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

14 November 2016
Water defenses and slope stability

MHW / Toetspeil 2000.0

gem. getij

klei en veen

zandlaag

peilbuis

stijghoogte zandlaag

slap klei/veen pakket

waterdruk

= situatie voor afschuiven

= situatie na afschuiven

Deltares

14 november 2016
Slope instability Lekdijk Streefkerk 1984
Slope instability Zuiderlingedijk 2006
Slope instability field test IJkdijk 2008
Field test Uitdam – Dijken op Veen 2013

14 november 2016
Shear strength from lab tests

Dutch Cell test

Triaxial test
Shear strength from lab tests

Mohr-circles from cell test  Stress paths from triaxial test
Mohr Coulomb model = current practice in NL

\[ \tau = c' + \sigma' \tan \phi' \]
Current practice in NL

Shear strength determined for chosen strain level - $c'$ and $\phi'$ depend on strain level
Excess pore water pressure due to undrained shearing not in slope stability analysis
Critical State Soil Mechanics
(Schofield and Wroth, 1968)

Coupling of stress, void ratio, ‘state’, compression and shear strength

(Figure from Wroth, 1984)
Critical State Soil Mechanics (Schofield and Wroth, 1968)

Critical State Line

Tension cut off

residuele sterke

OCR = 1

OCR = 1.5

OCR = 3

OCR = 4

\[ s' = \frac{(\sigma'_v + \sigma'_h)}{2} \] [kN/m²]

\[ t = \frac{(\sigma'_v - \sigma'_h)}{2} \] [kN/m²]
Shear strength model SHANSEP

\[ s_u = \sigma'_{vi} \times S \times OCR^m \]

\[ OCR = \sigma'_{vy} / \sigma'_{vi} \quad \text{en POP} = \sigma'_{vy} - \sigma'_{vi} \]

- \( s_u \): Undrained shear strength (kN/m\(^2\))
- \( \sigma'_{vi} \): 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 (-)
- \( \sigma'_{vy} \): 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)
Shear strength model SHANSEP

\[ s_u = \sigma'_v \cdot S \cdot OCR^m \quad \text{with} \quad OCR = \frac{\sigma'_{vy}}{\sigma'_v} \]
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

\[ S_u = \frac{(q_t - \sigma_v)}{N_{kt}} = \frac{q_{net}}{N_{kt}} \]

Empirical correlation Lekdijk Streefkerk

14 November 2016
Undrained shear strength from CPTu
Interpretation lab tests

Gorkum / Echteld klei zwaar

Triaxial tests single stage with anisotropic consolidation
s_u / \sigma'_{vi} increases with increasing OCR
At 25% axial strain no clear critical state
At critical state theoretically no effect of OCR
Interpretation lab tests

$s_u/\sigma'_{vc}$ from triaxial tests

OCR from oedometer tests and CRS tests

$s_u/\sigma'_{vc}$ increases for increasing OCR

SHANSEP (Ladd et al 1974 en Ladd 1991)
Friction angle increases with decreasing soil unit weight
Undrained shear strength ratio $S$ increases with decreasing soil unit weight
• 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 $q_{lc}$)
Comparison of the ‘operational’ undrained shear strength at slope failures with shear strength from lab tests (Jardine and Hight, 1987)
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
Dikes that withstand high water levels are (just) stable with undrained shear strength
Thank you for your attention

Questions and discussion