Introduction to Unsaturated Soils

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The Suction Scale

Suction (kPa)	Suction (pF)	Reference points	Moisture Condition
1,000,000	7	Oven dry	Dry
100,000	6		
10,000	5		
1,000	4	Wilting point for plants; Plastic Limit	Moist
100	3		
10	2		Wet
1	1	Liquid Limit	
0.1	0	Saturated	

pF units represent the logarithm (to base 10) of the suction expressed in centimetres of water (Schofield, 1935)

Suction (kPa) = $9.81 \times 10^{[pF-2]}$

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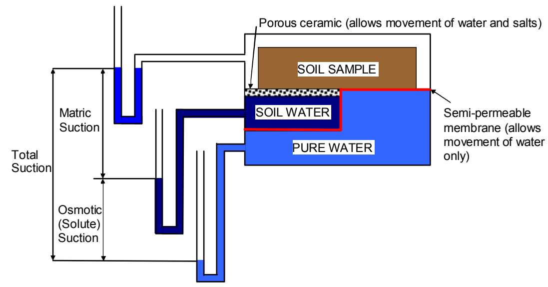
Suction Components



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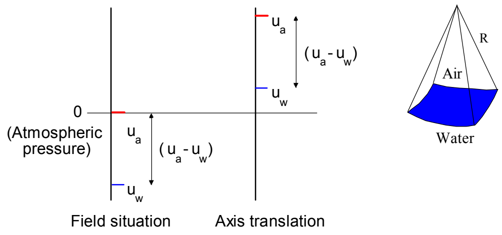
Axis Translation



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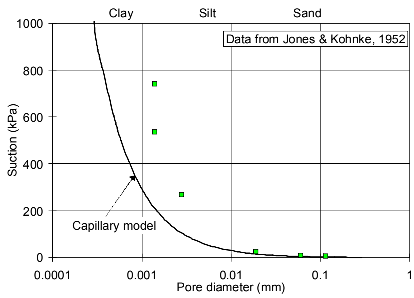
Sustainable suctions



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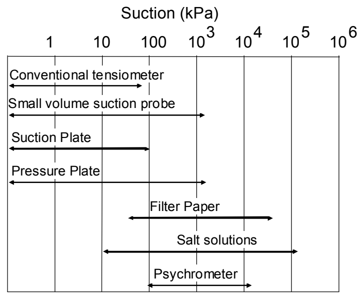
Measurement Techniques



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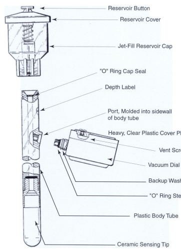
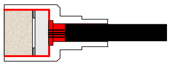
Direct Measurement of Suction

Jetfill tensiometers



Suction Probes

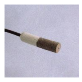
(small volume – high capacity tensiometers)



Lourenço, S.D.N., Gallipoli, D., Toll, D.G. and Evans, F.D. (2006) *Development of a Commercial Tensiometer for Triaxial Testing of Unsaturated Soils*, Proc. 4th International Conference on Unsaturated Soils, Phoenix, USA, Geotechnical Special Publication No. 14., Reston: ASCE, Vol.2, pp. 1875-1886.

Indirect Methods for Suction Measurement

- Porous block sensors
  - Electrical Conductivity
  - Thermal Conductivity
  - Equitensiometer
- Filter paper methods
- Psychrometer



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Electrical Conductivity

Gypsum Block

Range: -50kPa to –1.5MPa

Watermark

Silt granular matrix

Range: 0kPa to –200kPa

- Inexpensive - suitable for trend measurement rather than accuracy
- Gypsum blocks have limited life. Skinner *et al* (1997) suggest a life of 5 years in alkaline or neutral soils but they usually need to be replaced every 2-3 years in acid soils
- Johnston (2000) reports that suctions recorded with gypsum blocks at 2 field sites compared favourably with filter paper estimates for suction, provided blocks are individually calibrated (range -20 to -2100 kPa)
- Bertolino *et al* (2002) show response of Watermark sensors is slow compared to tensiometers (lags by about 2 days) but results are similar

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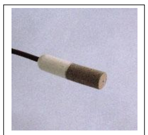
Thermal Conductivity



Thermolink

Model TLS-2

Sensor material : Porous ceramic

Size: 50 mm long, 14 mm dia.

Range: -10kPa to -10MPa

- Oloo & Fredlund (1995) report a high failure rate of sensors for field trials in Kenya (50% failed within 1 year)
- O'Kane *et al* (1998) report suctions measured in excess of 400kPa which showed sensible responses to rainfall
- Shuai & Fredlund (2000) show full equalisation time can be about 2 weeks although a dry sensor may take 4 days
- Devices need corrections for temperature changes and hysteresis (Flint et al, 2002; Feng & Fredlund, 2003)
- Nichol *et al* (2003) identified sensor drift – either due to "relaxation" when operated at low matric suctions or alteration of the ceramic over time
- Ng *et al* (2002) show general agreement between thermal conductivity sensors and tensiometers (suction around 20kPa) although one sensor showed a significantly higher value (250kPa). The thermal conductivity sensors showed a slower response (2 days lag)

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Equitensiometer

Delta-T Equitensiometer

Sensor material: "Specially formulated porous matric material"

Type: Theta-probe

Size: 215 mm long, 40 mm dia.

Range: 0kPa to –2.5MPa (standard probe range is –1.0MPa)

- Pressure equalisation 6 kPa/hour
- Unsuitable for use in saline soils
- Mahler *et al* (2004) report that the equitensiometer shows agreement with a high-suction tensiometer to -300kPa
- Ireson *et al* (2005) shows that the Equitensiometer cannot be used for low suctions (less than –10kPa). Comparisons with tensiometer data between –10kPa and –80kPa correspond reasonably well, but there may be some hysteresis in the sensor

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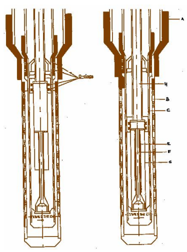
Filter paper measurements in the field



Greacen *et al* (1987) described equipment for field measurement using filter paper. Campbell and Gee (1986) identified a number of sources of error (equilibration time, temperature differences between soil and filter paper)

Field probe for filter paper measurements developed by Crilley *et al* (1991). Based on non-contact (total suction) measurement. Used in studies in UK and Kenya (Kihuha, 1990; Gourley and Schreiner, 1995)

Wang and Lao (2002) developed a contact field method. Expanding rubber tube presses the filter paper against the side of a borehole

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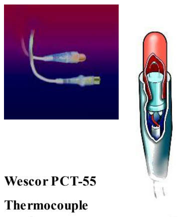
Psychrometer



Wescor PCT-55

Thermocouple psychrometer

- Temperature variation means they are not good for use in the field
- Manufacturers suggests that to maintain temperature equilibrium, the psychrometer must be buried at least 150 mm under the soil surface
- However, for a temperature variation of ± 5°C, suctions can vary as much as ± 0.5 MPa in a dry soil

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Field Measurement of Water Permeability

- Infiltrometer
- Disc Permeameter
- Guelph Permeameter
- Cone Permeameter

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Infiltrometer

Double-ring Infiltrometer

Photo: NTU

- Simple and widely used.
- Double ring infiltrometer ensures 1-D vertical flow
- Tensiometers used to observe movement of wetting front and calculate hydraulic gradient
- Sealed double ring infiltrometer needed to prevent evaporation for long term tests (Daniel & Trautwein, 1986).

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Disc Permeameter

Tension Infiltrometer

Soil Measurement Systems

- Tension disc permeameter can be used to determine near saturated permeability
- Limited to suctions of 3-5kPa
- Bubbling tower used to create negative pressure
- Nishimura *et al* (2003) report good agreement between field measurements and laboratory measurements on cores

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Guelph Permeameter

Guelph Permeameter

Photo: Molly Gribb

- Tension adapter allows measurement under suction
- Coutinho *et al* (2000) show that for a residual soil k/k_{sat} drops to 10^{-5}-10^{-12} at a suction of 20kPa
- Morii *et al* (2003) used TDR for moisture content measurement near the Guelph ring and used an unsaturated flow finite element code to back-analyse unsaturated permeability

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Cone Permeameter

Cone Permeameter

Photo: Molly Gribb

- The device has a porous filter close to the penetrometer tip and two tensiometer rings 50 and 90mm above the filter. A constant head is applied to the filter for 5-10 mins and tensiometer readings are observed during water redistribution (Simunek *et al*, 1998)
- Inverse analysis used to determine α^w, α^d, *n*, k_{sat} and k^A (k_h/k_v)
- Gribb *et al* (2004) shows that for a silty sand k/k_{sat} drops to virtually zero by suctions of 10-20kPa

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Shear Strength of Unsaturated Soils

- Effective Stress Approach (60's)
- Extended Mohr-Coulomb Approach (70's)
- Critical State Approach (90's)
- Combined Stress Approach (90's …)

Toll, D.G. (2003) *On the Shear Strength of Unsaturated Soils*, Keynote Lecture, Proc. Int. Conf. on Problematic Soils, Nottingham, UK (eds. Jefferson, I. and Frost, M.), Singapore: CI-Premier, Vol. 1, pp. 127-136.

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The Effective Stress Approach

Bishop (1959) proposed:

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

Where: $\chi = f\,(S_r)$

Which gives:

$$\tau = c' + [(\sigma - u_a) + \chi\,(u_a - u_w)] \tan\phi'$$

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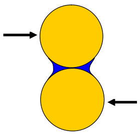
Limitations to Bishop's approach

- The function for χ was found to be different for shear strength and volume change. Therefore, σ' was not unique.
- $(\sigma - u_a)$ and $(u_a - u_w)$ were combined into a single variable even though they act differently.



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The Combined Stress Approach

$$\sigma^* = \sigma - [S_r\,u_w + (1-S_r)\,u_a]$$

(variously described as *Bishop's stress* [Bolzon et al, 1996] or *average soil skeleton stress* [Jommi, 2000])

$$\sigma^* = \sigma - u_a + \frac{v_w}{v}(u_a - u_w) \qquad \text{[Murray, 2002]}$$

where v_w is specific water volume = $[1 + S_r(v - 1)]$
v is the specific volume (1+e)

Other examples by:
- Kohgo et al (1993)
- Karube et al (1994, 2001)

The use of a combined stress is not the same as using an "effective" stress. We still need to use suction as an additional variable to describe soil behaviour

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The Extended Mohr-Coulomb Approach

Fredlund *et al* (1978) proposed:

$$\tau = c'' + (\sigma - u_a)\tan\phi^a + (u_a - u_w)\tan\phi^b$$

Assumed: $\phi^a = \phi'$
$c'' = c'$

Which gives:

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

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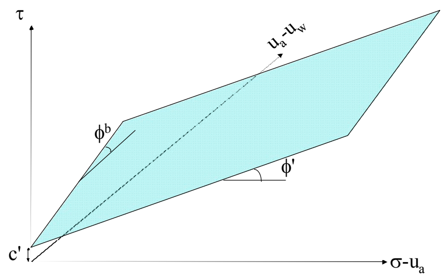
Extended Mohr-Coulomb Failure Envelope



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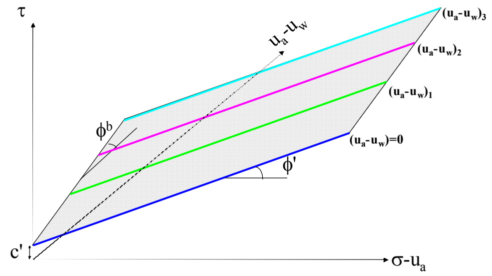
Extended Mohr-Coulomb Failure Envelope



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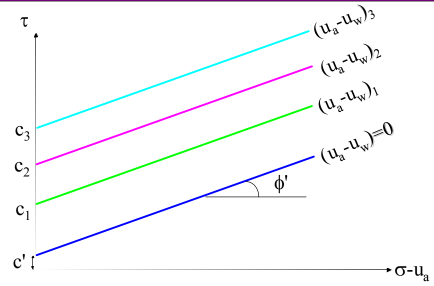
Net stress (σ-u_a) plane



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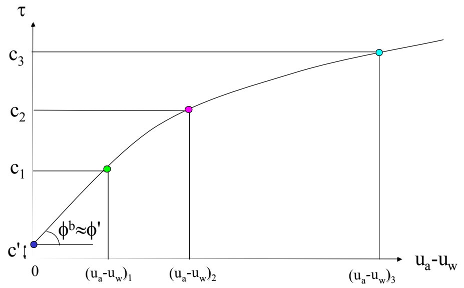
Matric Suction (u_a-u_w) plane



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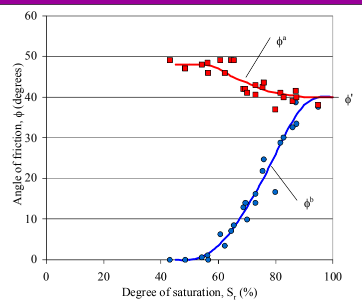
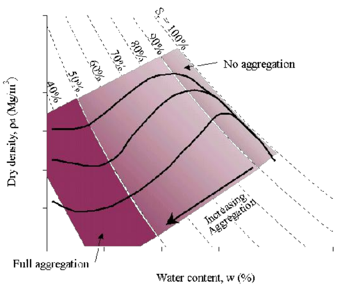
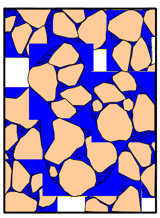
Variation of angles of friction



Toll, D.G. (2000) *The Influence of Fabric on the Shear Behaviour of Unsaturated Compacted Soils*, in Advances in Unsaturated Soils (eds. C. Shackleford, S.L. Houston and N-Y. Chang) Geotechnical Special Publication No. 99, Reston: American Society of Civil Engineers, pp 222-234.

Aggregated or 'Packet' fabric





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Conclusions

- Understanding suction and its role is vital for unsaturated soil behaviour. The matric suction component is most important for understanding shear strength, but osmotic suction is important for volume change
- New devices for direct measurement of suction (in the lab. and field) will make more measurements possible which will add greatly to our understanding of unsaturated soils
- The shear strength of unsaturated soils can be explained by separate stress state variables of net stress and matric suction
- The fabric of unsaturated soils has a significant effect on the engineering behaviour (more-so even than in saturated soils)

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