+Sheets A&B

II CLAY-WATER FORCES

(1.361 Refer.)

1. WATER VAPOR SORPTION ("Adsorbed" Water) (II 2-2.1)

1.1 Water Content vs. Relative Humidity (RH)

1) Relative humidity, RH(%)

$$RH(\%) = 100 \times \frac{P_w}{P_s}$$

P_w = partial pressure of (pore) water vapor

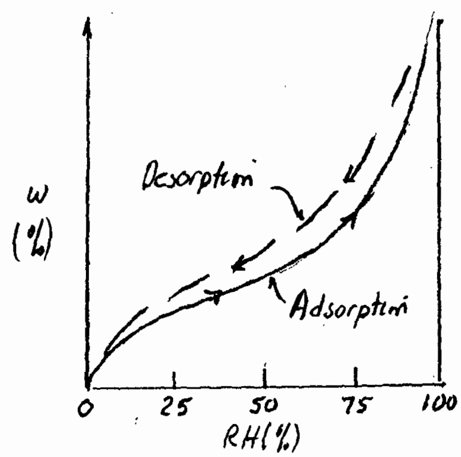
P_s = saturation pressure of pure H_2O (flat surface) at same temp.

$[\log P_s(kPa) \approx -0.174 + 0.0265\,T(°C)\ ;\ T = 20 \pm 15°C]$

{ Actual T = 10 20 30°C; P_s = 1.23 2.34 4.245 kPa }

Table 2.7 Fredlund & Rahardjo (1993) Soil Mech. for Unsaturated Soils, Wiley textbook

2) Adsorption - desorption curves (starting from oven dry soil)



3) Values of water content

a) RH = 50% → 1-2 molecular thicknesses of water : $t \approx 5Å$ $w_{50}(\%) \approx 0.05 \times SSA(m^2/g)$

$\phi_{H_2O} = 3Å$

$\{ t(Å) = 100\,w(\%) / SSA(m^2/g) \}$

• Empirical data from Ladd / Lambe (1961) $w_{50}(\%) \approx (0.2 \pm 0.05)\,I_p(\%)$

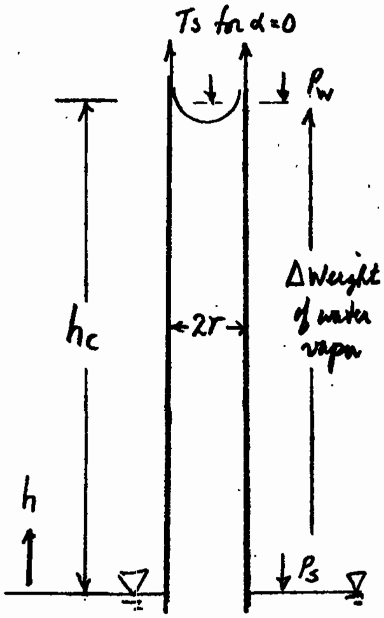
b) RH ≈ 99% → $t \approx 10\text{-}15Å \approx$ 3-5 molecular thicknesses

Often referred to as thickness of tightly bound "adsorbed" water

(1.361 Refs.)
(II 2 - 2.1; IV 1-2)

1.2 Capillary Pressure (u_c) vs. Relative Humidity

1) Theoretical relationship



- 1.361 Eqn. $u_c = h_c \cdot \gamma_w = \frac{2T_s}{r}$, T_s = surface tension of H_2O = 72.75 N·m/m² at 20°C (energy/unit area)

$u_c = u_a - u_w$

$pV = nR_gT$ + $\frac{dp}{dh} = -\rho_{wv} \cdot g$ ↑ mass density of water vapor

- Revised eqn. to include reduced vapor pressure of curved miniscus & wgt water vapor

$$h_c \cdot \gamma_w = \underbrace{\frac{2T_s}{r} + P_s - P_w}_{\text{Force} \uparrow}$$ } At bottom of tube

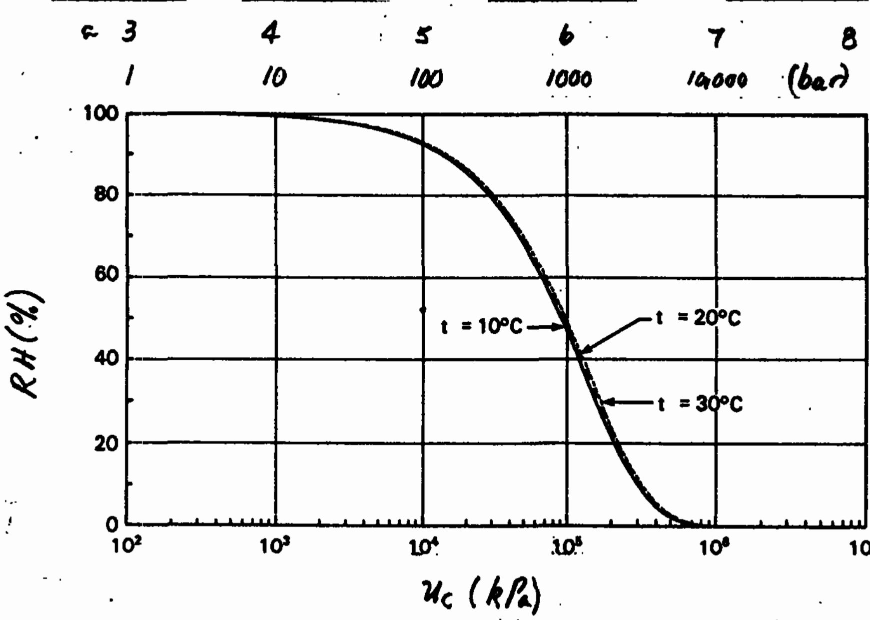
($h_c \cdot \gamma_w$: Force ↓)

- $u_c = h_c \gamma_w = -\frac{\rho_w R_g T}{M} \ln\left(\frac{RH}{100}\right)$

$\rho_w = 998\ kg/m^3$
$R_g = 8.314\ J/mol \cdot °K$
$T = °K$
$M = 18.015\ g/mol$
$(J = N \cdot m)$

- For T=20°C $u_c\ (kPa) = -1.35 \times 10^5 \ln\left(\frac{RH}{100}\right)$

$u_c\ (bar) = -1350 \ln\left(\frac{RH}{100}\right)$



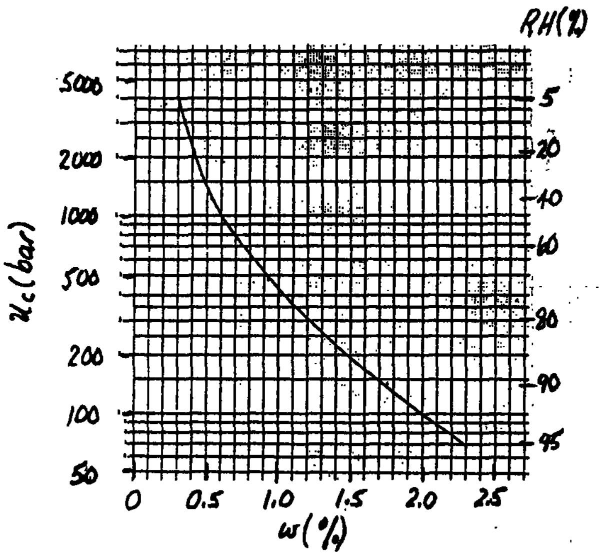
$pF = \log(h_c \cdot cm)$

$h_c = 1000\ cm = 10\ m$
→ $pF = 3.00 \approx 1\ atm \approx 1\ bar = 100\ kPa$

- 1 bar = 100 kPa ÷ $\gamma_w = 9.81\ kN/m^3 = 10.2\ m$ (= 1020 cm)
- 1 atm = 1.013 bar

RH(%) =	99.9	99.5	99	95	90
u_c(bar) =	1.35	6.77	13.5⁵	69	142
pF =	3.1⁵		4.1⁵		5.1⁵

(1.2 Cont) 2) Water content vs capillary pressure (1.361 Ref)

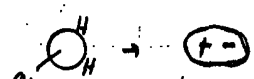


Computed from w vs RH data on Peerless (Li) Kaolinite with
CEC = 2.7 meq./100g (SSA = 9 m²/g for σ_o = 0.3)
Adsorption curve for RH = 0 to 95%

{ W vs RH data by R.T. Martin, 1958, Proc. 5th Nat. Conf. Clays & Clay Mineralogy NAS/NRC Publ. 566, p 23-38 }

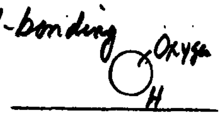
1.3 Mechanisms of Water Vapor Adsorption (CCL + Mitchell (1993), Chap 6)

Note: H_2O molecule = dipole

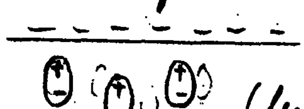


Starting from ovendry soil

Mechanism	Remarks	(II 2-2, p6)
1) H-bonding	Very important for 1st layer	
2) Cation hydration	Very important ; Hydrated dia. of cations ≈ 15 ± 5 Å	
3) Orientation of H_2O dipole in electric field	Uncertain importance	
4) van der Waals attraction	" "	



Oxygen or OH



(less mobile → less free energy)

Cation	K^{+1}	Na^{+1}	Ca^{+2}	Mg^{+2}	Li^{+1}
Hydrated Dia (Å)	9±2.5	13.5±2	19	21.5	17.5±2.5

(JKM 1993, p122)

(1.361 Ref)

1.4 Measurement of Water Content

1) ASTM 2216 $T = 110 \pm 5°C$ really doesn't remove all H_2O; need more like 200°C. Is that of practical significance? ____

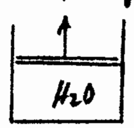
2) Don't leave soil in humid environment before weighing after remove from oven

1.5 Tensile Strength of Water [Ridley & Burland 1993, Geot 43(2)]

(Can $u_c \rightarrow$ 10's to 100's atm. in cohesive soils? ____)

1) Tabor (1979): theoretical tensile strength, $u_w = -5000$ atm.
However, very small amount of dissolved gas → cavitation at
$u_w \gg$ theoretical value ($u_c \ll 5000$ atm). Typical lab test → ? ____

2) Temperley & Chambers (1946 Proc. Royal Soc., London)



Carefully degassed, smooth-walled chamber → $u_w \approx -500$ atm

3) Conclusion: answer to ( ) is YES, e.g. drying of initially sat. clay to the shrinkage limit
(see p8)

2. SOIL SUCTION (S) [Also see 1.361 Section 2.6 of Part IV-1]

2.1 Overview

- Used as a measure of the "free energy" of the bulk pore water in soil*
(at constant elevation) relative to pure water at atm. pressure
at same temperature when this free energy is less than zero.

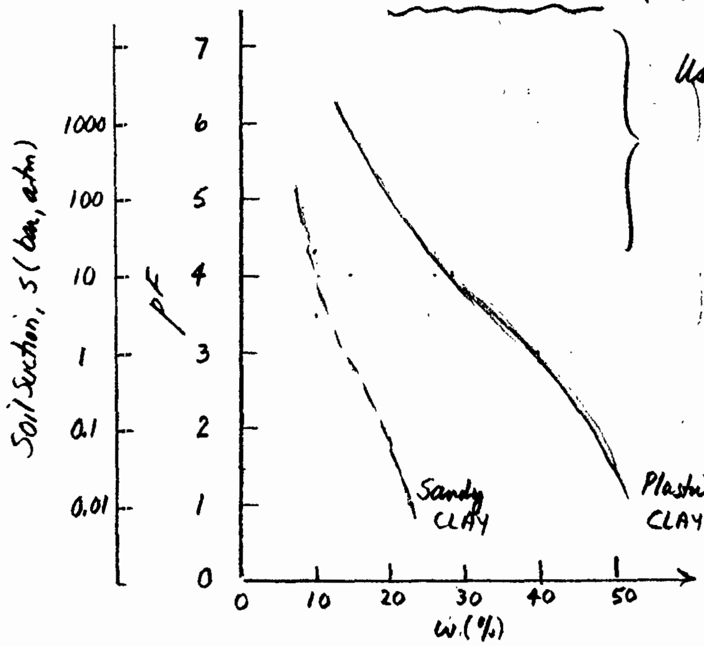
- Free energy can be expressed in terms of: potential - J/kg
pressure - kPa } most common
head - m } most common

CCL tentative definition
S = free energy of pure H_2O in contact with soil having $\sigma - u_a = 0$

→ * Questions: (1) Restricted to soil with $\sigma - u_a = 0$?
(2) Physical meaning when low % sat. → no bulk water?

2.1 Cont

Soil suction curves (location = f wetting vs drying)



Usually indirect, e.g. relative humidity (psychrometer) or filter paper

(CCL believes that most data are not very reliable)

Various direct measurements, e.g. suction plate ($u_a = 0$), • pressure plate ($u_c = u_a - u_w$), • tensiometer = piezometer with v fine porous stone à la Section 2.4

Note: Most reported data are for drying; will show wetting/drying cycles when cover compacted soils. Also usually use Θ_V = volumetric water content = V_w/V (p8)

2.2 Components of Soil Suction (Aitchison & Richards, 1965) (1.361 II 2, p8)

1) Total suction (s) = matric suction (s_m) + solute suction (s_s)

2) Solute suction (s_s) = osmotic pressure due to salt concentration in bulk pore water of soil

s_s (atm) ≈ 24 (salt conc., M = moles/l) for both cations & anions) for T≈20°C

(Sea water ≈ 35 g/l → ≈1.1 M → ≈ 26 atm!)

3) Matric suction (s_m) = ($u_a - u_w$), where pore water in measurement system has same salt conc. as bulk pore water in soil

matric = matrix

NOTE: In CCL opinion, matric suction denotes s_m for soil having $\sigma - u_a = 0$ (at least via techniques used in lab to measure s_m). We should discuss difference between s_m & σ'

2.3 Mechanisms Causing Matric Suction

1) Those for water vapor sorption in Section 1.3 (i.e., for "adsorbed" H_2O)

2) Osmotic pressure due to depressed double layer, i.e., need apply neg. u_w to prevent soil from sucking in more water (≠ solute suction)

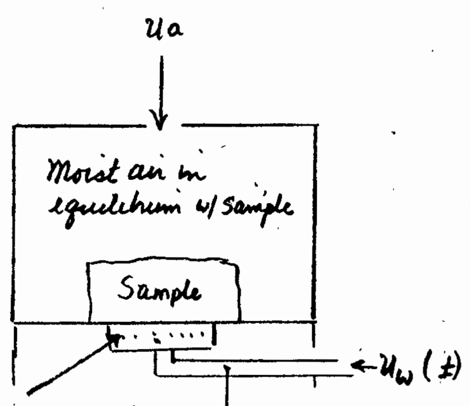
need 2d > 10-15Å

3) Elastic deformation of platy particles (mechanical) drying → bending, wetting → unbending

4) Net contact stress ($\bar{\sigma}''_{ac}$) > 0

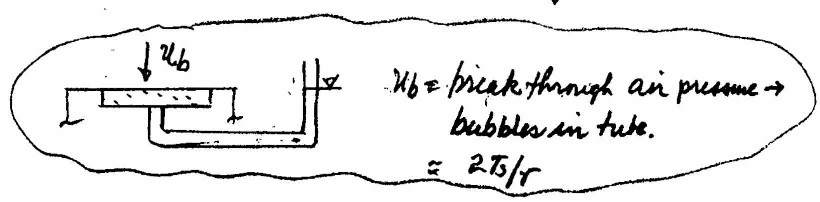
2.4 Direct Lab Measurements of Soil Suction (Sheet A)

1) Experimental set-up for: • Suction plate ($u_a = 0$)
• Pressure plate ($u_a > 0$) – Requires continuous air voids — "axis translation"
• Miniature piezometer ($u_a = 0$) à la Ridley & Burland (1993) with $u_b = 15$ bar & ~~Germaine~~ – Sjoblom MIT research



Saturated Fine porous stone with bubbling pressure (u_b) > S to be measured

Pore fluid in stone + line (measurement system)



2) Test conditions & measured soil suction = $(u_a - u_w)$

Sample	Case	System Pore Fluid	Does Stone Act as Semi-Perm. Membrane?	Meas. Soil Suction	Remarks
Clay with salt in bulk pore fluid	1	Same as soil pore fluid	Both Yes & No, i.e. makes no difference	Matric	—
"	2a	Pure H_2O	Yes	Total	**
	2b	"	No	Matric	**

** Whether or not 15 bar stone will ~~exhibit~~ a significant "osmotic efficiency" (i.e., act as partial semi-permeable membrane) is somewhat controversial. For example, discussion[(1)] to Ridley & Burland concludes that 15 bar stone approaches total suction, whereas authors disagree. Kurt Sjoblom's (9/00) data indicate that ~~measure~~ matric suction

(1) Geotechnique 1994, 44(3), 551-556

2.5 Soil Suction Measurement Techniques

1) See Sheet A for overview & schematic of direct measurements

2) " " B for info. on filter paper technique *

3) See Stannard [1992: ASTM, GTJ, 15(1)] for SOA paper on field measurement techniques

* Note that calibration curve becomes very flat (hence very imprecise) at low suctions. Also exact details of "contact" vs "noncontact" very important, plus may have different calibration curves for these 2 conditions (R&B, 1994 closure)

3. NATURE OF ADSORBED WATER

3.1 Total vs. Pressure Head and Attraction Pressure

1) Components of total head (total free energy)

$$\text{Total head } h = h_t = h_e + h_p + h_s + h_v + h_{pc}$$

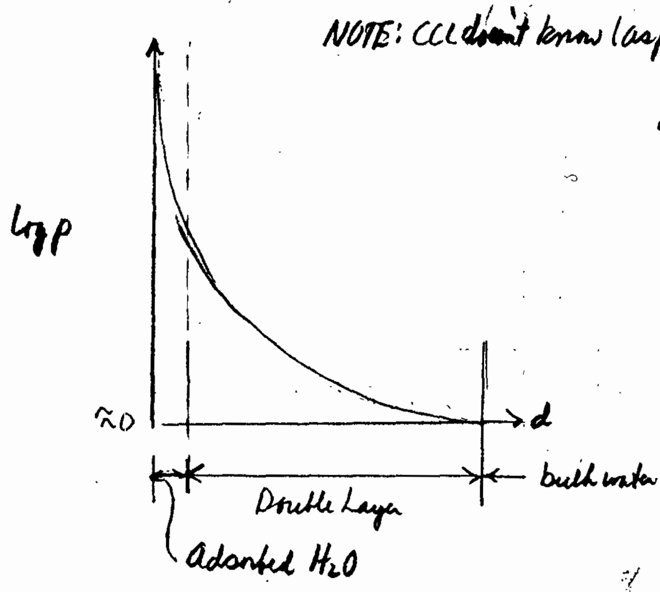
where $h_s = \frac{s_s}{\gamma_w}$, $h_v = \frac{1}{2}\frac{v^2}{g}$, h_{pc} = physico-chemical within double layer (DL)

$h_p = -\frac{s_m}{\gamma_w}$ for bulk water beyond DL at $h_e = h_s = h_v = 0$

(JKM 1993 Section 9.5)

2) Attraction pressure (p) vs distance (d) from particle surface

NOTE: CCL doesn't know (as per writing) shape of curve



- Discussion of actual pressure in H_2O → can't have very high s_m, but still have large $+p$ in adsorbed water
- Values of p within adsorbed H_2O

  $d = 10\text{-}15\,Å \rightarrow$ 10's atm

  $d = 3\text{-}6\,Å \rightarrow$ 100's-1000's atm.

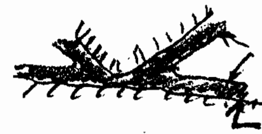
3) Discussion: what is meaning of h_t, h_p, s_m etc. when low % sat. → no bulk water?

(1.361 Ref)

3.2 Physical Properties of Adsorbed Water

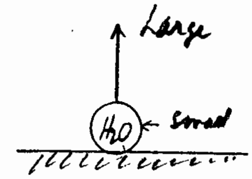
(II 2, p6)

1) Is "ice-like"



- Very high viscosity
- Causes cohesion & creep (e.g., Terzaghi, Bjerrum 1973)
- Don't get mineral-mineral contacts (or greatly inhibits) in clay

2) Like 2-D liquid (R.T. Martin)

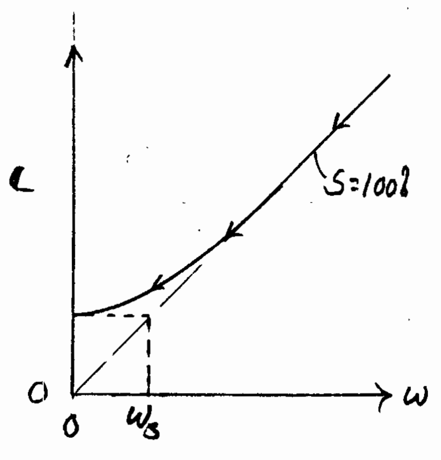


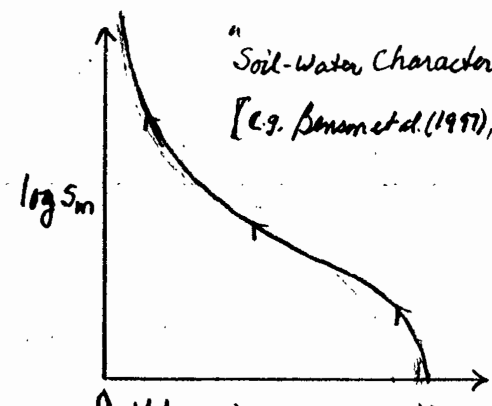
- Like ball bearings on magnet
- Does not cause strength, but does inhibit min.-min. contact

3) Discussion -

- Story of discussion at 1961 ICSMFE, Paris (Geuze of Holland: "adsorbed H_2O → clay strength → creep." TWL reply =

- Predicted unconfined s_u of initially saturated clay during drying.





Volumetric w.c. $= \Theta_w = \frac{V_w}{V} = \frac{SV_v}{V} = S \cdot n$

$= \frac{Se}{1+e} = \frac{G_s w}{1+G_s w/S}$

- From 1.361
  - Strength of oven-dried BBC & what happened when put in water
  - Part IV-1, p5 → $\sigma'_{nt} \approx 70$ bar at shrinkage limit of BBC

22-141 50 SHEETS 22-142 100 SHEETS 22-144 200 SHEETS AMPAD

cce 2/6/96
1/99

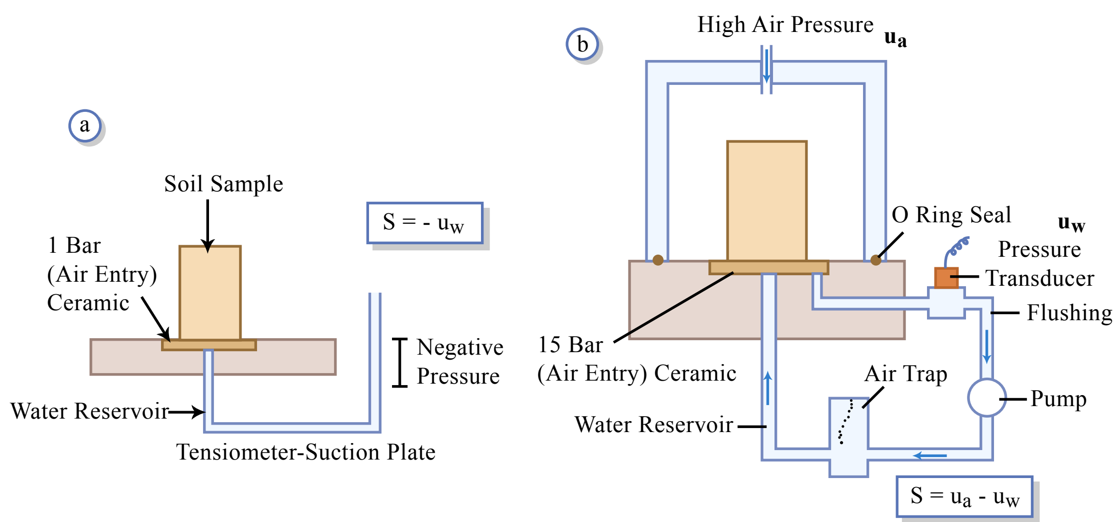
1.322 Part A-II

Adapted from RIDLEY AND BURLAND (1993)

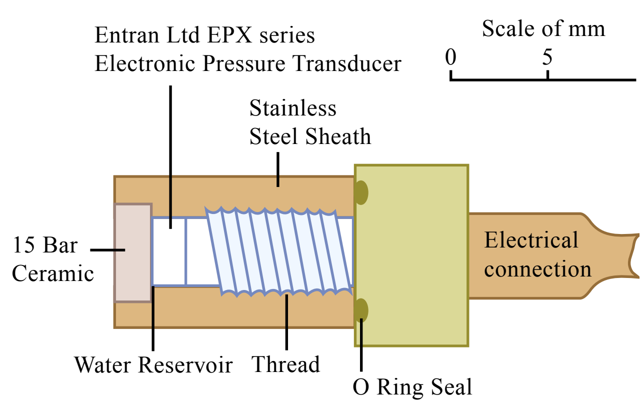
Suction Measurement Techniques

	Suction Value#	Principal Usage	Direct/ Indirect	Range: kPa	Equilibrium Time
Vacuum Desiccator	Total	Lab.	Indirect	10^3-10^6	Months
Psychrometer	Total	Field	Indirect	300-7000	Months
Filter Paper	Total	Field	Indirect	1000-30000	Weeks
	Matrix	Lab.	Indirect	30-30000	1 week
Porous Block	Matrix	Field	Indirect	30-3000	Weeks
Thermal Block	Matrix	Field	Indirect	0-175	Days
Suction Plate	Matrix	Lab.	Direct	0-90	Hours
Tensiometer	Matrix	Field	Direct	0-90	Hours
Pressure Plate	Matrix	Lab.	Direct	0-5000	Hours
Osmotic Tensiometer	Matrix	Field	Direct	0-1500	Days

As defined by Aitchison and Richards (1965).



Direct Measurement of Soil Suction: a) Tensiometer; b) Pressure Plate Apparatus



The New Instrument

Figure by MIT OCW.

Adapted from:

Geotechnique (1993) 43(2), 321-324

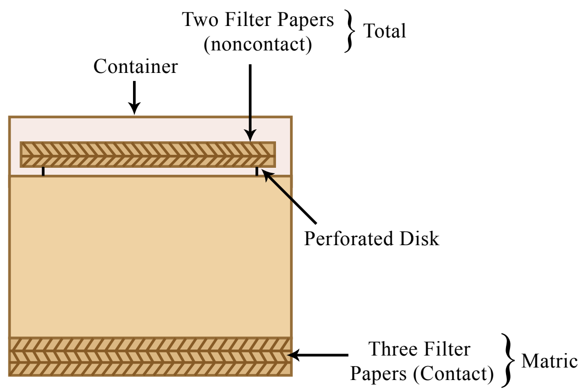
Also see discussion by Marinho & Chandler (1994) & closure
by Ridley & Burland - Geot 44(3), 551-556

CCL 2/6/96 1.322 Part A-II

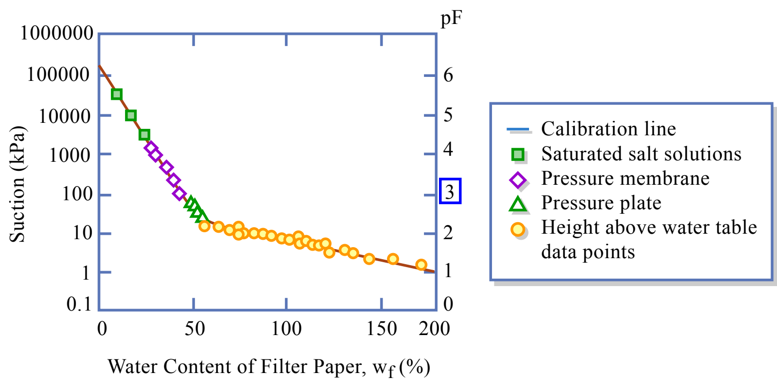
1/31/97

Adapted from Fredlund & Rahardjo (1993) Soil Mechanics for Unsaturated Soils, John Wiley & Sons

Filter paper technique

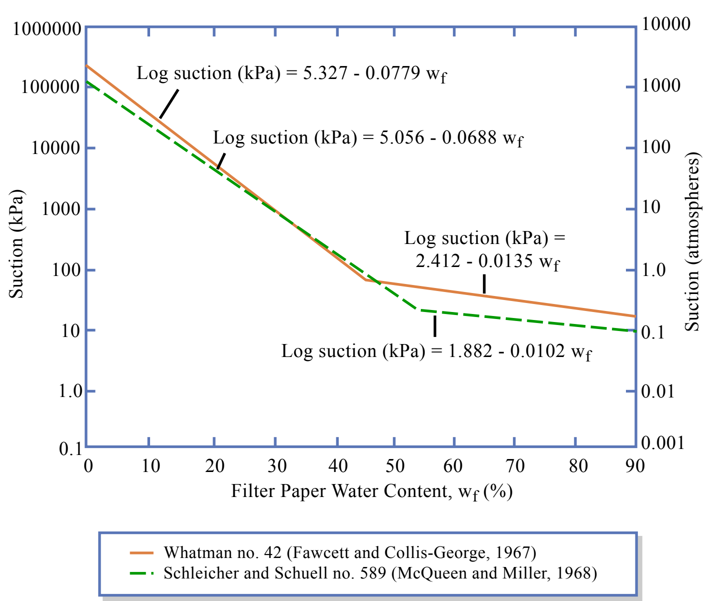


Contact and noncontact filter paper methods for measuring matric and total suction, respectively.



A typical calibration curve showing measured filter paper water contents for applied suctions.

Figure by MIT OCW.



Calibration Curves for Two Types of Filter Paper

Figure by MIT OCW.

B