Design of monopiles for multi-megawatt wind turbines at 50 m water depth

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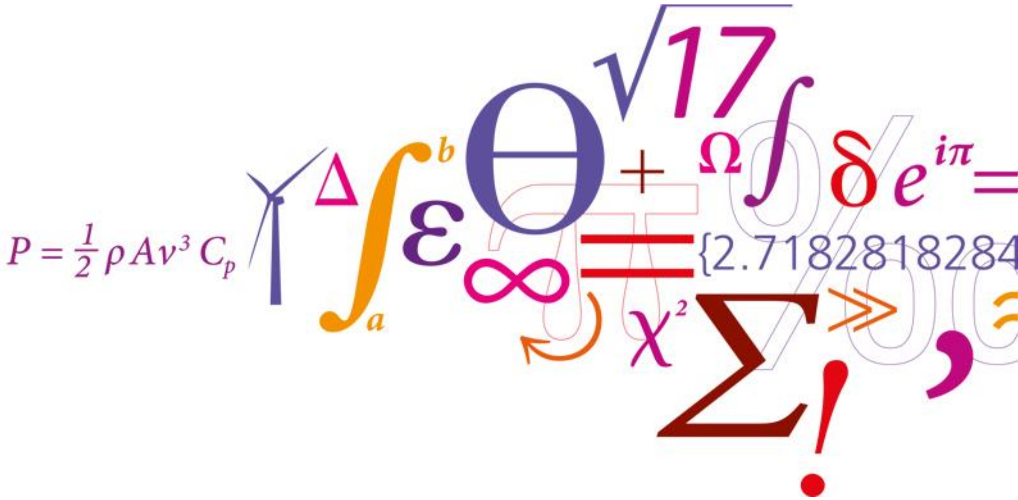
Design of monopiles for multi-megawatt wind turbines at 50 m water depth



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Problematic

Design difficulty		Water depth	
		shallow	deep
Turbine size	small	mild	medium
	large	medium	high

Is the design of large diameter monopile placed at deep waters a straightforward extrapolation process from mild or medium designs?

Agenda

- Design Environment
- Medium Turbine
- Large Turbine
- Perturbation Analysis
- Conclusion

Design Environment

Site Conditions: Metocean conditions and soil properties are presented in the paper.

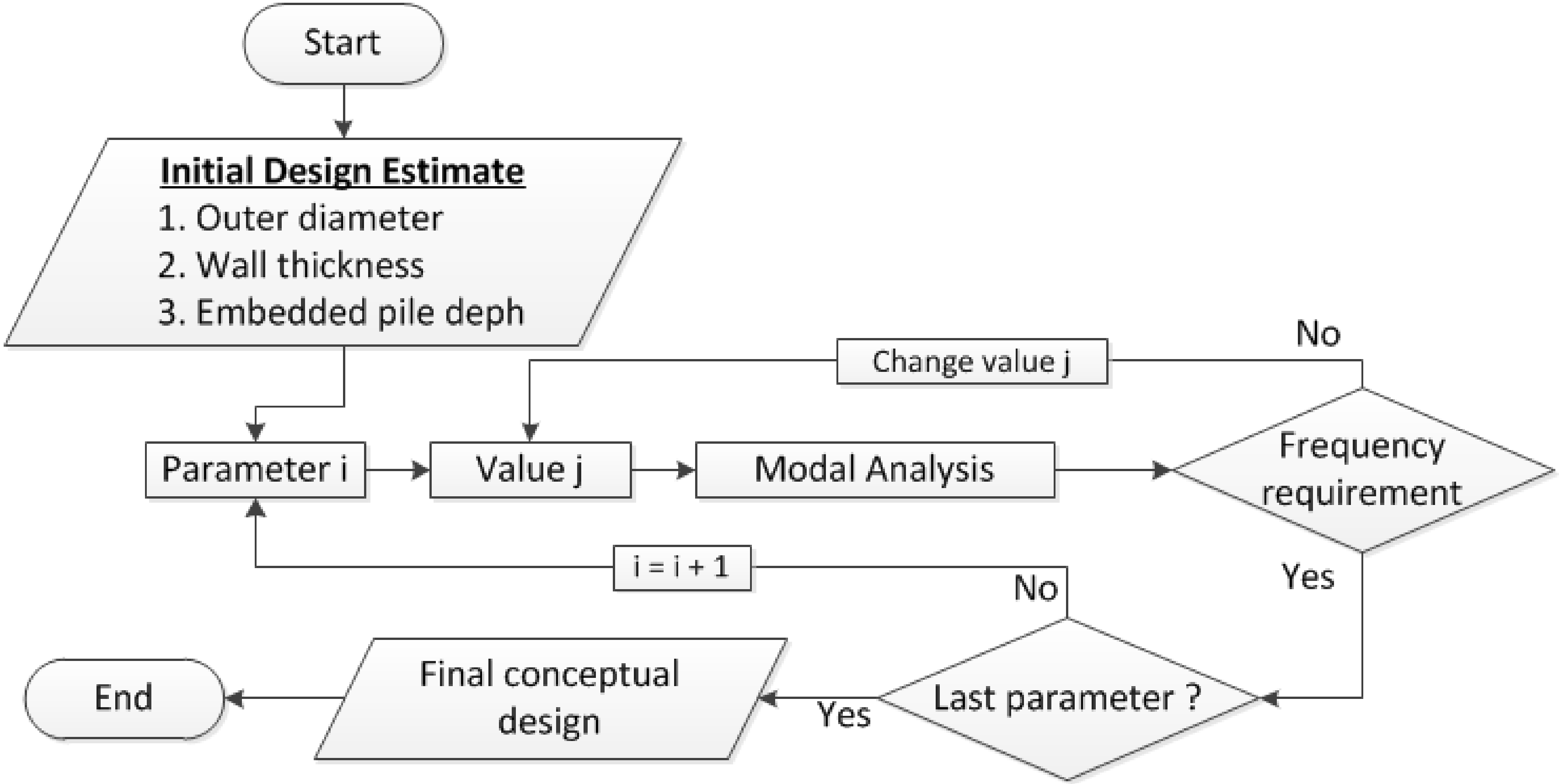
Structure: DTU 10 MW RWT

Design Constraints:

- Conflicting aspects: manufacturing, mass, wave loading
- Natural frequencies
- Maximum outer diameter 10.0 m
- Minimum wall thickness
- Maximum displacement at mudline and toe
- Soil plastification

Computer software: aero-hydro-servo-elastic package, HAWC2

Geometry Design Process



Start

Initial Design Estimate
1. Outer diameter
2. Wall thickness
3. Embedded pile deph

Parameter i

Value j

Modal Analysis

Frequency requirement

No

Change value j

Yes

Last parameter ?

No

i = i + 1

Yes

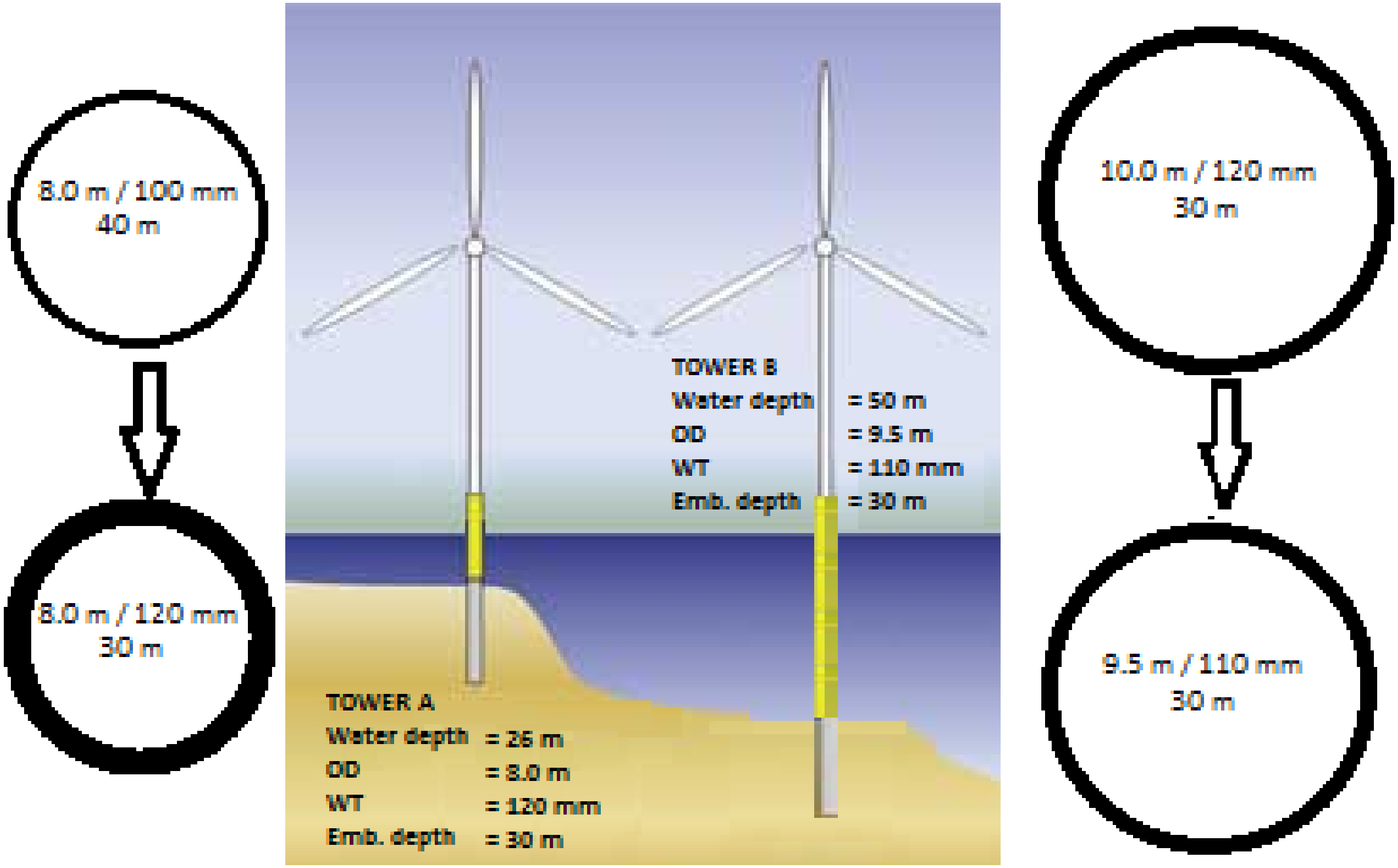
Final conceptual design

End

Specificity of large diameter monopile

- Structural stiffness distribution
- Influence of wave diffraction
- Soil-structure interaction

Geometry design



8.0 m / 100 mm
40 m

8.0 m / 120 mm
30 m

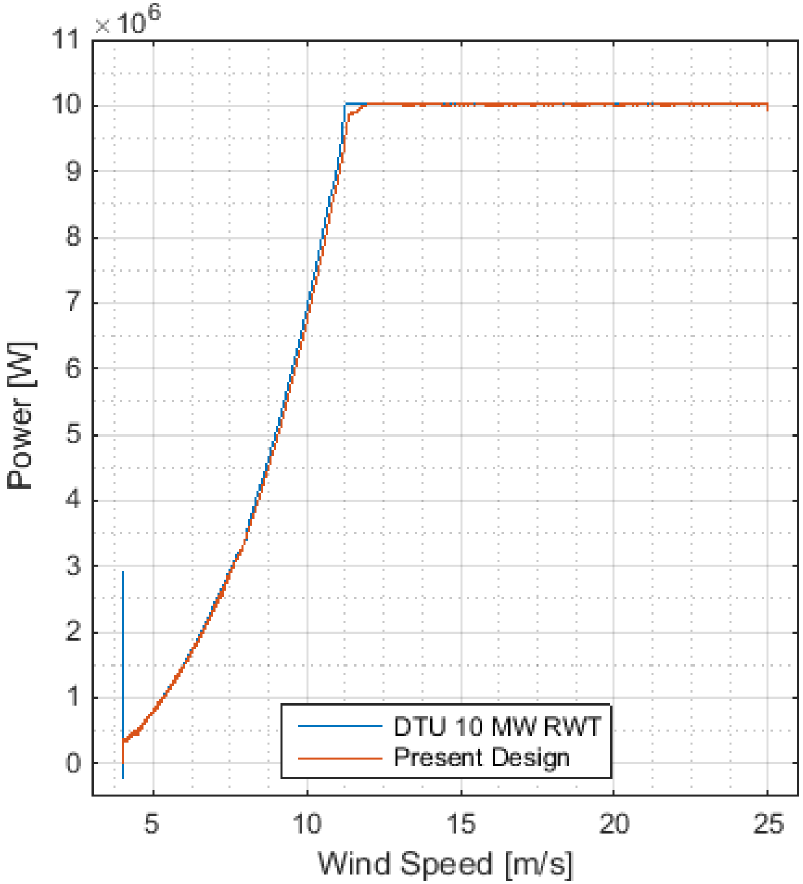
TOWER A
Water depth = 26 m
OD = 8.0 m
WT = 120 mm
Emb. depth = 30 m

TOWER B
Water depth = 50 m
OD = 9.5 m
WT = 110 mm
Emb. depth = 30 m

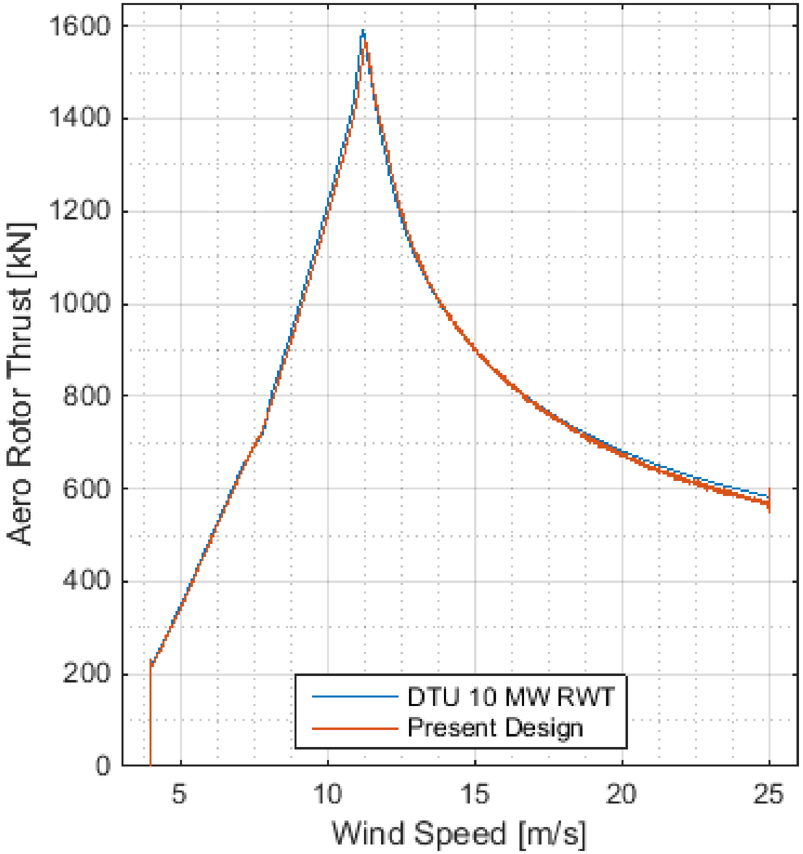
10.0 m / 120 mm
30 m

9.5 m / 110 mm
30 m

Global Performance



Power curve

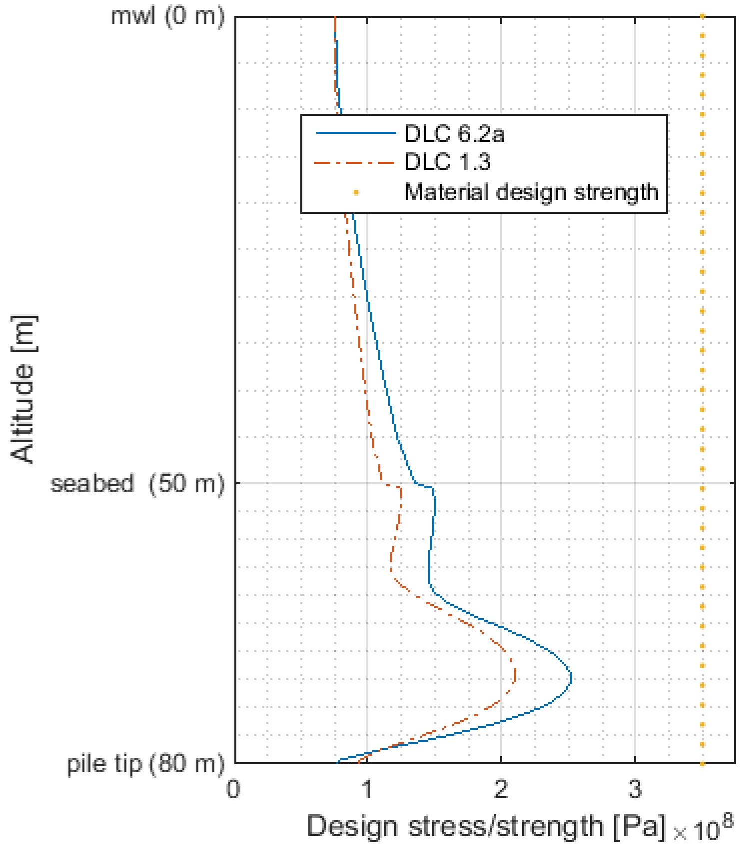


Aero rotor thrust curve

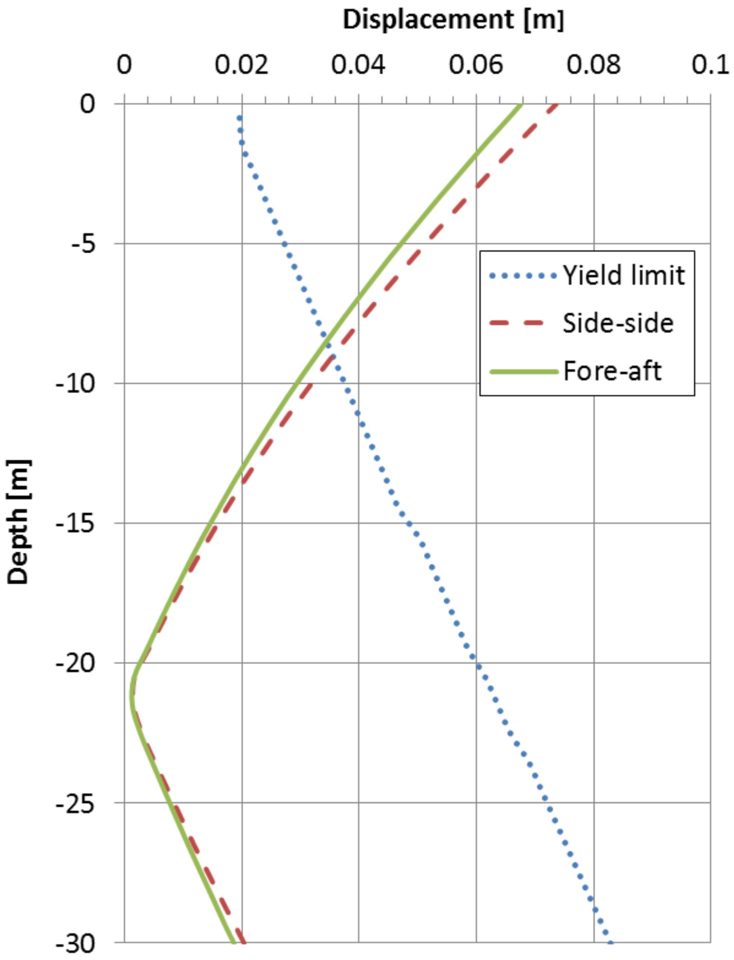
Ultimate Limit state: Load cases and Stress vs strength

DLC 1.3: Ultimate loading resulting from extreme turbulence conditions with normal sea states.

DLC 6.2a: Ultimate loading resulting from turbulent extreme wind model with extreme sea states, coupled with loss of electrical power.



Ultimate Limit state: soil plasticization



Perturbation Analysis: Definition

- **Baseline** – Toe as joint with restrained yaw and vertical motions. Contribution of axial skin friction. Wall thickness: 110 mm. Embedded depth: 30 m. Soil internal friction angle: 35^0.

- Perturbation A – **Toe boundary condition**. The pile tip is fixed, i.e. all degrees of freedom are restrained.

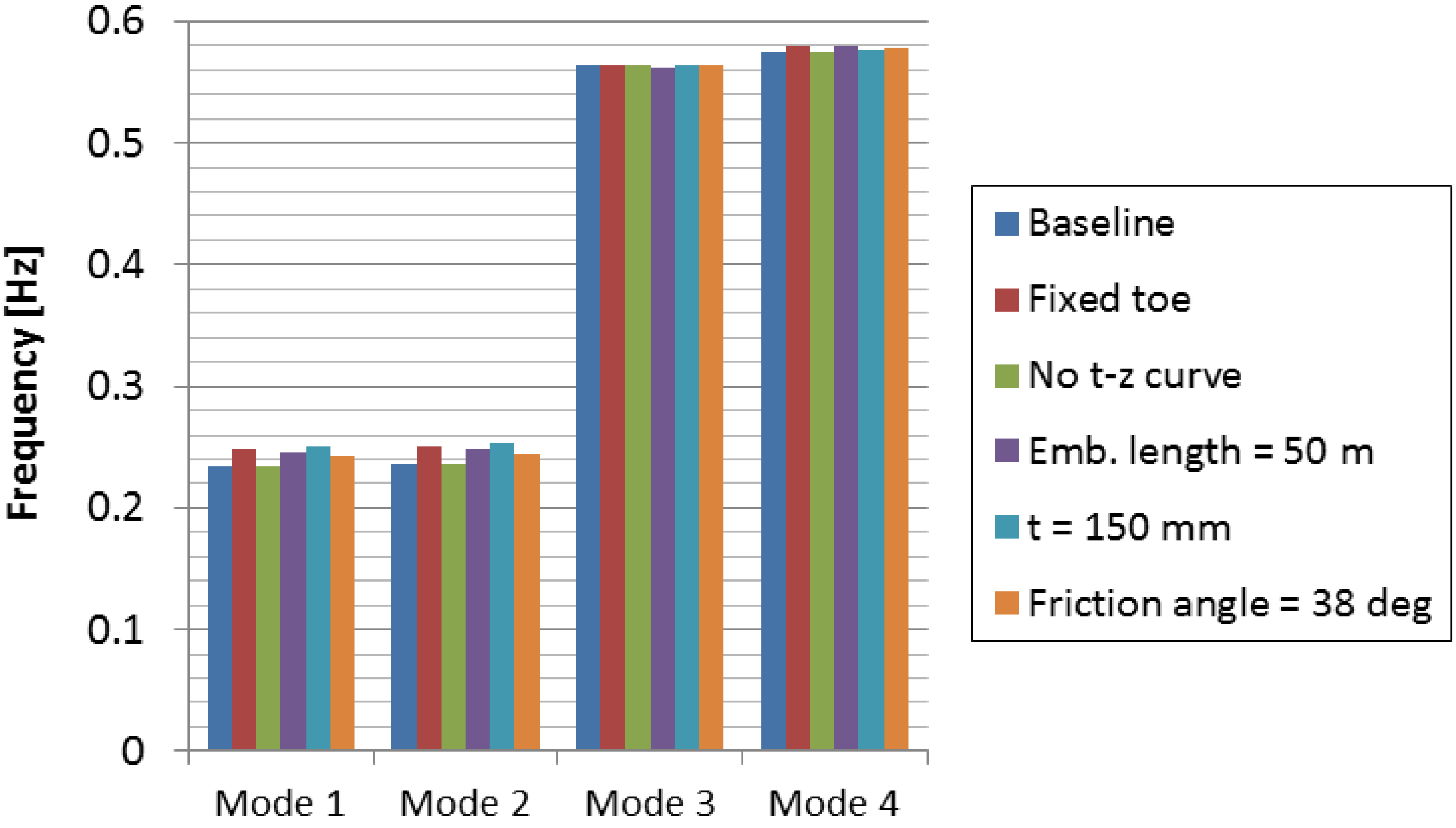
- Perturbation B – **Axial skin friction contribution**. The contribution of skin friction to the pile axial equilibrium has been annihilated.

- Perturbation C – **Deeper pile**. The embedded length of the pile has been changed from 30 m to 50 m.

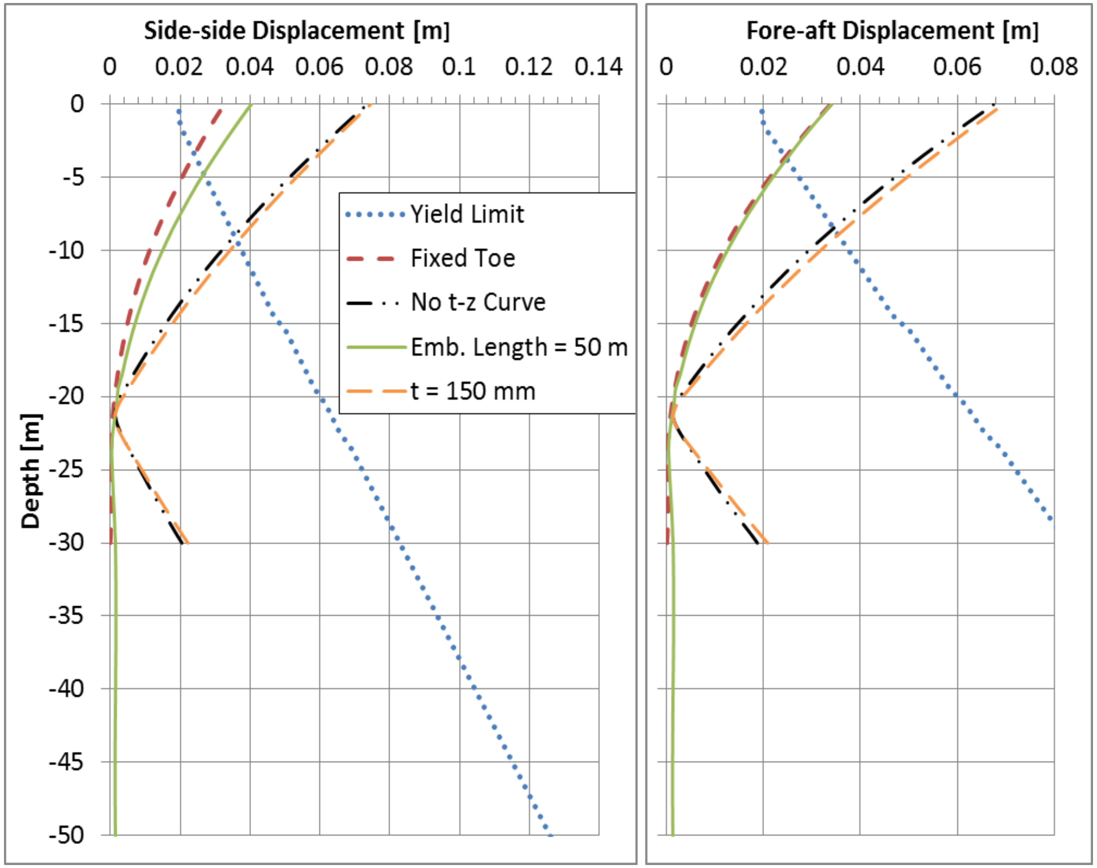
- Perturbation D – **Thicker wall**. The wall thickness has been increased to 150 mm.

- Perturbation E – **Soil friction angle**. The soil around the pile is set denser; its internal angle has been improved from 35^0 to 38^0.

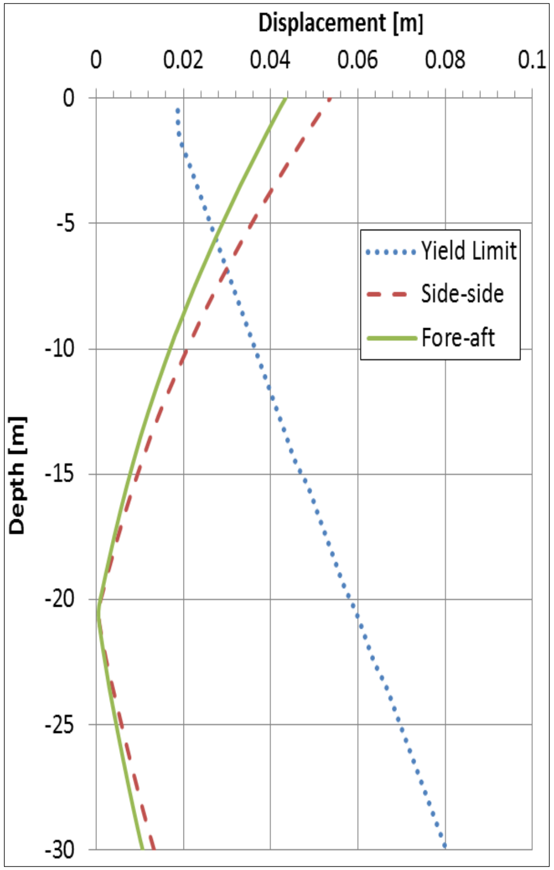
Perturbation Analysis: Dynamic stiffness



Perturbation Analysis: Deflection and plastic zone



Perturb. A, B, C, D



Perturb. E

Perturbation Analysis: Bill of material

Case	Baseline	A, B, E	C	D
Mass [t]	2700	2700	3210	3666
Rel. diff. [%]	-	0.00	18.87	35.78

Perturbation Analysis: Ultimate loads

At the interface

	Fres [kN]	Fz [kN]	Mres [kNm]	Mz [kNm]
Baseline	3500	13000	290000	-38000
Pert. A	0.0%	0.0%	3.4%	36.8%
Pert. B	0.0%	0.0%	0.0%	-234.2%
Pert. C	-2.9%	7.7%	-3.4%	-415.8%
Pert. D	-2.9%	0.0%	3.4%	-218.4%
Pert. E	2.9%	0.0%	3.4%	36.8%

At the mudline

	Fres [kN]	Fz [kN]	Mres [kNm]	Mz [kNm]
Baseline	11000	40000	730000	-38000
Pert. A	0.0%	0.0%	2.7%	39.5%
Pert. B	9.1%	0.0%	0.0%	-236.8%
Pert. C	9.1%	0.0%	8.2%	-442.1%
Pert. D	0.0%	17.5%	2.7%	-221.1%
Pert. E	9.1%	0.0%	5.5%	39.5%

Discussion

- Similar dynamic stiffness but different lateral deformations
- Increase wall thickness is inefficient
- Axial skin friction is non-influential
- Fixed toe may be misrepresentative

Conclusion

- Distribute flexural stiffness along the whole length – Tower Change.
- Start with the traditional procedure, and progressively adjust the design parameters.
- Target the centre of the soft-stiff range – resulting lateral deformations will be moderate.
- Mind the soil status – consider monopile deepening.

THANK YOU
FOR YOUR ATTENTION

Medium size turbine

	Initial design estimate:	**Final design:**
Outer diameter	8.0 m	8.0 m
Wall thickness	100 mm	120 mm
Embedded part	50.0 m	30.0 m

Wall thickness [mm]	**Eigen frequencies [Hz]**			
	Mode 1	Mode 2	Mode 3	Mode 4
90	0.224	0.227	0.544	0.584
100	0.229	0.232	0.545	0.584
120	**0.238**	**0.242**	**0.546**	**0.585**

Embedded length [m]	**Eigen frequencies [Hz]**			
	Mode 1	Mode 2	Mode 3	Mode 4
25.00	0.218	0.221	0.548	0.580
30.00	**0.227**	**0.230**	**0.548**	**0.587**
50.00	0.238	0.242	0.546	0.585

Geometry design

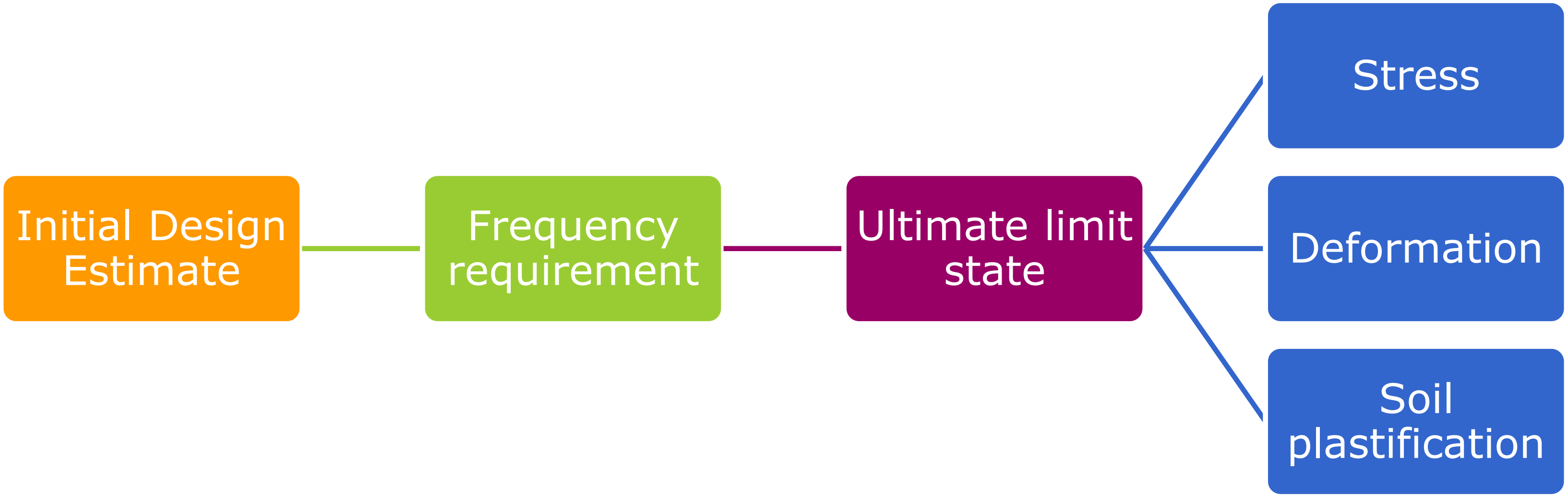
	Initial design estimate:	**Final design:**
• Outer diameter	10.0 m	9.5 m
• Wall thickness	120 mm	110 mm
• Embedded part	30.0 m	30.0 m

Outer diameter [m]	**Eigen frequencies [Hz]**			
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
9.50	**0.218**	**0.267**	**0.548**	**0.564**
10.00	0.225	0.227	0.549	0.565

Tower type and mass [t]	**Eigen frequencies [Hz]**			
	Mode 1	Mode 2	Mode 3	Mode 4
A: 426.293	0.218	0.267	0.548	0.564
B: 511.131	**0.239**	**0.241**	**0.563**	**0.576**

Wall thickness [mm]	**Eigen frequencies [Hz]**			
	Mode 1	Mode 2	Mode 3	Mode 4
110	**0.234**	**0.236**	**0.563**	**0.575**
120	0.239	0.241	0.563	0.576

Conclusion



Initial Design Estimate

Frequency requirement

Ultimate limit state

Stress

Deformation

Soil plastification