$$

Range: > 300 kPa

Equilibrium times: minutes

Challenge in measuring soil suction

- Direct measurement method:
 - Limited range of suction measurement
 - Limited measurement duration due to air diffusion
- Indirect measurement
 - Long equilibrium time
 - Accuracy
- Field/in situ measurement
 - Must be portable
 - Must have short equilibrium time to avoid delay
 - Must have high endurance in measuring suction
 - Must be maintainable

Moisture Measurement

Time Domain Reflectometry (TDR) Moisture Sensor

Courtesy to: Wykeham Farrance Singapore



TDR sensor propagate voltage pulse down a line into the soil and then reflected at the end of the probe with wave guide (rod)

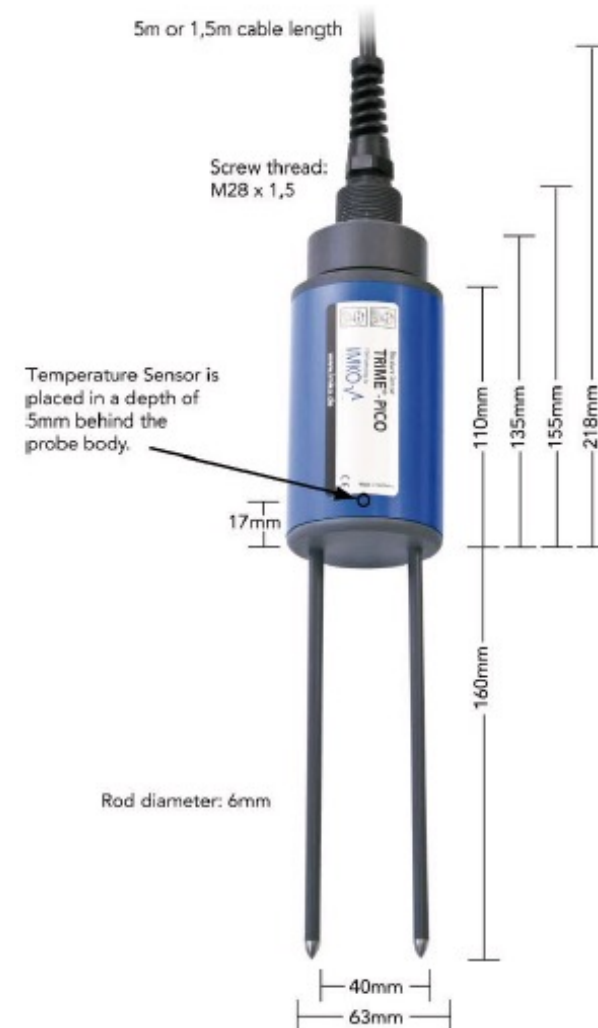
Measurement is done by measuring the duration required by the pulse to come back

Disadvantage: Sensitive to salinity, Slower response (about 10s)

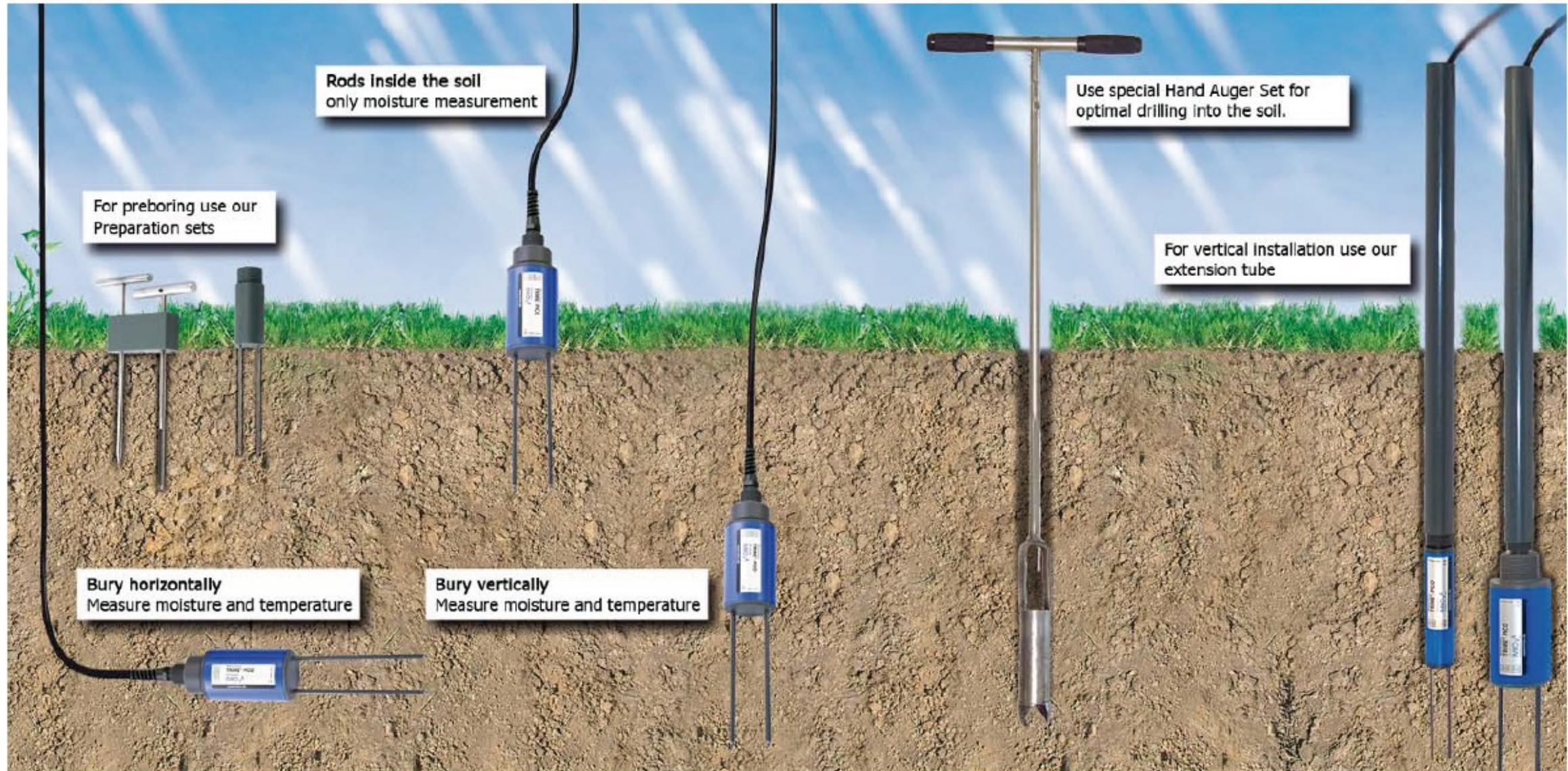
Advantage: Less sensitive to soil type

2.1 TRIME-PICO64

For in situ monitoring of volumetric moisture in soils. The large measuring volume is particularly suitable for applications in heterogeneous and skeletal media. Burying capability for both horizontal and vertical orientation.



Installation



Material Calibration

Moisture sensor is calibrated to a specific material. Example:

Your TRIME measuring system operates with a universal calibration for mineral soils as a standard.

The following parameters limit the application range of the universal calibration:

- *Clay content:* >50%
- *Organic content:* >10%
- *Bulk density:* <1.1kg/dm³ or >1.7kg/dm³

Material calibration is required if the soil does not meet the standard specification

Material Calibration

Courtesy to: Dr. Alfrendo Satyanaga

Witteveen

Bos

GEONAMICS

CONSTRUCTION

Soil Moisture Calibration Sheet

Project title:

Soil Investigation and Instrumentation at 8 Slopes

Site:

NTU CEE Slope facing Nanyang Drive

Sensor Type

Soil Moisture CS616

Date of testing :

28-Jul-19

Location of testing:

Geonamics Lab

Test by:

Ian / Boon Han

Checked by :

Rozy

0.60

0.50

0.40

0.30

0.20

0.10

0.00

Volumetric water content (V/V)

15.00

20.00

25.00

30.00

35.00

Period (μs)

$y = 0.0098e^{0.1187x}$

$R^2 = 0.994$

0.6

0.5

0.4

0.3

0.2

0.1

0

Measured Volumetric Water Content (V/V)

0

0.1

0.2

0.3

0.4

0.5

0.6

Target

Ori Calibration

New Calibration

Remarks:

Old calibration Equation $y = -0.0063 - 0.0063x + 0.0007x^2$

New calibration equation $y = 0.0098e^{(0.1187x)}$

with new calibration, the reliability of the sensor is $\pm 4\%$ VWC

This is cause by the higher density and electric conductivity of the soil in the project sites.

Figure 1: Relationship between measurement period vs measured volumetric water content

Figure 2: Target volumetric water content vs measured volumetric water content



Frequency Domain Reflectometry (FDR) Moisture Sensor

Cheaper, smaller and faster but **very sensitive to soil** type due to complex electrical field around the probe

Oscillator propagate an electromagnetic signal through a wave guide.

Difference between output wave and return wave frequency is measured.

Dielectric constant is measured from the change in frequency of a reflected radio wave or resonance frequency (Kelleners 2004)

Dielectric constant of water (80) is greater than dielectric constant of soil solid (glass 5 to 10, paper 2 to 4, body tissue 8, soil 4, air 1)

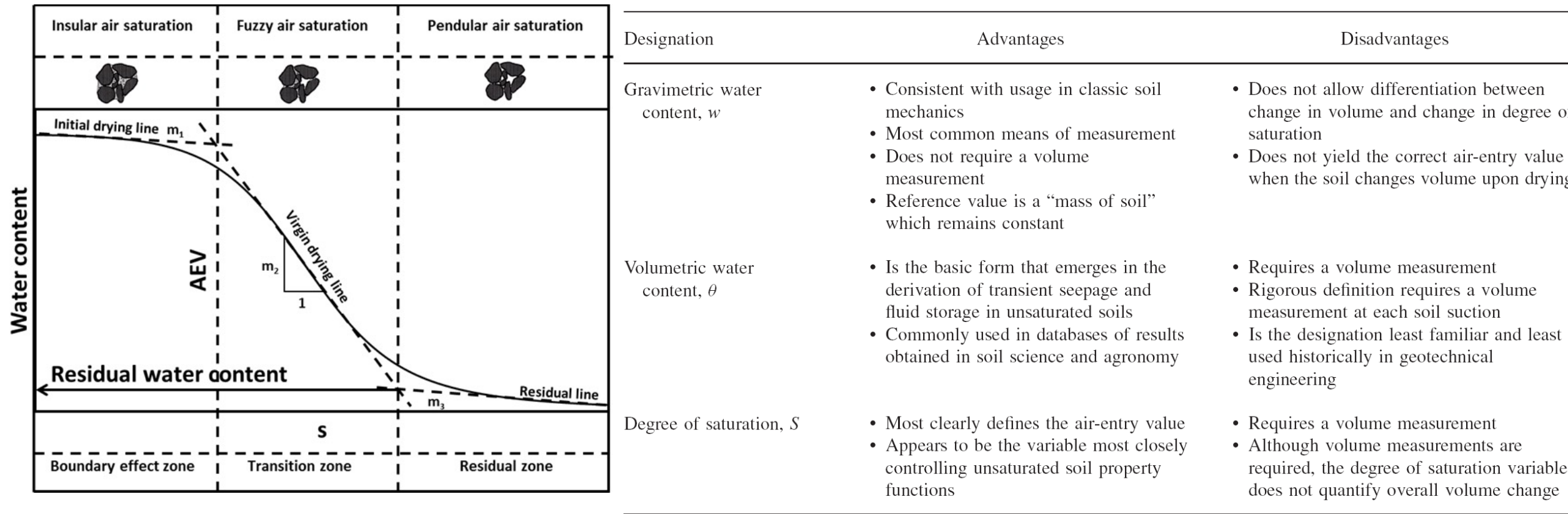
Soil with more water has higher dielectric constant and correlation can be made

<https://soilsensor.com/articles/capacitance-frequency-frequency-domain-reflectometry-fdr/>



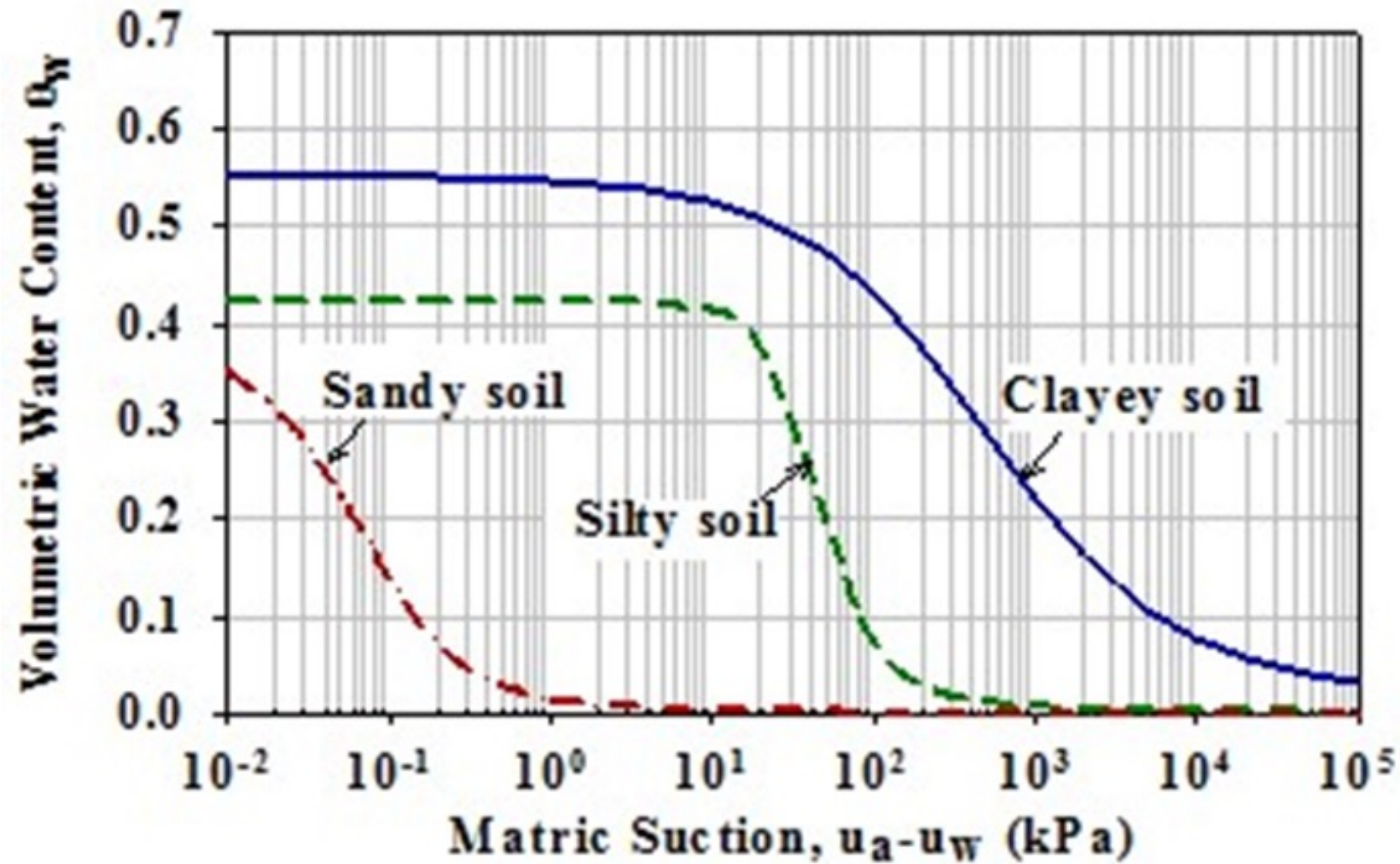
Soil-Water Characteristic Curve (SWCC)

Soil-Water Characteristic Curve



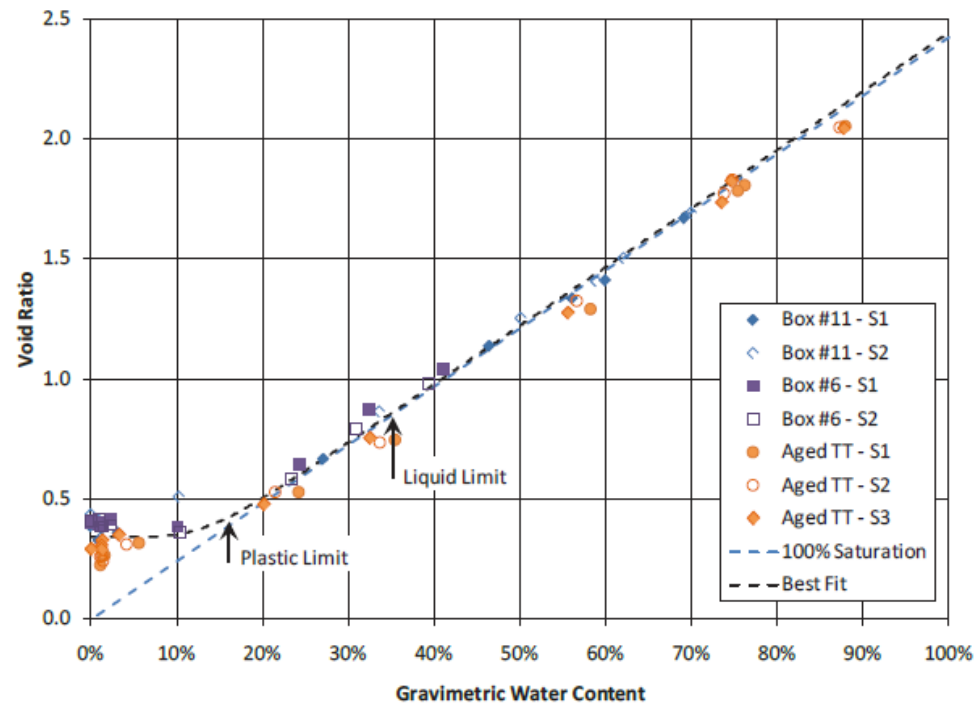
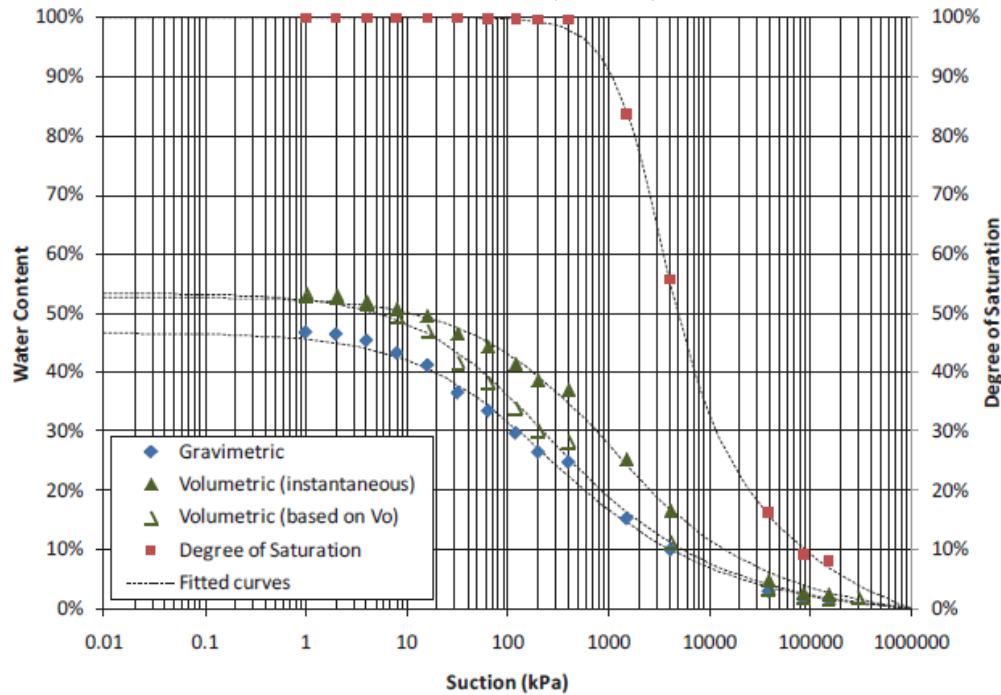
1. One of the most important properties for unsaturated soil analysis.
2. The Y axis (water content) can be either gravimetric water content (SWCC- w), volumetric water content(SWCC- θ) or degree of saturation (SWCC- S).
3. Air entry value (AEV) can only be determined when the Y axis is degree of saturation.
4. θ and S_r can only be accurately determined if volume change (shrinkage and swelling) is considered.
5. Shrinkage curve and SWCC- w can be used to determine SWCC- θ and SWCC- S .

Typical SWCC



Effect of shrinkage to SWCC

Source: Fredlund et al. (2011)



If SWCC-w or SWCC- θ should not be used to determine AEV for soil experiencing significant volume change due to drying as it will underestimate AEV

Suction and Moisture Measurement

Time Domain Reflectometry (TDR) Moisture Sensor

Courtesy to: Wykeham Farrance Singapore

TDR sensor propagate voltage pulse down a line into the soil and then reflected at the end of the probe with wave guide (rod)

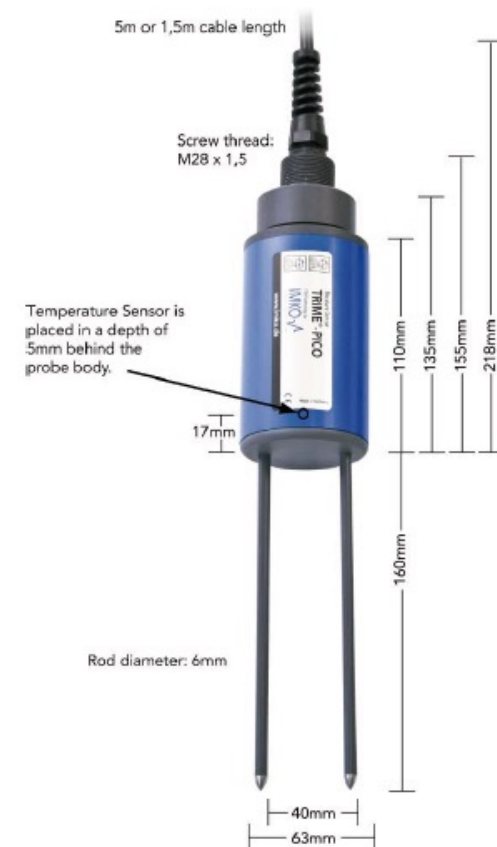
Measurement is done by measuring the duration required by the pulse to come back

Disadvantage: Sensitive to salinity, Slower response (about 10s)

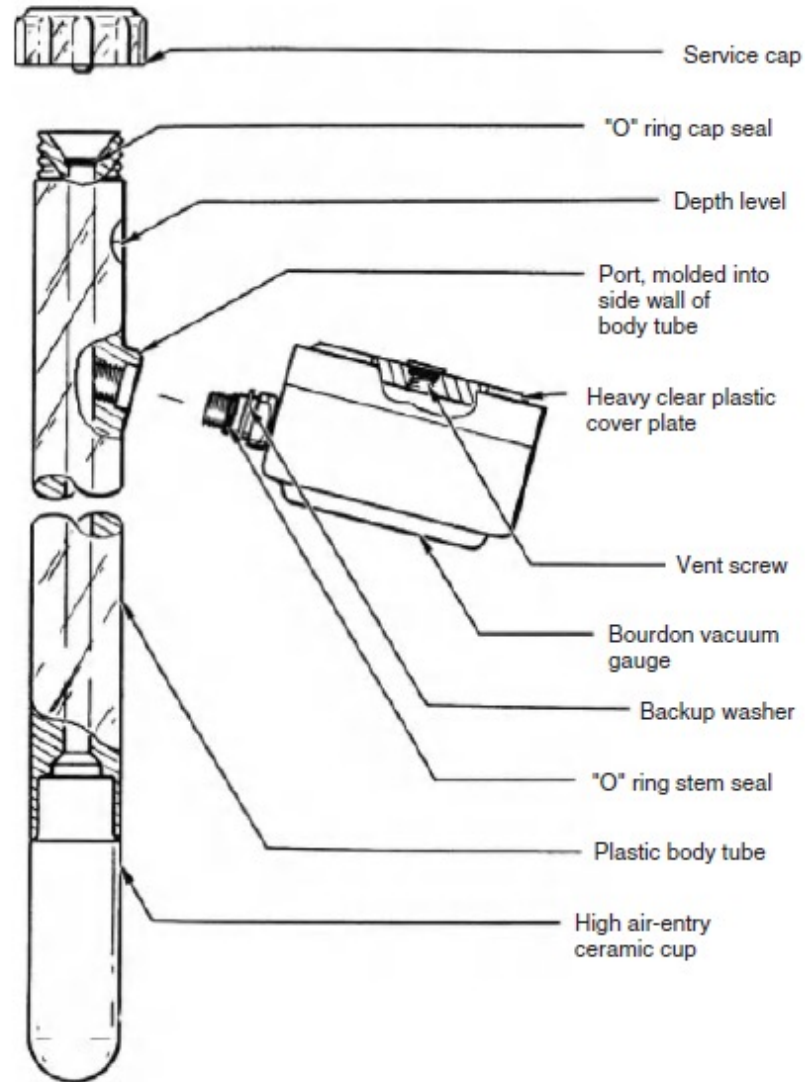
Advantage: Less sensitive to soil type

2.1 TRIME-PICO64

For in situ monitoring of volumetric moisture in soils. The large measuring volume is particularly suitable for applications in heterogeneous and skeletal media. Burying capability for both horizontal and vertical orientation.



Tensiometer



1. High air entry (HAE) ceramic disk to separate air with water at the water reservoir
2. Water pressure (read at bourdon vacuum gauge) at the water reservoir will slowly decrease according to the soil specimen pore-water pressure (u_w)
3. Frequent flushing at the water reservoir is required to development of air bubble due to diffusion
4. Contact between specimen and ceramic disk is important. Some recommended method:
 1. Kaolin paste is placed at the ceramic disk

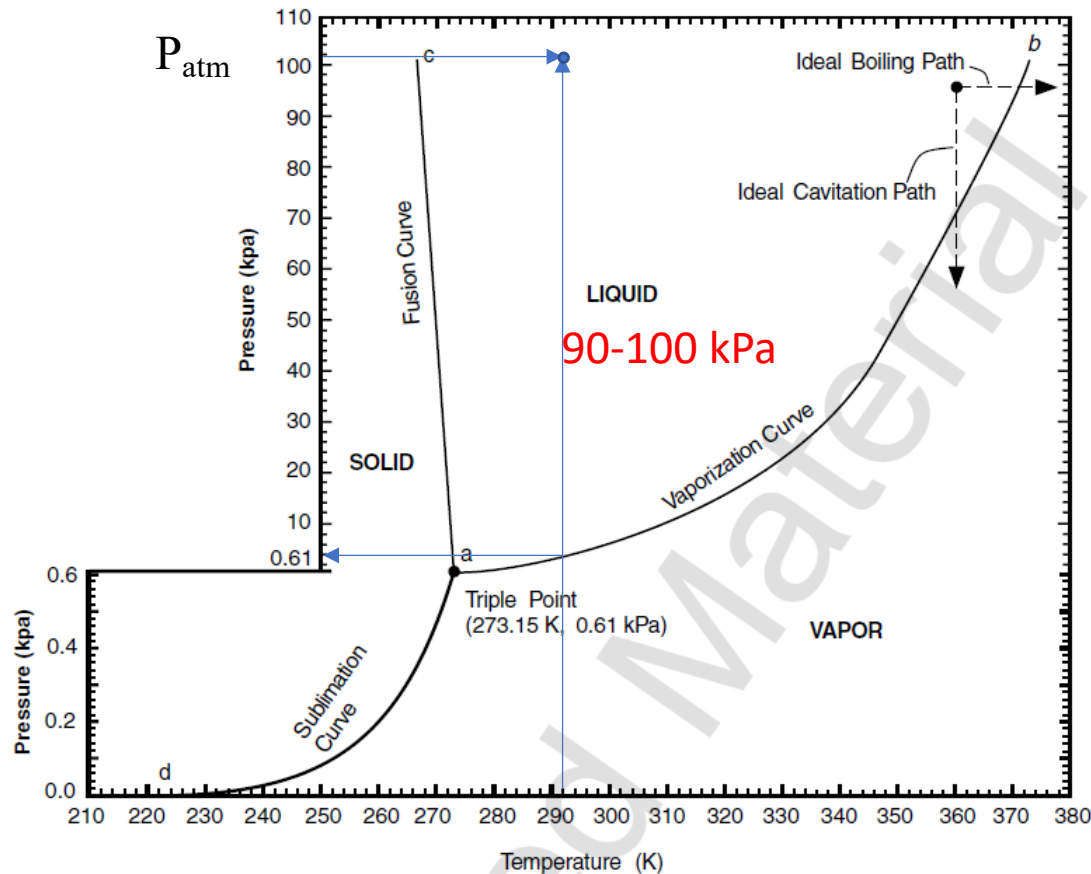
Typical range of suction measurement: 0- 90 kPa (limited by cavitation)
Cavitation will occur around 70-100 kPa. The range drop when there are a lot of impurities in water
Equilibrium times: Hours

Source: Fredlund et al. (2012)

Cavitation: Formation of vapor bubbles in liquid due to a decrease in pressure (water is under tensile/rupture)

Atmospheric pressure (P_{atm}) is approximately 101 kPa
absolute pressure (0-gauge pressure)

$$\text{Gauge pressure} = \text{Absolute pressure} - P_{\text{atm}}$$



Why soil suction can be very high i.e. 1000000 kPa?

If the radii of the cavitation nuclei in the water are sufficiently small, the water will be able to sustain high tensile stress without undergoing cavitation (Fredlund et al., 2012)

Why do we care with cavitation?

It limits our ability to measure suction

Source: Lu and Likos (2004)

Polymer Based Tensiometer



Geotechnical Testing Journal

Hariato Rahardjo,¹ Yuanjie Shen,² Daryl Lee Tsen-Tieng,³
Johnatan Ramos-Rivera,⁴ Xue-Feng Nong,² and Abdul Halim Hamdany²

DOI: 10.1520/GTJ20190451

New Osmotic Tensiometer Development

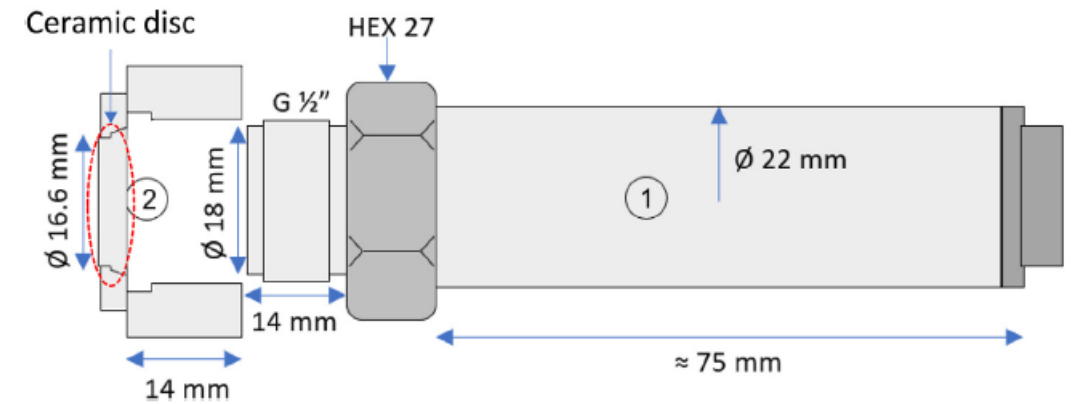


Fig. 3. Schematic drawing of NTU Osmotic Tensiometer (1) PAA-35X Keller Transmitter and (2) New design of cap.

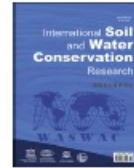
Field Monitoring

International Soil and Water Conservation Research 10 (2022) 586–596



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International Soil and Water Conservation Research

journal homepage: www.elsevier.com/locate/iswcr



Original Research Article

Field instrumentation for real-time measurement of soil-water characteristic curve

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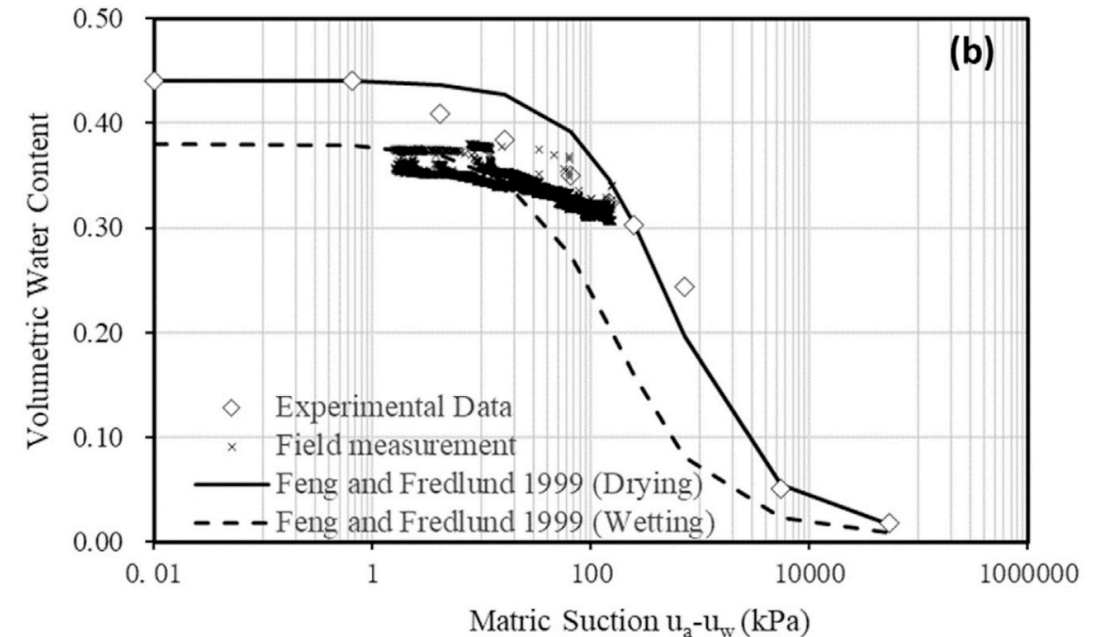
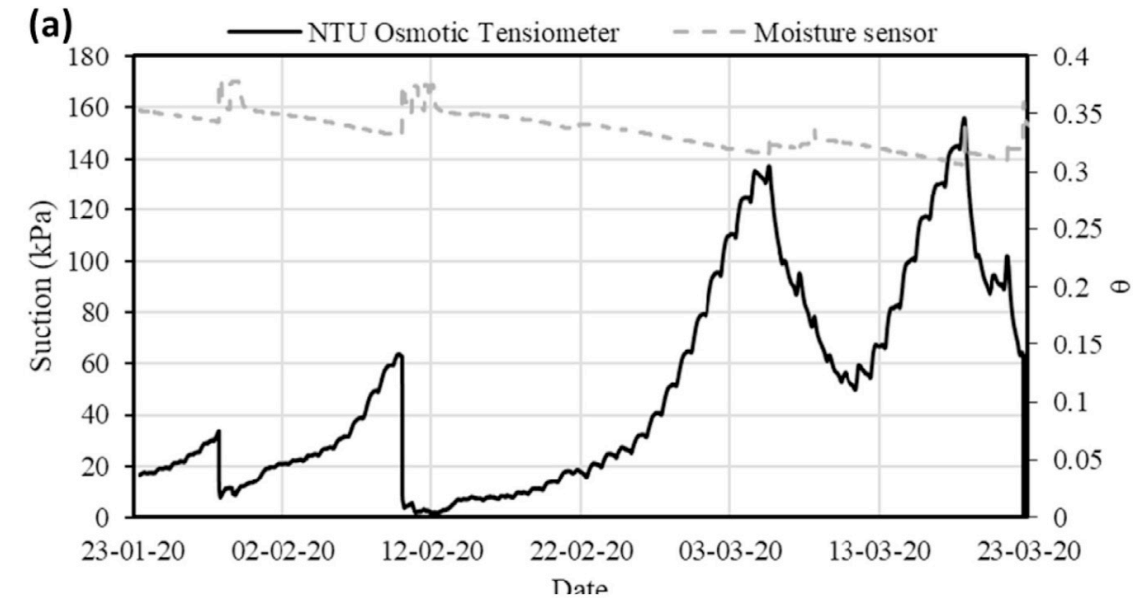
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Field measurement

ABSTRACT

Suction measurement has a vital role in unsaturated soil analysis. However, measuring soil suction remains a challenging task due to a number of issues such as the limited range of suction measurement, cavitation, or long equilibrium time. It is even more challenging when the suction measurement is to be carried on the field. Hence, the development of a new suction measurement device which is able to measure high suction range for a long duration without tedious maintenance and yet portable enough for site measurement is required. In this study, a new sensor which is referred to as NTU Osmotic Tensiometer was developed along with the method to correct for decay and temperature. The NTU osmotic tensiometer is based on polymer swelling capacity in order to measure in-situ soil suction in real time for a very long duration. It requires minimum maintenance as the polymer-based sensor is not affected by the cavitation phenomenon. However, correction for decay and temperature is of paramount importance and therefore explained in this paper. Verification of the NTU osmotic tensiometer was carried out by comparing the field measurement results from the NTU osmotic tensiometer and the small tip tensiometer. The performance of the NTU osmotic tensiometer was found to be comparable with that of the small tip tensiometer, but the NTU osmotic tensiometer is able to measure more than 100 kPa soil suction. Therefore, it is possible to obtain the field soil-water characteristic curve by combining the measured in-situ soil suction from the NTU osmotic tensiometer with the measured in-situ water content from the moisture sensor as illustrated in the paper.

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Field Monitoring

Hamdany et al. (2020)



Decay Problem



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Long-term decay of the water pressure in the osmotic tensiometer

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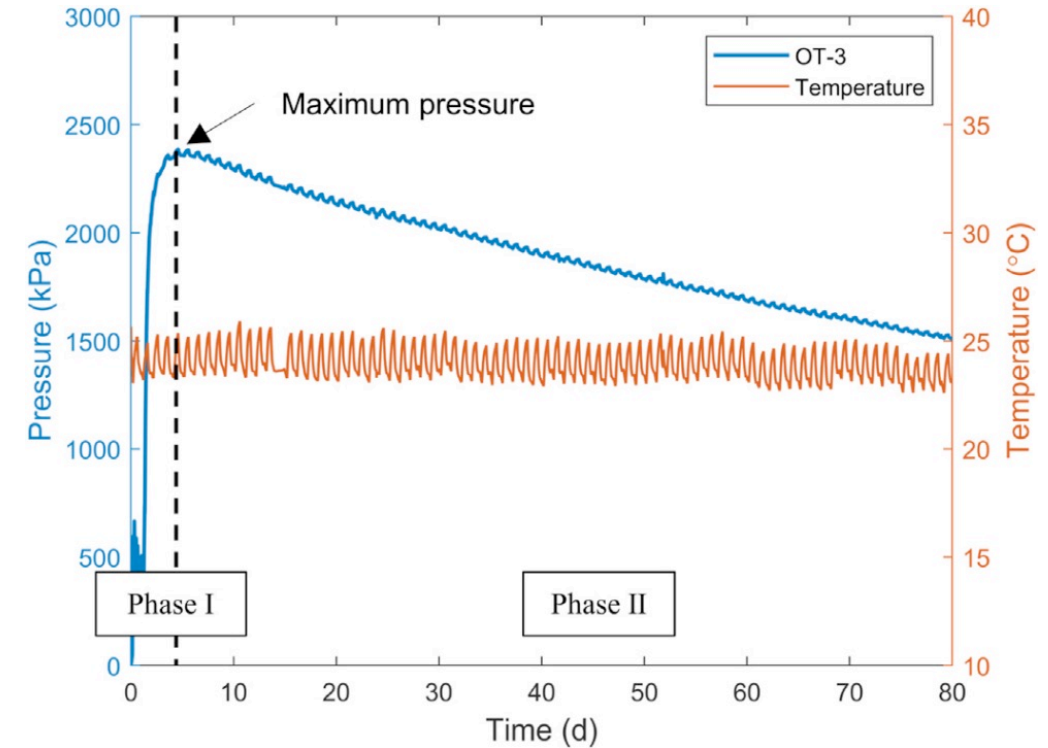
Polymer leakage

Viscoelasticity of polymers

ABSTRACT

Matric suction is an important state variable required for the assessment of unsaturated soil properties. Tensiometers are commonly used for direct matric suction measurement but have a limited measuring range up to 90 kPa due to the cavitation problem. Osmotic tensiometer (OT) can improve the measuring range of tensiometers by increasing the osmotic pressure of water to avoid the cavitation. However, the long-term water pressure decay that appeared in OTs caused a gradual decrease in their measuring range. In this study, crosslinked poly(acrylamide-co-acrylic acid) potassium salt (PAM-co-PAAK) was used for the preparation of OTs (five in total) to explore the mechanism of water pressure decay of OTs. The maximum water pressure in the OT versus the volume fraction of polymer filled in the OT was described based on the Flory-Huggins polymer theories and validated using WP4C dewpoint hygrometer. The long-term pressure decay of OT-1, OT-2, and OT-3 was observed for 130 d and constant pressures were found for OT-1 and OT-2, indicating that the pressure decay of OT was mainly caused by the stress relaxation of the polymer hydrogels, and standard linear solid (SLS) rheological model was appropriate to fit the decay data. For OT-1, OT-2 and OT-3, the theoretical osmotic pressure that was calculated based on the mass of retrieved polymer from OTs after 130-d pressure observation was higher than the actual osmotic pressure as observed, indicating that polymer leakage cannot explain the pressure decay of the OT. The ultraviolet-visible (UV-visible) spectrophotometry examined the change in polymer concentrations in the water containers of OT-4 and OT-5 and demonstrated that there was no increase in polymer leakage during the period of pressure decay of OT-4 and OT-5. As a result, the pressure decay of OT was not caused by polymer leakage. The results of this research suggested that the viscoelastic properties of polymers should be taken into consideration in further OT development.

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Polymer relaxation

Polymer Synthesis

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Use of synthesised polymers for the development of new osmotic tensiometers

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Compared with conventional water-filled tensiometers, polymer-filled osmotic tensiometers (OTs) can measure a higher matric suction by increasing the osmotic pressure of the water inside the tensiometer. The measuring range of an OT is equal to the osmotic pressure of water inside the OT. All previous research has used commercial polymers in developing OTs and the mechanism of long-term pressure decay of OTs was not found. In this study, polymers including polyacrylamide (PAM) and sodium polyacrylate (NaPA) with different degrees of cross-linking were synthesised by ultraviolet polymerisation to develop new OTs. Long-term pressure variations of OTs indicated that the pressure decay was more likely due to the stress relaxation of polymer materials instead of polymer leakage. PAM-filled OTs have a faster stress relaxation behaviour than NaPA-filled OTs, so that they can keep constant pressure (i.e. constant measuring range) for a long time and there is no need for pressure correction based on the pressure decay rate. However, the measuring range of PAM-filled OTs is lower than that of NaPA-filled OTs. The result of matric suction measurements demonstrated that the proposed OTs can be used to measure matric suction both in low and high ranges with fast response and high accuracy.

KEYWORDS: field instrumentation; monitoring; suction

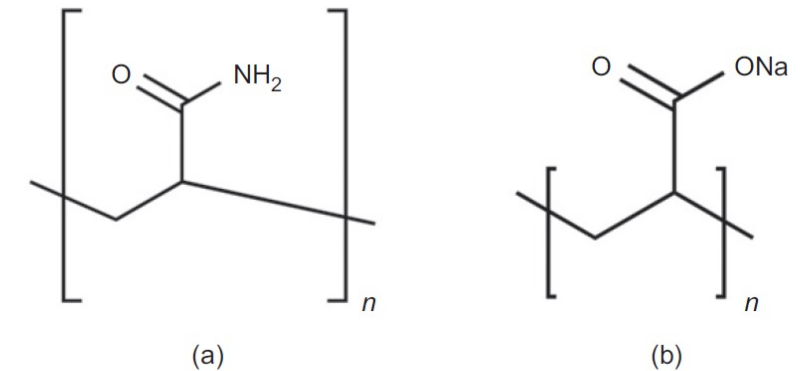


Fig. 1. Structural formulas of (a) polyacrylamide (PAM) and (b) sodium polyacrylate (NaPA)

Degree of cross-linker

Polymer based tensiometer 3.0

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Laboratory investigation of osmotic tensiometers filled with cross-linked polyacrylamide

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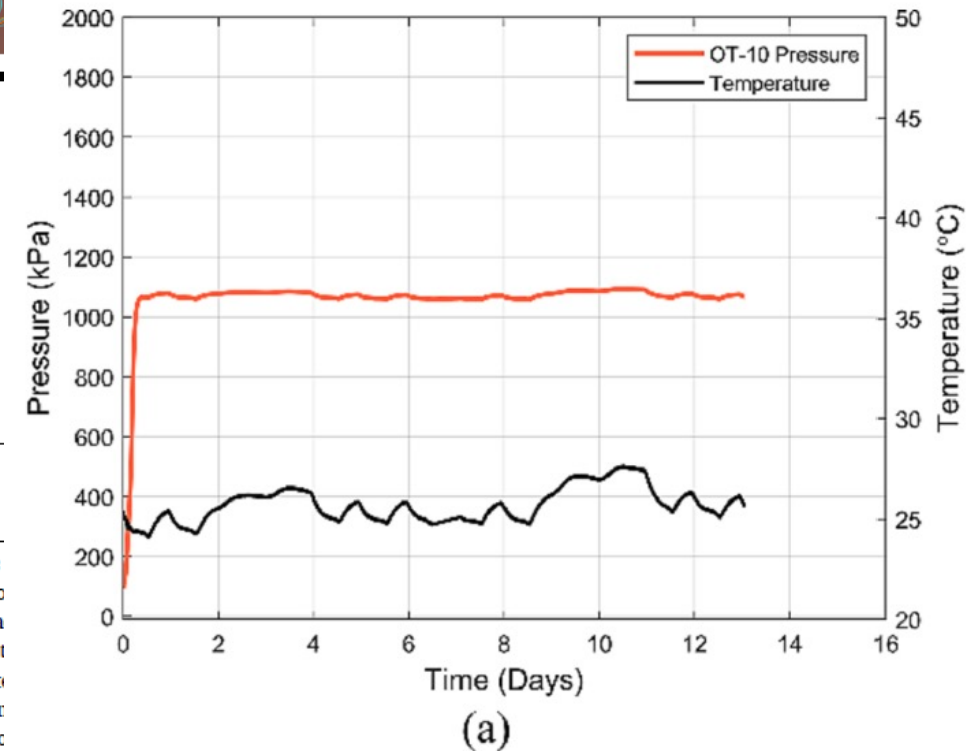
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ABSTRACT

Soil suction measurement is required for the analysis of slope stability and soil-structure interactions unsaturated soils below transportation infrastructures. Osmotic tensiometers (OT) can measure so higher than 1000 kPa but suffer from the pressure decay problem. The OT filled with cross-linked polyacrylamide can maintain a stable pressure for a long time but the research on this type of OT is quite limited. In this study, the behaviors of OTs filled with synthesized non-ionic cross-linked polyacrylamide were investigated experimentally and explained in accordance with Flory-Huggins polymer theories. A generalized calibration was proposed to reduce the pressure fluctuation of OT caused by temperature. The pressure variations were observed for more than 100 days and several cycles of drying tests were conducted. The results show that the pressure of the OT recovered after it was dried in the air for tens of minutes. In contrast, a slight pressure decay appeared when the OT was dried in the air for several days. However, as more cycles of drying tests were conducted, the pressure decay caused by the drying tests gradually became negligible. The relationship between the pressure of the OT at the end of observation and the volume fraction of the polyacrylamide inside the chamber of the OT was established by considering the confinement effect on the polyacrylamide hydrogel inside the OT. Finally, it is proved that salt solutions will not affect the pressure variation of OT filled with cross-linked polyacrylamide so the OT measures the matric suction of the soil.



Application

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Full length articles

High-suction polymer sensor for measurement of soil suction under freezing and thawing conditions

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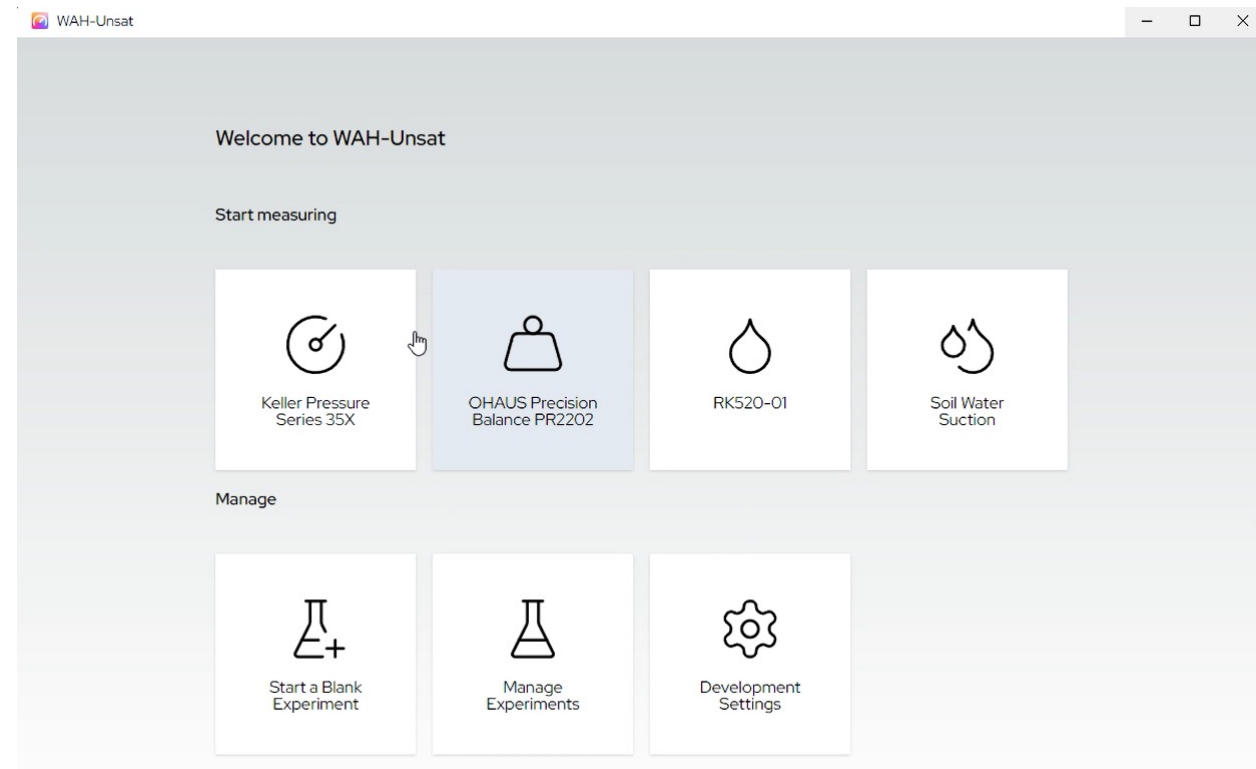
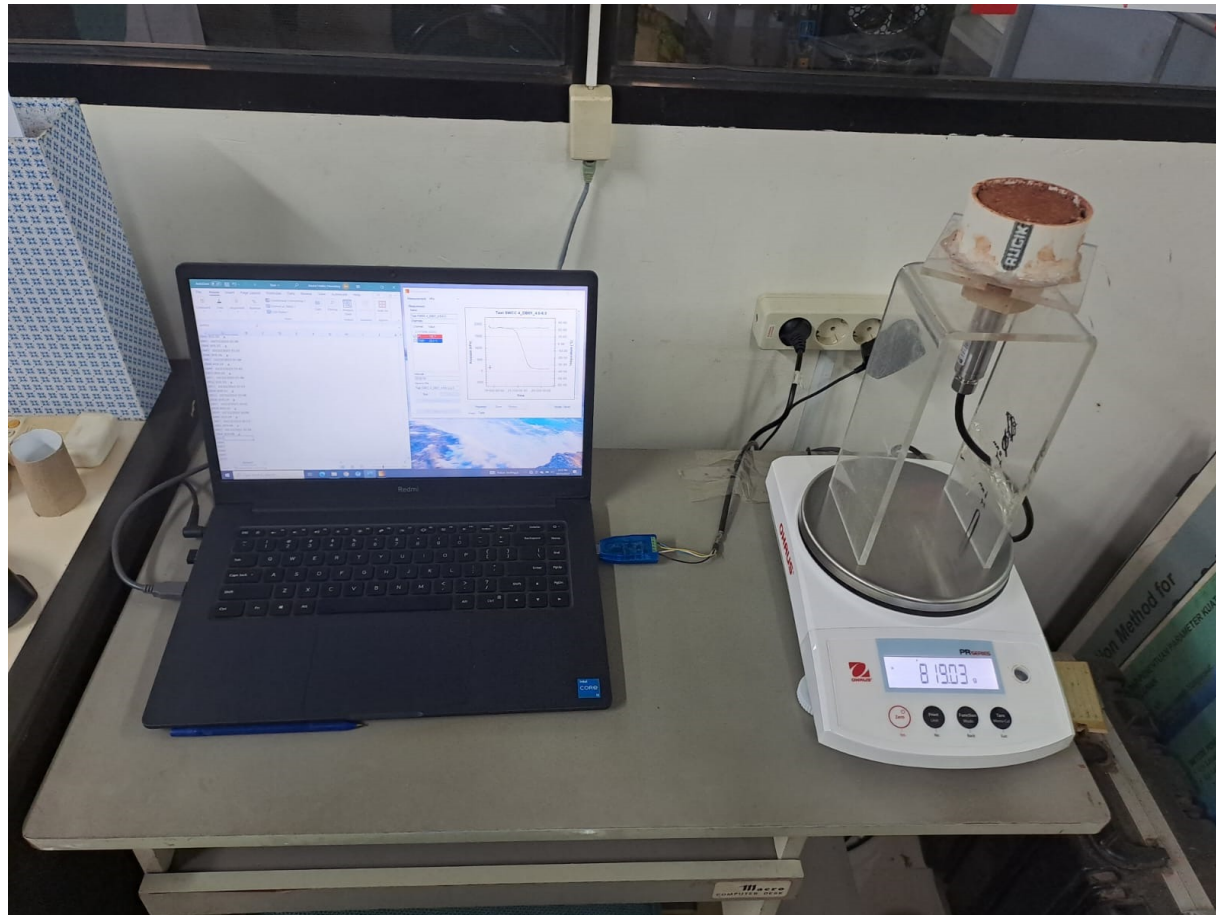
Keywords:

High-suction polymer sensor
Polyacrylamide
Soil suction
Soil-water characteristic curves (SWCC)
Freeze-thaw cycles

ABSTRACT

Soil-water characteristic curves (SWCC) are one of the most essential elements of unsaturated soil properties, yet the instruments employed for acquiring them have distinct limitations, for example, the tests are time-consuming, tedious and costly. High-suction polymer sensor (HSPS) with modified polyacrylamide (PAM) polymer is an alternative of measuring soil suction that relies on osmosis pressure rather than capillary pressure alone. The sample examined originated in Astana and was defined as clayey sand (SC). The ambient temperature of the Astana soil (sample 1) was used to assess soil suction using HSPS, which was verified by typical unsaturated equipment such as the Tempe Cell and dew-point potentiometer (WP4C). Once confirmed and SWCC was formed, the HSPS was utilized to detect soil suction during freeze-thaw cycles to simulate the climate in Astana. Based on the durability test, with the anticipated outcome lasting up to a year, PAM can resist the pressure for >200 days. Additionally, the modified PAM generated a stable response compared to the conventional PAM. The results from laboratory testing indicated that sample 2 has a greater average suction during freezing, while sample 3 has a higher average suction during thawing. In general, freezing cycles should produce more suction than thawing; yet, in sample 3, the water was still in supercooling stage, resulting in freezing having a lower suction average than thawing.

SWCC direct measurement in Lab



Stress State Variable in Unsaturated Soil

Stress State Variable in Unsaturated soils

- Saturated soil stress state variable

- Terzaghi effective stress

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

- Unsaturated soil stress state variable:

- Bishop effective stress

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$

$$\sigma' = (\sigma - u_a) + \chi s$$

- Independent stress state variable

$$(\sigma - u_a) \quad (u_a - u_w)$$

- Suction Stress

$$(\sigma - u_a) \quad S_e(u_a - u_w)$$

- Many more....

Bishop Effective Stress

$$\sigma' = (\sigma - u_a) + \chi s$$

Why a lot of software still preferred to use Bishop effective stress:

1. Simple and easy to be implemented
2. Gives reasonable result for shear strength related problem
3. χ is often replaced by degree of saturation (S_r) and hence easy to determine

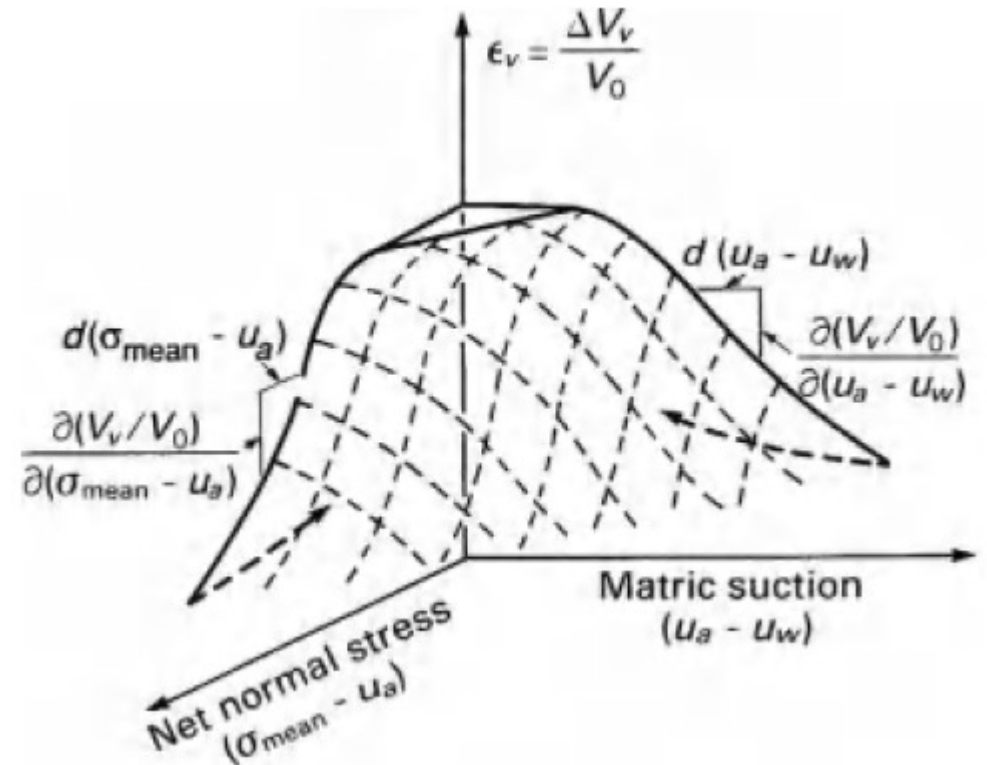
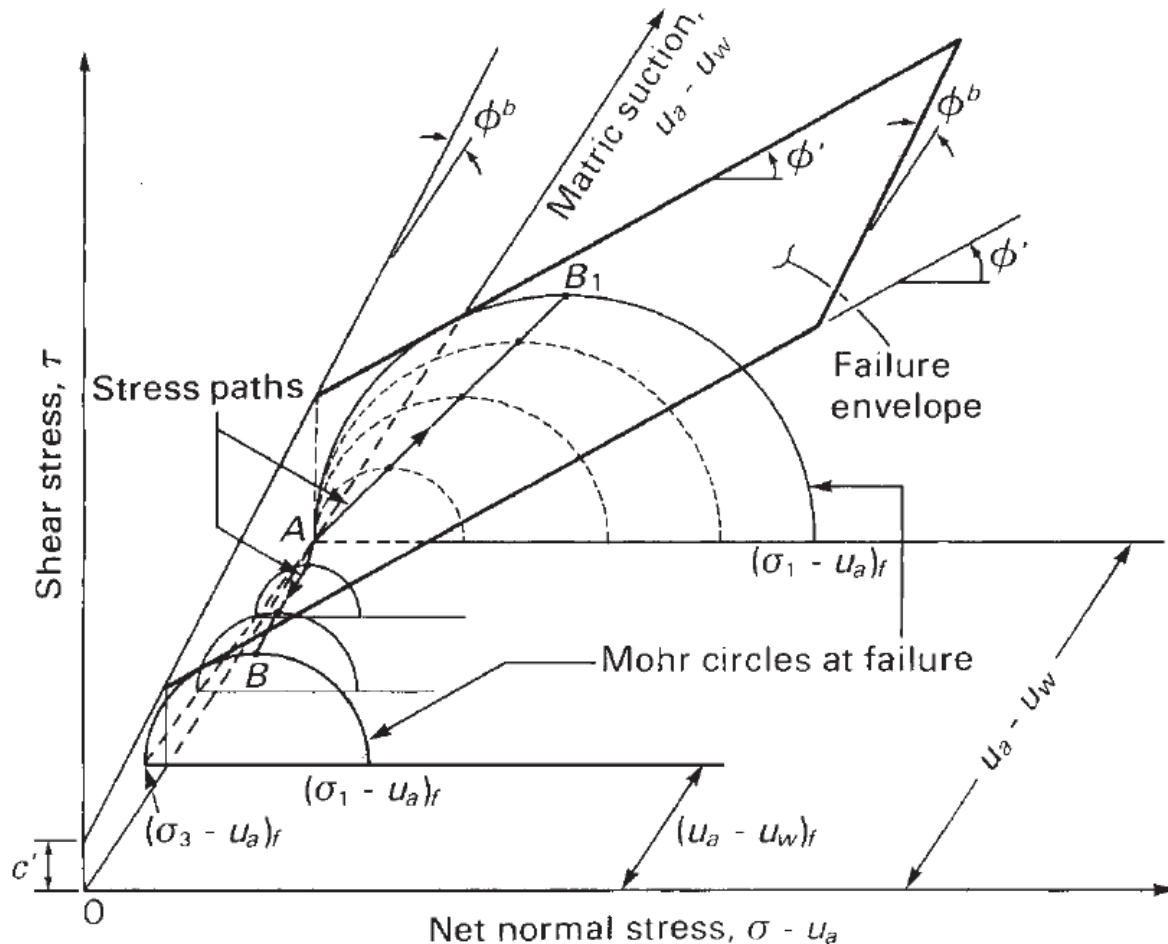
Controversy regarding effective stress:

1. The value of χ when determined for volume change was found to be different when determined for shear strength (Morgenstern, 1979).
2. The collapse phenomenon which was observed in the double oedometer test by Jennings and Burland (1962) invalidates the concept of effective stress as the inundation which decreases the value of effective stress causes the soil to decrease in volume while it is expected to increase in volume.
3. The χ parameter is commonly related to degree of saturation which often leads to significant error and unrealistic value especially for clay (Alonso et al., 2010).

Independent stress state variable

$$(\sigma - u_a) \quad (u_a - u_w)$$

Change in net normal stress and suction affects shear strength and volume change by using independent parameters



Thank you!