The mechanics of unsaturated soils and tailings

With comments on practical applications

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Adrian R. Russell

Professor
ARC Future Fellow

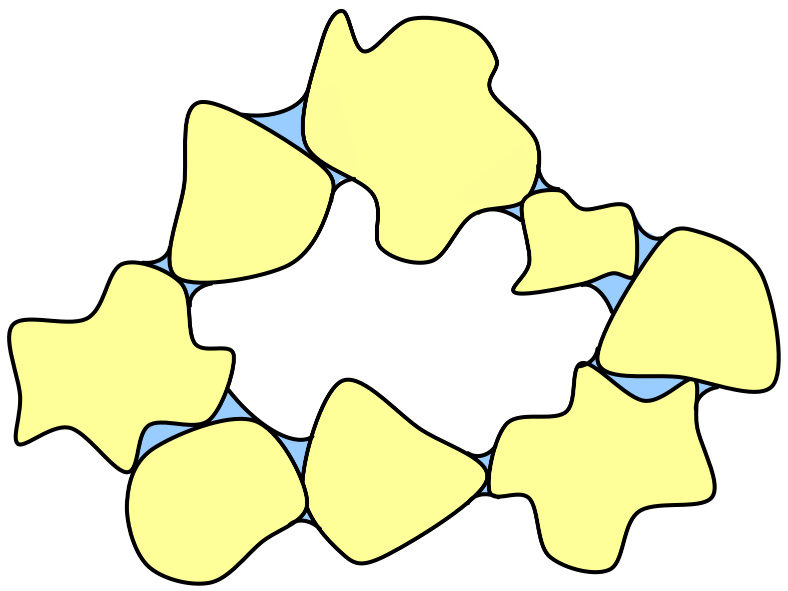
Part 1: Basic concepts

- An unsaturated soil or tailings has a mixture of air and water in the pore space.

$$S_\mathrm{r} = \frac{V_\mathrm{air}}{V_\mathrm{air} + V_\mathrm{water}} \qquad 0 < S_\mathrm{r} < 1$$

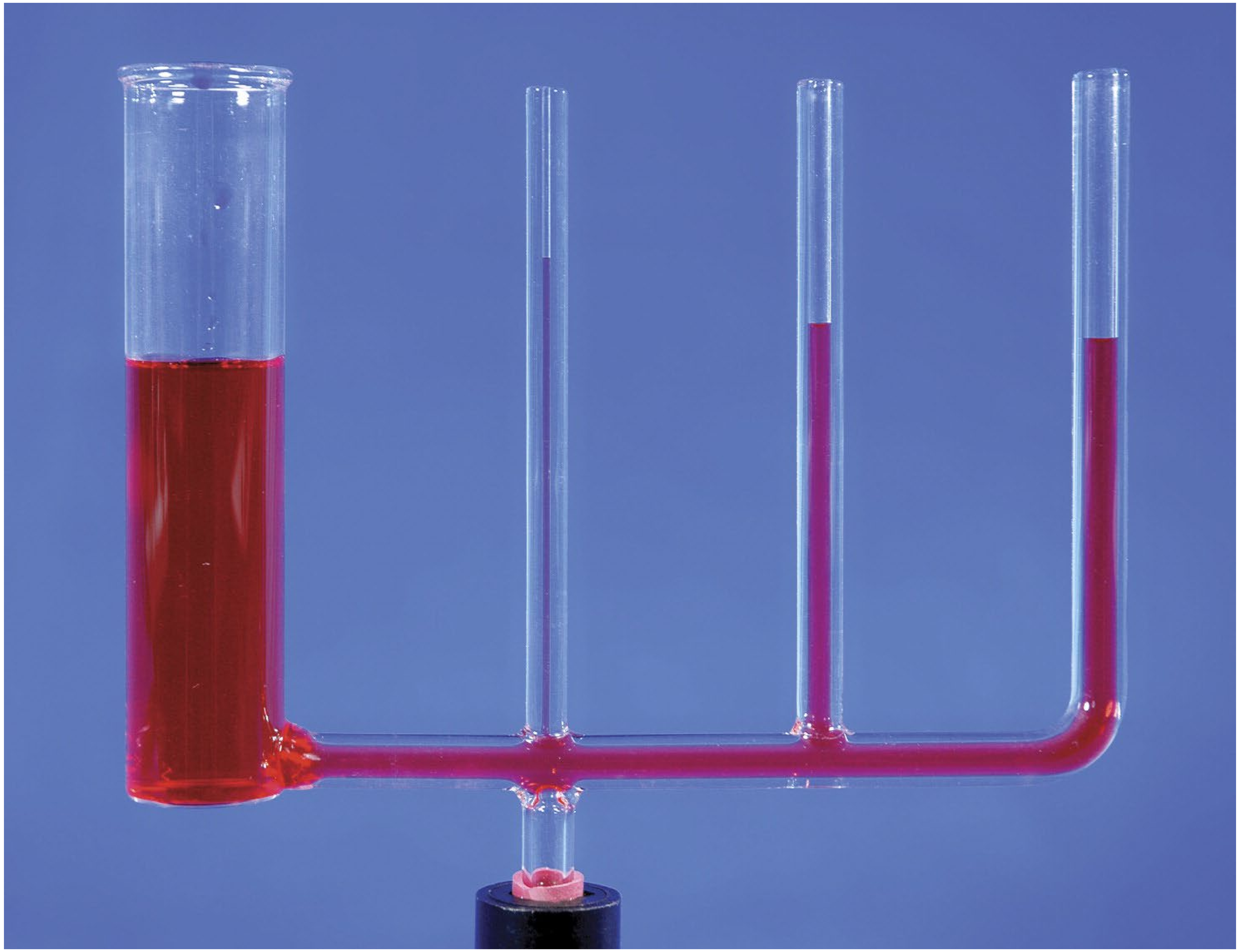
- Water accumulates at the grain contacts.
- Capillary action makes the water go in to tension and pulls the particles towards each other. This is called suction.
- Particle contact forces increase, so does the effective stress σ' and strength τ.

$$\tau = c' + \sigma' \tan\phi'$$



Strength is increased due to suction (capillary forces). A collapsible structure may exist.

$$s = u_a - u_w$$



$$u_{\mathrm{w}} = \lambda_{\mathrm{w}} h_{\mathrm{w}} = -\frac{4T\cos\theta}{d}$$

T = water surface tension, θ = contact angle between water and tube, d = tube diameter

Effective stress

- The effective stress is important

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

χ = effective stress parameter
χ = 0 for dry soil/tailings
χ = 1 for saturated soil/tailings
0 < χ < 1 for unsaturated soil/tailings
$\sigma_{net} = \sigma - u_a$ = net stress (total stress in excess of the pressure datum u_a, usually u_a = atmospheric pressure = 0)

- For dry:

$\sigma' = \sigma - u_a = \sigma$ (effective stress = total stress, u_a = 0 usually applies)

- For saturated:

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

- For unsaturated:

$$\sigma' = \sigma + \chi s \qquad s = u_a - u_w$$

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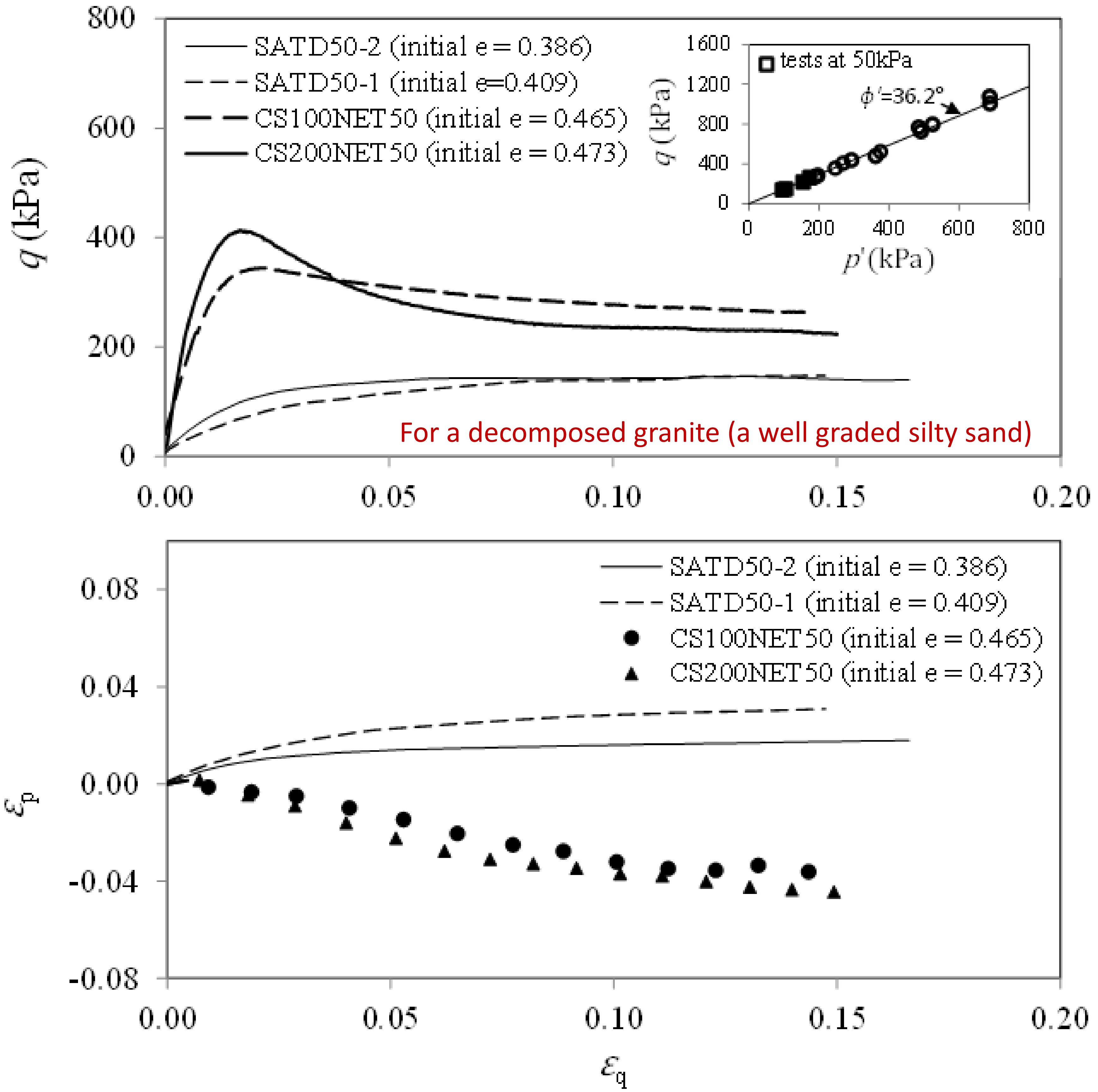
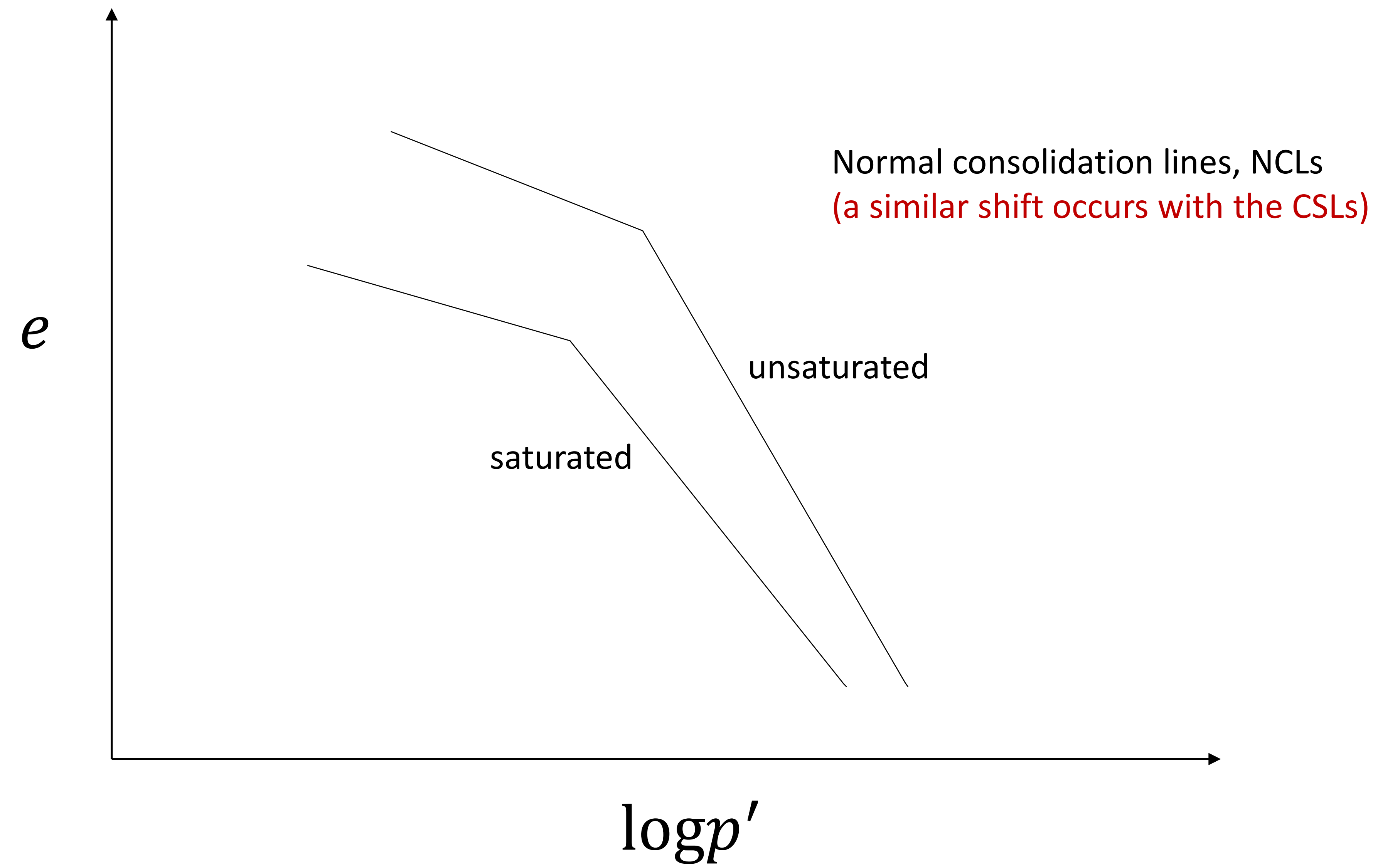
Strength

- c' and ϕ' are suction independent at the critical state (softened) condition, as long as suction's contribution to effective stress (χs) is correctly determined (critical state data points shown in the inset to the figure opposite)
- c' and ϕ' at peak strength (small strains) may be slightly larger for unsaturated conditions compared to saturated/dry conditions. The difference depends on soil or tailings type. In general:
  - For sand/silt/clay mixtures, and most tailings, ϕ' is 2º to 6º larger for unsaturated conditions compared to saturated conditions
  - For sand, the same ϕ' applies to saturated and unsaturated conditions
- The difference of ϕ' at peak strength arises due to a phenomenon known as suction hardening. Suction shifts the NCL and CSL leftwards in the $e - \log p'$ plane, making the soil/tailings behave as though it is more overconsolidated when unsaturated.

$$\tau = c' + \sigma' \tan\phi'$$

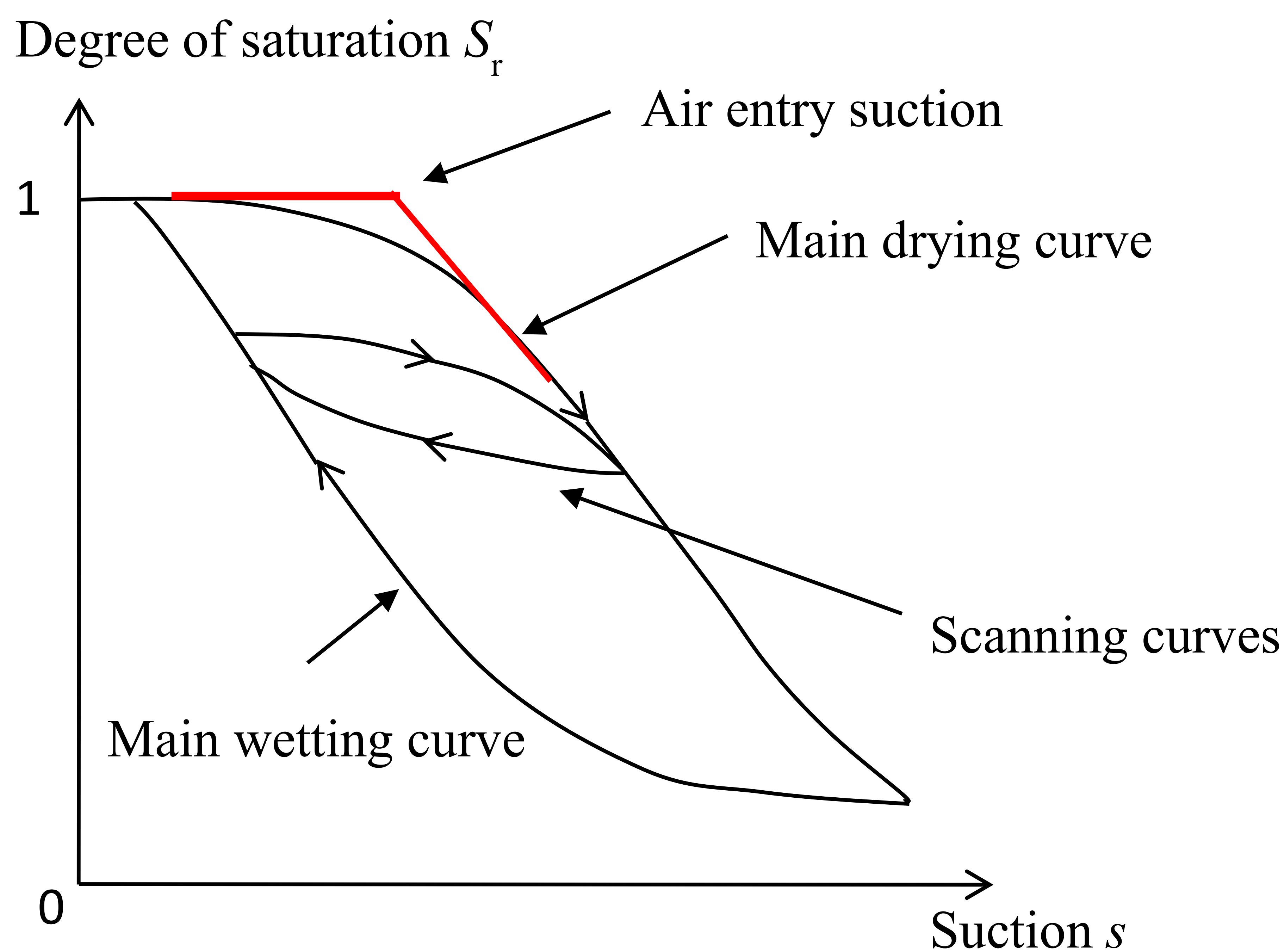


Strength increase due to suction hardening



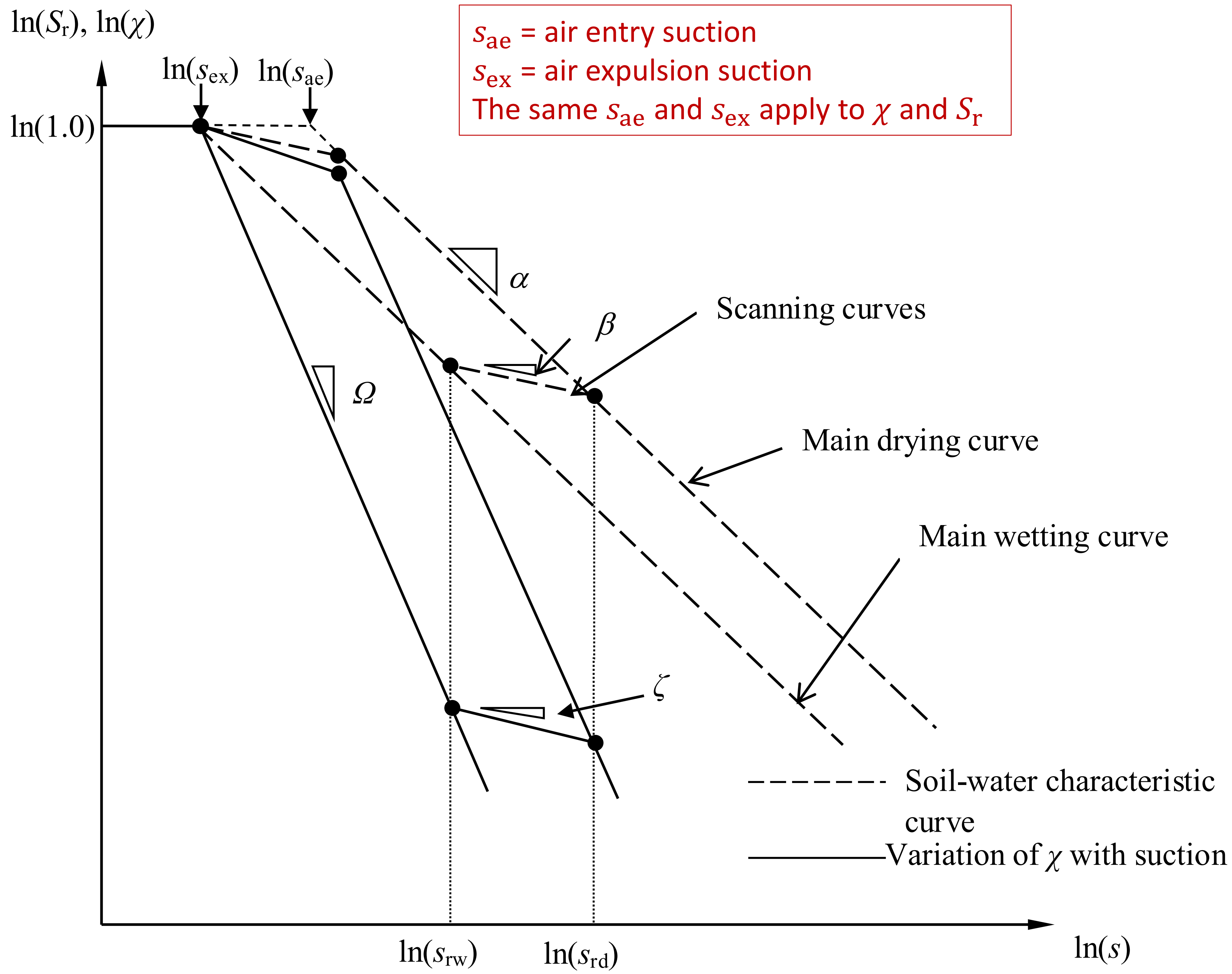
Determining χs for strength and stability problems

Water retention properties are important



We call this a water retention curve (WRC) or soil water characteristic curve (SWCC)

s_{ae} = air entry suction
s_{ex} = air expulsion suction
The same s_{ae} and s_{ex} apply to χ and S_r



$$S_r = \begin{cases} 1 & \text{for} \quad s \le s_e \\ \left(\frac{s}{s_e}\right)^{\alpha} & \text{for} \quad s \ge s_e \end{cases}$$

s_e is either s_{ae} or s_{ex}

$$\chi = \begin{cases} 1 & \text{for} \quad \frac{s}{s_e} \le 1 \\ \left(\frac{s}{s_e}\right)^{\Omega} & \text{for} \quad \frac{s}{s_e} \ge 1 \end{cases}$$

Typical values:

Ω = -0.55,
α = -0.25 to -0.85,
β = 0.08α to 0.33α,
ζ is determined using the compatibility requirement $\frac{\alpha}{\beta} = \frac{\Omega}{\zeta}$.

D_s = fractal dimension of the particle size distribution. Typical values lie between 2.2 and 2.8.

C_1 = 4 kPa to 5500 kPa.
C_2 = 0.125 to 0.0002.

Void ratio dependence is captured through s_{ae} and s_{ex} in well-graded (fractal) materials

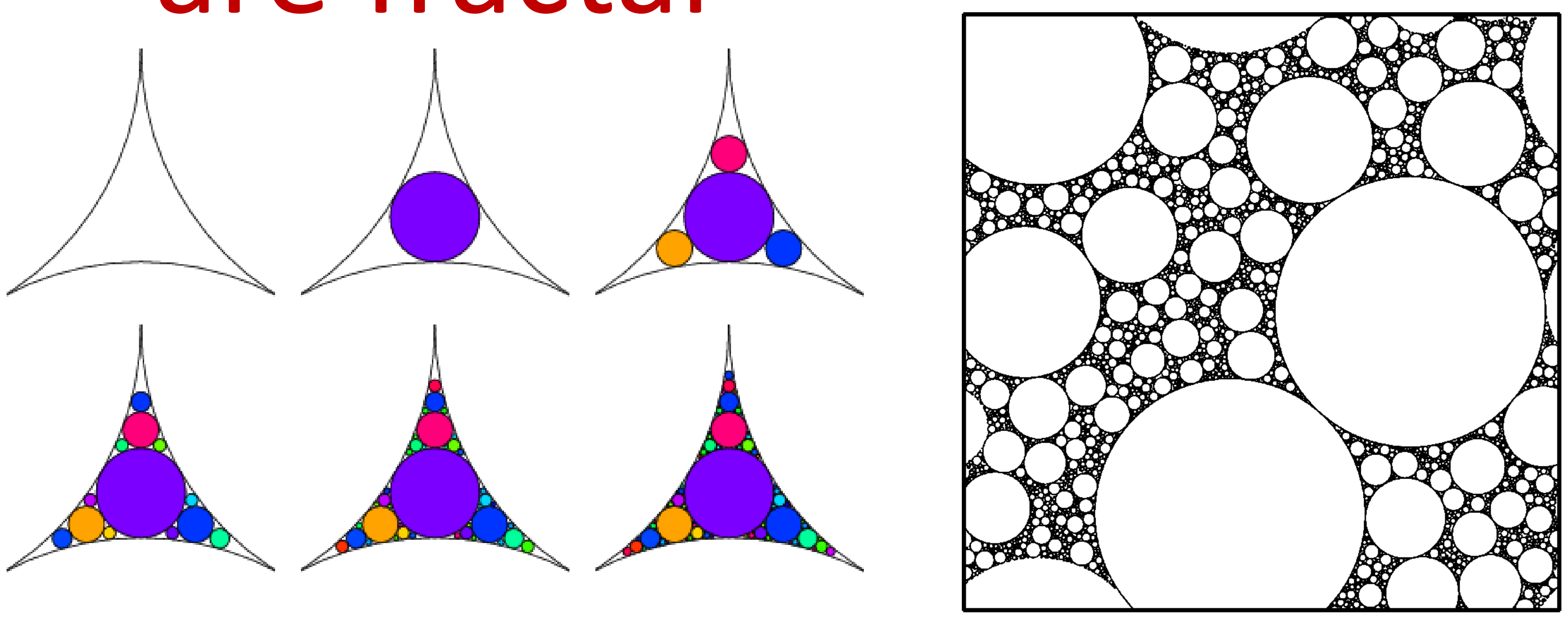
$$s_{ae} = C_1 e^{-D_s} \qquad s_{ex} = C_1 C_2 e^{-D_s}$$

Leads to a simple expression for χs in terms of e and ω (gravimetric water content)

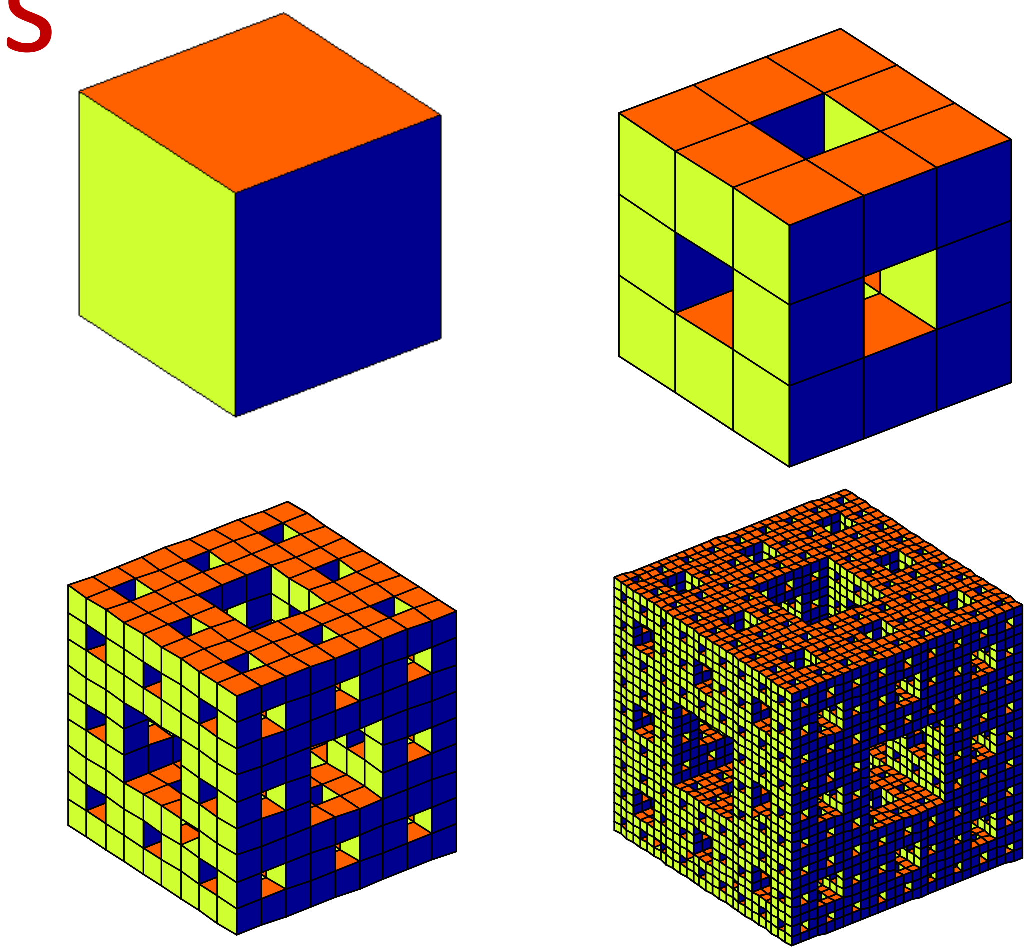
$$\chi s = C(G_s \omega)^{(1+\Omega)/\alpha} e^{-D_s-(1+\Omega)/\alpha}$$

$C = C_1$ if on main drying, $C = C_1 C_2$ if on main wetting

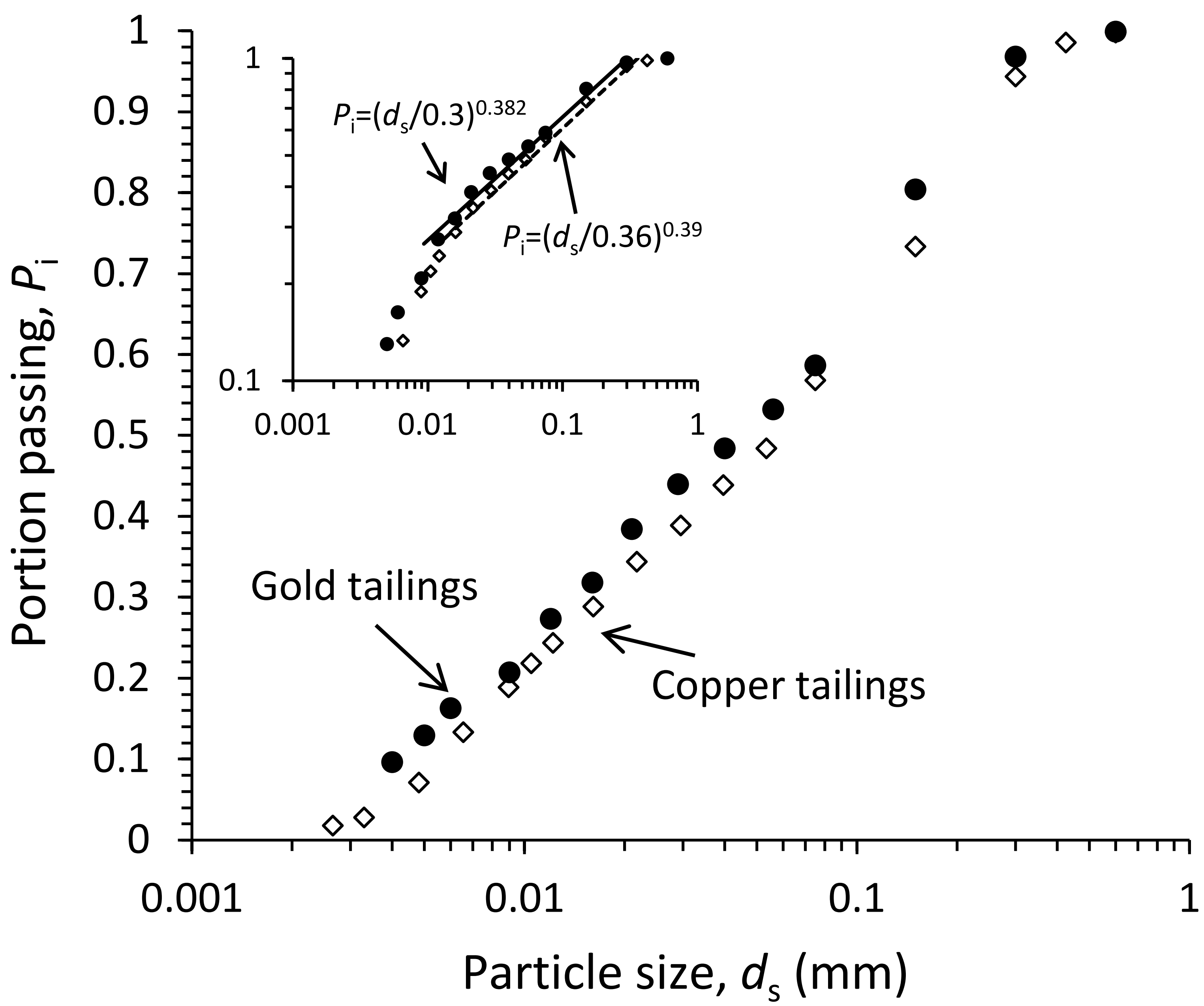
Fun fact: Many soils and tailings are fractal



Apollonian packing



Menger sponge

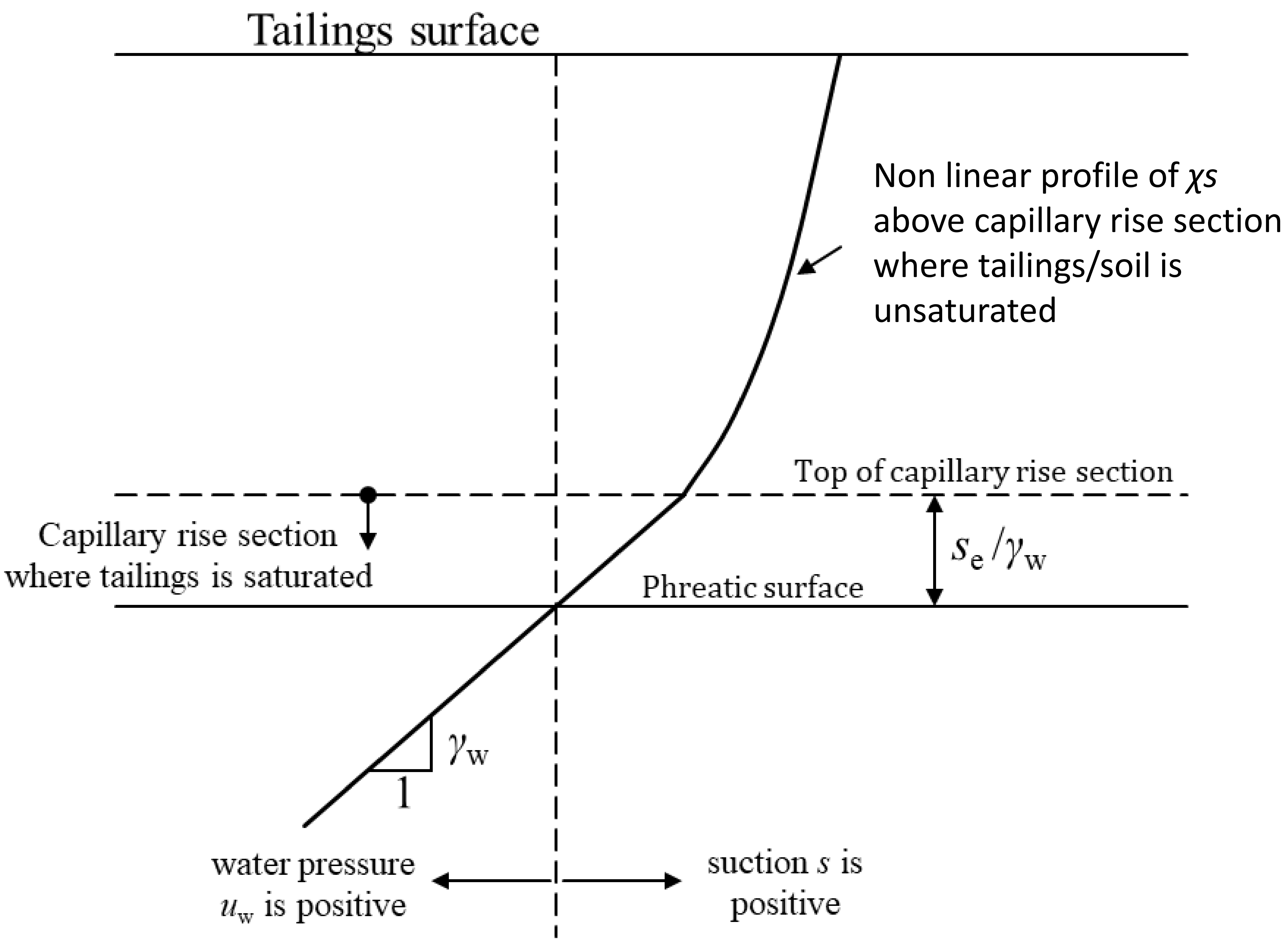


Particle size distributions for gold tailings and copper tailings. When fractal, data plotted in a double logarithmic plane (inset) will be linear and have a slope (or exponent of the fitted power law to the linear section) that is $3\text{-}D_s$, where D_s is the fractal dimension of the distribution. D_s is 2.618 for the gold tailings and 2.61 for the copper tailings

χ and S_r

- χ, S_r, s_ae and s_ex depend on soil/tailings density and type and moisture content
- s_ae and s_ex increase as pore sizes reduce (i.e. as soil/tailings becomes finer and denser)
- Typically:

  s_ae = 1 kPa to 8 kPa for a clean sand/tailings
  s_ae = 1 kPa to 100 kPa for a soil/tailings that is a sand-silt mixture
  s_ae = 10 kPa to 10MPa for clay rich soil/tailings



Variation of water pressure u_w and χs relative to phreatic surface and capillary rise section

Part 2: Applications

- Relevant codes
- Policy and industry changes
- What industry is doing
- Incorporating suction in to strength and stability problems
- Examples in the Civil sector
- Examples in the Mining sector
- Key messages

Relevant code: Residential slabs and footings (AS2870)

- A characteristic surface movement y_s is determined and controls footing depths

$$y_s = \frac{1}{100}\sum_{n=1}^{N}\left(I_{pt}\ \overline{\Delta u} h\right)_n \qquad \text{. . . 2.3.1}$$

where

y_s = characteristic surface movement, in millimetres

α = lateral restraint factor (see Clause 2.3.2)

I_{pt} = instability index, in %/picofarads (pF) (see Clause 2.3.2)

$\overline{\Delta u}$ = soil suction change averaged over the thickness of the layer under consideration, in picofarads (pF)

h = thickness of layer under consideration, in millimetres

N = number of soil layers within the design depth of suction change

- $\overline{\Delta u} = \log_{10}(s_2/s_1)$ (typical values recommended for different regions and soil types, maximum of 1.2 across soil depth where suction change occurs [95% exceedance probability in design life – not extreme case])
- $I_{pt} = \alpha \frac{(\varepsilon_{sw}/2+\varepsilon_{sh})}{1.8}$ (ε_{sh} = axial strain during free shrinkage, ε_{sw} = axial strain in 1D swell, 1.8 = typical suction ratio of 63 in dried [wilting point] and wetted [near saturated] states in field in which most volume change occurs)
- Correctly acknowledges total suction is the sum of osmotic and matric
- Implies an equal change of osmotic and matric would give the same soil volume change. **This is completely wrong for most soils. If it is true (approximately) for Adelaide clays then we don't know why (yet)**

Recent policy and industry changes

- DPTI (a South Australia Government department) in 2015 installed a requirement that unsaturated soil mechanics must be used in the design of state-owned infrastructure
- Light weight retaining walls and unsupported cuts stand for 80+ years

- Departments in other states may follow
- A shift in industry practice is underway

What Industry is doing (the good and the bad) (share with others)

- Large companies are producing infrastructure designs using unsaturated soil mechanics

- Trends:
  - Engaging university laboratories to determine WRCs/SWCCs (filter paper, WP4C dewpoint)
  - Strength/stability: using equivalent cohesion $c_{eq} = c'_0 + (\chi s)_0 \tan \varphi'$
  - Serviceability: adapting I_{pt} parameter to predict movements in multiple directions, exploiting it connection to elasticity

- Mistakes:
  - Assuming total suction contributes to strength, irrespective of individual contributions of matric and osmotic suctions (AS2870 implies this is acceptable)
  - Not understanding hydraulic hysteresis, e.g. supposing a hydraulic state lies on the main dry curve when designing for a wetting event
  - Not realising a suction needs to be scaled down using a multiplier χ or tanφ_b/tanφ' before incorporating into strength
  - Not appreciating importance of material type, e.g. presuming a suction of 1000kPa in a clean rock fill will provide significant strength gain
  - Using MPS-6 (Teros 21) devices without realising they are only calibrated for when undergoing drying, and only after prolonged drying (i.e. not when drying occurs immediately after a wetting event). The same may apply to other devices that do not measure suction directly (e.g. those using electric resistivity [GMS], thermal conductivity, capacitance)
  - Using language and concepts only suited to saturated soil mechanics like ‘undrained shear strength’
  - Inserting piezometers in unsaturated soil, unaware it may desaturate and become unreliable, to identify a rise in water table/phreatic surface and trigger alarms in the future
  - Not realising soils above phreatic surface can be saturated but have negative water pressures due to capillary rise
  - Treating saturated soils with negative water pressures (in capillary zone) as though they are unsaturated. Neglecting negative water pressures in determinations of effective stress when doing stability calculations or interpreting in situ test results

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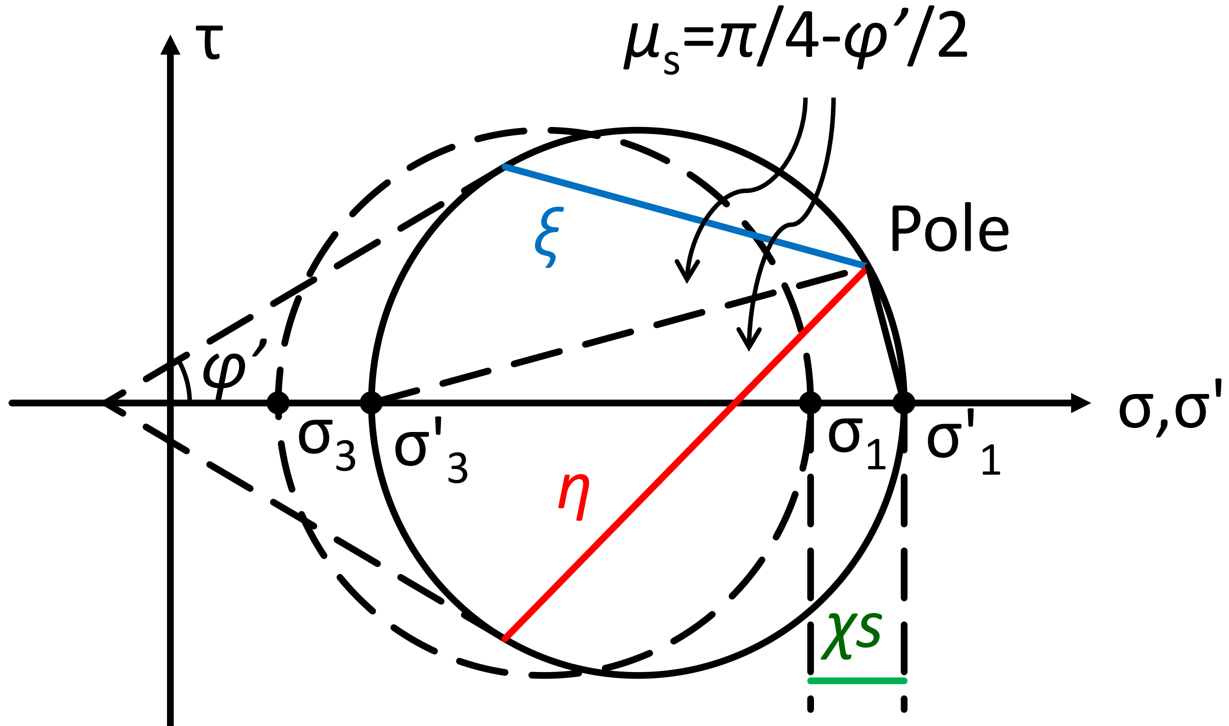
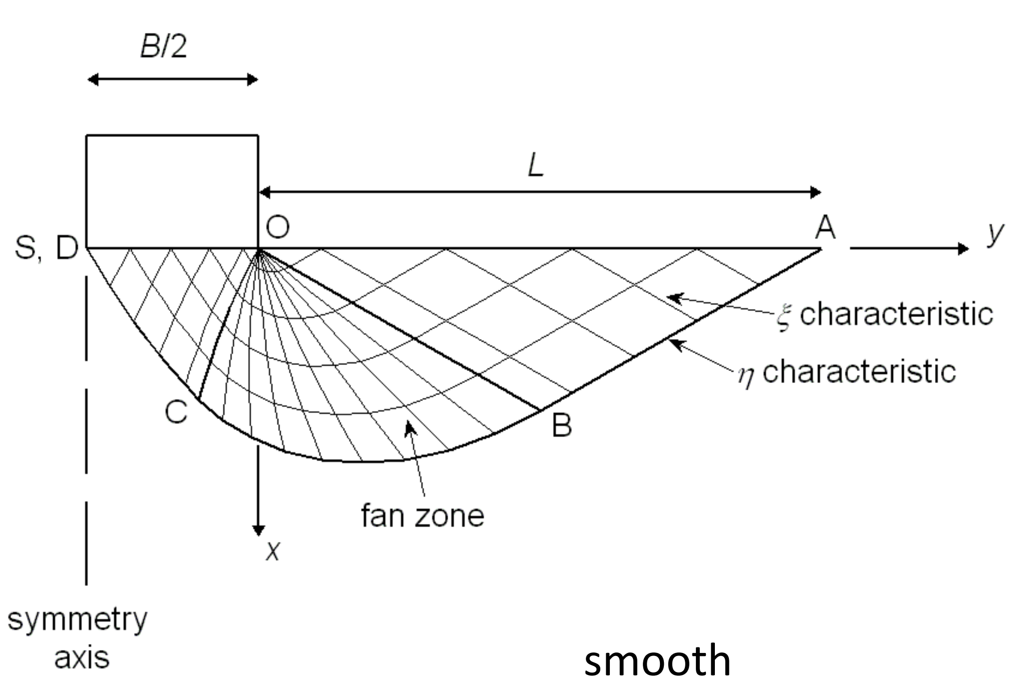
A way forward: Strength and stability problems have been solved using slip line theory

- Perfectly plastic ‘heterogeneous’ soil
- Two families of slip lines define a new coordinate system, failure occurs along one of them

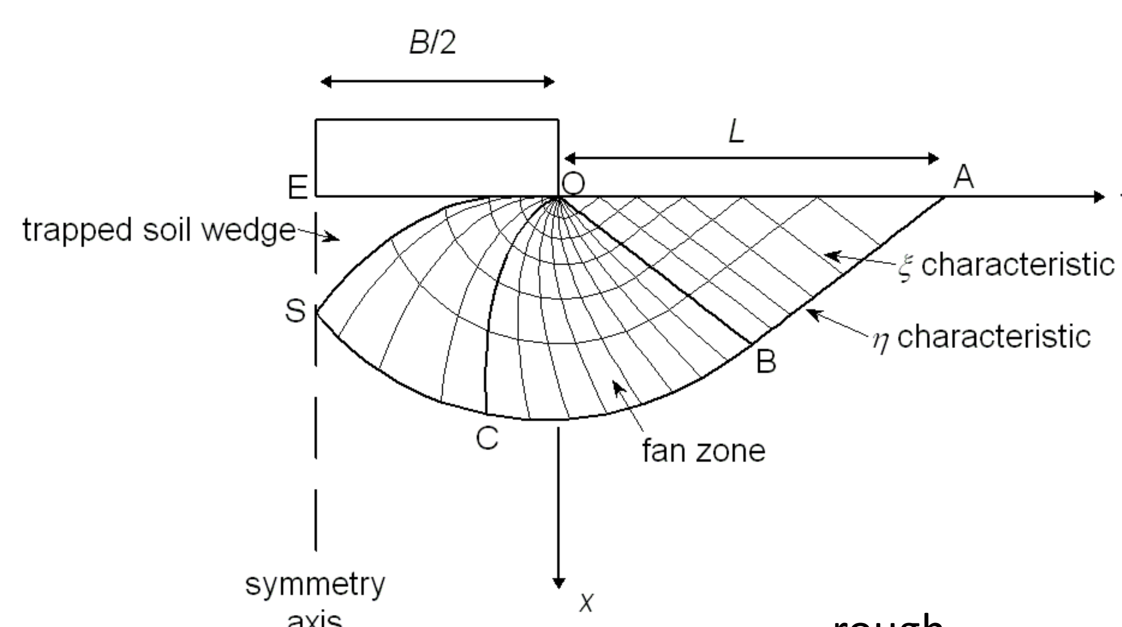


$$\langle\eta\rangle \equiv \begin{cases} dx = \tan(\theta+\mu)\mathrm{dz} \\ d\sigma'_\mathrm{m} + 2\tan\varphi'\,\sigma'_\mathrm{m}d\theta = \left(\gamma_\mathrm{t} + \dfrac{\partial(c'\cot\varphi' + \chi s)}{\partial z}\right)(\mathrm{dz} - \tan\varphi'\mathrm{dx}) \end{cases}$$

$$\langle\xi\rangle \equiv \begin{cases} dx = \tan(\theta-\mu)\mathrm{dz} \\ d\sigma'_\mathrm{m} - 2\tan\varphi'\,\sigma'_\mathrm{m}d\theta = \left(\gamma_\mathrm{t} + \dfrac{\partial(c'\cot\varphi' + \chi s)}{\partial z}\right)(\mathrm{dz} + \tan\varphi'\mathrm{dx}) \end{cases}$$



smooth



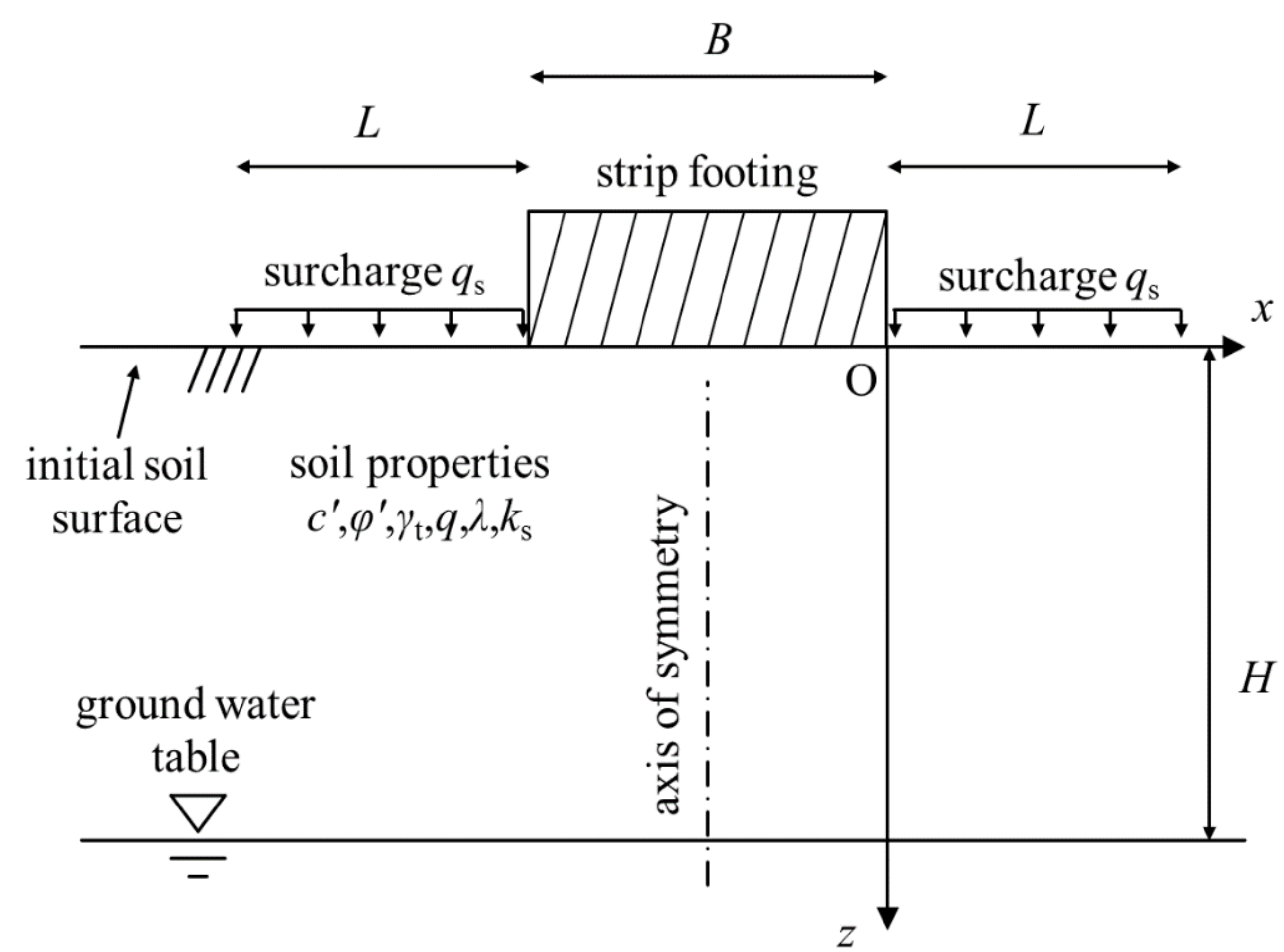
rough

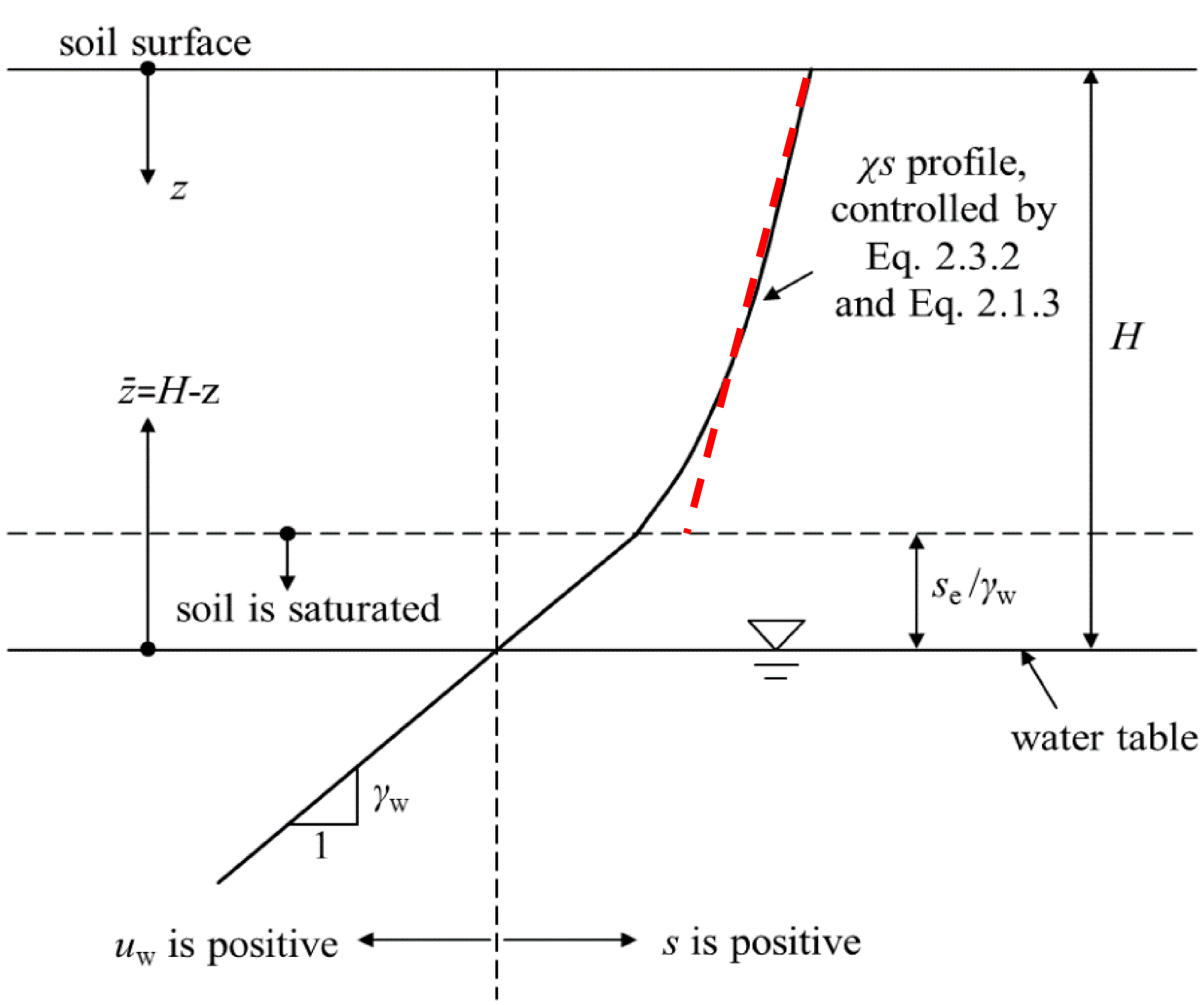
Shallow foundations

- Suppose φ' and γ_t are constant and that c' and χs vary linearly with depth

$$c' = c'_0 + K_c z$$

$$\chi s = (\chi s)_0 + K_{\chi s} z$$

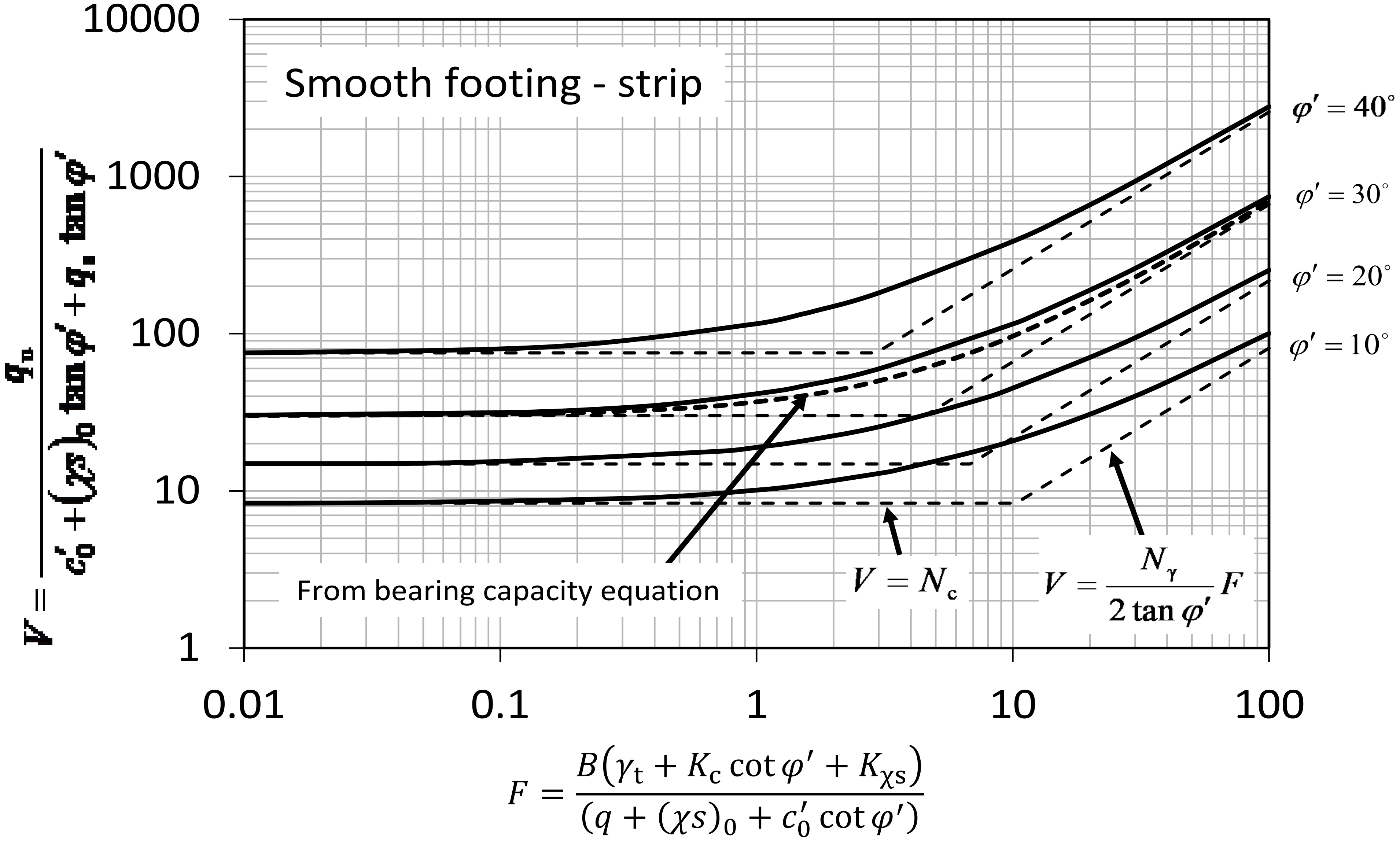




Shallow foundations

- Stability (i.e. bearing capacity q_u) is controlled by three dimensionless groups

$$V = \frac{q_u}{c_0' + (\chi s)_0 \tan\varphi' + q_s \tan\varphi'} \qquad F = \frac{B\left(\gamma_t + K_c \cot\varphi' + K_{\chi s}\right)}{\left(q + (\chi s)_0 + c_0' \cot\varphi'\right)} \qquad \varphi'$$

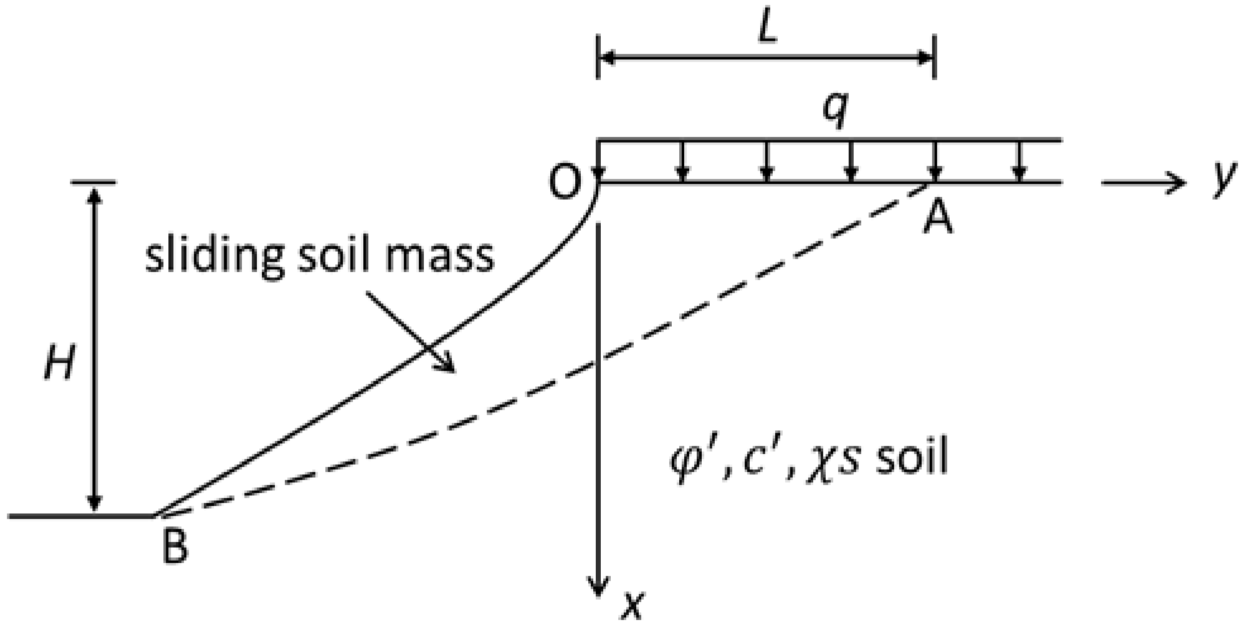


Values of N_c and N_γ for smooth and rough circular footings.

	Smooth circular footing		Rough circular footing	
φ' (degrees)	N_c	N_γ	N_c	N_γ
5	7.430	0.05975	8.058	0.08063
10	9.987	0.2059	11.09	0.3224
15	13.88	0.5346	15.85	0.9323
20	20.08	1.271	23.68	2.416
25	30.52	2.971	37.32	6.073
30	49.28	7.111	62.72	15.52
35	85.85	18.03	114.0	41.88
40	164.7	50.16	228.5	123.7
45	358.1	159.8	519.6	417.7
50	921.4	617.8	1397.0	1710.0

Slopes

- Again suppose φ' and γ_{t} are constant and that c' and χs vary linearly with depth



- Again stability is controlled by three dimensionless groups

$$F = \frac{L\left(\gamma_{\mathrm{t}} + K_{\mathrm{c}} \cot\varphi' + K_{\chi\mathrm{s}}\right)}{\left(q + (\chi s)_0 + c_0' \cot\varphi'\right)} \qquad T = \frac{\cot\varphi'}{2} \ln\left|\frac{\left((\chi s)_0 + c_0' \cot\varphi'\right)(1 + \sin\varphi')}{\left(q + (\chi s)_0 + c_0' \cot\varphi'\right)(1 - \sin\varphi')}\right| \qquad \varphi'$$

These studies form a basis for simple analysis, called the ‘equivalent method’

- In software or hand analysis capture suction (and the varying c') through:
  - An equivalent cohesion: $c_{eq} = c_0' + (\chi s)_0 \tan\varphi'$
  - An equivalent unit weight: $\gamma_{eq} = \gamma_{\mathrm{t}} + K_{\mathrm{c}} \cot\varphi' + K_{\chi \mathrm{s}}$
- Ensures the dimensionless quantities do not change thus the stability you compute is representative of the real problem
- The χs profile must be representative of the worst case (involving the main wetting curve in some way)
- There is no need to use the inbuilt unsaturated soil features of a software

This is useful when χs doesn’t change a lot during deformation. This may be true when S_r is small for slow or fast loading situations, and for larger S_r for slow (drained) loading situations.

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It reduces to what we do for saturated soils

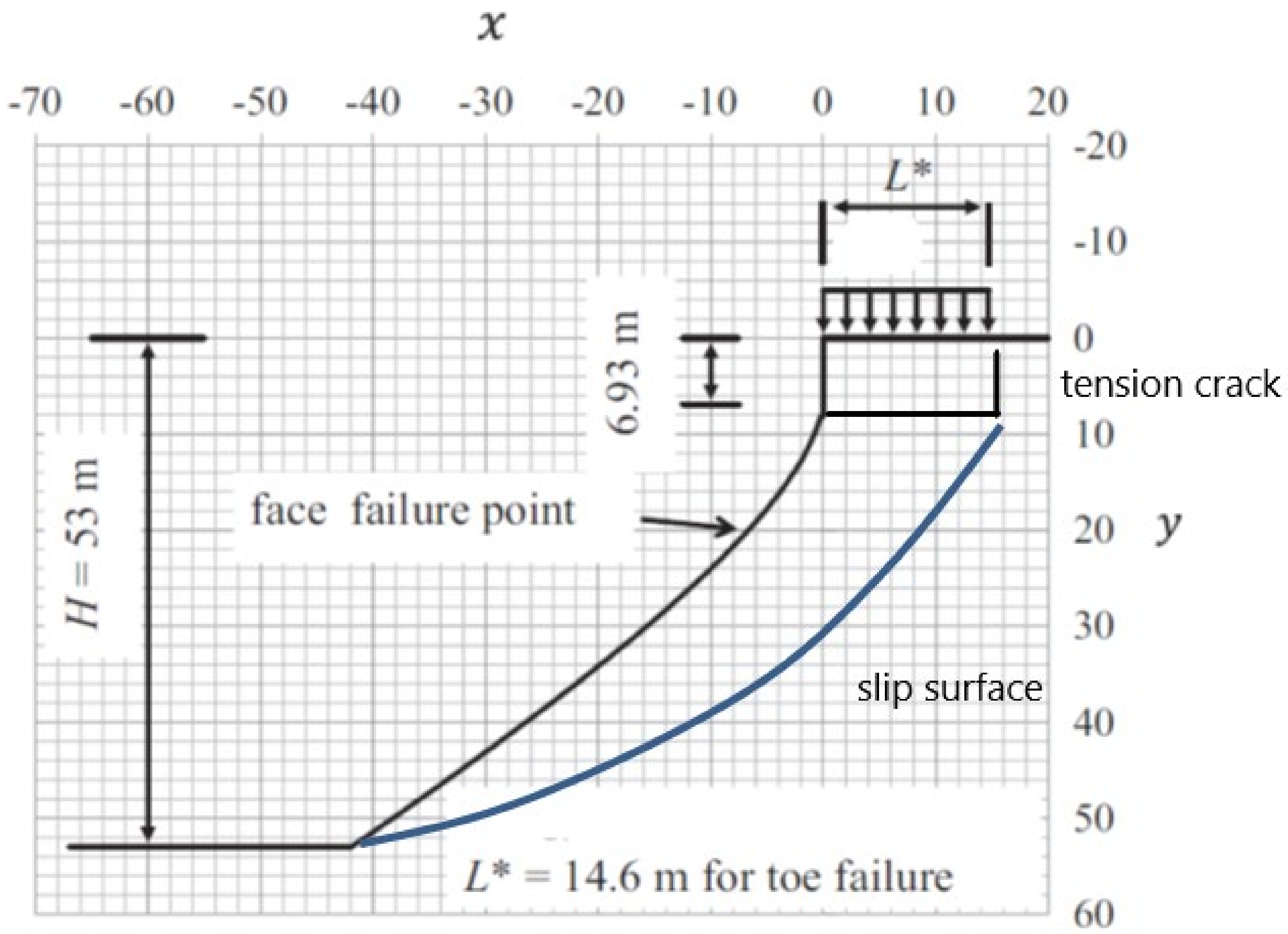
- For a soil that is saturated all the way to the ground surface, $(\chi s)_0$ may be interchanged with 0 and $K_{\chi s}$ may be interchanged with $K_{\mathrm{u_w}} = \partial(-u_\mathrm{w})/\partial z$. For hydrostatic conditions $K_{\mathrm{u_w}} = -\gamma_\mathrm{w}$

$$F = \frac{B(\gamma_\mathrm{t} + K_\mathrm{c}\cot\varphi' + K_{uw})}{(q + 0 + c_0'\cot\varphi')}$$

$$F = \frac{B(\gamma_\mathrm{t} + K_\mathrm{c}\cot\varphi' - \gamma_\mathrm{w})}{(q + c_0'\cot\varphi')}$$

$$F = \frac{B(\gamma' + K_\mathrm{c}\cot\varphi')}{(q + c_0'\cot\varphi')}$$

The dimensionless group quantities are important, not the parameters used in them



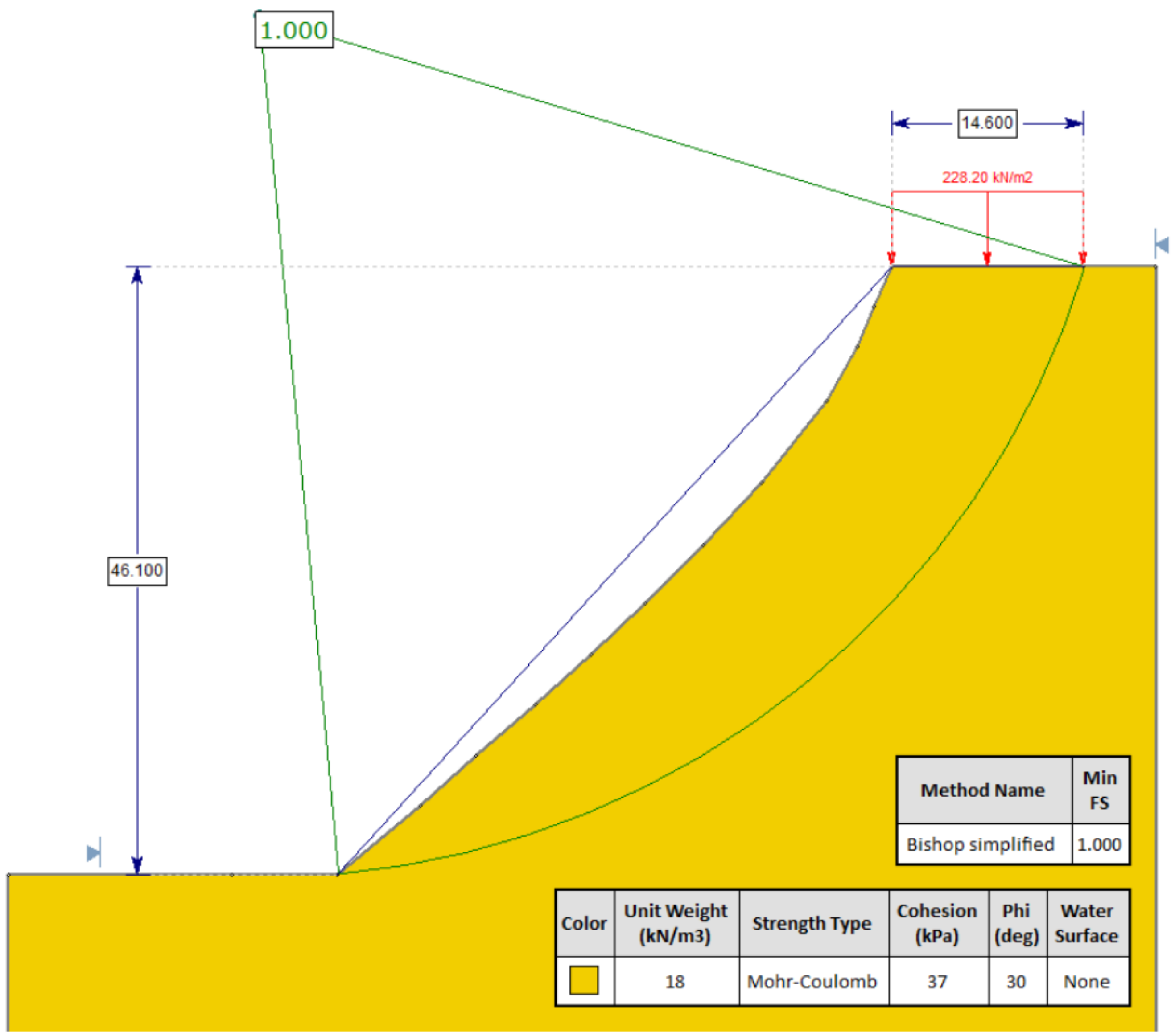
The dimensionless group quantities are:
F = 0.90, *T* = -0.363, φ' = 30°

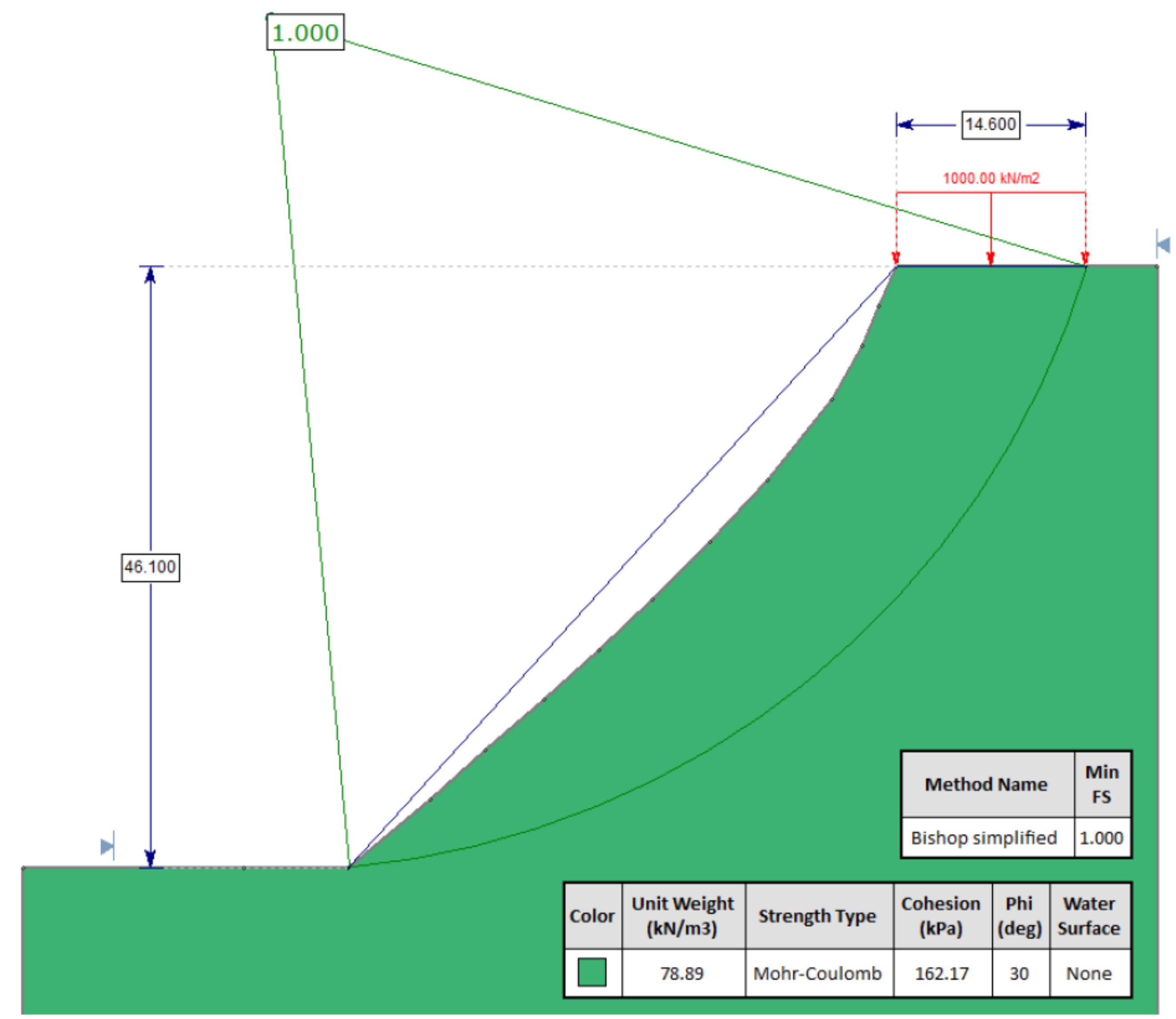
A FoS = 1 is achieved for each of the following:

The real case:
γ_t = 18.5 kN/m^3, c' = 16.8 kPa,
χs = 35-0.5y kPa, q = 228 kPa

The 'equivalent method' case:
γ_{eq} = 18 kN/m^3, c_{eq} = 37.0 kPa,
χs = 0 kPa, q = 228 kPa

The 'outrageous' case:
γ_{eq} = 78.9 kN/m^3, c_{eq} = 162 kPa,
χs = 0 kPa, q = 1000 kPa





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χs = 0 kPa, q = 1000 kPa

From Rohan Stocker, when an MEngSc student at UNSW, now at PSM

Example 1 in Civil sector

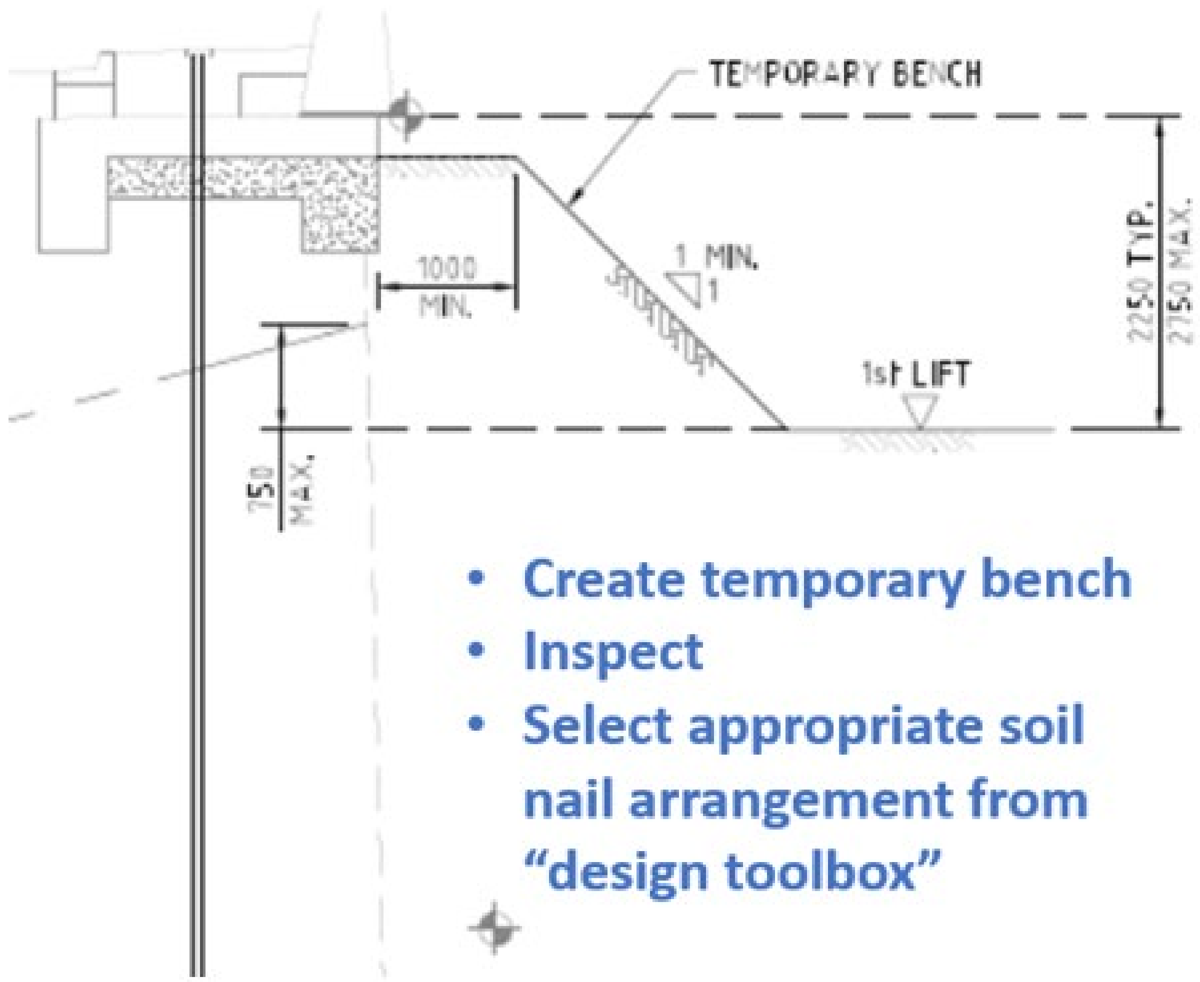
Torrens to Torrens (T2T) road project South Australia

- 2km of cutting up to 10m deep in unsaturated stiff clays with sand lenses and fissures/slickensides
- Used a 'lightweight' shotcrete/nailed wall instead of a heavier shotcrete wall or soldier pile system
- Saved $20 million (AUD)
- Used equivalent cohesion and effective stress concept to assess stability

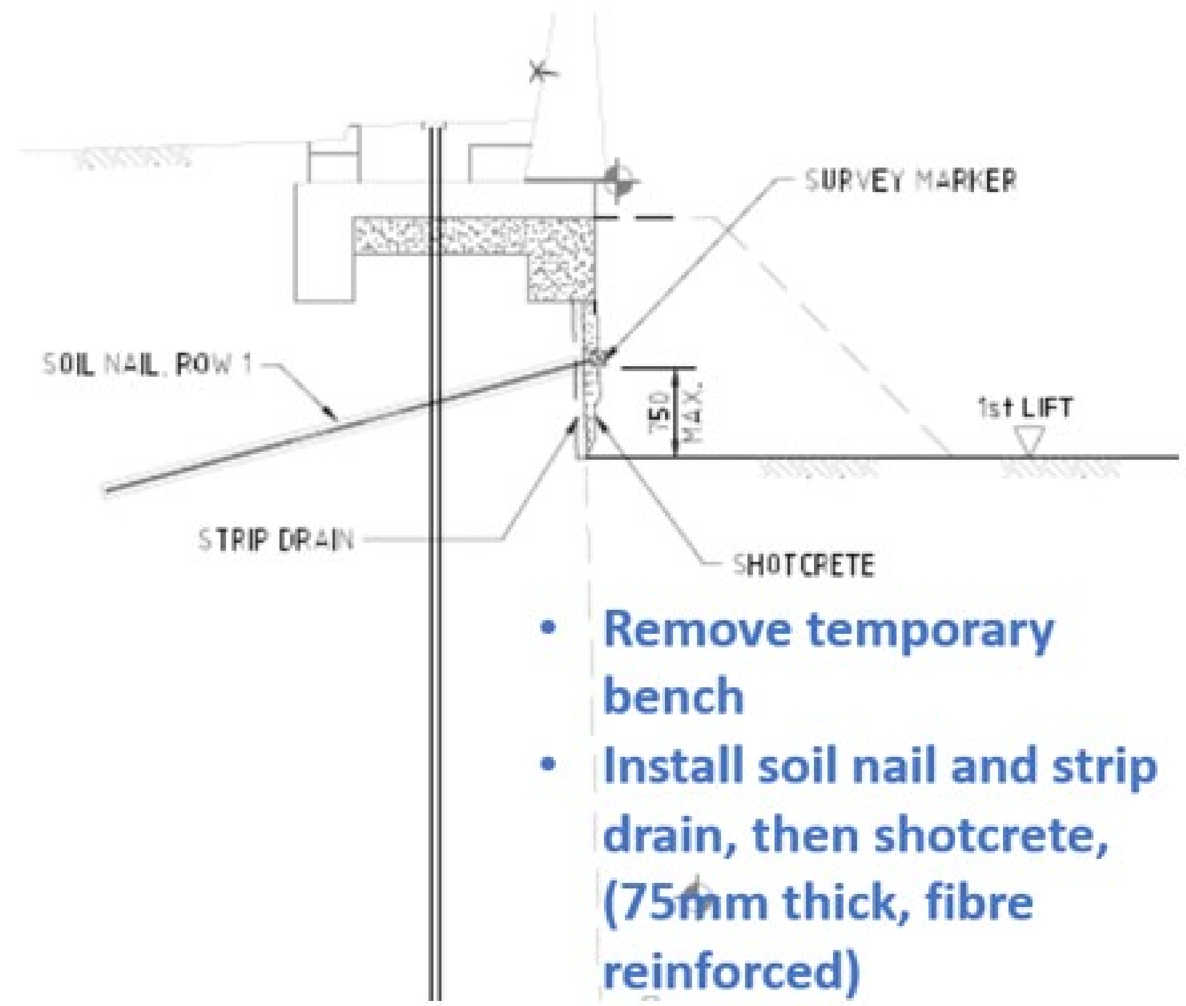
	T2T Design (clay profile)	Conventional Design (Gallipoli Underpass)
Shotcrete thickness	75 mm (typ)	175 mm
Shotcrete reinforcement	Macro synthetic fibre (typ)	SL81 mesh
Nail length	4 – 6 m (typ)	10 m (max)
Nail rows	3	7
Nail diameter	150 mm	125 mm
Nail spacing	3.0 x 2.5 m	1.25 x 1.1 m
Nail head	SL81 mesh + bar cog	Anchor plate + nut

Herraman, R. (2019). A Lightweight Soil Nail Retaining Wall in Unsaturated Clay, Vol. 5, Issue 1, p.1-11. doi: 10.4417/IJGCH-05-01-01

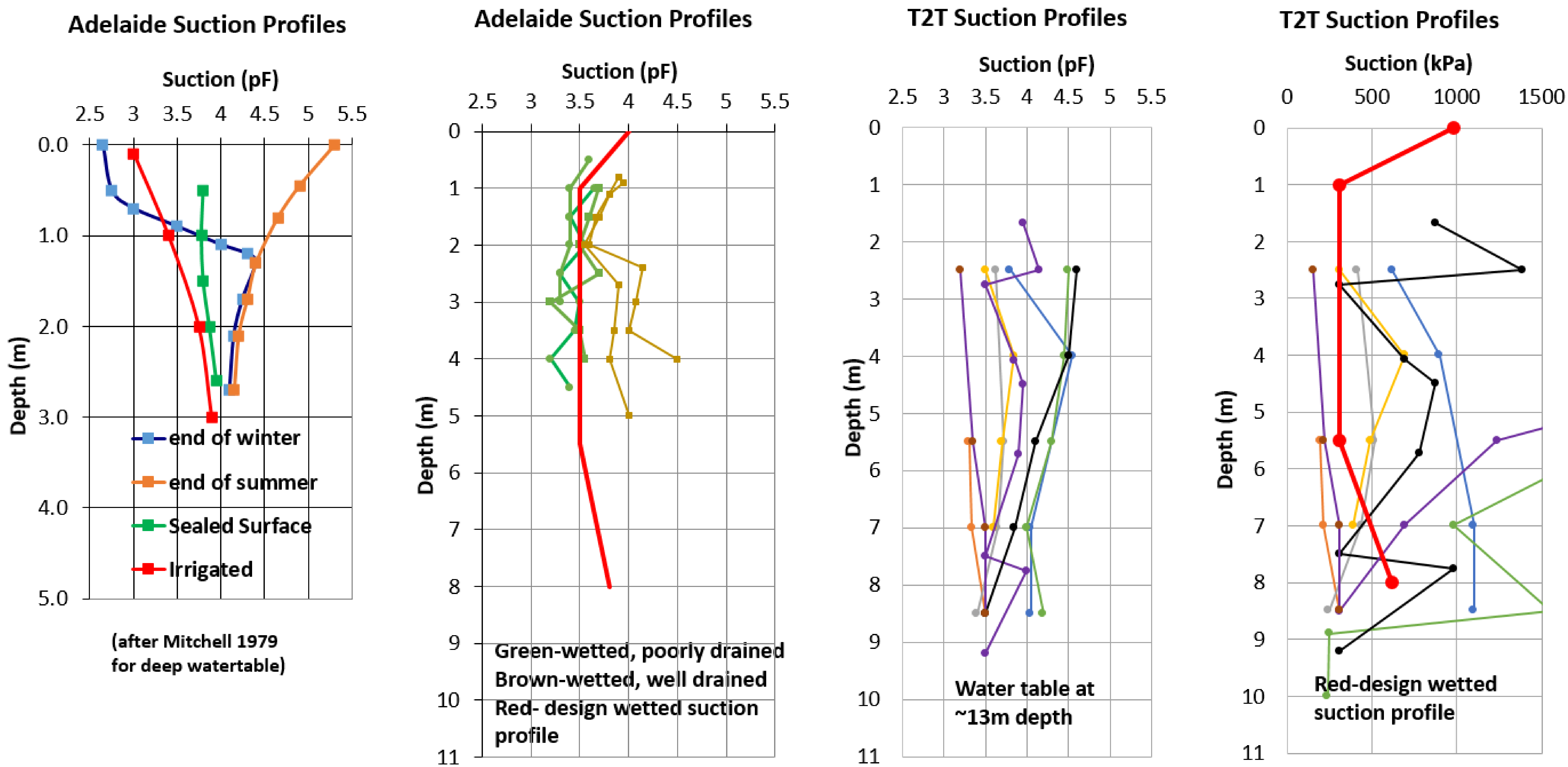
Observational method used to deal with variability, having predetermined nail configurations in a ‘design toolbox’ for different ground conditions



- Create temporary bench
- Inspect
- Select appropriate soil nail arrangement from “design toolbox”



- Remove temporary bench
- Install soil nail and strip drain, then shotcrete, (75mm thick, fibre reinforced)



(a) Typical Adelaide suction profiles

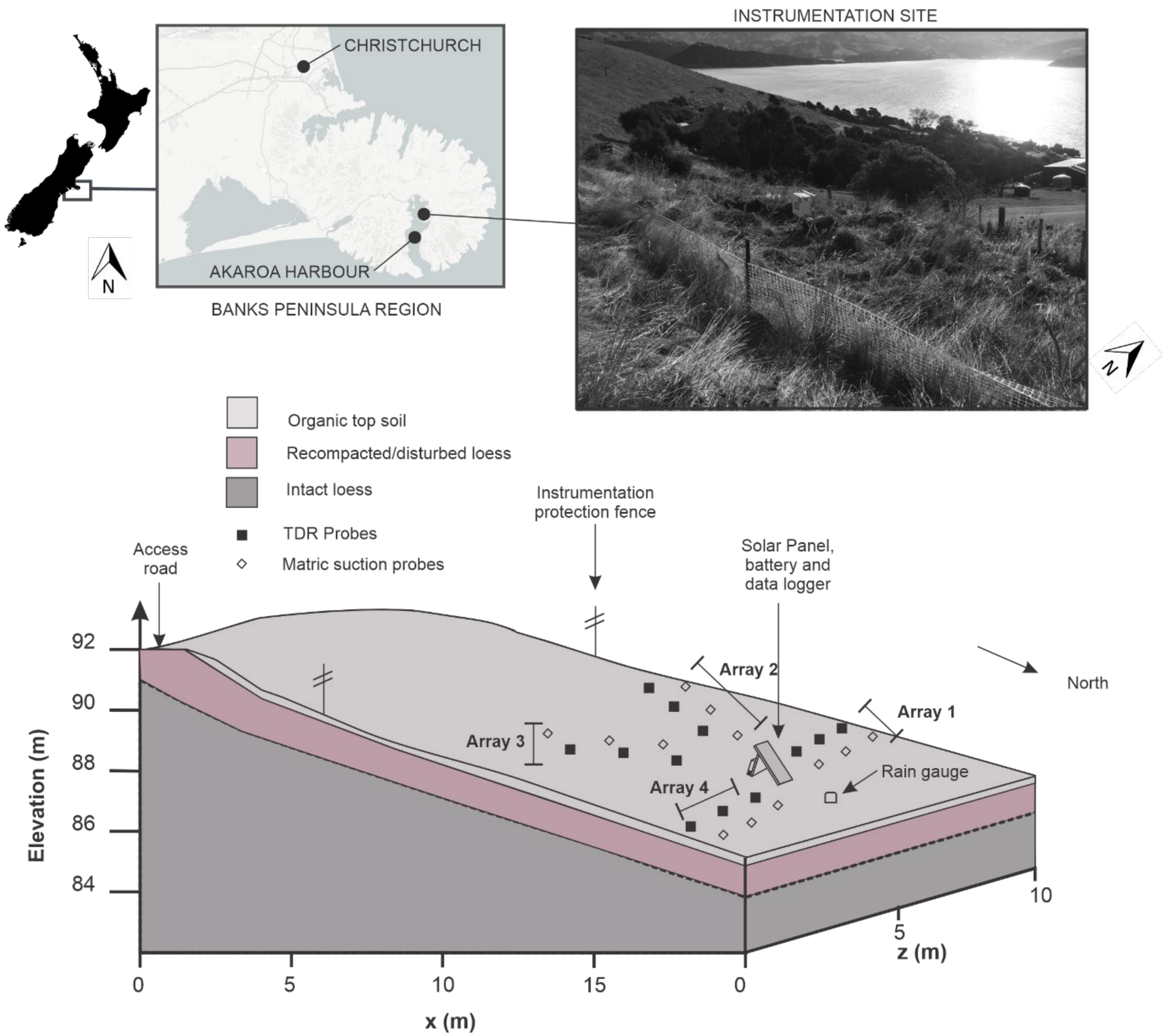
(b) Adelaide suction profile for sites with surface and subsurface wetting. Poorly drained sites shown green. Well drained sites shown brown. Design wetted suction profile for T2T shown red

(c) Some T2T suction profiles plotted using pF units for suction

(d) Some T2T suction profiles and the Design wetted suction profile (shown red) plotted using kPa units for suction

Example 2 in Civil sector

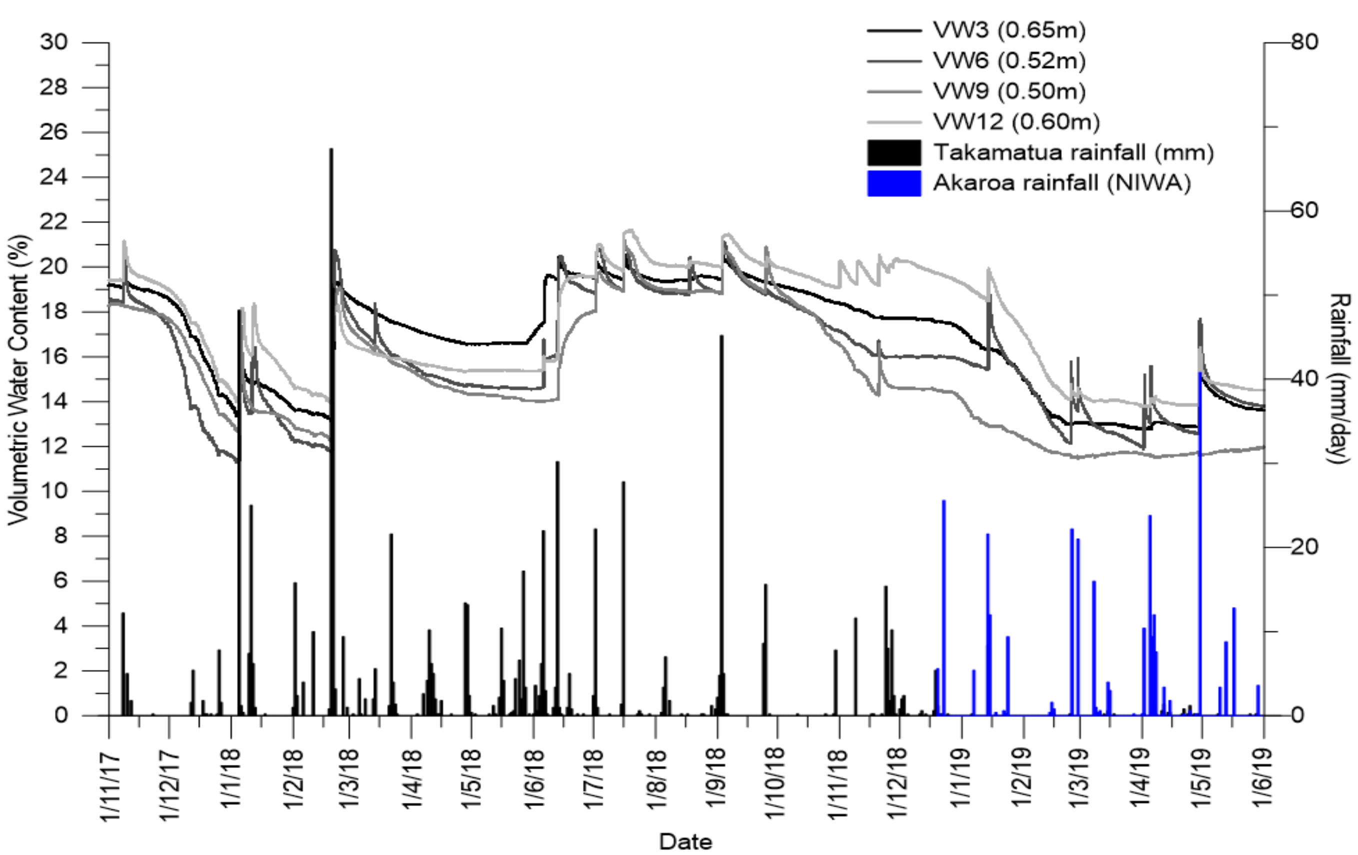
A loess slope stability problem, New Zealand



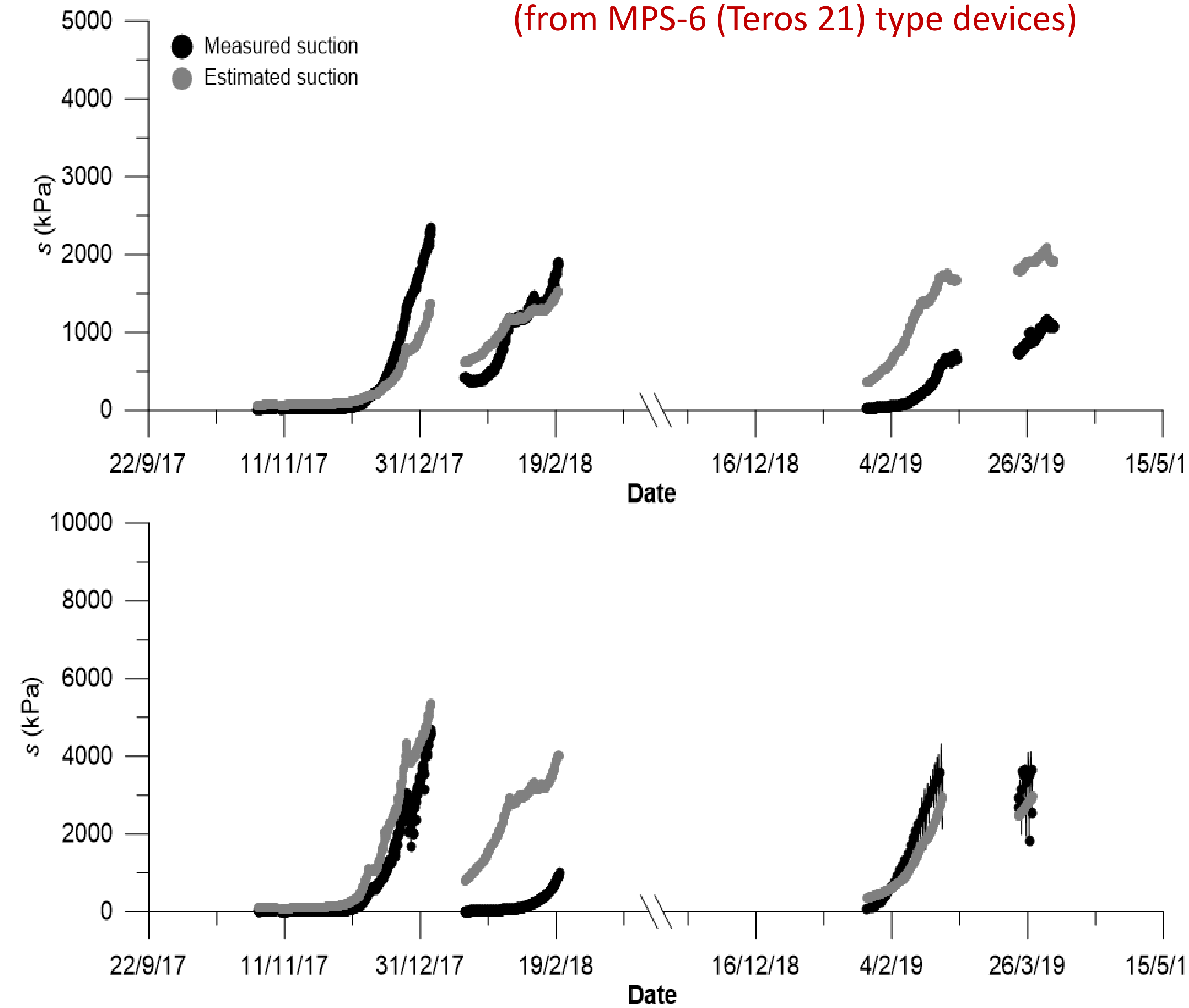
Yates & Russell (2022) *Geotechnique*.

(a) Photograph of field instrumentation site with location diagram, (b) schematic of field instrumentation showing plan view of instrument installation locations in arrays and soil model.

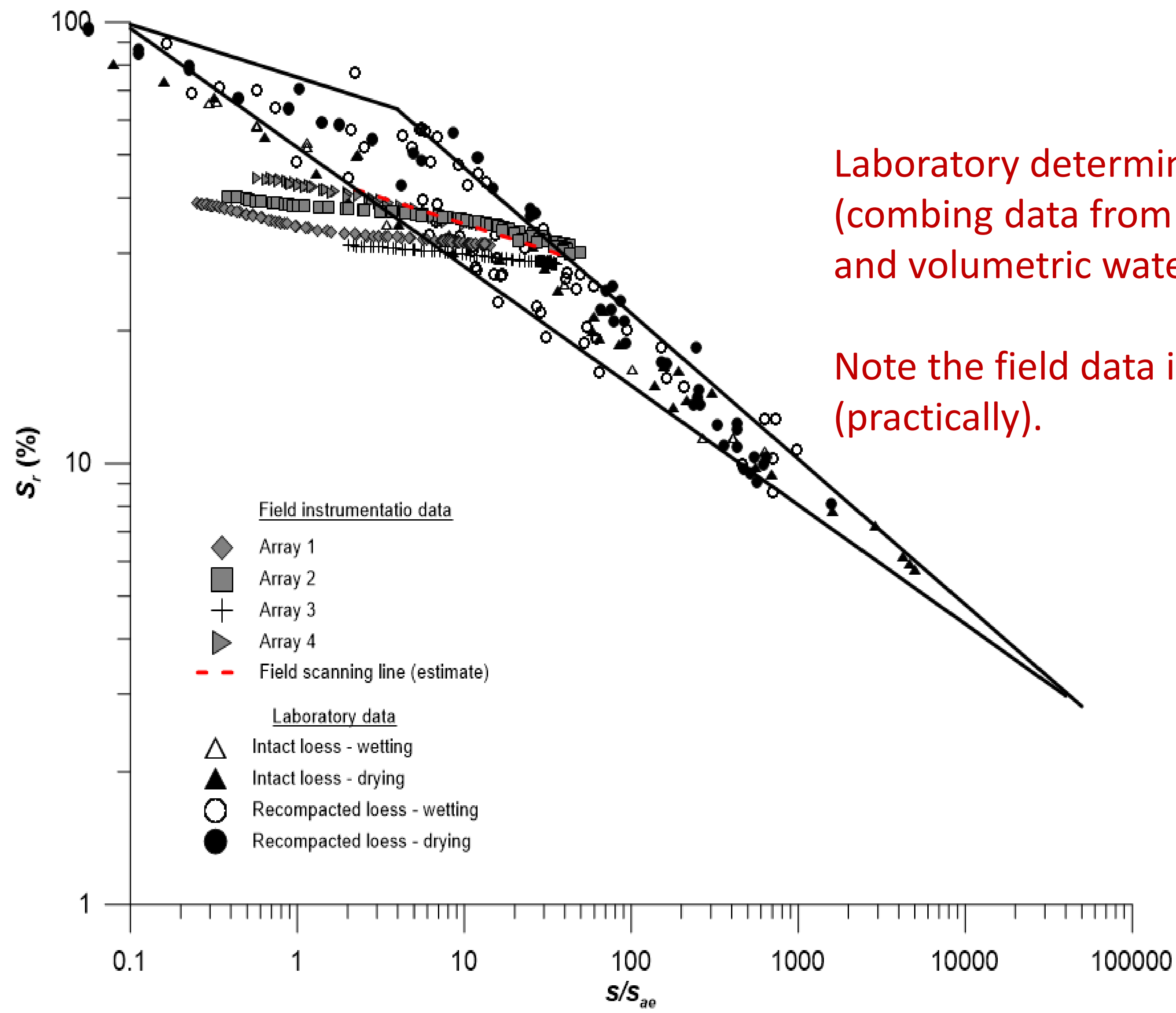
Volumetric water content measurements
and rainfall data



Suction measurements, drying data only,
(from MPS-6 (Teros 21) type devices)

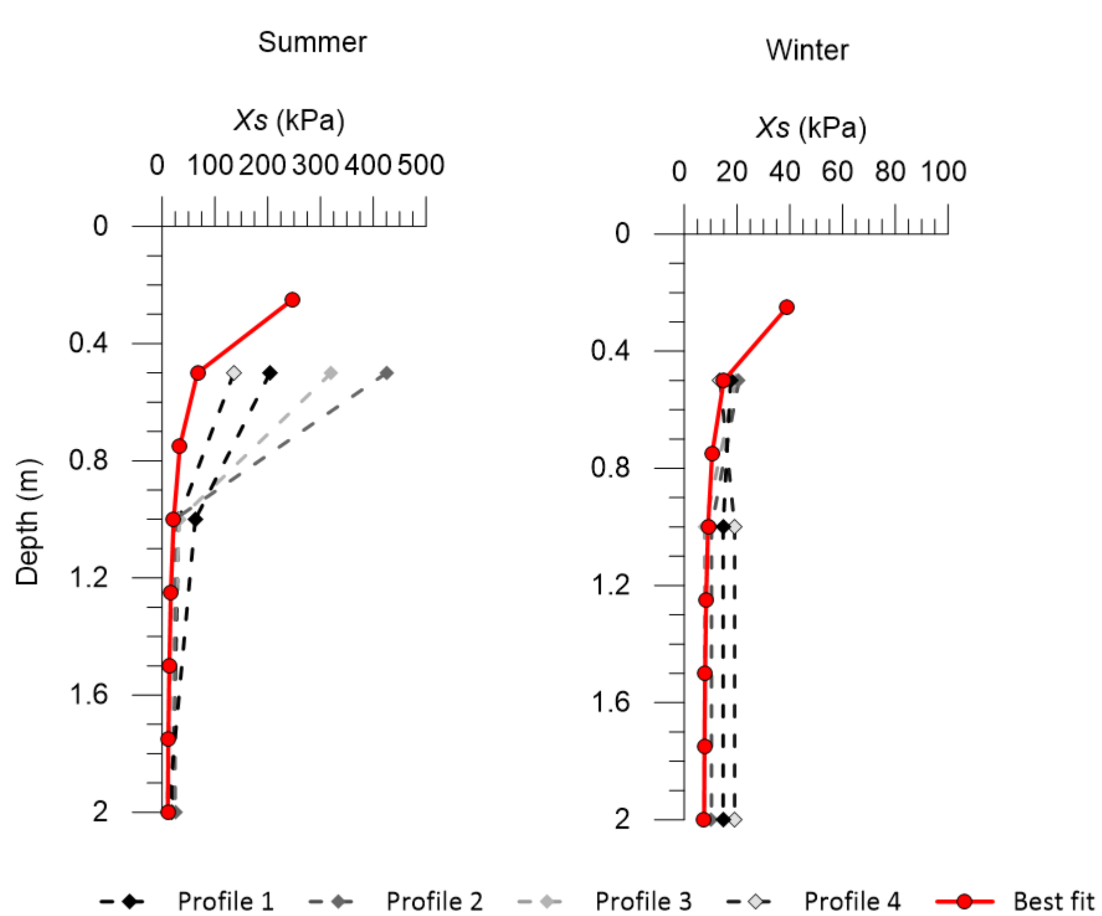


Yates & Russell (2022)
***Geotechnique*.**



Laboratory determined and field-inferred WRC data (combing data from MPS-6 (Teros 21) type devices and volumetric water content measurements).

Note the field data is always on the same scanning curve (practically).



Implementing the equivalent cohesion in to an infinite slope analysis

$$\chi s = k_1 + k_2 z^n$$

$$c_{eq} = c' + (k_1 + k_2 z^n)\tan\varphi'$$

$$FoS = \frac{\frac{c_{eq}}{\gamma z_s} + \cos^2\beta\tan\varphi'}{\sin\beta\cos\beta} = \frac{\frac{c'}{\gamma z_s} + \left(\cos^2\beta' + \frac{k_1 + k_2 z^n}{\gamma z_s}\right)\tan\varphi'}{\sin\beta\cos\beta}$$

Yates & Russell (2022)
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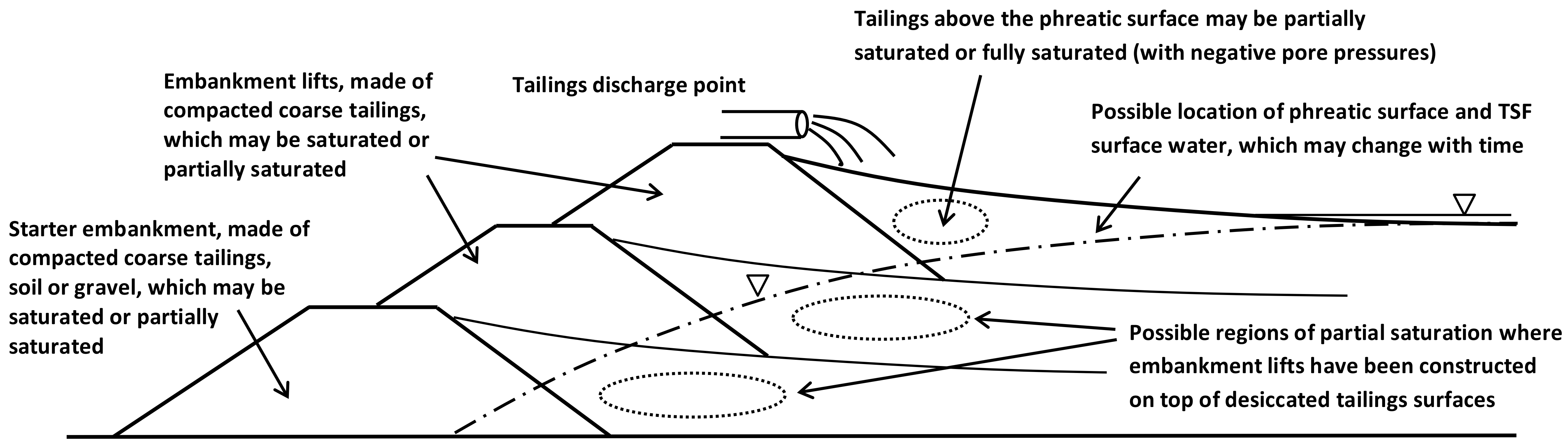
Example in Mining sector

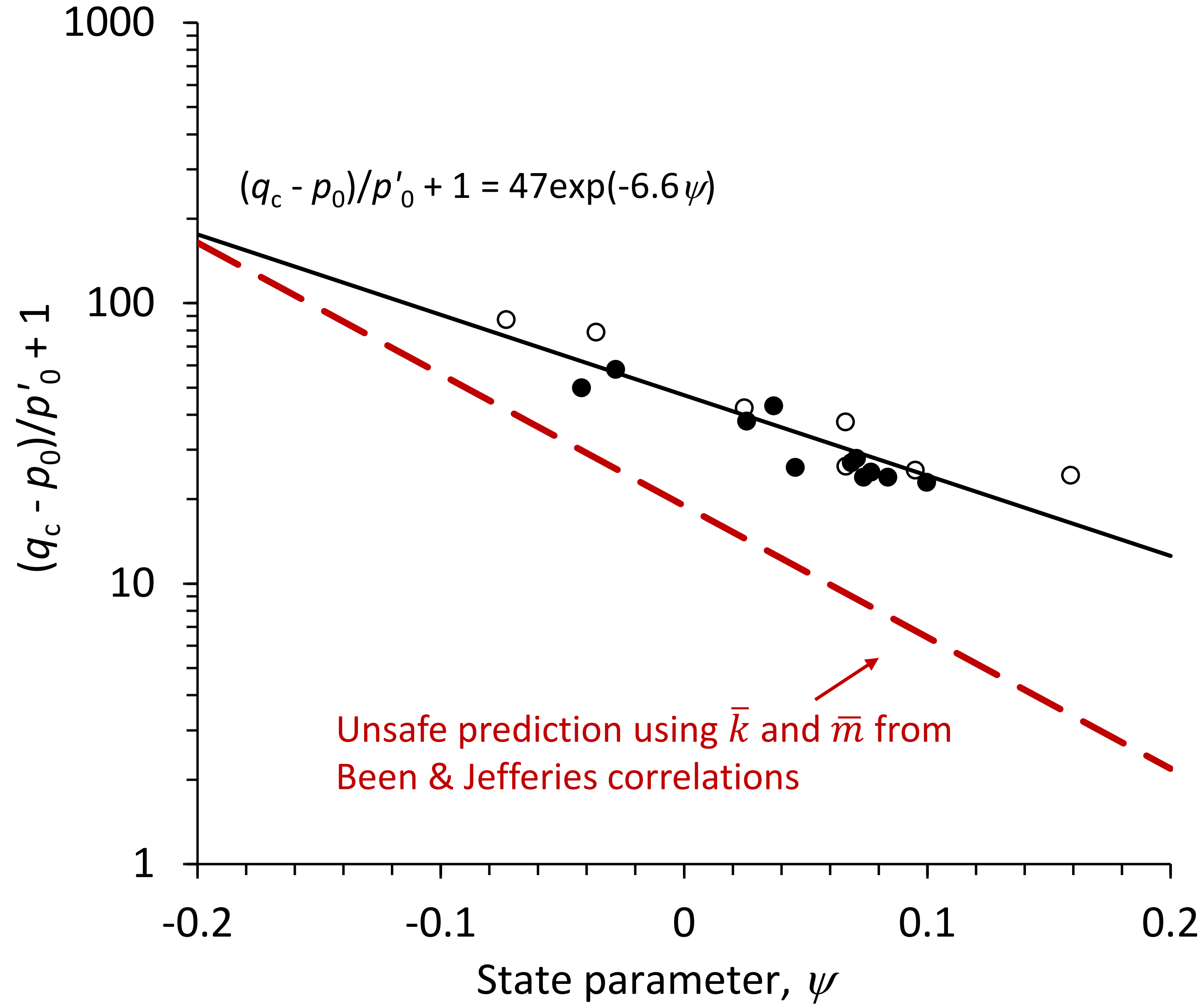
Liquefaction assessment of tailings storages



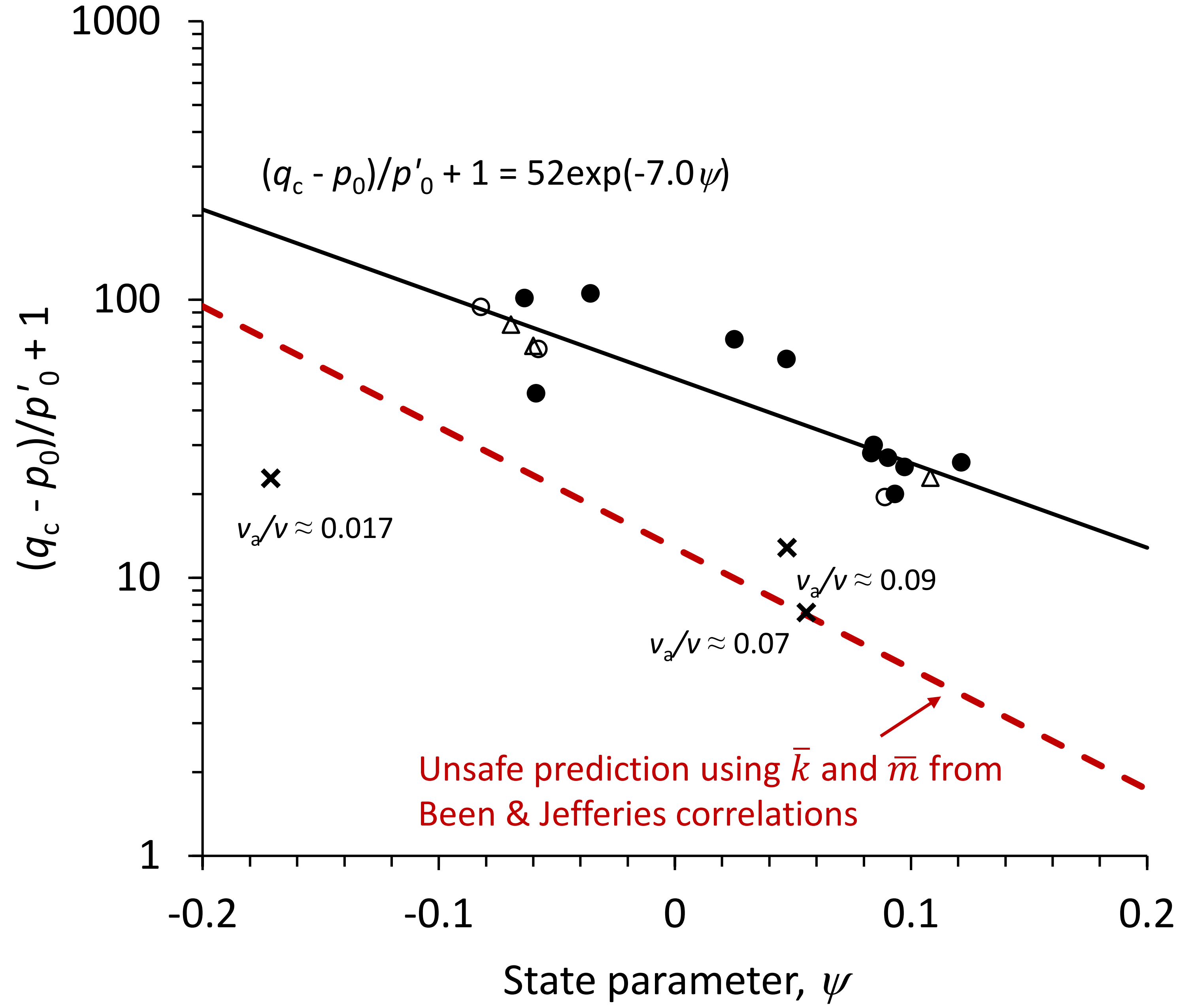
- CPT data
  - Increased awareness that CPT data above water table is affected by suction. That data is usually ignored. Negative water pressures in capillary rise zone are not considered though
- Liquefaction
  - Increased acceptance that unsaturated tailings can liquefy
  - Some companies have their own internal assessment procedures stating a degree of saturation of 80% is the lower limit for liquefaction possibility

CPT results (using two calibration chambers at UNSW and UWA, one large and one small)

Drained (or pseudo drained) conditions prevailed in all tests, requiring slow penetrations in the saturated samples



Normalised cone resistance $\frac{(q_c - p_0)}{p'_0} + 1$ against ψ for saturated and unsaturated gold tailings, in which $v_a/v > 0.15$ and the influences of suction were accounted for in the computations of p', λ, Γ and ψ. Solid symbols represent data for saturated tests and hollow symbols represent data for unsaturated tests. Red dashed lines are from Jefferies & Been screening level assessment correlations



Normalised cone resistance $\frac{(q_c - p_0)}{p'_0} + 1$ against ψ for saturated and unsaturated copper tailings, in which the influences of suction were accounted for in the computations of p', λ, Γ and ψ. Solid symbols represent data for saturated tests and hollow symbols represent data for unsaturated tests with $v_a/v > 0.15$. Hollow circular symbols are for the slow unsaturated tests and hollow triangular symbols are for the fast unsaturated tests. Cross symbols represent data for unsaturated tests with $v_a/v < 0.15$.

Russell, Vo, Ayala, Wang, Reid, Fourie (2022) *Geotechnique*. (Part of TAILLIQ, LP and FT, sponsored by ARC and Anglo American, BHP, Freeport-McMoran, Newmont, Rio Tinto and Teck)

Conditions required for uniqueness of saturated and unsaturated CPT results

- Psuedo drained conditions prevail in the tests on unsaturated samples as long as $v_a/v > 0.15$. This requires enough air in the pore space so that the volume change which occurs in the unsaturated samples is similar to that around drained tests in the saturated samples. [Fun fact: The deformation of the soil/tailings skeleton (volume change) controls the q_c the most.]

- When $v_a/v < 0.15$ the response becomes an *unsaturated pseudo partially drained* condition. We do not yet know how to interpret CPTs for these conditions

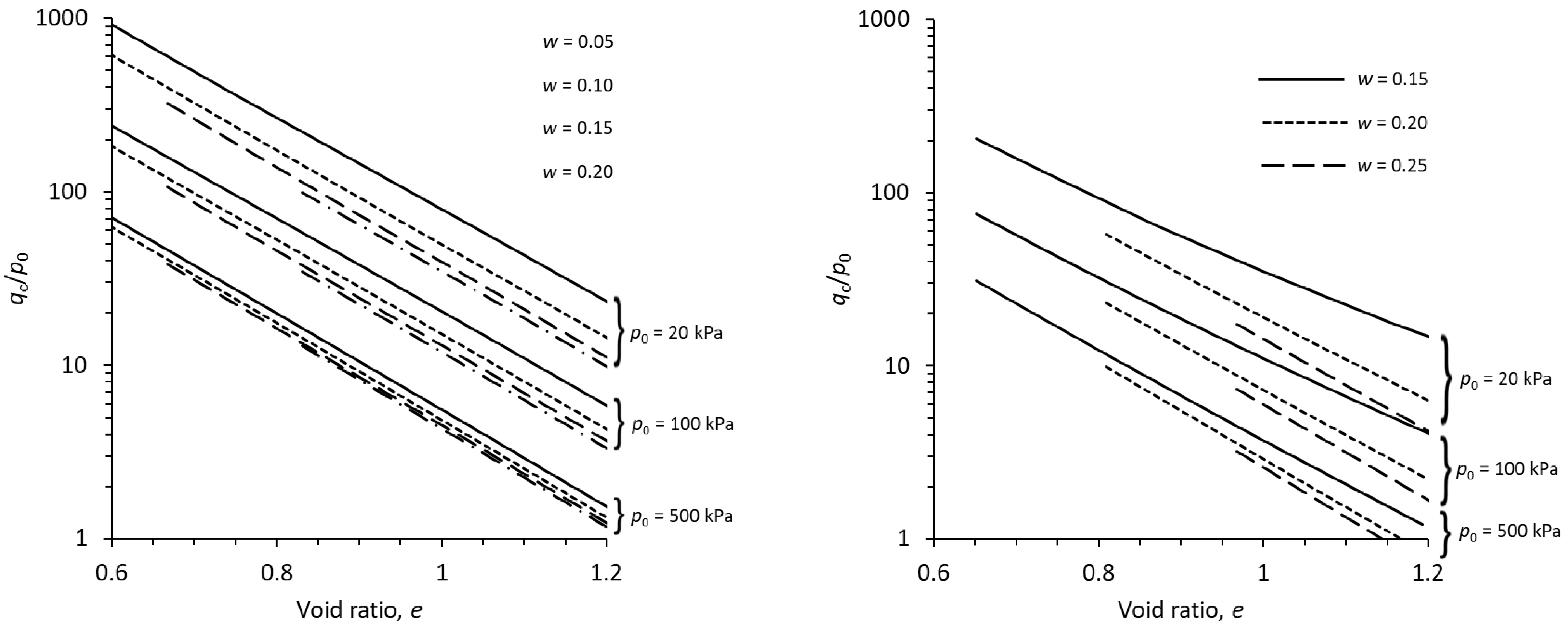
- Note that the saturated tests were performed very slowly so drained conditions prevailed. Normal cone sizes and penetration velocities would have seen undrained responses.

- Also note that the penetration rate is not so important in the unsaturated samples when $v_a/v > 0.15$. Psuedo drained conditions always prevailed.

Russell, Vo, Ayala, Wang, Reid, Fourie (2022) *Geotechnique*. (Part of TAILLIQ, LP and FT, sponsored by ARC and Anglo American, BHP, Freeport-McMoran, Newmont, Rio Tinto and Teck)

Alternate presentations

- Useful in practice when CSLs, knowledge of suction hardening and WRCs are unavailable



The relationships between q_c/p_0 and e, for gold (left) and copper (right) tailings, for certain values of p_0 and w, enabling estimation of e. The relationships apply when $v_a/v > 0.15$ and the hydraulic states are at the midpoints of scanning curves

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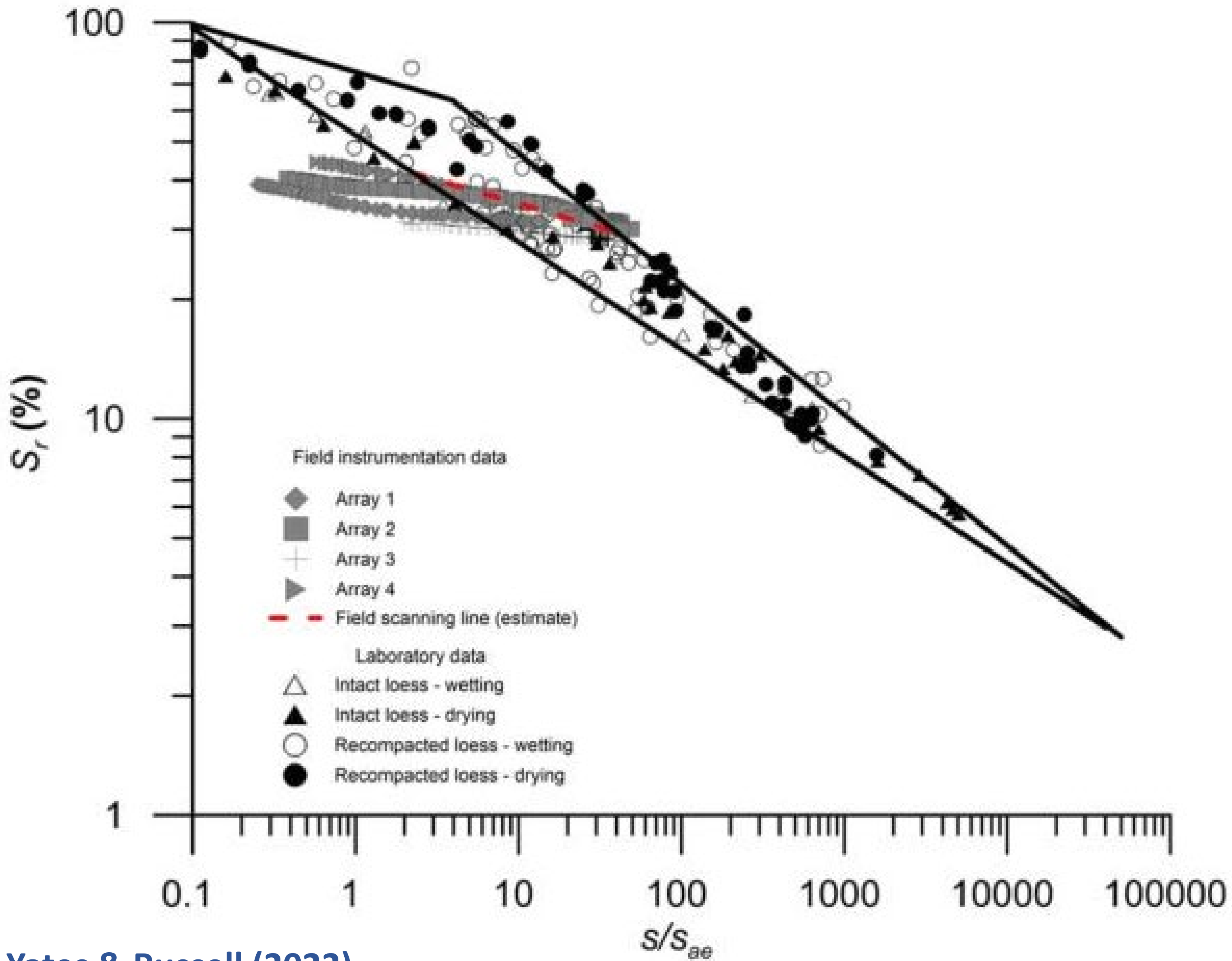
Why the mid point of a scanning curve assumption?

- In the field normal seasonal cycles may see the hydraulic state transition between wetting and drying, never reaching the main wetting or drying curve, instead remaining on a scanning curve the whole time.
- Unusual and prolonged wetting or drying, e.g. extreme floods or drought, may be exceptions that cause the hydraulic state to locate on a main wetting or drying curve.
- The direct evidence that the state usually stays on a scanning curve under normal climatic conditions is limited, although it is a view held by several in the unsaturated soil mechanics community. The study of Yates & Russell (2022), and two years of monitoring, shows that the hydraulic state of a loess soil slope is always on a scanning curve.



Yates & Russell (2022) *Geotechnique*.

Russell, Vo, Ayala, Wang, Reid, Fourie (2022) *Geotechnique*. (Part of TAILLIQ, LP and FT, sponsored by ARC and Anglo American, BHP, Freeport-McMoran, Newmont, Rio Tinto and Teck)

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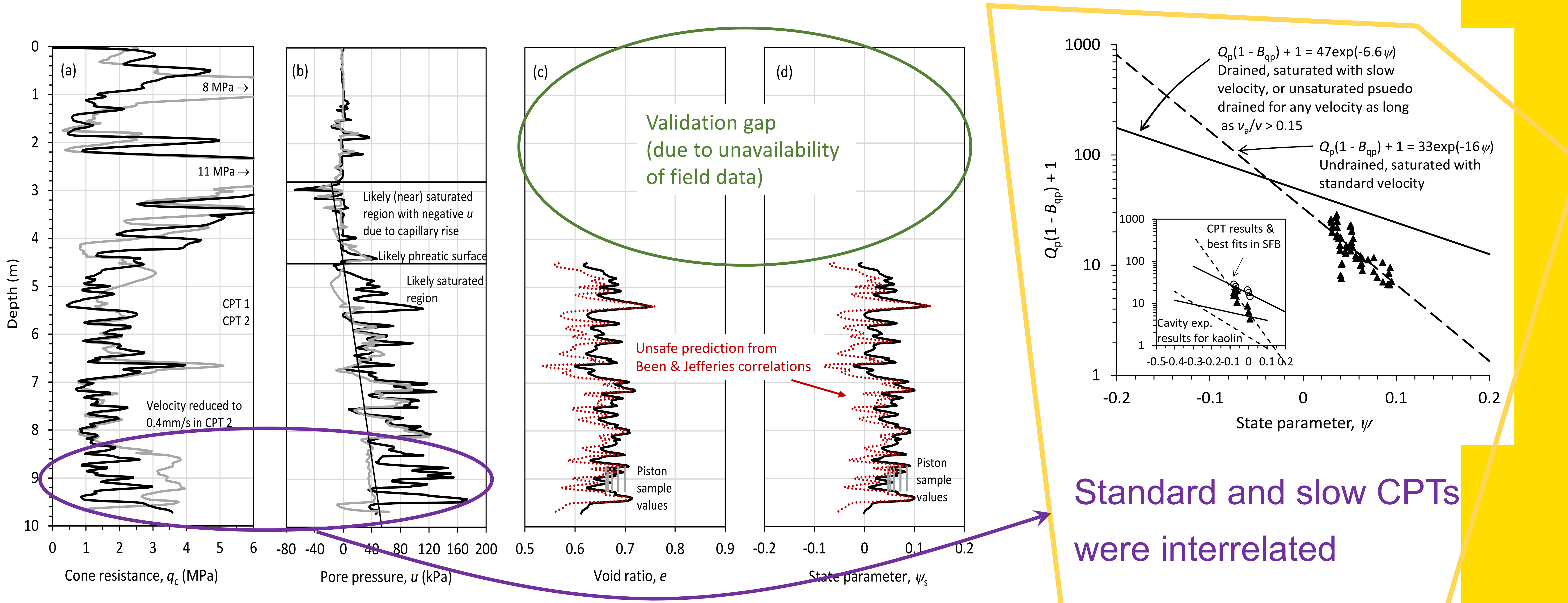
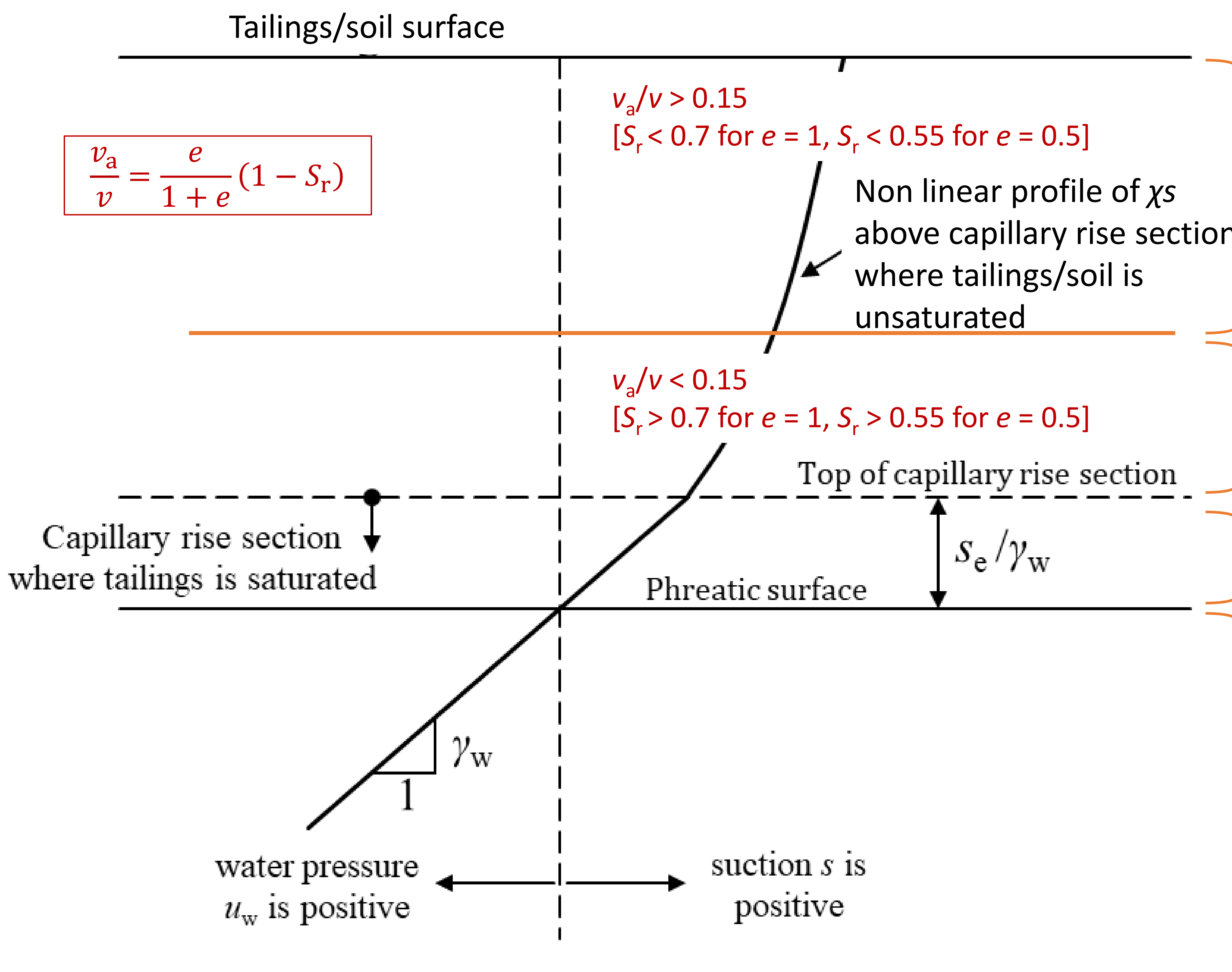
Validation - Using laboratory correlations to interpret field data



Two sets of CPT results and inferred properties from a section of unsaturated and saturated tailings inside a storage facility. A slower than standard penetration velocity was used in CPT 2 between depths of 8.48 m and 9.48 m. Also shown in (c) and (d) are e and ψ_s values determined for five piston samples taken from 8.75 m to 9.25 m depths. Red dashed lines in (c) and (d) are from Jefferies & Been screening level assessment correlations

Russell, Vo, Ayala, Wang, Reid, Fourie (2022) *Geotechnique*. (Part of TAILLIQ, LP and FT, sponsored by ARC and Anglo American, BHP, Freeport-McMoran, Newmont, Rio Tinto and Teck)

Summary (share with others)



Use either unsaturated soil mechanics, or equivalent method and total stresses (although requires estimations of χs profile to get c_{eq}, γ_{eq}). Soil/tailings will behave as pseudo drained whatever the loading rate and χs can be assumed constant. Limited concepts apply ($\frac{(q_c - p_0)}{p_0'} + 1 = \bar{k}\exp(-\bar{m}\psi)$; c_{eq}, ϕ').

Here are many knowledge gaps and uncertainties. Could use unsaturated soil mechanics, or a total stress analysis with similar load paths as field setting to establish c^T, ϕ^T.

Use saturated soil mechanics, and account for negative water pressure in effective stress which may be hydrostatic in many cases. Established concepts apply (Skempton's A, B_bar; $s_u = (q_c - \sigma_v)/N$ or $\frac{(q_c - p_0)}{p_0'} + 1 = \bar{k}\exp(-\bar{m}\psi)$; s_u/σ'_v; c', ϕ'; E', E_u)

Use saturated soil mechanics

Key messages

- Strength/stability, dealt with using:
  - Equivalent cohesion $c_{eq} = c_0' + (\chi s)_0 \tan\varphi'$
  - Equivalent unit weight $\gamma_{eq} = \gamma_t + K_c \cot\varphi' + K_{\chi s}$

  Suitable when c' and χs vary linearly with depth

$$c' = c_0' + K_c z \qquad \chi s = (\chi s)_0 + K_{\chi s} z$$

  - Can model use commercial softwares without resorting to inbuilt unsaturated soil features
- It is often adequate to capture only the contribution of suction to effective stress and ignore enhancement of φ' due to presence of suction
- Use saturated soil mechanics in capillary rise region, which can be up to 10 m above phreatic surface. Account for negative u_w when computing σ' (e.g. in CPT interpretations and stability analyses)
- Above capillary rise region use c_{eq}, φ' and γ_{eq} and a total stress analyses, as long as χs does not change much, which will be the case where $v_a/v > 0.15$. The same is not true where $v_a/v < 0.15$.
- Determination of properties/laboratory testing, especially WRC, to become less reliant on universities
- Fully coupled hydro-mechanical analyses likely to be rare and involve universities

- **Include an expert's time in your budget. A few hours may be all that is required to ensure you are on the right track and not making mistakes**

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Useful references and further reading
(consistent in the mechanics and terminology used)

Applications (written for the practitioner)

- Russell, A.R., Vo, T., Ayala, J., Wang, Y. & Reid, D. & Fourie, A.B. 2022, 'Cone penetration tests in saturated and unsaturated silty tailings', *Geotechnique*, pp. In press. Accepted 4th May 2022. (The most complete CPT study so far, with demonstrations of field application)
- Yates, K. & Russell, A.R. 2022, 'The unsaturated characteristics of natural loess in slopes, New Zealand', *Géotechnique*, doi:10.1680/jgeot.21.00042. (Shows how to interpret field suction measurements, conduct triaxial tests and combine with WRC data, and integrate results and use in stability calculations)
- Vo, T., Yang, H. & Russell, A.R. 2016, 'Cohesion and suction induced hang-up in ore passes', *International Journal of Rock Mechanics and Mining Sciences*, vol. 87, pp. 113-128, doi:10.1016/j.ijrmms.2016.05.002. (Section 3 shows the triaxial testing and interpretations using total stresses, and integration of the WRC to interpret the data in terms of c_{eq}, ϕ', with the c_{eq} dependency on gravimetric water content and void ratio captured analytically)
- Pournaghiazar, M., Russell, A.R. & Khalili, N. 2013, 'The cone penetration test in unsaturated sands', *Geotechnique*, vol. 63, no. 14, pp. 1209-1220, doi:10.1680/geot.12.P.083.
- Tang, Y., Taiebat, H. & Russell, A.R. 2018, 'Influences of suction on plate load tests on unsaturated silty sands', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 8, no. 144, article-no. 4018043, doi:10.1061/(ASCE)GT.1943-5606.0001897.
- Russell, A.R. & Reid, D. 2018, 'Pitfalls in interpretation of cone penetration test data recovered from unsaturated geomaterials', in RJ Jewell & AB Fourie (eds), *Paste 2018: Proceedings of the 21st International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 483-492, doi.org/10.36487/ACG_rep/1805_40_Russell

Underlying concepts (understandable by the practitioner)

- Vo, T. & Russell, A.R. 2017, 'Stability charts for curvilinear slopes in unsaturated soils', *Soils and Foundations*, vol. 57, no. 4, pp. 543-556, doi:10.1016/j.sandf.2017.06.005. (Underpins the equivalent method. Shows how suction contributes to strength and stability)
- Vo, T. & Russell, A.R. 2016, 'Bearing capacity of strip footings on unsaturated soils by the slip line theory', *Computers and Geotechnics*, vol. 74, pp. 122-131, doi:10.1016/j.compgeo.2015.12.016. (Underpins the equivalent method. Shows how suction contributes to strength and stability)
- Russell, A.R. 2014, 'How water retention in fractal soils depends on particle and pore sizes, shapes, volumes and surface areas', *Geotechnique*, vol. 64, no. 5, pp. 379-390, doi:10.1680/geot.13.P.165. (How to make WRC curves independent of void ratio, and how to identify and exploit fractal properties of soils)
- Khalili, N. and Khabbaz, M.H. (1998). Unique relationship for χ for the determination of the shear strength of unsaturated soils. *Géotechnique* **48**, No. 5, 681-687. (Development of χ and the suction contribution to effective stress)
- Loret, B. & Khalili, N. (2002). An effective stress elastic-plastic model for unsaturated porous media. *Mechanics of Materials* **34,** 97–116. (Extension of a cam-clay type model. Explains concept of suction hardening and suction dependant CSLs and NCLs)
- Khalili, N. (2018). Guidelines for the application of effective stress principle to shear strength and volume change determination in unsaturated soils. *Australian Geomechanics Journal*. 53 (1), 37-47. (Good general overview)