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Effects of Soil Suction on Resilient Modulus and Pavement Design

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Topics

1. Soil suction – soil movements
2. Resilient modulus (M_R)
3. M_R and Soil suction
4. Predictive models for M_R
5. Australian research
6. Conclusion / future work

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1. INTRODUCTION

- Clay soils expand or shrink as moisture is gained or lost
- Soil make-up and clay mineralogy impact on the rate of movement
- So too does the soil mass structure

  - shrinkage cracking in particular

- "Suction" better identifies soil desiccation than moisture content

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1.1 Soil Suction - introduction

- Soil suction = affinity for water
- Dry soils soak up water like a dry sponge
  = matric suction, u_m
- Matric suction = capillary action + particle attraction
- Fine soils have tremendous capillary potential due to small voids
- Saline soils attract water (osmosis)
  = solute suction, u_s

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Soil Suction - intro cont'd

- Desiccation = increase in total *or* matric suction
  - *solute suction increases **if** salts remain, since salt concentration increases in pore fluid*
- Recent theory re unsaturated soil behaviour has concentrated on matric suction
- Solute suction can provide significant total suctions even when the soil is almost saturated (+1MPa)
- Matric suction dominates seasonal suction change

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Soil Suction

- Matric suction is expressed as the difference between pore air, u_a, and pore water pressure, u_w (pore water is in tension), i.e. $(u_a - u_w)$
  - *Saturated soil*, $u_m = 0$
- Suction related to effective stress?

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

χ = proportion of water in the voids

χ = 0 for dry soil and 1 for saturated soil

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Soil Suction

- Khalili & Khabbaz 1998 gave empirical estimates of variation of χ based on ratio of u_m to AEV
  - AEV = value of suction when air enters the soil during drying
  - Requires determination of the Soil Water Retention Curve or SWRC

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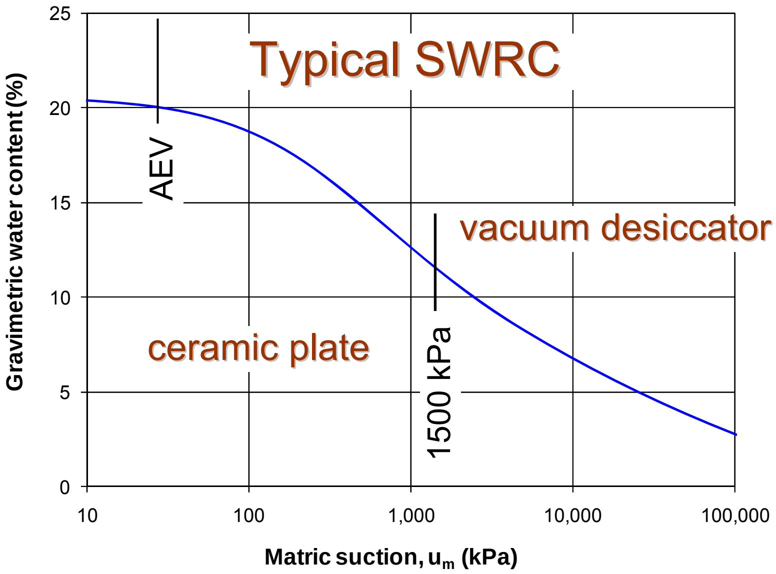

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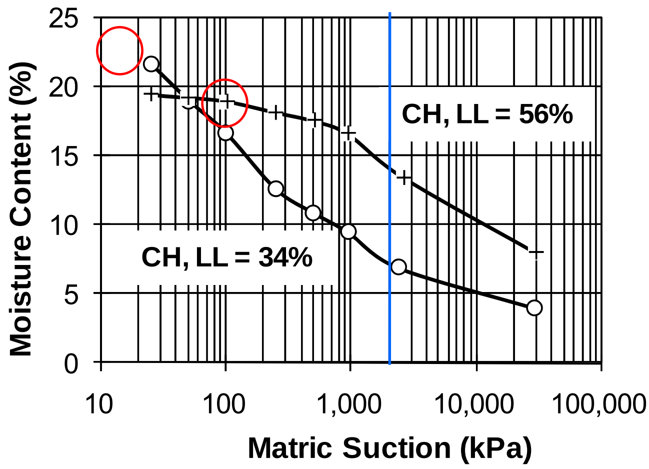
Examples of SWRC's



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Drawbacks of SWRC

- Initial saturation process
- Curves can take +3 months to generate
- Volume changes should be measured
- Highly plastic clays (“expansive clays”) difficult to work with and interpret

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Units of suction

- Pressure - kPa or MPa
  - Field maximum usually 10 MPa
- Log of suction has been shown to be best for correlations with most soil properties
- Old pF unit:
  - $Log_{10}(u\ (kPa)) + 1.01$
  - Field maximum usually 5 pF
  - Field total suction minimum > 3 pF (100 kPa)

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Routine measurement of suction

- UniSA, Wescor Dew Point Hygrometer
  - Relative Humidity (RH) approach
  - Measures **total suction**
  - RH of small air space in equilibrium with sample reflects soil suction level
  - Dew point temperature more reliable than RH
  - High relative humidities usually 95-100%
  - Constant temperature room and careful operators

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Wescor dew point hygrometer

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Routine measurement of suction

- To estimate matric suction, need to measure solute suction
- Electrical conductivity measurements of solutions
  - One week of readings
  - Simple measurement, EC proportional to u_s
  - Correct for water content
  - Does not indicate types of salt - can lead to errors
- Alternatively try filter paper technique

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1.2 Suction and soil movement

- AS2870 pragmatic approach to estimating soil movements
- Shrinkage index, I_{ps}, is the rate of vertical strain of soil subjected to a pF change in total suction
  - Assumes little influence of load
  - Soil is laterally unrestrained
- I_{ps} adjusted before estimating movement to account for:
  - increasing overburden & lateral restraint with depth

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Suction and soil movement

- I_{ps} from Shrink-Swell testing?
  - simple equipment
  - no suction measurement
  - one week to test
  - full range of moisture change – wetting & drying
  - larger sample
  - empirical derivation

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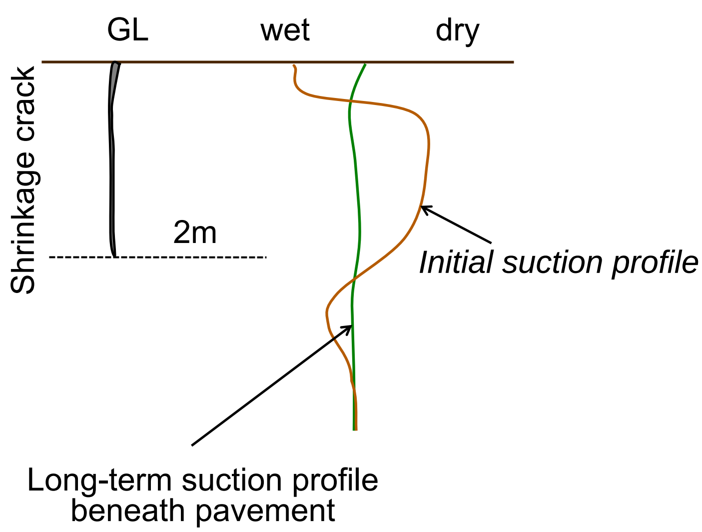
Total Suction profiles



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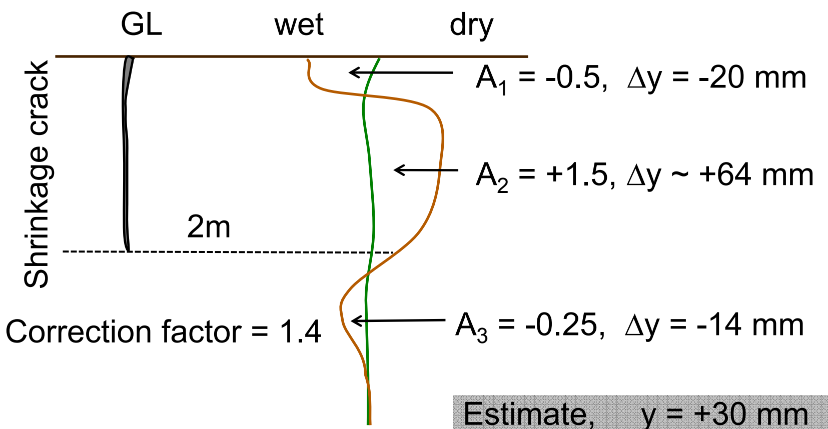
Movement Estimate for Ips = 4 % per pF



Estimate, y = +30 mm heave

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1.3 Suction and soil strength

- Fredlund, Vanapalli, Xing and Pufahl (1995)

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

- tan ϕ^b concept OK until a threshold suction reached – thereafter, lower rate of strength increase

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Resilient Modulus

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Modern Pavement Design

Subgrade Deformations:

elastic & permanent

1. Resilient modulus, M_R
   - elastic strains under cyclic loading
2. Permanent strains?
   - Frost et al. 2005 – permanent strains accelerate after reaching a deviator stress level

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Permanent strains?

$$\varepsilon_p = AN^b$$

where $$A = a\left(\frac{\sigma_d}{\sigma_s}\right)^m$$ (Li & Selig 1998)

where σ_s = static unconfined compressive strength

(Li & Selig 1998)

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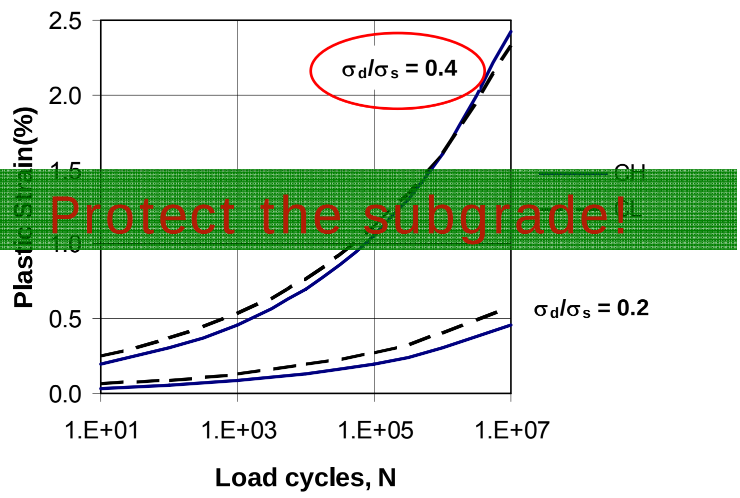
Permanent strain estimates



Protect the subgrade!

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2. Resilient modulus, M_R

cyclic deviator stress

$$M_R = \frac{\sigma_d}{\varepsilon_{vr}}$$

cyclic resilient strain

σ_3 = constant

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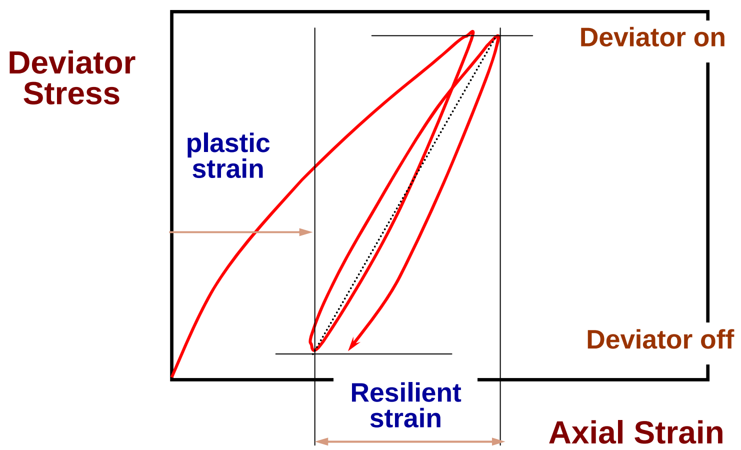
Resilient Modulus



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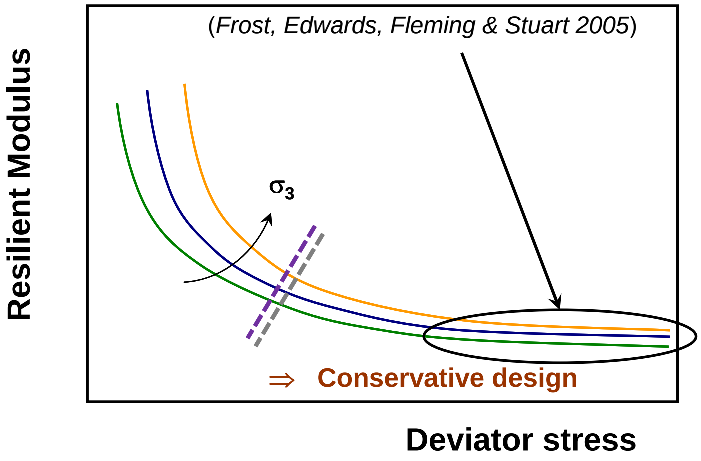
Resilient modulus of clay soils

M_r decreases with σ_d to an "asymptotic value"



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M_R & Moisture Content, w

- Res Mod varies non-linearly with w
- Res Mod of compacted samples varies with density & moisture state (*relative to OMC*)
- Soil ***plasticity*** also contributes: $M_R = fn(w/PI)$

Edwards, Frost & Thom (2005) – PI = Plastic Index

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3.1 M_R & Matric Suction, u_m

Compacted samples, **unconfined** M_R

I. Richards (1968) $M_R \propto \sqrt[3]{\sigma'}$

→ *M_R increase greatest for changes of u_m from wet to moist*

Soil strength – similar observations

Fredlund, Vanapalli, Xing & Pufahl (1995)

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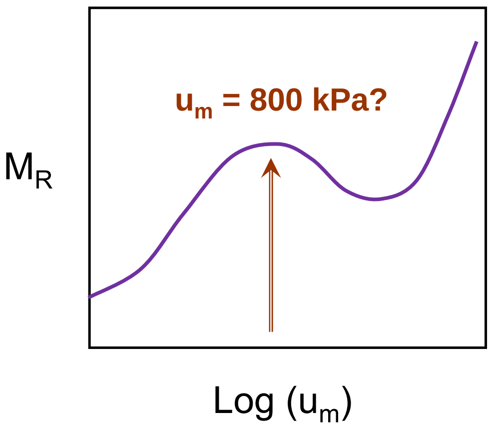
(II) Edil & Motan 1982
- *unusual result*



3.2 M_R & Total Suction, u_T

- $M_R \propto \log(u_T)$
  - compacted samples, constant dry density

    Phillip & Cameron (1995)
- $M_R \propto u_T$
  - compacted Kirkland soil

    Khoury & Zaman (2005)

4. Models for Prediction of M_R

4.1 Models based on stress

$$M_R = K_o \left(\frac{\sigma_m}{p_a} \right)^{k_1} \left(\frac{\tau_{oct}}{\tau_{ref}} \right)^{k_2}$$

May & Witczak (1981)

p_a = *atmospheric pressure*

Octahedral shear stress ratio

AASHTO 2002 Model

Large database - statistical analysis

$$M_R = k_1 p_a \left(\frac{\sigma_m}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

- constants = *fn*(mc, density, compaction parameters, psd & other soil indices)
- k_2 not dependent on moisture content

4.2 M_r models with suction

1. M_R = linear *fn* of (σ_d , u_m & PI)

- Brown (1996)
- 3 remoulded clays, M_R to 80 MPa

2. May & Witczak equation modified

- Phillip & Cameron (1995)
- K_o, k_1 & k_2 = *fn*(log(u_T))
- 2 remoulded clays

5. RECENT RESEARCH

- Poorly-drained clay subgrades are weak & will settle under repeated loading
- Recent research on rail formations on expansive soils

  Rail Cooperative Research Centre for Railway Engineering & Technologies Project 86

  Funding ended in 2007

OVERVIEW – cont'd

- Phillips & White 2002 - *ballast collects and retains moisture, wetting the subgrade on poorly drained sites*
- Potter & Cameron 2005

  - *demonstrated the detrimental effect of moisture on clay subgrades (Victoria and Queensland)*

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Initial Objective Project 86

- Maintenance engineers had noticed less track/ballast maintenance near treed areas, **Melbourne-Adelaide line**
- 3 problem site areas identified where vegetated & non-vegetated sections could be compared
- 4th site chosen in central Queensland
- Sampling and testing program over seasons

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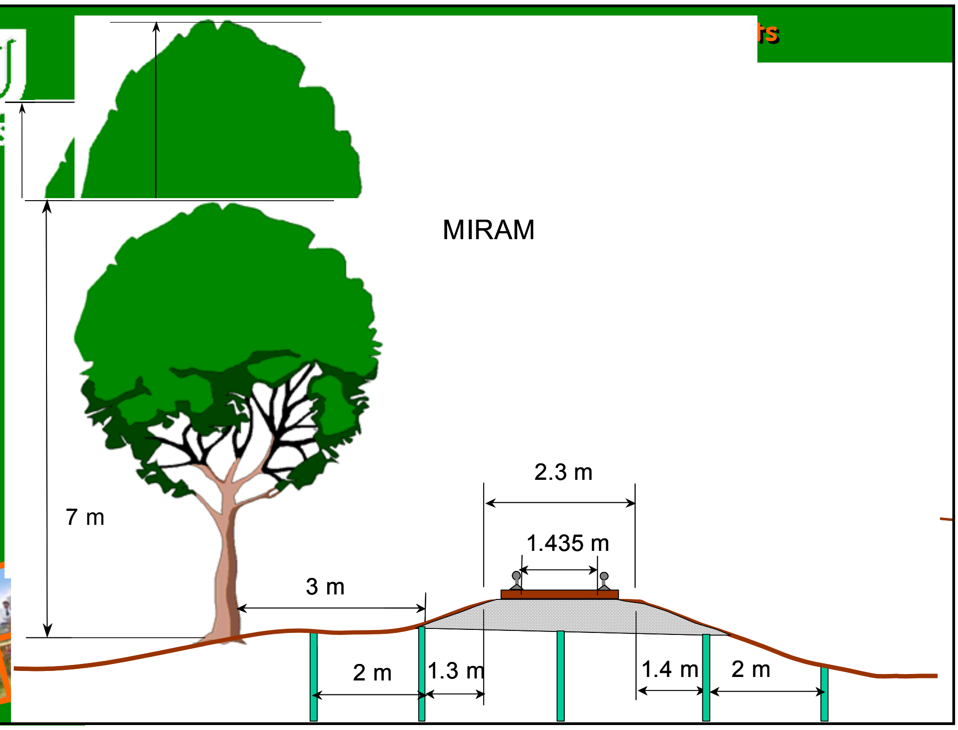

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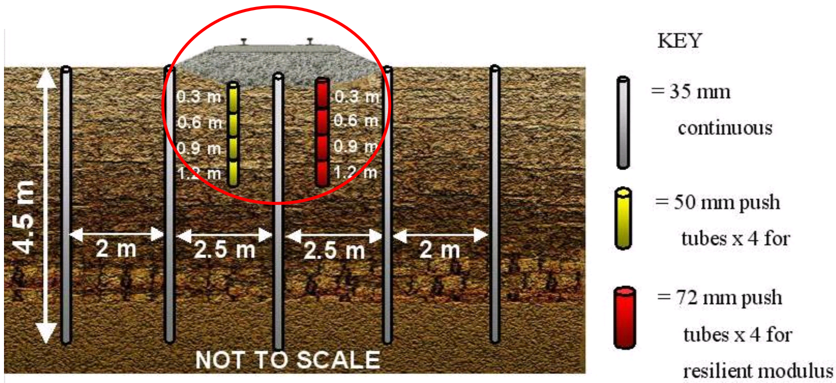
Sampling Scheme:

vegetated & non-vegetated sites



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pneumatic cyclic triaxial device

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Comparison: companion sites

- sampling over wet & dry periods
- non-vegetated sites considerably wetter
- consequently, lower shear strengths & M_R values
- Emerald site (Qld) less clear
  – high aridity, high suctions

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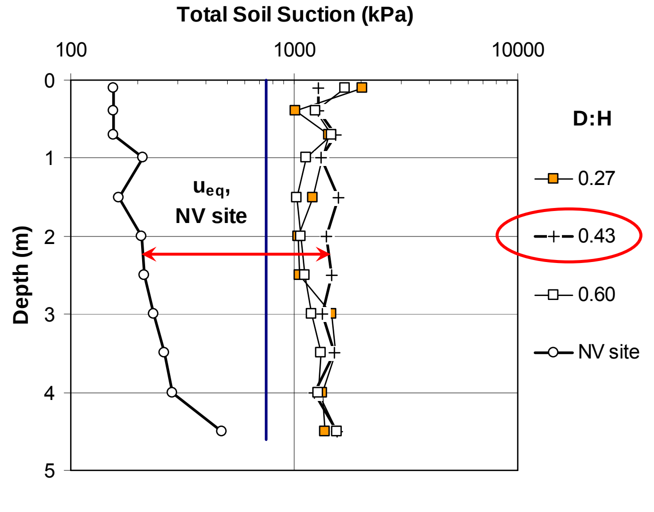
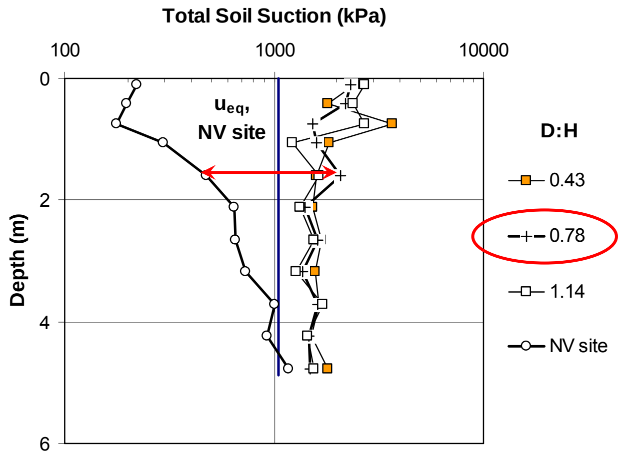
Horsham (dry) – total suctions



Miram (dry) – total suctions



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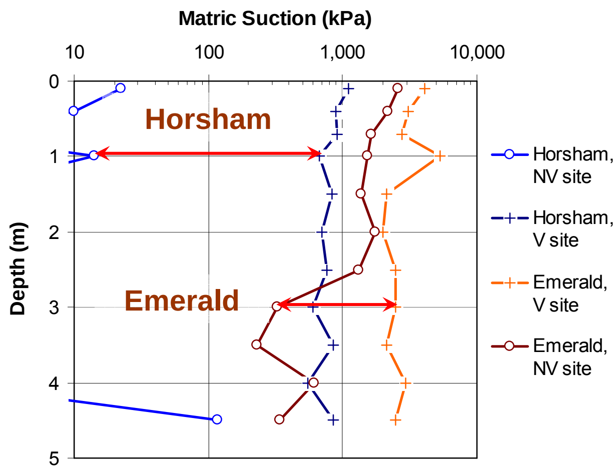
Matric suctions – track centres



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Impacts on Soil Properties (wet)

Site	τ_{50} (kPa)	
	Non-vegetated	Vegetated
Miram	13 - 25	74 - 432
Horsham	**13 - 17**	**43 - 53**
Wal Wal	49 - 80	61 - 238

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Impacts on Soil Properties (wet)

Site	$M_{r\ asymptote}$ (MPa)	
	Non-vegetated	Vegetated
Miram	24 - 41	174 - 347
Horsham	**22 - 27**	**61 - 118**
Wal Wal	22 - 58	86 - 271

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5.2 Review of M_R data

- "**Asymptotic**" modulus, "**undisturbed**" samples
- More data from Miram & a new site in Queensland
  - *no **shear strengths** – unconfined compression strengths instead, performed on res mod samples*

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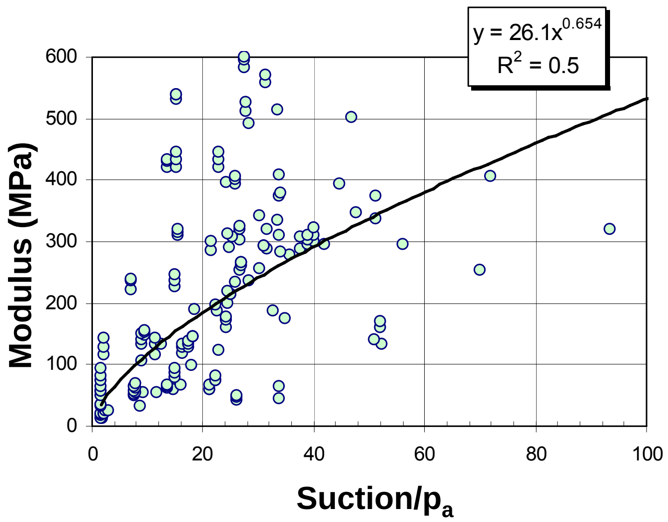
$M_{R\ asymptote}$ v suction, u_T



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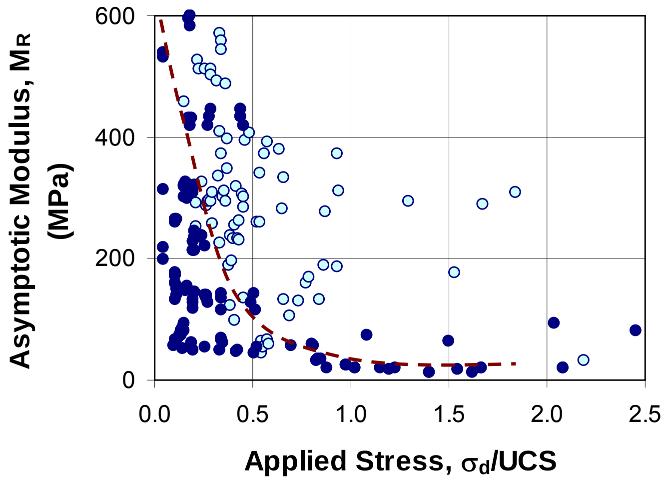
M_R *asymptote* & shear stress level



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Prediction of $M_{R\ asymptote}$

- Simple format based on stress level & suction (*Cameron & Potter 2008*)

$$M_{R-as} = 960\left(\frac{UCS}{\sigma_d}\right)^{0.012} + 22\left(\frac{u_T}{p_a}\right)^{0.574} - 944$$

- Design estimate for M_R < 300 MPa

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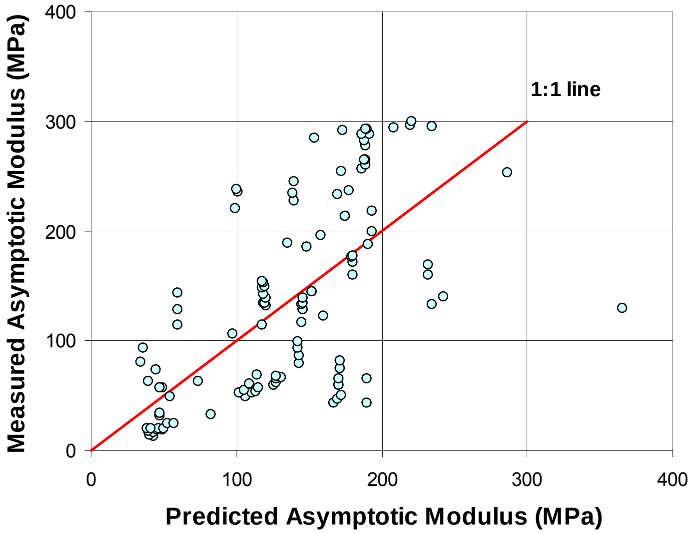
First design estimate?



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Incorporation of soil plasticity

- Since *Cameron & Potter 2008*, further Atterberg Limit testing conducted to enable a review of the influence of soil plasticity
- Liquid Limit (LL) chosen
  - Plastic Index less successful

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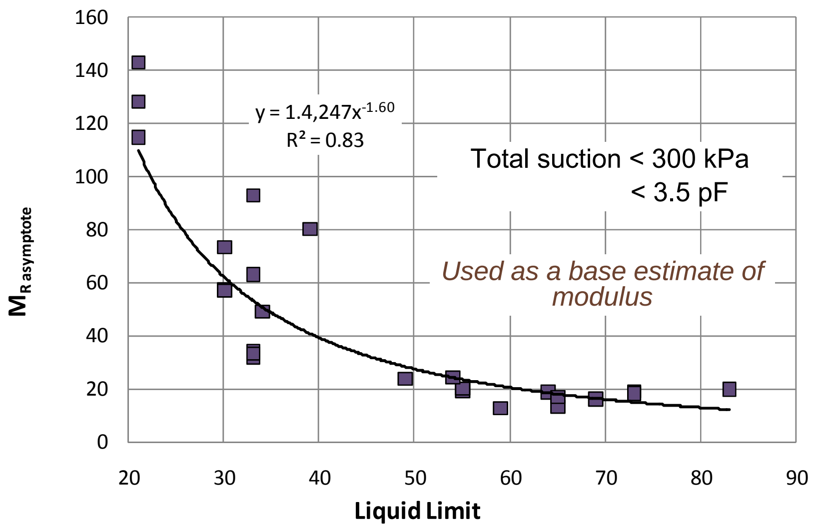
Plasticity effect on wet soils



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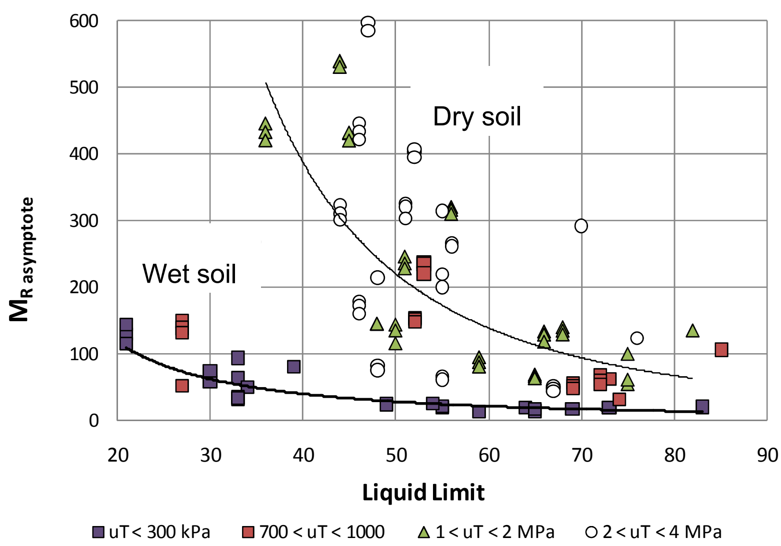
Plasticity effect overall



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Revised correlation (1)

for M_R < 300 MPa

$$M_R = 14{,}250\left(\frac{1}{LL}\right)^{1.6} + 49.6\left(\log\left(\frac{u_T}{p_a}\right)\right)^{2.12} + 290\left(\frac{UCS}{\sigma_d}\right)^{0.063} - 286$$

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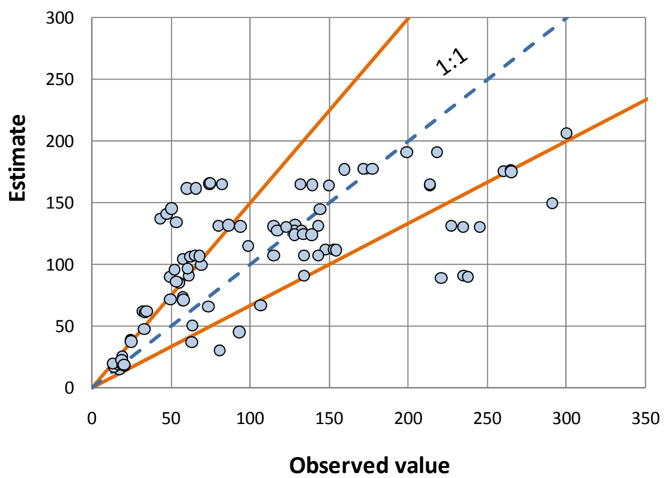
Revised correlation (1)



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Correlation 2

for M_R < 300 MPa

Combined effects of suction & stress level in power functions added to base estimate for “wet soils”

$$M_R = 14{,}250\left(\frac{1}{LL}\right)^{1.6} + 59\left(\log\left(\frac{u_T}{p_a}\right)\right)^{1.41}\left(\frac{UCS}{\sigma_d}\right)^{0.21}$$

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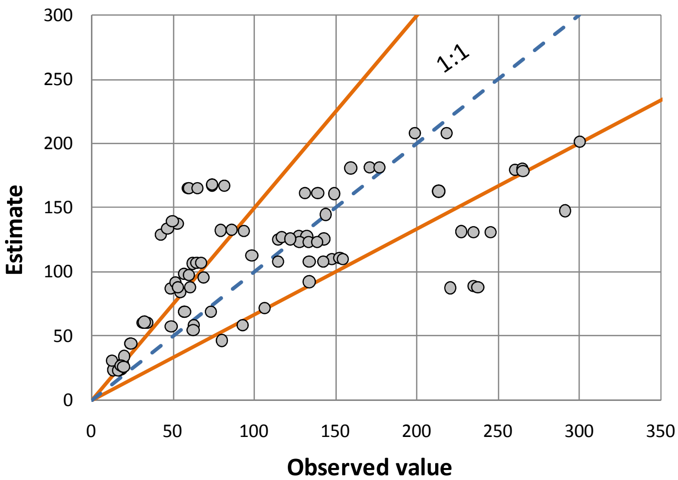
Correlation (2)



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Discussion

- Neither equation permits M_R to exceed 210 MPa, although observed values reached 300 MPa
- However, some over-prediction evident at low levels of observed modulus
- Correlation 1 suggests deviator stress to UCS ratio is not so important: negligible if >1, may gain 45 MPa if ratio drops to 0.1 *– should be low!*

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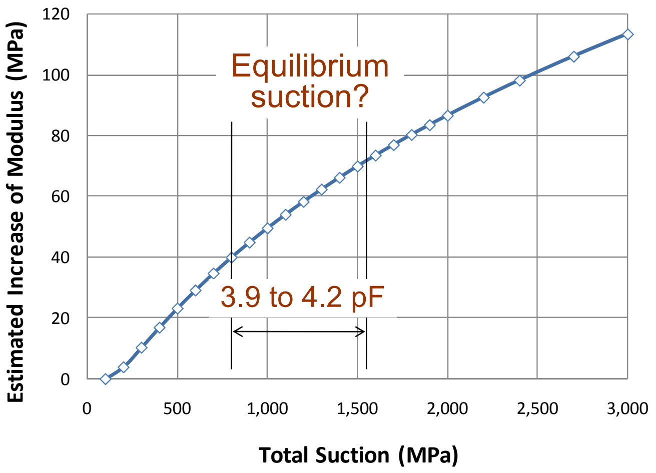
Correlation 1 – effect of suction



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5.3 Impact on Pavement Design

- Pavements undergo moisture changes
  - Edges most vulnerable to seasonal moisture change
  - Centre should reach equilibrium with shallow water table or deep suction values
- High plasticity subgrades are not easily avoided
- M_R = 10 CBR and soaked CBRs lead to quite conservative design values, i.e. < 100 MPa

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6. SUMMARY

- Designers should be conservative in their approach to choosing resilient modulus from triaxial test data
  - asymptotic modulus may be appropriate
- Soil suction has a significant impact on M_R
  - effective stress theory not easy to apply, however
- Prediction of M_R of undisturbed clays is complex
  - shear stress ratio, suction & plasticity all have influence
  - equations presented to predict $M_{R\ asymptote}$ to 210 MPa

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Thank you for your attention