Soil impedance of monopiles for offshore wind turbines

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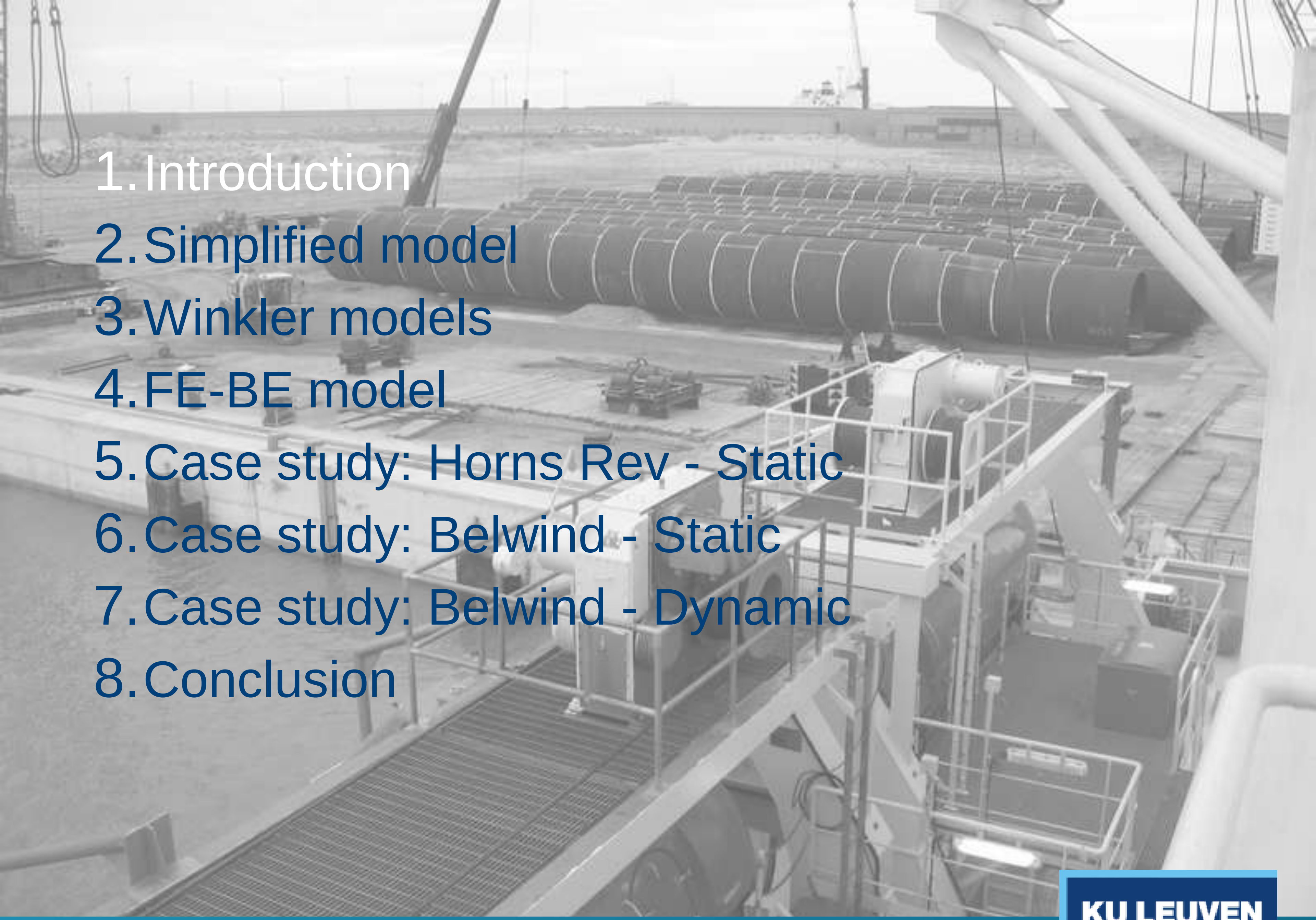

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1. Introduction

DONG Energy enters into cooperation with University of Oxford

DONG Energy has entered into cooperation with an academic consortium of three leading universities to work on a unique R&D project aimed at reducing the cost of energy from offshore wind turbines. The academic consortium, led by the University of Oxford and including Imperial College London and University College Dublin, will investigate, along with DONG and its partners, how offshore wind turbine foundations can be designed more effectively in the future.

"We expect to find significant savings by trimming monopile sizes and finding new ways of installing the foundations, amongst others. Consequently, we believe a significant contribution can come from this area towards our efforts of reducing the price of offshore wind power by 35-40 per cent by 2020."

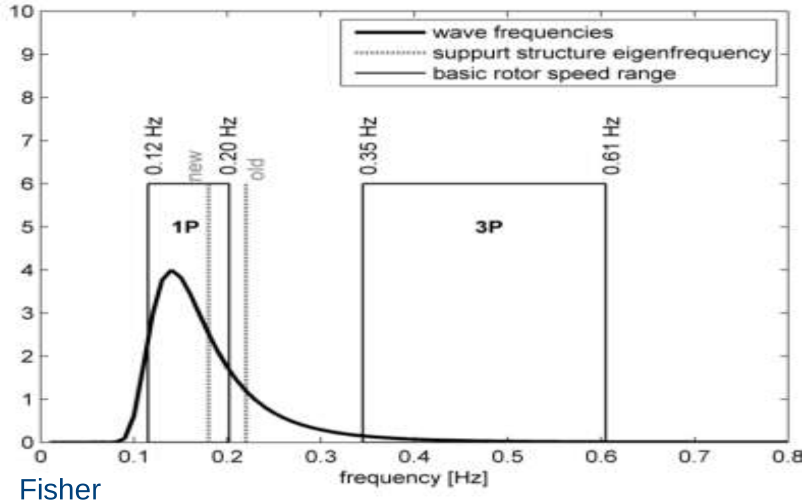
Steel may be the solution

Currently, the monopile foundation for a typical offshore wind turbine weighs approximately 600 tonnes and primarily consists of steel. For a wind farm of 100 or more turbines this represents a substantial fabrication and installation cost. The thickness of the steel used for each pile is about 100mm. If this can be reduced, even by a fraction, without compromising the load-carrying capacity and stiffness of the foundation, there will be significant savings made in developing offshore wind.

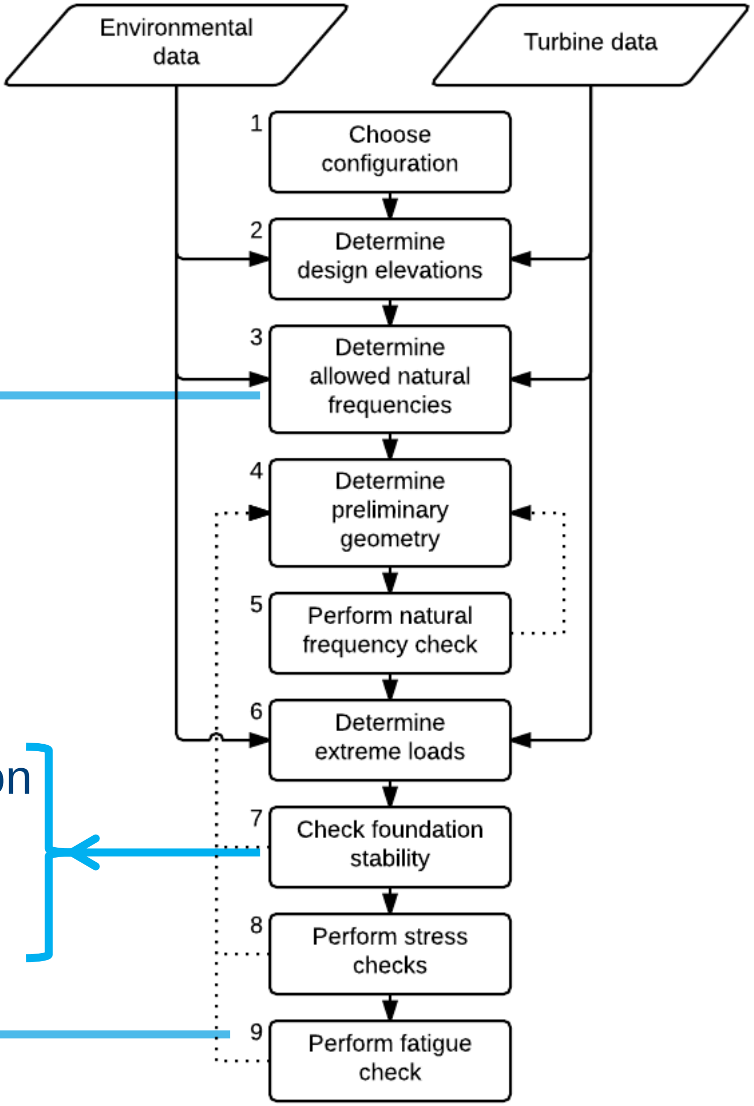
Turbine foundation on its way to Anholt Offshore Wind Farm. Photo: DONG Energy.

Ramboll Group

1. Introduction



Fisher



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1. Maximum monopile head translation and rotation
2. Maximum monopile toe displacement
3. (Vertical tagent criterion)

Damping (aero/hydro/soil) reduces fatigue

<u>Certifier:</u> accumulated life time displacement of the foundation pile

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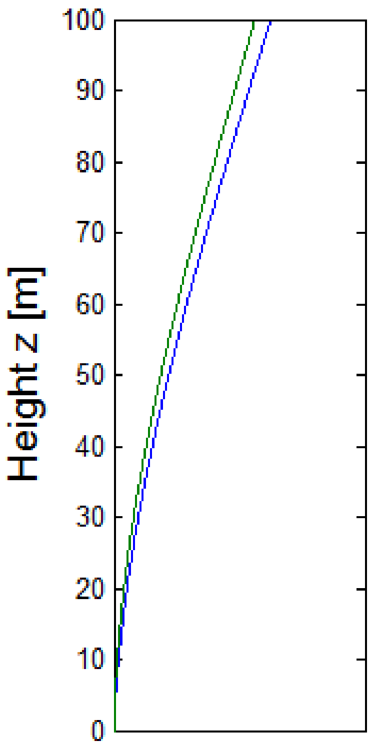
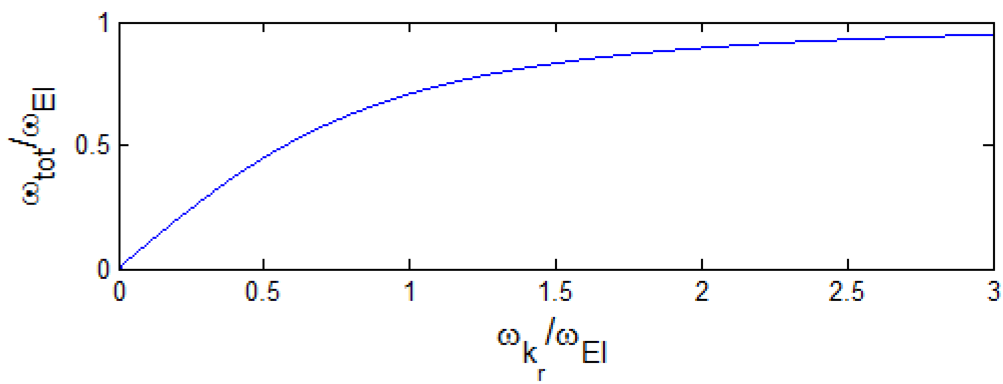
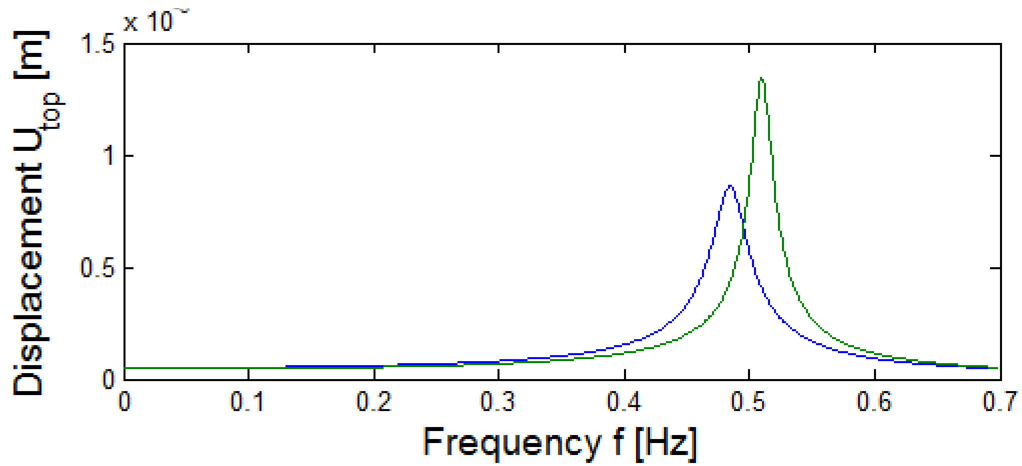
2. Simplified model

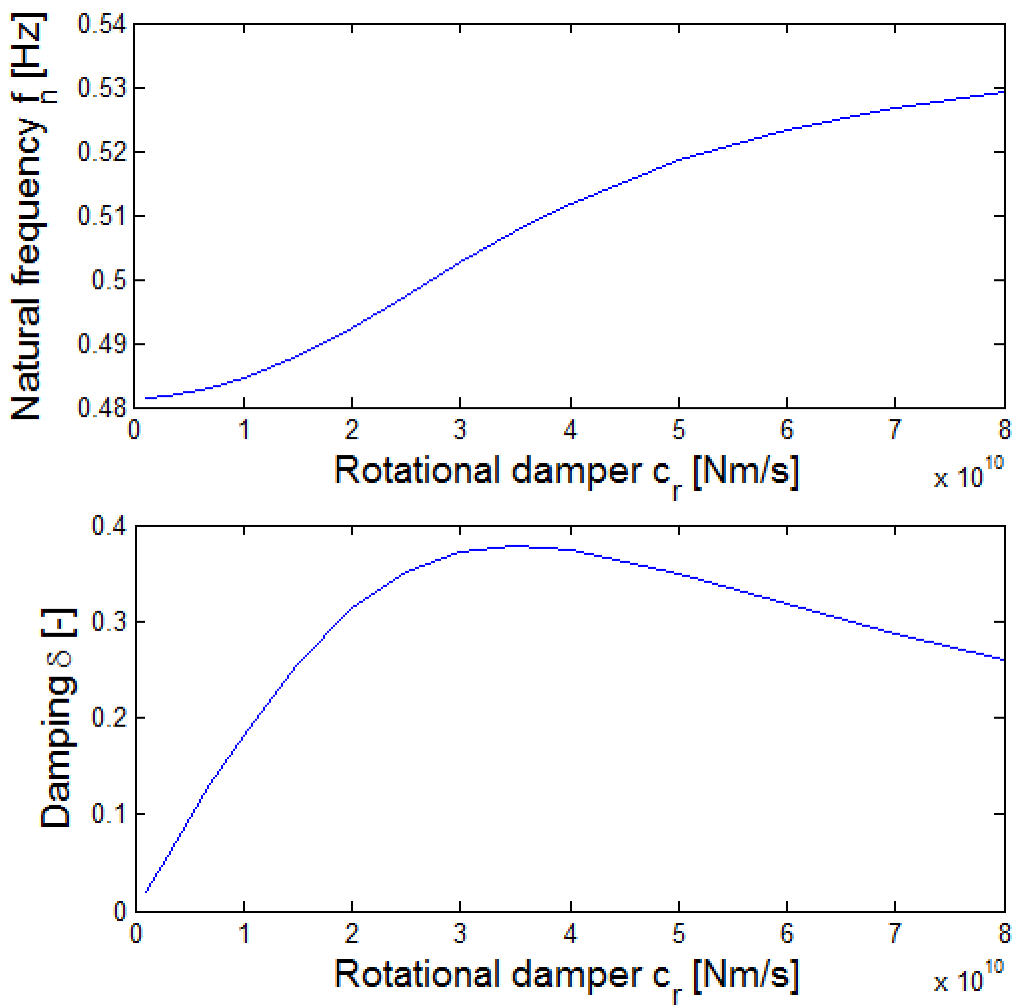
Parameter	M [kg]	L [m]	EI [Nm²]	k_r [Nm]	c_r [Nm/s]
Case 1	2.2e5	100	8.4e11	1e11	1e10
Case 2	2.2e5	100	8.4e11	2e11	2e10







2. Simplified model



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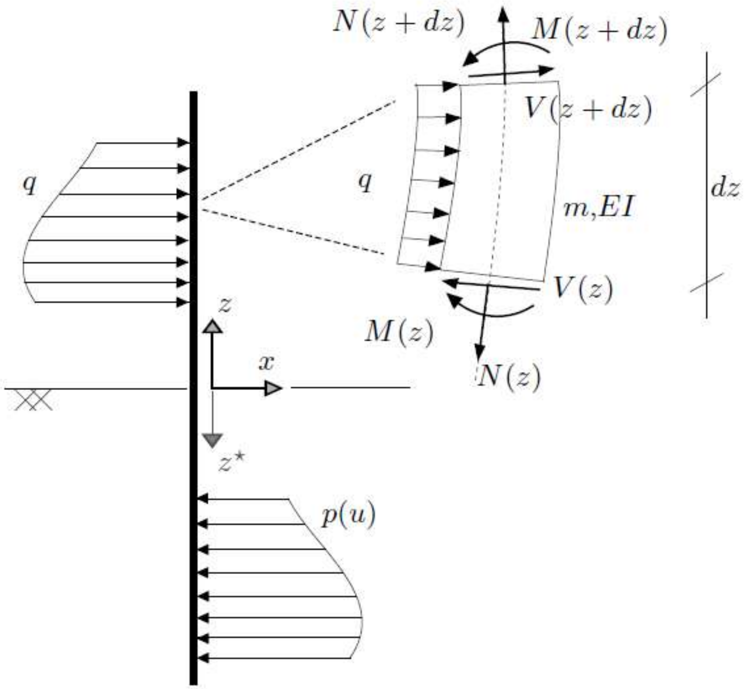
3. Winkler models



$$m\frac{\partial^2 u}{\partial t^2} + EI\frac{\partial^4 u}{\partial z^4} - N\frac{\partial^2 u}{\partial z^2} + p(u) = q$$

Current design guidelines (API, DNV)

$$p(u) = Ap_u \tanh\left(\frac{kz^*}{Ap_u}u\right)$$

$$E_{py} = \left(\frac{dp(u)}{du}\right)_{u=0} = kz^*$$

Sorensen et al. (FLAC 3D)

$$E_{py} = 50\ MPa\left(\frac{z}{1\ m}\right)^{0.6}\left(\frac{D}{1\ m}\right)^{0.5}\varphi^{3.6}$$

Kallehave et al. (“theoretical considerations”)

$$E_{py} = k\ 2.5\ m\left(\frac{z}{2.5\ m}\right)^{0.6}\left(\frac{D}{0.61\ m}\right)^{0.5}$$

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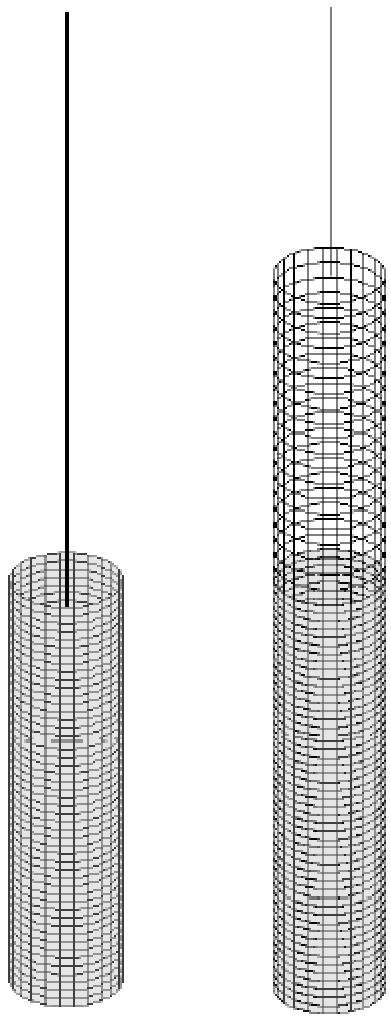
4. FE-BE model



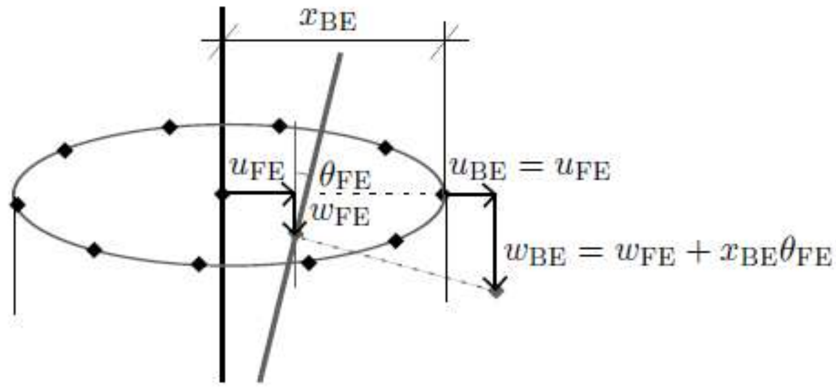
System of equations

$$\left(\begin{bmatrix}K_{11} & K_{12}\\ K_{21} & K_{22}\end{bmatrix}+\begin{bmatrix}0 & 0\\ 0 & \widehat{K}_s\end{bmatrix}-\omega^2\begin{bmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{bmatrix}\right)\begin{Bmatrix}\hat{u}_1\\ \hat{u}_2\end{Bmatrix}=\begin{Bmatrix}\hat{p}_1\\ \hat{p}_2\end{Bmatrix}$$

Calculation $\widehat{K}_s$ using BEMFUN and EDT

Transformation matrix for beam

$$K_s^{beam} = T_r{}'\widehat{K}_s T_r$$



BEMFUN: François
EDT: Schevenels et al.

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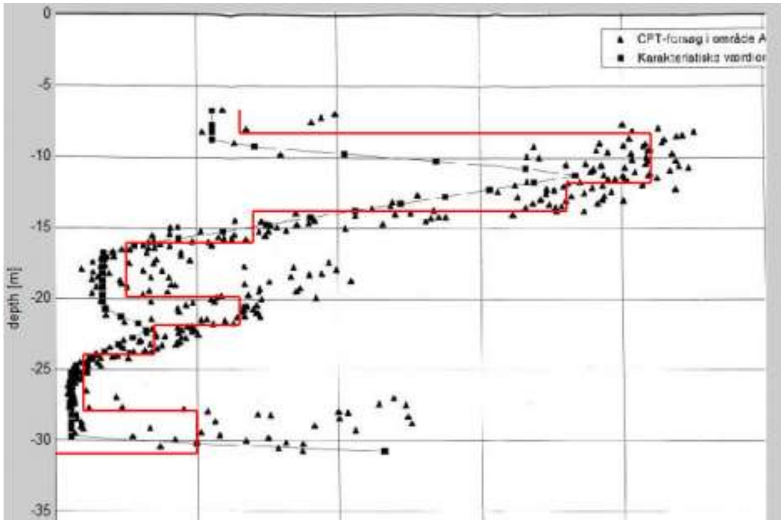
5. Case study: Horns Rev - Static

Soil characteristics



Depth [m MSL]	Soil type	Density [kN/m^3]	Friction angle	Reinterpreted Friction angle
-9.9	SAND	20	44	42 - 45
-12.8	SAND	20	40	42 - 45
-15.8	SAND	20	33	40 - 43
-18.8	SAND	20	33	33 - 38
-21.8	SAND	20	33	33 - 38
-24.8	SAND	17	22	34 - 38.7
-26.8	SAND	17	22	28 - 34
-28.8	SAND	17	22	28 - 34
-29.8	SAND	20	28	28 - 34
-30.8	SAND	20	28	28 - 34

Hald et al.

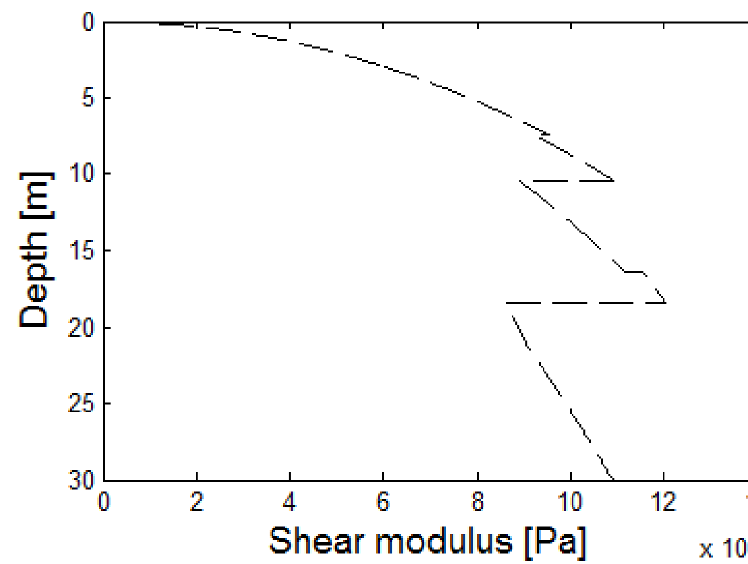
Elastic soil parameters:

Shear modulus: → Seed et al.

$$G_{max} = 220(K_2)_{max}(\sigma'_m)^{1/2}$$
$$(K_2)_{max} = f(\phi)$$

Poisson's ratio (drained):

$$\nu = 0.3$$



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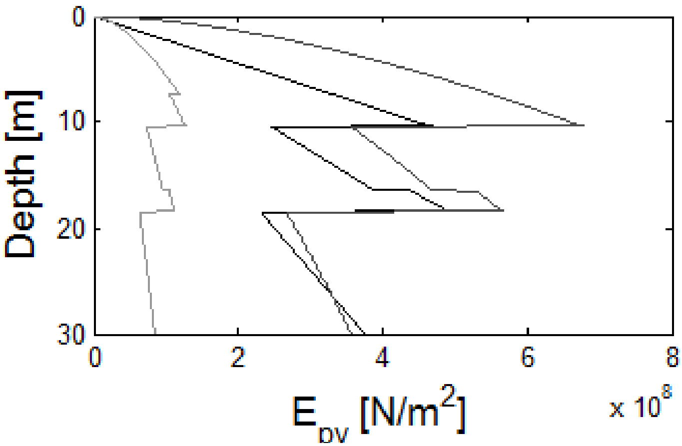
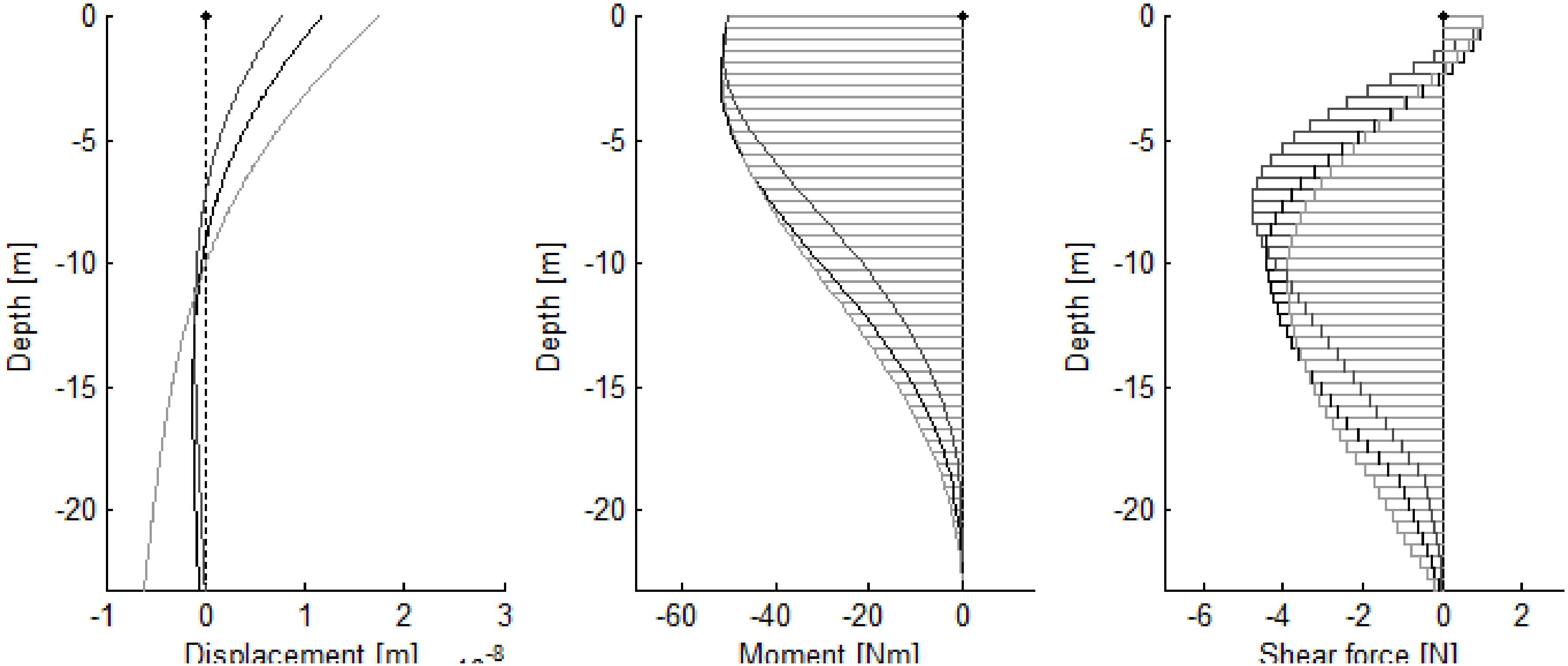
5. Case study: Horns Rev - Static



Current design practice
Kallehave et al.
Sorensen et al.



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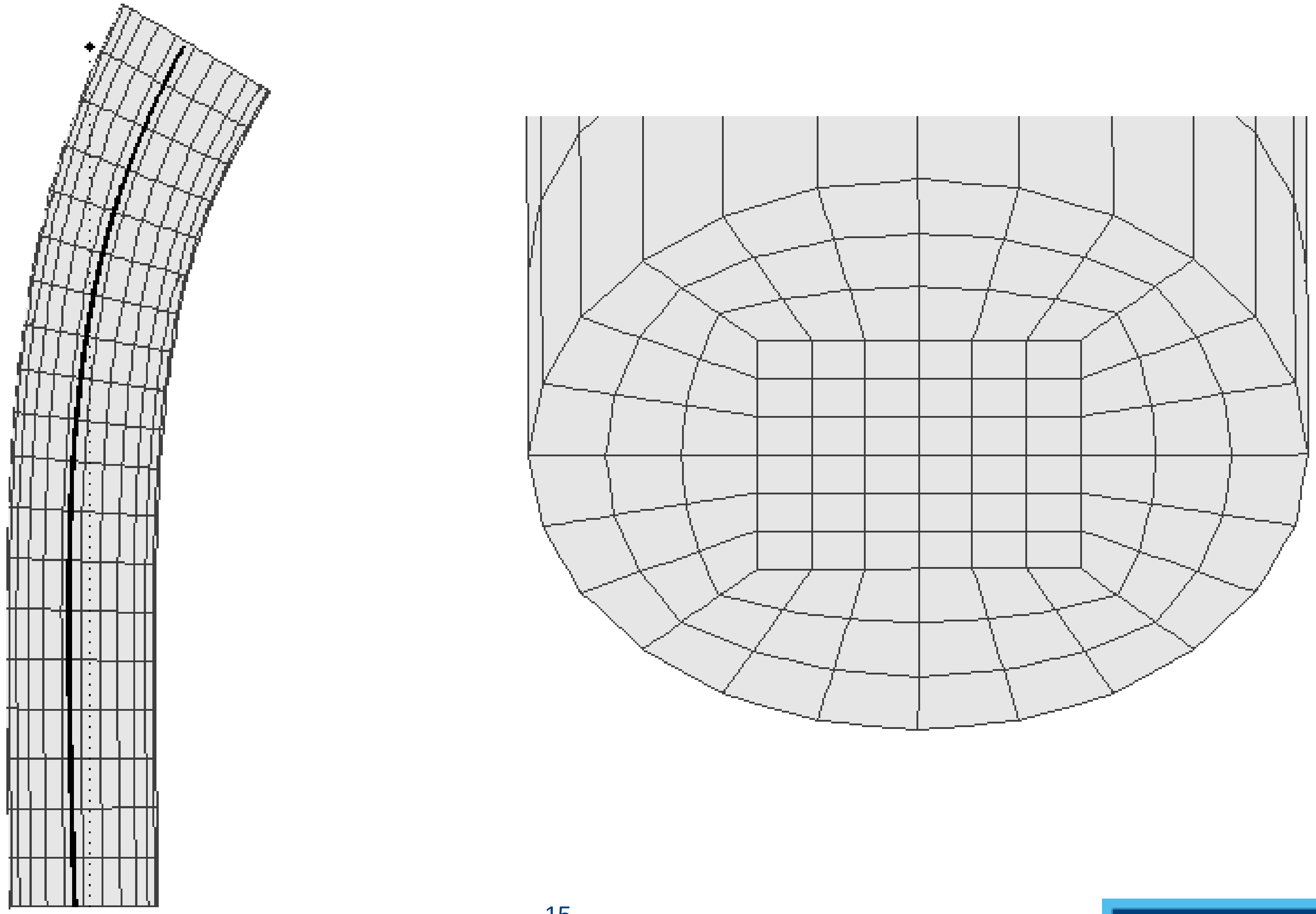
5. Case study: Horns Rev - Static



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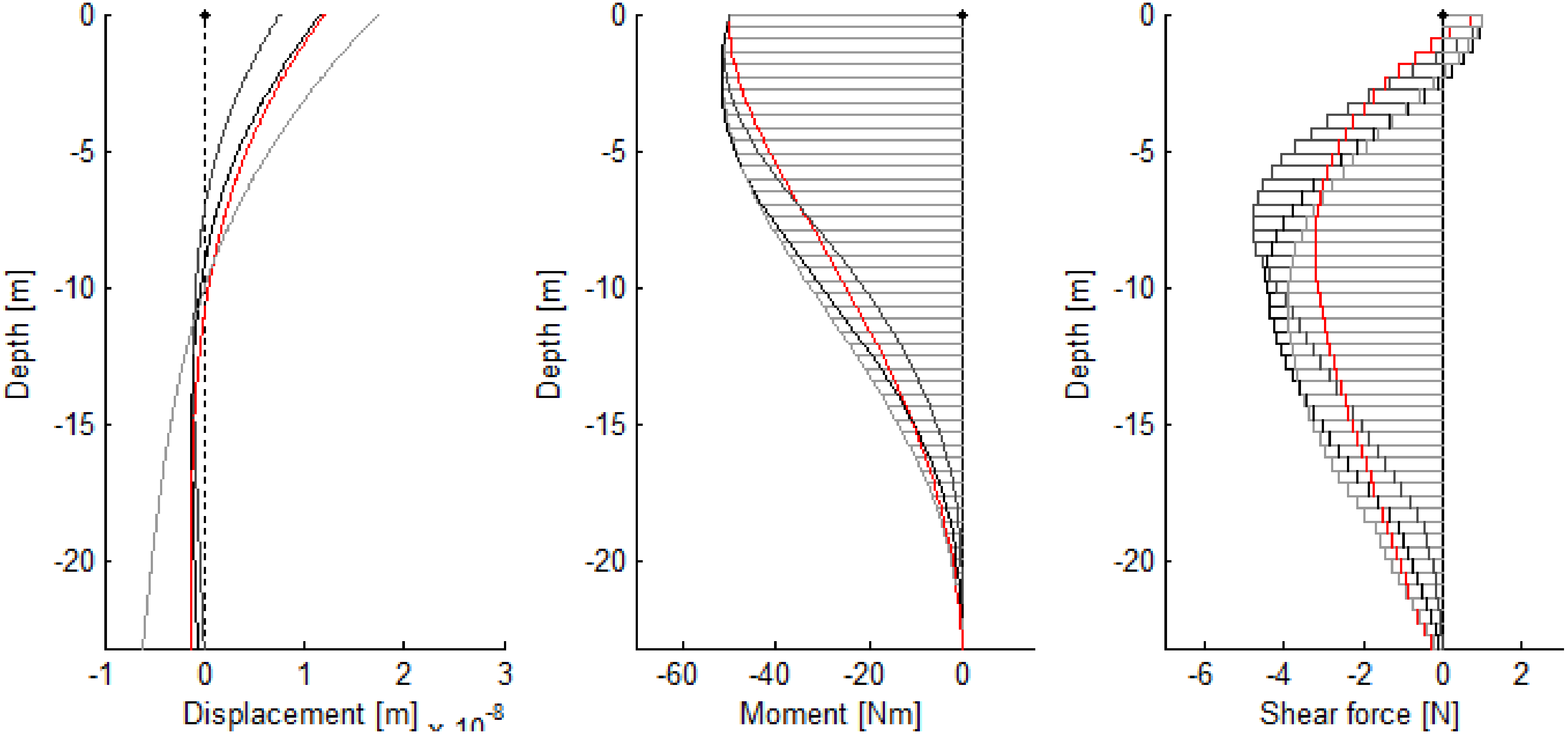
5. Case study: Horns Rev - Static

FE-BE model
Current design practice
Kallehave et al.
Sorensen et al.



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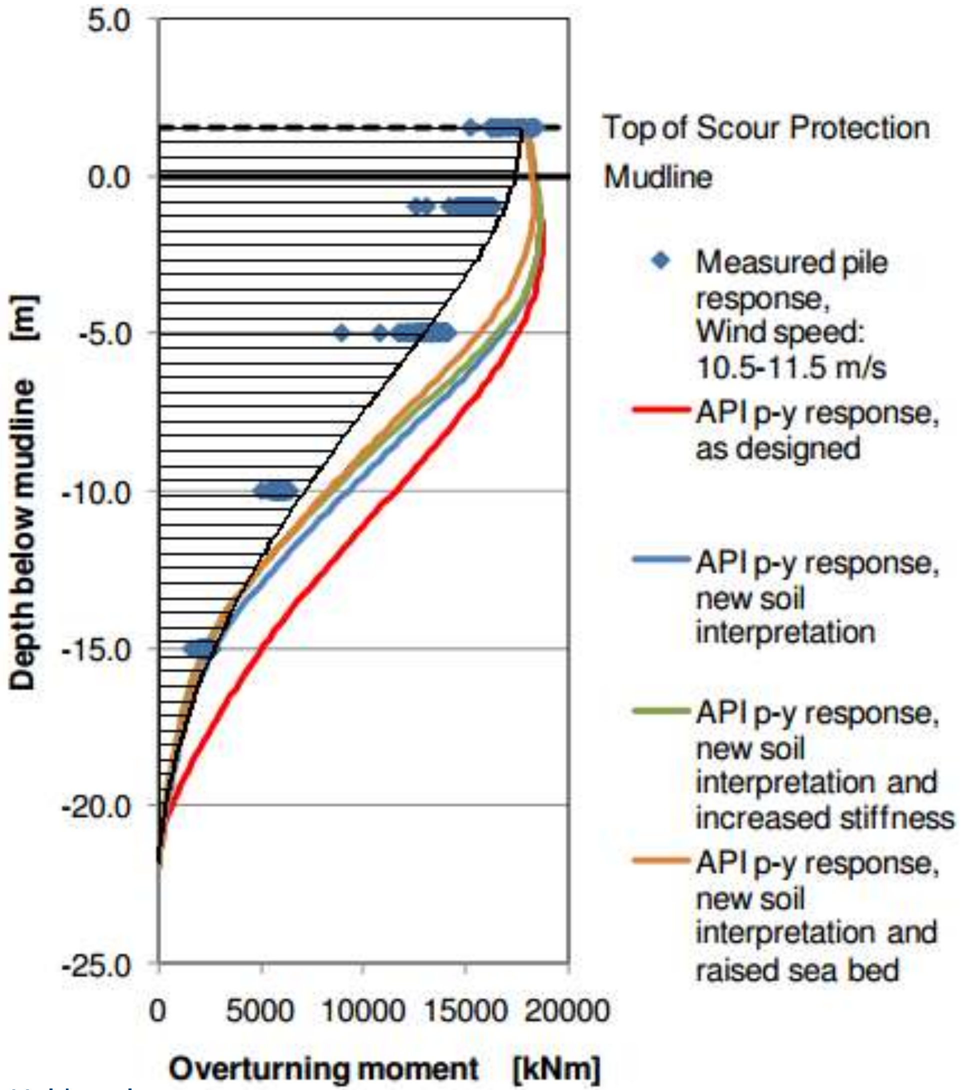
5. Case study: Horns Rev - Static



Hald et al.

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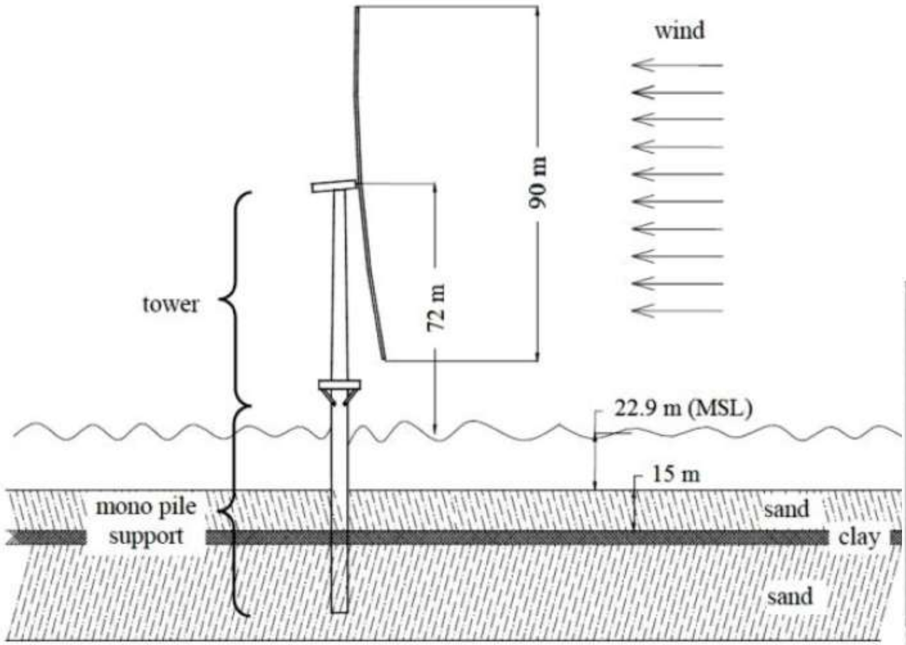
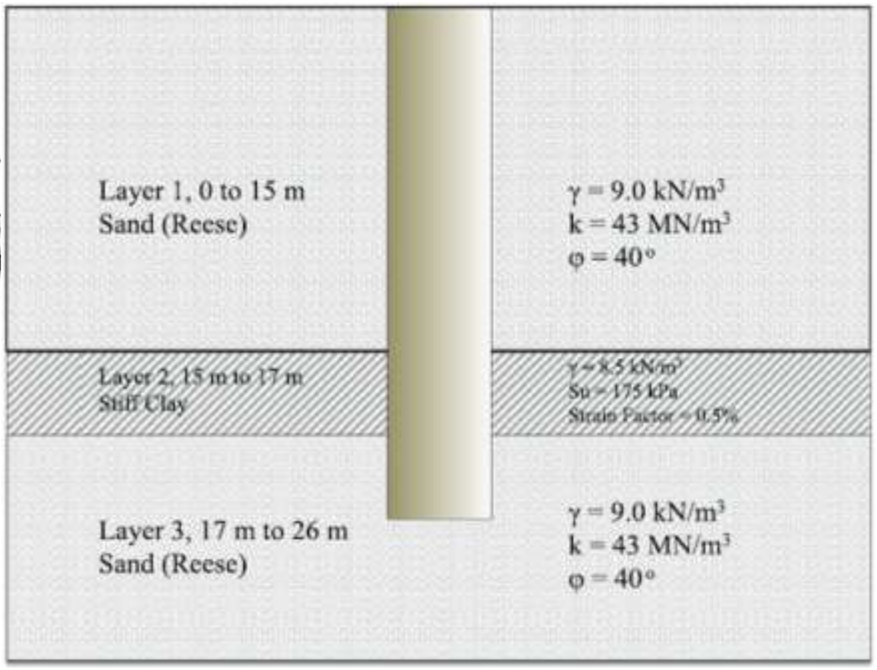
Belwind Media

6. Case study: Belwind - Static

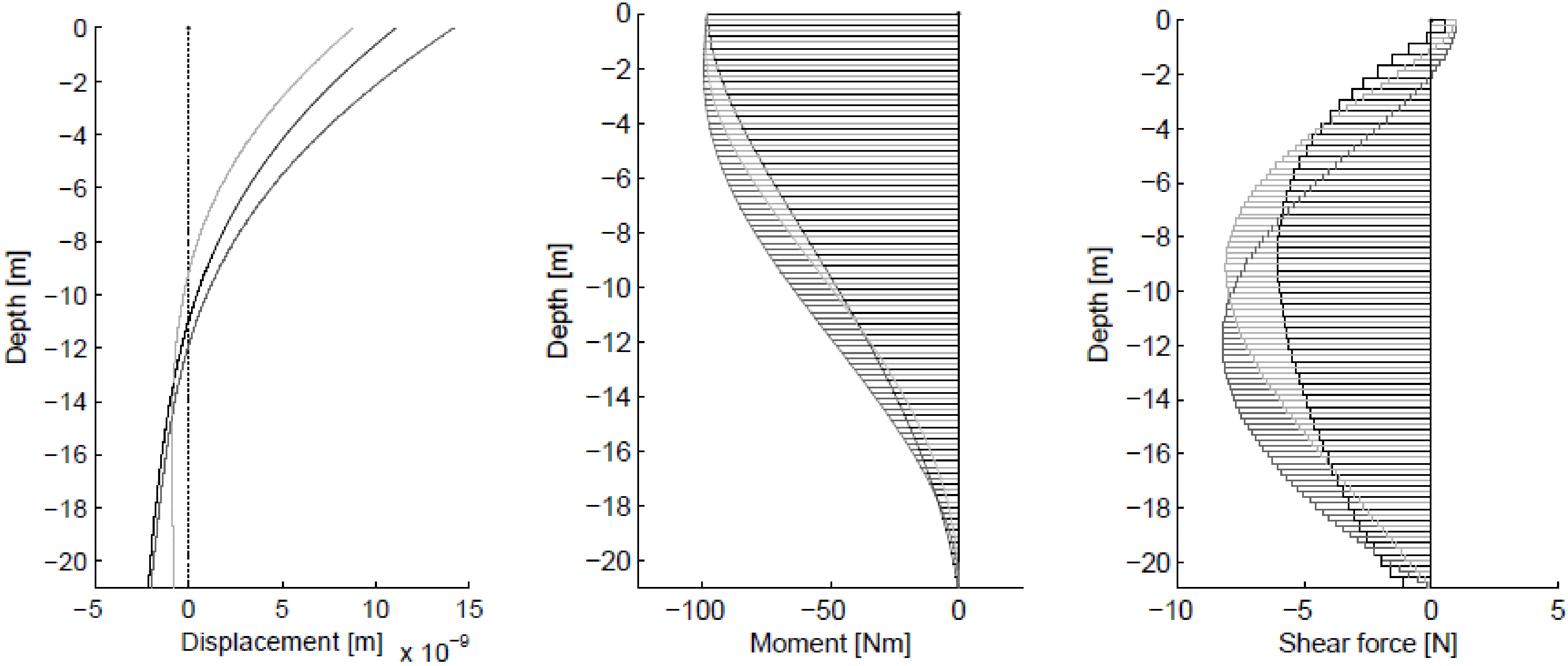




Devriendt et al.

6. Case study: Belwind - Static

FE-BE model
Current design method
Kallehave et al.



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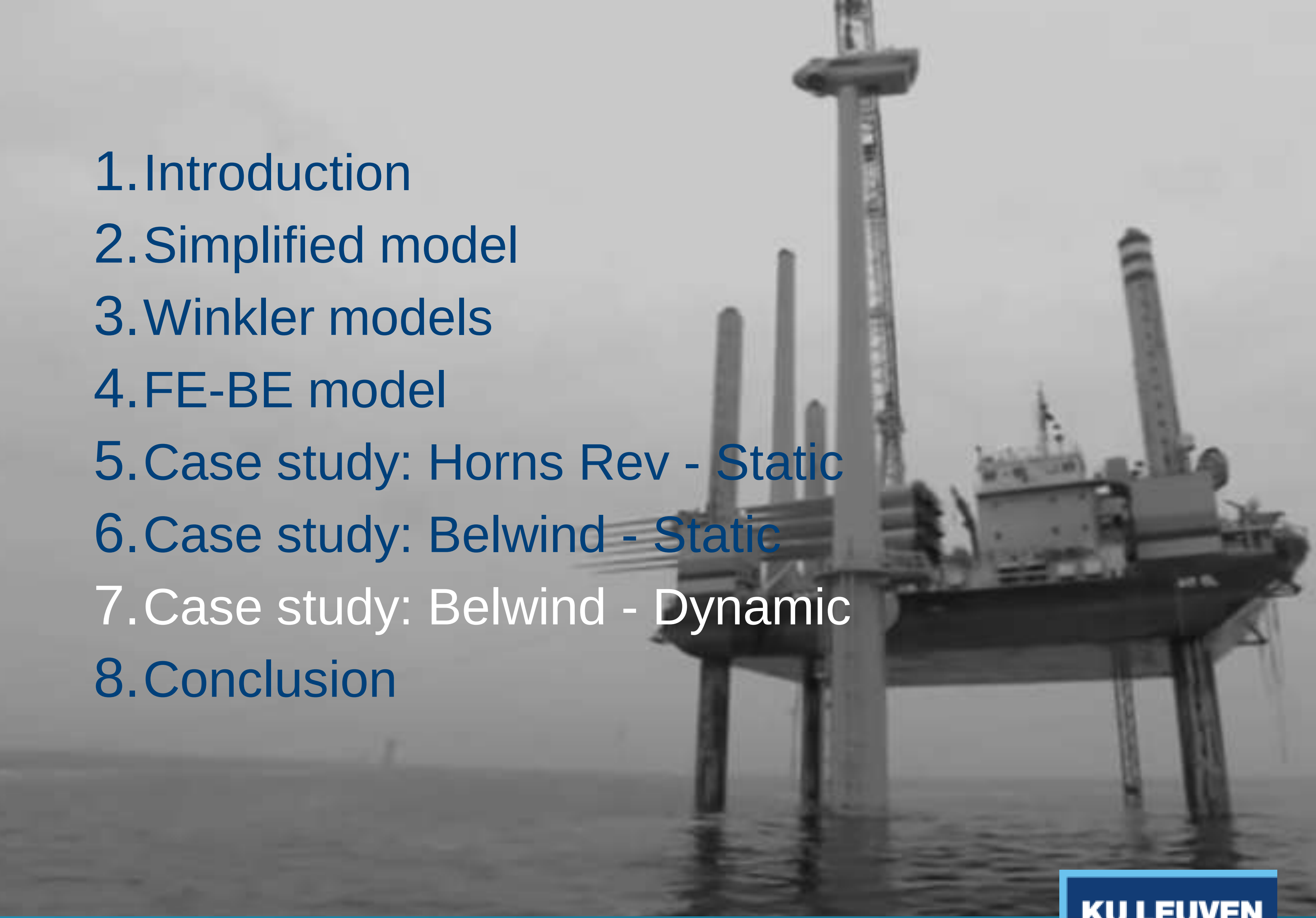

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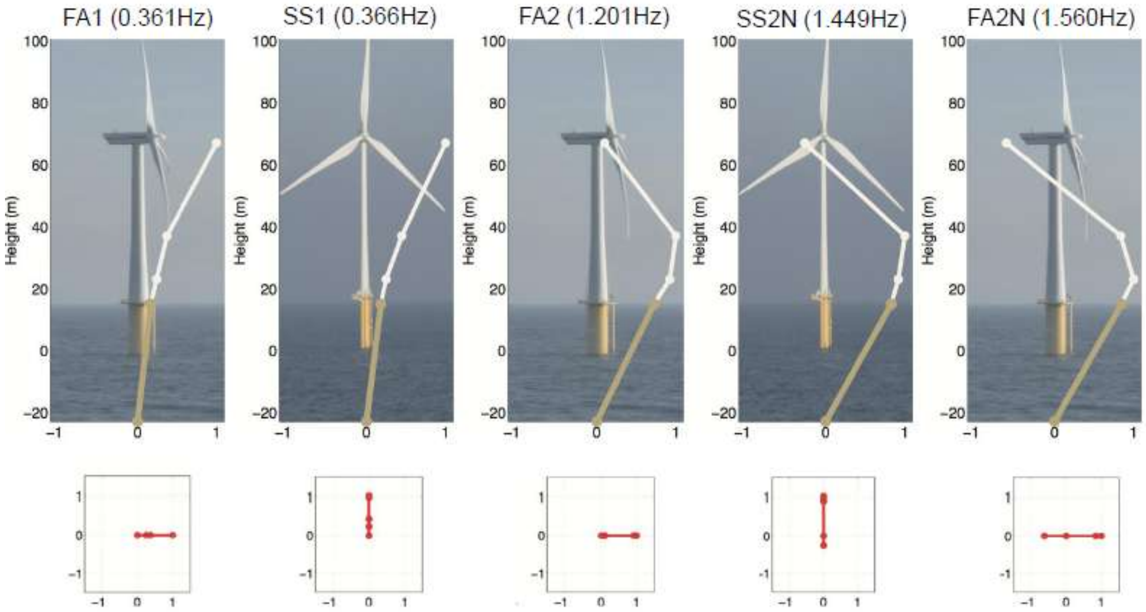
7. Case study: Belwind - Dynamic

OWI-lab: accelerometers → 5 modes



Mode	f_n [Hz]	δ [%]
FA1	0.361	11.7
SS1	0.365	15.7
(FA2)	1.204	4.52
SS2N	1.449	8.67
FA2N	1.560	7.16

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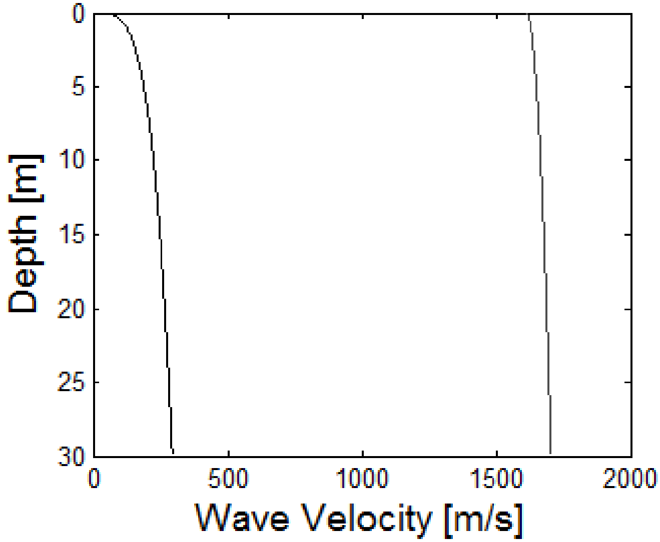
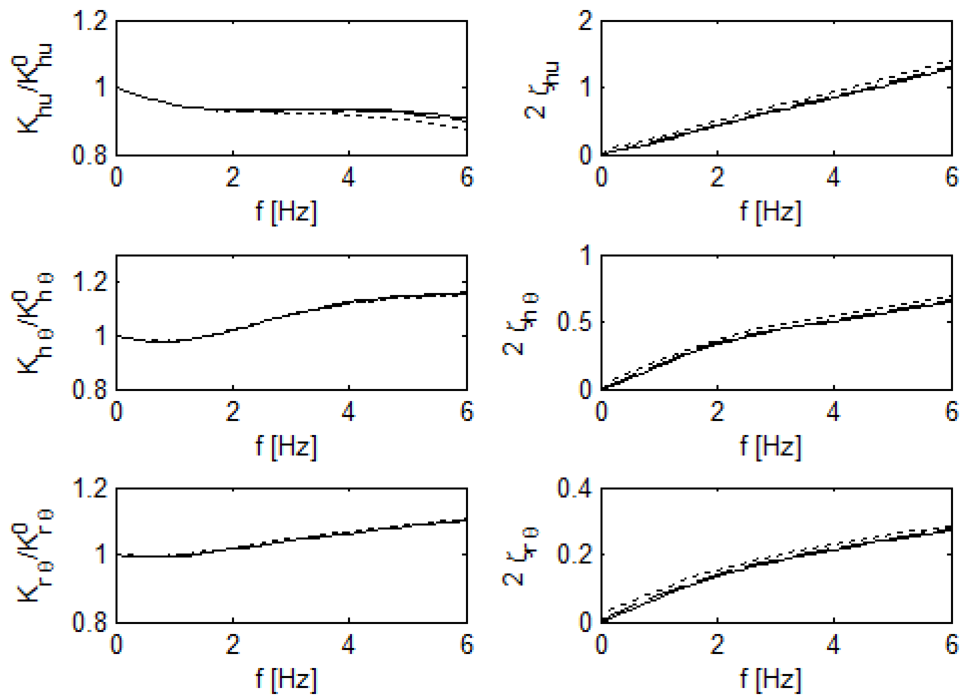
7. Case study: Belwind - Dynamic

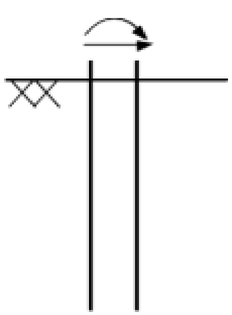
Primary wave (undrained)

Secondary wave



$$D_s = D_p = \begin{cases} 0.6\% & - \\ 2\% & - - \\ 5\% & \cdots \end{cases}$$





$$\begin{bmatrix} \tilde{K}_{hu} & \tilde{K}_{h\theta} \\ \tilde{K}_{ru} & \tilde{K}_{r\theta} \end{bmatrix} \begin{Bmatrix} u \\ \theta \end{Bmatrix} = \begin{Bmatrix} P_h \\ M_r \end{Bmatrix}$$

$$\tilde{K}_{hu} = K_{hu}(1 + 2\zeta_{hu} i)$$

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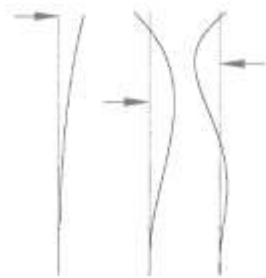
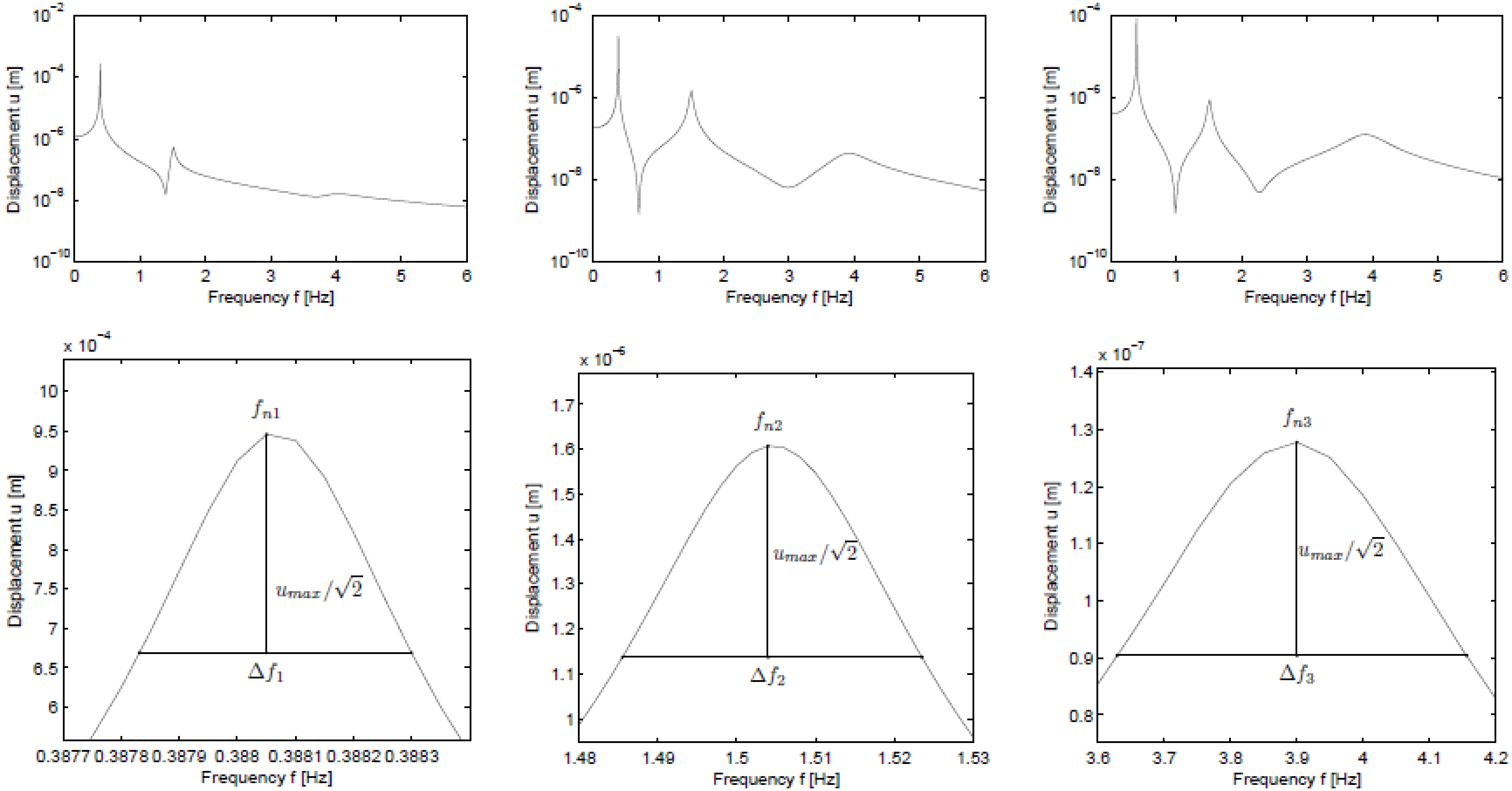
7. Case study: Belwind - Dynamic





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7. Case study: Belwind - Dynamic

Method	f_{n1} [Hz]	f_{n2} [Hz]	f_{n3} [Hz]
Current design method	0.381	1.46	3.81
Kallehave et al.	0.392	1.57	4.05
FE-BE model	0.391	1.53	3.94

Devriendt et al.

Method	f_{n1} [Hz]	f_{n1} [Hz]
Measured FA1	0.361	- 5.3
Measured SS1	0.365	- 4.2
CDM literature	0.345	- 9.5
CDM calculat	0.381	-
Kallehave et al.	0.392	+ 2.9
FE-BE model	0.391	+ 2.6

7. Case study: Belwind - Dynamic

β [%]	0,6	2	5
f_{n1} [Hz]	0.391	0.391	0.391
f_{n1} [Hz]	0.34	1.04	2.55
δ_1 [%]	1.53	1.53	1.54
	6.68	8.58	12.5
f_{n3} [Hz]	3.94	3.94	3.94
	42.1	43.4	46.1

Devriendt et al.

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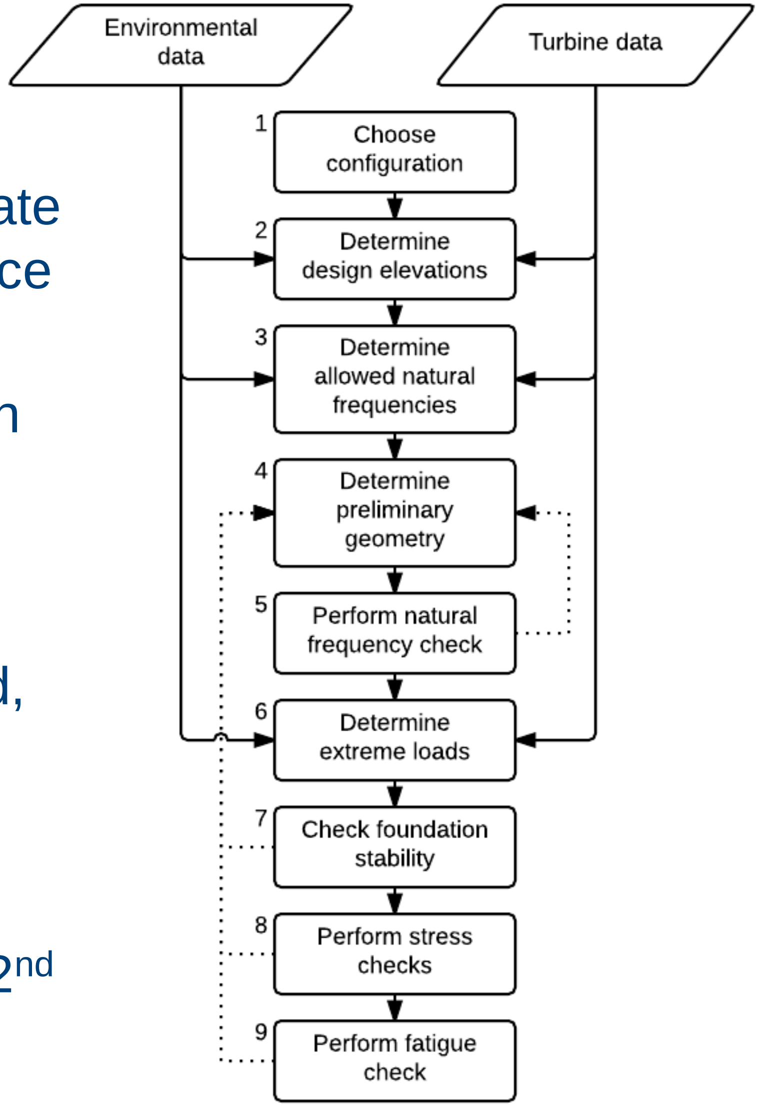
1. The current design guidelines overestimate the displacement, moment and shear force for XL monopiles
2. The underestimated soil stiffness result in lower natural frequencies
   → FE-BE makes better predictions (*importance elastic soil properties)*
3. Dynamic variation of foundation is limited, but can increase for layered soil profiles
4. Material damping is dominant for the 1st resonace mode
5. Radiation damping is dominant from de 2nd resonance mode onwards



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Belwind Offshore Energy

OWI lab Offshore Wind Infrastructure Application Lab

Thank you for your attention

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Referenties

- American Petroleum Institute. *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platform – Working Stress Design*. Number RP 2A-WSD. Washington, D.C., October 2005
- BAM Energie. Belwind Phase 1, Belgium. http://www.bamenergie.nl/projecten/belwind-phase-1-belgium, visited 2014-06-23.
- BelwindMedia. Belwind Offshore Energy. https://www.youtube.com/watch?v=x9IntSh2K7c, visited 2014-06-23.
- Contractors World. Belwind monopiles installed. http://cwmags.com/cw-1-3/basic/page9.php, visited 2014-06-23.
- Det Norske Veritas. *Offshore Standard DNV-OS-J101, Design of Offshore Wind Turbine Structures*. Hovak, Norway, October 2010.
- C. Devriendt, P.J. Jordaens, Y. Van Ingelgem, G. De Sitter, and P. Guillaume. Monitoring of resonant frequencies and damping values of an offshore wind turbine on a monopile foundation. In *Proceedings of EWEA, Vienna*, 2013.
- DONG Energy. Dong Energy enters into cooperation with University of Oxford. http://www.dongenergy.com/EN/Media/Newsroom/News/Pages/DONGEnergyentersintocooperationwithUniversityofOxford.aspx, visited 2014-06-23.

Referenties

- Electrawinds. Concessie voor offshore windark Mermaid België, August 2012. http://www.e-mailinglist.be/Electrawinds/archief/Augustus2012.html, visited 2014-03-16.
- European Investment Bank. Belwind: EIB finances Europe’s largest offshore wind farm. http://www.eib.org/infocentre/press/news/stories/2010-june-02/eib-finances-europes-largest-offshore-wind-farm.htm, visited 2014-06-23.
- T. Fisher. Integrated wind turbine design: final report task 4.1, Deliverable D 4.1.5 (WP4: Offshore Foundations and Support Structures), Technical report, UpWind, 2011.
- S. François. *Nonlinear Modelling of the Response of Structures due to Ground Vibrations*. PhD thesis, Katholieke Universiteit Leuven, 2008.
- T. Hald, C. Mørch, L. Jensen, C. LeBlanc Bakmar, and K. Ahle. Revisiting monopile design using p-y curves, Results from full scale measurements on Horns Rev. In *EOW*, 2009.
- H. Hillewaert. Belwind windmolenpark. October 2012. http://nl.wikipedia.org/wiki/Belwind#mediaviewer/Bestand:Belwind.jpg, visited 2014-06-23.
- D. Kallehave, C. LeBlanc Thilsted, and M.A. Liingaard. Modification of the API p-y formulation of initial stiffness of sand. September, 2012.

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Referenties

- M. Novak, M. Asce, T. Nogami, and F.A. Ella. Dynamic soil reactions for plane strain case. *Journal of the Engineering Mechanics Division*, 104(4):953-959, July/August 1978.
- Pile soil analysis project (PISA). http://www.eng.ox.ac.uk/geotech/research/PISA, visited 2014-04-05.
- Ramboll Group. Offshore substation design. http://www.ramboll.com/services/energy%20and%20climate/offshore-wind-consulting, visited 2014-06-23.
- A. Sawangsuriya. *Wave Propagation Methods for Determining Stiffness of Geomaterials.* Pasquale Giovine, ISBN 978-953-51-0821-4, October 2012.
- M. Schevenels, G. Degrande, and S. François. EDT: an ElastoDynamics Toolbox for MATLAB. In *Proceedings of the Inaugural International Conference of the Engineering Mechanics Institute (EM08)*, Minneapolis, Minnesota, U.S.A., May 2008.
- M. Schevenels, G. Degrande, and S. François. EDT: an ElastoDynamics Toolbox for MATLAB. *Computers & Geosciences*, 35(8):1752-1754, August 2009.
- H. Seed, R. Wong, I. Idriss, and K. Tokimatsu. Moduli and damping factors for dynamic analyses of cohesionless soils. *Journal of Geotechical Engineering*, 112(11):1016-1032,1986.

Referenties

- M. Segeren. Offshore wind support structures: monopile design – part I. University Lecture, Delft University of Technology, 2013.
- J.-G. Sieffert and F. Cevear. *Handbook of Impedance Functions – Surface Foundations*. Ouest Editions Presses Academiques, 1995.
- S.P.H. Sorensen, L.B. Ibsen, and A.H. Augustesen. Effects of diameter on initial stiffness of p-y curves for large-diameter piles in sand. *Numerical Methods in Geotechnical Engineering*, (ISBN 978-0-415-59239-0), 2010.
- Van Oord. Belwind Phase 1 Offshore Wind Farm. http://www.vanoord.com/activities/belwind-phase-1-offshore-wind-farm, visited 2014-06-23.