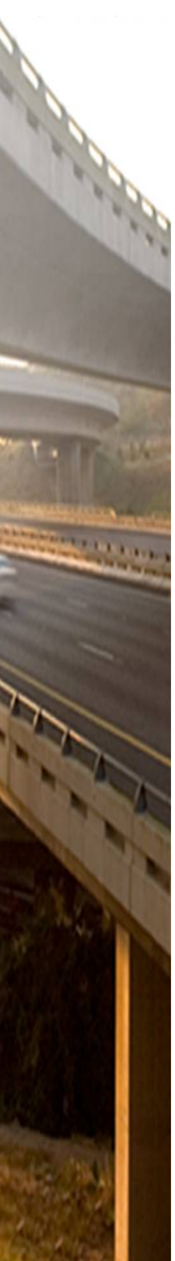
Revision of the Flexible Pavement Design Method Phase 3

Industry feedback – 17th RPF

14 May 2009

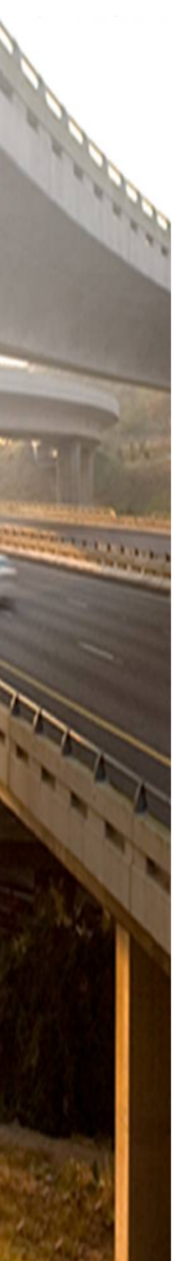
H L Theyse



ME-design model for unbound material

- Components
  - Resilient response - SAPDM/B-1a
    - Resilient modulus (stiffness)
    - Poisson's ratio
  - Yield strength or shear strength - SAPDM/D-2
  - Damage model - SAPDM/D-2
    - Permanent deformation - plastic strain
- Preliminary model development based on available data

ME-design model for unbound material



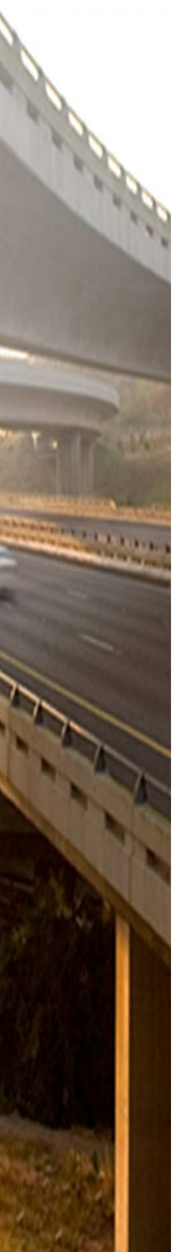
- Models complicated
- Relate model parameters to basic engineering parameters
  - Grading
  - Atterberg indicators
  - Density
  - Moisture content (saturation)
- Hide complexity behind engineering interface

Project SAPDM / B-1a
Resilient response modelling for unbound material

Planned tasks – SAPDM / B-1a

Task	Activity	Deliverable number
Density, saturation and stress-dependent resilient modulus (chord modulus) models for unbound granular material (1)	Refine model formulation (a)	B-1a/1(a)
	Models for realistic density estimates (b)	B-1a/1(b)
	Validation of SA model moisture sensitivity (c)	B-1a/1(c)
Density, saturation and stress-dependent tangent modulus models for unbound granular material (2)	Model formulation and calibration (a)	B-1a/1(b)
Predictive resilient modulus models for unbound granular material and material modelling related to project SAMDM/B-2 [4(a)]		B-1a/4(a)

Resilient modulus model refinement

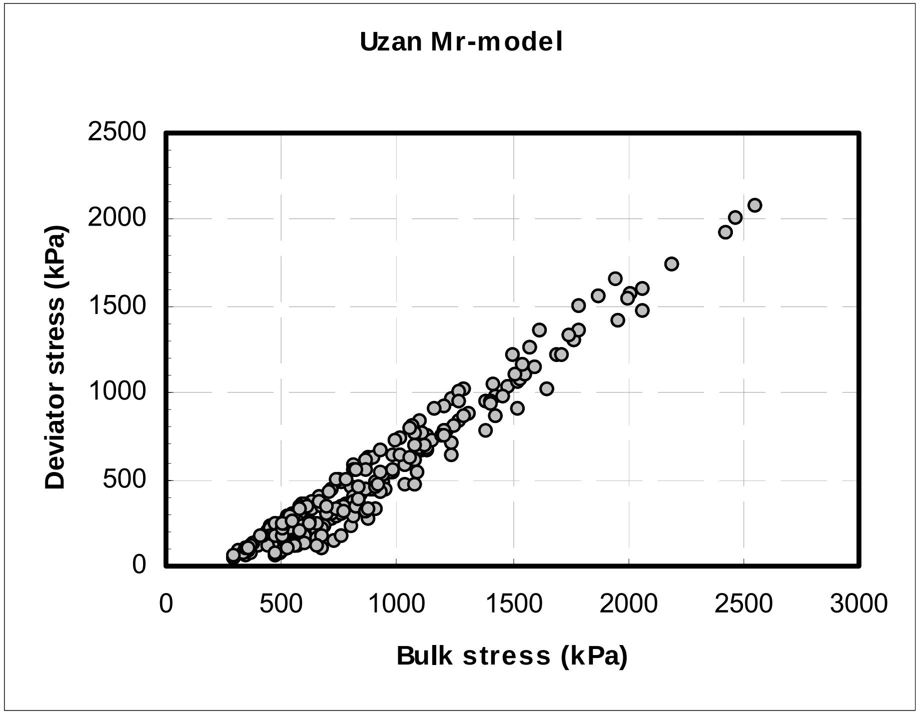


- Objectives
  - Rectify model formulation and include significant variables
  - Ensure model satisfies statistical requirements for regression
  - Explore development of predictive model for design
  - Provide guidance on additional work

Current model: Uzan

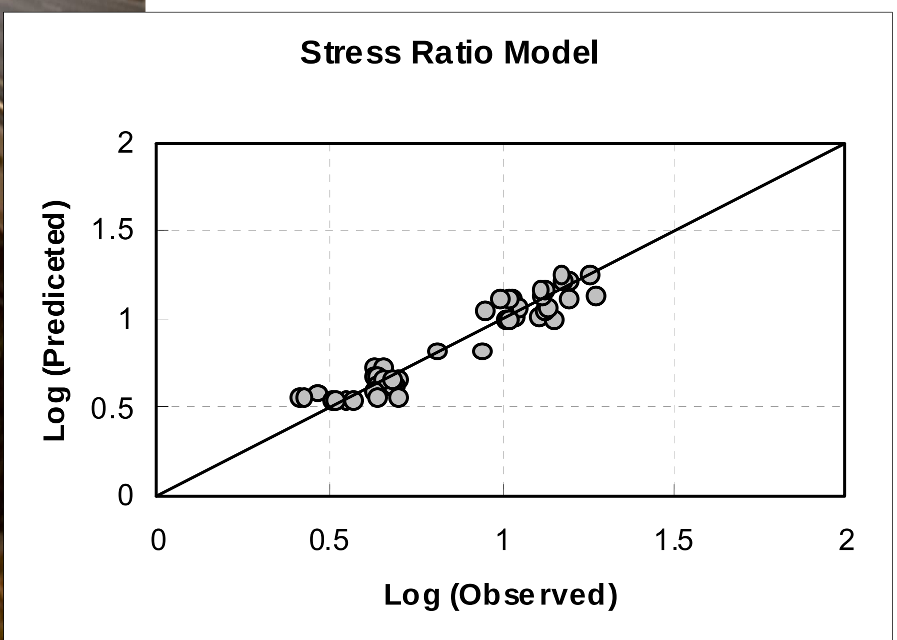
$$M_r = p_{atm} 10^{K_0} \left(\theta' / p_{atm} \right)^{K_1} \left(\sigma_d / p_{atm} \right)^{K_2}$$

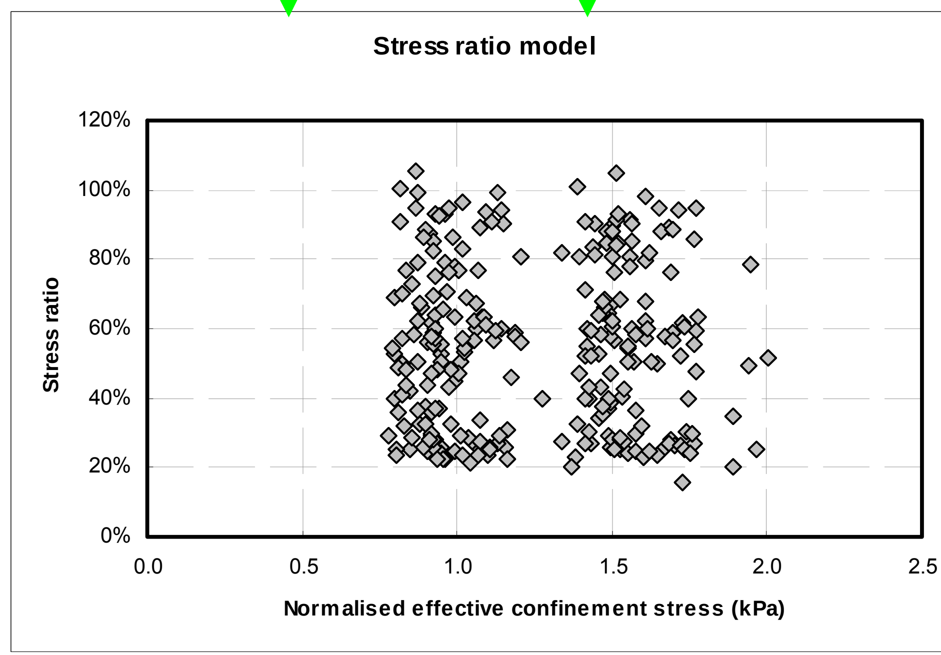
- Problems
  - Does not include density and saturation
  - Does not satisfy statistical requirements



1st alternative: SR-model for individual materials

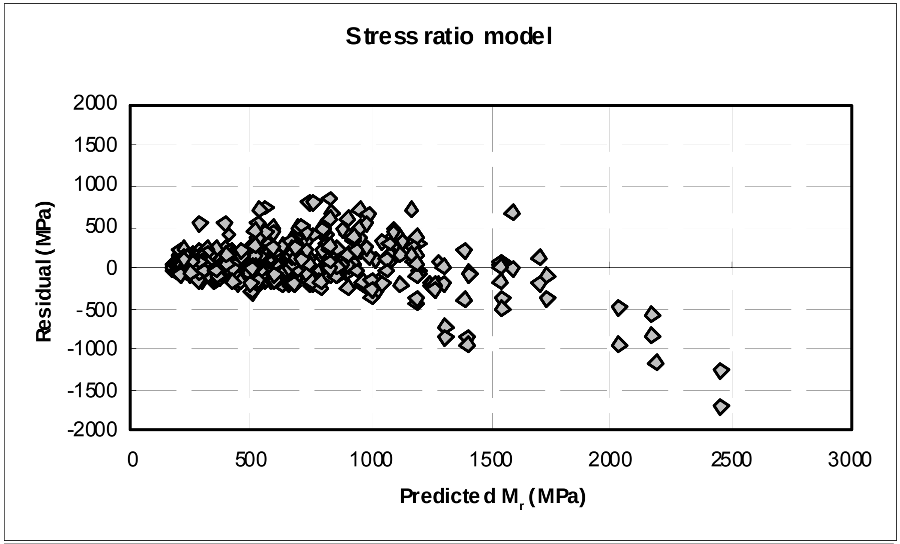
$$M_r = p_{atm} 10^{K_0} VD^{K_{VD}} S^{K_S} \left(\frac{\sigma'_3}{p_{atm}} \right)^{K_C} \left(\frac{\sigma'_1}{\sigma_1^y} \right)^{K_{SR}}$$

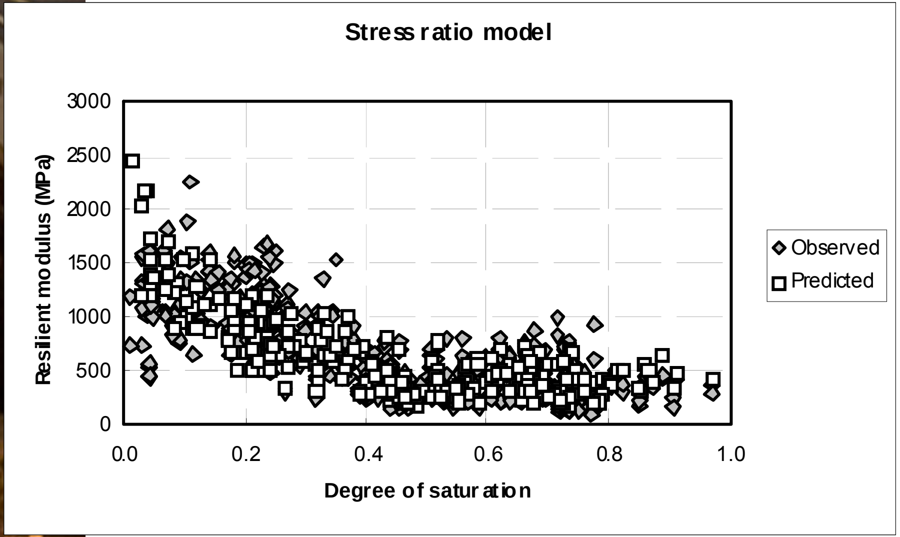


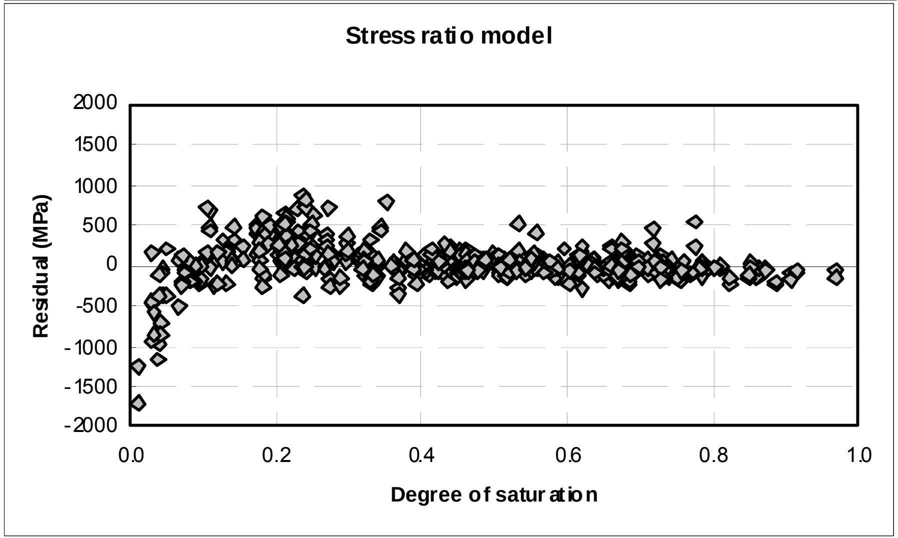


Design model: SR-model for combined materials

- Problems
  - Model over estimates stiffness at low saturation

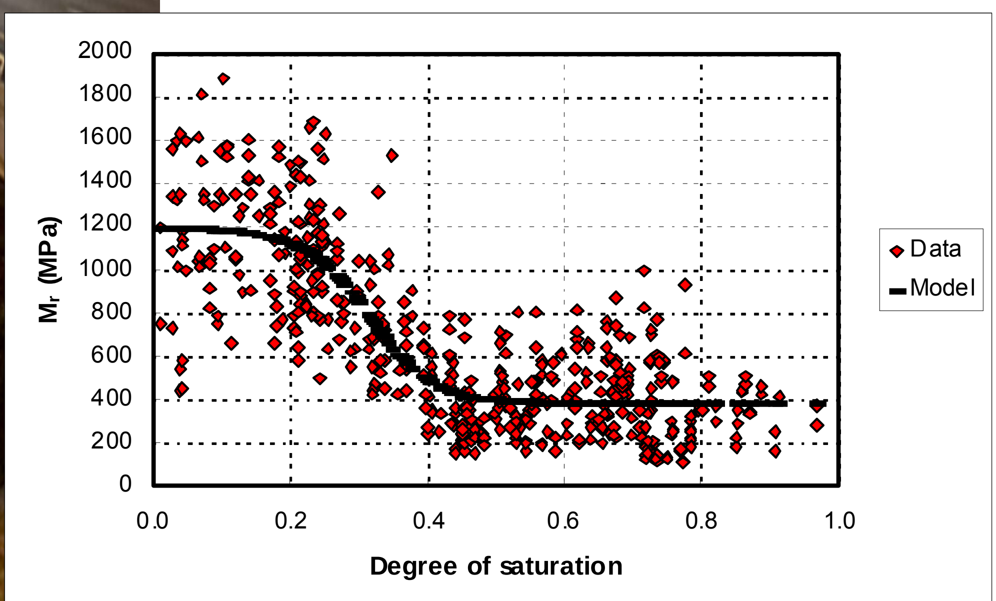


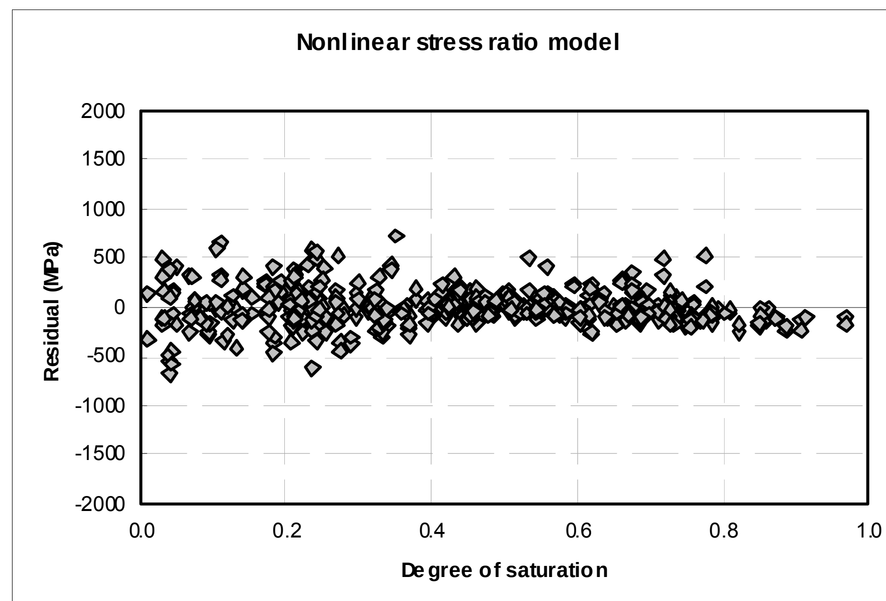




2nd alternative: NLSR-model or Theyse Mr model

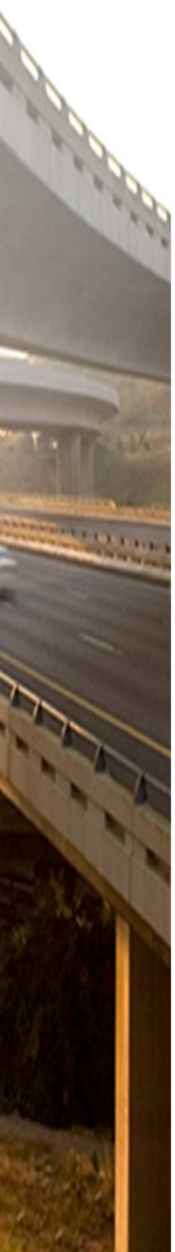
$$M_r = p_{atm} K_0 VD^{K_{VD}} \left\{ \frac{\exp\left[d\left(S-s\right)\right]+1}{\frac{1}{b}+\frac{1}{a}\exp\left[d\left(S-s\right)\right]} \right\} \left(\frac{\sigma_3'}{p_{atm}} \right)^{K_C} \left(\frac{\sigma_1'}{\sigma_1^y} \right)^{K_{SR}}$$





Aspects of model calibration

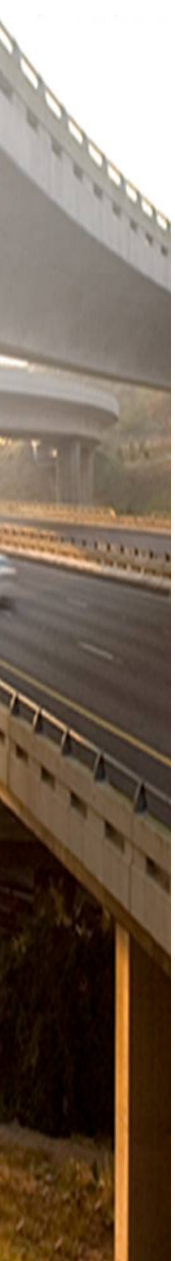
- Calibration - extreme caution
  - Model for all materials combined
    - Explains inter-material variation but not intra-material variation
  - Crushed stone
    - Single model calibrated without material bias
  - Crushed gravel
    - Calibrated for one material
  - Natural gravel
    - No single saturation-stiffness relationship



Aspects of design application

- Model formulated in terms of effective stress - suction pressure estimates required
  - SAPDM/D-2 predictive models available
- Accurate yield strength estimates required
  - SAPDM/D-2
- Formulation appears complicated but model reduces to stress-stiffening, stress-softening model for given density and saturation levels

$$M_r = p_{atm} K_0 VD^{K_{VD}} \left\{ \frac{\exp\left[d\left(S-s\right)\right]+1}{\frac{1}{b}+\frac{1}{a}\exp\left[d\left(S-s\right)\right]} \right\} \left(\frac{\sigma_3'}{p_{atm}}\right)^{K_C} \left(\frac{\sigma_1'}{\sigma_1^y}\right)^{K_{SR}}$$

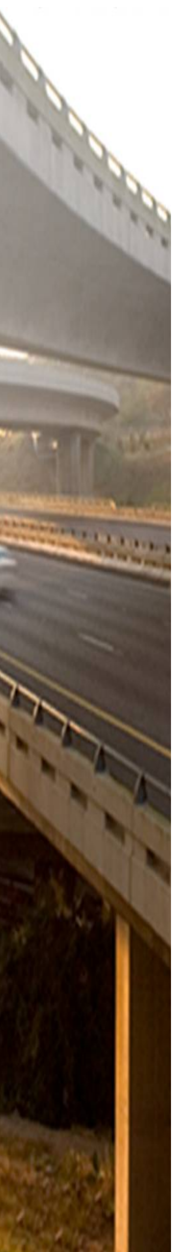


Aspects of design application (continued)

- Density and saturation terms included in pre-processing
- Stress-dependent terms require feedback from continuum mechanics model and an iterative solution
  - ELSYM5 becomes a bit more complicated, more like ELSYM50
- Implementation in primary pavement response model (SAPDM/C-3)
  - Stress-dependent Poisson's ratio model, Bonaquist and Witczak (1997)
  - NLSR resilient modulus model

Future work under project B-1a

- Focus on moisture sensitivity of natural gravel material, test at
  - 10 % saturation
  - 20 - 25 % saturation
  - 35 - 40 % saturation
  - 80 % saturation
- Test additional crushed gravel material
- Assess prediction accuracy
  - data other than calibration data set

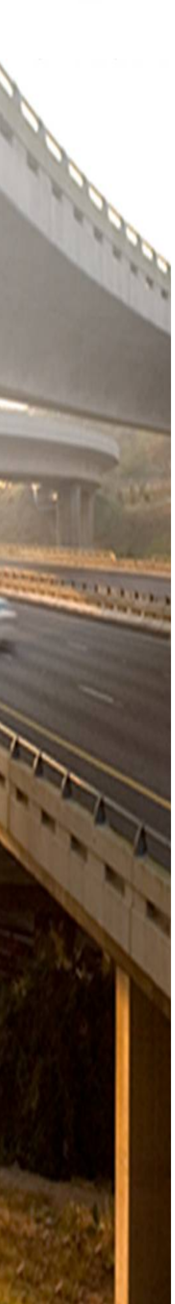


Project SAPDM / D-2
Damage modelling for unbound material

Planned tasks

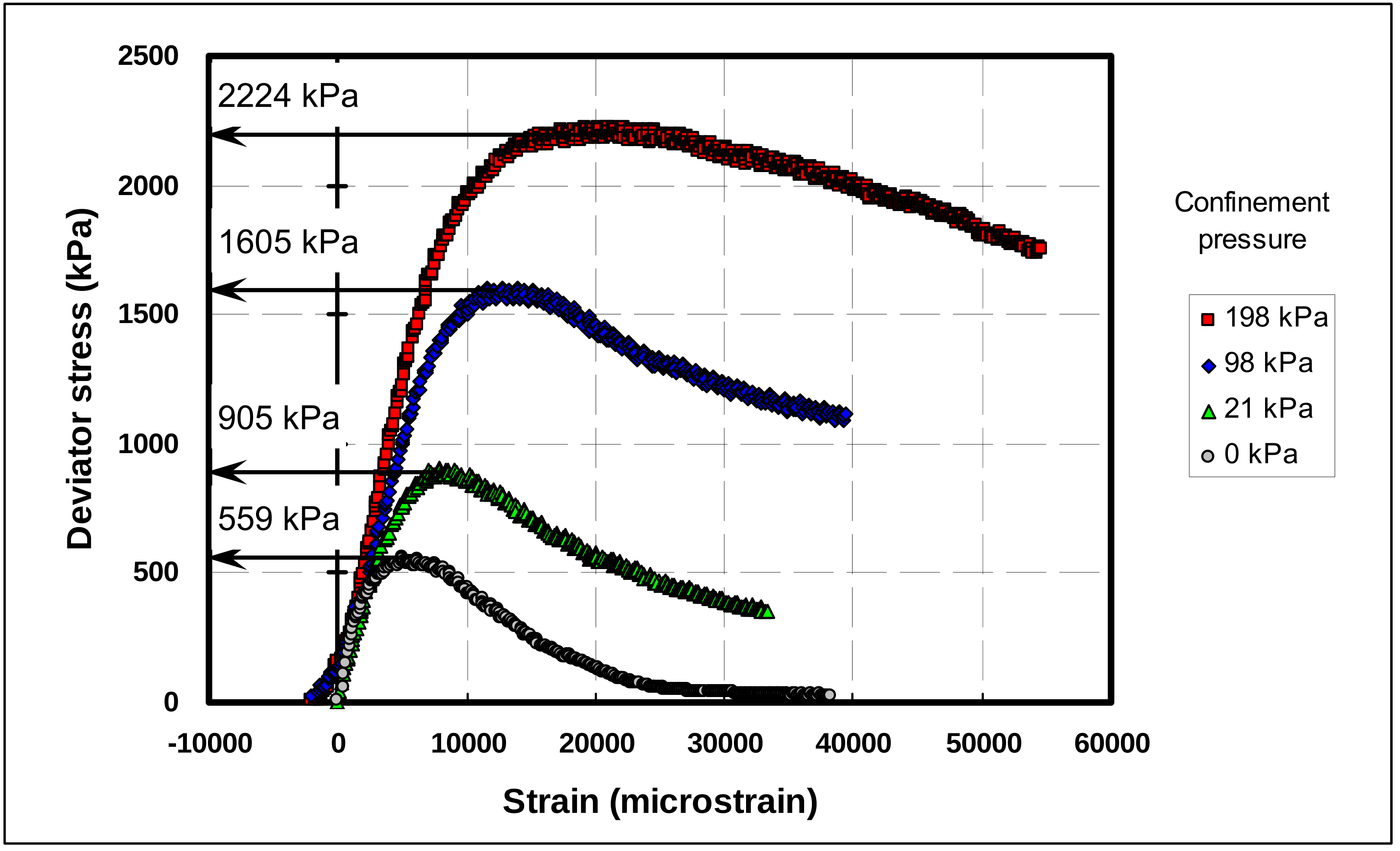
Task	Activity	Deliverable number
Permanent deformation damage models for pavement subgrades (1)	Process W-Cape HVS data (a)	D-2/1(b)
	Calibrate S-N subgrade PD model (b)	
	Calibrate continuous model for recursive analysis (c)	D-2/1(c)
Yield strength models for unbound granular material (2)	Assess NCHRP SWCC predictive model (a)	D-2/2(a)
	SWCC predictive model for SA material (b)	D-2/2(b)
	Calibrate predictive yield strength model (c)	D-2/2(c)
Plastic strain damage models for unbound material (3)	Calibrate S-N type PS model for natural gravel (a)	D-2/3(a)
	Calibrate continuous PS model for recursive analysis (b)	D-2/3(b)

Yield strength of unbound material

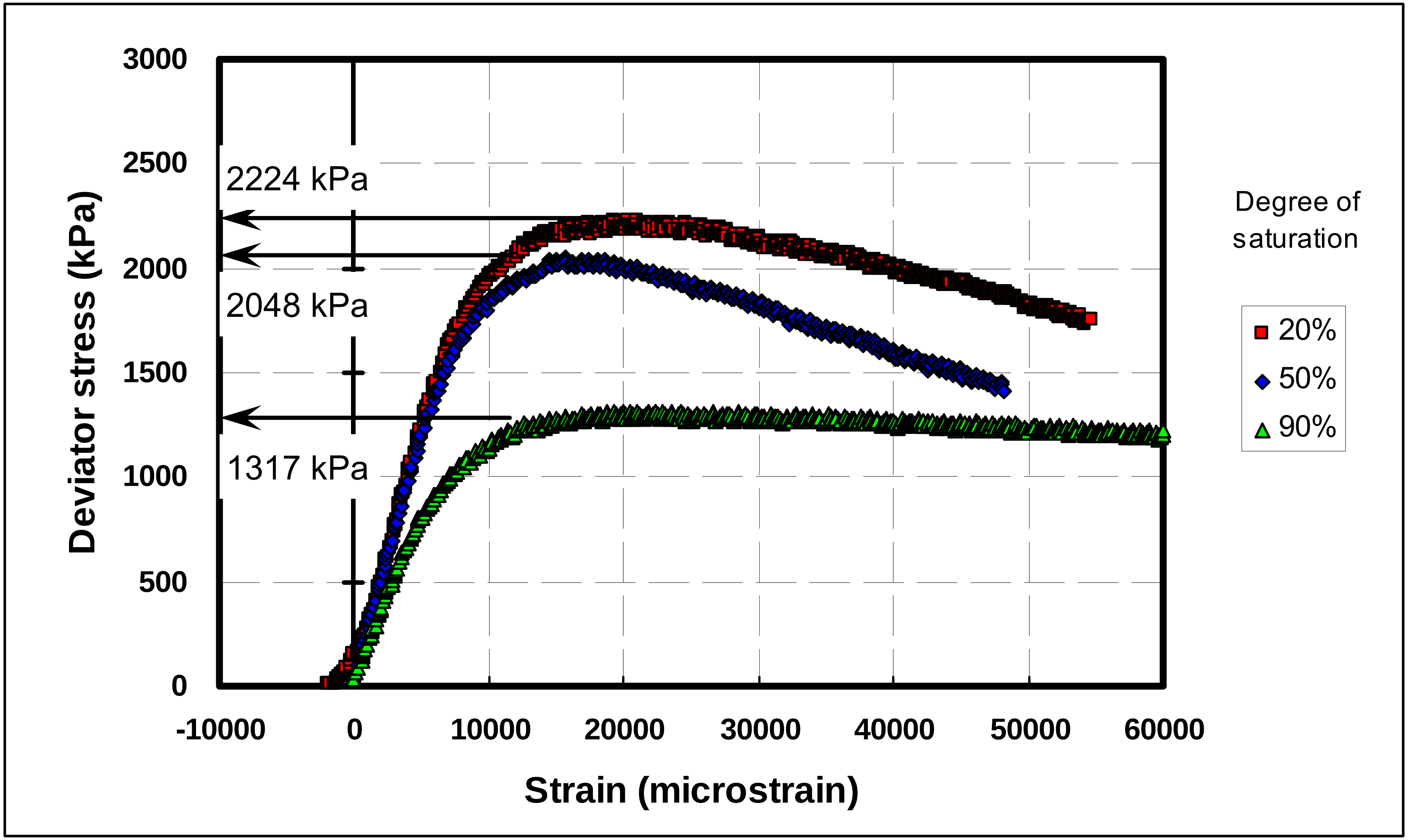


- All aspects of unbound material behaviour affected by yield strength
  - Resilient modulus and Poisson's ratio affected by stress ratio
    - Yield strength in stress ratio
  - Plastic strain related to stress ratio
    - yield strength in stress ratio
- Suction pressure affects
  - Effective stress
  - Yield strength

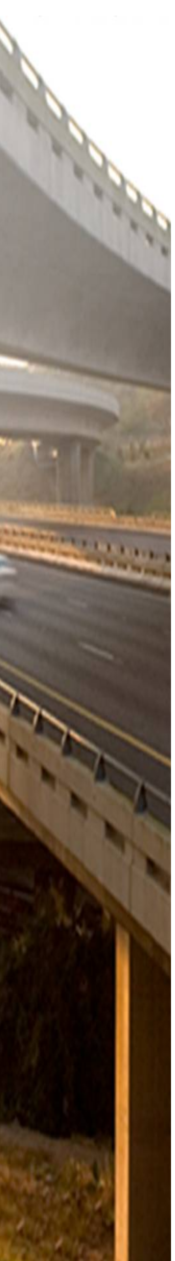
Yield strength of partially saturated, unbound granular material

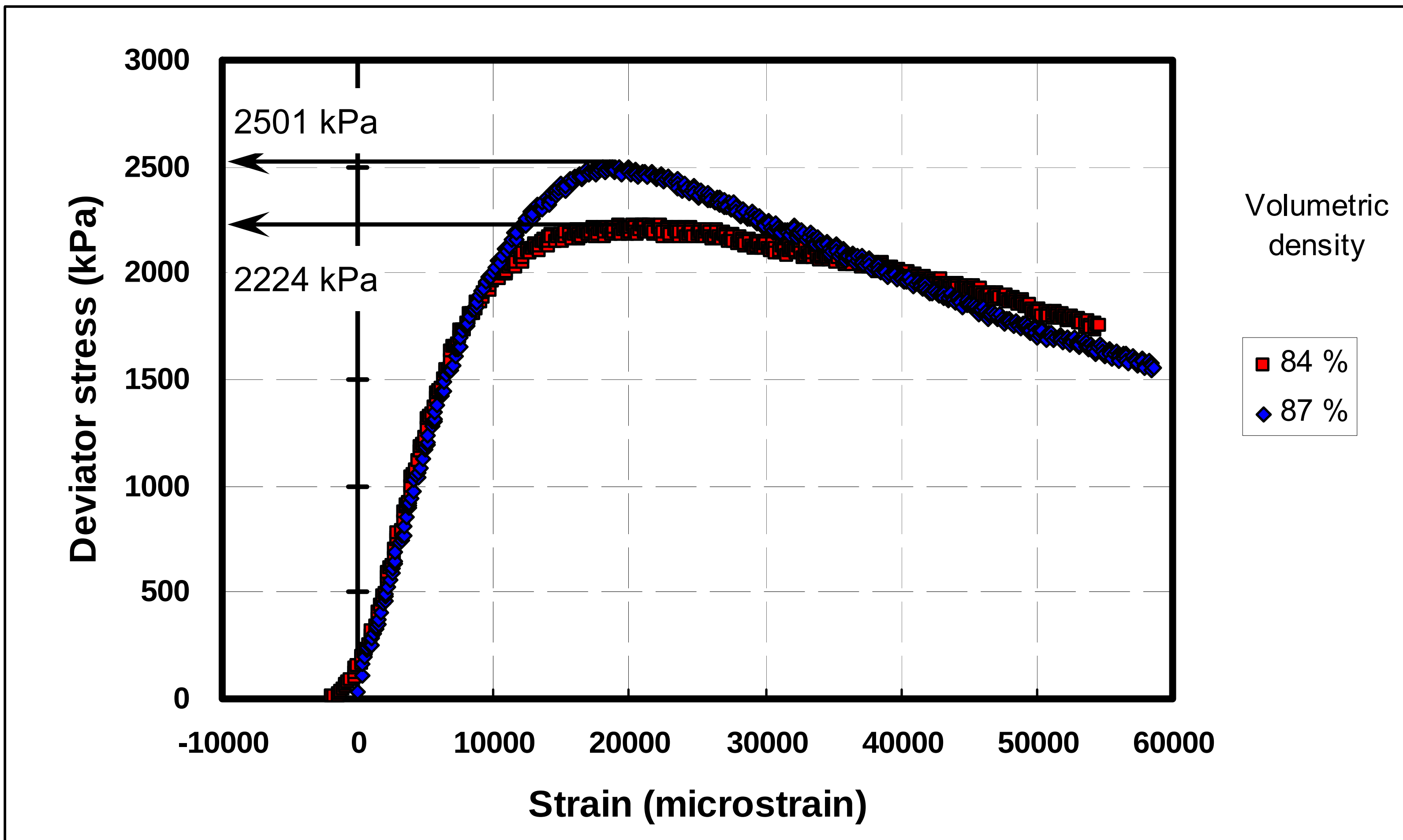


Yield strength of partially saturated, unbound granular material

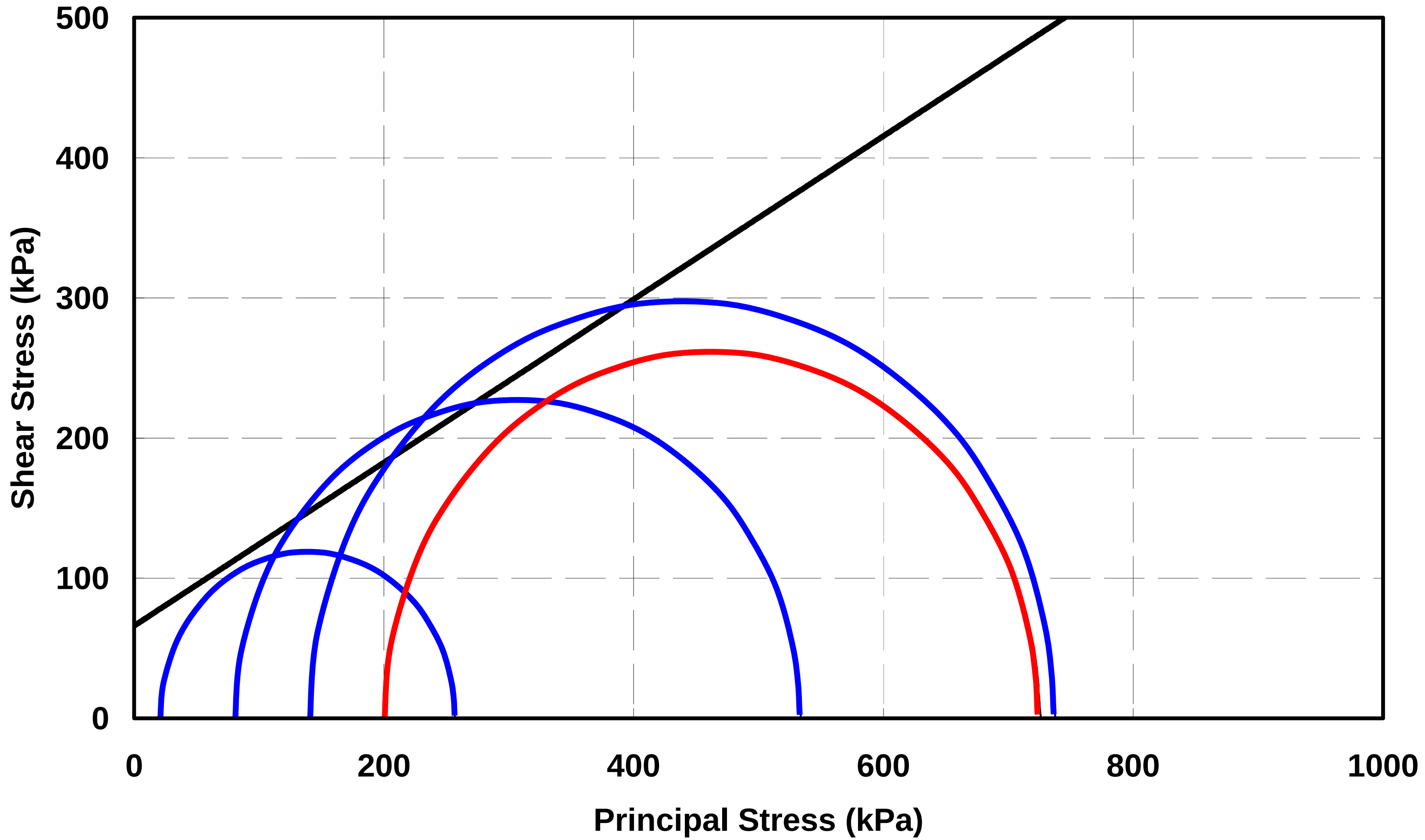


Yield strength of partially saturated, unbound granular material





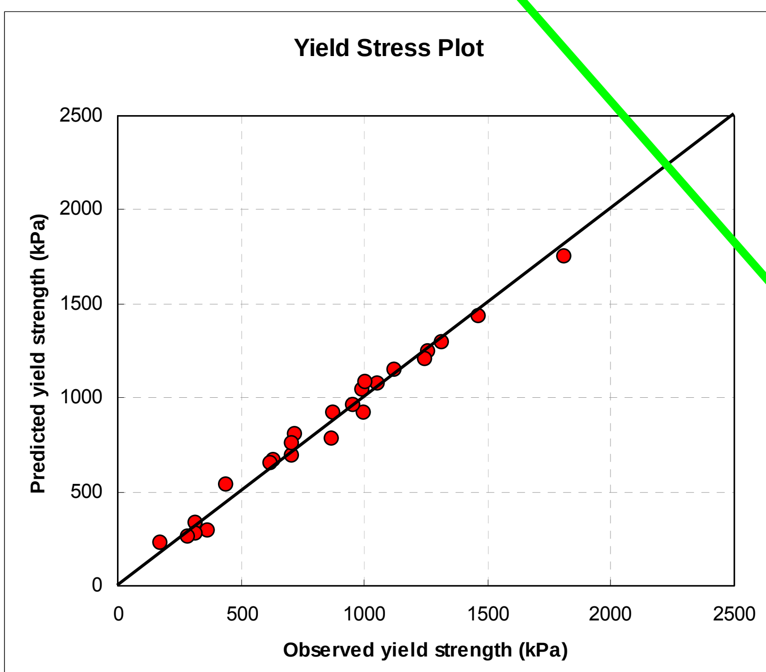
Yield strength of partially saturated, unbound granular material



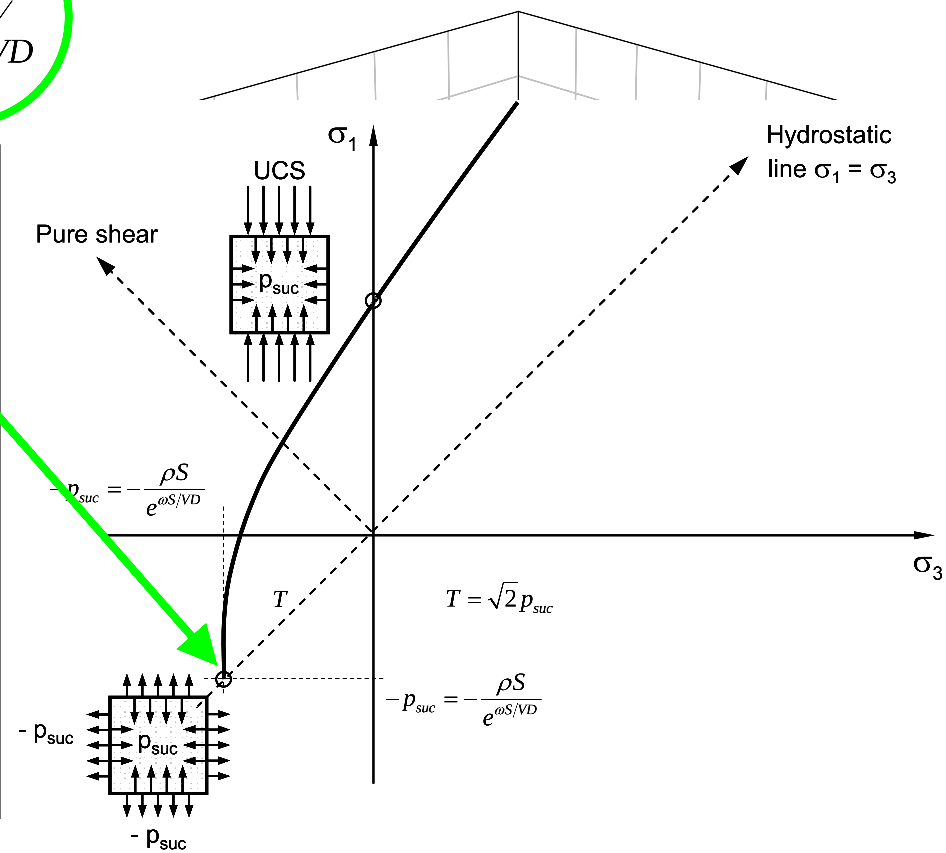
Yield strength of partially saturated, unbound granular material

$$\sigma_1^y = \frac{e^{aVD}}{e^{bS}}\left(\sigma_3 + p_{suc}\right)^c - p_{suc}$$

$$= \frac{e^{aVD}}{e^{bS}}\left(\sigma_3 + \frac{\rho S}{e^{\omega S / VD}}\right)^c - \frac{\rho S}{e^{\omega S / VD}}$$



Yield Strength Model with Suction Pressure
Shale base (P10-2)

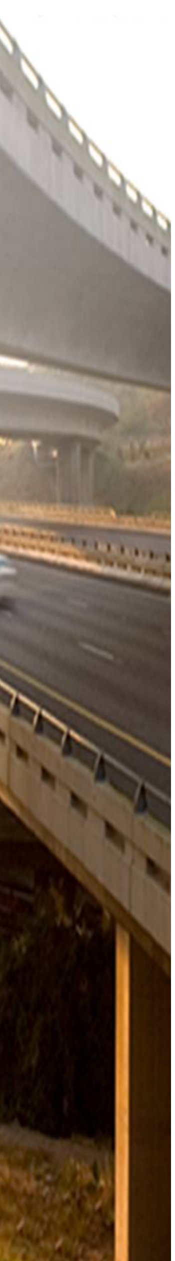


STEP 1: Suction pressure model

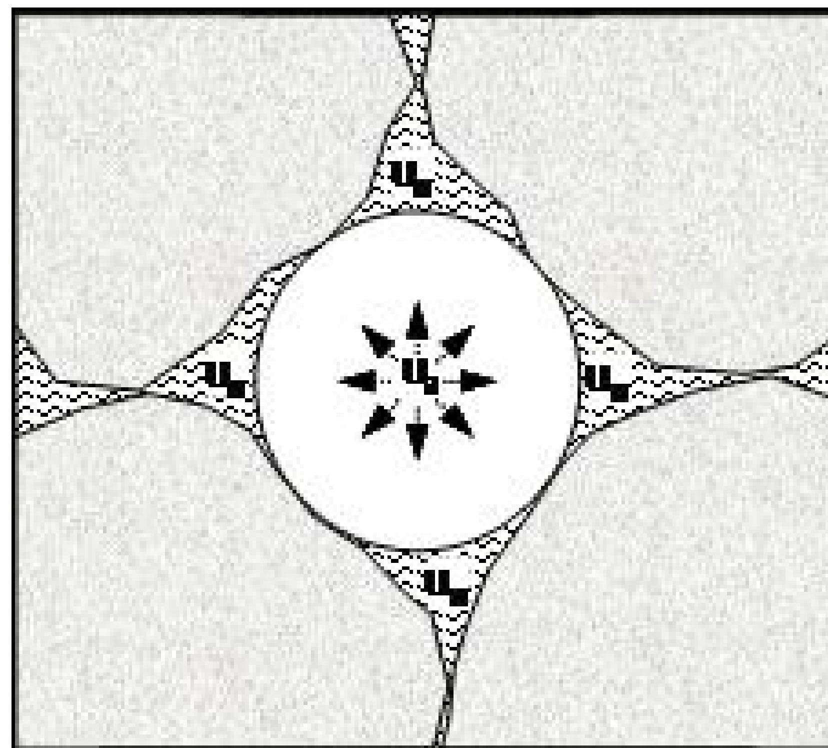
- Objective
  - Explore the development of predictive SWCCs for SA unbound materials
  - SWCC → Matric suction → suction pressure
  - Options
    - NCHRP 1-37a
    - Heath
    - Theyse

Suction pressure, matric suction, SWCC?

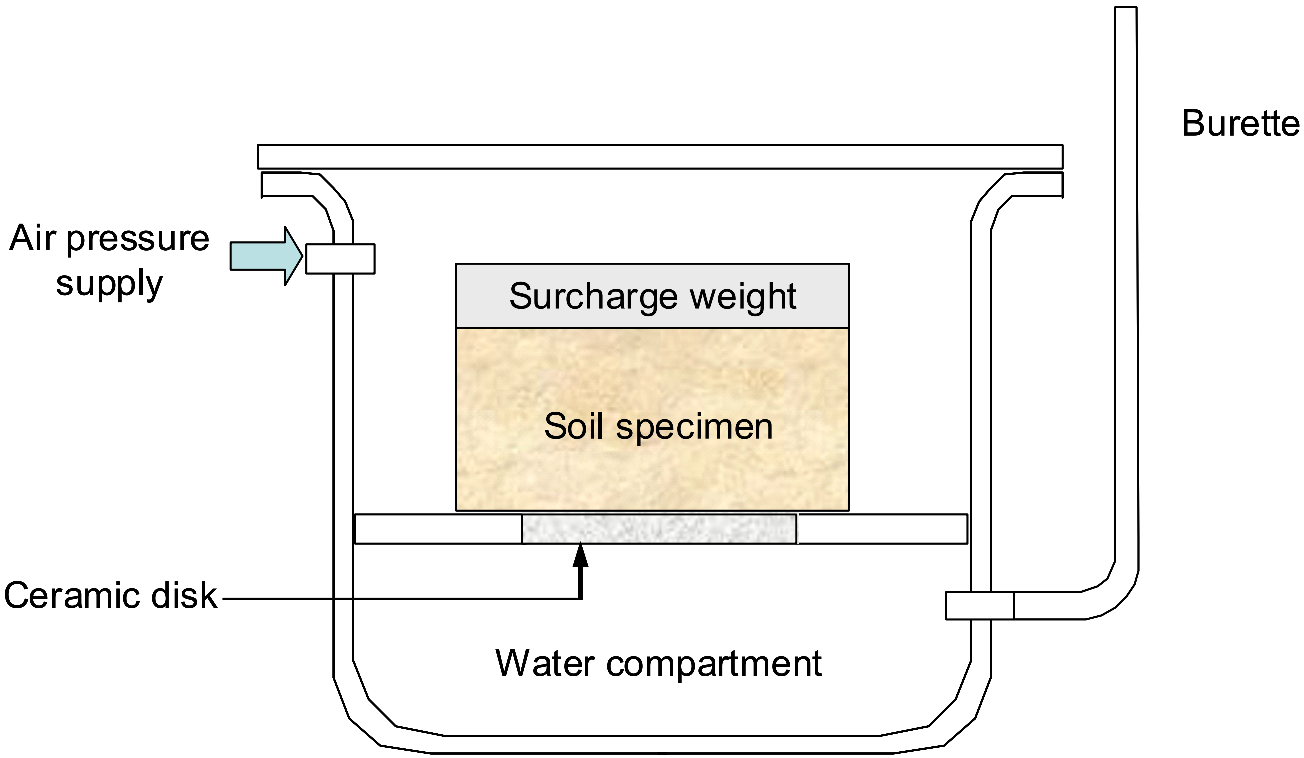
$$matric\ suction = (u_a - u_w)$$



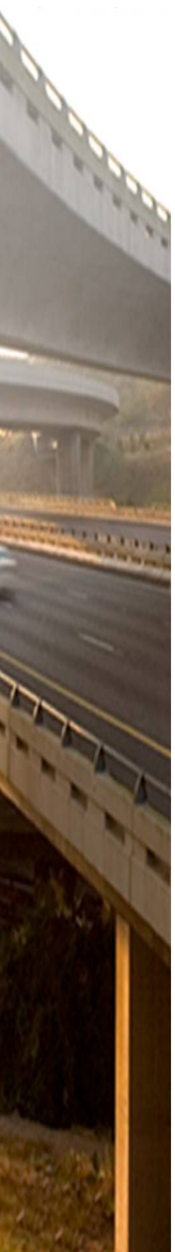
- Matric suction
  - Measure of how easy it is to expel water from material
- SWCC
  - Relationship between matric suction and saturation

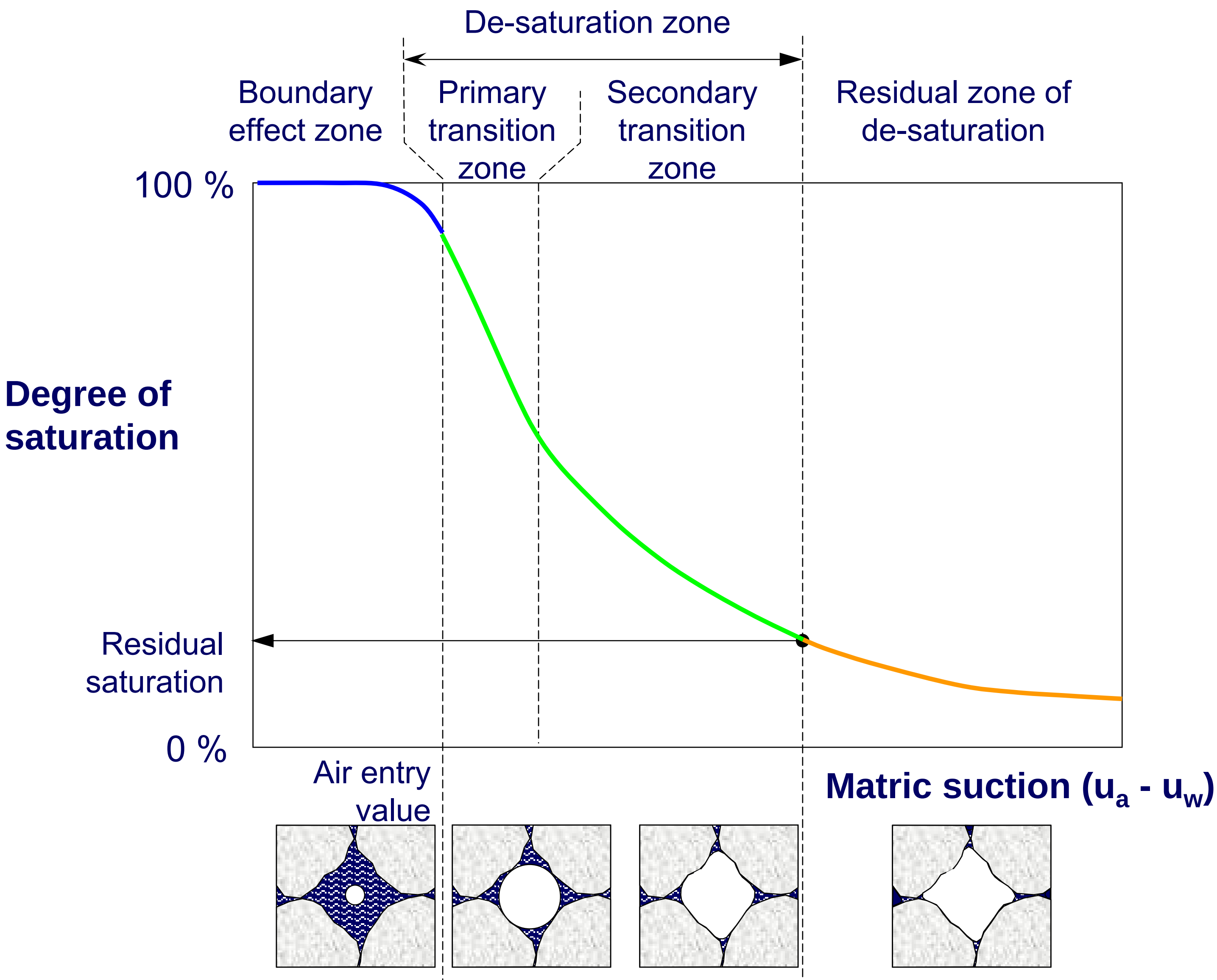


Soil-water characteristic curve – pressure plate equipment



Soil-Water characteristic curve



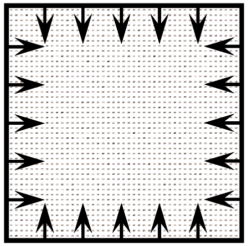


Matric suction and effective stress

- Bishop
  - Suction pressure = Bishop parameter x matric suction
- Heath
  - Suction pressure ≅ Saturation x matric suction

$$p_{suc} = S\left(u_a - u_w\right)$$

Internal stress



Soil suction

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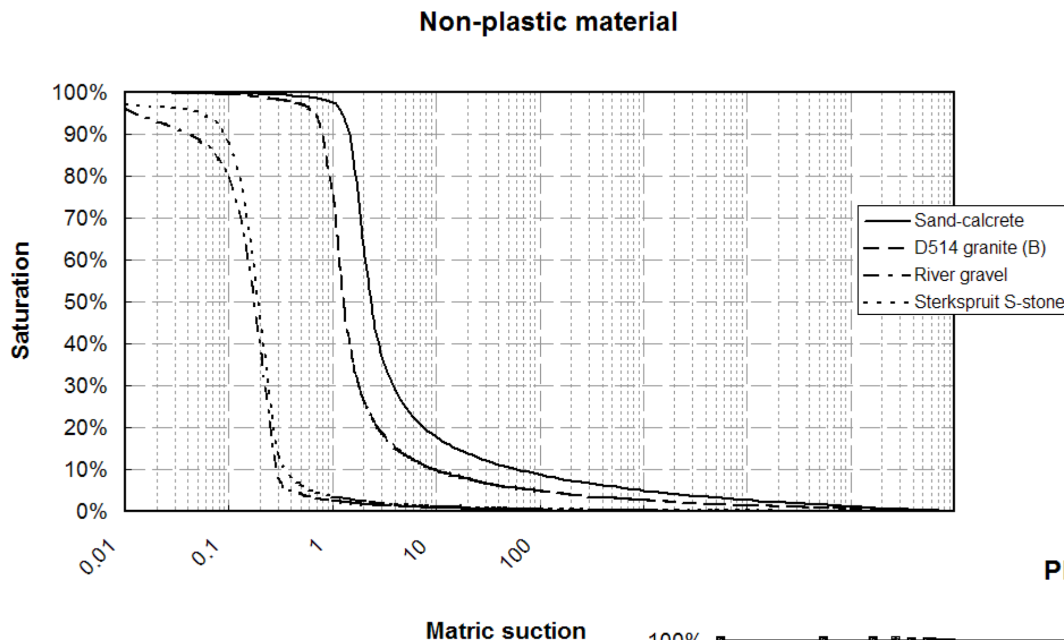
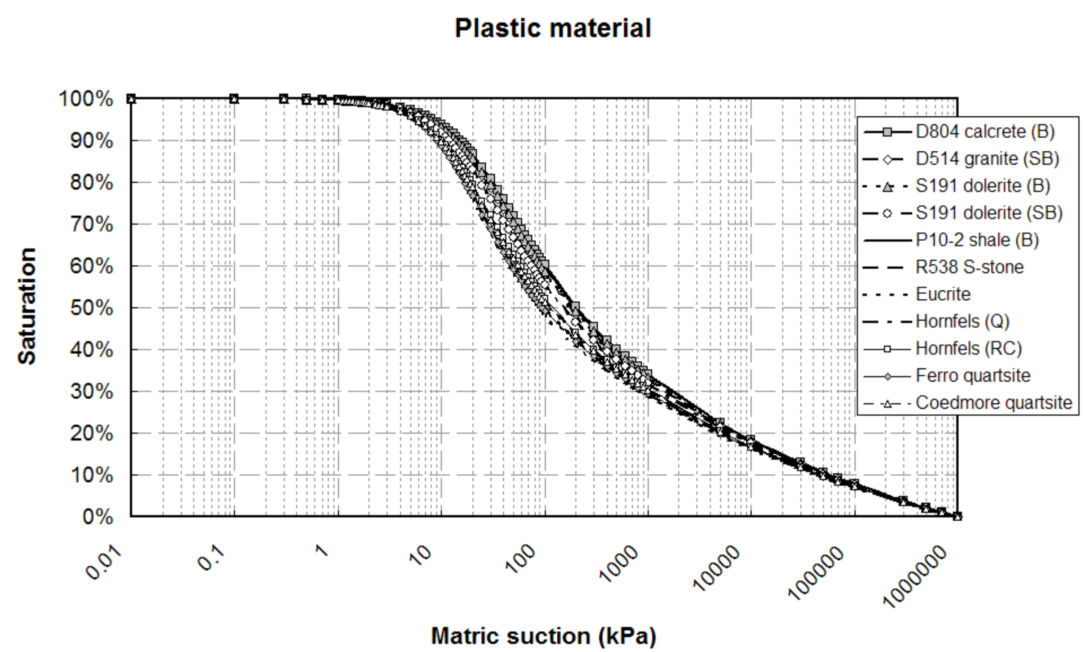
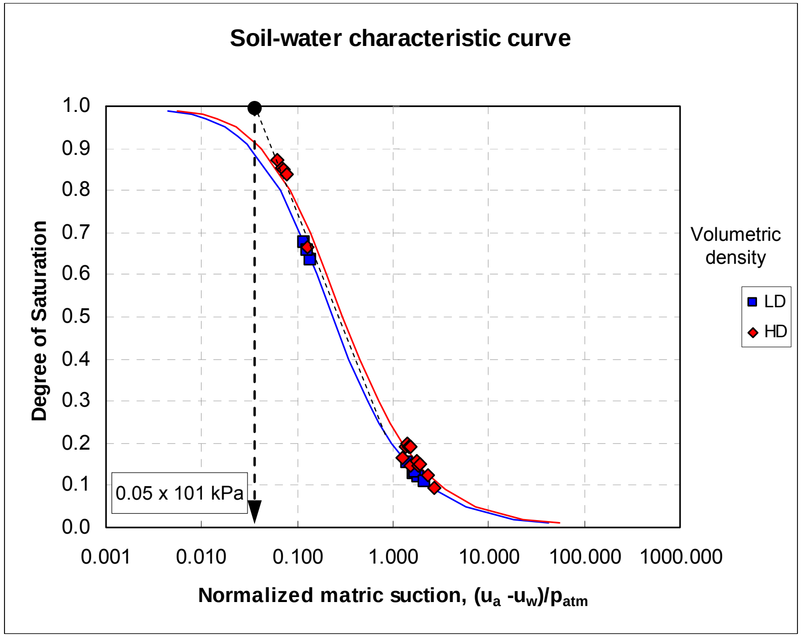
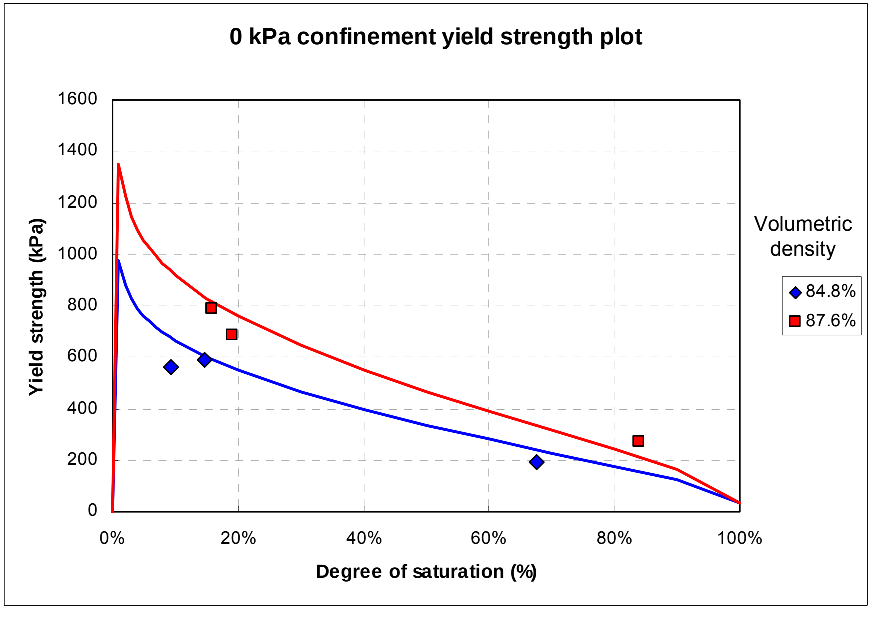
Option 1: NCHRP 1-37a SWCCs



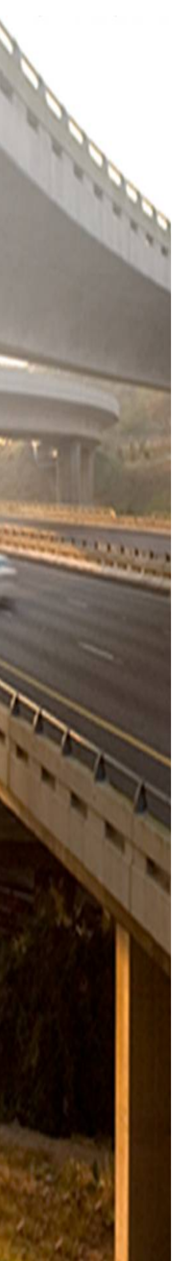


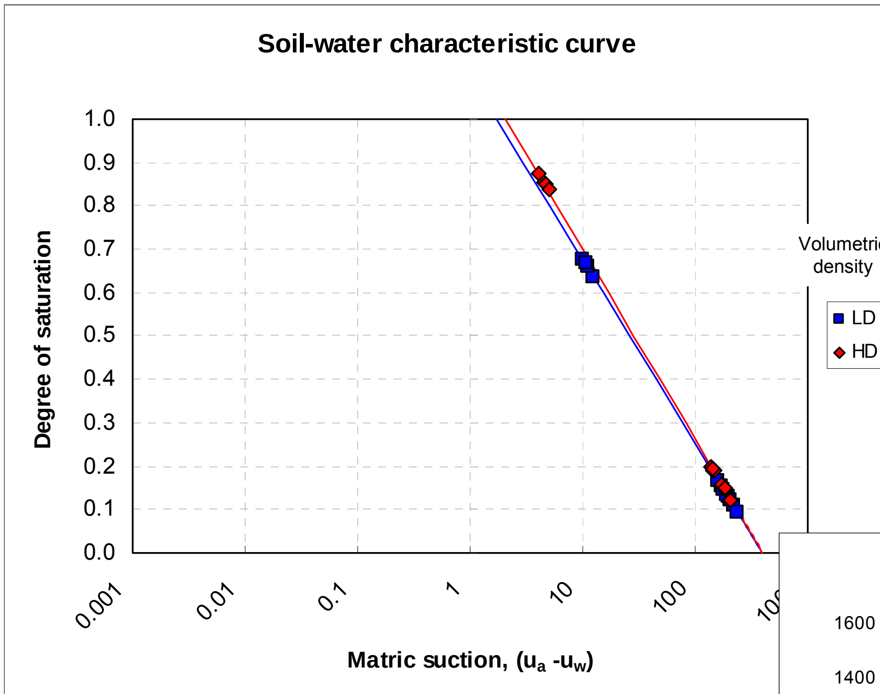
Option 2: Heath SWCC from suction pressure model

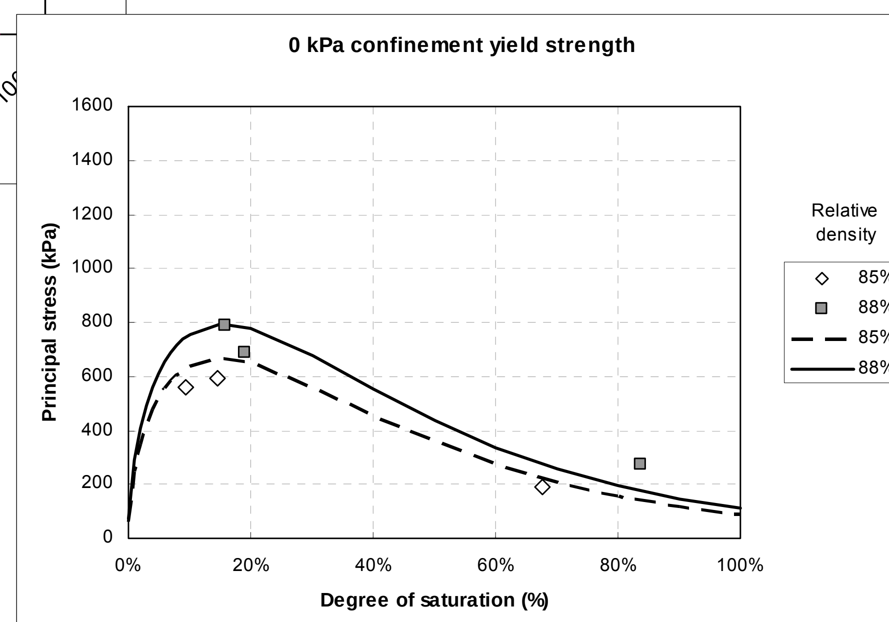




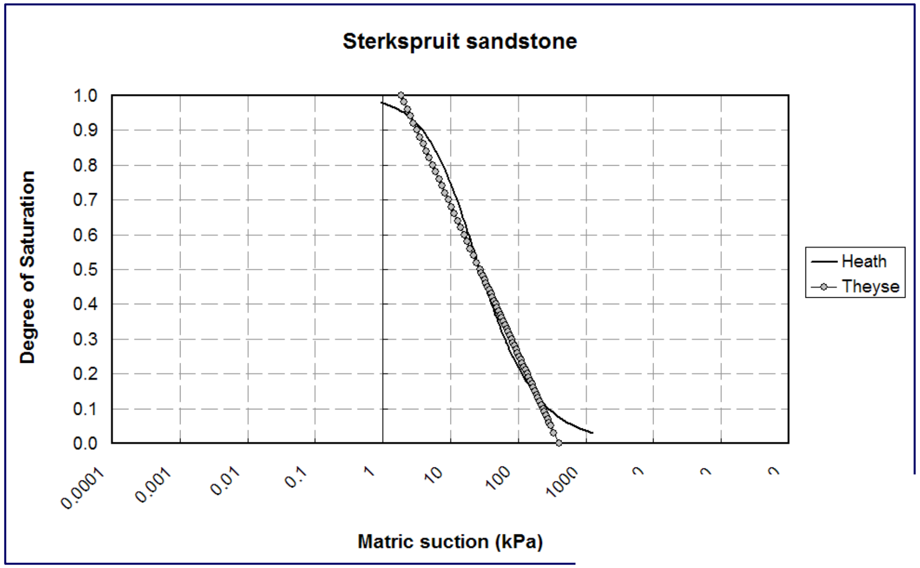
Option 3: Theyse SWCC from suction pressure model

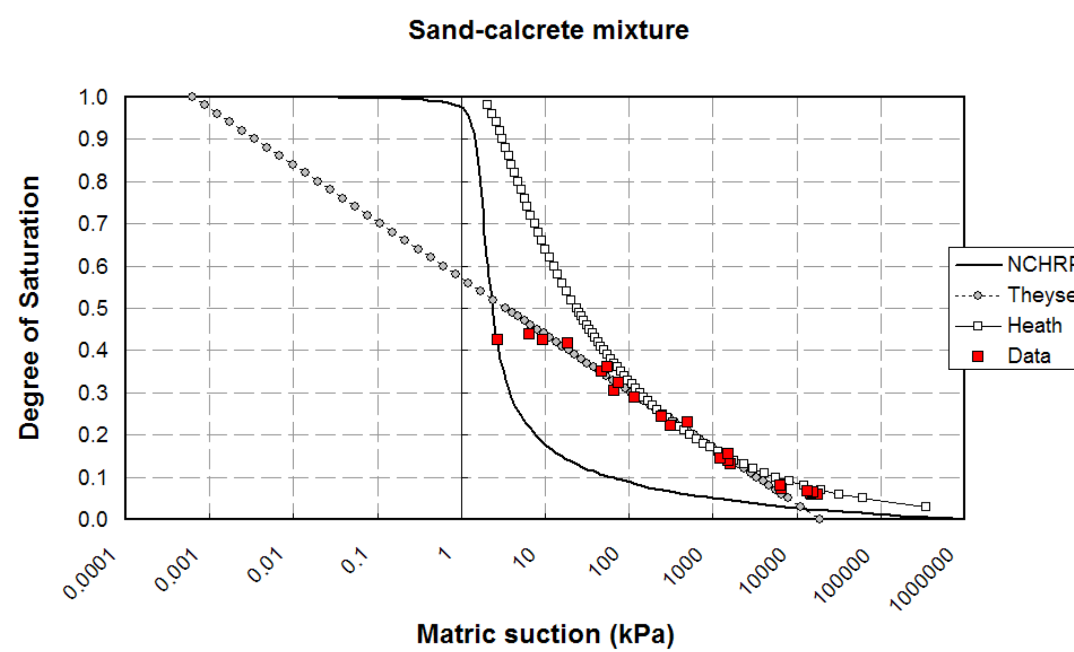




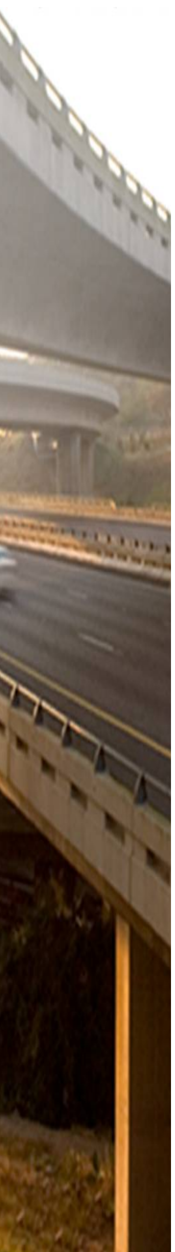


Heath - Theyse comparison

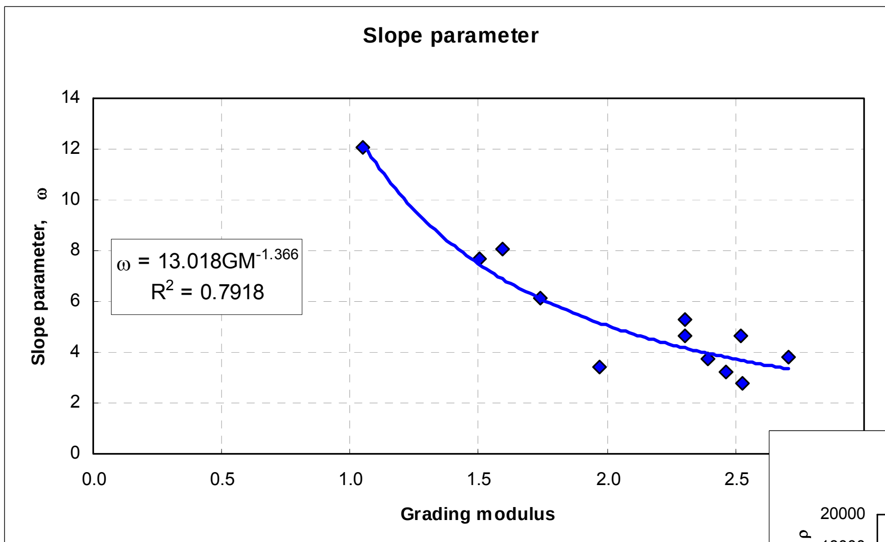


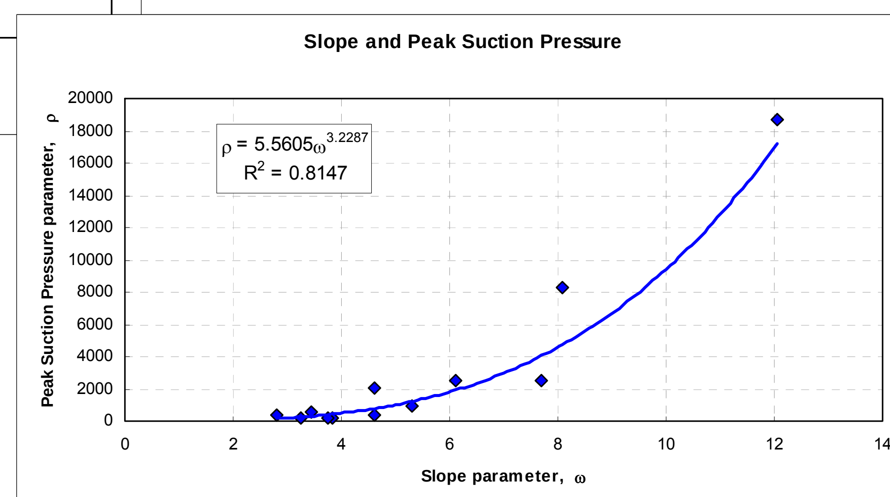


Predictive model development

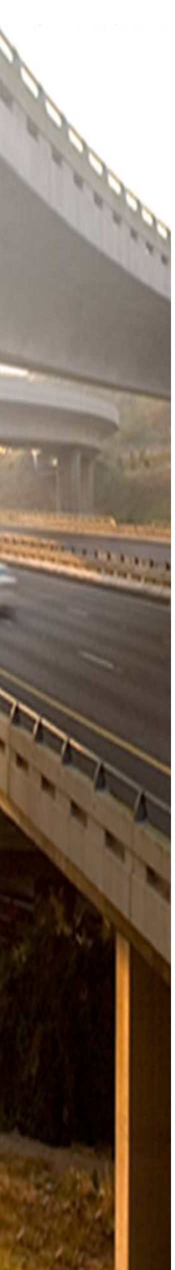


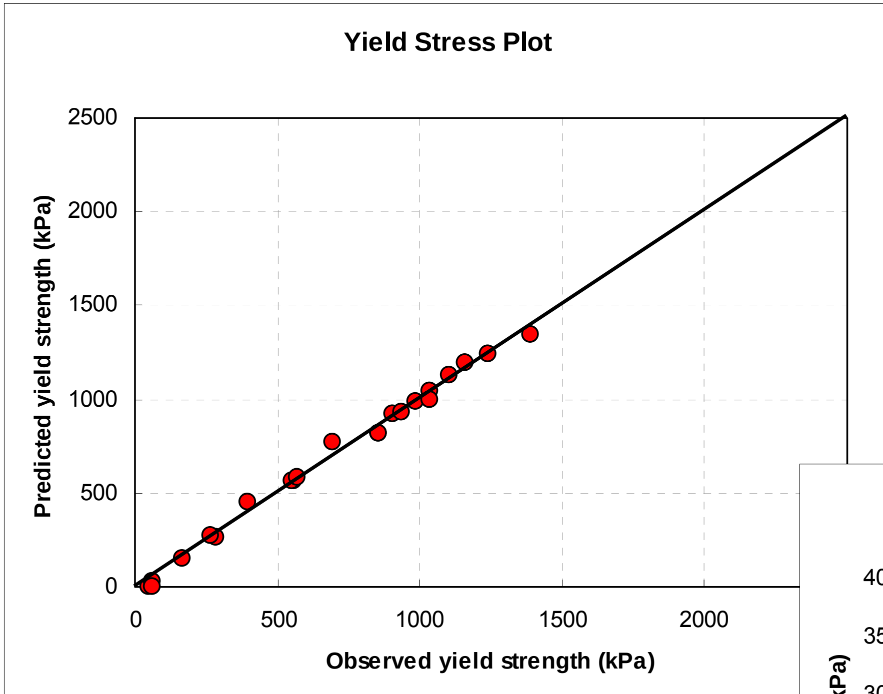
$$p_{suc} = \frac{\rho S}{e^{\omega S/VD}}$$

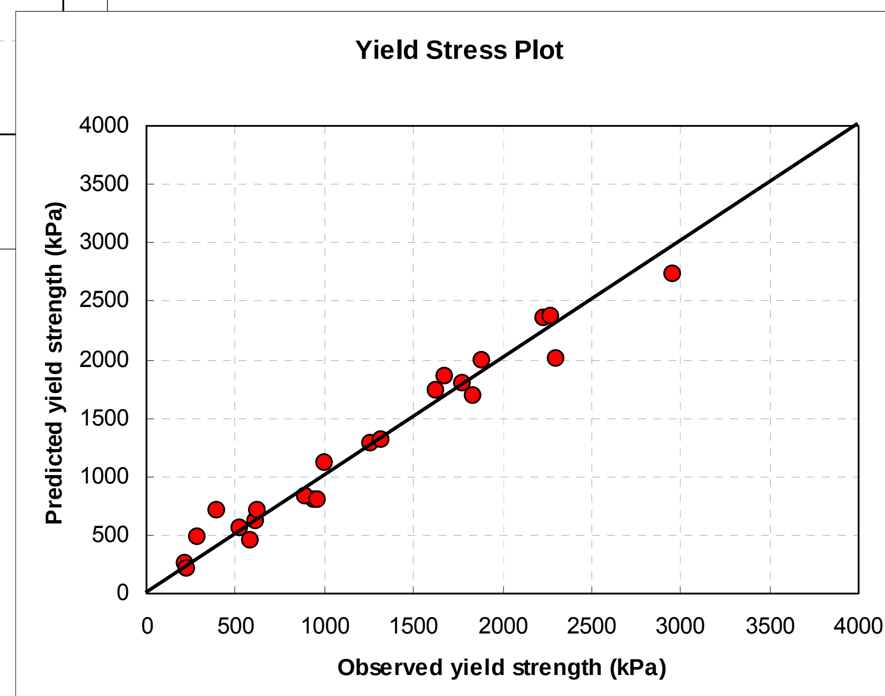


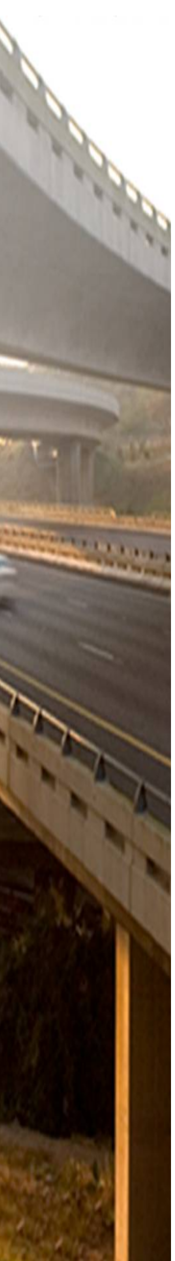


How does the predictive P_{suc} model affect ability to model yield strength?





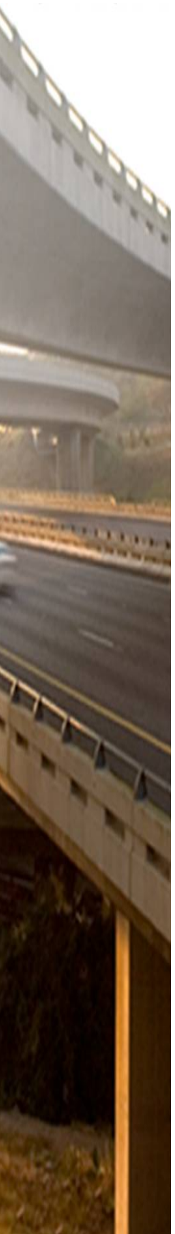


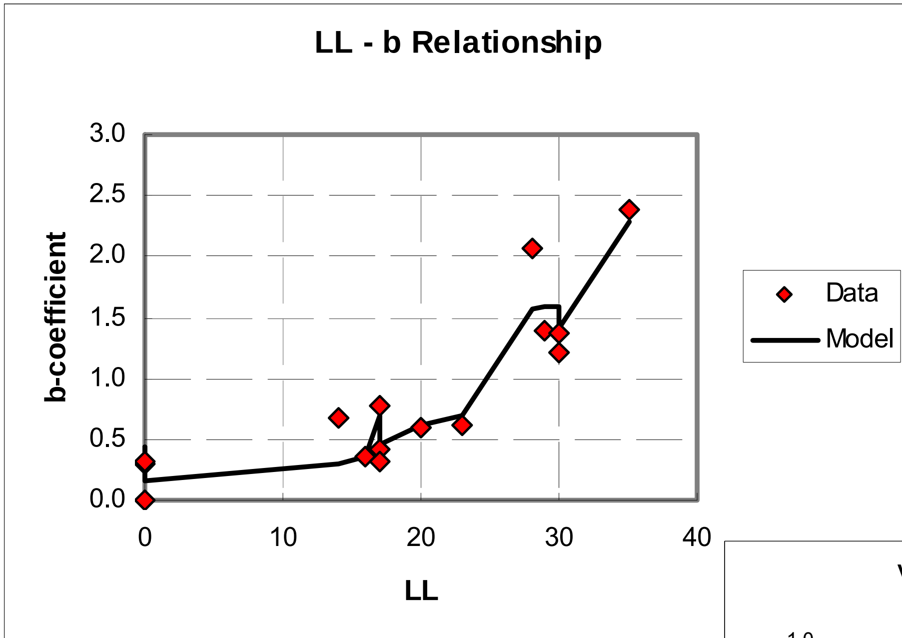


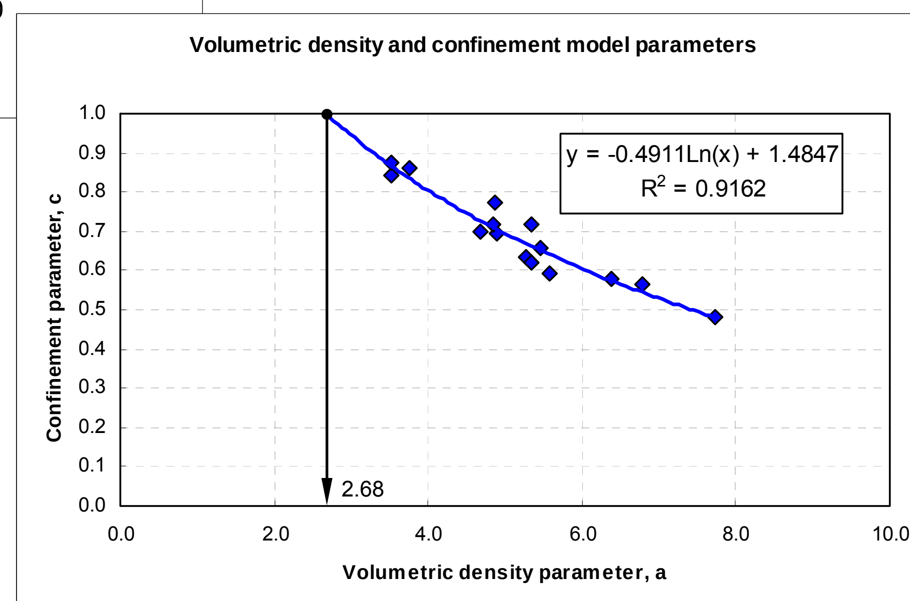
STEP 2: General yield strength model

- Objective
  - Explore the relationship between engineering parameters and yield strength model coefficients
  - Develop a general (predictive) yield strength model

General yield strength model

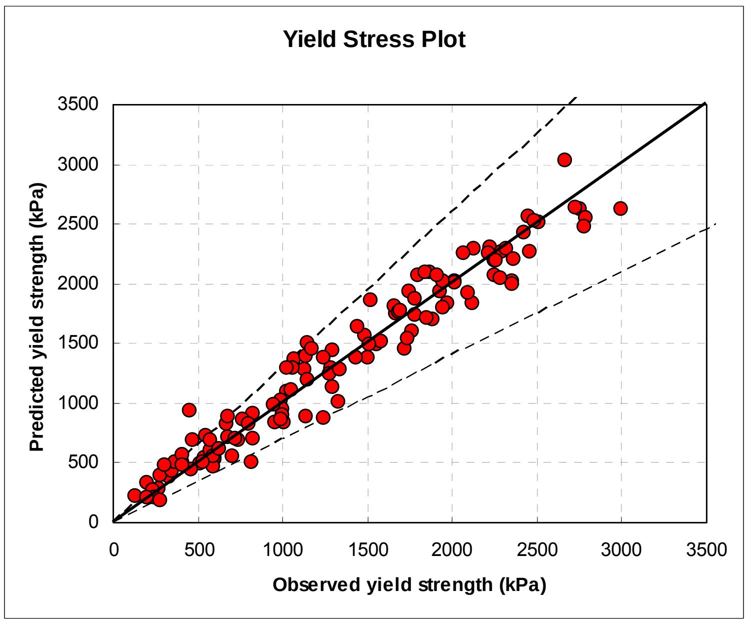




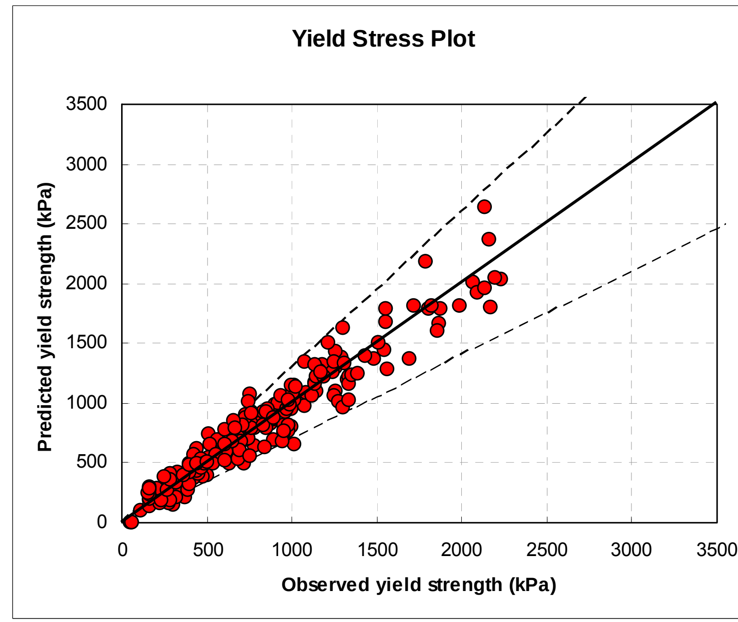


General yield strength model – calibration data

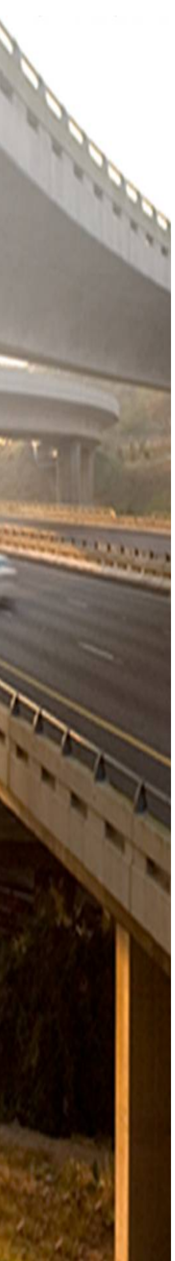
Crushed stone



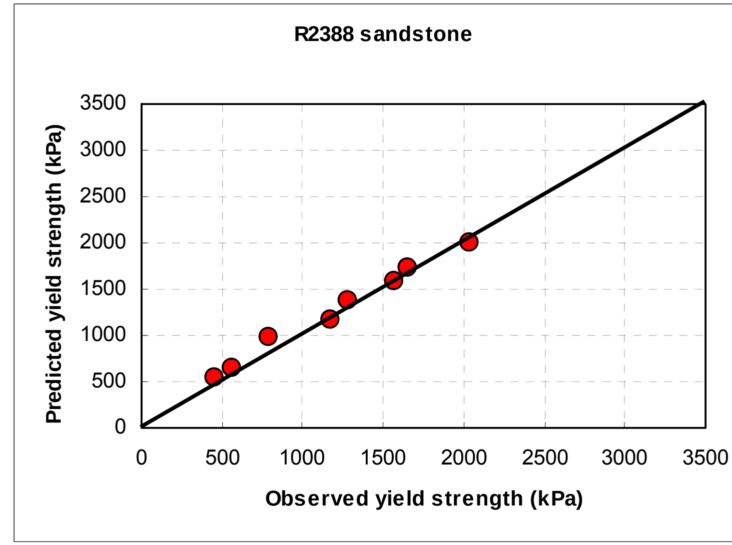
Natural gravel

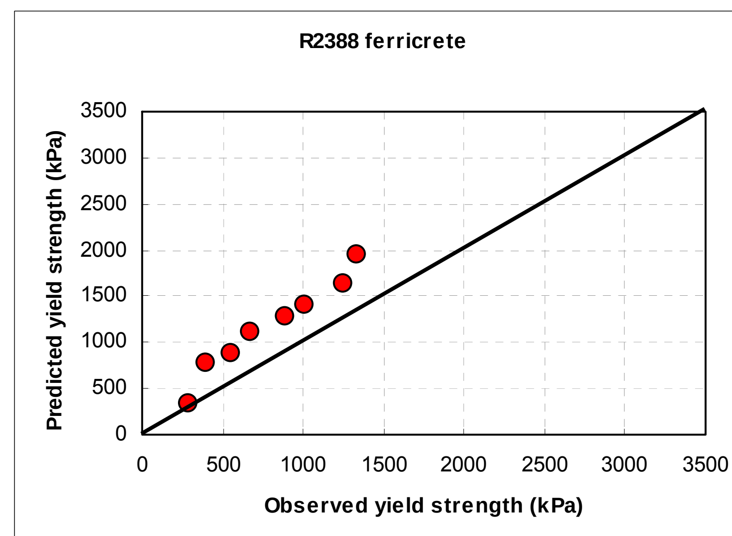


General yield strength model – validation data

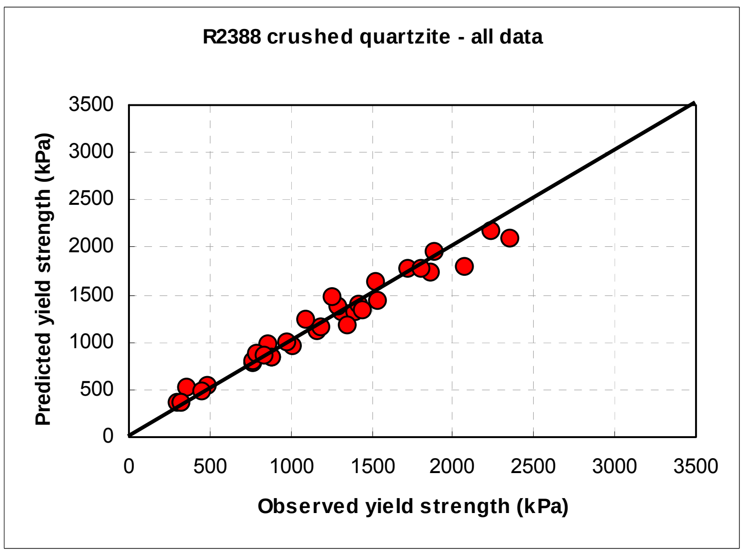


Natural gravel

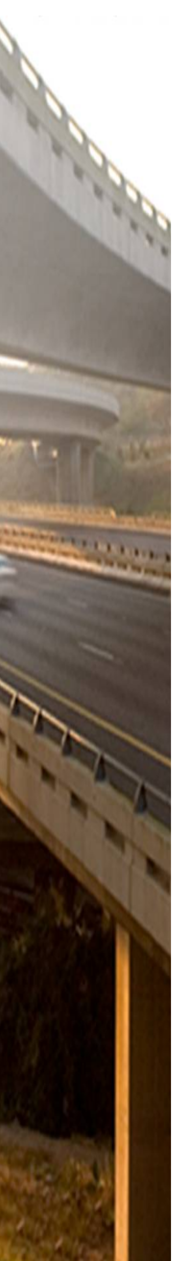


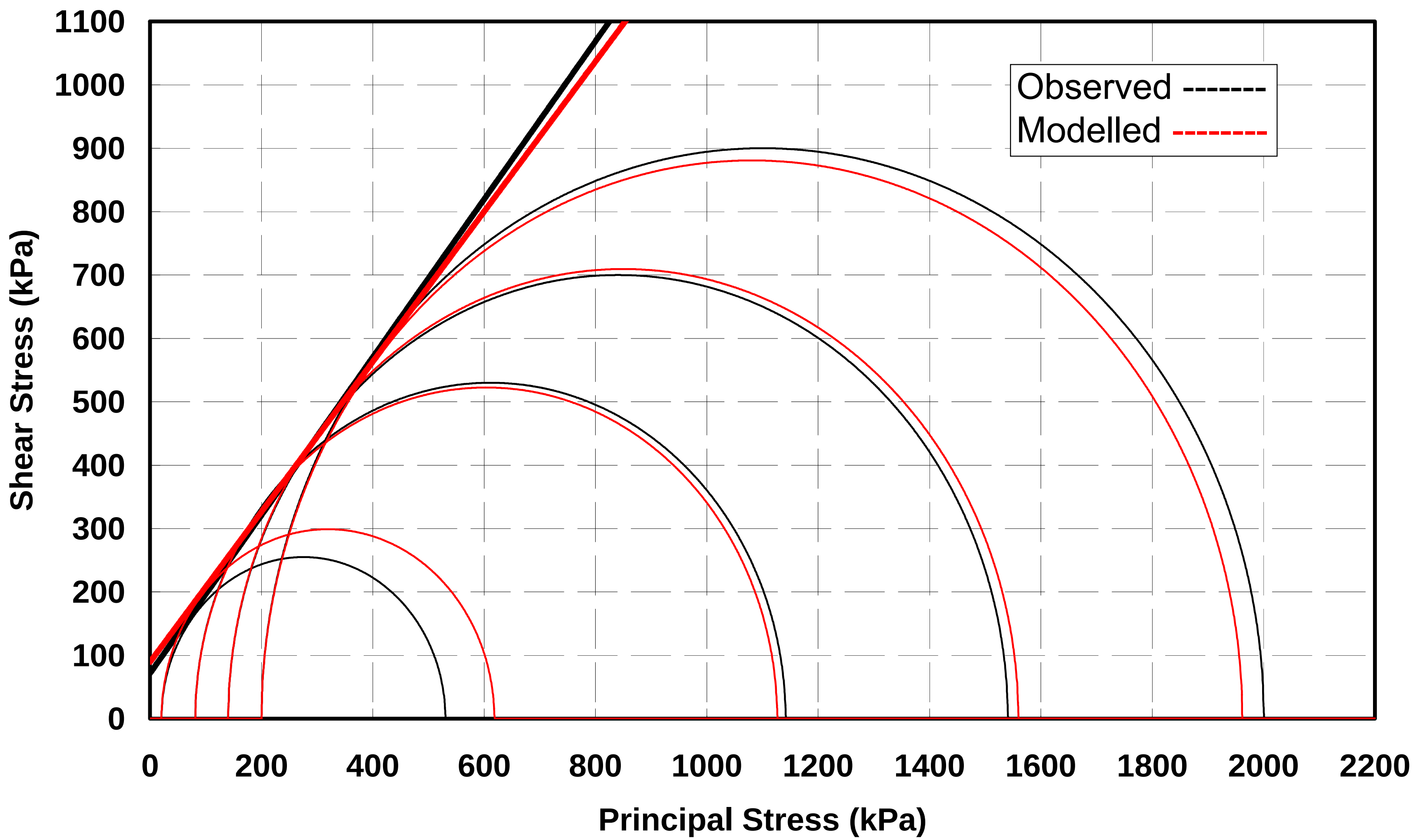


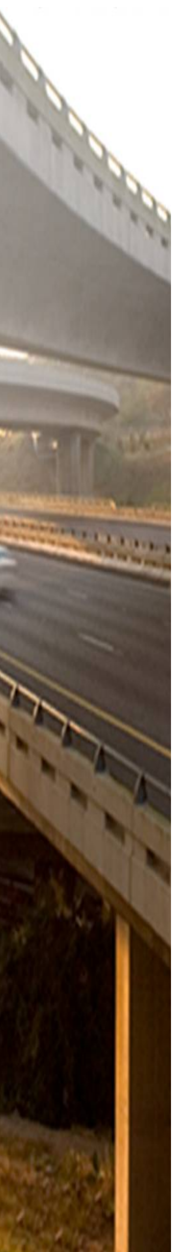
Crushed stone



General yield strength model – application







Closure

- Resilient response modelling
  - Correlation between independent variables eliminated
  - Density and saturation introduced in model
    - Highly significant variables
  - Single model for crushed stone
    - Use for design
  - Moisture content is the primary independent variable for natural gravel
    - Further testing required to relate effect of MC to engineering parameters

Closure

- Yield strength
  - Suction pressure and effective stress introduced in model
  - General predictive model developed
    - Grading modulus and -0.075 mm fraction
    - LL and BLS
    - Replace C and ϕ table in current SAMDM
      - Seasonal MC variation
      - Construction related spatial density variation
  - Primary independent variables
    - Density
    - Saturation
    - Confinement