Creep modelling of soft soils: September 2014

Introduction

From field and laboratory observations
to simple creep models and their parameters
Towards extended creep models

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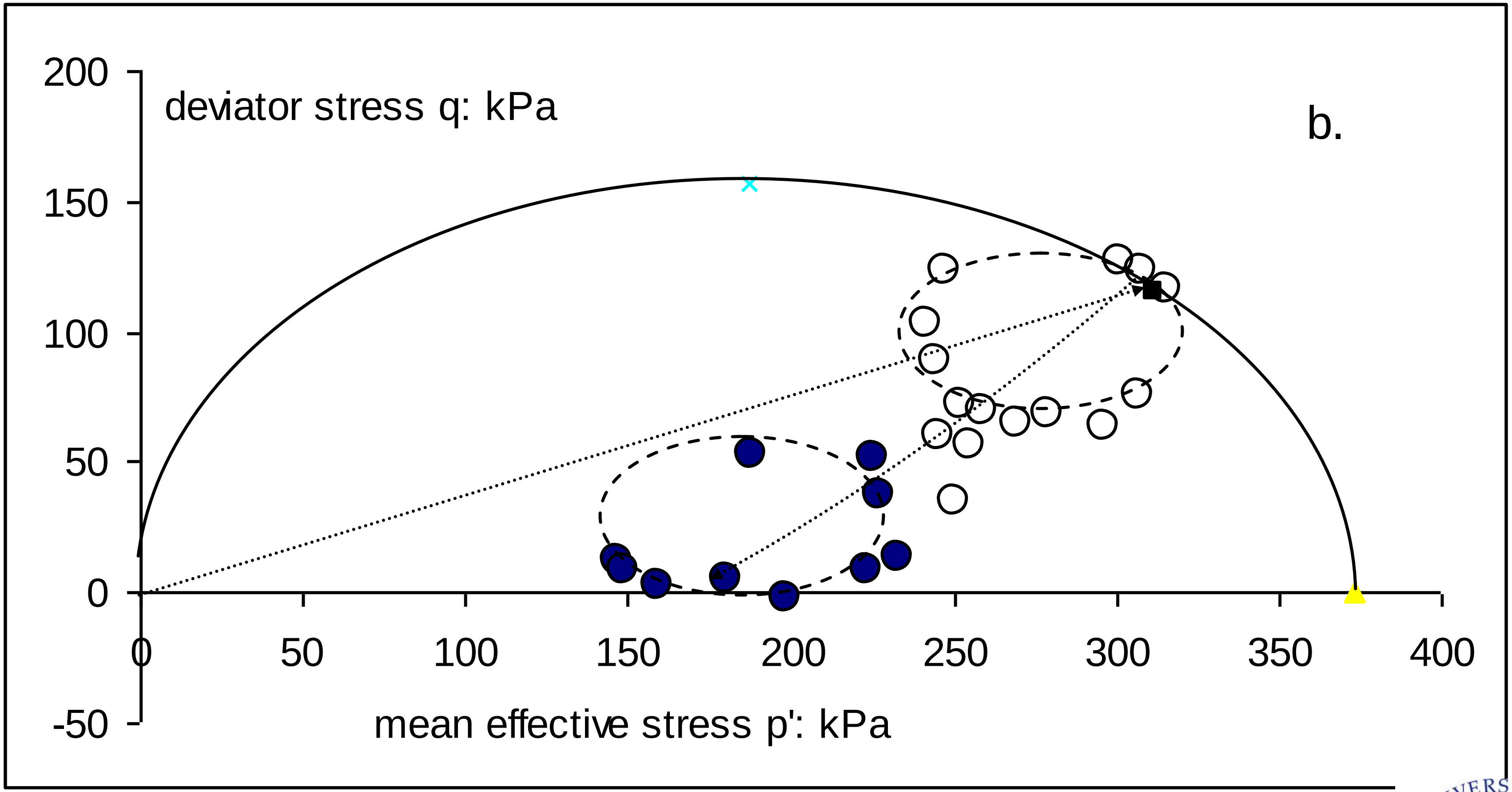
(Dundee University, Bristol University)

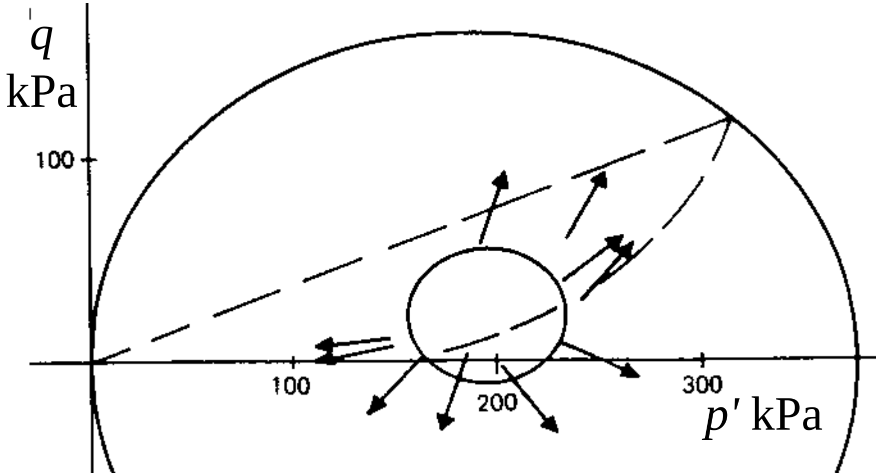
Creep modelling of clay
- stress/strain reversal

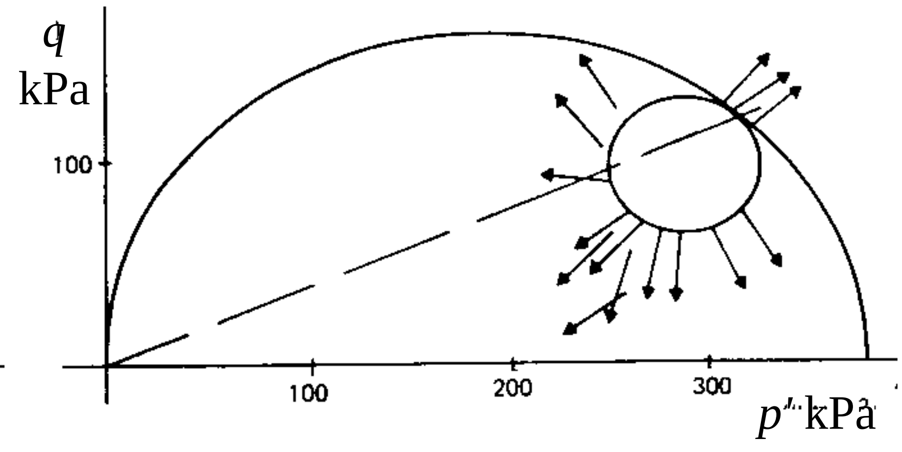
kaolin revisited: yield points?

one-dimensional consolidation histories

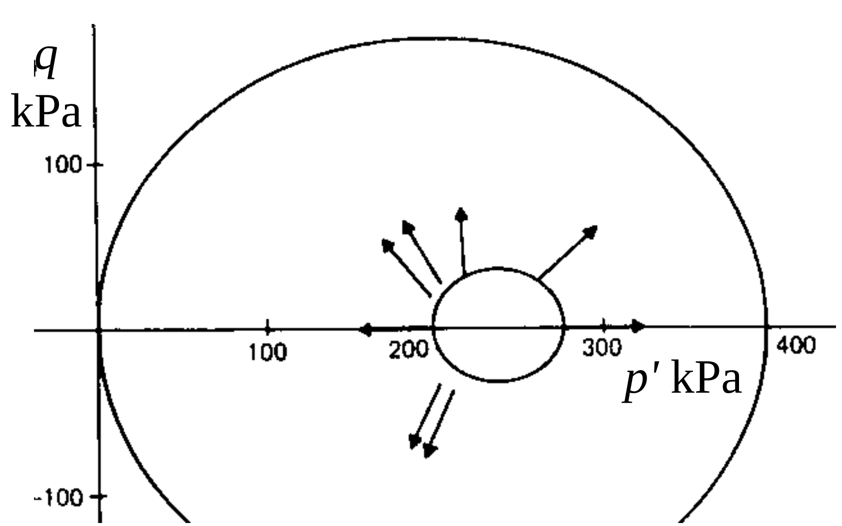


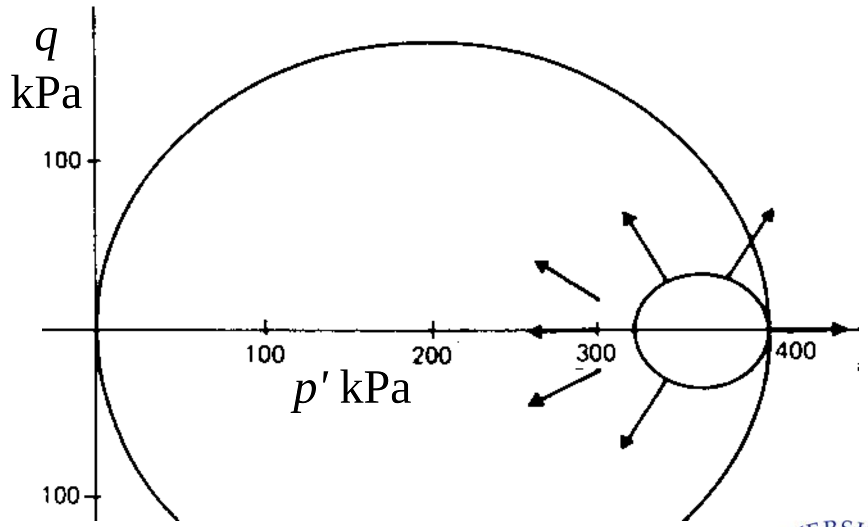
data from Al-Tabbaa (1987)





plastic strain increments: approximate normality to kinematic yield loci





kaolin: Al-Tabbaa, 1987

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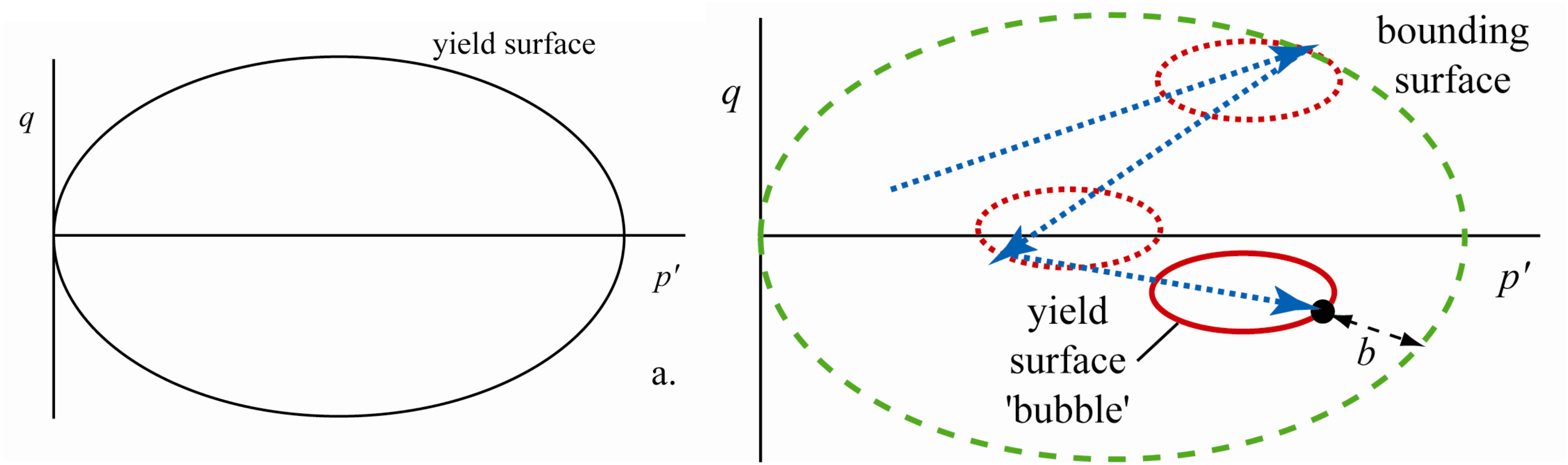

kinematic hardening extension

yield locus carried around with stress state – 'bubble' – strongly influenced by recent history

stiffness falls as yield 'bubble' approaches bounding surface – controlled by distance *b*

when loading with 'bubble' in contact with bounding surface model is identical to Cam clay

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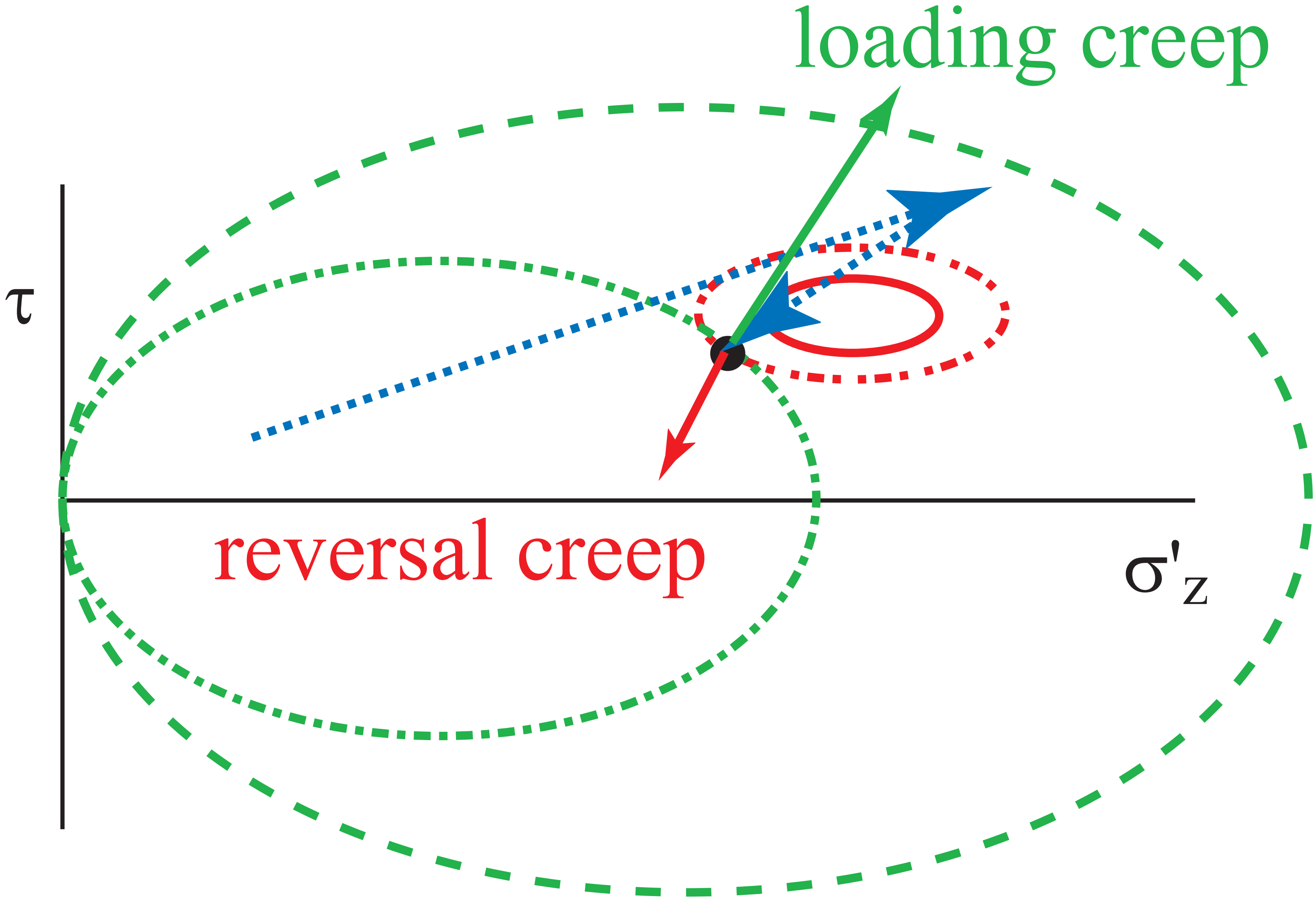
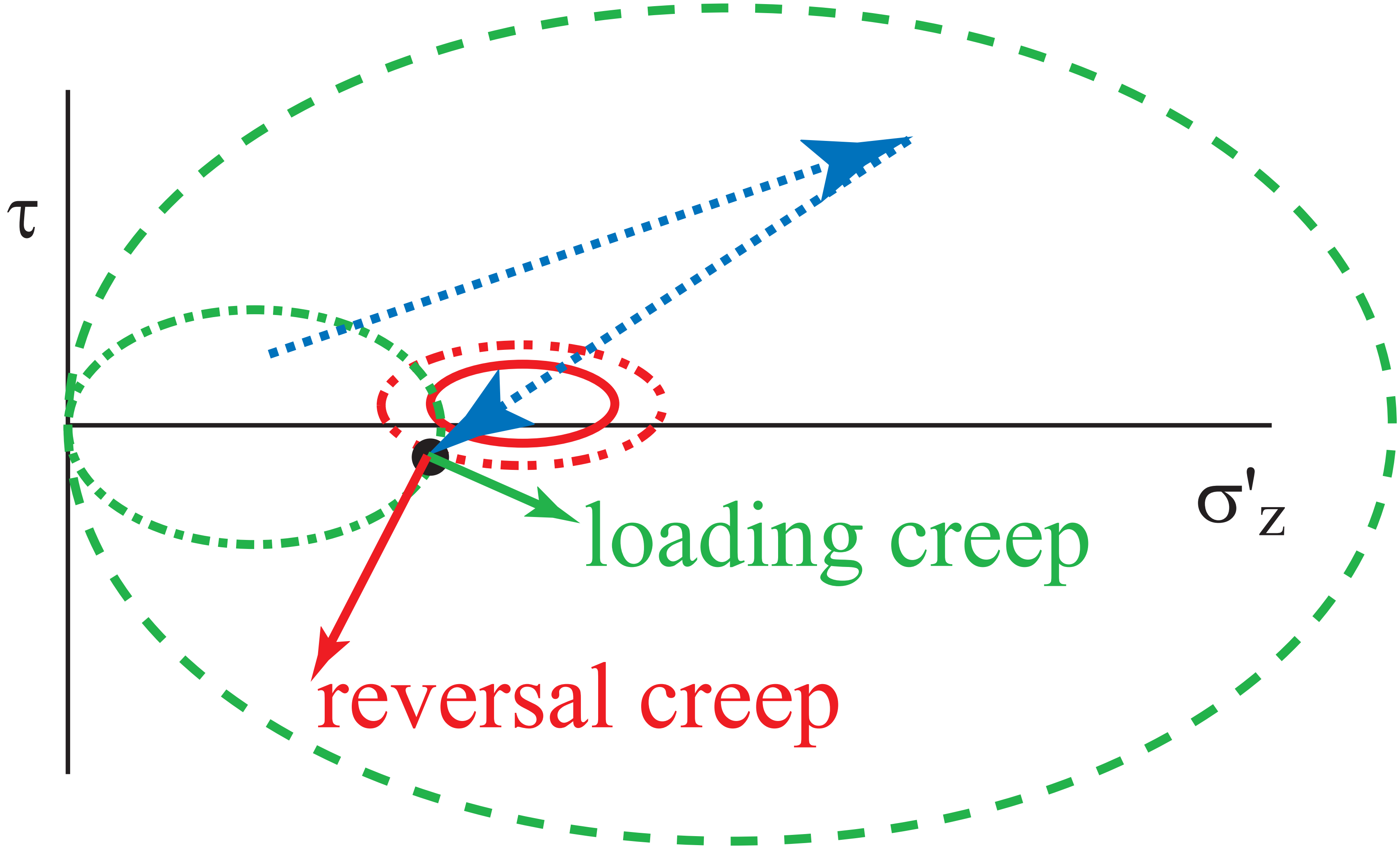
creep modelling of clay - stress reversal



competing mechanisms

creep modelling of clay - stress reversal



competing mechanisms

creep modelling of clay - stress reversal

- reversal of stress or strain path for clays (and other soils) shows reverse plasticity and hysteretic, dissipative response in unloading-reloading cycles
- yielding of clays (and other soils) is convincingly described using kinematic hardening combined with bounding surface plasticity
- anticipate that *viscoplasticity* of clays should also be described by a kinematic hardening/bounding surface modelling framework
- 'overstress' approach applied to two mechanisms of creep: referred to 'bounding surface' and to kinematic yield surface ('bubble')
- expect 'loading' creep to dominate as unloading begins
- expect 'reversal' creep to dominate as overconsolidation increases

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Creep modelling of peat
= soil + fibres?

- Peat: partially decayed plant matter
- recognisable mass of roots and woody tissue at the surface $\Rightarrow$ partially decayed layer $\Rightarrow$ soil-like material at depth of $\sim$10m
- highly compressible
- important contribution of fibrous material

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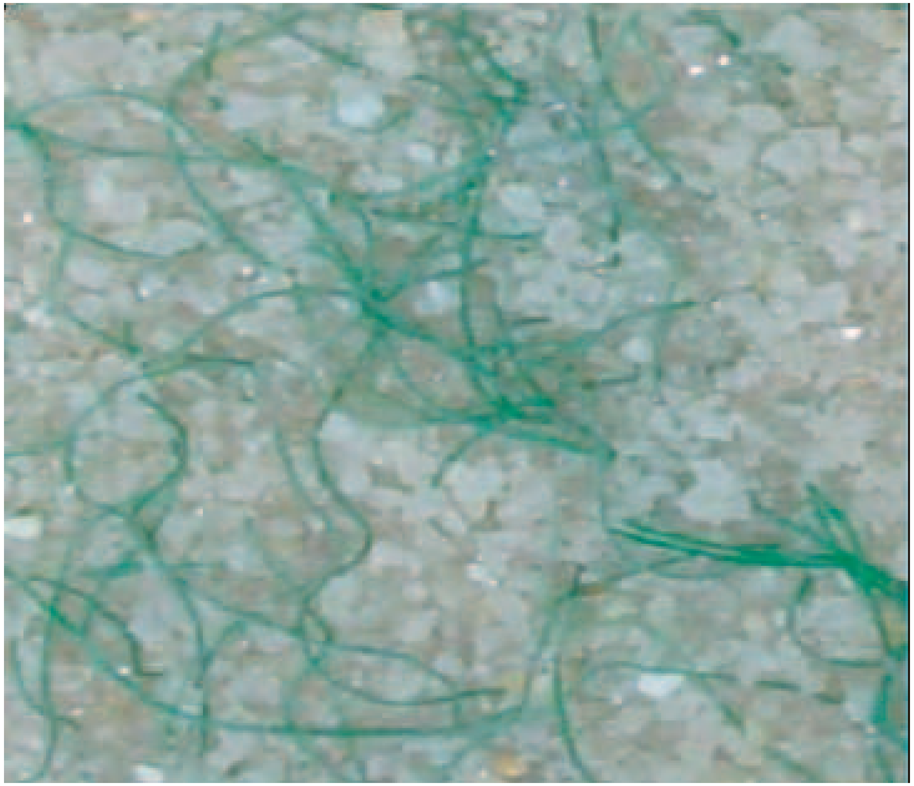
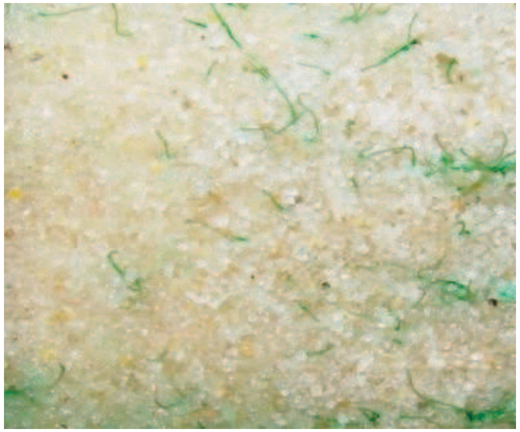


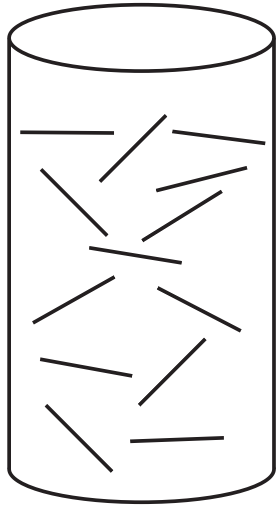
flexible polypropylene fibres

fibres 35mm long, 0.1mm diameter

analogy for roots?

mixtures with Hostun sand
$d_{50} = 0.38\text{mm}, C_u = 1.9$

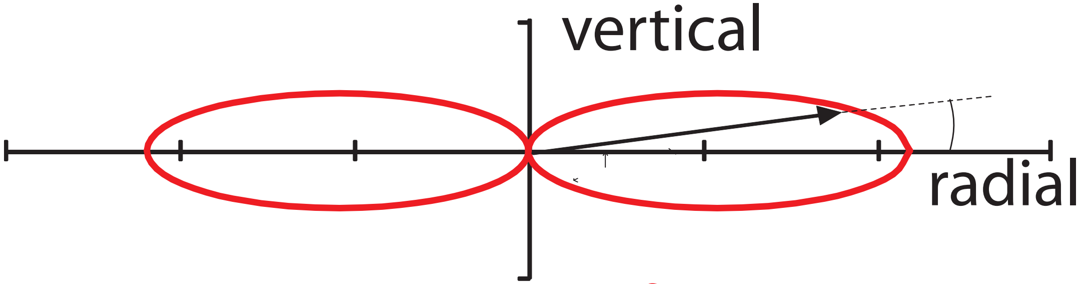




freeze sample

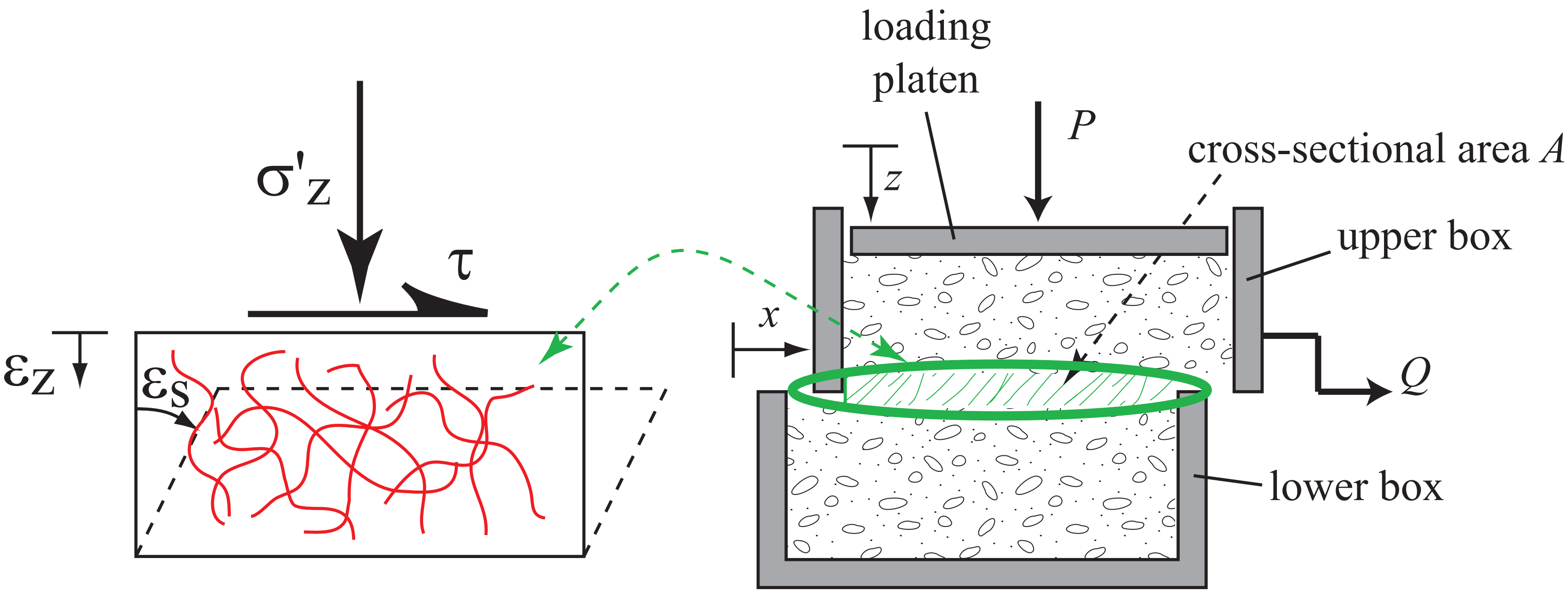
cut into slices

count visible fibres



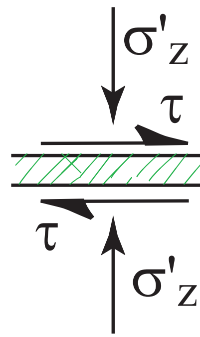
deduce distribution of orientations

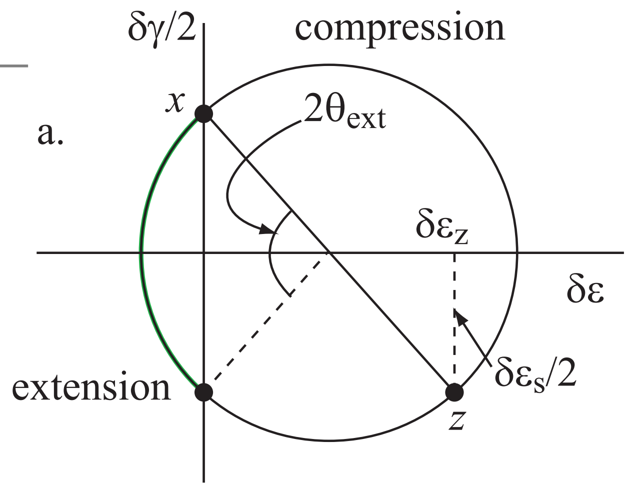
moist tamping leaves most fibres within $\pi/4$ of horizontal

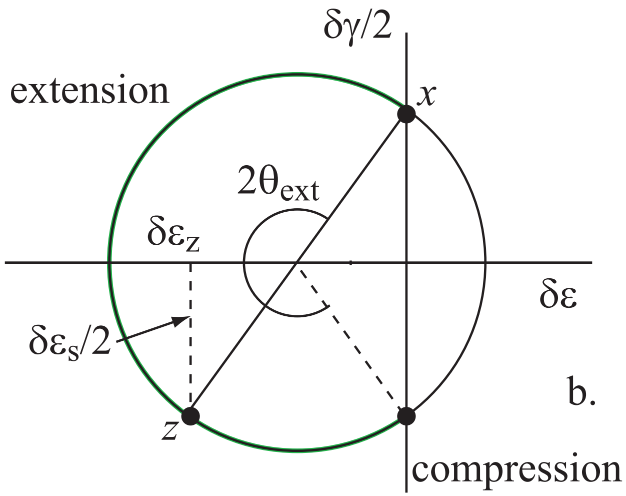


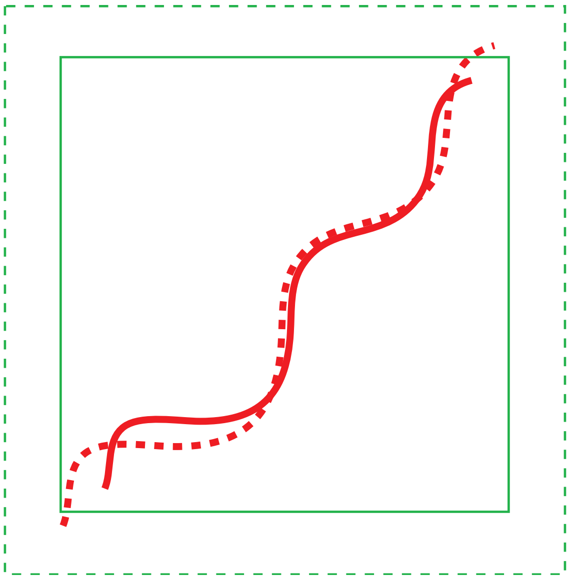
simple shear of soil with fibres

'equivalent' to central zone of shear box



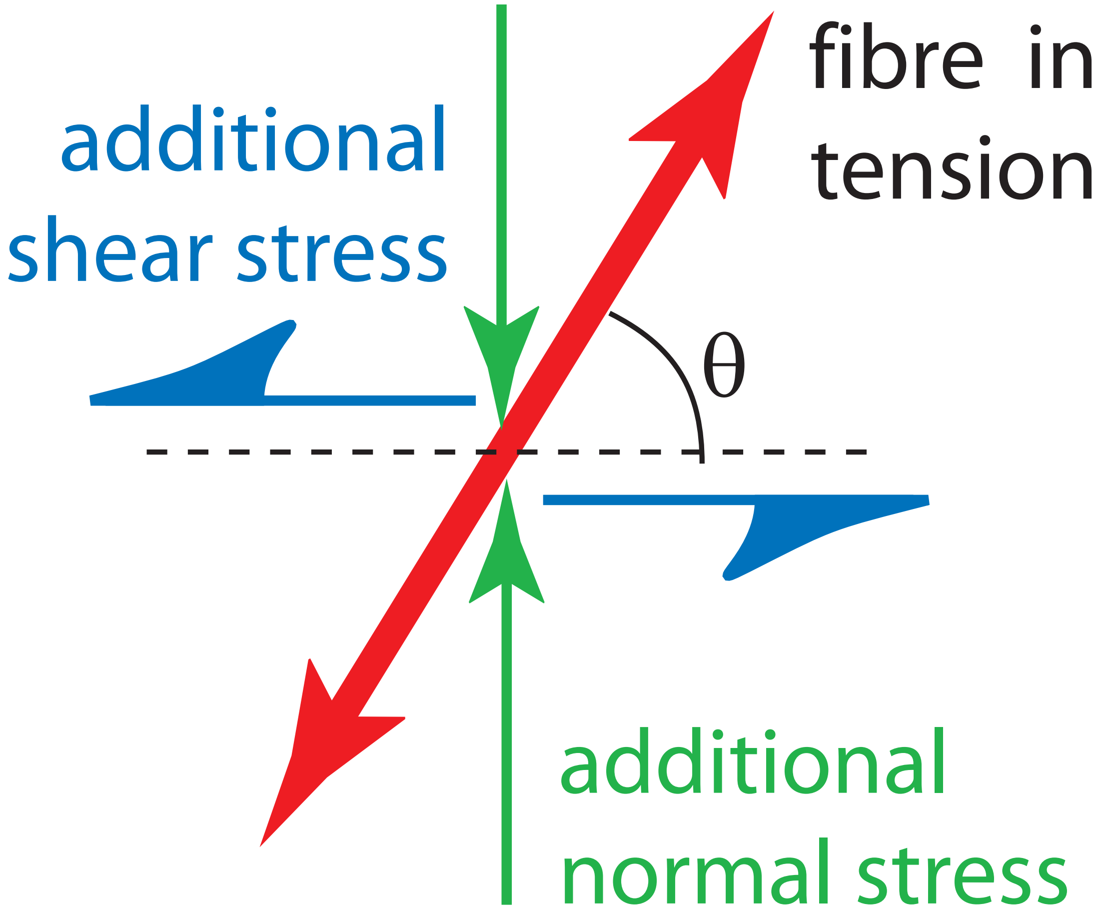






tensile strain in soil ⇨
tensile strain in fibres

- hypothesis 1: tensile strains in soil try to stretch fibres



- hypothesis 2: stretched fibres tend to increase normal stress on soil and contribute to shear stress tensile strain in soil ...

... not completely transferred to fibre

slip depends on normal stress

- hypothesis 3: bond between fibres and soil not perfect
- $\varepsilon_f / \varepsilon_m = 1 - \lambda \exp(\sigma'_z / \sigma_{rf})$
- ε_f strain in fibre; ε_m strain in soil

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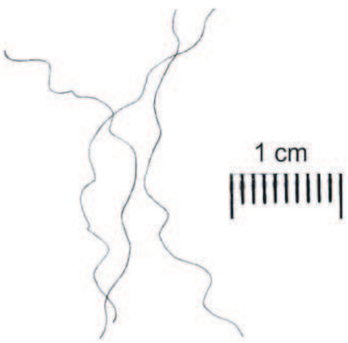
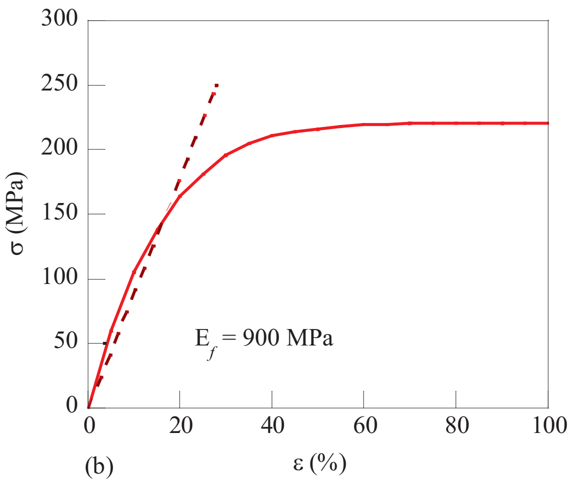
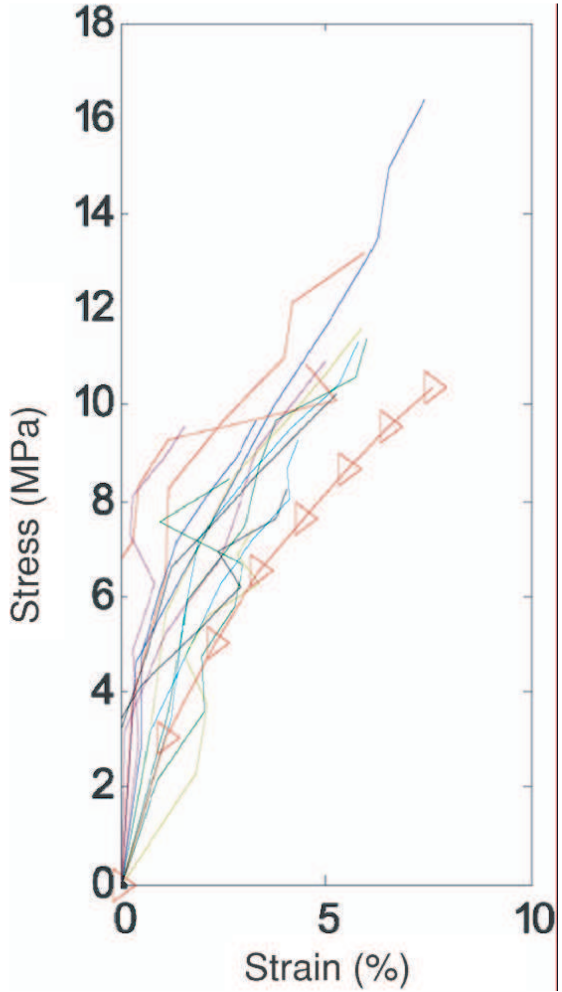
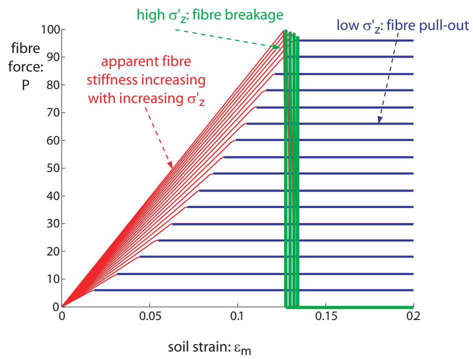


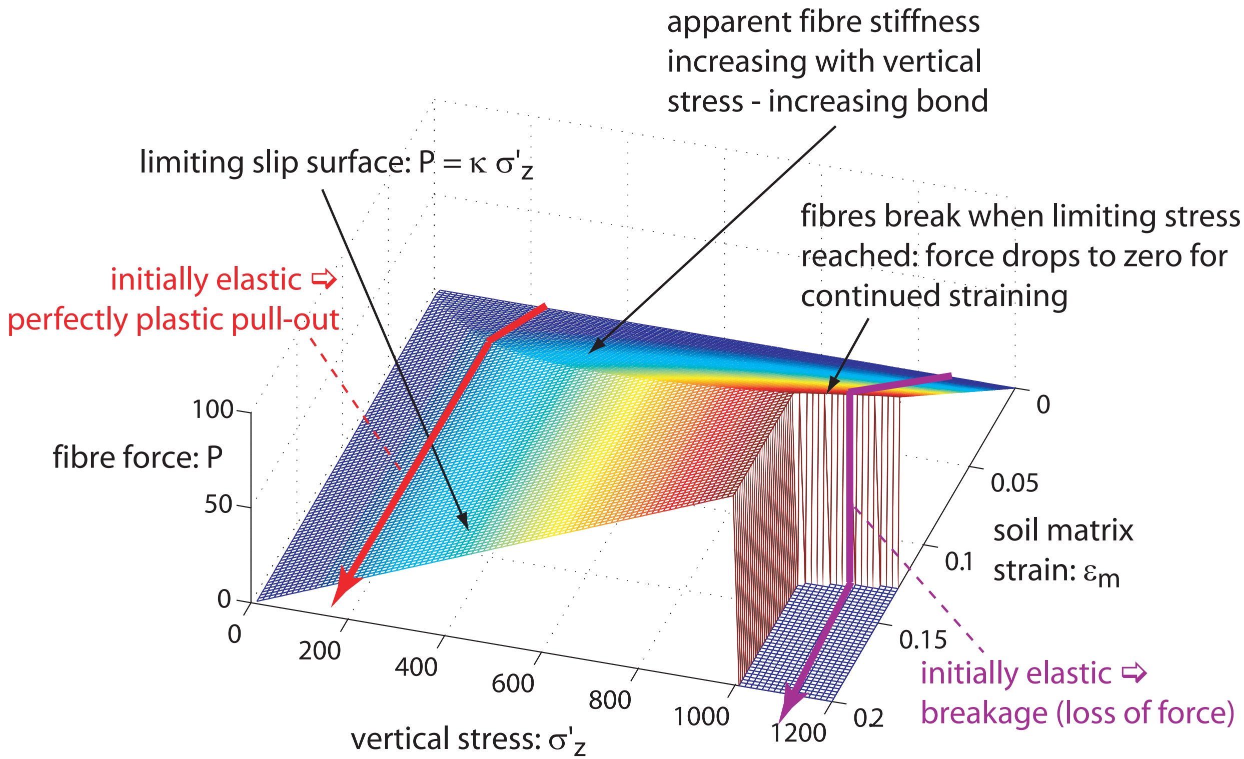


stress-strain response of fibres: $E_f = 900$ MPa



- hypothesis 4: fibres *(may pull out of soil or)* may reach tensile strength and snap





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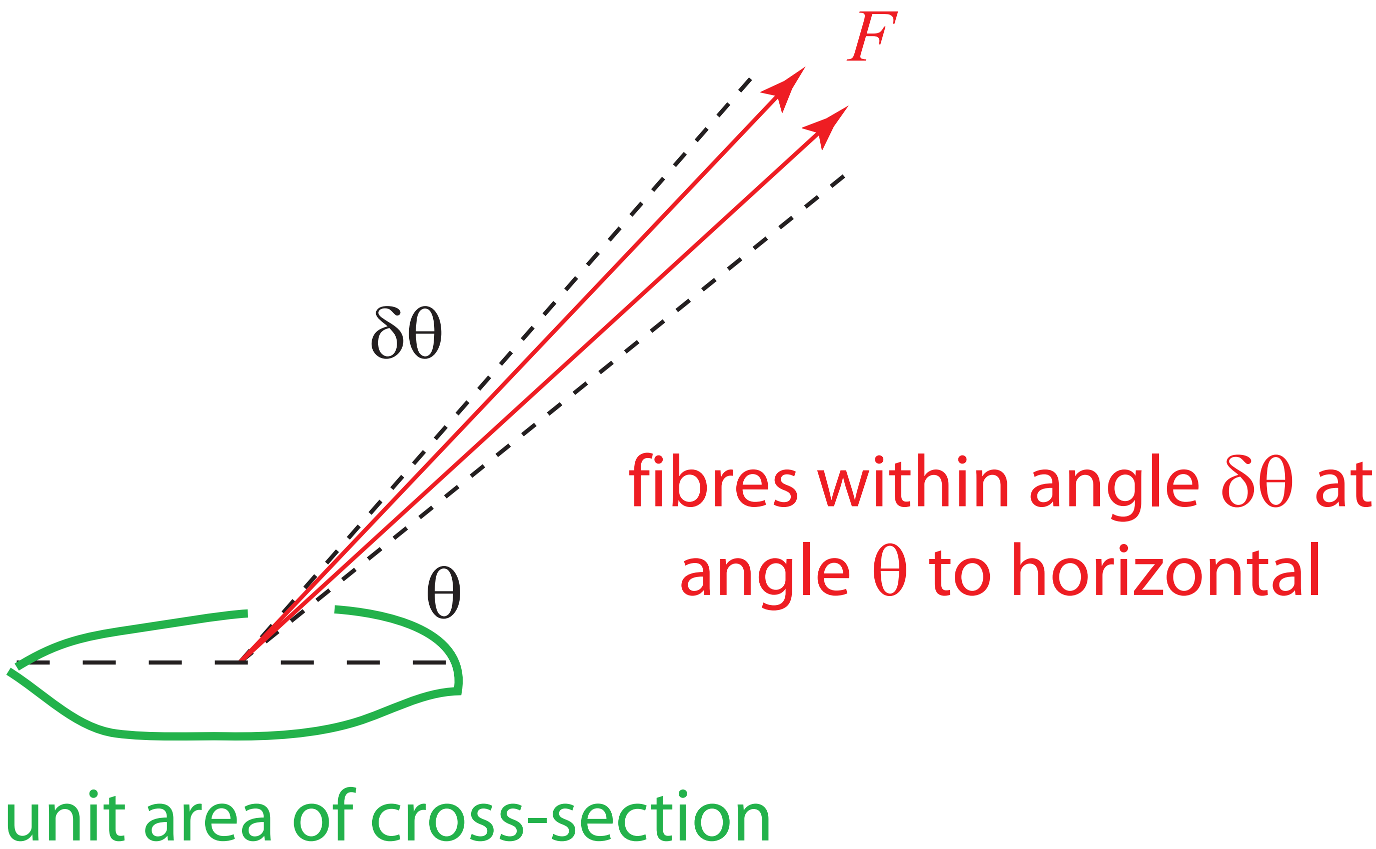
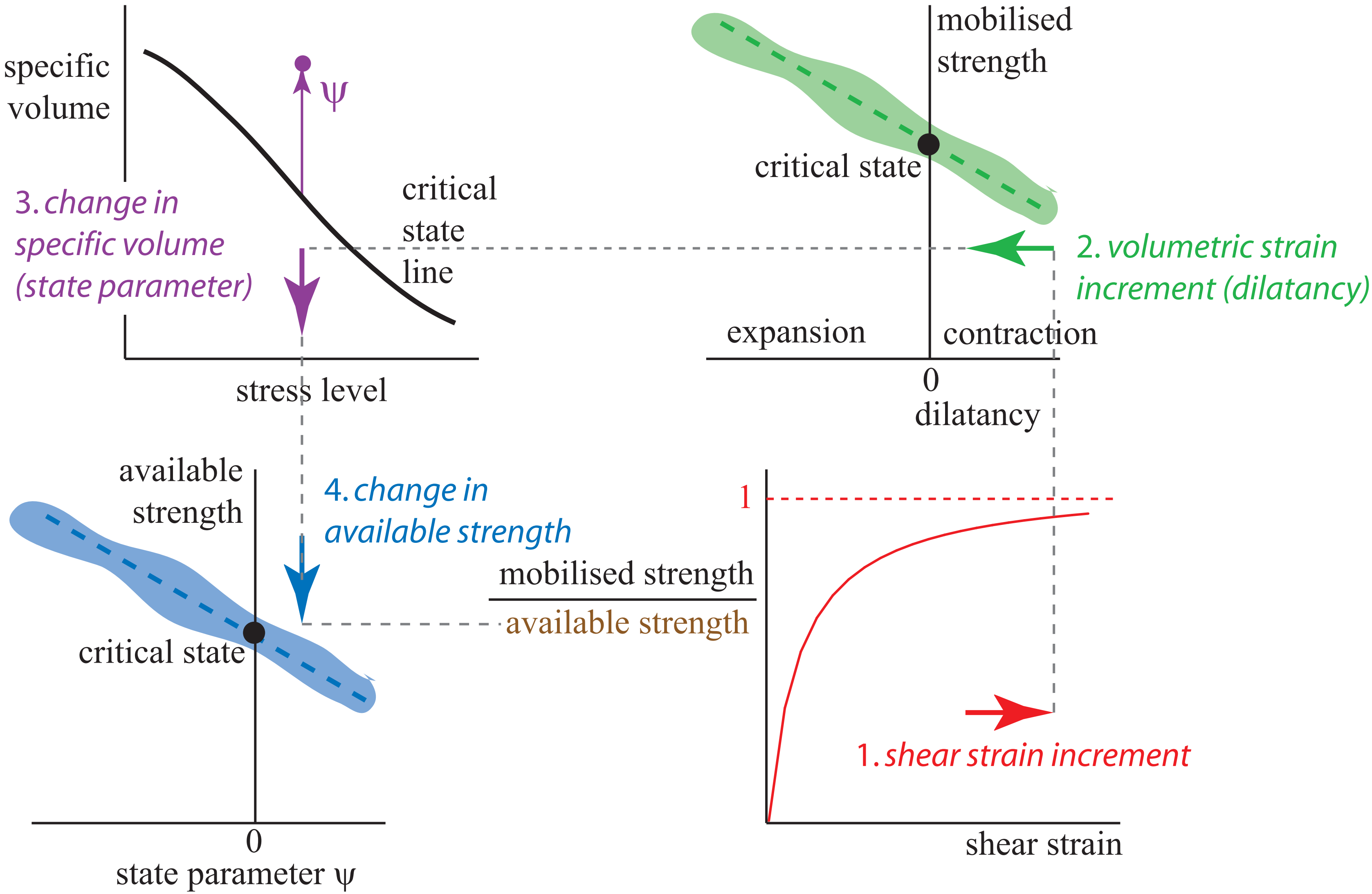


- hypothesis 5: fibres treated as forces with orientation (not continuous material)

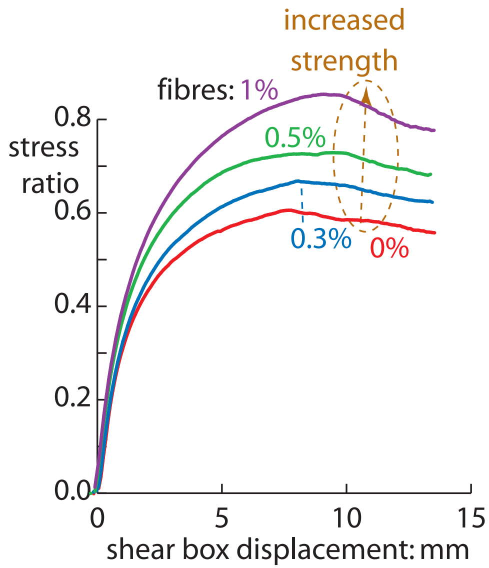
5. Modelling of sand/fibre mixture

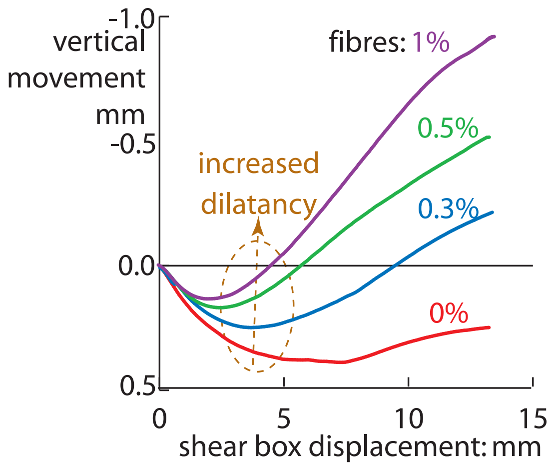


- Severn-Trent sand: simple mathematical relationships: automatic convergence on critical state

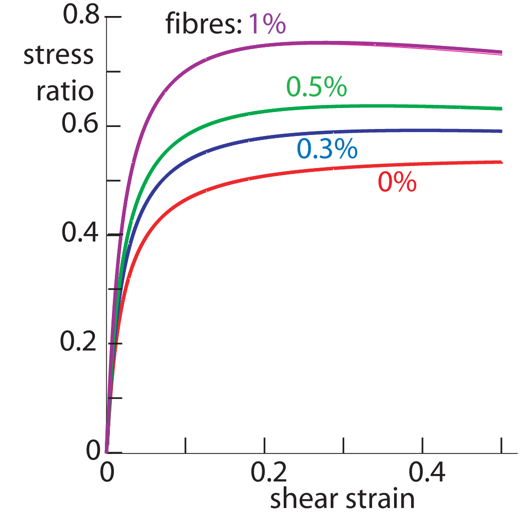
7. Applications?

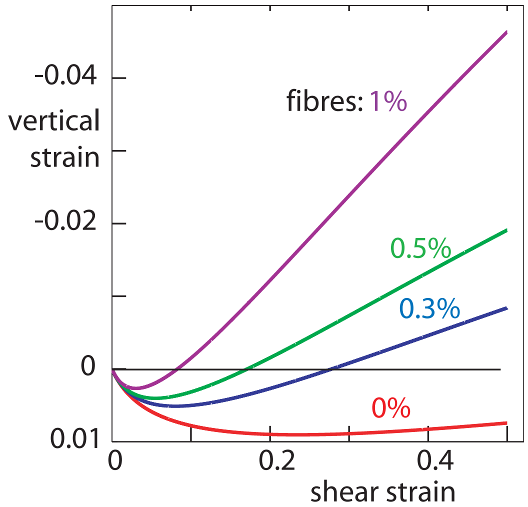
shear box tests on fibre-sand mixtures





simulations

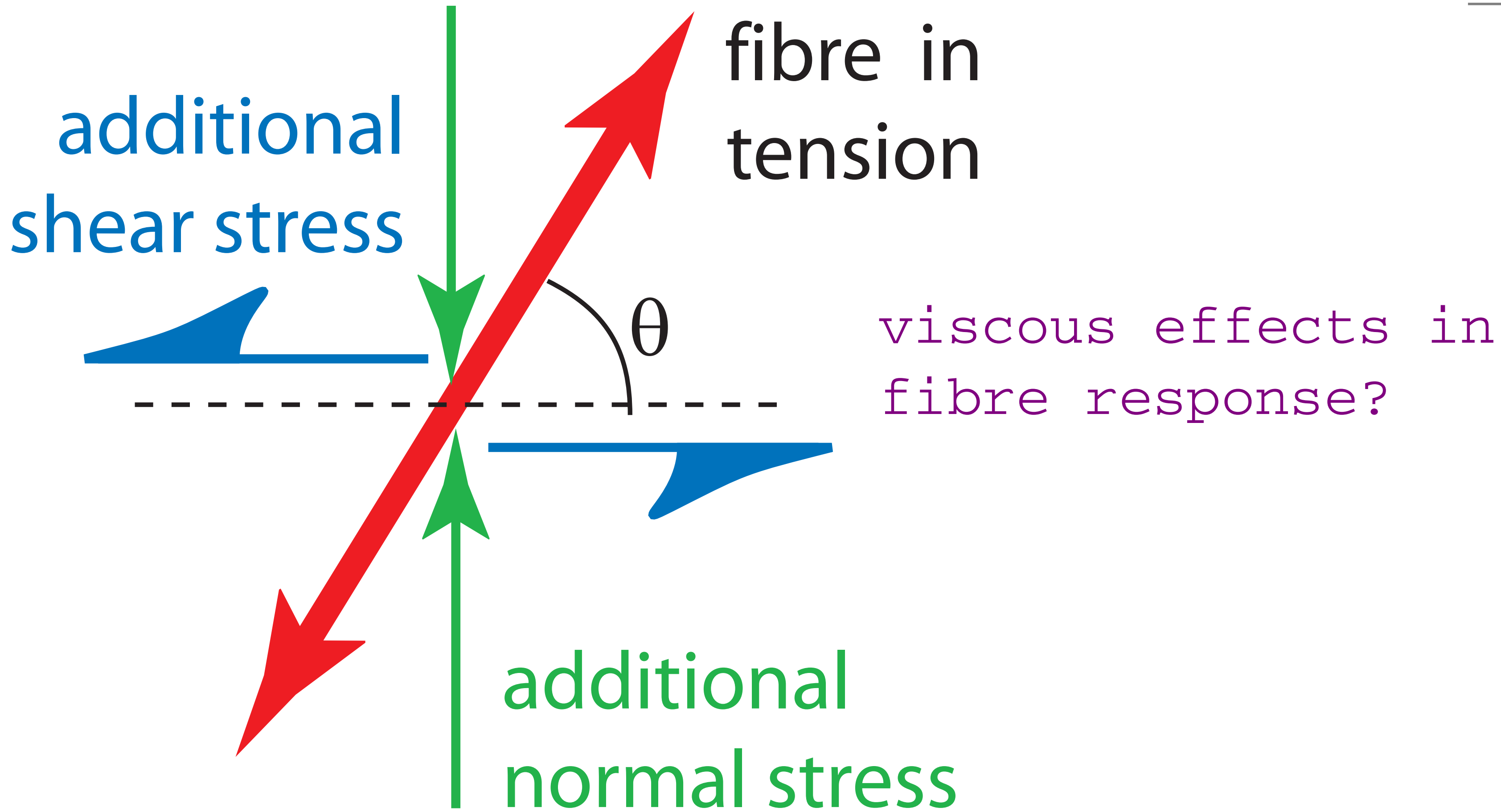




- simulations of shear box tests on fibre-sand mixtures
- fibre orientations $-\pi/4 < \theta < \pi/4$
- dominant effect from fibrespace densification

- Peat: partially decayed plant matter
- recognisable mass of roots and woody tissue at the surface $\Rightarrow$ partially decayed layer $\Rightarrow$ soil-like material at depth of $\sim$10m
- highly compressible
- important contribution of fibrous material

`treat as fibres + clay?`



- hypothesis 2: stretched fibres tend to increase normal stress on soil and contribute to shear stress viscous effects in soil:fibre interaction?

tensile strain in soil ...

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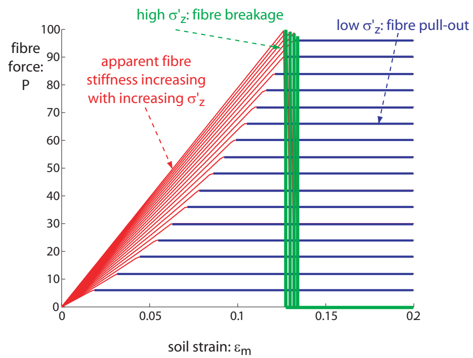
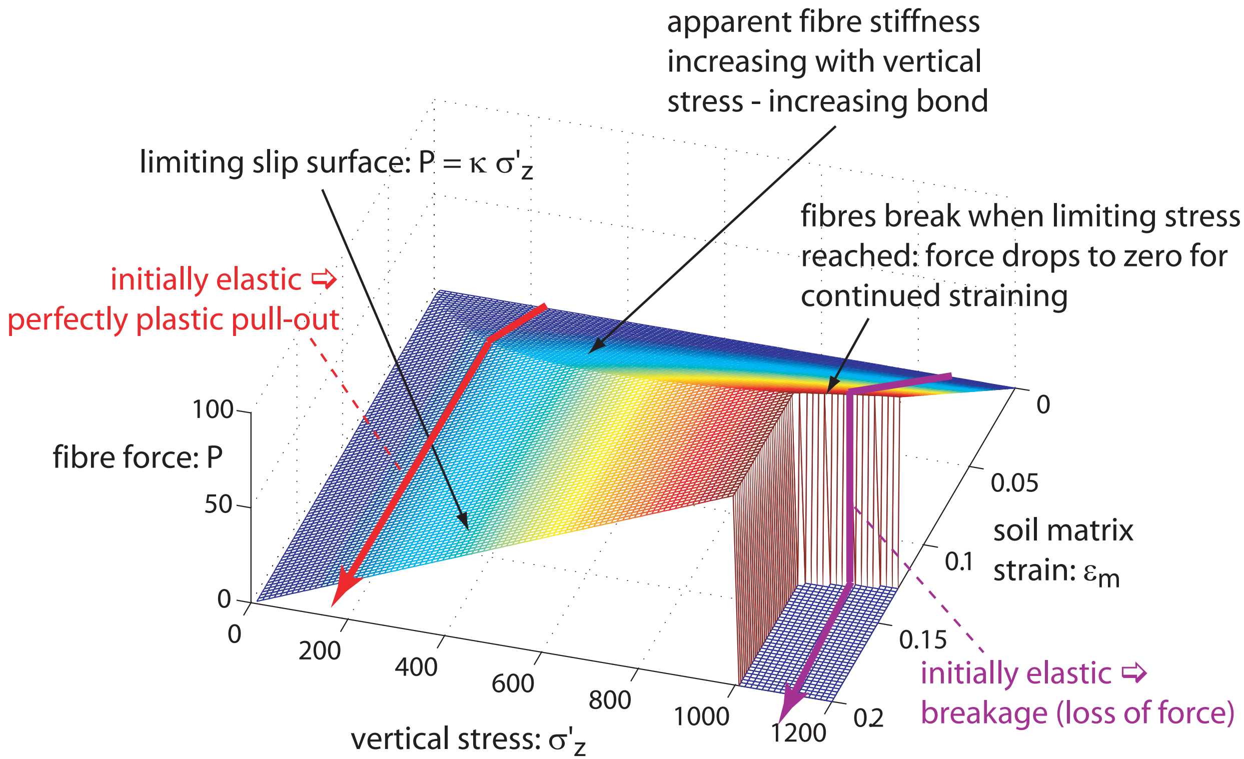
viscous effects in soil:fibre interaction?





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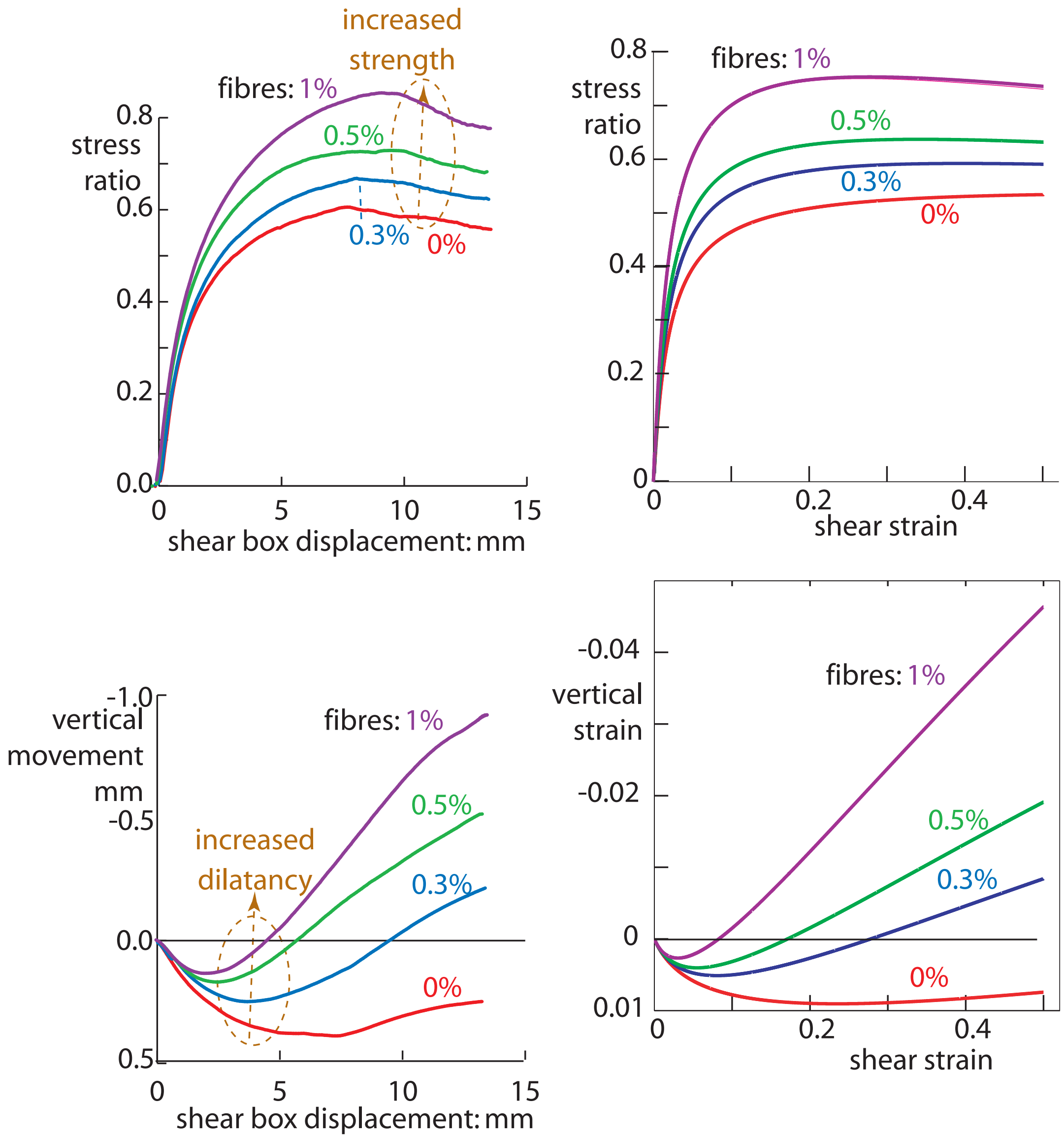

- simulations of shear box tests on fibre-sand mixtures
- fibre orientations $-\pi/4 < \theta < \pi/4$
- dominant effect from fibrespace densification

fibre-sand mixtures modelled ... fibre-clay?

viscous effects in soil model?

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Creep modelling of sand
- role of particle breakage/damage

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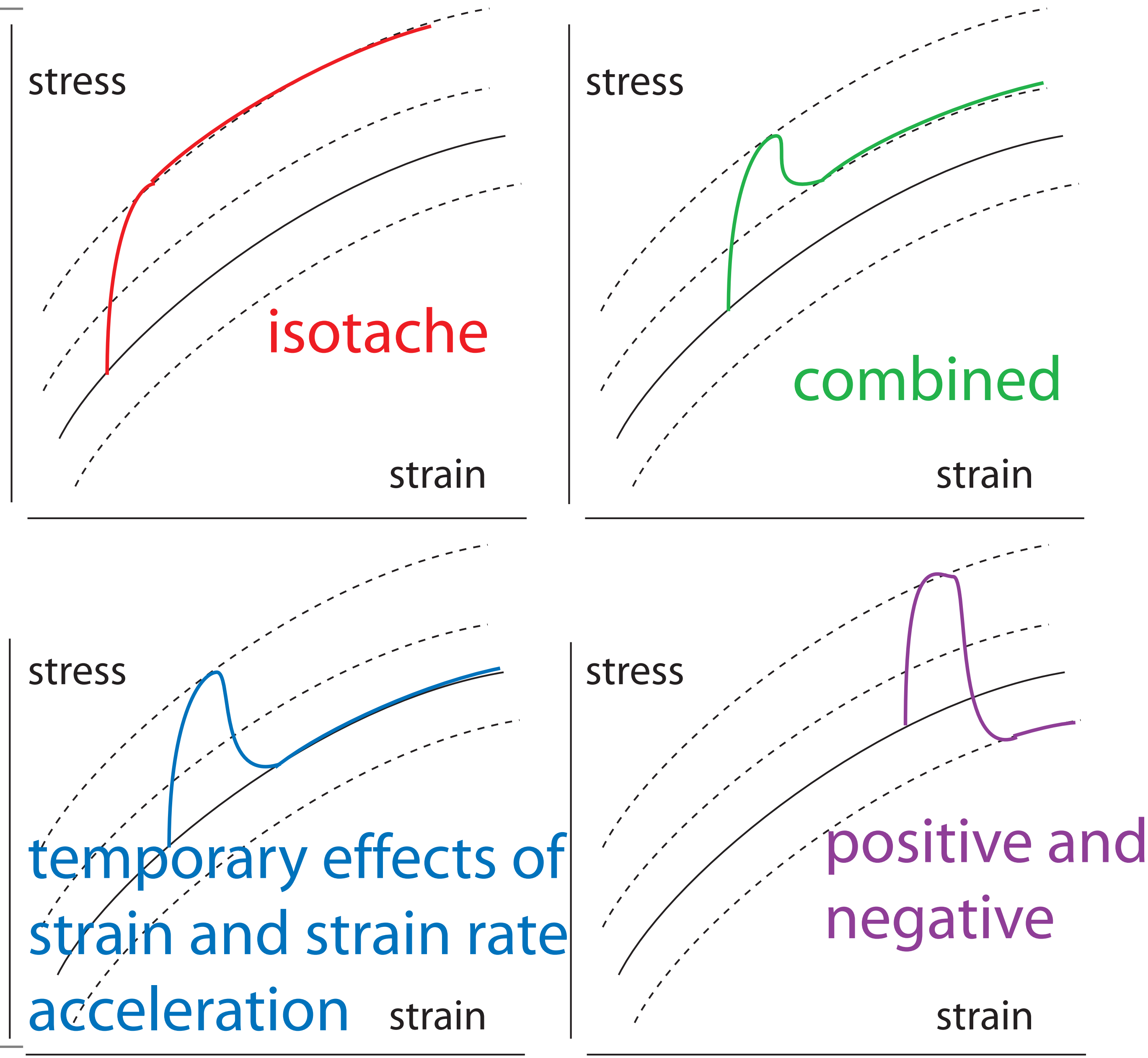
creep modelling of sand



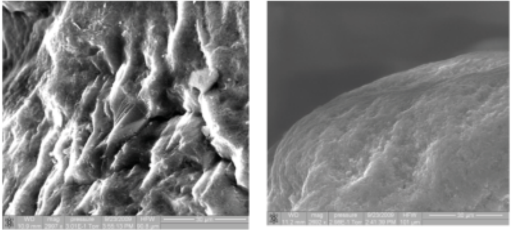
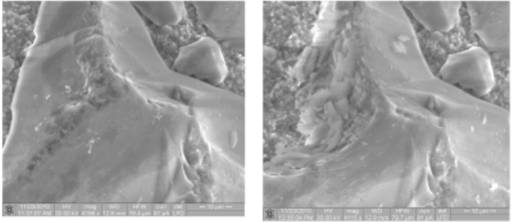


Figure 1. SEM images of Ottawa sand and Lake Michigan Dune Sand grain surfaces (image width $\approx 100\,\mu$m).



(a) (b)

Figure 4. Damage of a large asperity at a contact loaded with 0.7 N (SEM image width $70 \approx \mu$m).

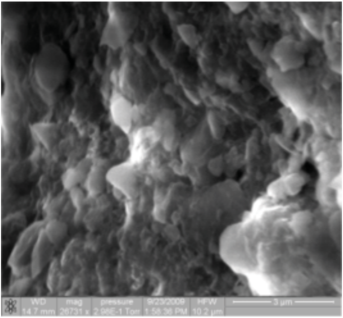


Figure 2. SEM image of Lake Michigan Dune Sand (image width $\approx 10\ \mu$m).

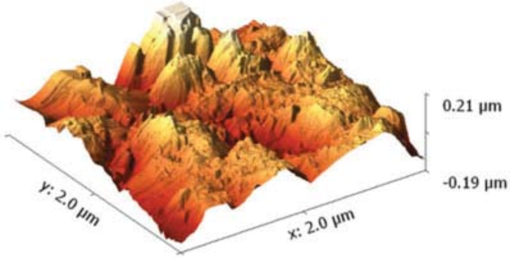
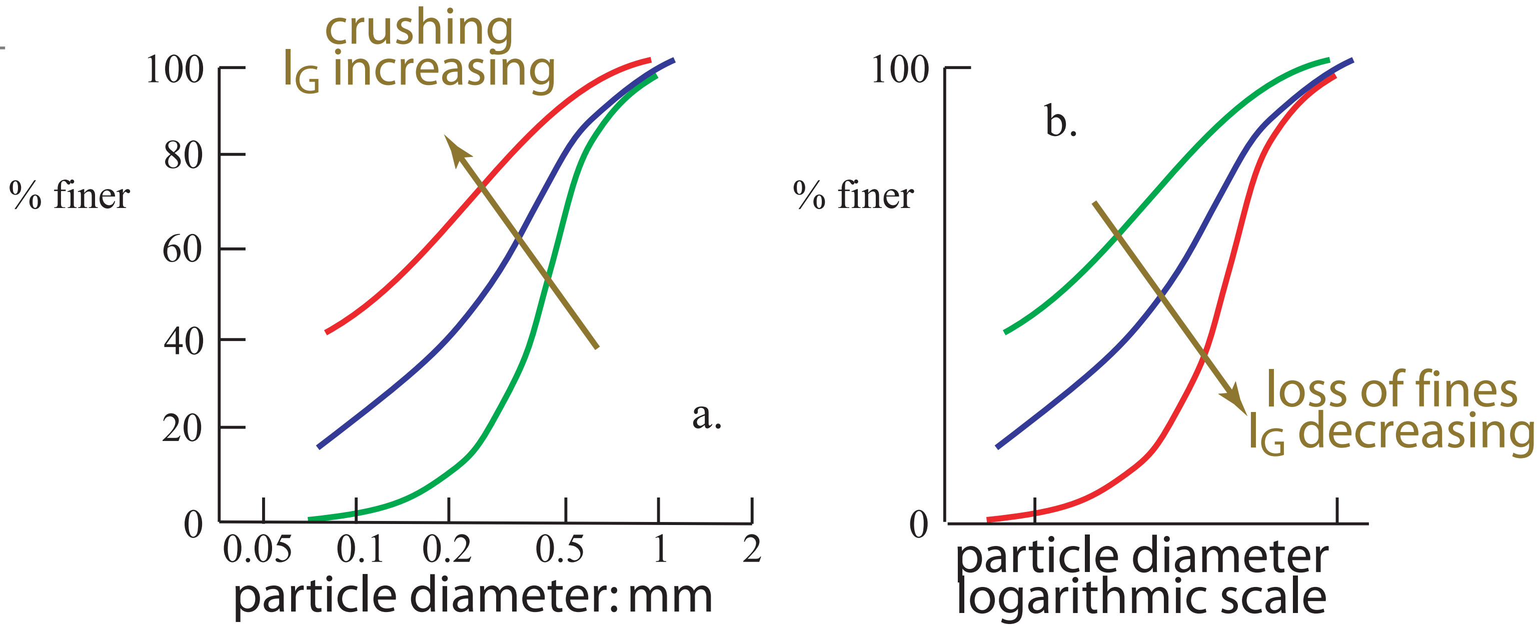


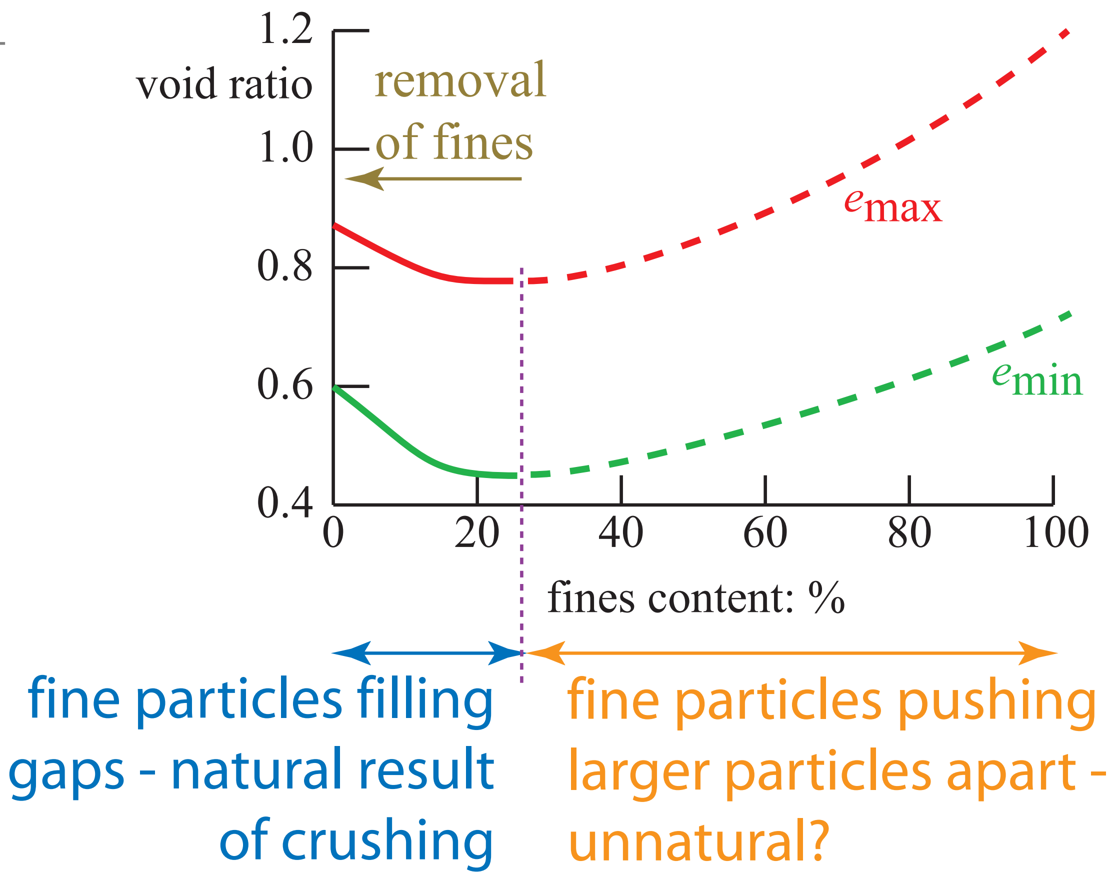
Figure 3. AFM scan of Ottawa sand grain surface ($2 \times 2\ \mu$m).

particle breakage/suffusion



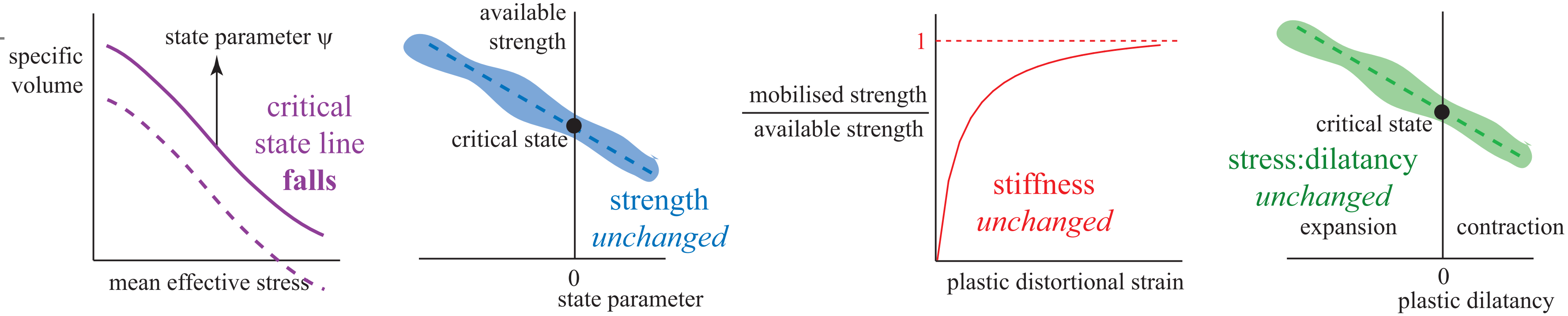
- particle breakage broadens grading
- internal erosion (suffusion) narrows grading

particle breakage/suffusion



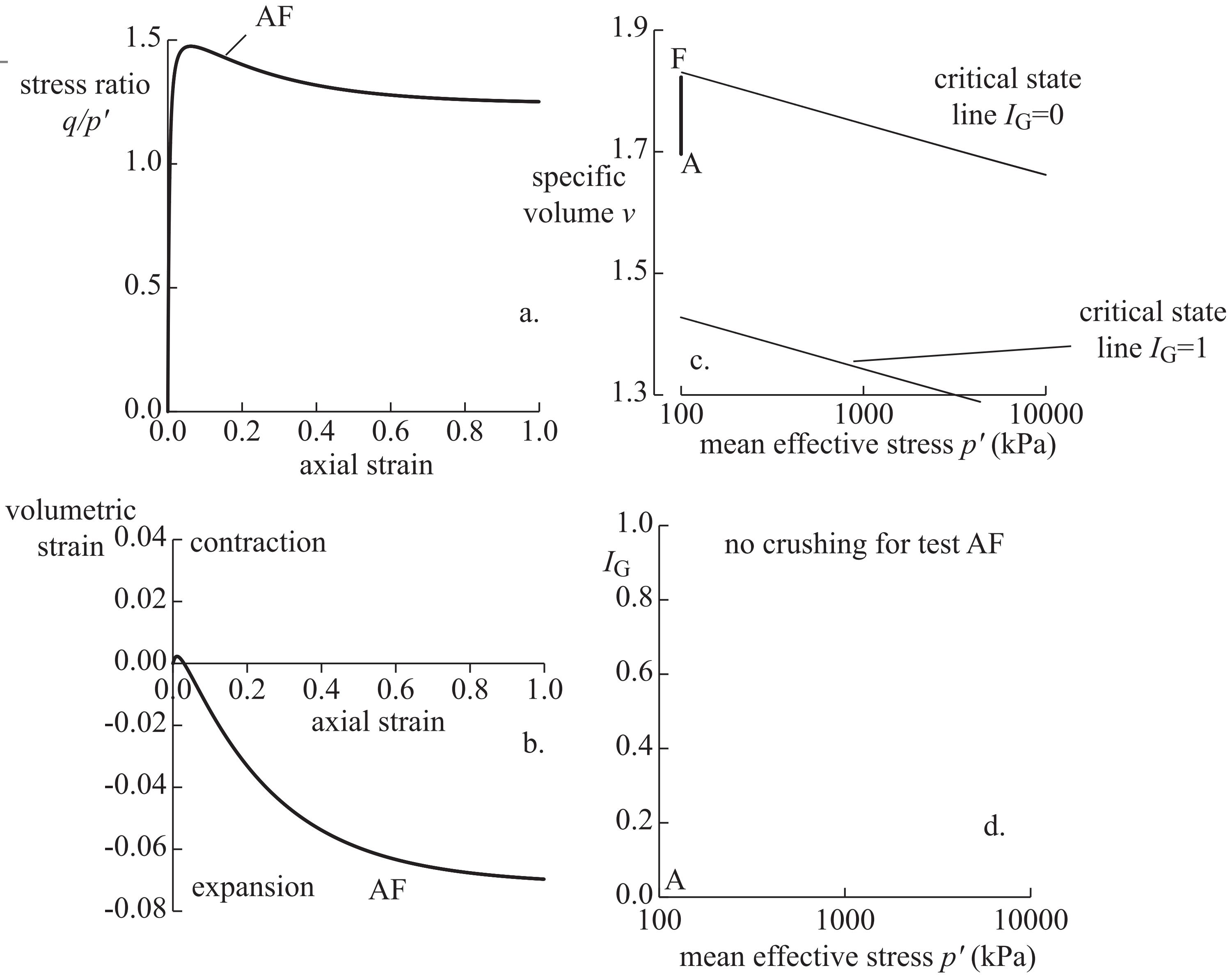
- broader gradings pack more efficiently
- limiting densities increase
- critical state line falls
- state parameter increases - soil feels looser

particle breakage/suffusion

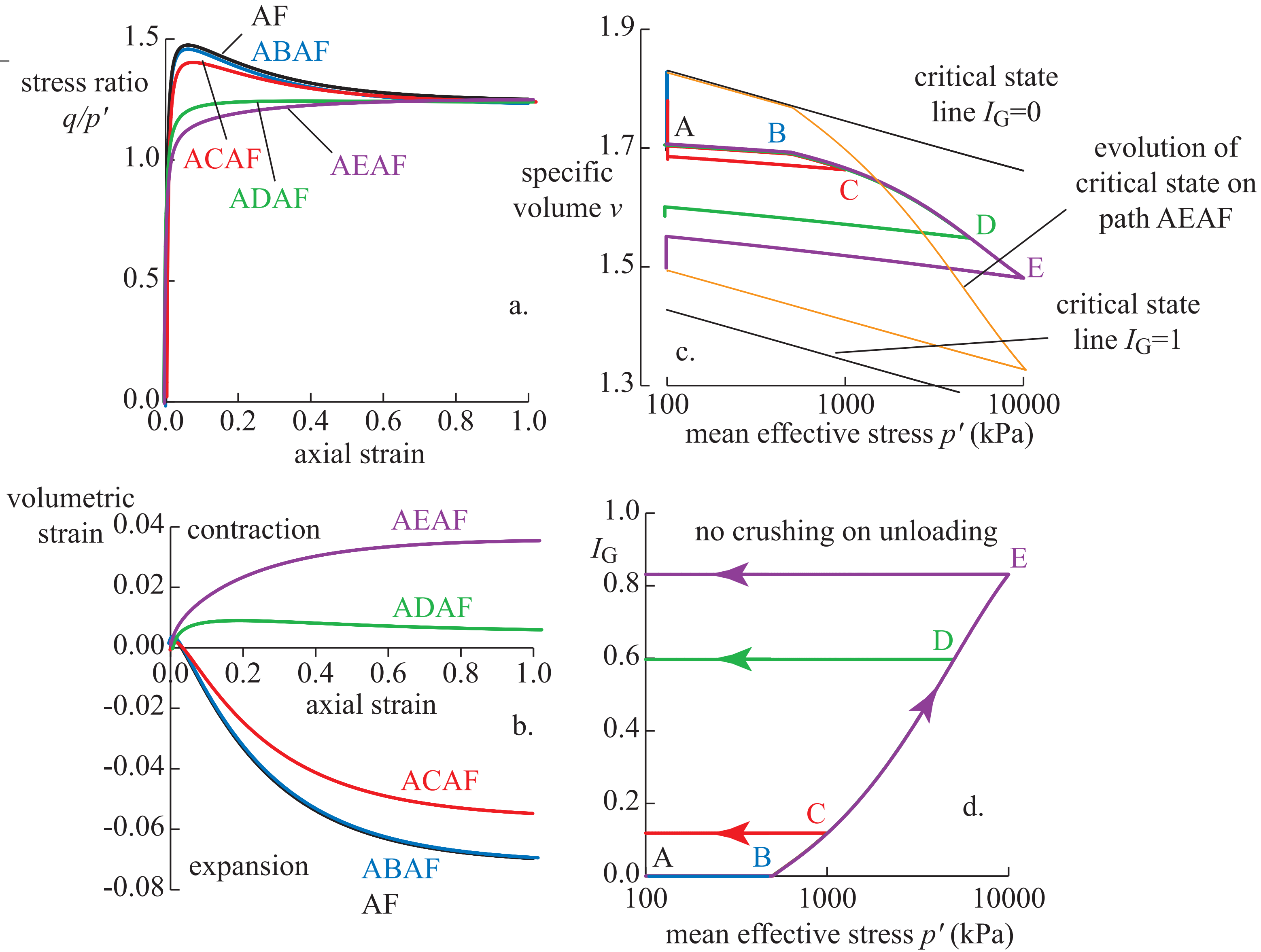


- characterise grading and grading evolution
- link grading evolution and critical state line
- particle breakage criterion - stress (strain?)
- other aspects of model unchanged *(first order)*

particle breakage + Severn-Trent sand



particle breakage + Severn-Trent sand



creep modelling of sands

- complex patterns of response observed - ‘descriptive’ titles but little attempt to understand physical mechanisms (Tatsuoka *et al.*)
- time effects in sands relate to the amount of grain crushing (Lade)
- creep effects observed in absence of particle breakage (Airey)
- experimental evidence consistent with static fatigue: time dependent fracturing of micro-morphologic features at inter-granular contacts (Michalowski)
- model for soil with varying particle size distribution

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Creep of Soft Clay: "Classical" to "Current Practice"

Hans Petter Jostad

Discipline leader in numerical modeling at NGI

Adjunct Professor at NTNU

2st CREEP Course, Trondheim, Norway,

15-16. September 2014

NGI

Key questions:

What is the definition of creep?

Do we have creep deformations at the same time as we have deformations due to pore pressure/stress changes?

When does creep start?

What controls the (volumetric) creep deformation?

How to expand from 1D to a general 3D stress state?

Motivation

How to calculate long term settlements in soft clay?

A) Primary and secondary compression phases?

B) Coupled consolidation and creep?

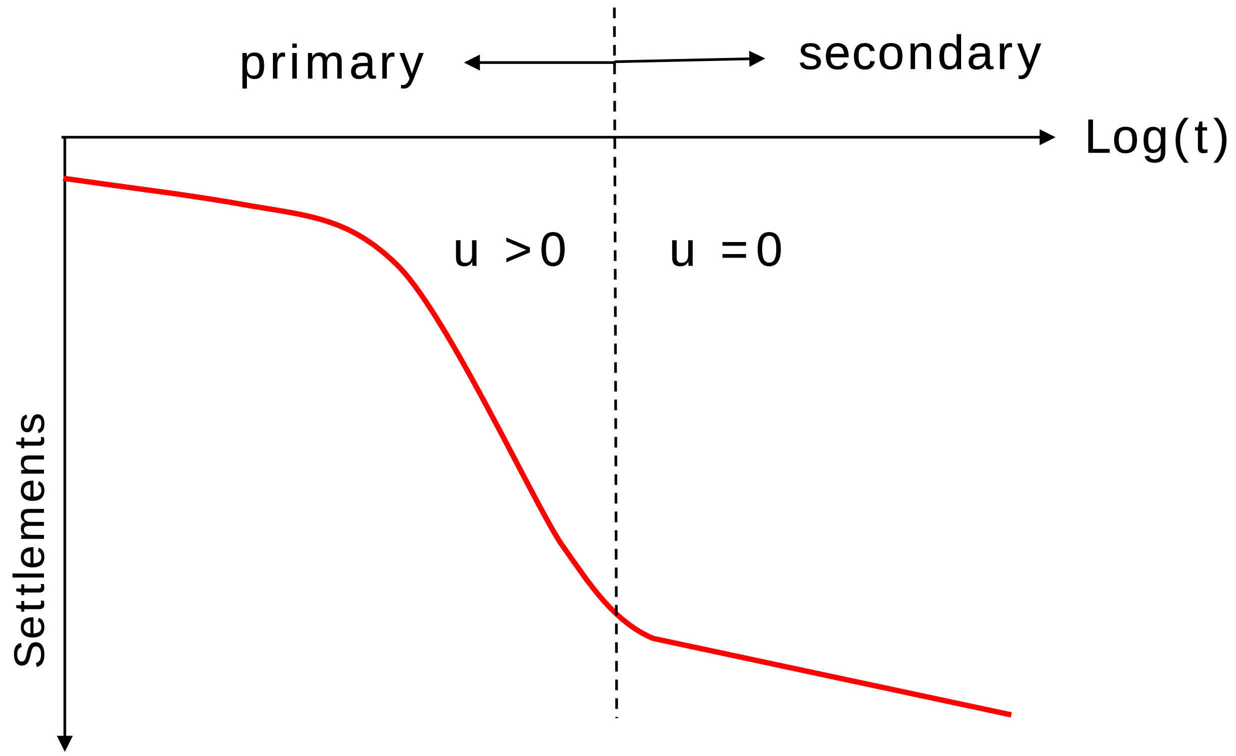
$$\frac{de}{dt} = \left(\frac{\partial e}{\partial \sigma'}\right)_t \frac{d\sigma'}{dt} + \left(\frac{\partial e}{\partial t}\right)_{\sigma'} + \left\{\frac{\partial e}{\partial T}\frac{dT}{dt}\right\} + \left\{\frac{\partial e}{\partial \theta_i}\frac{d\theta_i}{dt}\right\}$$

stress induced creep (temperature) (chemical)

$$\Delta e = \int_0^{t_p}\left[\left(\frac{\partial e}{\partial \sigma'}\right)_t \frac{d\sigma'}{dt} + \left(\frac{\partial e}{\partial t}\right)_{\sigma'}\right]dt + \int_{t_p}^{t}\left[\left(\frac{\partial e}{\partial t}\right)_{\sigma'}\right]dt$$

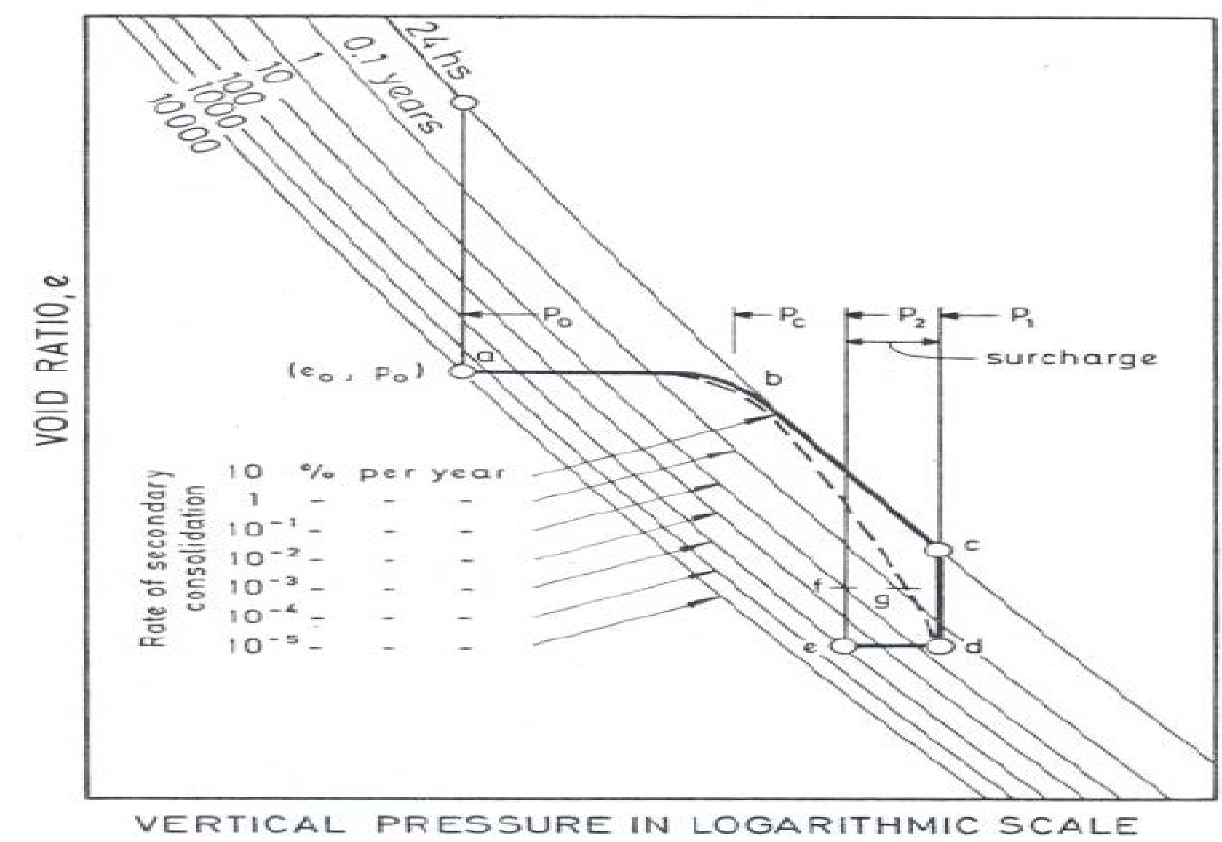
Primary (consolidation) Secondary (creep)

Secondary consolidation (creep)



The classical approach for creep settlements!

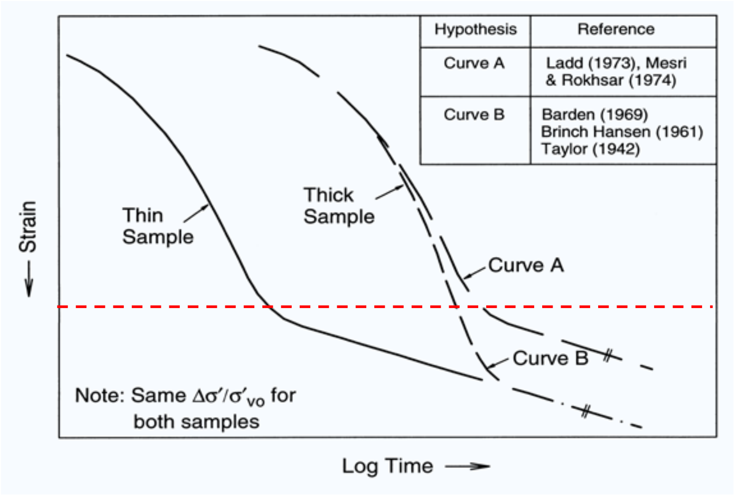
Bjerrum's delayed compression concept



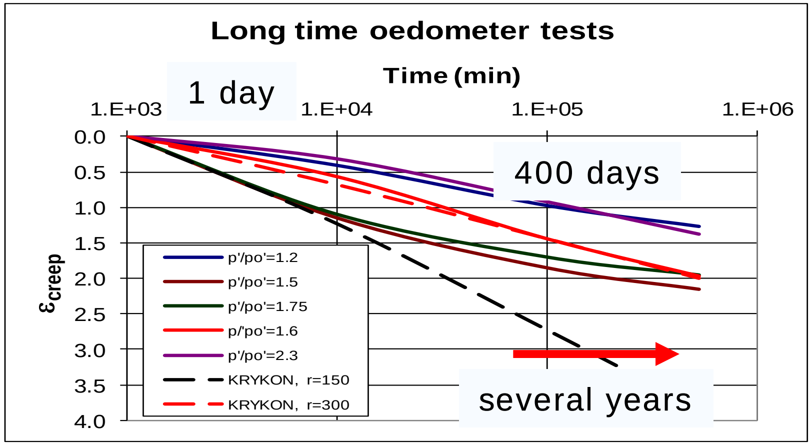
Unique relationship between creep rate, effective (vertical) stress and void ratio

Key questions related to long term settlements

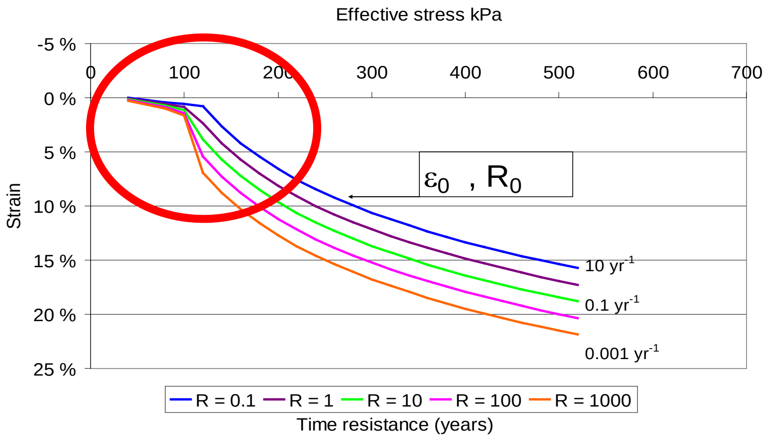
Extrapolation of laboratory data; rate?



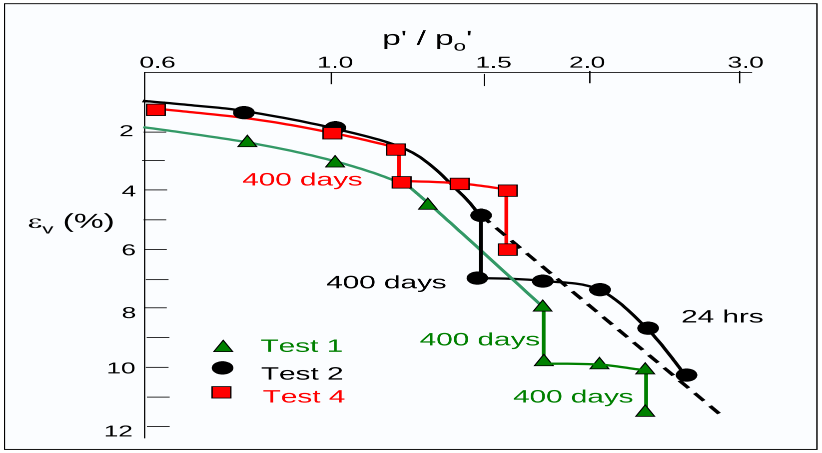
Extrapolation of laboratory data; time?



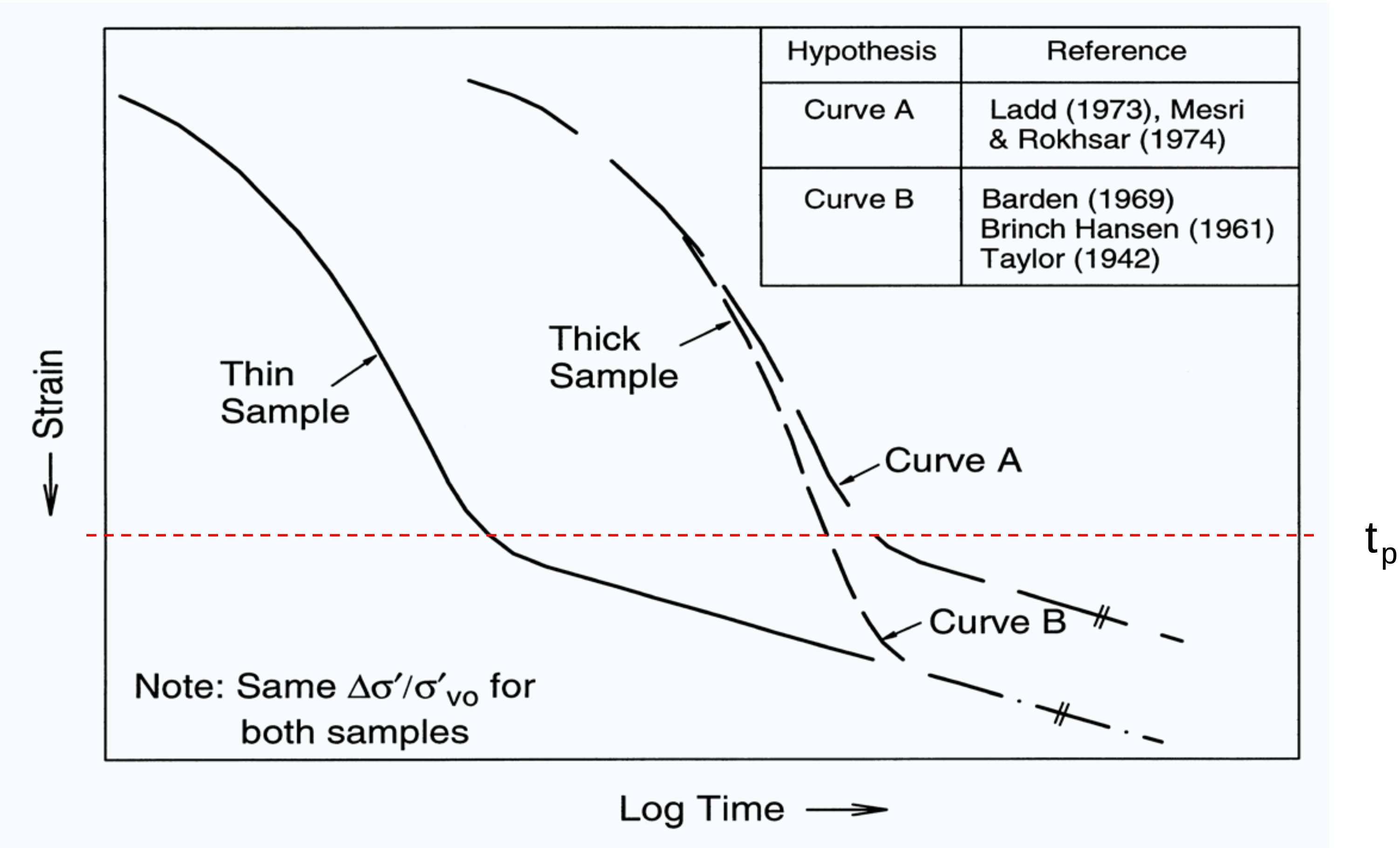
Behaviour around p_c' (destructuration)?



Effect of varying load history?



Unique end-of-primary (EOP) void ratio



Need this assumption in order to divide into primary- and secondary phases

A or B most correct?

Unique end-of-primary (EOP) void ratio

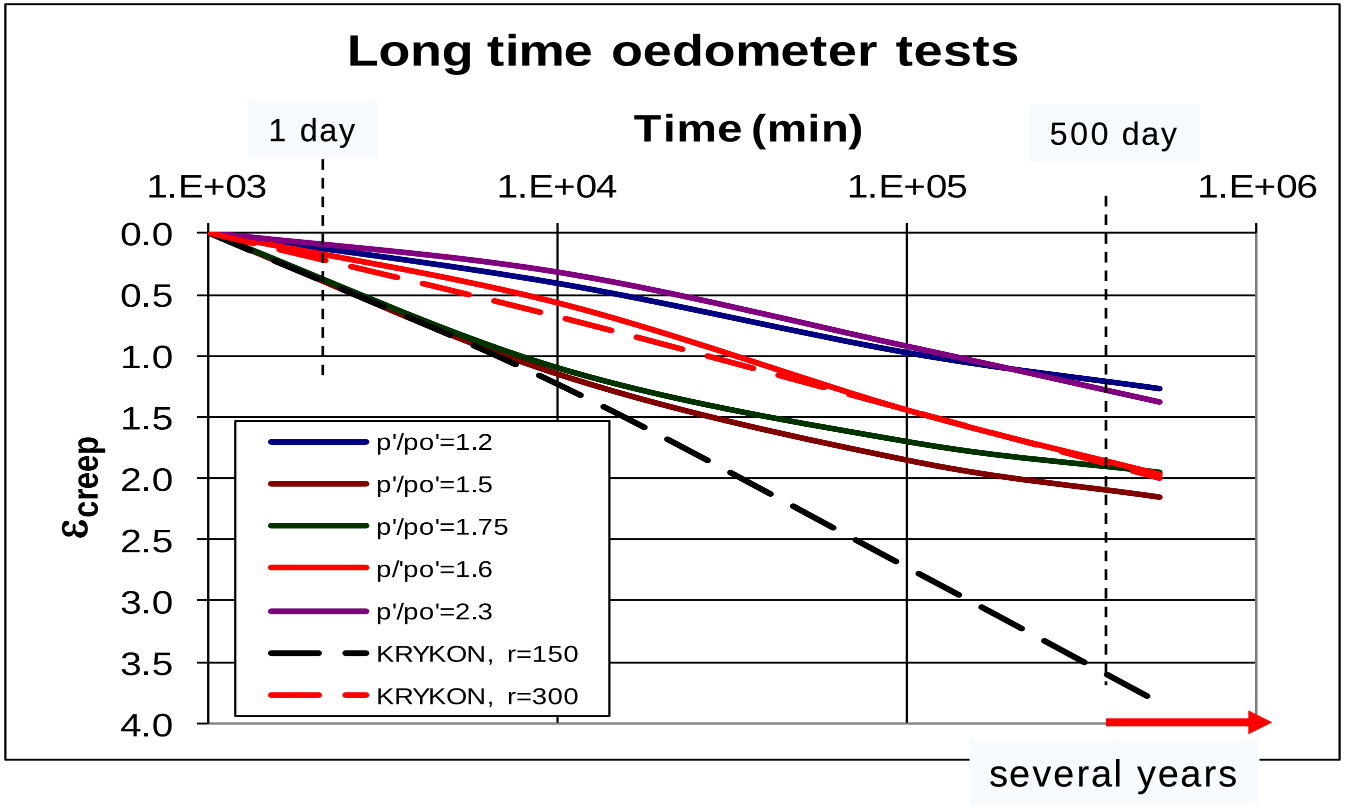
Arguments against the approach:

- How does a soil element "feel" that it is in a primary consolidation state?
  - Elements close to a drainage condition with almost constant effective stresses during the consolidation phase
  - Time of primary consolidation governed by a low permeable layer

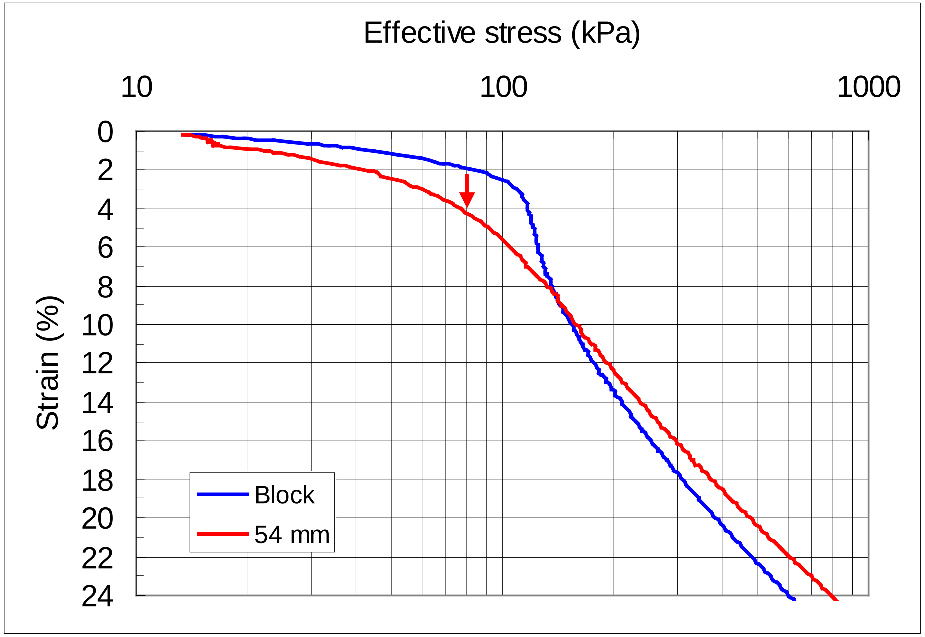
- Difficult to define a unique EOP state
  - u_{excess}/q = 0.1, 0.05 or 0.01

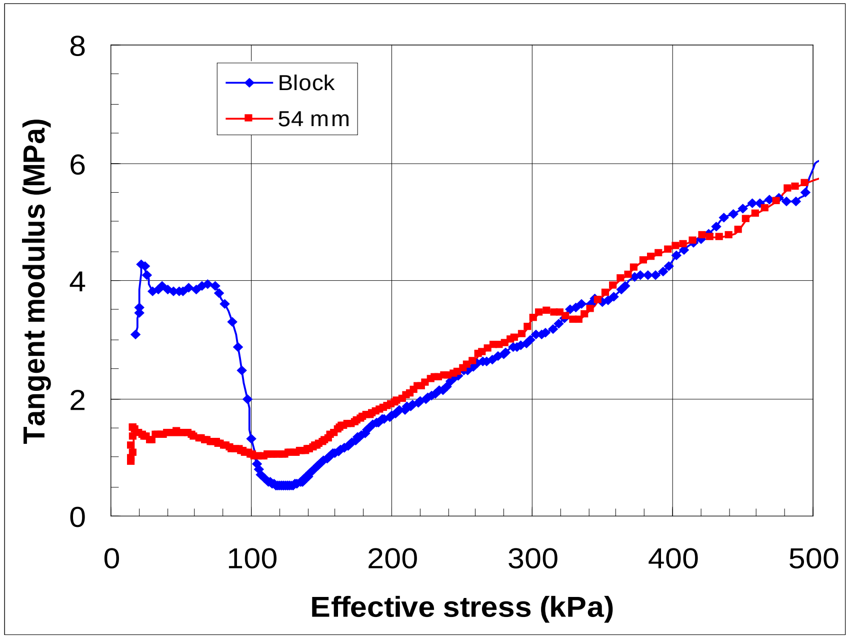
Main challenges

Due to significantly different time scale in field and laboratory conditions, the deformation in the field must be described (extrapolated) by a creep model based on input from laboratory tests.



Sample disturbance (apparent creep)





Is soil disturbance the reason for good agreements between standard consolidation analyses (without creep) and field observation?

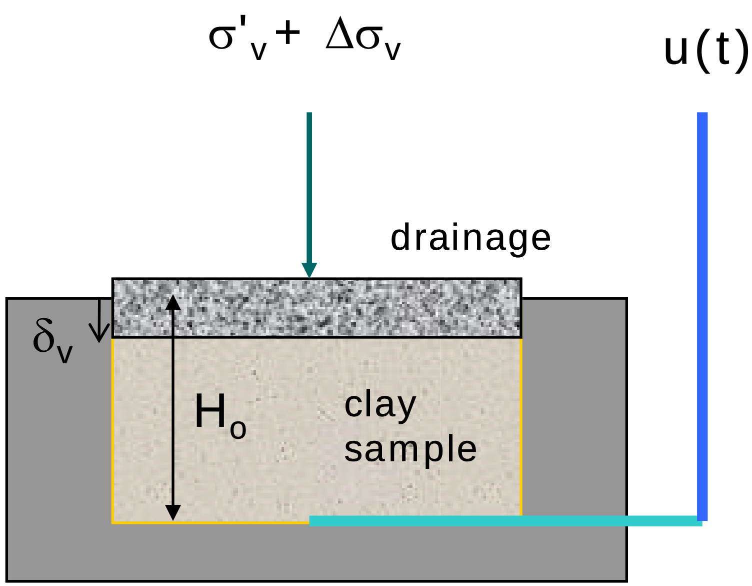
$$M_{oc} = a \cdot M_{pc}$$

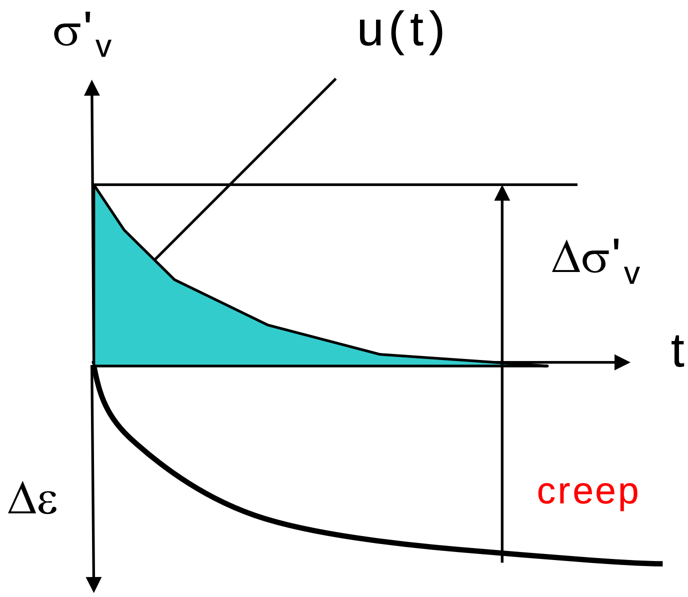
$$a = 5 \rightarrow 15$$

Verification/calibration of creep models

- Back-analyses of measured field data
  - Generally large number of uncertainties
- Back-analyses of idealised model tests (e.g. oedometer tests with different specimen heights)
  - Extrapolation is still necessary
- Long term laboratory tests
  - Extrapolation is still necessary

Oedometer test (Incremental Loading Tests)

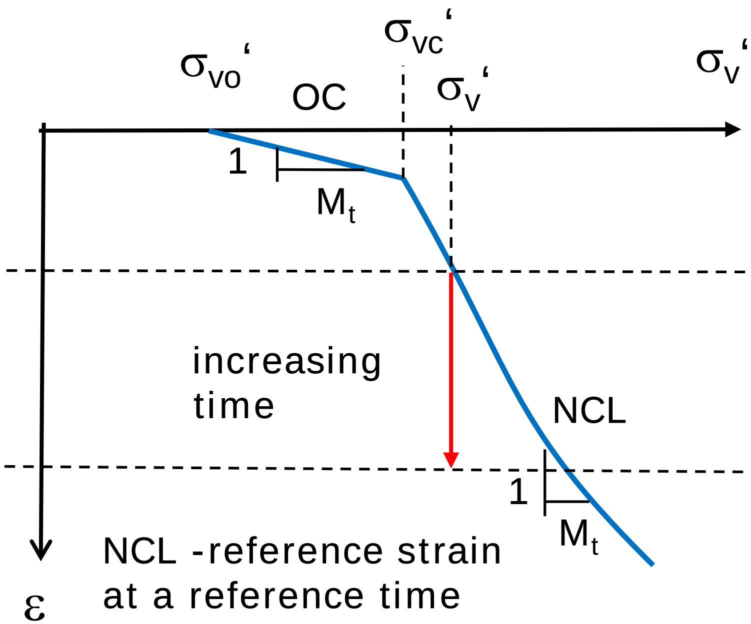


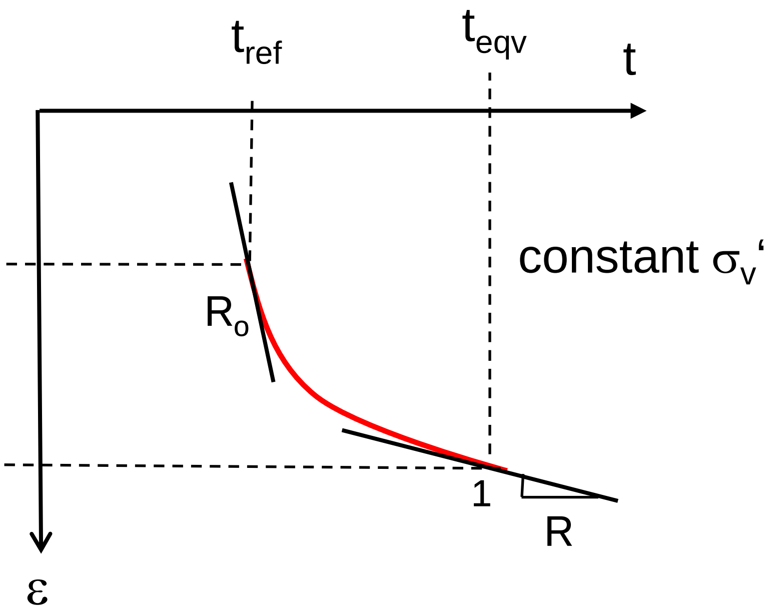


Need to separate into contributions
from effective stress changes and creep:

- Creep “starts” when u ~ 0 or after 1 day (as a reference)?
- Or, all plastic strains are time dependent (Soft Soil Creep Model)

Janbu's resistance concept (EP+VP)





$$\boxed{\frac{d\varepsilon_v}{dt} = \frac{1}{M_t}\frac{d\sigma_v'}{dt} + \frac{1}{R}}$$

$M_t = f(\sigma_v')$

$R = f(\sigma_v', e \text{ or } \varepsilon)$

Need these relationships!

Creep is added to the elasto-plastic strains

Janbu's time resistance

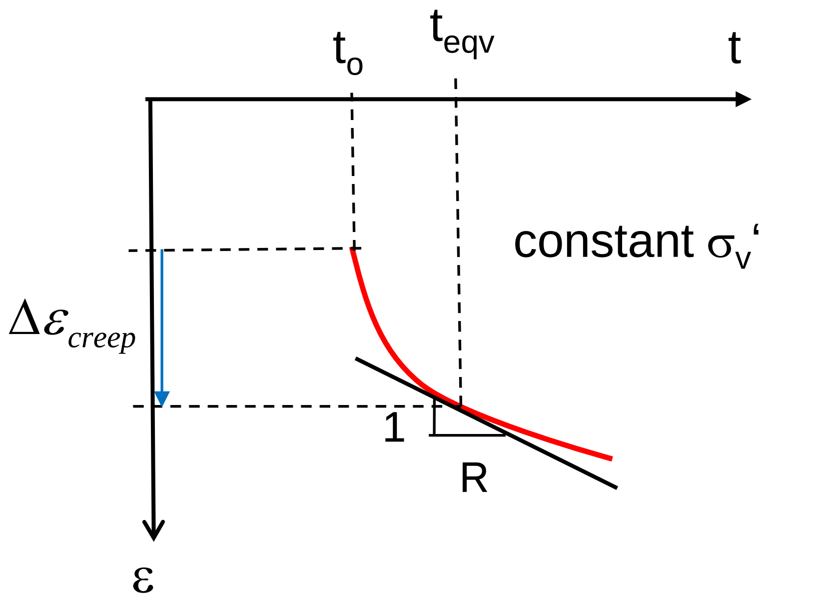
$$R = R_o + r\ (t - t_o)$$

$$\Delta\varepsilon_{creep} = \frac{1}{r}\ln\left(\frac{t}{t_o}\right) = \frac{1}{r}\ln\left(\frac{R}{R_o}\right) \longrightarrow t_{eqv}$$

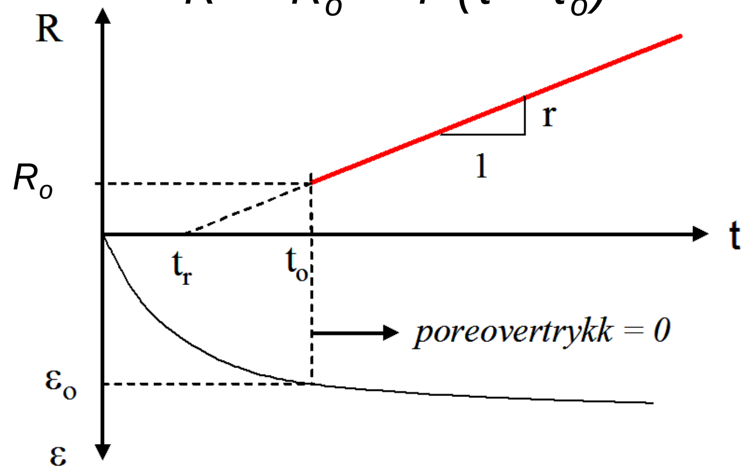
$$\Delta\varepsilon_{creep} = \varepsilon_{tot} - \varepsilon_o(\sigma_v')$$

$$R = R_o e^{(r\,\Delta\varepsilon_{creep})}$$

The accumulate creep strain is the state parameter for creep rate



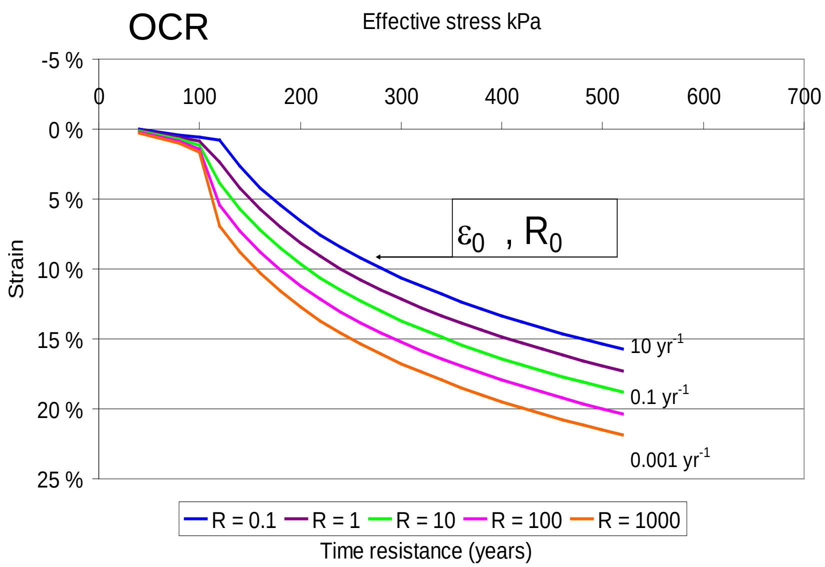
$$R = R_o + r\ (t - t_o)$$

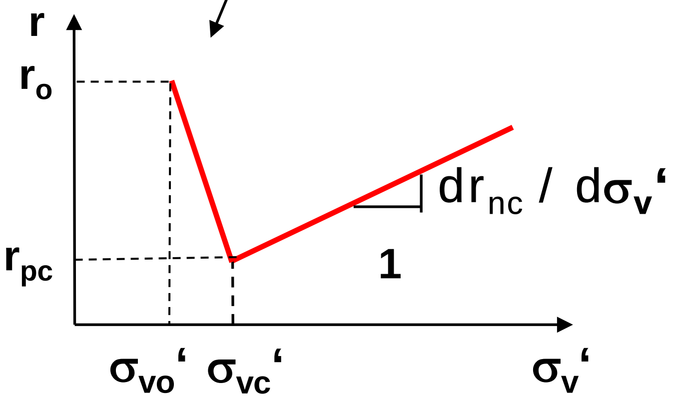


Effective stress dependency

Stress or OCR dependent?

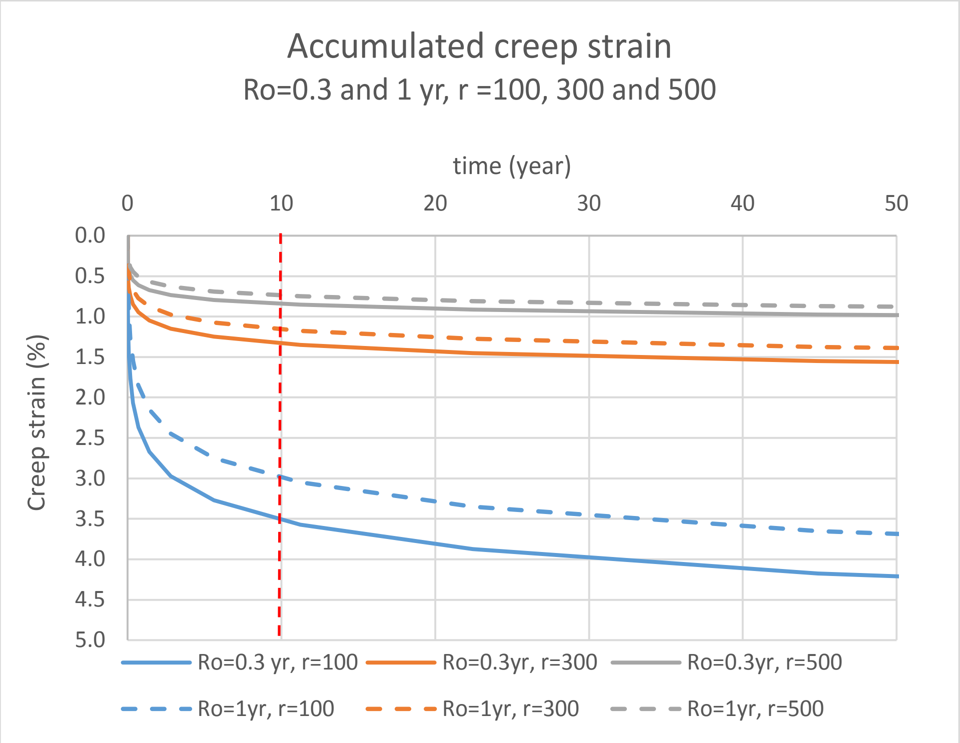
$$R = R_o + r\,(t - t_o)$$

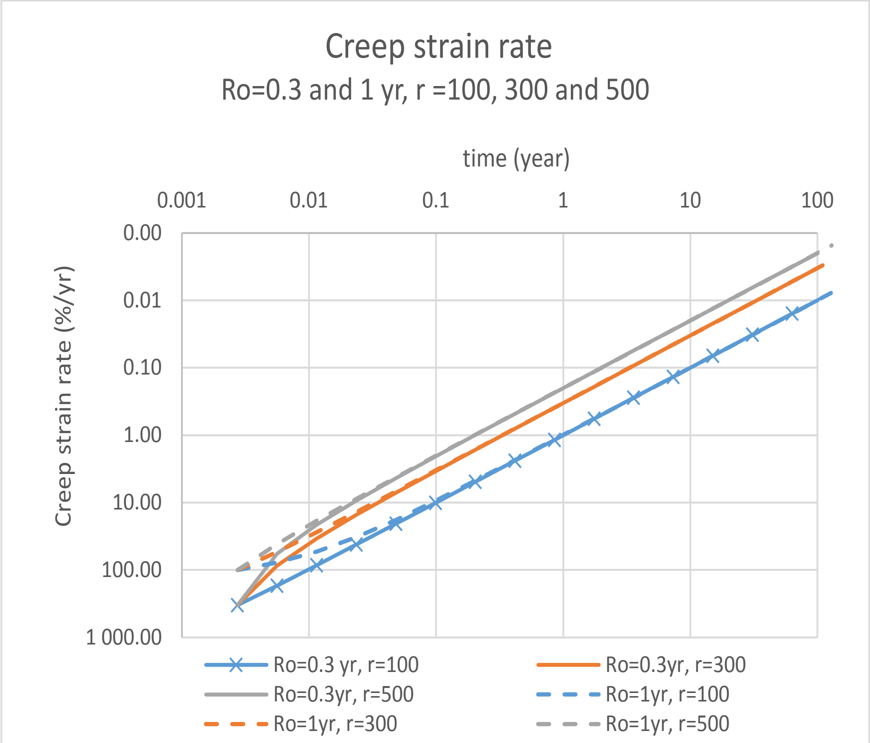




Example

Ro = 0.3 and 1 year, r = 100, 300 and 500

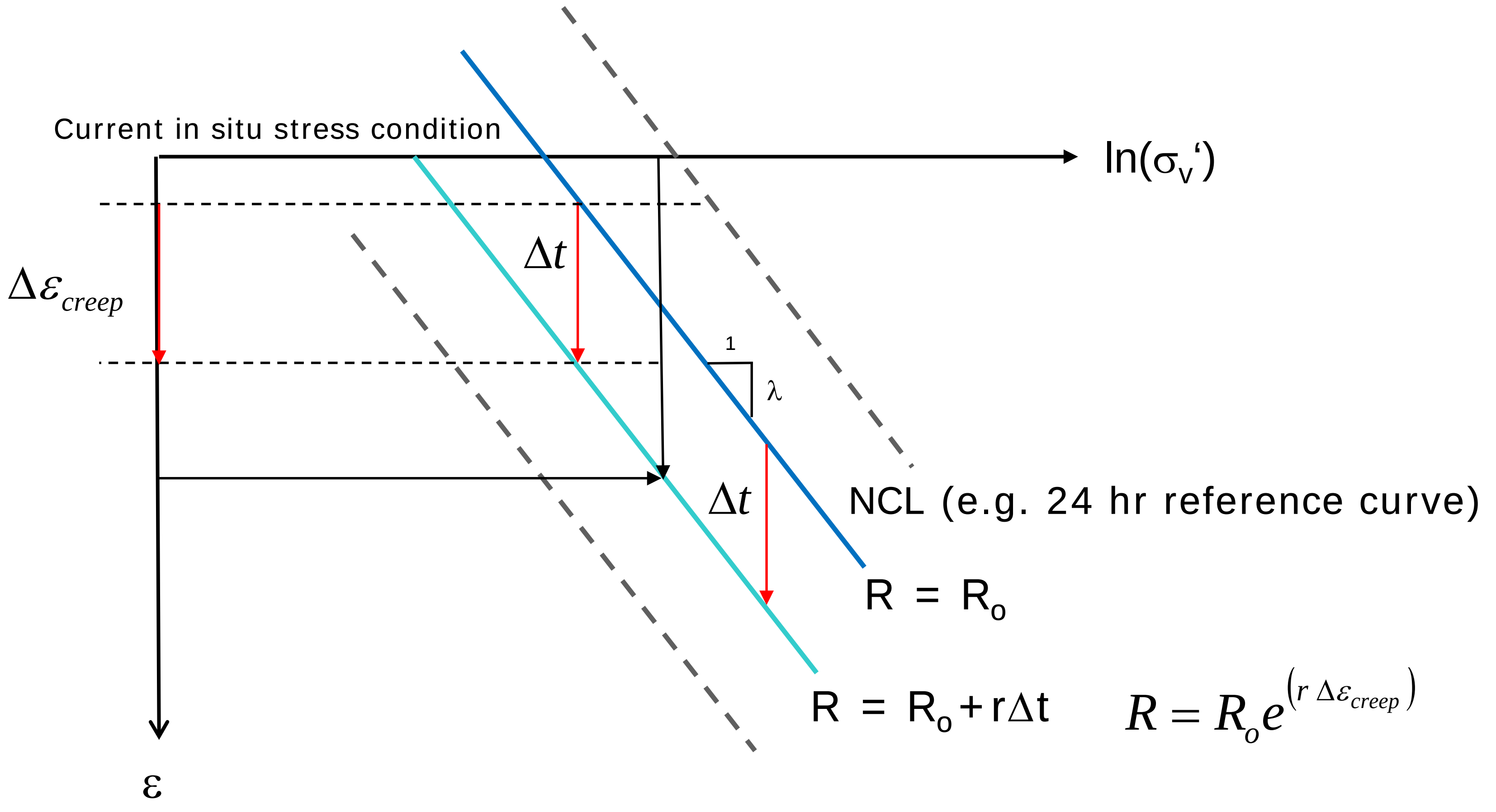




A large contribution of creep may occur during primary consolidation

Isotaches – lines of constant (creep) strain rate

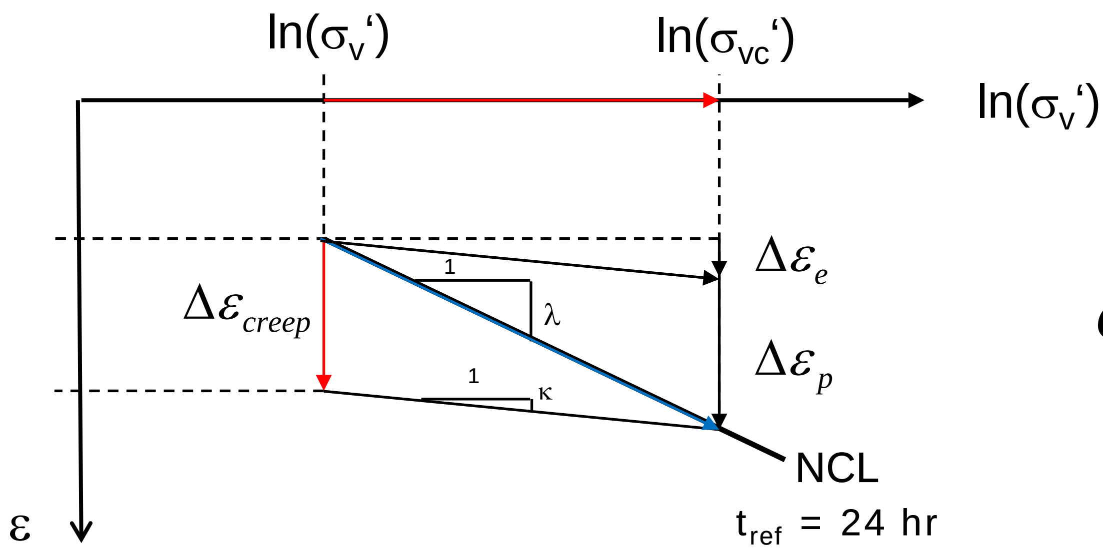
unique relationship between effective stress – strain (void ratio) – strain rate



These curves may be non-linear (curved)!

“Apparent” pre-consolidation pressure

Plaxis - Soft Soil Creep Model (E+EVP)



$$OCR = \left(\frac{\sigma_{vc}'}{\sigma_v'}\right)$$

$$r = \frac{1}{\mu^*}$$

$$\Delta\varepsilon_{creep} = \frac{1}{r}\ln\left(\frac{R}{R_o}\right) = \mu^*\ln\left(\frac{R}{R_o}\right) = (\lambda^* - \kappa^*)\ln\left(\frac{\sigma_{vc}'}{\sigma_v'}\right) = (\lambda^* - \kappa^*)\ln(OCR)$$

$$R = R_o e^{(r\,\Delta\varepsilon_{creep})} = R_o OCR^{\frac{\lambda^*-\kappa^*}{\mu^*}} = \frac{t_{ref}}{\mu^*} OCR^{\frac{\lambda^*-\kappa^*}{\mu^*}}$$

Solution algorithm – FE program

Input:

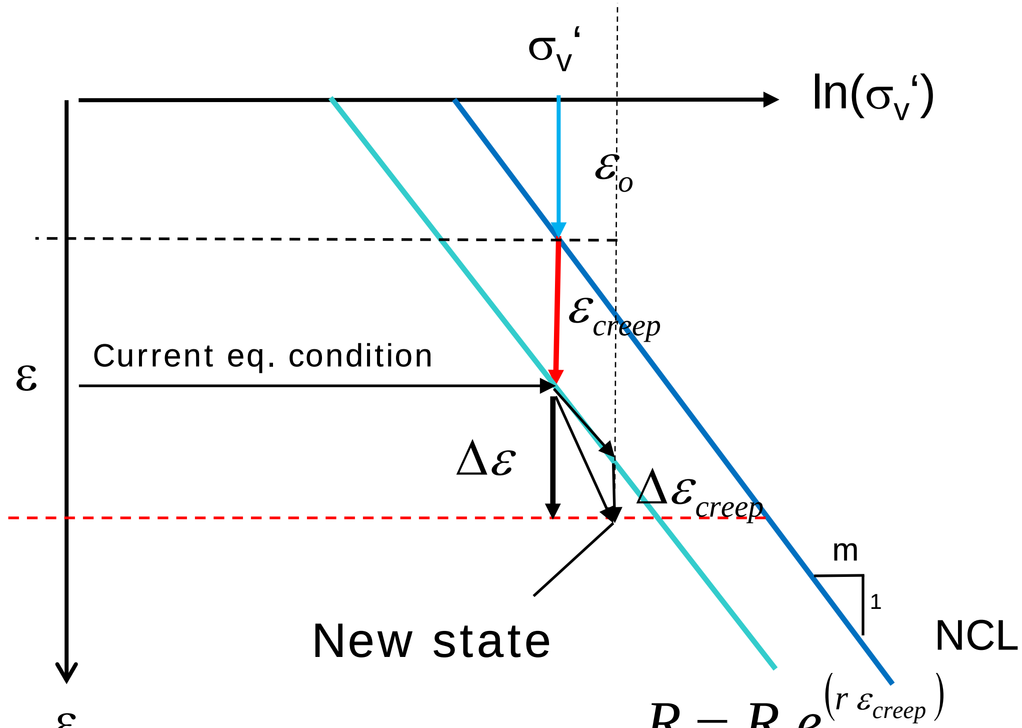
- Current equilibrium state:
  – σ_v' and ε
- New increment:
  – $\Delta\varepsilon$ (predictor)
  – Δt

Output:

- New stress state:
  – σ_v'

Calculations:

- $\varepsilon_o = f(\sigma_v')$
  – $\varepsilon_{creep} = \varepsilon - \varepsilon_o$
- $R = f(\varepsilon_{creep})$ Account for non-linear behaviour of R
  – $\Delta\varepsilon_{creep} = \Delta t / R$
  – $\Delta\sigma_v' = M_t(\sigma_v') \cdot (\Delta\varepsilon - \Delta\varepsilon_{creep})$



$$R = R_o e^{(r\,\varepsilon_{creep})}$$

Global equilibrium iteration!

Soil Investigation

Soil profile from e.g. CPTU and location of depth to bedrock (or a stiff layer)

In-situ pore pressure measurements (piezometers)

Soil samples from different depths/soil layers

Standard index tests

Oedometer tests

- constant strain rate (CRS) tests with unloading/reloading loops.
- x days creep test (and/or CRS tests with different rates)
- additional permeability tests?
- incremental loading (IL) tests (specification: Dq/q=1?, duration=24 hours or EOP, pore pressure measurements, long term creep phases, etc)

Recommendations of laboratory tests

IL tests are well suited to provide data on creep parameters and the location of the RTL

CRS tests is recommended to define the shape of one isotache specially around the yield stress

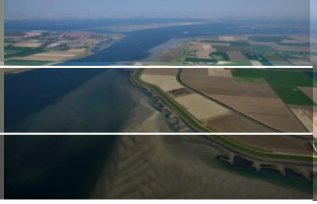
How should we define creep behaviour before pc?

Peat / organic soils

Dr ir C. Zwanenburg

23 september 2014

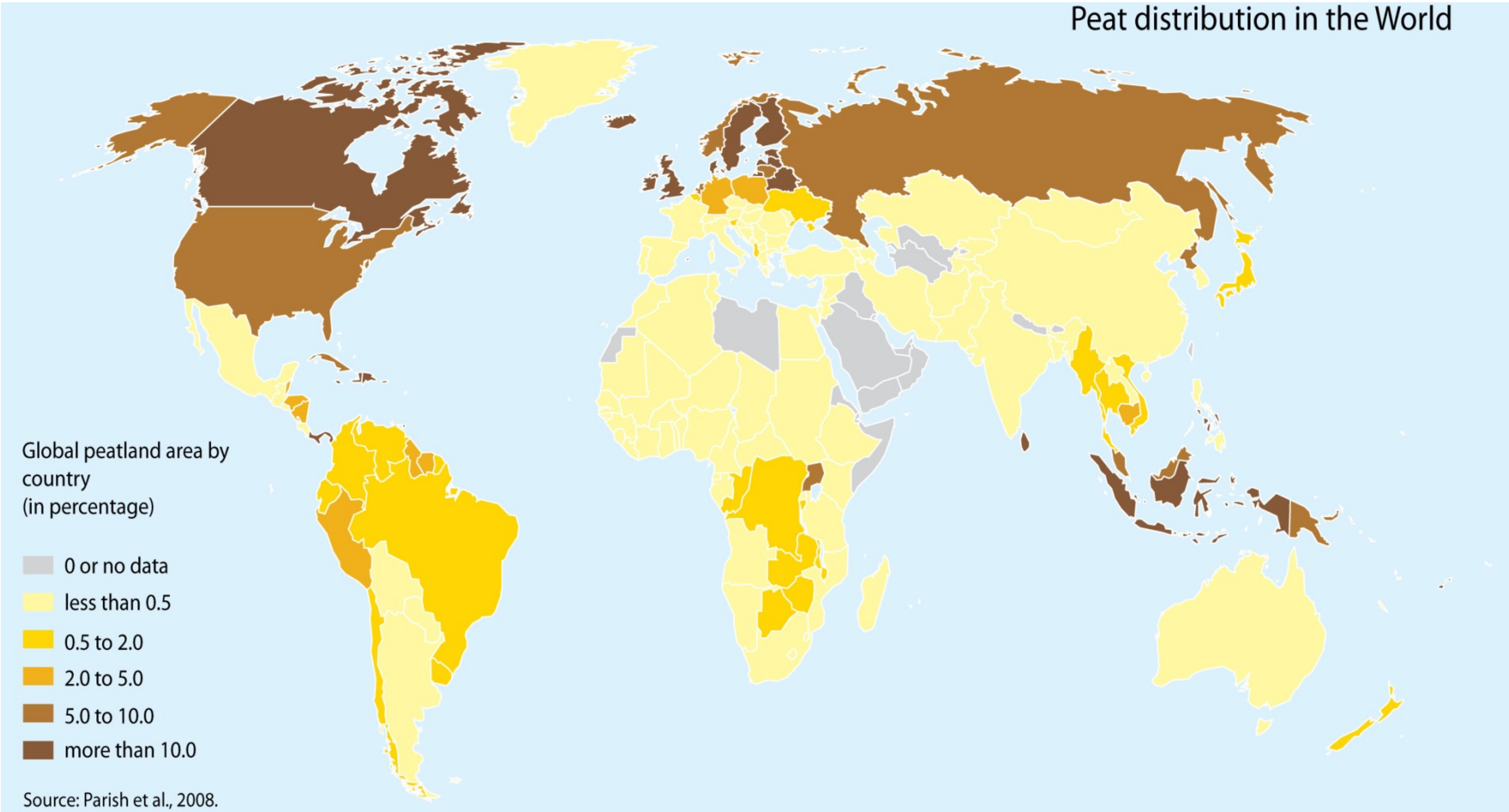
contents



- Intro
- Engineering problems
- Characterisation
- Engineering parameters
- Settlement and creep
- shortcomings

What is peat / organic soil?

Deposit of organic material, to some extent mixed with clay, silt sand particles

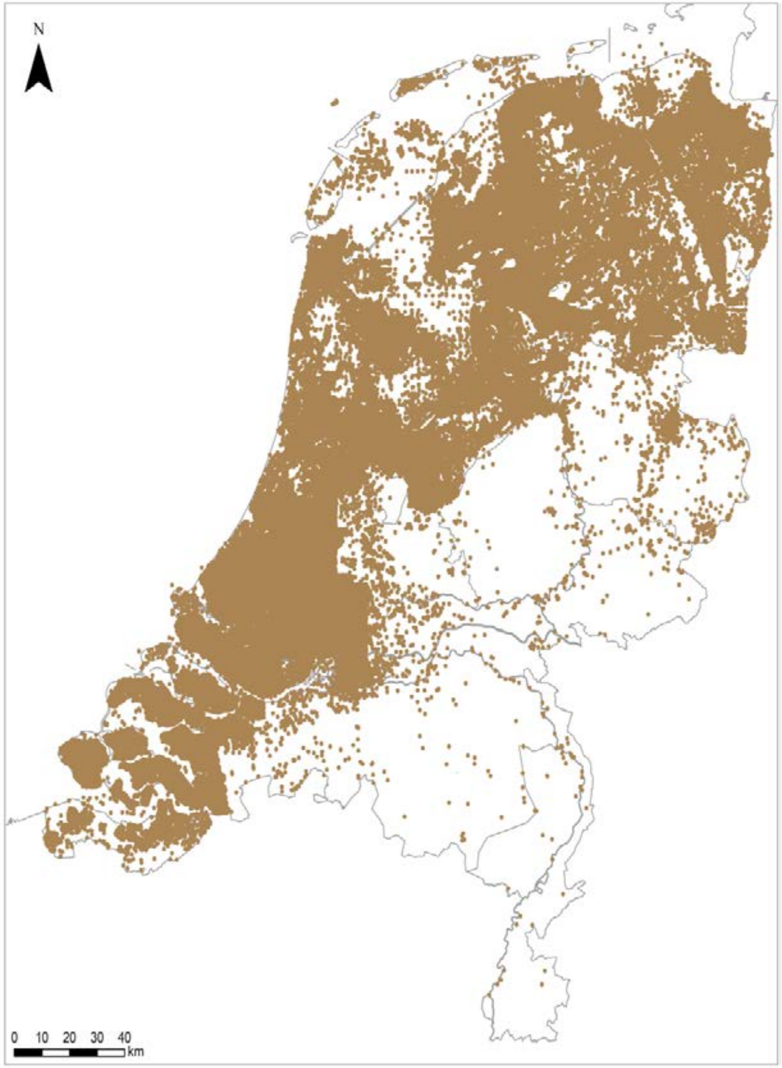


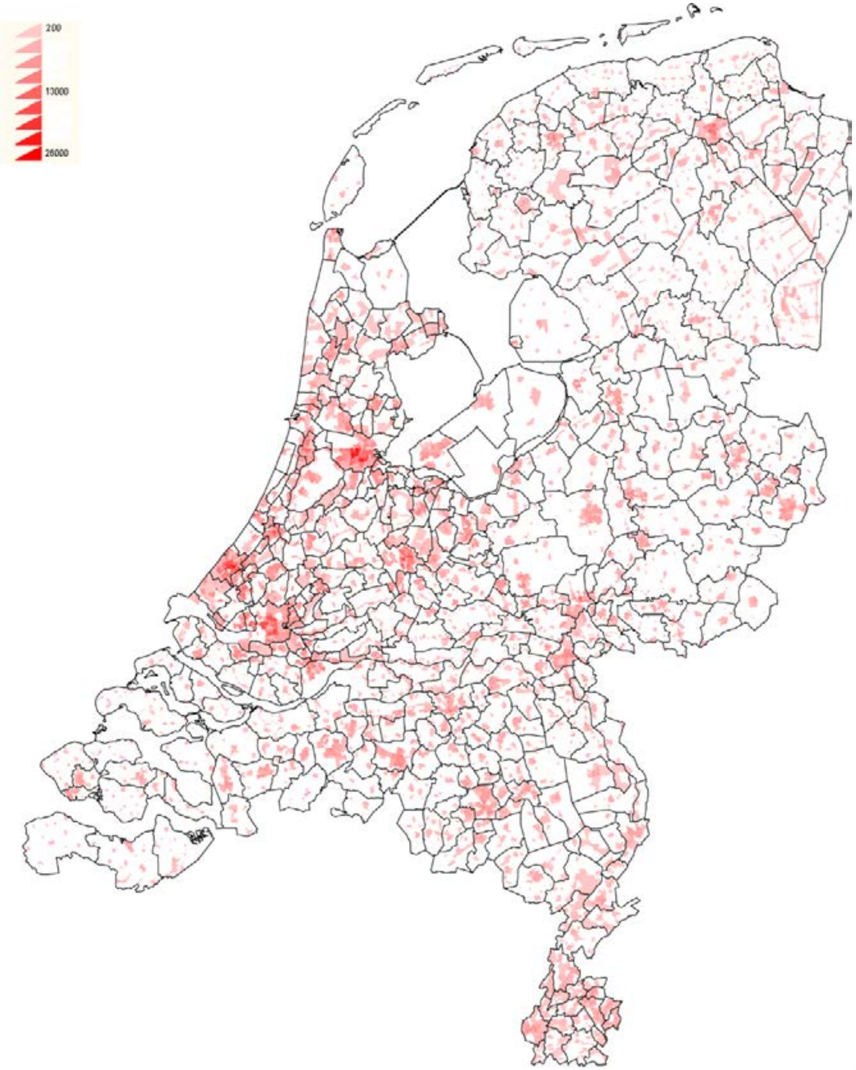
(http://www.grida.no/graphicslib/detail/peat-distribution-in-the-world_8660)

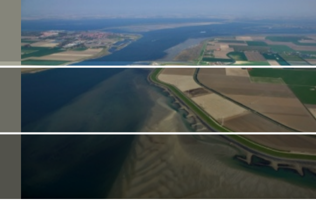
5-8% total land surface
8-11 % tropical / subtropical
(Mesri & Aljouni, 2007)

Deltares

Distribution of peat (Nieuwkoop formation) and population density

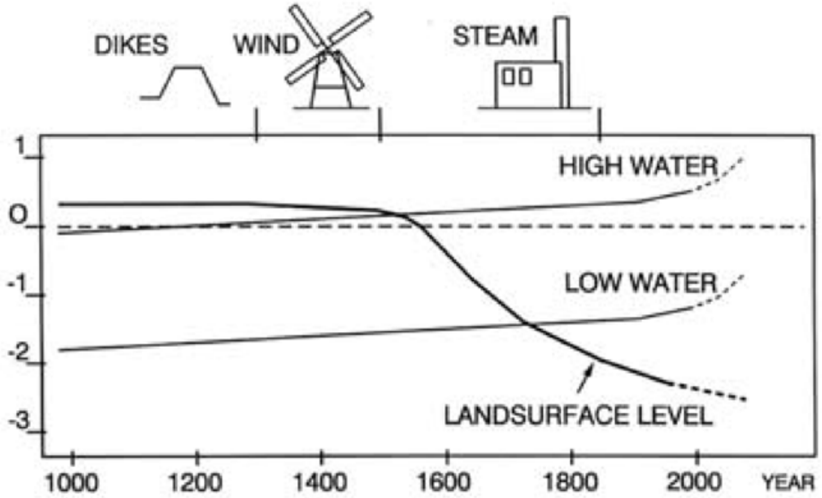




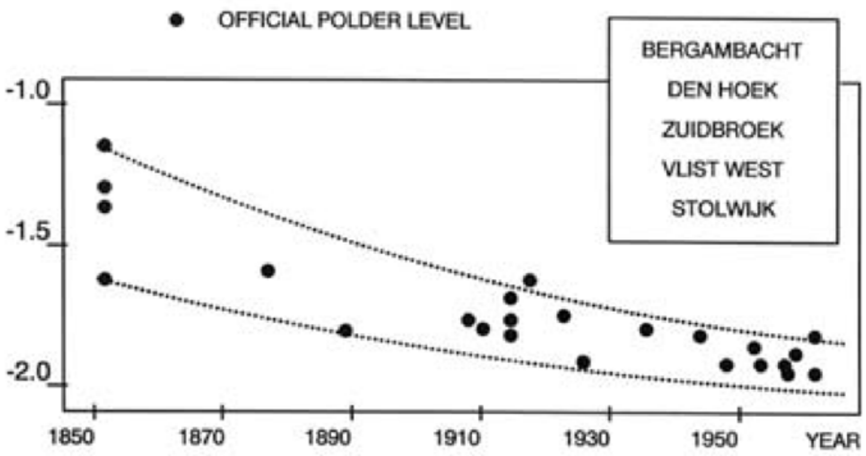



ENGINEERING PROBLEMS

Long term settlement



POLDER LAND SUBSIDENCE IN HOLLAND



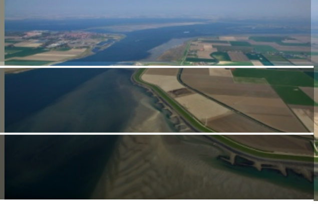
POLDER WATER LEVEL IN HOLLAND

(vertical scales give elevation in m relative to Dutch datum N.A.P.)

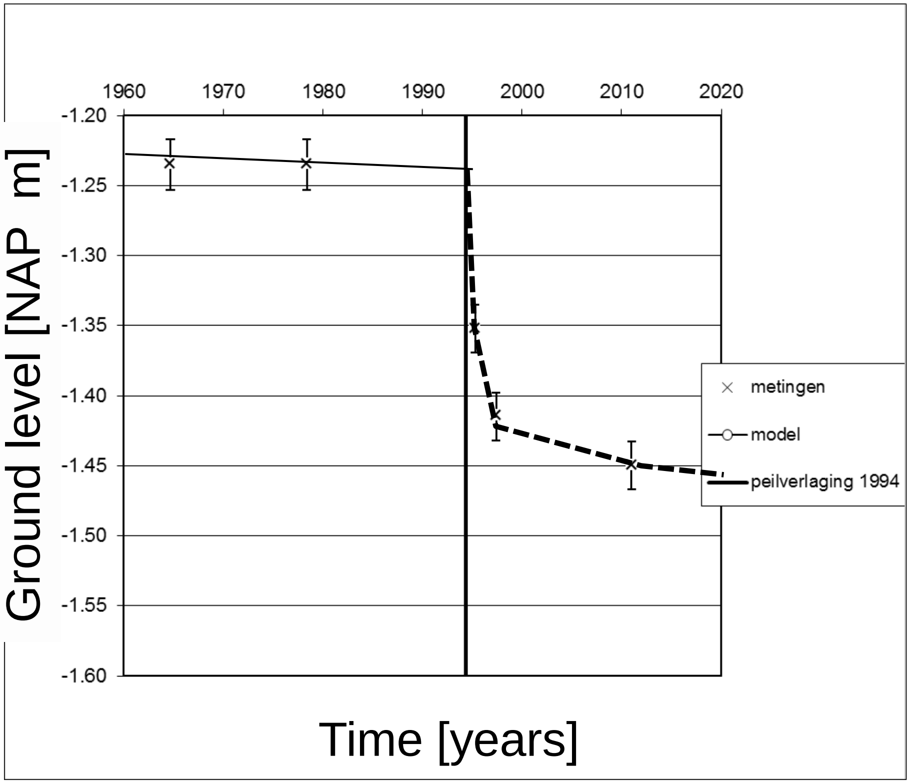
Dewatering

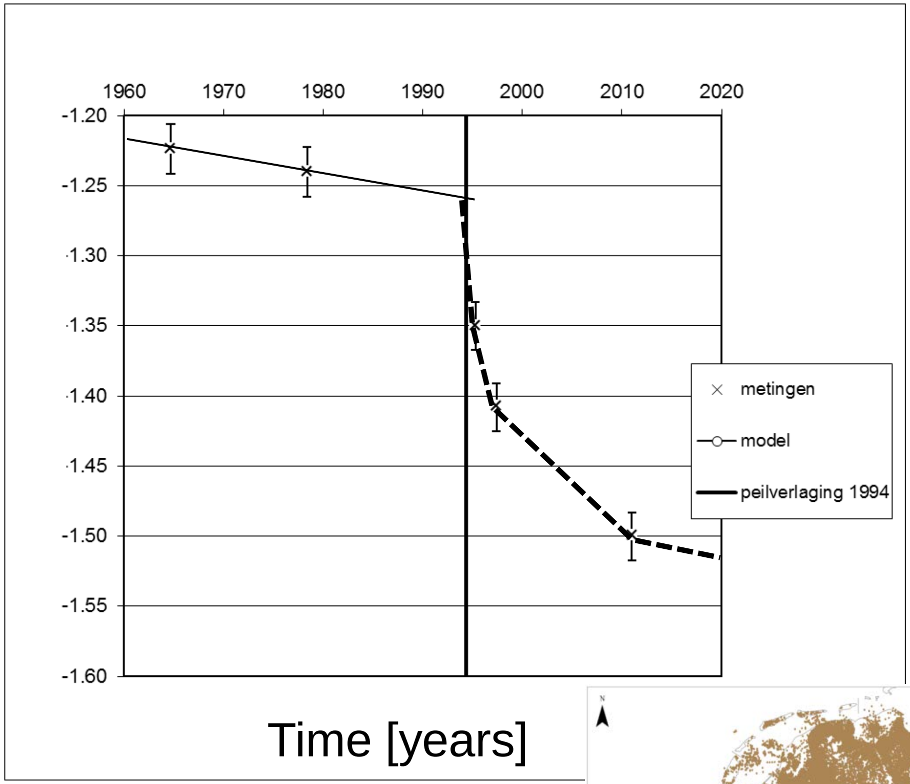
Kadijkselaan, omgeving Bergambacht

Consequences



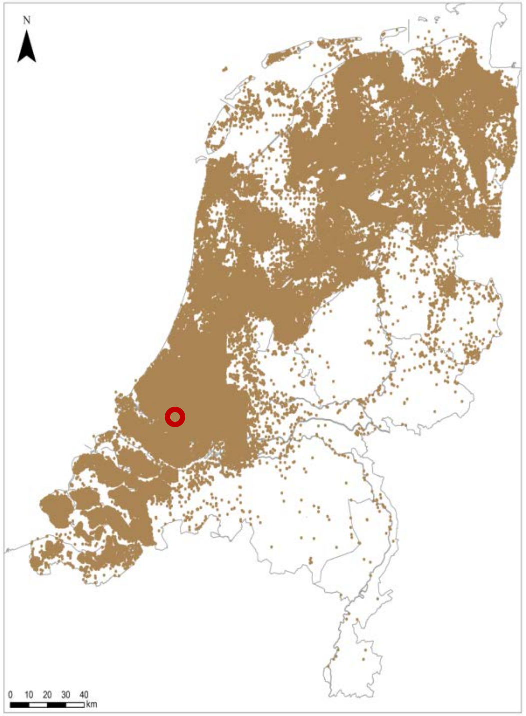
adjusting water table leads to extra settlement (location: Waterland)





	Year	Level adjustment
1	1976	NAP-1.43m - NAP-1.49m
2	20 May 1994	NAP-1.49 - NAP-1.96 m

Case Rotterdam, schiewijk

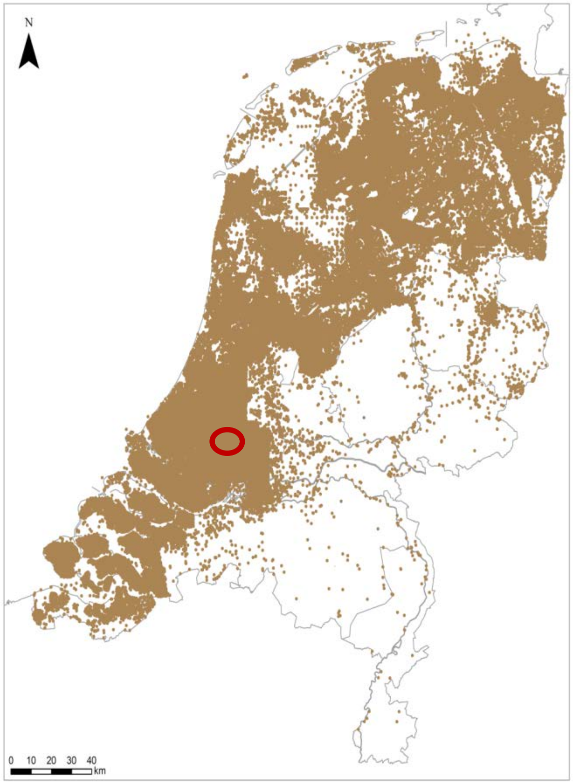


Deltares

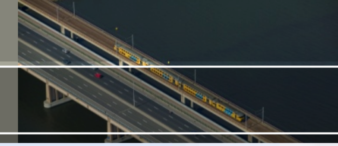
Residual settlement

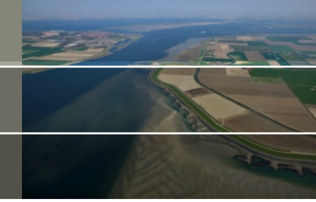
Skin friction on piled foundations

Case Gouda Goverwelle

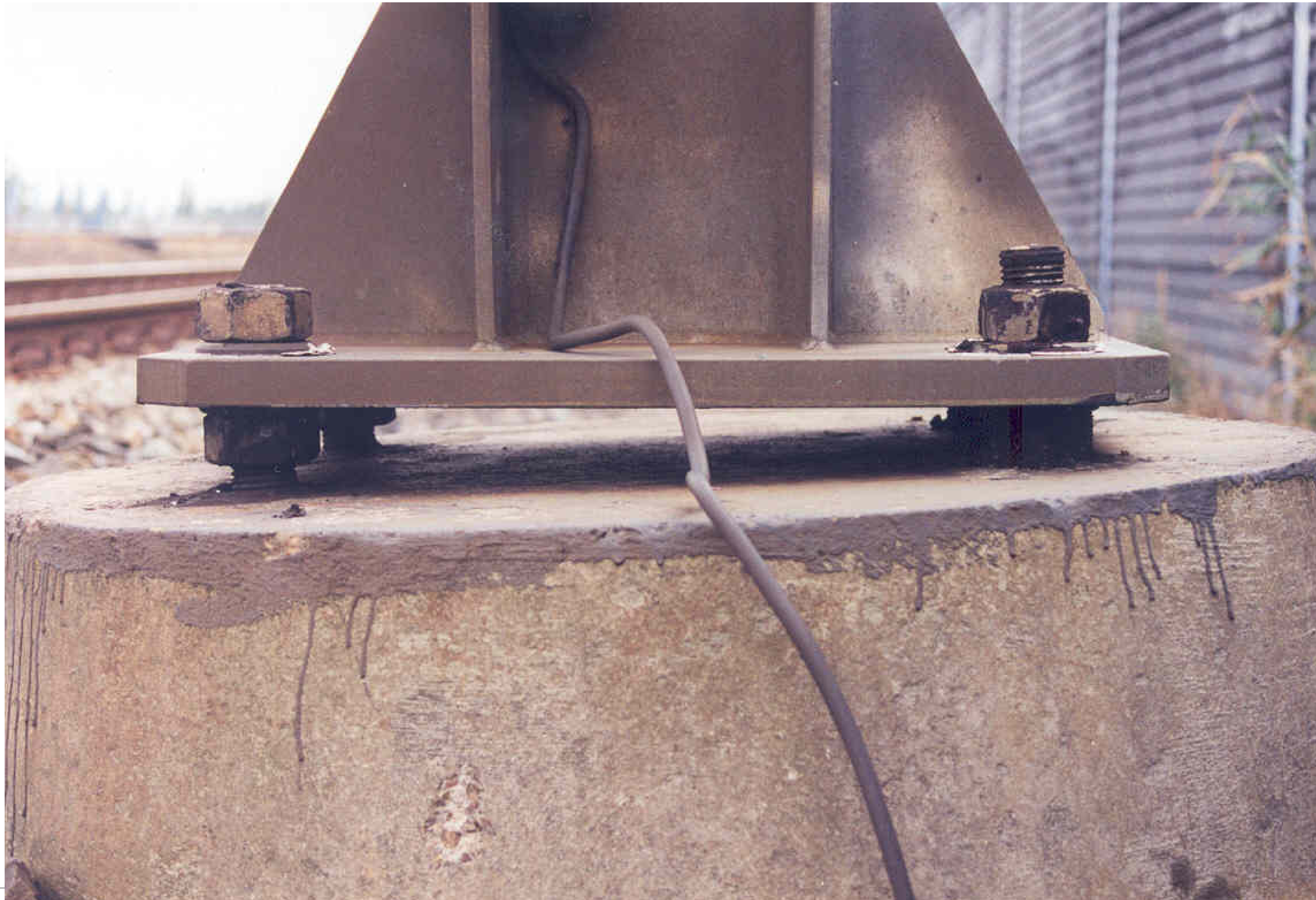


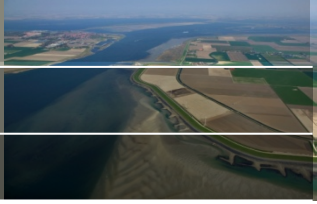
Deltares



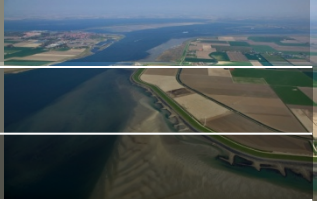
450
452





differential settlement

Goudse Houtsingel, near Gouda

CHARACTERISATION

Organic content

Organic content $P = M_{org} / M_{tot}$

Ash content = $1-P$

How to determine P:

- Determine dry solid mass (M_s), by drying sample for 24 h at 105°C
- Determine remaining mass (m_1) after drying for 4 h at 500 °C
- Loss on ignition $N = (M_s - m_1)/M_s$.
- Ash content = $1.04(1 - N)$
- $P = 1 - 1.04(1 - N)$

An error of 4% is assumed for organic particles that are lost in finding M_s

Definition

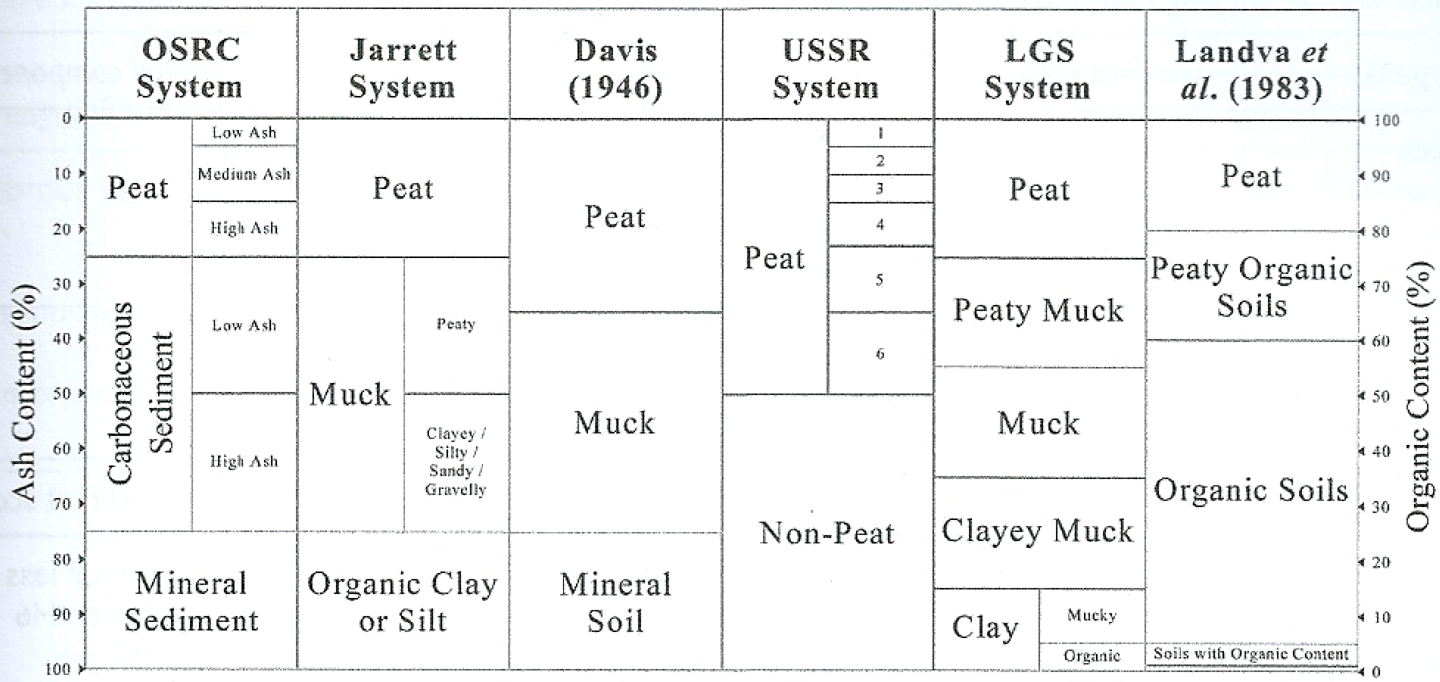


Figure 2.5 Comparison of classification systems used for peat and organic soils (*after* Andrejko *et al.*, 1983). (B.B.K. Huat et al 2014)

Deltares

Characterisation

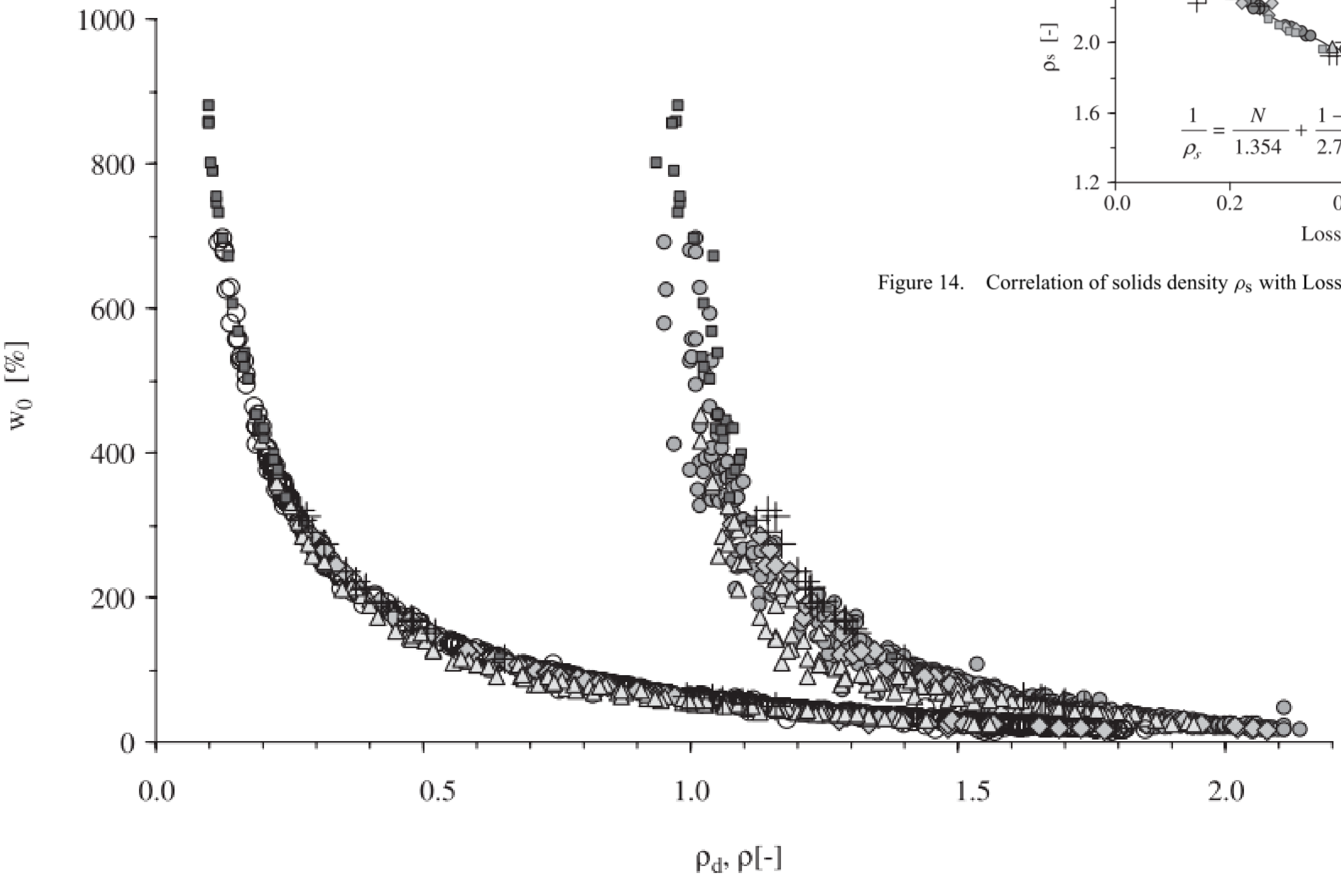


Figure 13. Correlation of wet and dry bulk density with natural water content for various Dutch peats and organic soils.

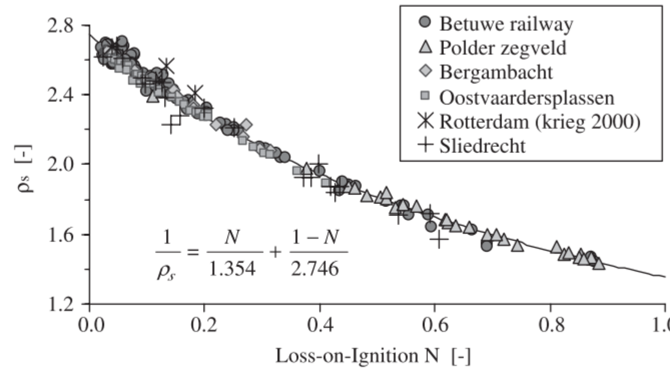
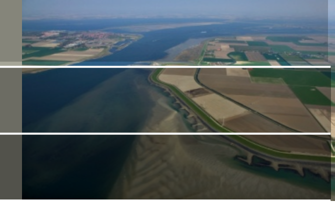


Figure 14. Correlation of solids density ρ_s with Loss-on-Ignition value N.

Den Haan & Kruse (2007)

Further classification



Many options:

- Von Post classification (decomposition)
- Fiberosity
- Botanical background
- Conditions during deposition (eutrophic, mesotrophic, oligotrophic)
- Type of additive (clay, sand etc.)
- ……..

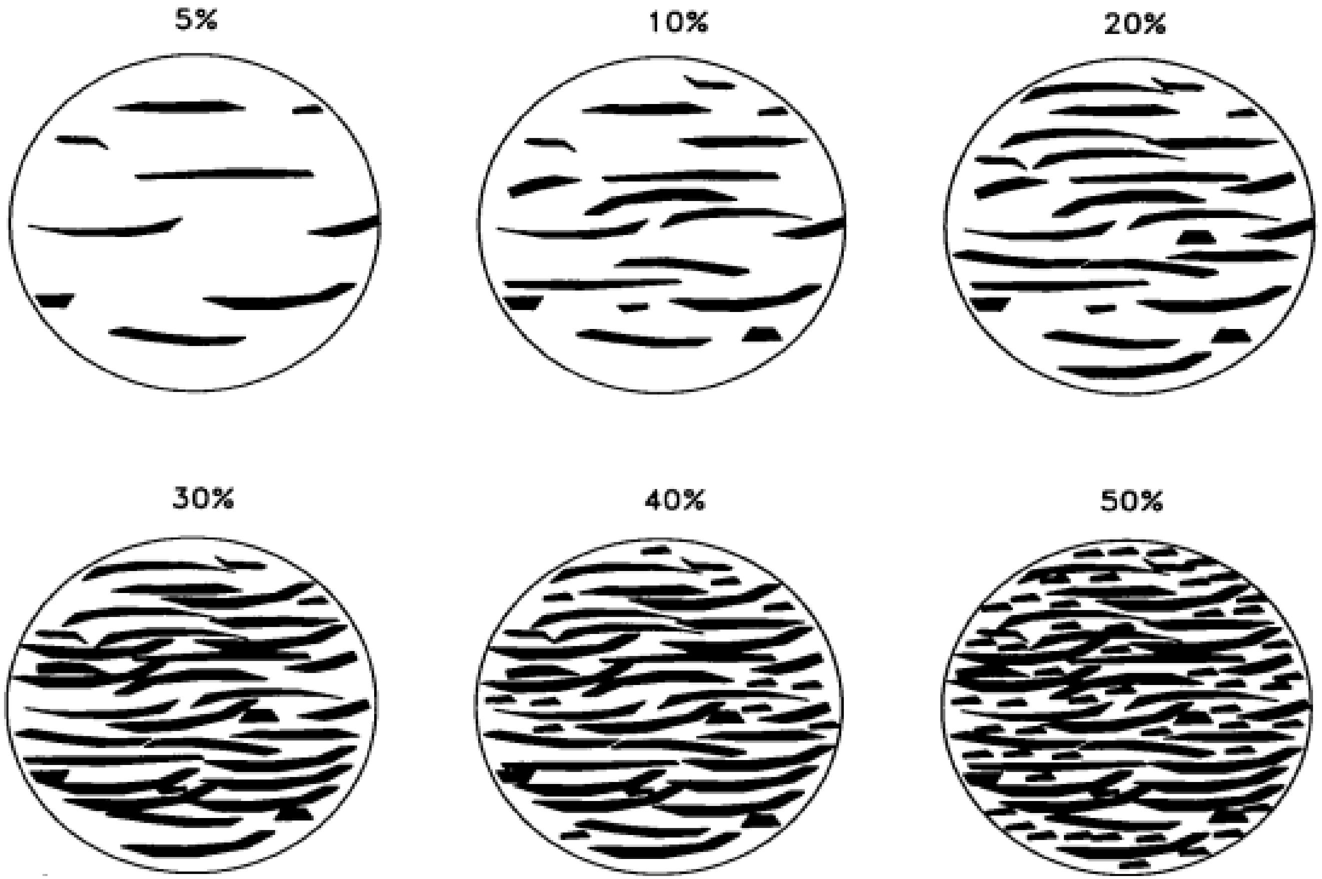
Von Post classification (field identification)

Table A1.   Degree of humification (von Post system).

Degree of humification	Decomposition	Plant structure	Content of amorphous material	Material extruded on squeezing (passing between fingers)	Nature of residue
H_1	None	Easily identified	None	Clear, colourless water	
H_2	Insignificant	Easily identified	None	Yellowish water	
H_3	Very slight	Still identifiable	Slight	Brown, muddy water; no peat	Not pasty
H_4	Slight	Not easily identified	Some	Dark brown, muddy water; no peat	Somewhat pasty
H_5	Moderate	Recognizable, but vague	Considerable	Muddy water and some peat	Strongly pasty
H_6	Moderately stong	Indistinct (more distinct after squeezing)	Considerable	About one third of peat squeezed out; water dark brown	
H_7	Strong	Faintly recognizable	High	About one half of peat squeezed out; any water very dark brown	
H_8	Very strong	Very indistinct	High	About two thirds of peat squeezed out; also some pasty water	Plant tissue capable of resisting decomposition (roots, fibres)
H_9	Nearly complete	Almost not recognizable		Nearly all the peat squeezed out as a fairly uniform paste	
H_{10}	Complete	Not discernible		All the peat passes between the fingers; no free water visible.	

(Landva 2007)

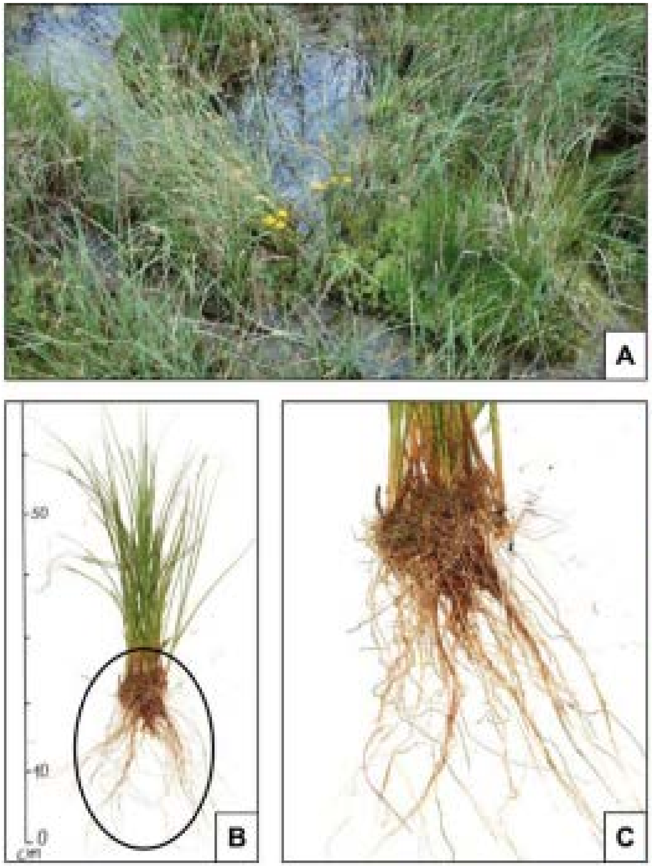
Fibrosity



(Source: TR-GCV , TAW 1996)

Either, dry, sieve and count or visual inspection

Botanical background, sedge



(Meier-Uhlherr et al 2011)

Photo G. Erkens

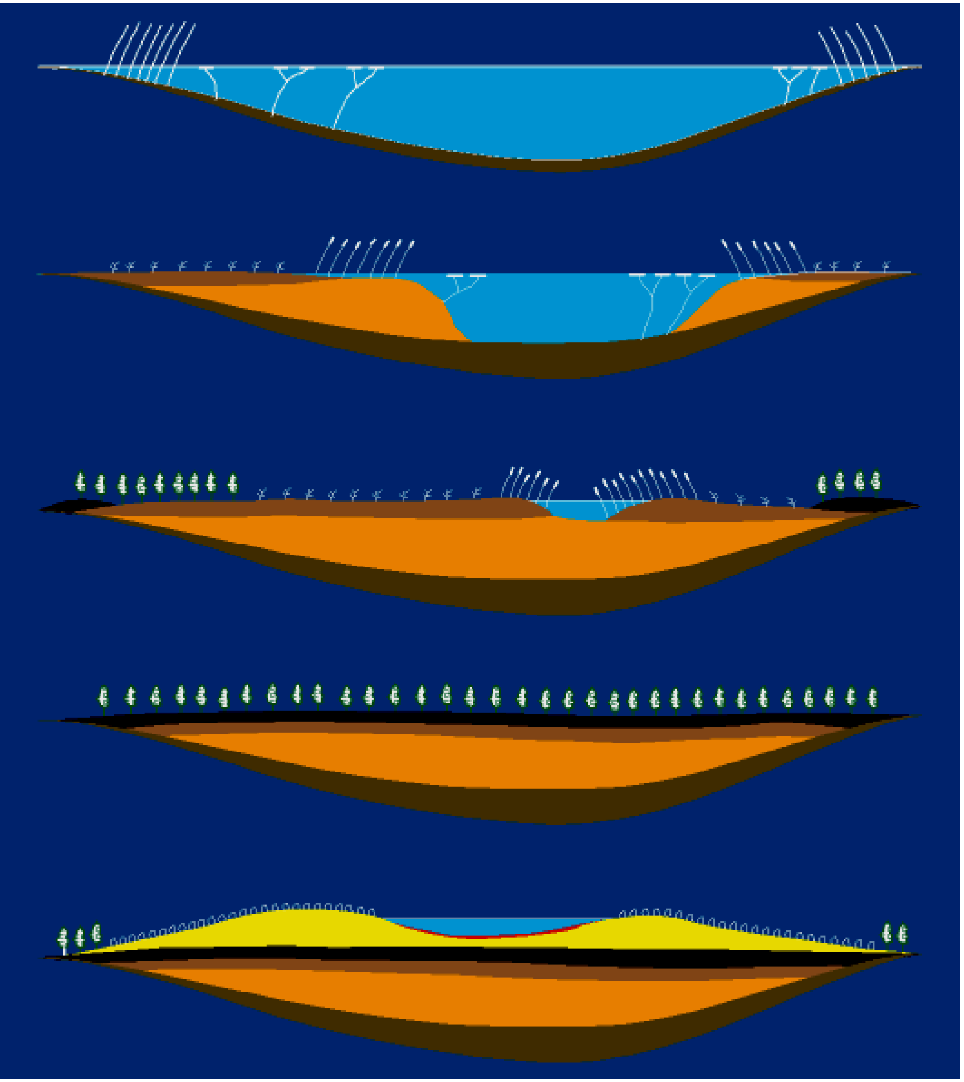
Deltares

Botanical background, Sphagnum

Photo G. Erkens 2012

(Meier-Uhlherr et al 2011)

Conditions during deposition

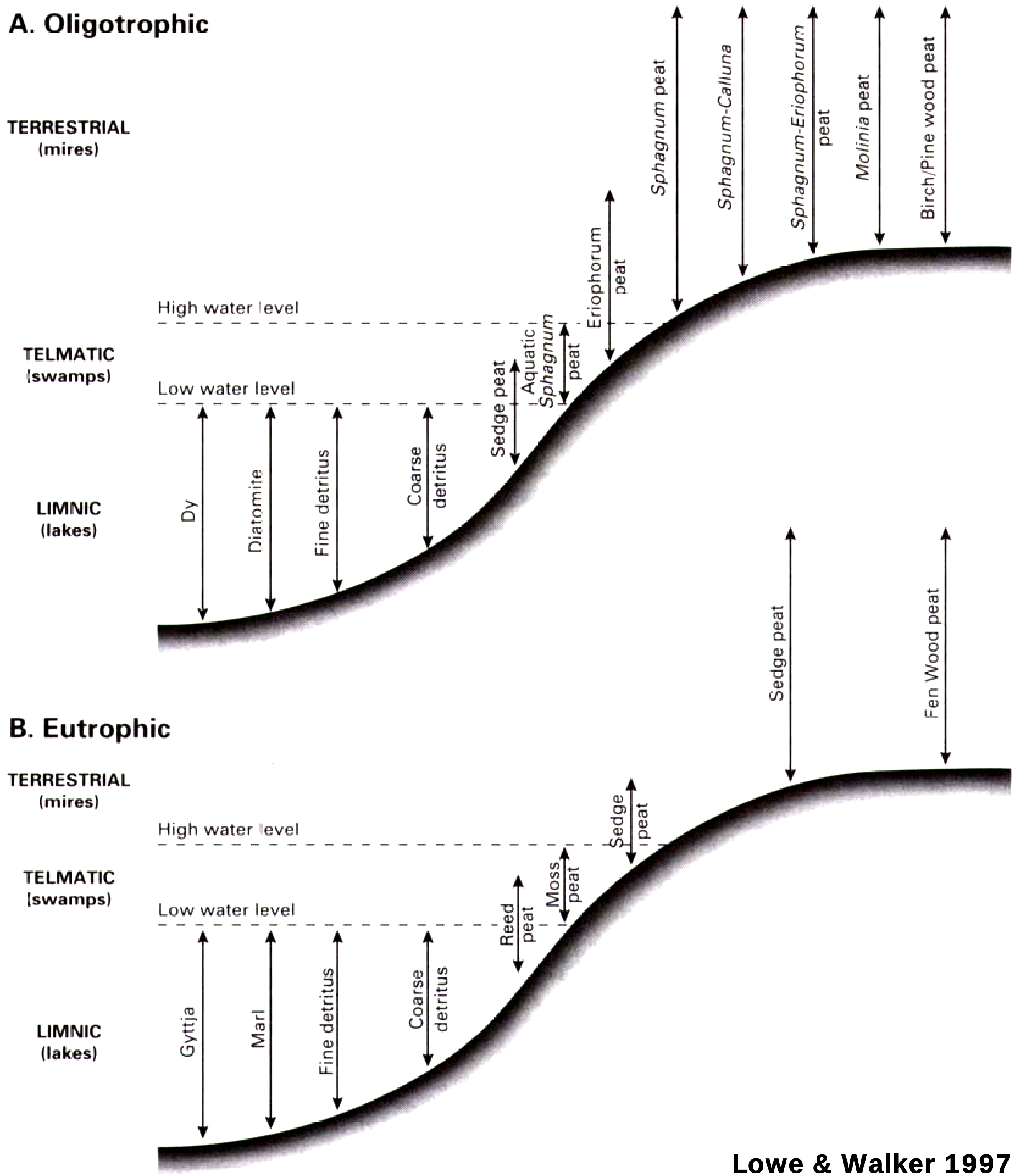


Lake

fen

Raised bog

(after Visscher 1949, Lowe & Walker 1997)



Lowe & Walker 1997

Deltares

Example, eutrophic lake

Examples of Marshes and Swamps

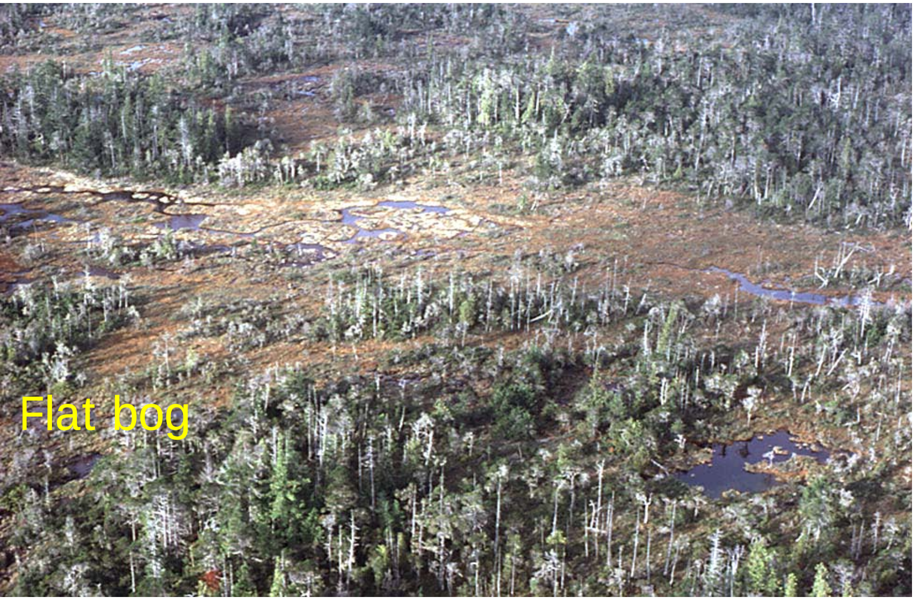
http://sts.gsc.nrcan.gc.ca/

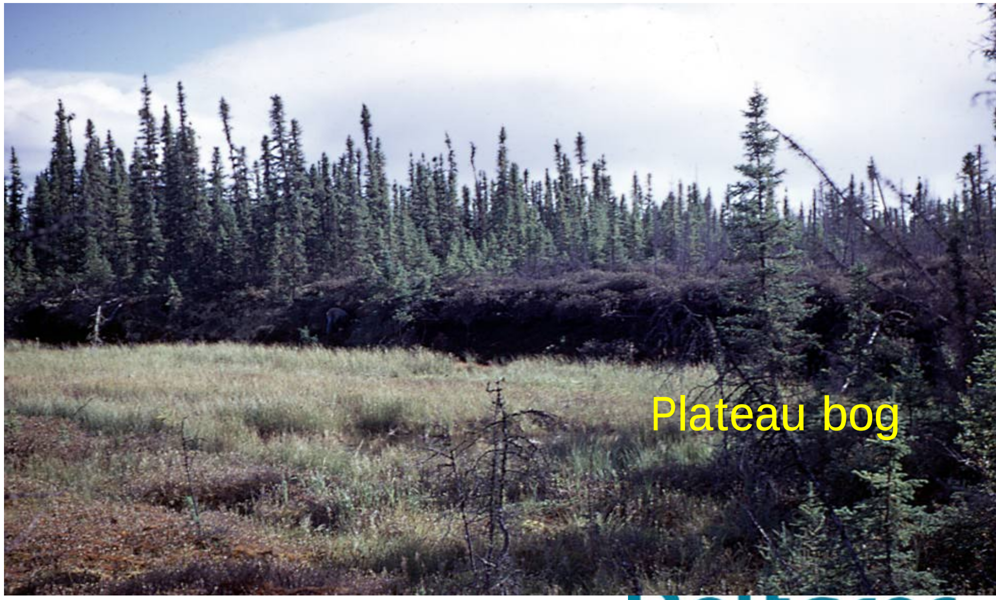
Marsh (= low wetland area, covered by reed, grass etc.)
Swamp (= low wetland area, covered by forest)

Fen (= low area covered by grass and reed)

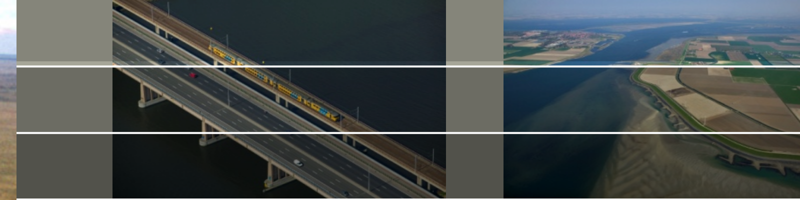
http://sts.gsc.nrcan.gc.ca/

Examples of raised bogs





http://sts.gsc.nrcan.gc.ca/

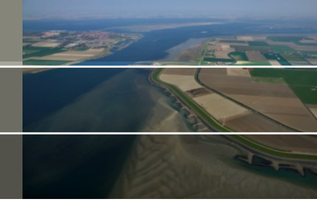


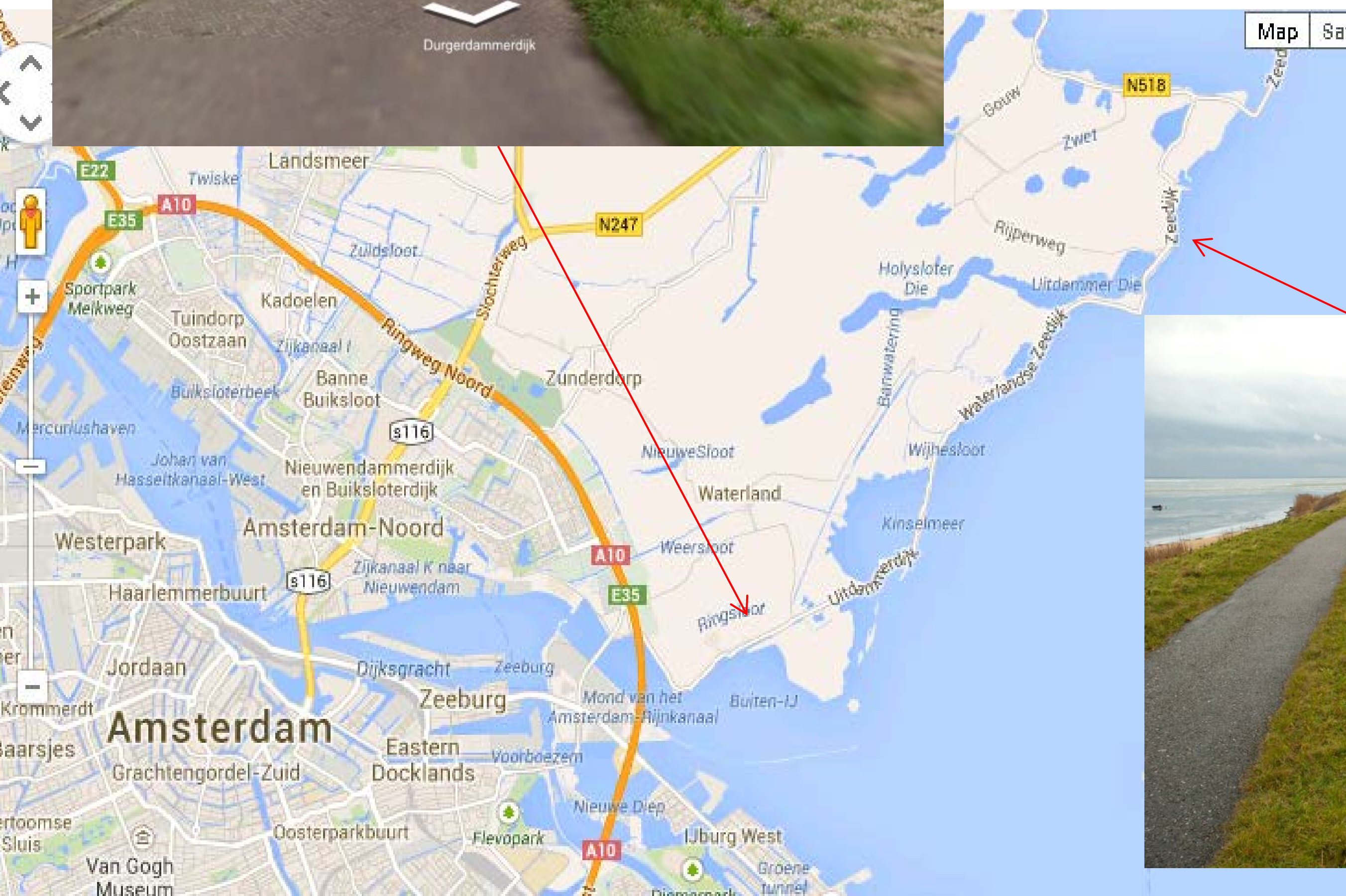
Raised bog in Siberia

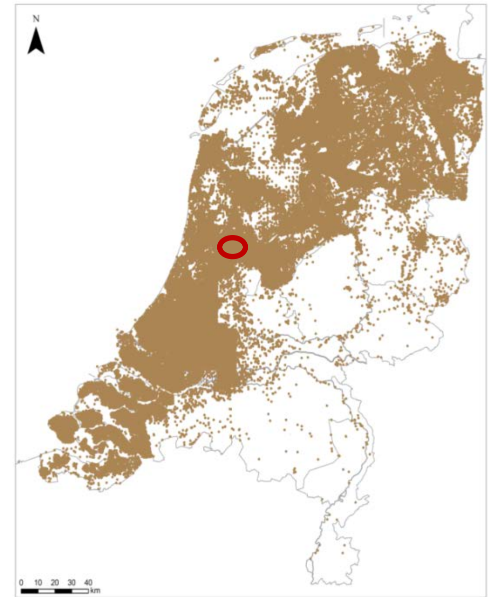


ENGINEERING PARAMETERS

Uitdam test side



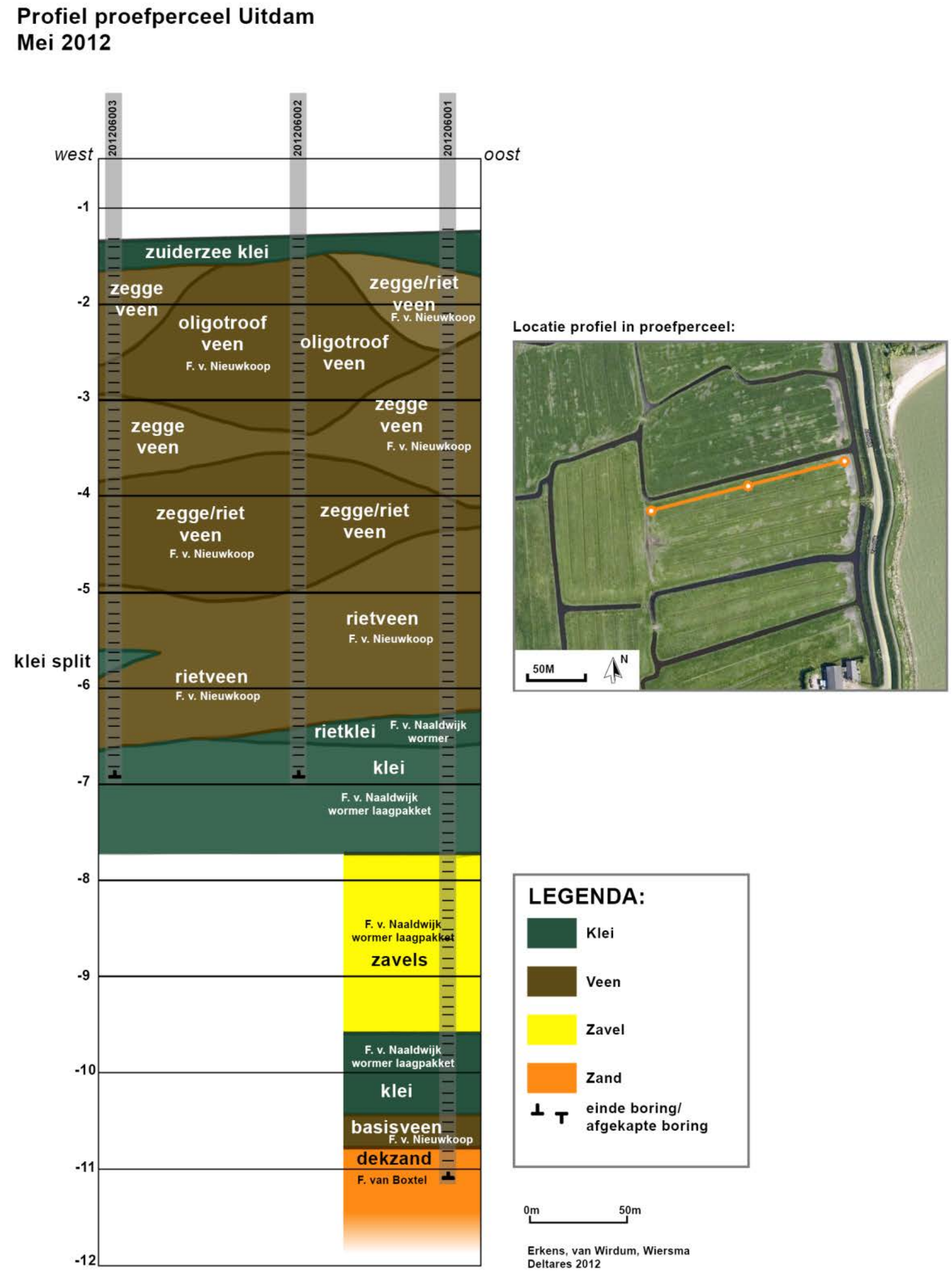


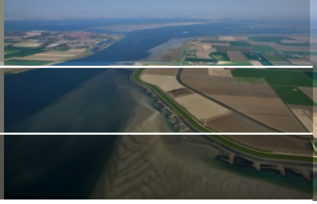


Characterisation

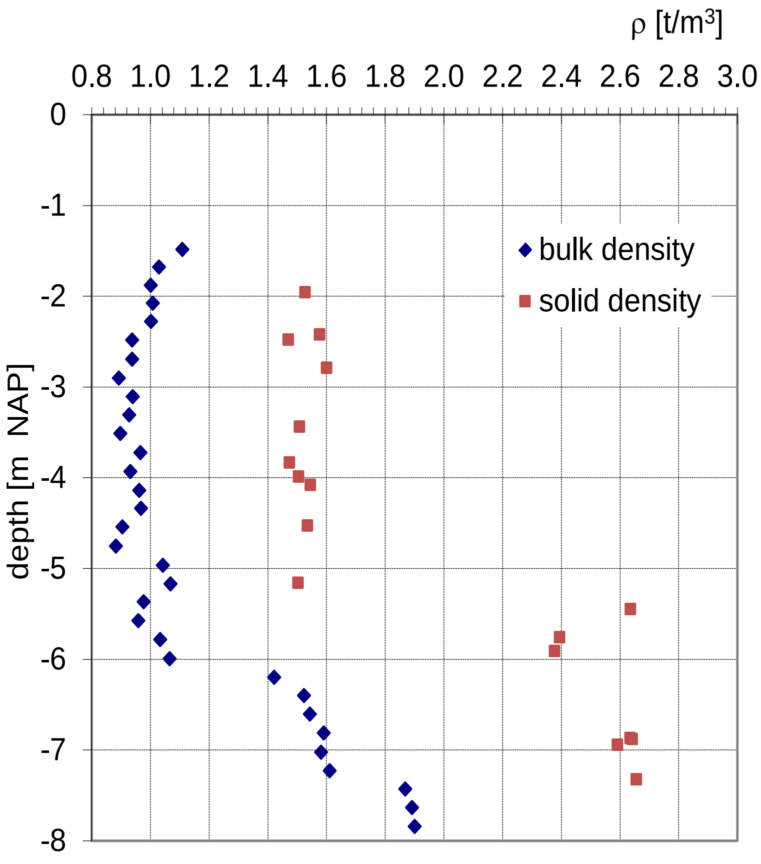
biological background peat: mainly sedge – reed

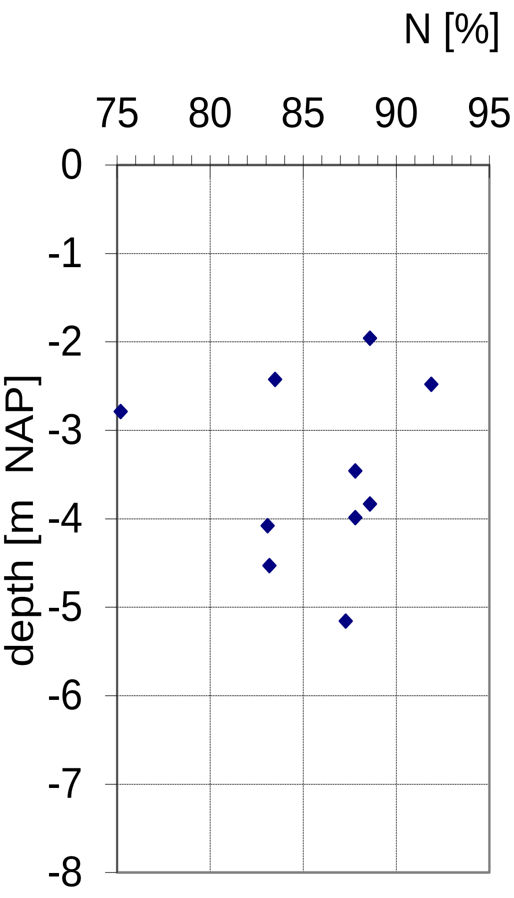
Von Post classification: H2 - H3, meaning that the peat is undecomposed (H2) or very slightly decomposed (H3). Plant remains are identifiable and no amorphous material is present.





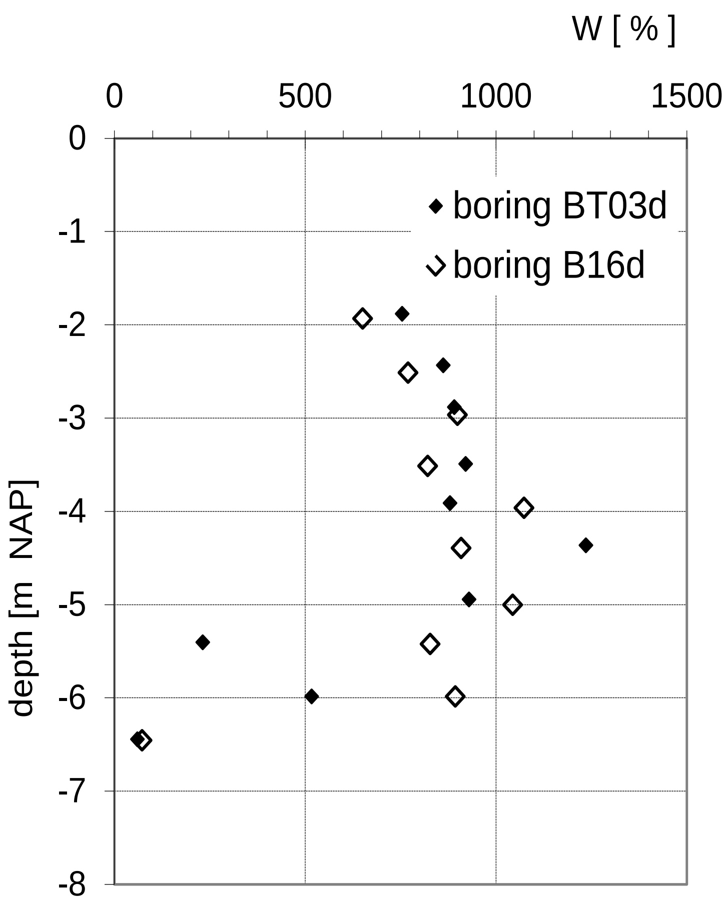
Characterisation of peat layer

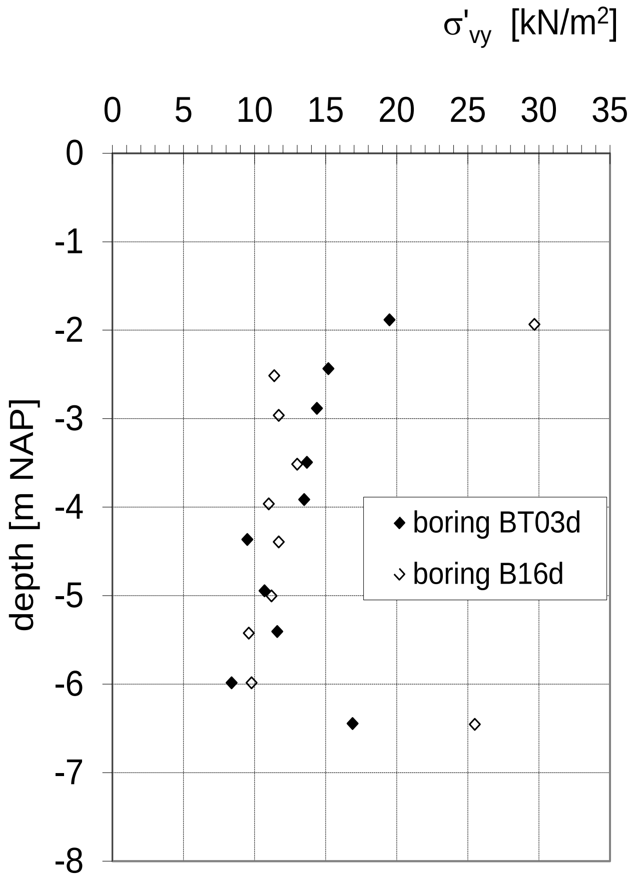


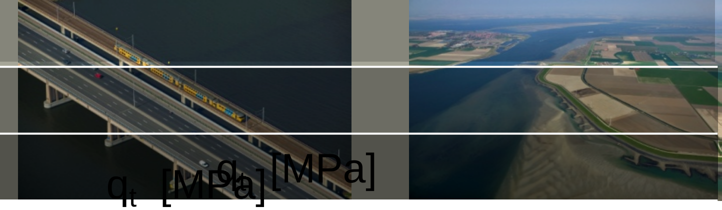


Deltares

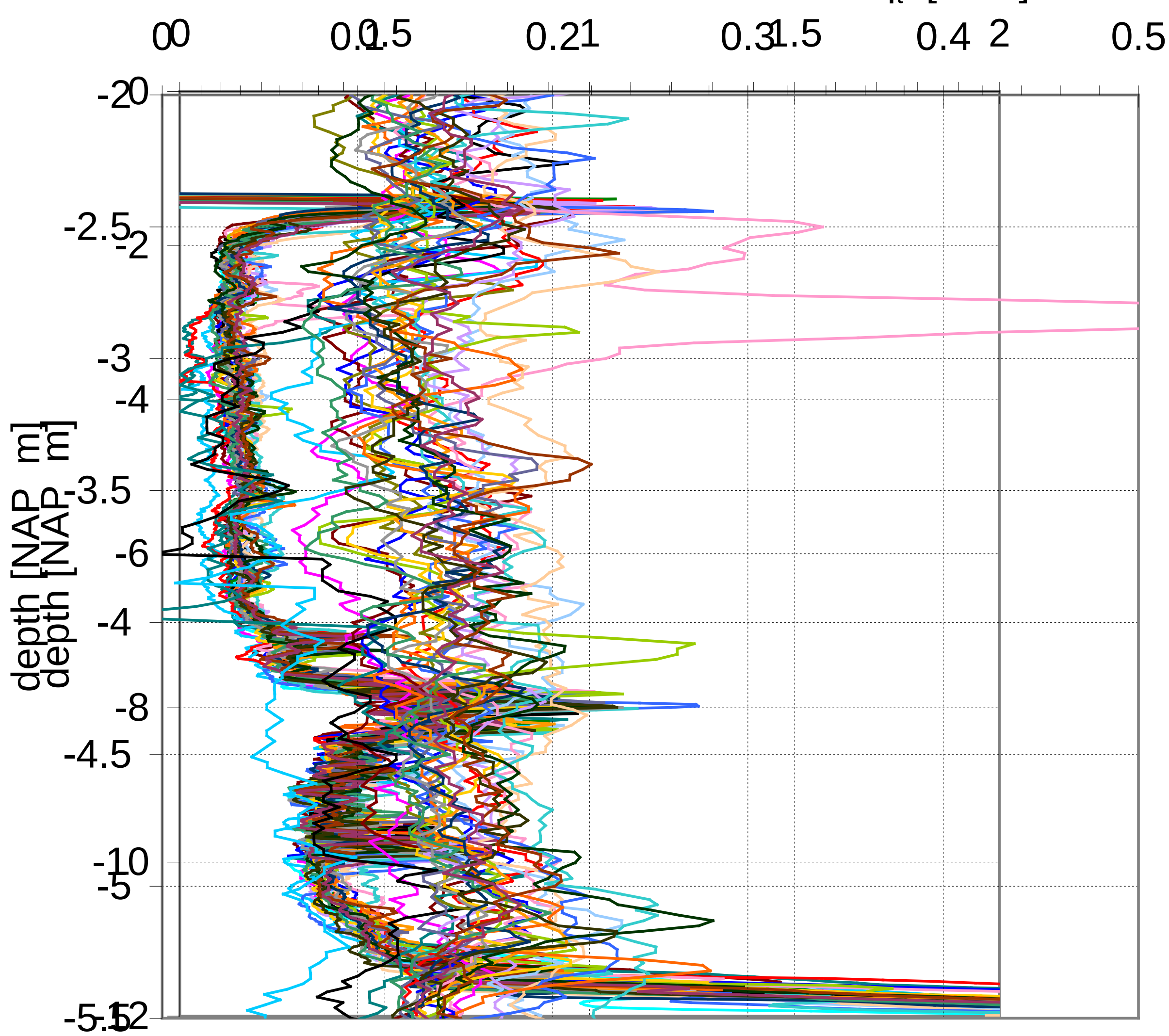
Characterisation of peat layer







CPTU, 10 cm^2 cone



Deltares

Comparison

	μ_{qt}, μ_{ball} [MPa]	V_{qt}, V_{qball} [-]
10 cm^2 cone	0.14	0.21
15 cm^2 cone	0.12	0.17
Ball penetrometer (1)	0.11	0.17
Ball penetrometer (2)	0.13	0.11

NEN-EN-ISO 22476-1: accuracy required for class 2 CPT(U) is 100 kPa (0.1 MPa)

Permeability

- Unloaded peat has an open structure
- Free water in (large) pores, bounded pore water in cell structure
- When loaded a rapid decay in permeability due to closing of the macro pores

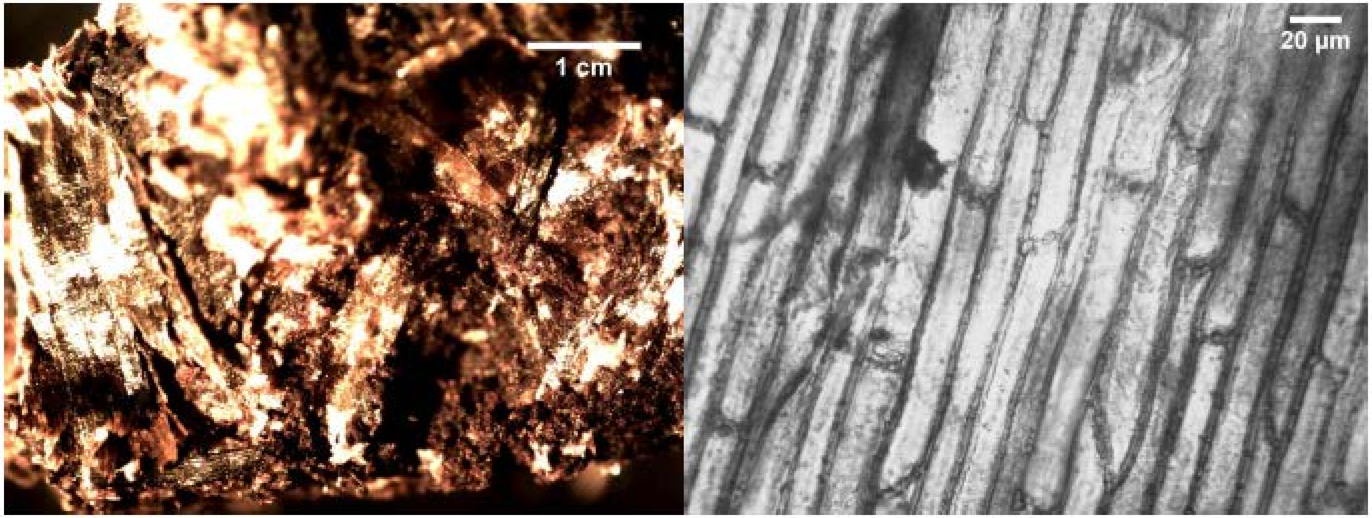


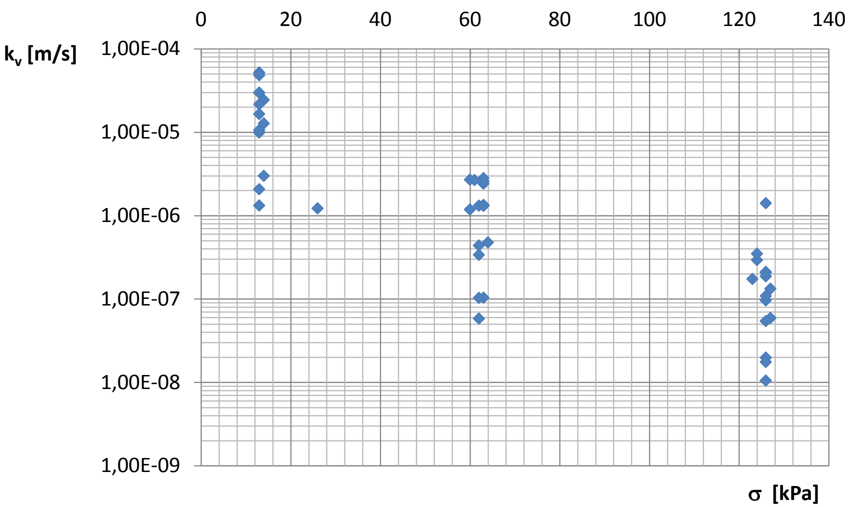
Photo G. Erkens

Permeability

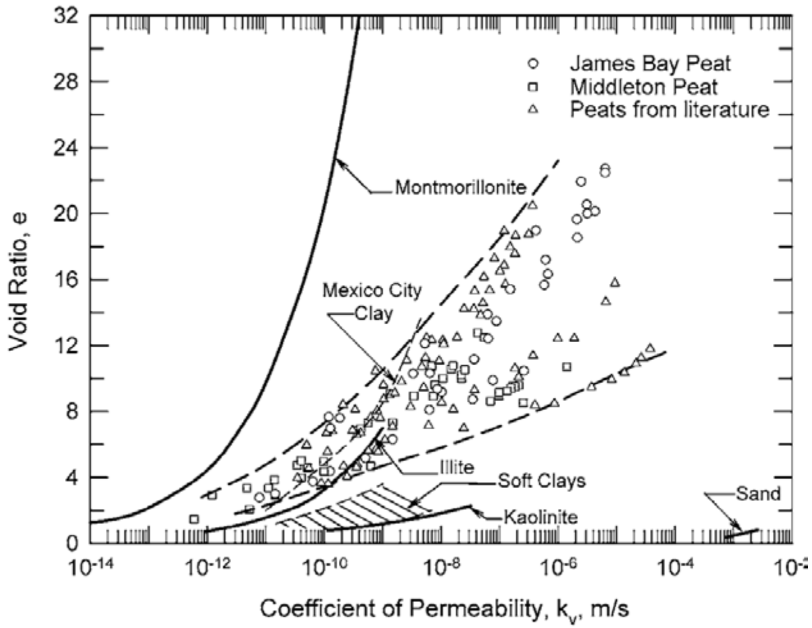
In situ Falling Head test

[m/s]	[m/d]	Depth [m]
8.0×10^{-7}	0.073	1.80
2.3×10^{-6}	0.199	3.49
7.0×10^{-7}	0.060	3.92

From laboratory tests



From literature



Mesri & Aljouni 2007

Deltares

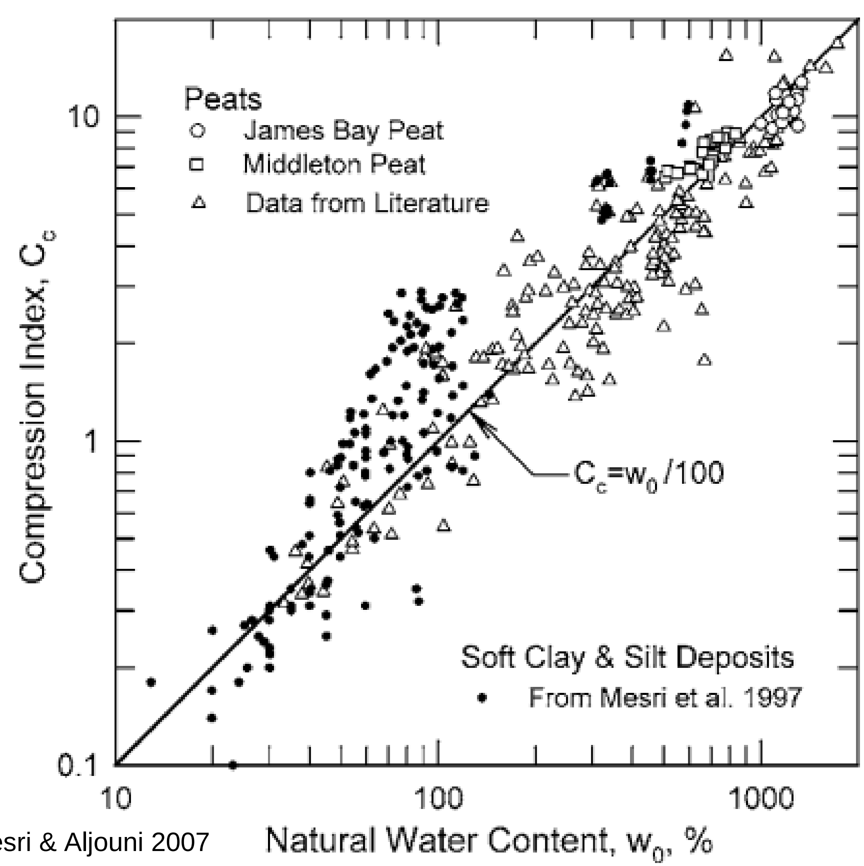
Compression indices

17 oedometer tests from test site

	min	max	average
w_0 [%]	518	1236	875
e_0 [-]	3.81	8.14	6.19
CR [-] C_c	0.39 2.53	0.58 4.04	0.45 3.21
C_α/CR	0.06	0.14	0.08
RR/CR	0.07	0.17	0.13

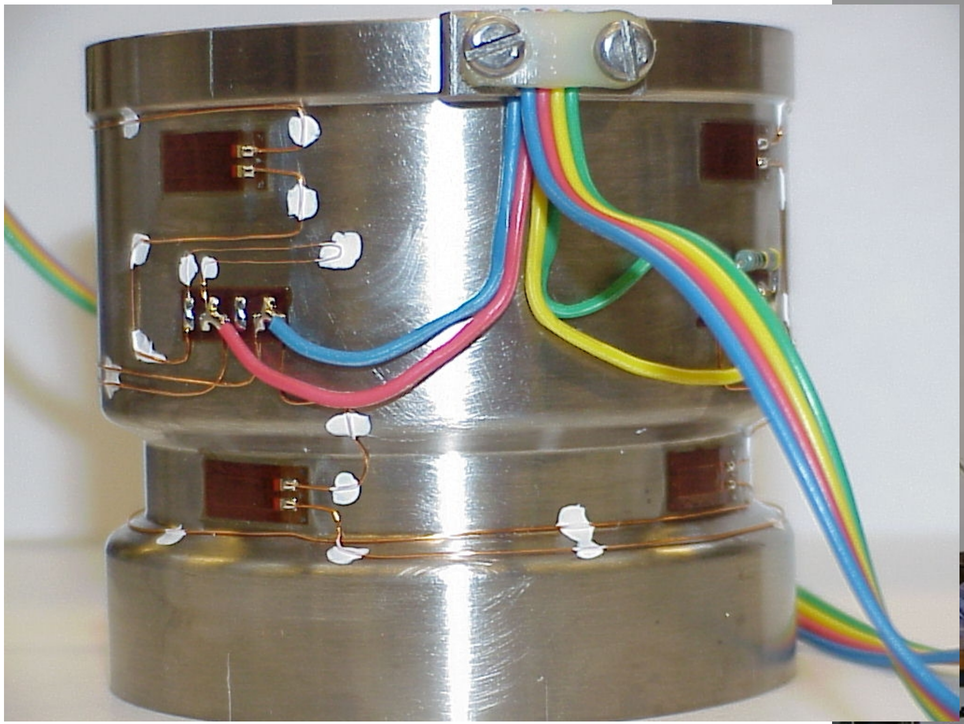
From literature

$C_\alpha/Cc = 0.06 \pm 0.01$

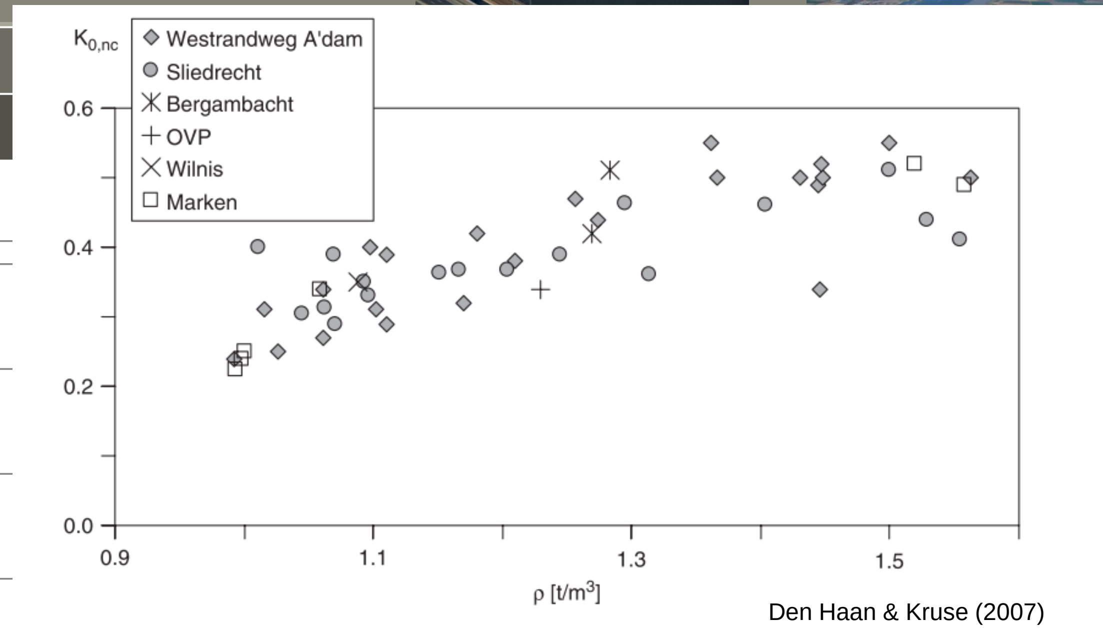


Mesri & Aljouni 2007

K_0-CRS test

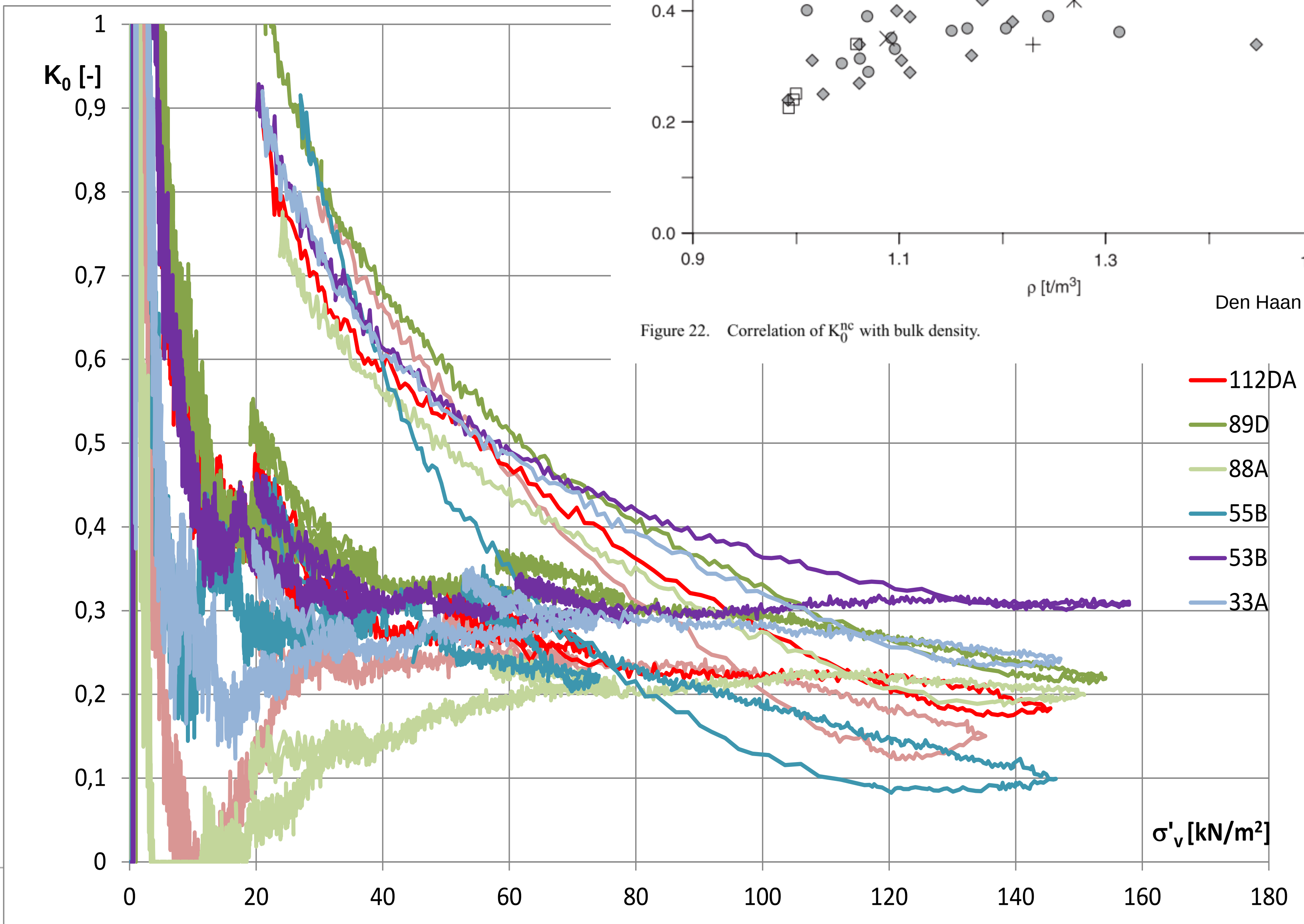


K0-CRS tests

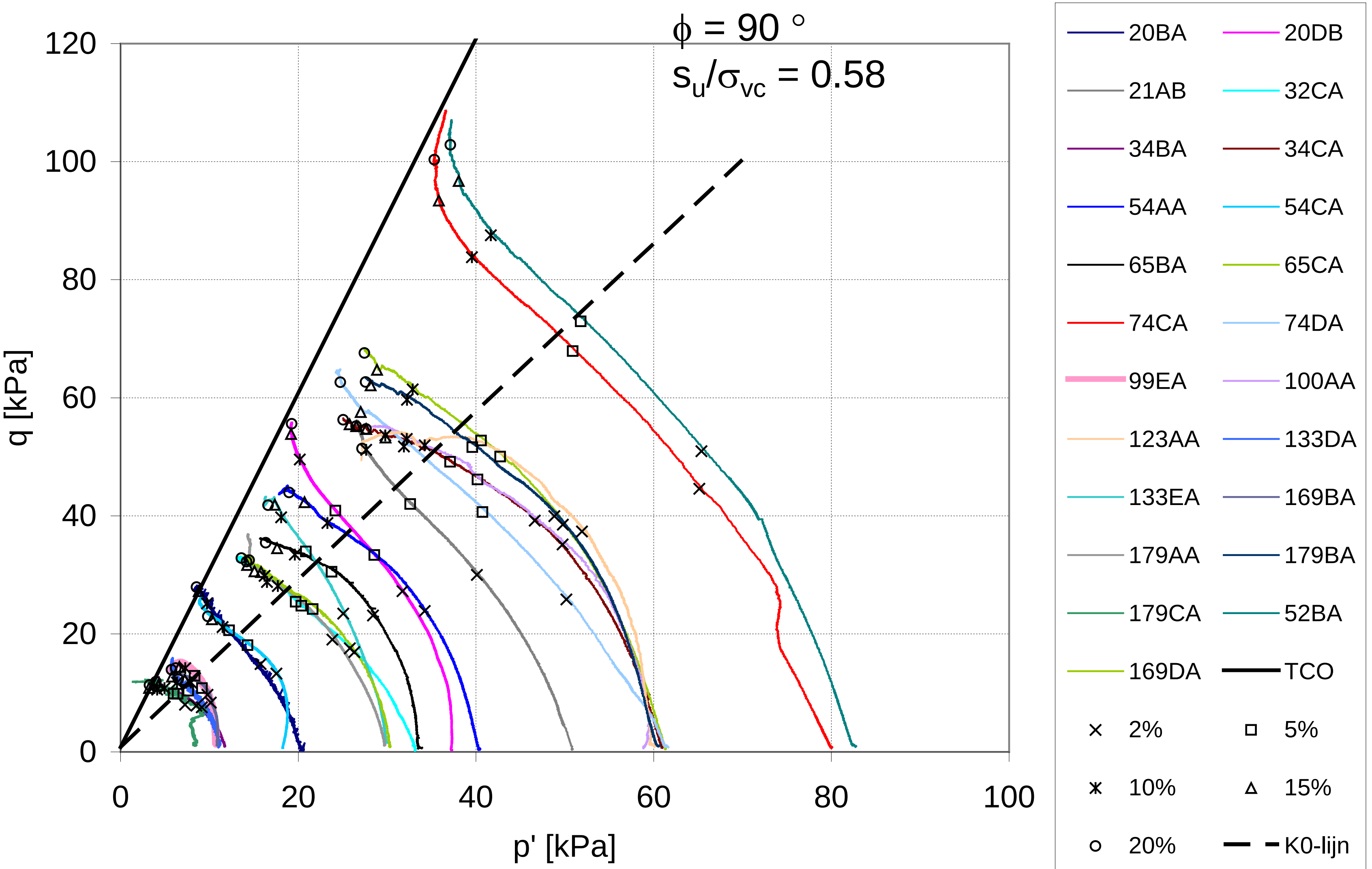


Den Haan & Kruse (2007)

Figure 22. Correlation of K_0^{nc} with bulk density.

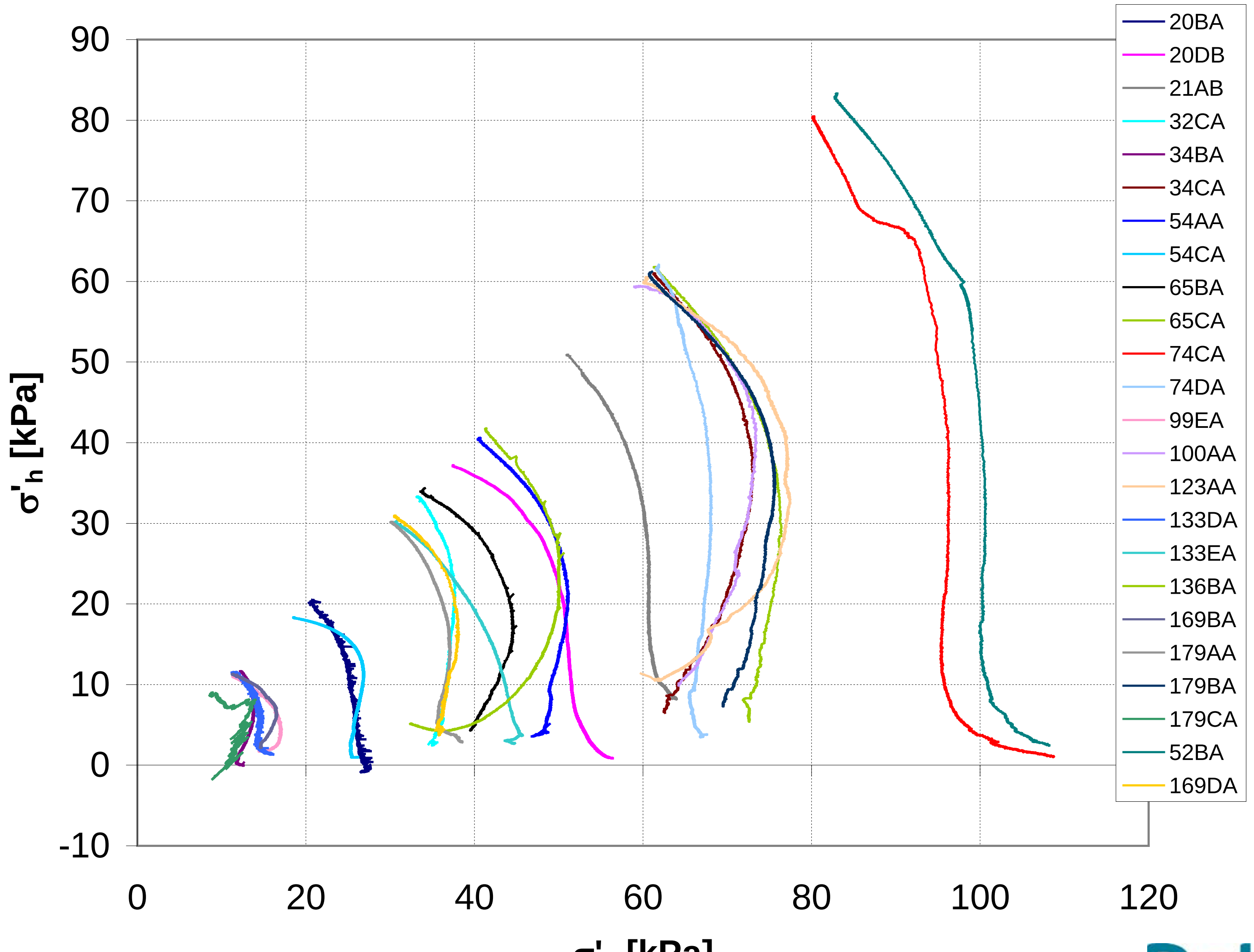


CIUC tests



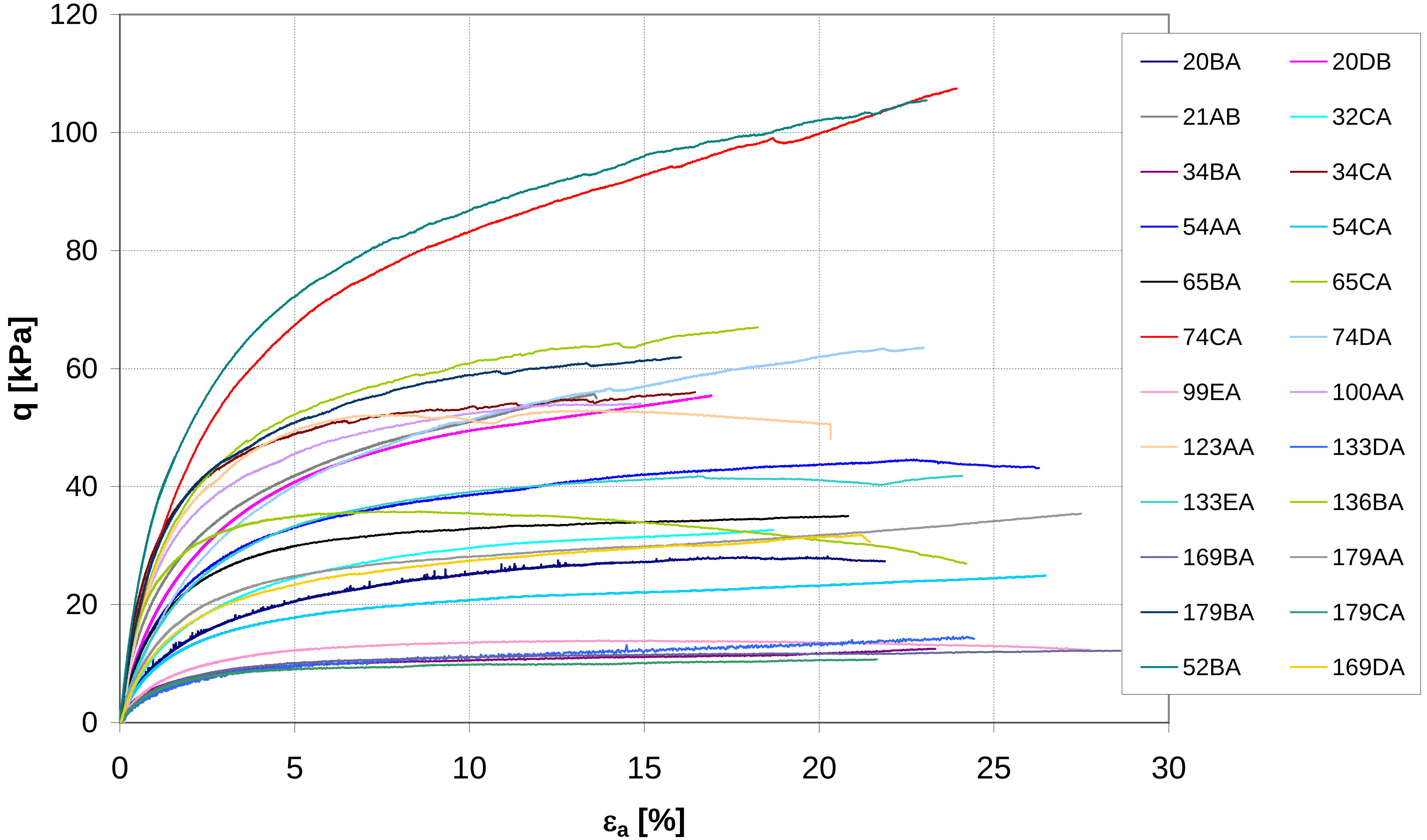
ϕ = 90 °
s_u/σ_{vc} = 0.58
q [kPa]
p' [kPa]
120
100
80
60
40
20
0
0
20
40
60
80
100
20BA
20DB
21AB
32CA
34BA
34CA
54AA
54CA
65BA
65CA
74CA
74DA
99EA
100AA
123AA
133DA
133EA
169BA
179AA
179BA
179CA
52BA
169DA
TCO
2%
5%
10%
15%
20%
K0-lijn

CIU tests



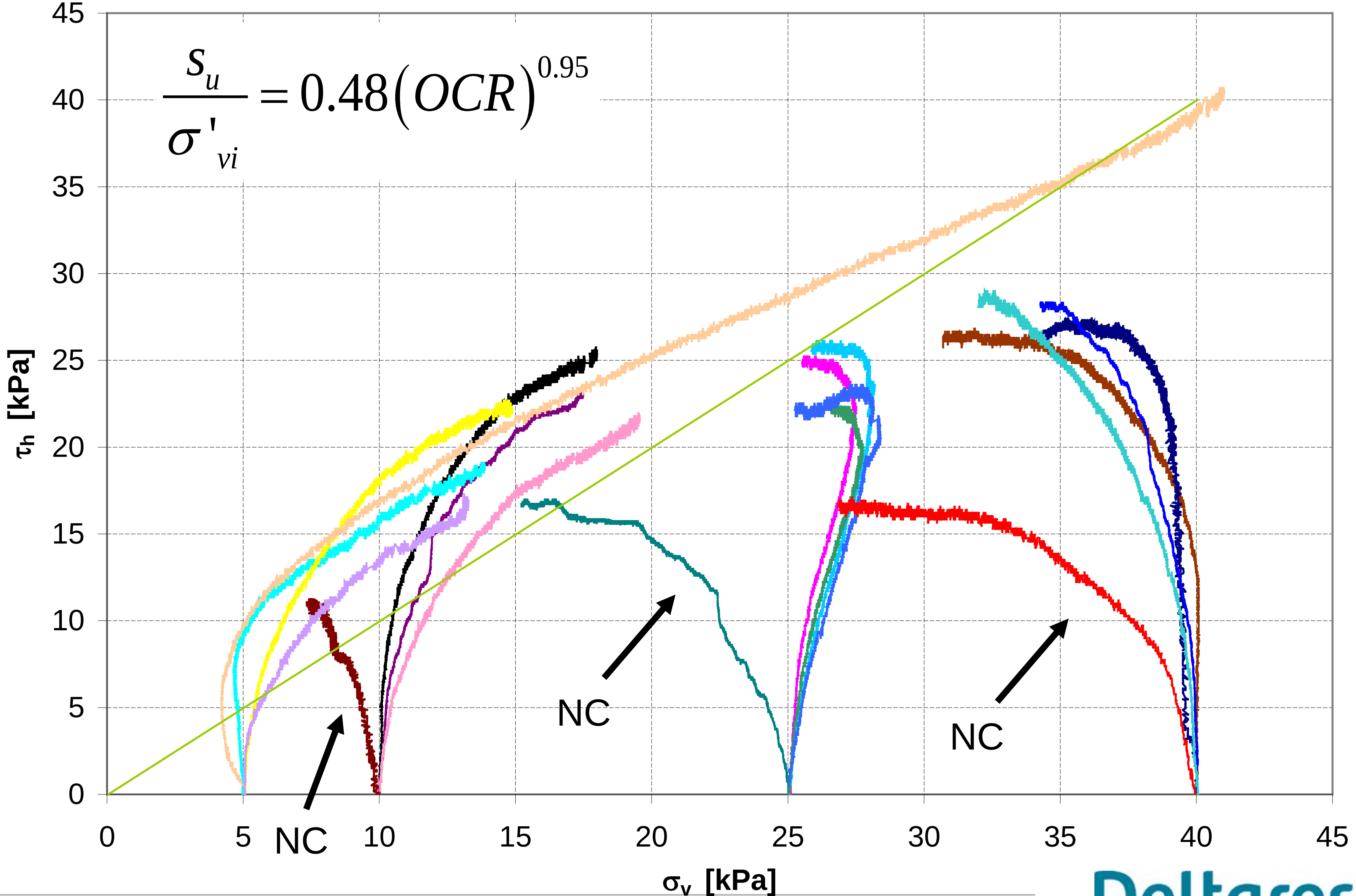
90
80
70
60
50
40
30
20
10
0
-10
0
20
40
60
80
100
120
σ'h [kPa]
σ'v [kPa]
20BA
20DB
21AB
32CA
34BA
34CA
54AA
54CA
65BA
65CA
74CA
74DA
99EA
100AA
123AA
133DA
133EA
136BA
169BA
179AA
179BA
179CA
52BA
169DA

CIU tests



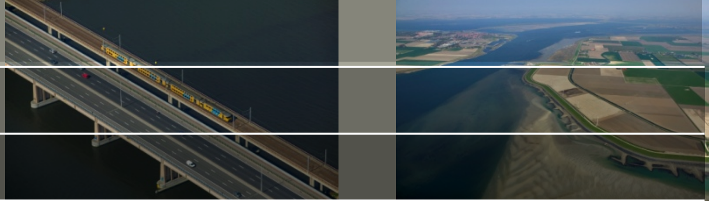
Deltares

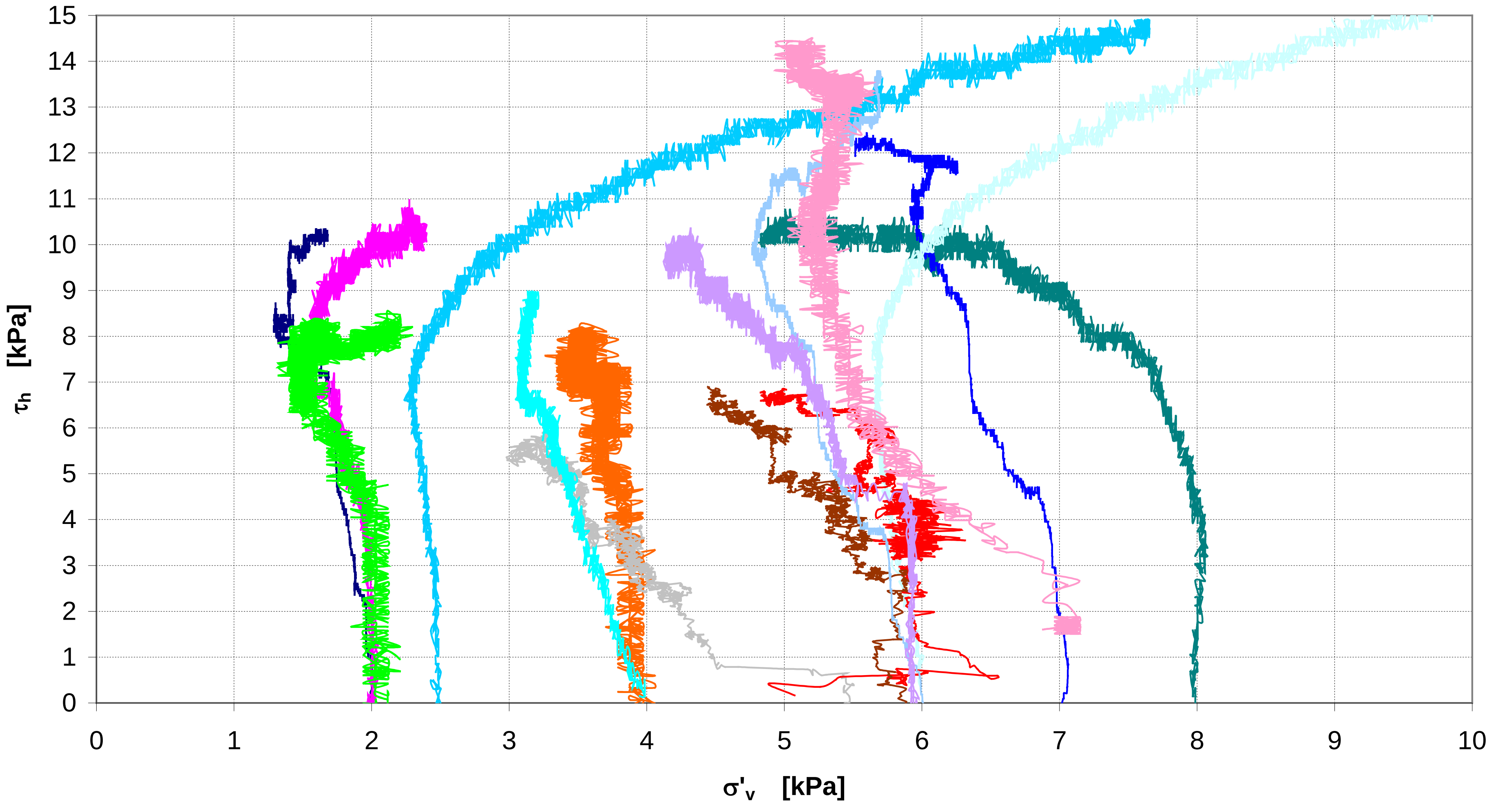
DSS, OC, σ_{vc} = 50 kPa



Deltares

DSS, Field stresses





Anisotropy

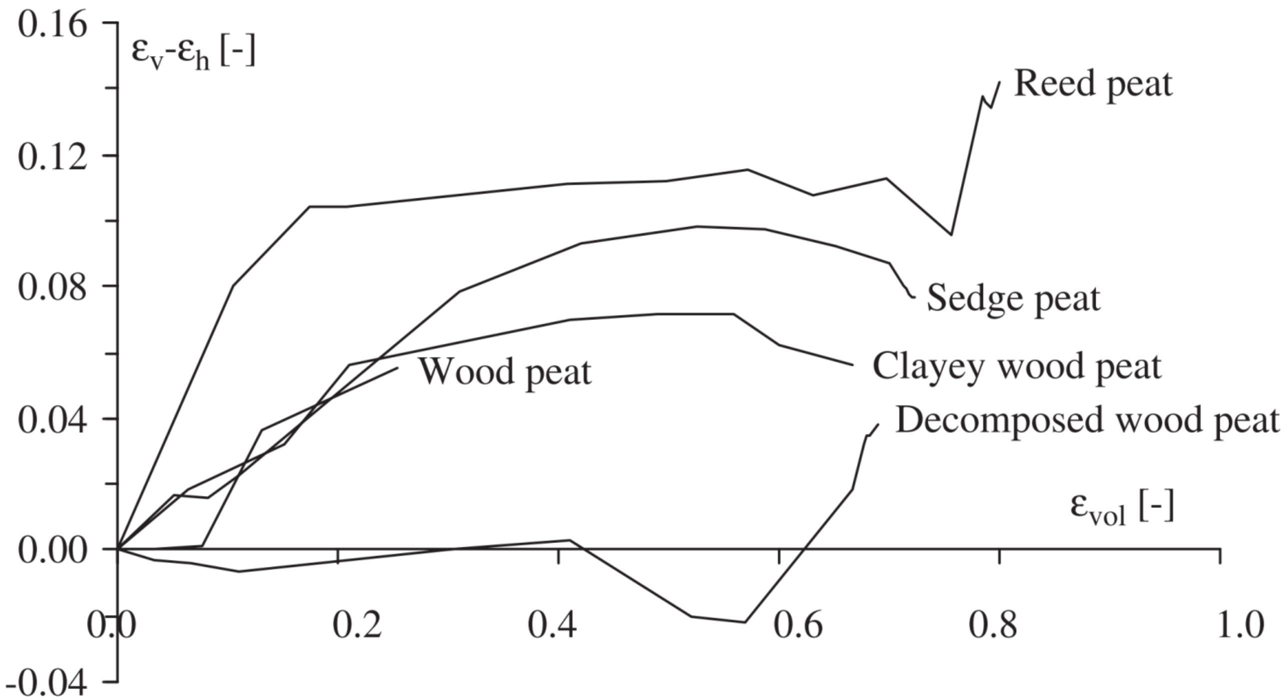
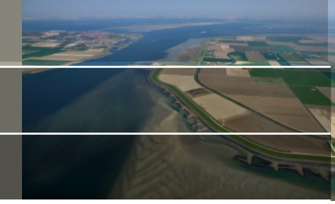


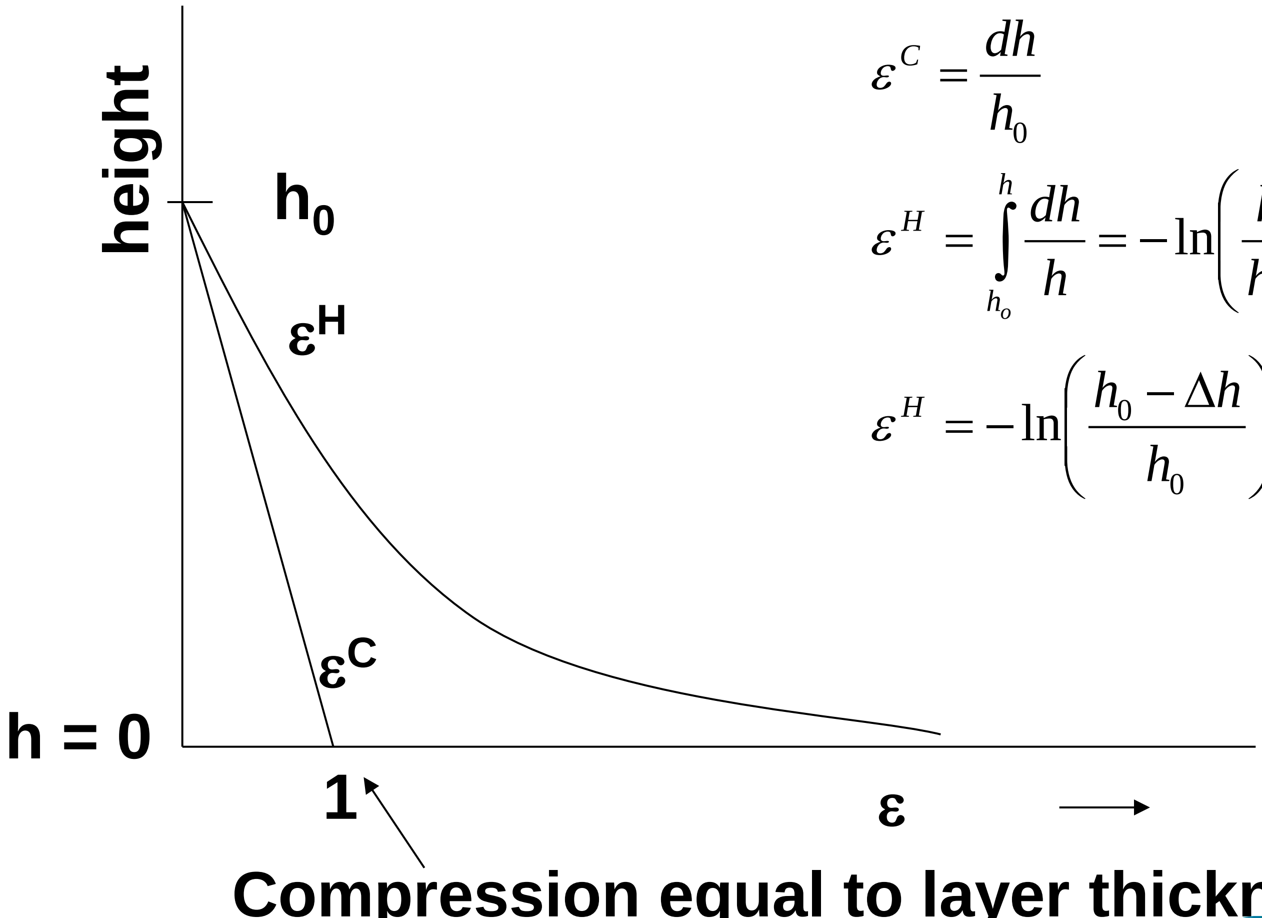
Figure 11. Anisotropy of peat revealed by shrinkage tests, Polder Zegveld.

Den Haan & Kruse (2007)



SETTLEMENT / CREEP

Linear strain - Natural strain

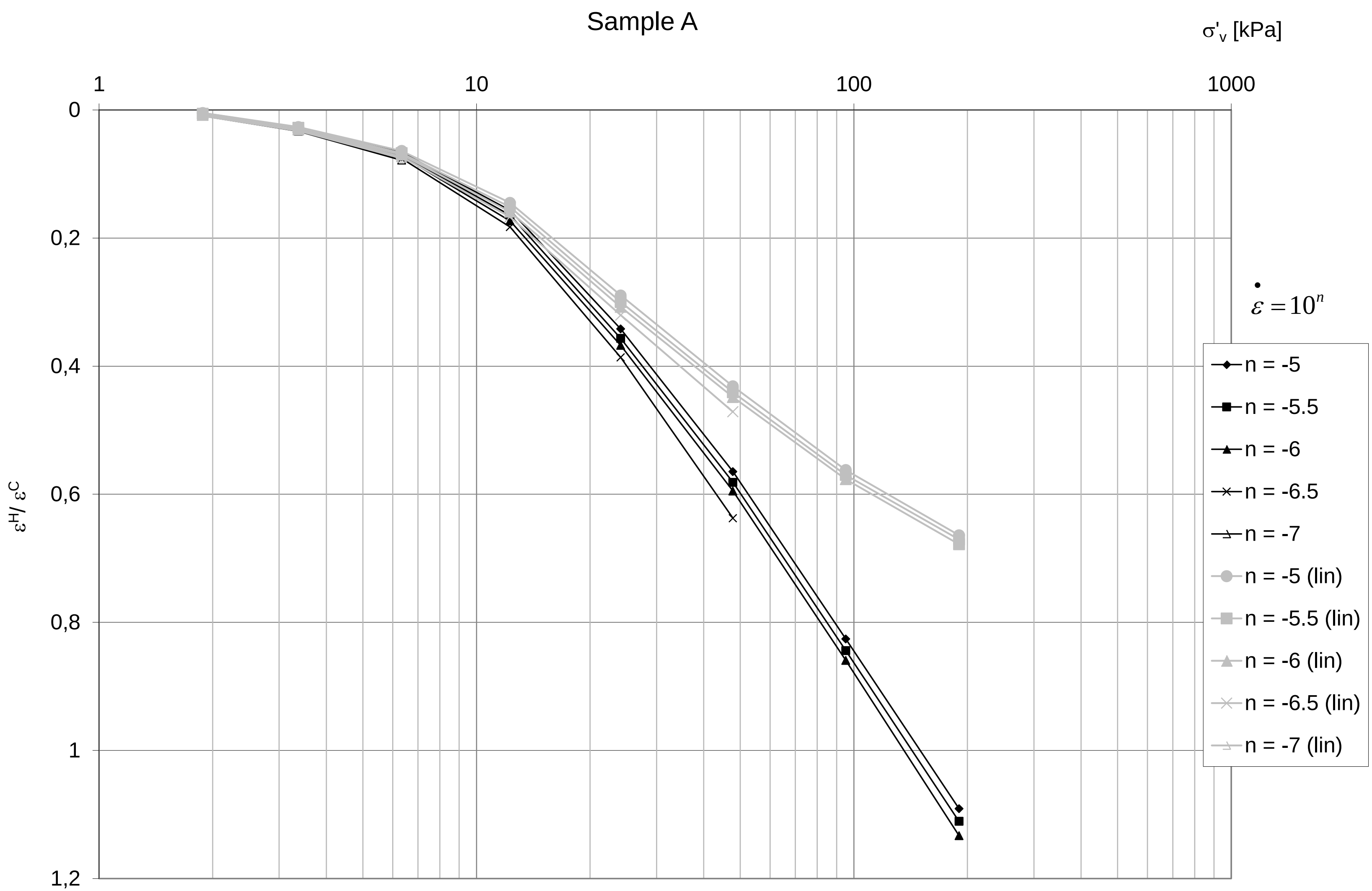


$$\varepsilon^C = \frac{dh}{h_0}$$

$$\varepsilon^H = \int_{h_o}^{h} \frac{dh}{h} = -\ln\left(\frac{h}{h_0}\right)$$

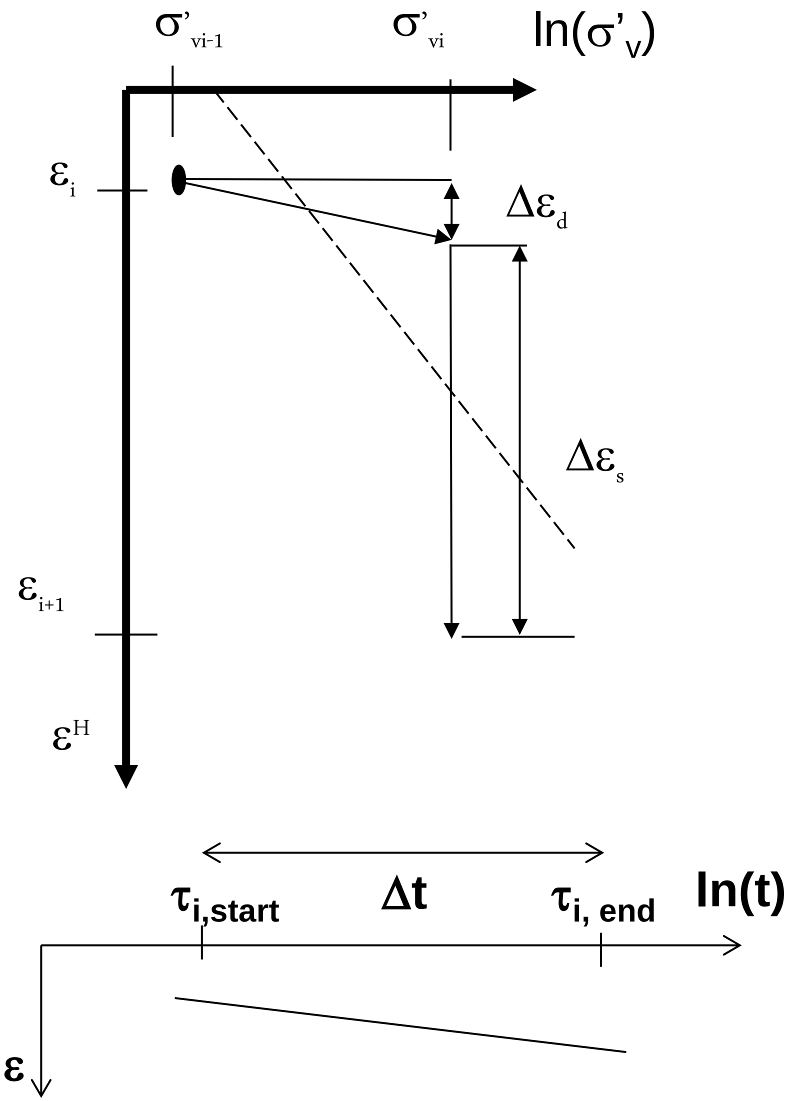
$$\varepsilon^H = -\ln\left(\frac{h_0 - \Delta h}{h_0}\right) = -\ln\left(1 - \varepsilon^C\right)$$

Oedometer test results in linear and natural strain



Deltares

Isotach model based on natural strain, Den Haan (1994) in incremental form



1. Direct strain:

$$\varepsilon_d^H = a\ln\left(\frac{\sigma_i}{\sigma_{i-1}}\right)$$

2. Equivalent time τ directly after loading

$$\tau_i = \tau_{i-1}\left(\frac{\sigma'_{i-1}}{\sigma'_i}\right)^{\frac{b-a}{c}}$$

3. Equivalent time τ end load step

$$\tau_{i,end} = \tau_i + \Delta t$$

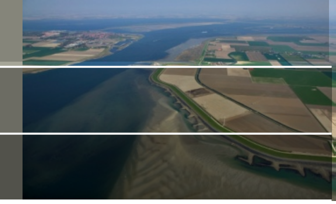
4. Viscous strain

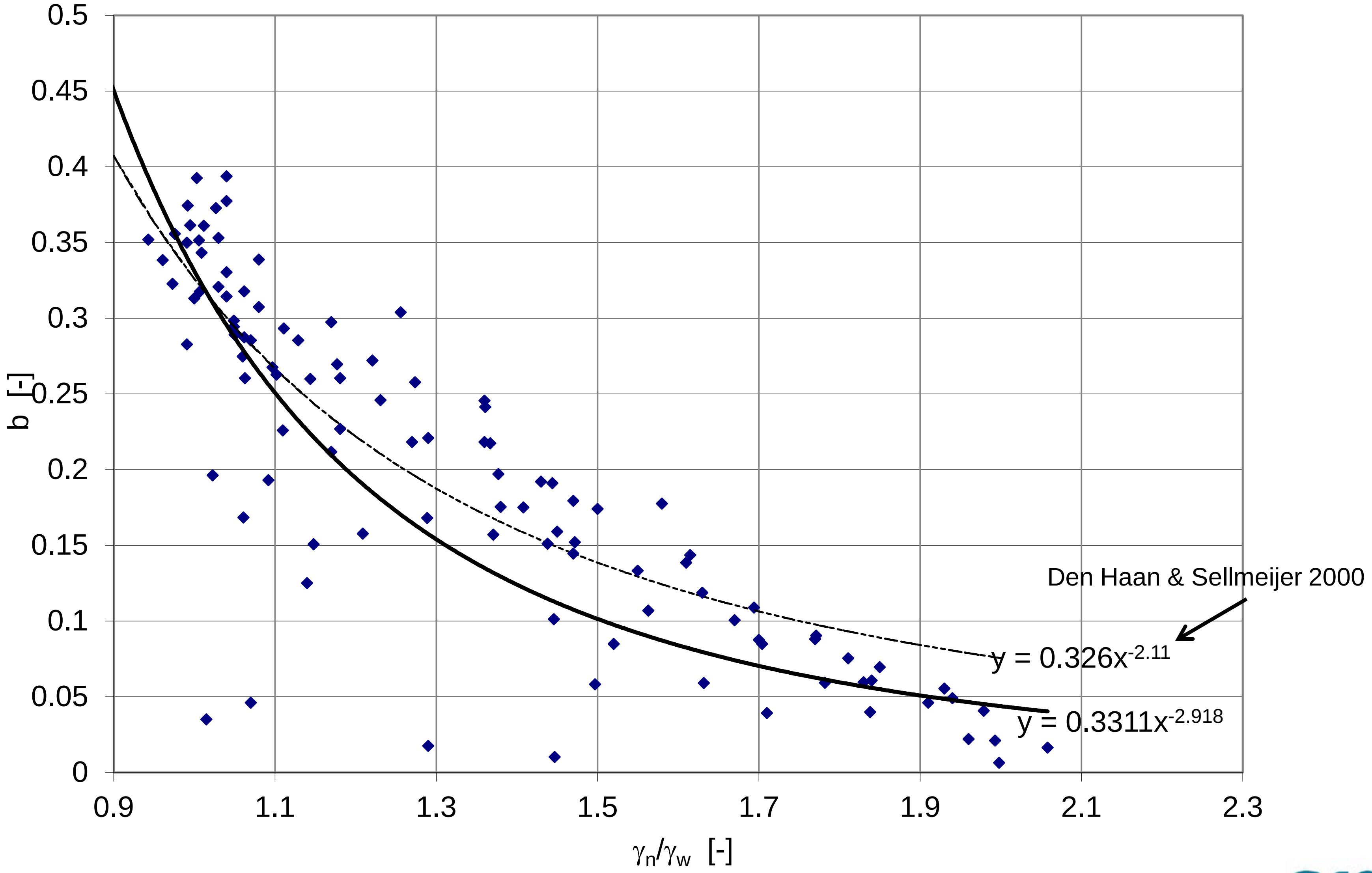
$$\varepsilon_s^H = c\ln\left(\frac{\tau_{i,eind}}{\tau_{i,begin}}\right)$$

5. Total strain and settlement

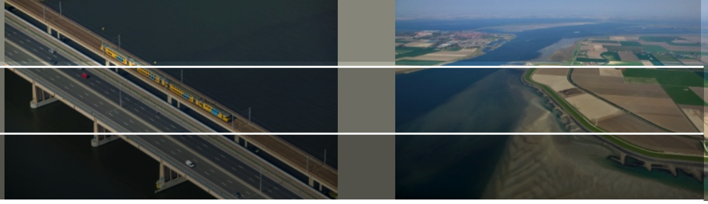
$$\varepsilon^H = \varepsilon_d^H + \varepsilon_s^H, \quad \Delta h = h_0\left(1-\exp(-\varepsilon^H)\right)$$

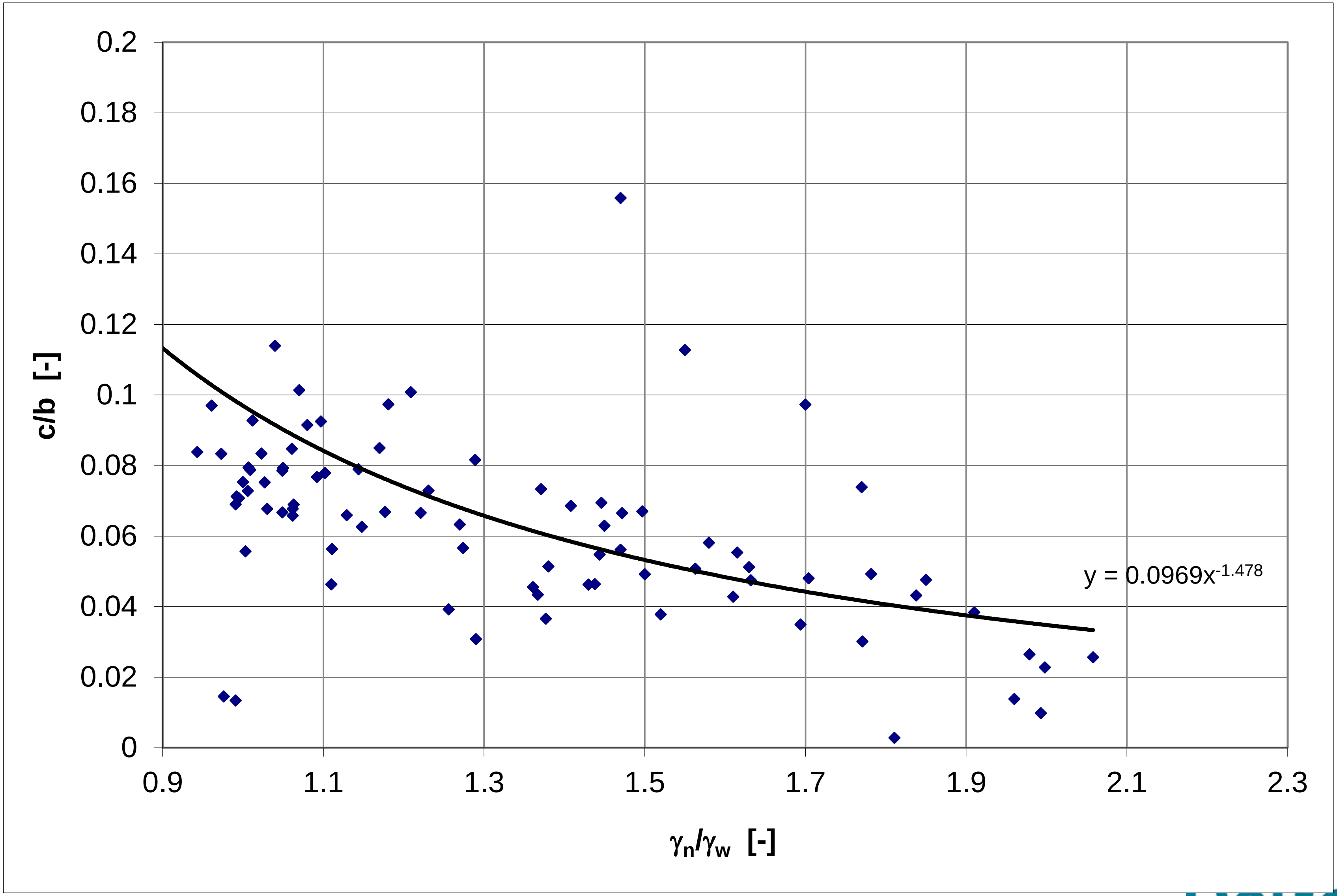
Results from 107 CRS tests





Results from 93 CRS tests

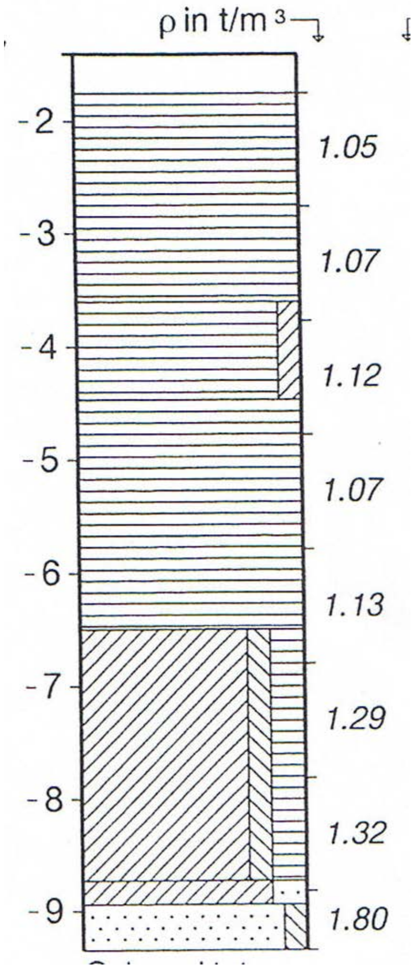




Deltares

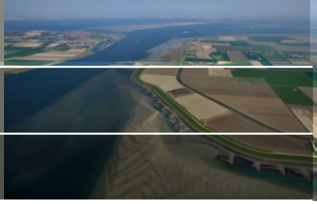
Case: Railway line Rotterdam – Germany

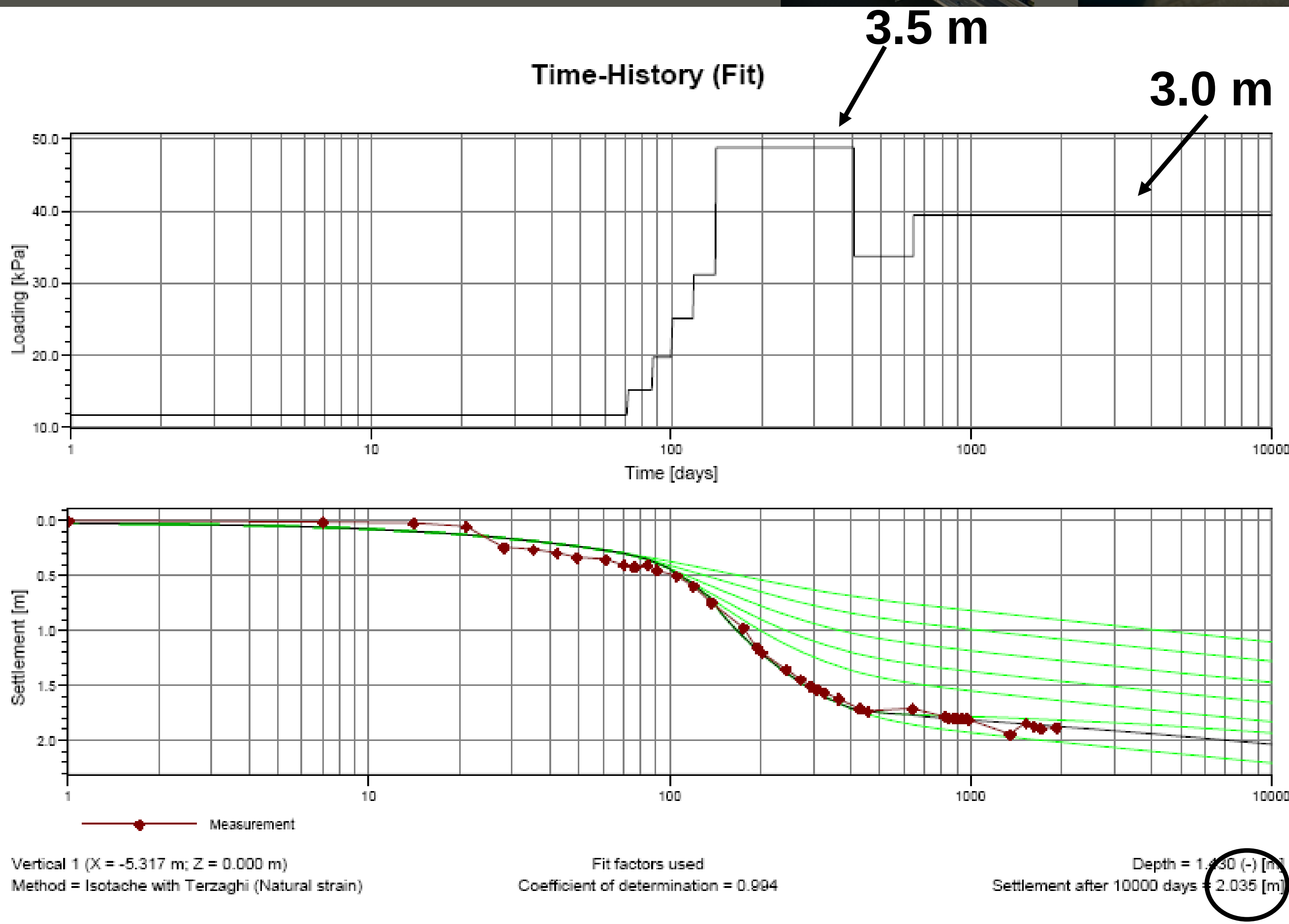
Soil profile



Deltares

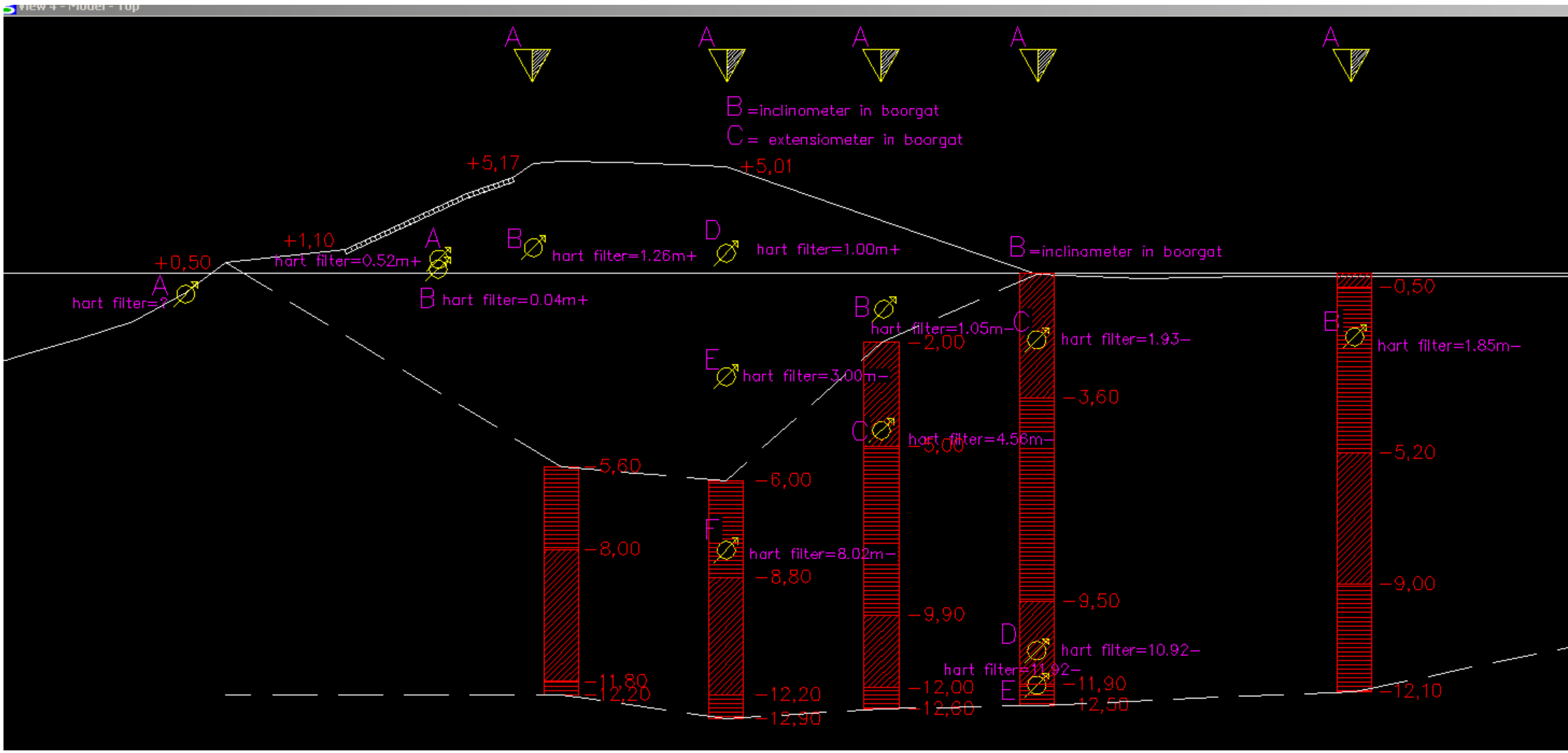
Calculation vs measurements





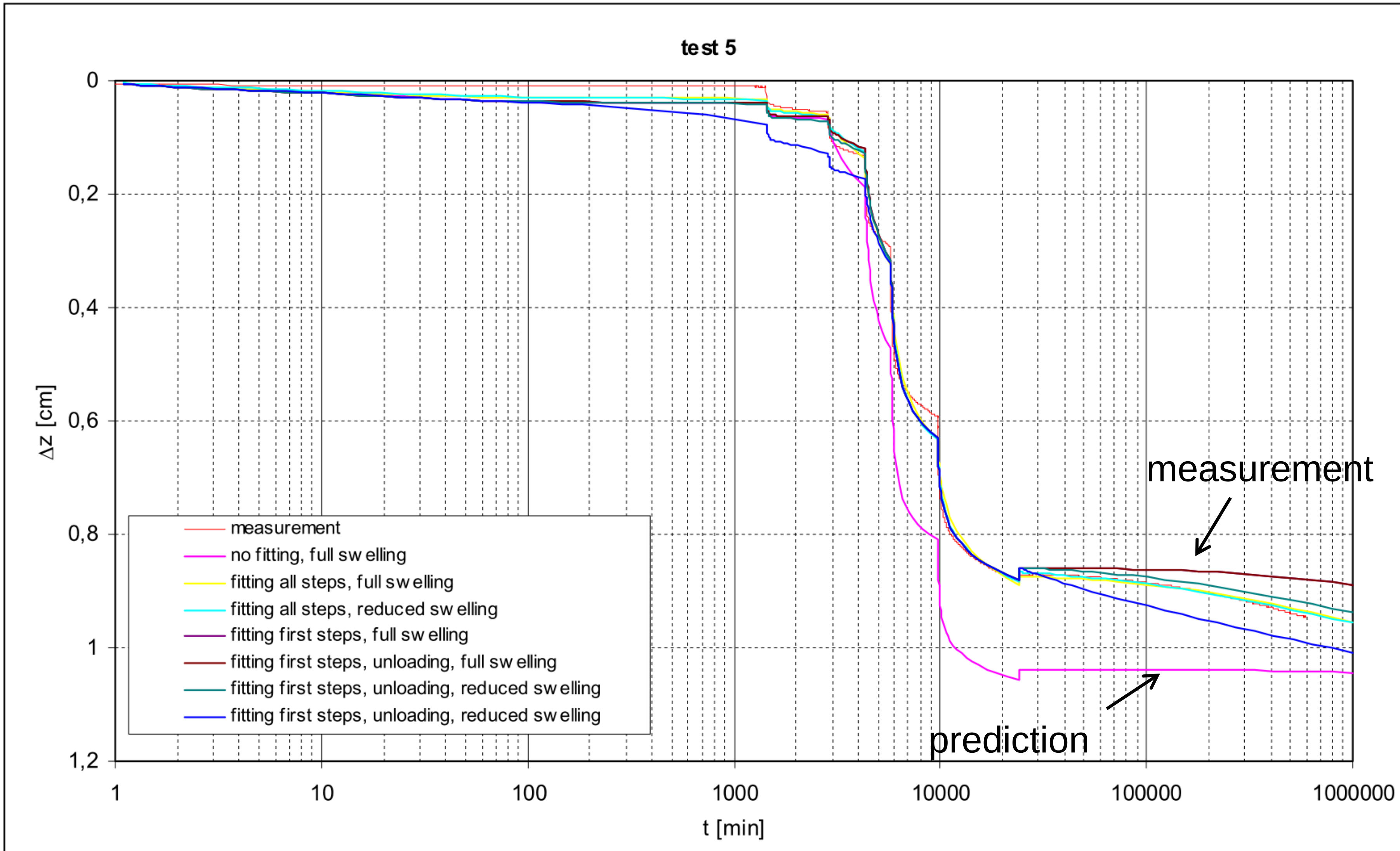
Long term settlement

Dike with medieval origin

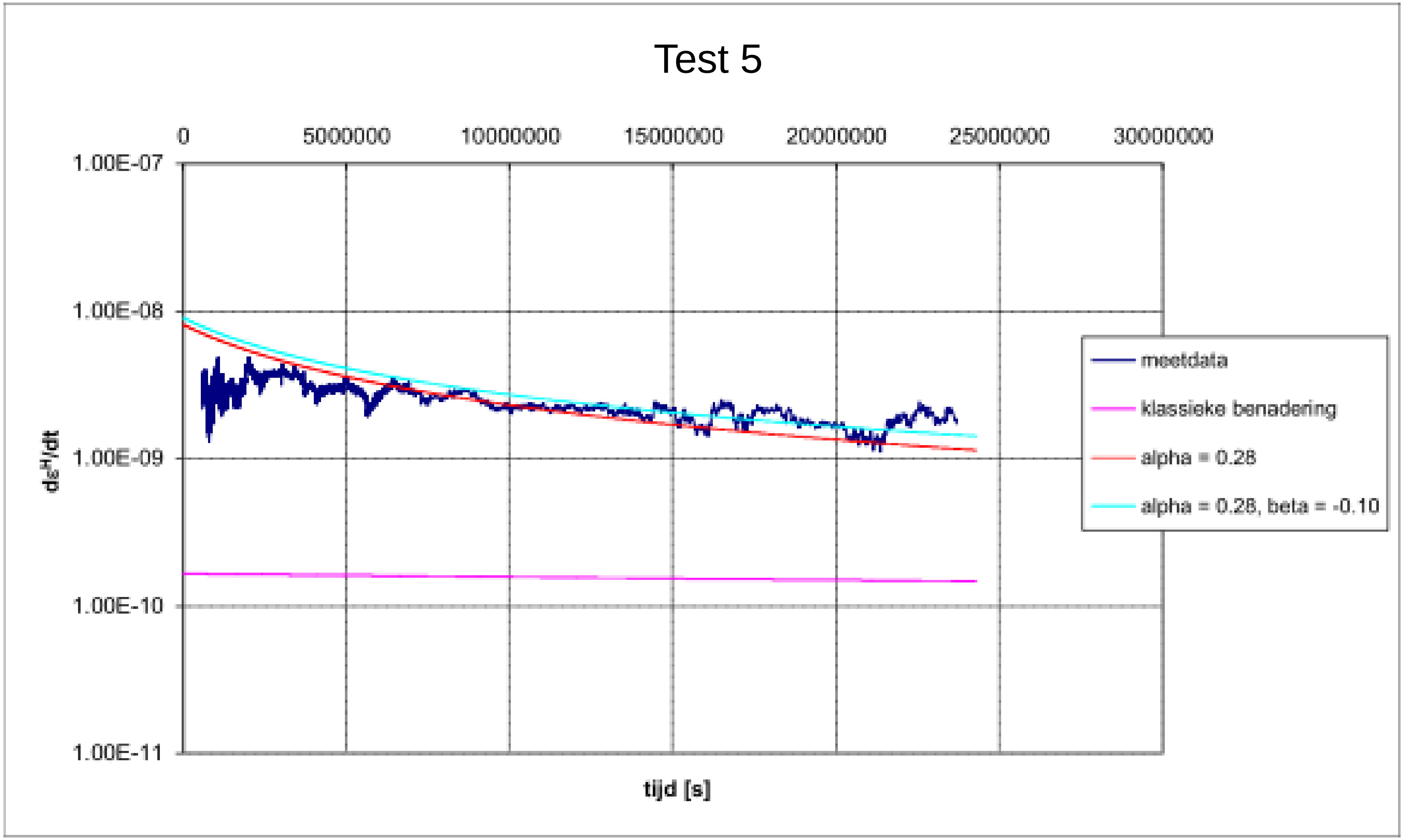


TO BE SOLVED

Creep after unloading modeling oedometer test, OCR = 1,8



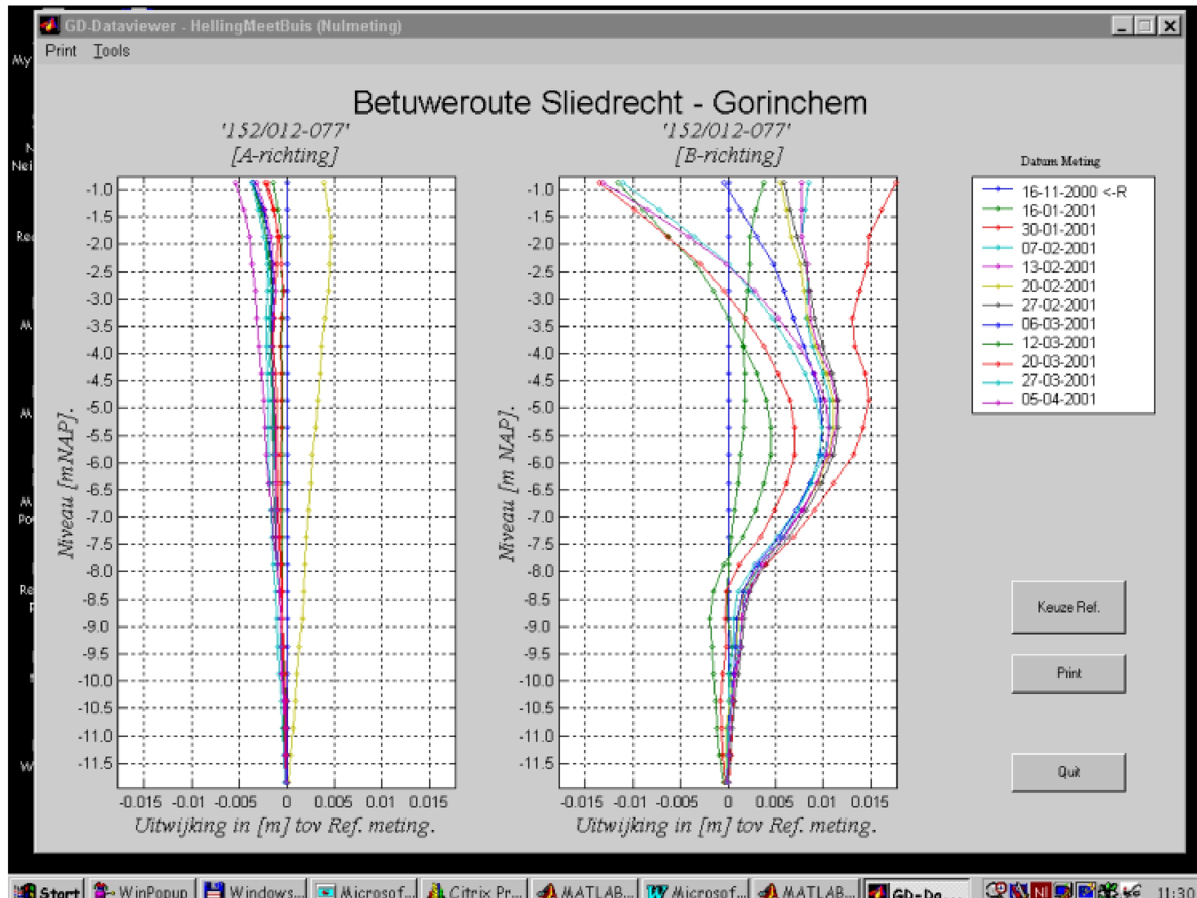
Creep after unloading modeling oedometer test, OCR = 1,8



Deltares

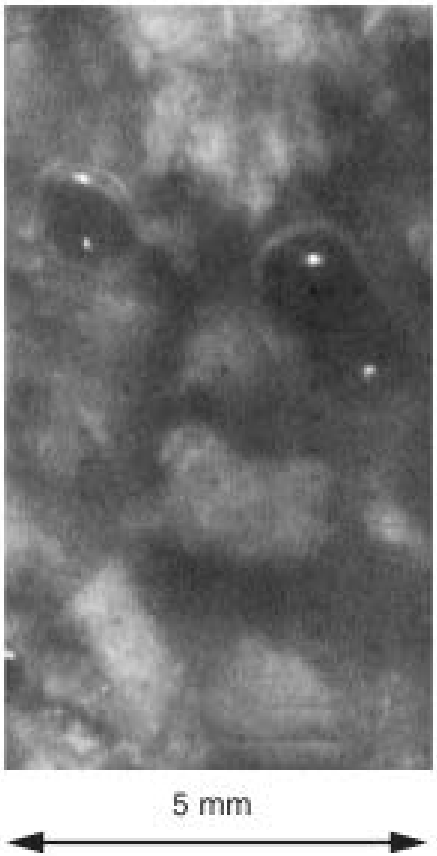
Further research

- Creep in 3D, little experience for modeling peat related problems



Influence of gas

Gas is not considered, but plays a role



Den Haan & Kruse 2007

Creep of Geomaterials

Rate-dependency based EVP modelling approach for clays: from 1D to 3D

Zhen-Yu YIN

Associate Professor, Ecole Centrale de Nantes, France

Guest Professor, Shanghai Jiao Tong University, China

15 September 2014

【PIAP-GA-2011-286397】 2nd CREEP Workshop & School, NTNU

Outline

1. Background- *Phenomena and problems*

2. Rate-dependency of clay

(1) *1D + remolded clay*

(2) *1D + intact clay*

(3) *3D + remolded clay*

(4) *3D + intact clay*

(5) *Applications*

3. Conclusions

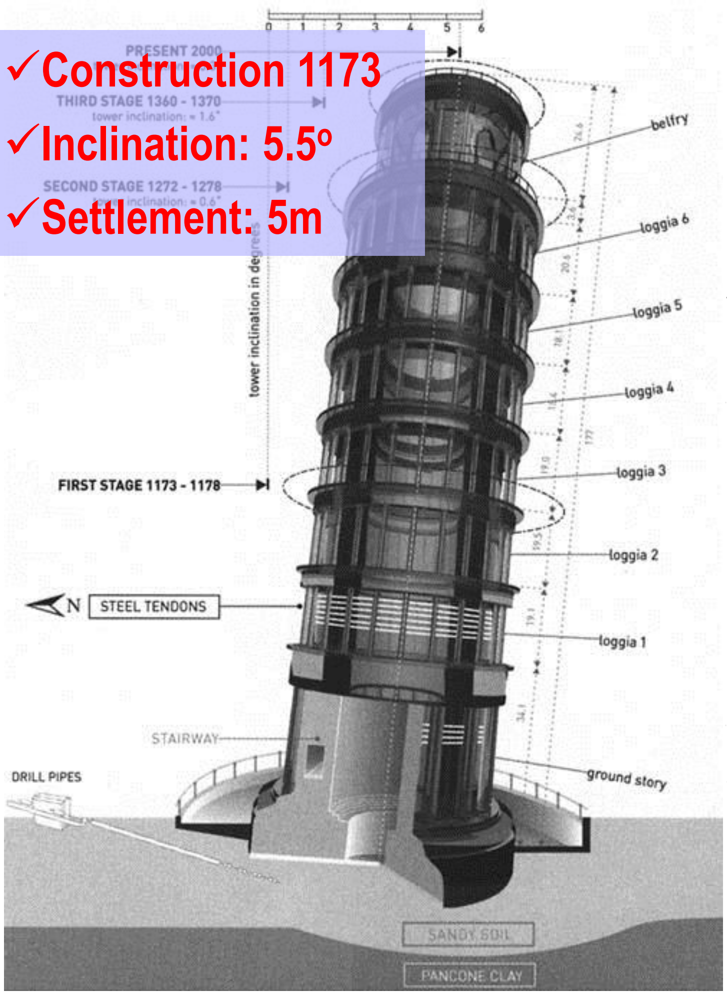
1. Phenomena and problems

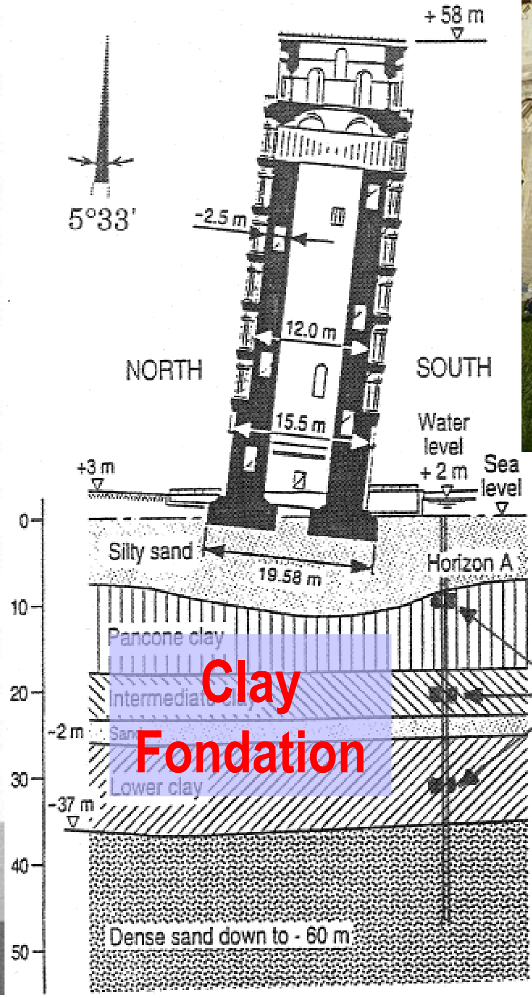
Clay

1. Phenomena and problems

Clay – *ancient construction*

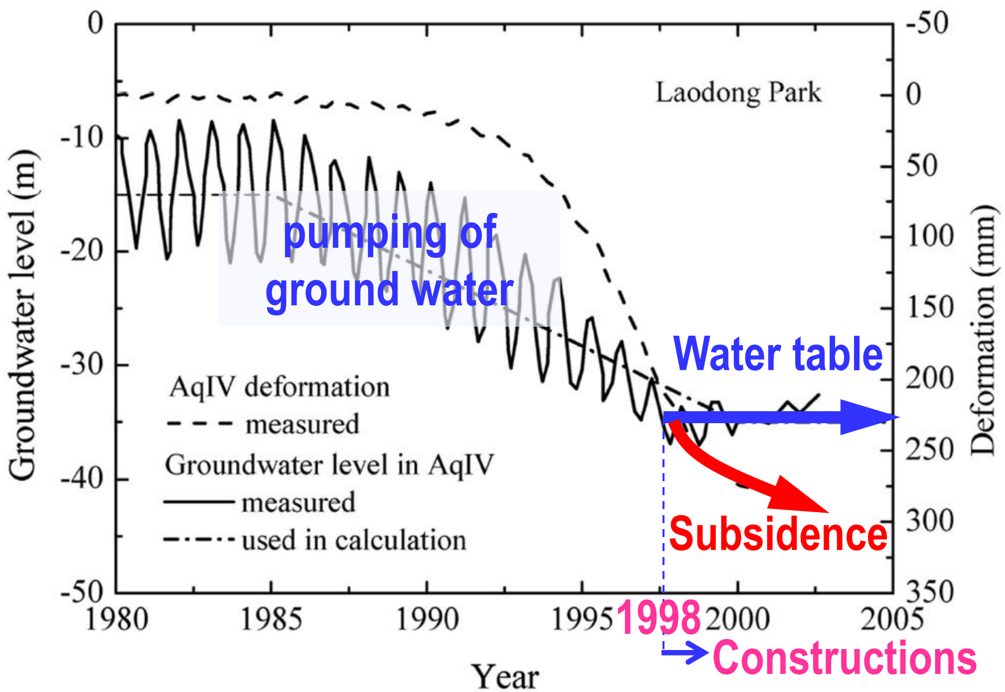
- ✓Construction 1173
- ✓Inclination: 5.5º
- ✓Settlement: 5m

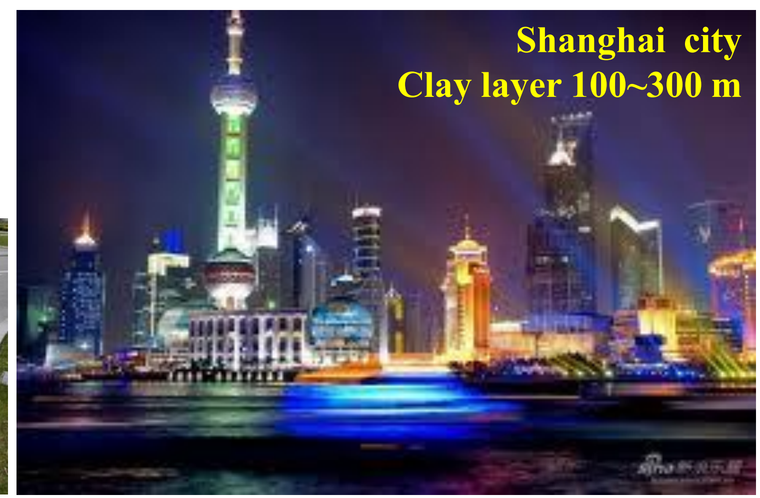




1. Phenomena and problems

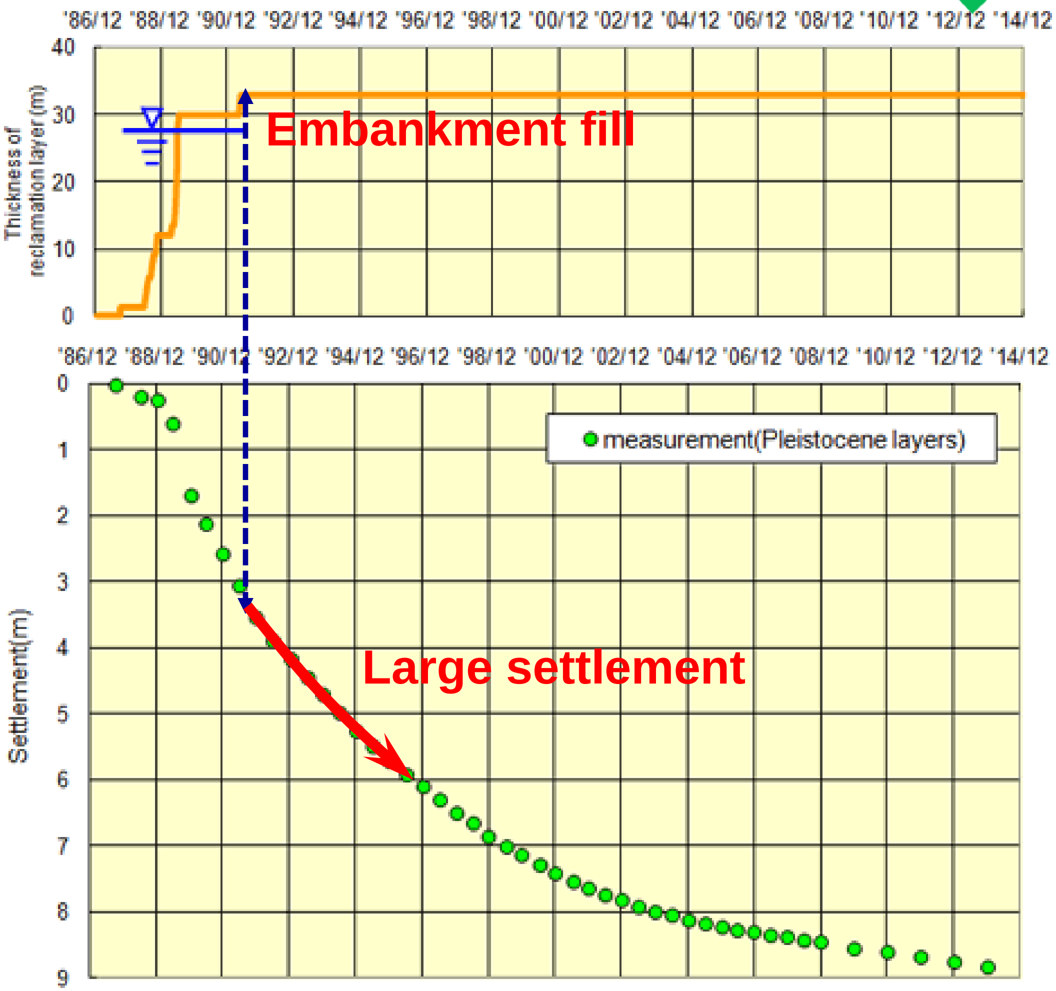
Clay – *Modern construction*





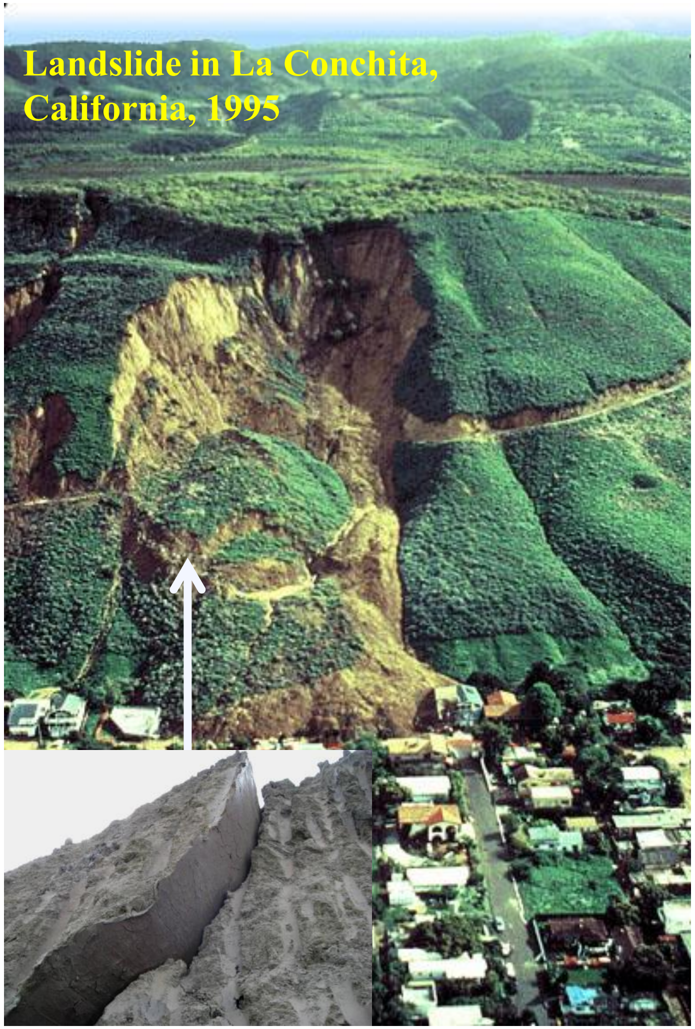
1. Phenomena and problems

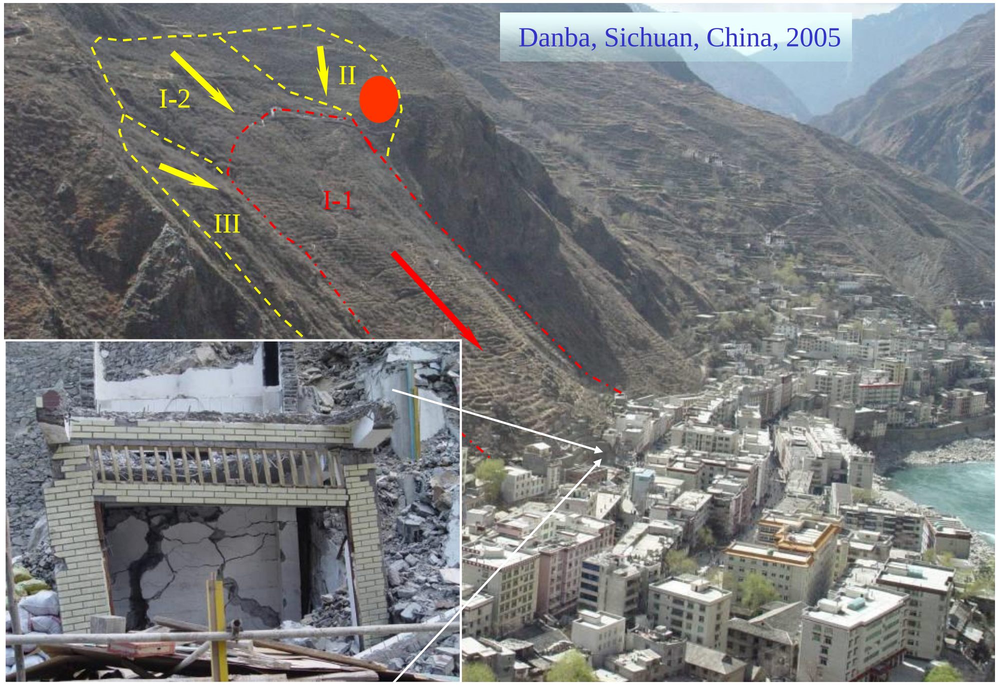
Clay – *Future construction*

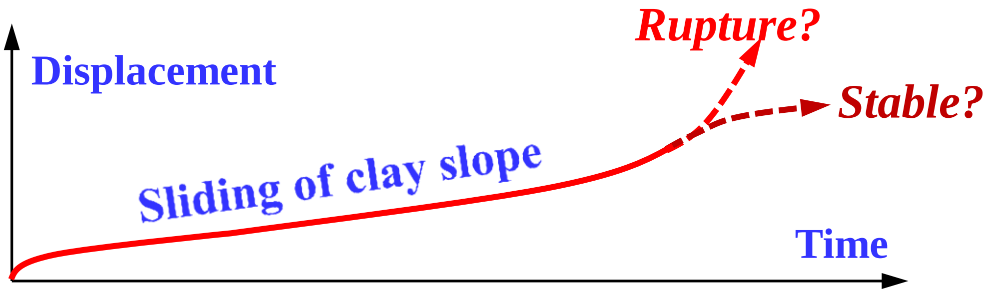


1. Phenomena and problems

Clay – *Natural hazards*

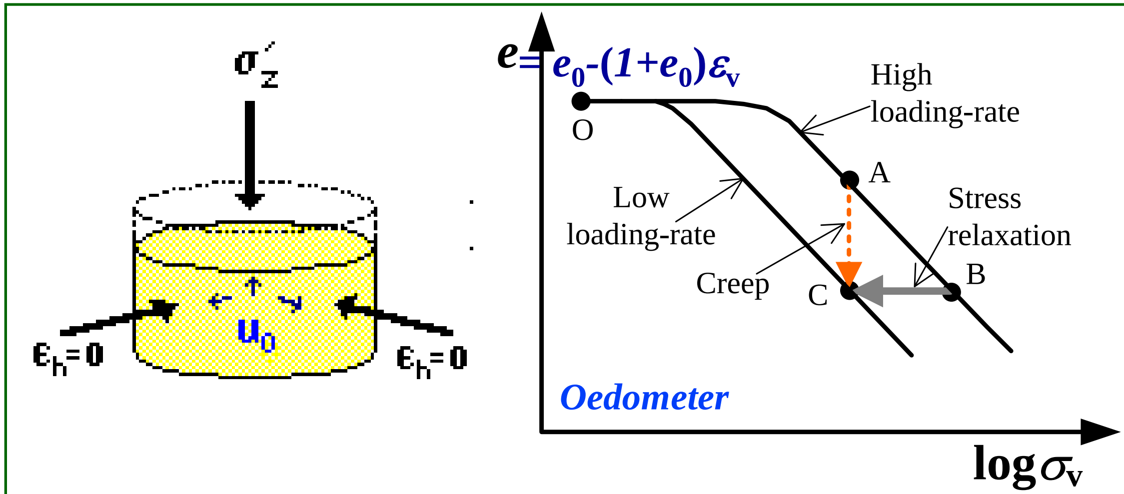


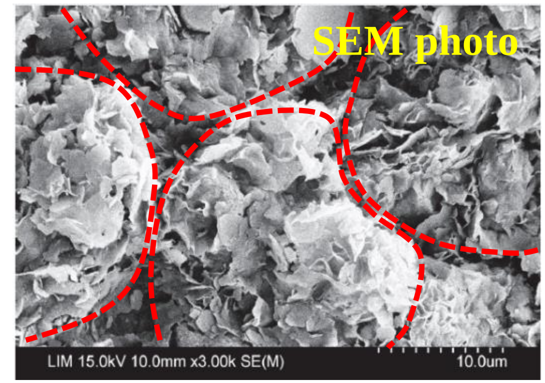




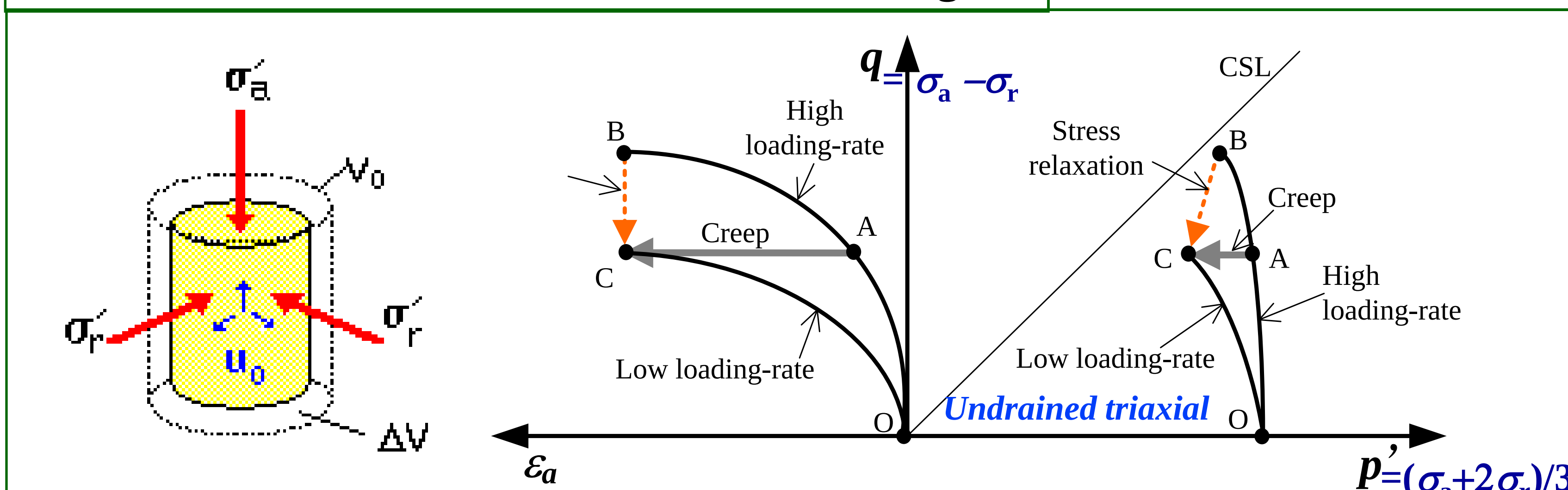
1. Phenomena and problems

Sample scale ***Micro scale***





Inter/intra-agregate void



Outline

1. Background

2. Rate-dependency of clay

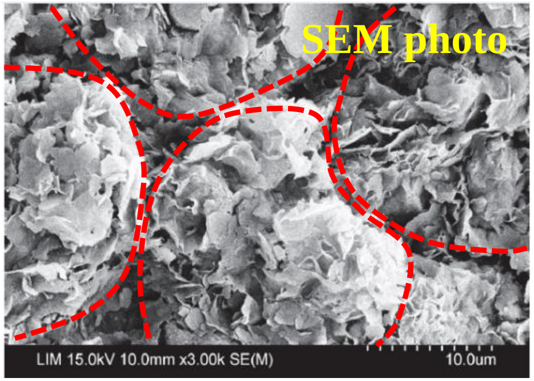
(1) *1D + remolded clay*

(2) *1D + intact clay*

(3) *3D + remolded clay*

(4) *3D + intact clay*

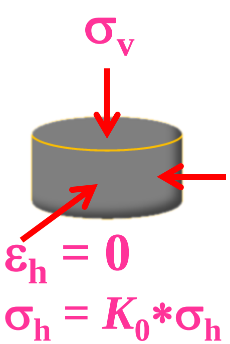
(5) *Applications*

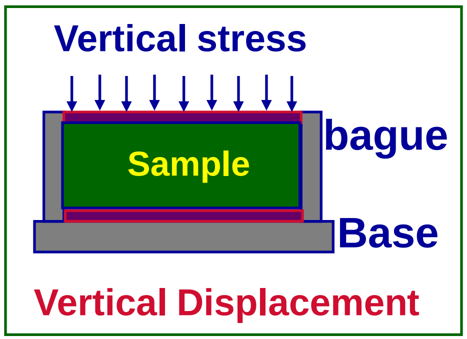


3. Conclusions

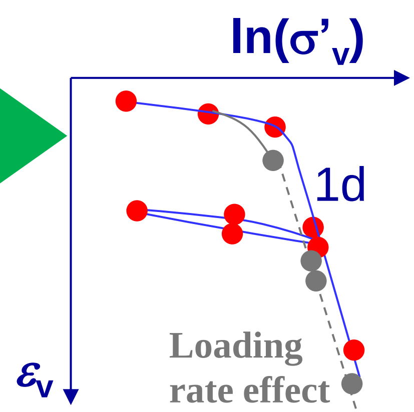
2.1 Rate-dependency – 1D & Remolded

❑ Creep based model





Stress control



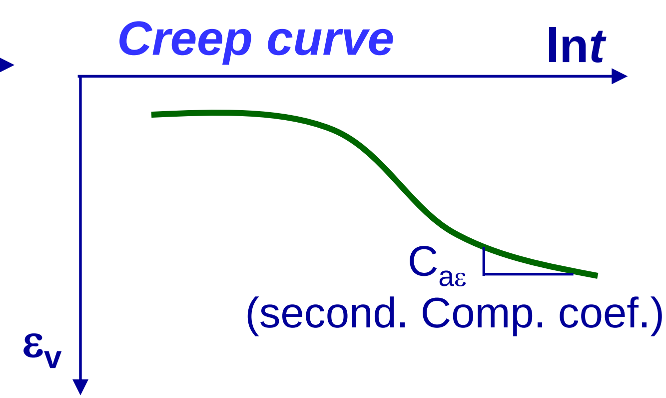
Some creep based models

✓ Yin JH et al. (1989, 1994, 2002)

$$\dot{\varepsilon}_v^{vp} = \frac{C_{\alpha e}}{(1+e_0)\tau}\left(1-\frac{\varepsilon_v^{vp}}{\varepsilon_{vl}^{vp}}\right)^2 \exp\left[\frac{-\varepsilon_v^{vp}}{\left(1-\frac{\varepsilon_v^{vp}}{\varepsilon_{vl}^{vp}}\right)}\frac{(1+e_0)}{C_{\alpha e}}\right]$$

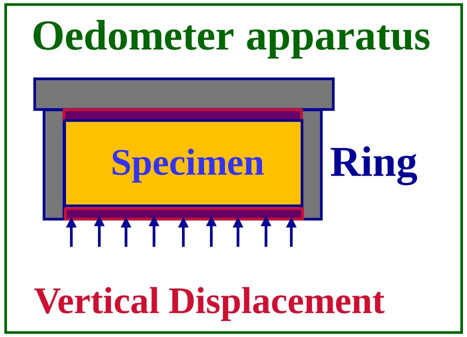
✓ Kutter & Sathialingam (1992); Vermeer (1999)

$$\dot{\varepsilon}_v^{vp} = \frac{C_{\alpha e}}{(1+e_0)t_0}\left(\frac{\sigma'_v}{\sigma'_p}\right)^{\frac{\lambda-\kappa}{C_{\alpha e}}}$$

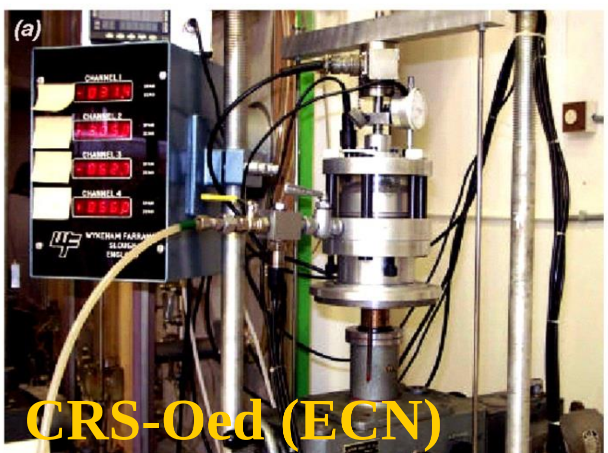


2.1 Rate-dependency – 1D & Remolded

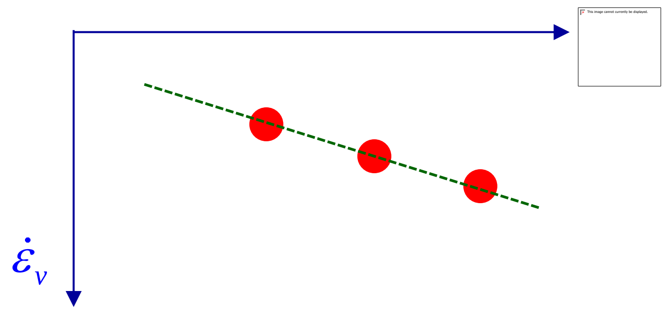
❑ Strain-rate dependency

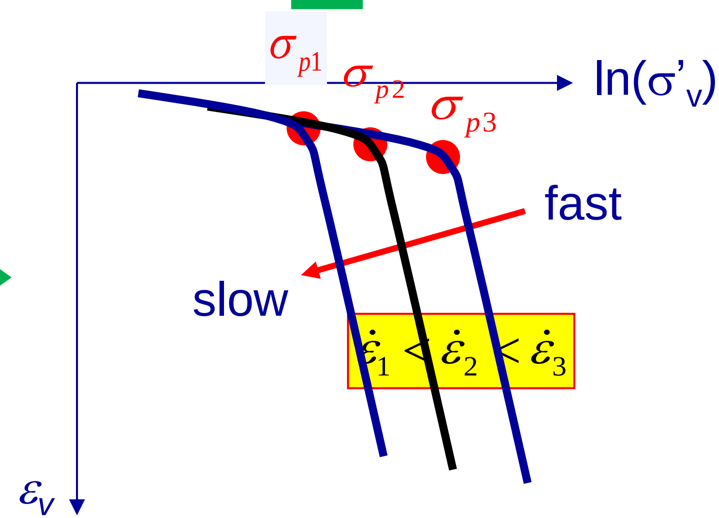


Strain control



Strain-rate dependency of σ'_{p0}

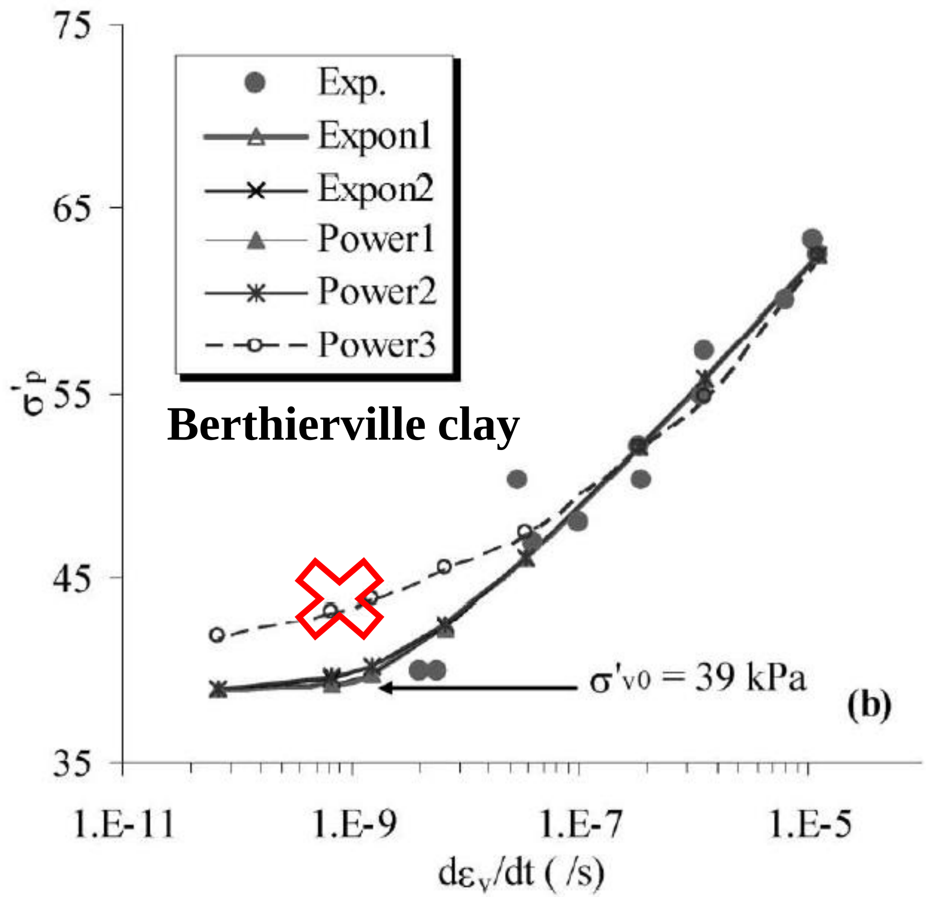


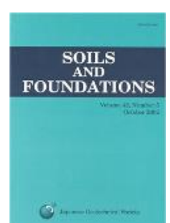


2.1 Rate-dependency – 1D & Remolded

❑ Strain-rate dependency

Expon1	$\dot{\varepsilon}_v = \mu \exp\left[N\left(\frac{p_m^d}{p_m^s} - 1\right)\right]$
Expon2	$\dot{\varepsilon}_v = \mu \left\{\exp\left[N\left(\frac{p_m^d}{p_m^s} - 1\right)\right] - 1\right\}$
Power1	$\dot{\varepsilon}_v = \mu \left(\frac{p_m^d}{p_m^s}\right)^N$
Power2	$\dot{\varepsilon}_v = \mu \left[\left(\frac{p_m^d}{p_m^s}\right)^N - 1\right]$
Power3	$\dot{\varepsilon}_v = \mu \left(\frac{p_m^d}{p_m^s} - 1\right)^N$





Yin Z-Y*, Karstunen M, Hicher PY. *Soils and Foundations*, 2010, 50(2): 203-214.

2.1 Rate-dependency – 1D & Remolded

❑ Strain-rate dependency

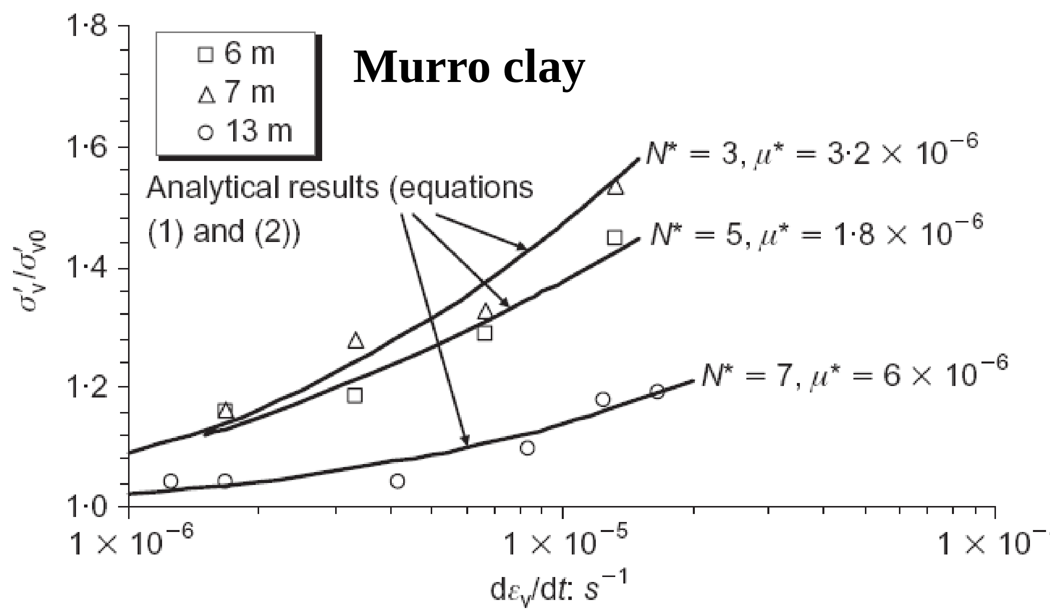
Expon1 $\dot{\varepsilon}_v = \mu \exp\left[N\left(\frac{p_m^d}{p_m^s}-1\right)\right]$

Expon2 $\dot{\varepsilon}_v = \mu\left\{\exp\left[N\left(\frac{p_m^d}{p_m^s}-1\right)\right]-1\right\}$

Power1 $\dot{\varepsilon}_v = \mu\left(\frac{p_m^d}{p_m^s}\right)^N$

Power2 $\dot{\varepsilon}_v = \mu\left[\left(\frac{p_m^d}{p_m^s}\right)^N-1\right]$

Power3 $\dot{\varepsilon}_v = \mu\left(\frac{p_m^d}{p_m^s}-1\right)^N$

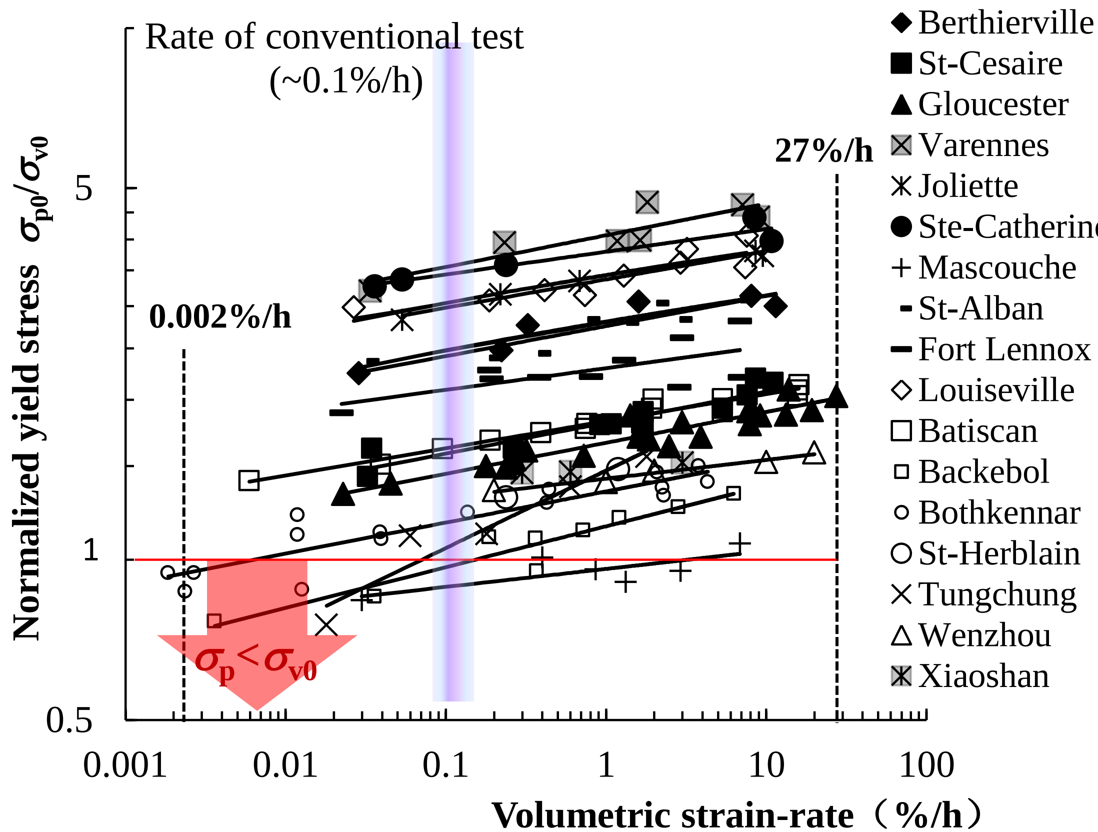


Karstunen M, Yin Z-Y*. *Géotechnique*, 2010, 60(10): 735-749.

2.1 Rate-dependency – 1D & Remolded

❑ Strain-rate dependency

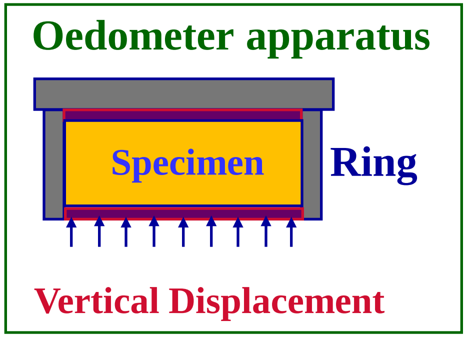
Expon1	$\dot{\varepsilon}_v = \mu \exp\left[N\left(\frac{p_m^d}{p_m^s} - 1\right)\right]$
Expon2	$\dot{\varepsilon}_v = \mu \left\{\exp\left[N\left(\frac{p_m^d}{p_m^s} - 1\right)\right] - 1\right\}$
Power1	$\dot{\varepsilon}_v = \mu \left(\frac{p_m^d}{p_m^s}\right)^N$
Power2	$\dot{\varepsilon}_v = \mu \left[\left(\frac{p_m^d}{p_m^s}\right)^N - 1\right]$
Power3	$\dot{\varepsilon}_v = \mu \left(\frac{p_m^d}{p_m^s} - 1\right)^N$



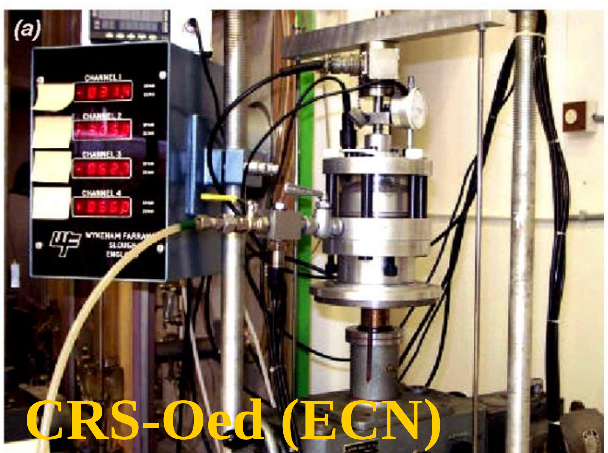
Yin Z-Y*, Chang CS, Karstunen M, Hicher PY. ***International Journal of Solids and Structures*, 2010, 47(5): 665-677.**

2.1 Rate-dependency – 1D & Remolded

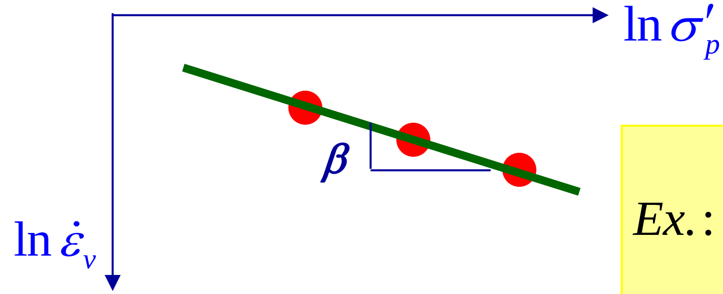
❑ Strain-rate dependency



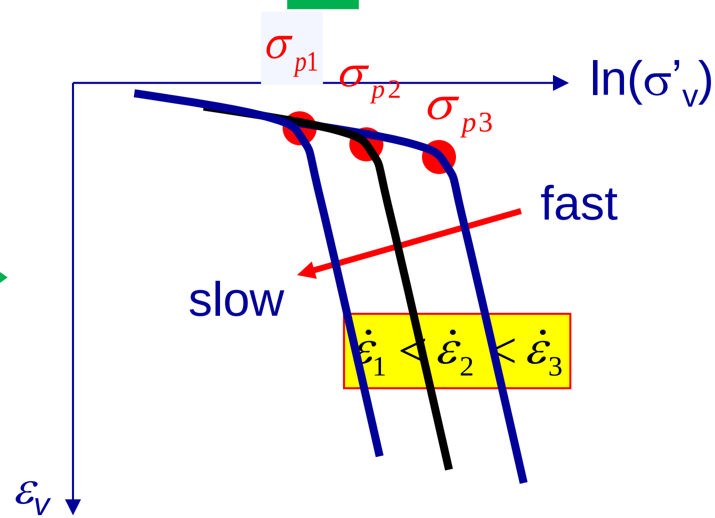
Strain control



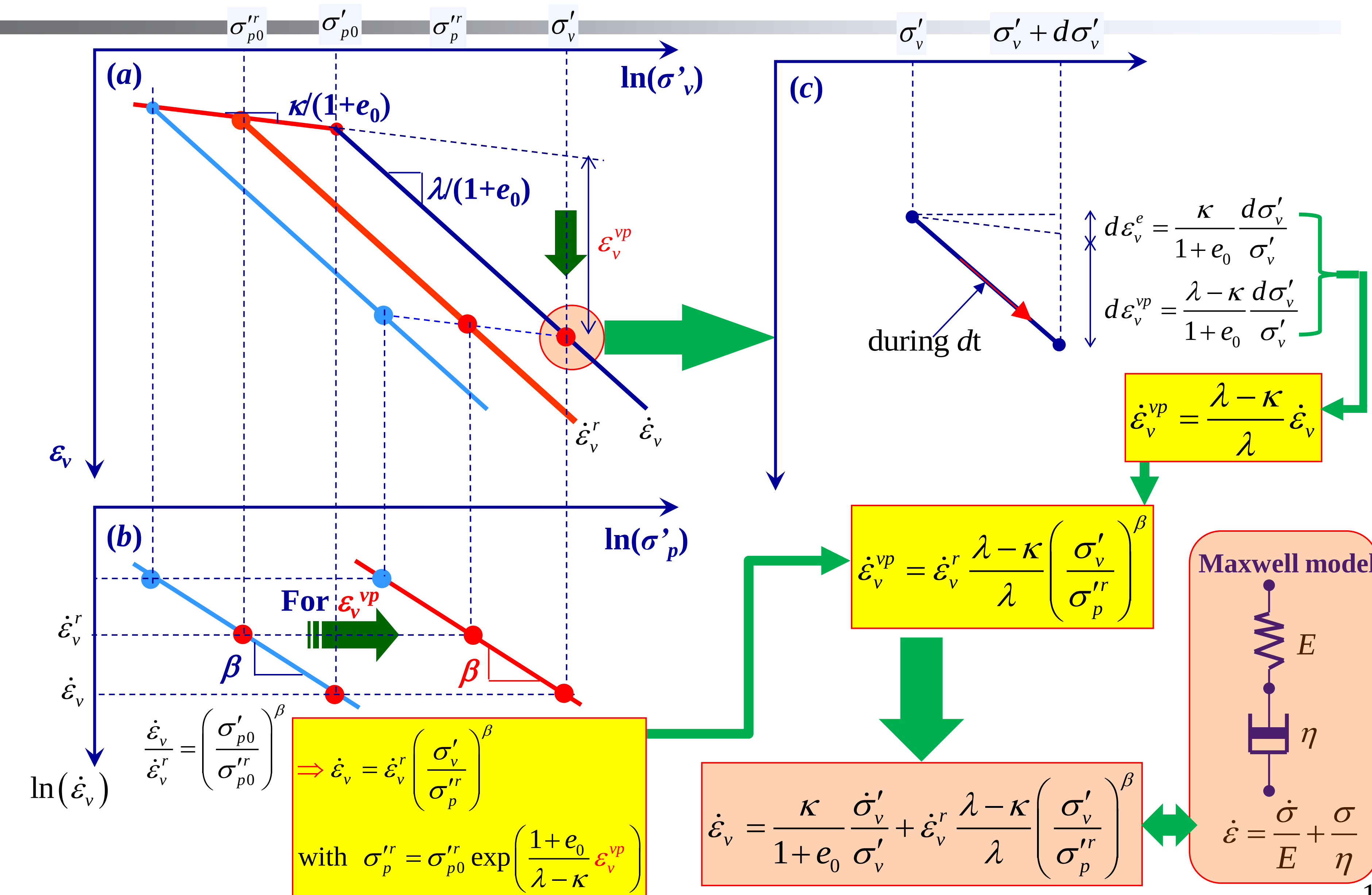
Strain-rate dependency of σ'_{p0}



$$Ex.: \quad \frac{\dot{\varepsilon}_v}{\dot{\varepsilon}_v^r} = \left(\frac{\sigma'_{p0}}{\sigma^r_{p0}}\right)^{\beta}$$



2.1 Rate-dependency – 1D & Remolded



2.1 Rate-dependency – 1D & Remolded

❑ Rate-dependency based model

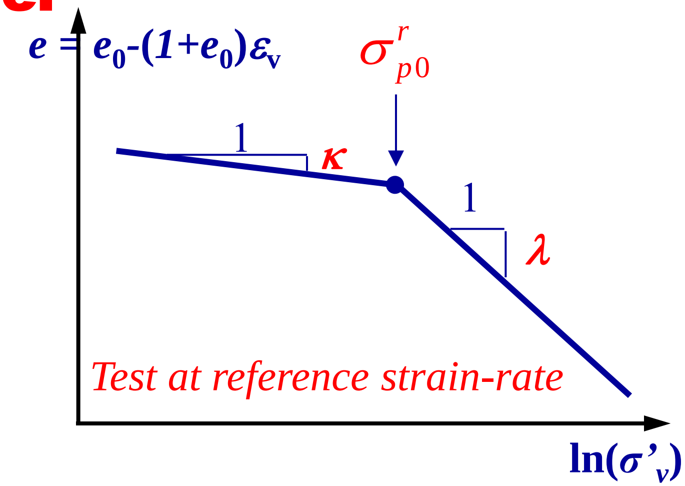
EVP model – 1D:

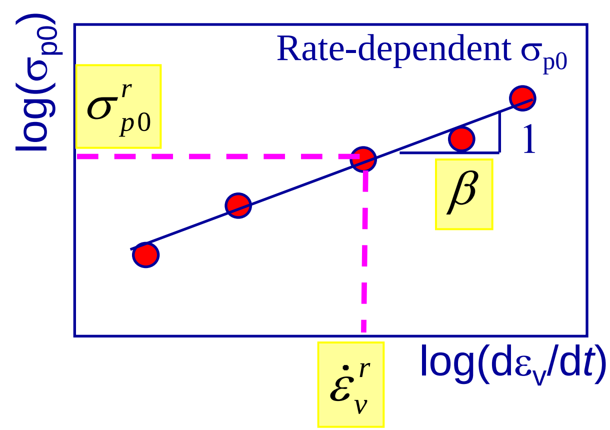
$$\dot{\varepsilon}_v = \dot{\varepsilon}_v^e + \dot{\varepsilon}_v^{vp}$$

$$\dot{\varepsilon}_v^e = \frac{\kappa}{1+e_0}\frac{\dot{\sigma}'_v}{\sigma'_v}$$

$$\dot{\varepsilon}_v^{vp} = \dot{\varepsilon}_v^r \frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_v}{\sigma_p^r}\right)^{\beta}$$

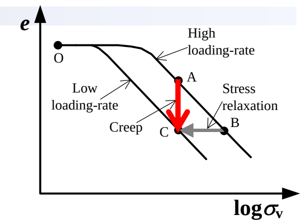
$$\sigma_p^r = \sigma_{p0}^r \exp\left(\frac{1+e_0}{\lambda-\kappa}\varepsilon_v^{vp}\right)$$





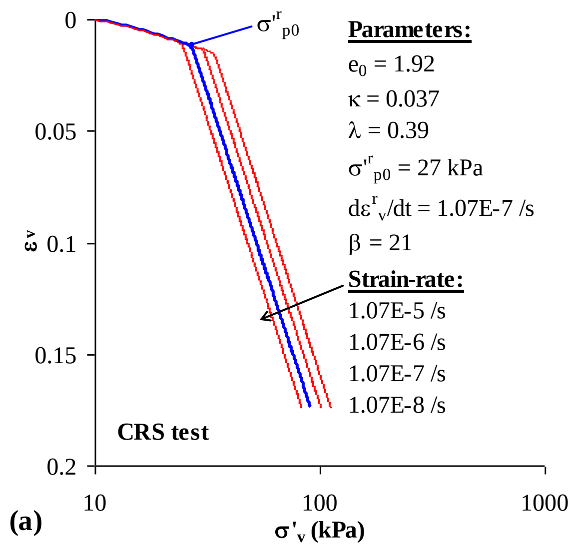
➢ ***Simple & easy to determine***

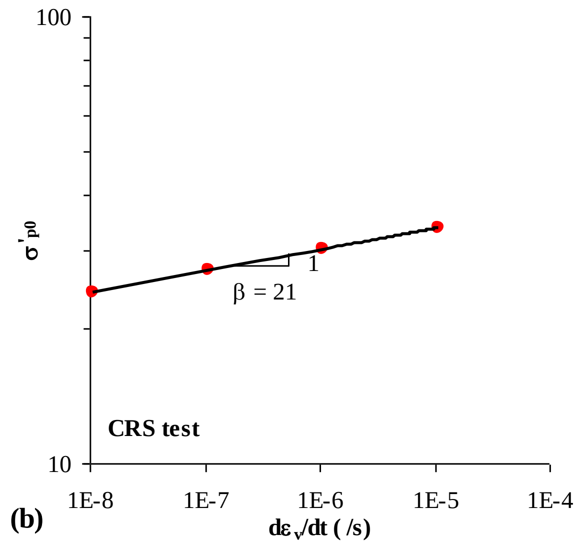
2.1 Rate-dependency – 1D & Remolded

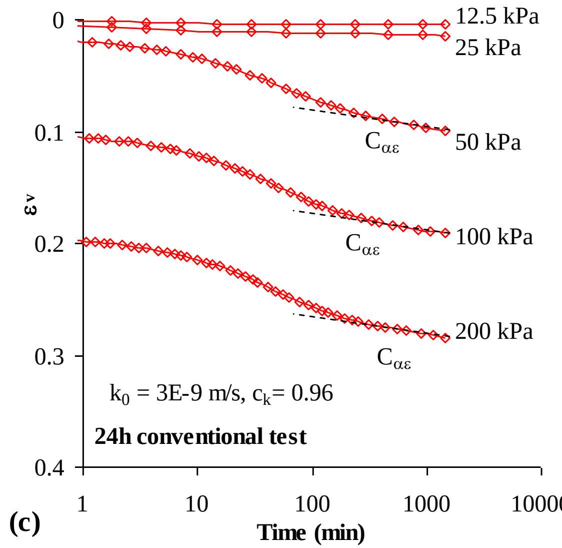


❑ Rate-dependency ↔ Creep?

Simulations by given values of parameters:







Rate-dependency formulation | **Creep of Vermeer**

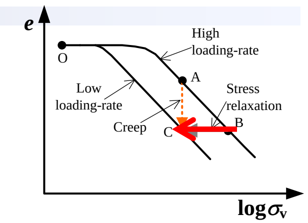
$$\dot{\varepsilon}_v^{vp} = \dot{\varepsilon}_v^r \frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_v}{\sigma_p^r}\right)^{\beta}$$

$$\dot{\varepsilon}_v^{vp} = \frac{C_{\alpha e}}{(1+e_0)t_0}\left(\frac{\sigma'_v}{\sigma'_p}\right)^{\frac{\lambda-\kappa}{C_{\alpha e}}}$$

$$\boxed{\beta = \frac{\lambda-\kappa}{C_{\alpha e}}}$$

2.1 Rate-dependency – 1D & Remolded

❑ Rate-dependency ↔ Stress relaxation?

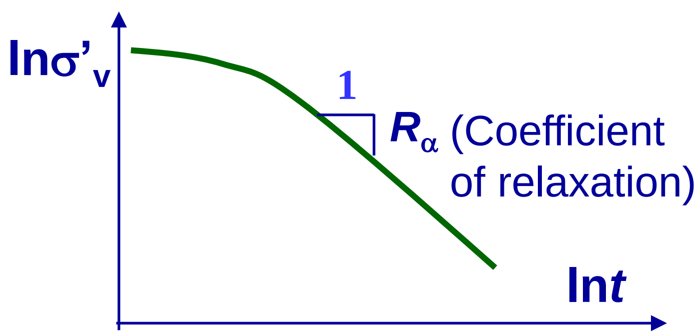


❖ Formulation of stress relaxation

$$\dot{\varepsilon}_v = \frac{\kappa}{1+e_0}\frac{\dot{\sigma}'_v}{\sigma'_v} + \dot{\varepsilon}^r_v \frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_v}{\sigma'^r_p}\right)^{\beta} \xrightarrow{\text{Stress relaxation}} = 0$$

$$\sigma'_{\mathrm{v}} = \left(\left(-\dot{\varepsilon}^{\mathrm{r}}_{\mathrm{v}} \frac{(1+e_0)(\lambda-\kappa)}{\lambda\kappa}\left(\frac{1}{\sigma'^{\mathrm{r}}_{\mathrm{pi}}\,\sigma'^{\frac{\kappa}{\lambda-\kappa}}_{\mathrm{vi}}}\right)^{\beta}\left(-\frac{\lambda\beta}{\lambda-\kappa}\right) t + \sigma'^{-\frac{\lambda\beta}{\lambda-\kappa}}_{\mathrm{vi}}\right)\right)^{-\frac{\lambda-\kappa}{\lambda\beta}}$$

❖ Coefficient of relaxation



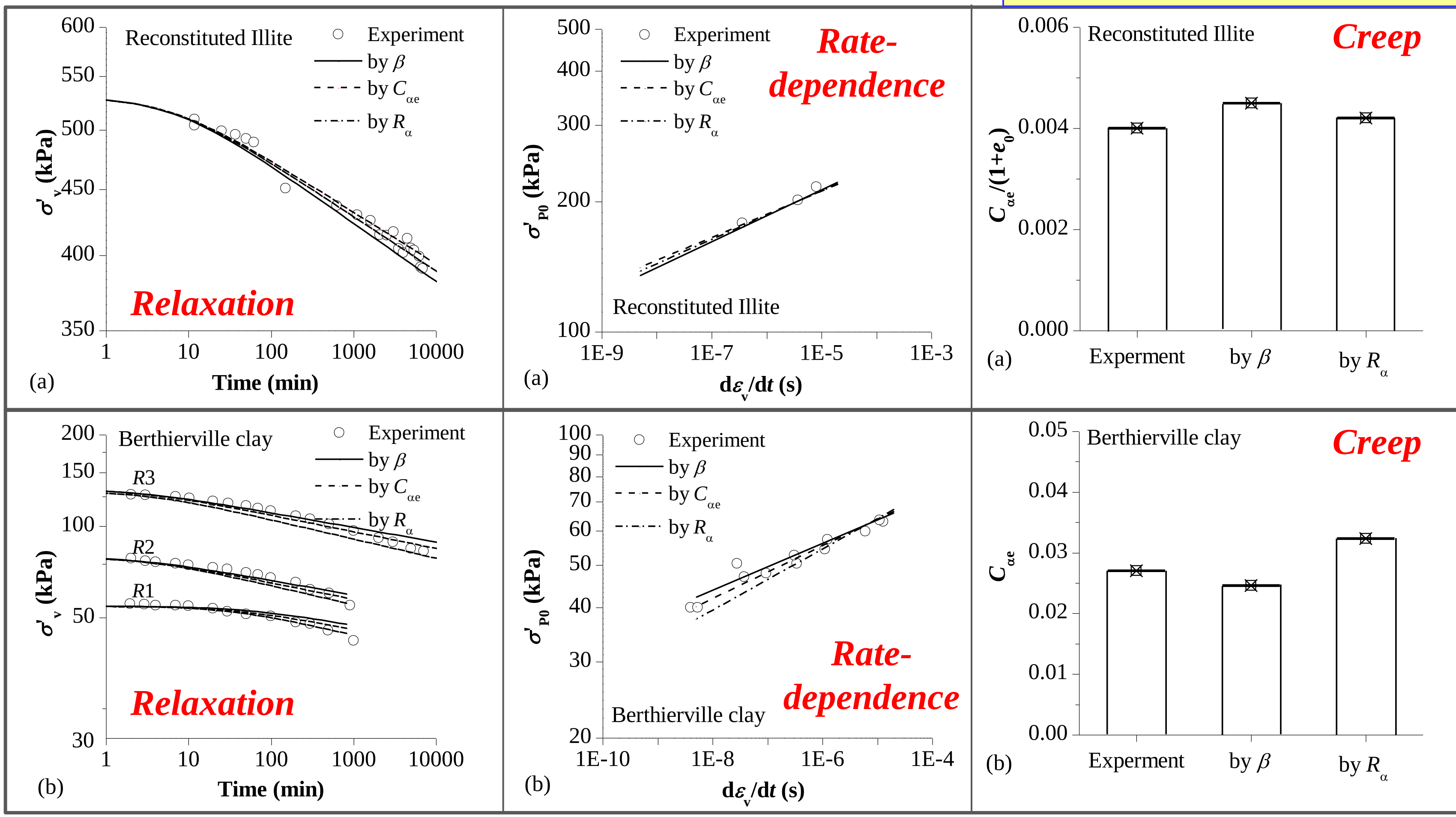
$$R_\alpha = -\frac{\partial \ln\sigma'_{\mathrm{v}}}{\partial \ln t} = \frac{\lambda-\kappa}{\lambda\beta} = \frac{C_{\alpha e}}{\lambda} \text{ or } \frac{C_\alpha}{C_c}$$

Uniqueness of time-dependencies

2.1 Rate-dependency – 1D & Remolded

❑ Uniqueness of time-dependencies

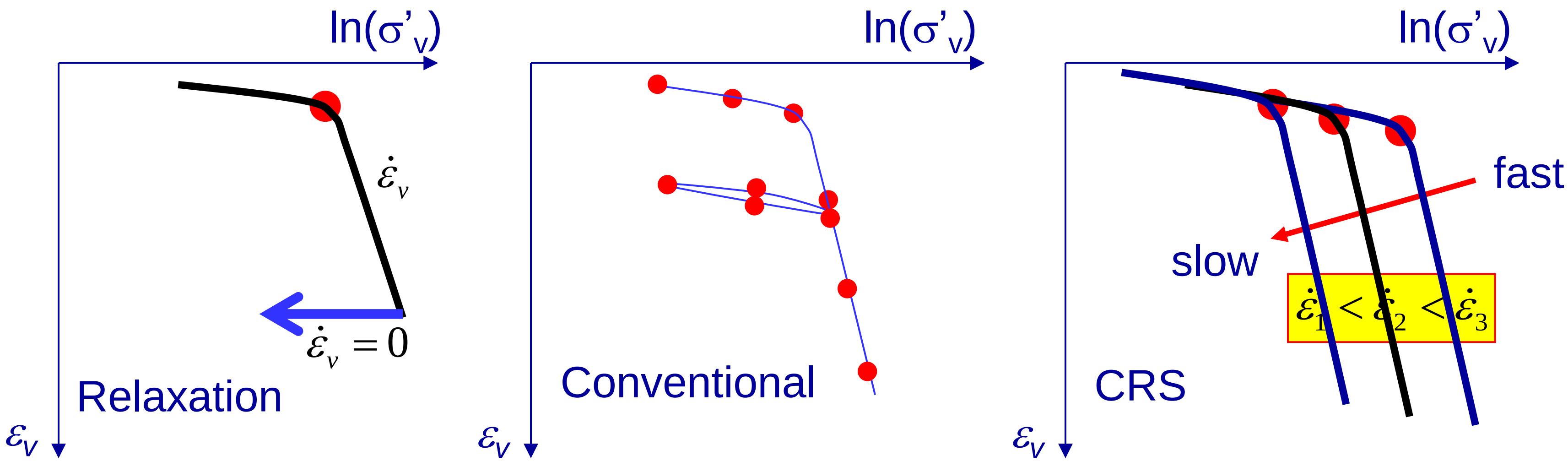
$$R_\alpha = -\frac{\partial \ln \sigma'_v}{\partial \ln t} = \frac{\lambda-\kappa}{\lambda\beta} = \frac{C_{\alpha e}}{\lambda} \text{ or } \frac{C_\alpha}{C_c}$$



2.1 Rate-dependency – 1D & Remolded

❑ Uniqueness of time-dependencies

$$R_\alpha = -\frac{\partial \ln \sigma'_v}{\partial \ln t} = \frac{\lambda - \kappa}{\lambda \beta} = \frac{C_{\alpha e}}{\lambda} \text{ or } \frac{C_\alpha}{C_c}$$



Duration: ∽ 3 d *Duration: ∽ 14 d* *Duration: >10 d*

Yin Z-Y*, **Zhu QY, Yin JH, Ni Q. Stress relaxation coefficient and formulation for soft soils. *Géotechnique Letters*, 2014, 4(1): 45-51.**

Outline

1. Background

2. Rate-dependency of clay

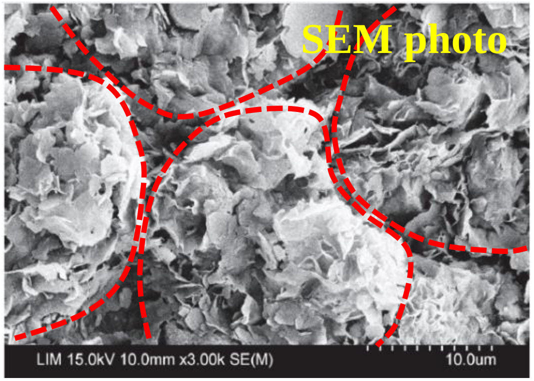
(1) 1D + remolded clay

(2) 1D + intact clay

(3) 3D + remolded clay

(4) 3D + intact clay

(5) Applications

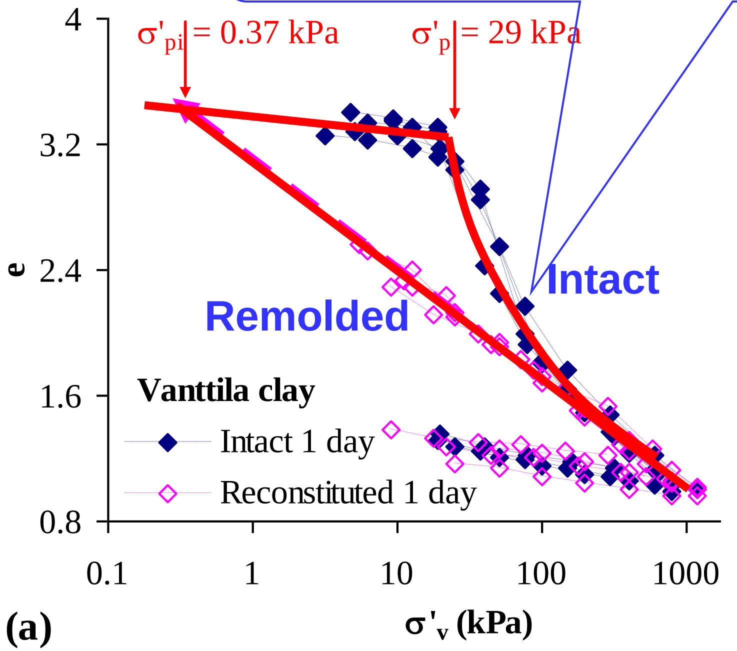


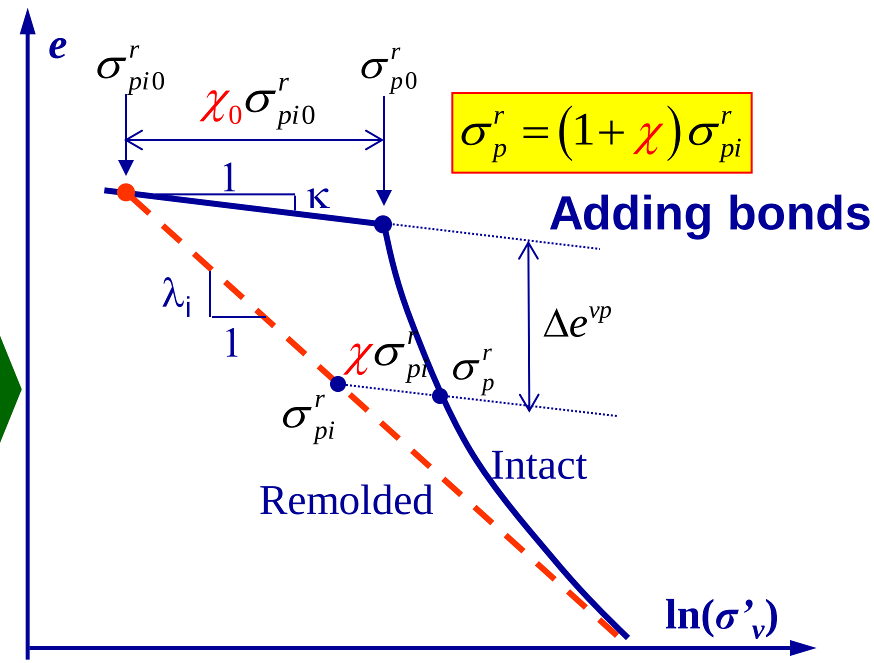
3. Conclusions

2.2 Rate-dependency – 1D & Intact

❑ Inter-particle bonds and debonding

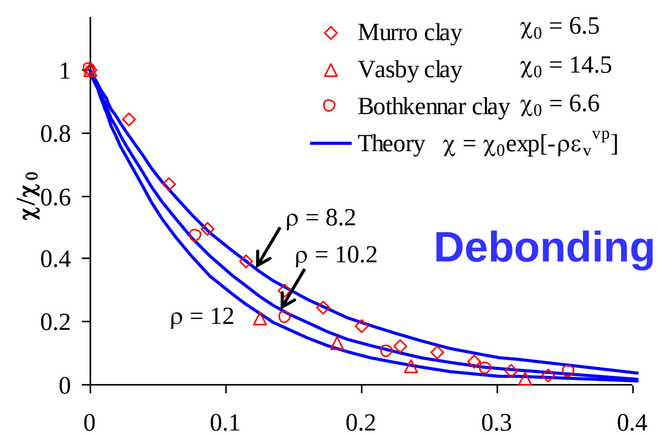
Progressive debonding during plastic strains





Debonding rule

$$\chi = \chi_0 e^{-\rho\varepsilon_v^{vp}}$$



2.2 Rate-dependency – 1D & Intact

$$\dot{\varepsilon}_v = \dot{\varepsilon}_v^e + \dot{\varepsilon}_v^{vp}$$

$$\dot{\varepsilon}_v^e = \frac{\kappa}{1+e_0}\frac{\dot{\sigma}'_v}{\sigma'_v}$$

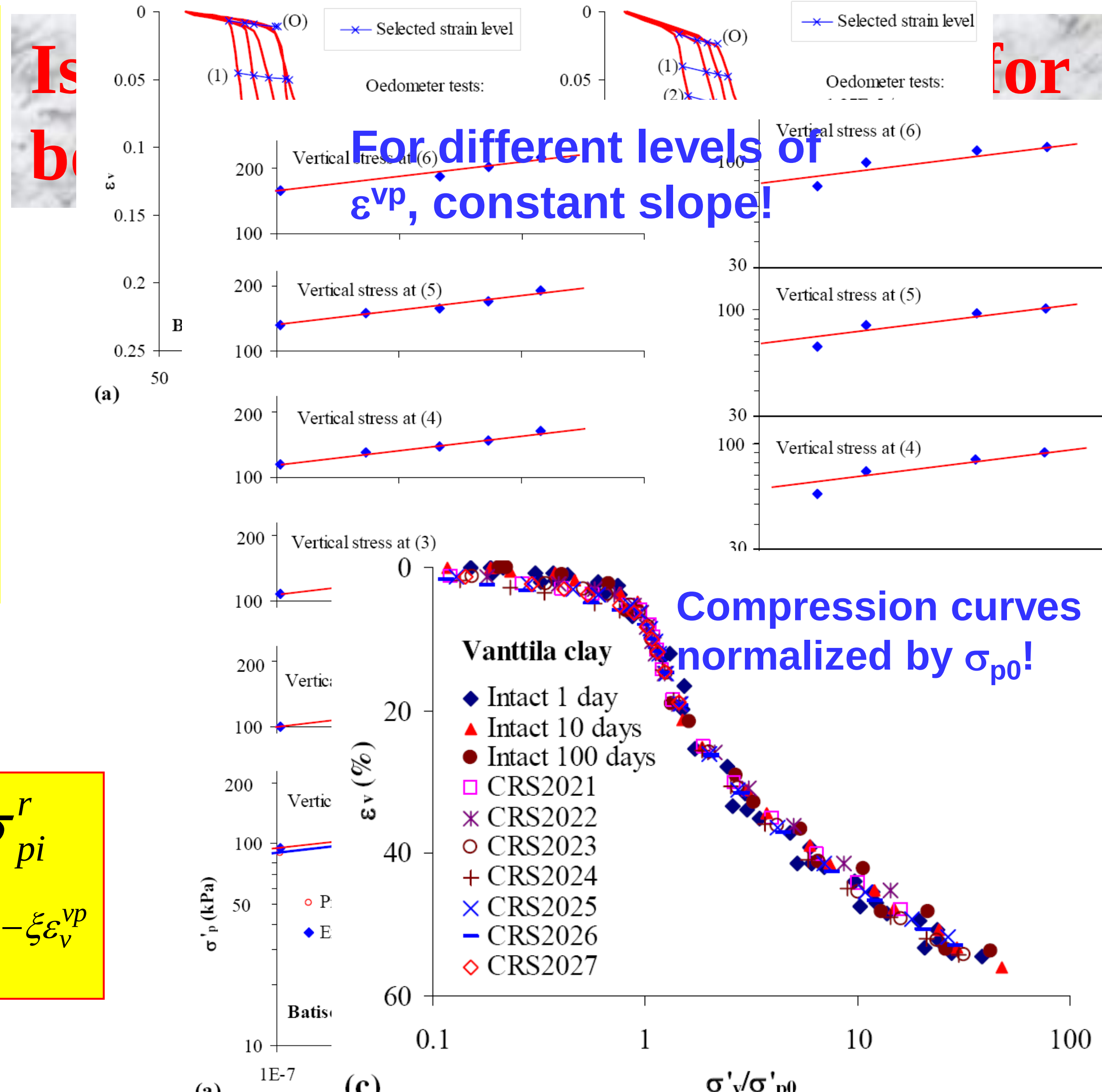
Constant?

$$\dot{\varepsilon}_v^{vp} = \dot{\varepsilon}_v^r \frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_v}{\sigma_p^r}\right)^{\beta}$$

$$\sigma_p^r = \sigma_{p0}^r \exp\left(\frac{1+e_0}{\lambda-\kappa}\varepsilon_v^{vp}\right)$$

$$\text{Bonds: } \sigma_p^r = (1+\chi)\sigma_{pi}^r$$

$$\text{Degradation: } \chi = \chi_0 e^{-\xi\varepsilon_v^{vp}}$$



For different levels of ε^{vp}, constant slope!

Compression curves normalized by σ_{p0}!

2.2 Rate-dependency – 1D & Intact

Equations of 1D model

Model of remolded clay

$$\dot{\varepsilon}_v = \frac{\kappa}{1+e_0}\frac{\dot{\sigma}'_v}{\sigma'_v} + \dot{\varepsilon}_v^r \frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_v}{\sigma'^r_p}\right)^{\beta}$$

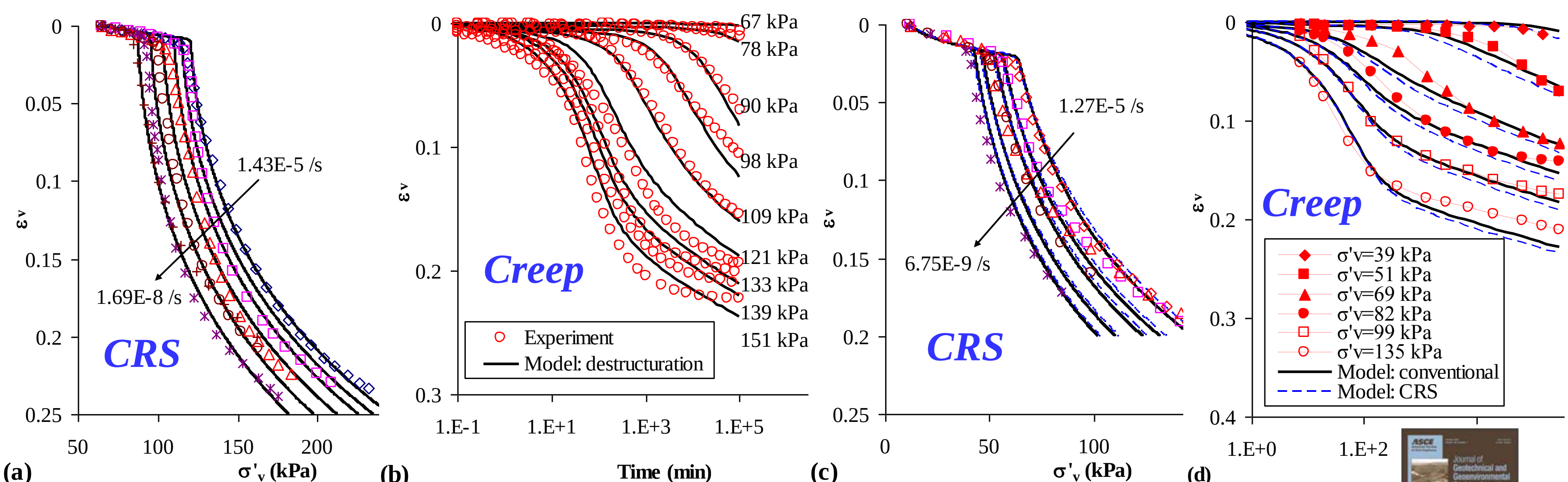
$$\sigma'^r_p = \sigma'^r_{p0}\exp\left(\frac{\lambda-\kappa}{1+e_0}\varepsilon_v^{vp}\right)$$

$$+\begin{cases}\sigma_p^r = (1+\chi)\,\sigma_{pi}^r \\ \chi = \chi_0 \exp\left(-\rho\varepsilon_v^{vp}\right)\end{cases}$$

Model of natural intact clay

$$\chi_0 = 0$$

Validation (natural soft clays)



1D-EVP model for natural soft clays. ***Yin et al. (2011)***

Outline

1. Background

2. Rate-dependency of clay

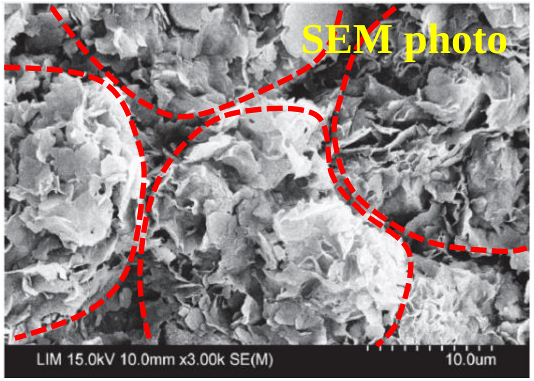
(1) 1D + remolded clay

(2) 1D + intact clay

(3) 3D + remolded clay

(4) 3D + intact clay

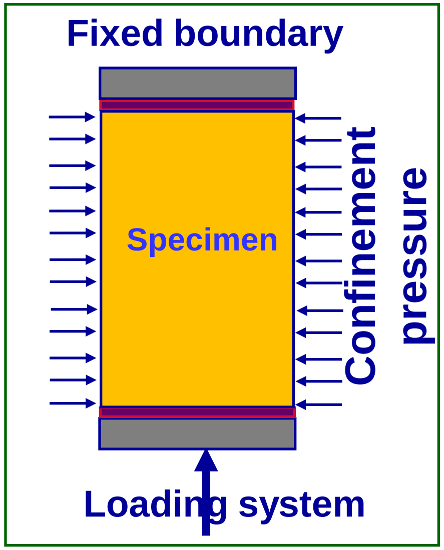
(5) Applications

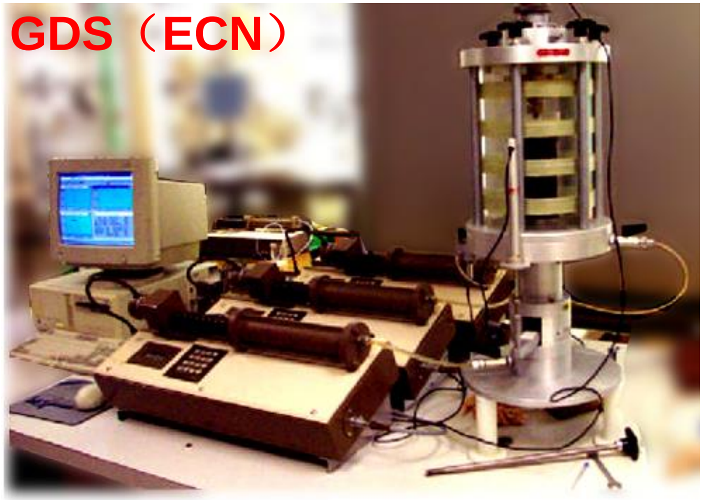


3. Conclusions

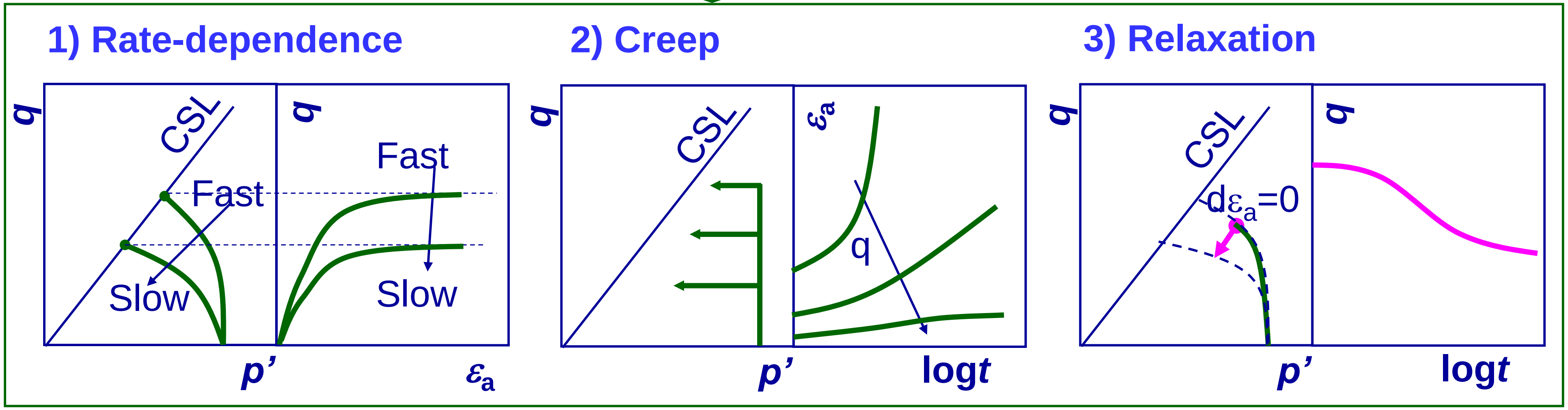
2.3 Rate-dependency – 3D & Remolded

- **Methodology**





Time effect in 3D



2.3 Rate-dependency – 3D & Remolded

❑ Elastoplasticity vs. Elasto-viscoplasticity

$$d\varepsilon_{ij} = \dot{\varepsilon}_{ij}$$

Strain increments

（EP model）

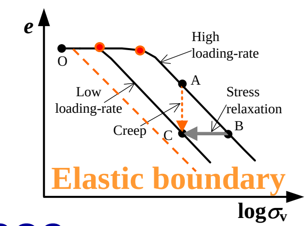
$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p}$$

$$\dot{\varepsilon}_{ij}^{p} = d\lambda \frac{\partial g}{\partial \sigma_{ij}}$$

$$d\varepsilon_{ij} = \dot{\varepsilon}_{ij} \cdot dt$$

Strain rates

（EVP model）



Elastoplasticity:

- ❖ Yield surface (f)
- ❖ Flow rule (f=g)
- ❖ Hardening rule（κ*）

$$df = 0 \Rightarrow$$

$$d\lambda = \frac{\left[\dfrac{\partial f}{\partial \sigma_{ij}}\right]^{T}\left[D_{ijkl}\, d\varepsilon_{kl}\right]}{\left[\dfrac{\partial f}{\partial \sigma_{ij}}\right]^{T}\left[D_{ijkl}\dfrac{\partial g}{\partial \sigma_{kl}}\right] - \dfrac{\partial f}{\partial \kappa^{*}}\dfrac{\partial \kappa^{*}}{\partial \varepsilon_{*}^{p}}\dfrac{\partial g}{\partial \sigma_{*}}}$$

Elasto-viscoplasticity:

- ❖ Static/reference surface
- ❖ Flow rule
- ❖ Hardening rule
- ❖ Scaling function（dλ）

$$d\lambda = \mu\left\langle \Phi\left(F\right)\right\rangle$$

Viscous parameter

Overstress measurement

2.3 Rate-dependency – 3D & Remolded

(1) Scaling function with flow rule

$$\dot{\varepsilon}_{ij}^{vp} = d\lambda \frac{\partial g}{\partial \sigma_{ij}} = \mu \left\langle \Phi(F) \right\rangle \frac{\partial g}{\partial \sigma_{ij}}$$

Equation from 3D to 1D:

$$\dot{\varepsilon}_{ij}^{vp} = d\lambda \frac{\partial g}{\partial \sigma_{ij}} \xrightarrow[\text{Oedometer}]{under K_0} \dot{\varepsilon}_{v}^{vp} = d\lambda \left(\frac{\partial g}{\partial p'} \right)_{K0}$$

Equation in 1D:

$$\dot{\varepsilon}_{v}^{vp} = \dot{\varepsilon}_{v}^{r} \frac{\lambda - \kappa}{\lambda} \left(\frac{\sigma'_v}{\sigma_p^r} \right)^{\beta}$$

$$d\lambda = \dot{\varepsilon}_{v}^{r} \frac{\lambda - \kappa}{\lambda} \left(\frac{p_c^d}{p_c^r} \right)^{\beta} \frac{1}{\left(\frac{\partial g}{\partial p'} \right)_{K0}}$$

$$\begin{cases} \mu = \dot{\varepsilon}_{v}^{r} \dfrac{\lambda - \kappa}{\lambda} \left(\dfrac{\partial g}{\partial p'} \right)_{K0}^{-1} \\ \left\langle \Phi(F) \right\rangle = \left(\dfrac{p_c^d}{p_c^r} \right)^{\beta} \end{cases}$$

$$\dot{\varepsilon}_{ij}^{vp} = \dot{\varepsilon}_{v}^{r} \frac{\lambda - \kappa}{\lambda} \left(\frac{\partial g}{\partial p'} \right)_{K0}^{-1} \left(\frac{p_c^d}{p_c^r} \right)^{\beta} \frac{\partial g}{\partial \sigma_{ij}}$$

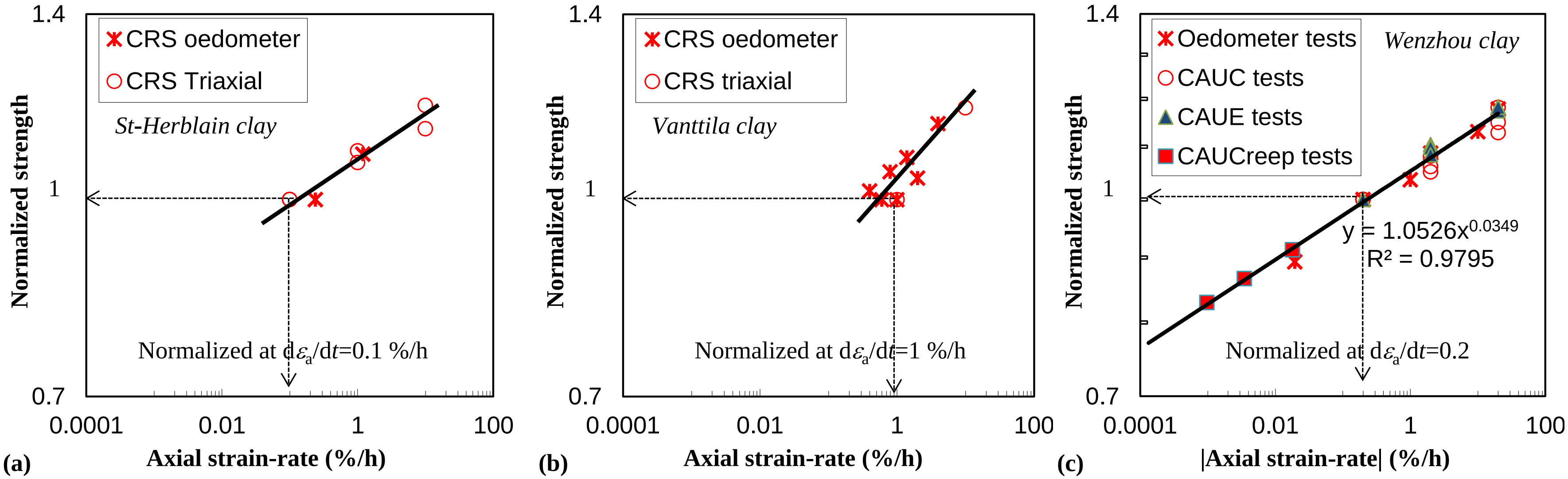
2.3 Rate-dependency – 3D & Remolded

(1) Scaling function with flow rule

Constant?

$$\dot{\varepsilon}_{ij}^{vp} = d\lambda \frac{\partial g}{\partial \sigma_{ij}} \xrightarrow[\text{condition}]{\text{Triaxial}} \dot{\varepsilon}_{d}^{vp} = \dot{\varepsilon}_{v}^{r} \frac{\lambda-\kappa}{\lambda} \left(\frac{\partial g}{\partial p'}\right)_{K0}^{-1} \left(\frac{p_c^d}{p_c^r}\right)^{\beta} \left(\frac{\partial g}{\partial q}\right)_{\eta=M}$$

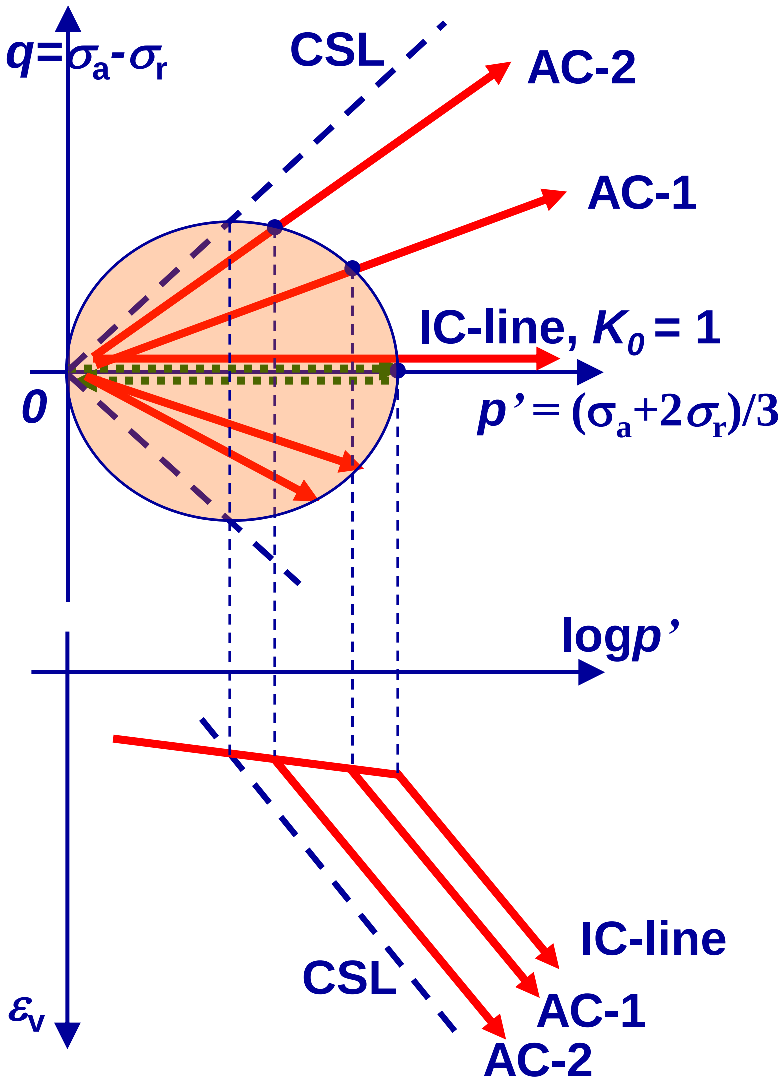
Rate-dependency from 1D to 3D?



Uniqueness of rate-dependency for σ'_{p0} and q_u. *Yin et al. (2013)*

2.3 Rate-dependency – 3D & Remolded

❑ Reference surface?



(2) Reference surface

$$f_r = \frac{q^2}{M^2} + p\left(p - p_c^r\right)$$

(3) Flow rule

$g = f_d$

$$\frac{\dot{\varepsilon}_v^p}{\dot{\varepsilon}_d^p} = \frac{M^2 - \eta^2}{2\eta}$$

(4) Hardening rule

$$\dot{\sigma}_v = \sigma_v \frac{1+e_0}{\lambda-\kappa}\dot{\varepsilon}_v^p \Rightarrow \dot{p}_c = p_c \frac{1+e_0}{\lambda-\kappa}\dot{\varepsilon}_v^p$$

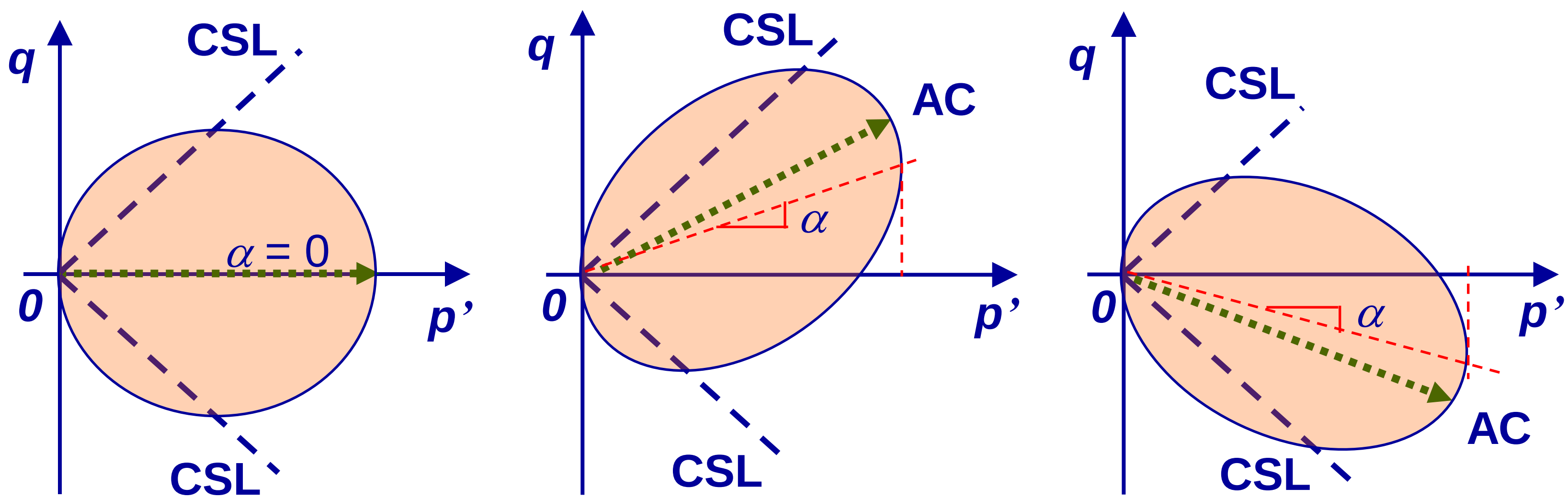
2.3 Rate-dependency – 3D & Remolded

➢ Stress history effect on reference surface

(1) Stress His. .: IC

(2) Stress His. : AC-C

(2) Stress His.: AC-E

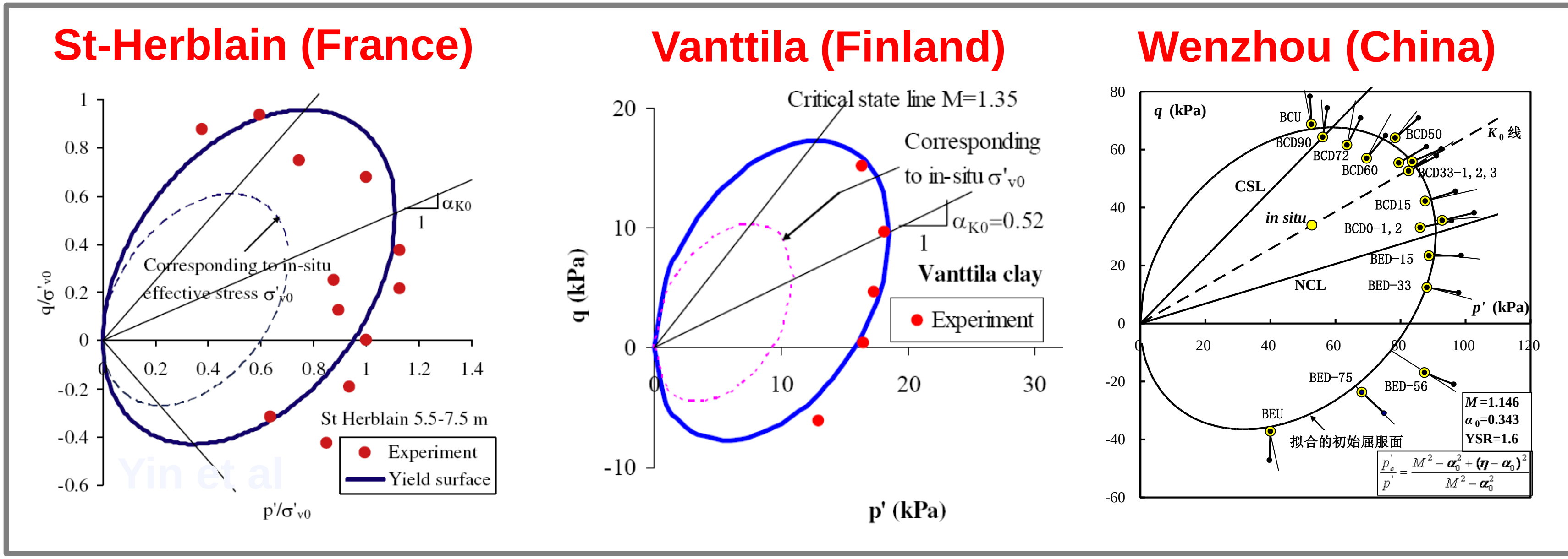


❑ **Mod.-1: Reference surface formulation**

$$f_r = \frac{q^2}{M^2} + p\left(p - p_c^r\right) \Rightarrow f_r = \frac{\left(q - p'\alpha\right)^2}{M^2 - \alpha^2} + p\left(p - p_c^r\right)$$

2.3 Rate-dependency – 3D & Remolded

Initial reference surfaces of some typical natural soft clays

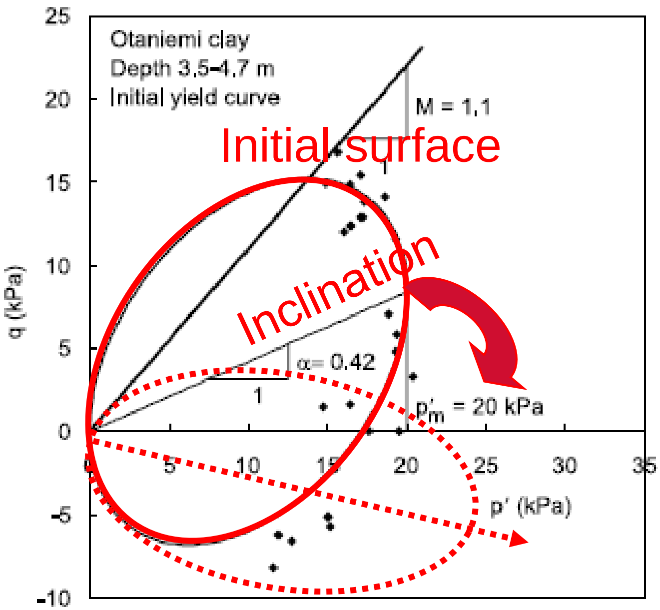


- ✓ Yin et al (2013), *Marine Georesources & Geotechnology*.
- ✓ Yin et al (2011), *ASCE Journal of Geotechnical and Geoenvironmental Engineering*.
- ✓ Yin et al (2010), *International Journal of Solids and Structures.*
- ✓ Karstunen & Yin (2010), *Geotechnique.*

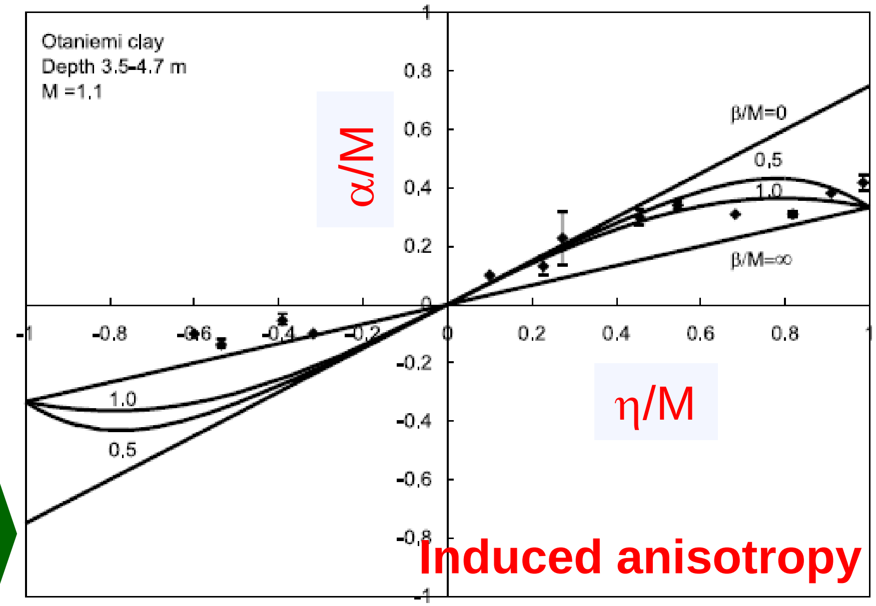
2.3 Rate-dependency – 3D & Remolded

❑ Mod.-2: Reference surface rotation

Initial Anisotropy



α Changing with stresses & strains



$$f_r = \frac{(q - p'\alpha)^2}{M^2 - \alpha^2} + p'\left(p' - p_c^r\right) = 0$$

+

$$d\alpha_d = \omega\left[\left(\frac{3\sigma_d}{4p'} - \alpha_d\right)\left\langle d\varepsilon_v^{vp}\right\rangle + \omega_d\left(\frac{\sigma_d}{3p'} - \alpha_d\right)d\varepsilon_d^{vp}\right]$$

$$\alpha_{K0},\ \omega,\ \omega_d = f(M)$$

Wheeler et al. (2003)

Avantage: ***No additional parameters!***

2.3 Rate-dependency – 3D & Remolded

❑ Parameters of ANICREEP model

$$e_0,\ \kappa,\ \lambda,\ \sigma_{p0},\ M_c$$ Parameters of MCC

$$C_{\alpha e} \text{ or } \beta \text{ or } R_\alpha$$ Viscosity

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An anisotropic elastic–viscoplastic model for soft clays

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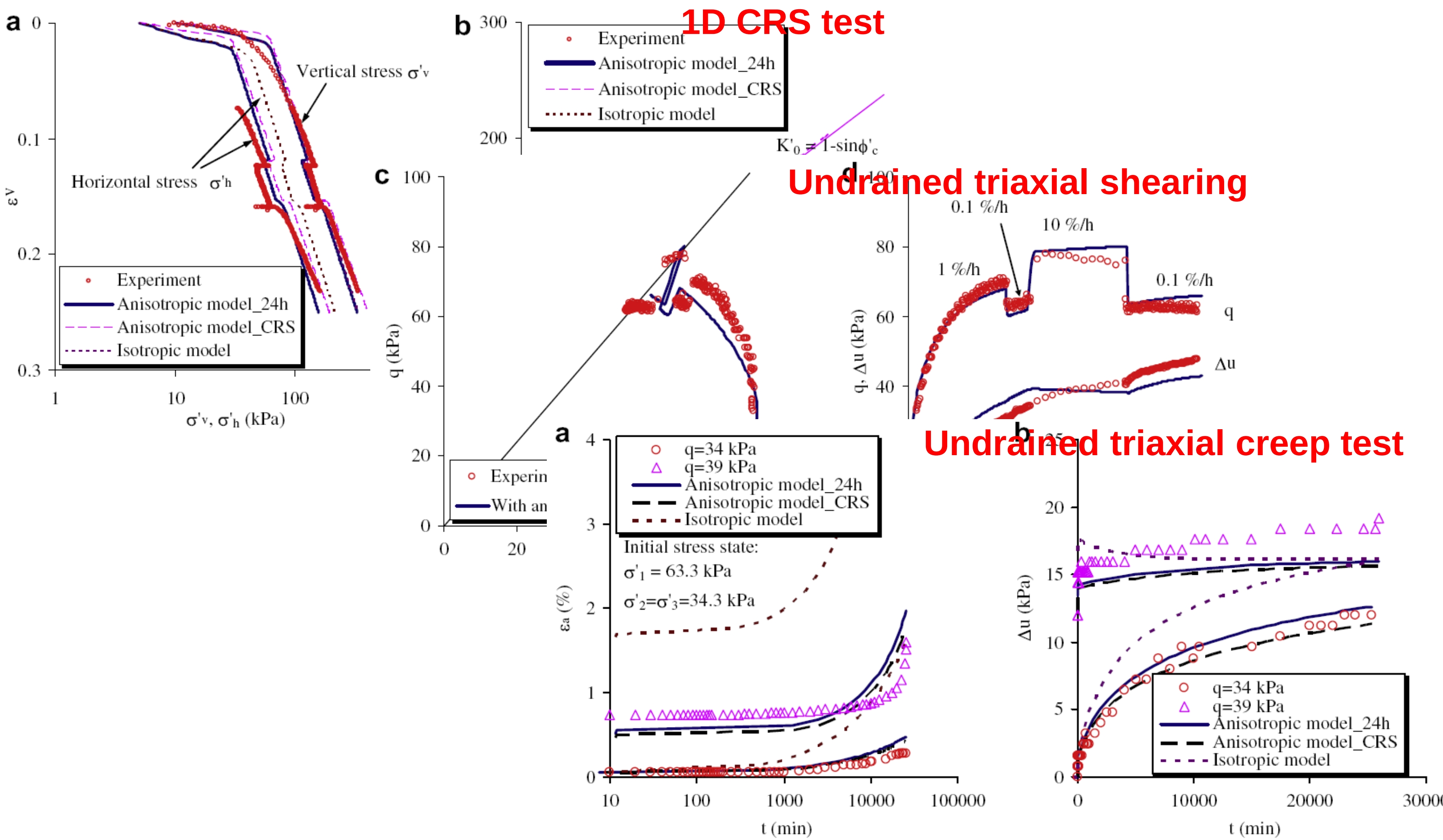
[b] Research Institute in Civil and Mechanical Engineering, GeM UMR CNRS 6183, Ecole Centrale de Nantes, BP 92101, 44321 Nantes Cédex 3, France
[c] Department of Civil Engineering, University of Strathclyde, John Anderson Building, 107 Rottenrow, Glasgow G4 0NG, UK

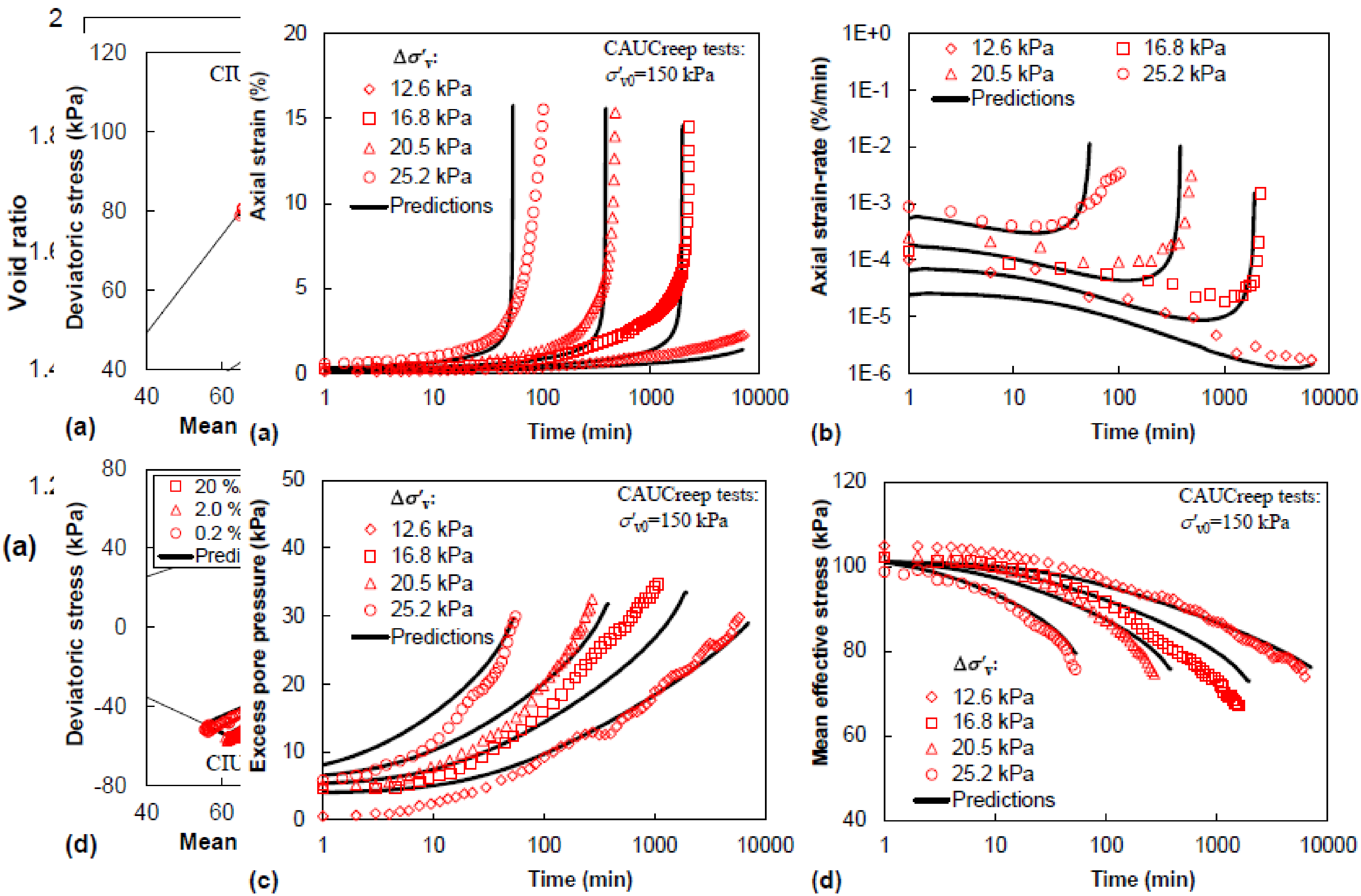
2.3 Rate-dependency – 3D & Remolded

❑ Test simulation (St-Herblain clay)



2.3 Rate-dependency – 3D & Remolded

❑ Test simulation (Wenzhou clay, China)



2.3 Rate-dependency – 3D & Remolded

❑ Remarks: Flow rule

for undrained test:

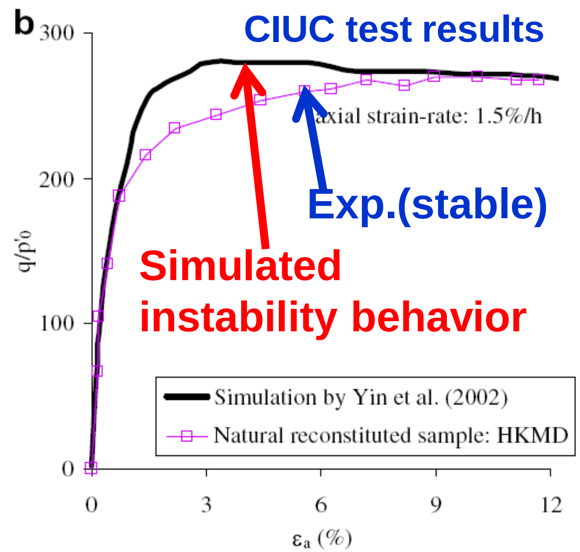
$\dot{\varepsilon}_v^{vp} > 0$

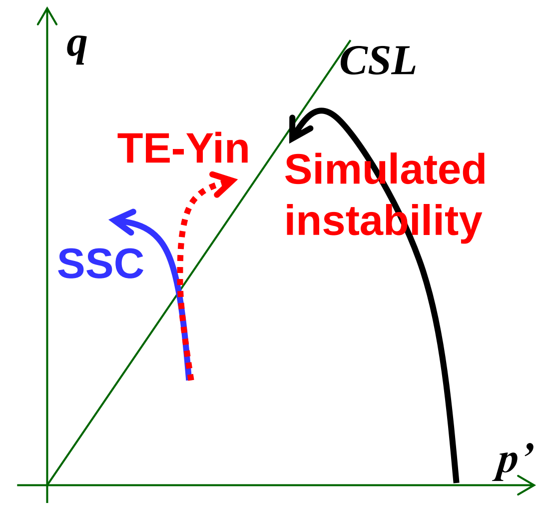
$\Rightarrow$ contraction ($\dot{p} < 0$)

$\Rightarrow \dot{q} < 0$ (along CSL)

$d^2W = \dot{p}\dot{\varepsilon}_v + \dot{q}\dot{\varepsilon}_d < 0$

$\Rightarrow$ *Instability*!





Vermeer (1999)

SSC model

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\mu\Phi(F)}{\frac{\partial f_d}{\partial p'}} \frac{\partial g}{\partial \sigma_{ij}}$$

$\Rightarrow$

$$\text{for any } \eta\text{: } \dot{\varepsilon}_v^{vp} = \mu\Phi(F)$$

Yin JH (2002)

TE model

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\mu\Phi(F)}{\left|\frac{\partial f_d}{\partial p'}\right|} \frac{\partial g}{\partial \sigma_{ij}}$$

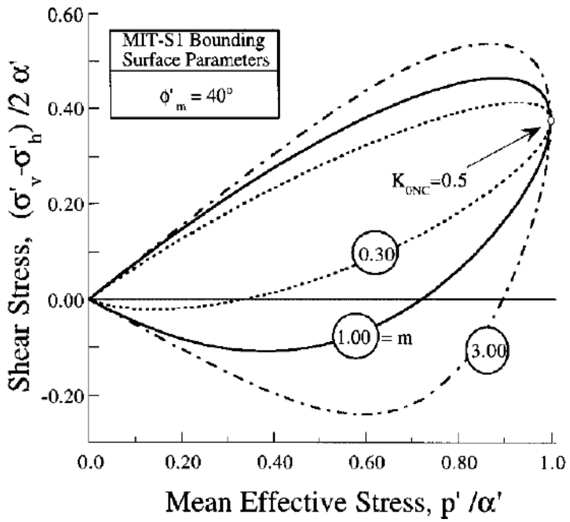
$$\dot{\varepsilon}_{ij}^{vp} = \frac{\langle \mu\Phi(F)\rangle}{\left[\frac{\partial f_d}{\partial p'}\right]_{K0}} \frac{\partial g}{\partial \sigma_{ij}}$$

((OK!))

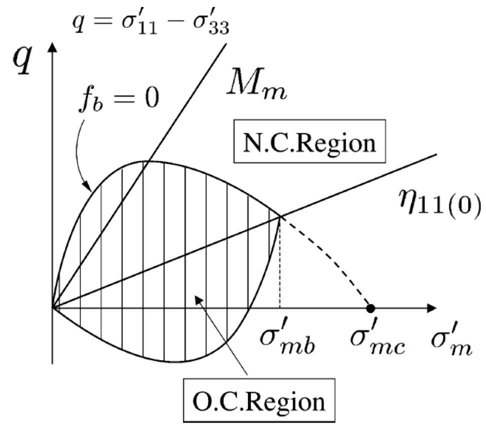
2.3 Rate-dependency – 3D & Remolded

❑ Remarks: Reference surface and rotation?

Pestana & Whittle (1999)



Oka et al (2002)



Refrence	Surface rotational law
Dafalias (1986)	$\dot{\alpha} = \langle L \rangle \frac{1+e_{in}}{\lambda-\kappa}\left\|\frac{\partial f}{\partial p}\right\| c \frac{p}{p_0}(\eta - x\alpha)$
Whittle (1993)	$(\dot{\alpha}\eta_{konc}) = \frac{b}{p_c}\left[\frac{k-\|\alpha\eta_{konc}-\xi\|}{k}\right](q - p'\alpha\eta_{konc})\dot{\varepsilon}_v^p$
Hueckel & Tutumluer (1994)	$(\dot{\alpha}\eta_{konc}) = b\left[\frac{q}{p}\exp(-b\varepsilon_s^p)\right]\dot{\varepsilon}_s^p + r\dot{\varepsilon}_r^p$
Newson & Davies(1996)	$\dot{\eta}_0 = \pm\left[1-(\eta_s/M)^2\right]\dot{p}\exp(\eta_s-\eta_{0s})\zeta$
Hashiguchi (1998)	$\dot{\alpha} = b\\|\eta-\alpha\\|\left(\frac{\eta-\alpha}{\\|\eta-\alpha\\|}m_b - \alpha\right)\dot{\varepsilon}_s^p$
Wheeler et al (2003)	$\dot{\alpha} = \mu\left[\omega_d\left(\frac{s_{ij}}{3p'}-\alpha\right)\|\dot{\varepsilon}_d^p\| + \left(\frac{3s_{ij}}{4p'}-\alpha\right)\langle\dot{\varepsilon}_v^p\rangle\right]$
Kobayashi et al (2003)	$\dot{\alpha} = \frac{J}{D}\left[\frac{(\beta_s+\|\beta_s\|\eta - 2\|\beta_s\|\alpha)}{2\\|\eta-\alpha\\|}\right]\sqrt{\frac{2}{3}}\\|D_s^p\\|$
Oka et al (2004)	$\dot{\alpha} = B_s + (B_0 - B_s)\exp(-B_t\varepsilon_d^p)(A\dot{\varepsilon}_v^p - \alpha\dot{\varepsilon}_d^p)$
Zhang et al (2007)	$\dot{\alpha} = \frac{J}{D}b_r(b_l M - \alpha)\sqrt{\frac{2}{3}}\\|D_s^p\\|\frac{\hat{\eta}}{\\|\hat{\eta}\\|}$
…	…

Outline

1. Background

2. Rate-dependency of clay

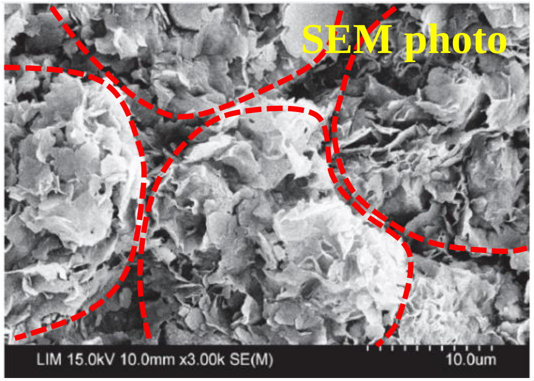
(1) 1D + remolded clay

(2) 1D + intact clay

(3) 3D + remolded clay

(4) 3D + intact clay

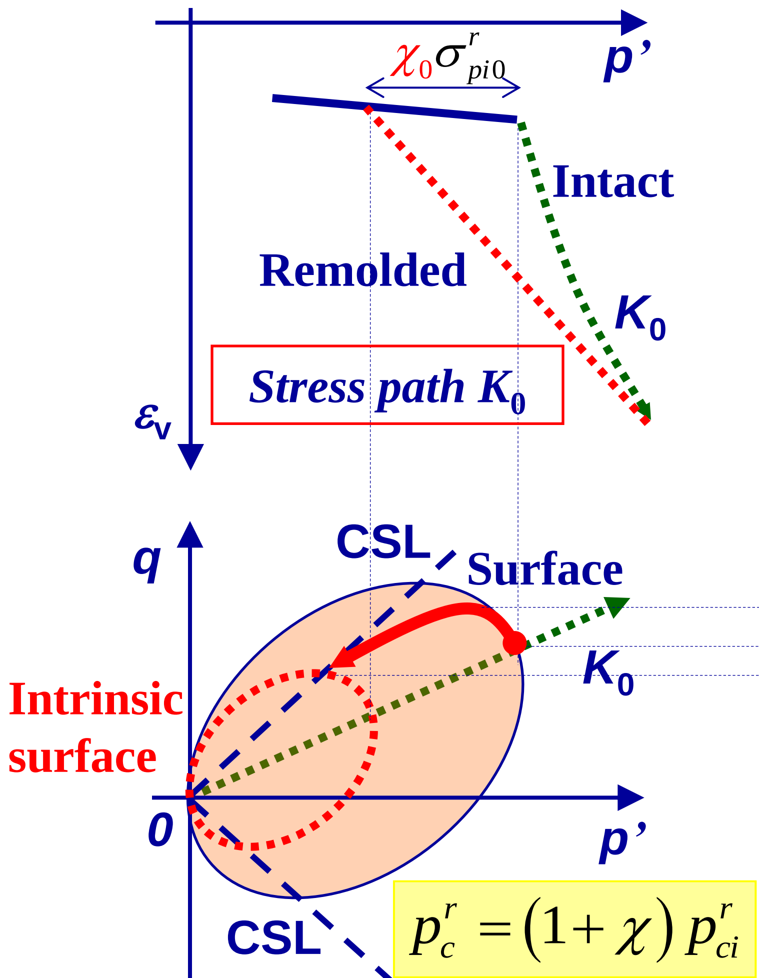
(5) Applications



3. Conclusions

2.4 Rate-dependency – 3D & Intact

❑ Extension of debonding rule from 1D to 3D

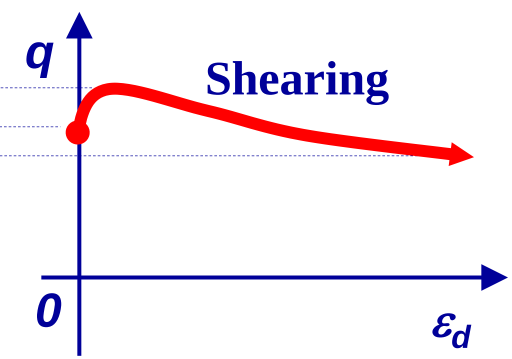


Debonding rule (1D to 3D)

$$\chi = \chi_0 e^{-\rho \varepsilon_v^{vp}}$$

$$\chi = \chi_0 e^{-\rho\left(\left|\varepsilon_v^{vp}\right| + \xi_d \varepsilon_d^{vp}\right)}$$

Gens & Nova (1993)



Time-dependent modeling of soft sensitive clay, *Yin et al (2011)*

2.4 Rate-dependency – 3D & Intact

❑ Parameters of ANICREEPS model

$$e_0,\ \kappa,\ \lambda,\ \sigma_{p0},\ M_c$$

Parameters of MCC

$$C_{\alpha e} \text{ or } \beta \text{ or } R_\alpha$$

Viscosity

$$\chi_0,\ \xi,\ \xi_d$$

Degradation
(remolded clay “=0”)

IC: $\xi = \dfrac{-(1+e_0)}{\Delta e^{vp*}} \ln\left[\dfrac{\sigma'_v}{\chi_0^* \exp\left(\dfrac{\Delta e^{vp*}}{\lambda_i - \kappa}\right) \sigma'^*_{pi0}} - \dfrac{1}{\chi_0^*} \right]$ and K_0: $\xi + \xi \cdot \xi_d \dfrac{2(\eta - \alpha)}{(M^2 - \eta^2)} = \dfrac{-(1+e_0)}{\Delta e^{vp}} \ln\left[\dfrac{\sigma'_v}{\chi_0 \exp\left(\dfrac{\Delta e^{vp}}{\lambda_i - \kappa}\right) \sigma'_{pi0}} - \dfrac{1}{\chi_0} \right]$

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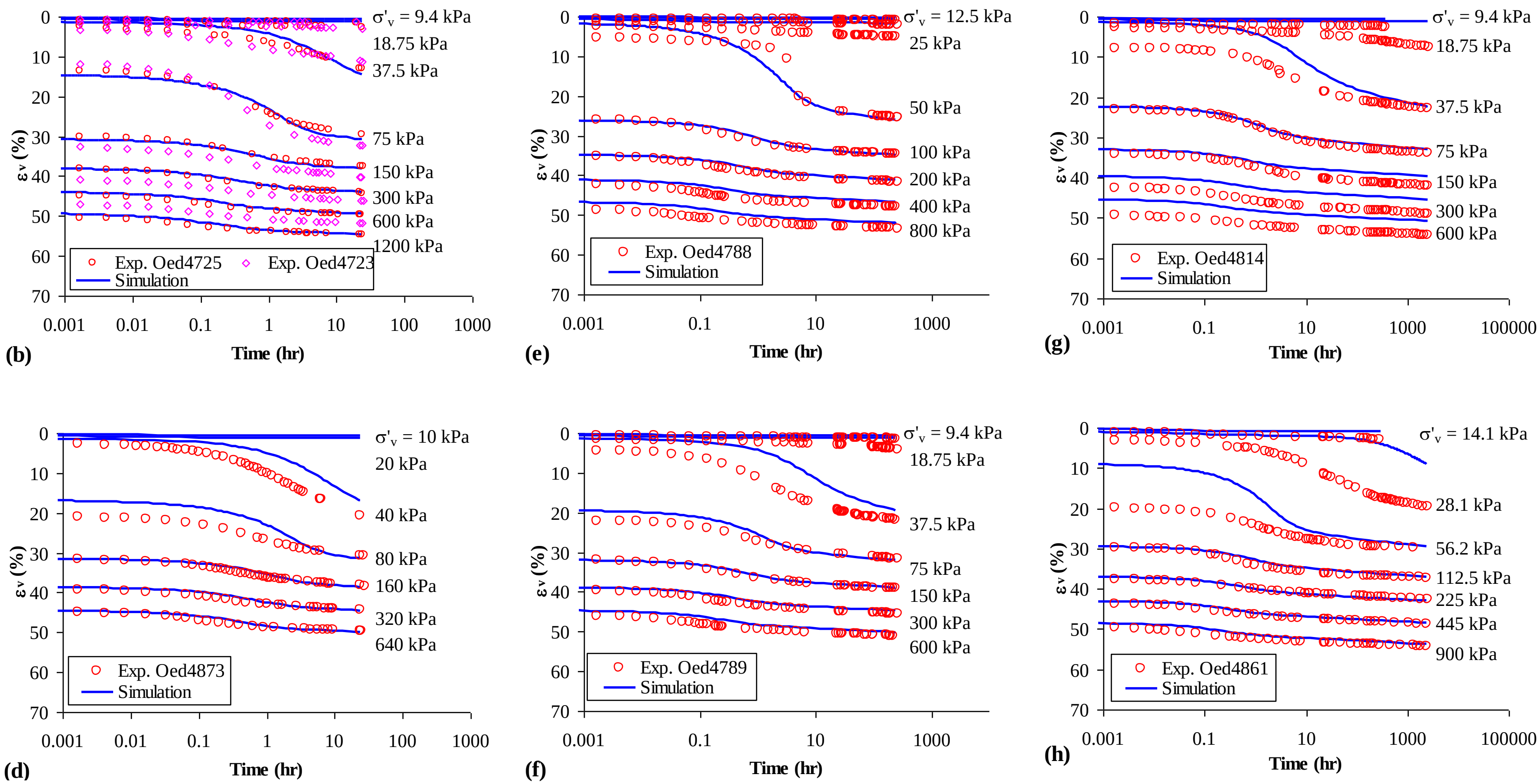
Modeling Time-Dependent Behavior of Soft Sensitive Clay

Zhen-Yu Yin[1]; Minna Karstunen[2]; Ching S. Chang, M.ASCE[3]; Mirva Koskinen[4]; and Matti Lojander[5]

2.4 Rate-dependency – 3D & Intact

❑ Test simulation (Vanttilla clay, Finland)

τ = 1 day（Conventional）　τ = 10 days　τ = 100 days

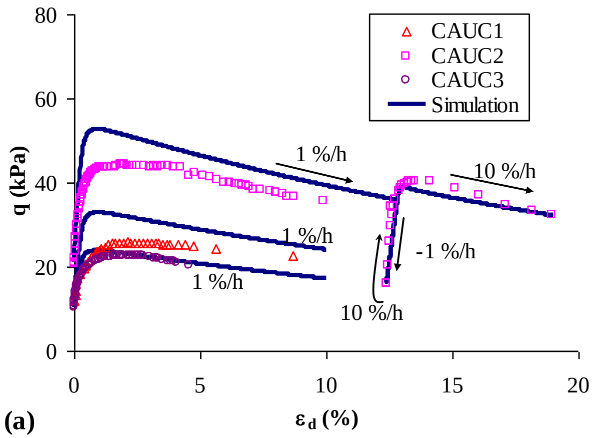


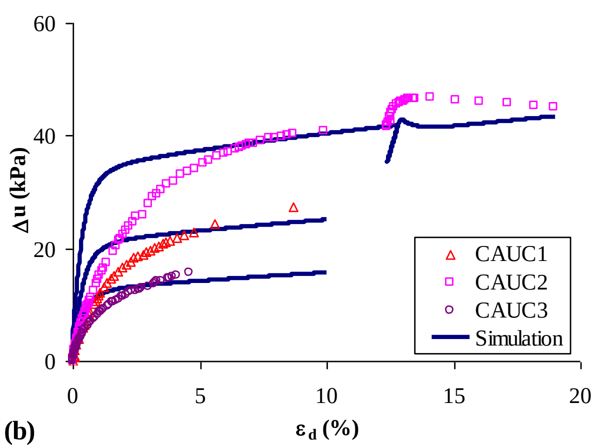
Each load increment lasts 1 d、10 d、100 d！

2.4 Rate-dependency – 3D & Intact

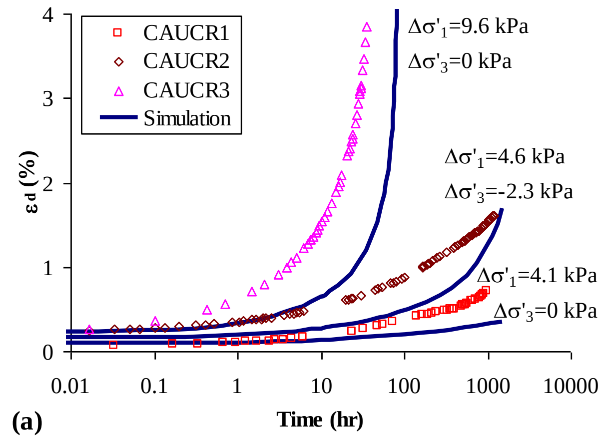
❑ Test simulation (Vanttilla clay, Finland)

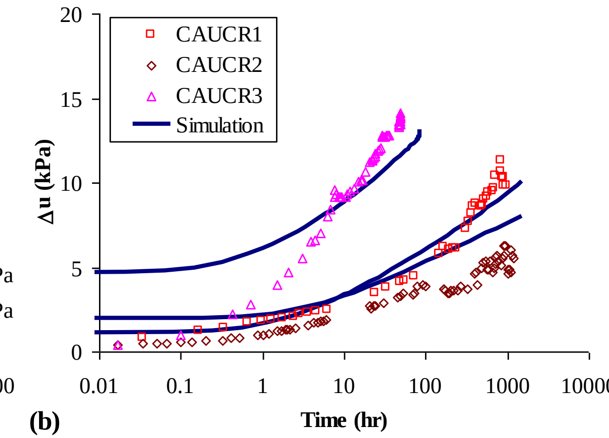
Undrained triaxial CRS tests

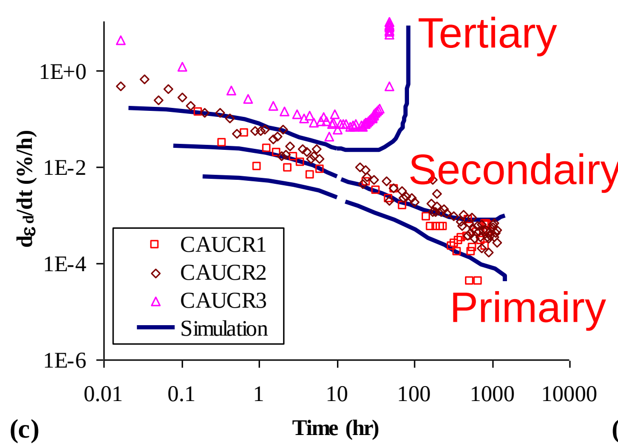


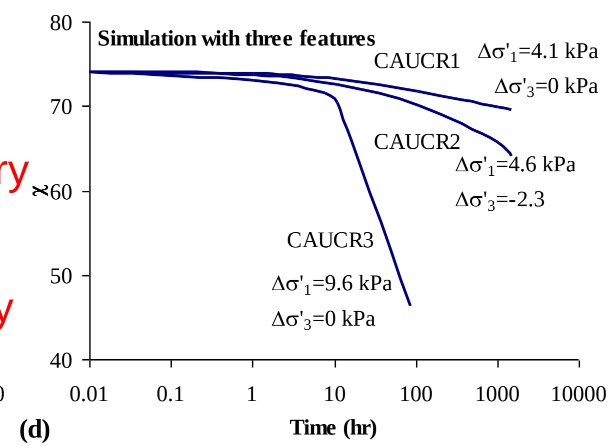


Undrained triaxial creep tests









Outline

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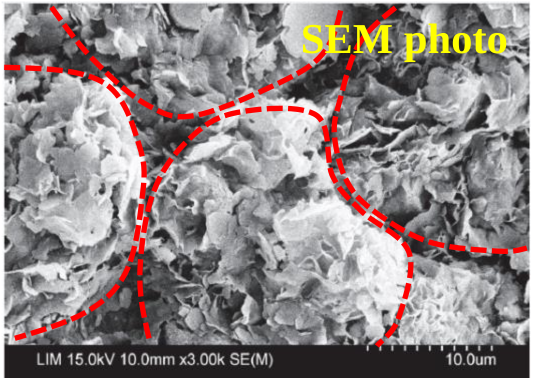


3. Conclusions

2.5 Rate-dependency – application

❑ Numerical solution of EVP model

$$\begin{cases}\Delta\sigma = D^e\cdot\Delta\varepsilon_e = D^e\cdot\left(\Delta\varepsilon-\Delta\varepsilon_{vp}\right)\\ \Delta\varepsilon_{vp}=\Delta t\cdot\left[\left(1-\theta\right)\dot{\varepsilon}_{vp}^{n}+\theta\cdot\dot{\varepsilon}_{vp}^{n+1}\right]\end{cases}$$

$$D^{-1}\sigma^{n+1}+\Delta t\cdot\theta\cdot\dot{\varepsilon}_{vp}^{n+1}=\Delta\varepsilon-\Delta t\cdot\left(1-\theta\right)\dot{\varepsilon}_{vp}^{n}+D^{-1}\sigma^{n}$$

$$\begin{cases}\sigma^{n+1}=\sigma^{i}+d\sigma^{i}\\ \dot{\varepsilon}_{vp}^{n+1}=\dot{\varepsilon}_{vp}^{i}+\dfrac{\partial\dot{\varepsilon}_{vp}^{i}}{\partial\sigma}d\sigma^{i}\end{cases}$$

$$D^{-1}\left(\sigma^{i}+d\sigma^{i}\right)+\Delta t\cdot\theta\cdot\left(\dot{\varepsilon}_{vp}^{i}+\frac{\partial\dot{\varepsilon}_{vp}^{i}}{\partial\sigma}d\sigma^{i}\right)=\Delta\varepsilon-\Delta t\cdot\left(1-\theta\right)\dot{\varepsilon}_{vp}^{n}+D^{-1}\sigma^{n}$$

$$\Rightarrow d\sigma^{i}=\left[D^{-1}+\Delta t\cdot\theta\cdot\frac{\partial\dot{\varepsilon}_{vp}^{i}}{\partial\sigma}\right]^{-1}\cdot\left[\left(\Delta\varepsilon-\Delta t\cdot\left(1-\theta\right)\dot{\varepsilon}_{vp}^{n}+D^{-1}\sigma^{n}\right)-\left(D^{-1}\sigma^{i}+\Delta t\cdot\theta\cdot\dot{\varepsilon}_{vp}^{i}\right)\right]$$

$$\Rightarrow d\sigma^{i}=\left[\frac{\partial G}{\partial\sigma}\right]^{-1}\cdot\left[Q^{n}-G^{i}\right]$$

Time = t_n $\sigma^n, \varepsilon^n, p_{mi}^n, \chi^n, p_m^n, \Delta t, \Delta\varepsilon, [D]^n$

Newton-Raphson return mapping loop

$$\dot{\varepsilon}_{vp}^{i}=\gamma\left\langle\phi\left(F\right)\right\rangle\frac{\partial f_d}{\partial\sigma}$$

$$\frac{\partial\dot{\varepsilon}_{vp}^{i}}{\partial\sigma}=\gamma\cdot\frac{\partial\left(\phi\left(F\right)\right)}{\partial\sigma_{kl}}\frac{\partial f_d}{\partial\sigma_{ij}}+\gamma\cdot\phi\left(F\right)\cdot\frac{\partial\left(\dfrac{\partial f_d}{\partial\sigma_{ij}}\right)}{\partial\sigma_{kl}}$$

$$d\sigma^{i}=\left[\frac{\partial G}{\partial\sigma}\right]^{-1}\cdot\left[Q^{n}-G^{i}\right]$$

Update states

$$\sigma^{i+1}=\sigma^{i}+d\sigma^{i}$$

$$\varepsilon_{vp}^{i+1}=\varepsilon^{n+1}-D^{-1}\sigma^{i+1}$$

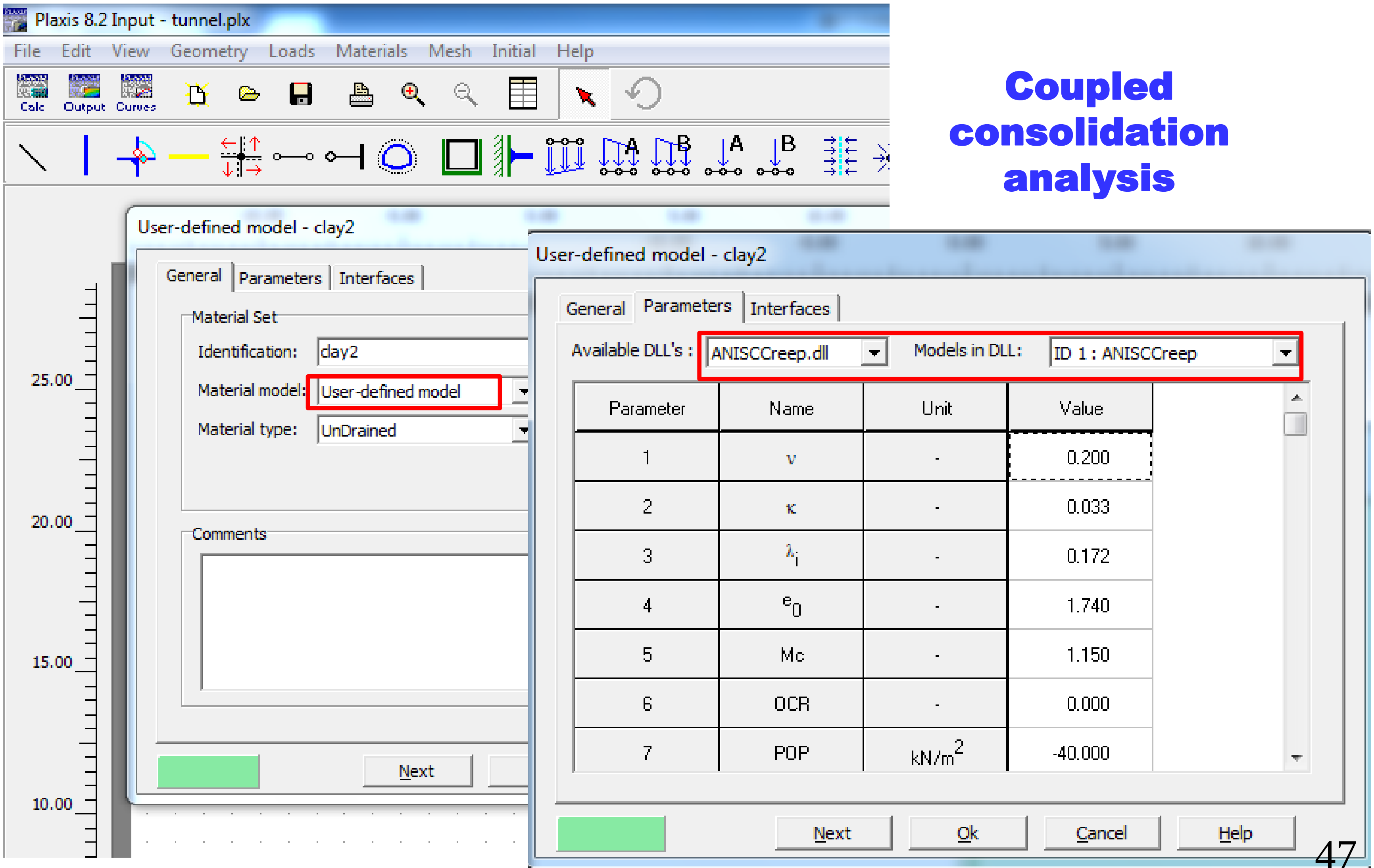
p_{mi}^{i+1}, χ^{i+1}, $p_m^{s,i+1}$

$|d\sigma^{i}| \le Tolerance$

Time = t_{n+1} $\sigma^{n+1}, \varepsilon^{n+1}, p_{mi}^{n+1}, \chi^{n+1}, p_m^{n+1}, [D]^{n+1}$

2.5 Rate-dependency – application

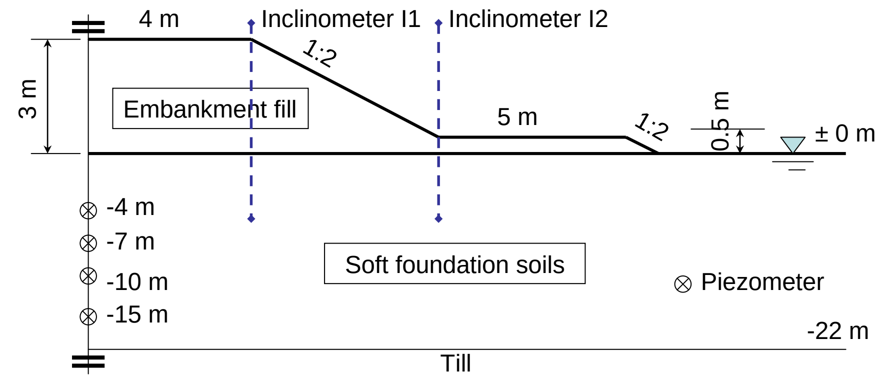
❑ Implementation of model into PLAXIS (user defined model)



Coupled consolidation analysis

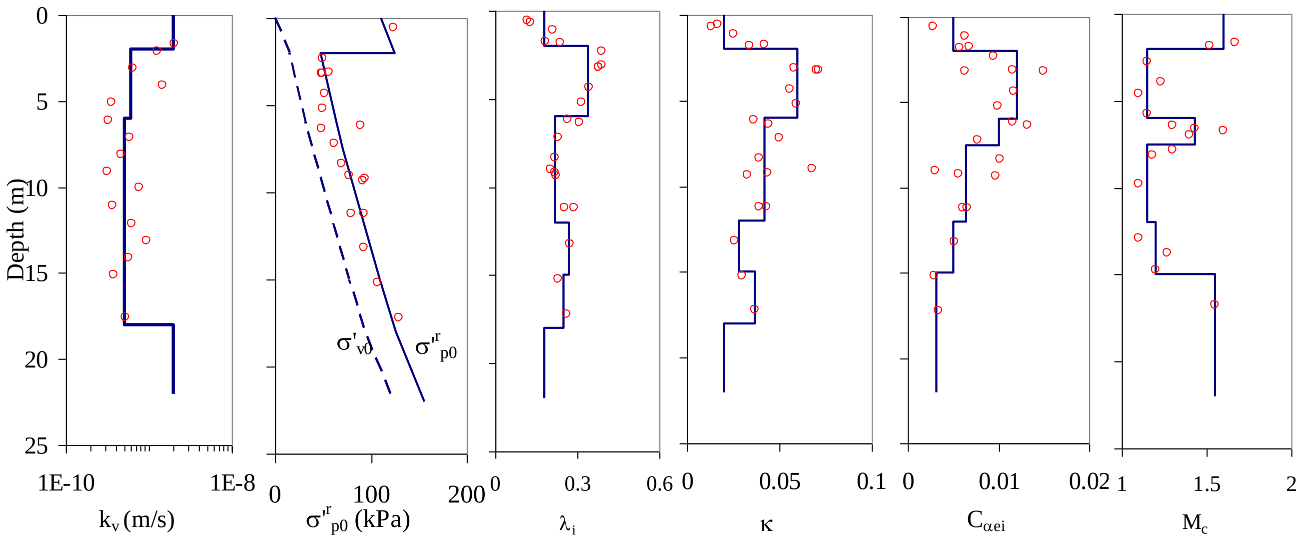
2.5 Rate-dependency – application

❑ Haarajoki embankment, Finland



Haarajoki test embankment

All parameters determined from conventional oedometer and triaxial tests:



2.5 Rate-dependency – application

❑ Finite element model

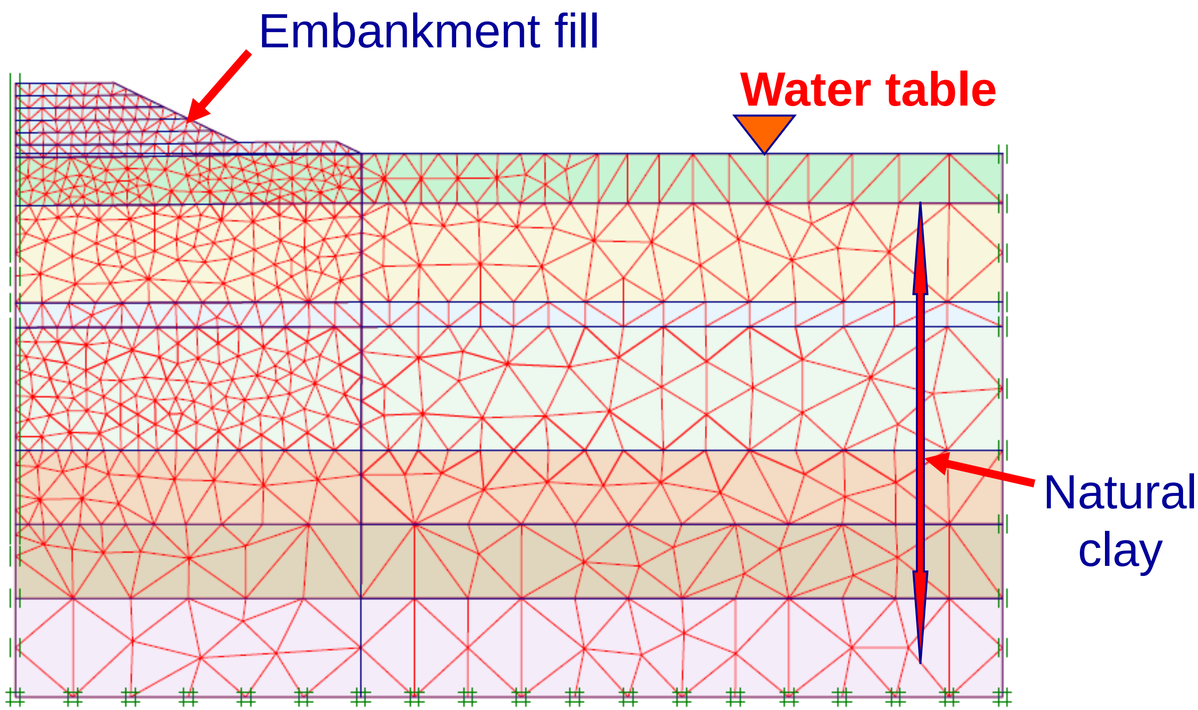
FE model

(PLAXIS v.8)

1257 elements

6-noded triangle

2626 points

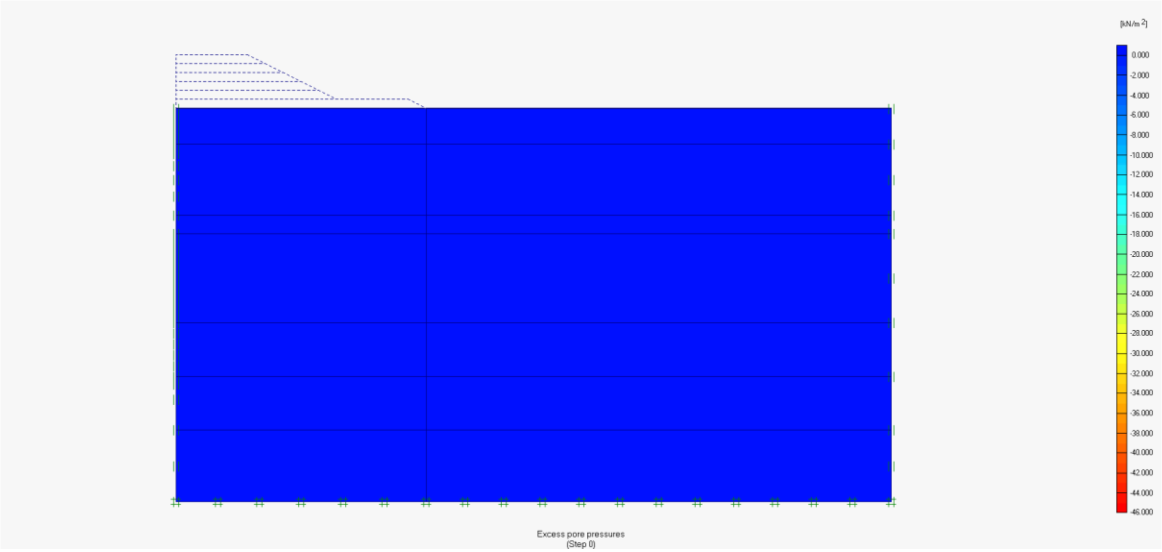


Embankment fill (Mohr-Coulomb)

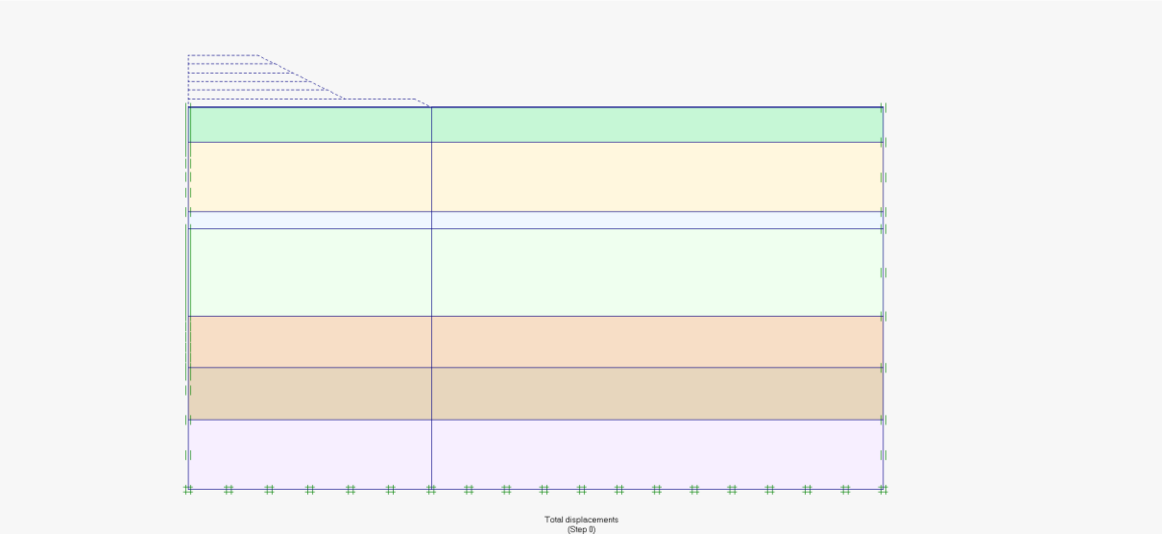
Thickness (m)	E (kN/m^2)	υ'	ϕ'	ψ'	c'(kN/m^2)	γ (kN/m^3)
0-3	40 000	0.3	38°	0°	1	21

2.5 Rate-dependency – application

Excess pore pressure

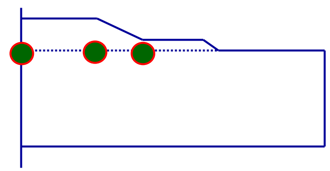


Total displacement

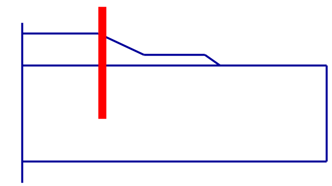


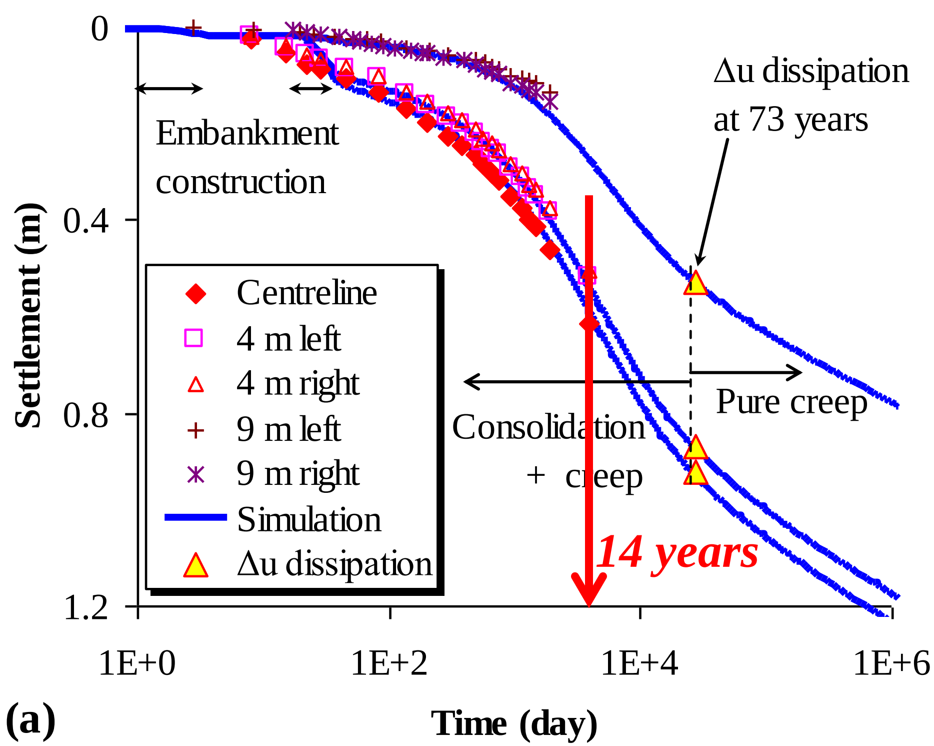
2.5 Rate-dependency – application

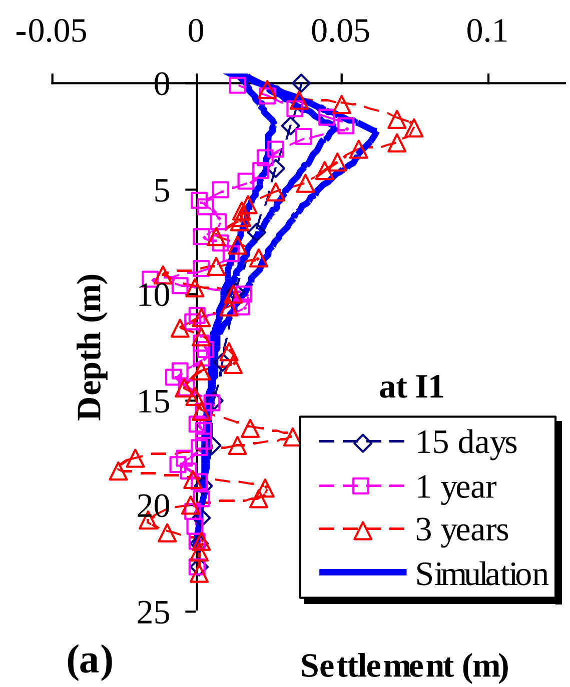
Settlement



Hor. Disp.





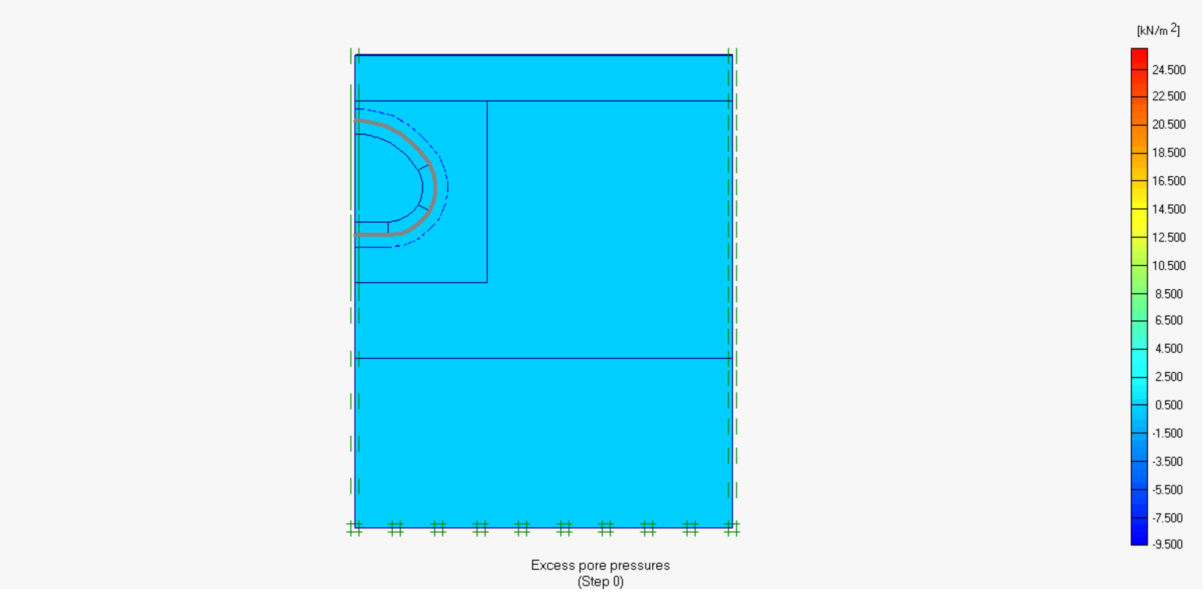


3D-EVP model coupling with consolidation for application. ***Yin et al. (2013)***

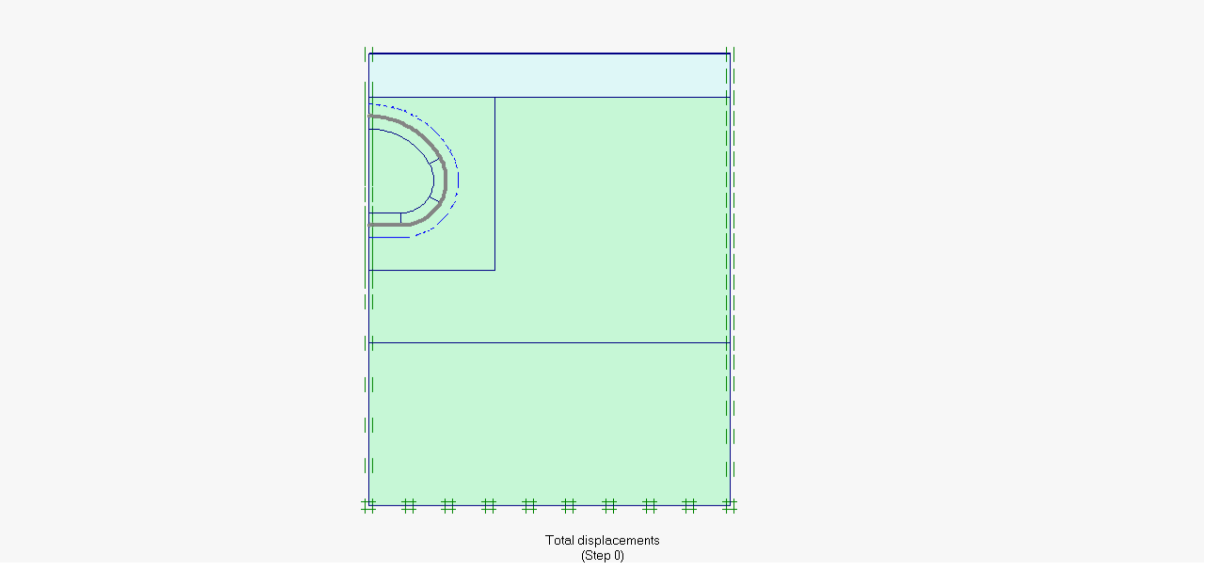
2.5 Rate-dependency – application

Over-excavation effect on long-term behavior of tunnel

Excess pore pressure



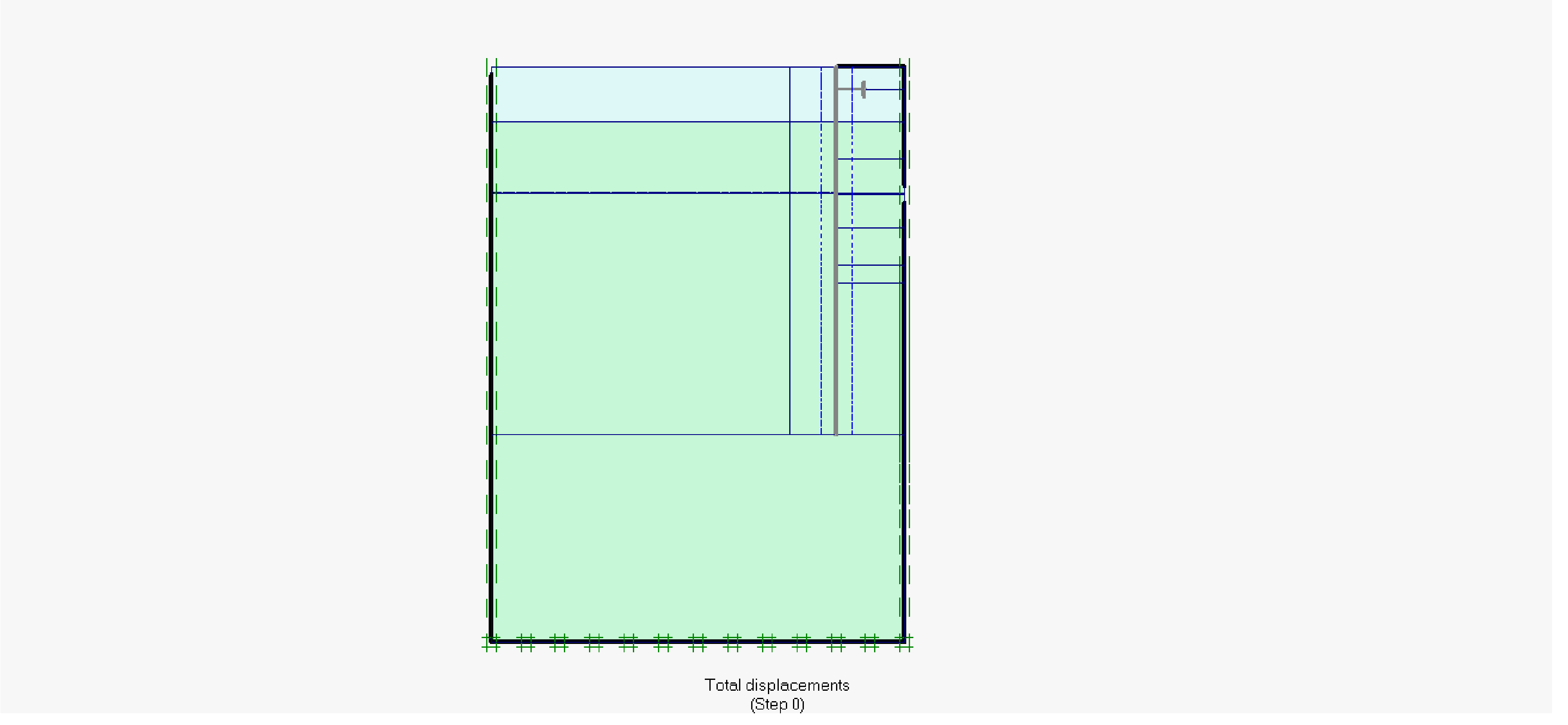
Total displacement



2.5 Rate-dependency – application

Construction time effect on excavation

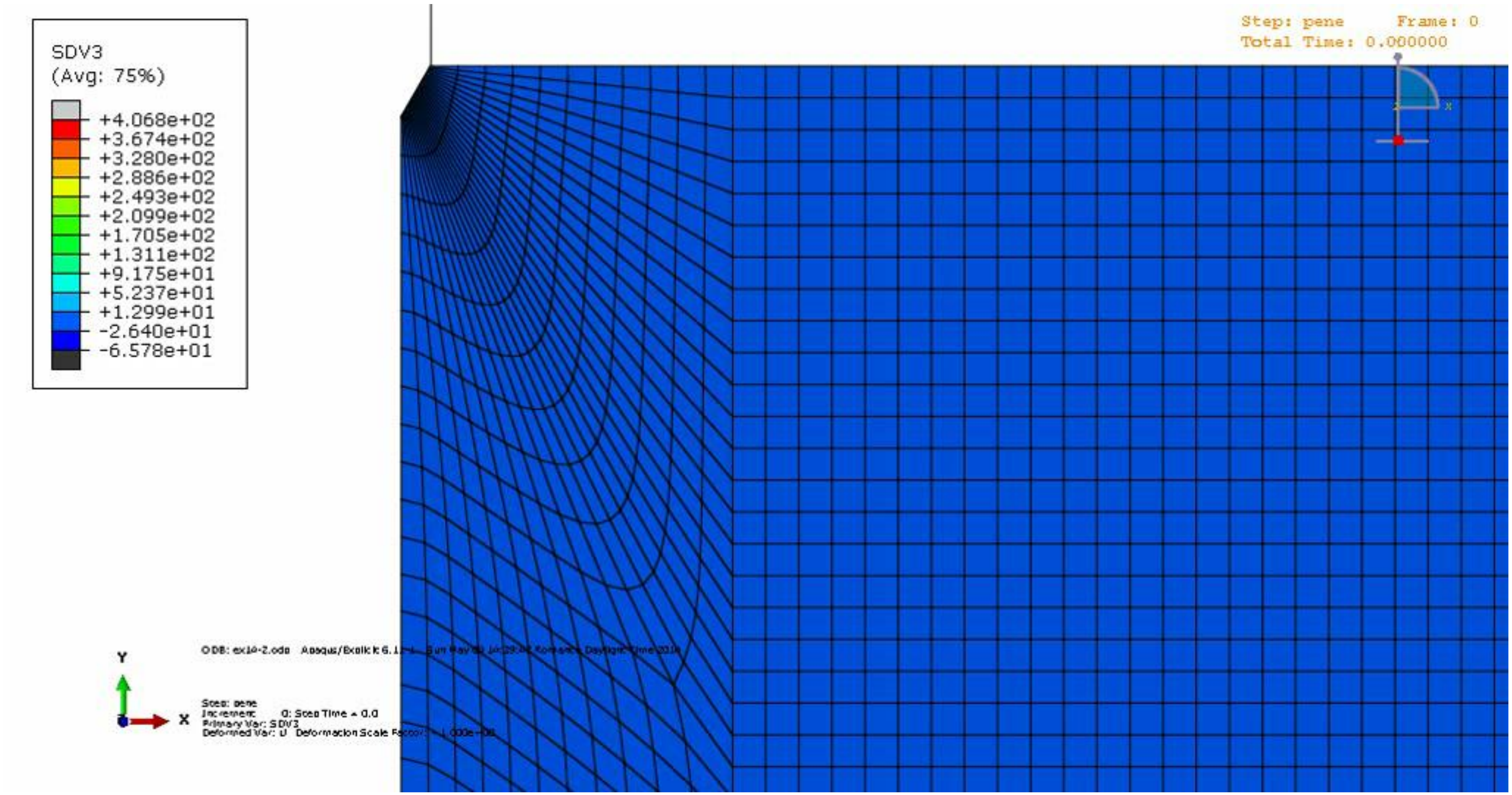
Total displacement



2.5 Rate-dependency – application

Pile construction (installation rate effect, by Abaqus)

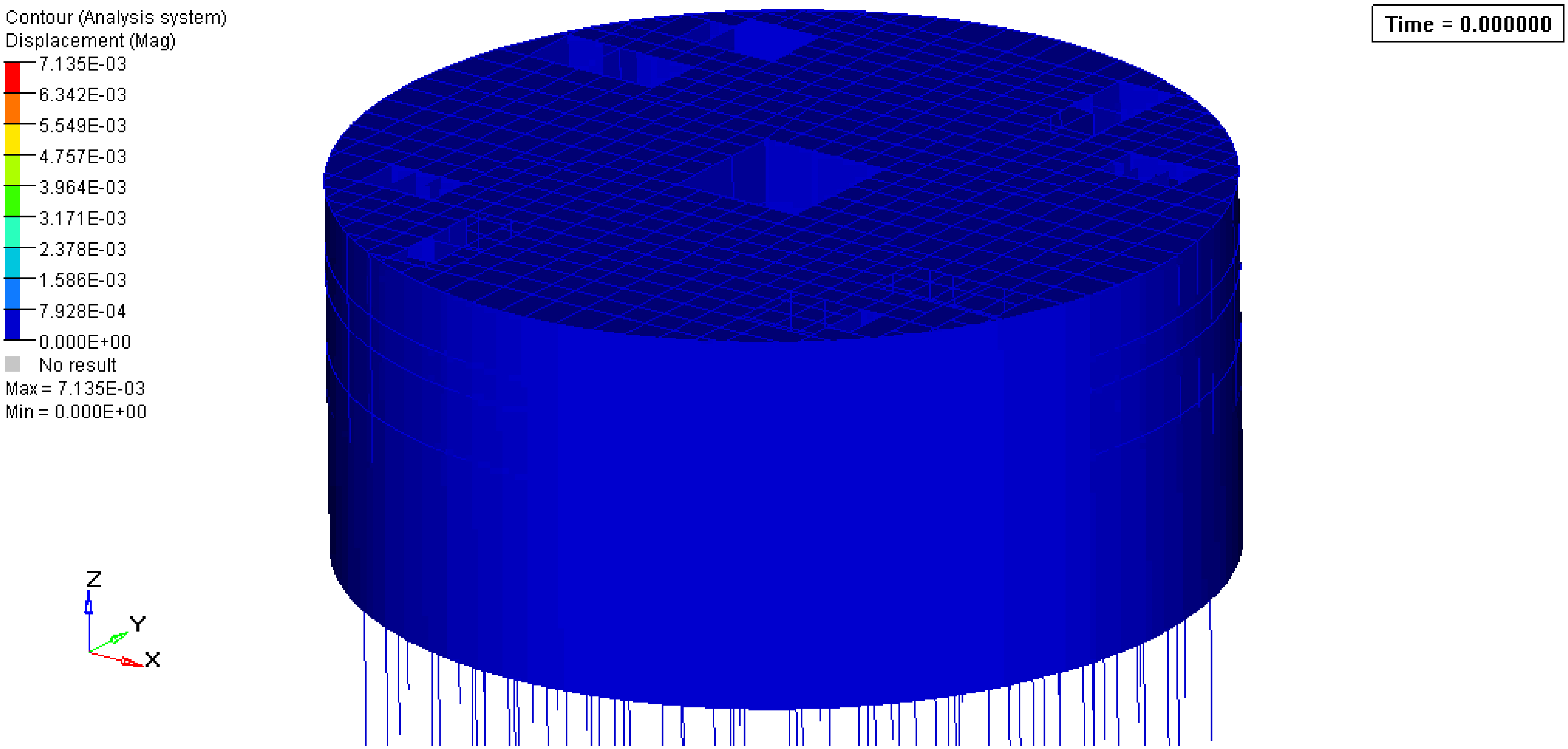
Excess pore pressure



2.5 Rate-dependency – application

Effect of explosion on clay excavation (terrorist attack, by LS-Dyna)

Total displacement



3 Conclusions

(1) Determination of 1D strain rate-dependency formulation;

(2) From 1D to 3D, attention to flow rule, reference surface, anisotropy, destruction;

(3) Applications on geotechnical structures.

Main collaborators

- ✓ Pierre-Yves HICHER (GeM-ECN)
- ✓ Minna KARSTUNEN (UT-Chalmers, Suède)
- ✓ Ching S. CHANG (Umass, USA)
- ✓ Jian-Hua YIN (HK-PolyTechU)




Related publications

Yin Z-Y*, Xu Q, Yu C. Elastic viscoplastic modeling for natural soft clays considering nonlinear creep. *ASCE International Journal of Geomechanics*, doi: 10.1061/(ASCE)GM.1943-5622.0000284.

Wang L-Z, Yin Z-Y*. Stress-dilatancy of natural soft clay under undrained creep condition. *ASCE International Journal of Geomechanics*, doi: 10.1061/(ASCE)GM.1943-5622.0000271.

Yin Z-Y*, Yin JH, Huang HW. Rate-dependent and long-term yield stress and strength of soft Wenzhou marine clay: experiments and modeling. *Marine Georesources & Geotechnology*, DOI:10.1080/1064119X.2013.797060.

Yin Z-Y*, Zhu QY, Yin JH, Ni Q. Stress relaxation coefficient and formulation for soft soils. *Géotechnique Letters*, 2014, 4(1): 45-51.

Yin Z-Y*, Karstunen M, Chang CS, Koskinen M, Lojander M. Modeling time-dependent behavior of soft sensitive clay. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 2011, 137(11): 1103-1113.

Yin Z-Y*, Karstunen M, Hicher PY. Evaluation of the influence of elasto-viscoplastic scaling functions on modelling time-dependent behaviour of natural clays. *Soils and Foundations*, 2010, 50(2): 203-214.

Yin Z-Y*, Chang CS, Karstunen M, Hicher PY. An anisotropic elastic viscoplastic model for soft clays. *International Journal of Solids and Structures*, 2010, 47(5): 665-677.

Karstunen M, Yin Z-Y*. Modelling time-dependent behaviour of Murro test embankment. *Géotechnique*, 2010, 60(10): 735-749.

Yin Z-Y*, Hicher PY. Identifying parameters controlling soil delayed behaviour from laboratory and in situ pressuremeter testing. *International Journal for Numerical and Analytical Methods in Geomechanics*, 2008, 32(12): 1515-1535.

Thanks a lot for your attention

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Use of advanced creep models and some pitfalls in creep modelling

G. Grimstad

Fundamental aspects of soft clay behavior

- Creep
- Anisotropy
  - Strength
  - Stiffness
  - Yield stress
- Structure and destructuration
- Unloading/reloading cycles – small strain
- Degradation during cyclic loading
- ALL ARE LINKED!

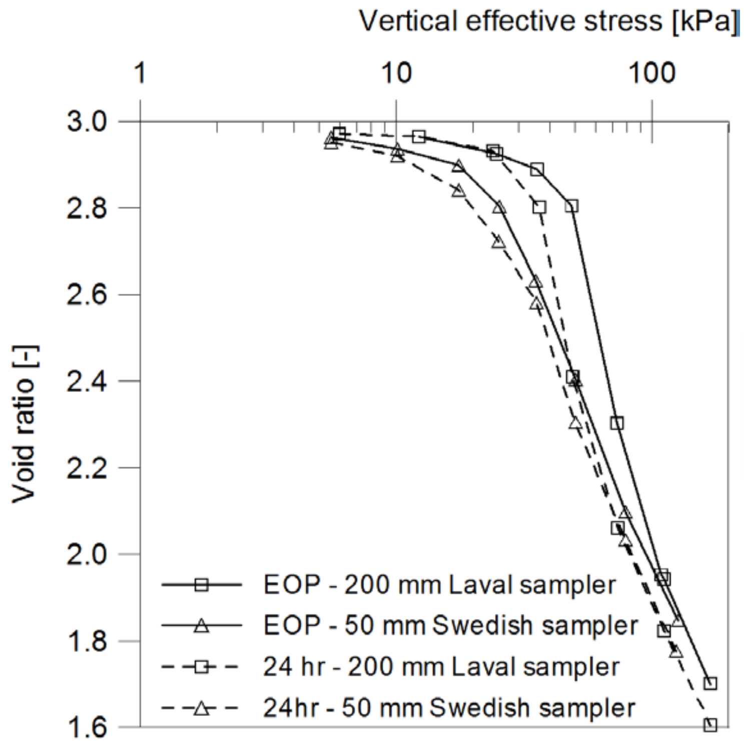
“1D” Creep – (24h) incremental oedometer test

- Advantages:
  - Gives *first estimate of* creep/consolidation parameters and the “vertical” pre-consolidation stress directly
- Disadvantages
  - Time consuming compared to CRS tests
  - Only average settlement parameters for large stress increments
  - Ideally back calculation with mathematical model is needed (FEA)

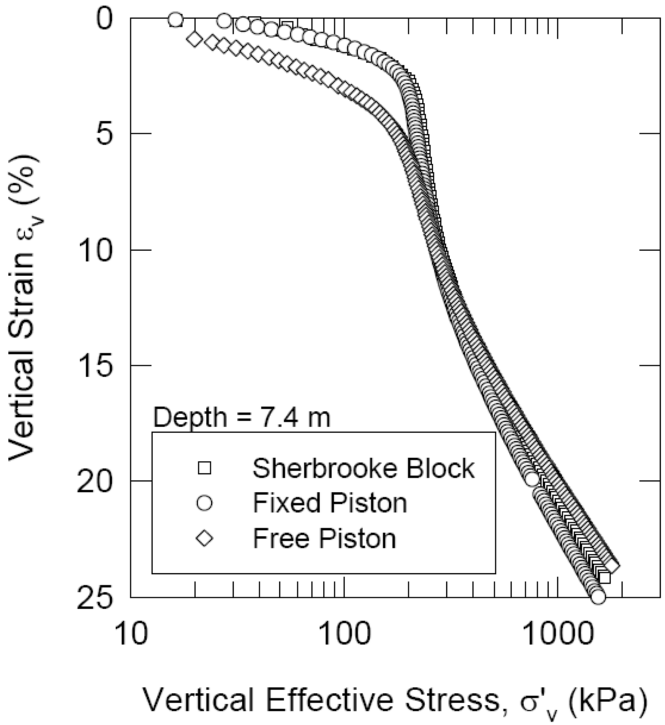
Current Norwegian engineering practice

- Using low OCR (if material has not been subjected to preloading an OCR of 1.0? is often used)
- Ignoring creep
- Adding creep after consolidation?(Hyp. A!)
- *Advanced:* Janbu´s time resistance concept
- **What about the selected pre-consolidation stress? IMPORTANT!!!**
- **What about sample quality?**

Sample quality



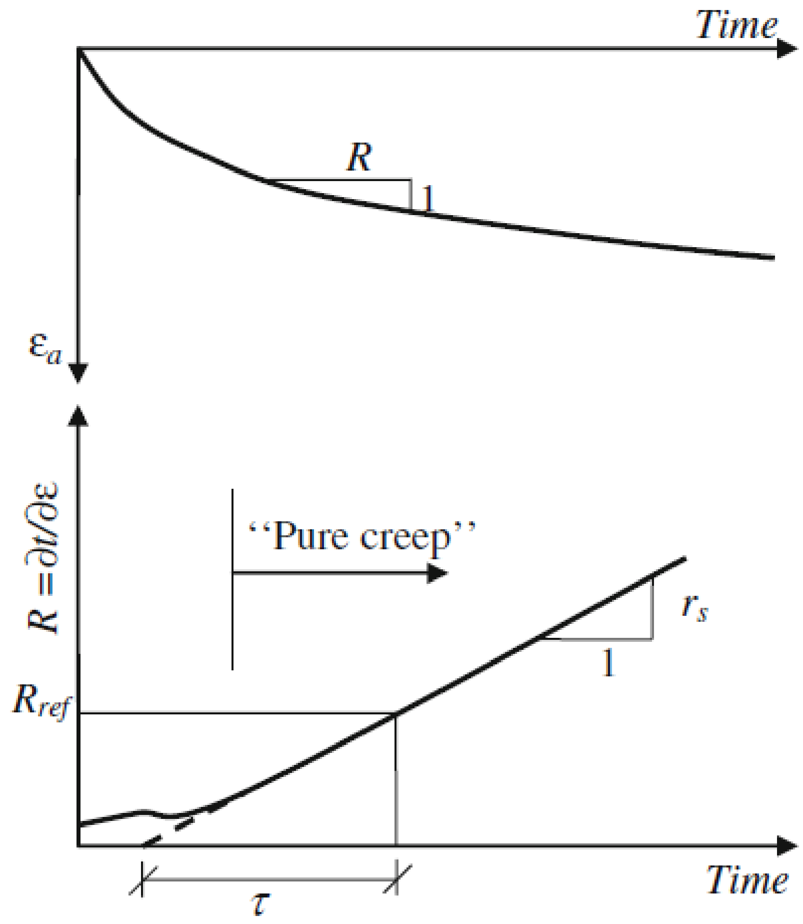
Compression curves for Väsby clay at a depth of 4.0 – 4.3 m (after Leroueil and Kabbaj, 1987)



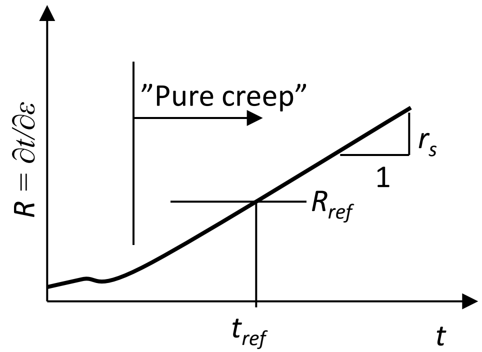
DeGroot et. al. (2005)

Janbu´s time resistance concept

- Increment in time divided by the increment in strain (Cause/Effect).

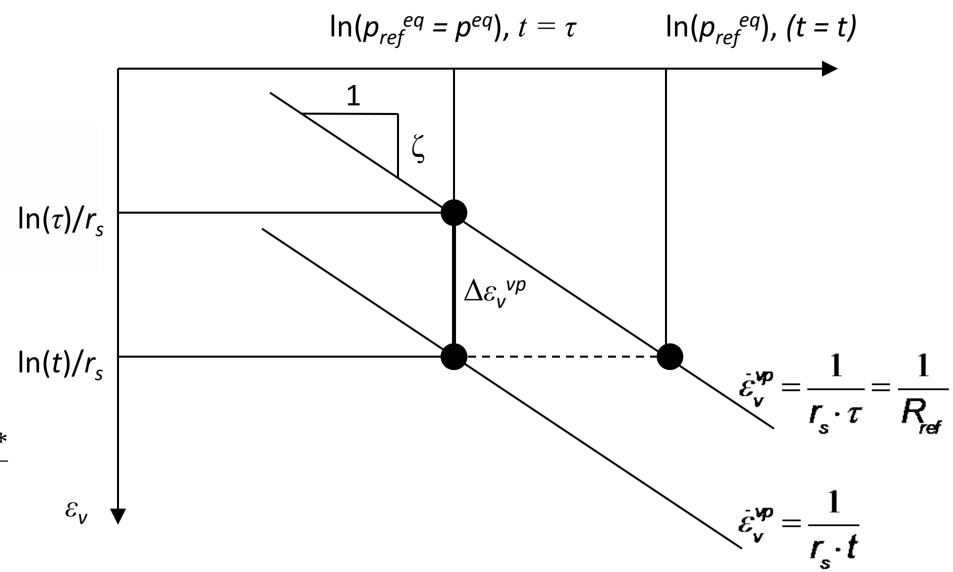


1D equation



$r_s \cdot t_{ref} \approx R_{ref}$ when $t_{ref} \gg t_p$

$$\frac{dt}{d\varepsilon_v^{vp}}(t) = r_s \cdot (t-\tau) + R_{ref} = r_s \cdot t$$



$$\frac{d\varepsilon_v^{vp}}{dt} = \frac{1}{r_s \cdot t} \Rightarrow \Delta\varepsilon_v^{vp} = \frac{1}{r_s}\ln\frac{t}{\tau}$$

$$\frac{dp_{ref}^{eq}}{d\varepsilon_v^{vp}} = \frac{p_{ref}^{eq}}{\zeta} \Rightarrow \Delta\varepsilon_v^{vp} = \zeta \cdot \ln\left(\frac{p_{ref}^{eq}}{p^{eq}}\right)$$

$$\boxed{\frac{d\varepsilon_v^{vp}}{dt} = \frac{1}{R_{ref}} \cdot \left(\frac{p^{eq}}{p_{ref}^{eq}}\right)^{r_s \cdot \zeta}} = \frac{\mu^*}{\tau} \cdot \left(\frac{p^{eq}}{p_{ref}^{eq}}\right)^{\frac{\lambda^* - \kappa^*}{\mu^*}}$$

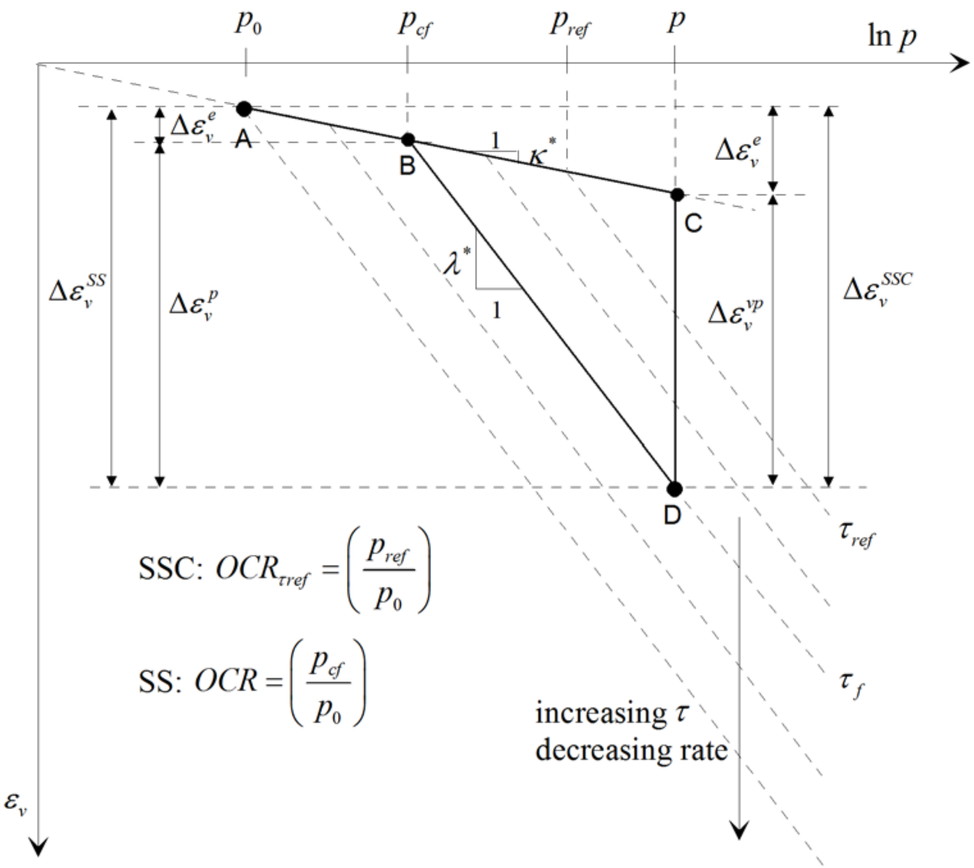
p_{ref}^{eq} is important for creep rate! Initial value is the pre-consolidation stress!

“Alternative approaches” to Janbu for 1D

- Yin and Graham (equivalent time approach) – Adopted from Bjerrum
- Leroueil
- Den Haan (ABC model)
- etc.

ALL ARE THE SAME?

Ignoring creep?



A case of SSC and SS model giving the same final settlement.

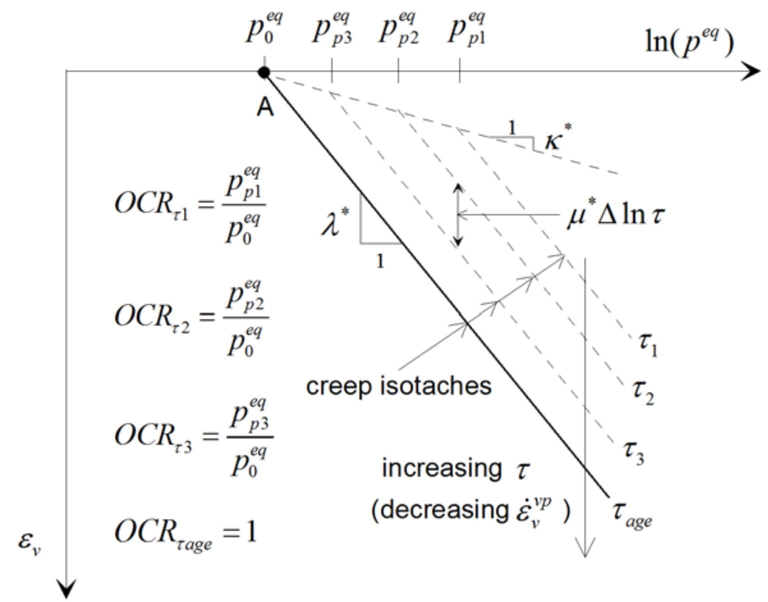
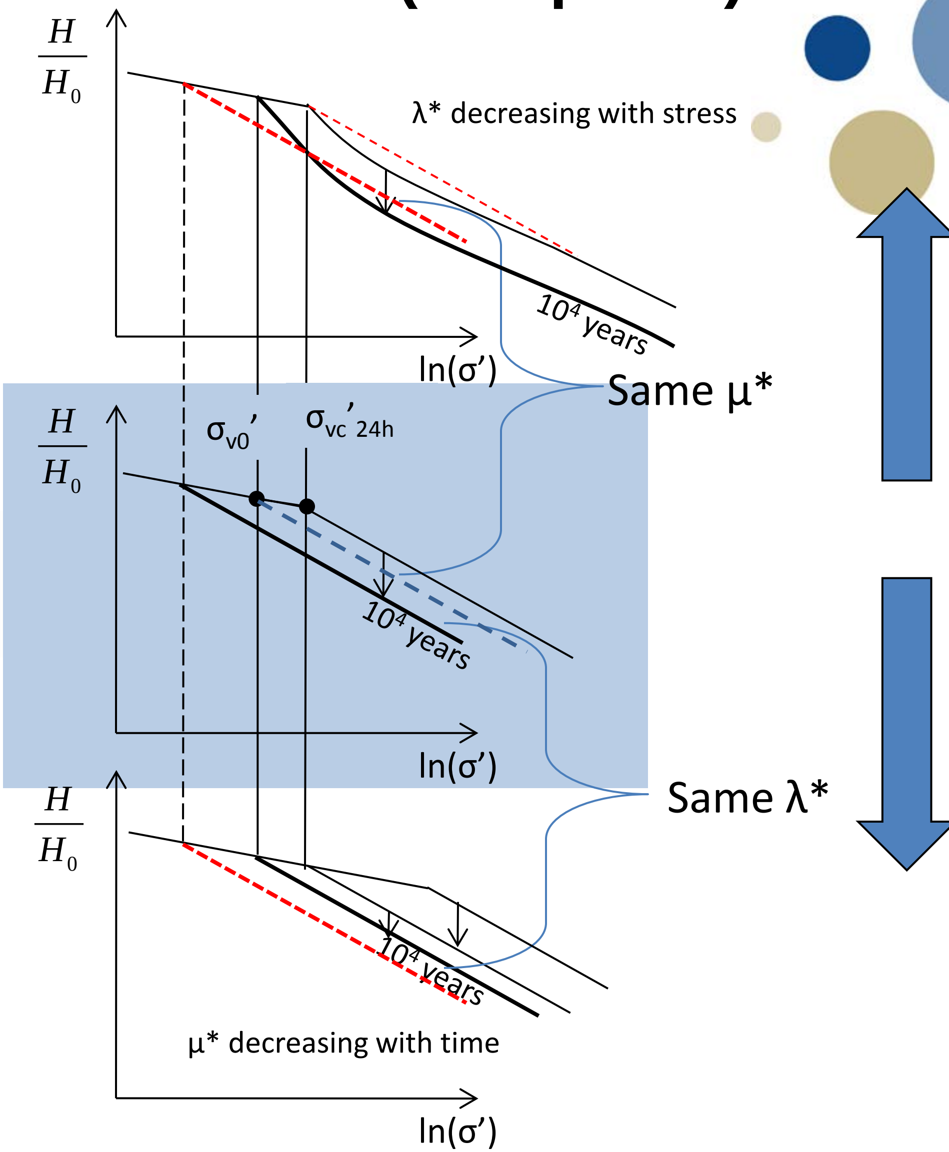


Illustration of dependence of OCR on the corresponding reference time (τ).

The effect of the μ*/(λ*-κ*) ratio on OCR (creep rate)

$\frac{\mu^*}{\lambda^*-\kappa^*} = \frac{1}{r_s \cdot \zeta}$	age = 10000 yrs OCR	OCR = 1.3 age
0.010	1.163	6.79E+08 years
0.015	1.254	1.08E+05 years
0.020	1.353	1.36E+03 years
0.025	1.459	98.9 years
0.030	1.574	17.2 years
0.035	1.697	4.93 years
0.040	1.830	1.93 years
0.050	2.129	0.518 years
0.070	2.880	0.113 years



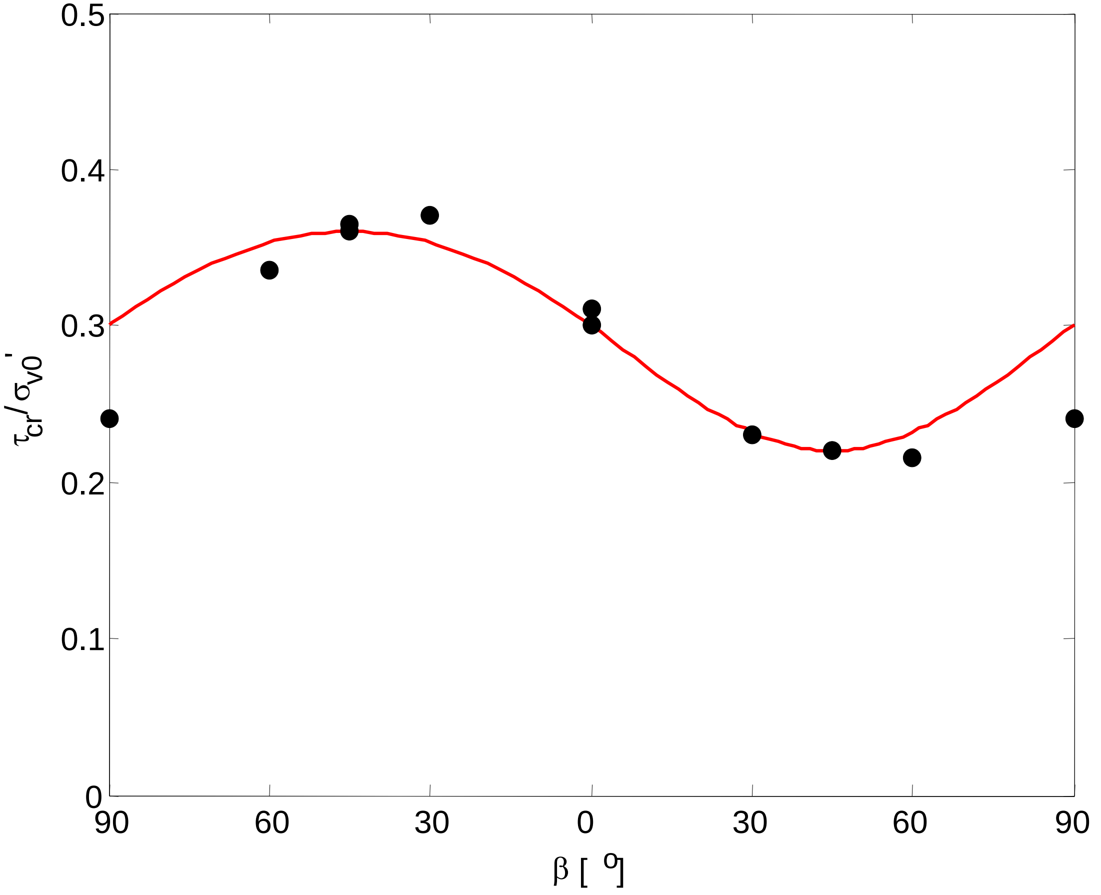
“Recommended” range (PLAXIS manual)
~0.04 - 0.07

Anisotropy

- First:
  - Undrained Triaxial Compression versus Undrained Triaxial Extension and Direct Simple Shear (Bjerrum 1973)
- Second:
  - Preconsolidation stress from Oedometer test versus isotropic consolidation test (Feng 1991)
- Third:
  - “Stress/strain induced anisotropy” – Changes in macroscopic yield surface (Wheeler 2003)

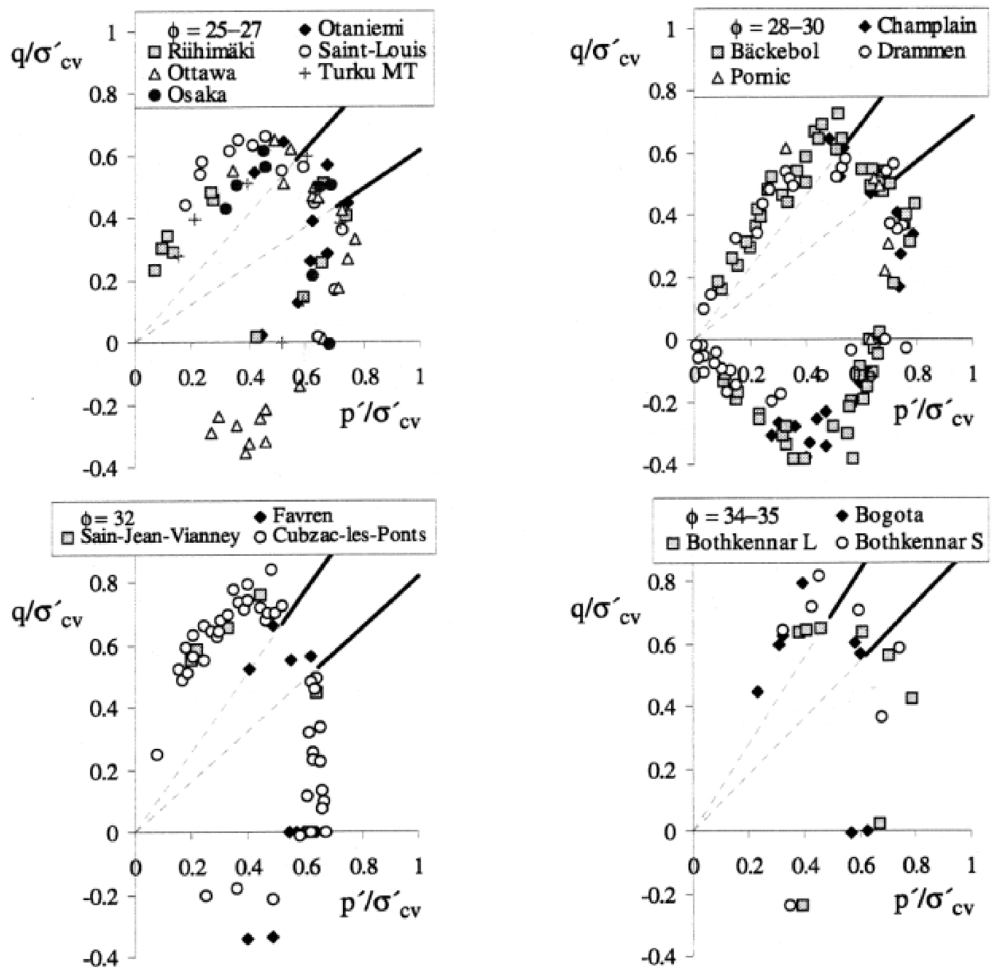
Undrained shear strength

- Used as basis for the NGI-ADP model



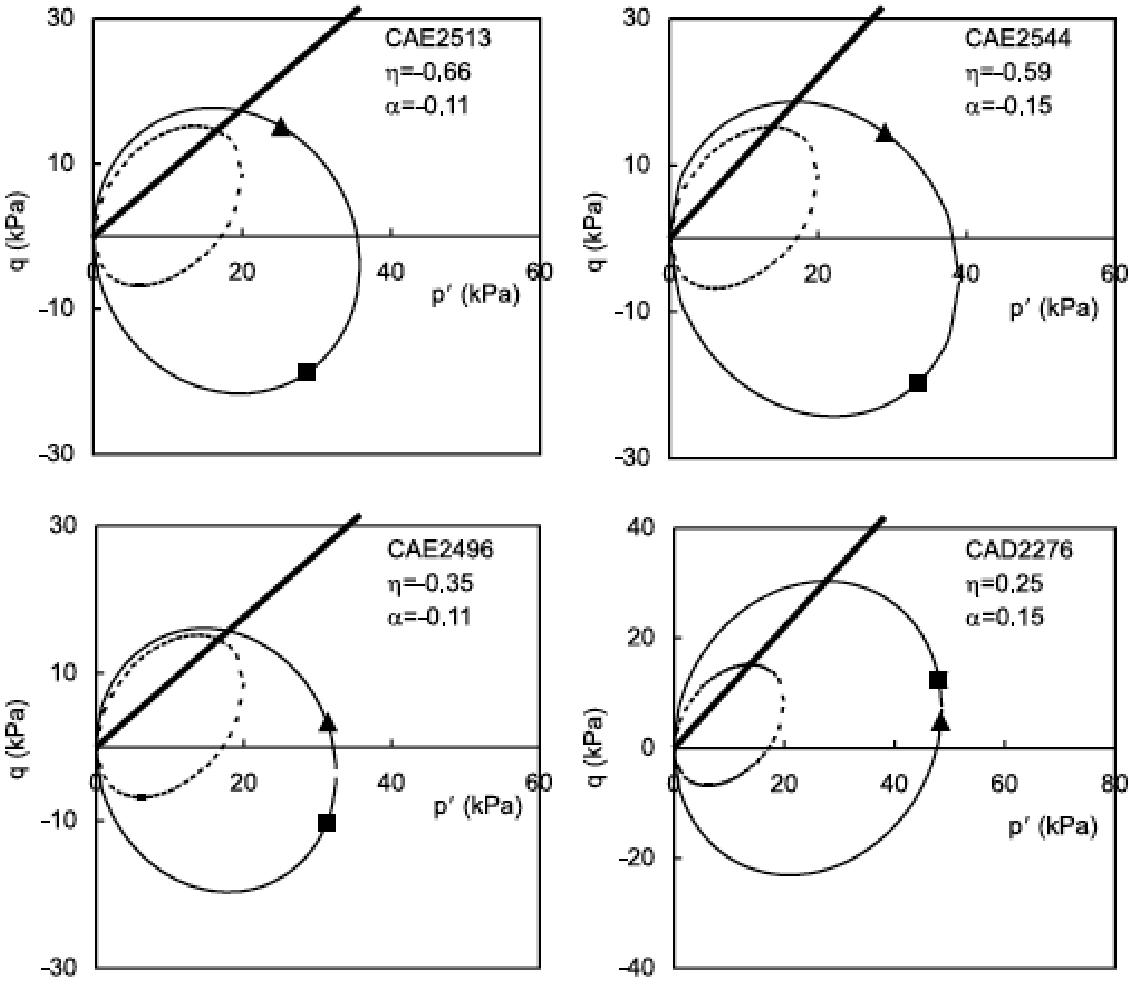
Pre-consolidation stress and ”cap” yield surface

- Experiments from literature on finding cap surface – yield points in p’ – q space

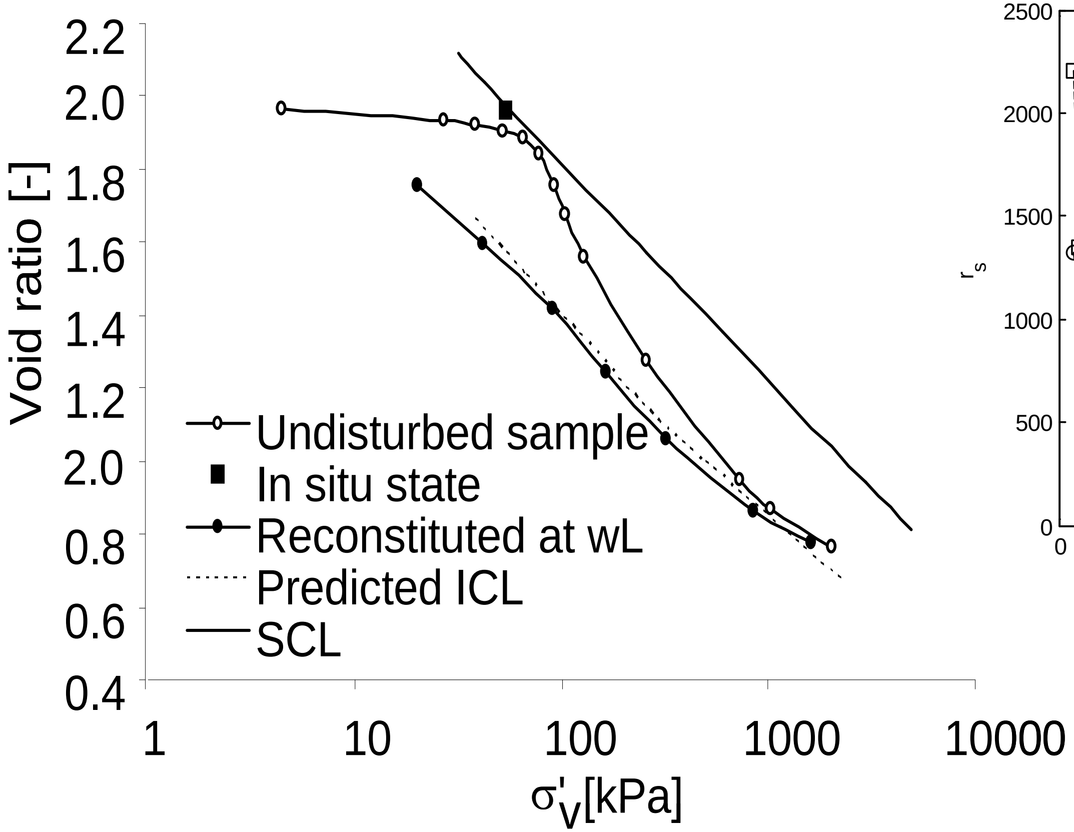


Stress/strain induced anisotropi

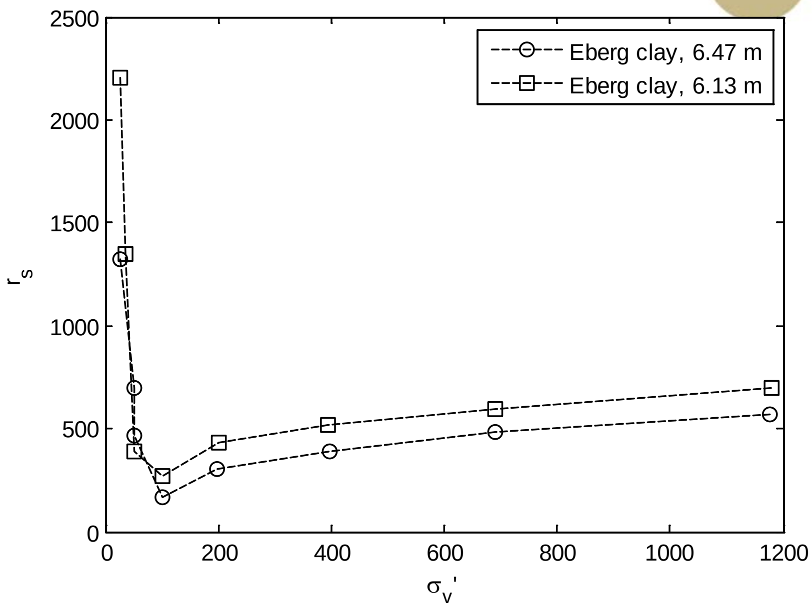
- Wheeler et al.



Destructuration



Burland (1990)

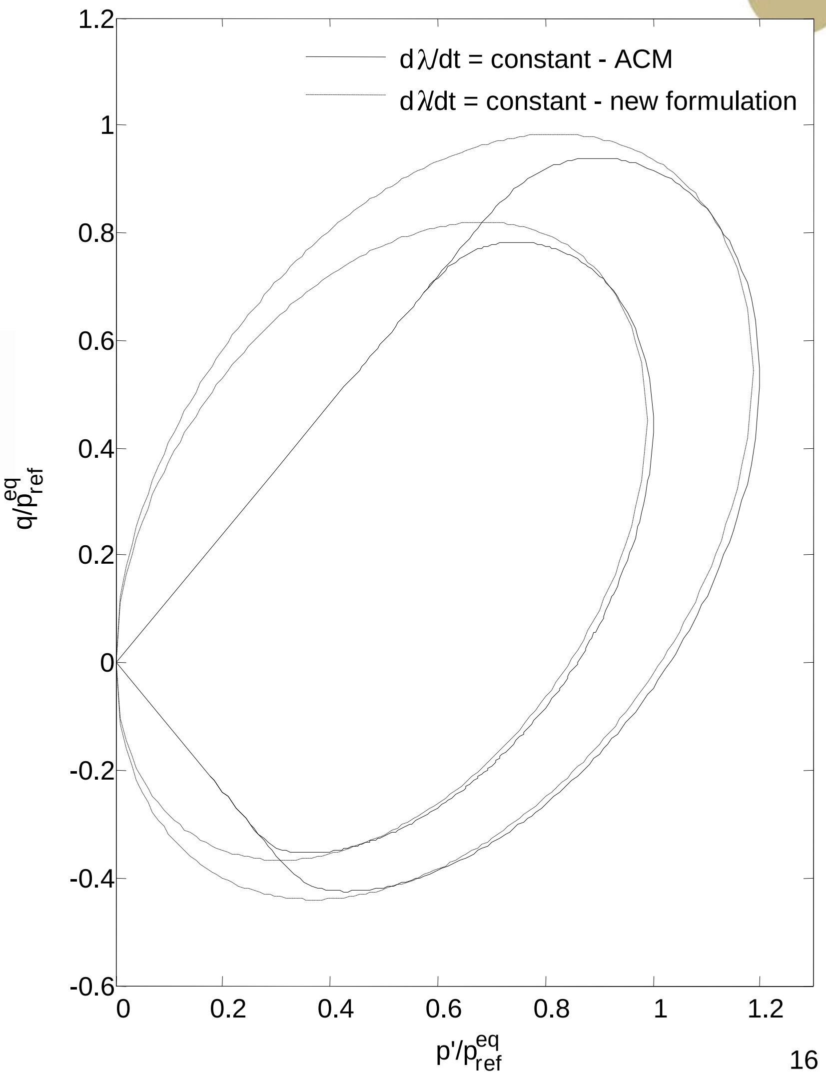


Christensen (1985)

Creep - Yield surface becomes reference surface

- Option 1 – extending by volume strain (ACM)
- Option 2 – extending by plastic multiplier directly

$$\dot{\lambda} = \frac{1}{r_s \cdot \tau} \cdot \left(\frac{p^{eq}}{p^{eq}_{ref}}\right)^{r_s \cdot \zeta} \cdot m_{K0NC}$$



Anisotropy and creep – The n-SAC model

- A non-associated creep model for structured anisotropic clay
- Non-associated because:
  - prediction of the strain behavior under various stress paths, based on experimental evidence from e.g. Feng (1991)

$$p^{eq} = p' + \frac{\frac{3}{2}\{\boldsymbol{\sigma}_d - p'\boldsymbol{\beta}_d\}^T\{\boldsymbol{\sigma}_d - p'\boldsymbol{\beta}_d\}}{\left(M^2 - \frac{3}{2}\boldsymbol{\beta}_d{}^T\boldsymbol{\beta}_d\right)p'}$$

where p' = mean stress; $\boldsymbol{\sigma}_d$=deviatoric stress vector; $\boldsymbol{\beta}_d$ = deviatoric rotational vector; M = Lode angle dependent peak of the reference curve of in p'-q space

$$Q = p' + \frac{\frac{3}{2}\{\boldsymbol{\sigma}_d - p'\boldsymbol{\alpha}_d\}^T\{\boldsymbol{\sigma}_d - p'\boldsymbol{\alpha}_d\}}{\left(M_f{}^2 - \frac{3}{2}\boldsymbol{\alpha}_d{}^T\boldsymbol{\alpha}_d\right)p'} - p_Q^{eq} = 0$$

where M_f is the Lode angle dependent citical state line in p'-q space; $\boldsymbol{\alpha}_d$ is the deviatoric rotational vector.

Modelling of destructuration

- Gens and Nova (1993)
- $p_{ref} = p_{mi} \cdot (1+x)$

  where x is the amount of structure that is unstable

  i stands for intrinsic

$$\dot{\lambda} = \frac{1}{r_{si} \cdot \tau} \cdot \left(\frac{p^{eq}}{(1+x) \cdot p_{mi}{}'} \right)^{r_{si} \cdot \zeta_i} \cdot m_{K0NC}$$

- x has to change with *vp* strain $\frac{dx}{d\lambda} = f(\mathbf{\Phi})$ State variables inc. x

Models with anisotropy and destructuration

- Option 1
  - ACM -> ACM-S (Leoni 2008, Kamrat-Pietraszewska 2011)
    - Extension of SSC (Stolle et al. 1999) (PLAXIS current model)
- Option 2
  - EVP-SCLAY1S (Karstunen and Yin 2010)
  - Ani-Creep (Yin et al. 2011)
  - n-SAC (Grimstad et al. 2010)
- n-SAC –using creep limit and option 2:

$$\dot{\lambda} = \frac{1}{r_{si} \cdot \tau} \cdot \left\langle \left(\frac{p^{eq}}{(1+x) \cdot p_{mi}'} \right)^{r_{si} \cdot \zeta_i} - \frac{\tau}{t_{\max}} \right\rangle \cdot m_{K0NC}$$

How to use/Parameters for analyses

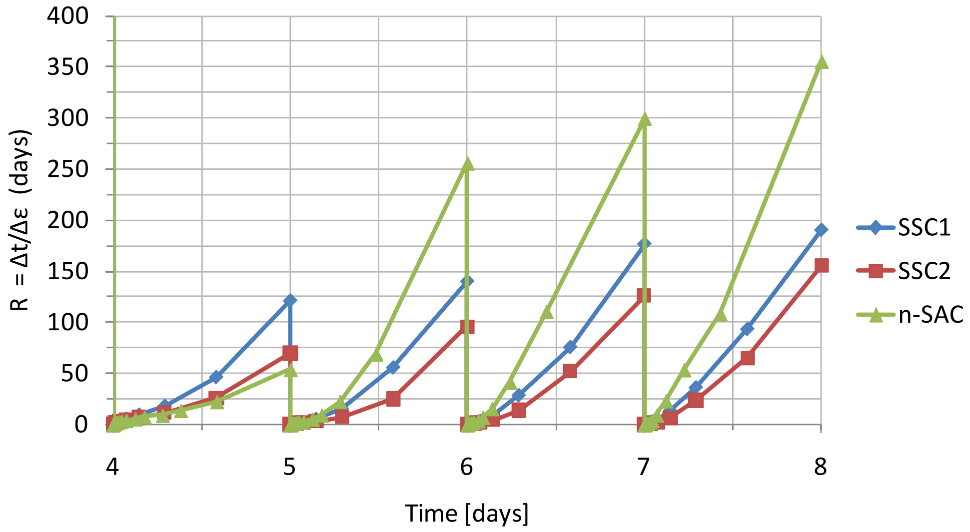
- Two models - SSC and n-SAC
- Three analysis cases - SSC1, SSC2 and n-SAC

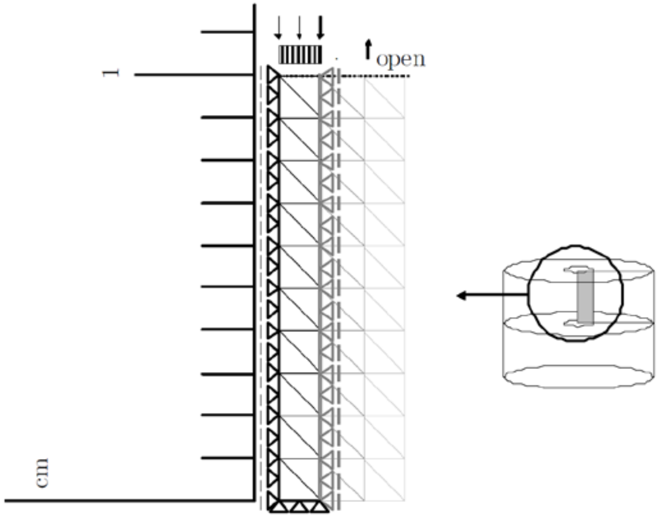
Model	ν	K_0^{NC}	E_{ref} / p_{ref}	$\{E_{oed}^{ref}\}_i$ / p_{ref}	r_{smin}	r_{si}	ω	ϕ_p	ϕ_{cs}
SSC1	0.15	0.54	200	9.5	-	267	-	-	35°
SSC2	0.15	0.54	200	6.0	-	233	-	-	35°
n-SAC	0.15	0.5	200	13.0	200	625	0.3	25°	35°

$k_v = k_h$ = 5e-5 m/day; γ' = 10 kN/m^3, K_0 = 0.54, OCR = 1.36

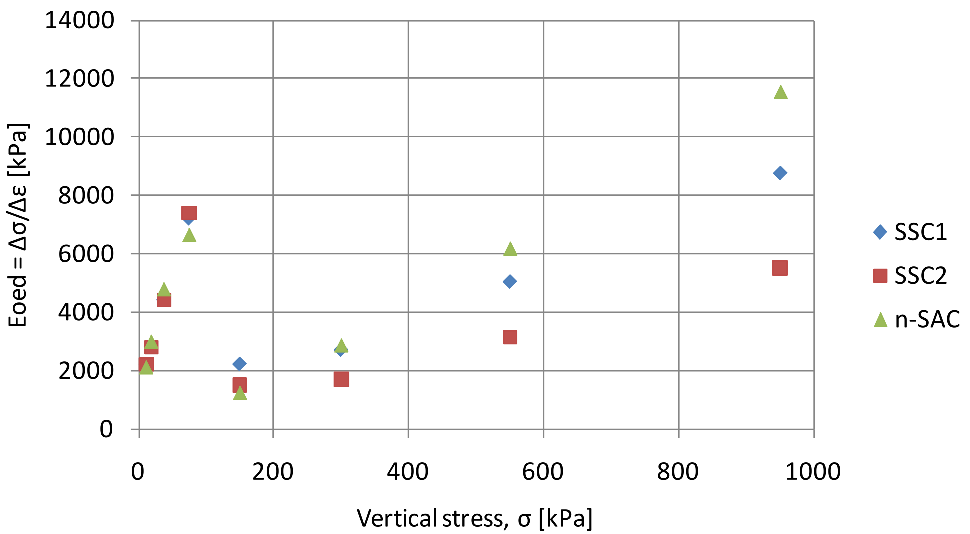
$$\kappa = \frac{3(1-2\nu)}{E_{ref}} \qquad \lambda = \frac{1}{\{E_{oed}^{ref}\}_i} \qquad \mu^* = \frac{1}{r_s}$$

Oedometer simulations

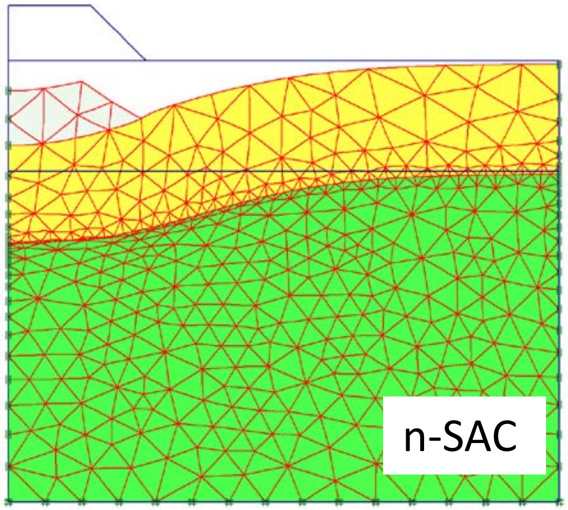


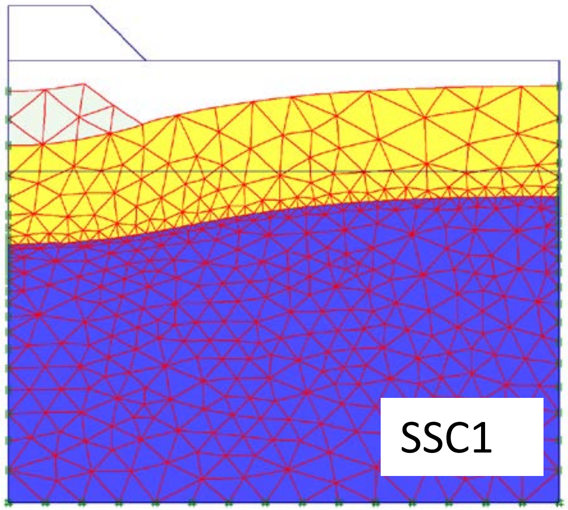


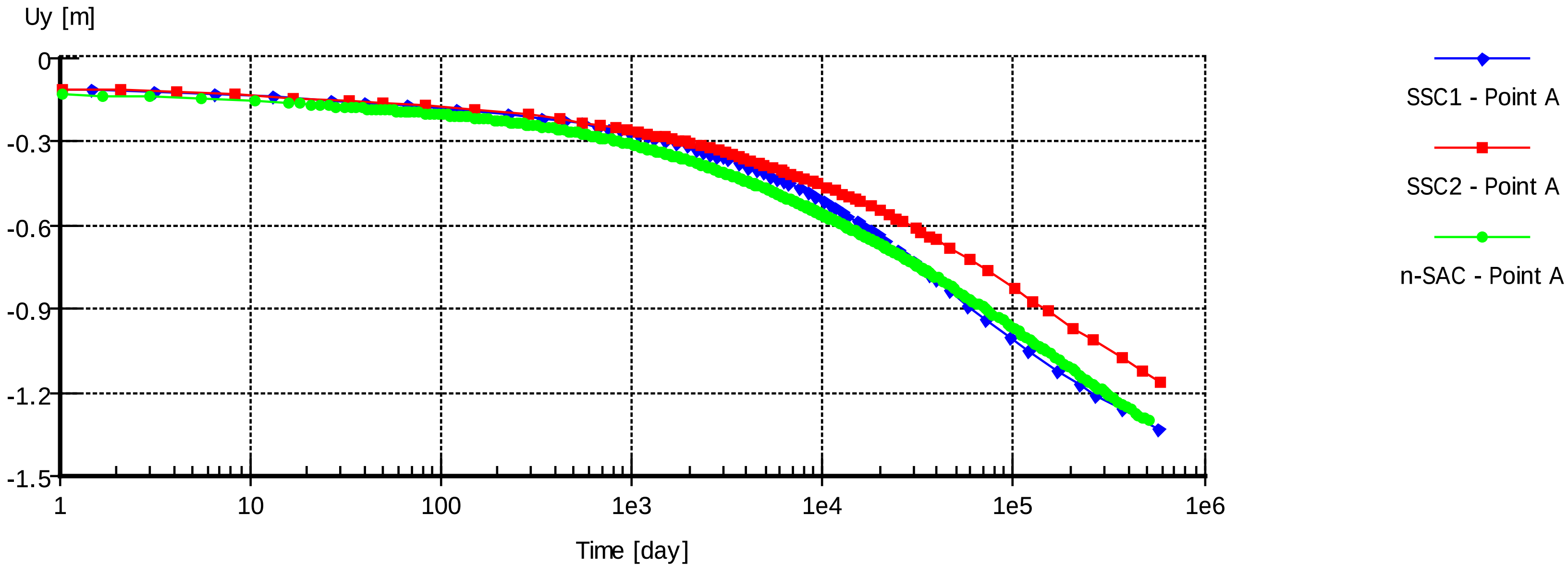
Two way drainage

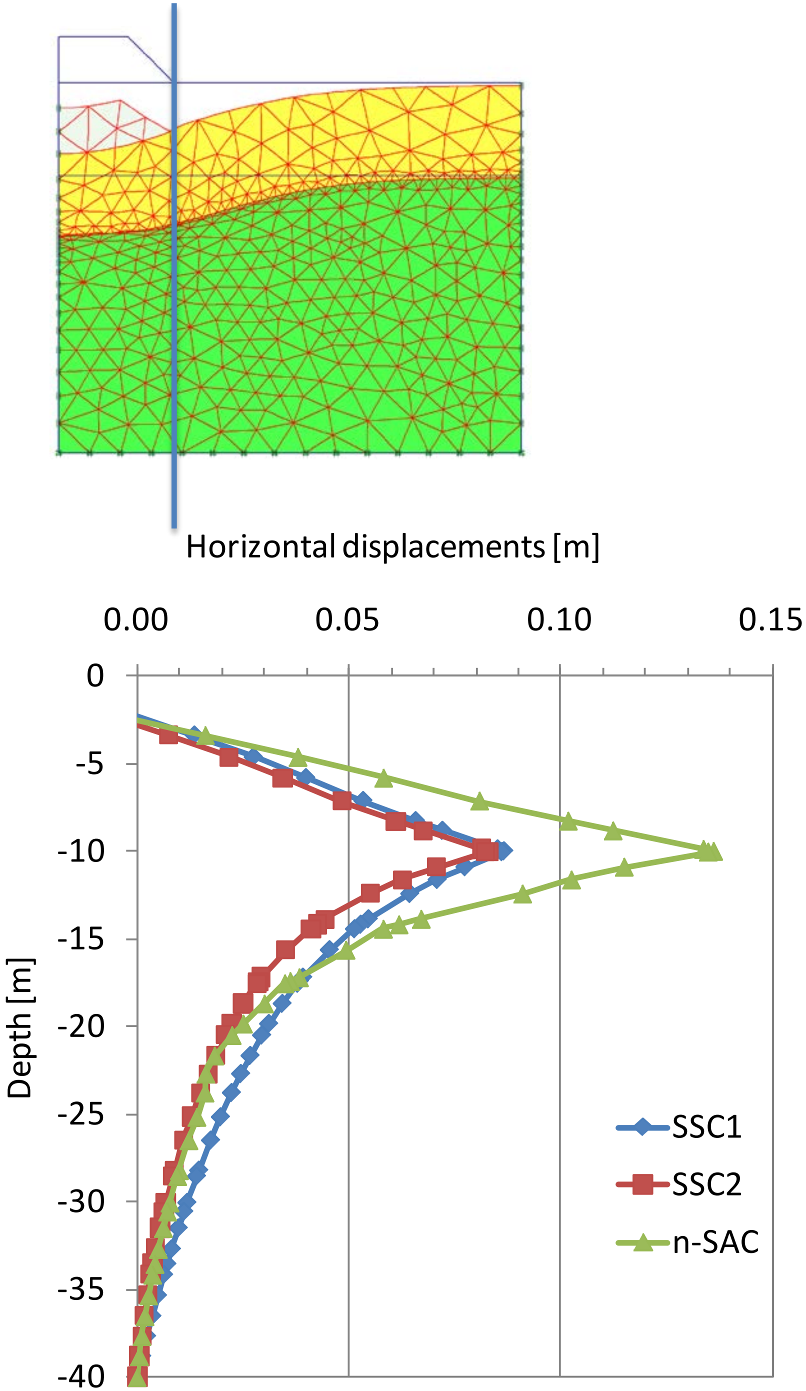


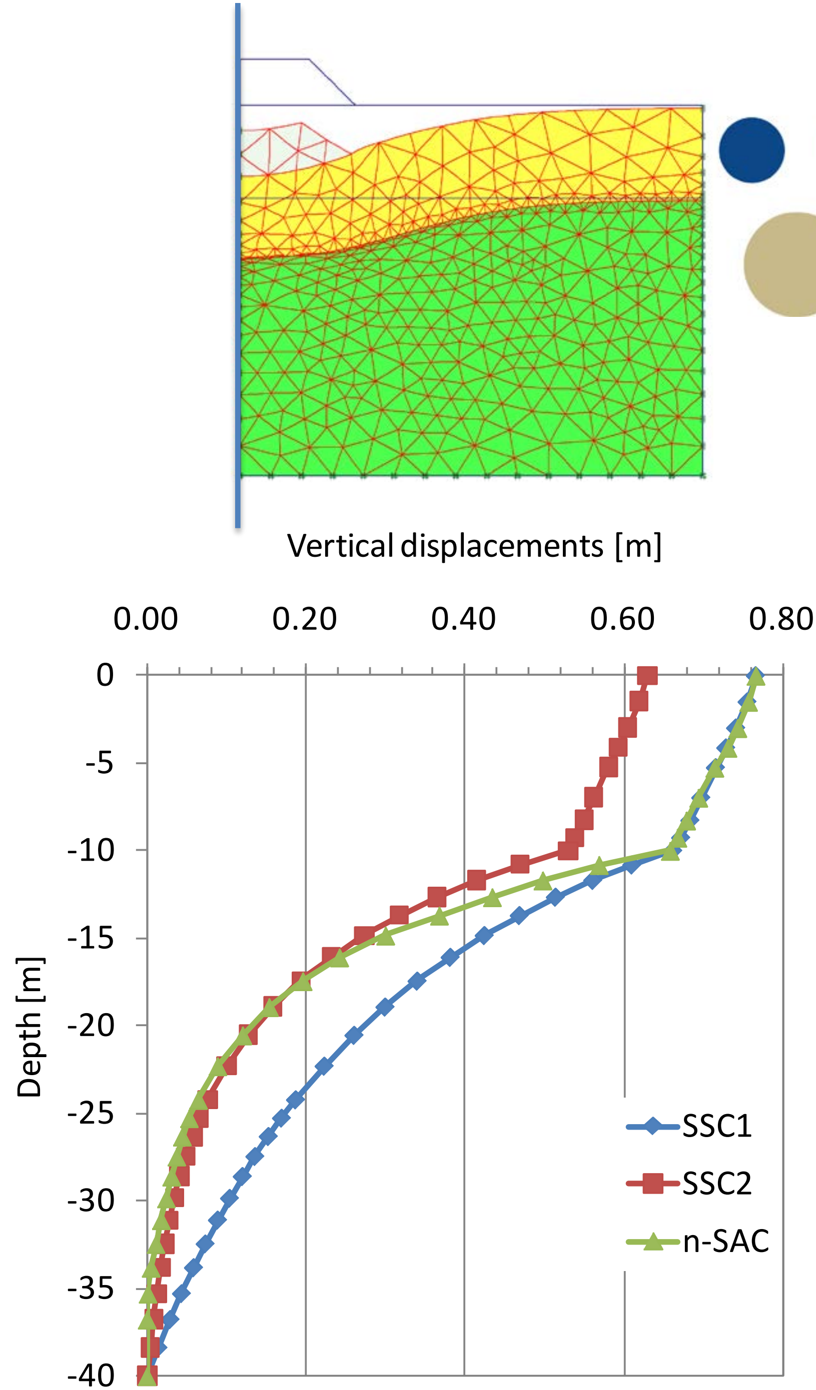
Example: settlement problem



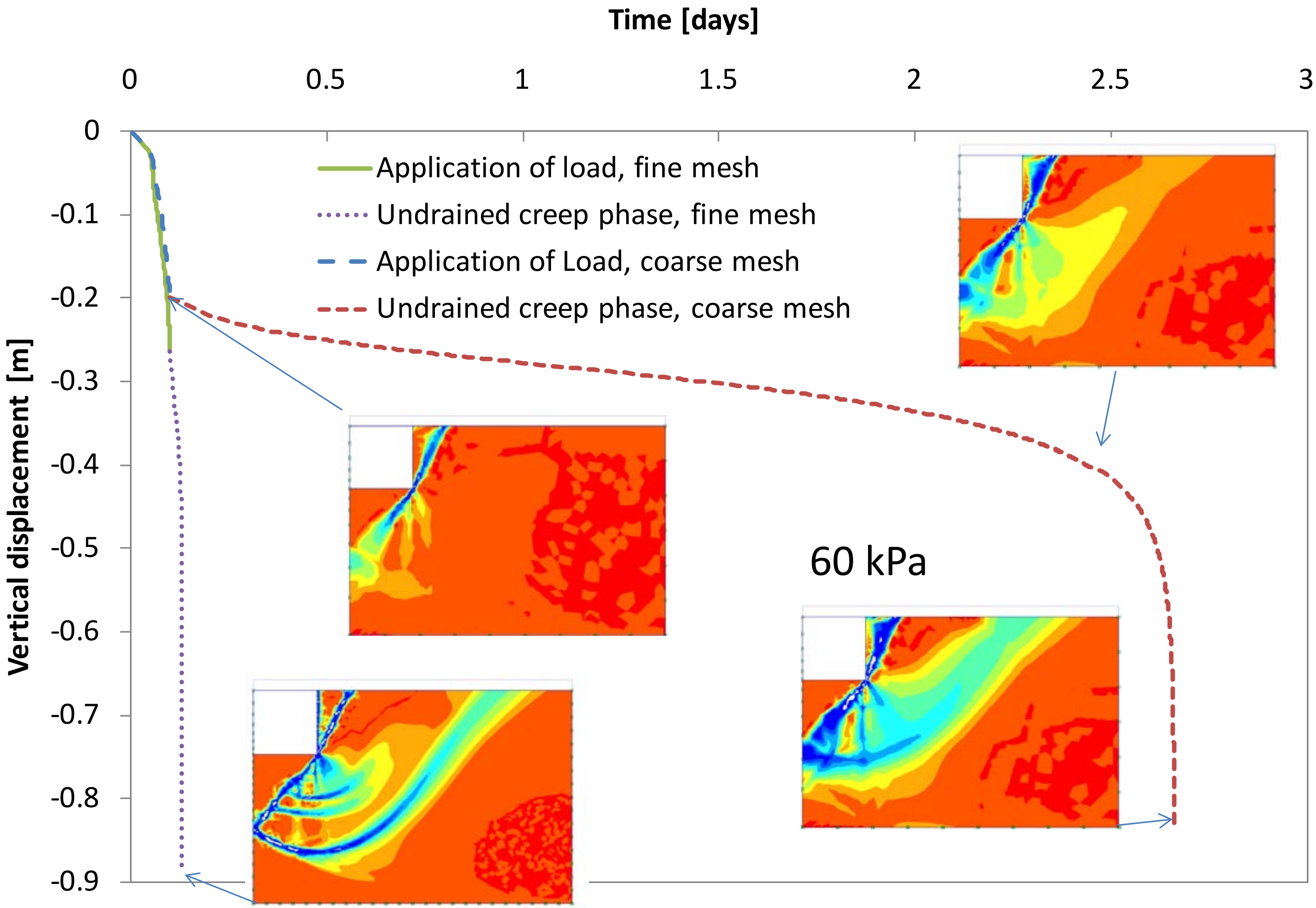





Horizontal displacements [m]
0.00
0.05
0.10
0.15
Depth [m]
0
-5
-10
-15
-20
-25
-30
-35
-40
SSC1
SSC2
n-SAC

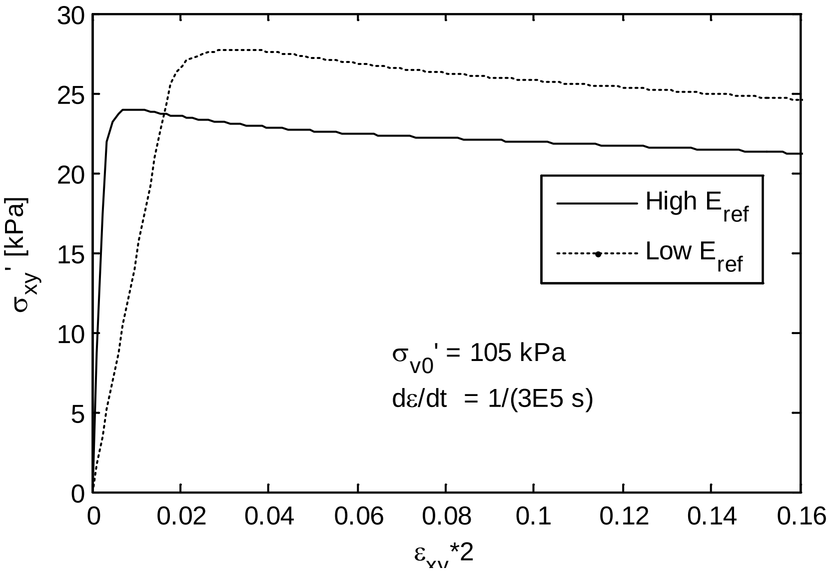

Vertical displacements [m]
0.00
0.20
0.40
0.60
0.80
Depth [m]
0
-5
-10
-15
-20
-25
-30
-35
-40
SSC1
SSC2
n-SAC

Mesh dependency due to softening

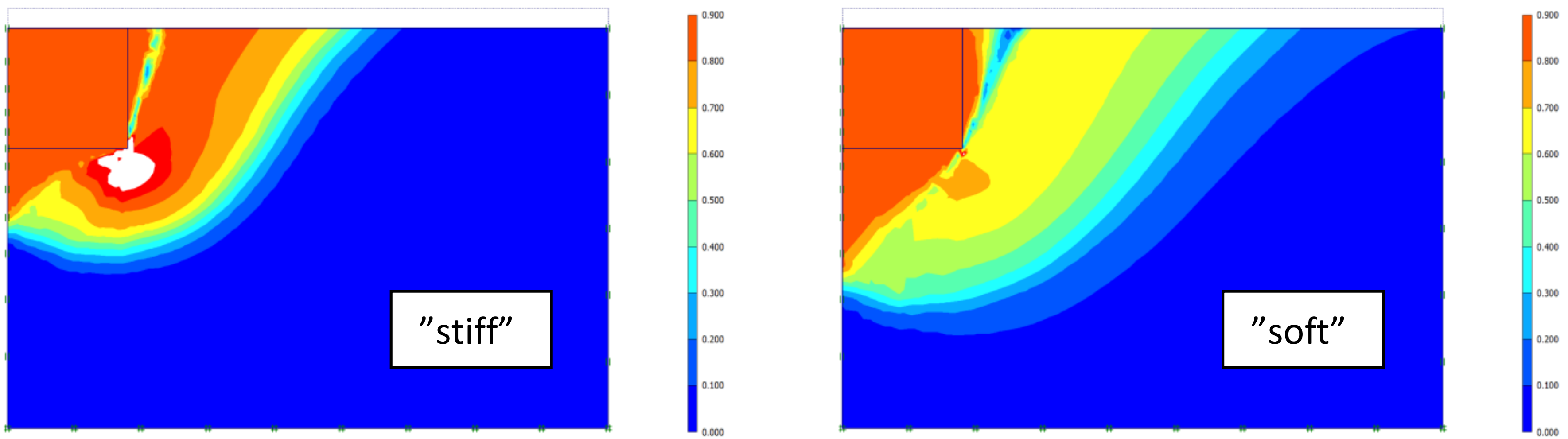


Shadings of "structure"

Effect of stiffness



DSS



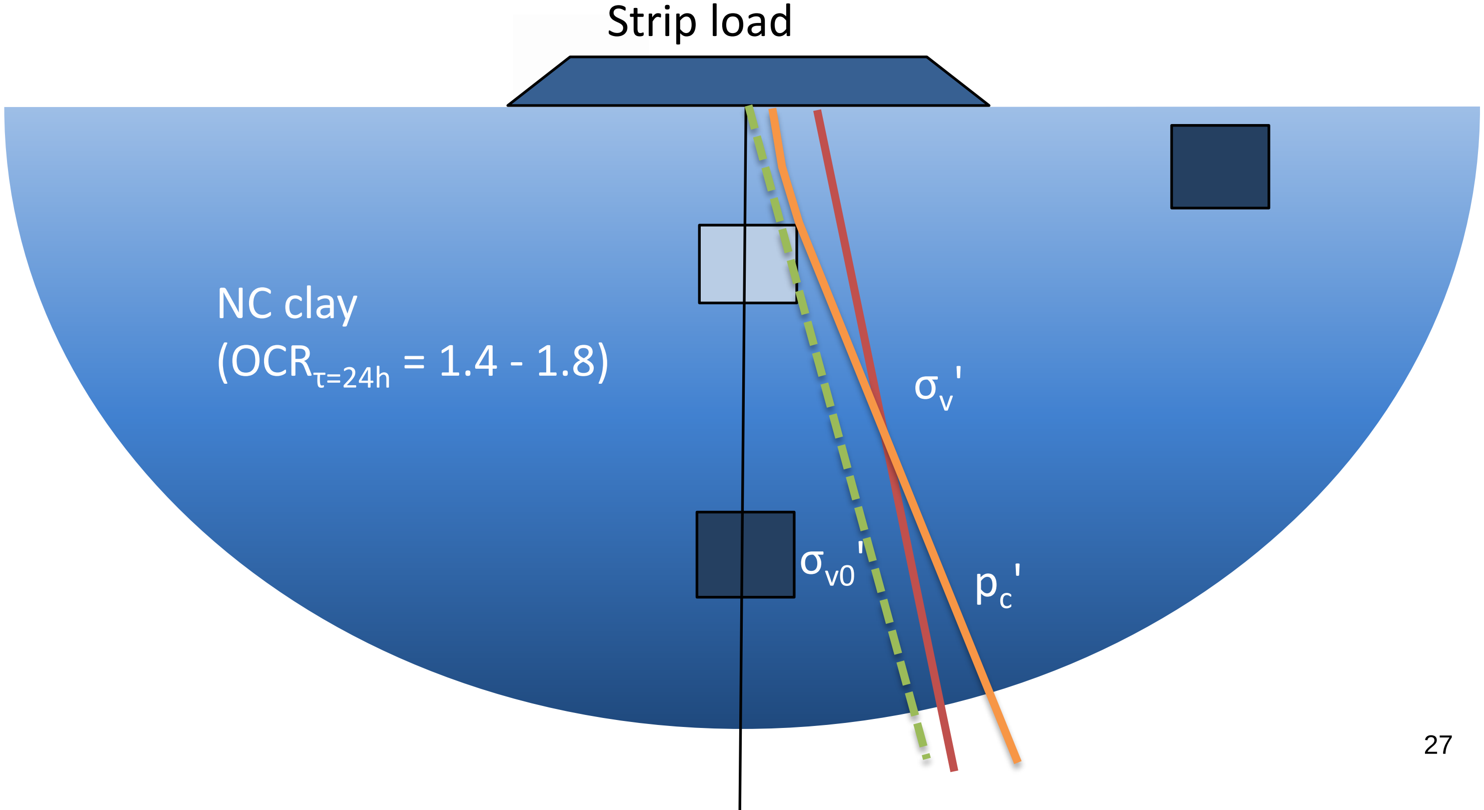
25.7 days. Looks more like perfectly plastic behavior!

Conclusions

- Creep/rate and anisotropy are important if we want to fully understand soil behavior.
- Sample quality is crucial and deserves more attention as it forms the basis for numerical modeling.
- With increased sample quality and testing procedure, the soil models also needs to be improved
- The “huge gap” between state-of-the-art and state-of-the-practice must be closed or at least narrowed down!

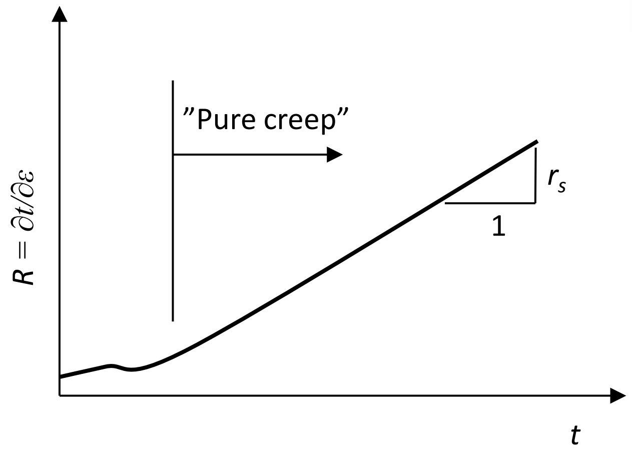
Use of creep models

- Expected new stress state to cross p_c' (24h)
- Expected new stress state below p_c' (24h)



Time resistance concept

- Described by in e.g. Janbu (1969)
- Used for 1D strain in KRYKON, Svanø & Emdal (1986)



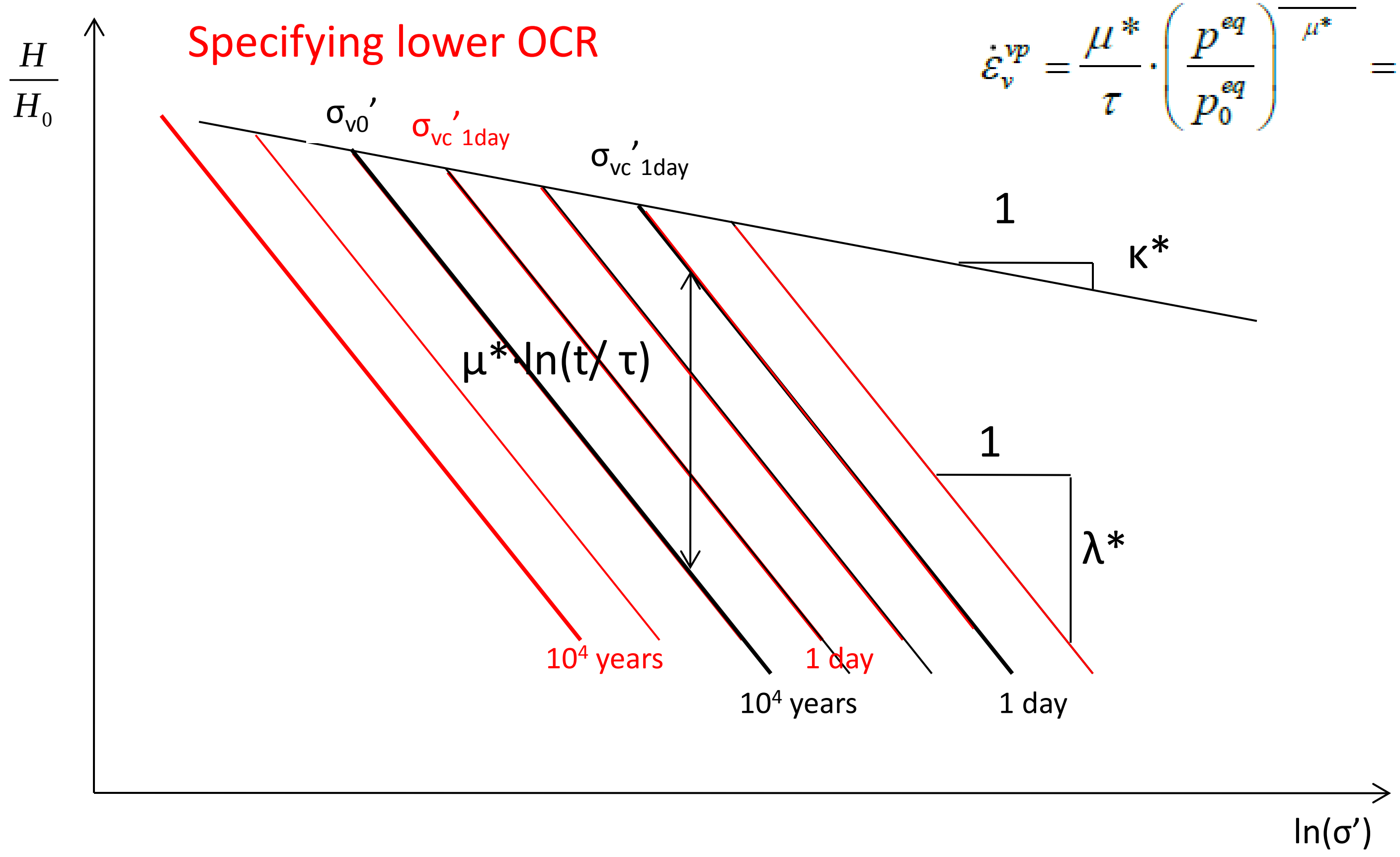
$$r_s = \frac{d\left(\dfrac{\partial t}{\partial \varepsilon}\right)}{dt} = \frac{dR}{dt} = \frac{1}{\mu^*}$$

$$\frac{d\varepsilon}{dt} = \frac{\mu^*}{t}$$

$$\Delta\varepsilon\left(\Delta t = t - \tau\right) = \mu^* \cdot \ln\left(t/\tau\right)$$

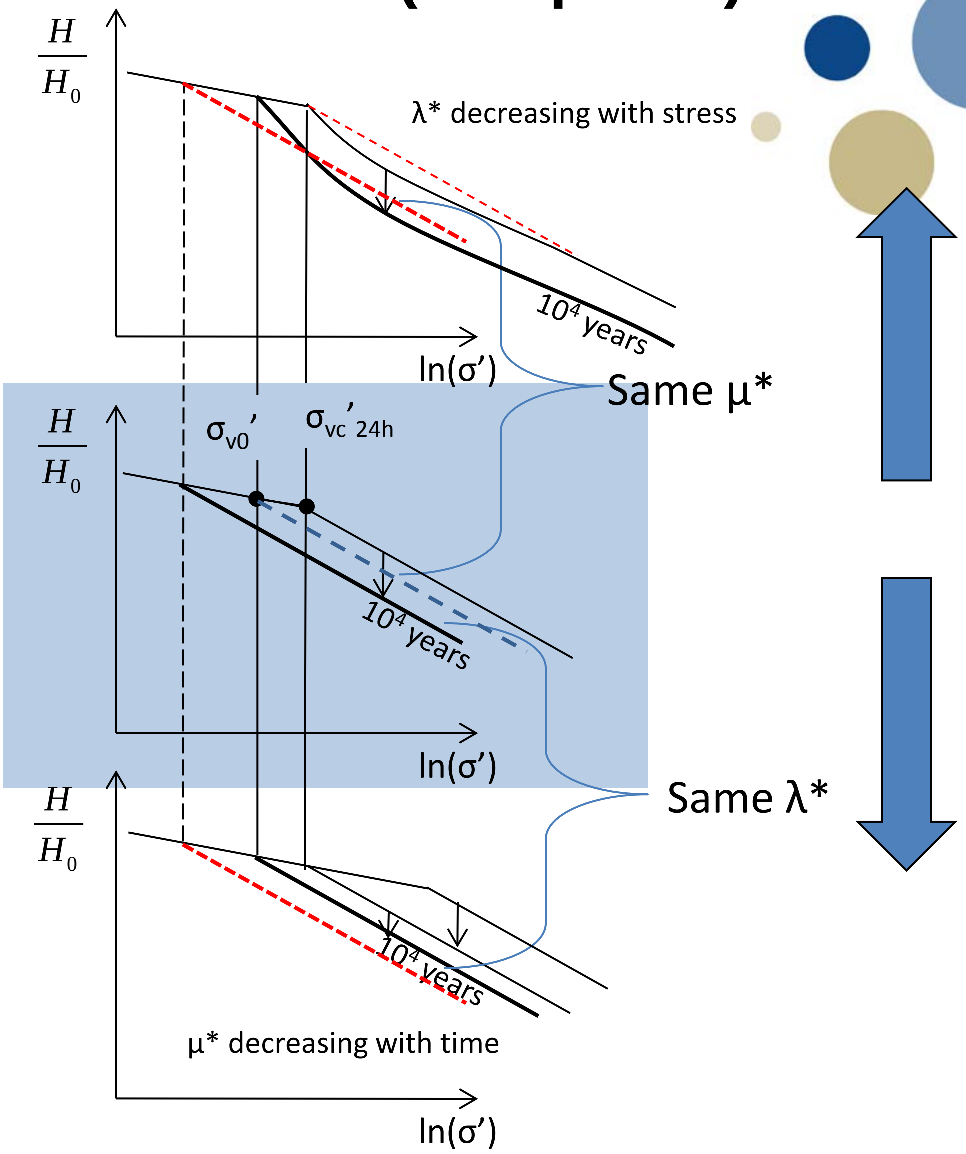
Example: SSC model - The effect of the μ*/(λ*-κ*) ratio on OCR (creep rate)

$$\dot{\varepsilon}_v^{vp} = \frac{\mu^*}{\tau} \cdot \left(\frac{p^{eq}}{p_0^{eq}} \right)^{\frac{\lambda^*-\kappa^*}{\mu^*}} = \frac{\mu^*}{\tau} \cdot OCR^{\frac{\mu^*}{\lambda^*-\kappa^*}}$$



The effect of the μ*/(λ*-κ*) ratio on OCR (creep rate)

$\dfrac{\mu^*}{\lambda^*-\kappa^*} = \dfrac{1}{r_s \cdot \zeta}$	$OCR_\tau = \left(\dfrac{t}{\tau}\right)^{\frac{\mu^*}{\lambda^*-\kappa^*}}$ $\tau = 1$ day $t = 10^4$ years	$t_{age} = \tau \cdot OCR_\tau^{\frac{\lambda^*-\kappa^*}{\mu^*}}$ $\tau = 1$ day $OCR_\tau = 1.3$
0.010	1.163	6.79E+08 years
0.015	1.254	1.08E+05 years
0.020	1.353	1.36E+03 years
0.025	1.459	98.9 years
0.030	1.574	17.2 years
0.035	1.697	4.93 years
0.040	1.830	1.93 years
0.050	2.129	0.520 years
0.070	2.880	0.116 years



"Recommended" range (PLAXIS manual)
~0.04 - 0.07

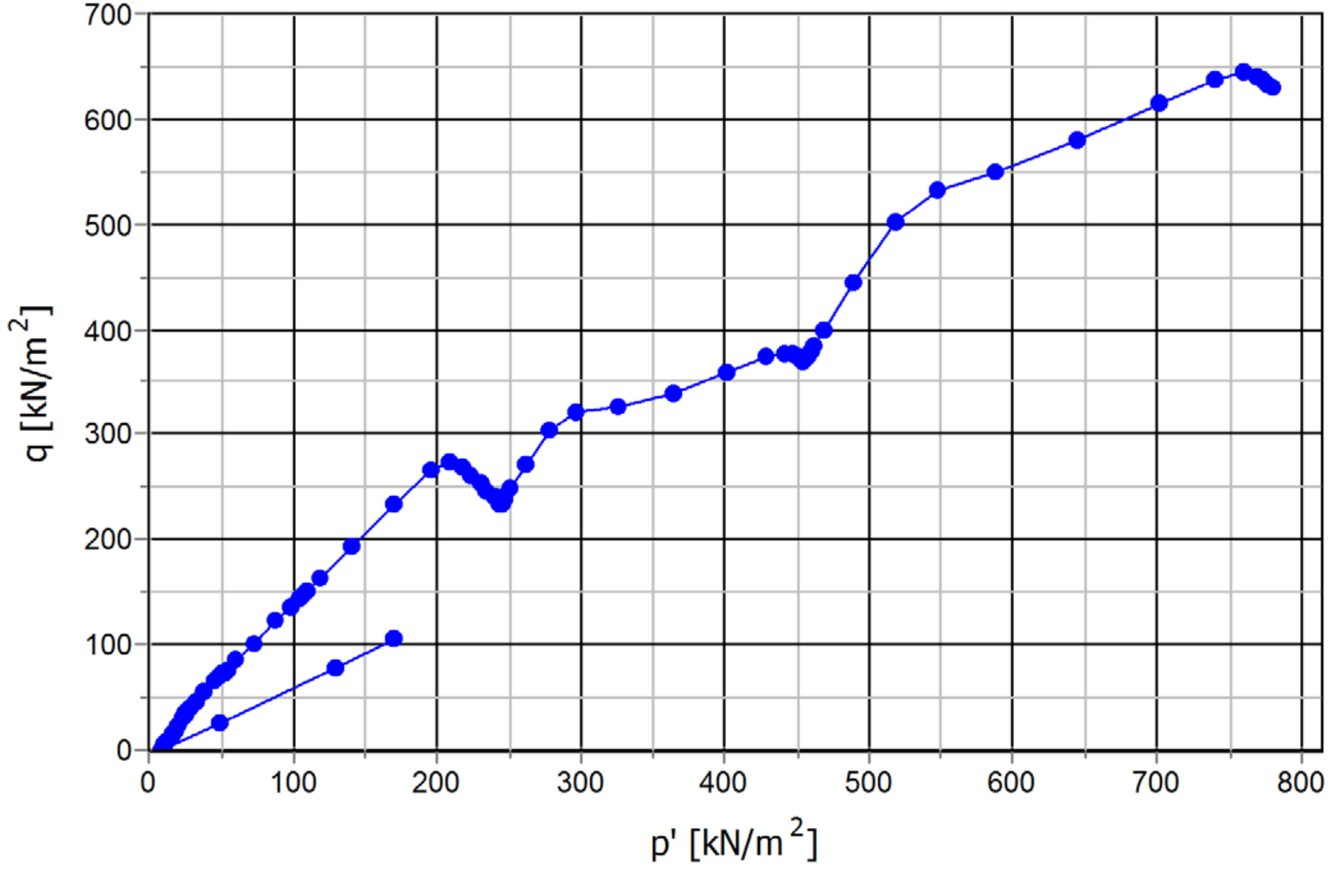
The oedometer test…

- Can we rely on OCR from IL oedometer tests?
  1) Sample disturbance? (we all know this)
  2) Stress condition?
     - Start at some unknown isotropic stress condition and consolidates to 12.5 kPa of vertical stress
     - Loads further along a line different from K_0^{NC} line (i.e. stress path hits the reference pre-consolidation at different place than it would in-situ!)

     → Do we need to simulate the oedometer test rather then interpret OCR from it?

     → Should we measure horizontal stress in the oedometer?
  3) Consolidation (is the effective stress constant for most of the 24h?, e.g. clays with low permeability)
  4) Extrapolation… (should model OCR and reality OCR be the same?)

Simulated oedometer with SSC

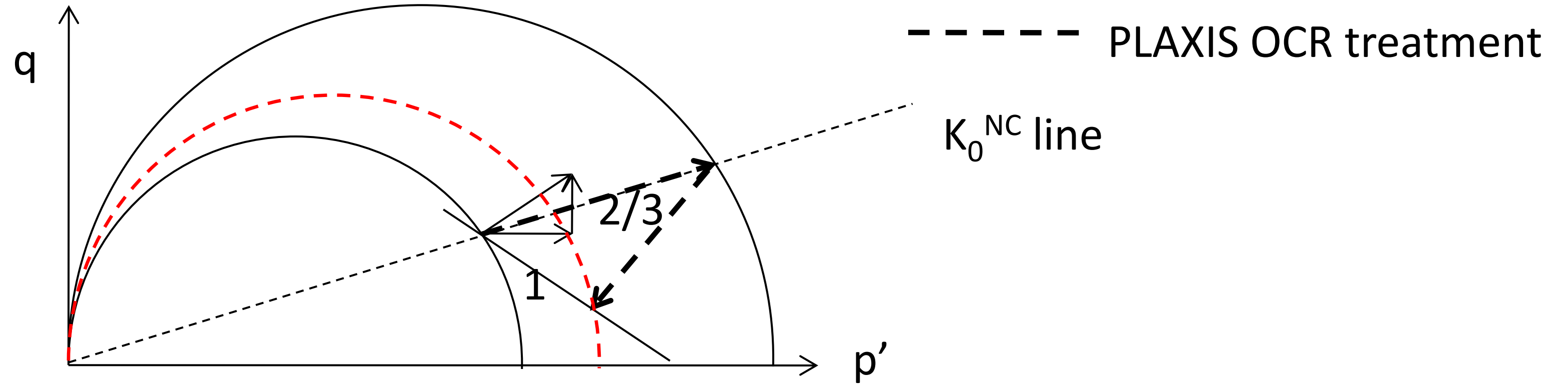


What about K_0?

- Is the in-situ K_0 affected by creep (NC clay)?
  - Model says: very limited influence, i.e. $K_0 \approx K_0^{NC}$
- Has the material been unloaded (OC clay)?
  - Model says: yes, but creep will try to make $K_0 \approx K_0^{NC}$ if the model is not changing its plastic potential, since the volumetric strain should be equal to the vertical strain
- Should we then set $K_0 \approx K_0^{NC}$ for models like SSC?

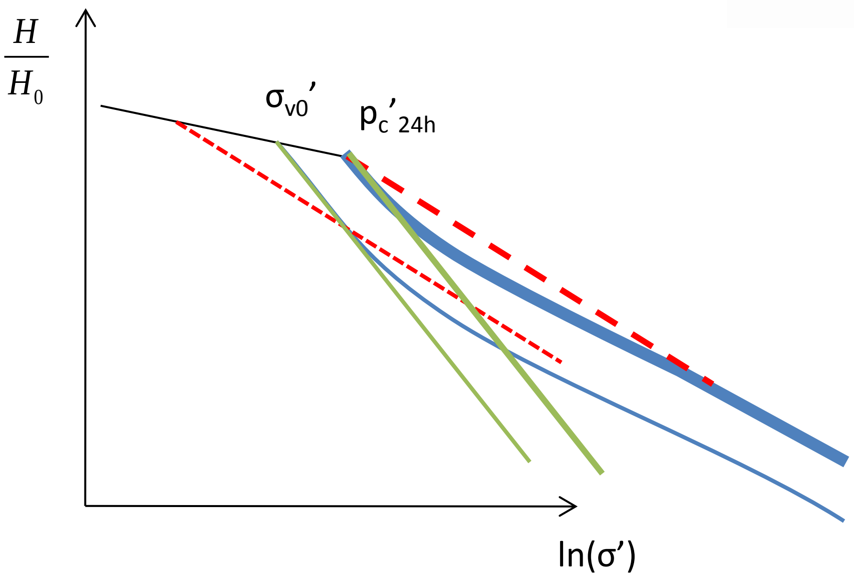
OCR and K_0

- The K_0 value does not change significantly in a 1D creep case due to the increase in OCR. Since 1D creep requires $d\varepsilon_1^{vp} = d\varepsilon_v^{vp}$, then the stress state is fixed to one point at the potential surface.
- In PLAXIS if one specify a OCR (due to creep alone), the suggested initial horizontal stress generated (suggested K_0) is based on the assumption of unloading. Remember to change this back to a value close to the real K_0^{NC}



Stress increment in the field

- No need to fit the whole lab curve…
  - What is the experienced stress change?
  - For most of the soil it is little change (around p_c' or less)



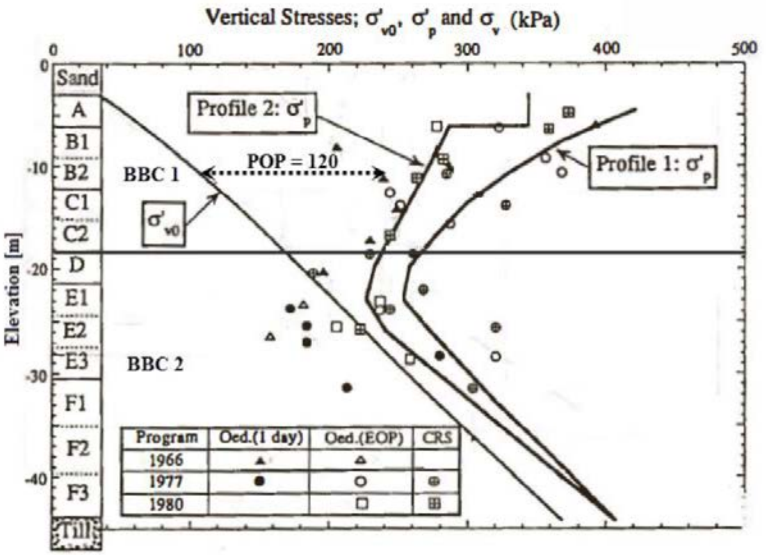
Accept wrong OCR – Fit at large stress change, well above p_c'

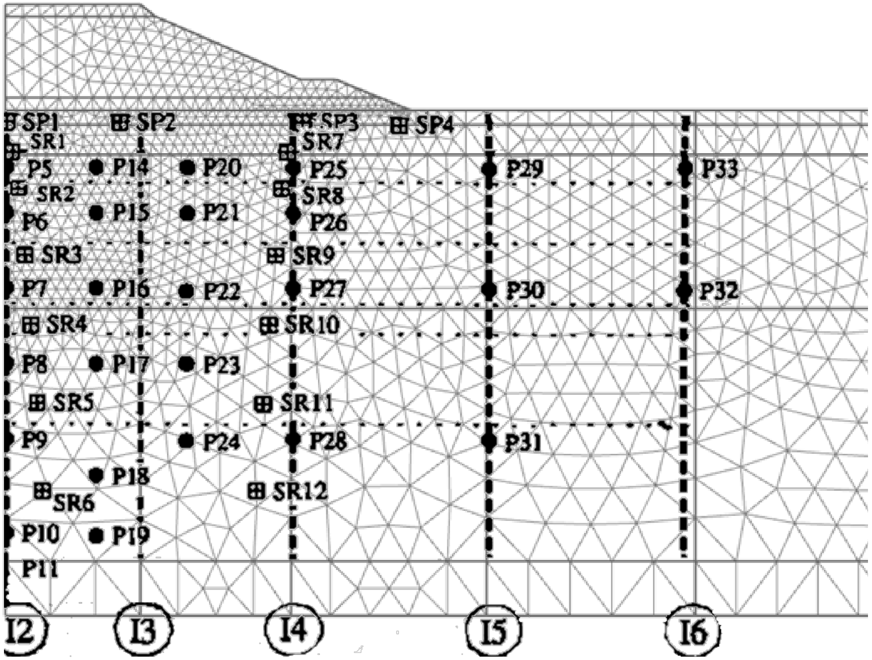
Accept that Inital creep rate is too big

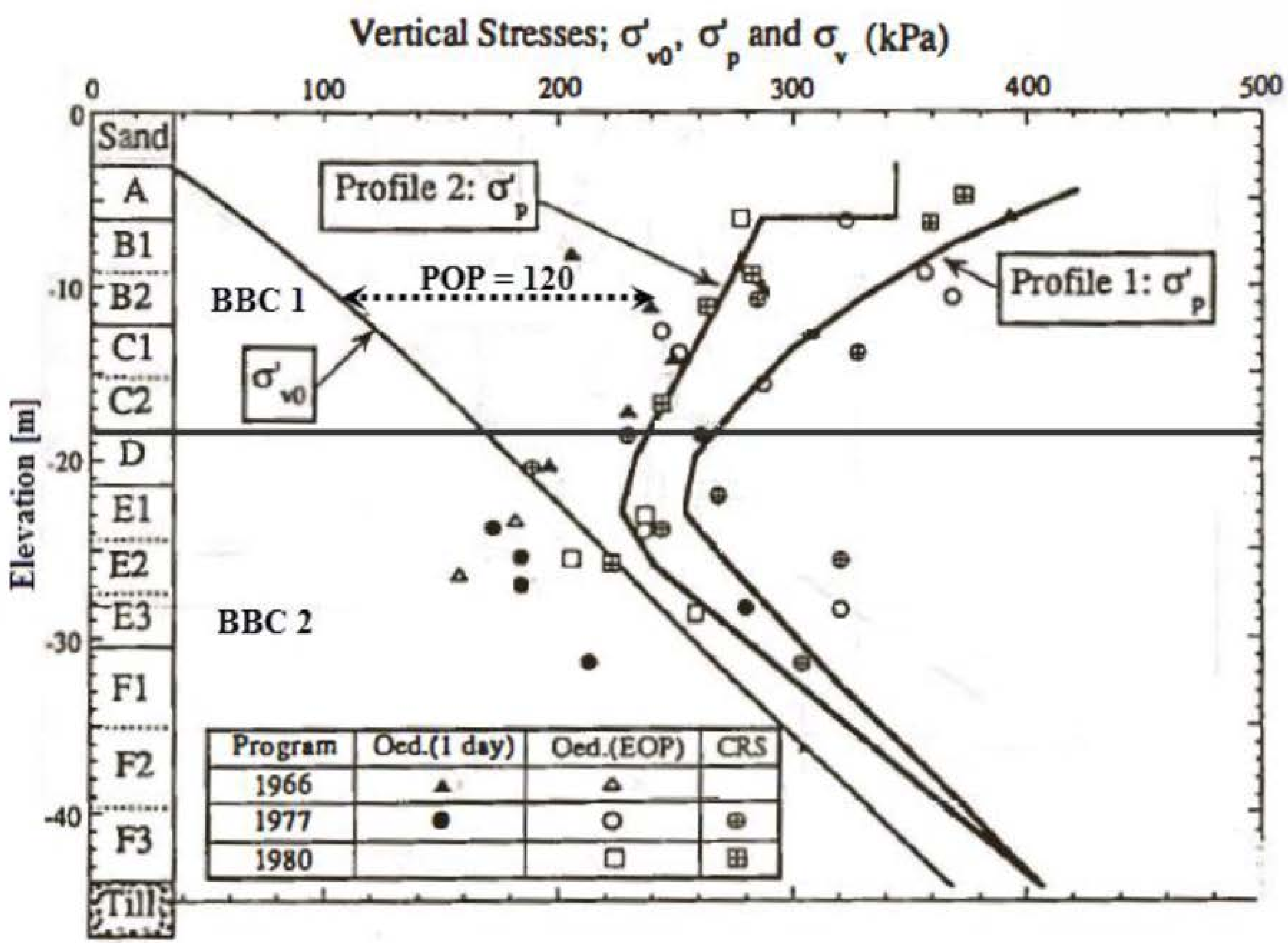
In most cases: Fit for the actual stress change in the region around p_c', higher λ* gives lower OCR for same μ*

The MIT–MDPW embankment

- Latest paper looking at back calculating this is from 2012 (Fatahi et al.)

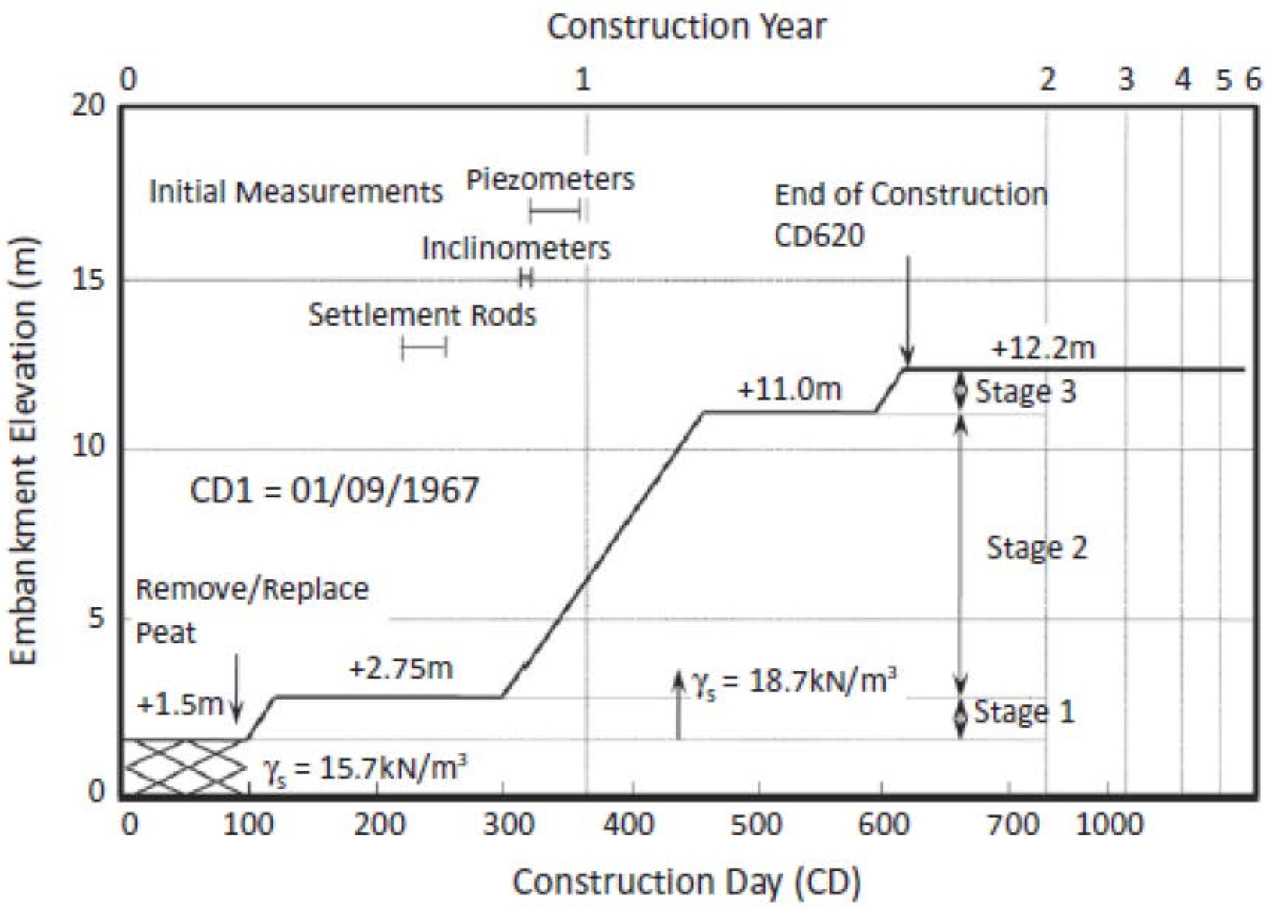




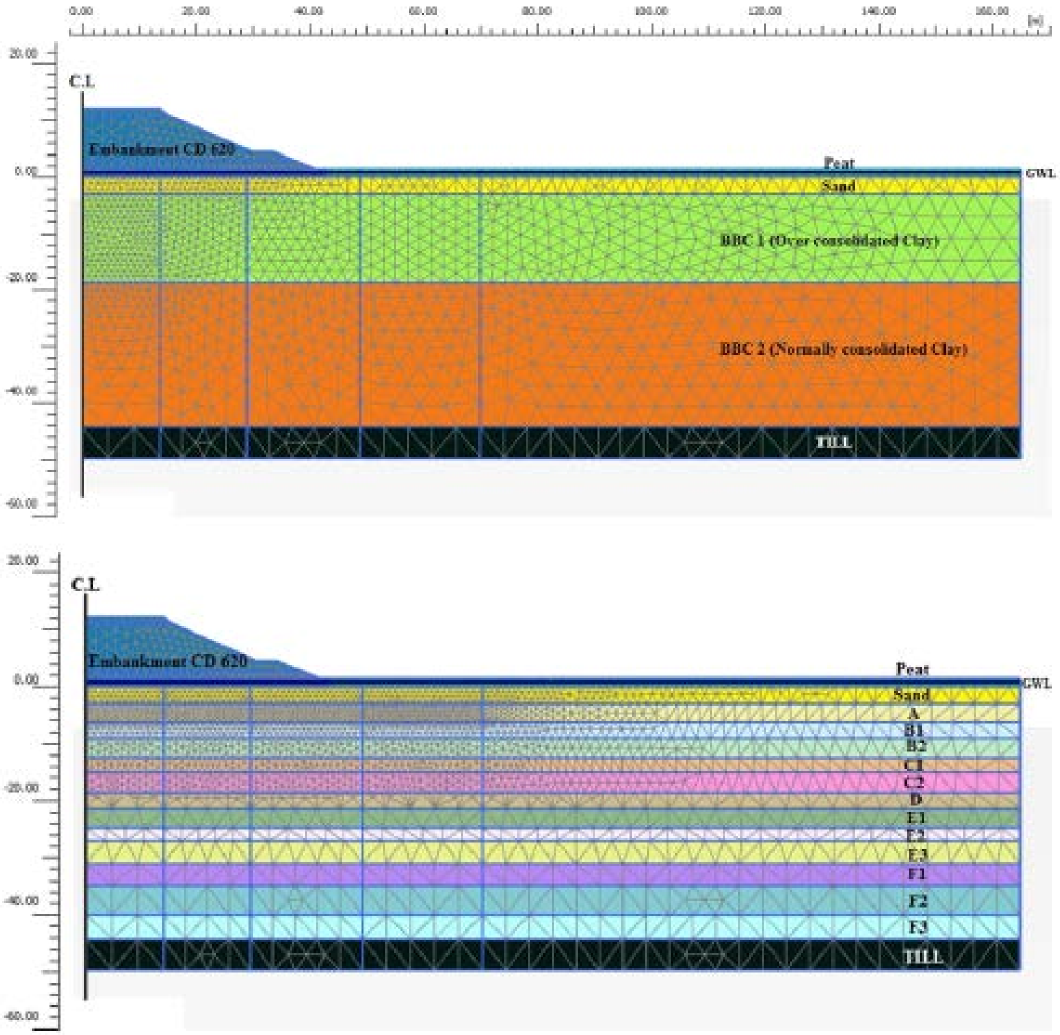


Vertical Stresses; σ'v0, σ'p and σv (kPa)
0
100
200
300
400
500
Elevation [m]
0
-10
-20
-30
-40
Sand
A
B1
B2
C1
C2
D
E1
E2
E3
F1
F2
F3
Till
BBC 1
BBC 2
POP = 120
Profile 2: σ'p
Profile 1: σ'p
σ'v0
Program
Oed.(1 day)
Oed.(EOP)
CRS
1966
1977
1980

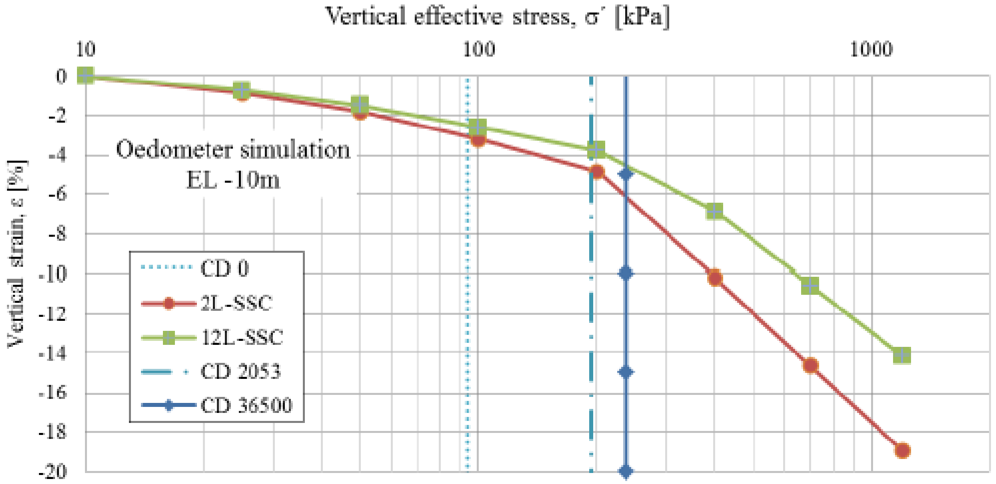
The trial embankment

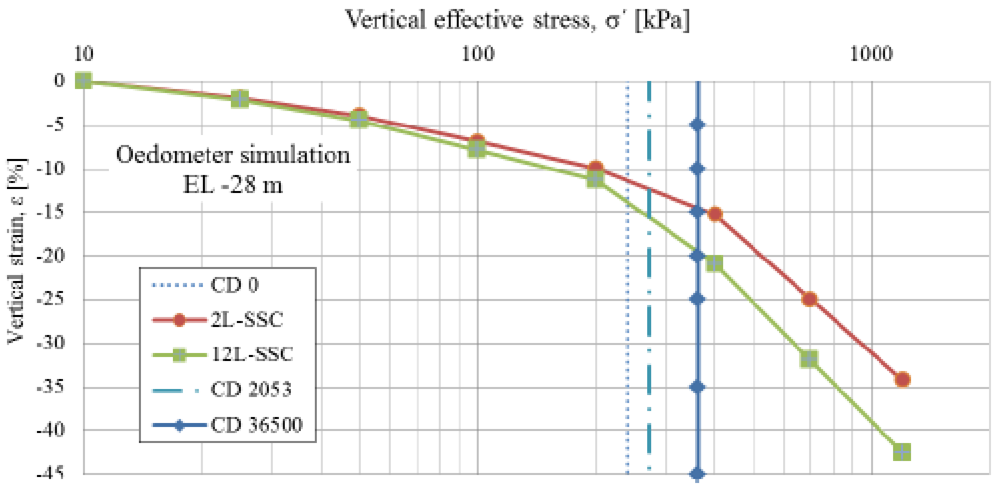


Alternative models

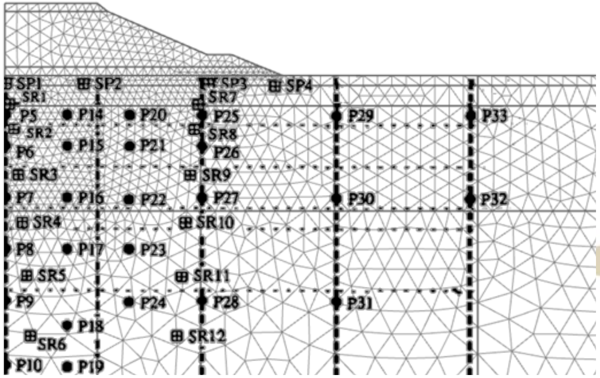


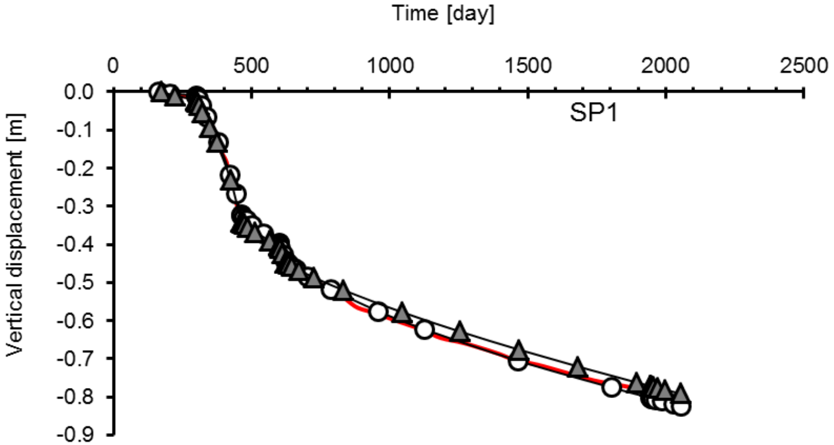
Oedometer simulations

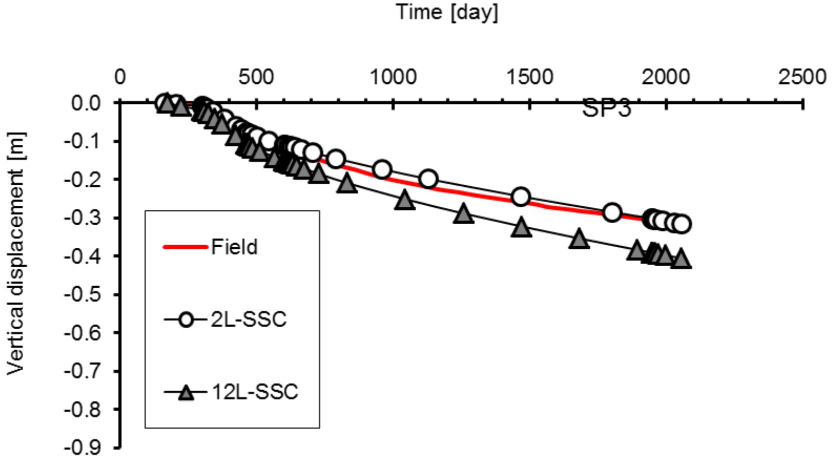


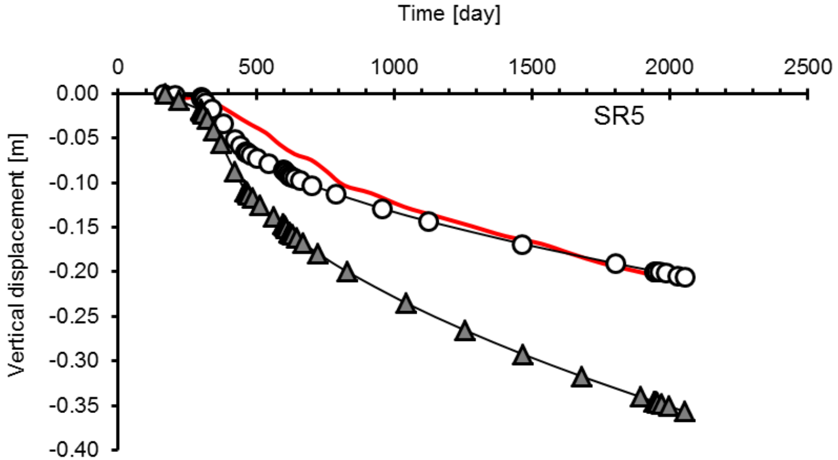


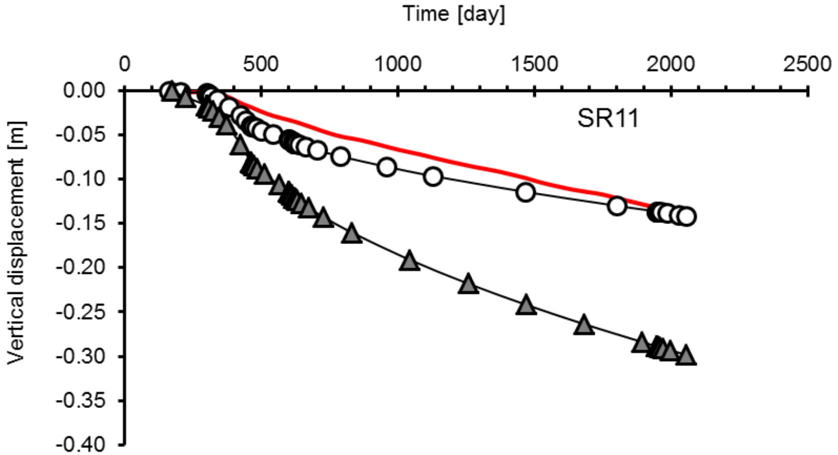
Results

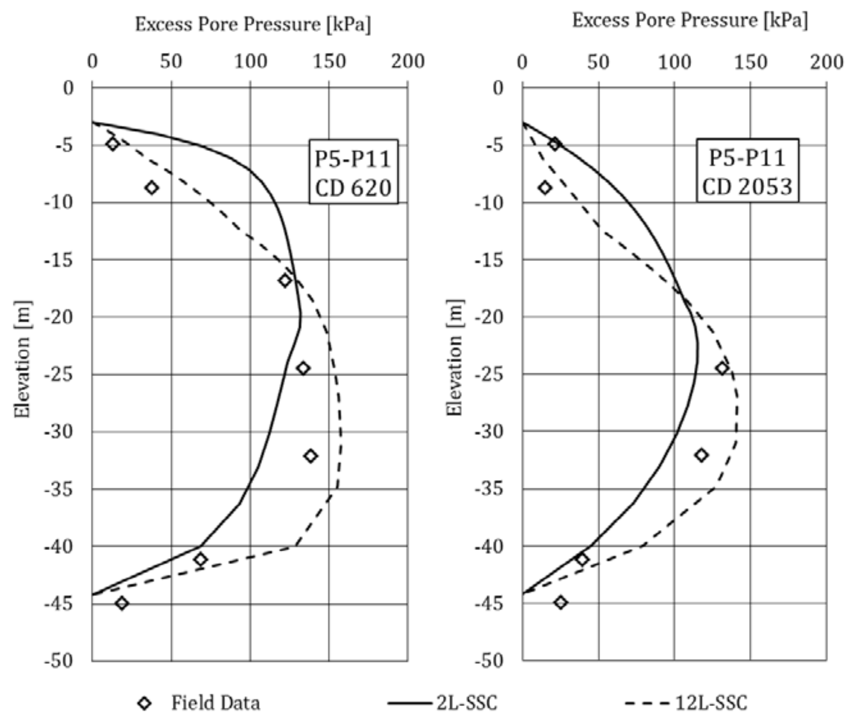

SP1
SR1
SP2
SP3
SR7
SP4
P5
P14
P20
P25
P29
P33
SR2
SR8
P6
P15
P21
P26
SR3
SR9
P7
P16
P22
P27
P30
P32
SR4
SR10
P8
P17
P23
SR5
SR11
P9
P24
P28
P31
P18
SR6
SR12
P10
P19

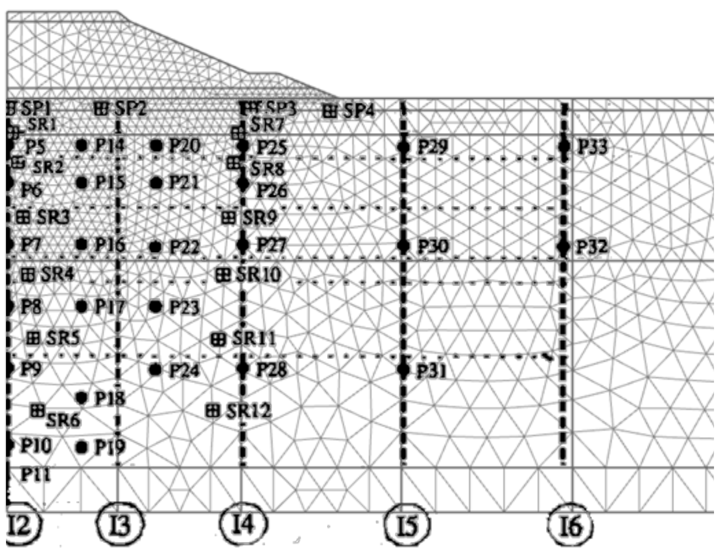

Time [day]
SP1
Vertical displacement [m]


Time [day]
SP3
Vertical displacement [m]
Field
2L-SSC
12L-SSC


Time [day]
SR5
Vertical displacement [m]


Time [day]
SR11
Vertical displacement [m]


Excess Pore Pressure [kPa]
Elevation [m]
P5-P11
CD 620
P5-P11
CD 2053
Field Data
2L-SSC
12L-SSC


SP1
SP2
SP3
SP4
SR1
SR2
SR3
SR4
SR5
SR6
SR7
SR8
SR9
SR10
SR11
SR12
P5
P6
P7
P8
P9
P10
P11
P14
P15
P16
P17
P18
P19
P20
P21
P22
P23
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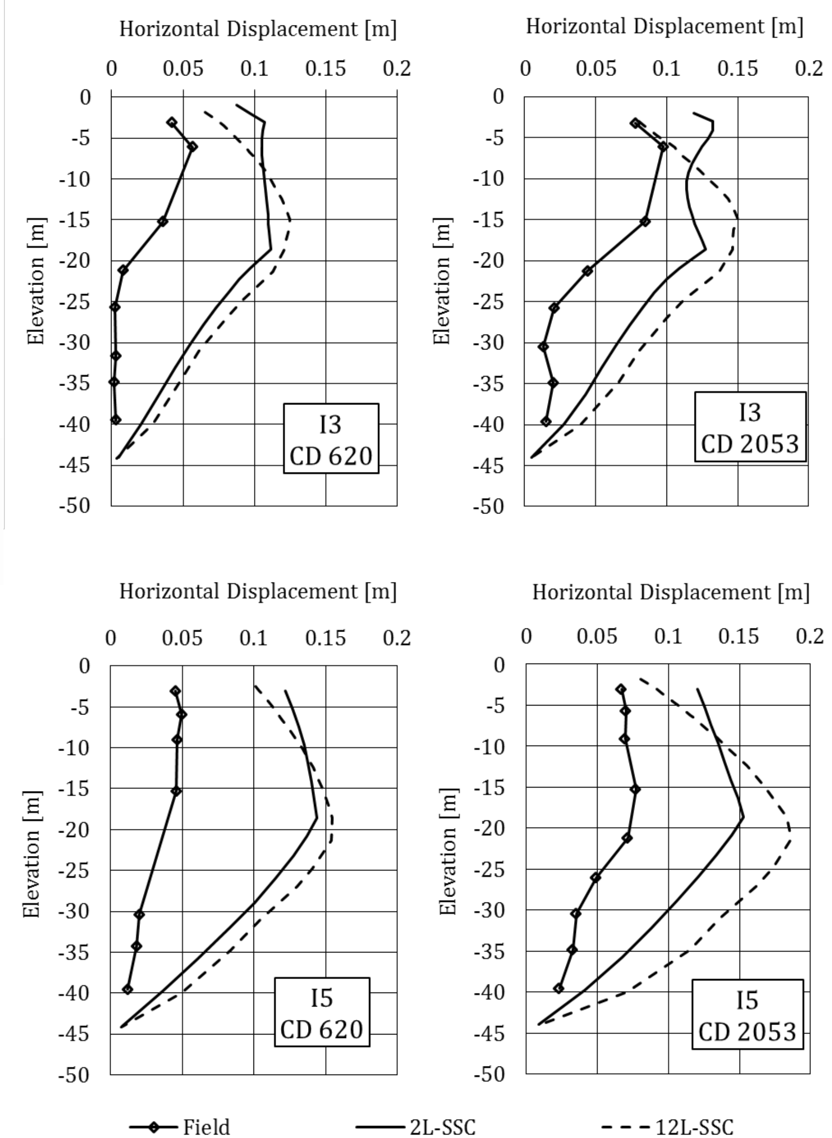
P32
P33
I2
I3
I4
I5
I6


Horizontal Displacement [m]
Elevation [m]
I3
CD 620
I3
CD 2053
I5
CD 620
I5
CD 2053
Field
2L-SSC
12L-SSC

Conclusions

- Evaluate the parameters over relevant stress increments
- Do not blindly take OCR from odeometer tests
  - Stress path
  - Sample disturbance
- The “simple” SSC model performs OK when we are after vertical deformation profile and pore pressure. As long as we take some care for the OCR we use in modelling.
  - NC clay does not usually have OCR of 1.1…
  - OCR in SSC is a material parameter that defines initial state of the soil (i.e. the state variable p_0^{eq}), it is not more holy than the other parameters that we use to fit our model to “reality”

$$\lambda^*,\ \kappa^*,\ \mu^*,\ \nu,\ \varphi,\ c,\ K_0^{NC}$$

Creep of Soft Clay: Exercise

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Adjunct Professor at NTNU

2st CREEP Course, Trondheim, Norway,

15-16. September 2014

NGI

CREBS

- 4 Workshops on CREep Behaviour of Soft clay)
  - NGI (Oslo, Norway, January 2006)
  - Univ. Stuttgart (Pisa, Italy, September 2007)
  - Univ. Chalmers (Gothenburg, Sweden, July 2009)
  - Deltares (Delft, Netherland, January 2014)

Establish a common basis of understanding “long term compaction in soft soil”

- analyse a set of well defined hypothetical cases

Example calculations

- Comparison of results obtained by different calculation programs (for a set of well defined cases)
- Comparison of material models
- Interpretation of laboratory tests (model dependent)
- Recommendations of laboratory tests and field investigation
- *Not a competition!*

Hypothetical cases

1. NC-behaviour (OCR=1)
2. NC-behaviour with apparent pre-consolidation
3. Varying time history (pre-loaded several years)
4. Layered soil profile (different permeability)
5. Stress distribution with depth (some shear strain)

The real case: Oslo Railroad Customs Building

- 50 years with measurements (may include additionally 30 years)

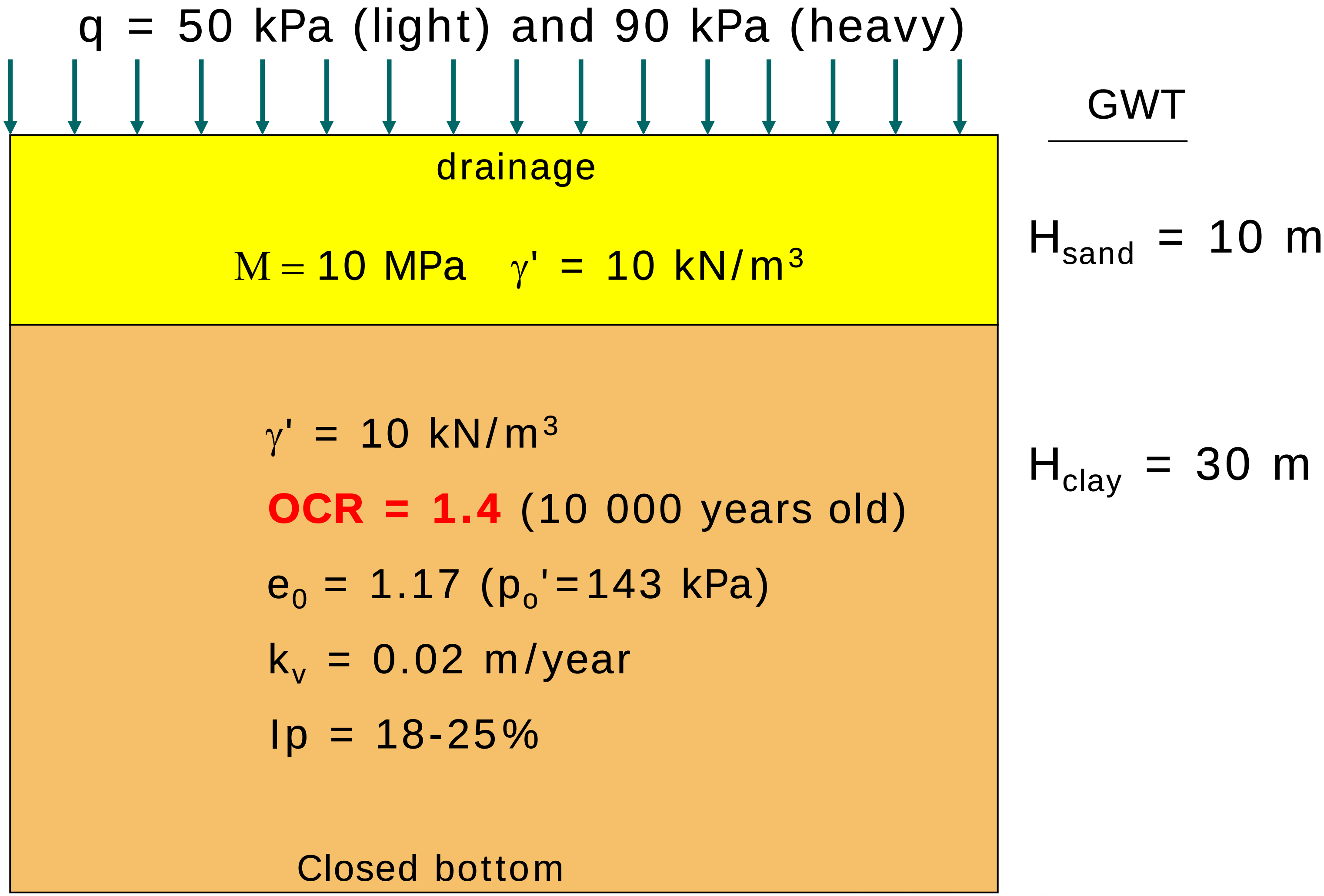
6 Participants

- University of Stuttgart
  - Dr. Martino Leoni and Professor Pieter Vermeer
- University of Strathclyde (and Ecole Central de Nantes)
  - Dr. Zhen-Yu Yin and Professor Minna Karstunen
- University of BRISTOL
  - Dr. David Nash
- Chalmers University of Technology (Gothenburg)
  - Mats Olsson and Professor Claes Alén
- Swedish Geotechnical Institute (SGI)
  - Per-Evert Bengtsson and Rolf Larsson
- Norwegian Geotechnical Institute (NGI)
  - Professor II Hans Petter Jostad

Models

- Plaxis (FE) with Soft Soil Creep and Anisotropic Creep (3D)
  - EVP, MCC, rotated modified CC, no structure, one creep parameter
- Plaxis (FE) with EVP SCLAY-1S (3D)
  - EVP, rotated modified CC, over-stress formulation, structure, two creep parameters
- Briscon (FD) with a general isotache model (1D)
  - EVP, structure, stress dependent creep parameter
- Embankco (FD) with an isotache model (1D)
  - EPVP, structure and threshold value for creep
- GeoSuite (FE) with two slightly different isotache models (1D)
  - EPVP, structure by stress dependent creep

Hypothetical case 2

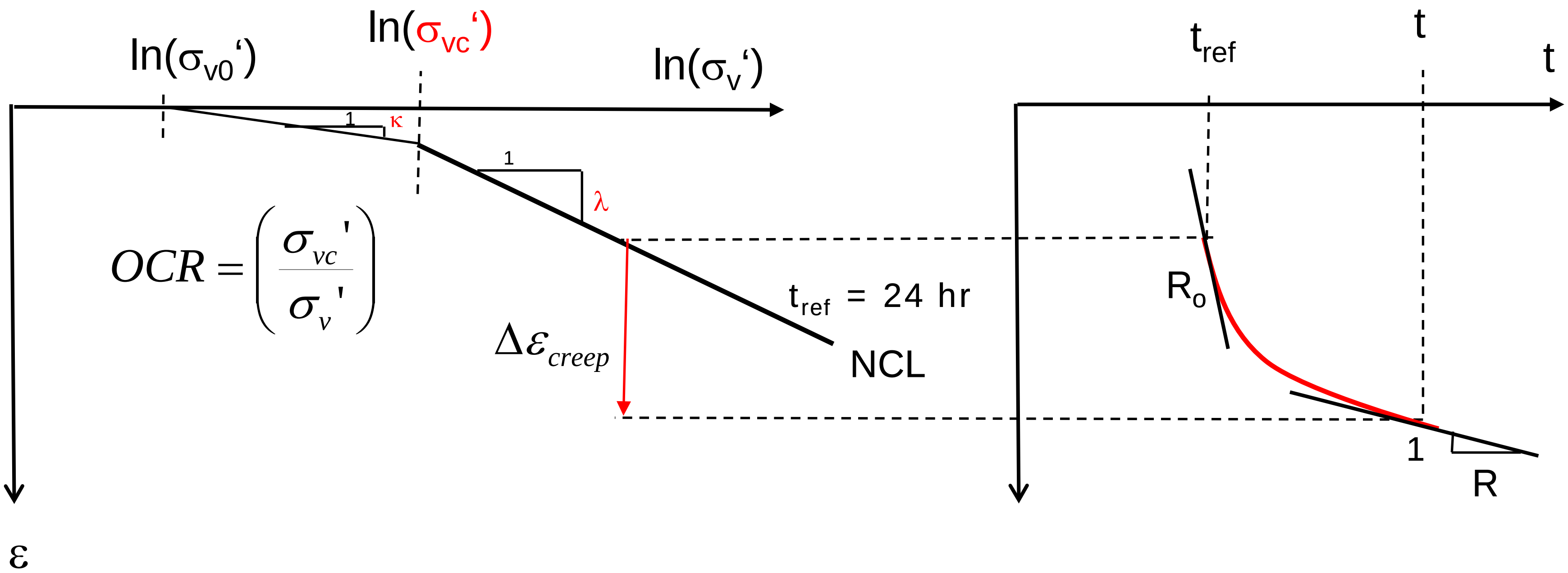


Main assumption

1. Fully saturated clay (incompressible pore water)
2. 1D Condition
   a. 1D pore water flow with defined drainage conditions
   b. Negligible horizontal strains (oedometer condition)
3. Uniform material (only changes in stress levels and initial void ratio) within the soil layers
4. Assumed “perfect” oedometer test data?

   Effect of sample disturbance?

Soft Soil Creep – input parameters



$$\Delta\varepsilon_{creep} = \mu^* / t_{ref} \ln\left(\frac{t}{t_{ref}}\right) = (\lambda^* - \kappa^*)\ln(OCR)$$

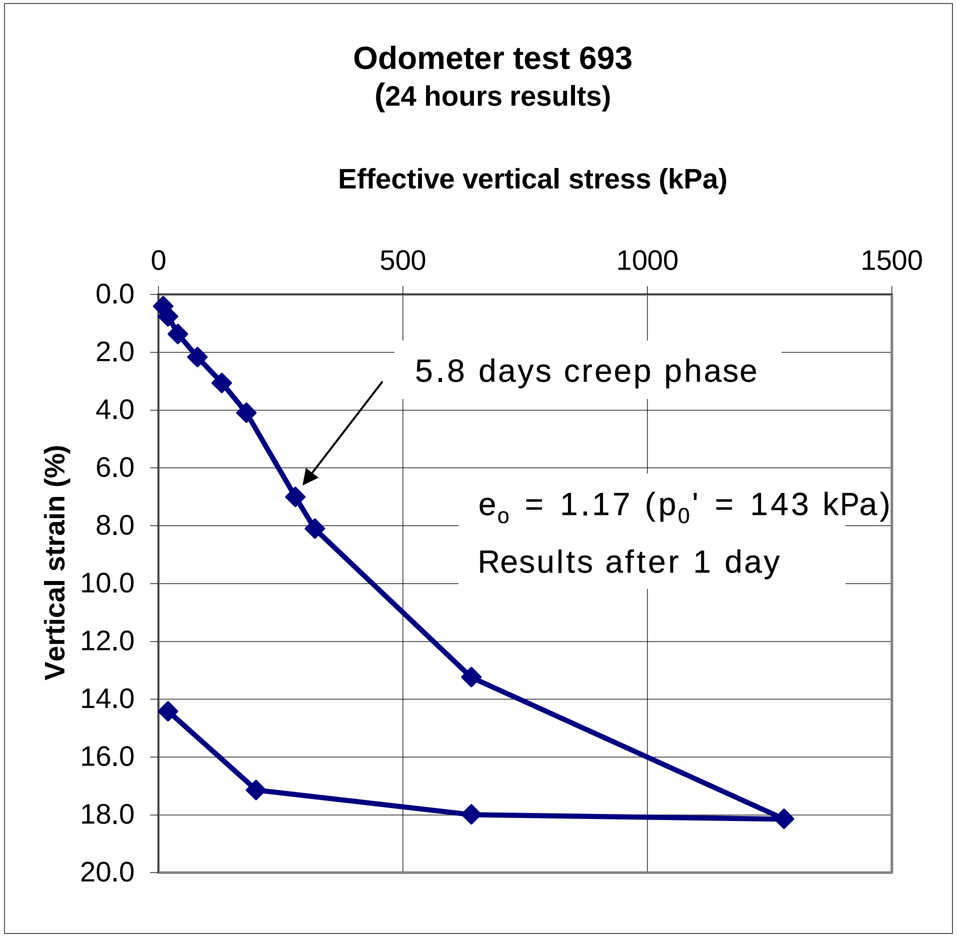
$$r = \frac{1}{\mu^*}$$

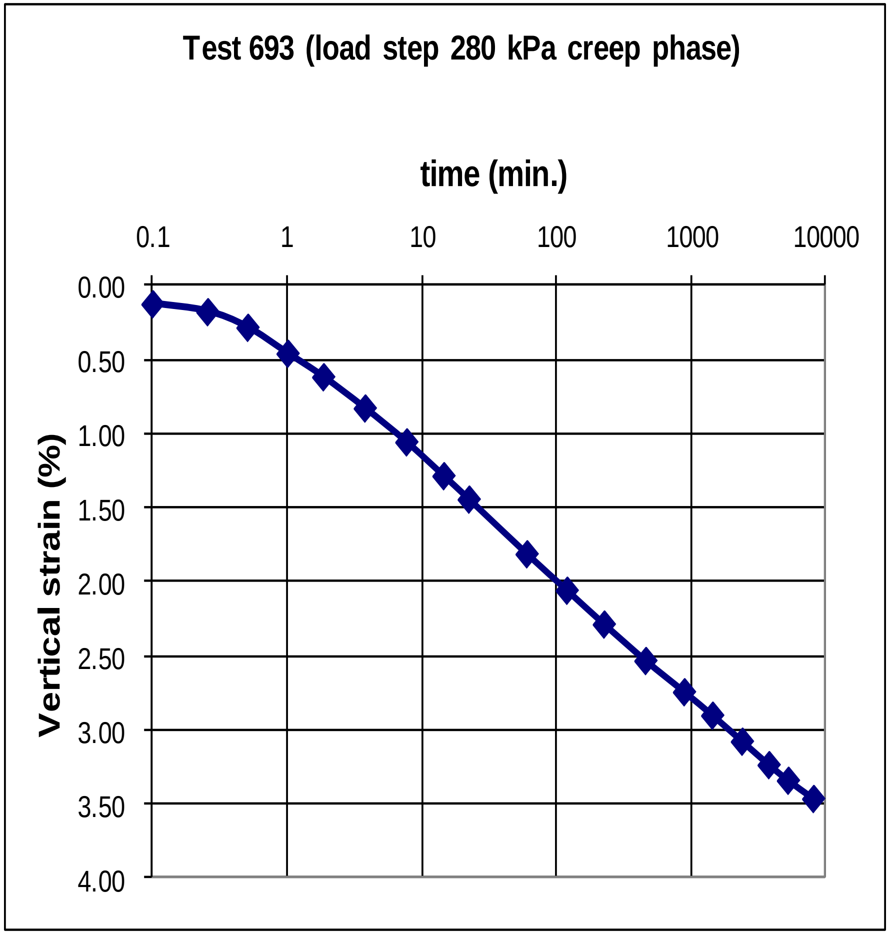
$$R = R_o e^{(r\,\Delta\varepsilon_{creep})} = R_o OCR^{\frac{\lambda^* - \kappa^*}{\mu^*}} = \frac{t_{ref}}{\mu^*} OCR^{\frac{\lambda^* - \kappa^*}{\mu^*}}$$

$$R_o = \frac{t_{ref}}{\mu^*}$$

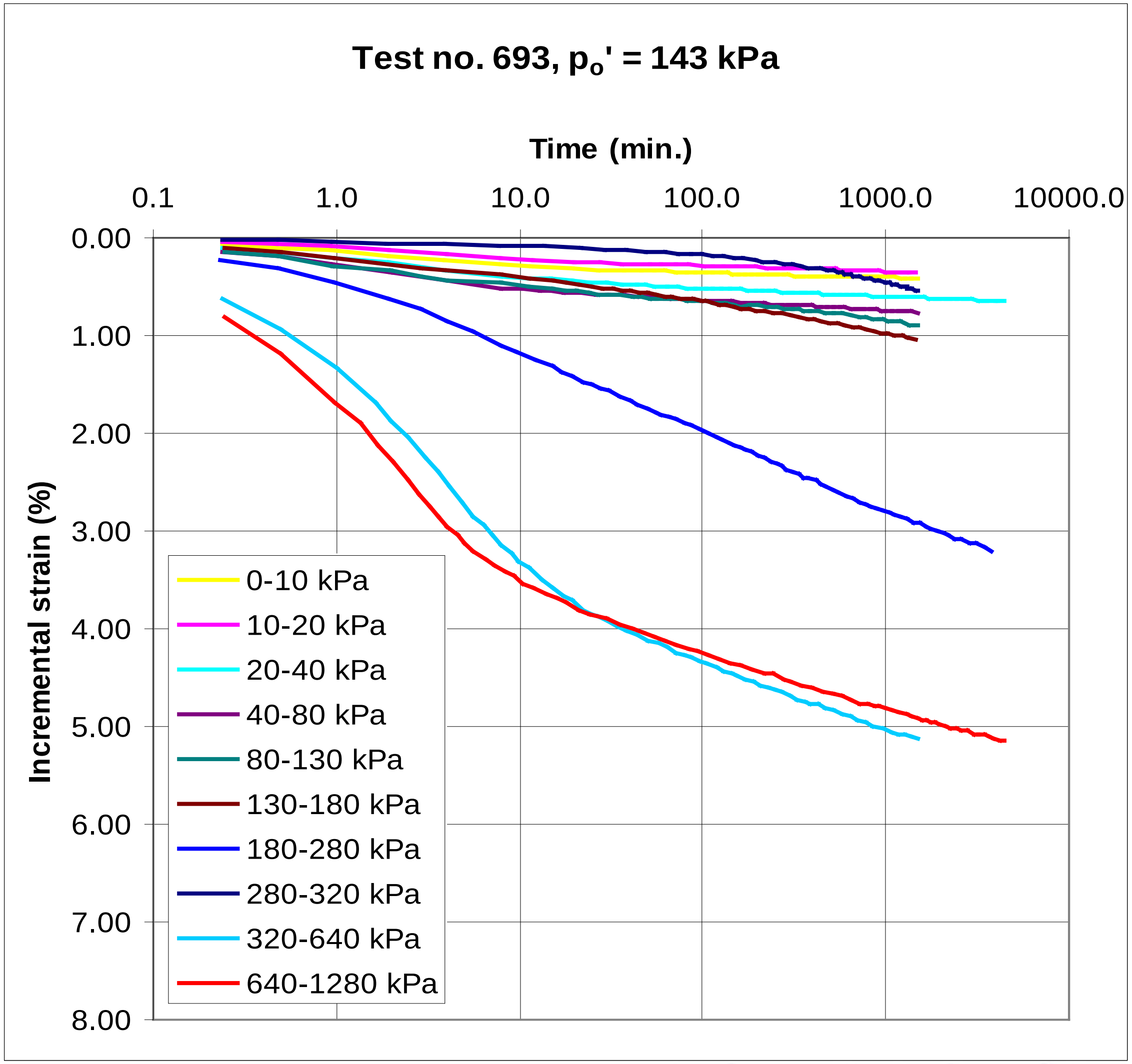
Oedometer results – standard IL test

20 mm sample with drainage at top and bottom

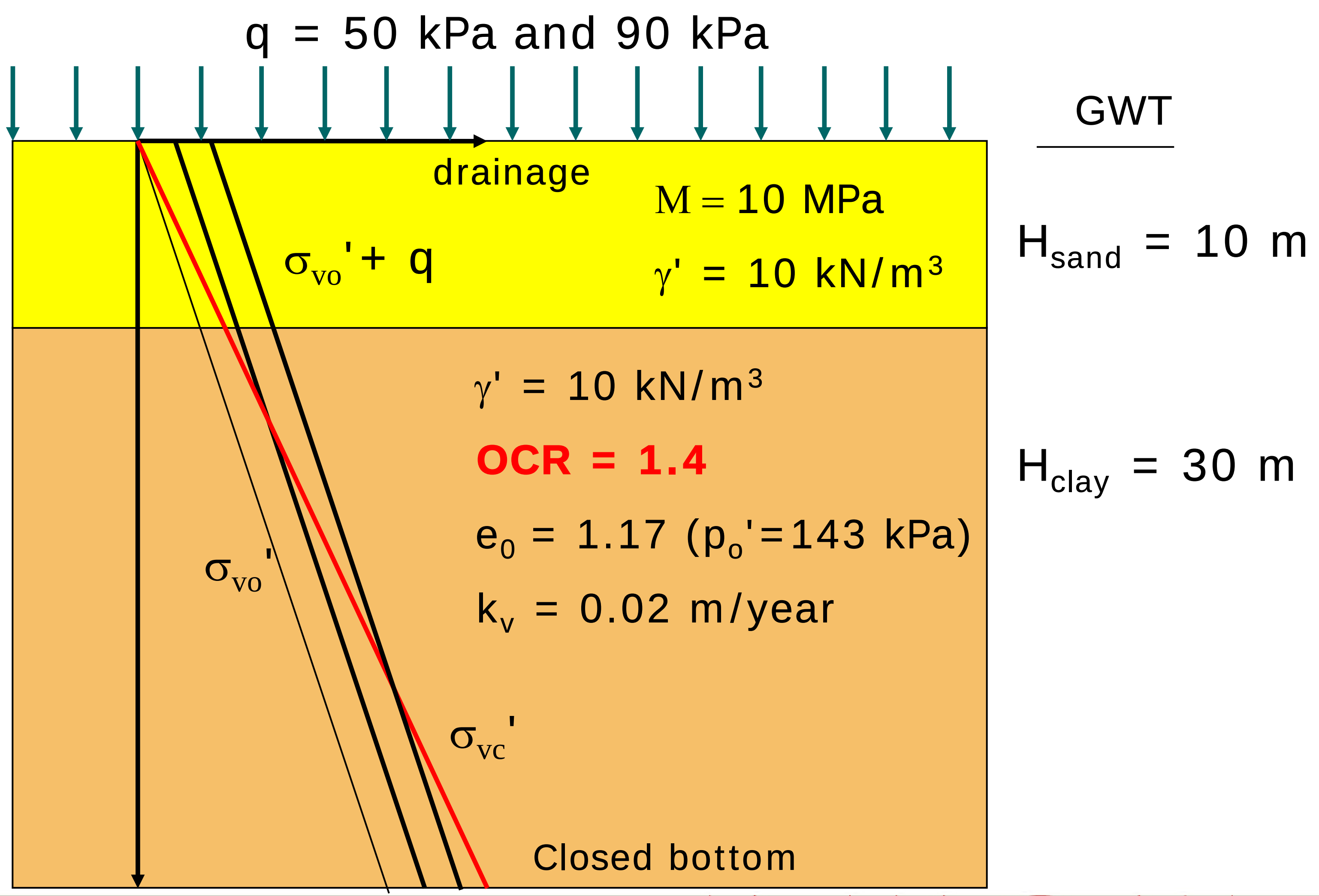


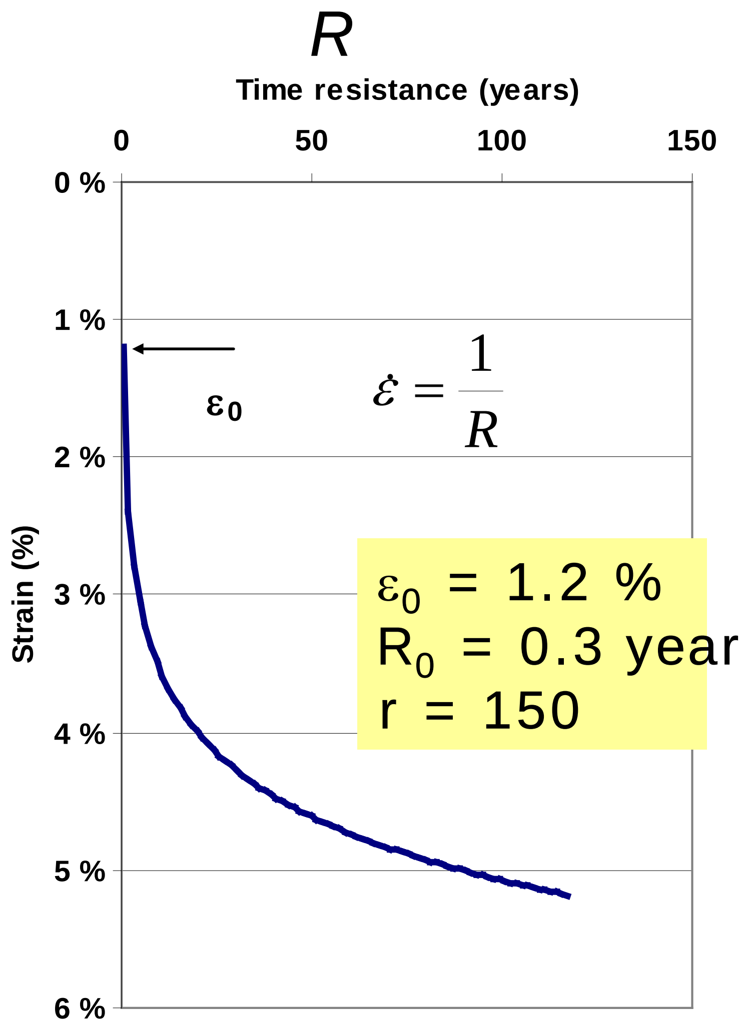


Oedometer test data

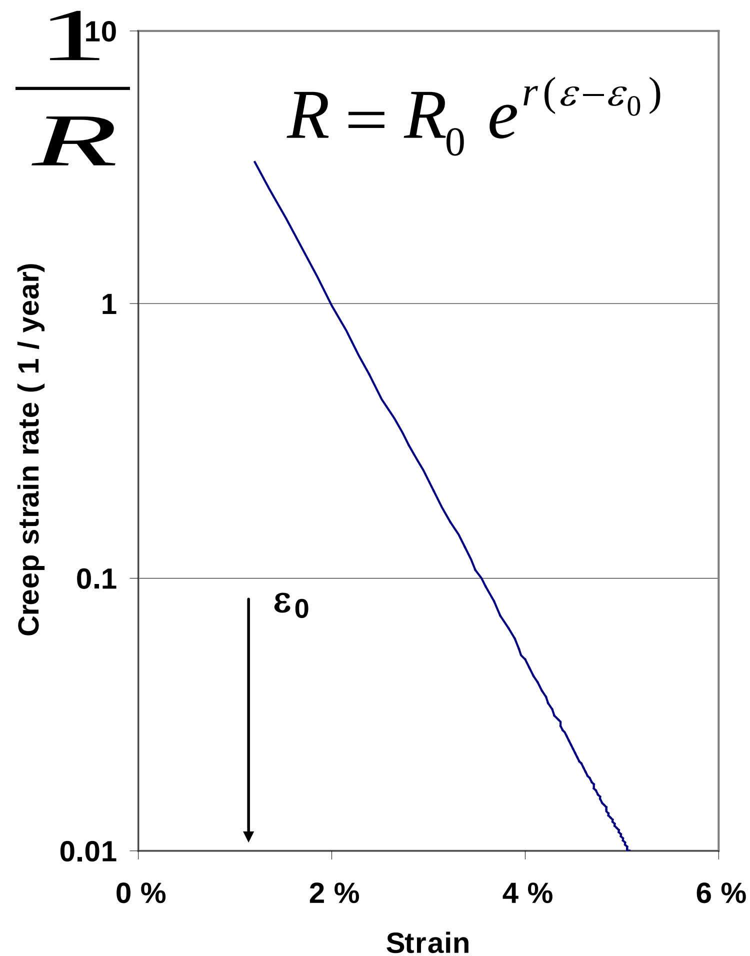


Hypothetical cases



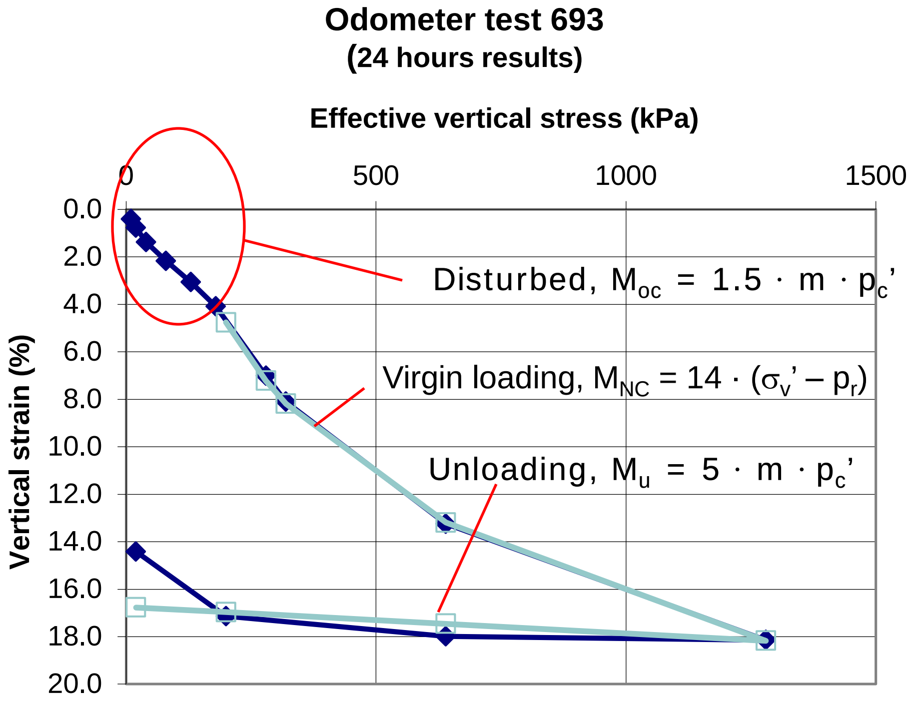


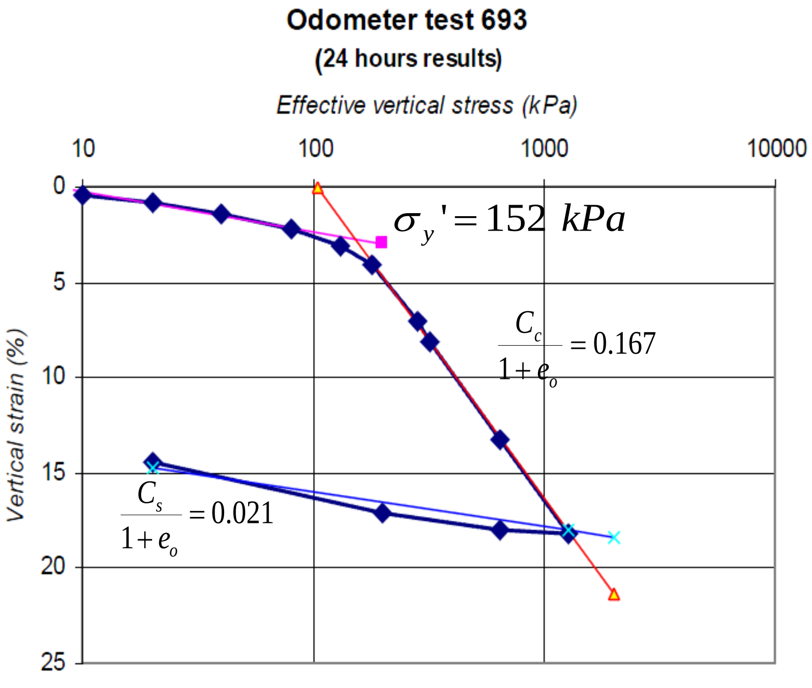
R
Time resistance (years)
0
50
100
150
0 %
1 %
2 %
3 %
4 %
5 %
6 %
Strain (%)
ε_0
$\dot{\varepsilon} = \frac{1}{R}$
ε_0 = 1.2 %
R_0 = 0.3 year
r = 150



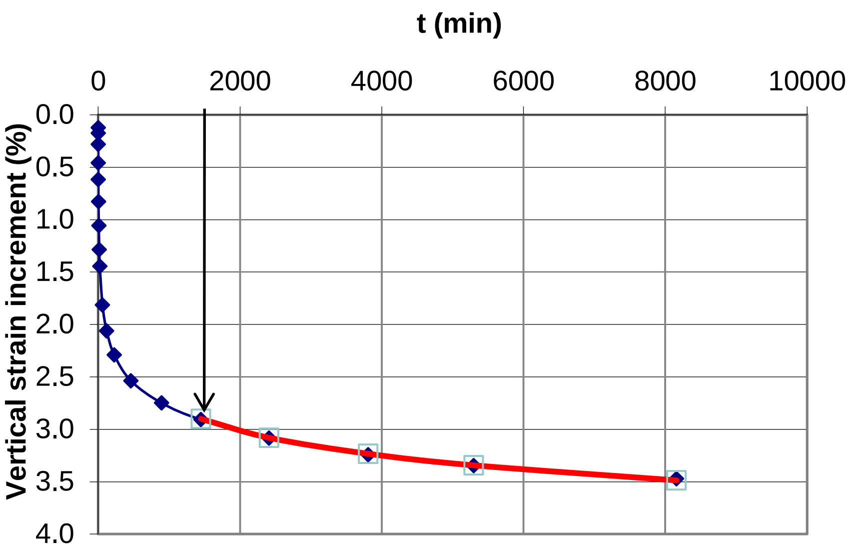
$\frac{1}{R}$
$R = R_0\, e^{r(\varepsilon - \varepsilon_0)}$
10
1
0.1
0.01
Creep strain rate (1 / year)
ε_0
0 %
2 %
4 %
6 %
Strain

Interpretation – reference strain (24 hours)

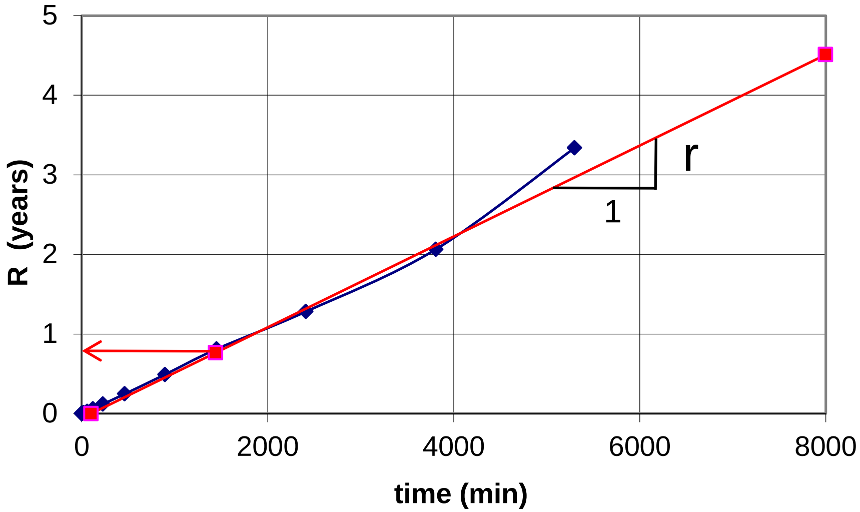




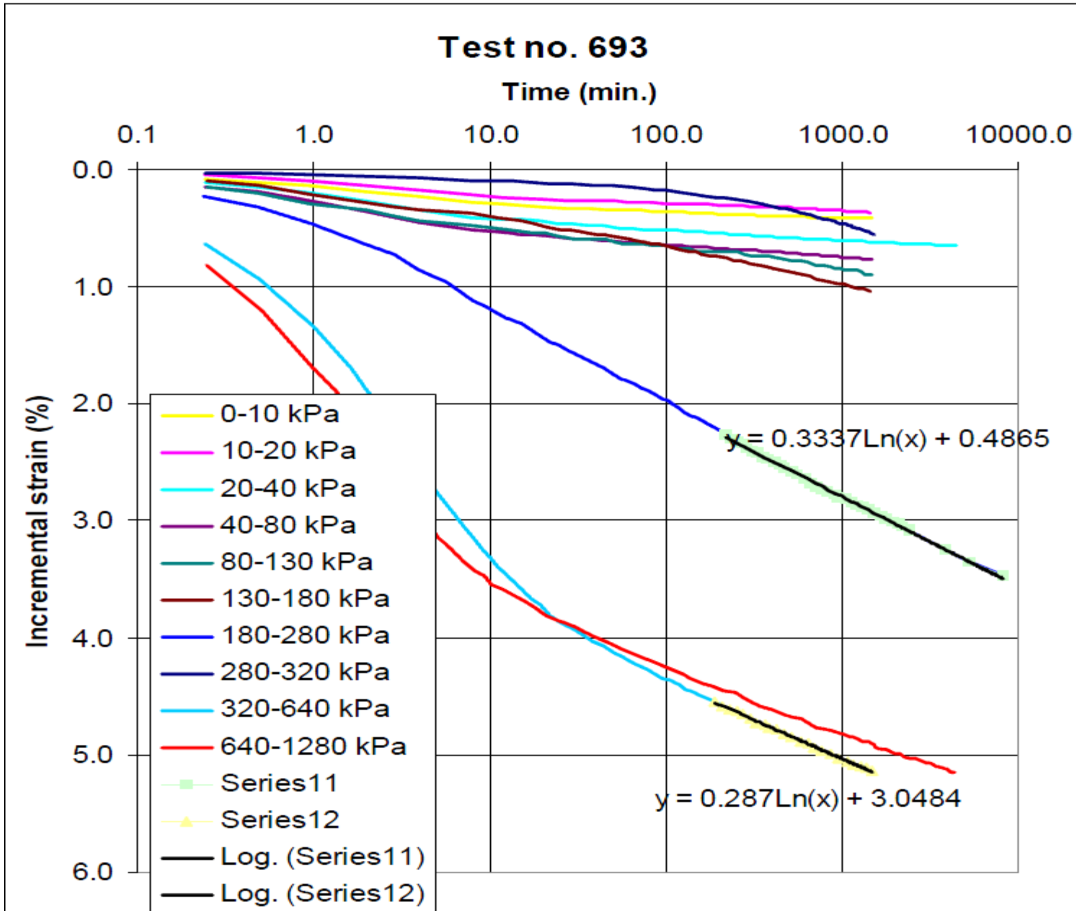
Interpretation - creep phase (NC-regime)



$$R = R_o + r\,(t - t_o)$$



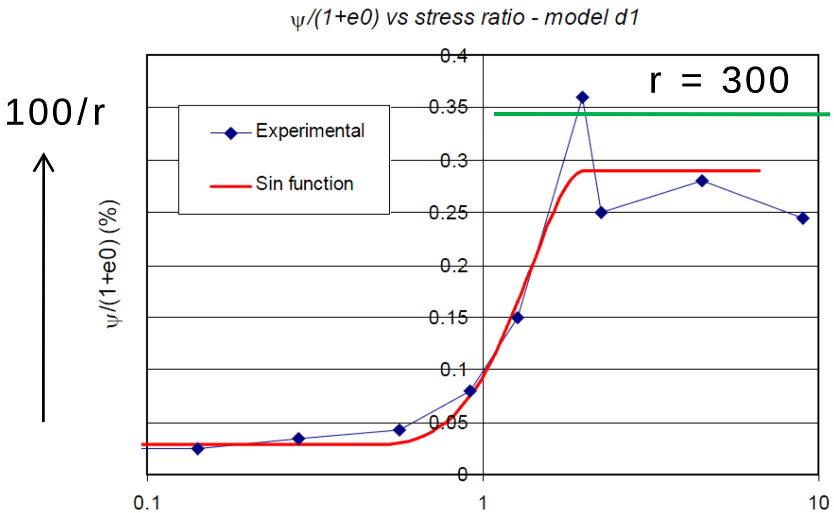
Interpretation - creep phase (NC-regime)

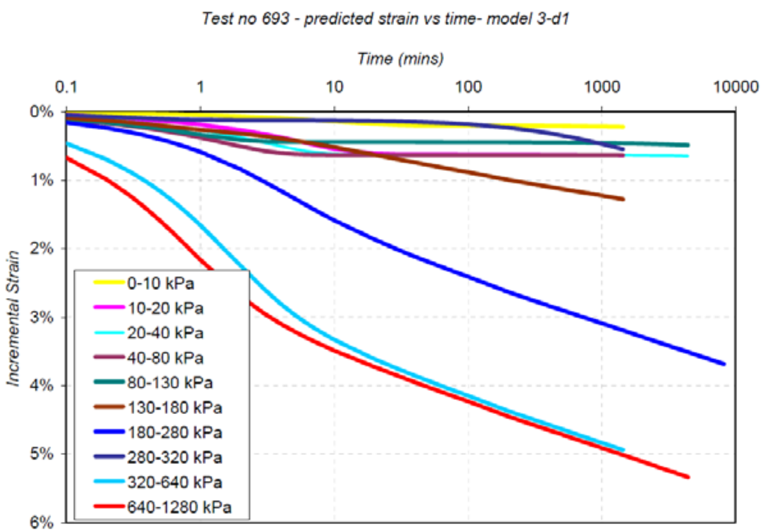


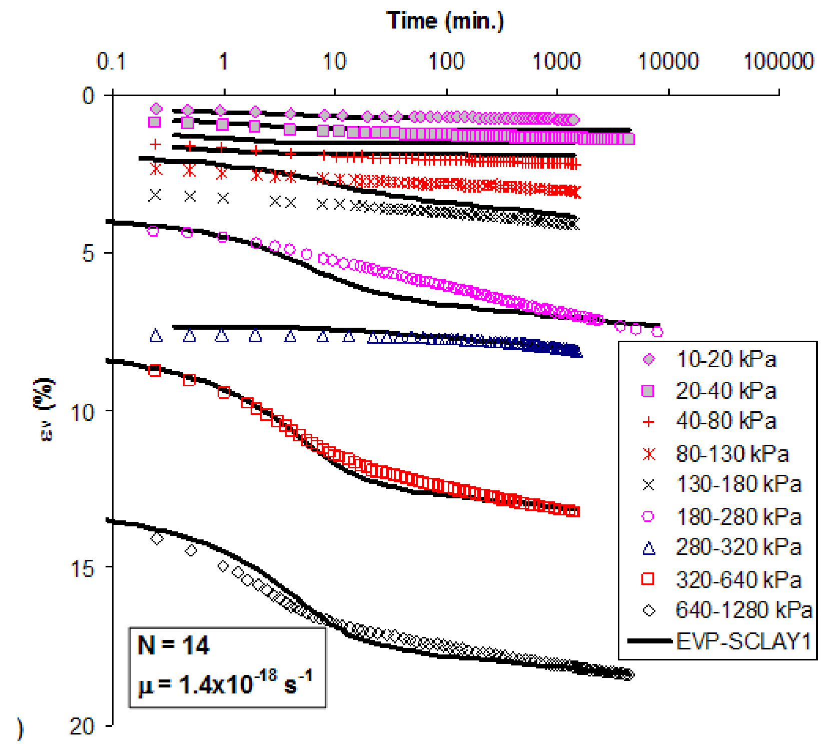
$$\Delta\varepsilon_{creep} = \frac{C_\alpha}{1+e}\log\left(\frac{t}{t_o}\right)$$

$$\Delta\varepsilon_{creep} = \mu^* \ln\left(\frac{t}{t_o}\right)$$

Interpretation - creep phase (OC-regime)

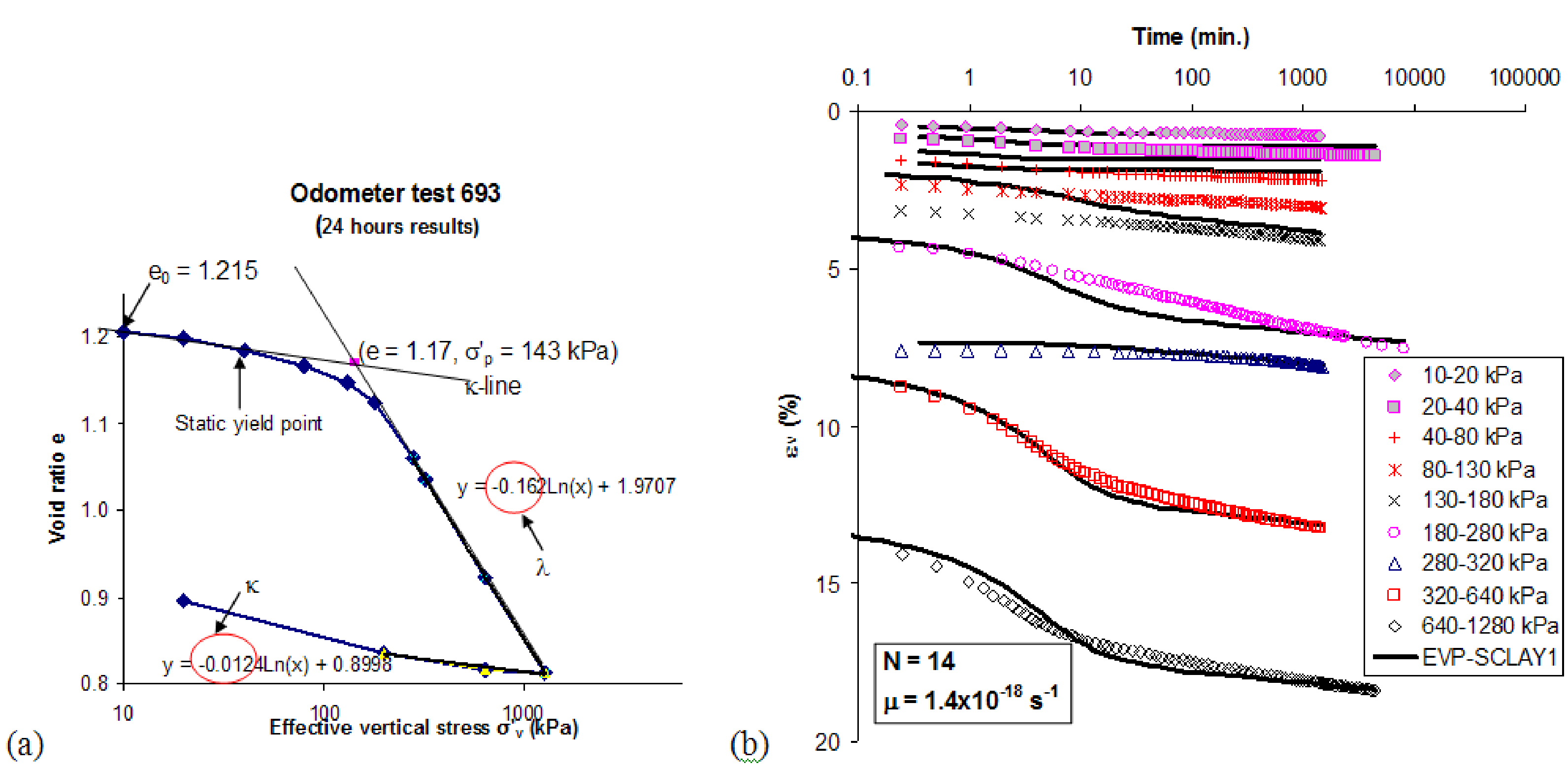






NB! Creep from one increment affects the creep in the next increment

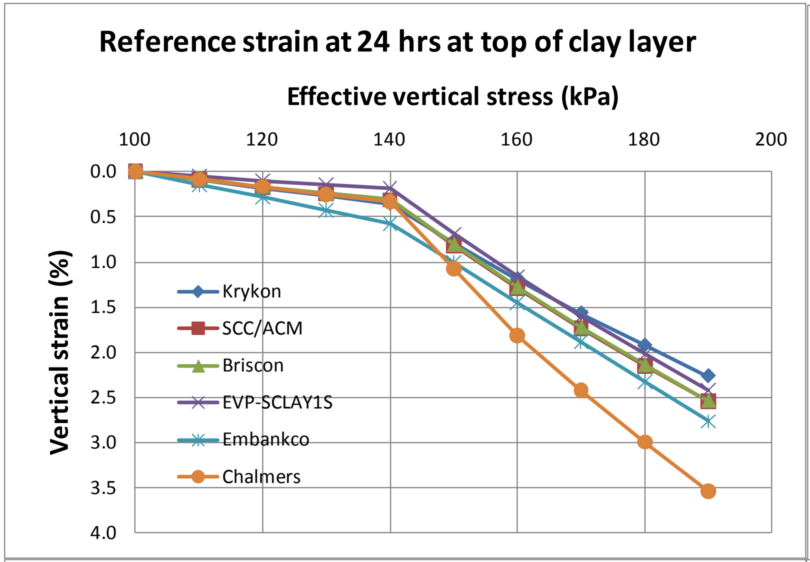
EVP-SCLAY1S - interpretation

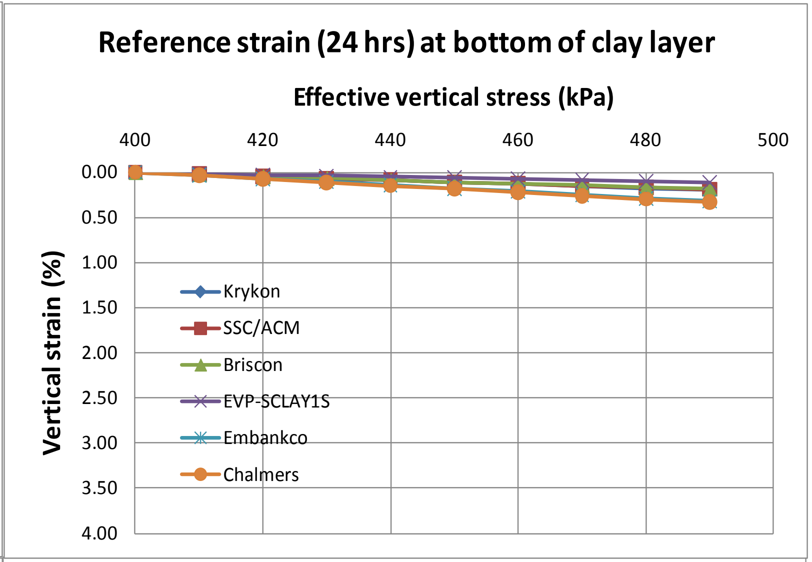


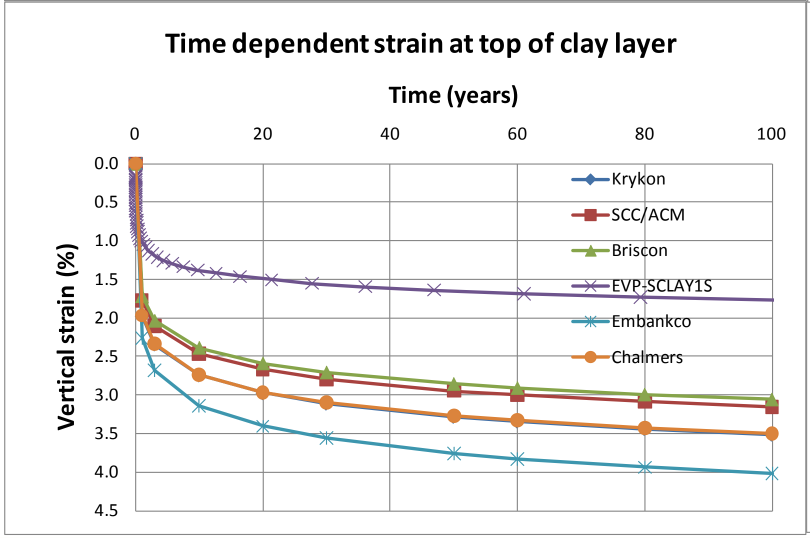
$$\lambda^* = \frac{\lambda}{1+e_o} = 0.162/(1+1.215) = 0.073$$

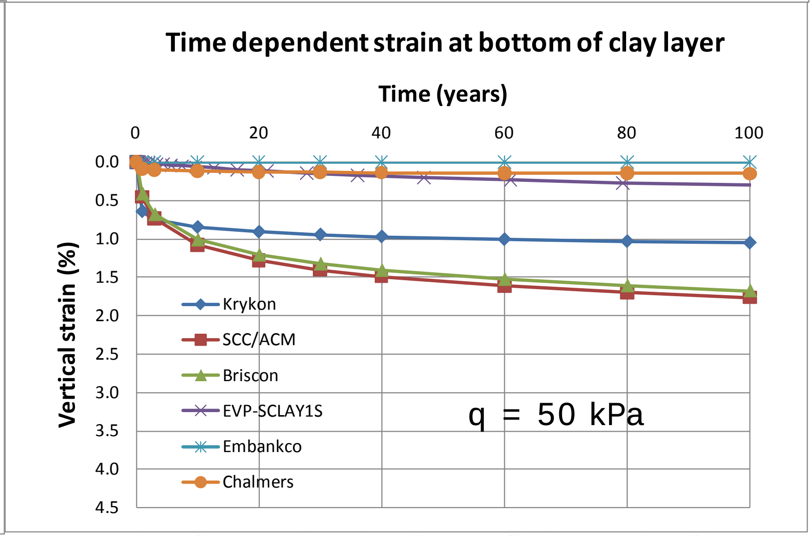
e_0	υ'	κ	λ	M	α_0	ω	ω_d	N	μ (s^{-1})
1.215	0.2	0.012	0.162	1.24	0.47	21	0.8	14	$1.4\text{x}10^{-18}$

Comparison of stress-strain-time curves

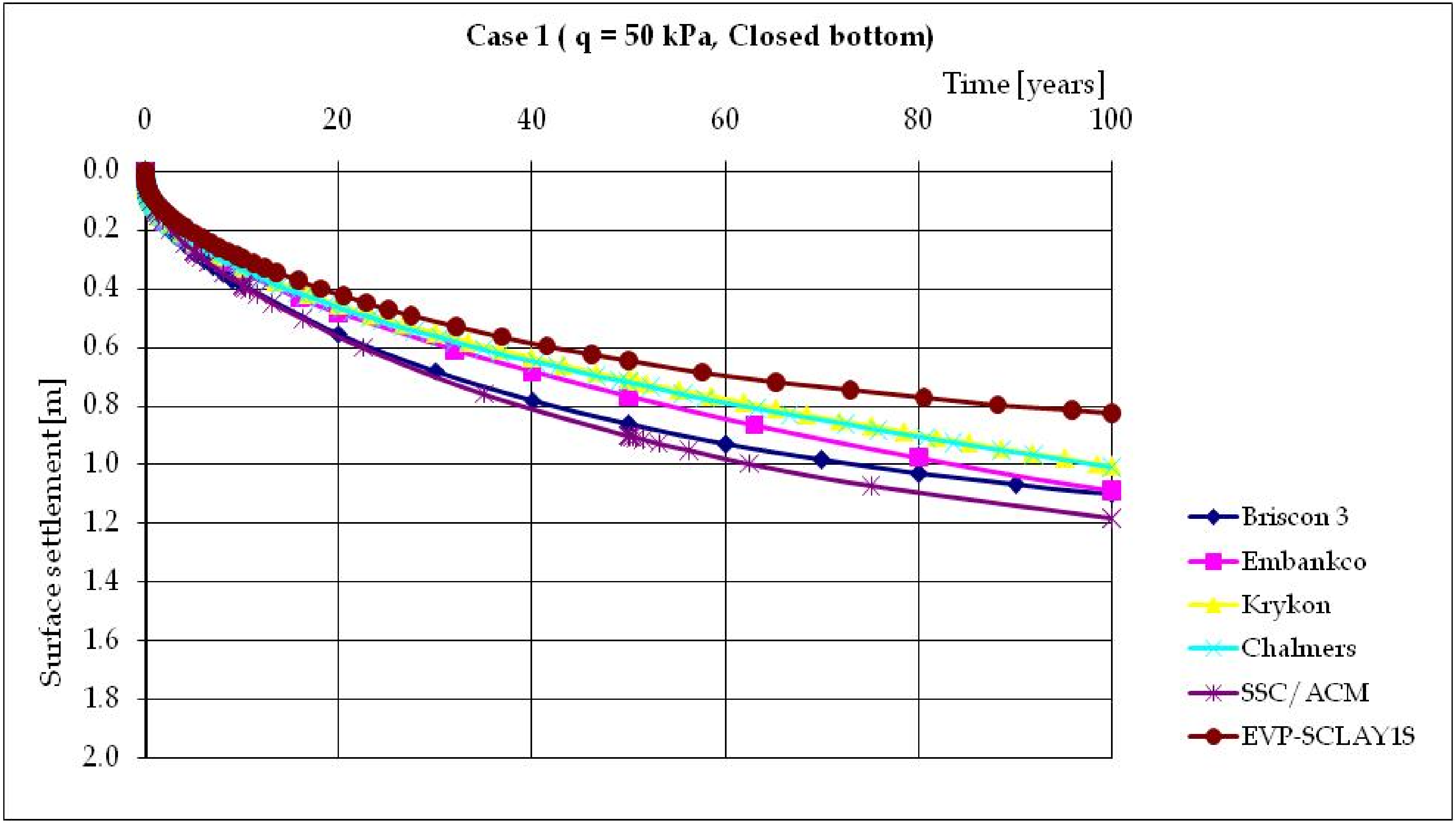




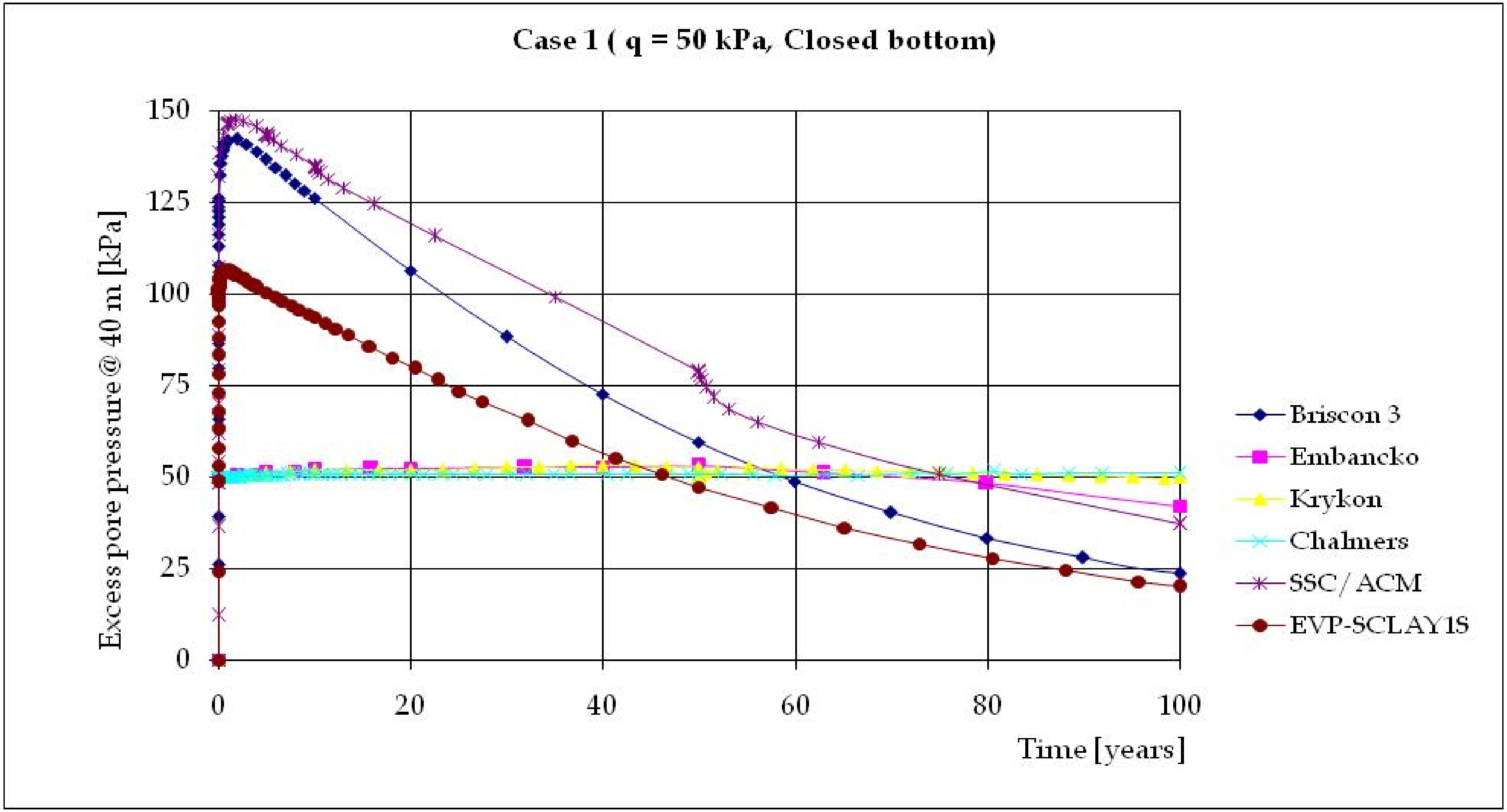




Results – Case 1

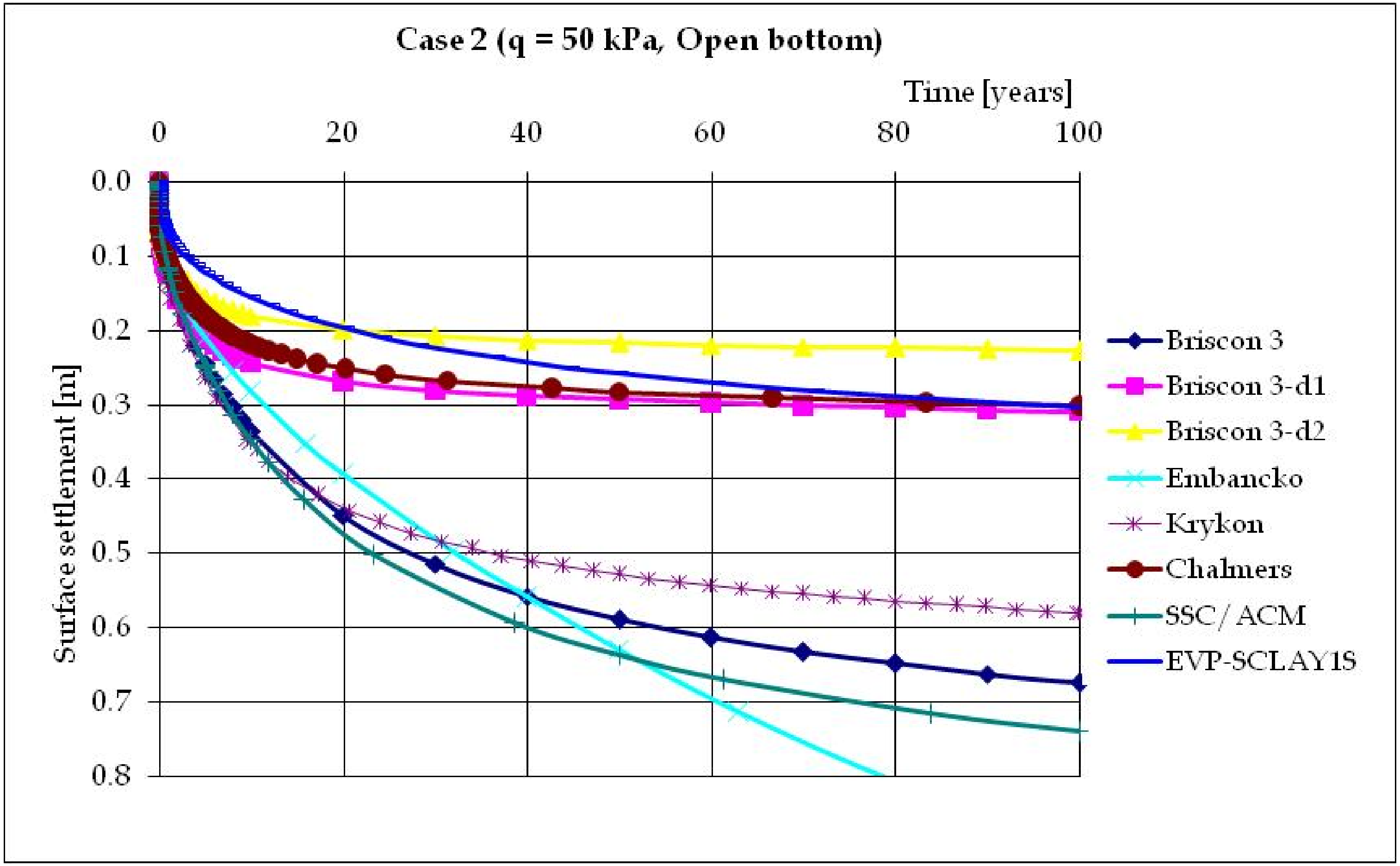


Results – Case 1

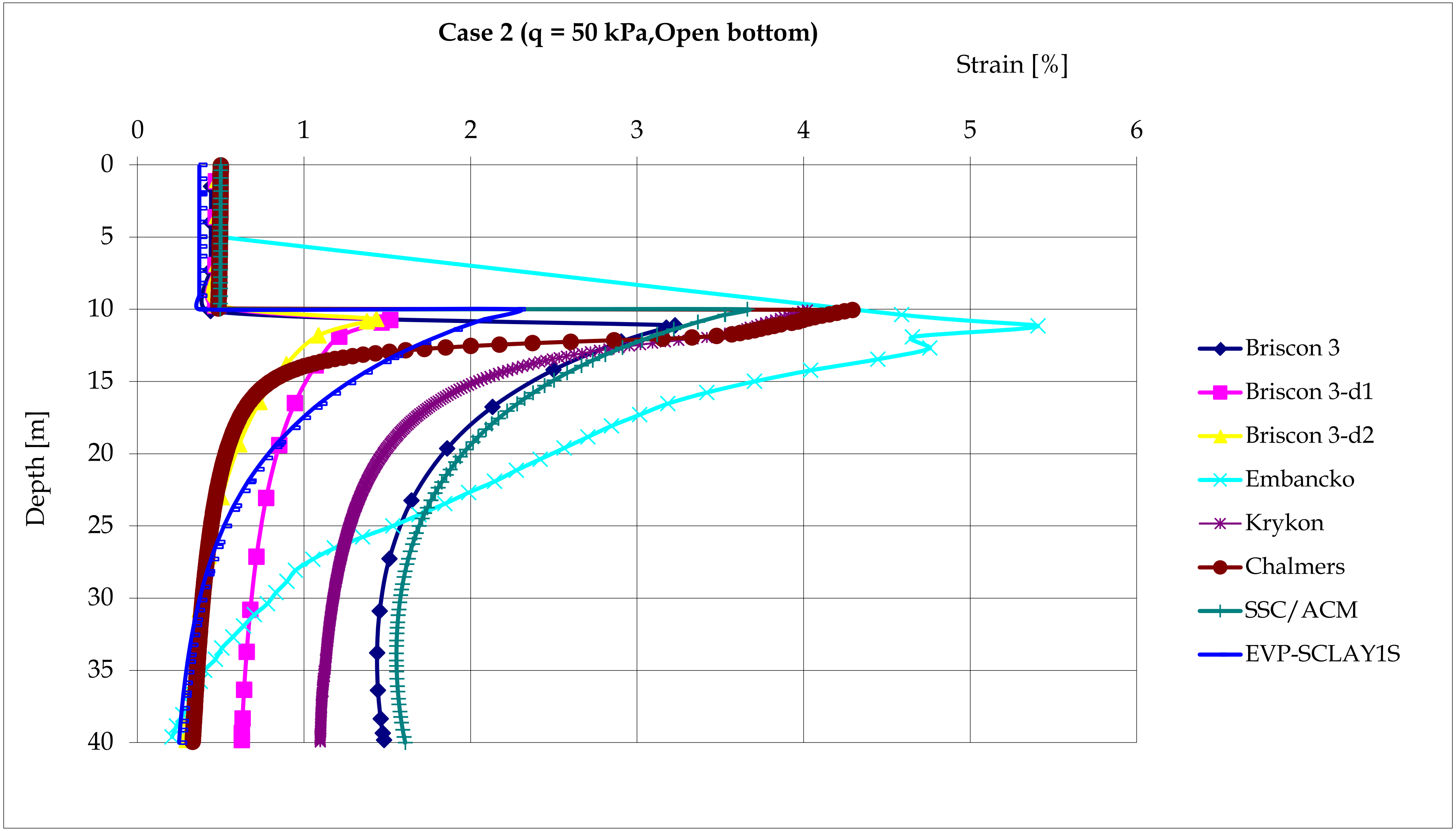


Generation of pore pressure due to creep? $\frac{\partial u}{\partial t} < 0?$

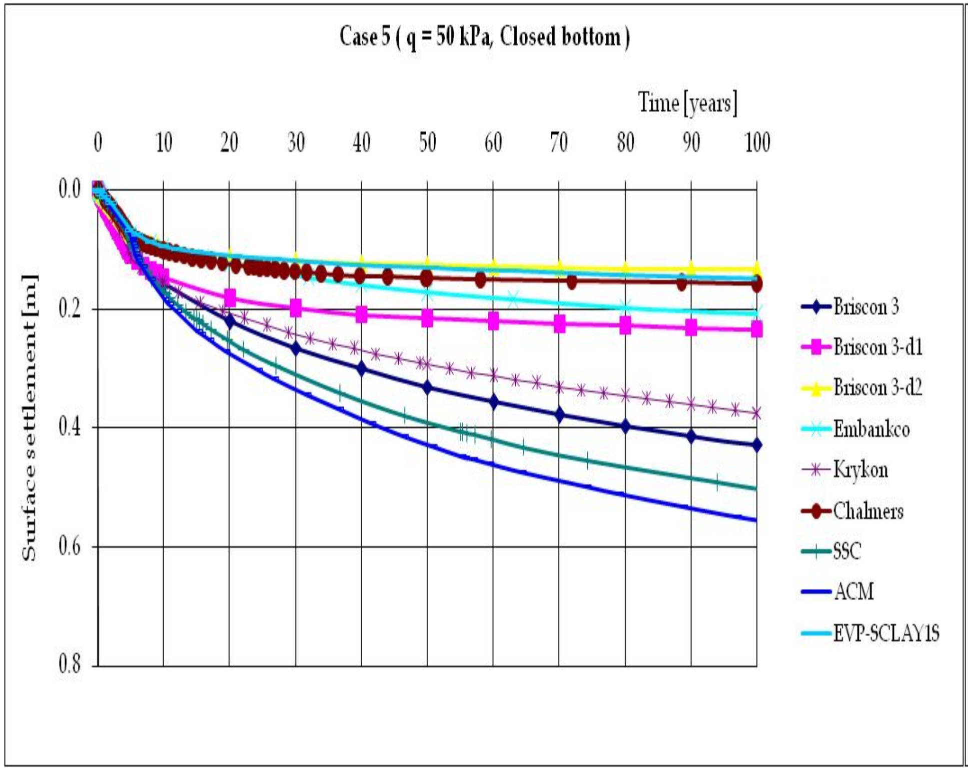
Results – Case 2



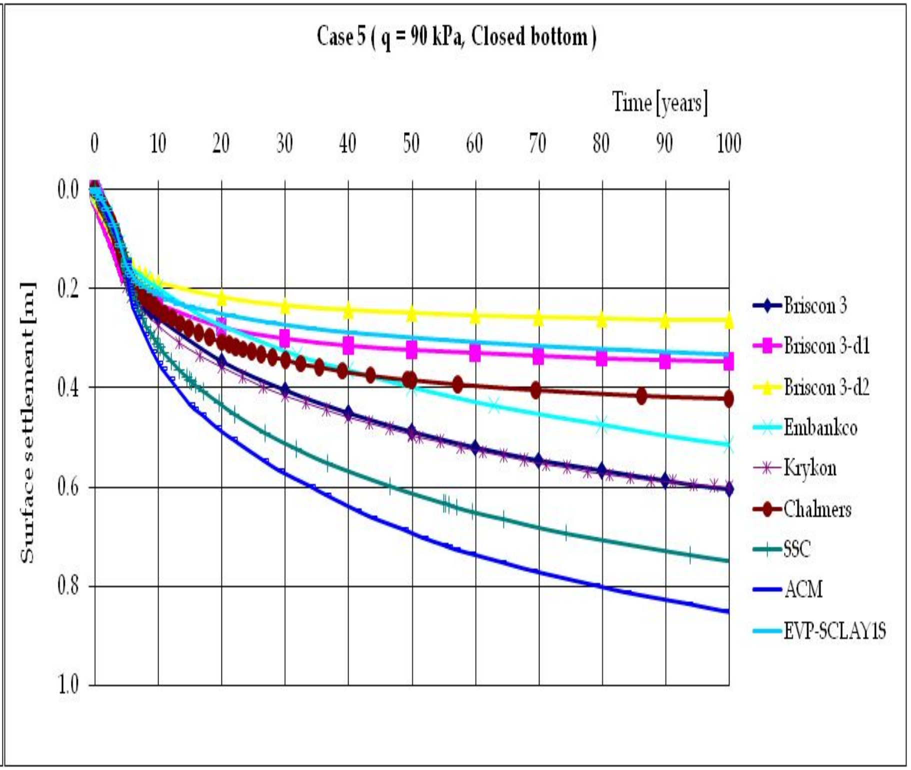
Results (strain after 50 yr)



Results – Case 5



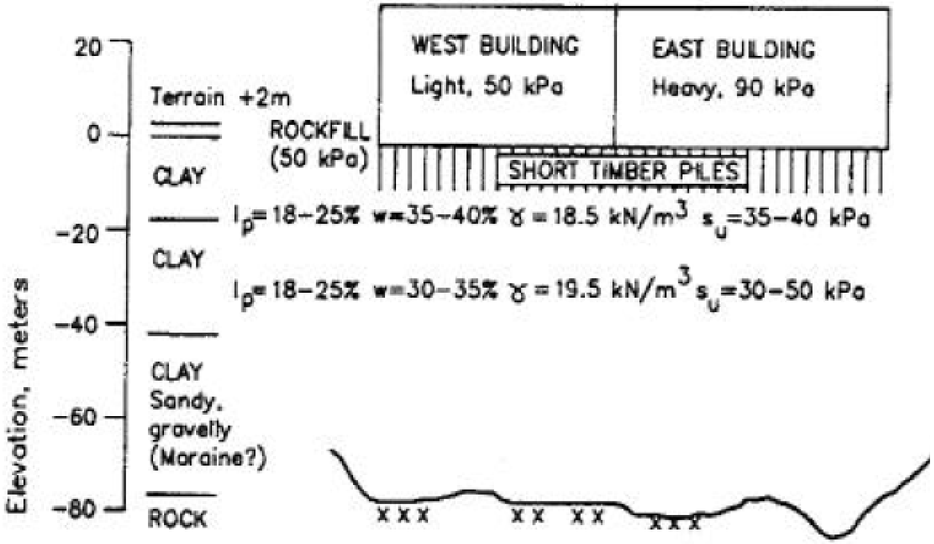
Light building

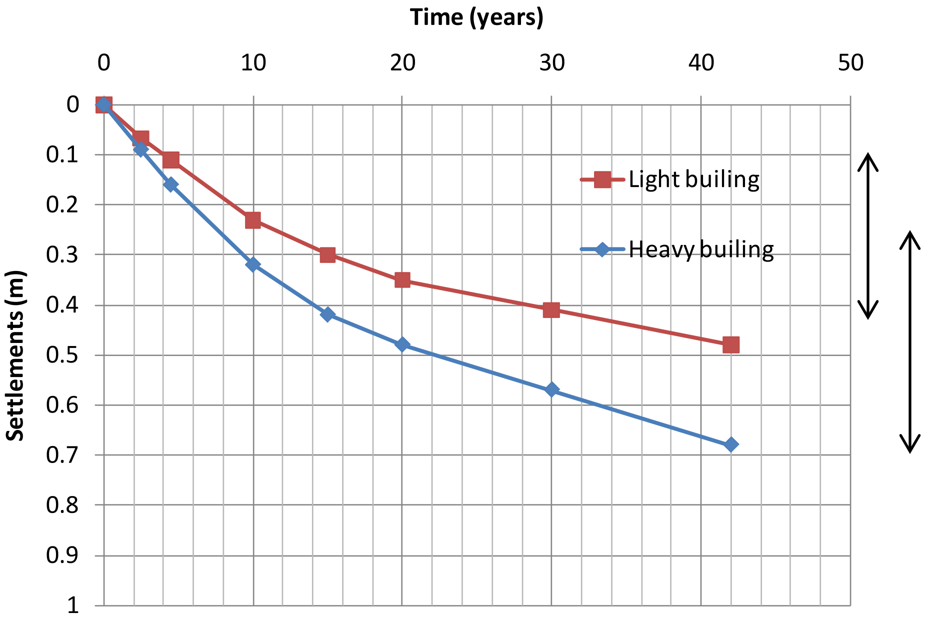


Heavy building

Oslo Railroad Customs Building

Measured Results





Conclusions

- *Large differences in settlements for well defined idealized examples*
- *The main reason is uncertainties in the creep behaviour before the yield stress (apparent pre-consolidation pressure)*
- *The differences may have been even larger due to uncertainties in the pre-consolidation pressure (if not given!)*
- *The programs and material models seems to work well (except EMBANCKO?)*
- *Difficult to check the results obtained with the general 3D models (especially EVP-SCLAY1)*
- *Difficult to compare models due to different sets of input parameter even when they are based on the same framework*

Creep Modelling of Soft Soils

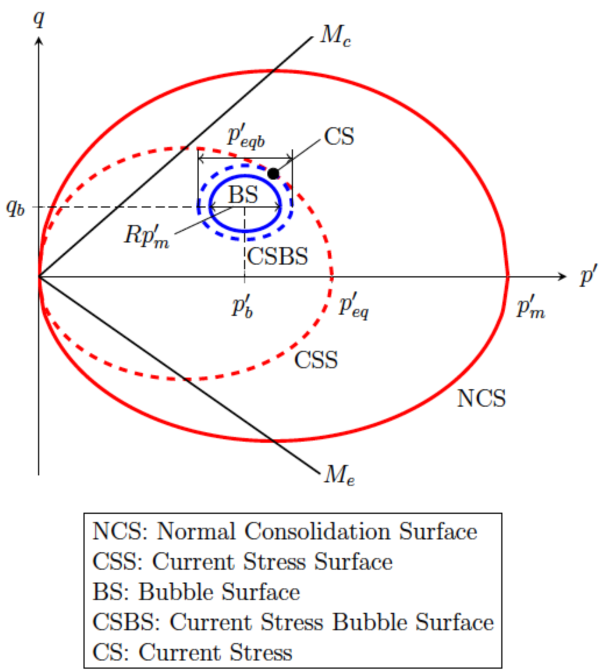
Final remarks

Jelke Dijkstra

Final Remarks

- Should we start incorporating kinematic hardening models to capture unloading/reloading + creep (DMW)
  - Already a model in development (Chalmers/NGI)

  by Nallatamby Sivasithamparam



Final Remarks

- Should we start incorporating kinematic hardening models to capture unloading/reloading + creep (DMW)
  - Already a model in development (Siva@NGI)
- Fibre overlay model + clay model = peat? (DMW)
- Creep in sand is not only governed by grain crushing (DMW)
- Hypothesis B is the only physical realistic explanation (HPJ)
- Extrapolation of laboratory time to in situ time scales remains challenging: 24 hrs << 50 years (HPJ)
  - Long-term field data is not easy to come by either
- Separation of consolidation & creep stage is challenging (HPJ)

Final Remarks

- Consider sample disturbance in the determination of the relevant parameters from lab data (HPJ)
  - can we correct oedometer data for apparent pre-consolidation pressure?
  - It is disappointing that you only know AFTER the test if your sample is of insufficient quality
- Peat classifcation is ambiguous (CZ)
  - So let's use the simplified Russian system …

Final Remarks

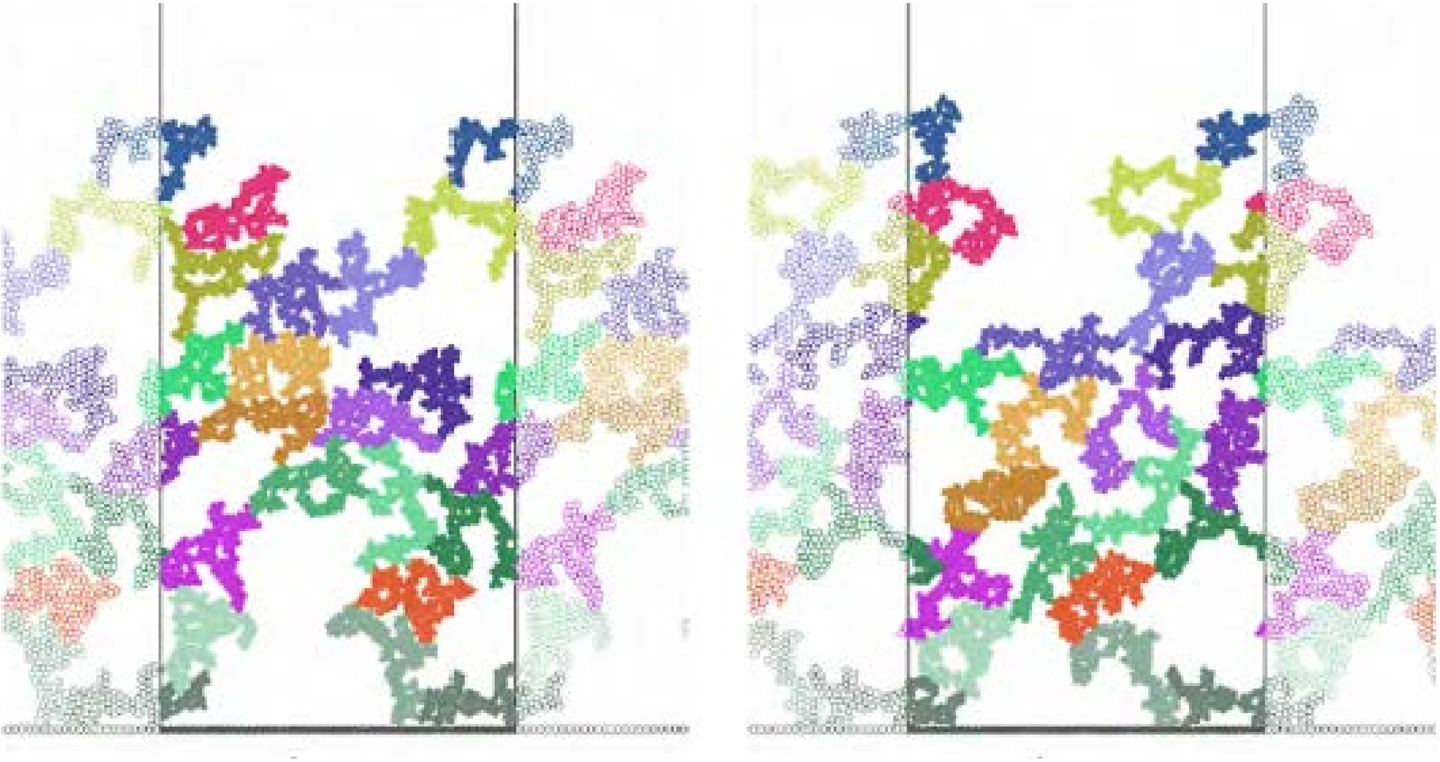
- Classic approach for calculation of consolidation and creep is surprisingly effective in 1D (CZ)
  - What is creep in peat anyway?
  - Is decay of peat also exponential, such as
    - chemical reactions, electric charge, discharge of fluid from a vessel, atmoshperic pressure, heat transfer, luminescence, biological half lives, electromagnetic radiation, radioactivity, thermoelectricity, damped mechanical oscillators etc.
  - Field data for calibration of predicitons
  - Extension to 2D & 3D required

Final Remarks

- Measurement at very low (effective) stress levels are not trivial to perform (CZ)
- Viscoplastic models capture the phenomenological system response very well (Yin)
  - Though not all input parameters are intuitive (or shown)
  - Sensitive for the structure parameters
- Smart use of simplified models will, in some cases, approach advanced models. Determine your parameters around your design point and tell Plaxis the ‘age’ of the soil (GG)
- Ranking of the most important parameters for Soft Soil Creep OCR, OCR, OCR, and OCR (GG)

Outlook

- Should we consider mesoscale modelling?



Matsushima (2014)

Outlook

- Or even on the molecular scale?
- Ebrahimi et al. 2014