Advanced structural and geotechnical analyses for offshore monopile design: a case study



Round Table Format

- Case study to be presented on design of Monopile foundation;
- Specific planned stop points for round table discussions;
- Round table image presented on slides where discussions to be held;
- Please get involved!

Round table image presented on slides where discussions to be held

Contents

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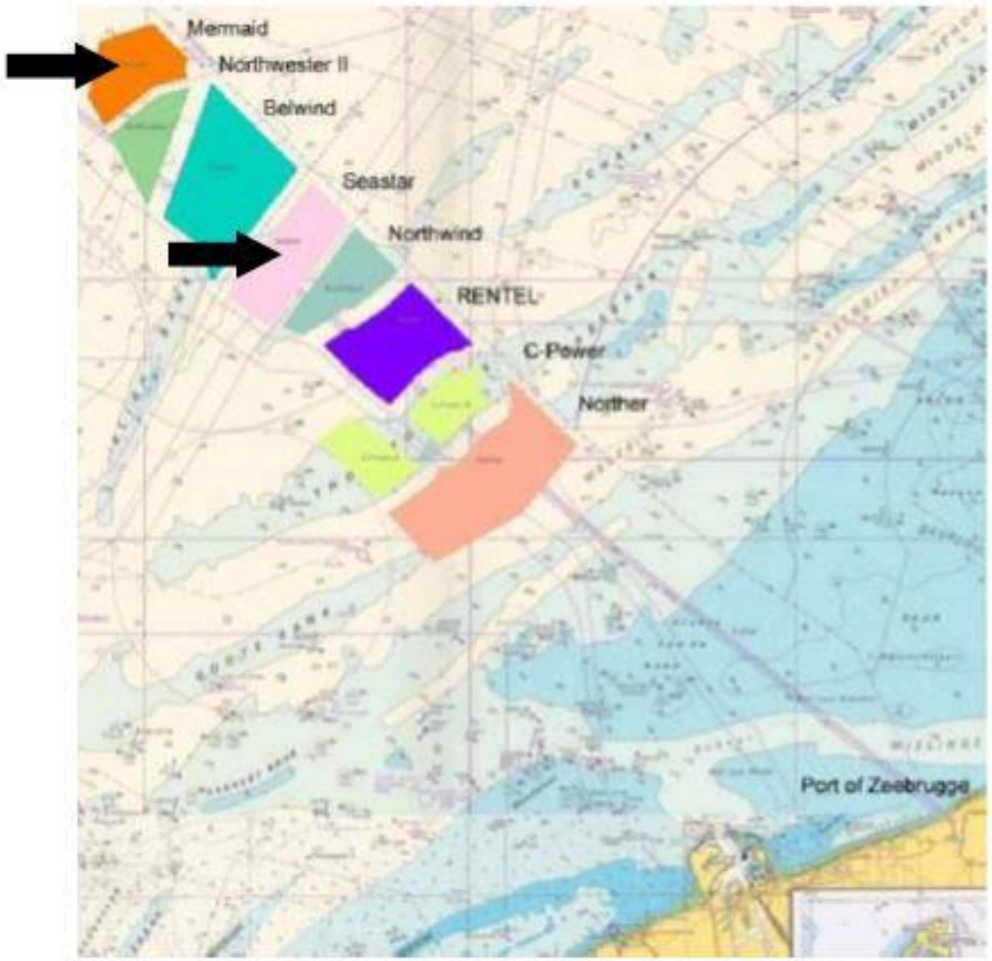
1. Introduction and Project Background

Project Background

Project Information	
Project Name	seamade
Project Type	Offshore Wind Farm 235 MW and 252 MW
Scope of Work	Offshore High Voltage Substation Support Structures
Owner	otary OFFSHORE ENERGY
Offshore Contactor	GeoSea Geotechnical & Offshore Solutions
Fabrication Contractor	EIFFAGE SMULDERS
HV Electrical Contractor	engie



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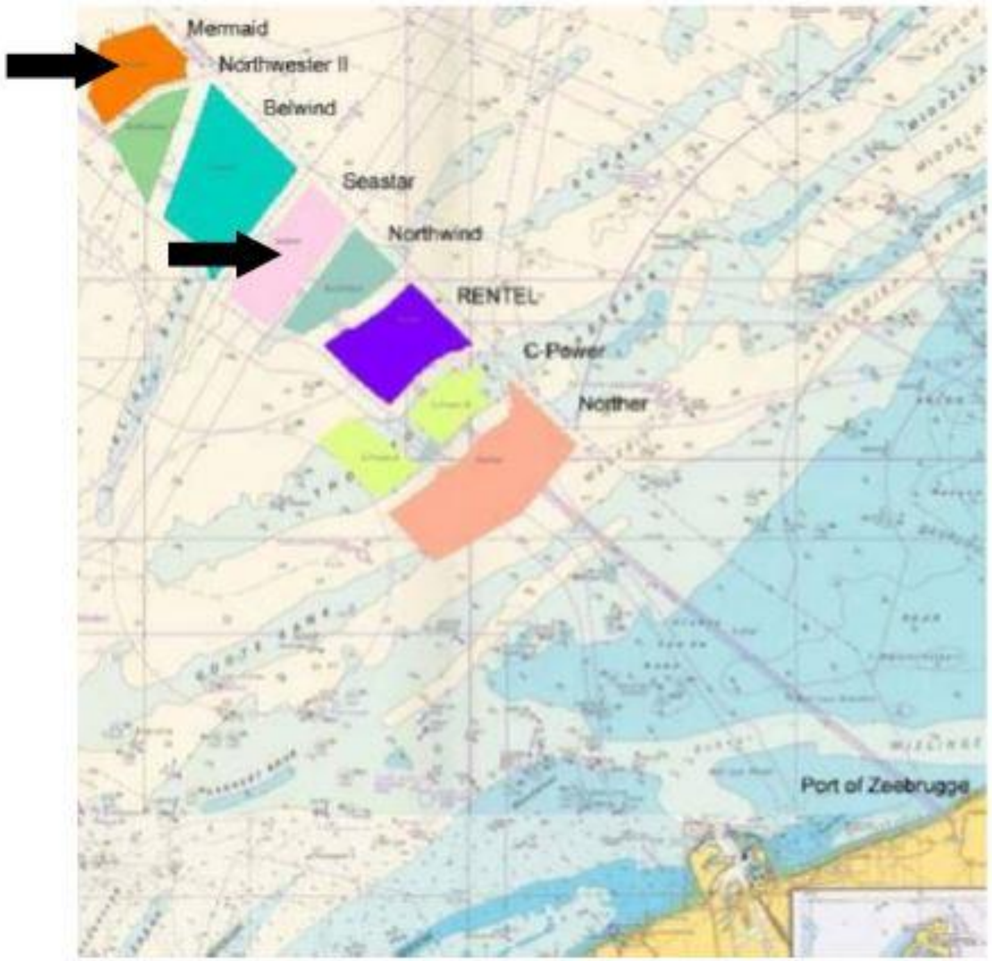
Site Conditions

Metocean Information	
Water depth	35m
Max. wave height	12.5m
Wind speed	c. 35 m/s
Current velocity	1.1 m/s

Soil Information	
0 – 4 m bsf	Medium dense SAND
4 – 28 m bsf	High strength CLAY
28 – 35 m bsf	Medium dense SAND
35 – 45 m bsf	High strength CLAY
45 – 65 m bsf	Medium dense SAND



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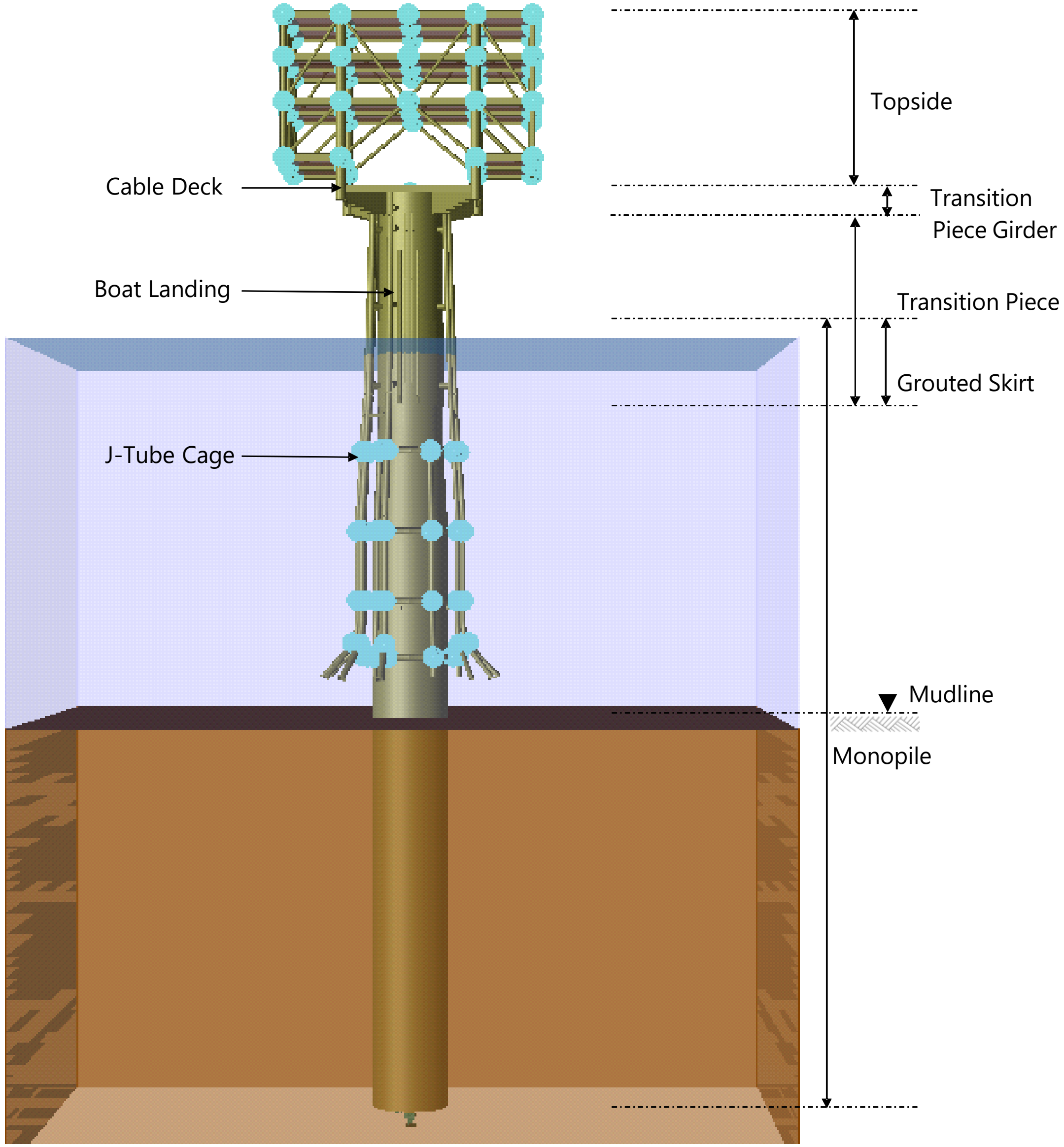
Project Background



Structural Concept	
Topside Weight	1150t
Support Structure	7.5m Diameter Monopile – Transition Piece
MP-TP Connection	Bolted Flange (grouted skirt)
Cable Deck	Integrated
J-tubes	External cage mounted on MP
Boat Landings	2 boat landings + access infrastructure
Installation Method	Direct drive on-flange
Piling Hammer	IHC S-4000

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2. Overview of Support Structure Design Approach

Overview of Support Structure Design Approach

Global Structure - Limit State Verification

Ultimate and Accidental Limit State

- Dynamic excitation
- Non-linear pile interaction
- Buckling phenomenon
- Directional hydrodynamics
- Large deflection (P-Δ)
- Ringing interaction (hydrodynamic)

SOFTWARE SESAM GeniE DNV·GL

PLAXIS

ANSYS

Fatigue and Serviceability Limit State

- Diffraction
- Directional hydrodynamics
- Bi-modal swell seas
- Significant driving fatigue
- Acceleration / motion limits

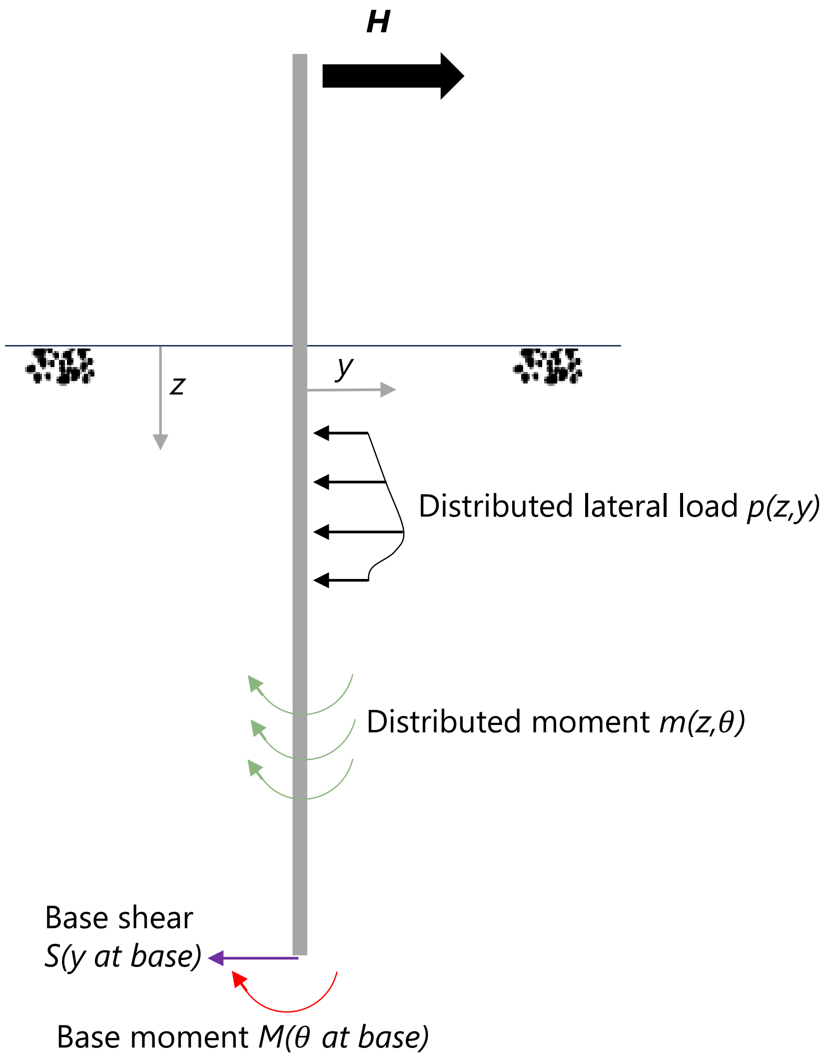
3. Overview of Geotechnical Approach

Overview of Geotechnical Approach

- Over last 5 to 10 years significant research shown that using design methods typically employed for slender piles of jacket structures not appropriate (e.g. using only p-y curves in 1D model)

- New methods recently proposed include additional soil reaction curves in 1D model (PISA Method)

- This presentation presents real application of PISA approach to monopile design project



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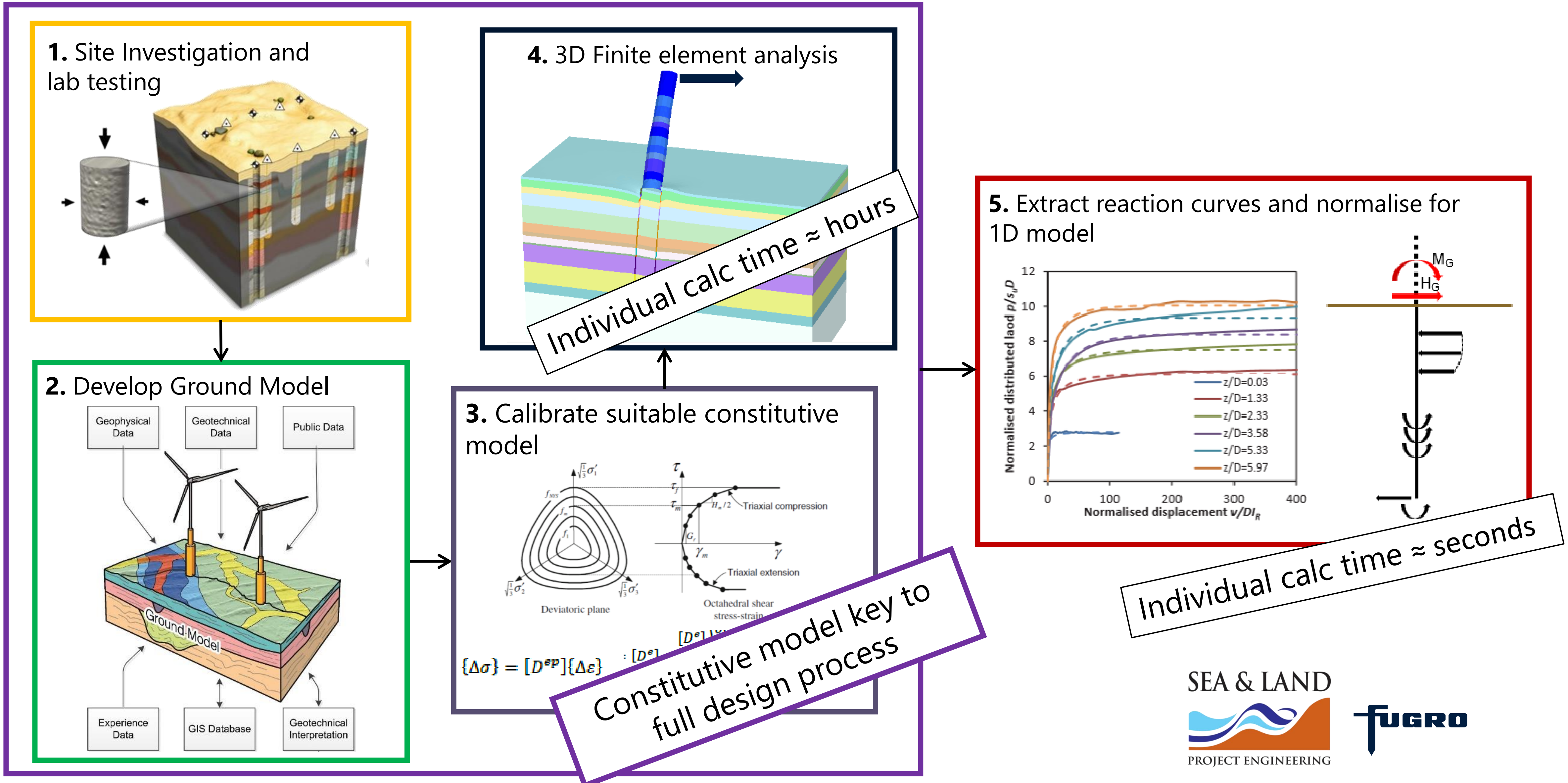
Overview of Geotechnical Approach

Improved Monopile Design Process



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4. 3D FEA and Constitutive Model

Constitutive Model

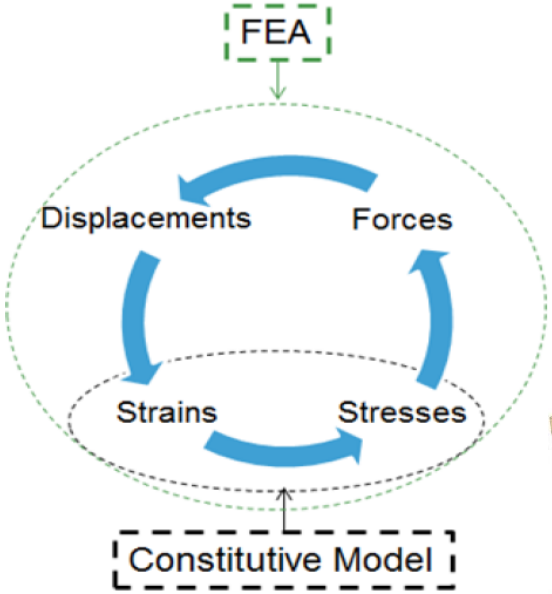
What is a constitutive soil model?

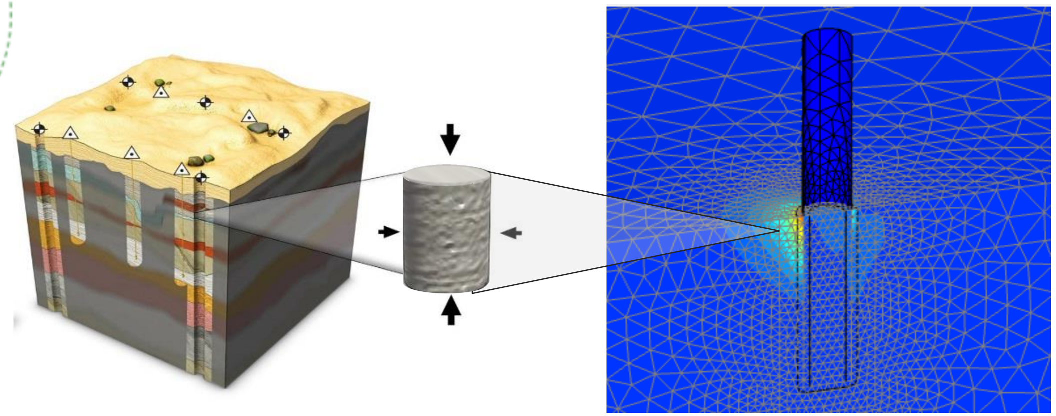
- The constitutive soil model is a mathematical representation of the mechanical behaviour of the soil and is fundamental part of FEA of a geotechnical problem.

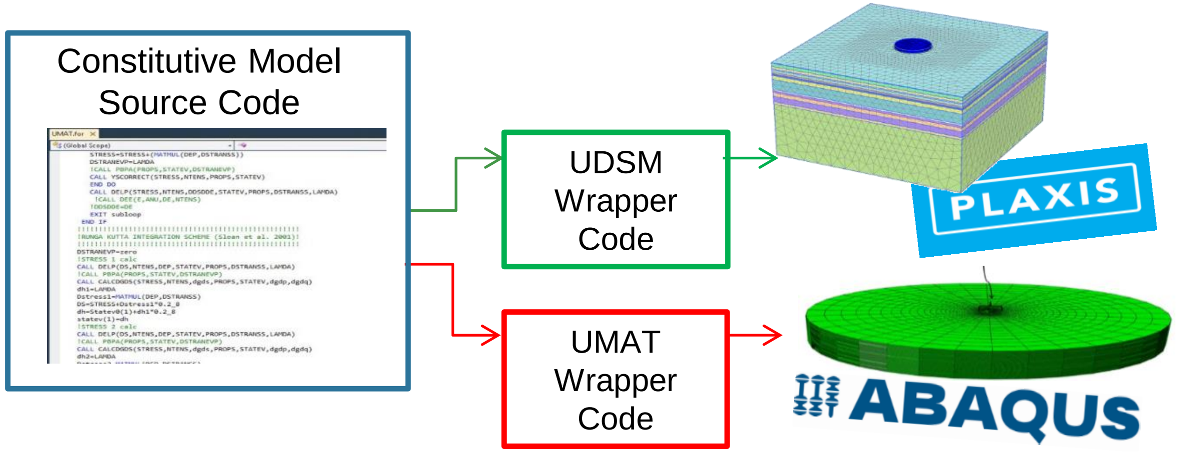
Is it important?

- <u>**Yes**</u>... it controls the response of the FEA prediction!

Often Important to implement bespoke soil models to capture the soil response. Library of bespoke models for different soil types needed.







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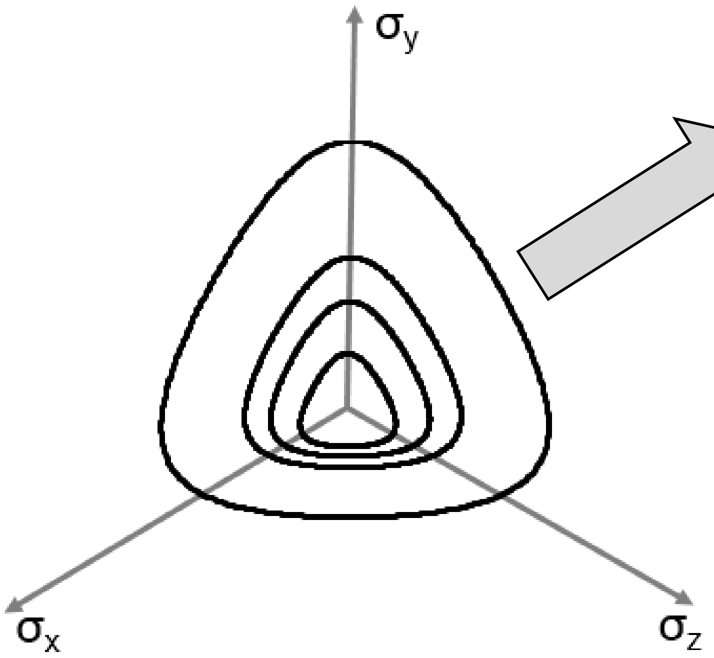
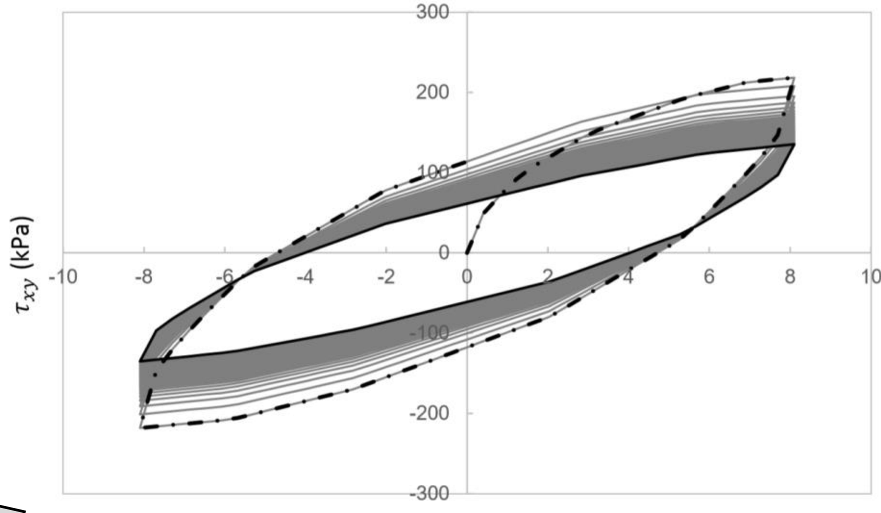
Fugro PIMS Model

- Most existing constitutive models not practical for performing 3D FEA under cyclic loading
- Parallel Iwan Multi-Surface (PIMS) model developed
- Multi-surface models historically not used due to computational cost
- New practical model termed the Parallel Iwan Multi-Surface (PIMS) model developed and implemented in 3D FEA (Plaxis & Abaqus) for design FEA

Multi Surface Anisotropic Model





Captures site specific cyclic degradation

Reference: Whyte S, Burd H, Martin C, Rattley M. 2019. *A practical total stress multi-surface cyclic degradation plasticity model*. Computers and Geotechnics Journal (Accepted)

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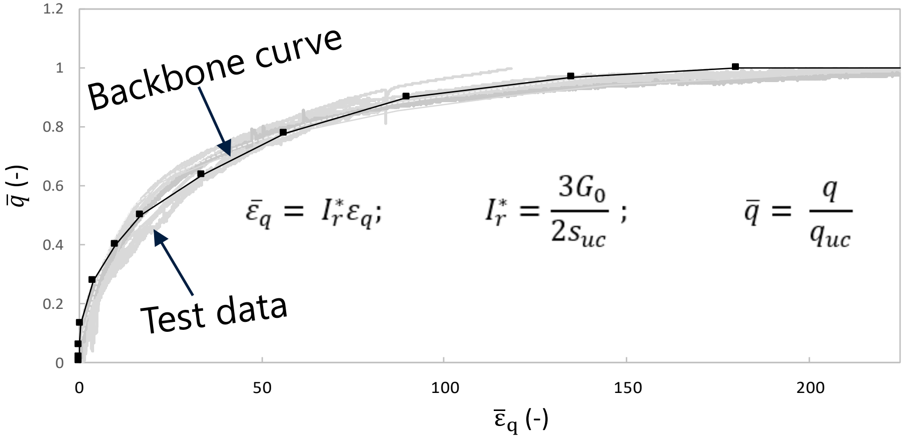
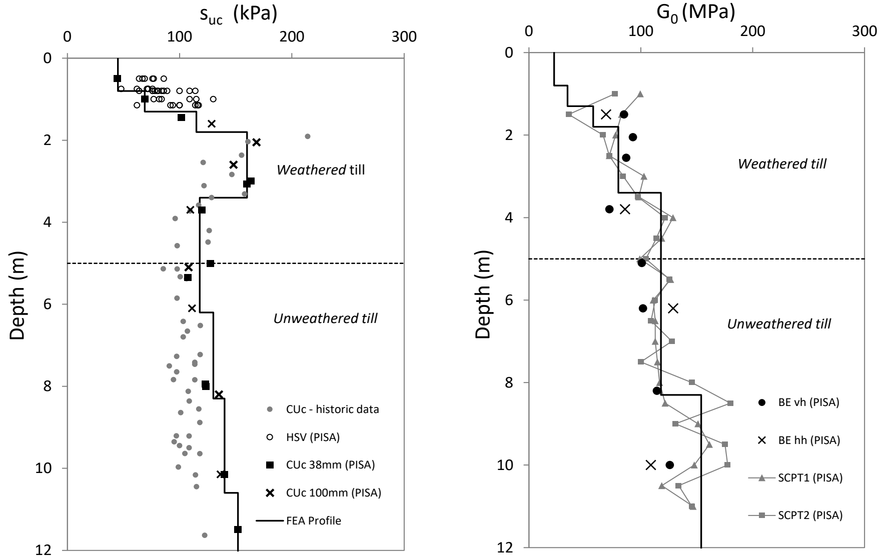
Fugro PIMS Model Calibration

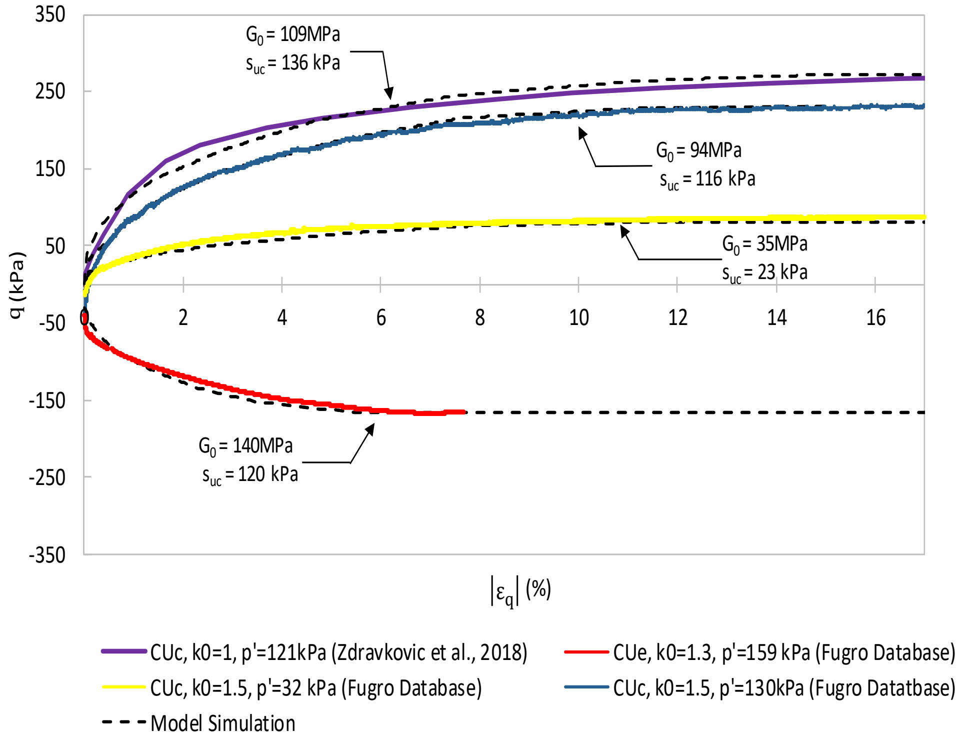
1. Calibrate to Normalised Triaxial extension and compression test data

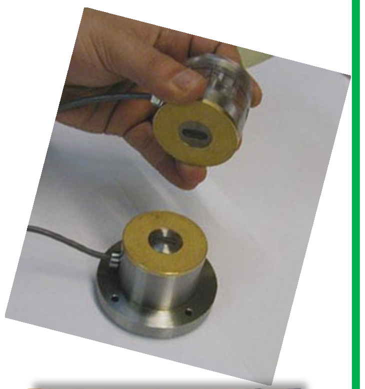


2. Determine local design profiles



3. Review of model performance to individual laboratory tests





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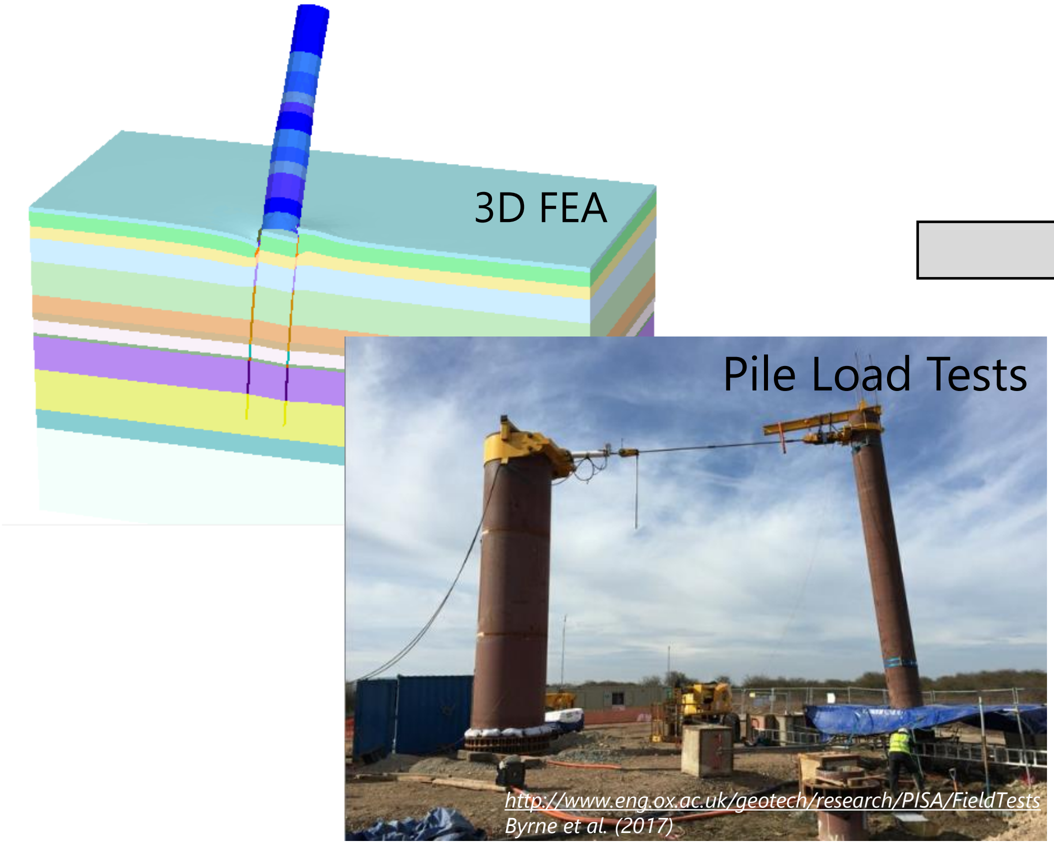
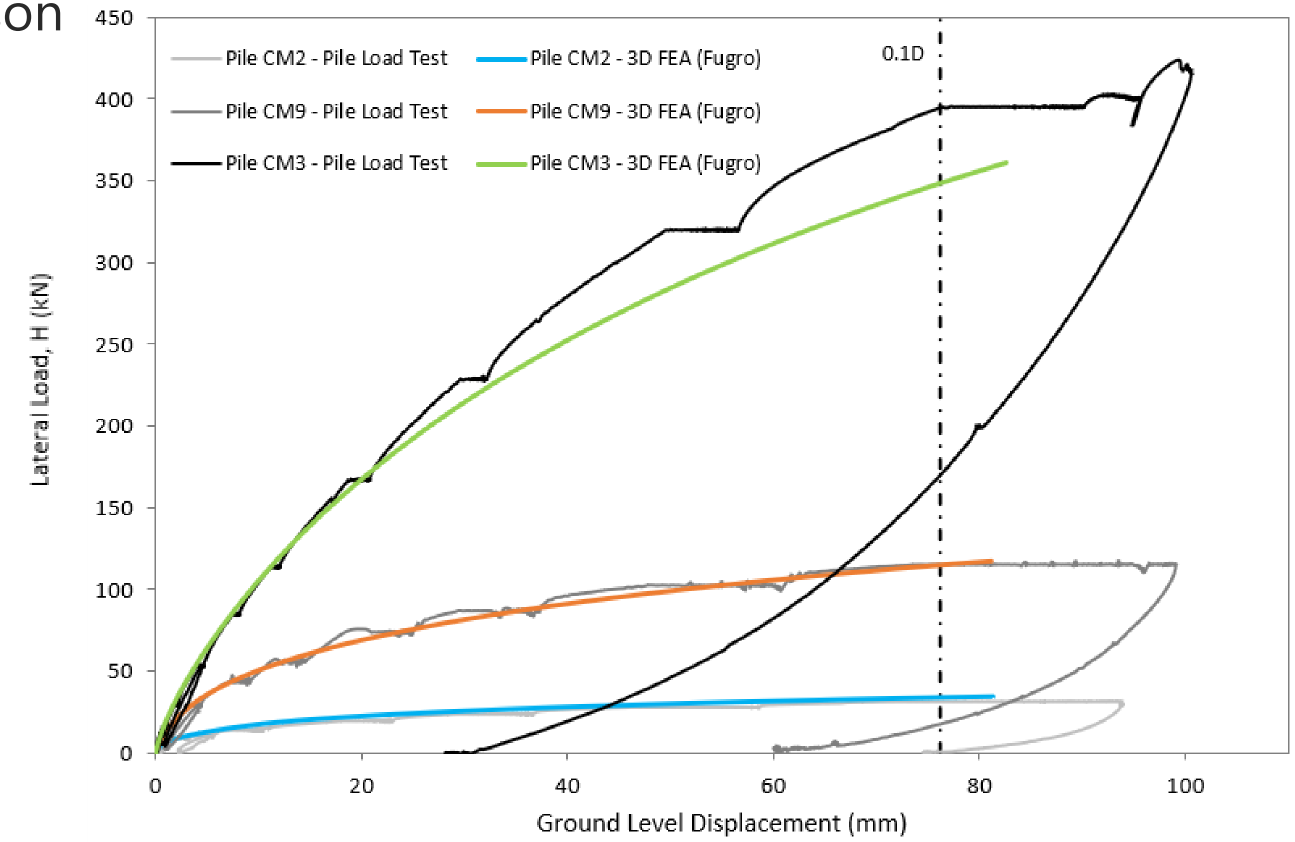
Fugro PIMS Model Performance

Why go to this trouble?

- **Constitutive soil model** used within FEA VERY important, particularly for complex soil types outside of standard practice!
- Fugro PIMS model shows good comparison to field test data.





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Constitutive Models

- How important is the constitutive model?
- What models are being used for different soil types etc.?
- Analysis run time issues with complex models?
- Issue of models becoming black box tools making certification difficult?
- Difficulty of parameterisation of models for large wind farms?

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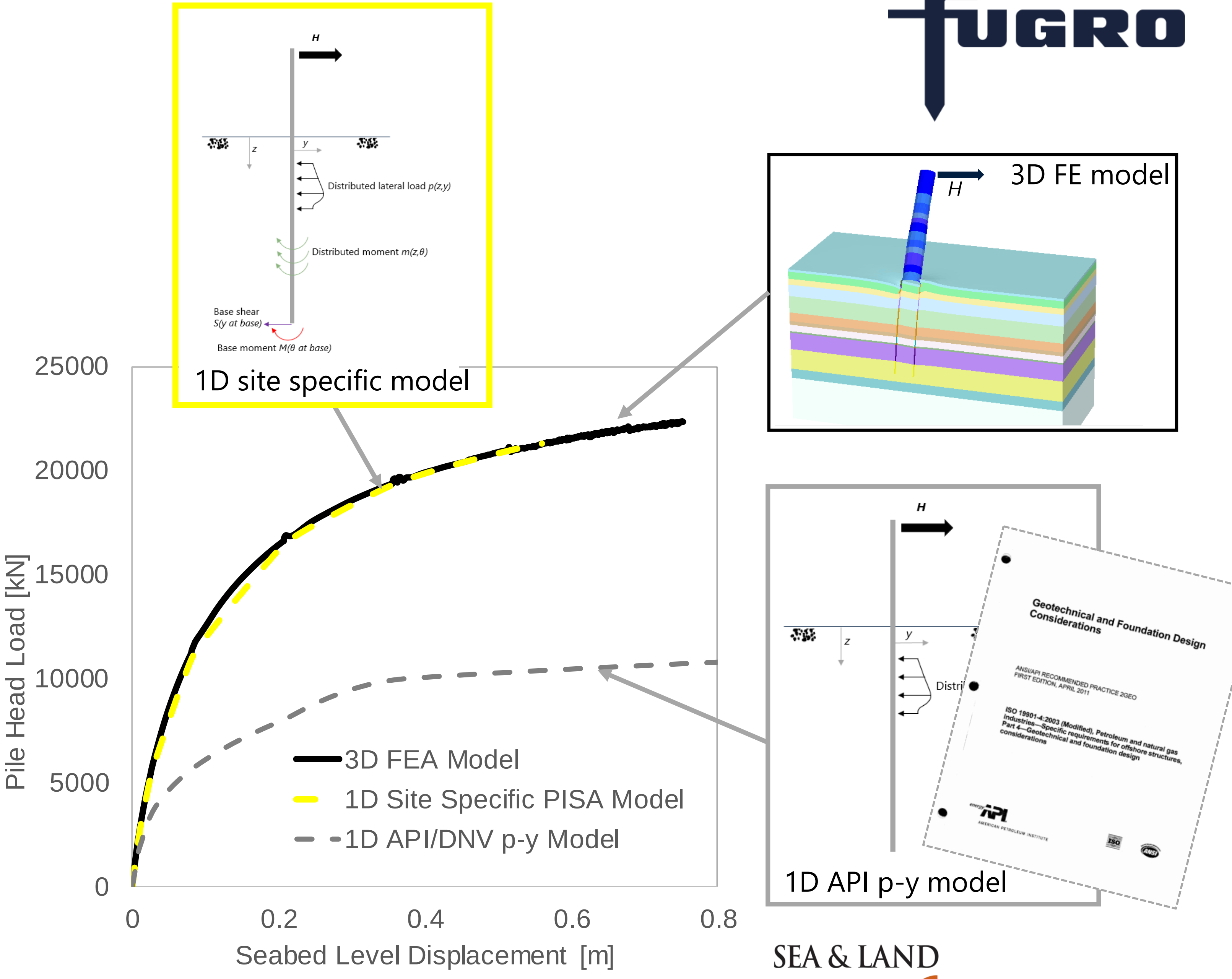
5. Geotechnical Analysis and Soil Reaction Curve Development

Seastar Monopile FEA – Monotonic

- Calibration 3D FEA runs performed to develop site specific reaction curves
- 8 hour run time per 3D FEA calibration model
- 1D model shows very good comparison to 3D FEA model
- API p-y approach shown to be highly conservative at Seastar site



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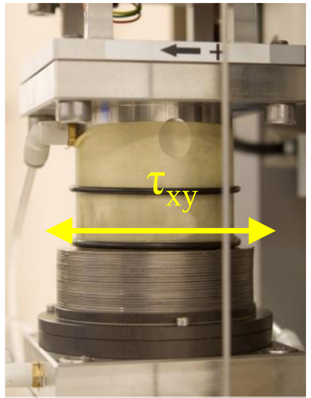
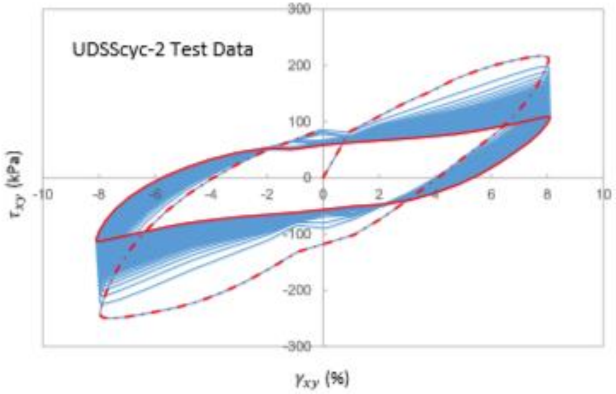
Seastar Monopile FEA – Cyclic

1) Calibration to laboratory testing of soils

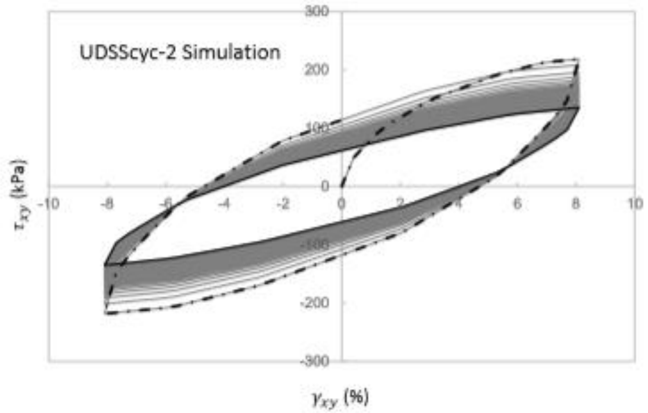


Cyclic Simple Shear

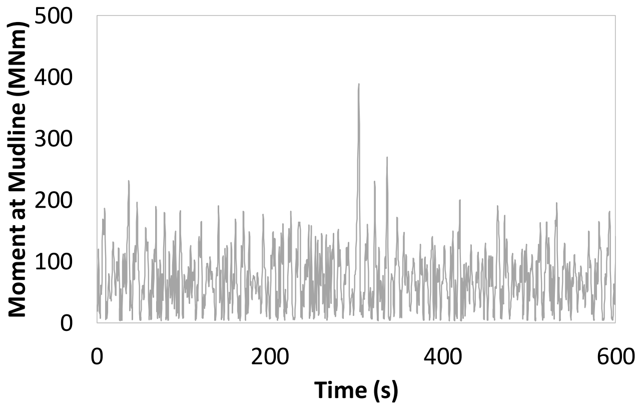
Laboratory data



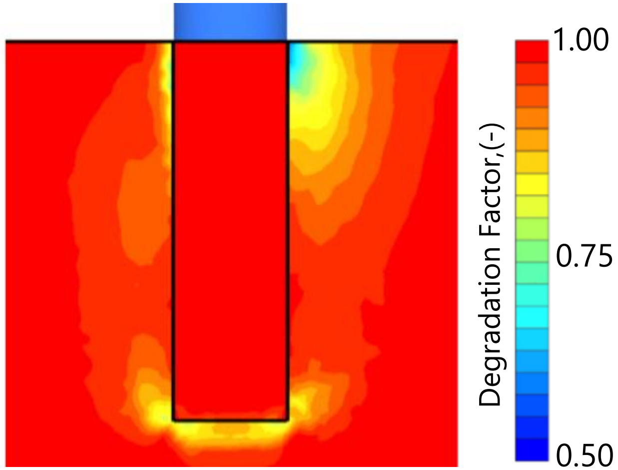
PIMS model simulation

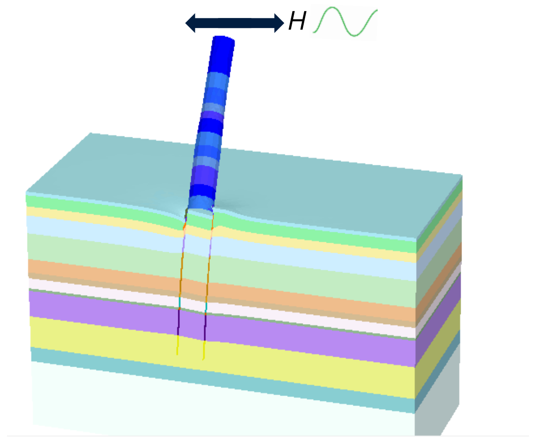


2) Site specific load time history

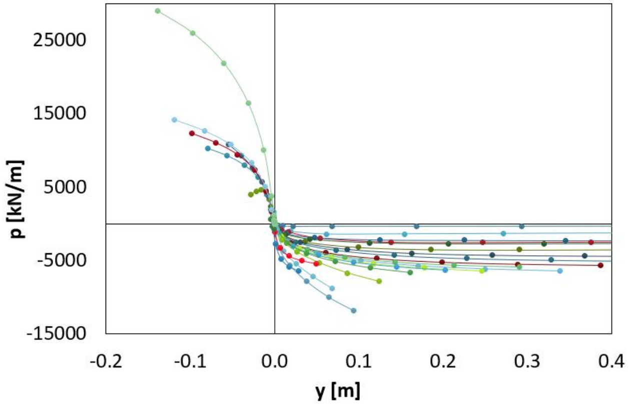


3) 3D FEA applying site specific storm





4) Extract cyclic degraded reactions curves for 1D model



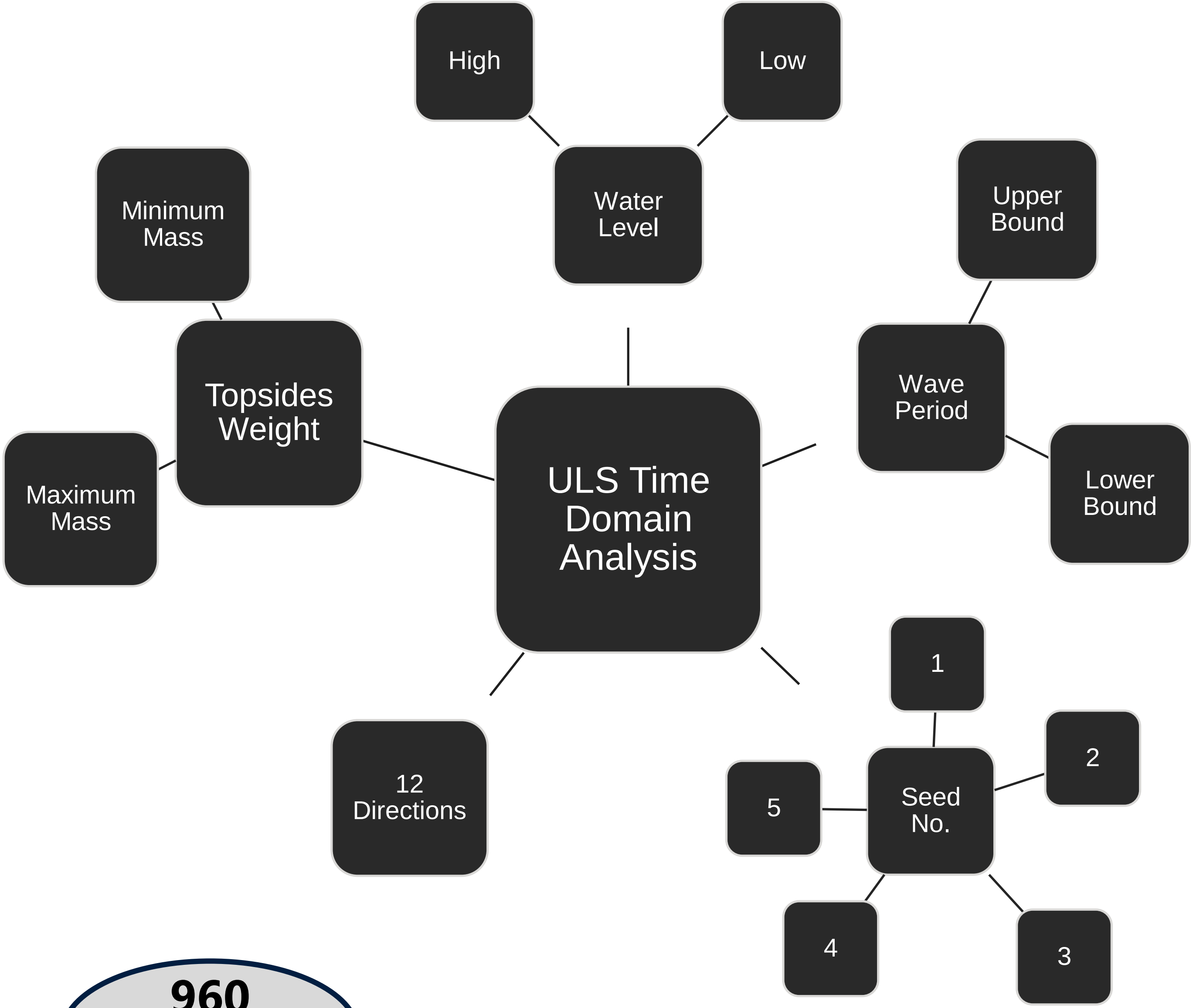
Monopile Design Methods

- Experiences of using numerically derived reaction curves for design?
- Experience of using PISA method?
- Challenges using such approaches?
- Considering layered soils?
- How to considering cyclic loading?

6. Structural Design Overview

ULS Structural Analysis

- Iterative pile linearization method (95th percentile)
- Iterative P-Δ loading
- Linear buckling
- Diffraction (MacCamy – Fuchs)
- High-order non-linear wave
- 5,800,000 code checks



960 simulations

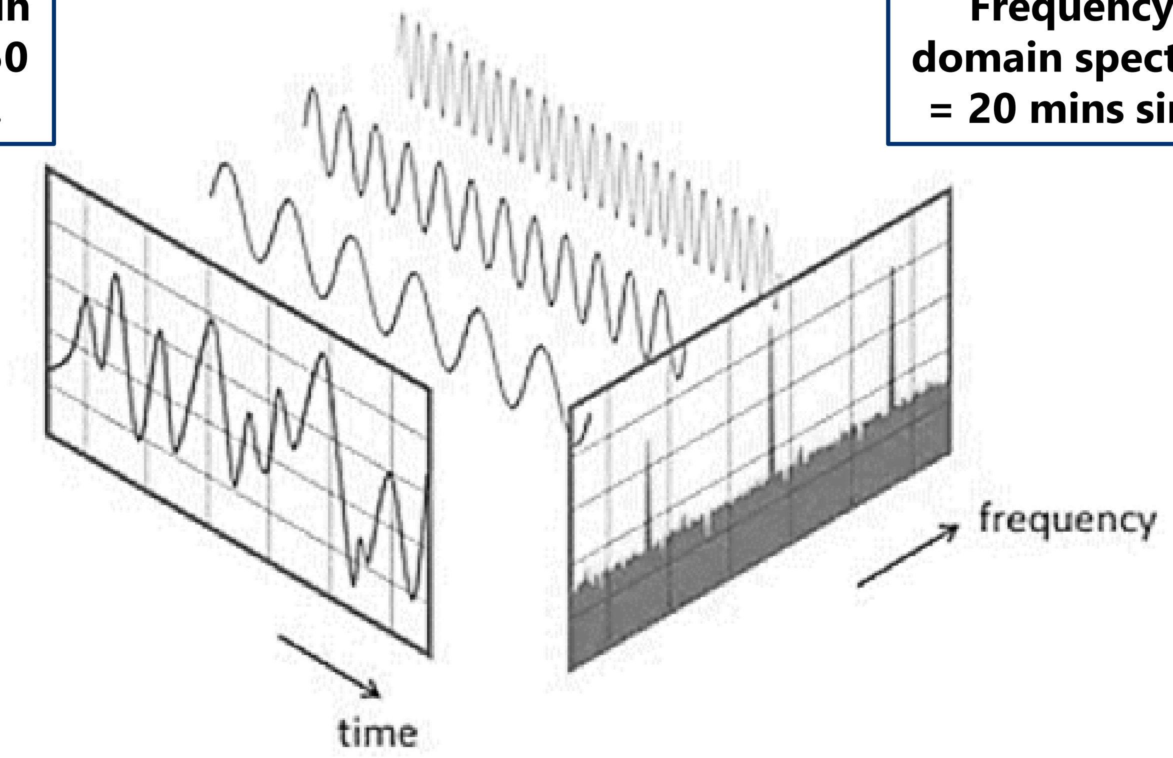
FLS Structural Analysis

- Multiple options available for OHVS Structures
- Varying level of complexity and run time
- Limited control over detailed inputs in commercial software
- **Which method to use and why?**

Time Domain vs Frequency Domain Analysis

Time domain analysis = 50 hours sim.

Frequency domain spectral = 20 mins sim.



Time domain spectral = 2 hours

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FLS Structural Analysis

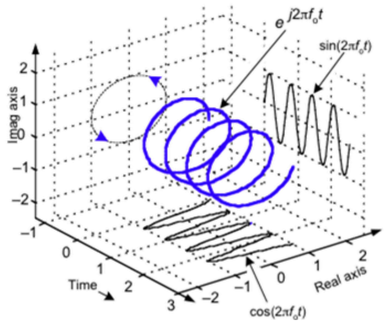
Basic Approach

vs

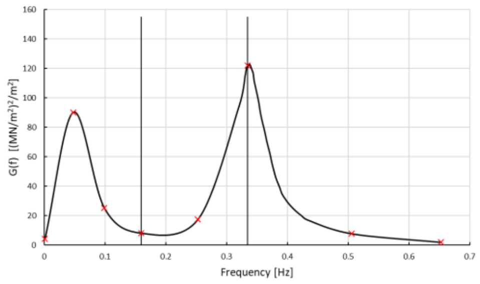
Advanced Approach

- Constant hydrodynamic coefficients vs. directional and frequency dependent.
- Constant stretching vs Wheeler stretching of wave kinematics
- MacCamy-Fuchs Diffraction (w. phase lag)

Frequency Domain Spectral Analysis

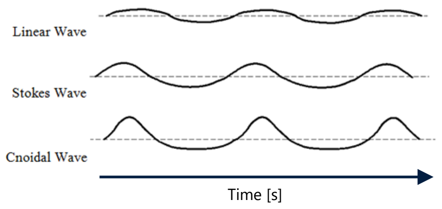


Frequency domain dynamic analysis – direct steady state solution

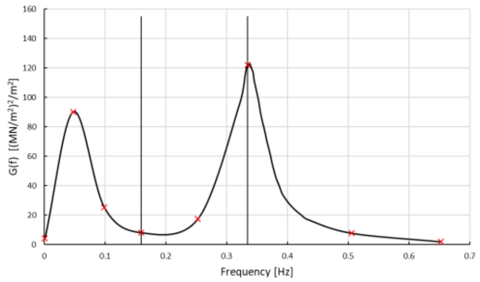


Complex harmonic regular waves → SOLVE → Stress transfer function

Time Domain Spectral Analysis



Time domain dynamic analysis – direct time integration solution



Deterministic regular waves → SOLVE → Stress transfer function

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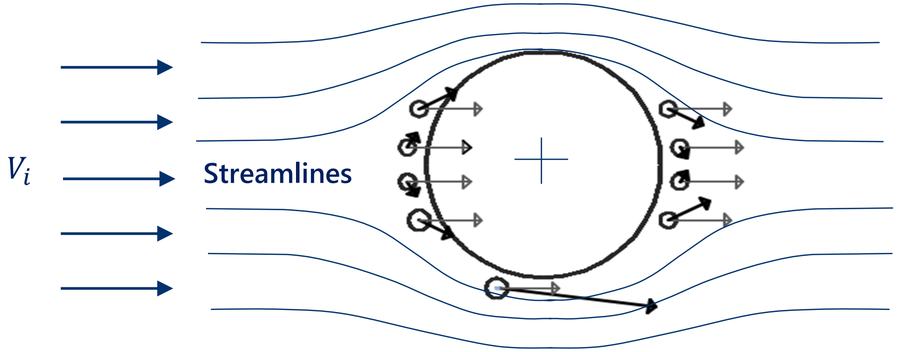
FLS Structural Analysis

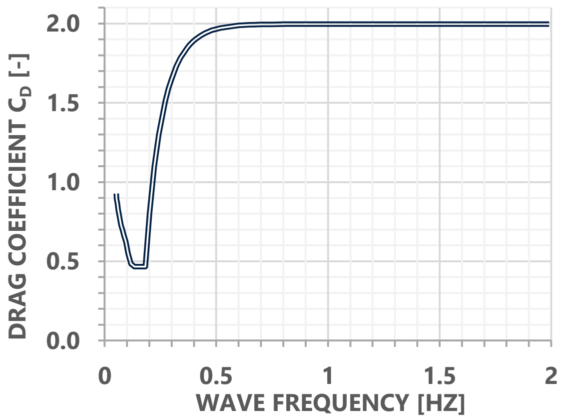
Advanced Approach

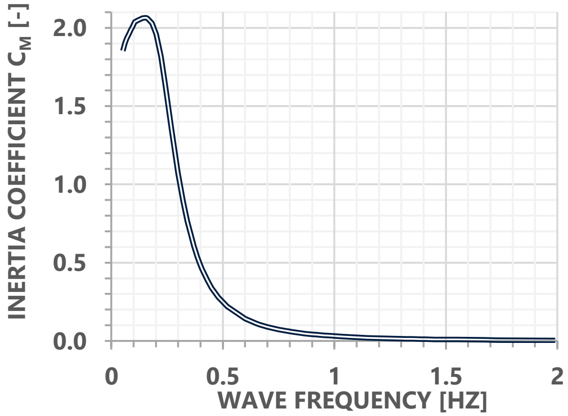
- Significantly improved control over the hydrodynamic load calculations.
- Instantaneous directional, Re and KC dependent wave force calculation
- MacCamy-Fuchs diffraction (without phase lag acceleration)

Time Domain Spectral Analysis



Deterministic regular waves → SOLVE → Stress transfer function





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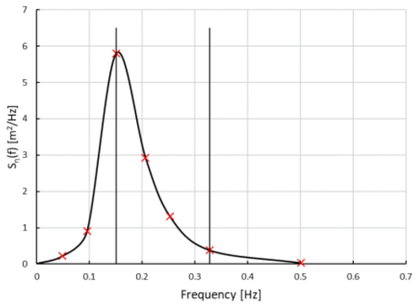
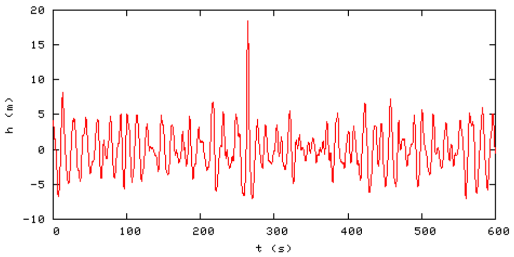
FLS Structural Analysis

Advanced Approach

- Instantaneous directional, Re and KC dependent wave force
- Wheeler stretching of wave kinematics
- Exact solution to MacCamy-Fuchs diffraction (with phase lag acceleration)
- Direction and frequency dependent wave force per structural member

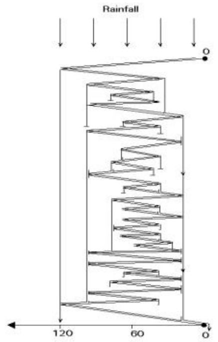
Time Domain – Time Integration

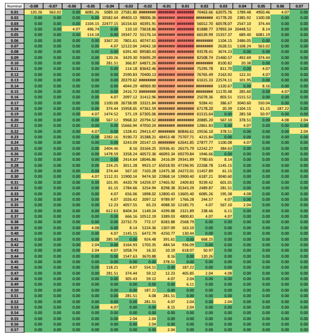


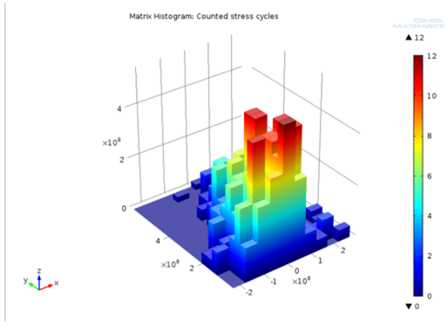


Time domain dynamic analysis – direct time integration solution

Wave spectrum → Irregular seastate waves → Solve







Rainflow counting → Stress histogram → Damage via stress histogram

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Structural Design

- Structural-geotechnical interfacing issues?
- Understanding of the impacts of linearising pile-soil model. How should this be done?
- State-of-the-art hydrodynamic modelling. What are the key phenomena / areas to look at?
- Limitations of commercial software and their impact on the design. What is the solution?

7. Results and Comparison

ULS Structural Analysis

Basic API Approach

vs.

Advanced PISA-type

- Significant increase in foundation stiffness (1st mode)
- Significant reduction in monopile design length
- Significant reduction in weight

Time Domain Analysis

Basic	Advanced PISA-type
1st Mode (T_n) = 2.62s	1st Mode (T_n) = 2.44s ΔTn = -7%
Mudline Moment = 476 MNm	Mudline Moment = 427 MNm ΔM = -10%
Mudline Shear = 14.8 MN	Mudline Shear = 14.0 MN ΔV = -6%
Design Penetration= 39m	Design Penetration = 30m ΔP = -23%
Monopile Weight = 1061t	Monopile Weight = 956t ΔW = -10%

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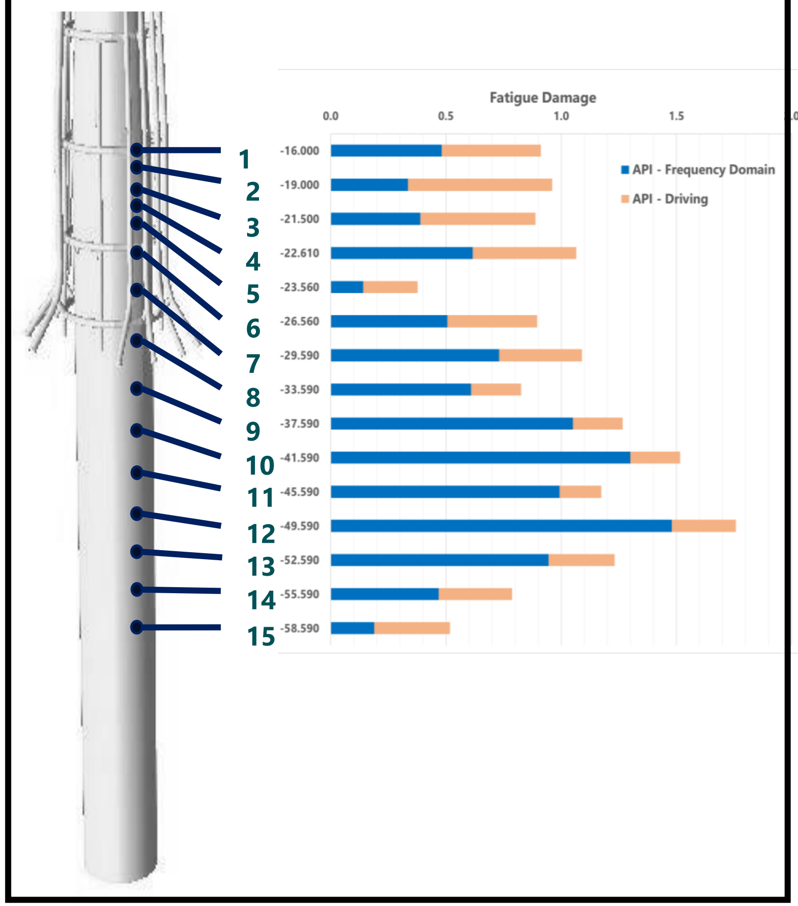
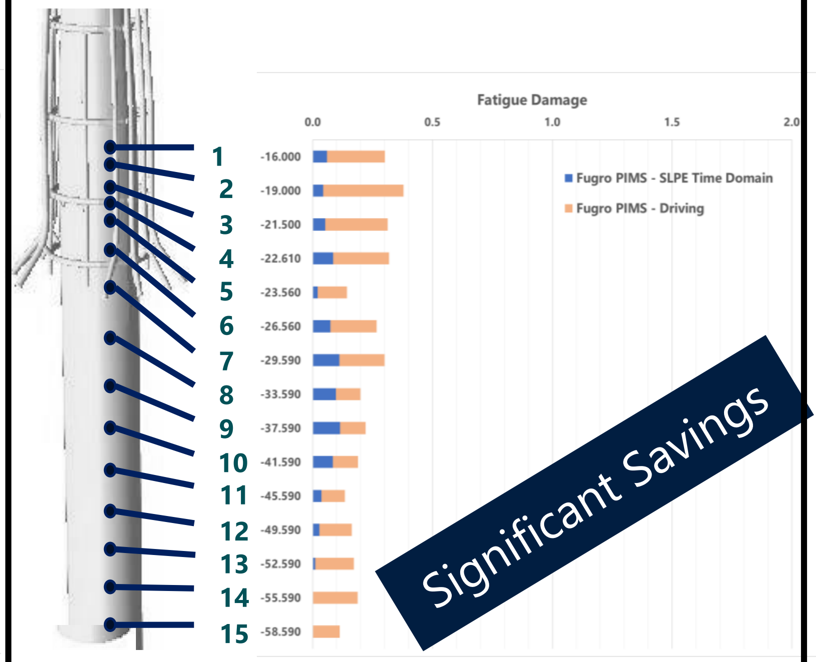
Conclusions

- Structural Engineers and Software Developers needs to keep up with geotechnical advancements
- Needs a truly collaborative or JV GeoStructural approach to realise potential full savings
- Demonstrated that significant de-risking and cost saving possible
- Further savings possible
- Saving for 1 Monopile scaled to 100 Monopiles are <u>significant</u>

Basic Design Approach



Advanced Integrated Geotechnical-Structural Design Approach



Monopile Design Optimisation

- Savings being realised in Europe?
- Further optimisation possible?
- Better understanding of cyclic loading needed?
- Next steps?