



*3<sup>rd</sup> ISSMGE McClelland Lecture*

# Cyclic soil parameters for offshore foundation design



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# Cyclic soil parameters for offshore foundation design

## Main goals

- ↗ Cyclic contour diagram framework
- ↗ Data base with contour diagrams and correlations of required parameters

# Presentation

- ↗ When do we need cyclic soil parameters?
- ↗ What parameters do we need?
- ↗ How does soil behave under cyclic loading?
- ↗ Cyclic contour diagram framework
  - Construction
  - Important parameters
  - Data base (diagrams and correlations with index parameters)
- ↗ Application of contour diagrams in design
- ↗ Calculation procedures
- ↗ Slope instability due to cyclic loading
- ↗ Verification by prototype observations and model tests

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# Wave loads: The Ekofisk Oil Storage Tank - 1973

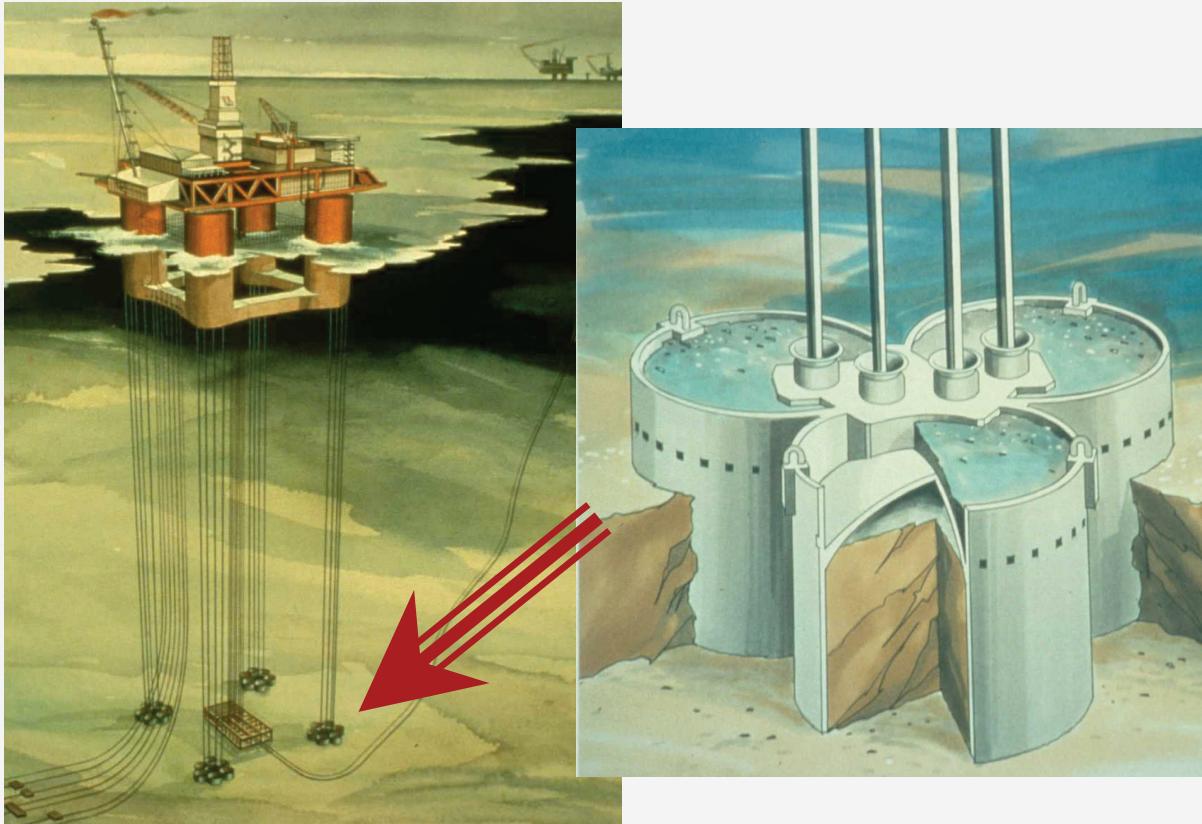


$H_{100} \approx 18 \rightarrow 24\text{?m}$

# Wave loads, Frigg TCP2, 1977



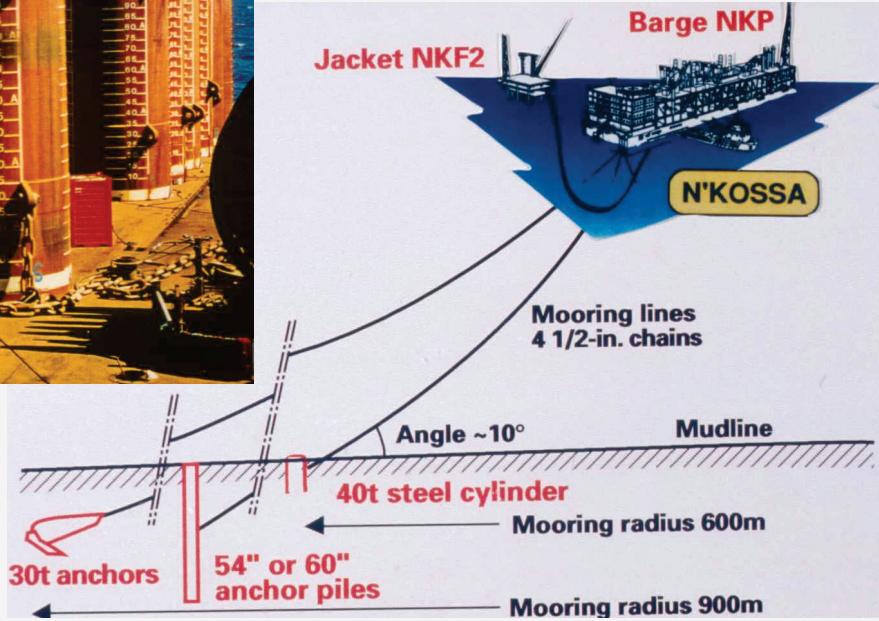
# Snorre tension leg platform (1991)



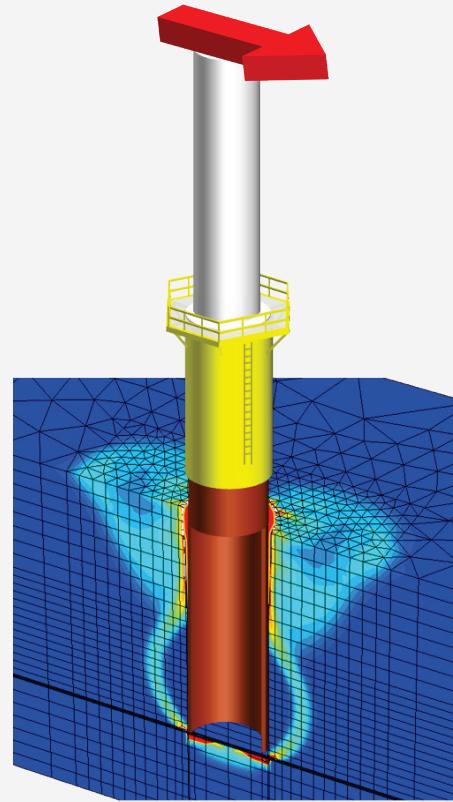
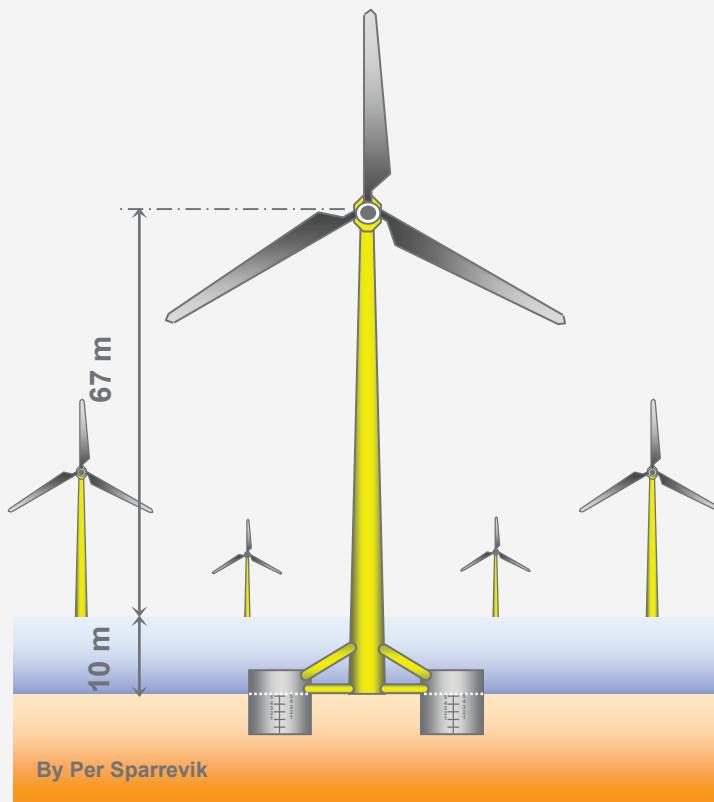
# Anchoring of floaters



2004:  
485 suction anchors, 50 sites  
2000m water depth



# Offshore wind power structures



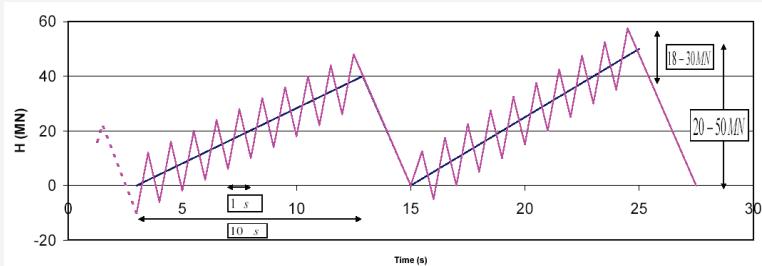
# Sea protection; Oosterschelde



# Wave loads on harbour structures - Amalfi, Italy



# Ice loading on bridge pillars; Great Belt bridge, Denmark

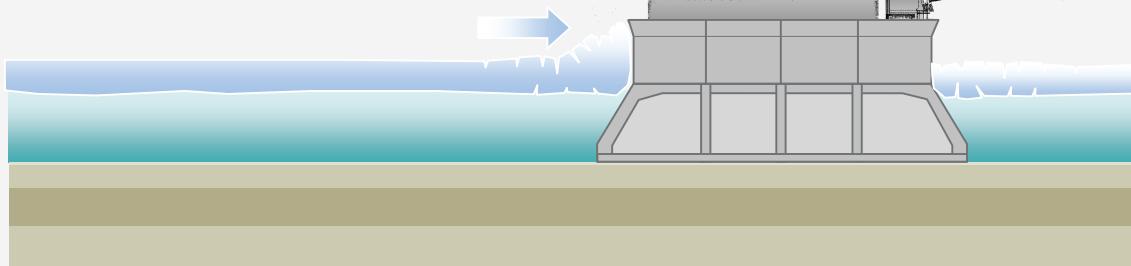
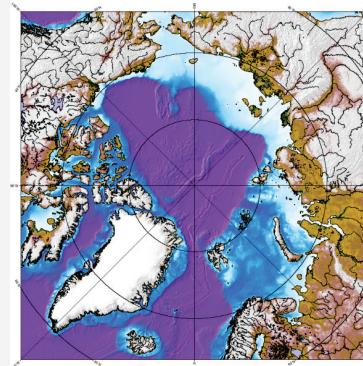


Low frequency 10 sec  
High frequency 1 sec

**1990**



# Arctic; ice loads



Drawing: Per Sparrevik

# Earthquakes



Photo: Amir Kaynia

# Earthquakes, slope instability

Earthquake induced  
slide, El Salvador,  
600 dead



# Foundation design topics

- ▼ Cyclic bearing capacity
- ▼ Cyclic displacements
- ▼ Soil stiffness in global dynamic analyses
- ▼ Permanent displacements (settlements) due to cyclic loading
  - Dissipation of pore pressure due to cyclic loading
  - Increased average shear strains
- ▼ Soil reactions
- ▼ Static capacity reduction due to cyclic loading

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# Cyclic soil parameters needed in design

- ☛ Cyclic shear strength
- ☛ Cyclic shear modulus
- ☛ Permanent shear strain due to cyclic loading
- ☛ Pore pressure generation
- ☛ Recompression modulus
- ☛ Damping
- ☛ Static strength reduction due to cyclic loading

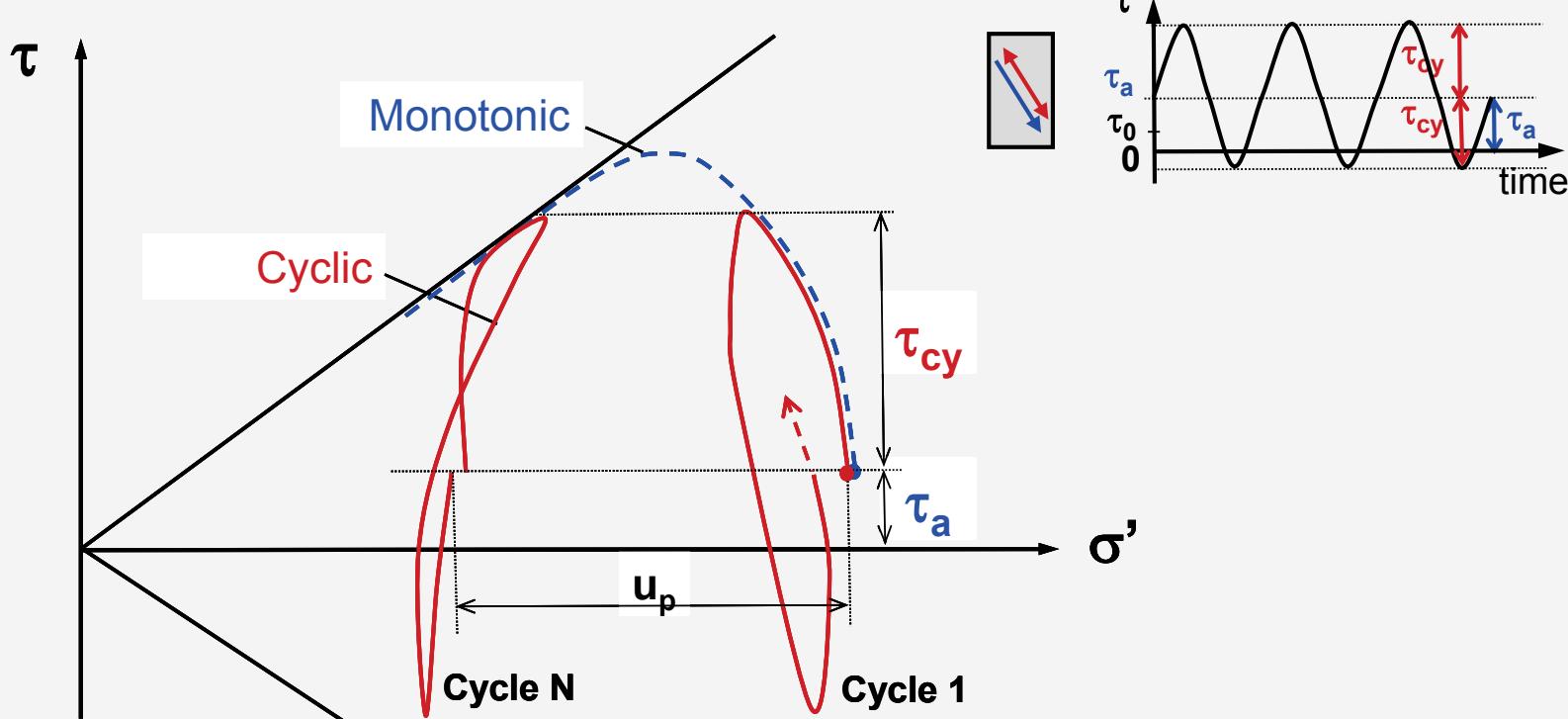
# Cyclic soil parameters needed in design

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# Presentation

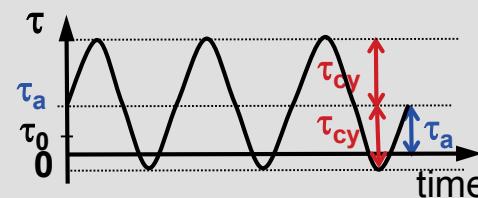
- ↗ When do we need cyclic soil parameters?
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# Cyclic loading generates pore pressure

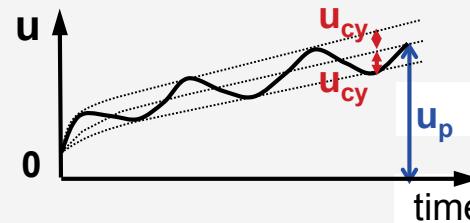


# Pore pressure & shear strain increase with no. of cycles

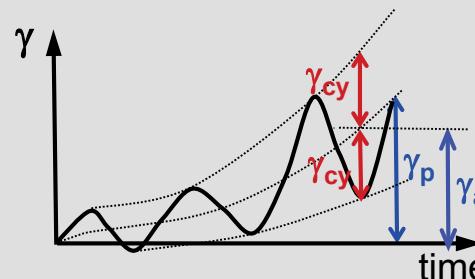
Cyclic and average shear stresses



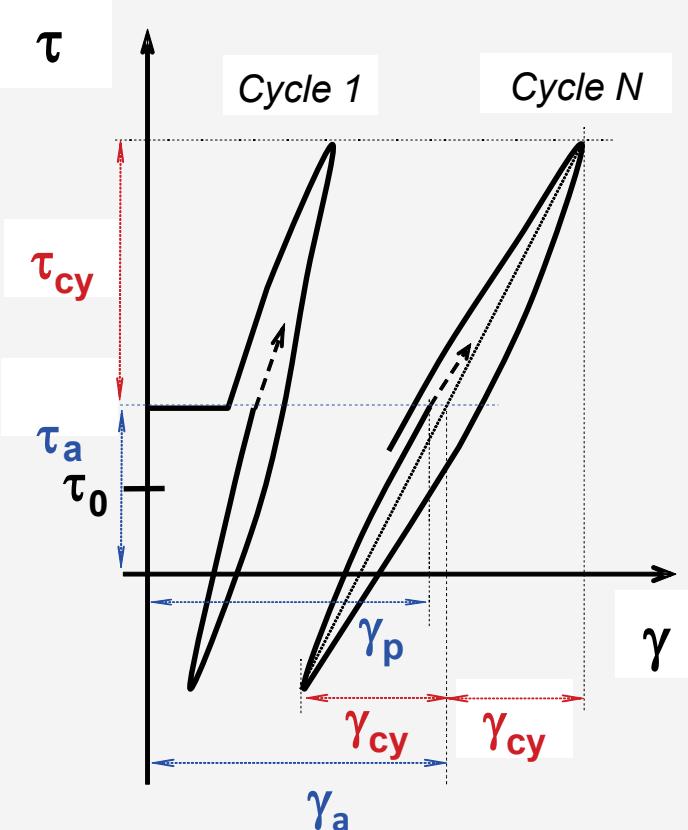
Pore pressure generation



Cyclic, average and permanent shear strains



# Shear strain definitions



$\gamma_{cy}$  -> Cyclic displacements and soil stiffness for dynamic analyses

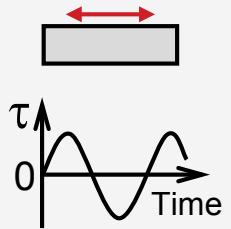
$\gamma_a + \gamma_{cy}$  -> Total displacements

$\gamma_p$  -> Displacements after storm

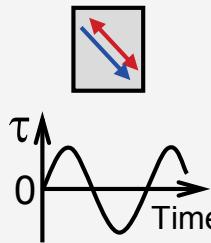
*Model to follow behavior during a cycle:  
Kanya & Andersen (2015)*

# Shear strains depend on test type and $\tau_a$

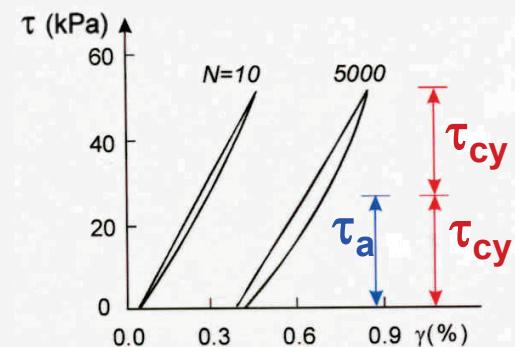
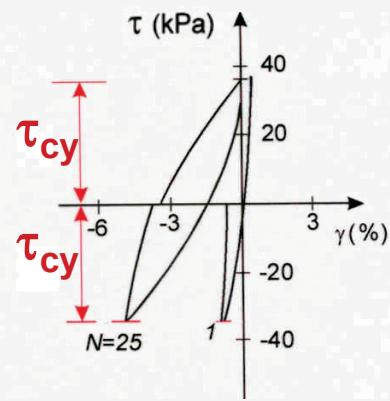
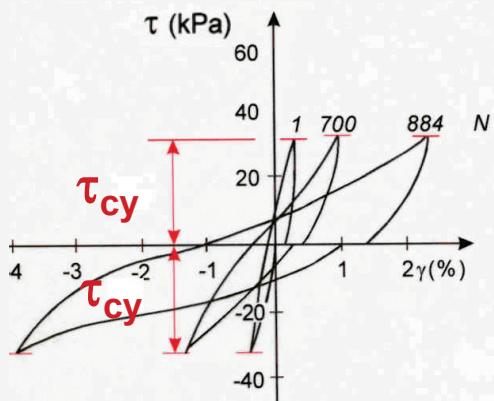
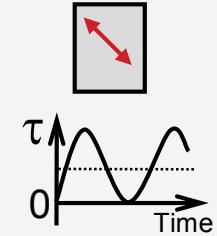
DSS,  $\tau_a=0$



Triaxial,  $\tau_a = 0$

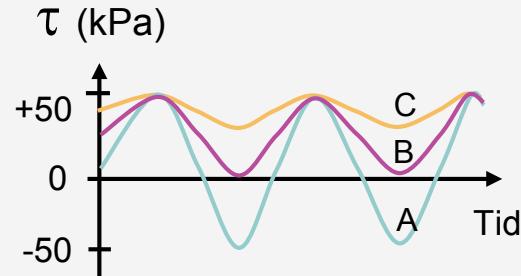
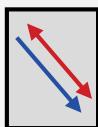


Triaxial,  $\tau_a = \tau_{cy}$



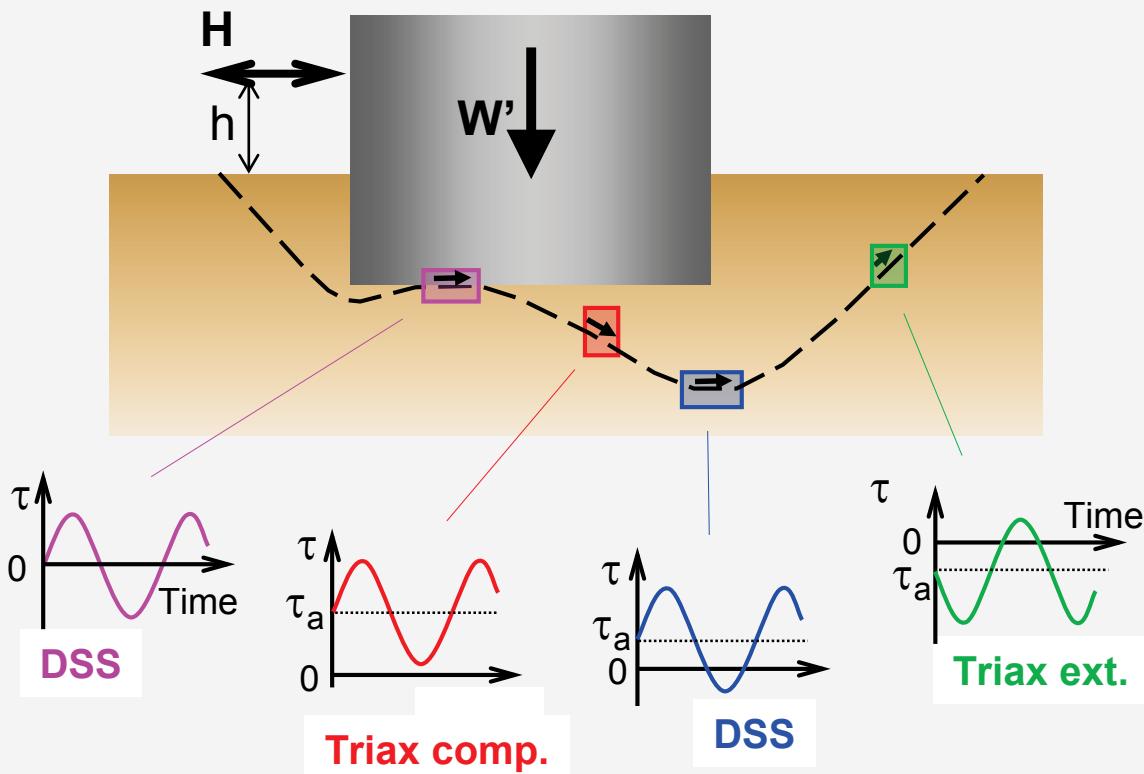
# Shear strains are not governed by $\tau_{\max}$

Triaxial



Test	$\tau_{\max}$	$\tau_a$	$\tau_{cy}$	Result
A	50	0	50	Failure ( $\gamma=15\%$ ) 10 cycles
B	50	25	25	$\gamma_p=0.8\%, \gamma_{cy}=0.3\%$ 2500 cycles
C	50	42.5	7.5	$\gamma_p=0.03\%, \gamma_{cy}=0.02\%$ 2500 cycles

# Soil elements follow different stress paths



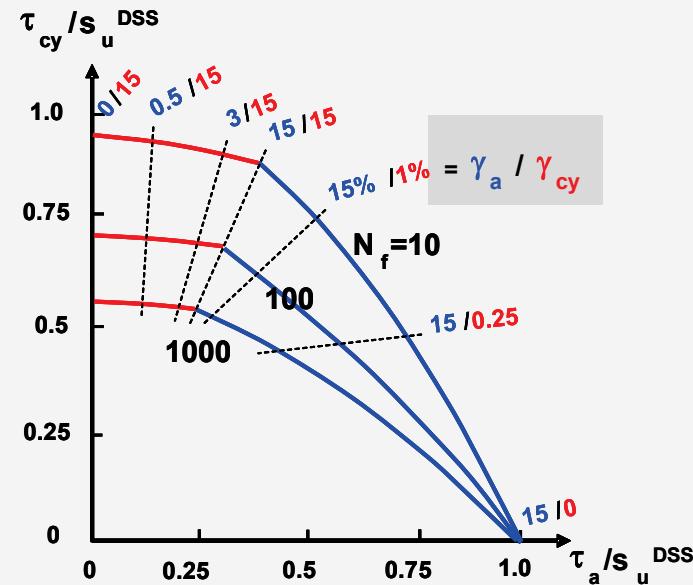
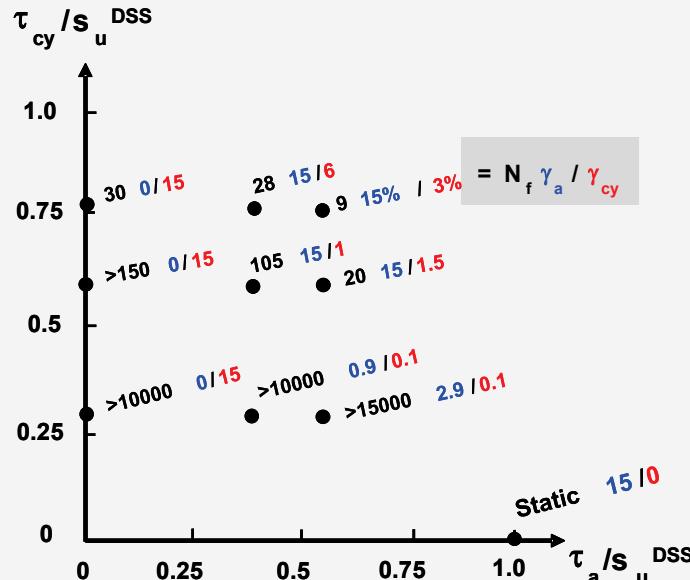
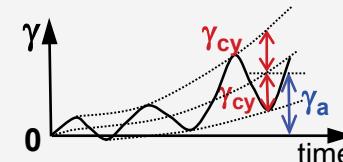
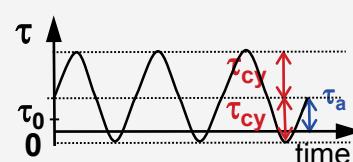
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# No. of cycles to failure depends on $\tau_a$ and $\tau_{cy}$

Drammen Clay, OCR=1

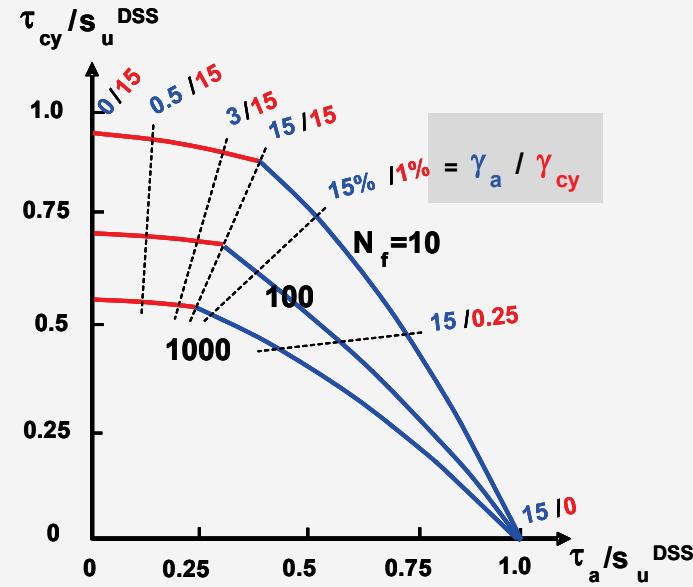
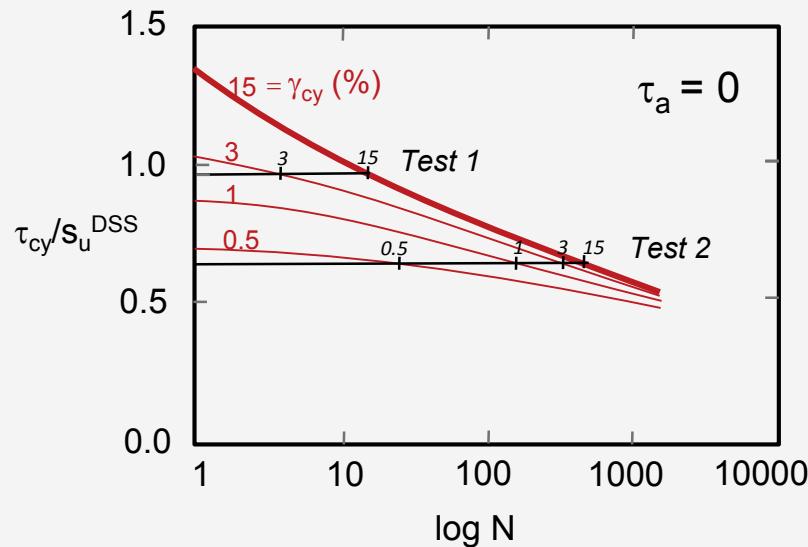
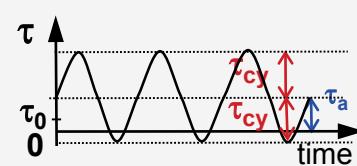
DSS



# No. of cycles to failure depends on $\tau_a$ and $\tau_{cy}$

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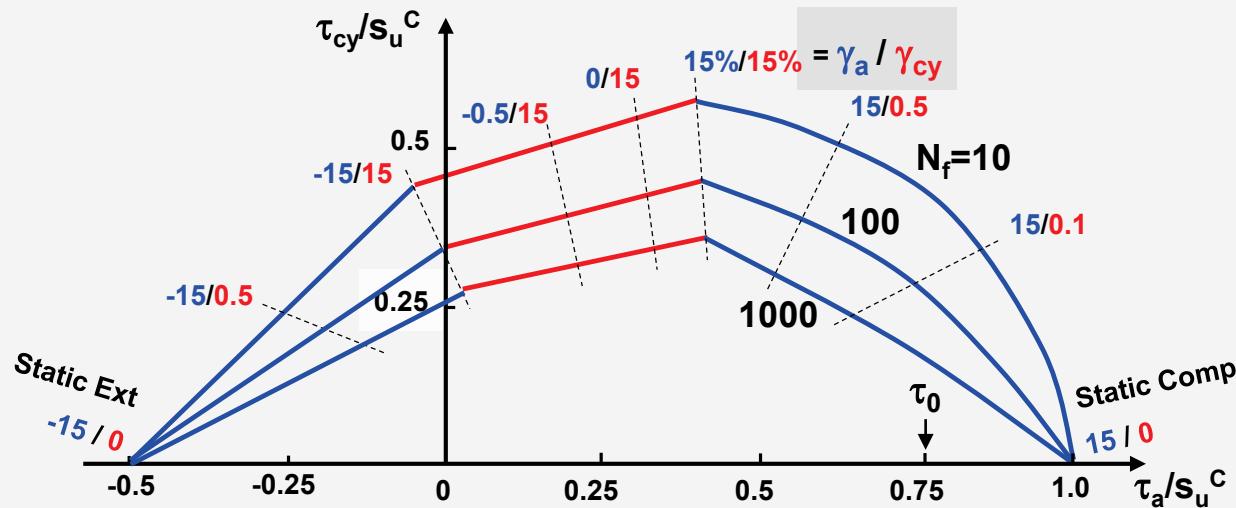
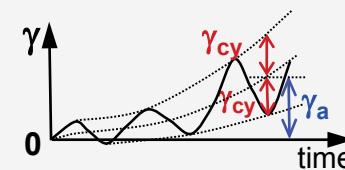
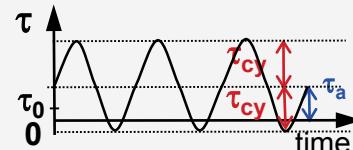
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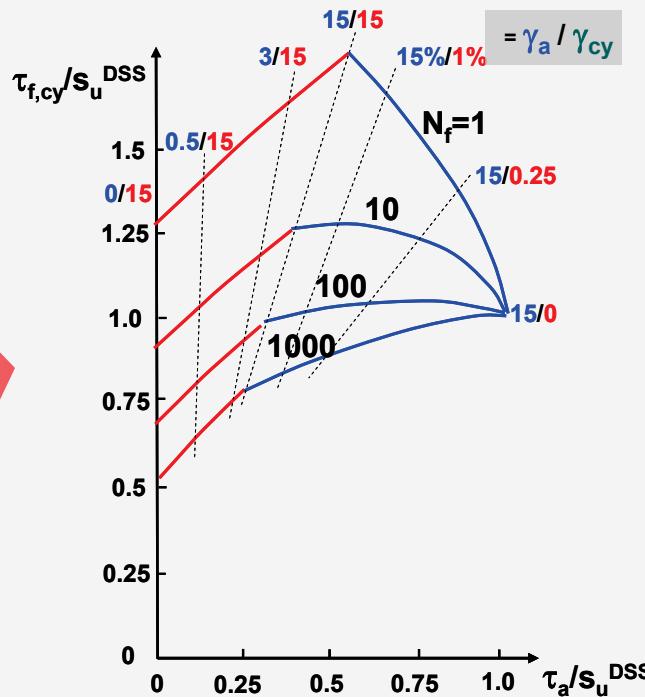
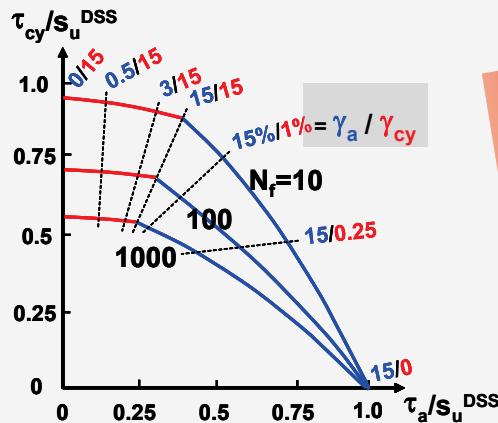
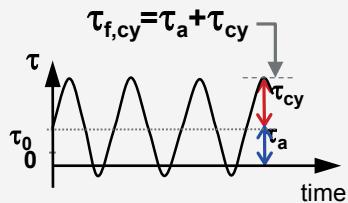
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Drammen Clay, OCR=1

Triaxial

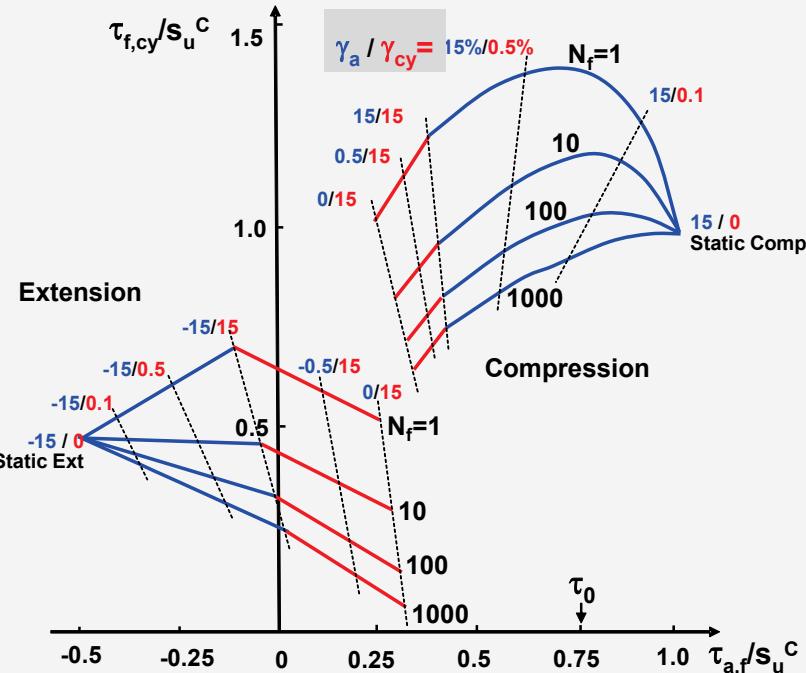
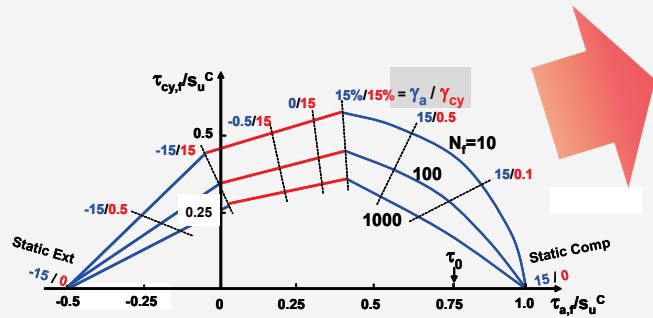
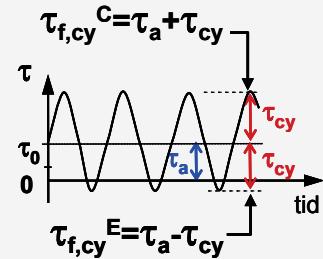


Cyclic shear strength is  $\tau_{f,cy} = \tau_a + \tau_{cy}$



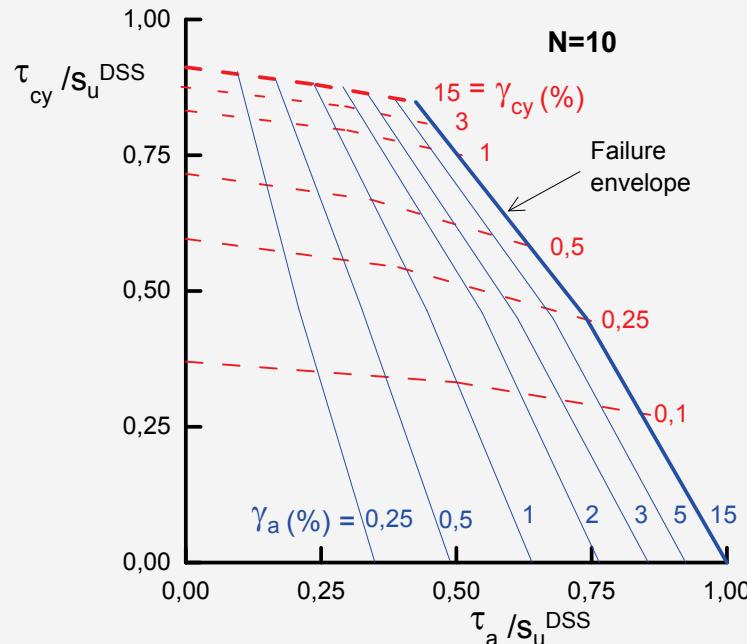
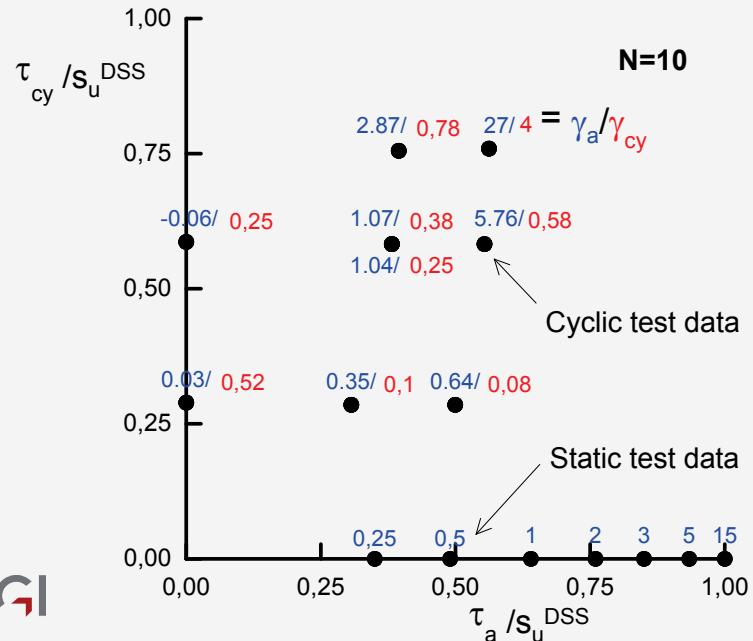
# Cyclic shear strength is $\tau_{f,cy} = \tau_a \pm \tau_{cy}$

**Triaxial**

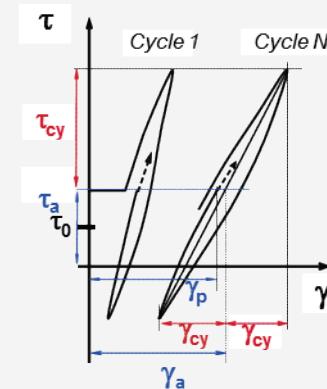
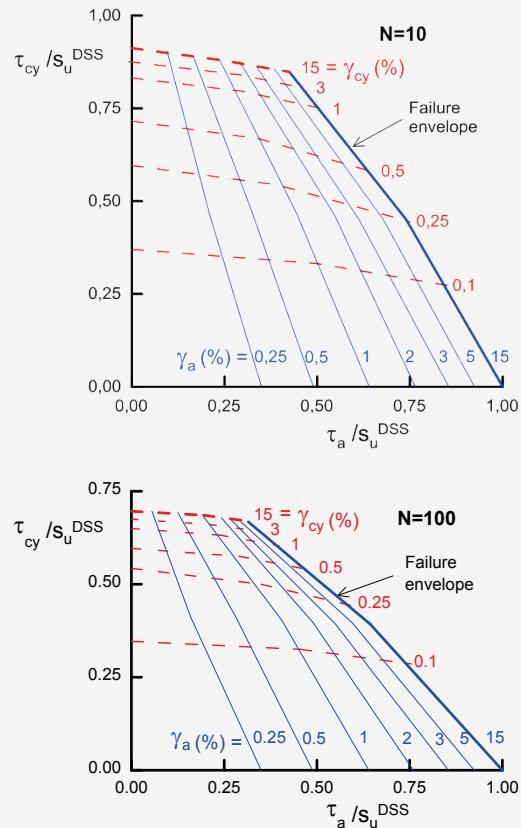


# Shear strains, DSS tests, N = 10

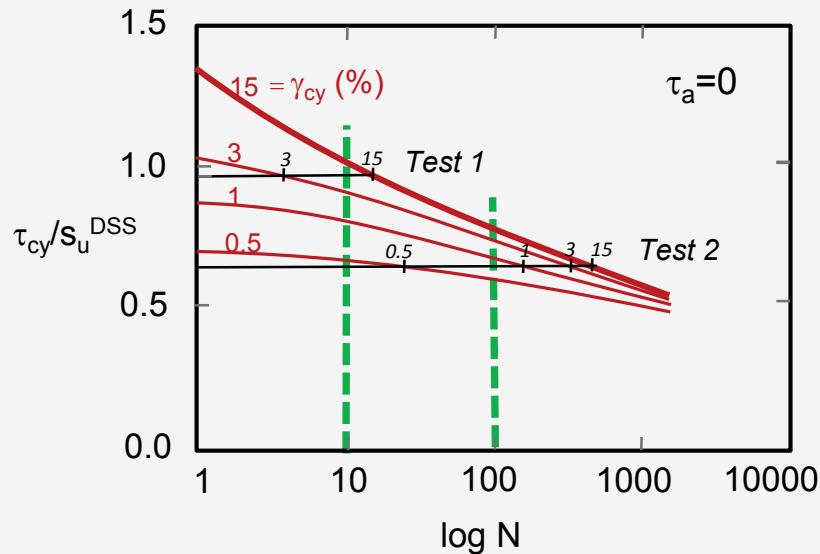
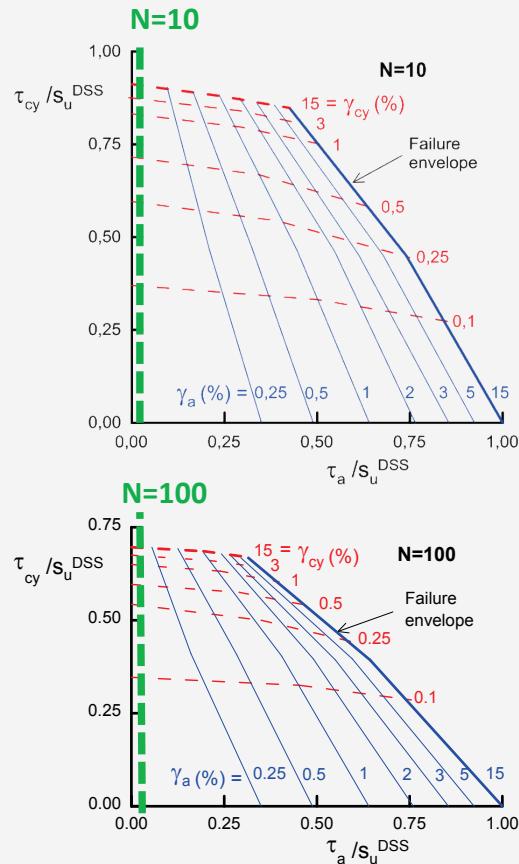
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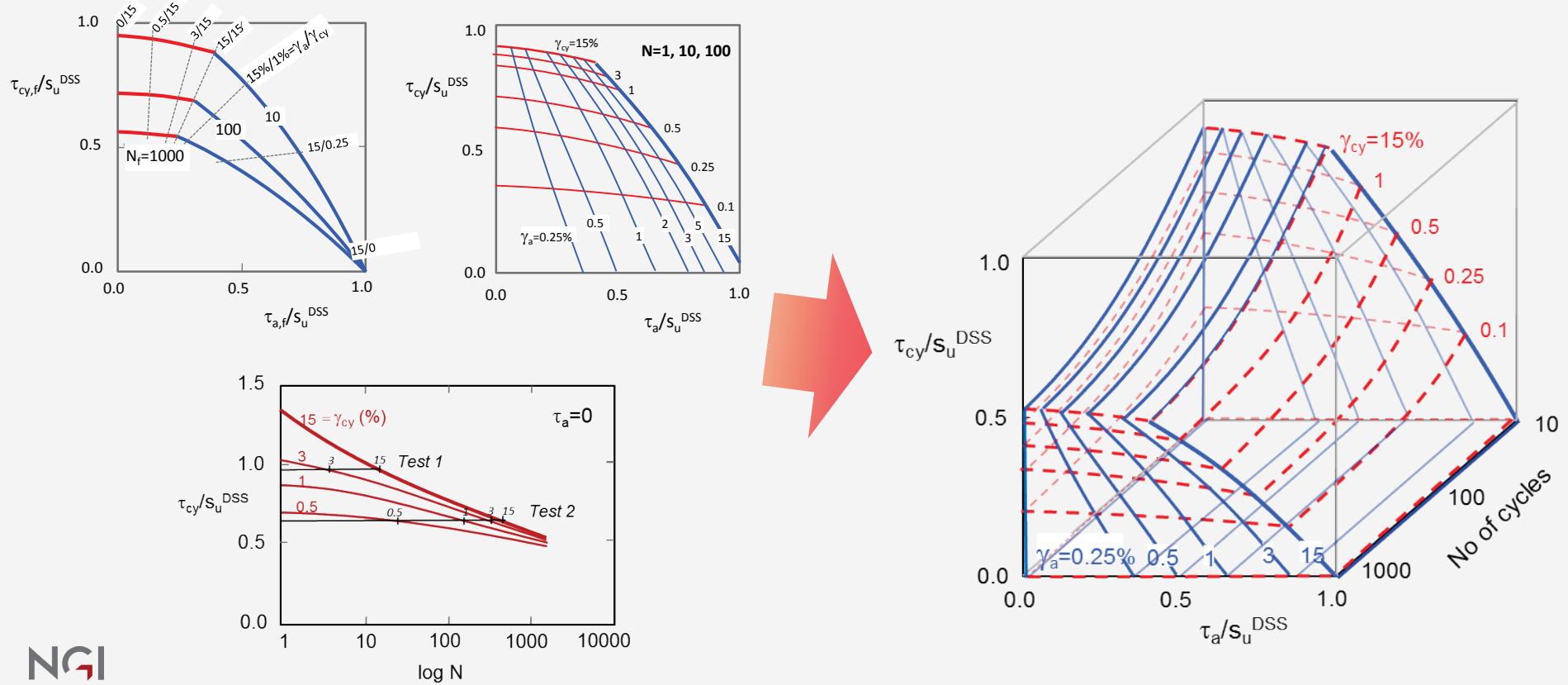
# Shear strains; DSS tests, N = 10 & 100



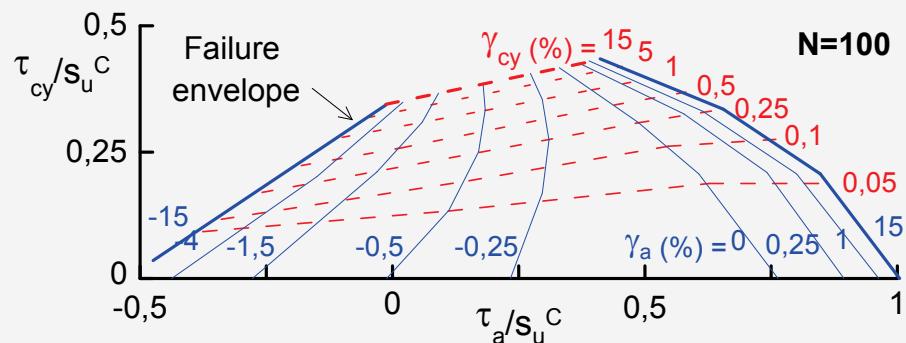
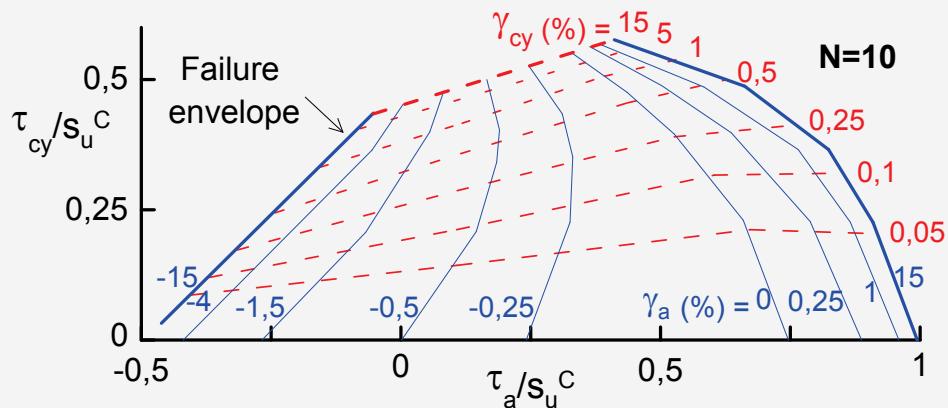
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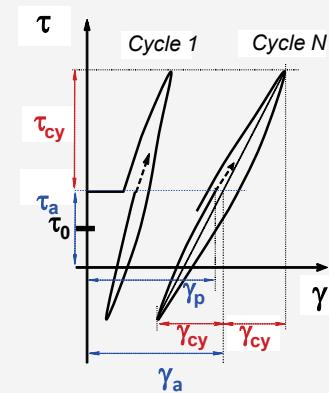
# 3D representation, DSS



# Shear strains; Triaxial tests, N = 10 & 100

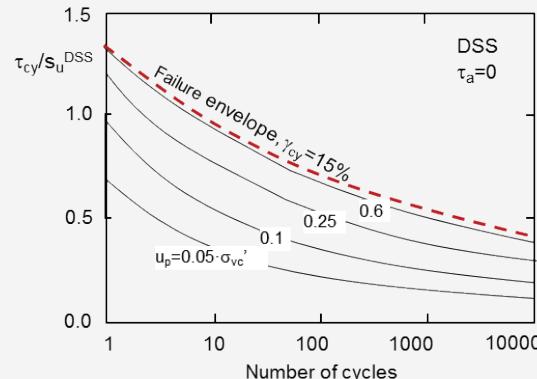
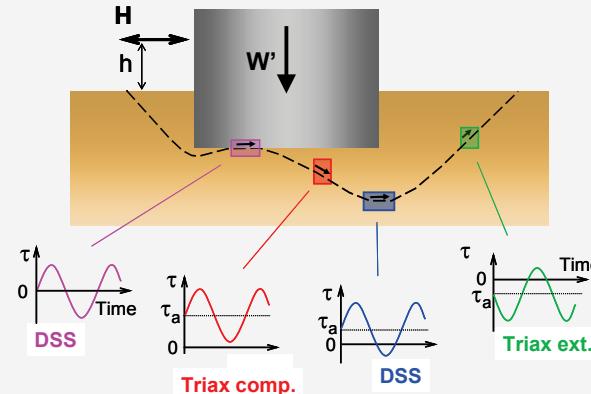
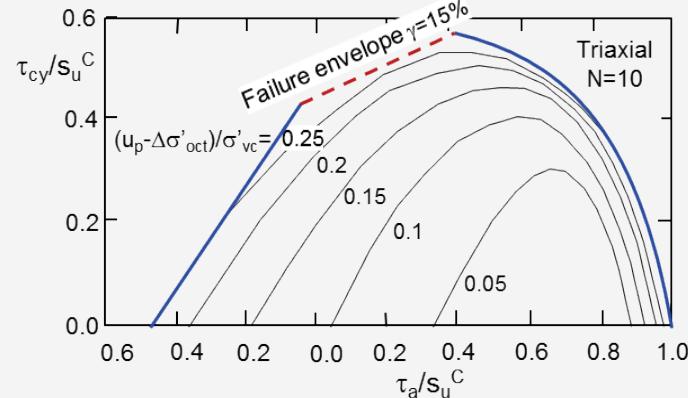
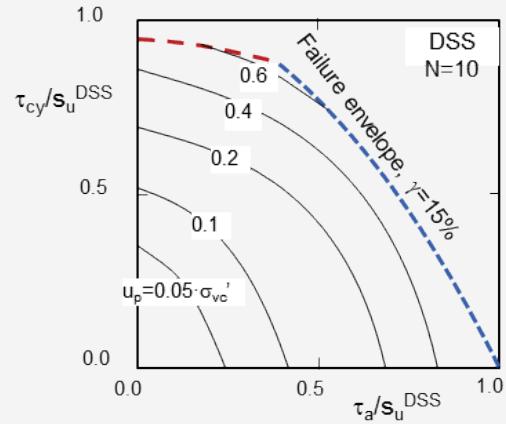


Triaxial



Drammen Clay, OCR=1

# Pore pressure due to cyclic loading, DSS, N = 10



# Use of contour diagrams

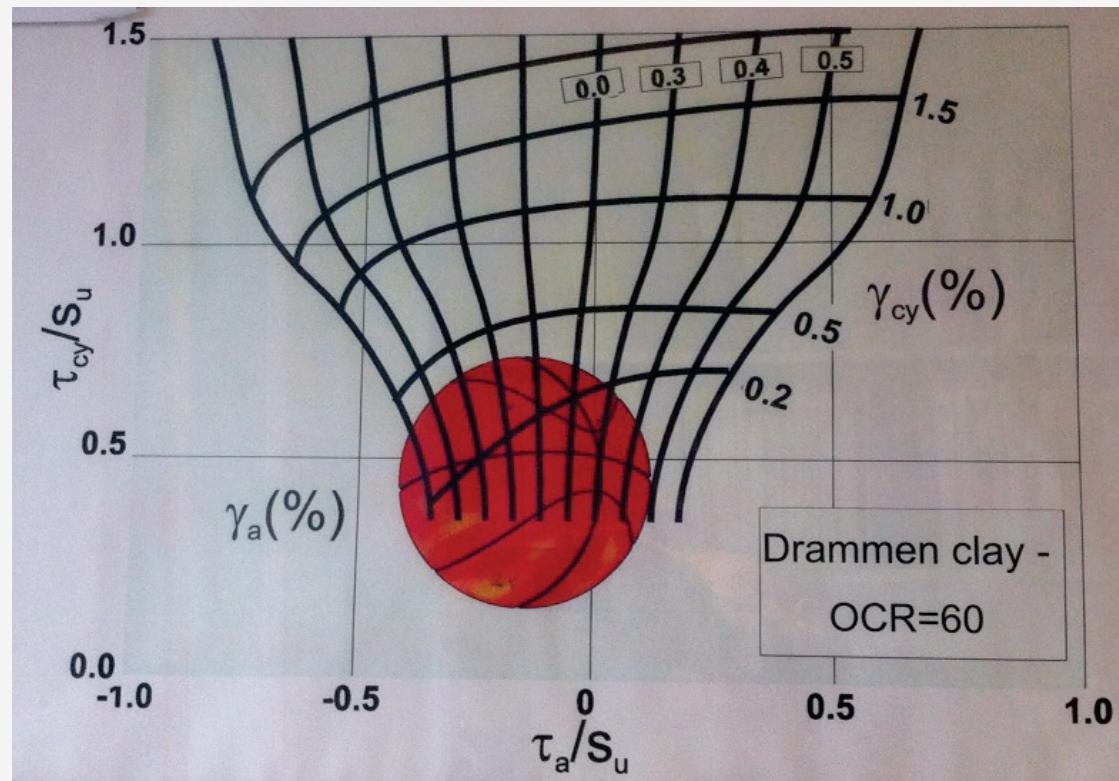
- Used directly in design
- Basis to develop constitutive models
- Check of constitutive models
- Framework for specification and interpretation of site specific cyclic laboratory tests

# NGI contour diagram - Cake version



Prepared by Ana Page

# NGI contour diagram – Basket ball version



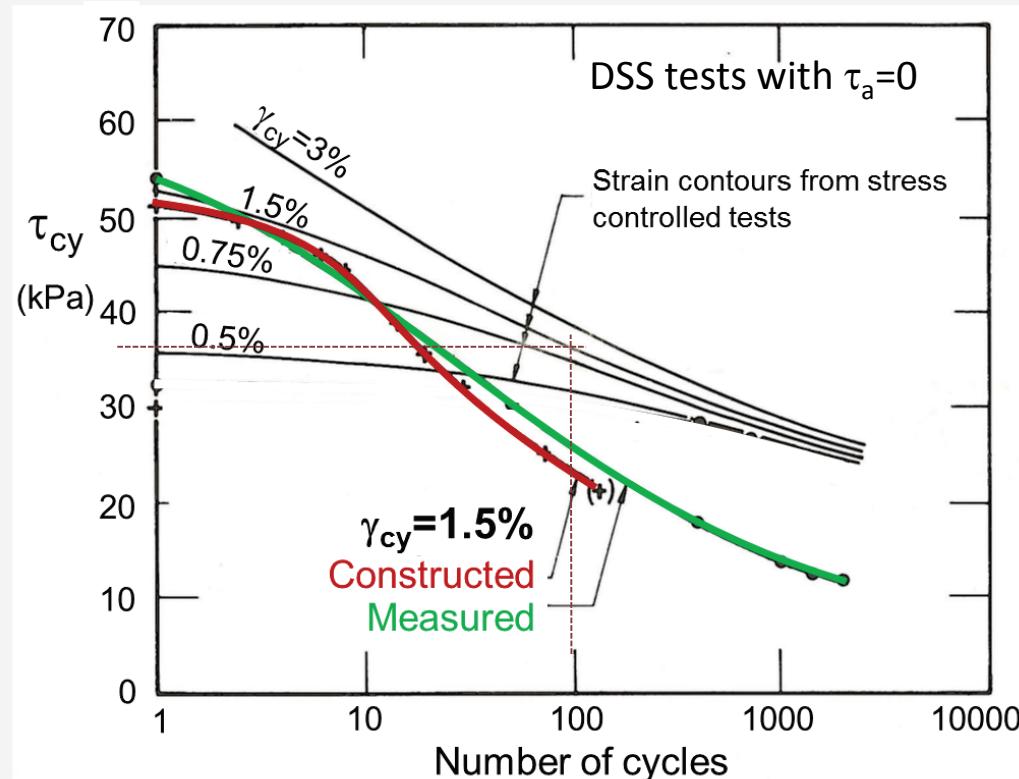
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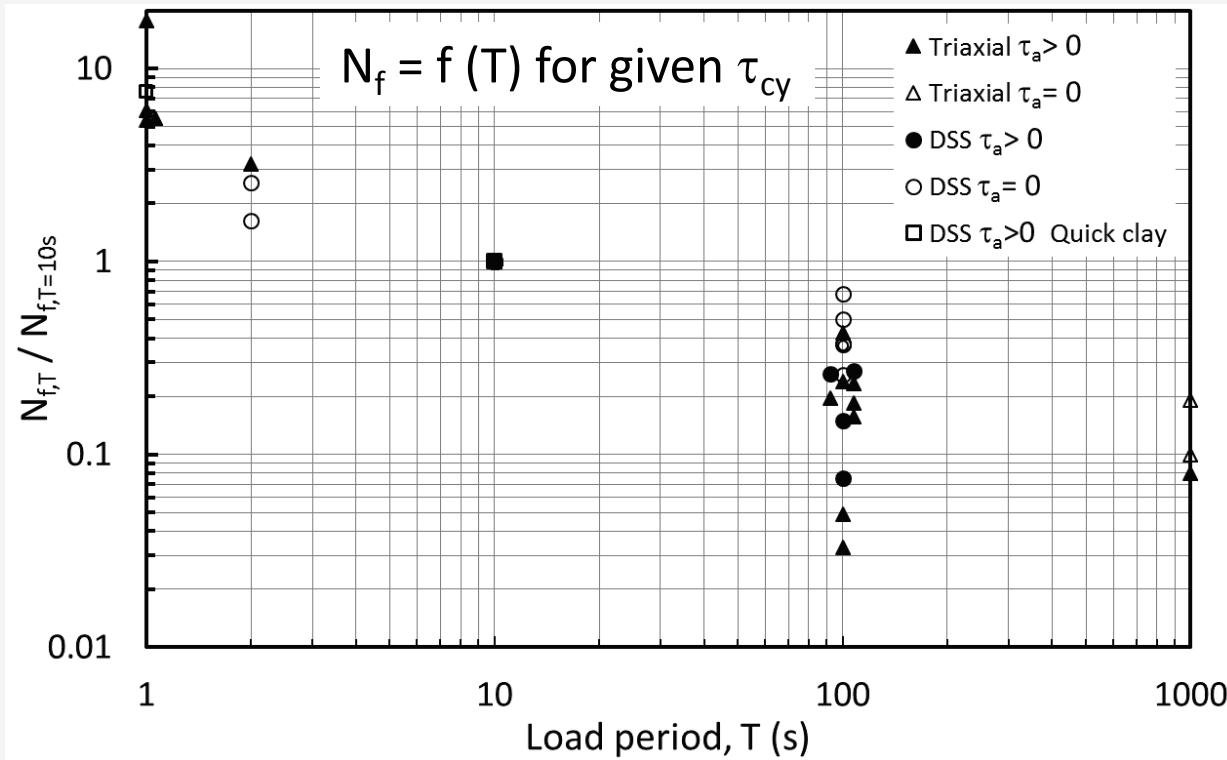
# Some important parameters for contour diagrams

- ☛ Stress vs. strain controlled cyclic loading
- ☛ Load period
- ☛ Preshearing
- ☛ Drained vs. undrained  $\Delta\tau_a$

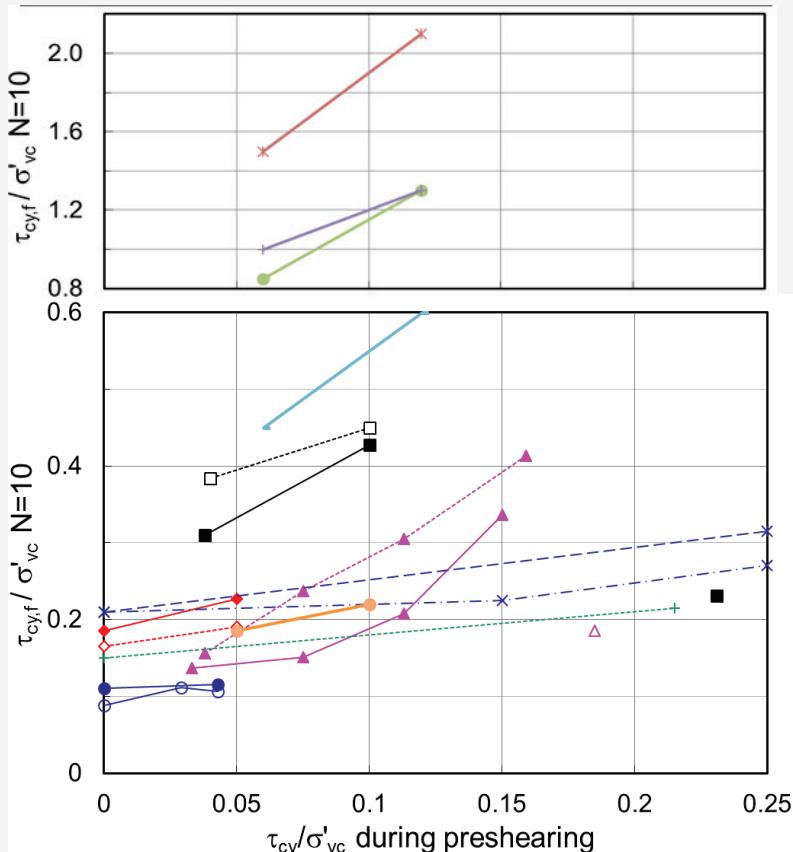
# Stress controlled and strain controlled tests give different strain contours



# Effect of load period - clay



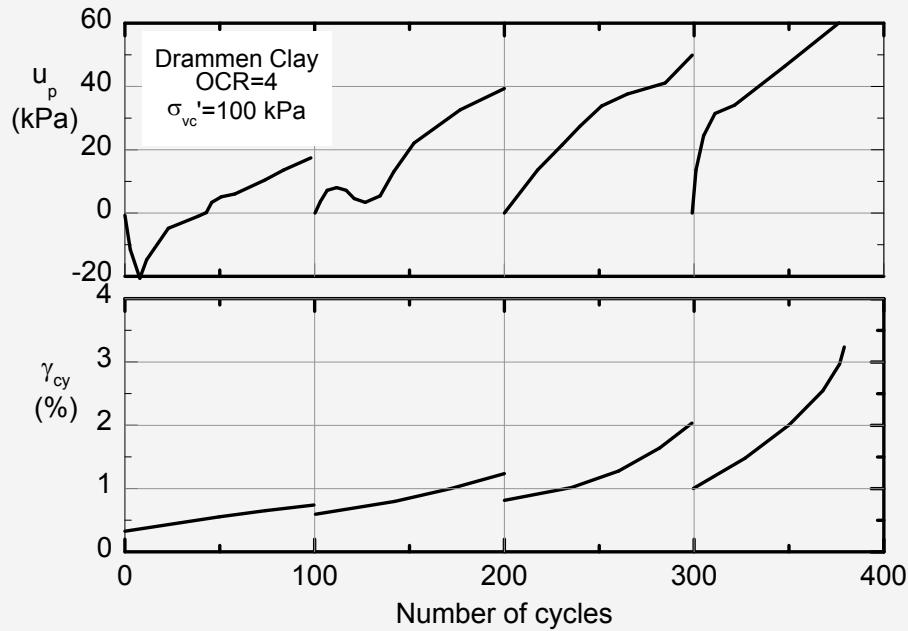
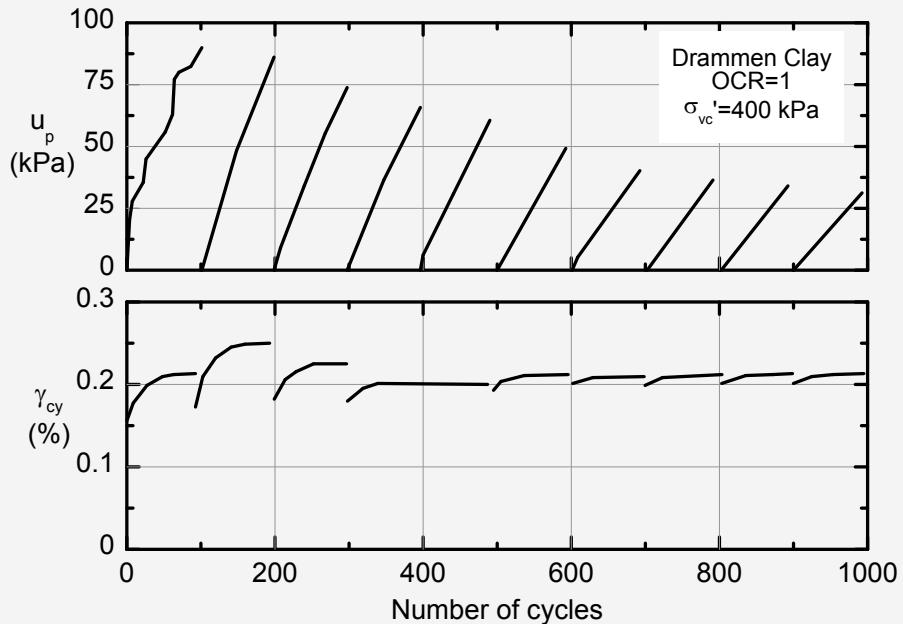
## Effect of preshearing – Sand and silt (OCR=1)



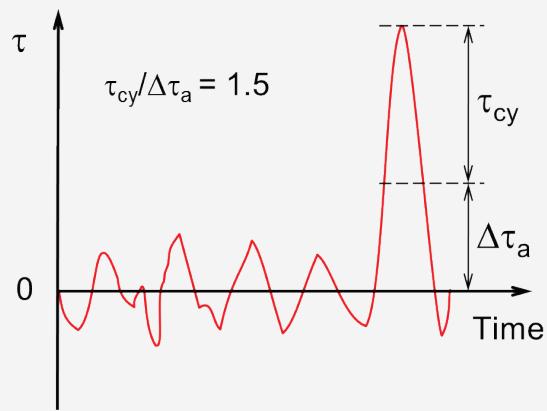
Effect may be negative  
(loosening of dense sand)  
if preshearing causes  
large  $\gamma$

# Effect of preshearing - Clay

DSS  $\tau_a=0$   $\tau_{cy} \sim 0.5 \cdot s_u$

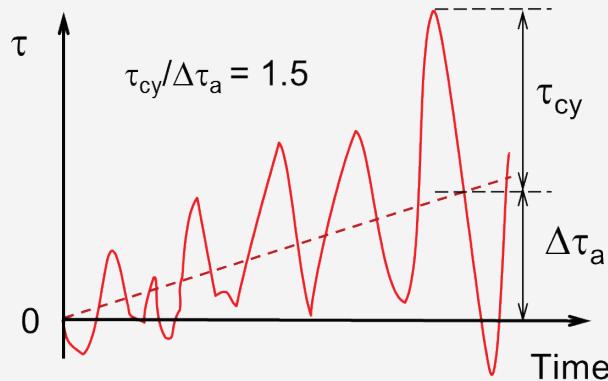


# Cyclic shear strength - Drained vs. undrained $\Delta\tau_a$



Clay:

$\Delta\tau_a$  is undrained



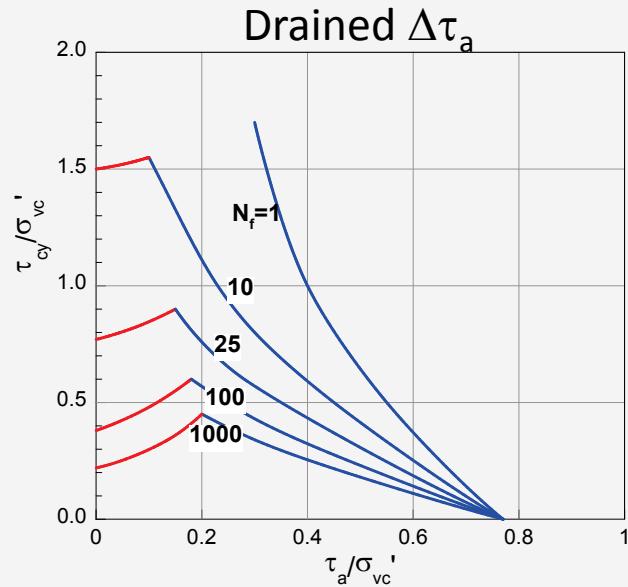
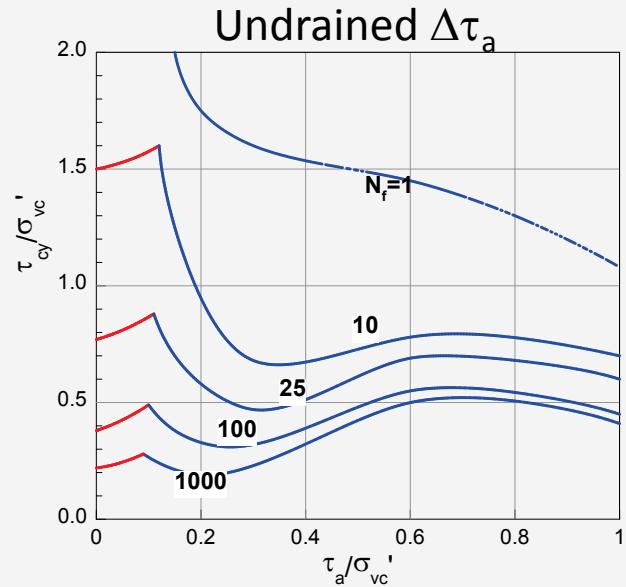
Sand & silt:

$\Delta\tau_a$  can be drained or undrained, depending on

- variation of  $\Delta\tau_a$  with time
- drainage path
- consolidation characteristics

# Cyclic shear strength - Drained vs undrained $\Delta\tau_a$ - DSS

Dense sand, OCR=1

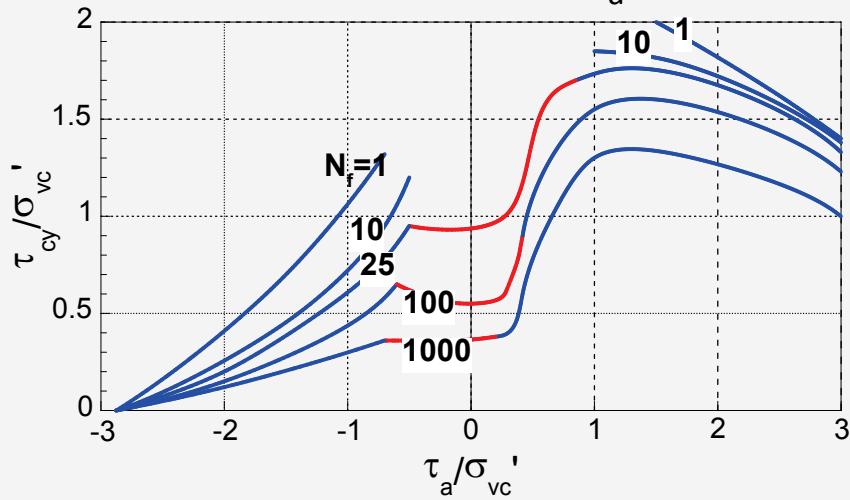


*Effect will be opposite for loose sand*

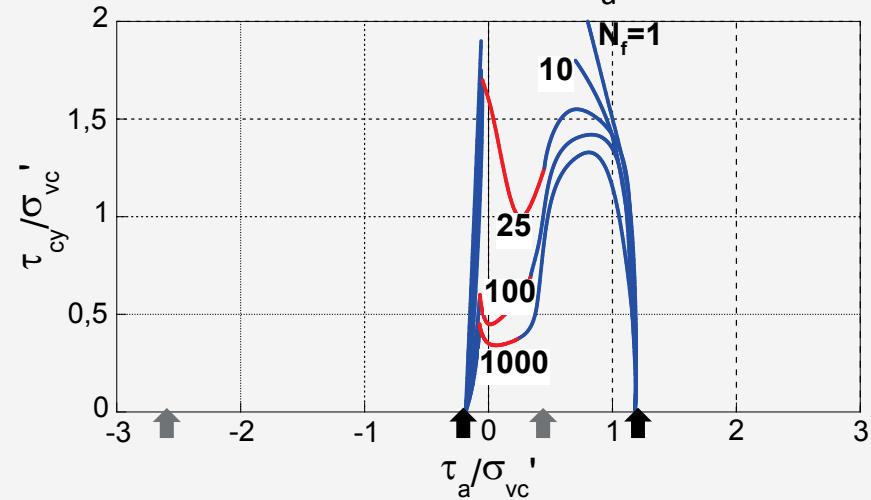
# Cyclic shear strength - Drained vs undrained $\Delta\tau_a$ - Triaxial

Dense sand, OCR=1

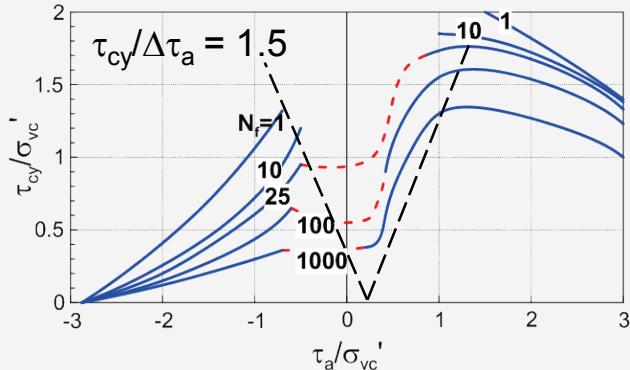
Undrained  $\Delta\tau_a$



Drained  $\Delta\tau_a$



# Cyclic shear strength - Drained vs. undrained $\Delta\tau_a$

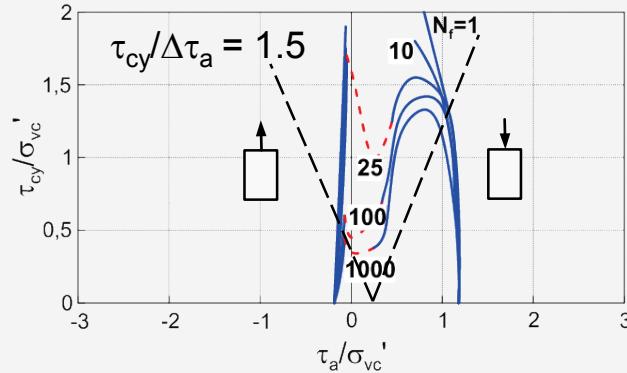


Undrained  $\Delta\tau_a$ ,  $N=10$

$$\tau_{f,cy}^C/\sigma'_{vc} = (1.47+1.83)=3.3$$

$$\tau_{f,cy}^E/\sigma'_{vc} = (0.5+1.2)=1.7$$

$$\tau_{f,cy}^{DSS}/\sigma'_{vc} = (0.47+0.71)=1.2$$



Drained  $\Delta\tau_a$ ,  $N=10$

$$\tau_{f,cy}^C/\sigma'_{vc} = (1.05+1.25)=2.3$$

$$\tau_{f,cy}^E/\sigma'_{vc} = (0.12+0.58)=0.7$$

$$\tau_{f,cy}^{DSS}/\sigma'_{vc} = (0.4+0.58)=0.98$$

Drained/Undrained

Compression: 0.70

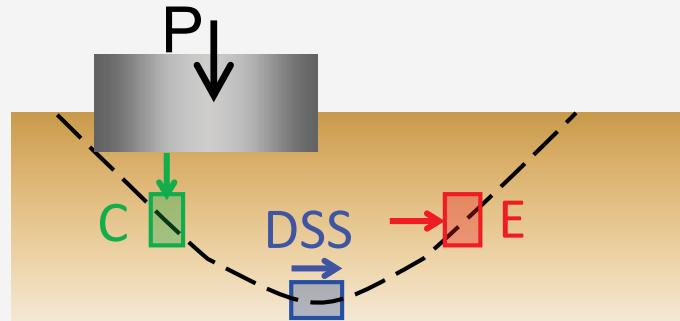
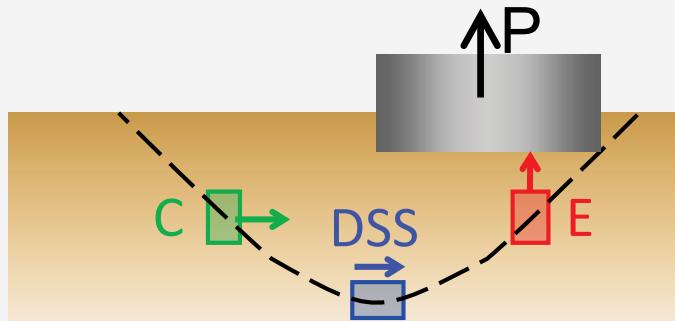
Extension: 0.41

DSS: 0.82

Average ratio ~65%

# Cyclic shear strength - Drained vs. undrained $\Delta\tau_a$

Example: Dense sand,  $N=10$ ,  $\tau_{cy}/\Delta\tau_a=1.5$



$$\text{Average } \tau_f (\text{Drained } \Delta\tau_a / \text{Undrained } \Delta\tau_a) = \\ 1/3 \cdot (0.7/1.7 + 1/1.2 + 0.55/3.3) = \mathbf{0.3}$$

$$\text{Average } \tau_f (\text{Drained } \Delta\tau_a / \text{Undrained } \Delta\tau_a) = \\ 1/3 \cdot (2.2/3.3 + 1/1.2 + 1.7/1.7) = \mathbf{0.83}$$

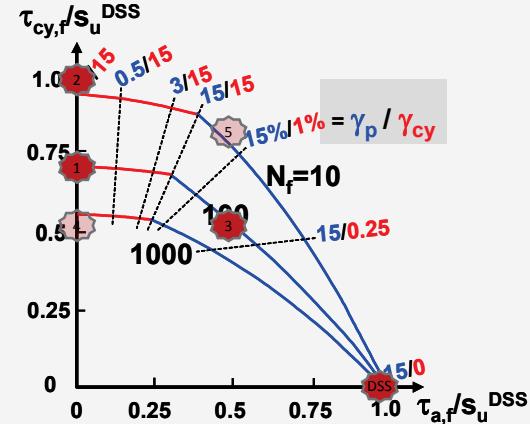
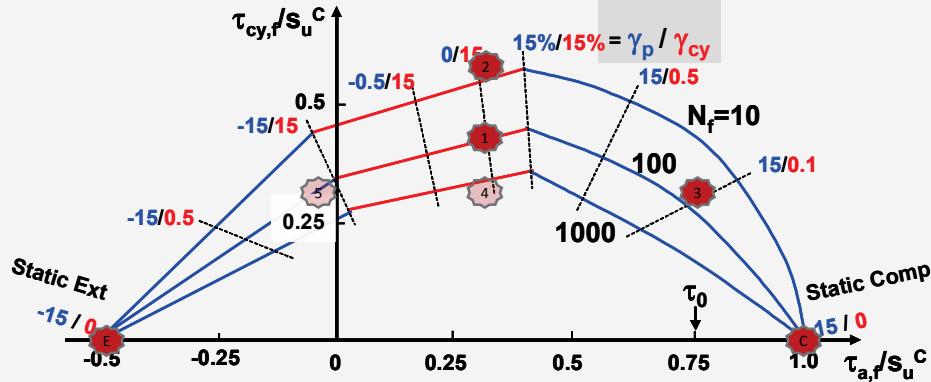
*Failure defined as  $\gamma=5\%$*

# Presentation

- ↗ When do we need cyclic soil parameters?
- ↗ What parameters do we need?
- ↗ How does soil behave under cyclic loading?
- ↗ **Cyclic contour diagram framework**
  - Construction
  - Important parameters
  - **Data base (diagrams and correlations with index parameters)**
- ↗ Application of contour diagrams in design
- ↗ Calculation procedures
- ↗ Slope instability due to cyclic loading
- ↗ Verification by prototype observations and model tests

# Strategy to establish cyclic contour diagrams

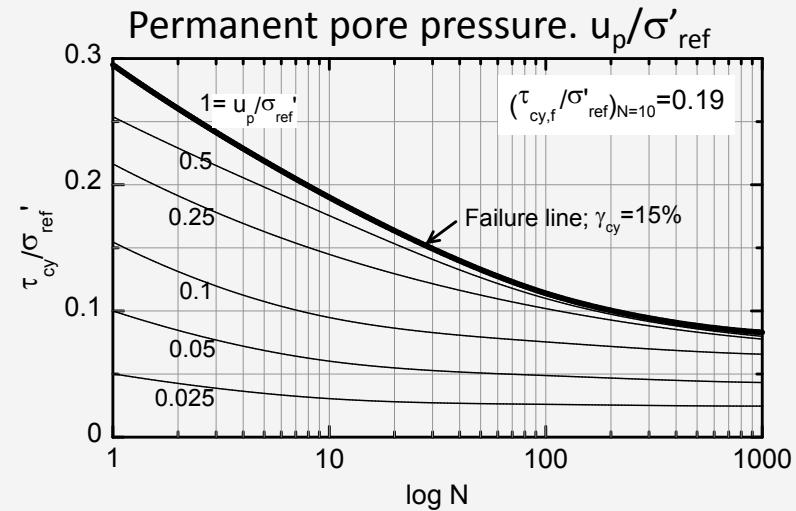
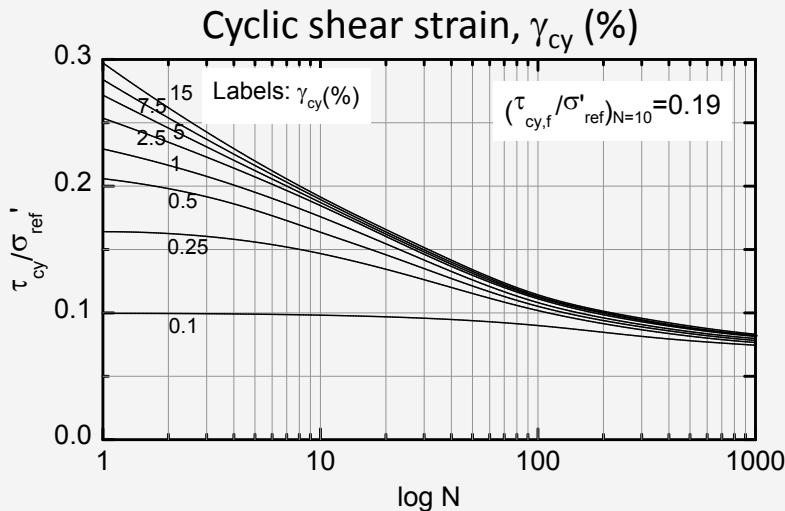
- Find contour diagrams for similar soil from database or establish contour diagrams from correlations
- Perform monotonic test(s) and 3 cyclic tests to see if results match with contours in existing data base
- Supplement with more cyclic tests if necessary  
*(depends on match, consequence and if full diagrams are needed)*



# Contour diagrams - Sand & silt - Examples

$\gamma$  and  $u_p = f(\tau_{cy}, N)$       DSS,  $D_r \sim 65\%$ .

DSS and triaxial with various  $D_r$  in paper.



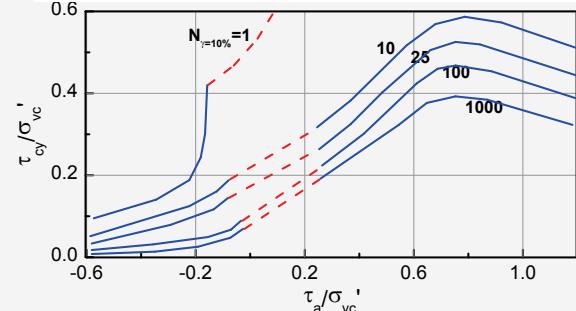
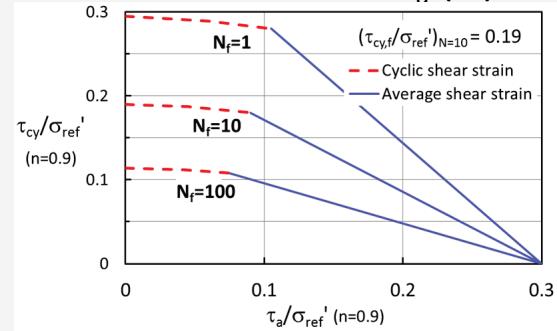
$$\sigma'_{ref} = p_a \cdot (\sigma'_{vc}/p_a)^n$$

# Contour diagrams - Sand & silt - Examples

Cyclic shear strength,  $D_r \sim 65\%$ .

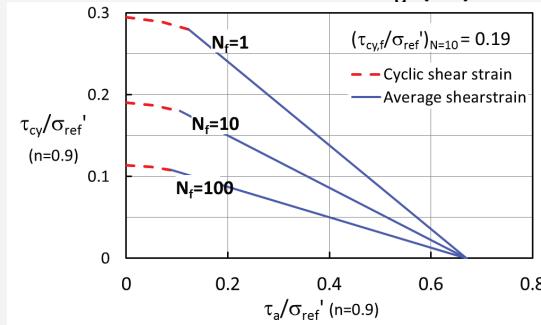
Various  $D_r$  in paper.

Undrained  $\Delta\tau_a$  (%)

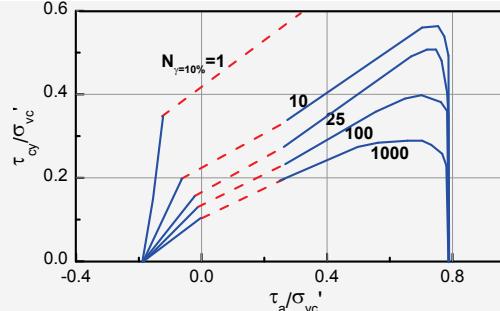


DSS

Drained  $\Delta\tau_a$  (%)



Triaxial

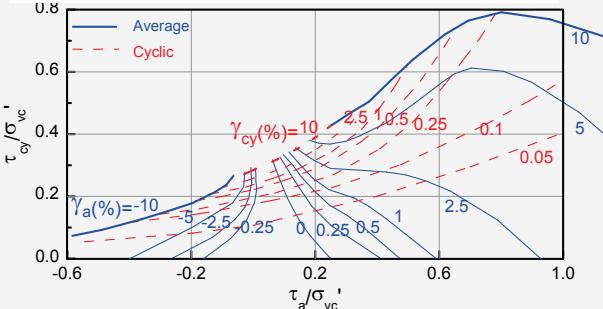
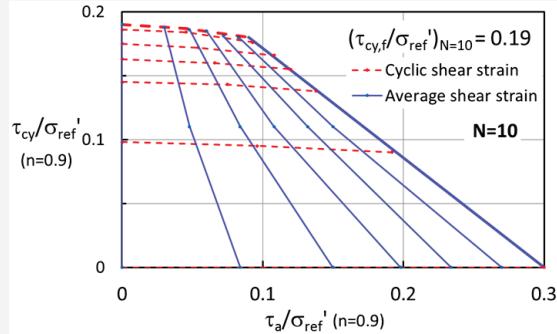


# Contour diagrams - Sand & silt - Examples

Average and cyclic shear strains,  $\gamma_a$  and  $\gamma_{cy}$ ,  $D_r \sim 65\%$ ,  $N=10$ .

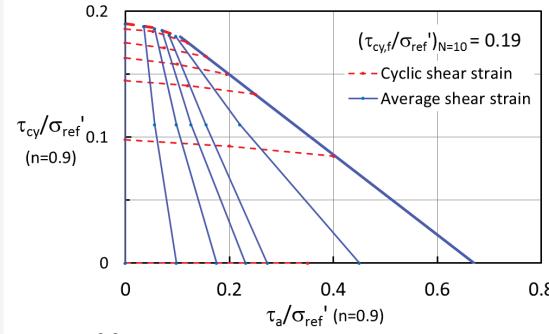
Various  $D_r$  and  $N=1, 10$  and  $100$  in paper.

Undrained  $\Delta\tau_a$  (%)

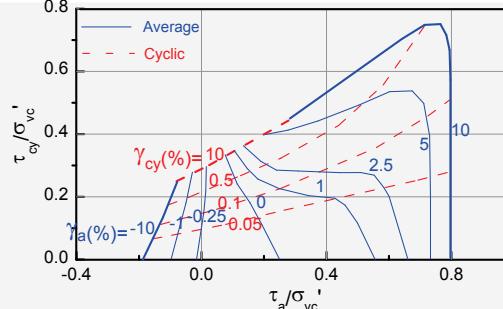


DSS

Drained  $\Delta\tau_a$  (%)

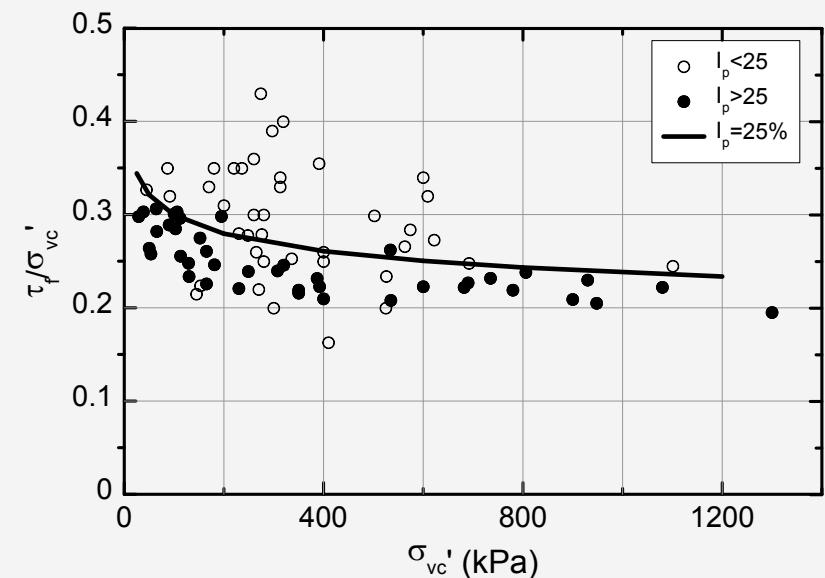


Triaxial



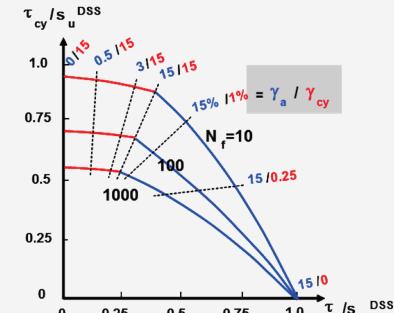
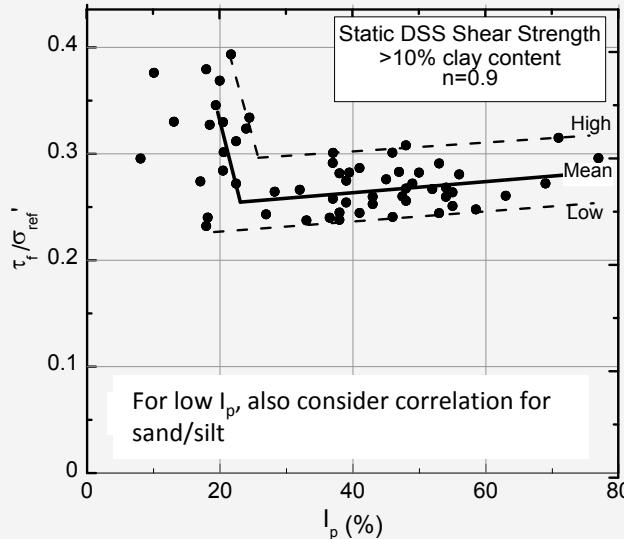
# Static shear strength correlation - Clay

DSS OCR=1



$$\sigma_{ref}' = p_a \cdot (\sigma_{vc}' / p_a)^n$$

$p_a = 100 \text{ kPa}$

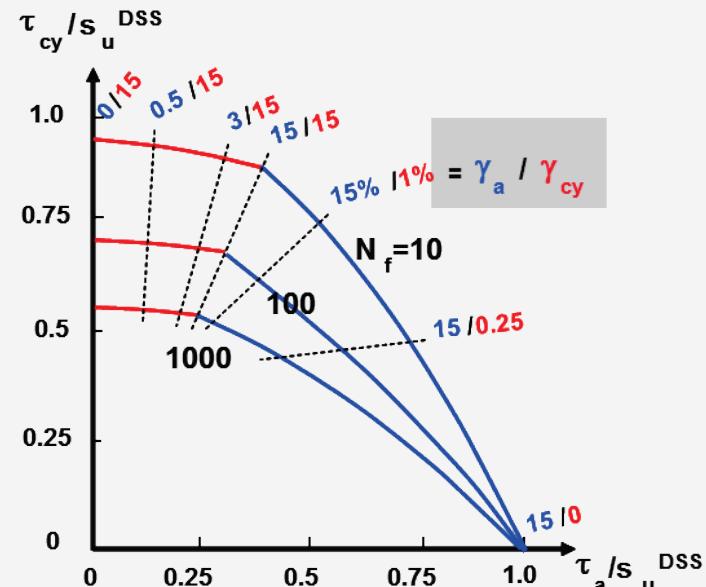
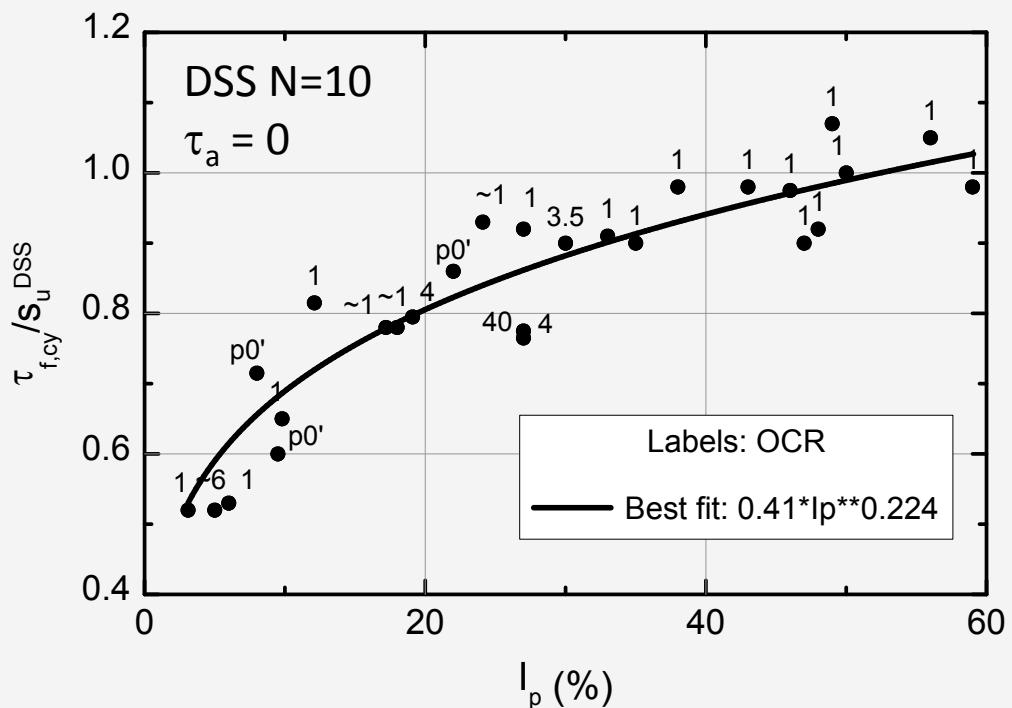


$n=0.9$ : static strength of clay

$n=0.1 - 0.9$ : static strength of sand & silt

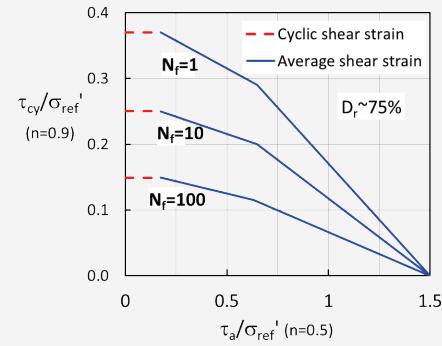
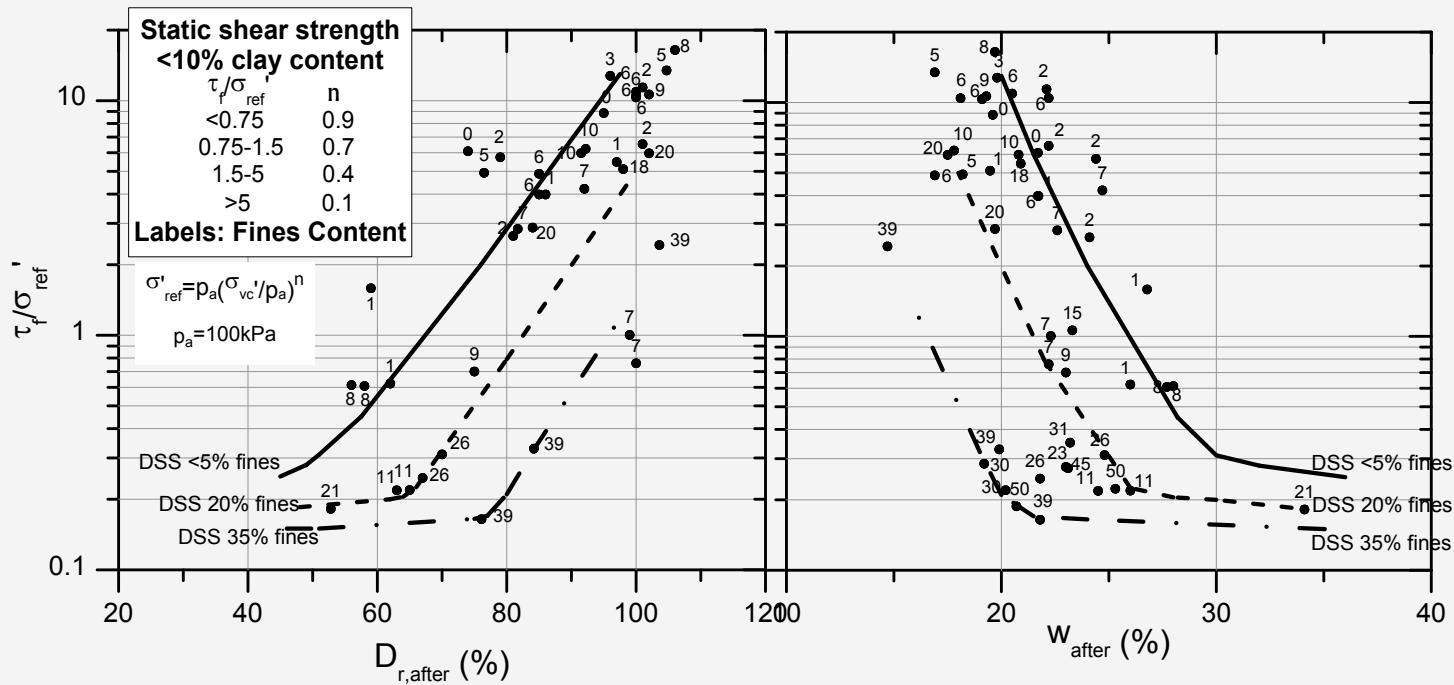
$n=0.9$ : cyclic strength of sand, silt & clay

# Cyclic shear strength correlation - Clay

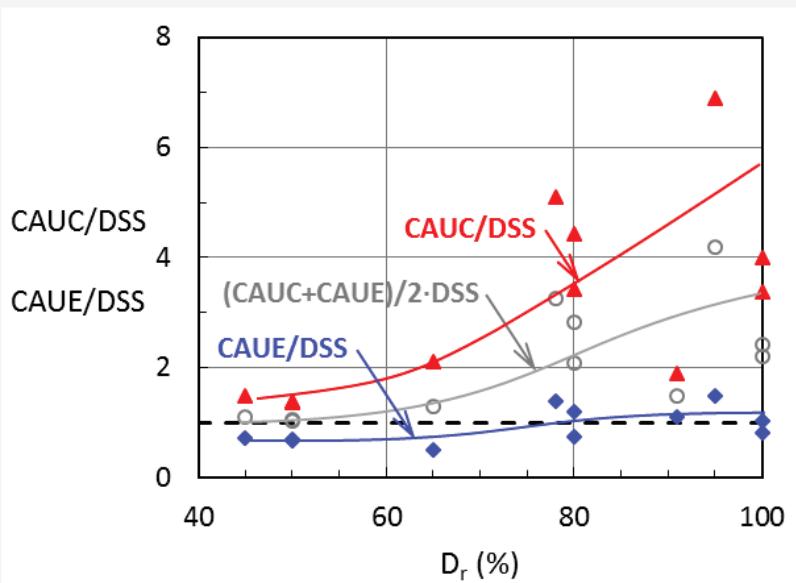
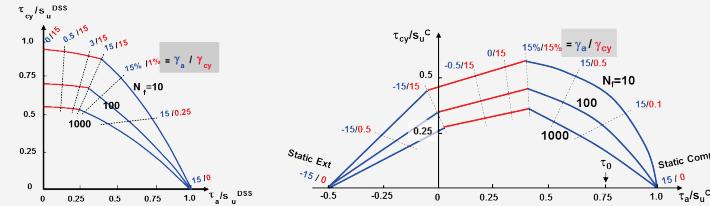
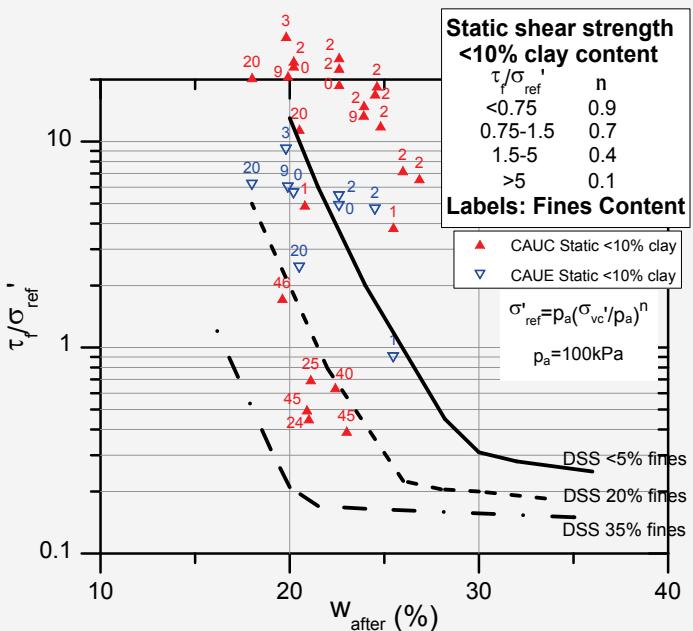


# Static shear strength correlations - Sand & silt

DSS OCR=1

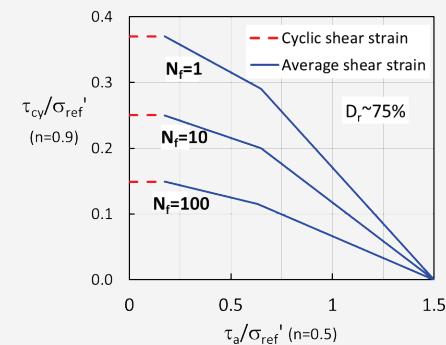
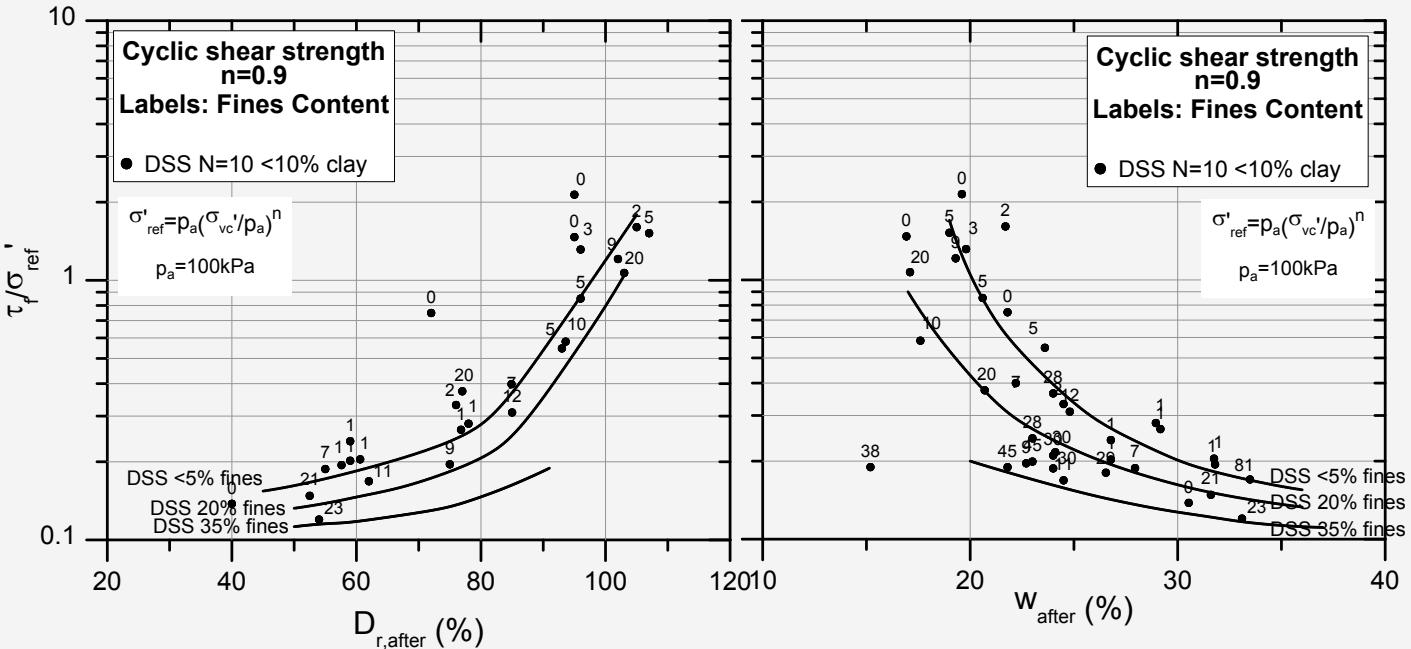


# Static shear strength correlation - Anisotropy



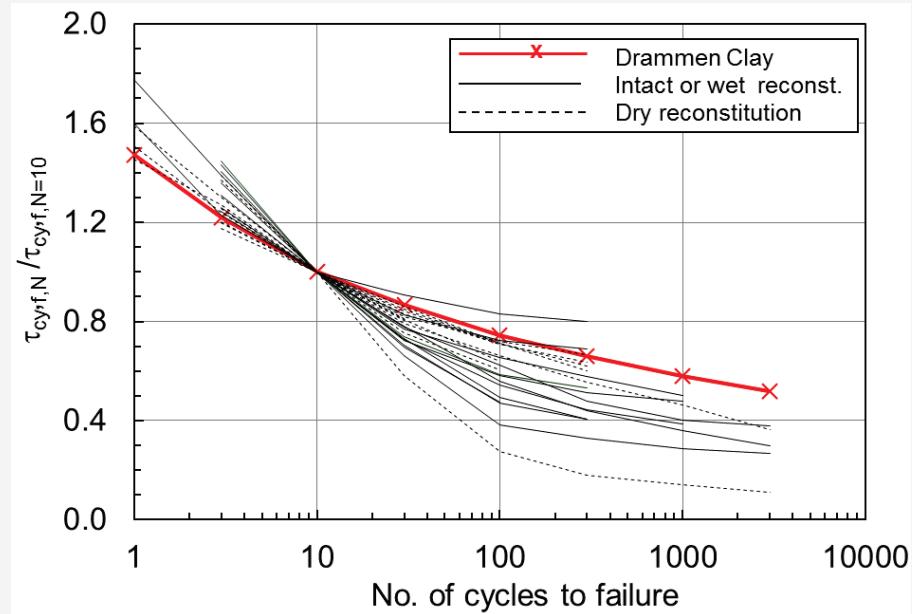
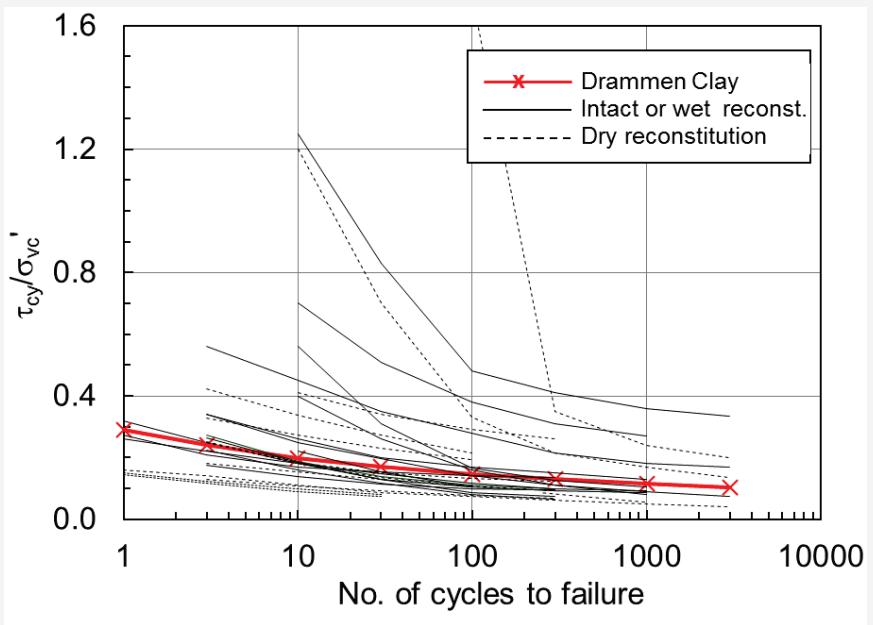
# Cyclic shear strength correlation - Sand & silt

DSS    OCR=1     $\tau_a=0$     N=10

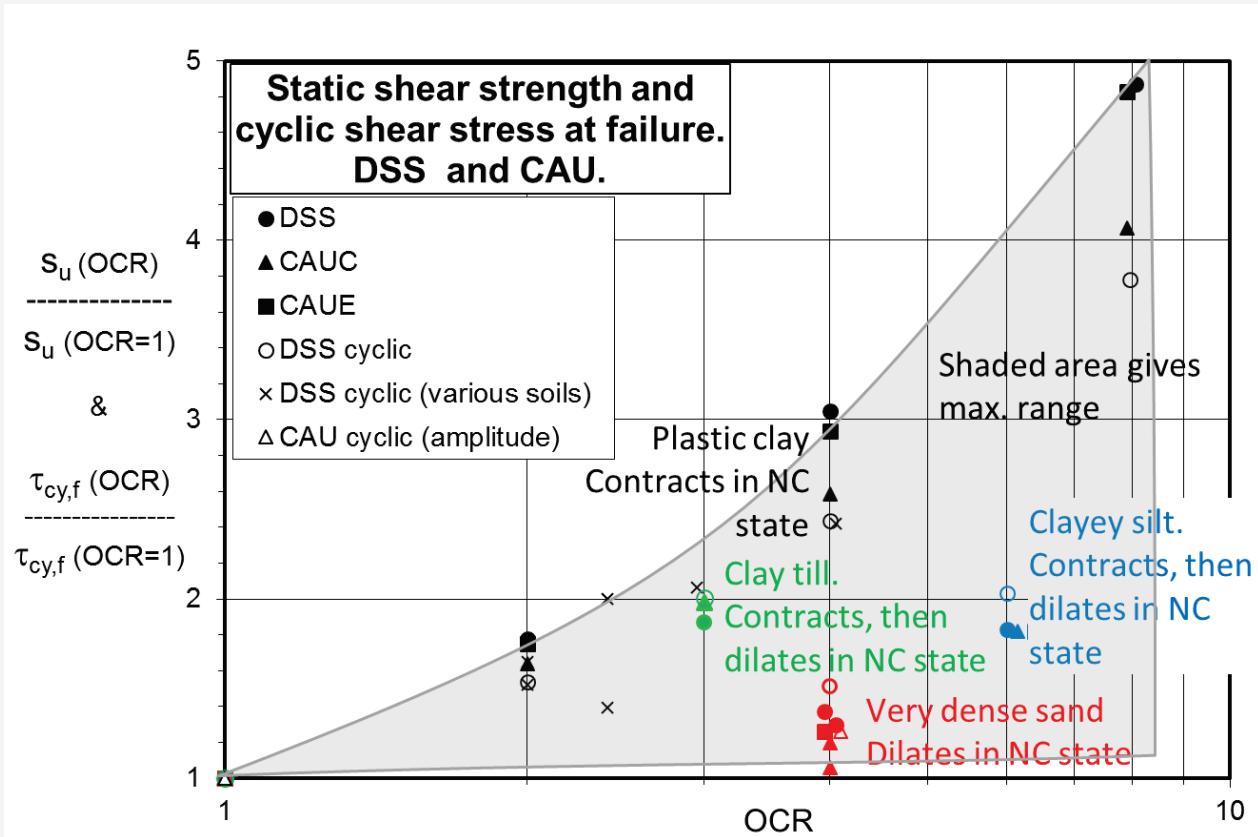


# Correlations for effect of N

DSS    OCR=1     $\tau_a=0$



# Shear strength correlation – Effect of OCR



# Presentation

- ☛ When do we need cyclic soil parameters?
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- ☛ **Application of contour diagrams in design**
- ☛ Calculation procedures
- ☛ Slope instability due to cyclic loading
- ☛ Verification by prototype observations and model tests

# Equivalent number of cycles

Contours show behavior as function of  $N$  with constant  $\tau_a$  and  $\tau_{cy}$

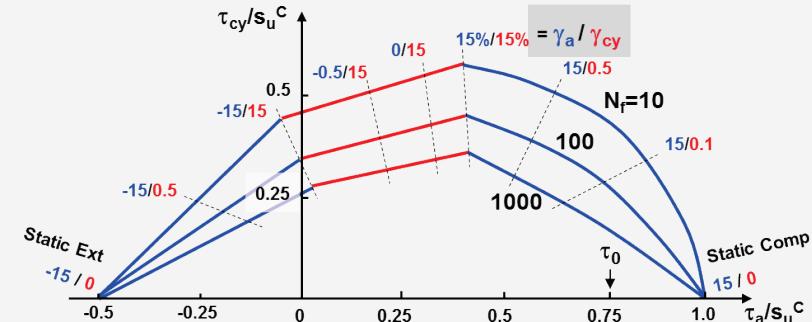
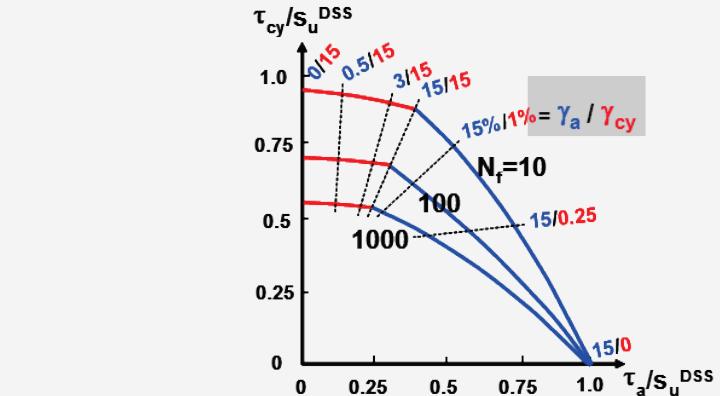
In a storm  $\tau_a$  and  $\tau_{cy}$  vary from one wave to the next

Storm can be transformed to an

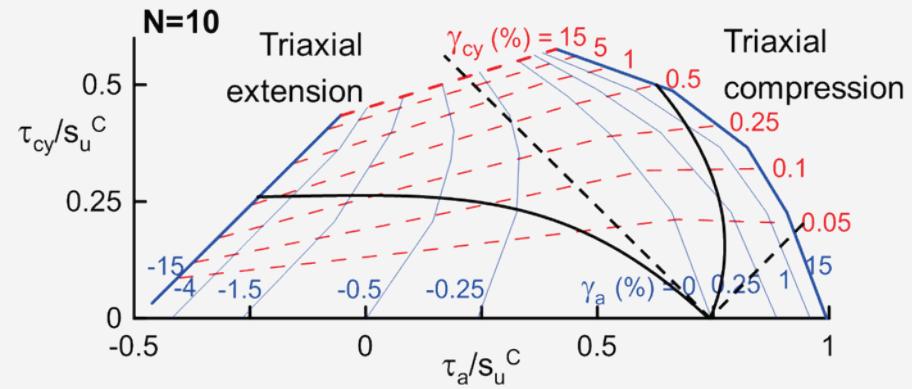
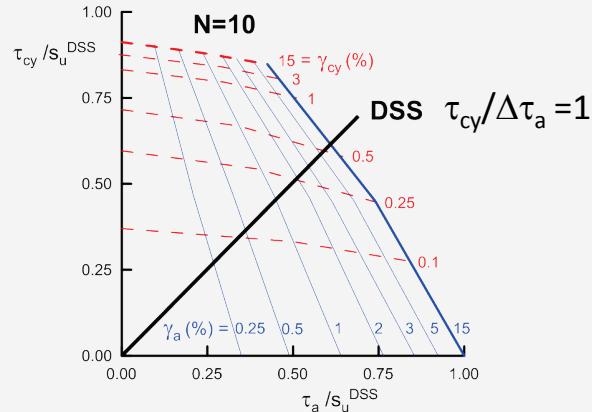
*Equivalent number of cycles of the maximum wave,  $N_{eq}$ , that gives the same effect as the irregular load history*

by

- Pore pressure accumulation
- Strain accumulation



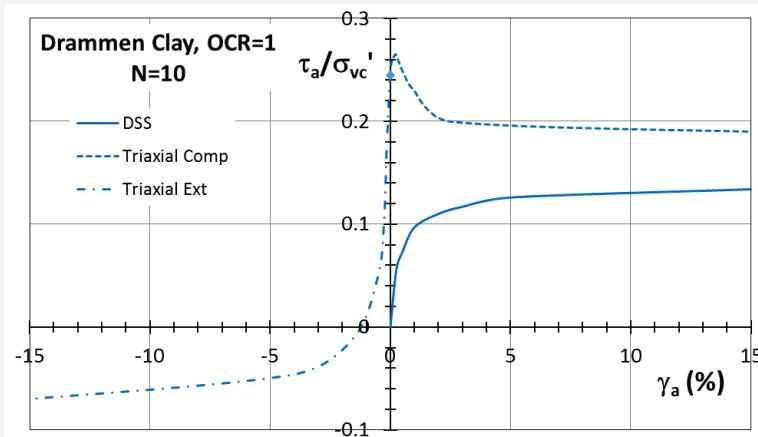
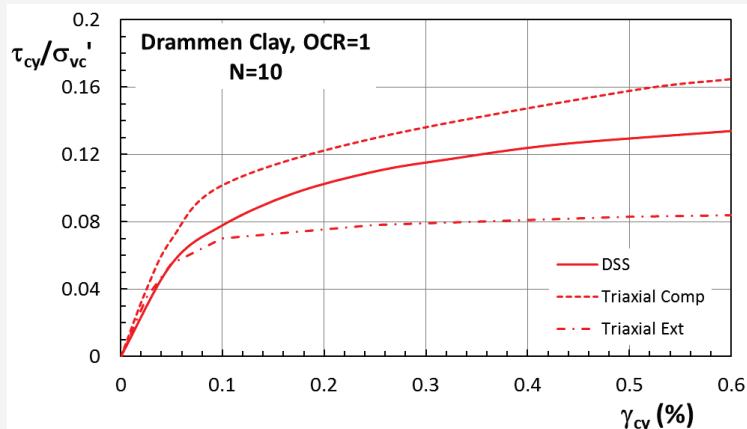
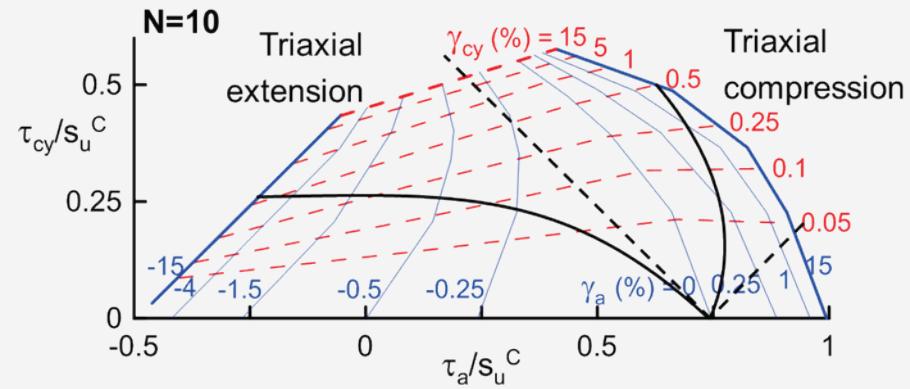
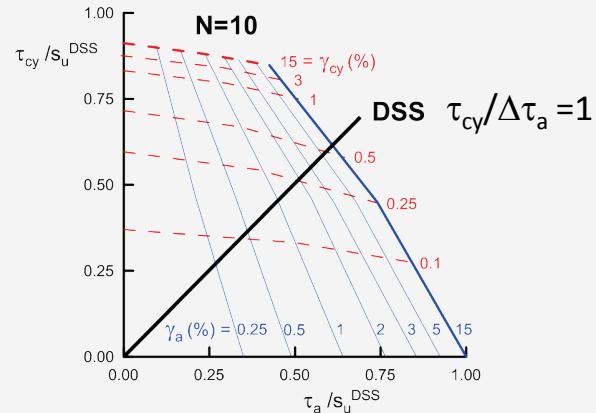
# Cyclic strength and stress-strain relations



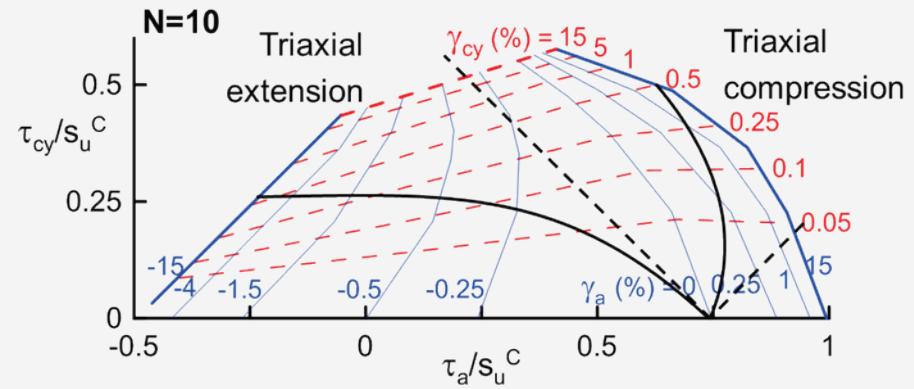
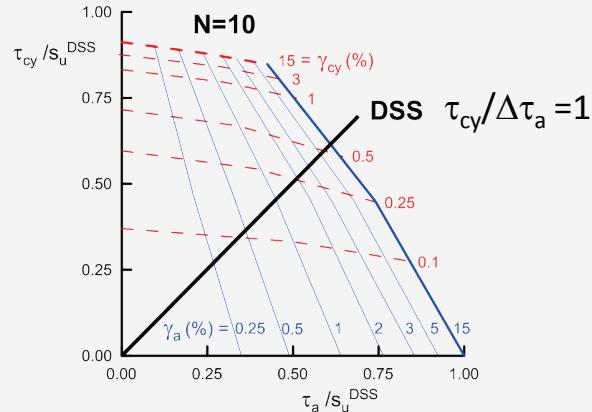
Determine stress path and anisotropy by assuming:

- For limit equilibrium & finite element:
  - $\tau_{cy}/\Delta\tau_a = P_{cy}/P_a$
  - Strain compatibility at failure (Andersen & Lauritsen, 1988)
- Special finite element (UDCAM & PDCAM; Jostad et al, 2014 & 2015)

# Cyclic strength and stress-strain relations



# Cyclic strength and stress-strain relations



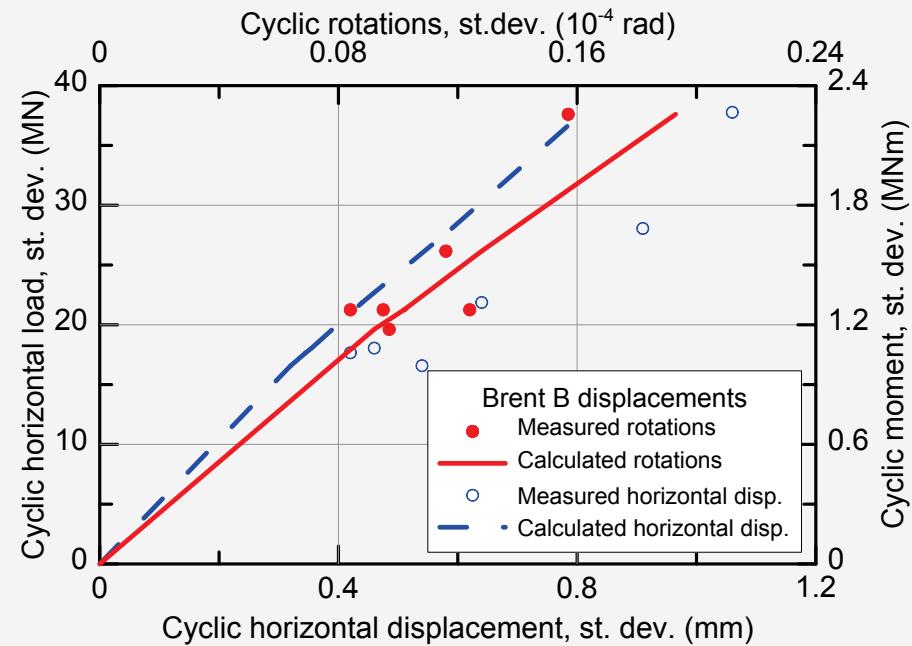
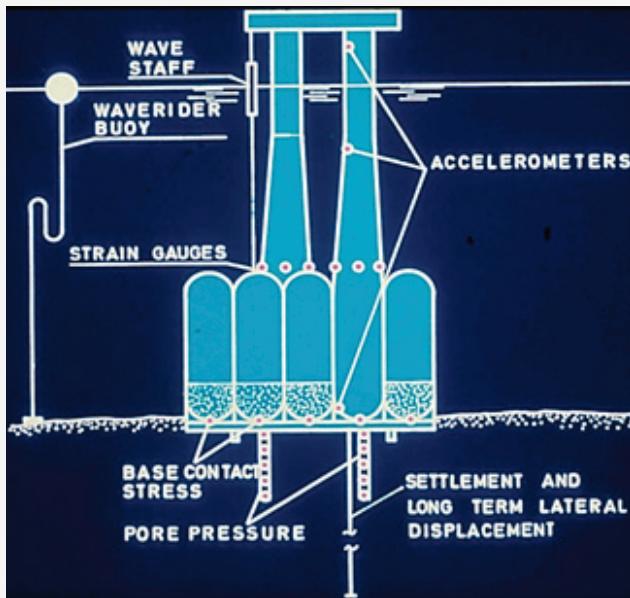
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- ☛ **Verification by prototype observations and model tests**

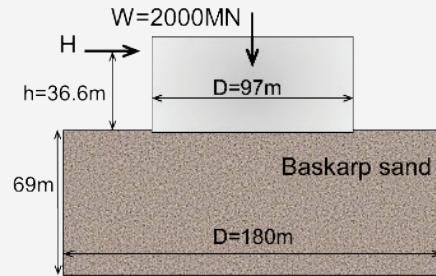
# Verification - Brent B Condeep platform



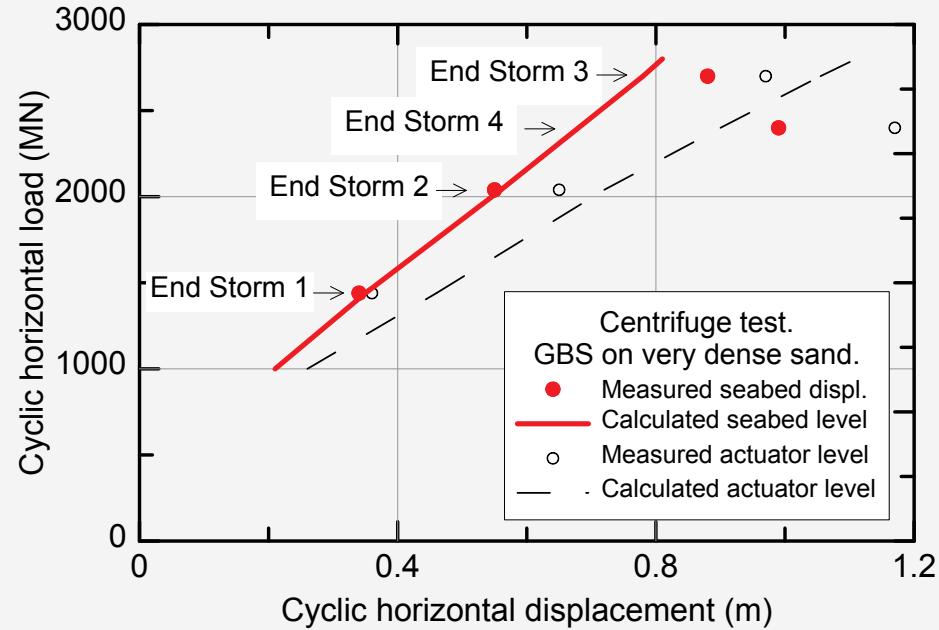
$$H_s = 10.3 \text{ m}$$

Calculated/Measured = 1.06 (rotation) and 0.71 (horizontal)

# Verification - Centrifuge tests of GBS on very dense sand

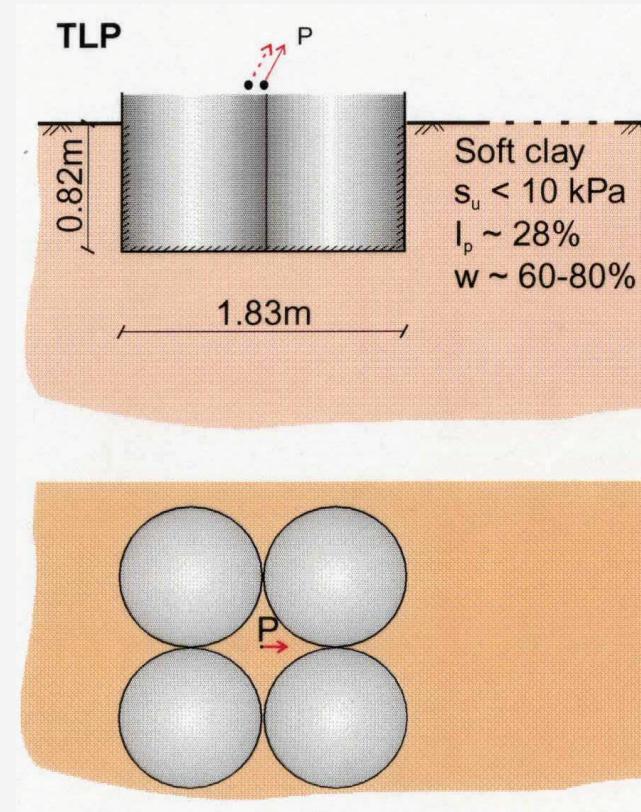
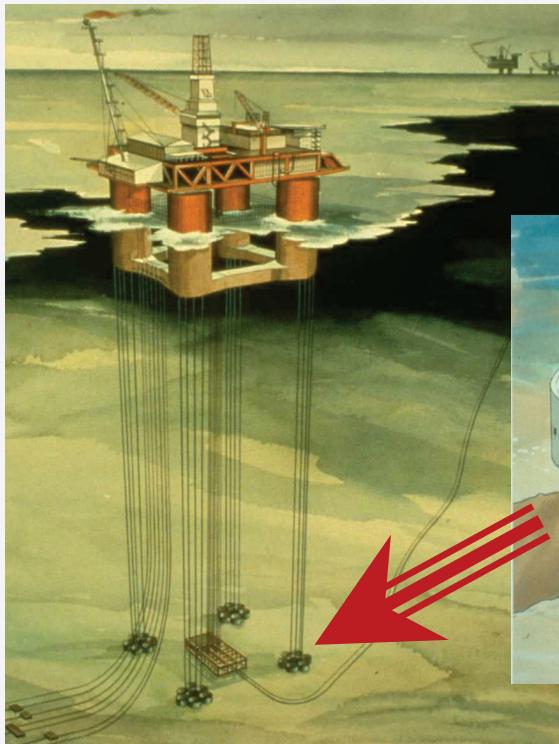


- Ekofisk Tank characteristic horizontal load: 786MN
- Displacements may govern rather than capacity
- Significant negative pore pressure underneath heel
- Cavitation during Storms 3 & 4



Centrifuge tests performed by Delft Geotechnics

# Verification - Snorre TLP anchor field model tests



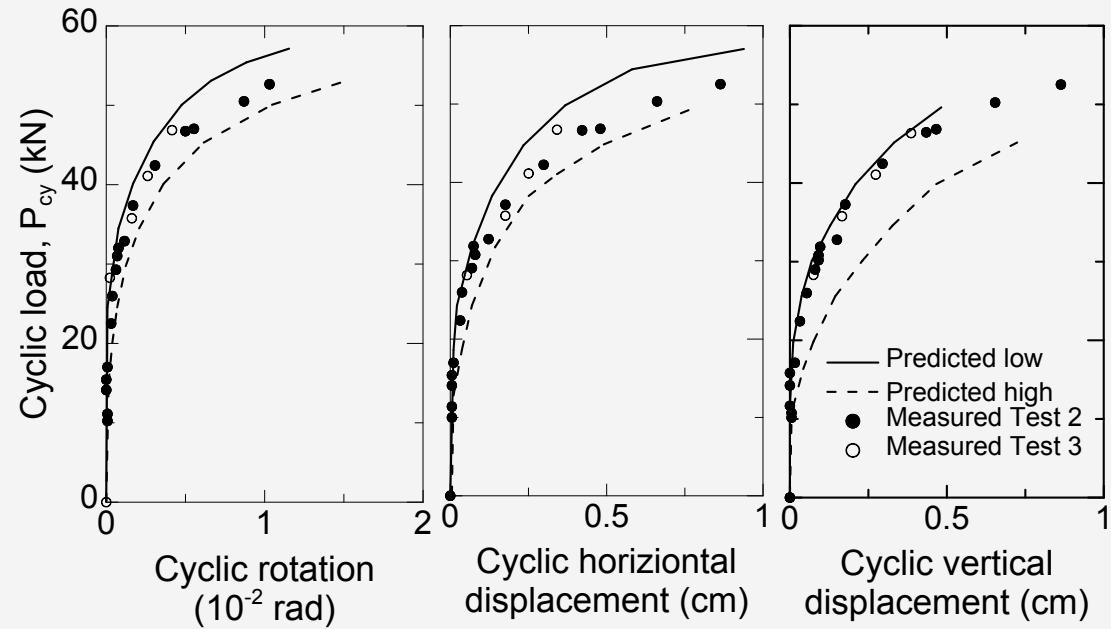
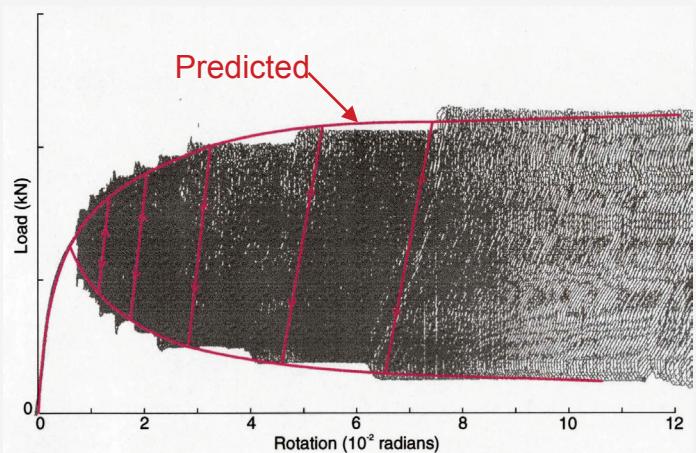
# Verification - Snorre TLP anchor field model tests



Photo: Rune Dyvik

<b>Test No.</b>	<b>Test type</b>	<b>Predicted/measured failure load</b>
1	Monotonic	1.00
2	Cyclic	1.05
3	Cyclic	1.06
4	Cyclic	1.01

# Verification - Snorre TLP anchor field model tests



# Summary and conclusions

- ☛ Cyclic soil behavior depends on
  - Stress path
  - Average and cyclic shear stresses
- ☛ Contour diagrams
  - Convenient presentation form
  - Provide parameters for capacity, displacements and stiffness
  - Verified by backcalculated prototype and model test behavior
  - Basis to formulate and verify constitutive models
  - Framework to specify and interpret site specific laboratory tests
- ☛ Data base
  - Contour diagrams for various soils and densities
  - Correlations with index parameters
    - Static and cyclic shear strengths
    - Stress-strain relations
    - $G_{max}$ , friction angles, consolidation characteristics

# Acknowledgement

- ☛ Based on more than 4 decades of research and project work at NGI
- ☛ Cooperation with NGI colleagues
- ☛ Colleagues in industry
  - Inspiring and rewarding cooperation
  - Identifying needs and challenges
- ☛ Funding from Industry and Research Council of Norway
  - Project work and JIPs

**Thank you for your attention!**