

ISSMGE TC209 Workshop
on
Challenges of Offshore
Geotechnical Engineering
25 September 2019
Bodrum - Turkey

Harun Kürşat ENGİN

Norwegian Geotechnical Institute (NGI) - Numerical Modelling Technical Group Coordinator

Challenges of geotechnical analysis and design of offshore foundations

Agenda

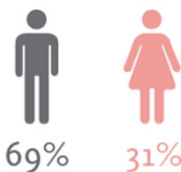
1. Analysis and design: Why? What? How?
2. Challenges in site specific soil assessment
 - Quantitative Ground modelling
 - Design parameters
 - Assessment of cyclic soil properties
3. Challenges in foundation analysis and design
 - Soil modelling
 - Foundation modelling
 - Interaction modelling
4. Closing remarks

Norwegian Geotechnical Institute

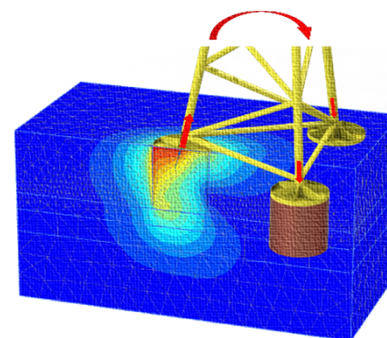
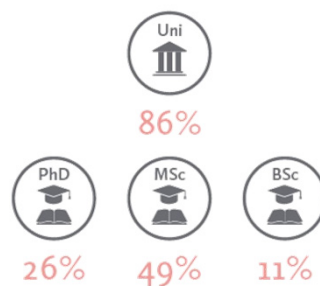


Total NGI
270
permanently employed
38
nationalities

Male / Female



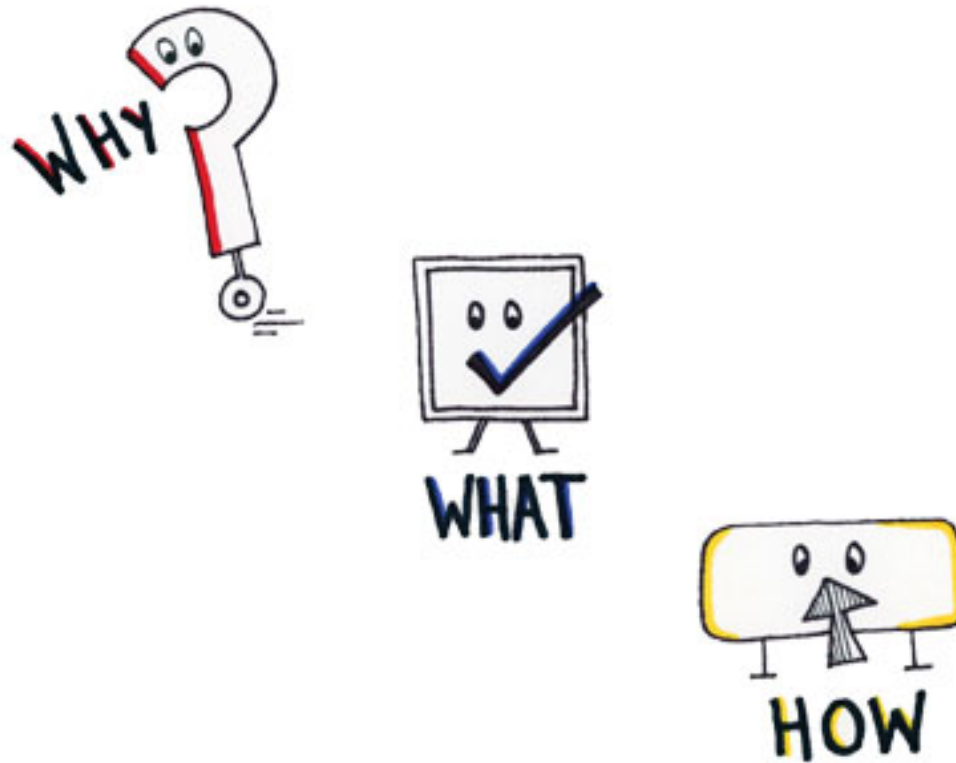
Education



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Bodrum, Turkey – September 2019

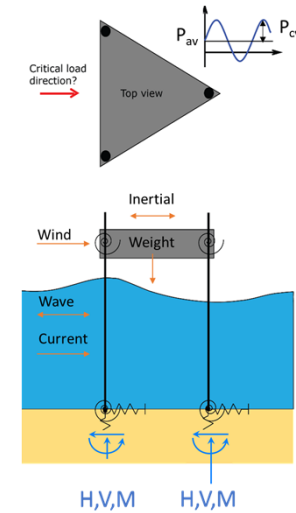
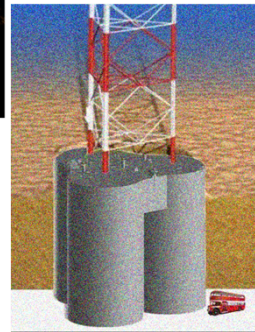
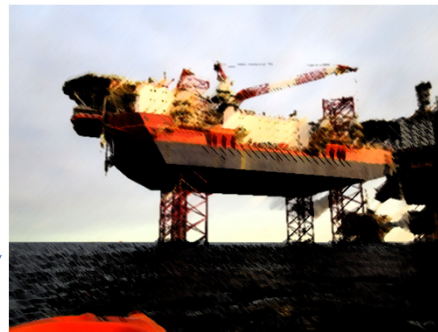
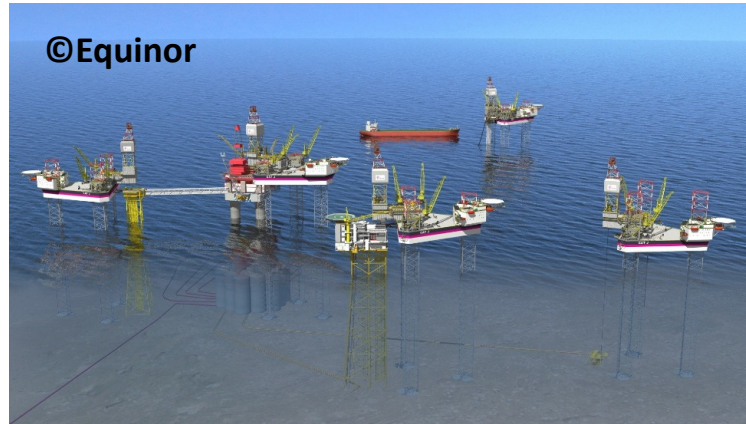
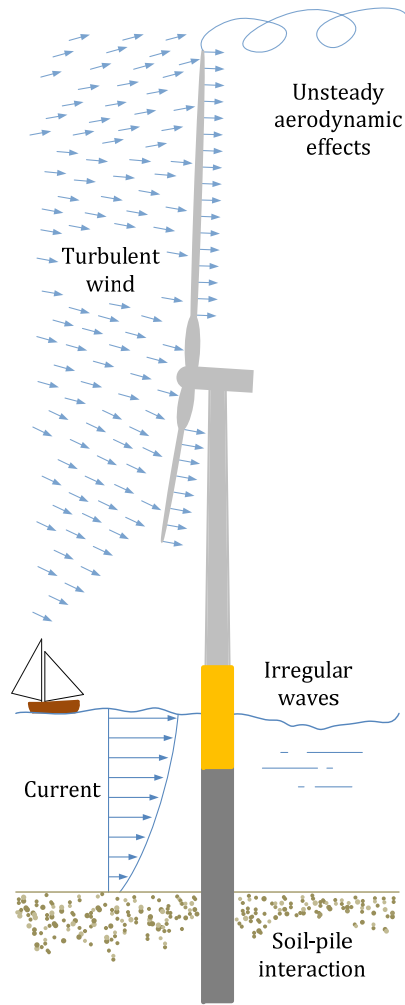
1. Analysis and design: **Why?** **What?** **How?**

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



1. Analysis and design: **Why?** What? How?

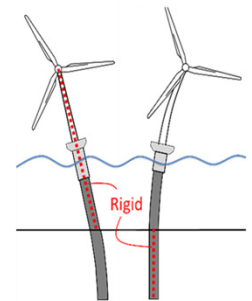
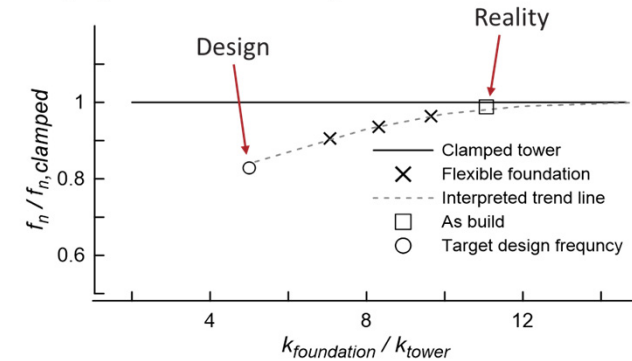
Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



Nonlinear foundation response

Engin et al. (2019)

Lack of agreement between predictions and measurements



Skau et al. (2018)

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1. Analysis and design: Why? What? How?

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



✓ Design Basis

- ✓ Structural data
 - ✓ Geometry
 - ✓ Loads
- ✓ SI reports*
- ✓ Requirements, constraints
- ✓ ...

☐ Soil Parameters Assessment

- ☐ Layering*
- ☐ Index properties*
 - ☐ Density
 - ☐ Ip, w, Pl, ...
 - ☐ Permeability
- ☐ Compressibility parameters*
- ☐ Drainage conditions
- ☐ Monotonic parameters
- ☐ Cyclic parameters
- ☐ ...

☐ Foundation Behavior Assessment (Monotonic & Cyclic)

- ☐ Penetration
- ☐ Capacity
- ☐ Stiffness
- ☐ Damping
- ☐ Interaction
- ☐ ...

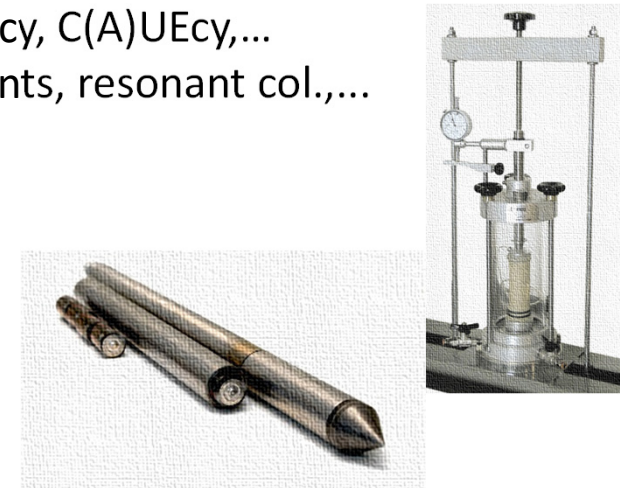
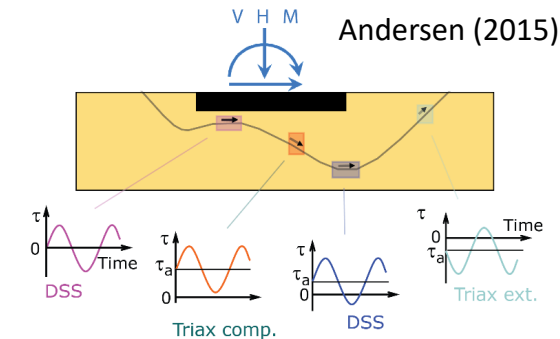
1. Analysis and design: Why? What? How?

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



❑ Soil Parameters Assessment

- ❑ Layering
 - ❑ Index properties
 - ❑ Density
 - ❑ I_p , w , PI , ...
 - ❑ Permeability
 - ❑ Compressibility parameters
 - ❑ Drainage conditions
 - ❑ Monotonic parameters
 - ❑ Cyclic parameters
 - ❑ ...
- ❑ Seismic inversion
 - ❑ BHs
 - ❑ Lab tests
 - ❑ Atterberg limits,...
 - ❑ Oedometer, CRS, DSS, C(A)UC, C(A)UE,...
 - ❑ DSScy, C(A)UCcy, C(A)UEcy,...
 - ❑ Bender elements, resonant col.,...
 - ❑ Field tests
 - ❑ Databases
 - ❑ Empirical correlations
 - ❑ Analytical solutions
 - ❑ ...



1. Analysis and design: Why? What? How?

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

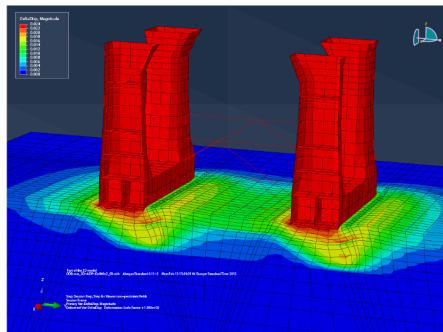


❑ Foundation Behavior Assessment

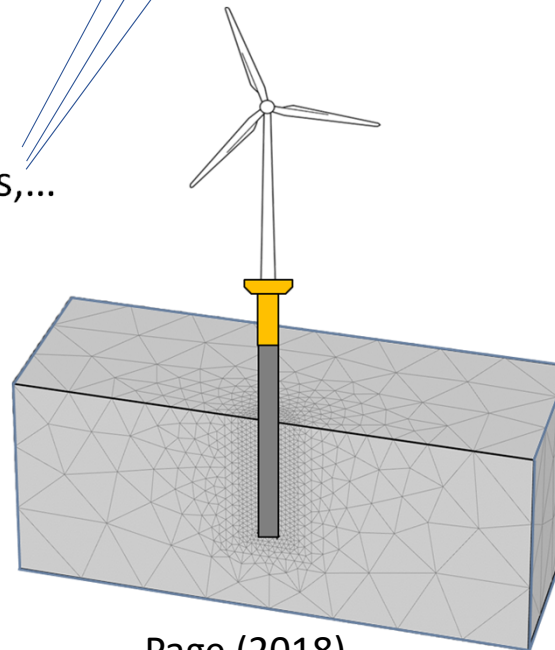
(Monotonic & Cyclic)

- ❑ Penetration
- ❑ Settlements
- ❑ Capacity
- ❑ Stiffness
- ❑ Damping
- ❑ Interaction
- ❑ Installation effects, set-up effects,...
- ❑ ...

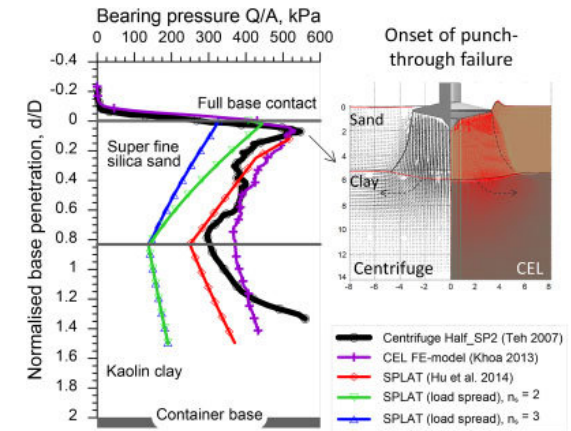
- ❑ Empirical correlations
- ❑ Analytical solutions
- ❑ Finite element analyses
- ❑ ...



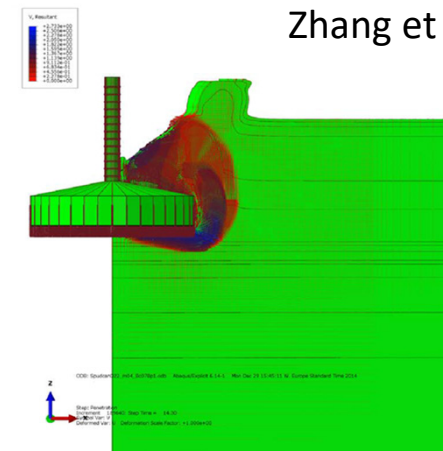
Sturm (2019)



Page (2018)



Zhang et al. (2015)



Engin et al. (2019)

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2. Challenges in site specific soil assessment – *Quantitative Ground modelling*



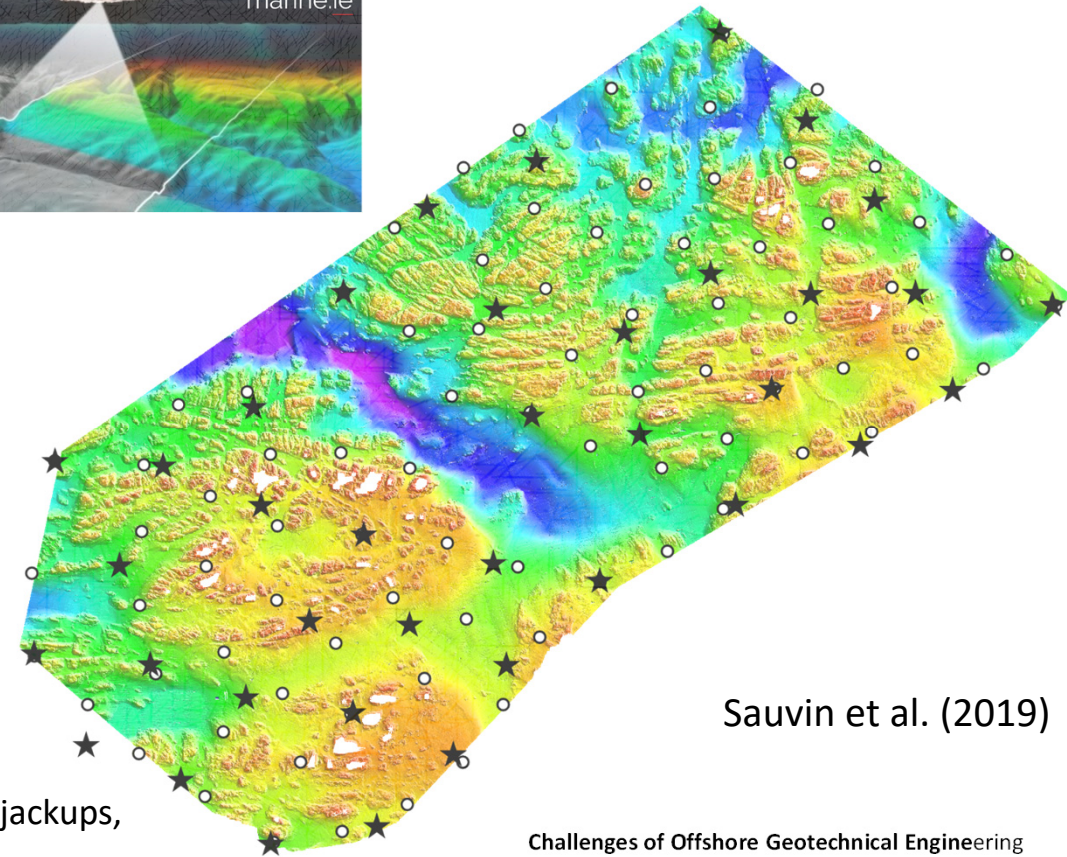
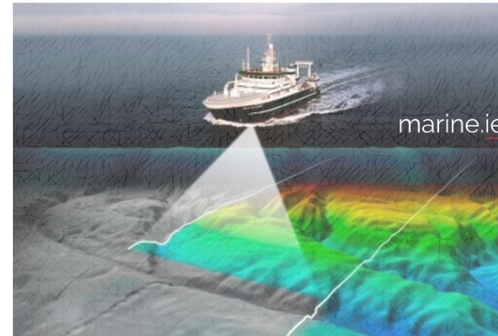
Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Challenges: i.e. OWF

- ☐ Turbine relocation common
- ☐ More fast-track projects
- ☐ Need to obtain quantitative soil parameters
- ☐ (Changing) metocean conditions
- ☐ SI optimization*

Solutions:

- ☐ Planning, Acquisition, Processing
- ☐ Use geophysical data to guide interpolation of 1D geotechnical data (e.g. CPT, ...)
 - **Quantitative Ground modelling**

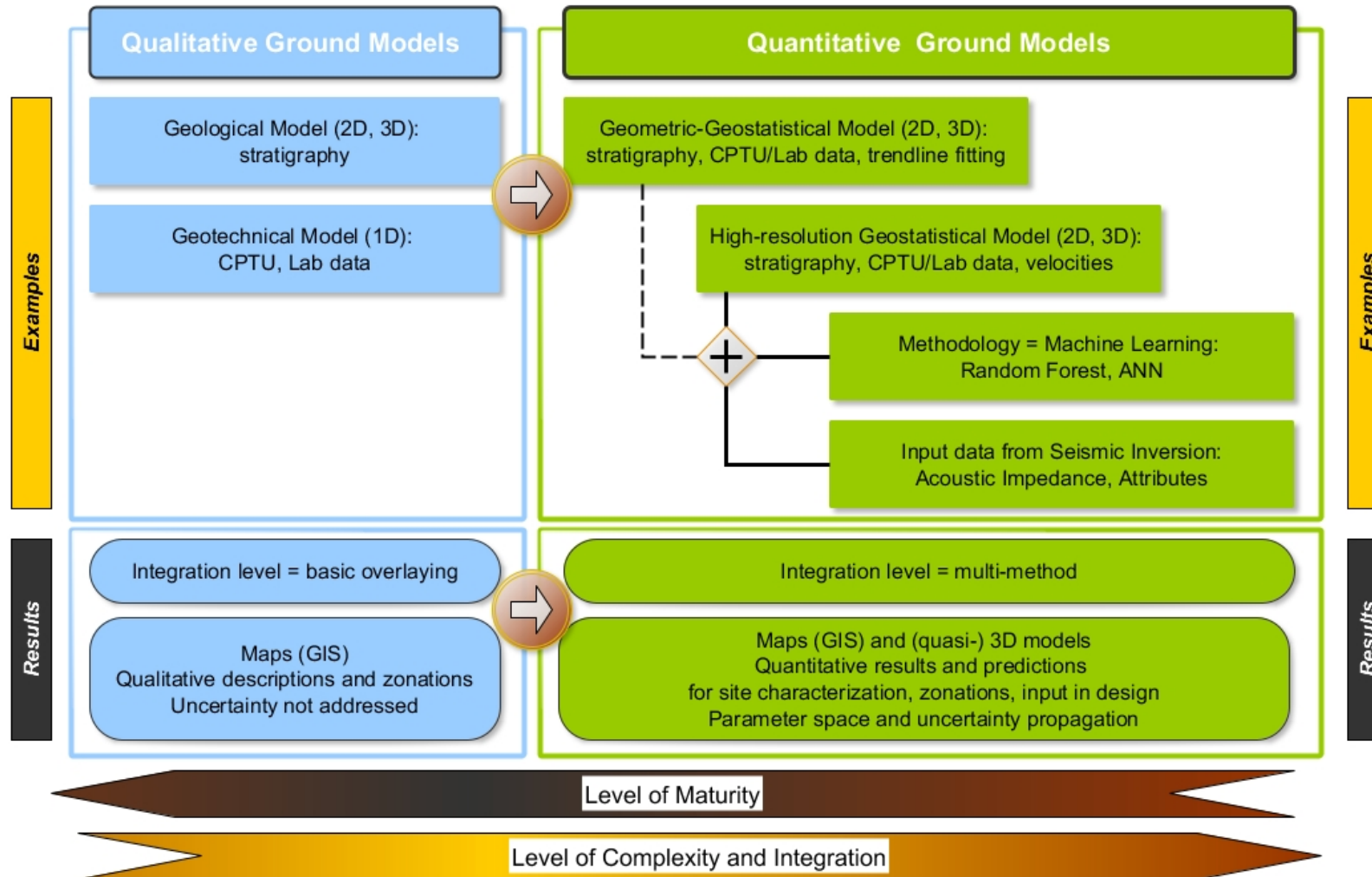


Sauvin et al. (2019)

* useful for spudcan penetration assessment for the wind farm installation jackups, which typically has no site specific SI

2. Challenges in site specific soil assessment – Quantitative Ground modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



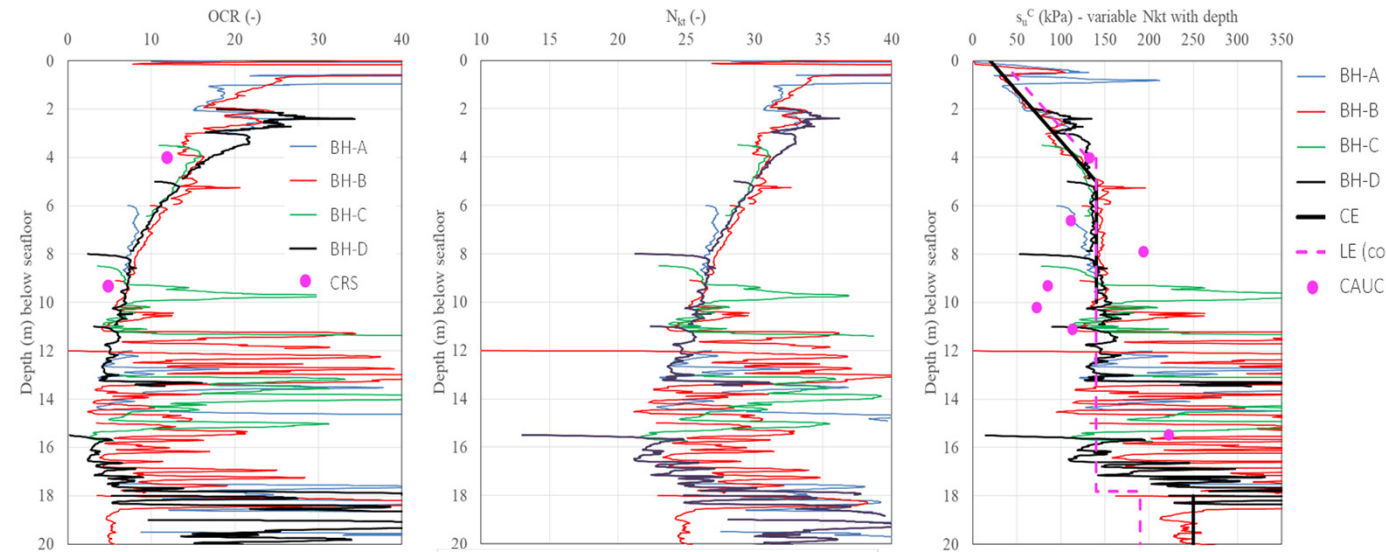
Sauvin et al. (2019)

Challenges

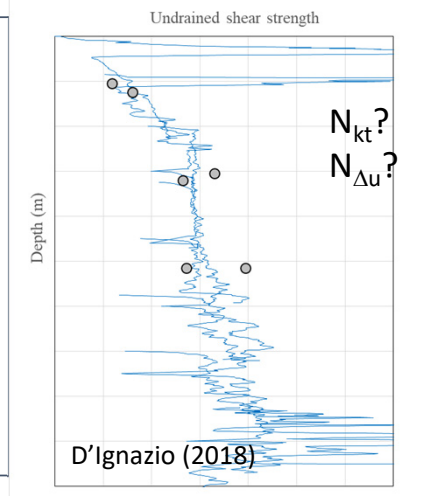
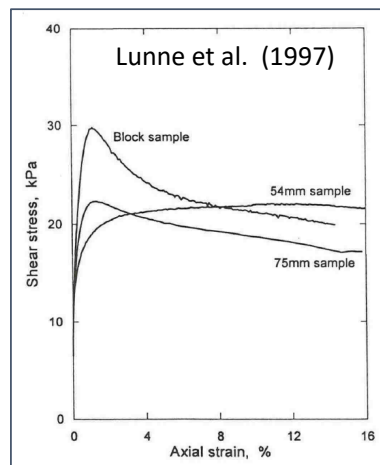
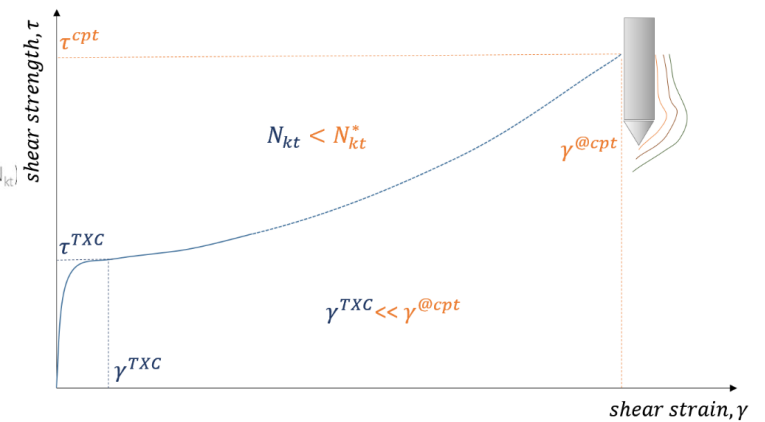
- ☐ Inversion
- ☐ Quantification
- ☐ Uncertainties

2. Challenges in site specific soil assessment – *Design parameters*

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Engin et al. (2019)



Challenges in estimating s_u :

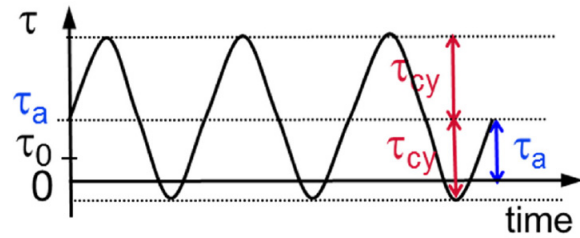
- ☐ Assess in-situ / undisturbed state:
 - ☐ OCR
 - ☐ Direction of loading (anisotropy)
 - ☐ Sample disturbance
- ☐ Rate and duration of loading
- ☐ ...

2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*

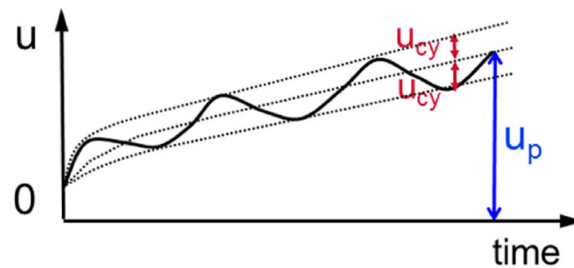


Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

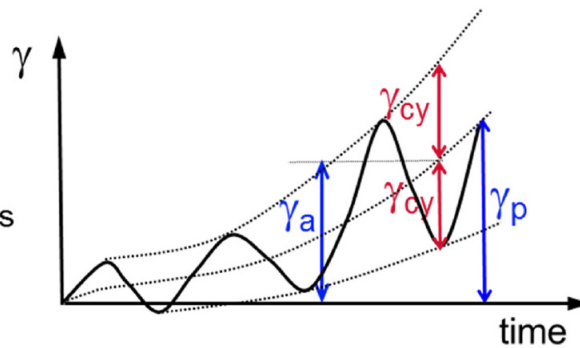
Cyclic and average
shear stresses



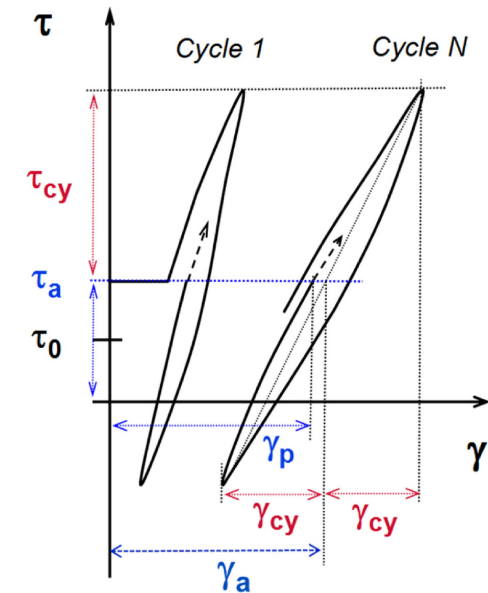
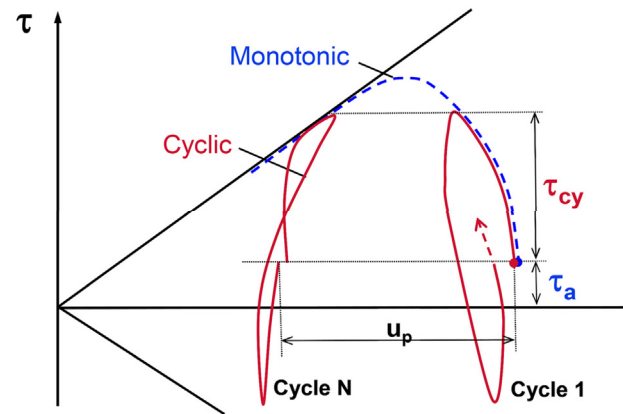
Cyclic, average and
permanent pore
pressure generation



Cyclic, average and
permanent shear strains



Andersen (2015)

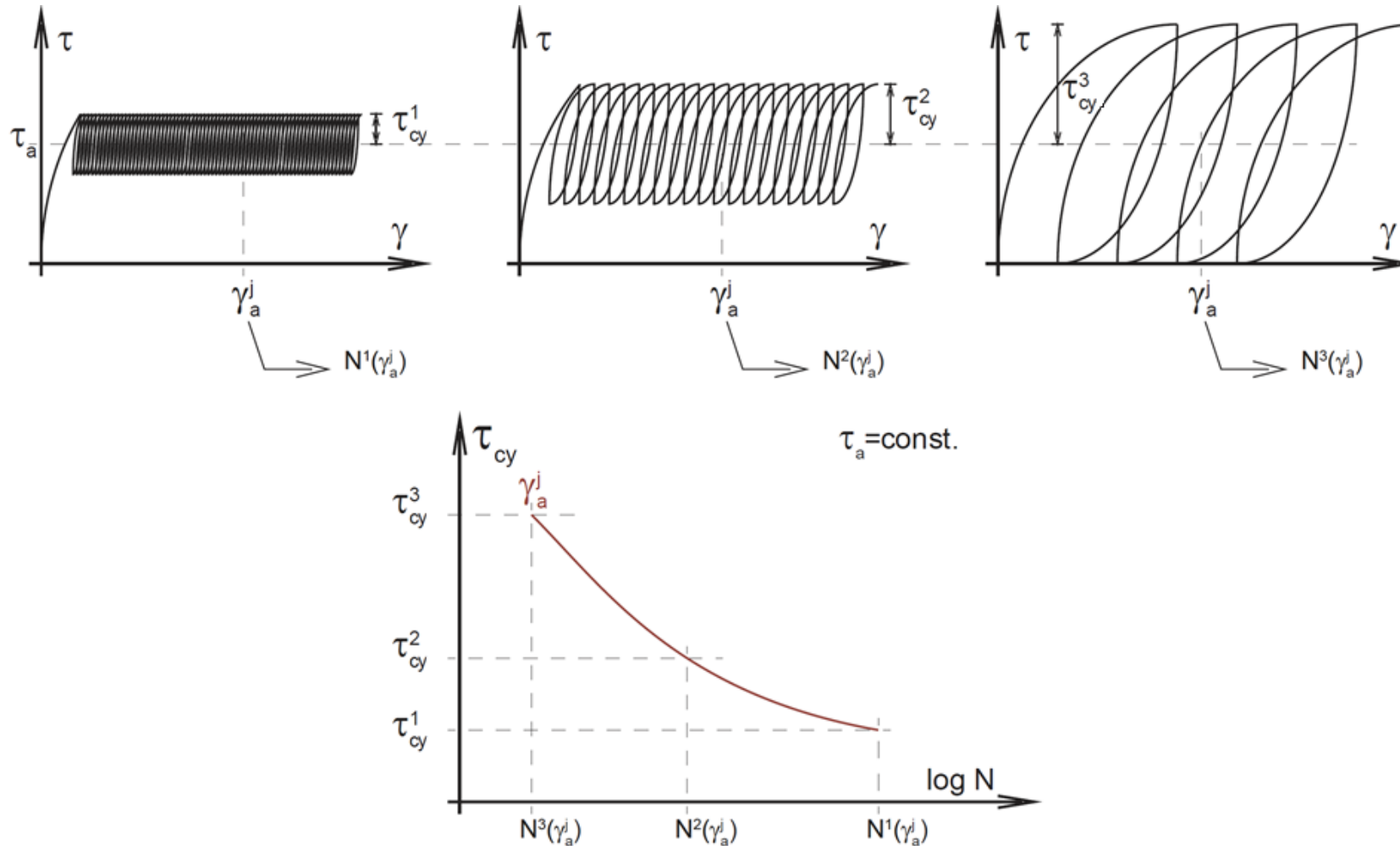


2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*



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Sturm et al. (2012)

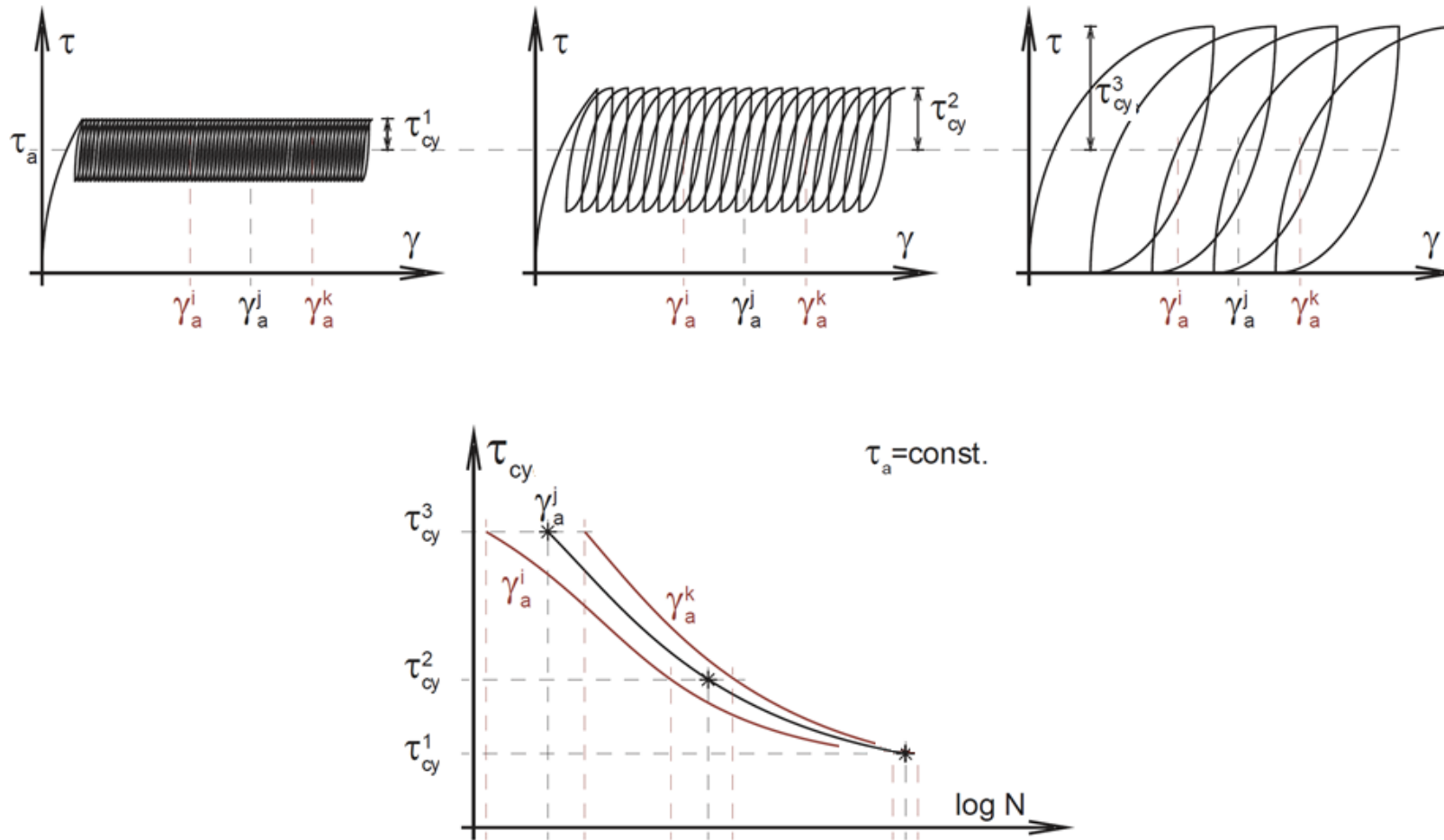


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Sturm et al. (2012)

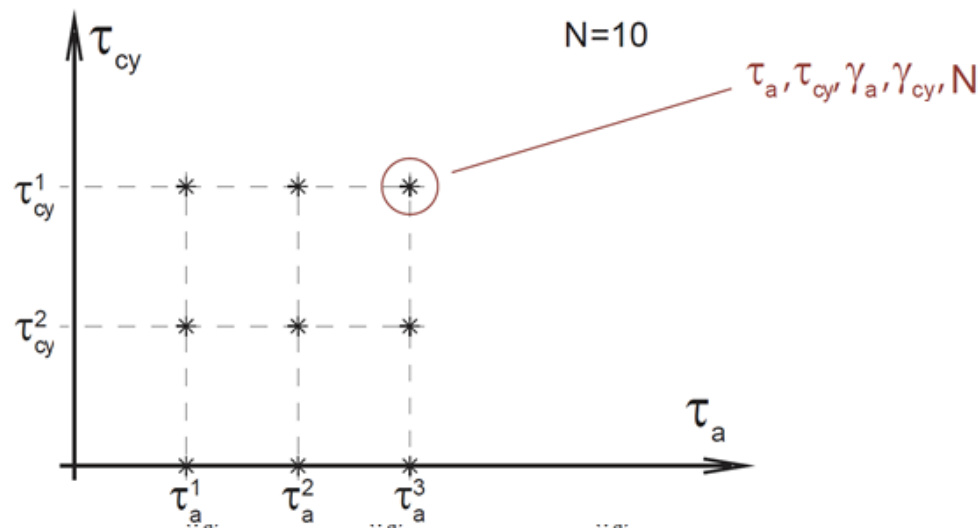
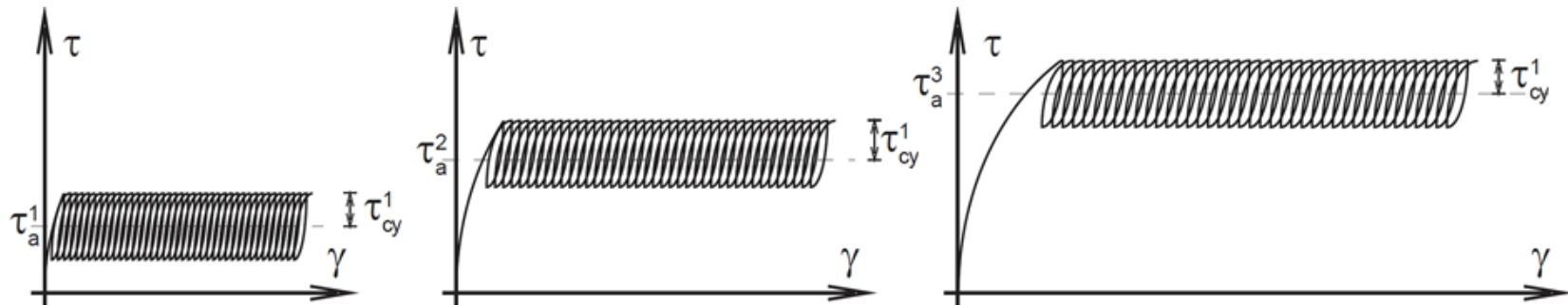


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Sturm et al. (2012)

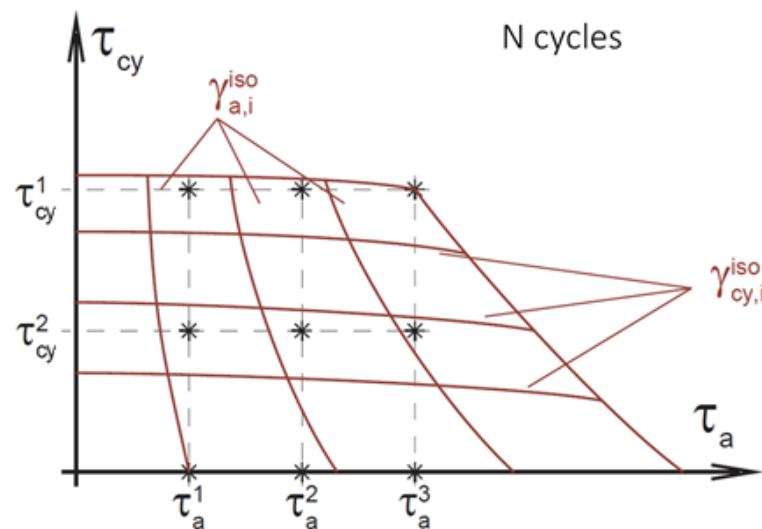
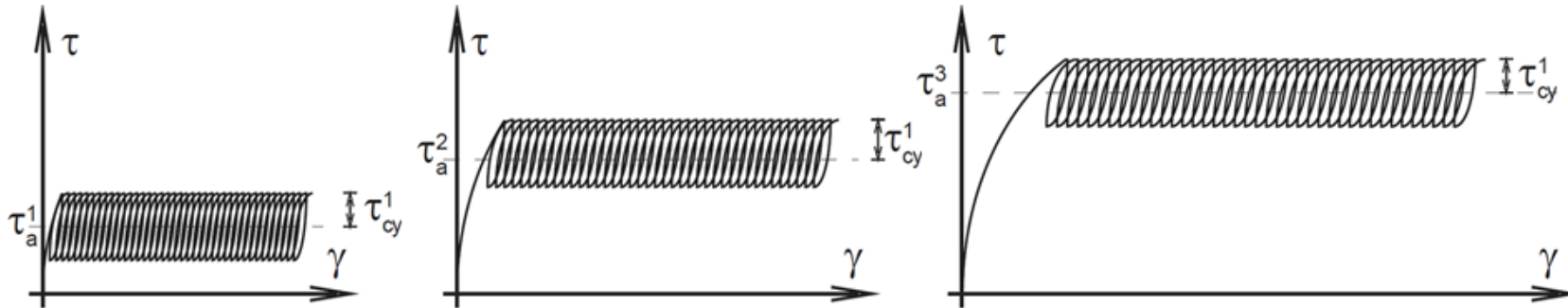


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Sturm et al. (2012)



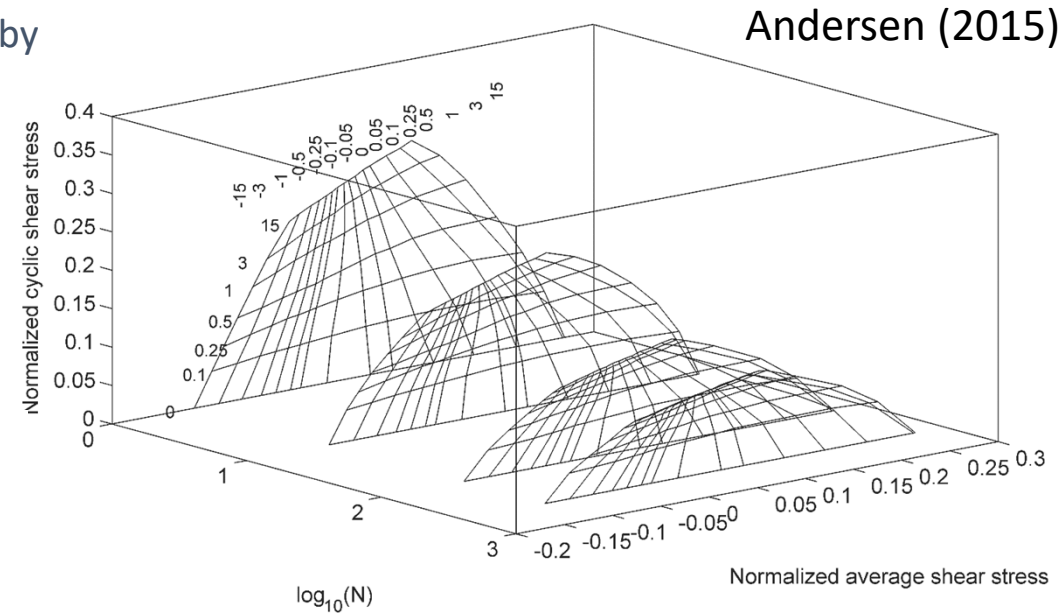
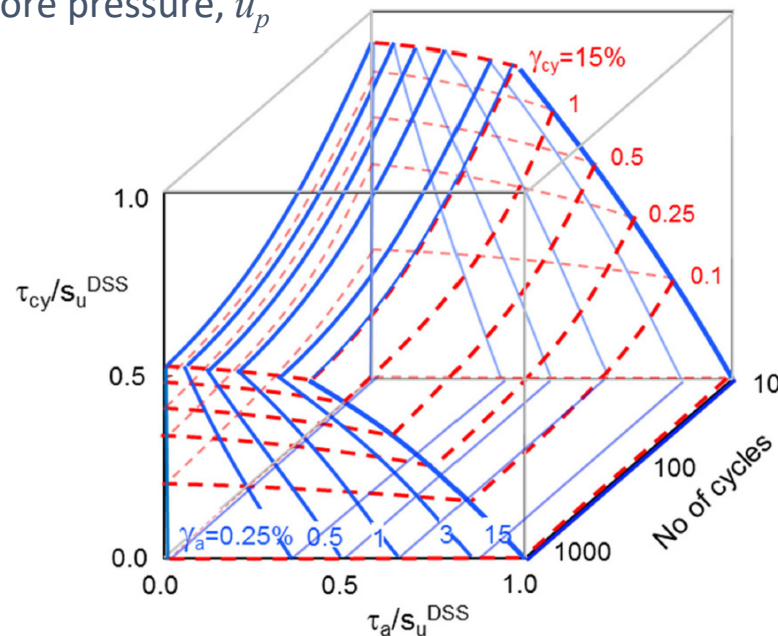
2. Challenges in site specific soil assessment – *Assessment of cyclic soil properties*



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The behaviour of the soil under cyclic loading can be described by **Contour diagrams**, which relate:

- ☐ Cyclic shear stress, τ_{cy}
- ☐ Cyclic shear strain, γ_{cy}
- ☐ Average shear stress, τ_a
- ☐ Average shear strain, γ_a
- ☐ Number of cycles, N
- ☐ Accumulated pore pressure, u_p



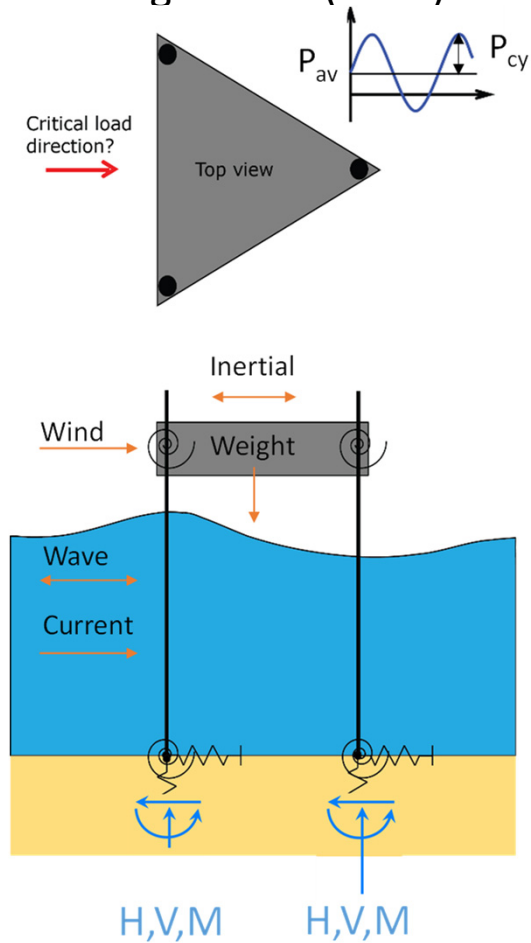
Andersen (2015)

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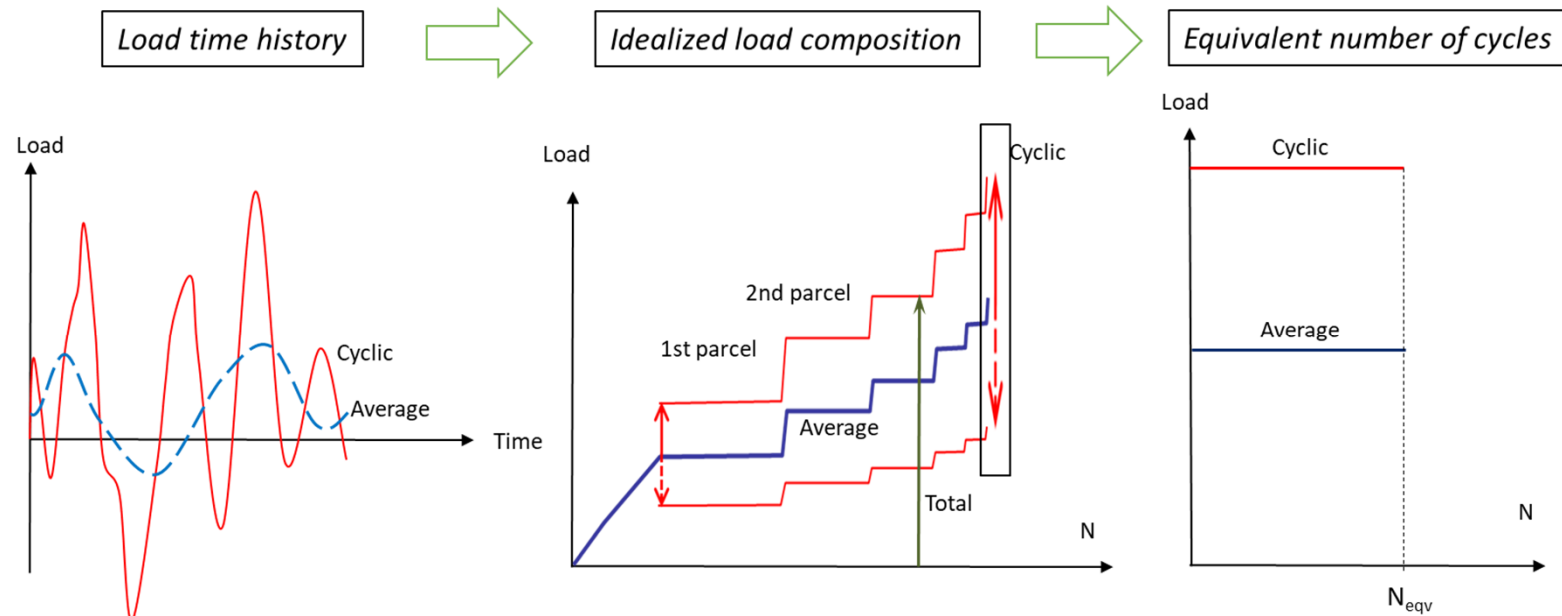


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Engin et al. (2019)



Norén-Cosgriff et al. (2015)

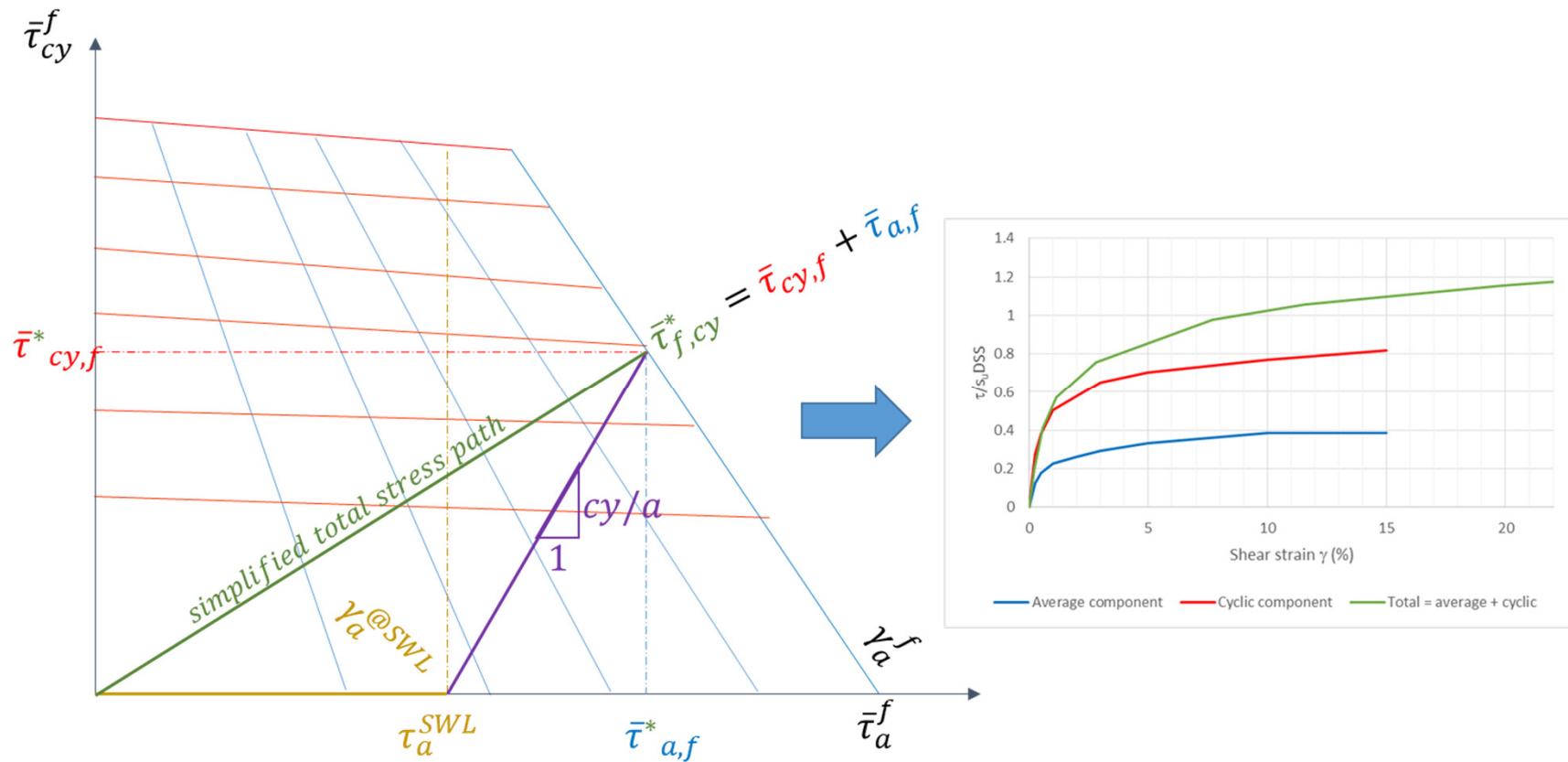


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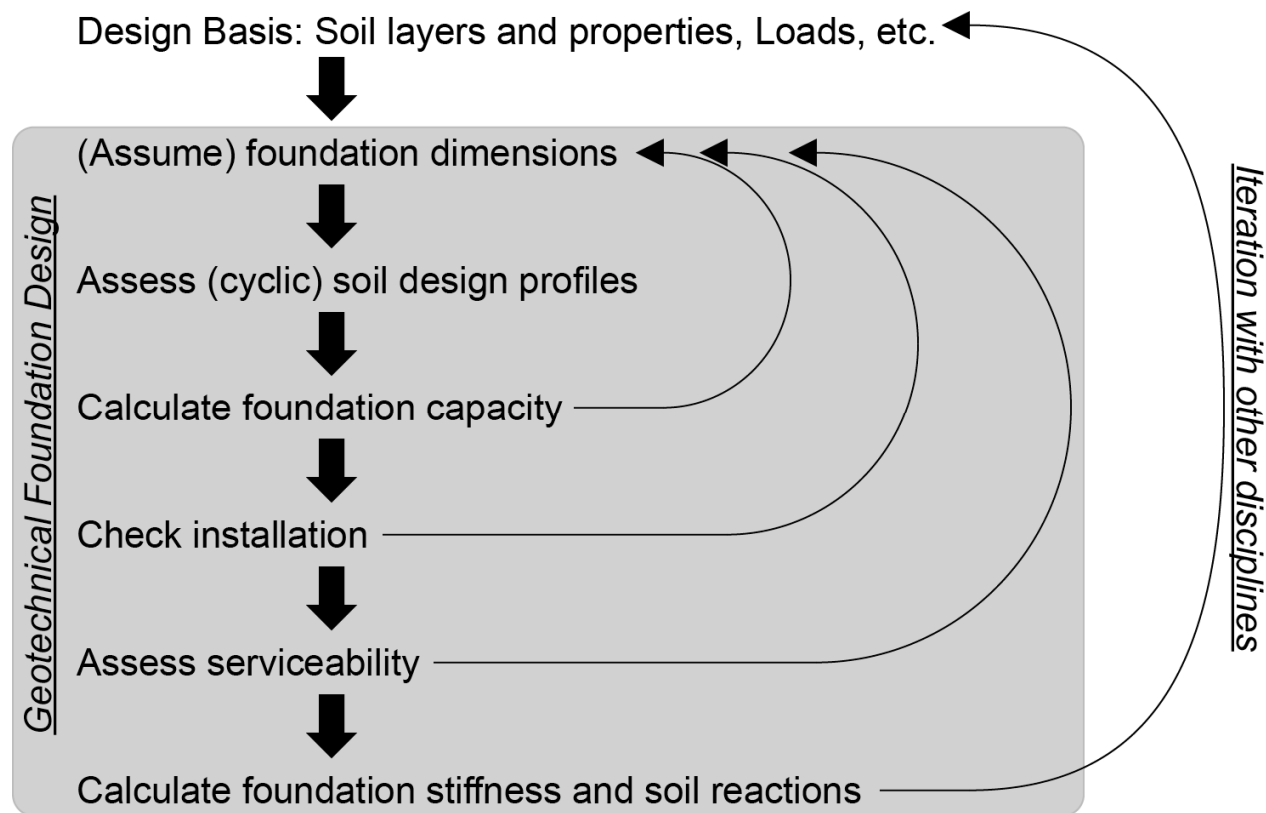
Engin et al. (2019)



3. Challenges in foundation analysis and design

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

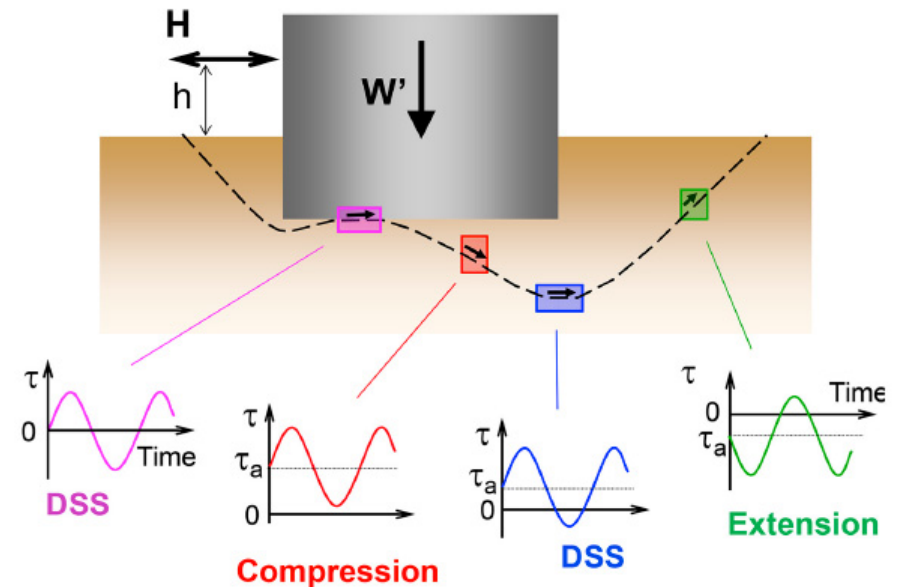
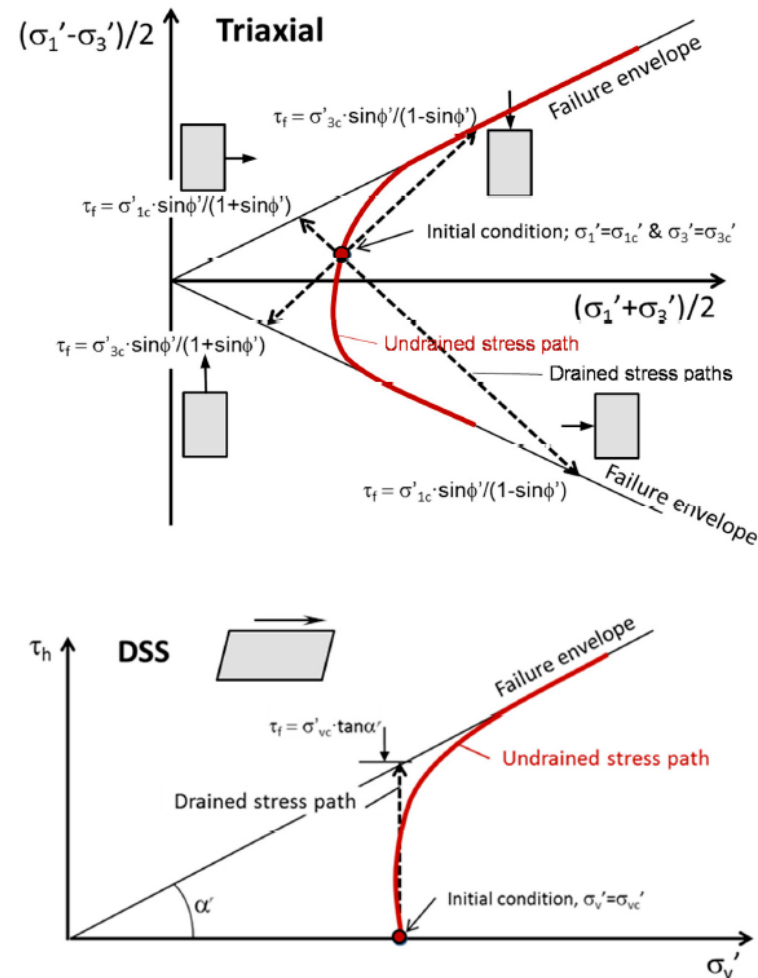
General design approach (Sturm, 2017)



3. Challenges in foundation analysis and design – *Soil modelling*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)

Andersen (2015)



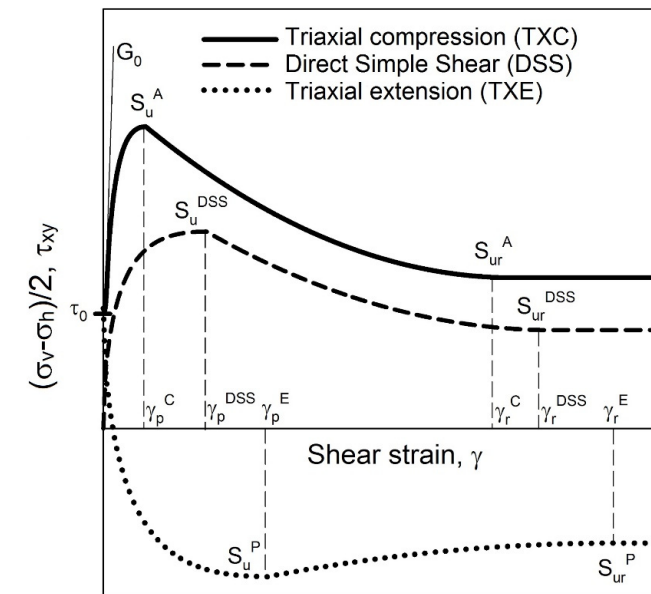
3. Challenges in foundation analysis and design – Soil modelling

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



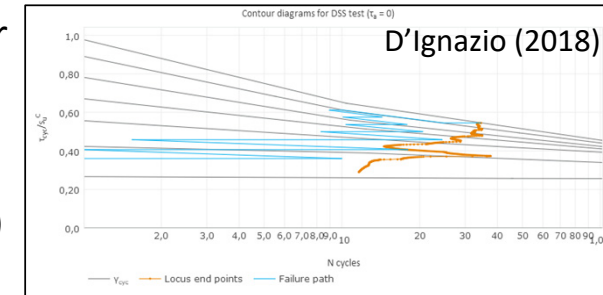
Soil modelling

NGI-ADPSoft

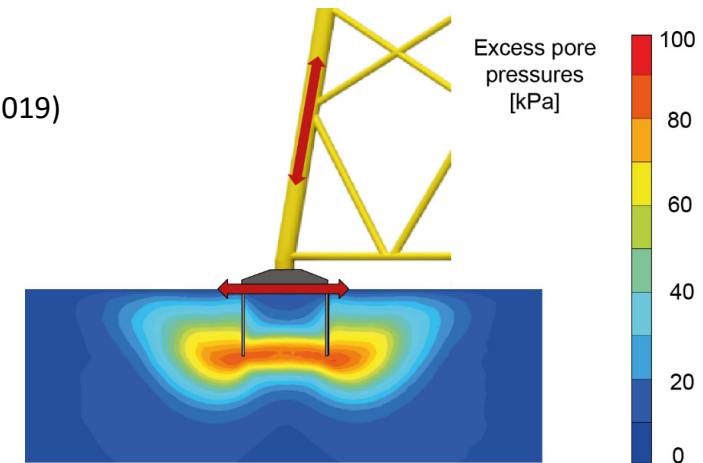
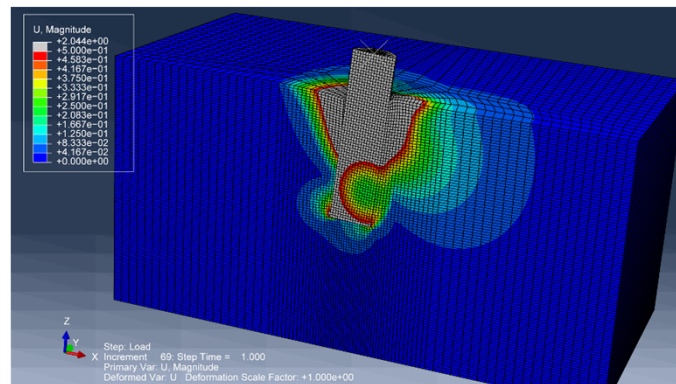


Grimstad et al. (2012), D'Ignazio et al.(2017)

- ❑ Semi-empirical approach: Using cyclic contour diagrams
- ❑ Implemented in FE:
 - ❑ **UnDrained Cyclic Accumulation Model (UDCAM)**
 - ❑ UDCAM- Simplified (implemented in Plaxis)
 - ❑ **Partially Drained Cyclic Accumulation Model (PDCAM)**
- ❑ High Cyclic Accumulation Model (HCAM)
- ❑ ...



Sturm (2019)



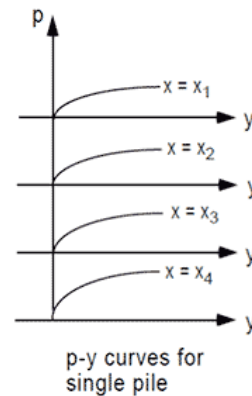
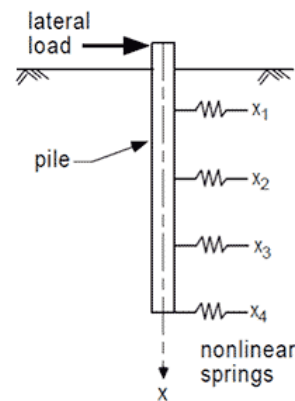
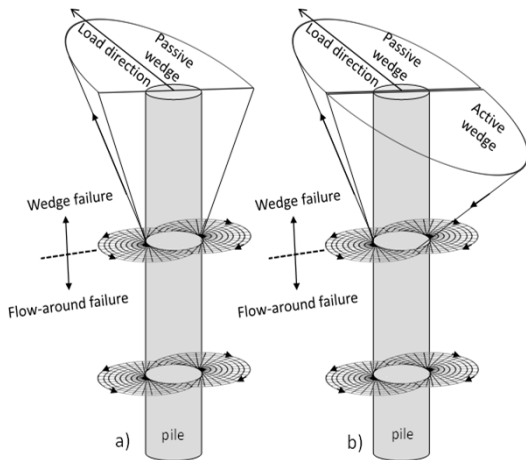
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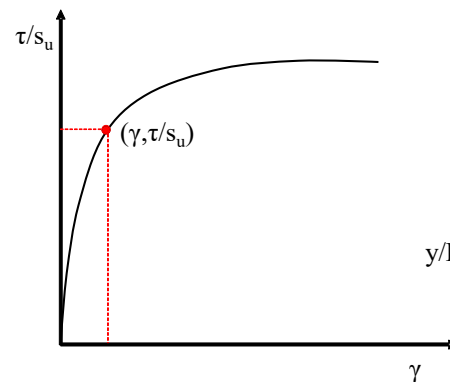
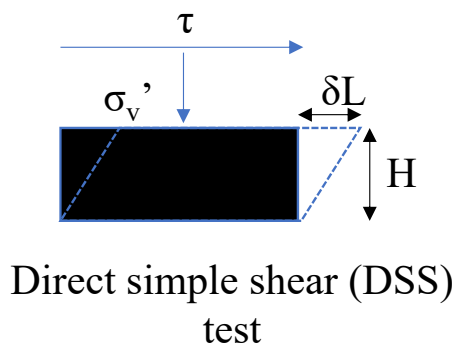
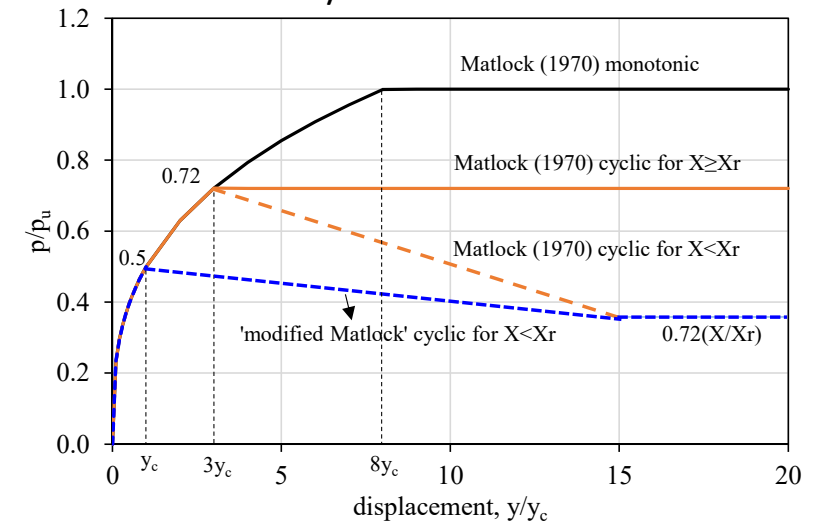


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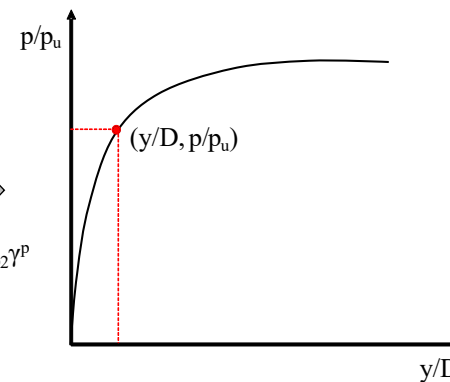
Pile analysis under lateral loading



API/Matlock curves



Scaling
 $p/p_u = \tau/s_u$
 $y/D = \xi_1 \gamma^e + \xi_2 \gamma^p$



$$\frac{p}{p_u} = 0.5 \left(\frac{y}{y_c} \right)^{0.33} \leq 1$$

$$p_u = N_p s_u$$

$$N_p = (3 + J z/D) + \gamma' z/s_u \leq 9$$

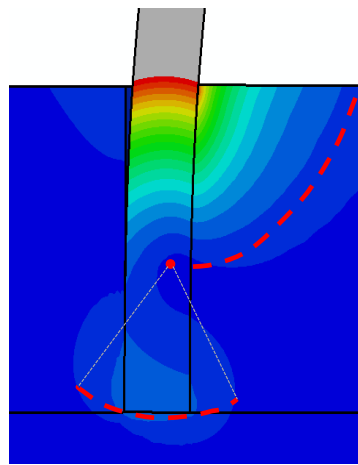
Zhang & Andersen (2017)

3. Challenges in foundation analysis and design – *Foundation modelling*

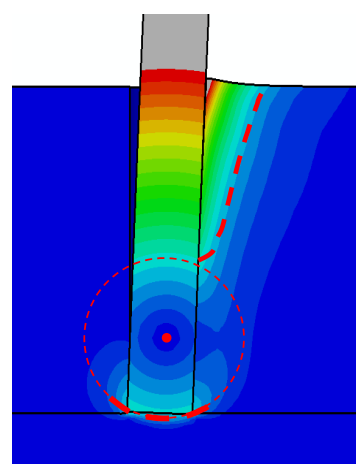
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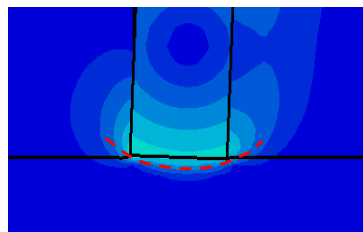
Pile analysis under lateral loading



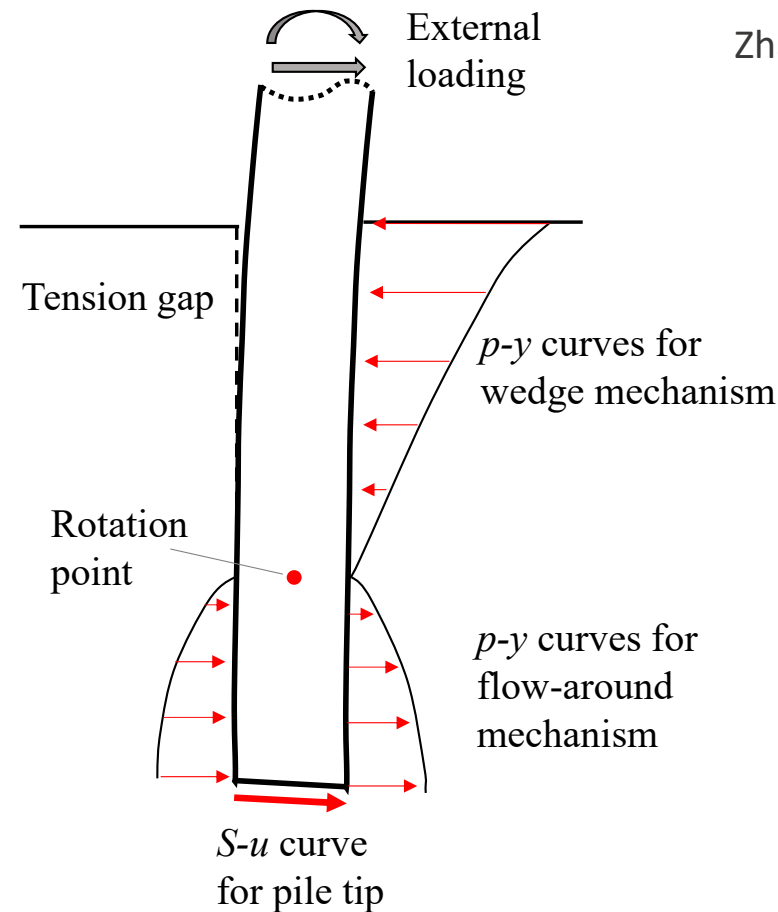
$$y_m/D = 0.2\%$$



$$y_m/D = 31\%$$



Essentially replace the
scoop failure surface with
a flat base shear plane



Zhang & Andersen (2019)

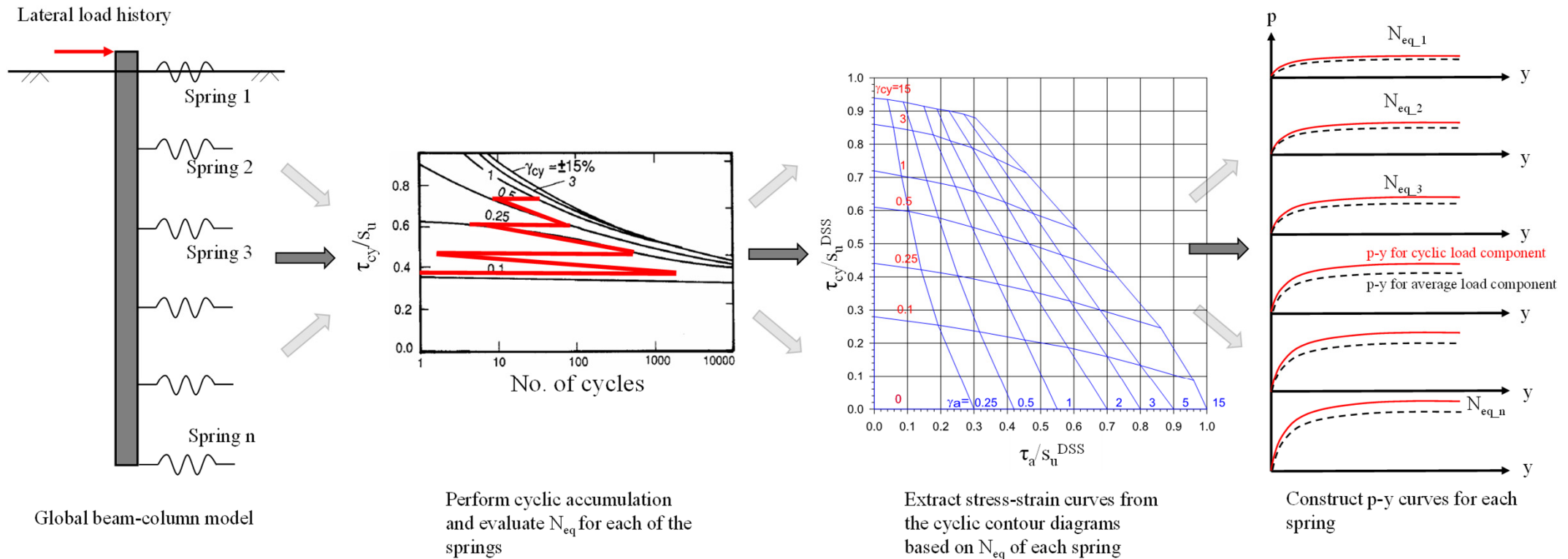
3. Challenges in foundation analysis and design – *Foundation modelling*

Challenges of geotechnical analysis and design of offshore foundations (Harun Kürşat ENGİN)



A computation procedure to analyse pile response after a cyclic load history

Zhang et al (2019)



3. Challenges in foundation analysis and design – *Foundation modelling*

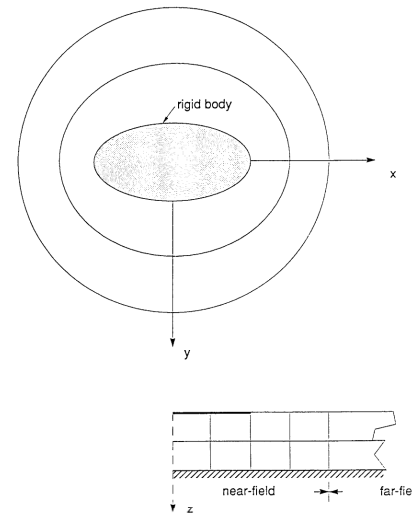


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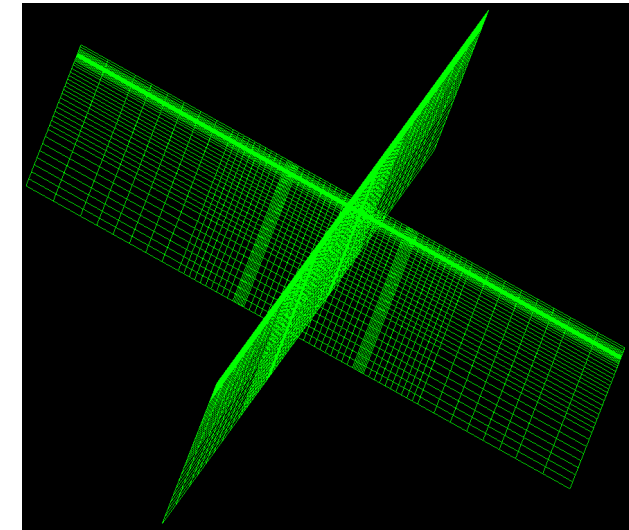
FEM

- ☐ Overshoot (undrained FEAs)
- ☐ Mesh dependency
- ☐ Simplifications
- ☐ Limitations
- ☐ ...

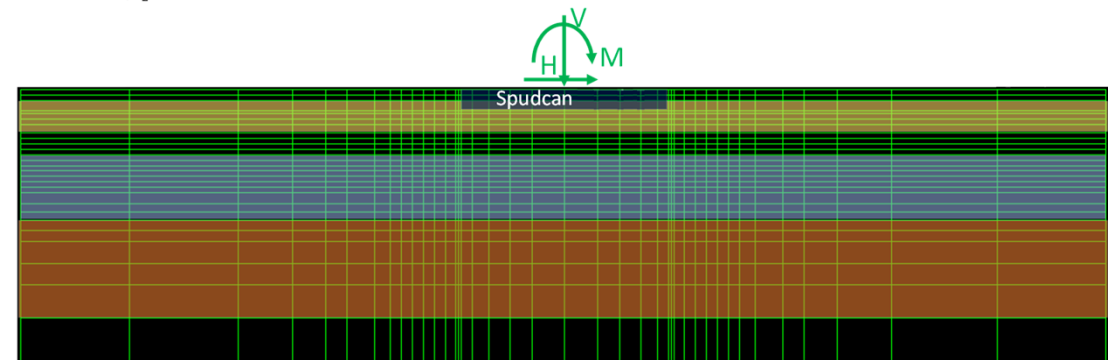
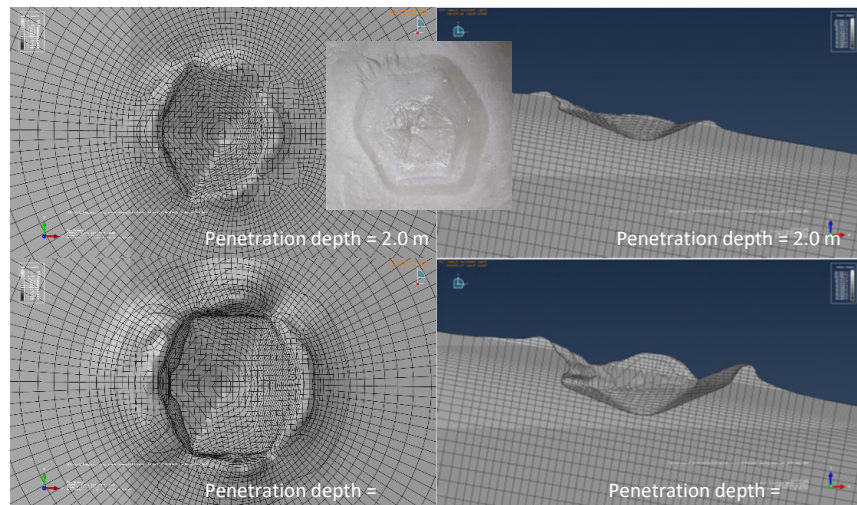
Engin et al. (2019)



INFIDEL



Shin et al. (2018)



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3. Challenges in foundation analysis and design – Foundation modelling



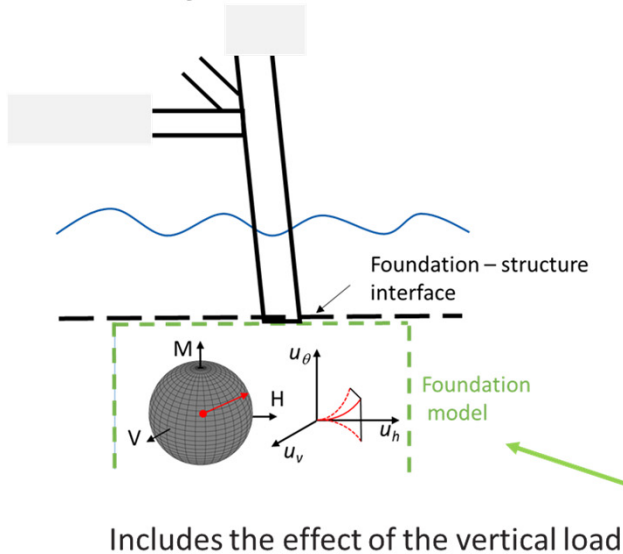
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Challenges

- ☐ nonlinear response
- ☐ hysteretic behavior
- ☐ effect of multidirectional loading
- ☐ iterative procedure (soil-structure interaction)

The REDWIN models

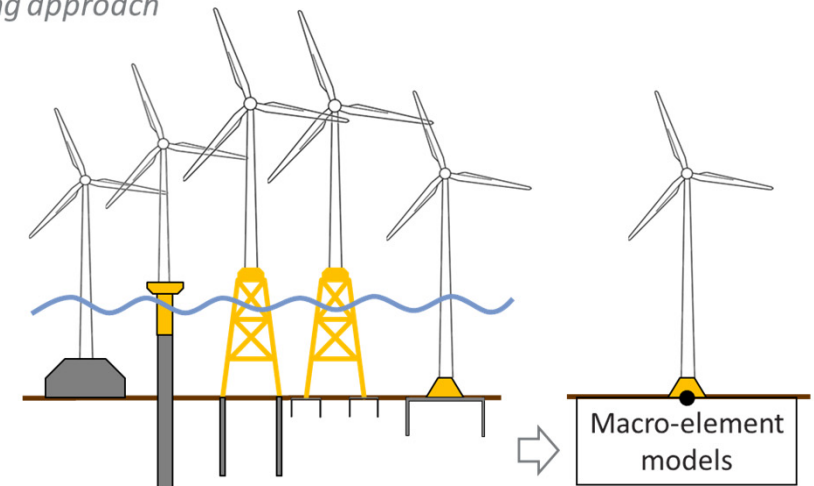
Bucket foundations



Foundation and substructure	Model applicable	Loading regime
	Redwin model 1 	Distributed 1D model to be applied to any DOF.
	Redwin model 2 	HM-loading
	Redwin model 3 	VHM-loading

The REDWIN models

Modelling approach



Skau et al (2018)

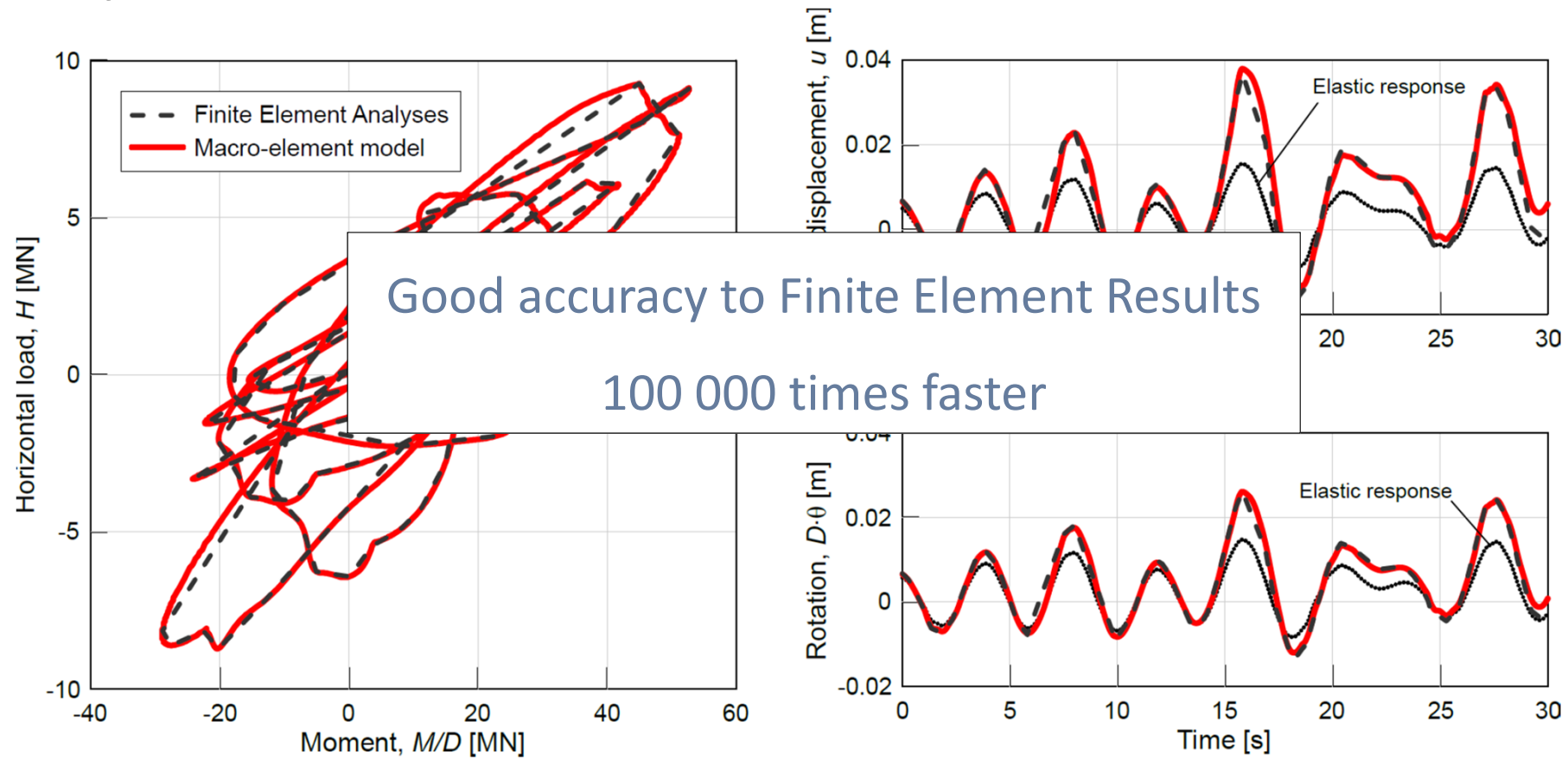
3. Challenges in foundation analysis and design – Foundation modelling



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Verification

The REDWIN models



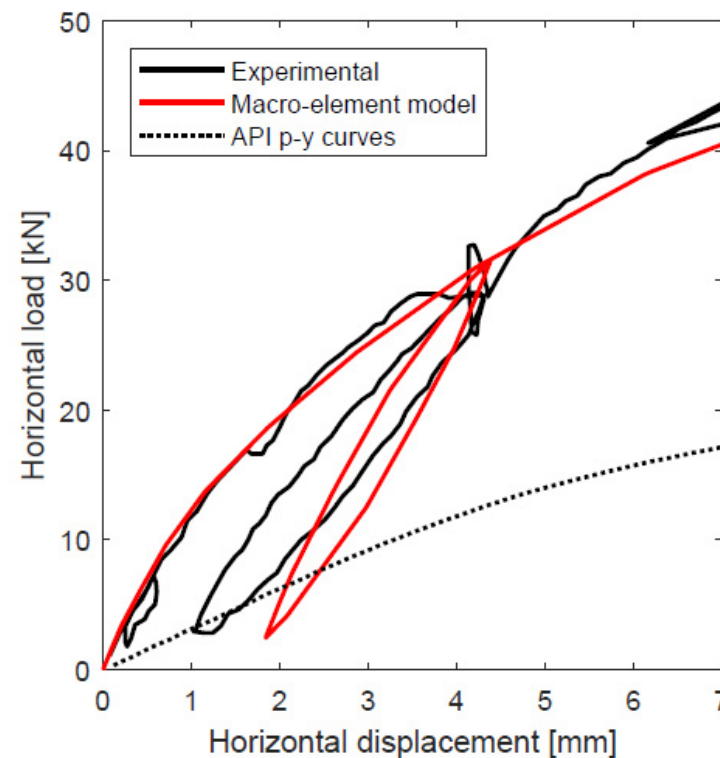
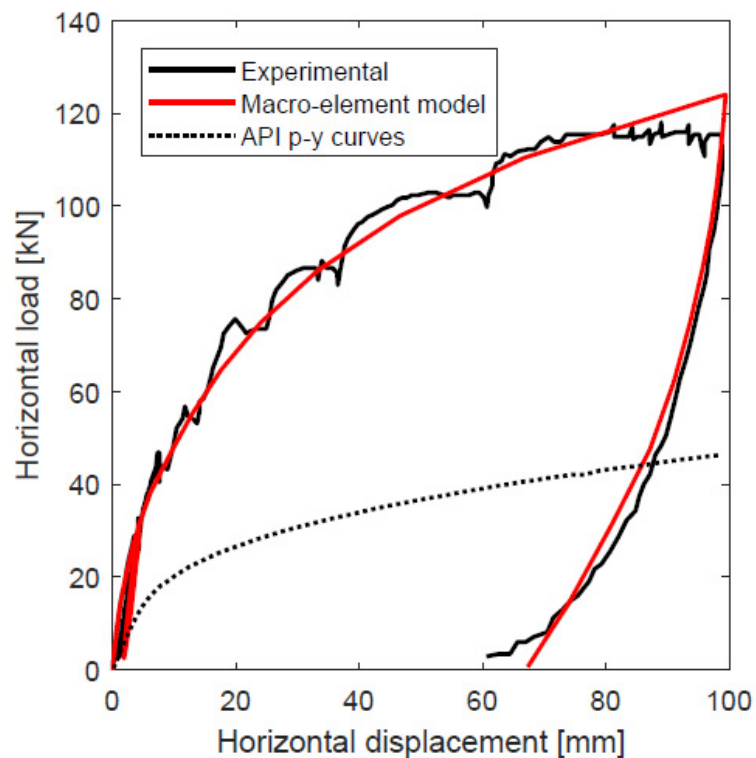
3. Challenges in foundation analysis and design – Foundation modelling



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Validation

The REDWIN models



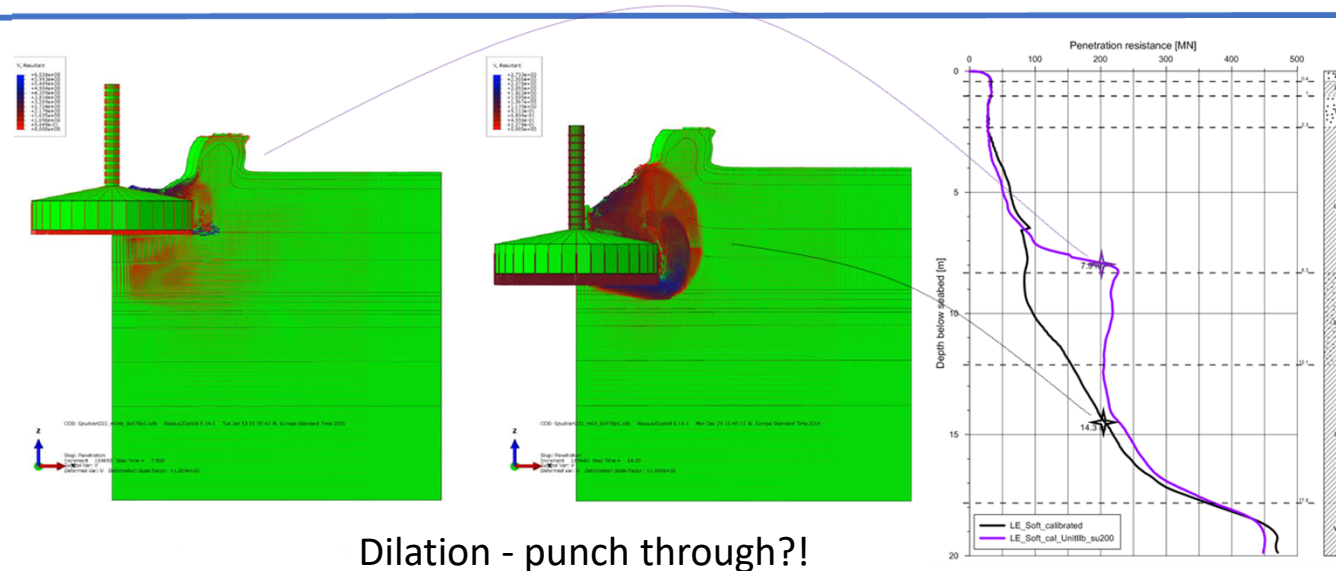
L/D = 5

Experimental data from:
Byrne, B., et al. (2017), PISA:
new design methods for offshore
wind turbine monopiles, in
'Proceedings of the Society for
Underwater Technology
Offshore Site Investigation and
Geotechnics'.

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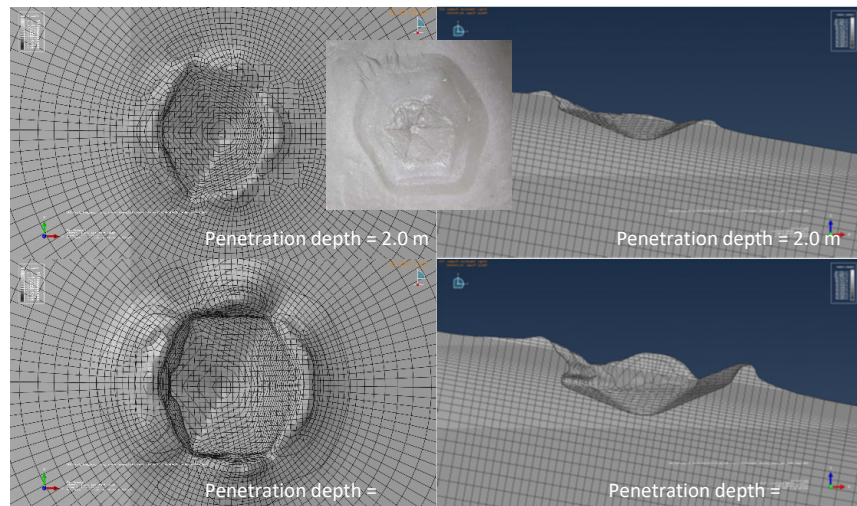
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Penetration analyses

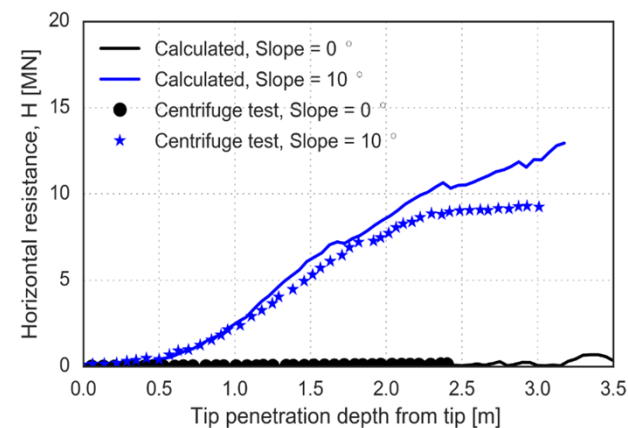


Sloping ground

Shin et al (2018)



Dilation - punch through?!



Shin et al (2018)

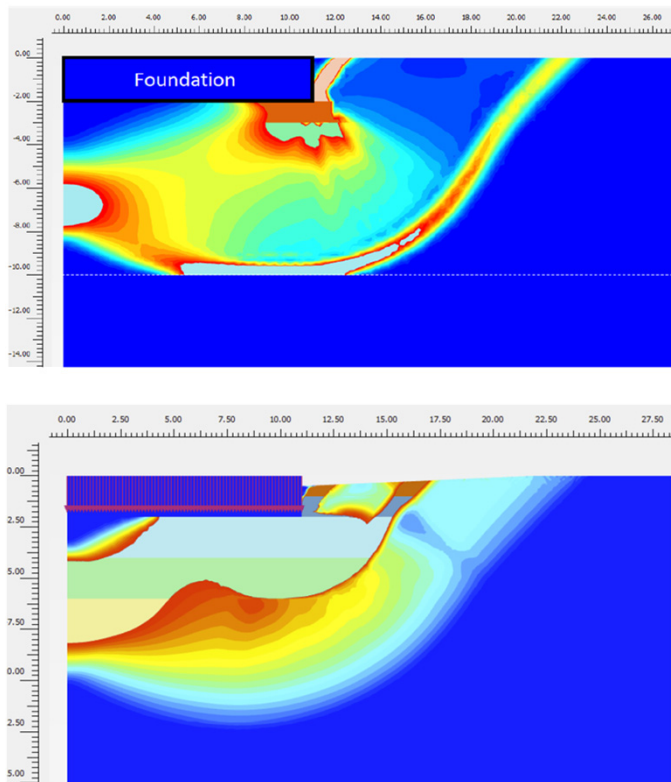
3. Challenges in foundation analysis and design – Foundation modelling



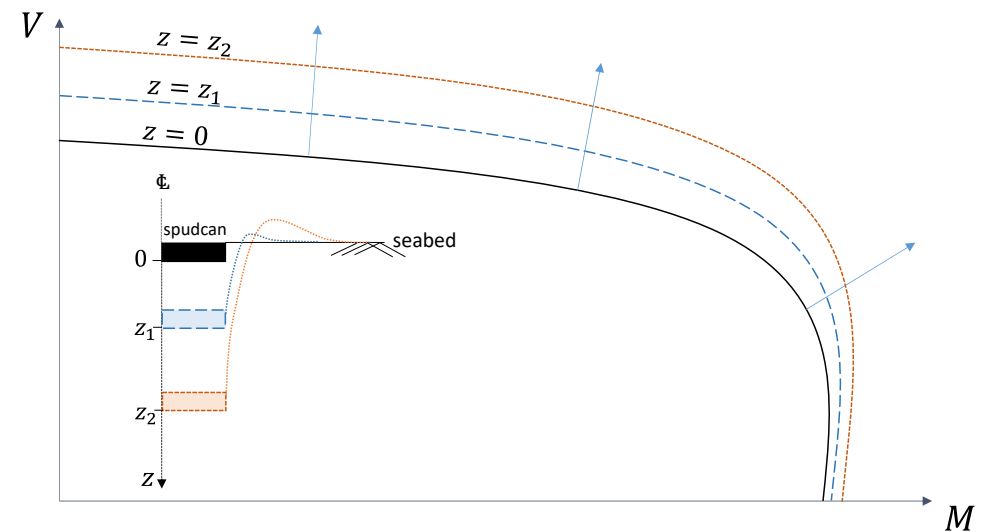
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Capacity

Engin et al. (2018)



Expansion of capacity envelope – geometrical effects



3. Challenges in foundation analysis and design – Foundation modelling

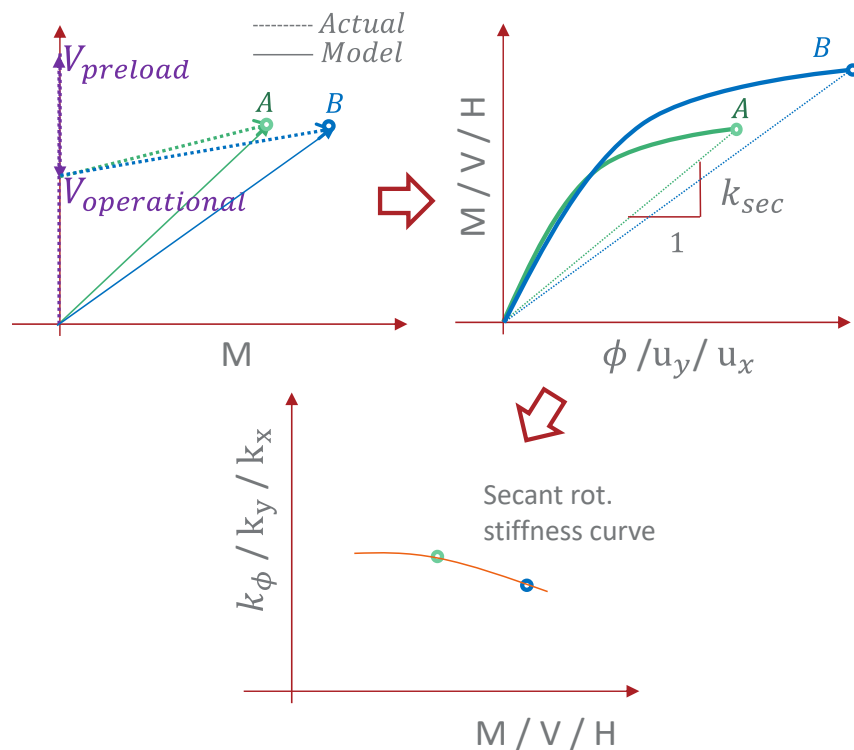


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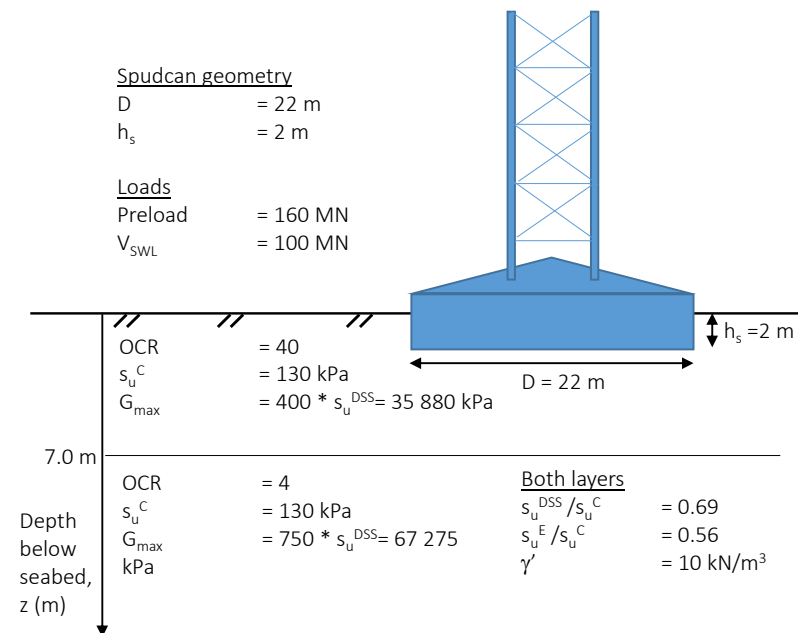
Jostad et al (2015)

Stiffness

- ☐ Loads and cy/a ratio depend on stiffnesses
- ☐ Load reference point



Engin et al (2018)



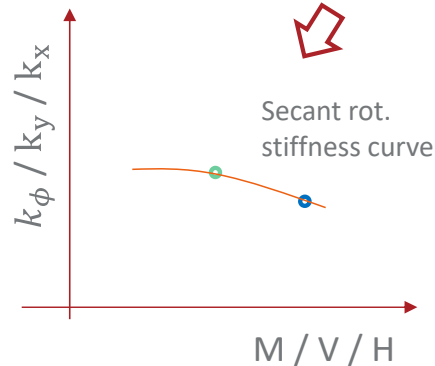
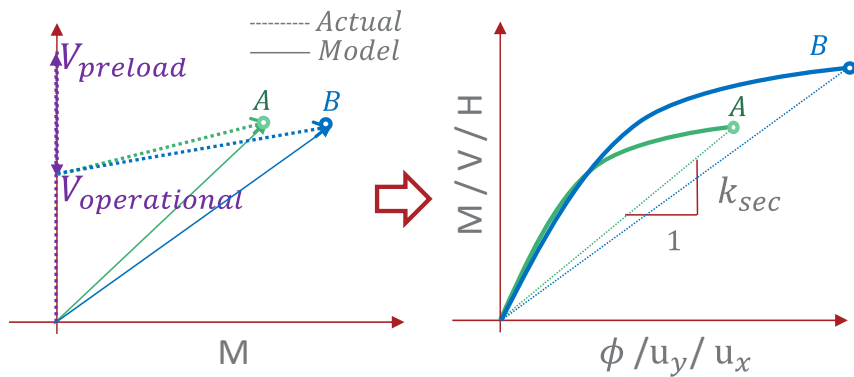
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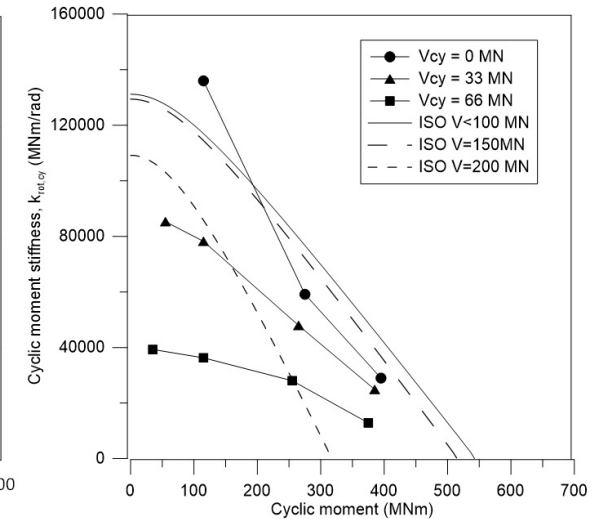
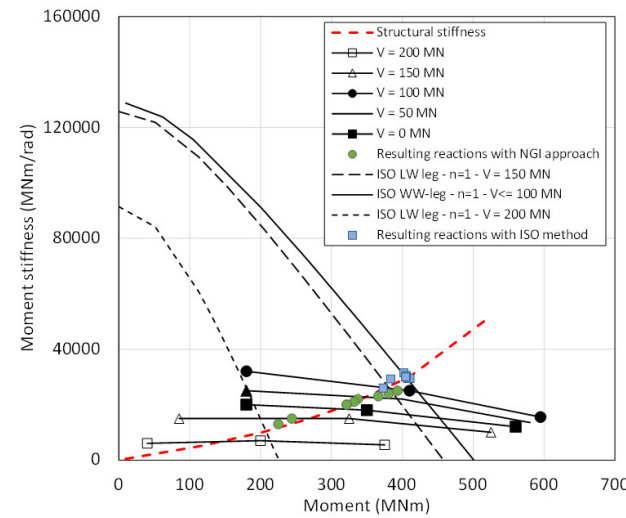
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Stiffness

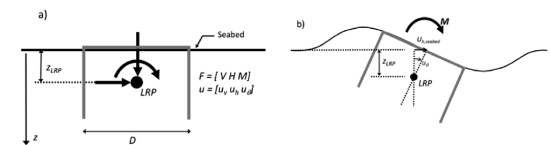
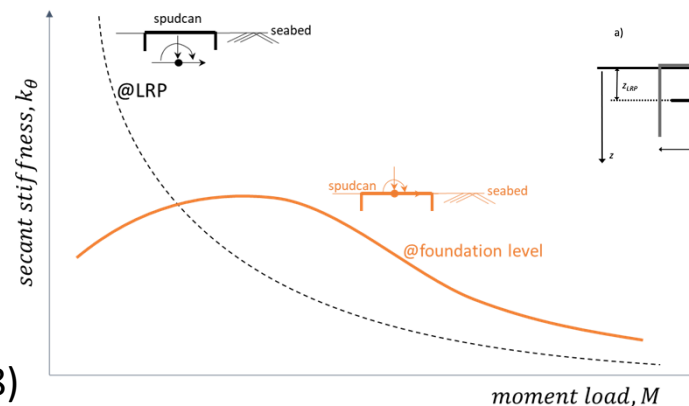
- ❑ Loads and cy/a ratio depend on stiffnesses
- ❑ Load reference point



Engin et al (2018)



Jostad et al (2015)



Skau et al (2018)

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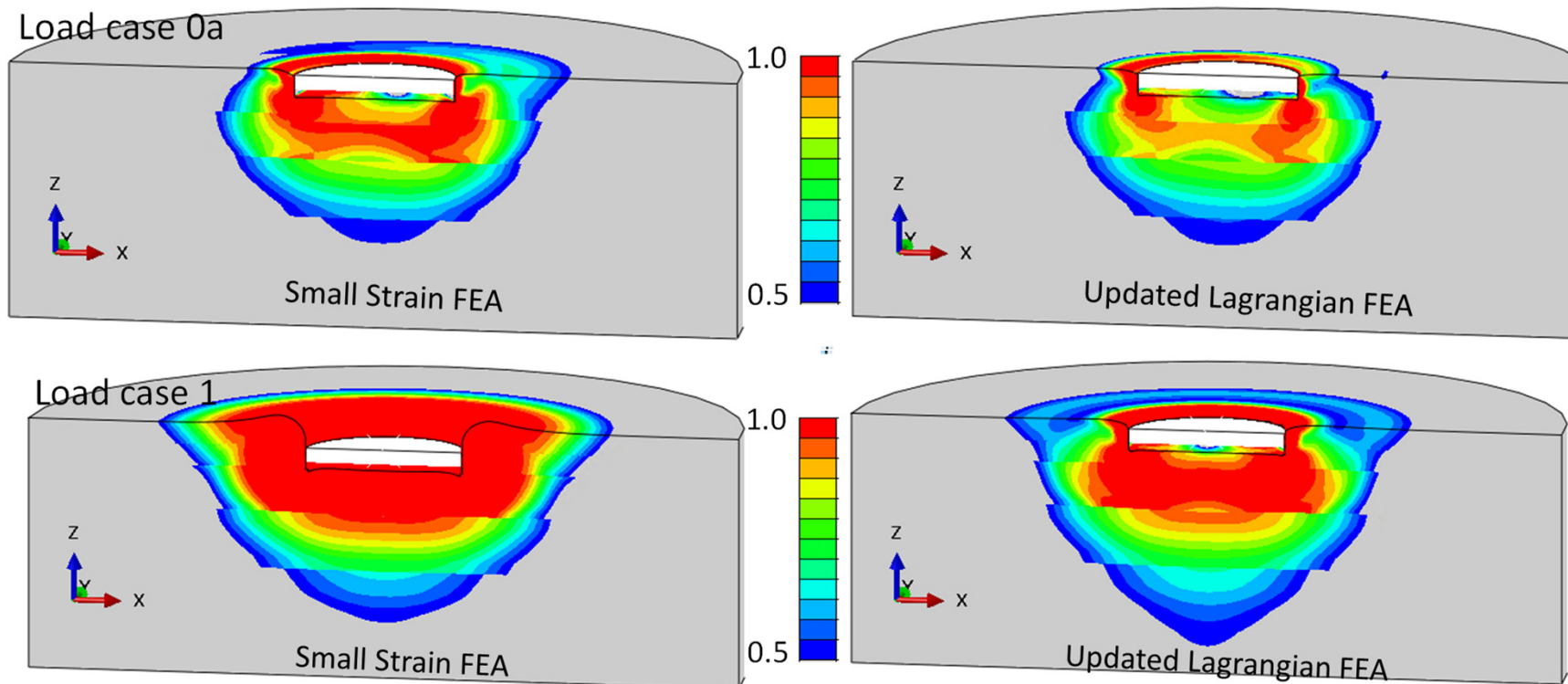
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Engin et al (2019)

Foundation stiffness – considering large deformation effects

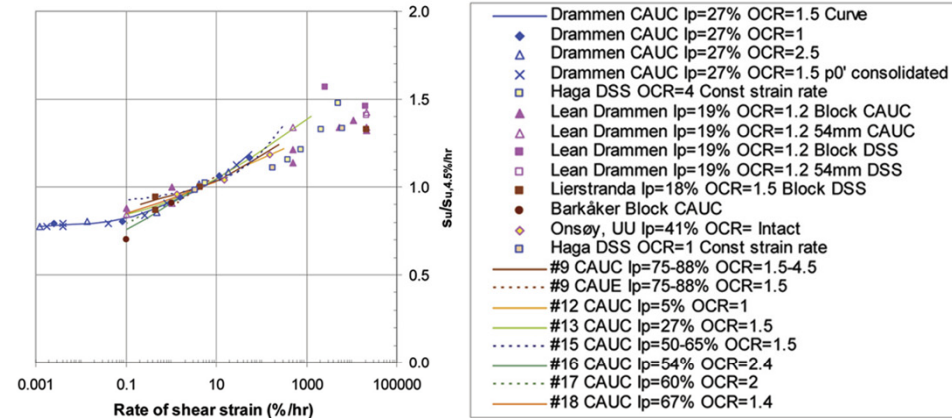
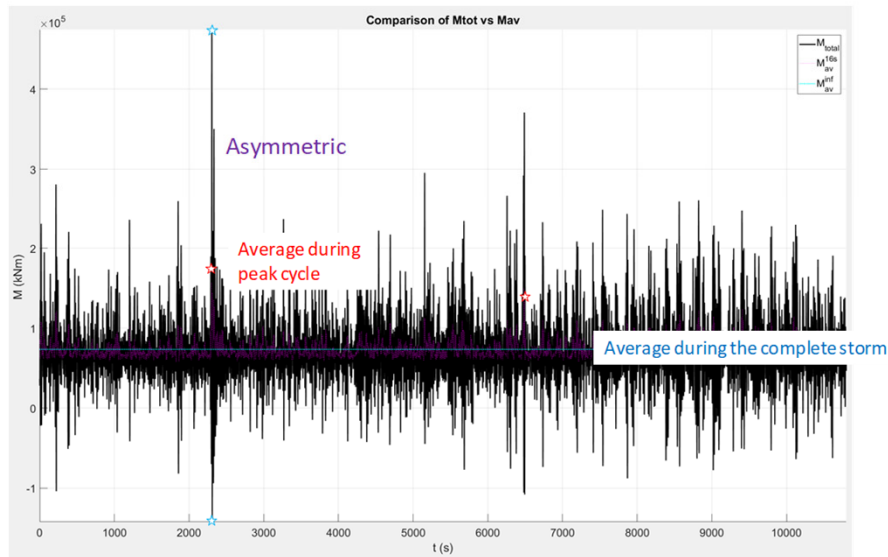


3. Challenges in foundation analysis and design – Foundation modelling

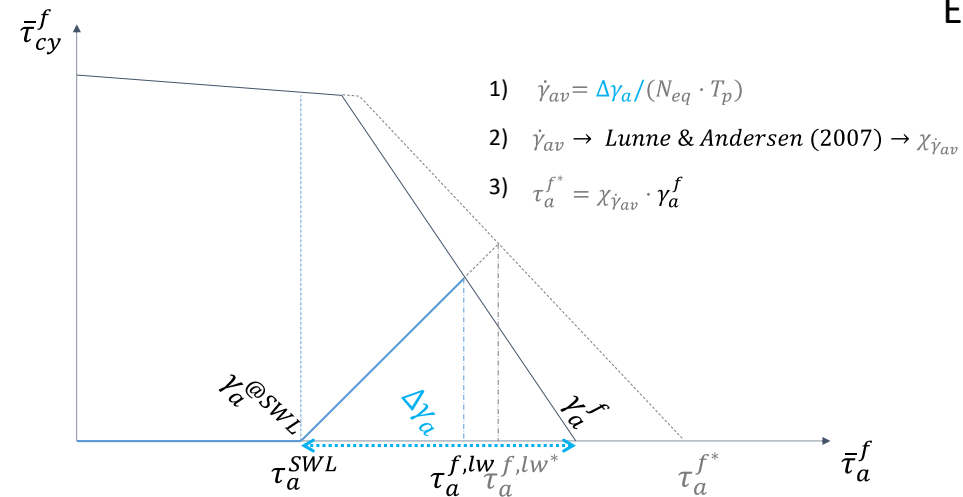


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Rate effects



Engin et al (2019)

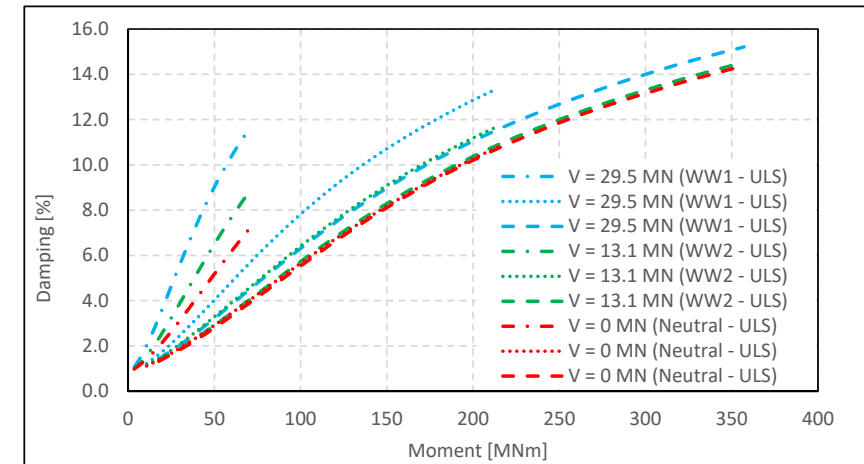
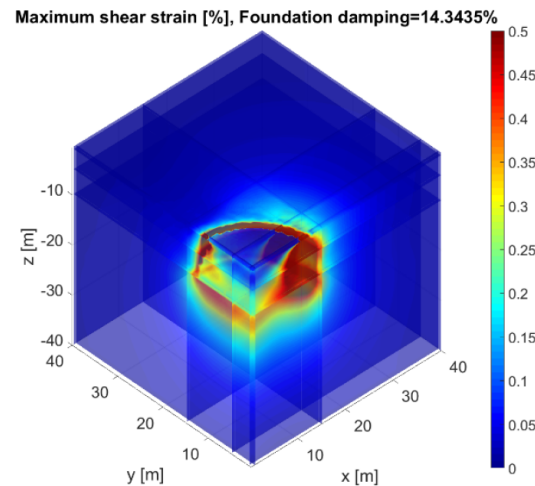
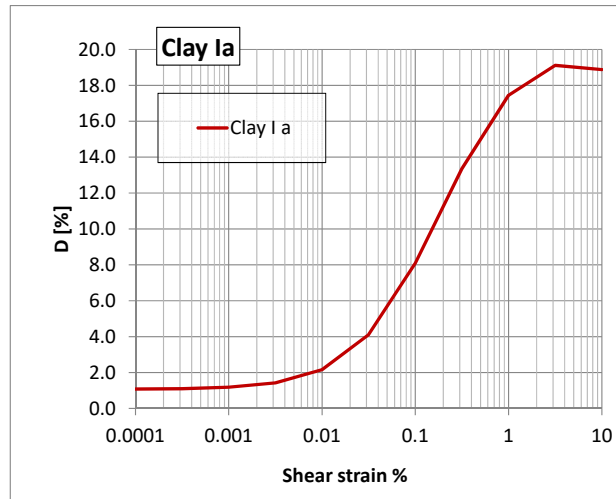


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Damping
$$D_{found} = \frac{E_h}{4\pi E_s}$$

Johansson et al. (2015)

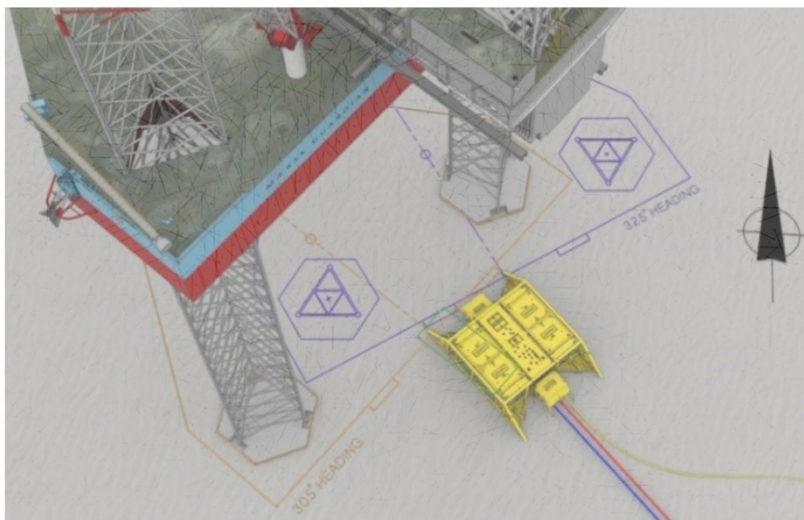


3. Challenges in foundation analysis and design – Foundation modelling

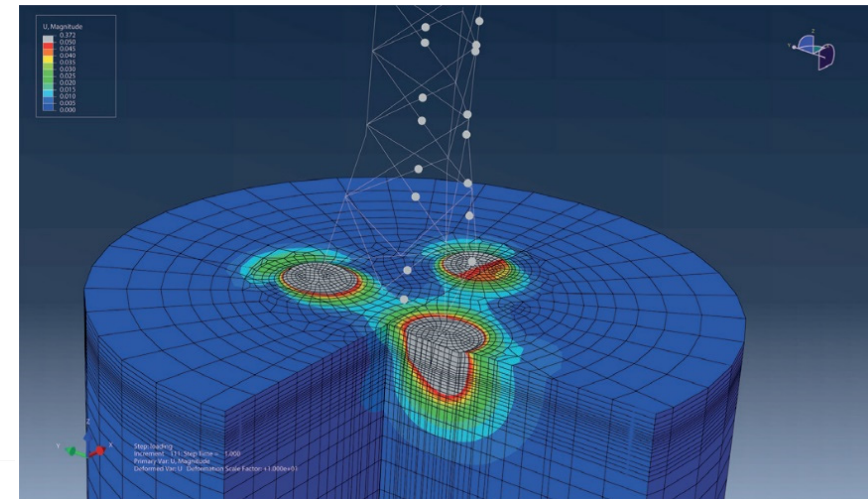
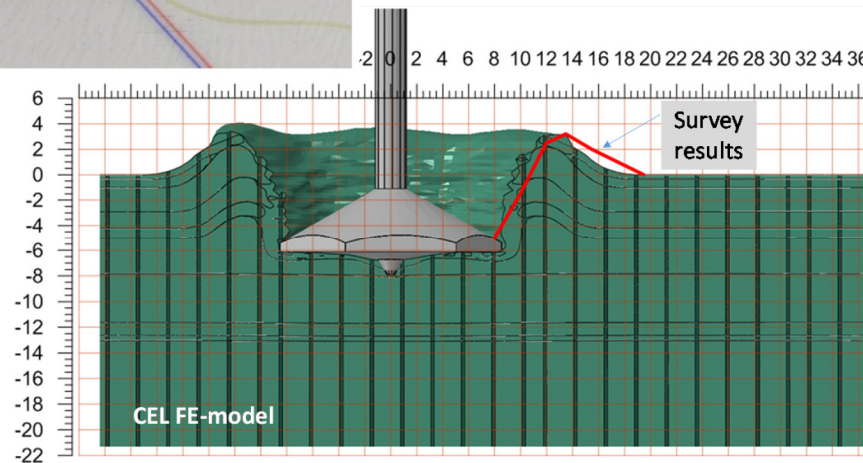


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Interaction modelling



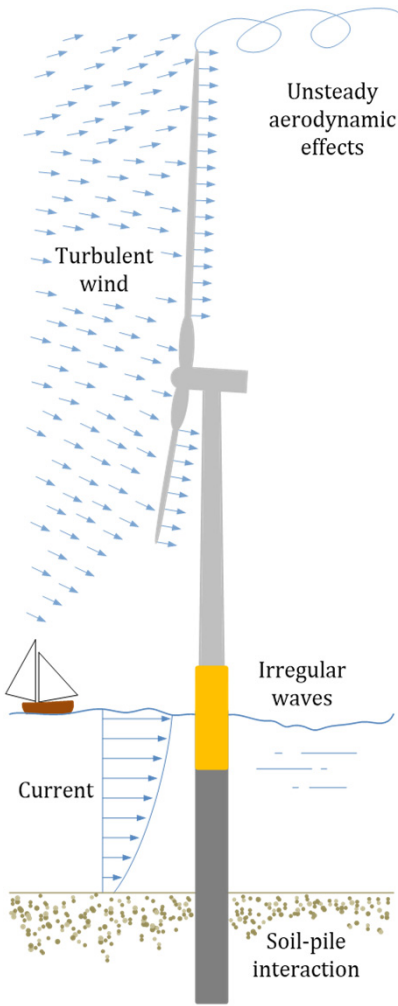
Engin et al. (2015)



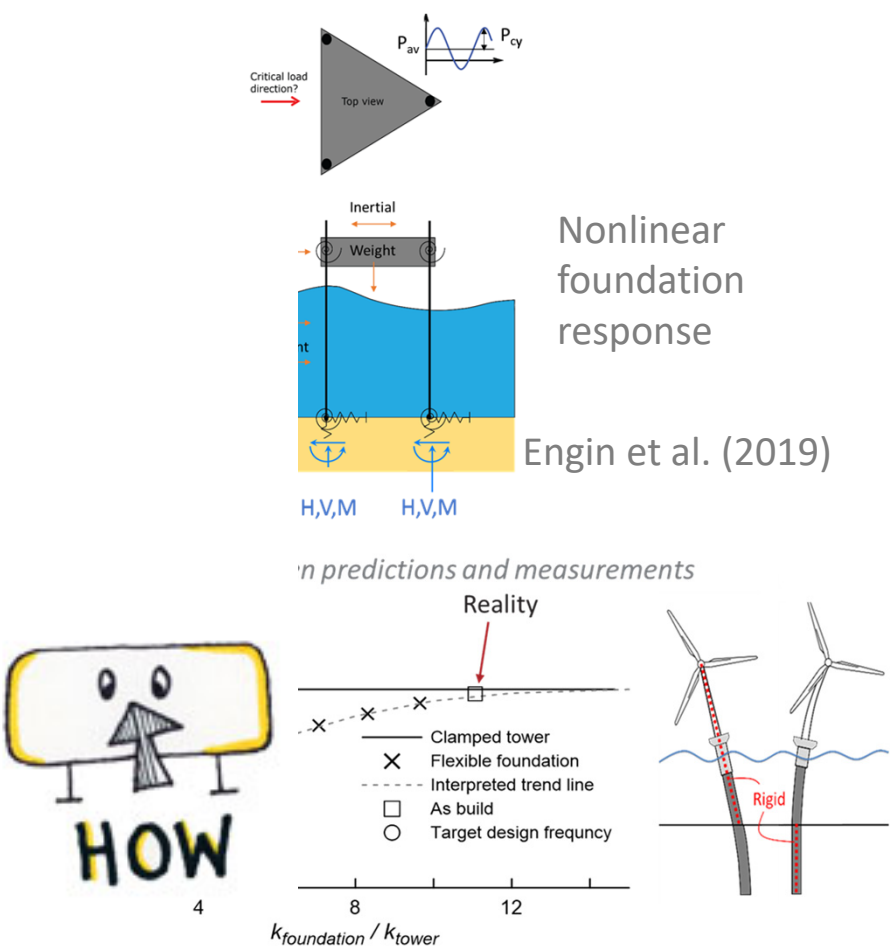
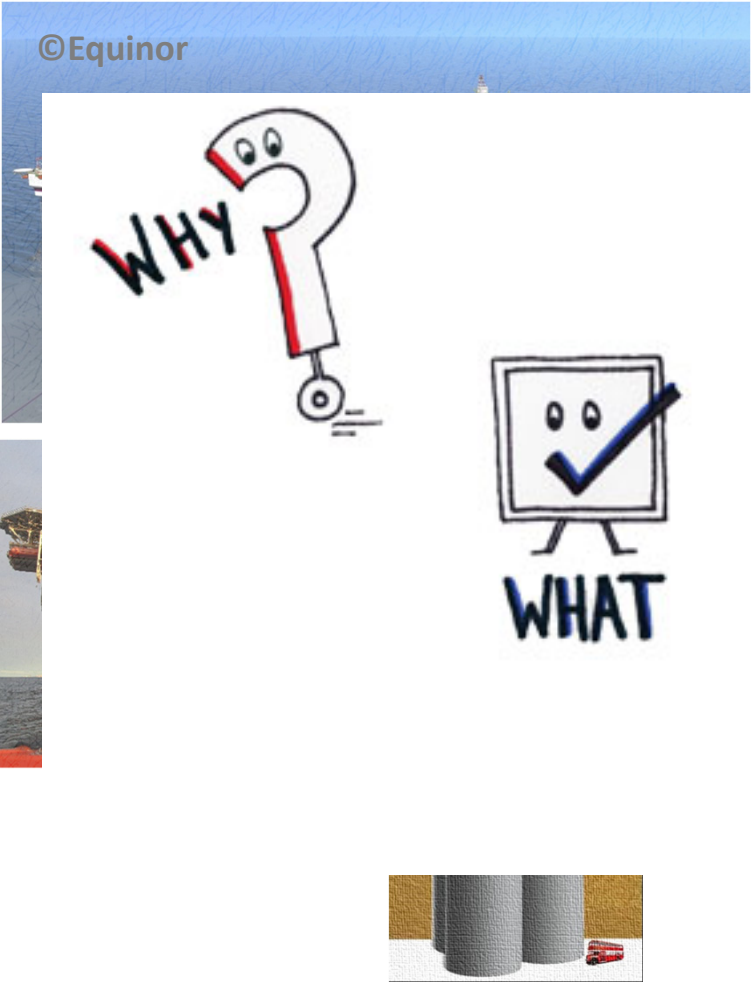
Sturm (2019)

5. Closing remarks

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Page (2018)



Skau et al (2018)

Acknowledgements

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Hans Petter Jostad



Knut H. Andersen



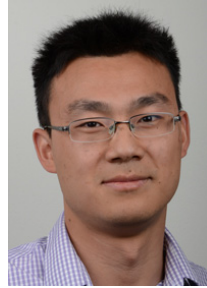
Hendrik Sturm



Ana M. Page



Marco D'Ignazio



Youhu Zhang



Maarten Vanneste



Huynh DV Khoa



Kristoffer Skjolden Skau



Victor Bjørn Smith



Guillaume Sauvin

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Thank you...