CYCLIC LOADING OF MONOPILES: ENGINEERING CHALLENGES AND INSIGHTS FROM RAMBOLL'S EXPERIENCE

Danish Geotechnical Society Seminar, Copenhagen

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Carlos Molina Mesa
Manuela Kanitz
…& many others

24 September 2025

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Outline

Monopile cyclic degradation methodology *in brief*

Challenges in selecting contour diagrams and design implications

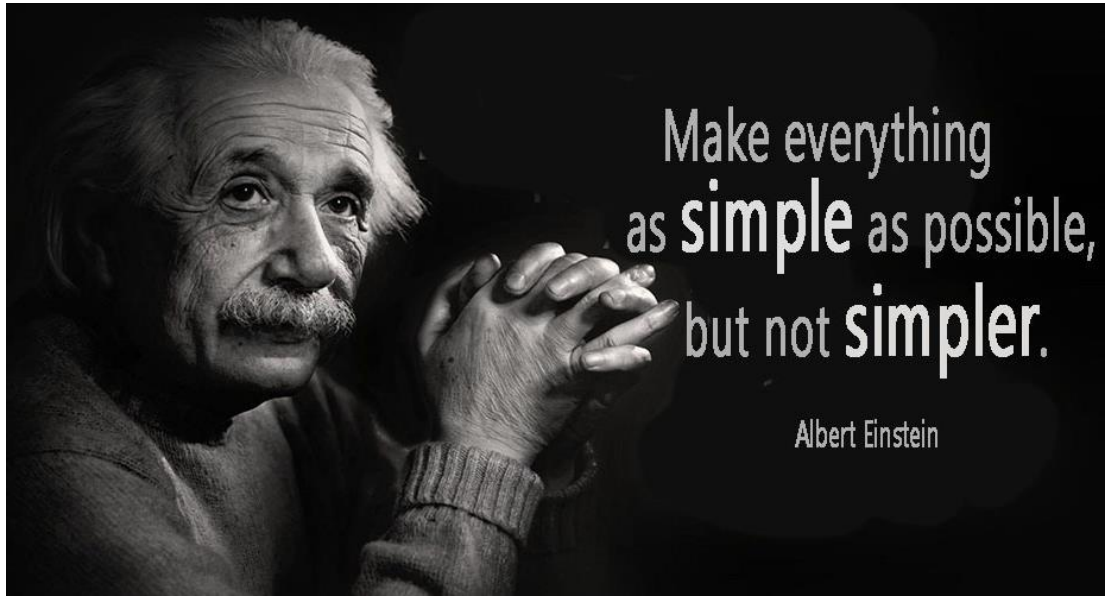
Development at Ramboll

Monopile cyclic degradation methodology

In brief

Key criteria

- ✓Robust but not overly conservative
- ✓Simple and efficient without many iterations
- ✓Certifiable
- ✓Based on cyclic contours as current industry best practice

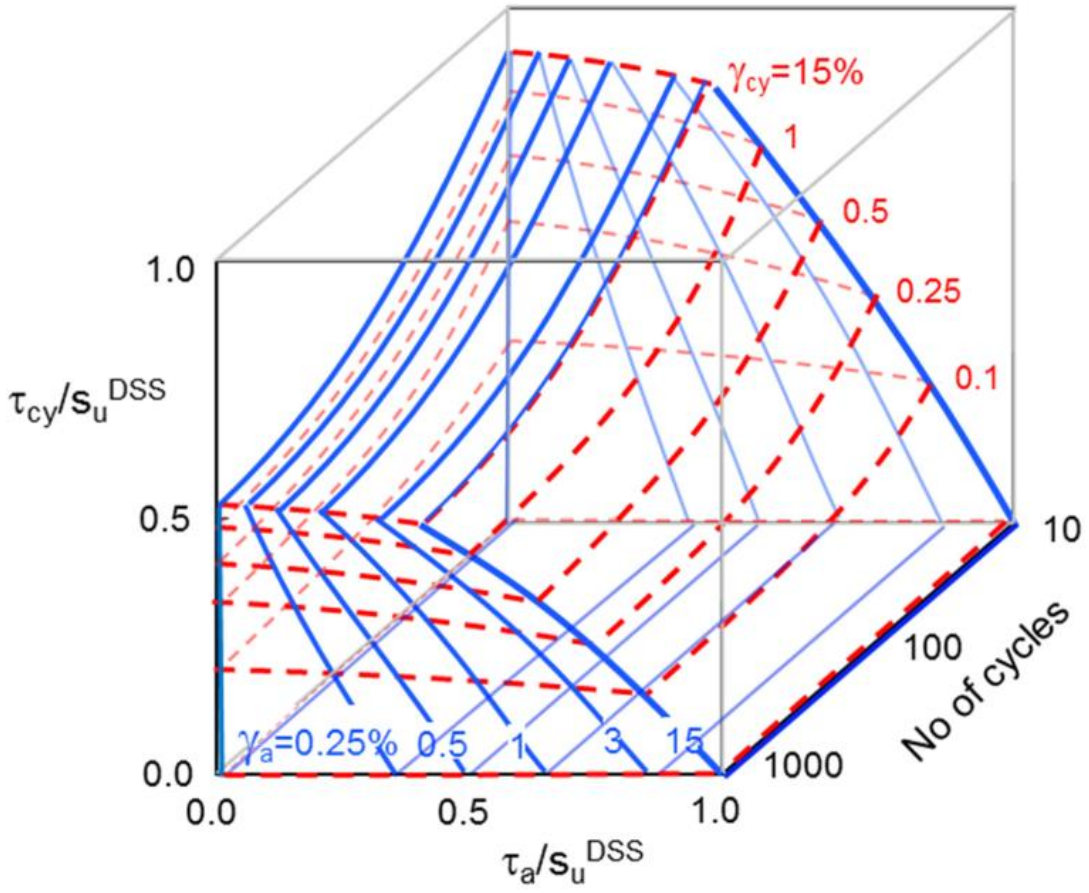


Ramboll's methodology – Main features

- **Based on cyclic contour diagrams**
- Accounts for partial drainage during pore water pressure accumulation
- Accounts for redistribution of load history along the monopile
- Cyclic degradation linked to soil spring's utilization

N_{eq} vs spring utilization relationship

- N_{eq} varies between N_{min} and N_{max} for a given soil unit
- $N_{max} \approx N_{eq}$ at largest soil utilization



Andersen (2015)

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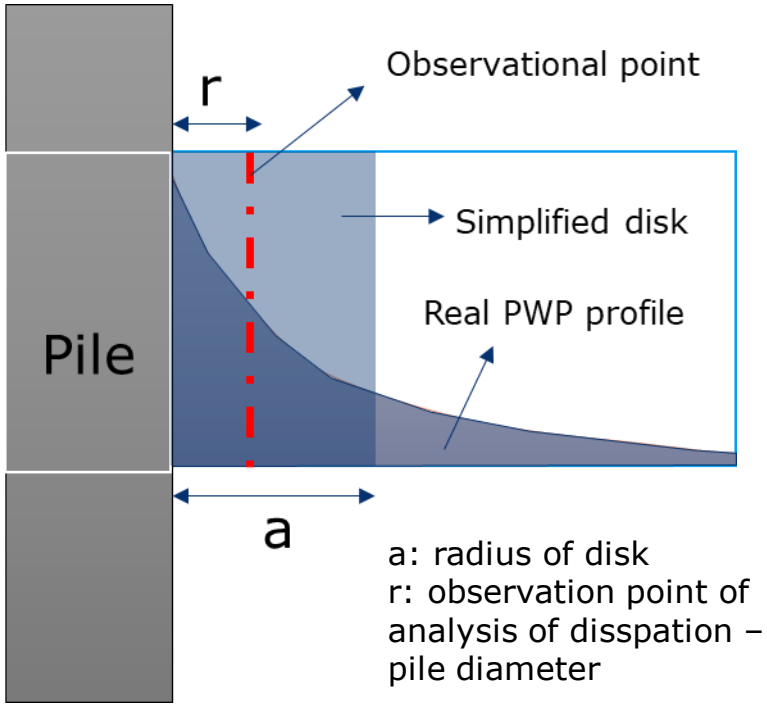

$$c_v = \frac{Mk}{\gamma_w}$$

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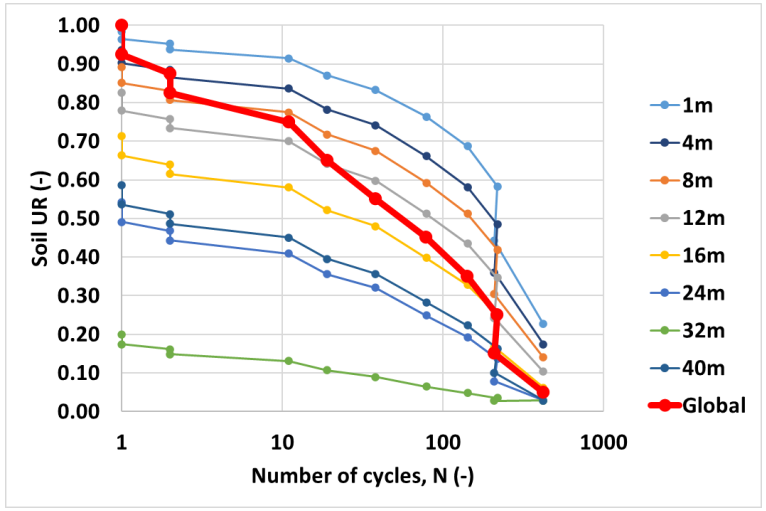

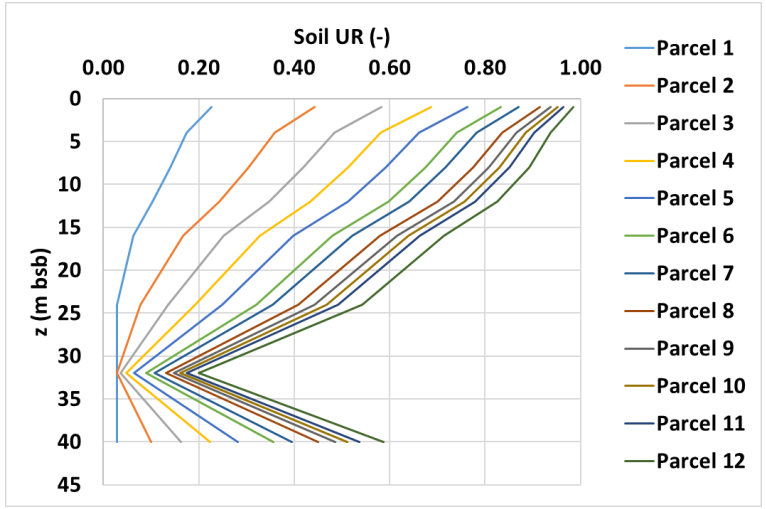

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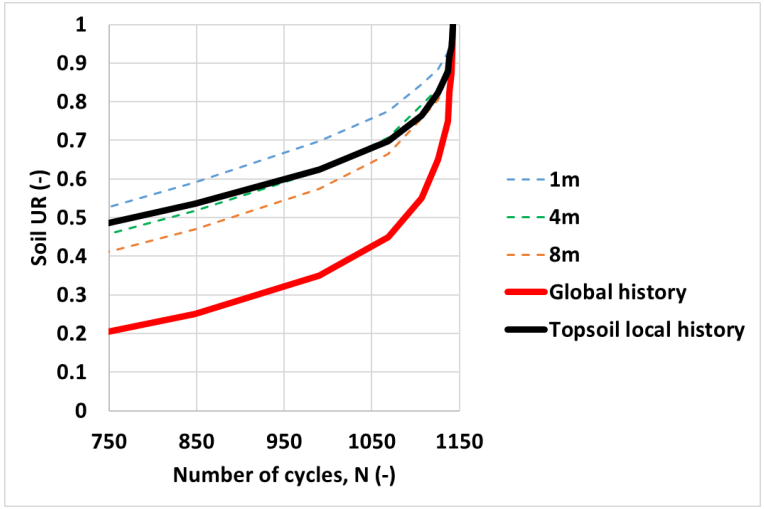

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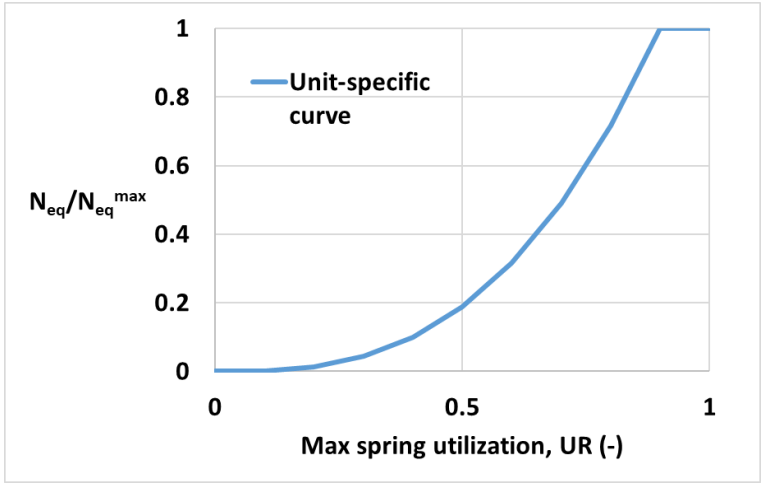
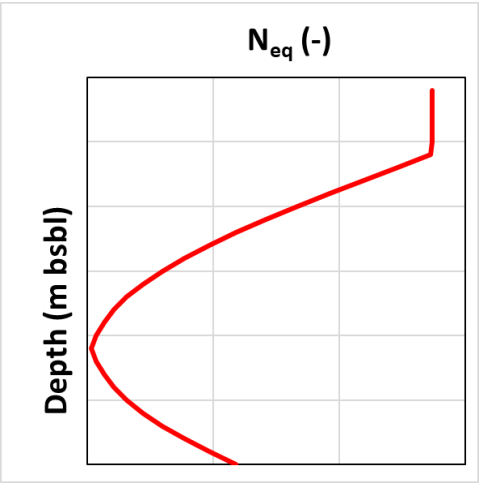
$$\frac{N_{eq}}{N_{eq}^{max}} = f(UR)$$





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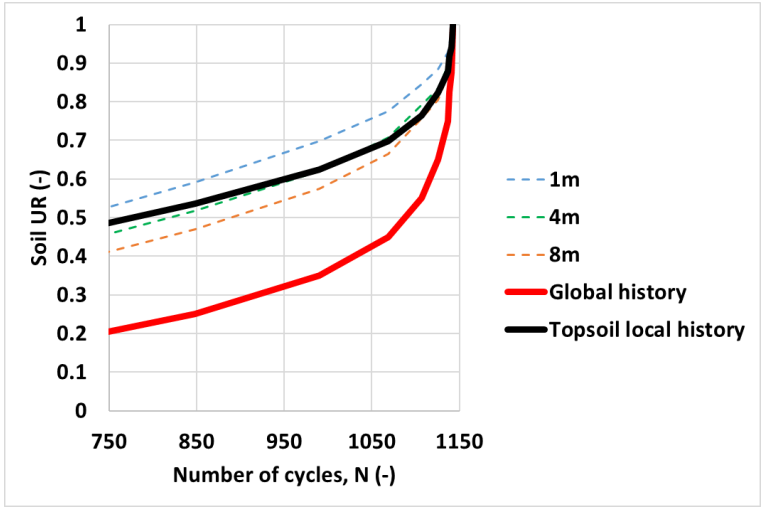
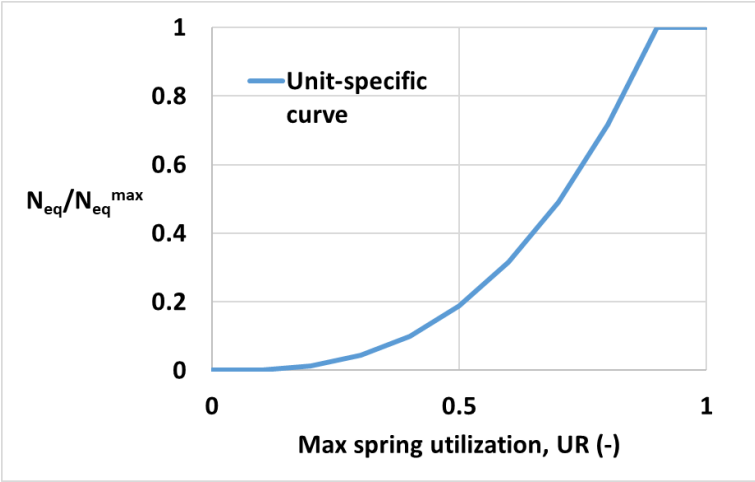
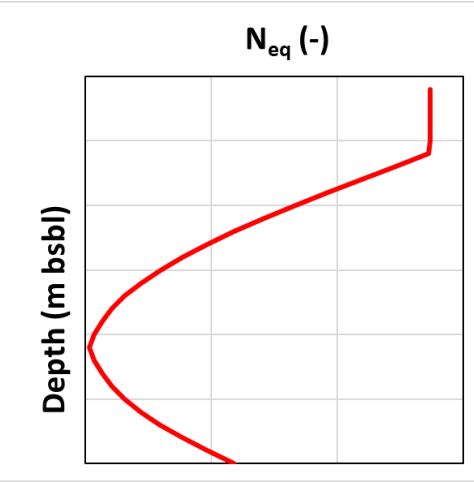


Key points:

- Calibrated at representative locations or clusters (FEA / 1D beam)
- Applicable to soil units across the OWF (advantage in large projects)



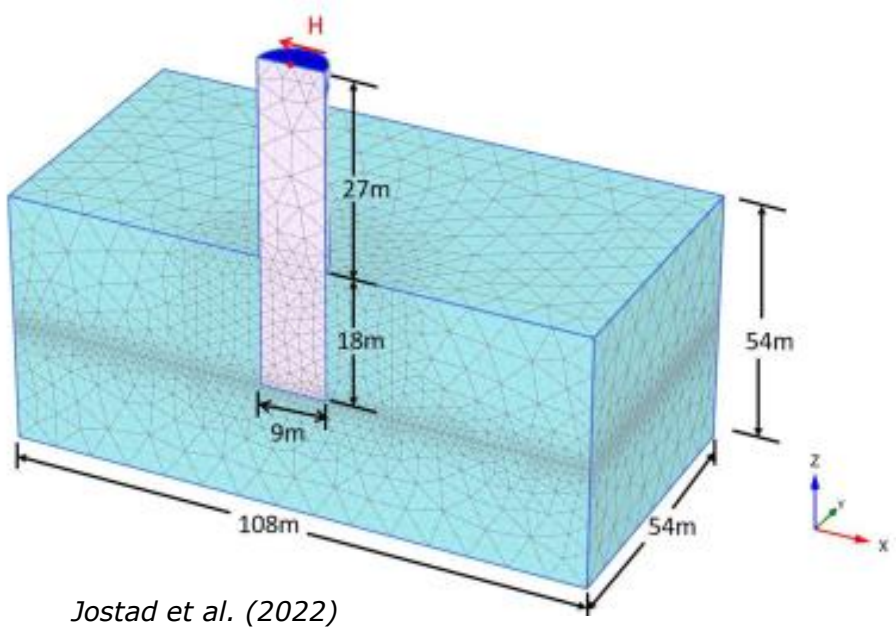


Methodology applied and certified in projects worldwide

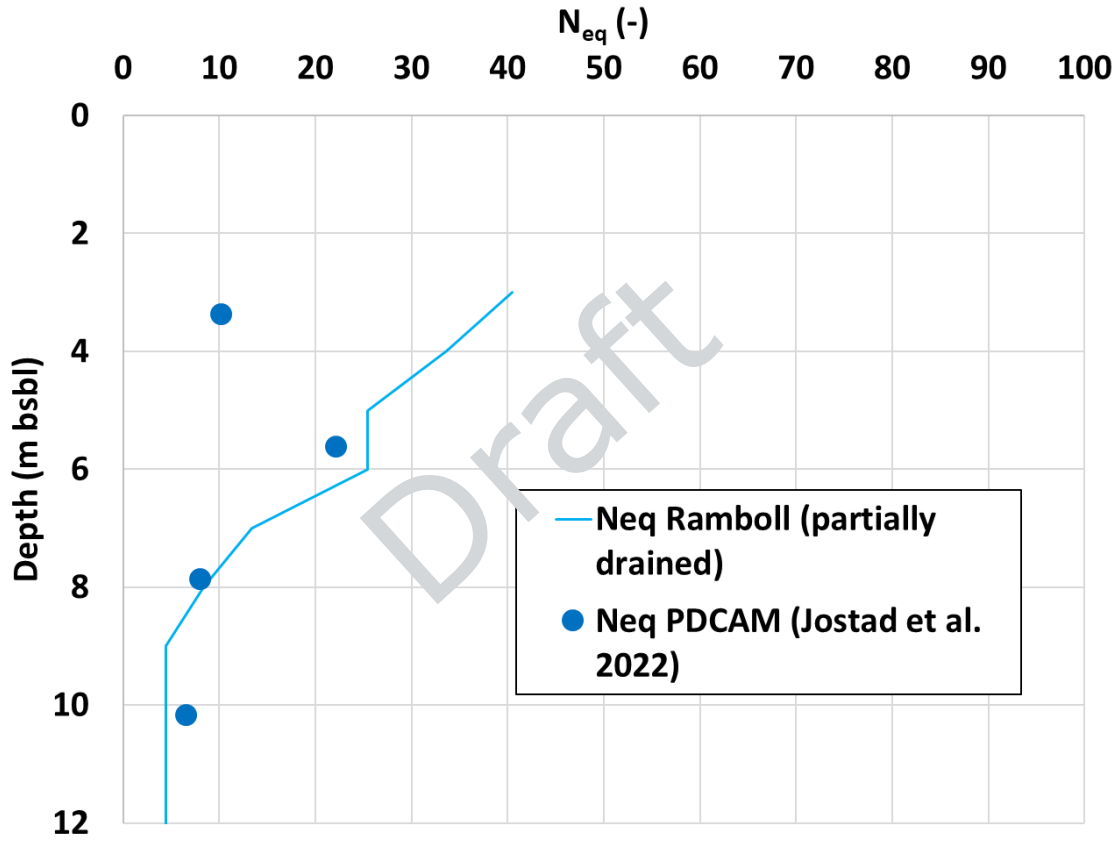
Ramboll's methodology – PDCAM comparison

Comparison with PDCAM analyses by Jostad et al. (2022)

- N_{eq} vs depth
- Effect of partial drainage



Jostad et al. (2022)



D'Ignazio et al., ISFOG 2025

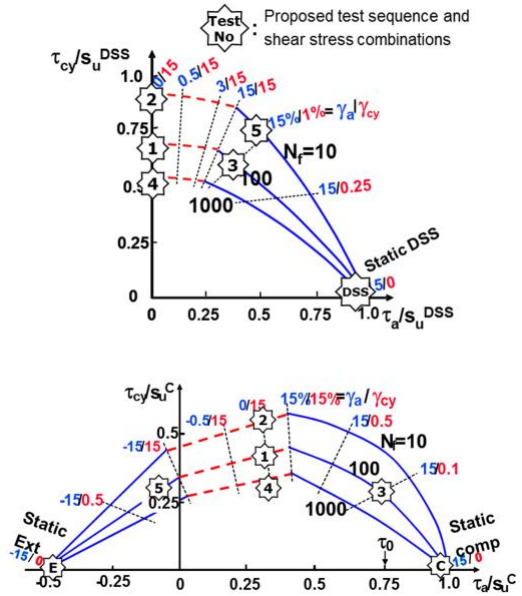
Challenges in selecting contour diagrams and design implications

Challenges in building contour diagrams

Challenges

- Choosing the most appropriate samples representative of a soil unit
- Having reliable monotonic tests with appropriate drainage conditions
- Planning (limited) cyclic tests (cyTX, cyDSS) for each unit
- Interpreting cyclic testing (strain/pwp accumulation)
- Building diagrams for different stress-paths

- **Limited cyclic tests**
- Where to focus?
- Which units have larger impact on design?



Andersen (2015)

Ramboll's role

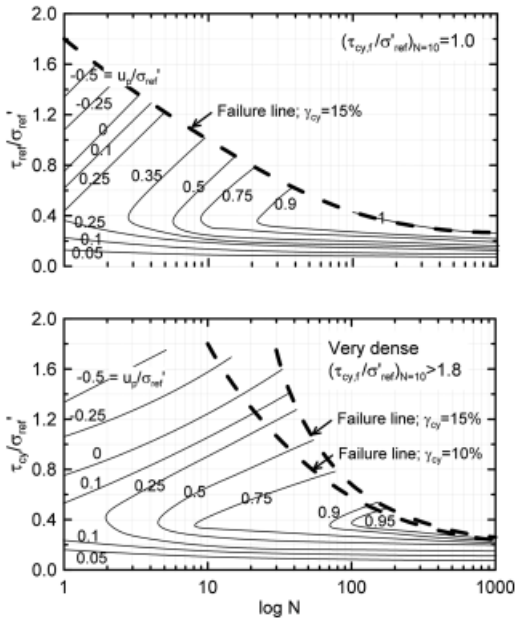
- Geotechnical Advisor
- Geotechnical Designer

Adapting testing strategy to reflect design methodology and needs

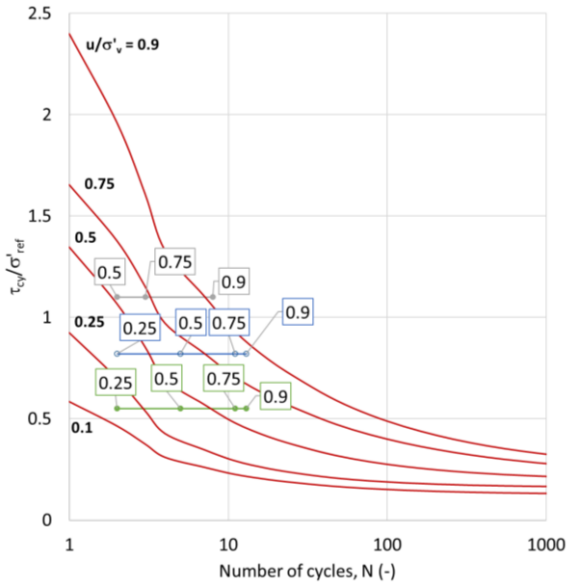
Challenges in building contour diagrams

Use of databases

- Literature (e.g. NGI)
- In-house contour data from nearby projects



Andersen, 2015



Kanitz et al., ISFOG 2025

When?

- Initial phases, no cyclic data available
- Planning lab testing conditions

After testing

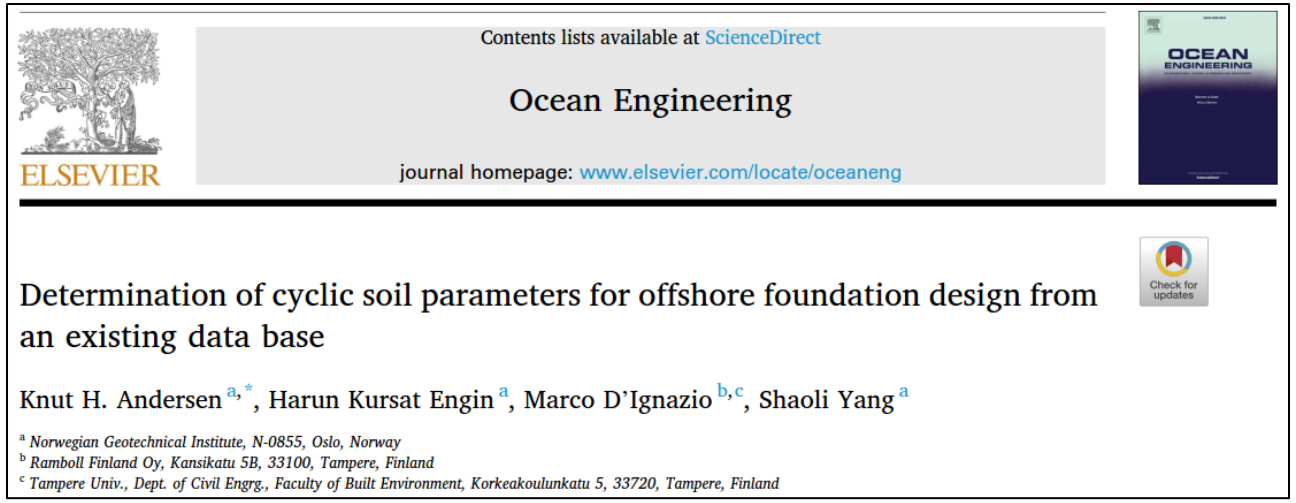
Drawing contour diagrams *Limited testing!*

- Fitting existing diagrams to test results
- Drawing project-specific diagrams

Scaling of existing contour diagrams – Ramboll's insights

Example: Large OWF project from US East Coast

- Contour diagrams pre-selected to design cyclic testing program (Method by *Andersen et al. 2023*)
- Comparing diagrams before and after testing (scaling)



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Determination of cyclic soil parameters for offshore foundation design from an existing data base

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[b] Ramboll Finland Oy, Kansikatu 5B, 33100, Tampere, Finland
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Contour selection from **NGI database** based on basic soil properties

- Non-cohesive units (D_r, w, FC, OCR, ϕ')
- Cohesive units (OCR, PI)

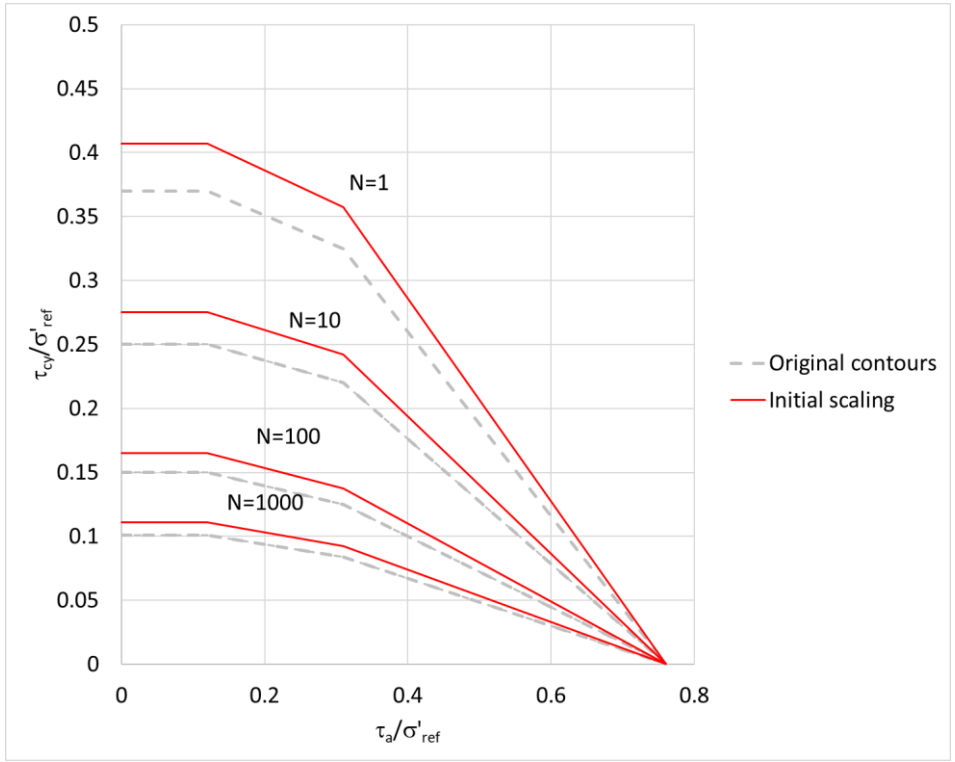
OCR effects in sand and silt

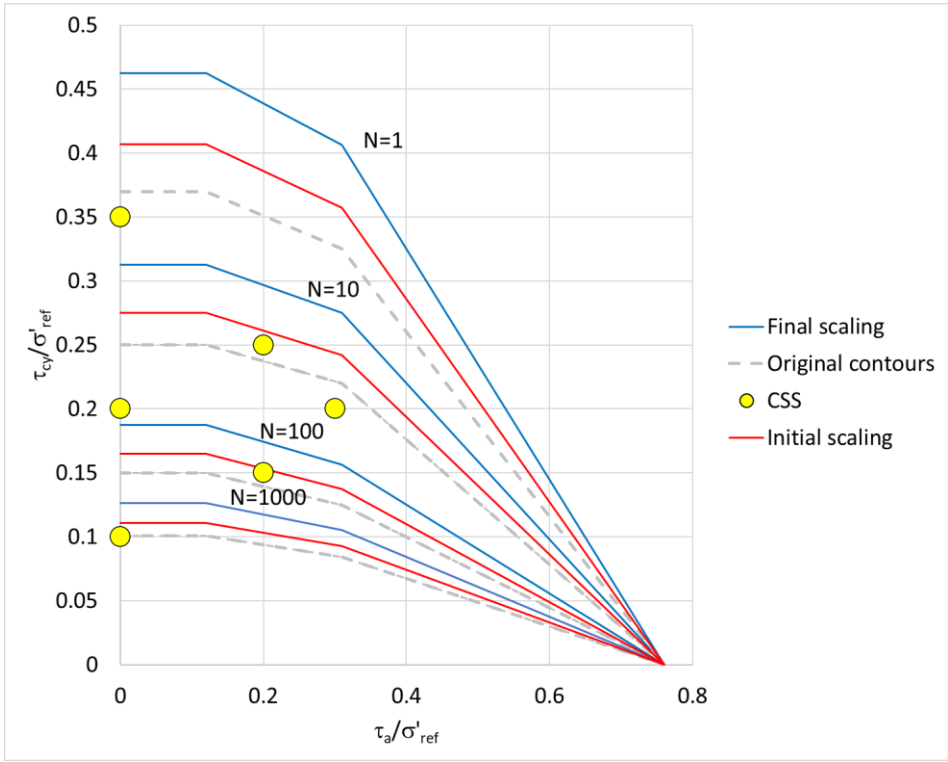
$$\left(\tau_f/\sigma'_{ref}\right)_{NC}/\left(\tau_f/\sigma'_{ref}\right)_{OC} = OCR^m$$

- *m* varying between 0 (very dense sands) and 0.8 (clays)

Scaling of existing contour diagrams – Ramboll's insights

- **Initial scaling** (soil properties / database) **vs final scaling** (CSS tests / n.6 tests per unit)
- Scaling of **y-axis** (τ_{cy}/σ'_{ref} or τ_{cy}/s_u)





Scaling of existing contour diagrams – Ramboll's insights

- Performance of Andersen et al. (2023) method:

Unit type	% diff. vs initial scaling (DSS, y-axis)
Non cohesive (n.8)	-24 / +11 **(avg -3%)**
Cohesive (n.6)	-32 / +12 **(avg -6%)**

- The method showed an overall bias factor of 95% and COV≈12% (n=14)
- Test data in line with database contours → scaled contours used in design

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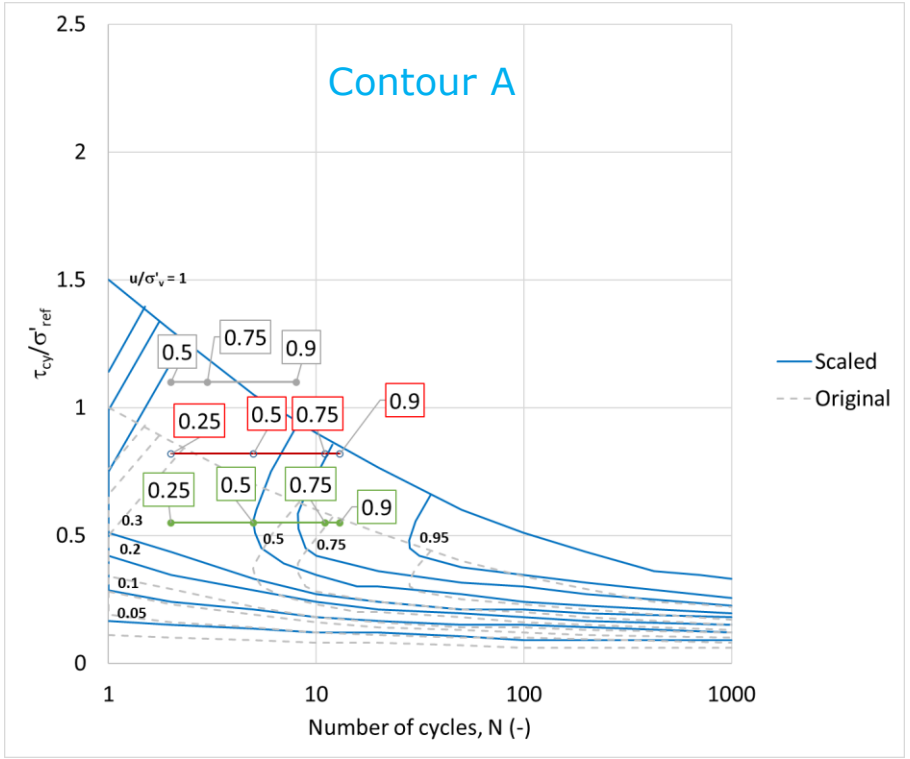
What impact on design when drawing contour diagrams from limited test data?

Scaling vs drawing diagrams from limited data

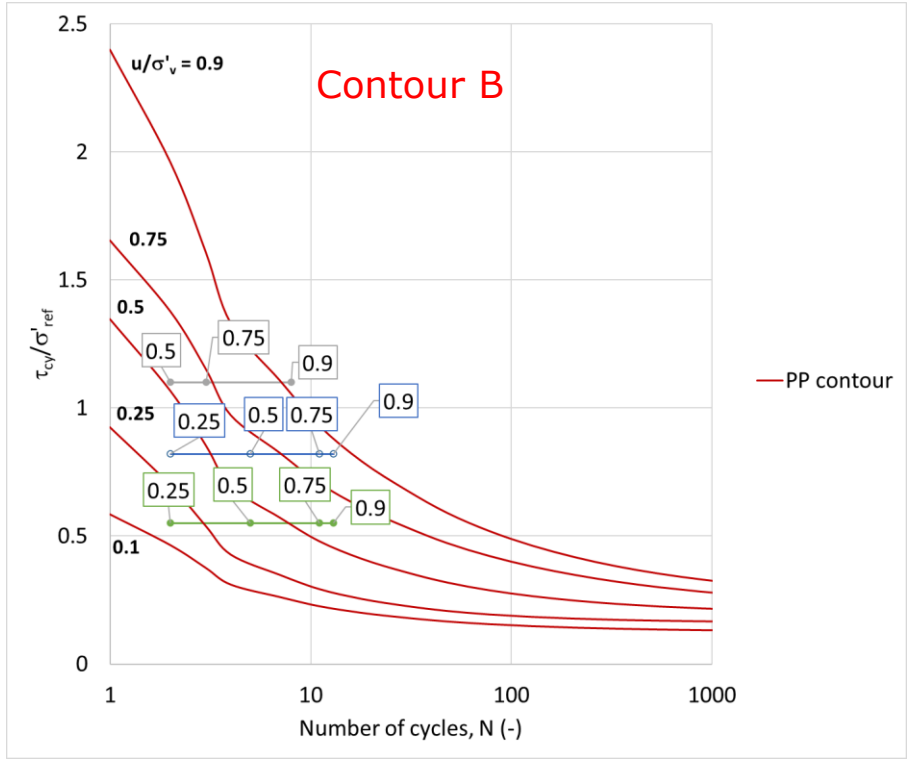
What impact on design when limited test data is available?

- Typically, 4-6 tests are carried out for each soil unit

Example: dense sand / *Kanitz et al. (ISFOG 2025)*



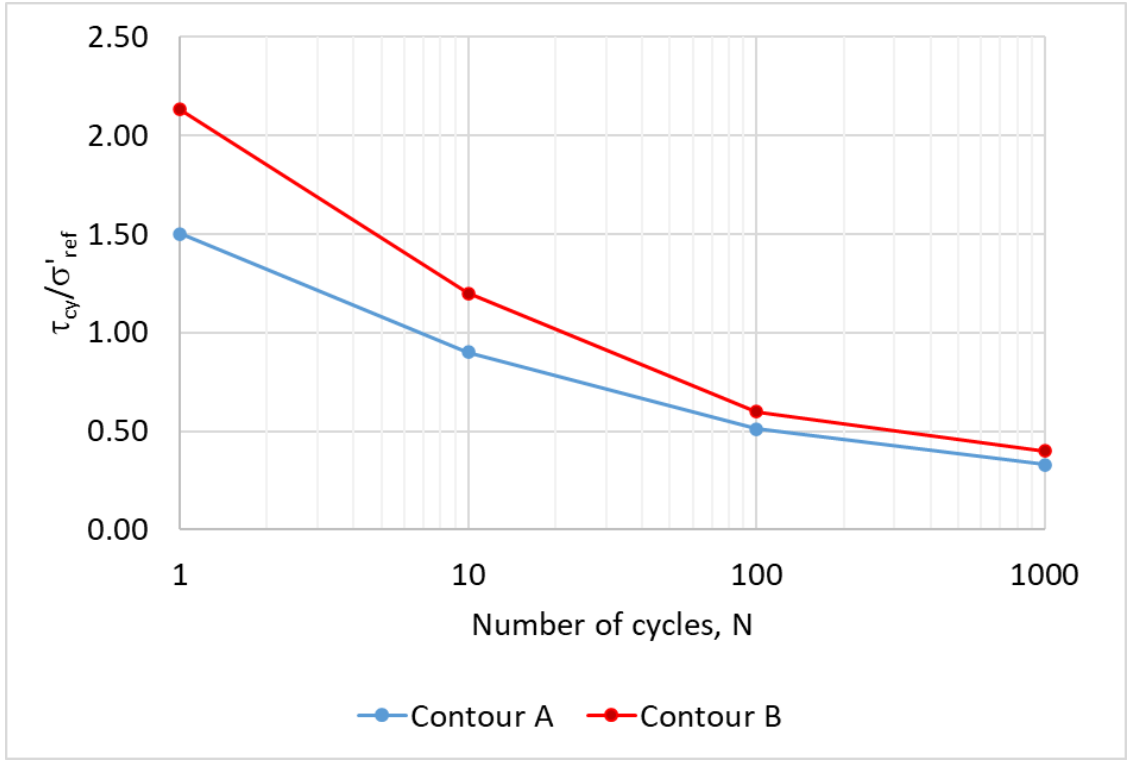
Scaled (Andersen, 2015)

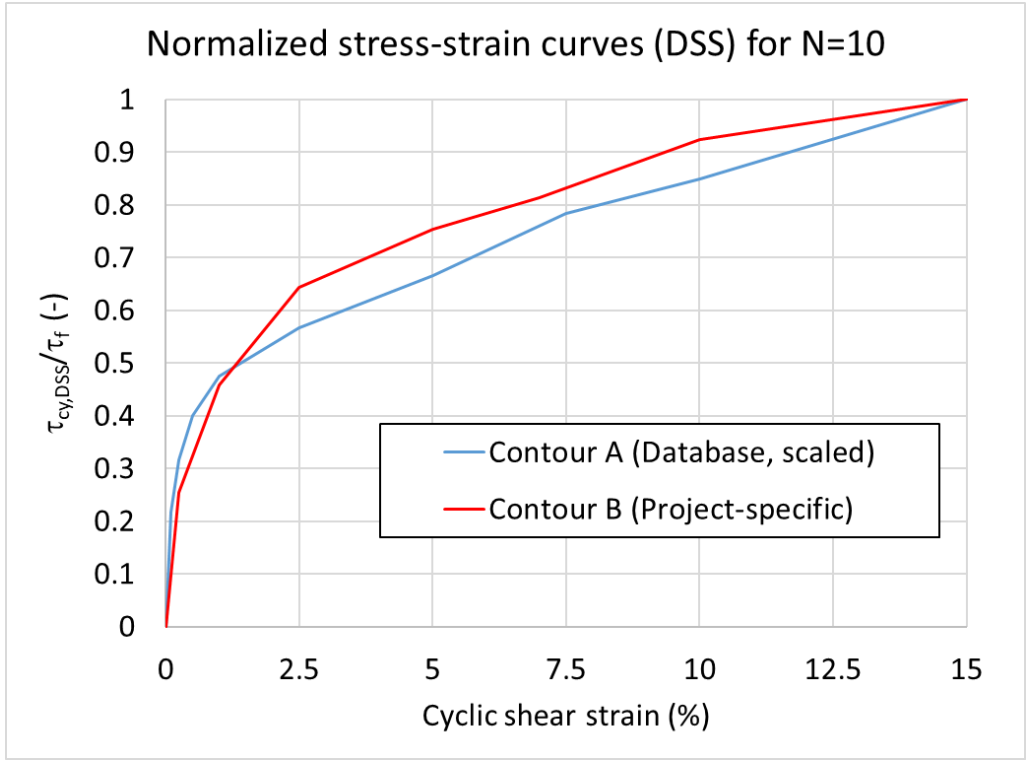


Project-specific (drawn)

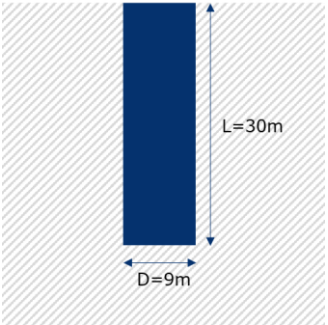
Scaling vs drawing diagrams from limited data

Impact of contours on cyclic shear strength and stress-strain behaviour



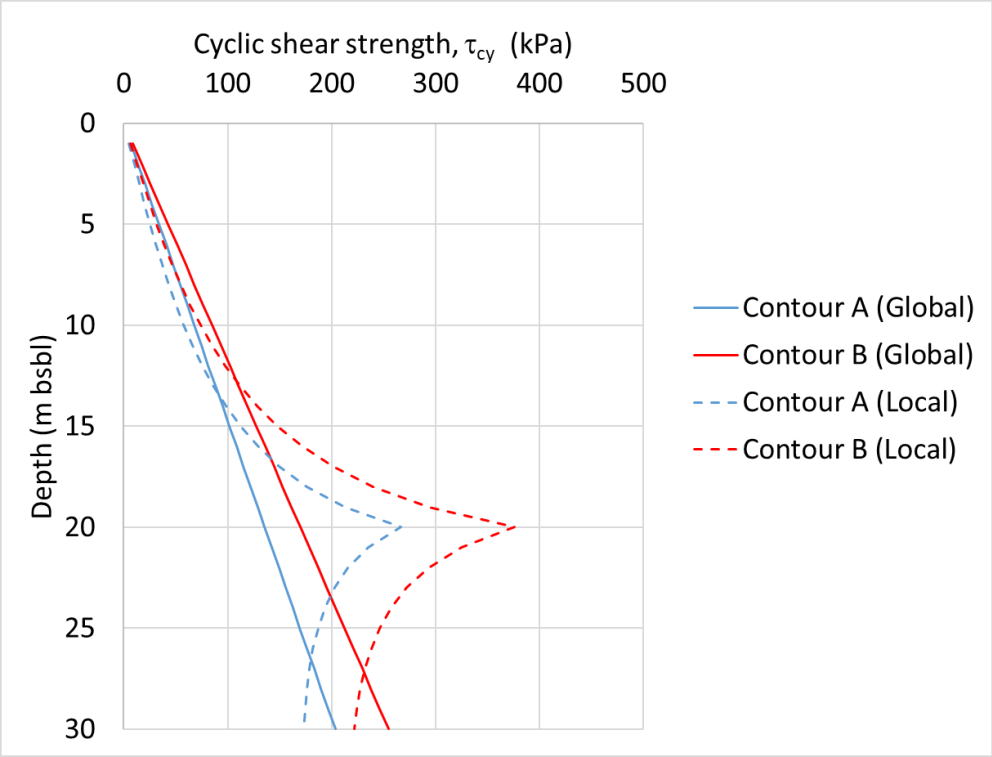


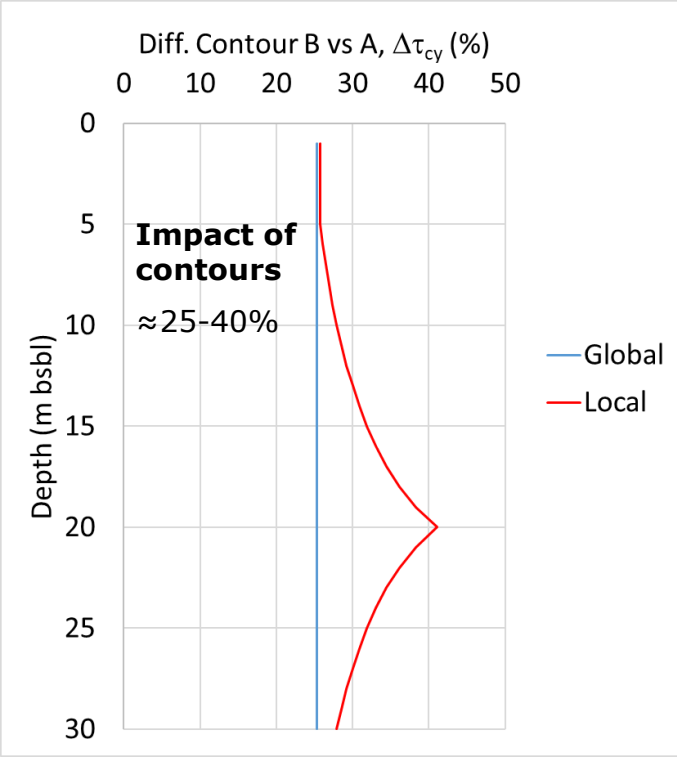
Scaling vs drawing diagrams from limited data

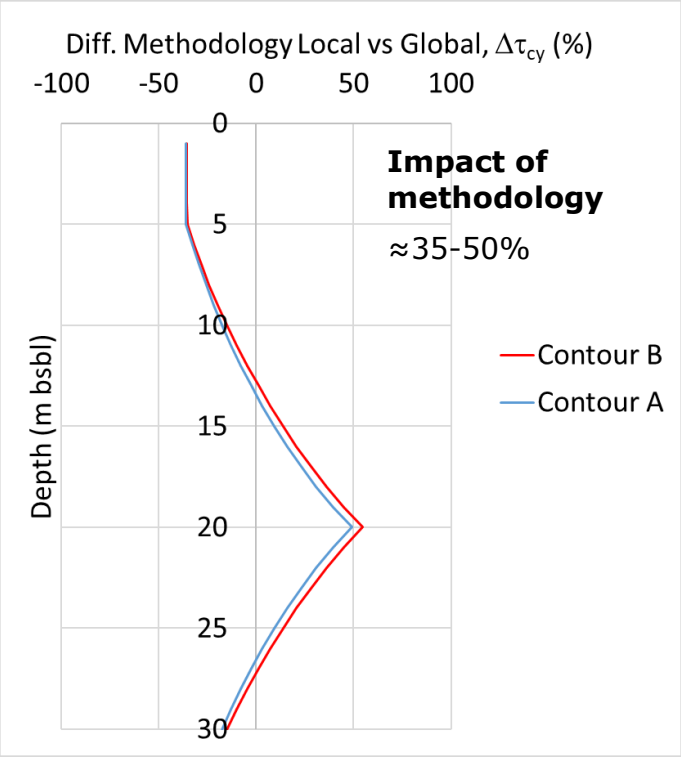


Impact of contours + cyclic methodology (homogeneous sand, D=9m, L=30m)

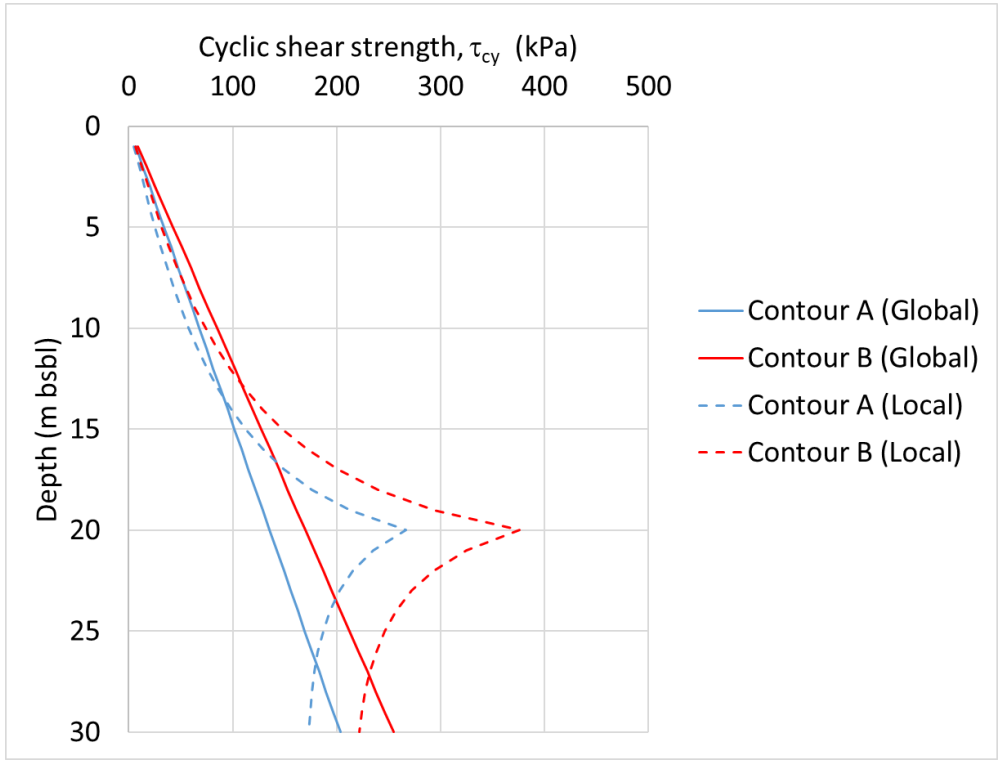
- *Method 1*: N_{eq} based on global load history (Global)
- *Method 2*: N_{eq} based on load redistribution (Local)

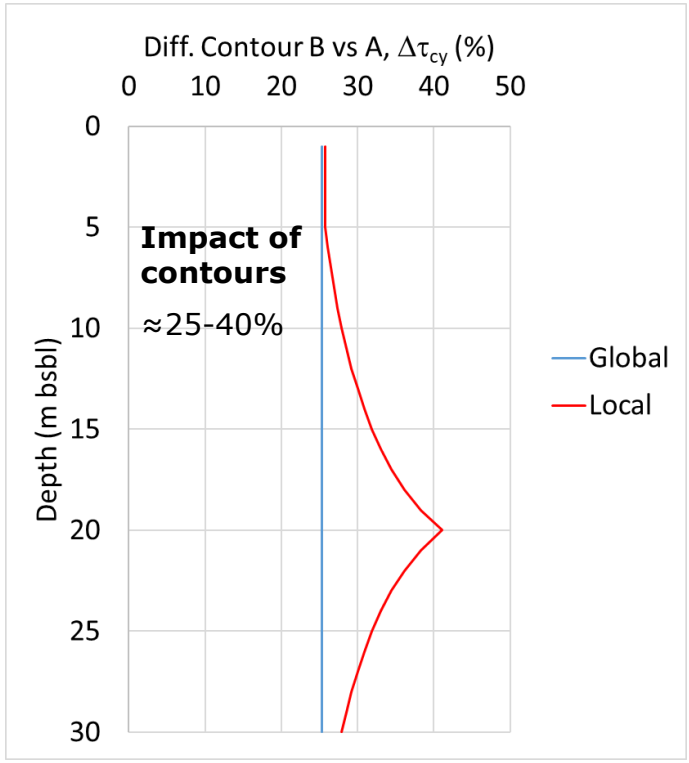


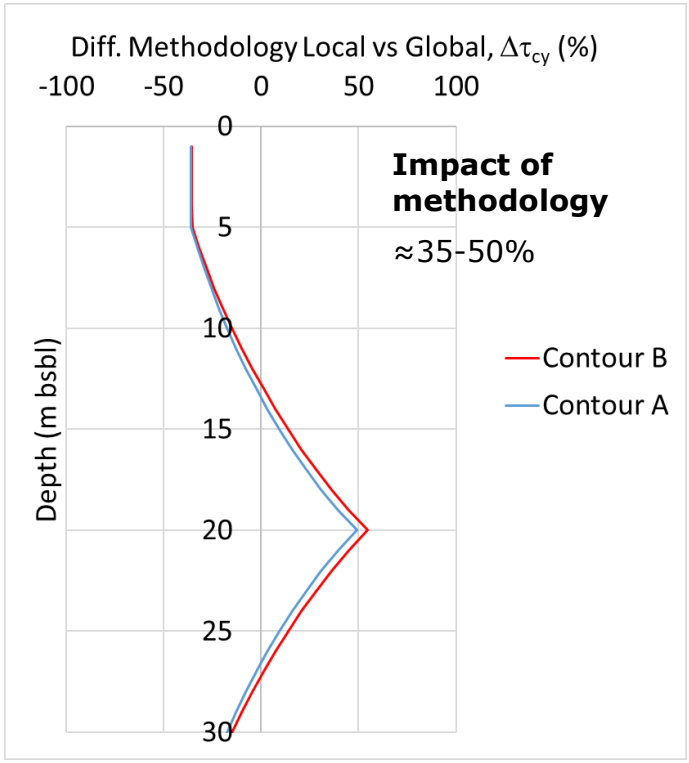




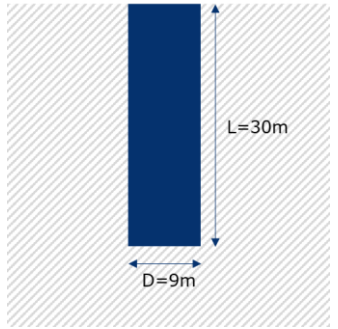
- **Methodology comparison:** Full profile degradation based on global load history might be too simplistic
- If we compared all the different methodologies accounting for load redistribution, we would likely end up with less than a 30% difference
- More significant impact of contour diagrams



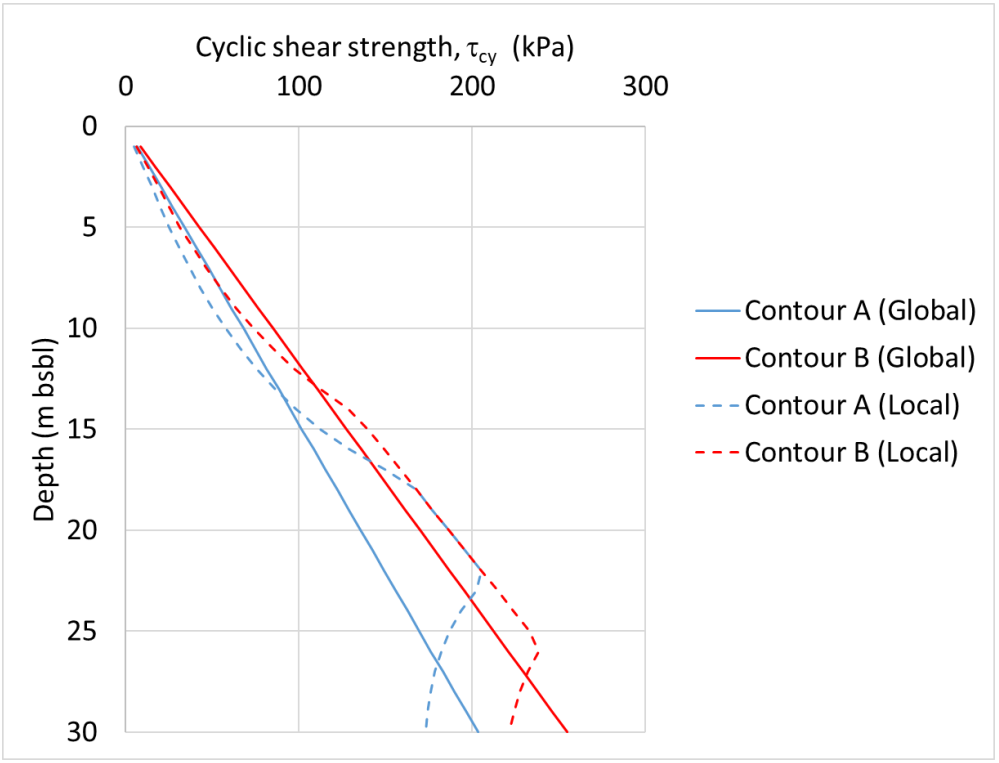


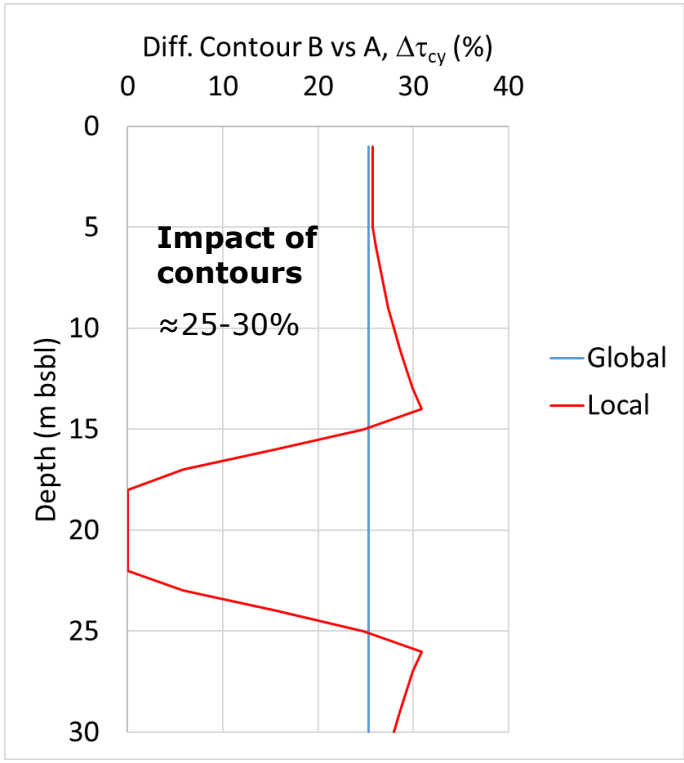


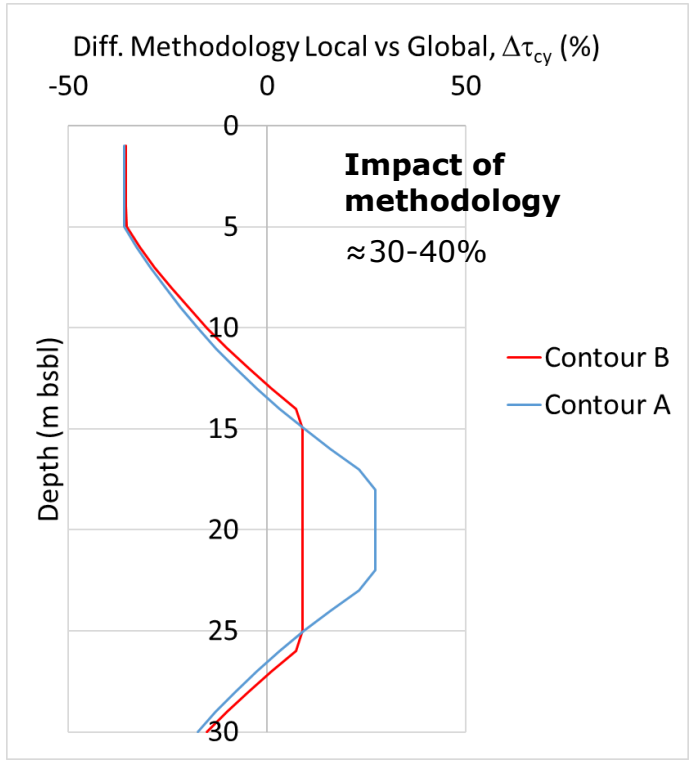
Scaling vs drawing diagrams from limited data
Alternative design scenario



- Shear strength cut-off at monotonic strength
- Design conservativism







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Reflection

Impact on monopile design:

- Project-specific vs databases when limited test data is available
- Contours may have a larger impact than a refined methodology!

Uncertainty in cyclic soil properties (*beyond cyclic methodology*)

- How cautious should we be when assessing cyclic properties?

Development at Ramboll

Development

Ideas for collaborations? Please reach out ☺

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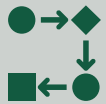
Cyclic contour drawing tool

Partial drainage accumulation tool – accounting for drainage towards seabed/coarse layers



In-house monopile design tool (PISA+cyclic)

Refining cyclic methodology (general formulation / validation of N vs UR curves)

Bright
ideas.
Sustainable
change.

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References

Andersen, K.H., (2015). Cyclic soil parameters for offshore foundation design. 3rd ISSMGE McClelland Lecture. In: *Frontiers in Offshore Geotechnics III, ISFOG'2015*, Meyer. Taylor & Francis Group, London, 978-1-138-02848-7. Proc., 5-82.

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