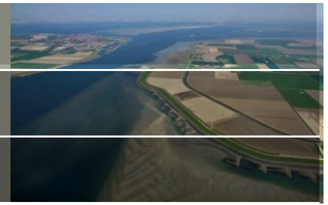
Undrained shear strength in the assessment of slope stability of water defenses

Geotechnical Lectures Evening - TU Delft

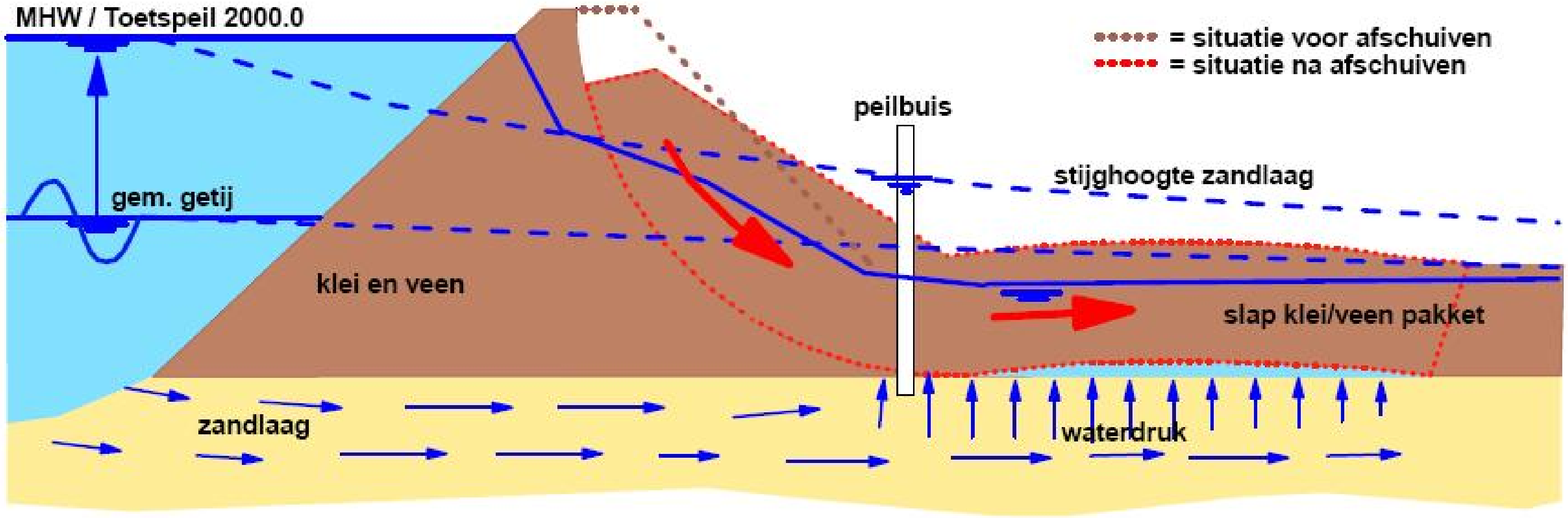
14 november 2016

Context



- New safety standards and assessment rules for water defenses (WBI 2017)
- From high water exceedance frequencies to flood risk approach
- Risk to loss life by flooding in whole NL: 10^{-5} per year
- Safety standards per dike section (was before dike ring)
- New hydraulic conditions
- New insights for different failure mechanisms
- For slope stability introduction of Critical State Soil Mechanics model and SHANSEP model

Water defenses and slope stability



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Slope instability Lekdijk Streefkerk 1984

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Slope instability Zuiderlingedijk 2006

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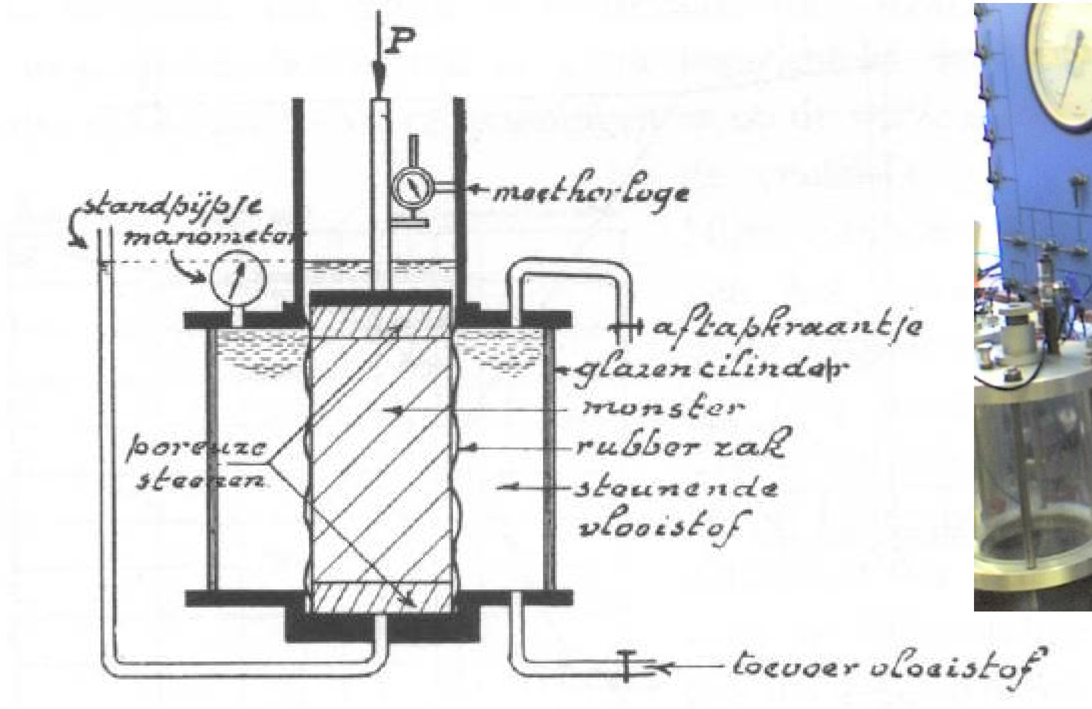
Slope instability field test Bergambacht 2001

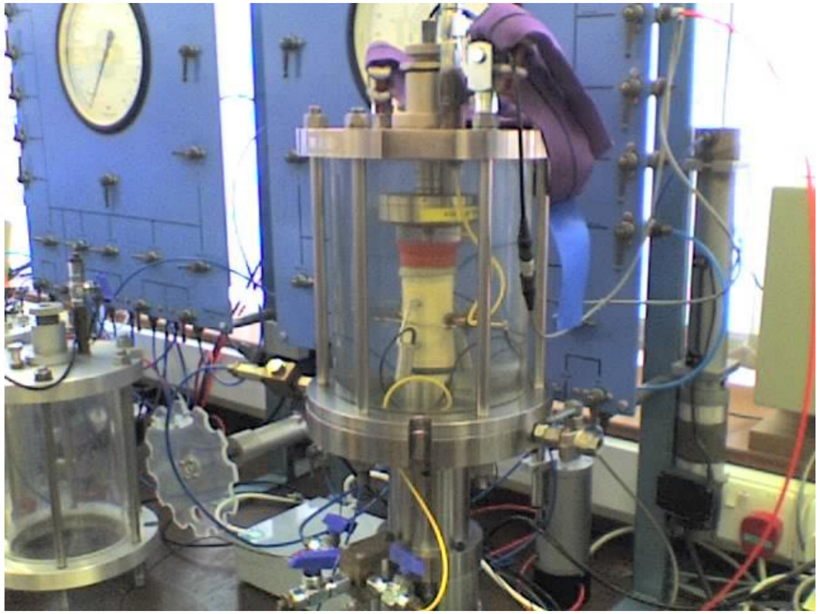
Slope instability field test IJkdijk 2008

Field test Uitdam – Dijken op Veen 2013

Shear strength from lab tests



Dutch Cell test



Triaxial test

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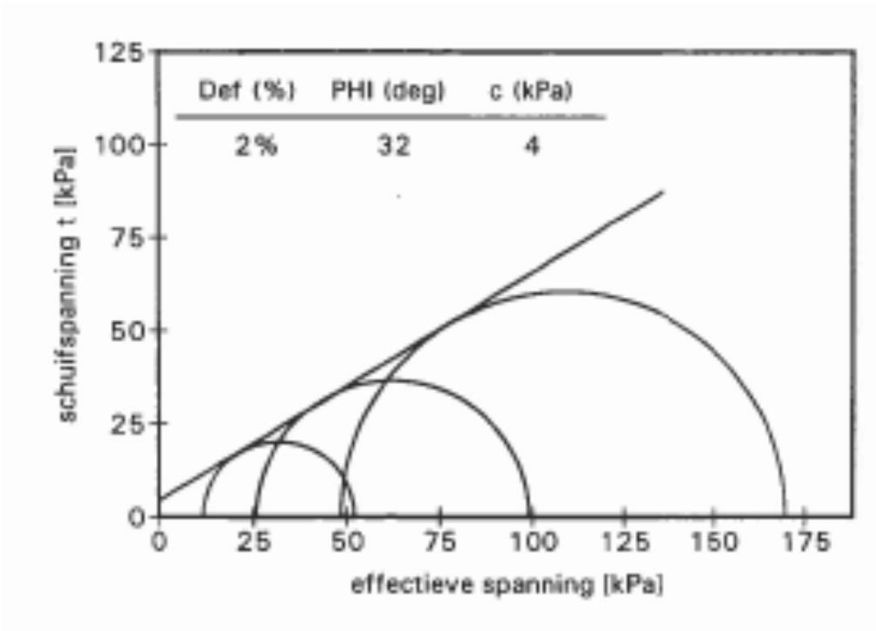
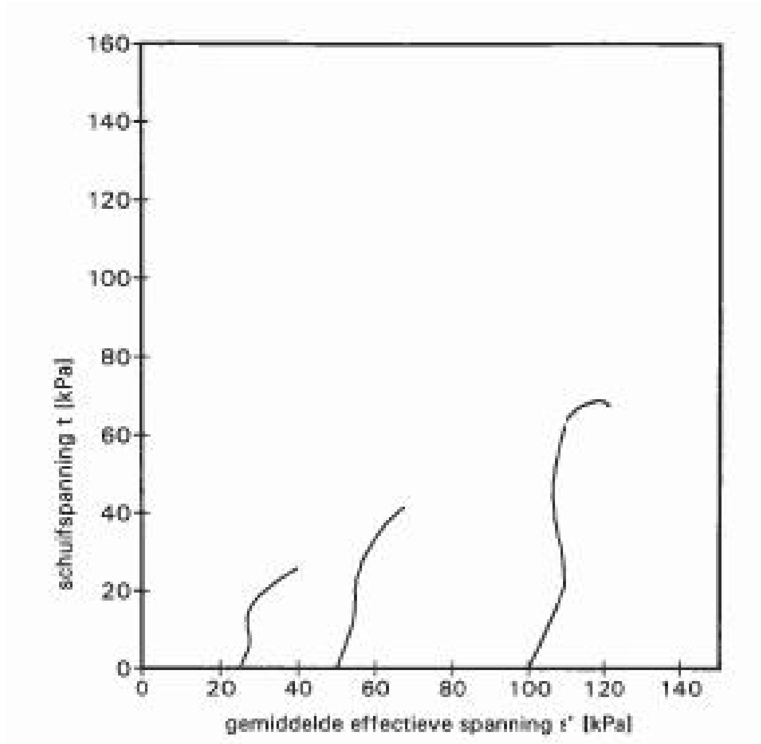
Shear strength from lab tests

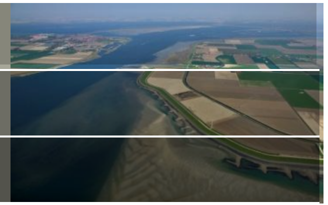


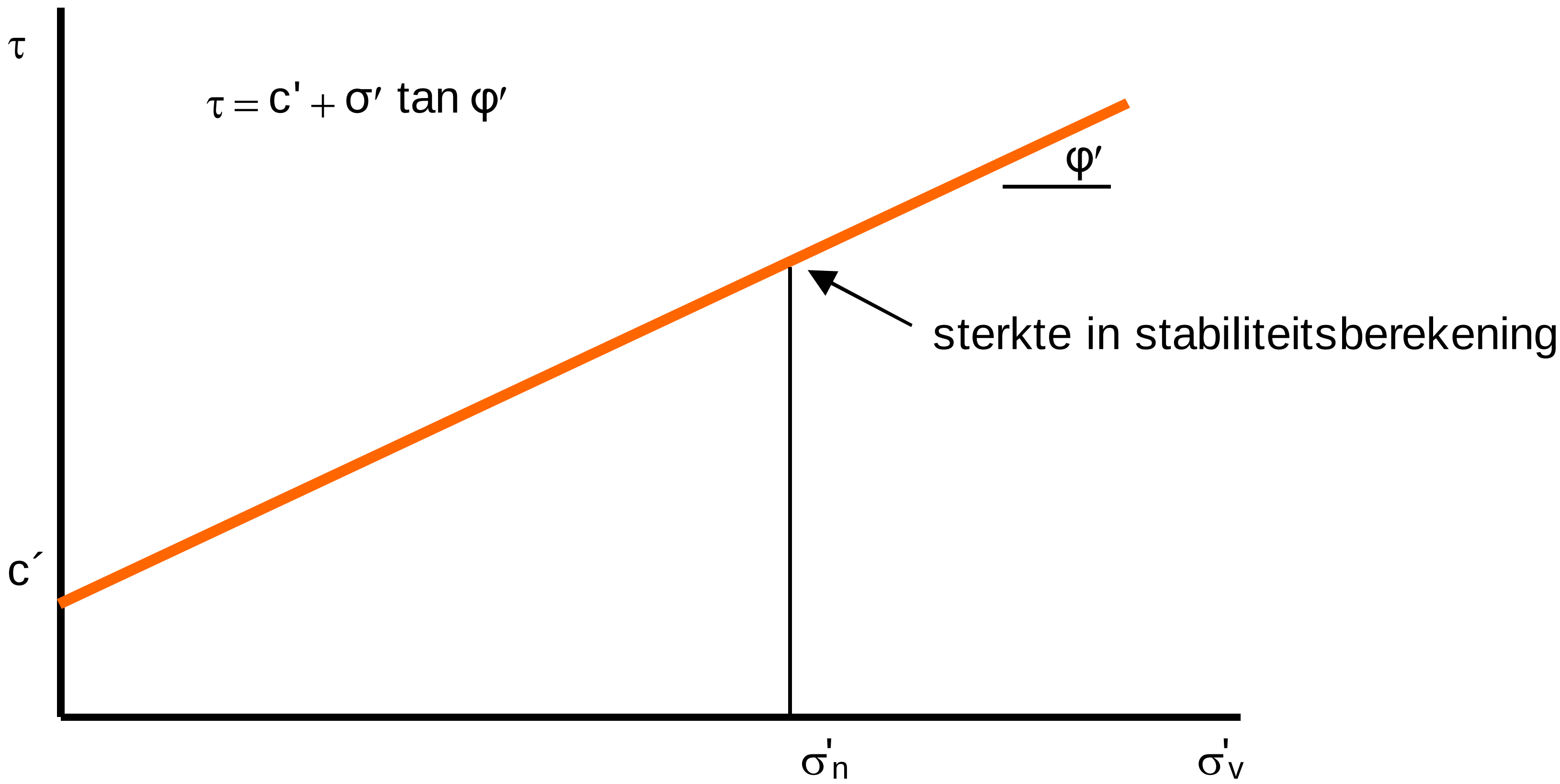


Mohr-circles from cell test

Stress paths from triaxial test

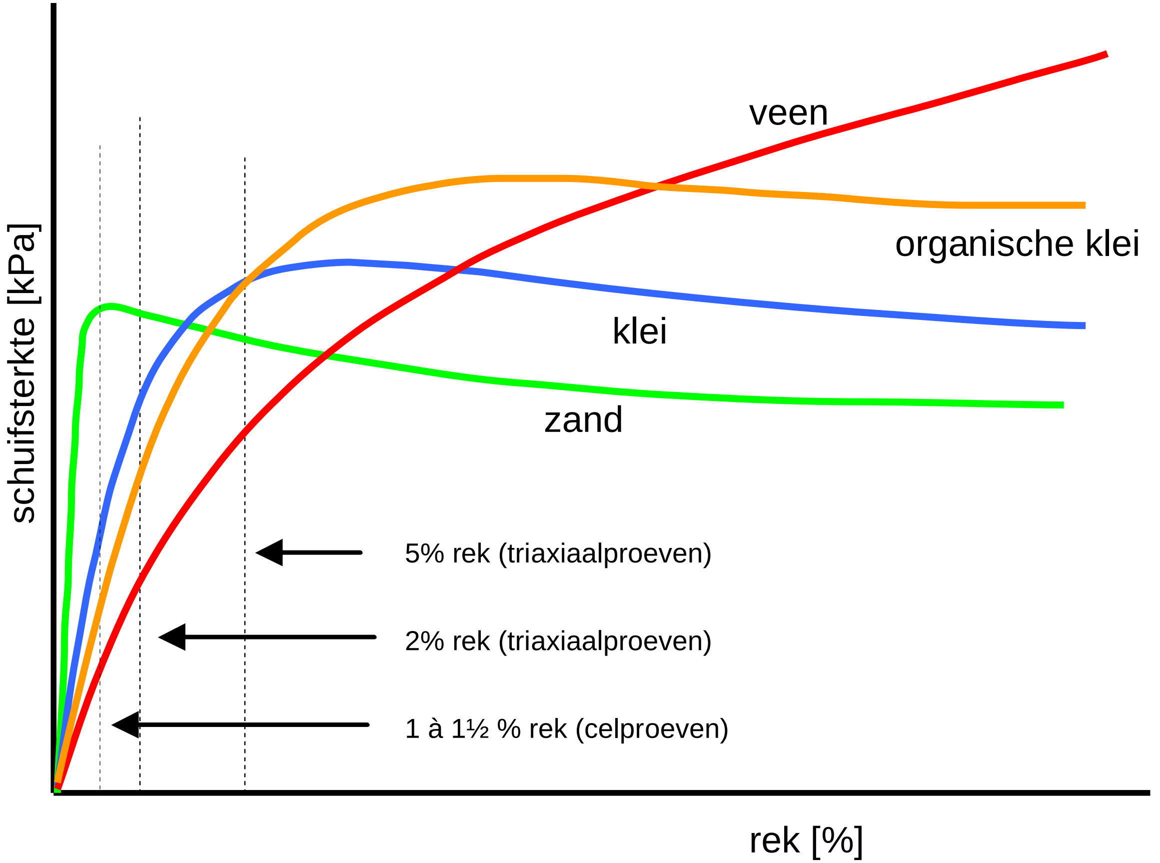
Current practice in NL





Mohr Coulomb model = current practice in NL

Current practice in NL



Shear strength determined for chosen strain level - c' and φ' depend on strain level

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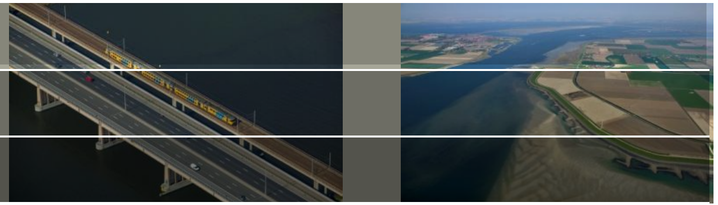
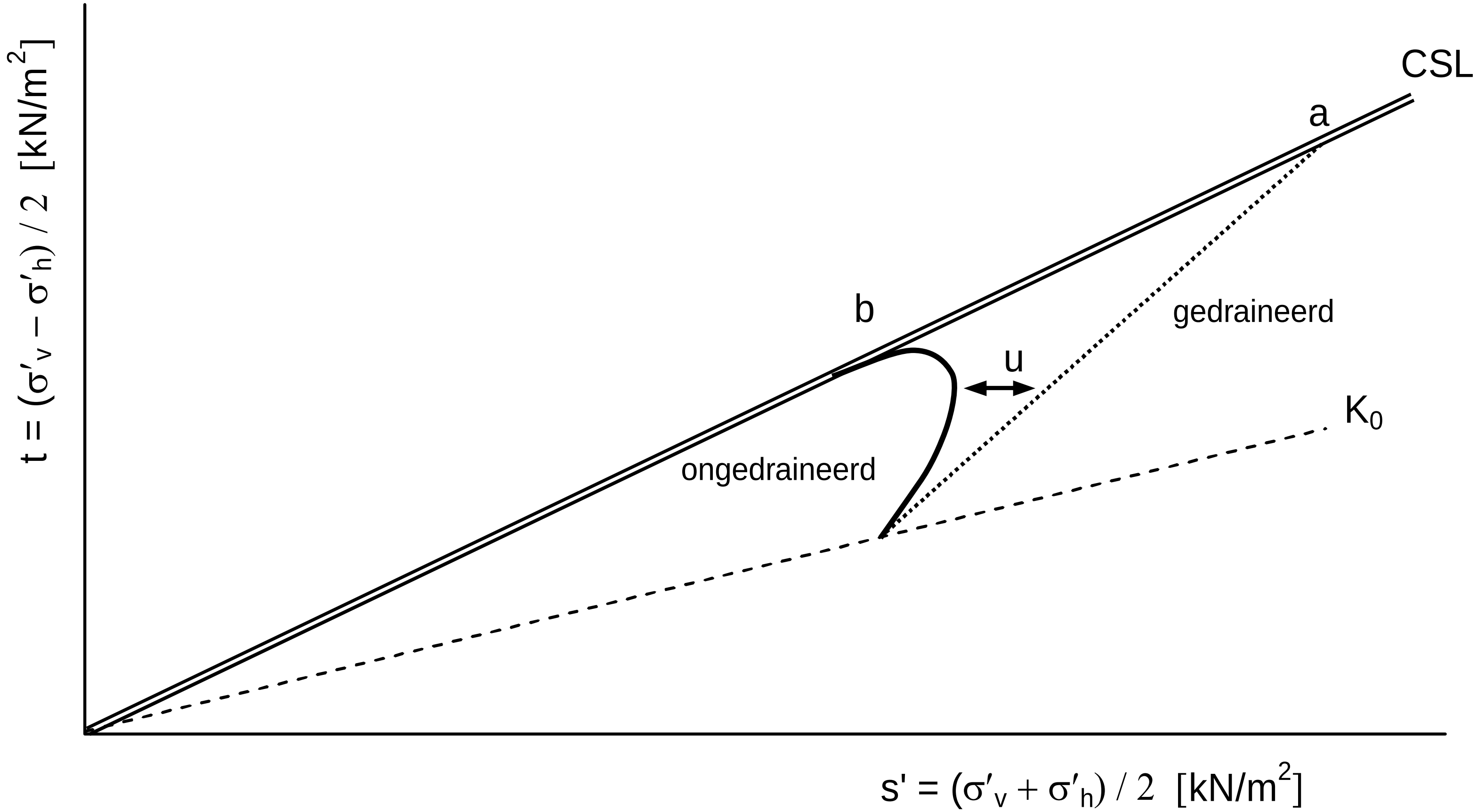
Current practice in NL





Excess pore water pressure due to undrained shearing not in slope stability analysis

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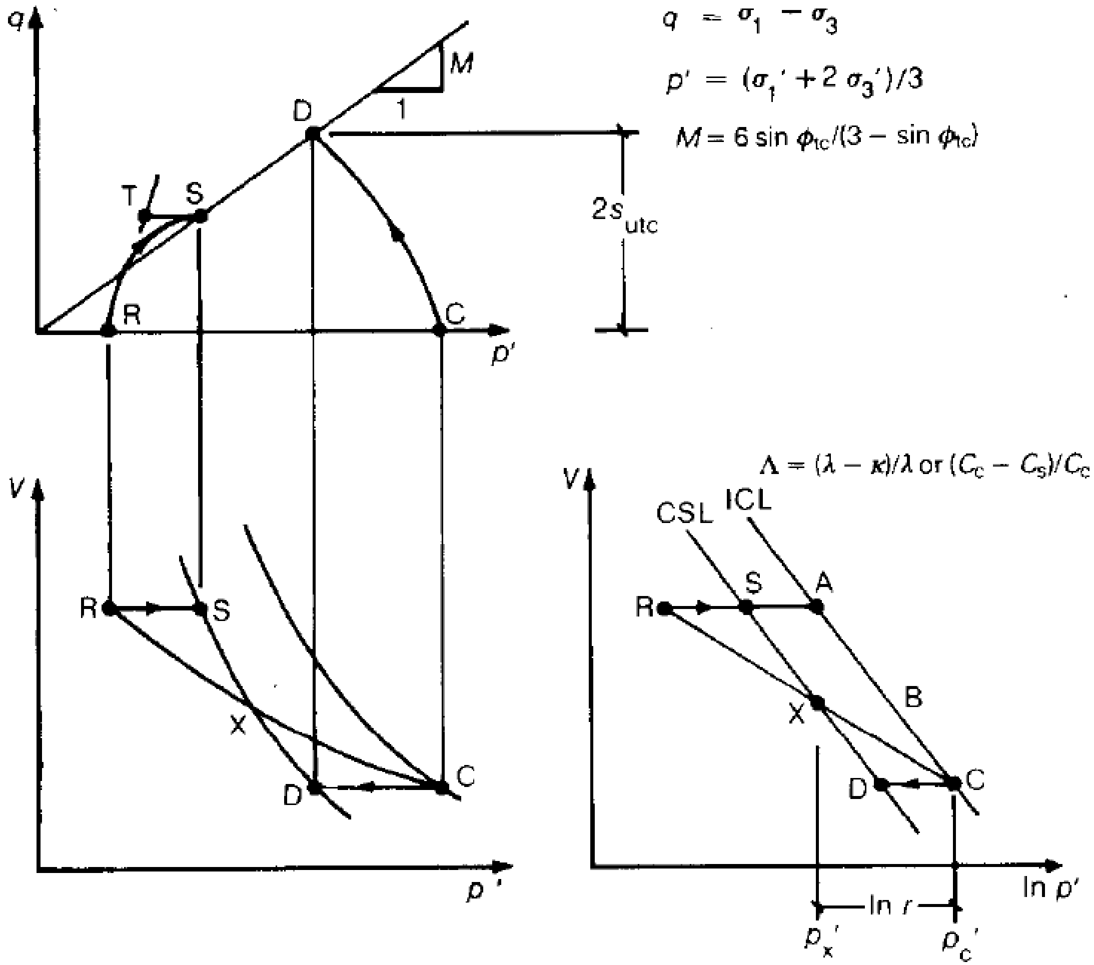
Critical state soil mechanics model



Critical State Soil Mechanics

(Schofield and Wroth, 1968)

Coupling of stress, void ratio, 'state', compression and shear strength

(Figure from Wroth, 1984)

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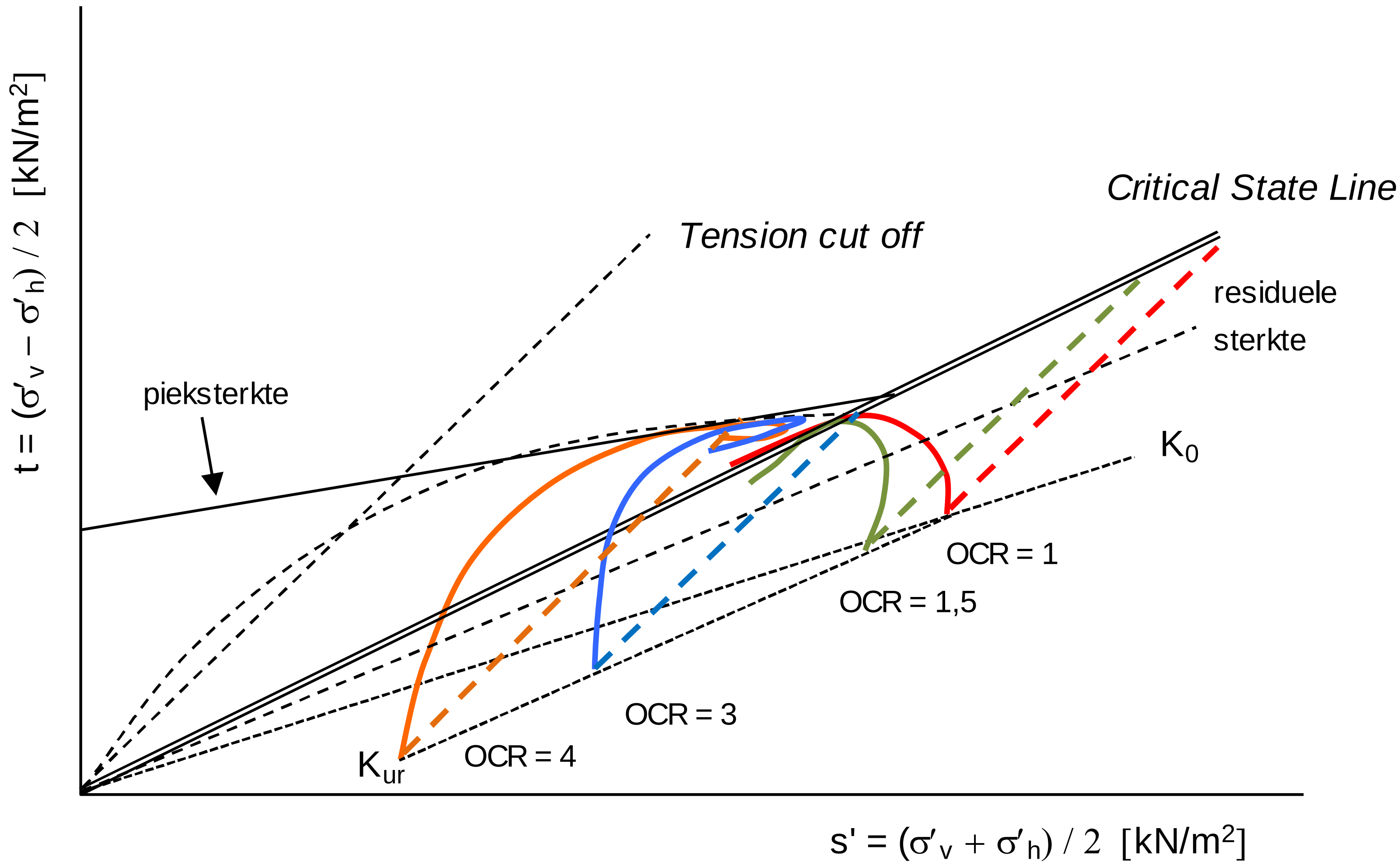
Critical State Soil Mechanics model



Critical State Soil Mechanics (Schofield and Wroth, 1968)

Shear strength model SHANSEP

$s_u = \sigma'_{vi}\ S\ OCR^m$

$OCR = \sigma'_{vy} / \sigma'_{vi}$ en $POP = \sigma'_{vy} - \sigma'_{vi}$

s_u	undrained shear strength(kN/m^2)
σ'_{vi}	in situ effective vertical stress (kN/m^2)
S	normally consolidated undrained shear strength ratio = $(s_u/\sigma'_{vc})_{nc}$ (-)
OCR	overconsolidation ratio (-)
m	strength increase exponent (-)
σ'_{vy}	yield stress (kN/m^2)
POP	pre overburden pressure (kN/m^2)

SHANSEP (Stress History And Normalized Soil Engineering Properties)
(Ladd et al 1974 en Ladd 1991)

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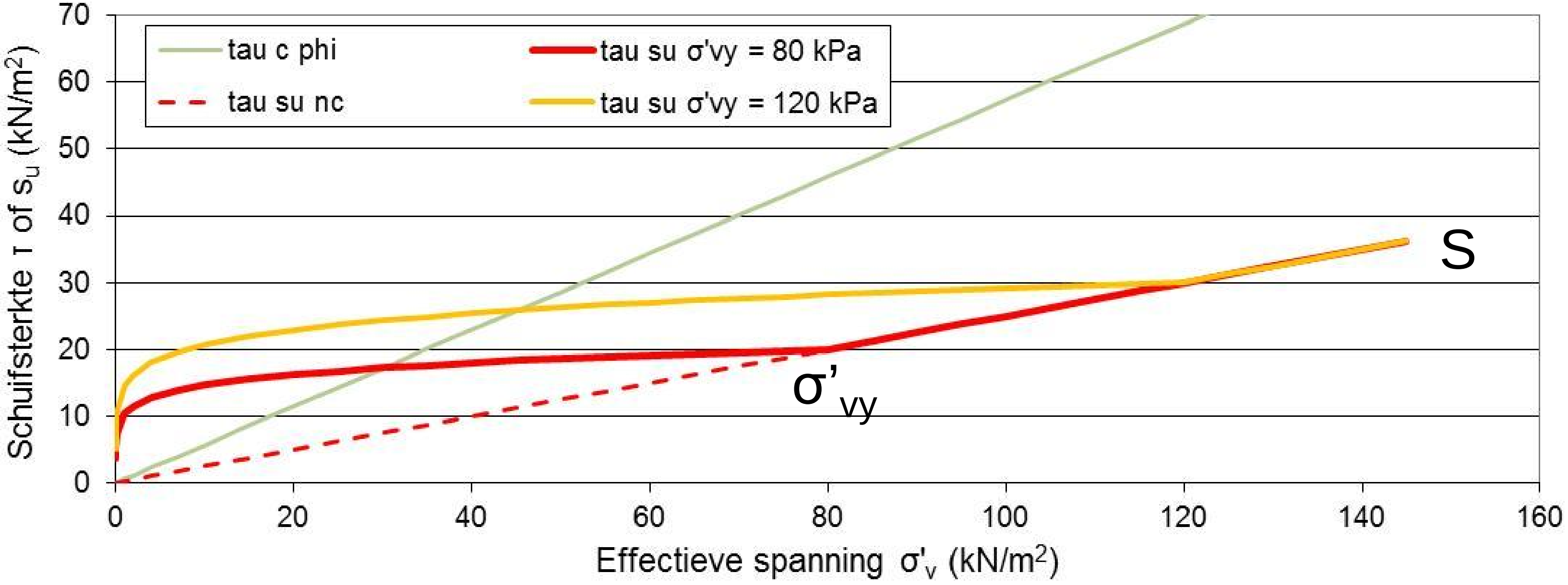
Shear strength model SHANSEP



$s_u = \sigma'_v \; S \; OCR^m \quad \text{with} \quad OCR = \sigma'_{vy} / \sigma'_v$

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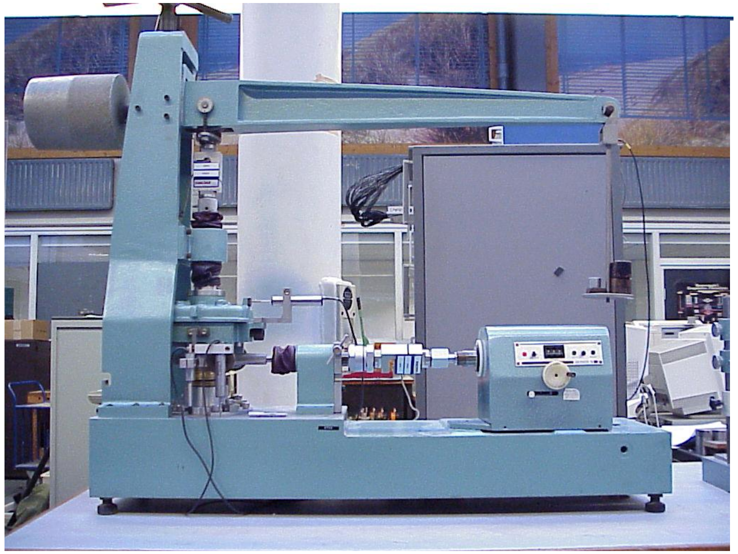
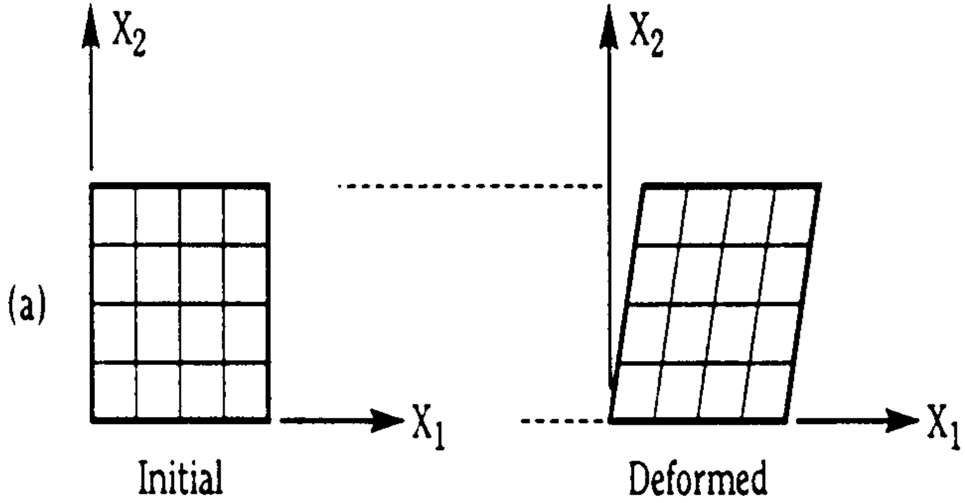
Direct Simple Shear test

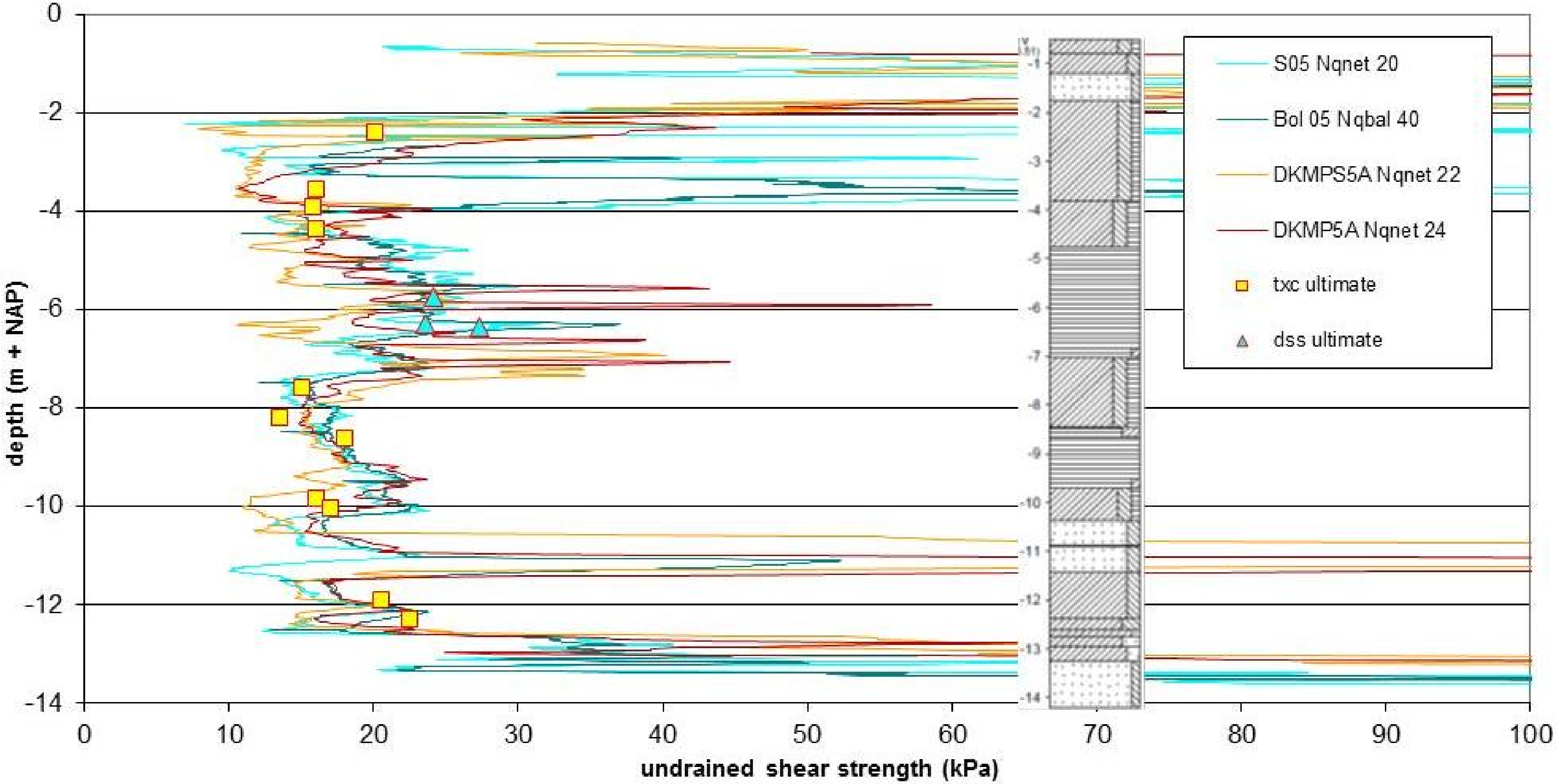




- Samples supported by membrane or stacked rings
- Stress conditions during test not fully clear
- Different possible interpretations of the test results
- Test with constant height assumed as undrained test
- No measurement of pore water pressures (no back pressure)
- Apply DSS test for peat (fibrous soils)

Undrained shear strength from CPTu

$$s_u = (q_t - \sigma_{v0}) / N_{kt} = q_{net} / N_{kt}$$



Empirical correlation Lekdijk Streefkerk

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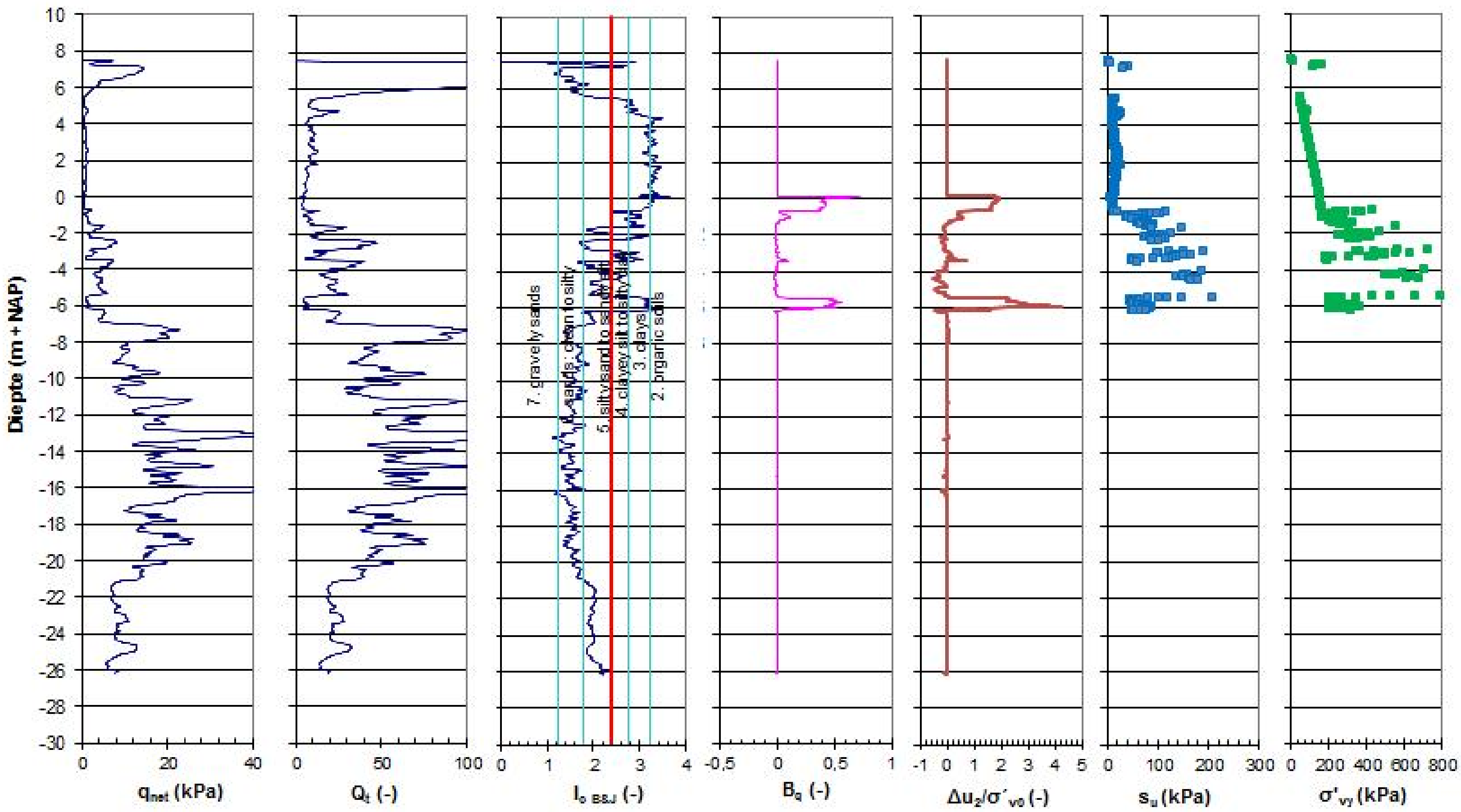
Undrained shear strength from CPTu



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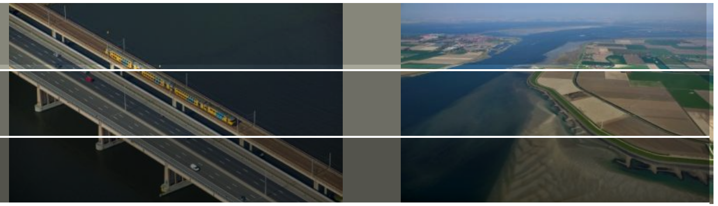
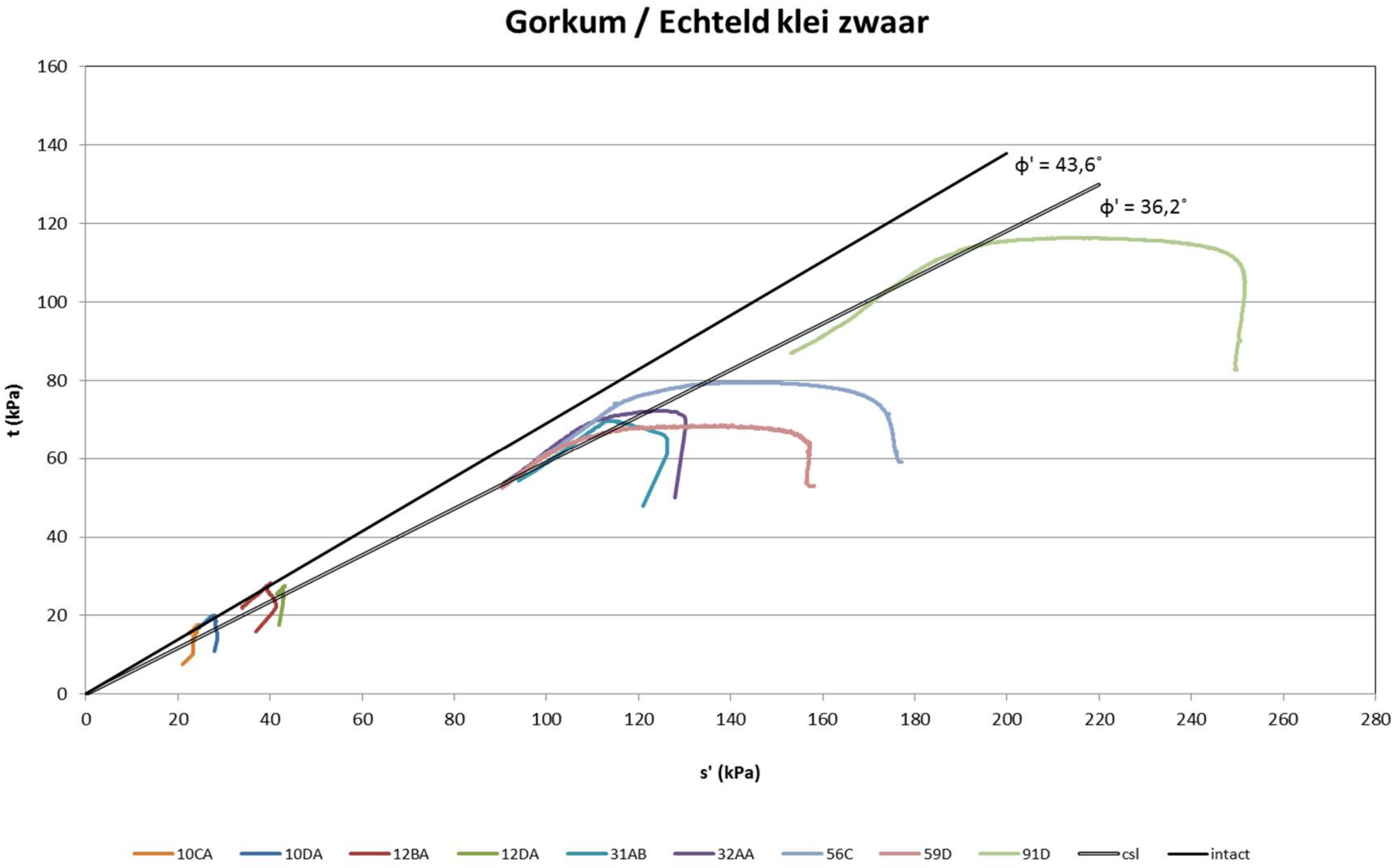
Interpretation lab tests





Triaxial tests single stage with anisotropic consolidation

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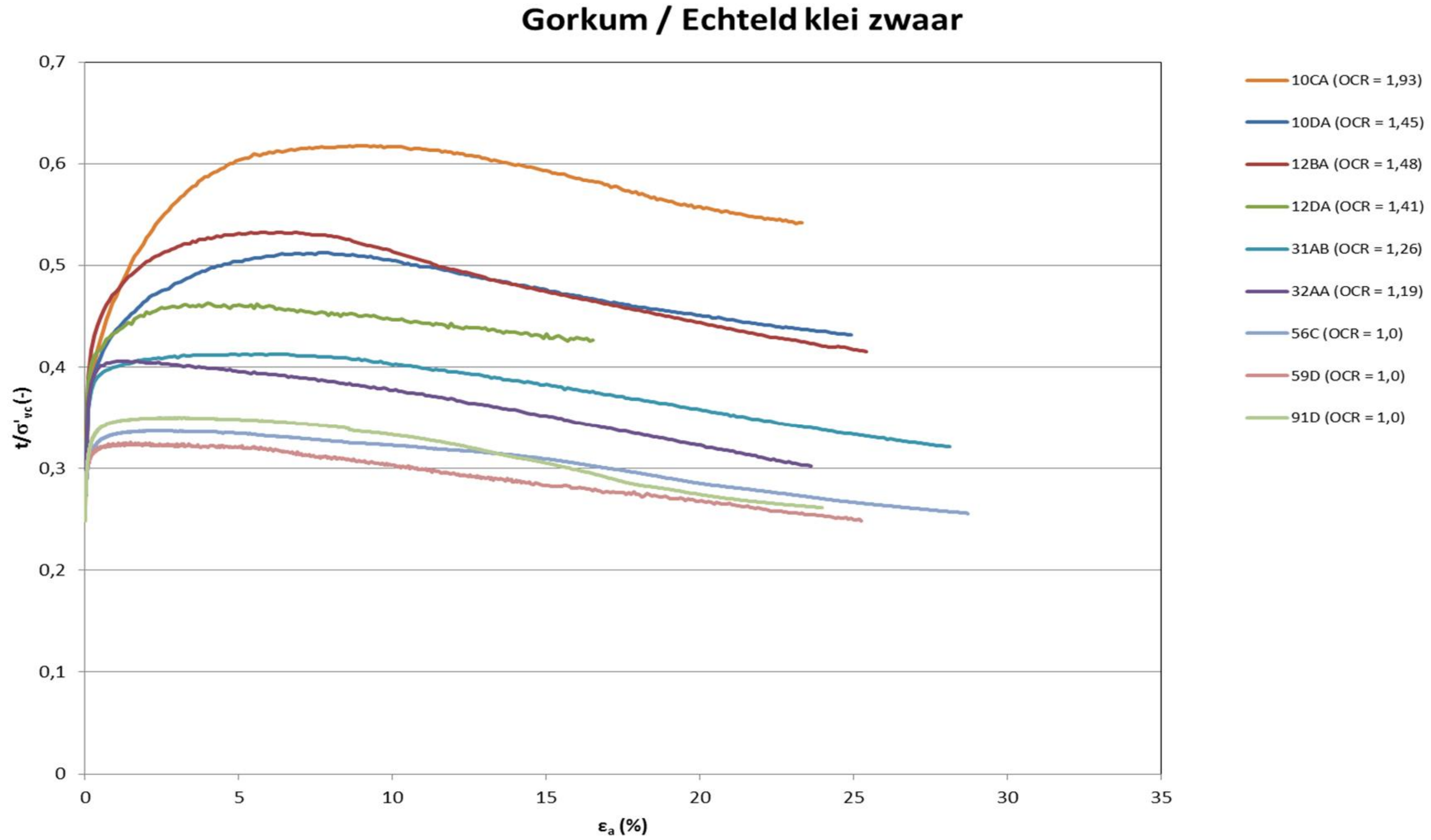
Interpretation lab tests



s_u/σ'_{vi} increases with increasing OCR
At 25% axial strain no clear critical state
At critical state theoretically no effect of OCR

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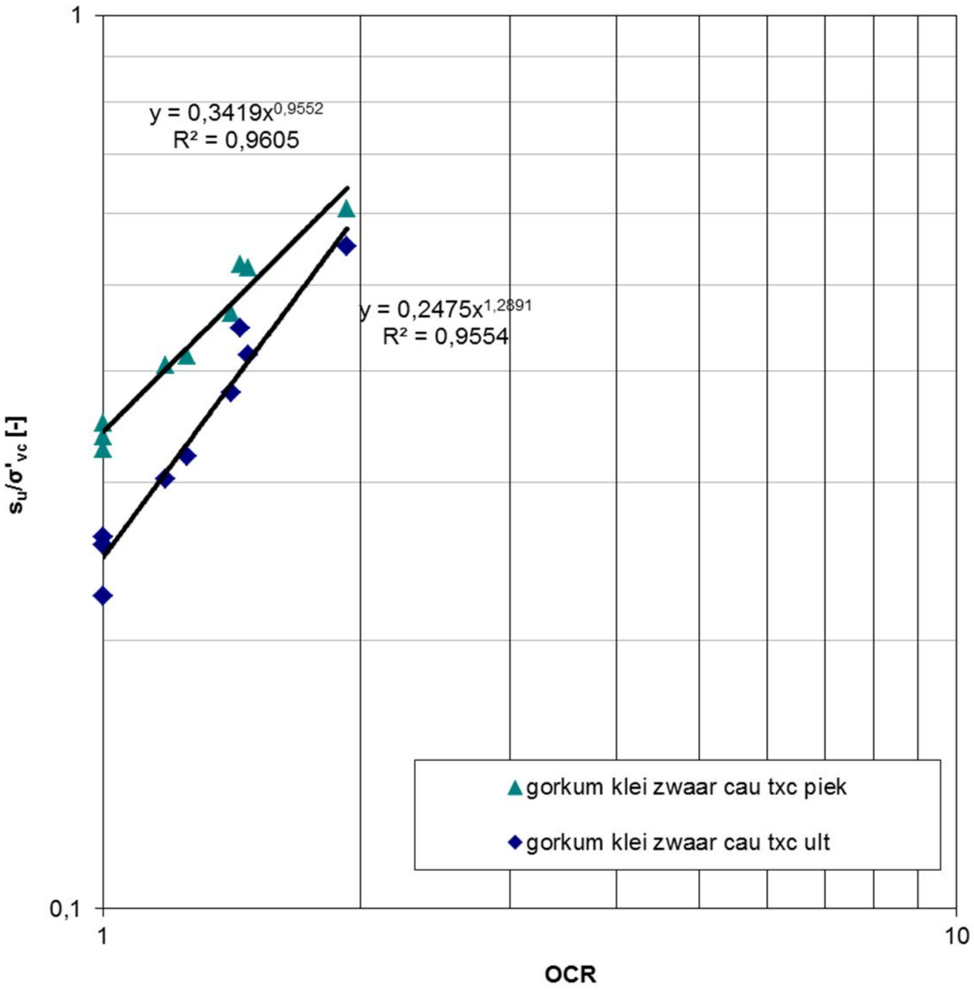
Interpretation lab tests



s_u/σ'_{vc} from triaxial tests

OCR from oedometer tests and CRS tests

s_u/σ'_{vc} increases for increasing OCR

SHANSEP (Ladd et al 1974 en Ladd 1991)

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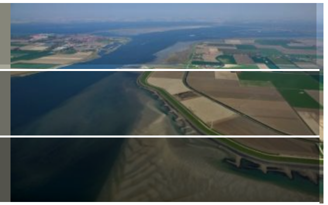
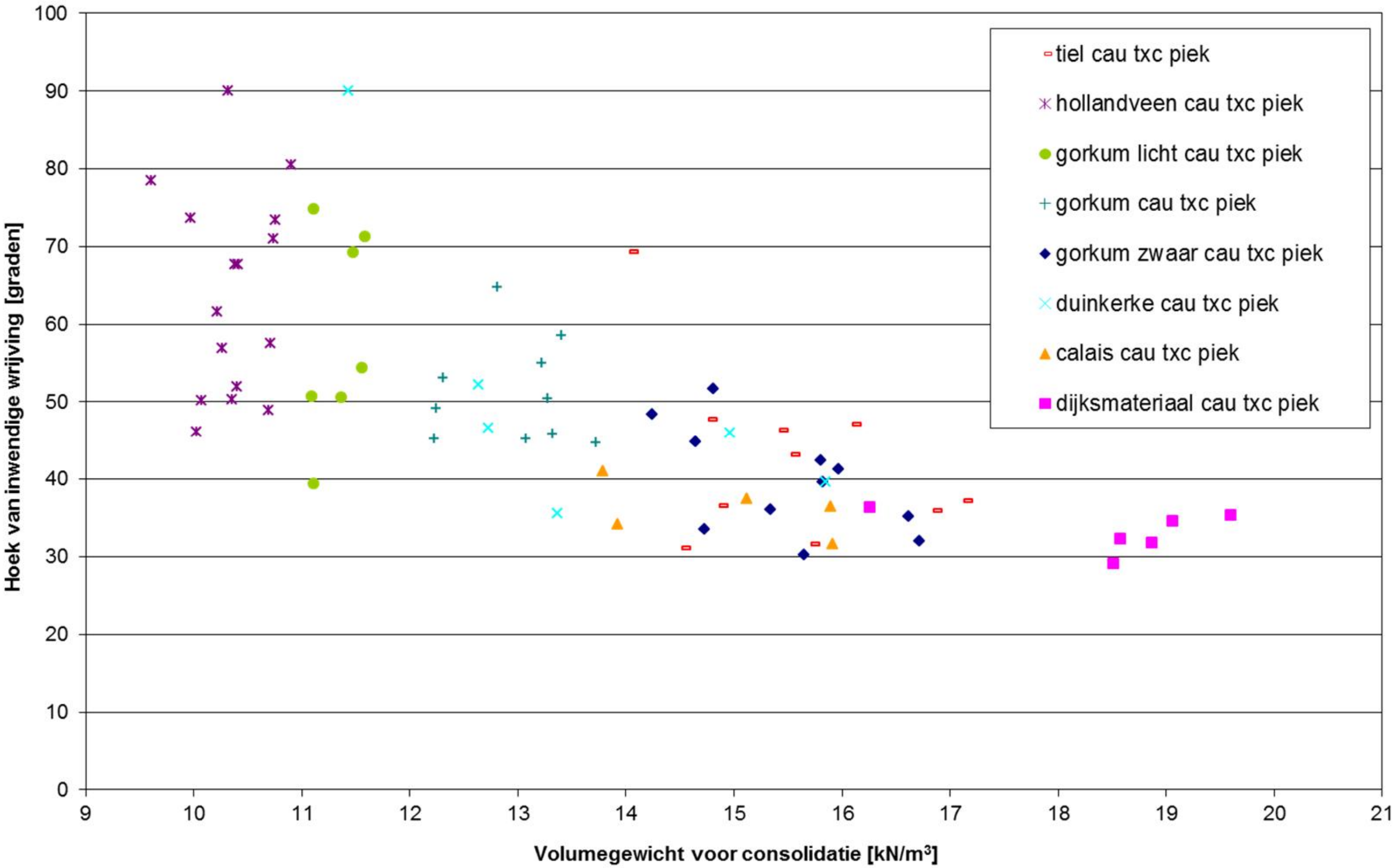
Interpretation lab tests





Friction angle increases with decreasing soil unit weight

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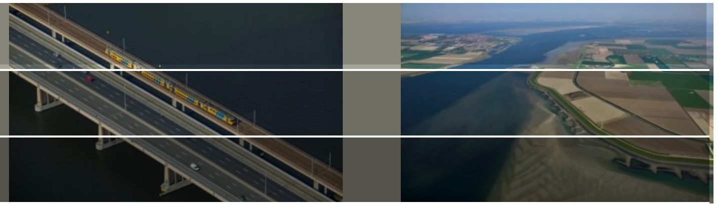
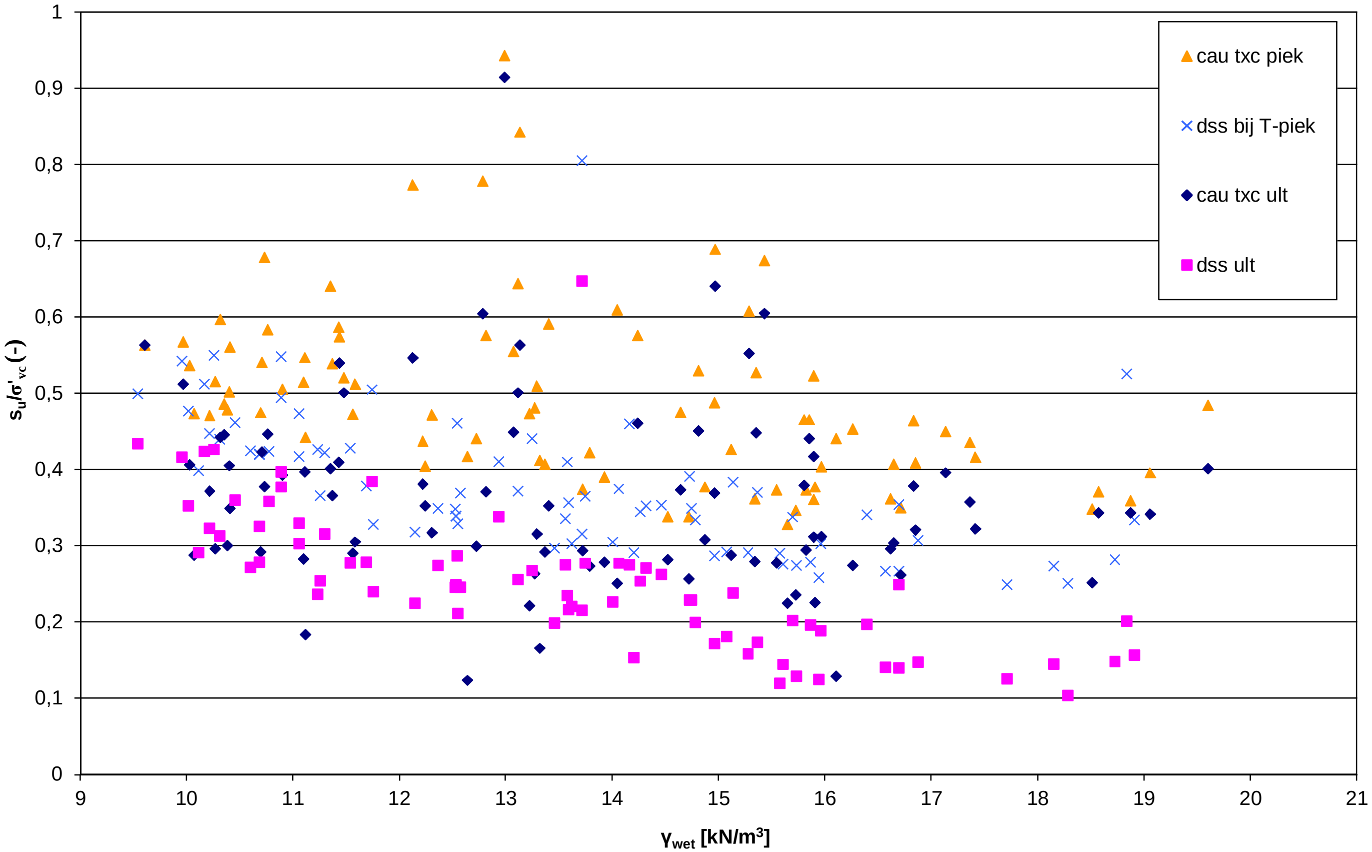
Interpretation lab tests





Undrained shear strength ratio S increases with decreasing soil unit weight

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Shear strength in WBI 2017

- Application of Critical State Soil Mechanics model and SHANSEP-model
- Distinguish between drained and undrained soil behaviour
- Take into account the state of the soil (yield stress, OCR) and distinguish between normally consolidated and overconsolidated behaviour
- Use the shear strength at failure (ultimate state) because of different strength mobilisation in active and passive zone and differences in stiffness

When apply s_u?

- When s_u results in the most critical analysis (minimum SF)
- Apply s_u for low permeable soil layers
- s_u most critical for higher stress levels and normally consolidated and light overconsolidated soils (contractant behaviour: OCR < 2,5 à 3,0)
- Drained shear strength most critical for lower stress levels and overconsolidated soils (dilatant behaviour: OCR > 2,5 à 3,0)
- Apply drained shear strength above phreatic level (especially in the top of the dike material with high q_c)

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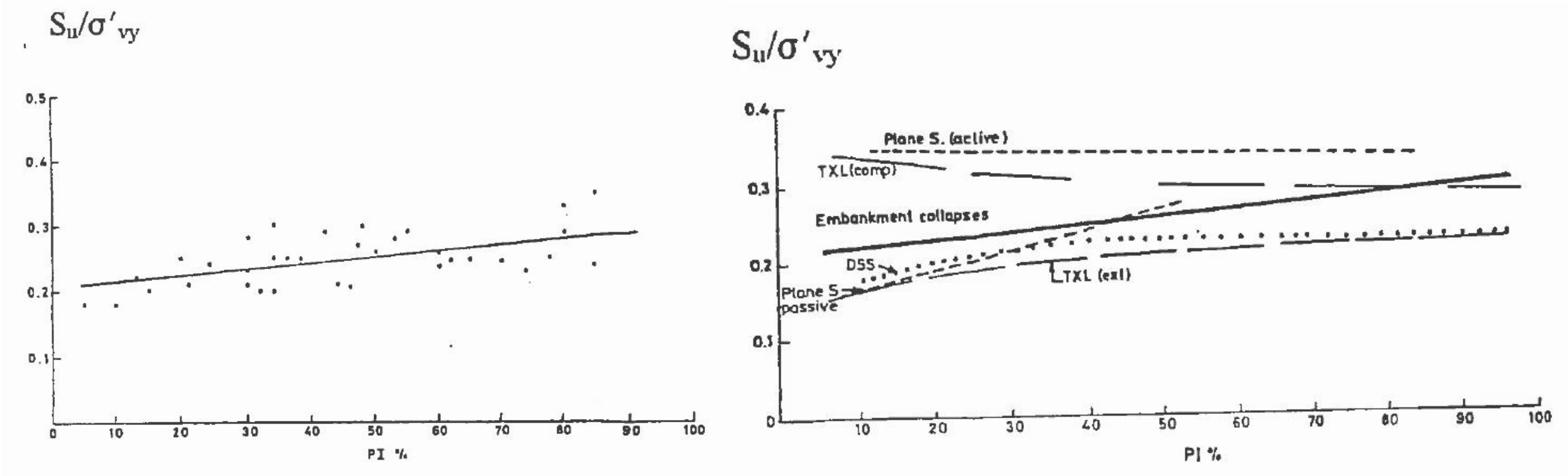
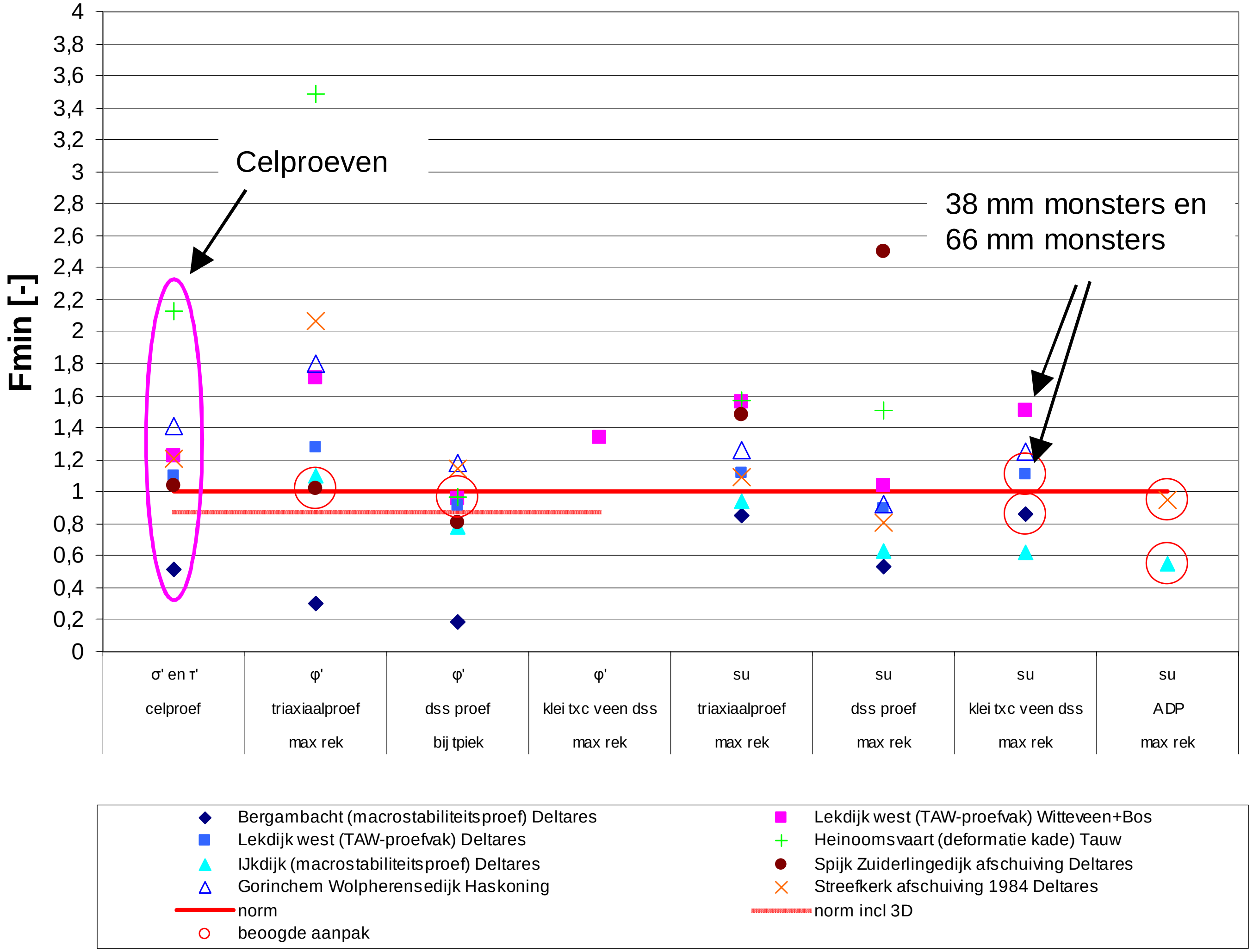
Validation



Comparison of the ‘operational’ undrained shear strength at slope failures with shear strength from lab tests

(Jardine and Hight, 1987)

Validation



Dutch Cell test overestimates 'operational' shear strength

With CSSM and SHANSEP more realistic estimate of the safety factor

Results based on bast estimates of the schematization and shear strength

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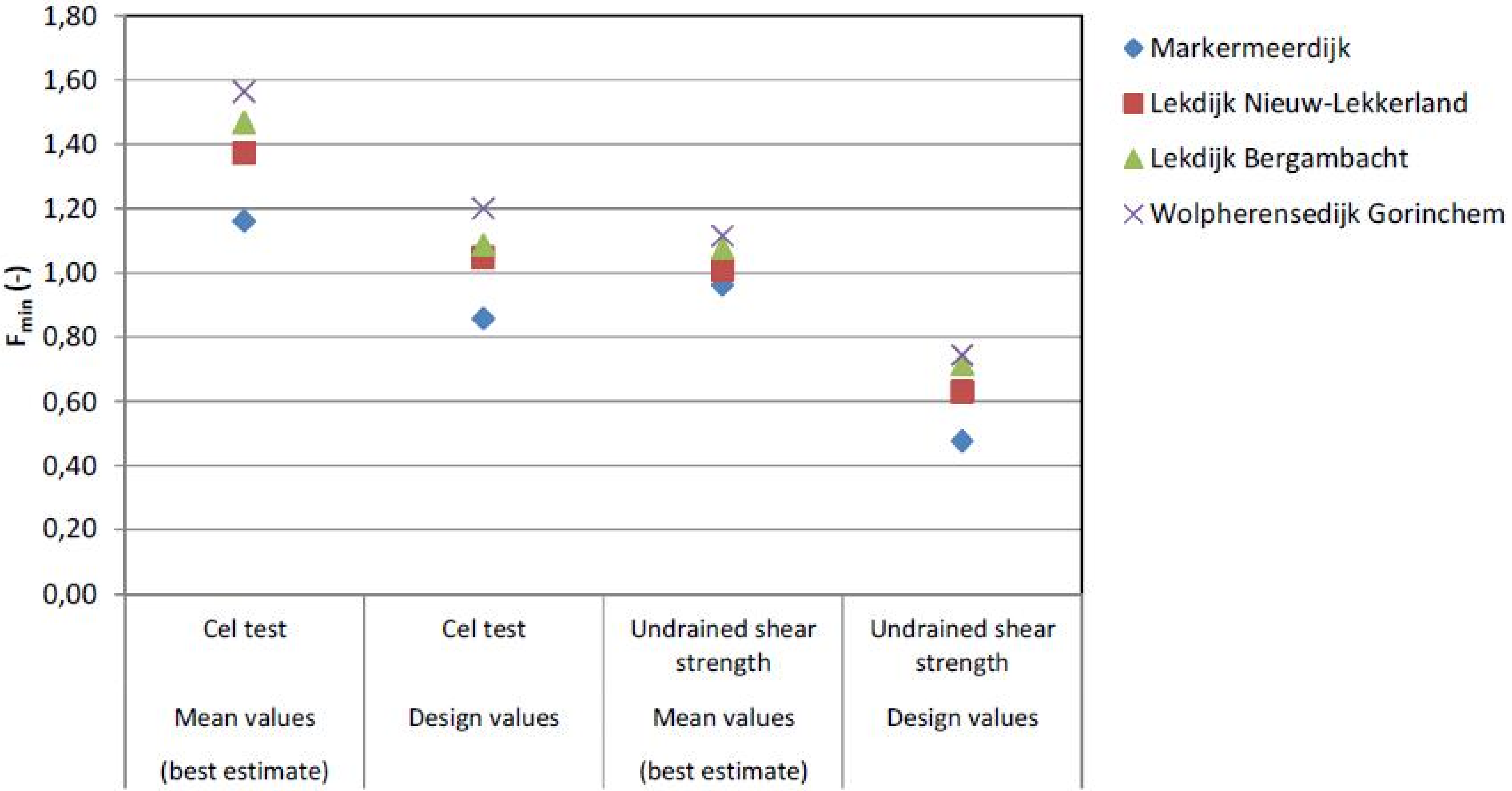
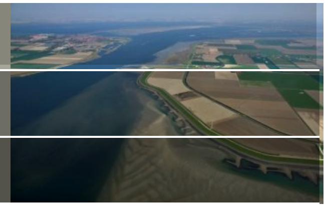
Validation



Dikes that withstand high water levels are (just) stable with undrained shear strength



Thank you for your attention

Questions and discussion