A design methodology for monopiles in sand and clays accounting for effects of cyclic loading

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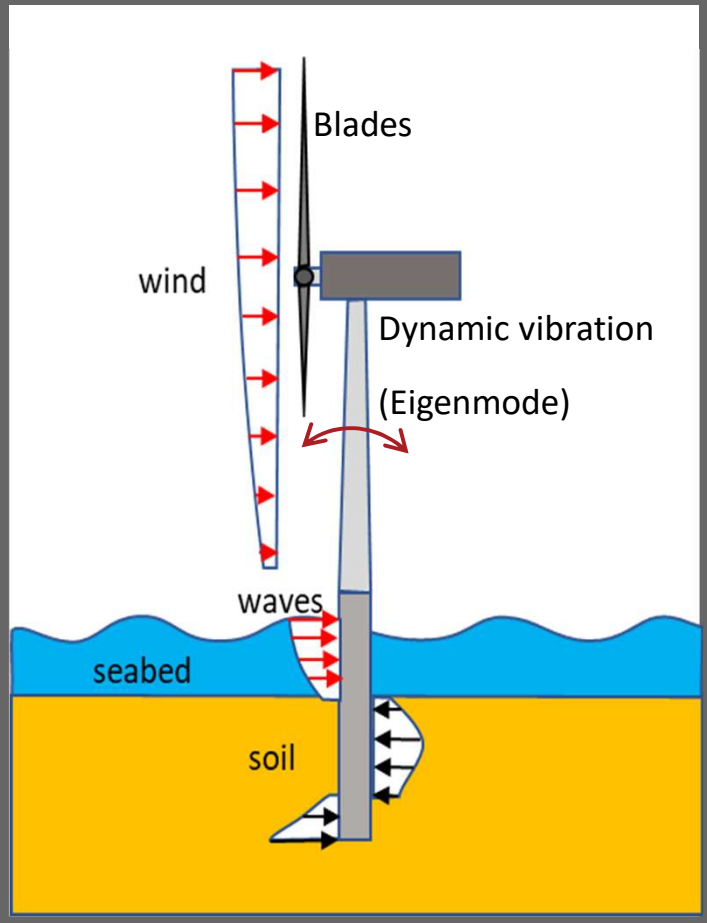
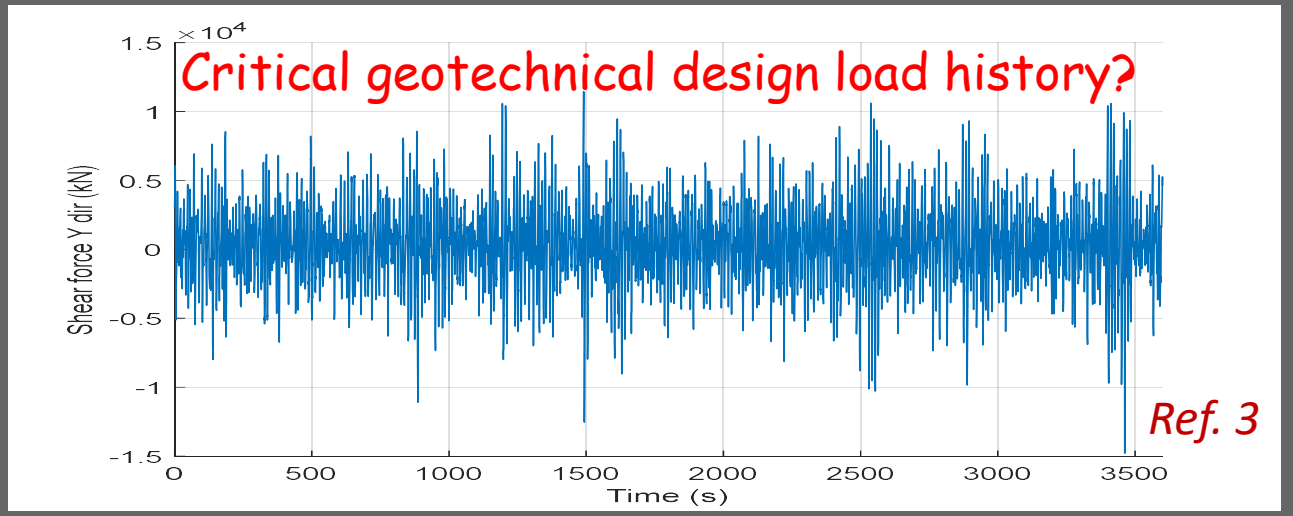
DGF Cyclic loading Seminar, Copenhagen, 24th September

Cyclic loads on OWT monopile foundations





- Loads from wind, waves and dynamic motion of the structure are (irregular) cyclic
- Different in operation and idling condition
- Needs to be considered in geotechnical design (DNV, 2016):
  - Cyclic foundation stiffnesses to be used in dynamic analyses of the whole system
  - Maximum allowable displacements and rotations (ULS, SLS)
  - Accumulated displacements during the lifetime (SLS)

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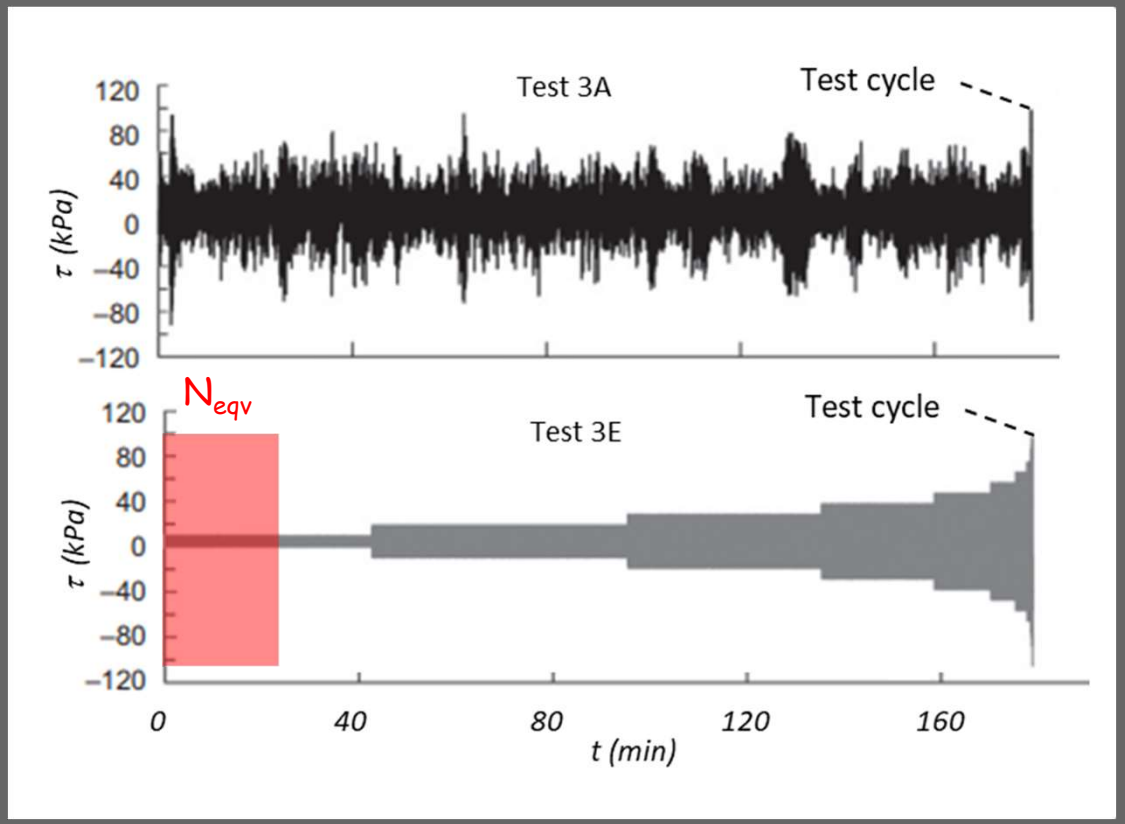
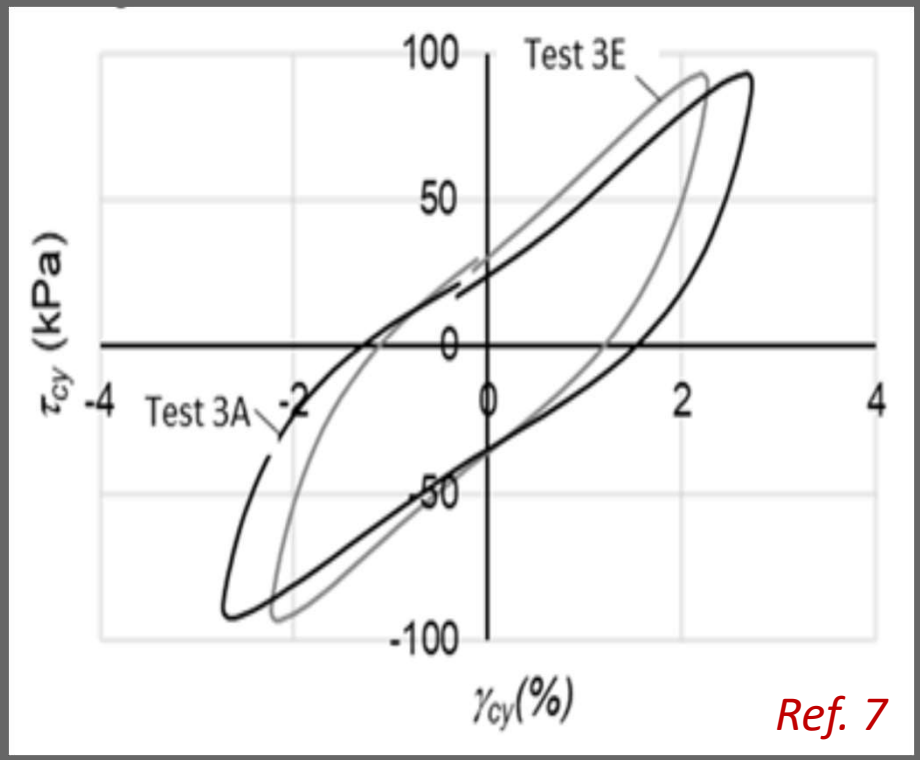
NGI's geotechnical design procedure

Troll A GBS

Geotechnical design storm composition



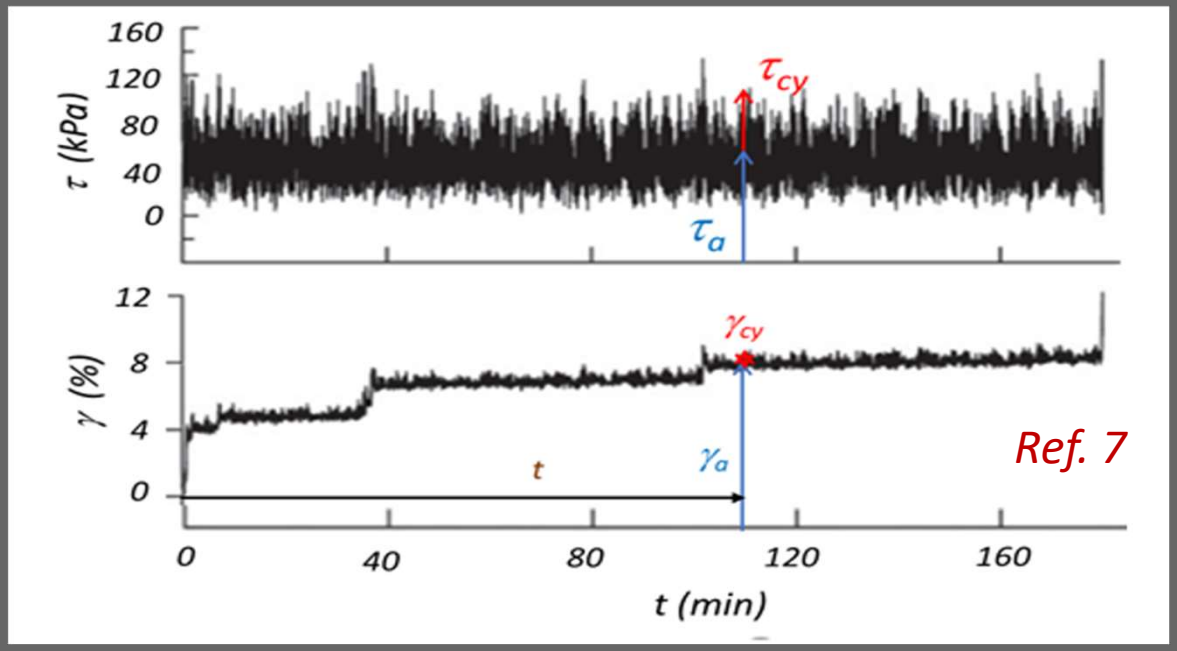
Equivalent number of cycles



Ref. 7

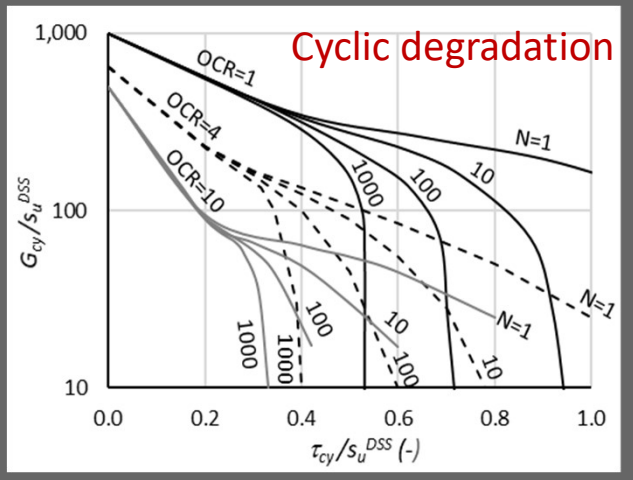
An idealized design storm composition obtained by rain flow counting

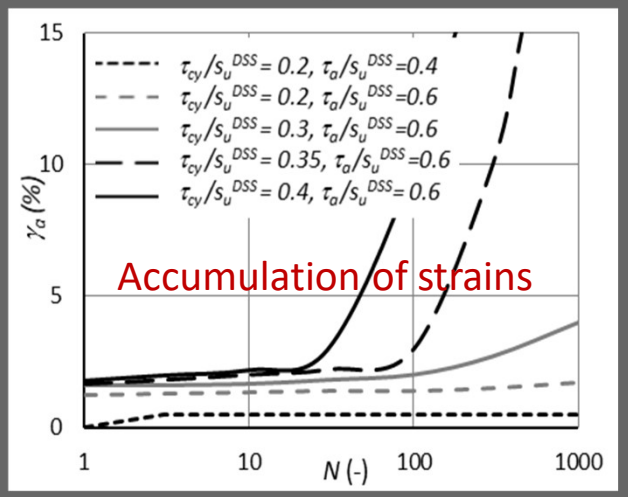
Behaviour of soil subjected cyclic loading



Ref. 7

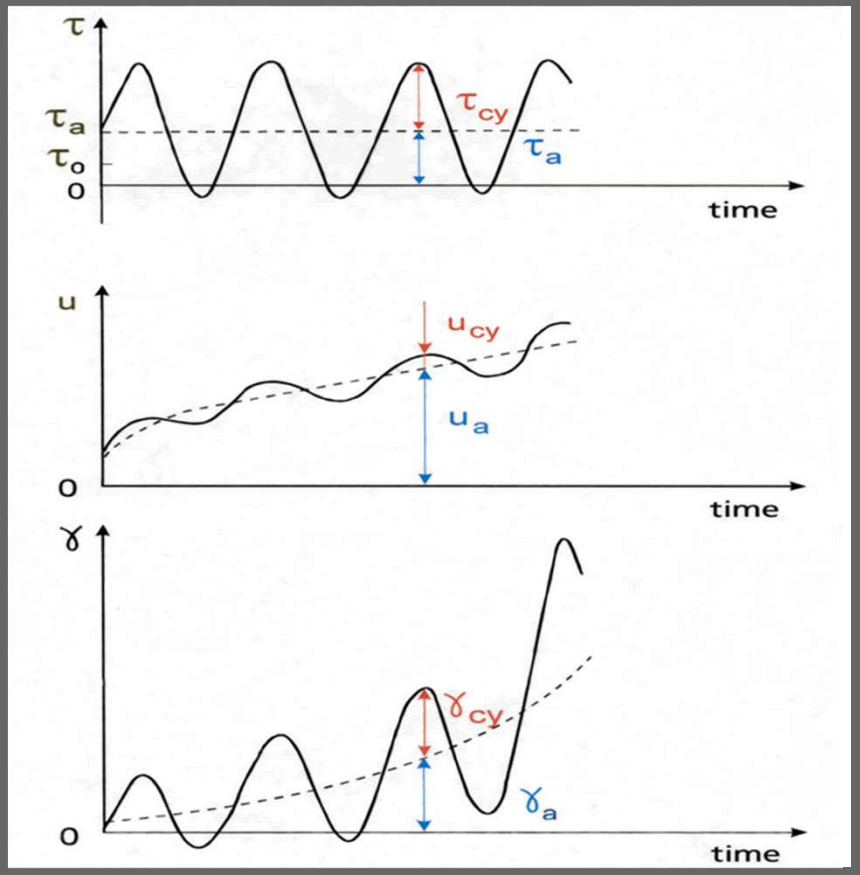
Average and cyclic shear stresses and resulting shear strains change with time (load history)





Ref. 1

Cyclic behaviour from standard cyclic tests



Tests with different combinations of constant average and cyclic shear stresses

DSS and triaxial tests

$\gamma_a = f(\tau_a, \tau_{cy}, N, \alpha)$

$\gamma_{cy} = f(\tau_a, \tau_{cy}, N, \alpha)$

$u_a = f(\tau_a, \tau_{cy}, N, \alpha)$

- Interpolation between a (large) number of tests
- Calibrate a suitable constitutive model
- **Make cyclic contour diagram**

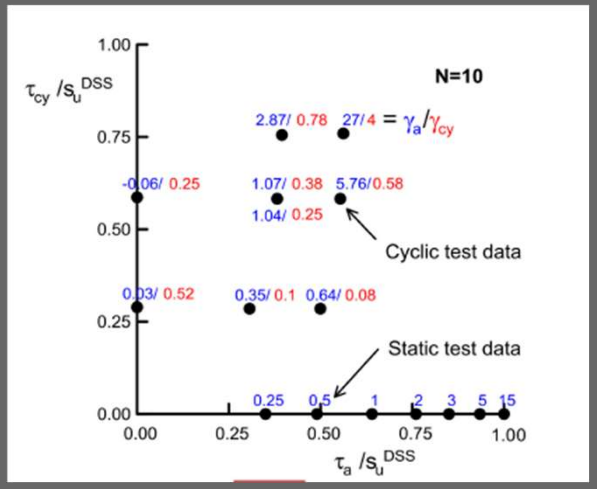
Ref. 1

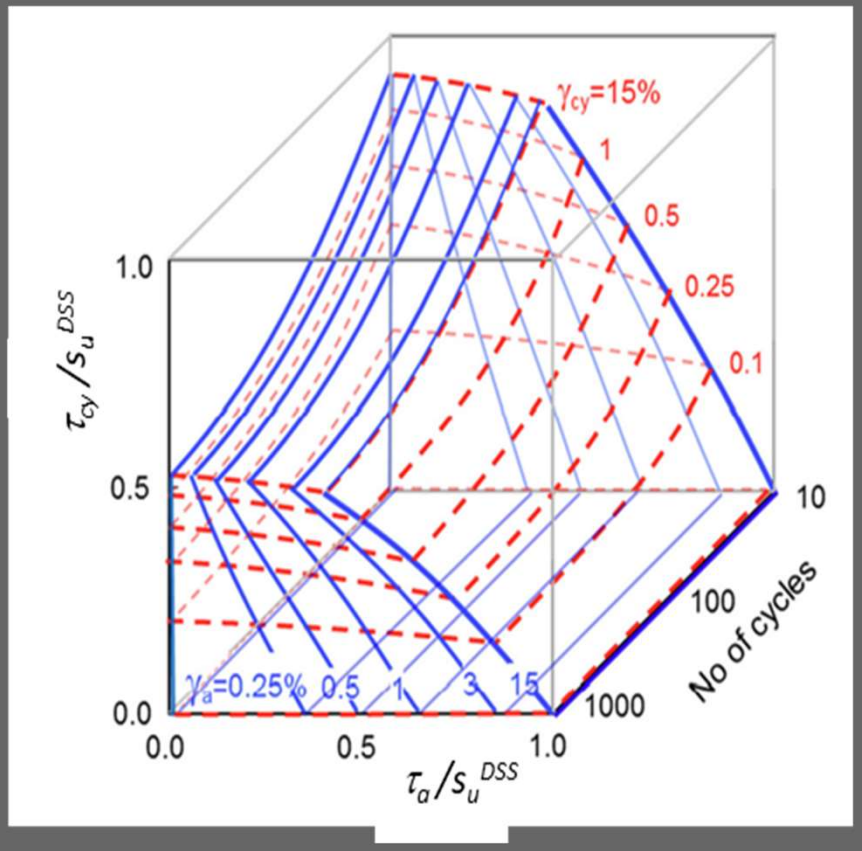
Cyclic contour diagrams

DSS and triaxial tests

$\gamma_a = f(\tau_a, \tau_{cy}, N, \alpha)$

$\gamma_{cy} = f(\tau_a, \tau_{cy}, N, \alpha)$





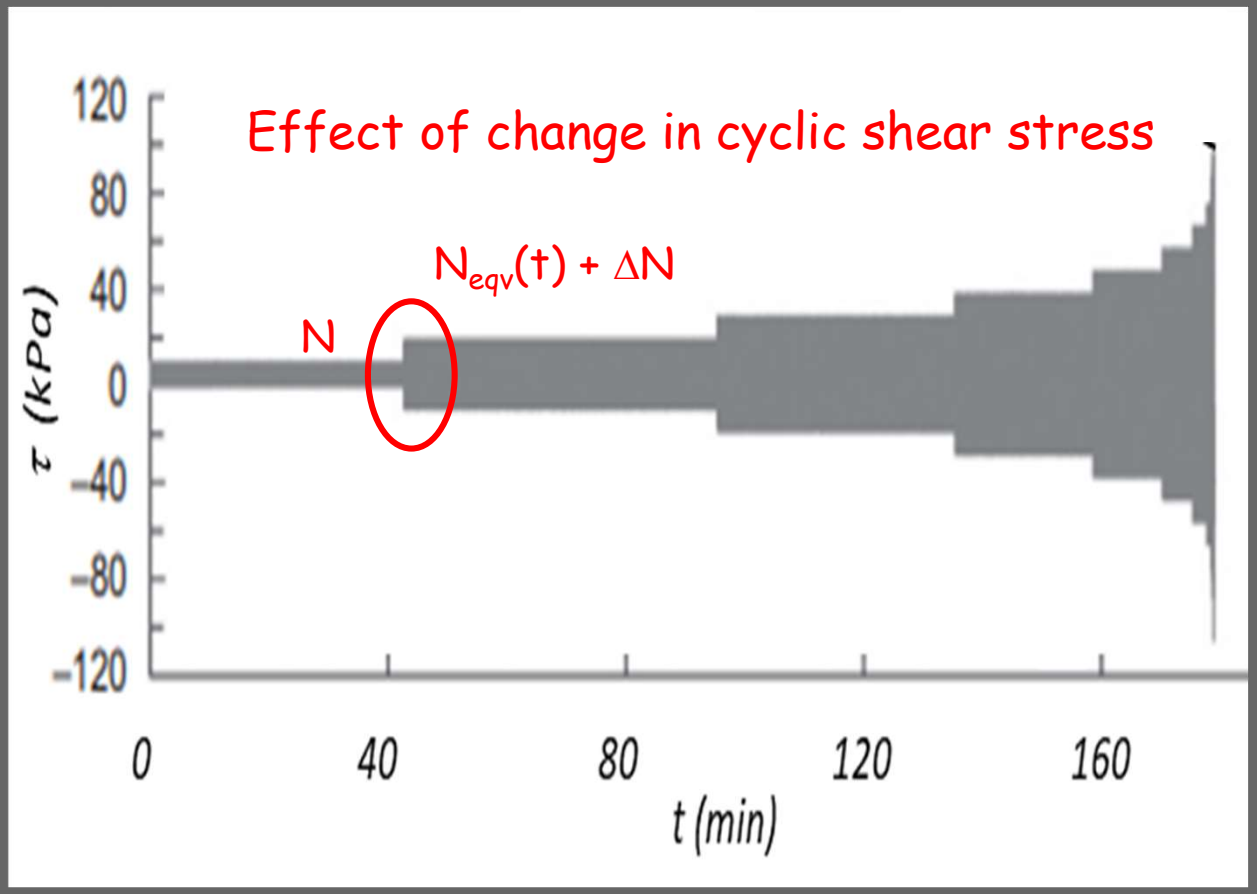
Knut H. Andersen

McClelland Lecture in 2015

Ref. 1

Reference contour diagrams are presented in Andersen (2015)
How to scale these diagrams is described in Andersen et al. (2022)

Equivalent number of cycles, N_{eqv}



State parameter:

- Accumulated strain
- Accumulated pore pressure (including pore pressure dissipation)
- Cyclic degradation (reduced G_{cy})

Ref. 2 and 5

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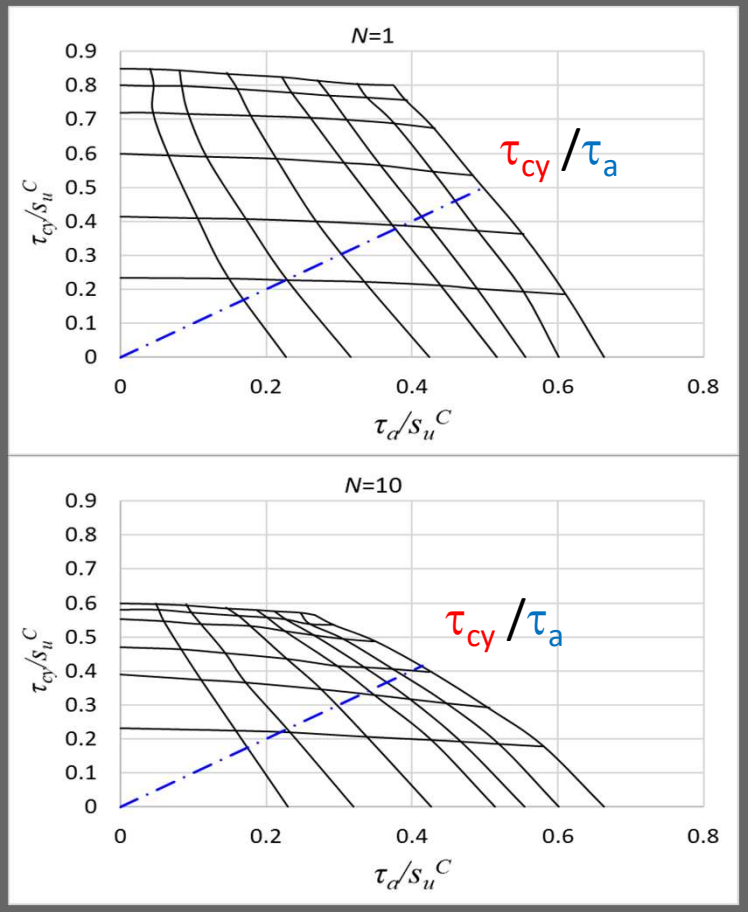
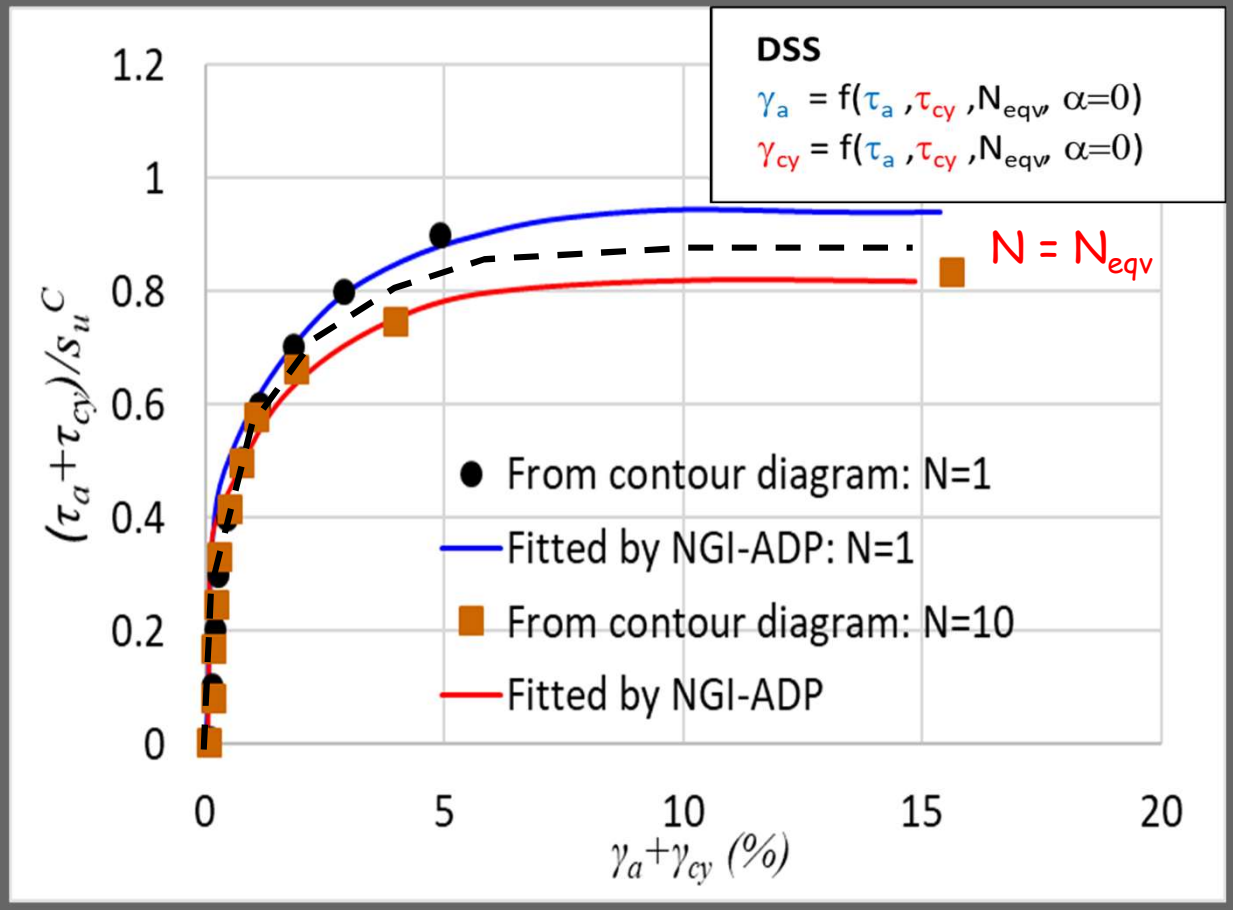
Stress-strain relationships accounting for cyclic effects





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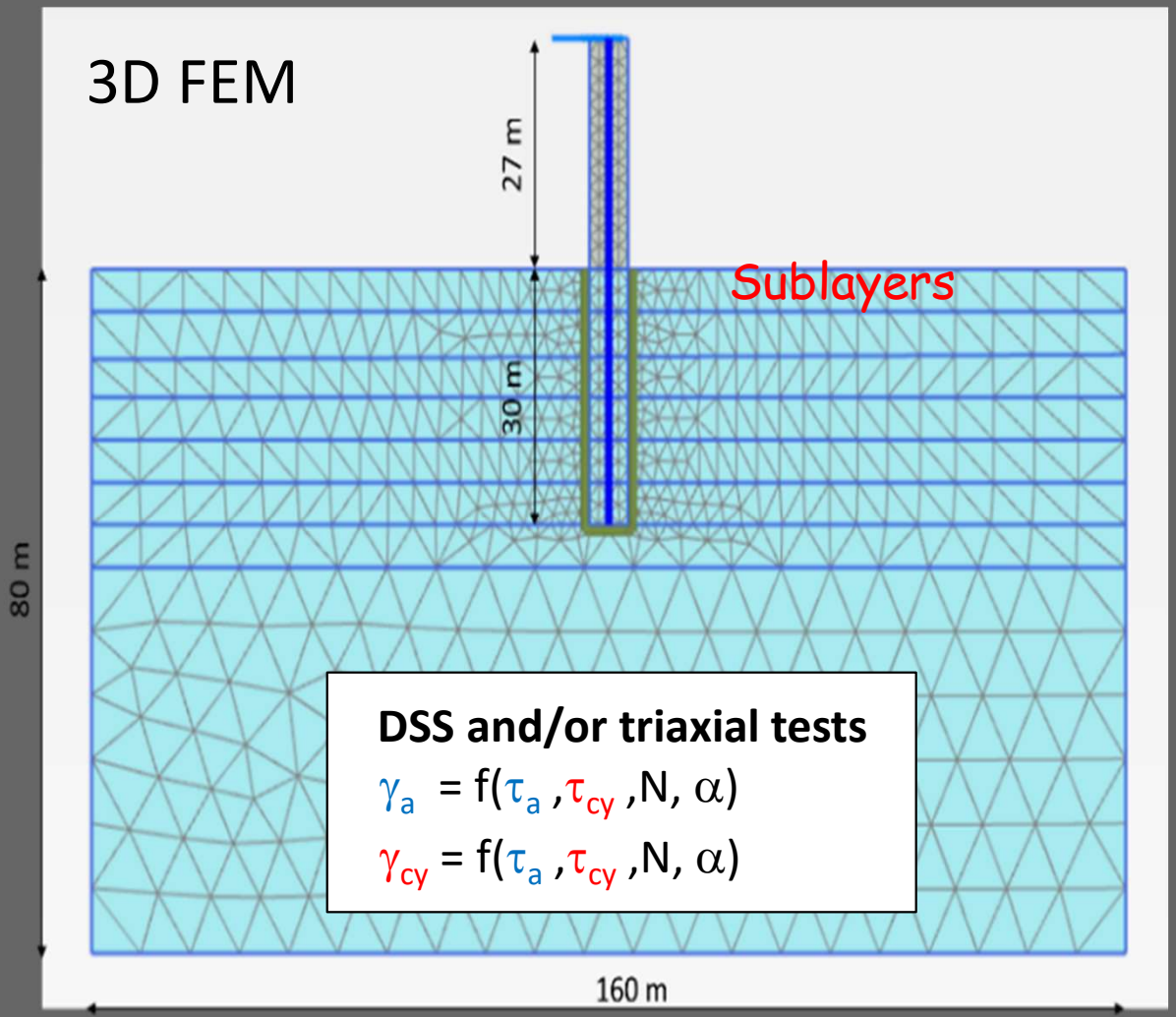
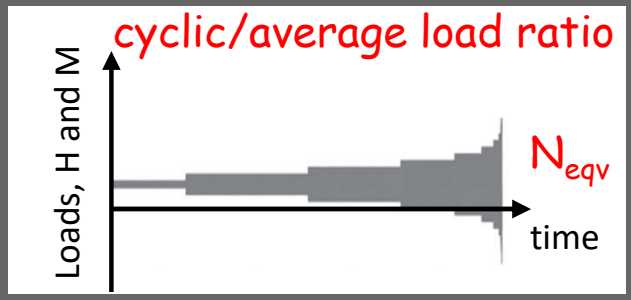
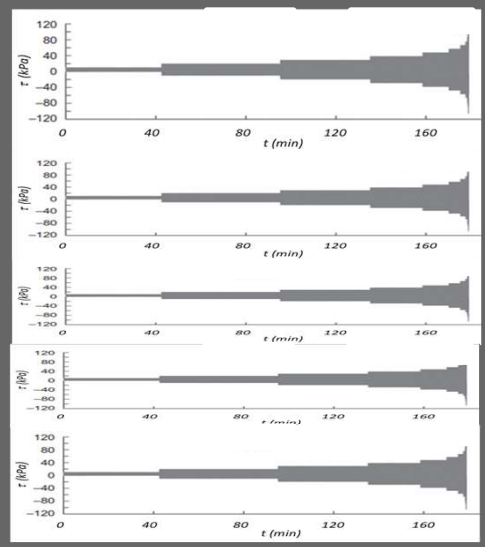
DSS *Ref. 2* Sum of cyclic and average components for max disp.

From global to local cyclic stress histories







$p_{cy}/p_f \approx \tau_{cy}/s_u$ *Ref. 2*

Calculation procedure

Ref. 2

1. Establish an idealized design load composition
2. Calculate N_{eqv} from the global load composition at a selected stress mobilisation
3. Establish stress-strain relationships from cyclic tests for τ_{cy}/τ_a and $N=N_{eqv}$
4. Calibrate a suitable constitutive model to the actual curves (NGI-ADP)
5. Establish a 3D finite element model with sub-layers (or clusters)
6. Run a 3D FEA where the load composition is applied monotonically
7. Extract the cyclic soil reaction composition in each sub-layer/cluster (p_{cy}/p_f)
8. Calculate $N=N_{eqv}$ for each sublayer/cluster
9. Continue from Step 3 until the results converge

Results:

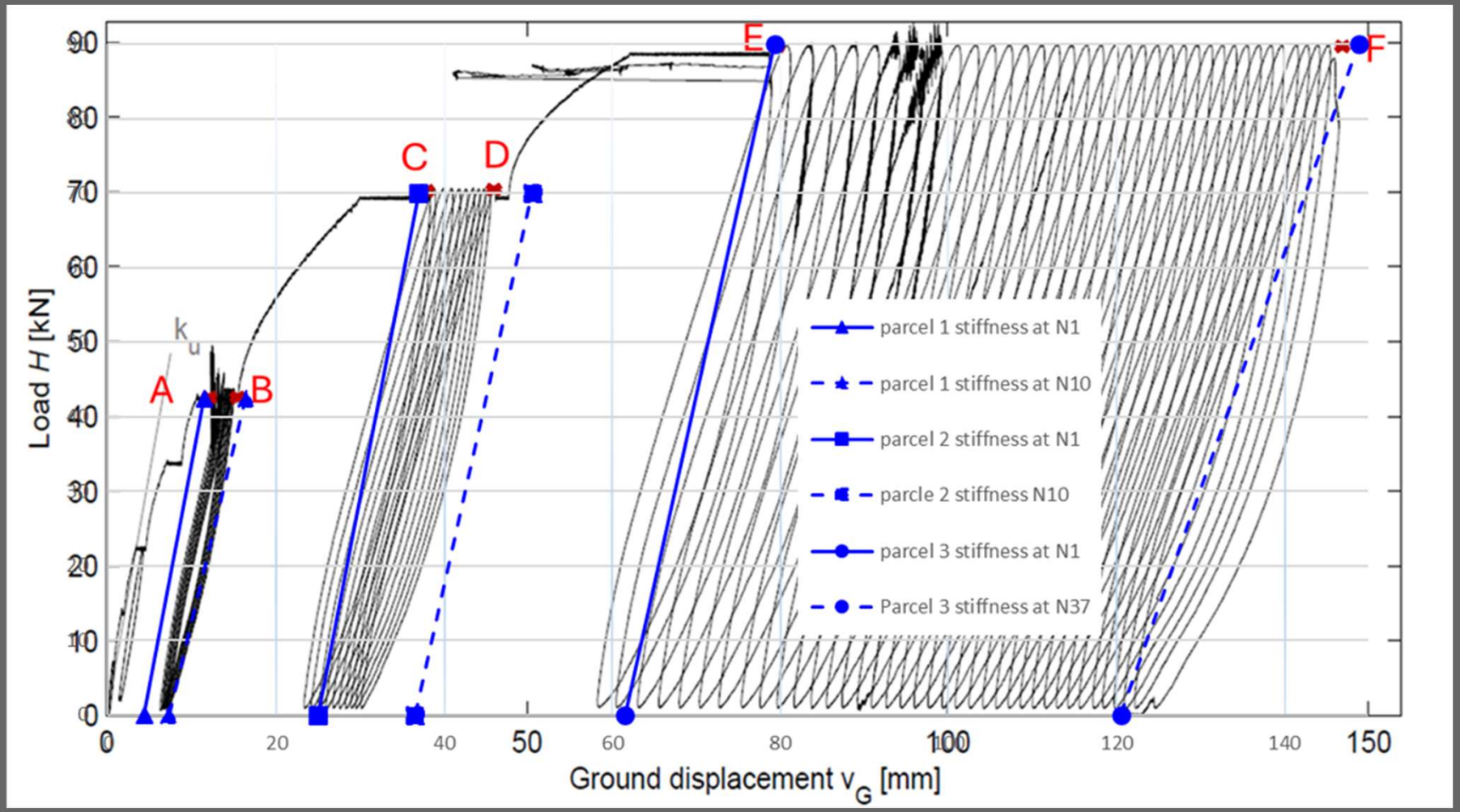
Alt. 1 Displacements and rotations at maximum loads (< allowable values)

Alt. 2 Accumulated displacements and rotations at end of a load history (< allowable)

Alt. 3 Non-linear cyclic foundation stiffnesses (structural motion)

Illustration of the approach

To be published



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