KIC InnoEnergy

Renewable Energy

The Leading Engine for Innovation and Entrepreneurship in Sustainable Energy

AFOSP: Alternative Floating Platform Designs for Offshore Wind Towers using Low Cost Materials

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Universität Stuttgart

gasNatural fenosa

1.- **Project overview**

1.1 Why a floating platform?
1.2 Goal of the project
1.3 Project Consortium and Tasks Allocation
1.4 Main results

2.- **Technical approach**

2.1 Why concrete
2.2 Design process
2.3 Verification: Experiments & Simulation
2.4 Construction & Installation

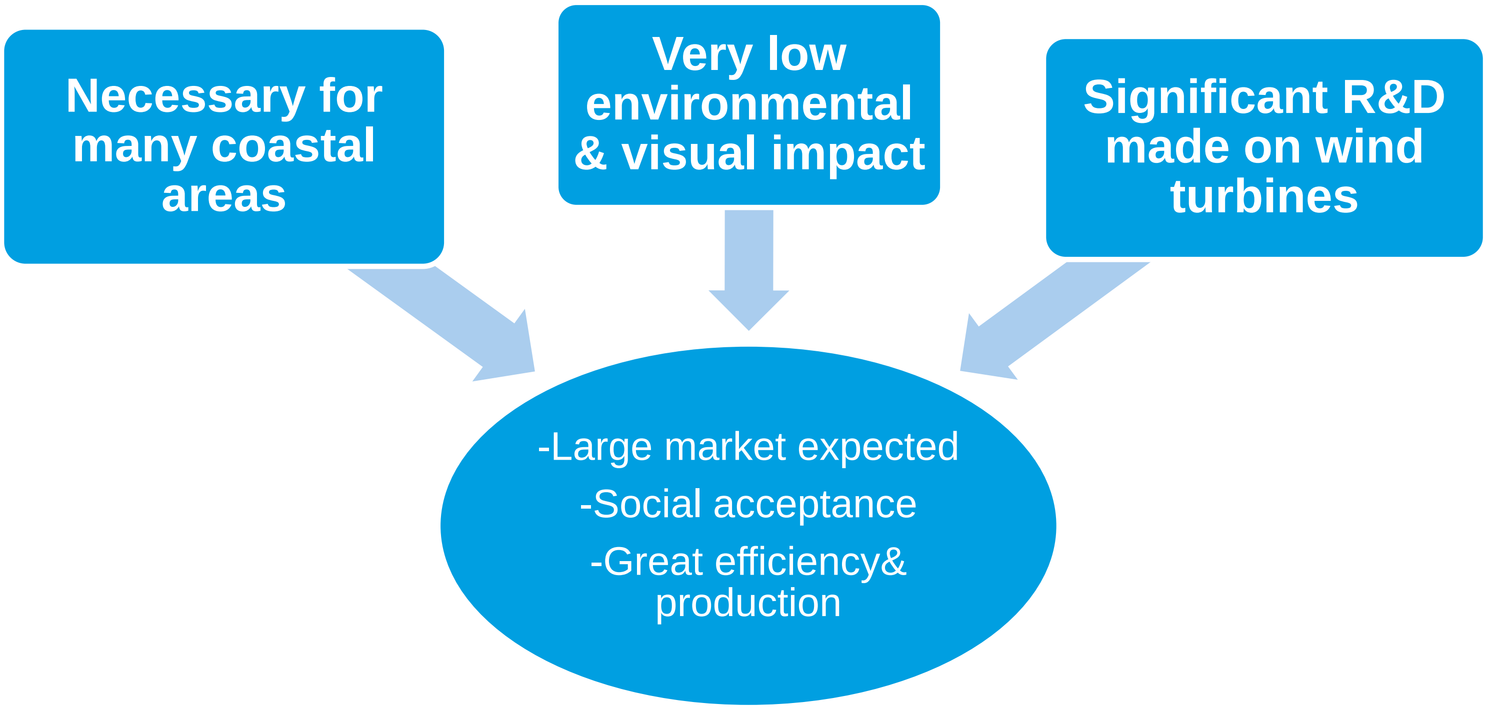
3.- **Conclusions**

4.- **Q&A**

Innovation project AFOSP

1.1 Why a floating platform?

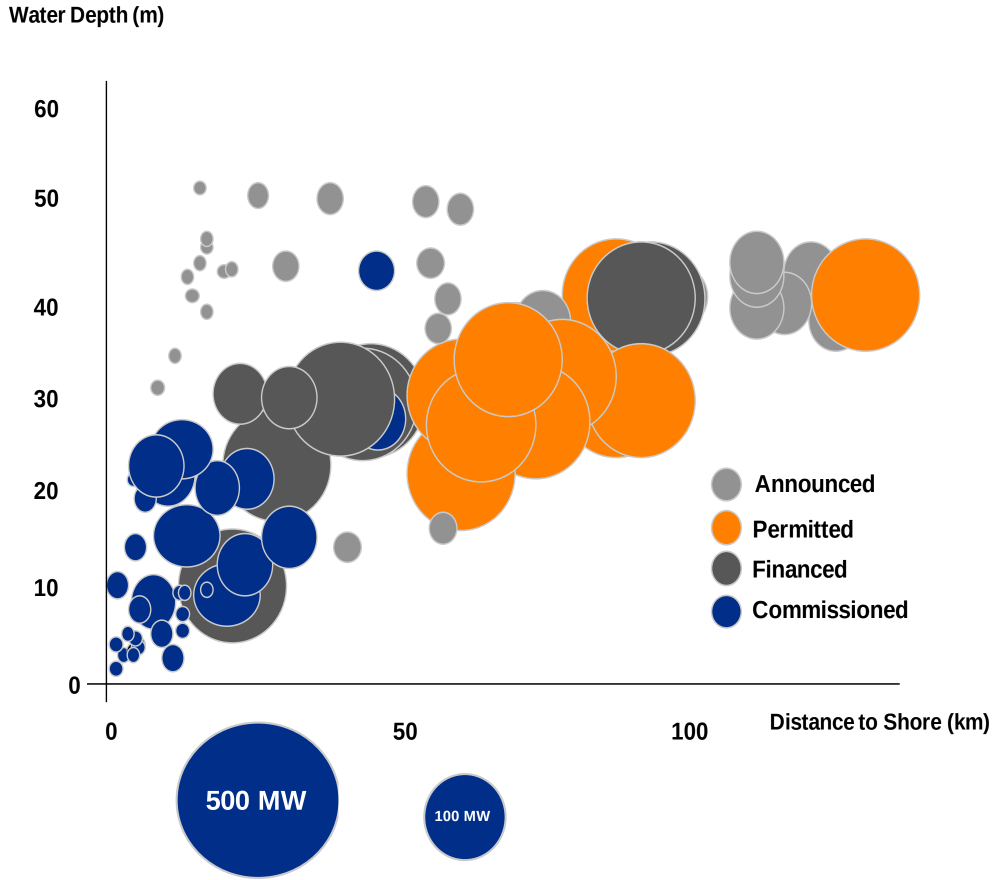
Floating offshore wind turbine support structure, WHY?

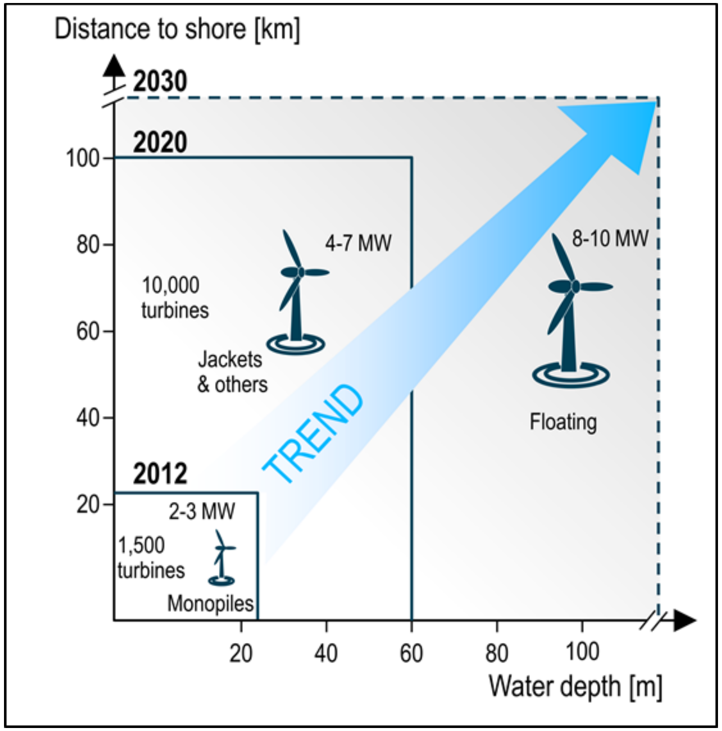


Importance to bring new low-cost prototypes to industry

Offshore Deep Water Market Overview

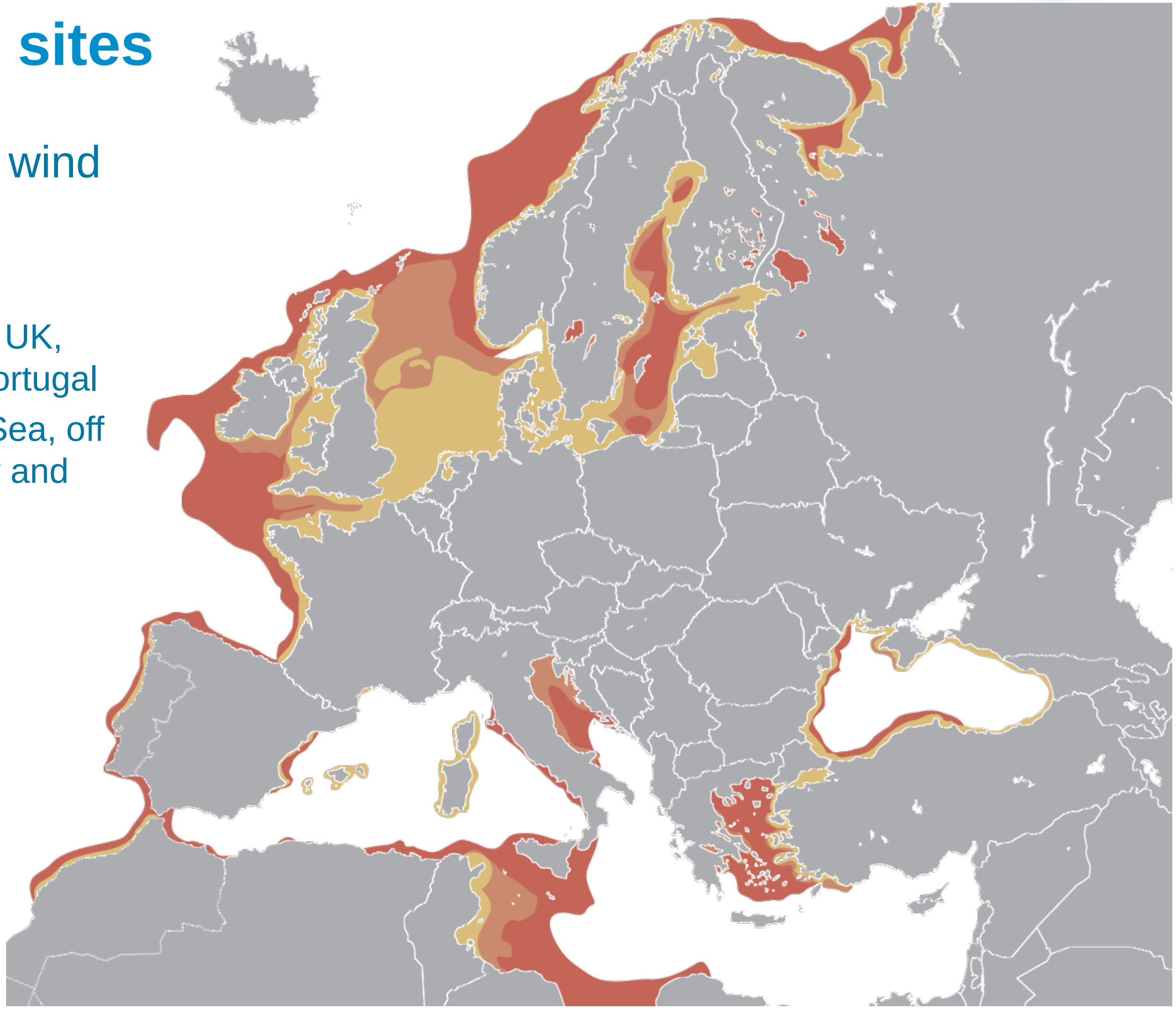
Projects Status
2001 - 2015





Potential: Suitable sites

- Hotspots for floating wind developments:
- **In Europe:**
  - Towards the Atlantic: UK, Ireland, Spain and Portugal
  - The Northern North Sea, off the coasts of Norway and the UK
- **The US**
- **Japan**



0-50 m
50-100 m
100+ m

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Design and construct a scale prototype
Alternative material: CONCRETE

\+

Proof of concept design
Laboratory tests
Coupled simulations

=

Proved design floating platform
↓↓€ct/kWh

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Innovation project AFOSP

1.3 Project Consortium and Task Allocation

Partners

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- Industrial partner
- Engineering *know-how*
- *Project management*

Universität Stuttgart

- Advanced design tools
- Expertise in coupled integrated IEC DLC simulations

Universitat Politècnica de Catalunya – BarcelonaTech (UPC)

- Expertise in structural and maritime engineering
- Large wave channel for scale model testing

PROJECT SUPPORTED BY KIC INNOENERGY

eit Knowledge & Innovation Community – KIC InnoEnergy

Governance

Project Agreement → CA Consortium Agreement → License Agreement

- Project Agreement: Management structure
- CA Consortium Agreement: Project background/foreground
- License Agreement: Exploitation foreground

Innovation project AFOSP

1.3 Project Consortium and Task Allocation

Planning

AFOSP: Project Schedule

WP0 Project Management & Communication

GNF
- T01- Market Analysis & Business Opportunities
- T02- Education coordination
- T03- Management, Dissemination & Reporting

WP1 Analysis of the State of the Art

USTUTT
- T11- State of Art Floating Platforms Concepts
- T12- State of Art Application of cost effective

WP2 Prototype Conceptual Design

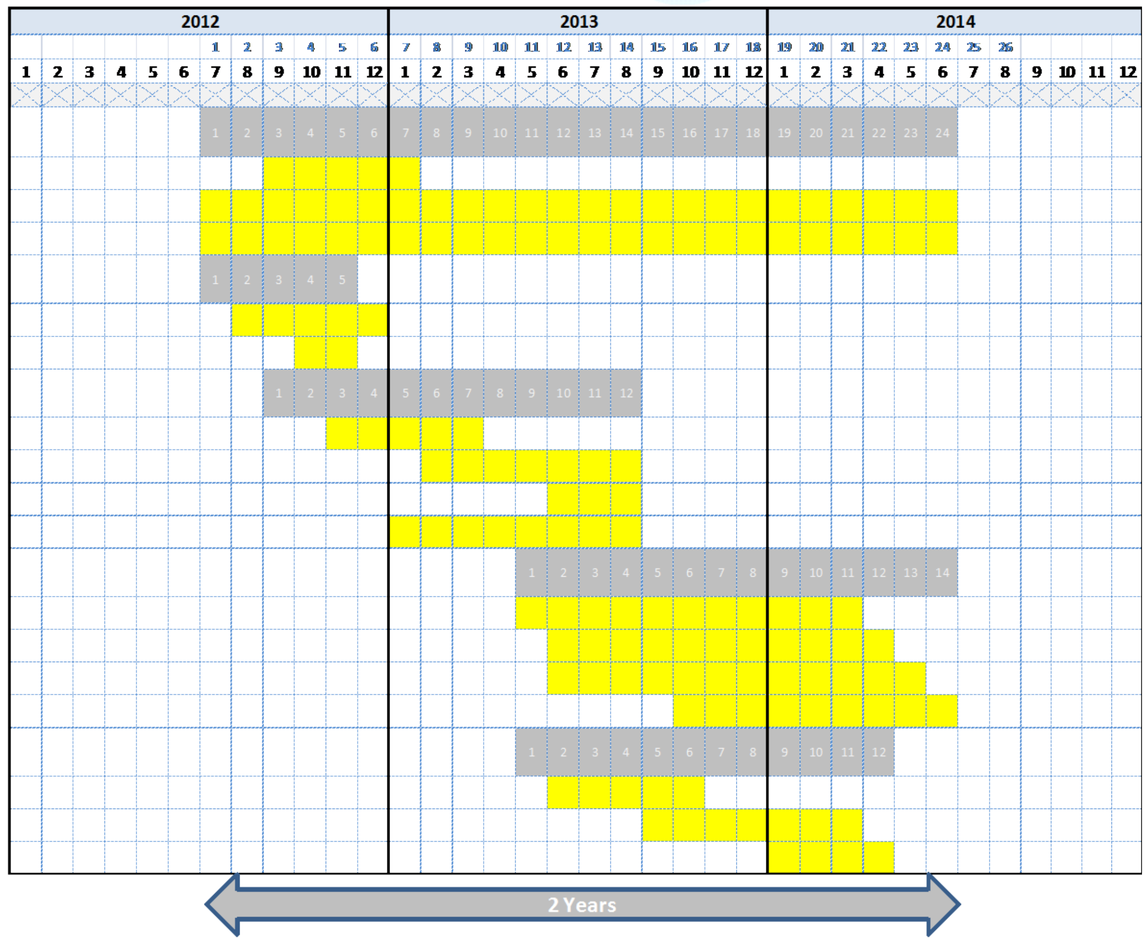
UPC
- T21- Study of Altrenative Materials and Platform
- T22- Predimensioning of prototype with Forces
- T23- Definition of Mooring Lines and Anchors
- T24- Definition of Control Strategy for a Floating

WP3 Prototype Verification

USTUTT
- T31- Model Setup
- T32- Loads Analysis
- T33- Feedback Loop
- T34- Comparisson of Scaled Test Results from WP4

WP4 Scaled Testing

UPC
- T41- Selection of the definitive Scale Model
- T42- Laboratory Test on the Model
- T43- Conclusion



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1.4 Main results

GNF — WP0
- Market Analysis
- LCOE analysis

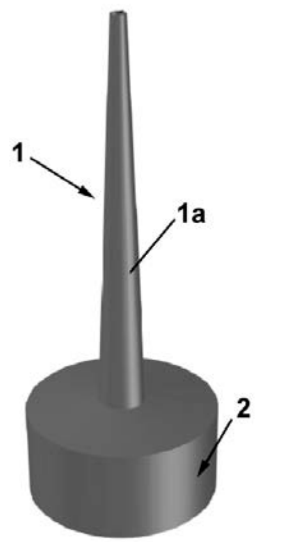
USTUTT — WP1
- Analysis of state of the art

UPC — WP2
- Prototype pre-design

→ Patented design

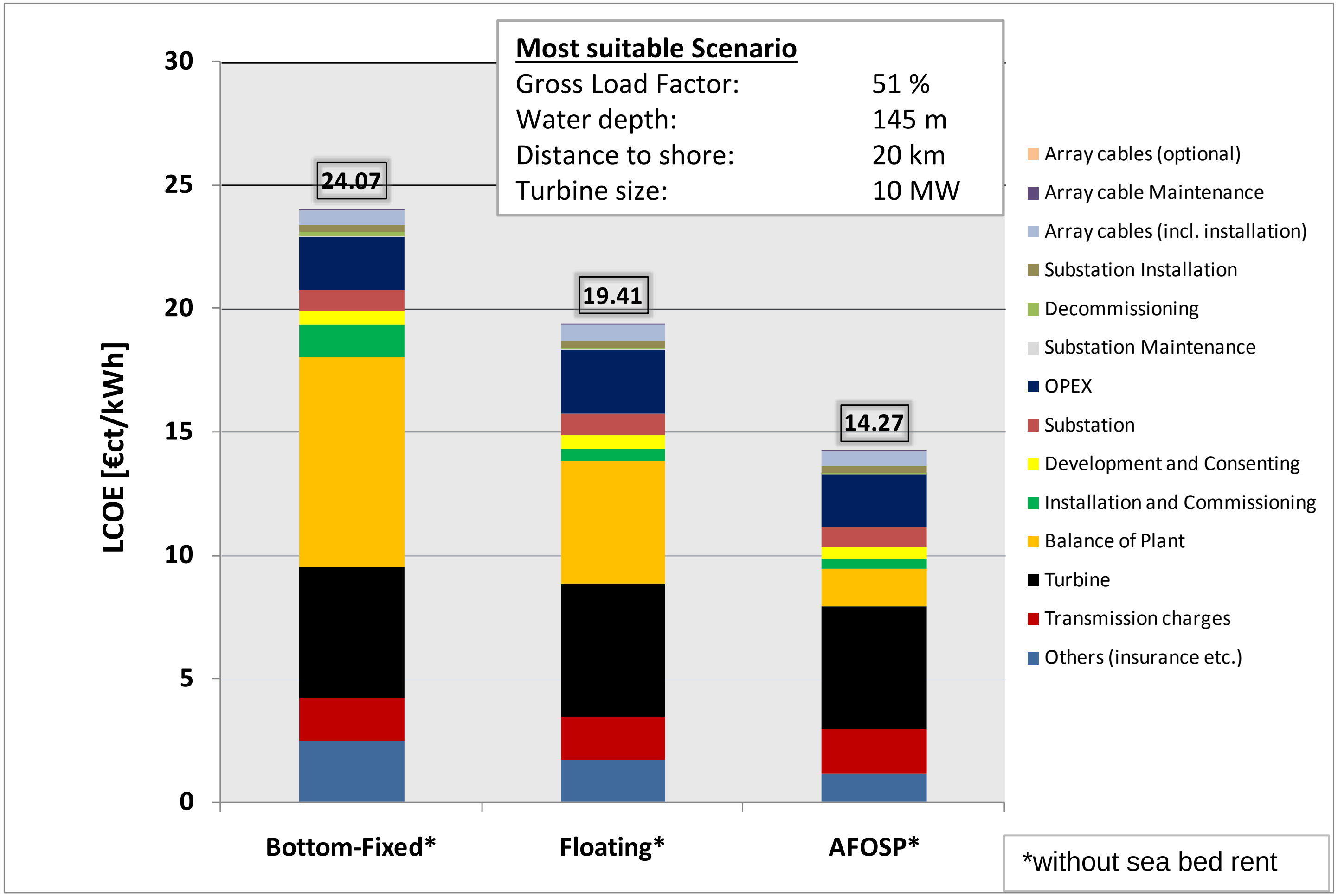
USTUTT — WP3
- Behavior of platform in coupled aero-hydro-servo-elastic simulations

UPC — WP4
- Verification of scaled model prototype in laboratory channel



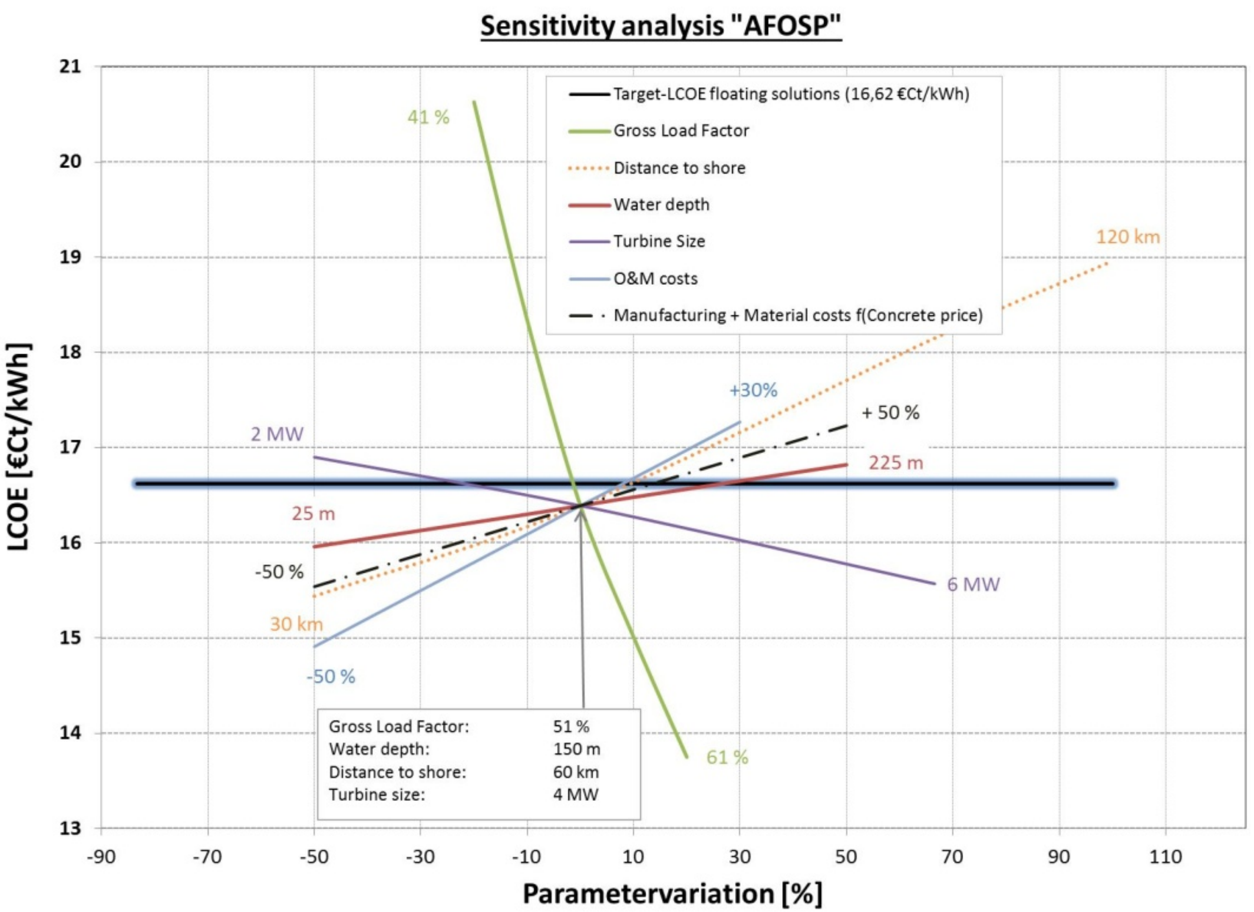
LCOE Analysis

The levelized cost of electricity (LCOE):
The cost of an electricity generation project over its lifetime in €/kWh, taking into account the present value of all the cost components (CAPEX & OPEX)



Innovation project AFOSP
1.4 Main results

- Sensitivity analysis



➡ Large dependency on the energy production and turbine size

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2.1 Why concrete?

- Significant CAPEX costs reduction against other steel floating solutions
- Almost free of maintenance platform, reducing OPEX costs
- Higher resistance to fatigue loads and marine environment, lifetime protracted to 50 years
- Avoids joints between the tower and the floater, which are very sensible to fatigue loads
- Easy to build at large scale

2.1 Why concrete? Cost comparisson

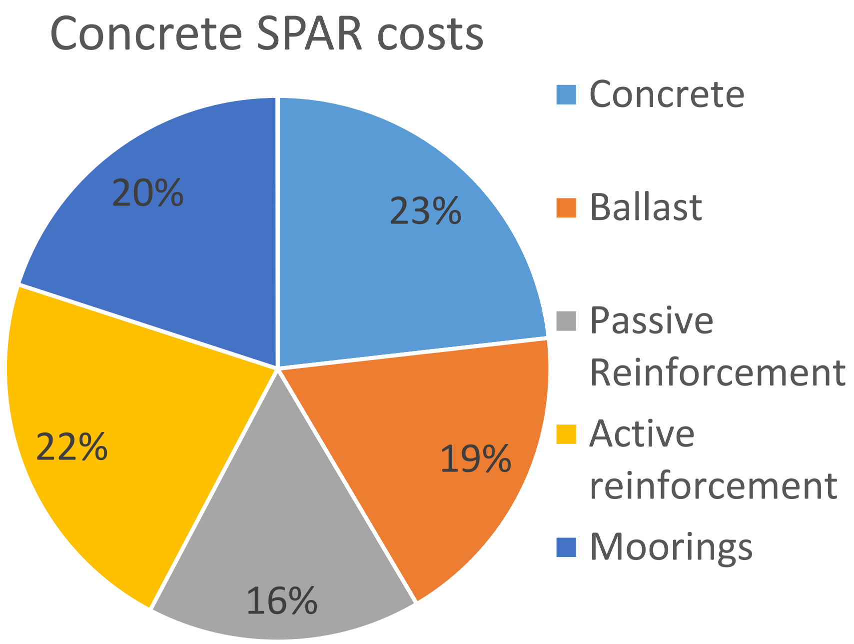
	Steel	Concrete
Diameter [m]	11.5	13
Water displ [m3]	1.297e+04	2.097E+04
Draft [m]	125	158
Structure mass [kg]	3.246E+06	1.219E+07
Ballast mass [kg]	9.698E+06	8.957E+06
RNA height (AMSL) [m]	87,6	87,6

Main design criteria

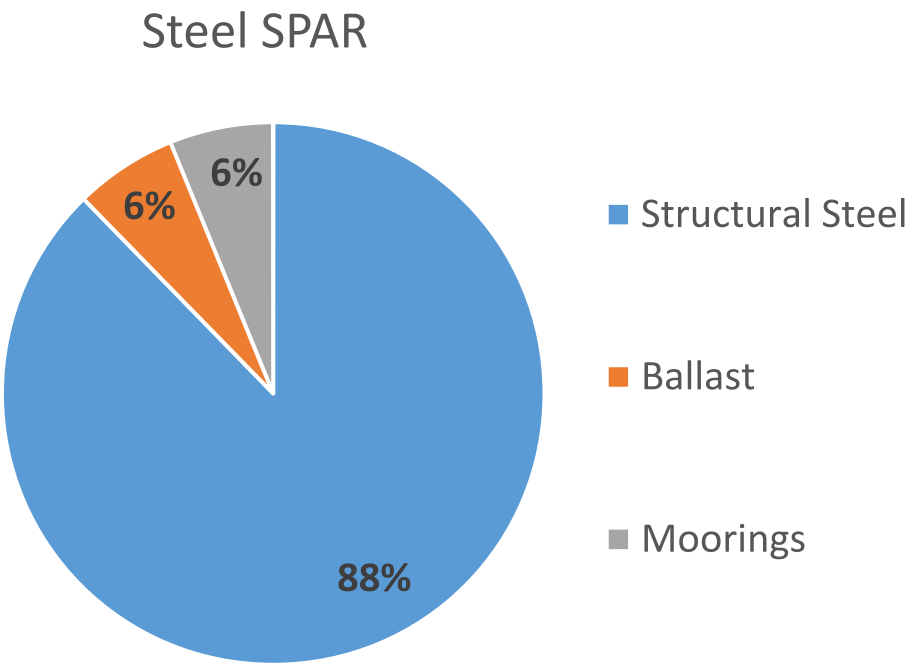
- Rotor weight 3.500 kN.
- Mean Thrust force 1.700 kN.
- Max. static tilt 5º.

Unit / Platform Type	Steel SPAR	Concrete SPAR
Concrete	--	795,000.00 €
Structural Steel	9,738,000.00 €	--
Ballast	678,860.00 €	626,990.00 €
Passive Reinforcement	--	556,500.00 €
Active reinforcement	--	763,200.00 €
Mooring lines	685,314.00 €	685,314.00 €
TOTAL	11,102,174.00 €	3,427,004.00 €

2.1 Why concrete? Cost comparison



3,427,004.00 €



11,102,174.00 €

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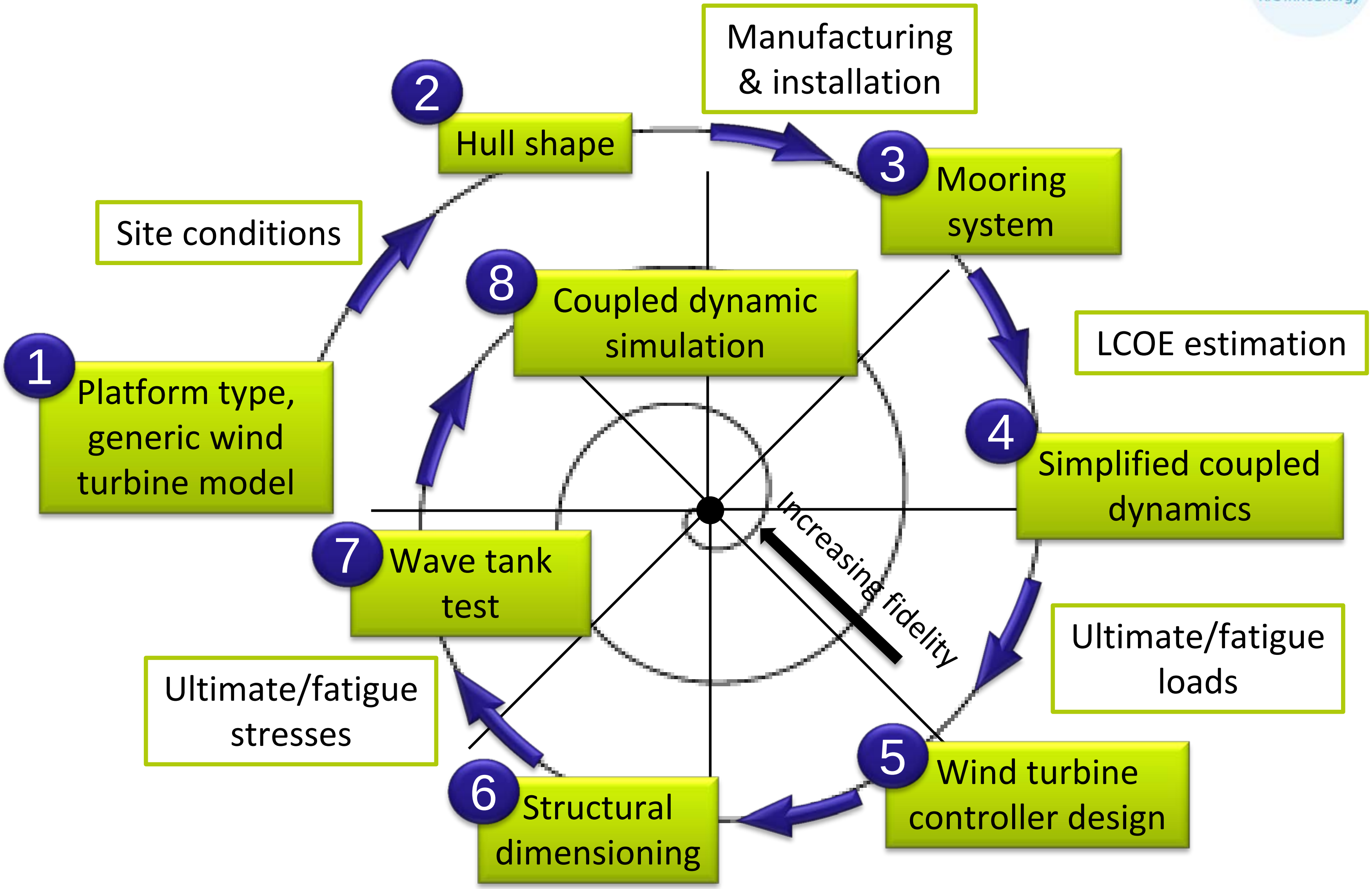
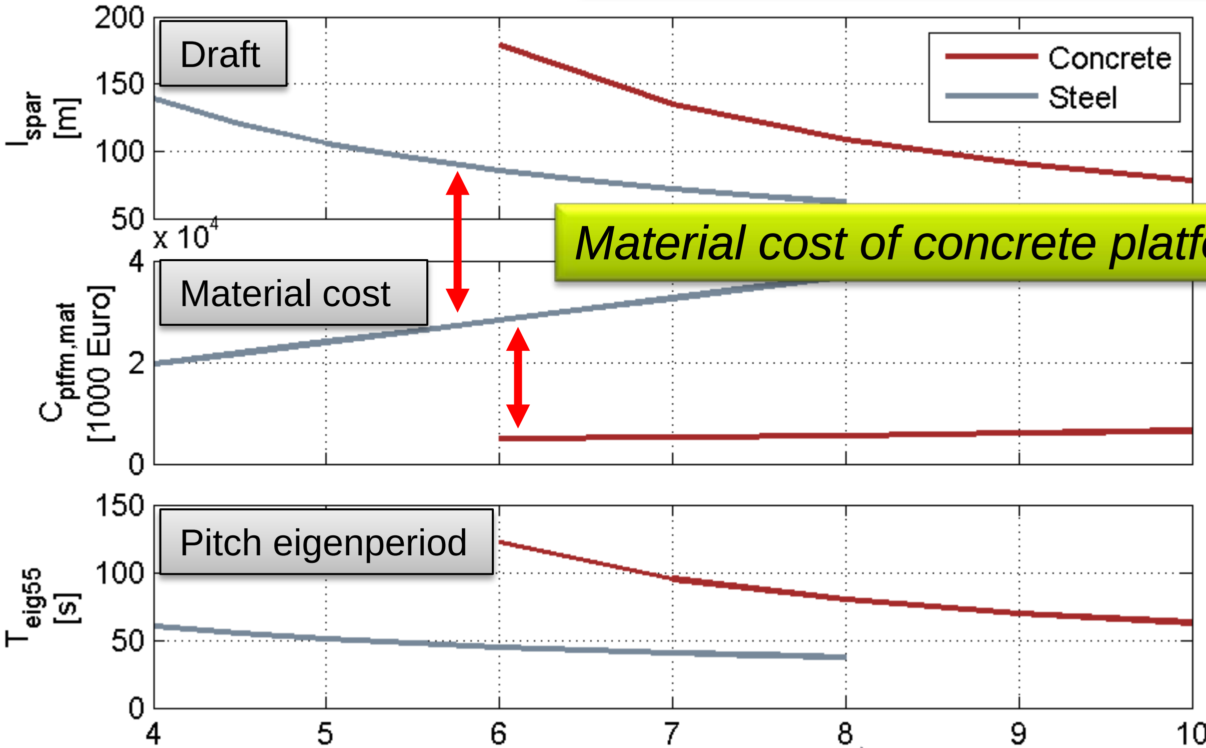

1
Platform type, generic wind turbine model
Site conditions
2
Hull shape
Manufacturing & installation
3
Mooring system
LCOE estimation
4
Simplified coupled dynamics
Ultimate/fatigue loads
5
Wind turbine controller design
6
Structural dimensioning
Ultimate/fatigue stresses
7
Wave tank test
8
Coupled dynamic simulation
Increasing fidelity

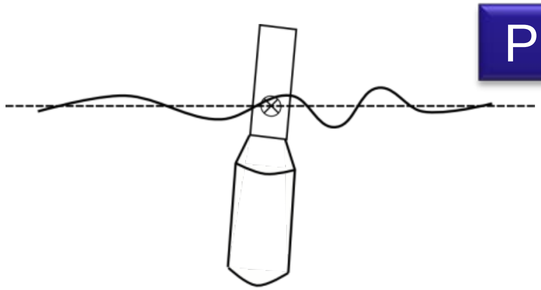
Spar hull design space

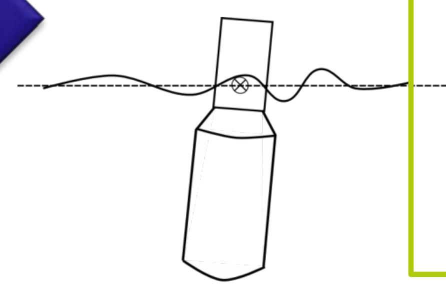
Cost increases with radius, draft decreases with radius

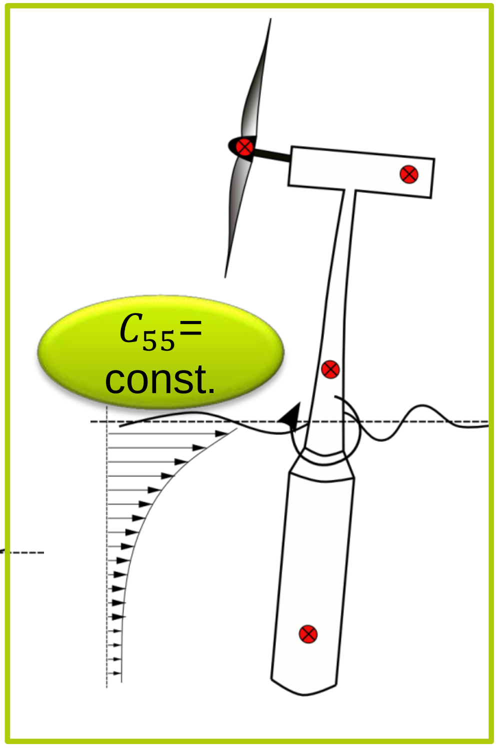


Material cost of concrete platform about 4 times smaller

Platform radius [m]



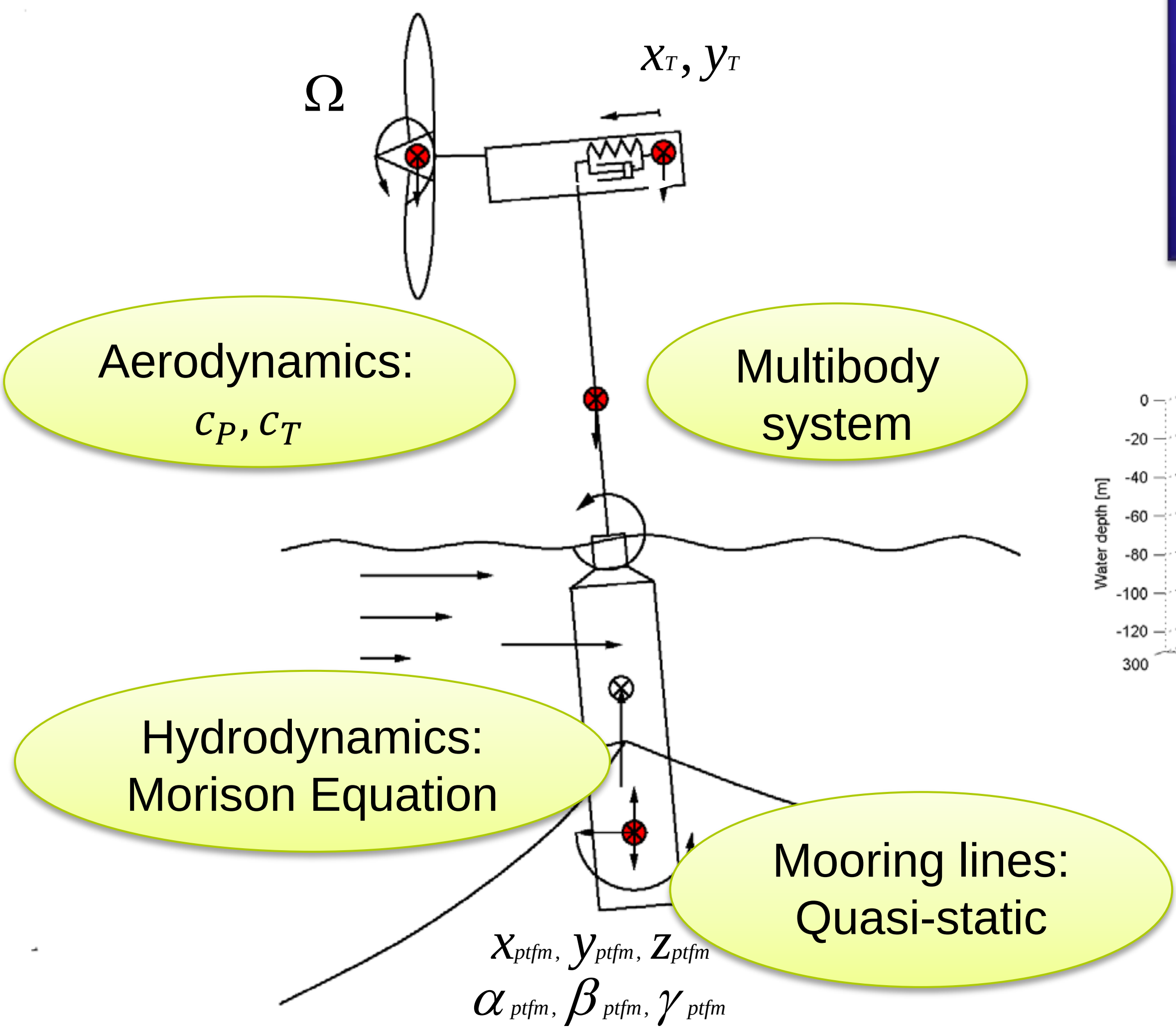




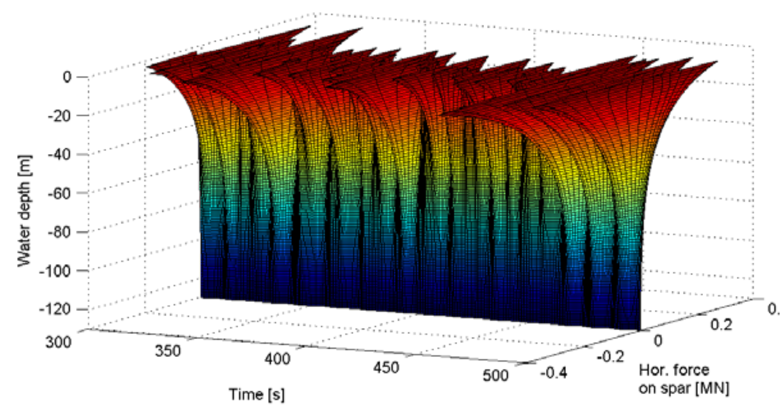
Innovation project AFOSP

2.2 Design process

Simplified dynamic simulation

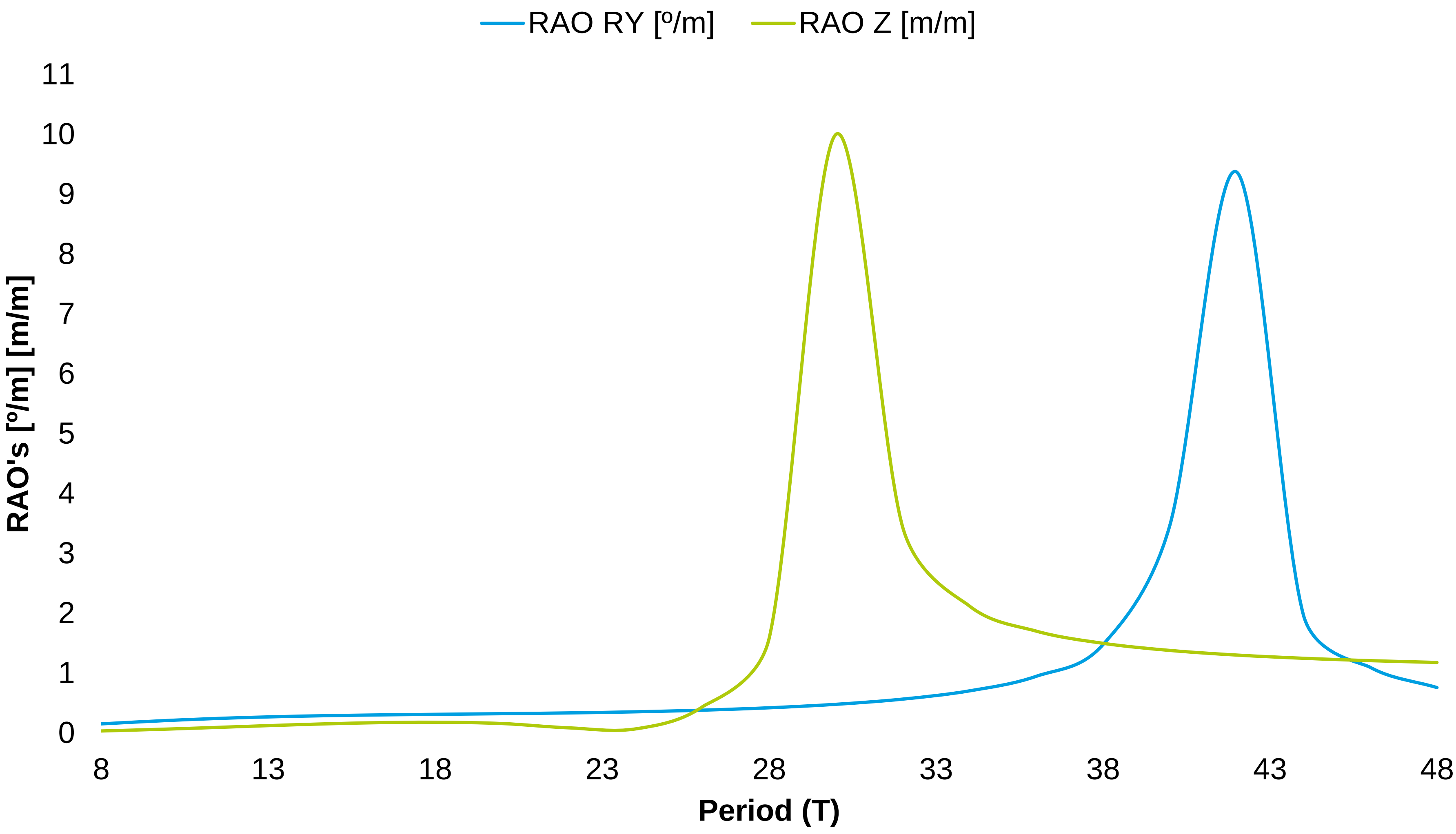


- 9 degrees of freedom
- Nonlinear
- Fully coupled
- Linearized for controller design

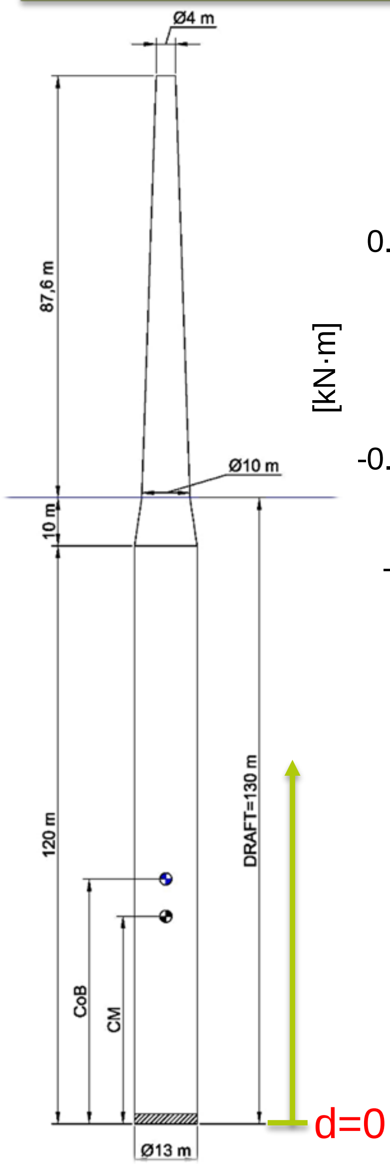


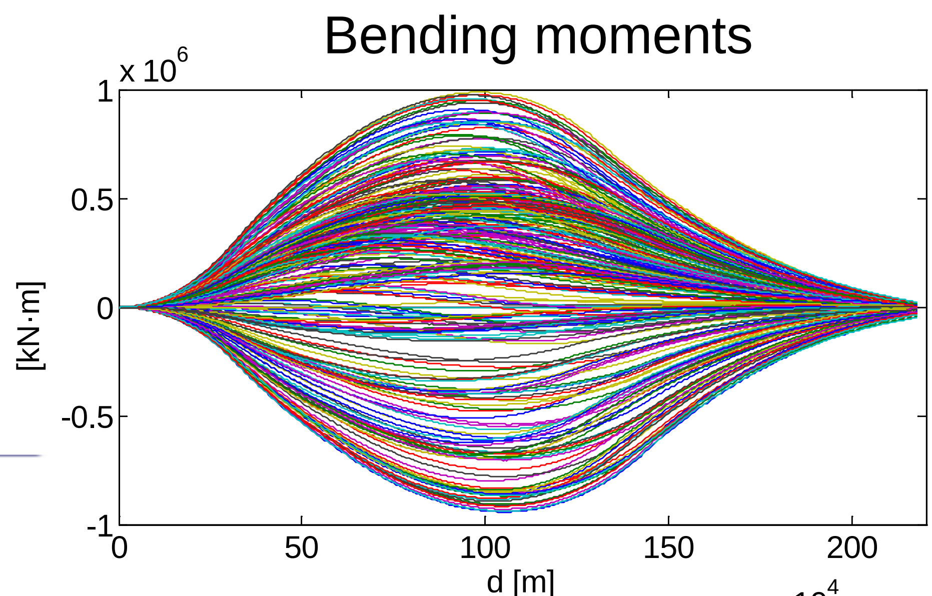
- ➢ Distributed external loads
- ➢ Ultimate/fatigue loads

RAOs

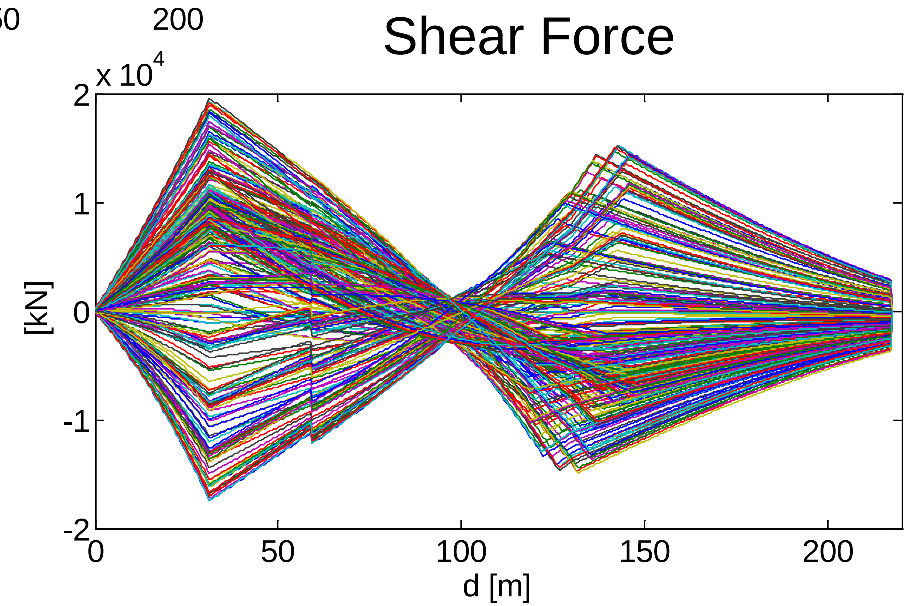

RAO RY [º/m]
RAO Z [m/m]
11
10
9
8
7
6
5
4
3
2
1
0
RAO's [º/m] [m/m]
8
13
18
23
28
33
38
43
48
Period (T)

Structural analysis

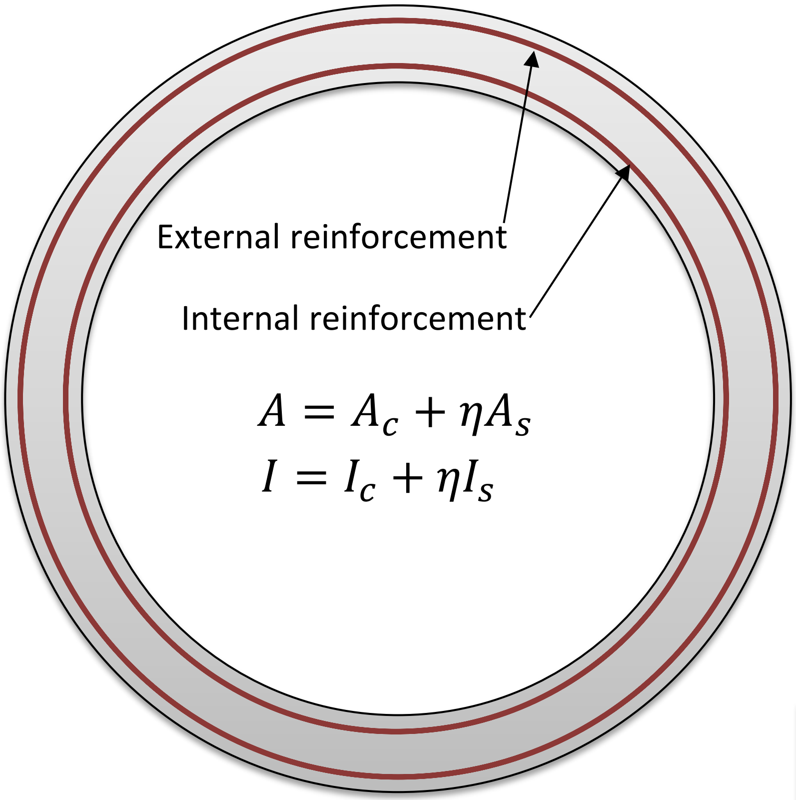




Limit State	SF
Ultimate Limit State	1.35
Fatigue Limit State	1.00



Structural analysis: ELU



$$A = A_c + \eta A_s$$
$$I = I_c + \eta I_s$$

EUROCODE-2

$$\sigma_{c,min} = \frac{N_k}{A} + \frac{\gamma_p P}{A} - \frac{M_k}{I} R_{ext}$$

$$0 \leq \sigma_c \leq 0.6 f_{ck}$$

MATERIAL	f_k	γ	f_d
Concrete	80 MPa	1.5	53.3 MPa
Prestressing steel	1,860 MPa	1.15	1617.4 MPa
Reinforcement steel	500 MPa	1.15	434.8 MPa

$$M_d \leq M_u$$

Section properties	Fp [kN]	Md [kN·m]	Mu [kN·m]
Floater	-359,652	1,055,000	1,167,000
Tower base	-394,740	843,100	912,000
Mid tower	-210,528	293,300	342,000

Structural analysis: Fatigue assessment

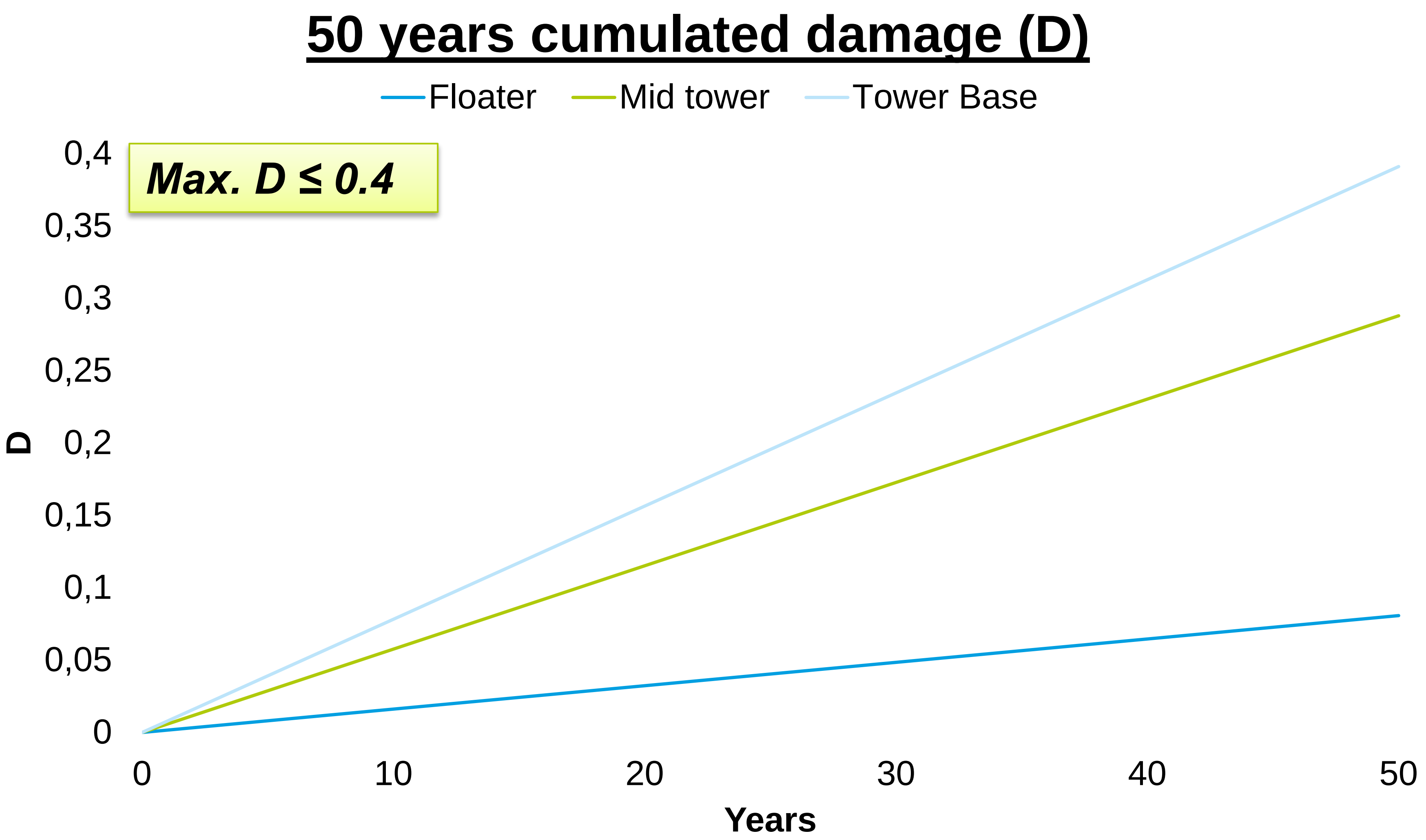
Fatigue Loadcase	Hs [m]	% Annual Time	Wind
50 year storm	13.8	0.02	Parked
1 year storm	10.8	0.08	Parked
1	2.5	68.8	≈14 m/s
2	3.0	19.5	≈14 m/s
3	5.0	10.7	≈14 m/s
4	7.0	0.8	Parked
5	9.0	0.2	Parked

DNV-OS-C502
LINEAR CUMULATIVE DAMAGE RULE

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \leq \eta$$

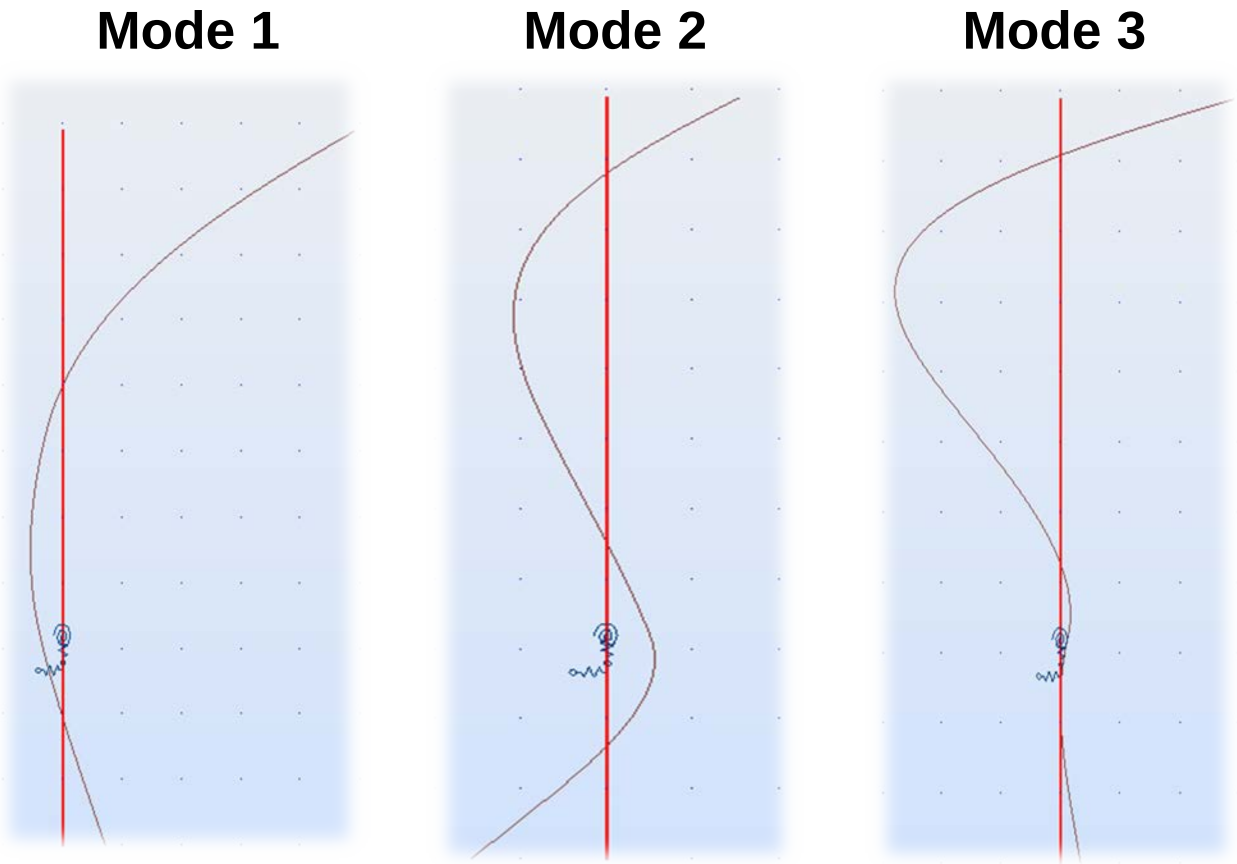
$$\log_{10} N = C_1 \frac{\left(1 - \frac{\sigma_{max}}{C_5 \cdot f_{rd}}\right)}{\left(1 - \frac{\sigma_{min}}{C_5 \cdot f_{rd}}\right)}$$

Structural analysis: Fatigue assessment



Structural analysis: Modal analysis

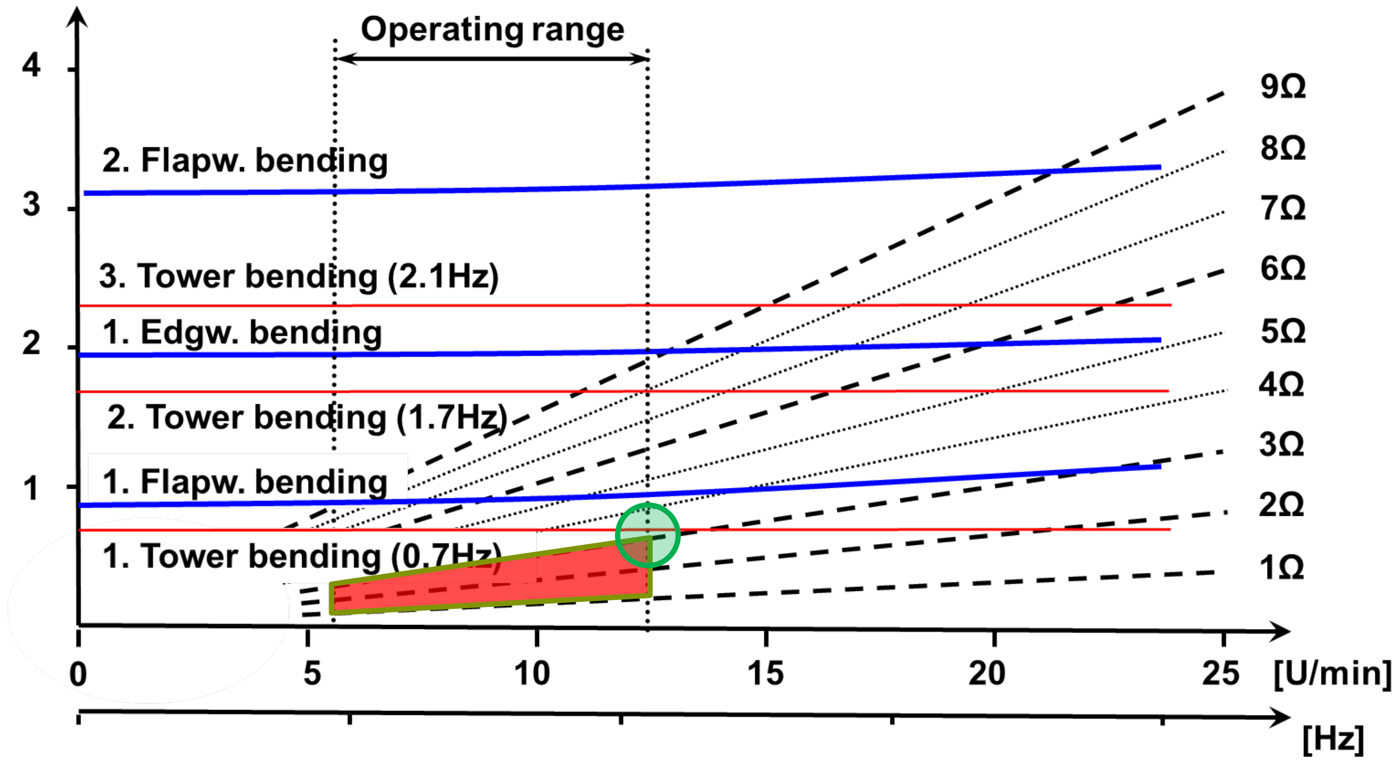
Modal shapes



Mode	Freq [Hz]	Period [s]
1	0.711	1.406
2	1.696	0.590
3	2.134	0.469

Structural analysis: Modal analysis

NREL 5MW WT Campbell diagram



1^{ST} STRUCUTRAL EIGENMODE FALLS OUT OF THE RANGE BETWEEN 1Ω & 3Ω

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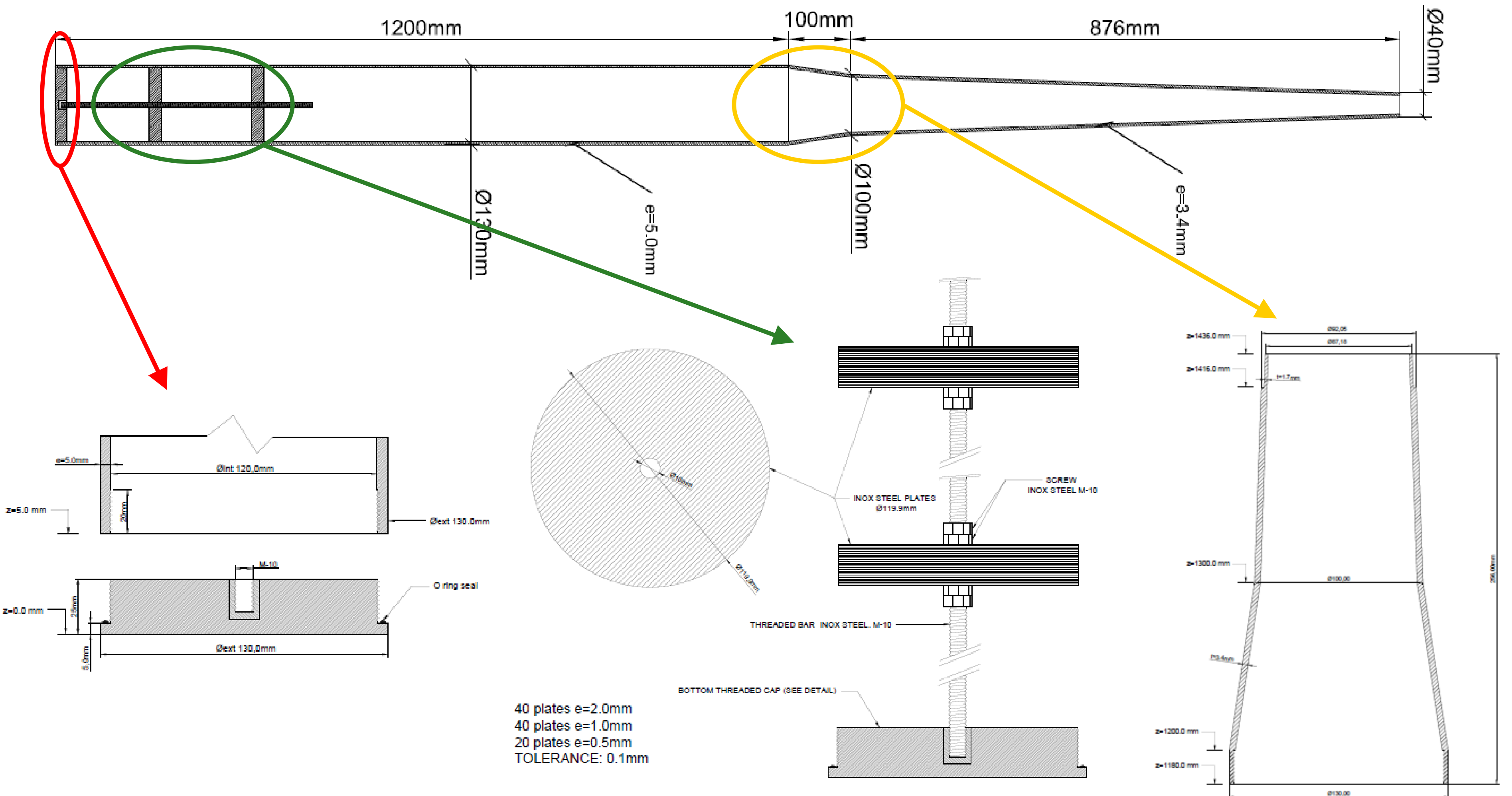
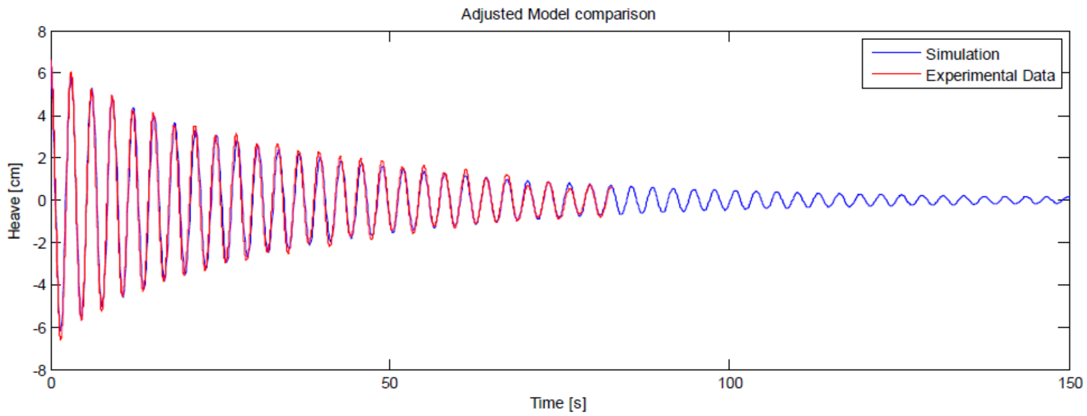
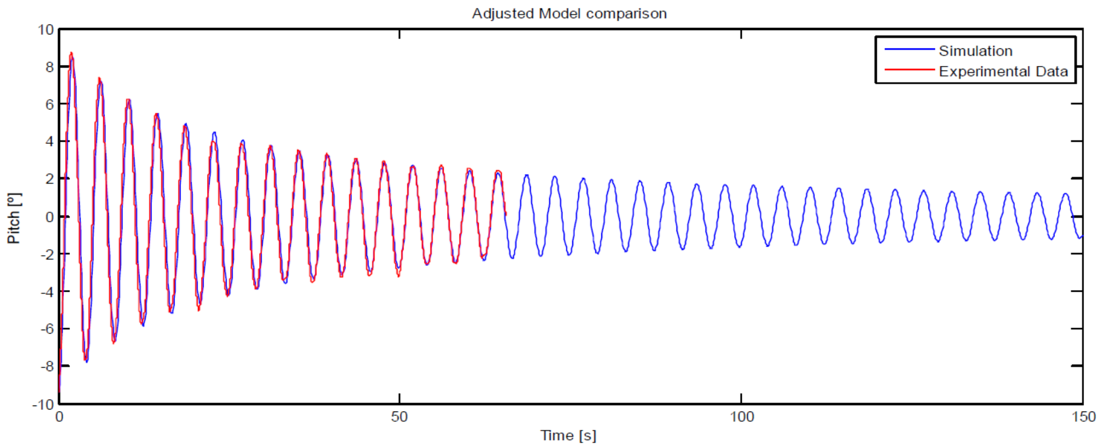
Froude similitude
Scale 1:100

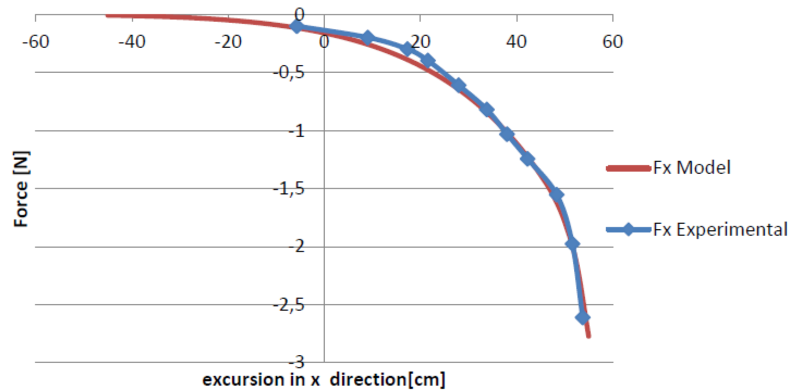


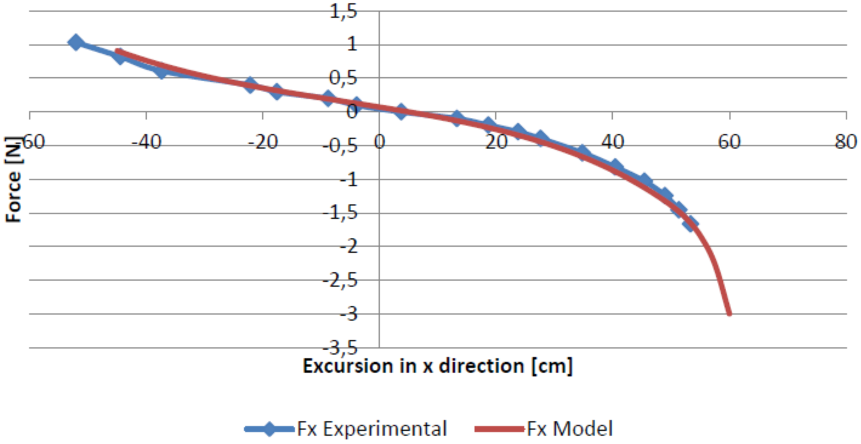
Scale testing: *Free decay tests*



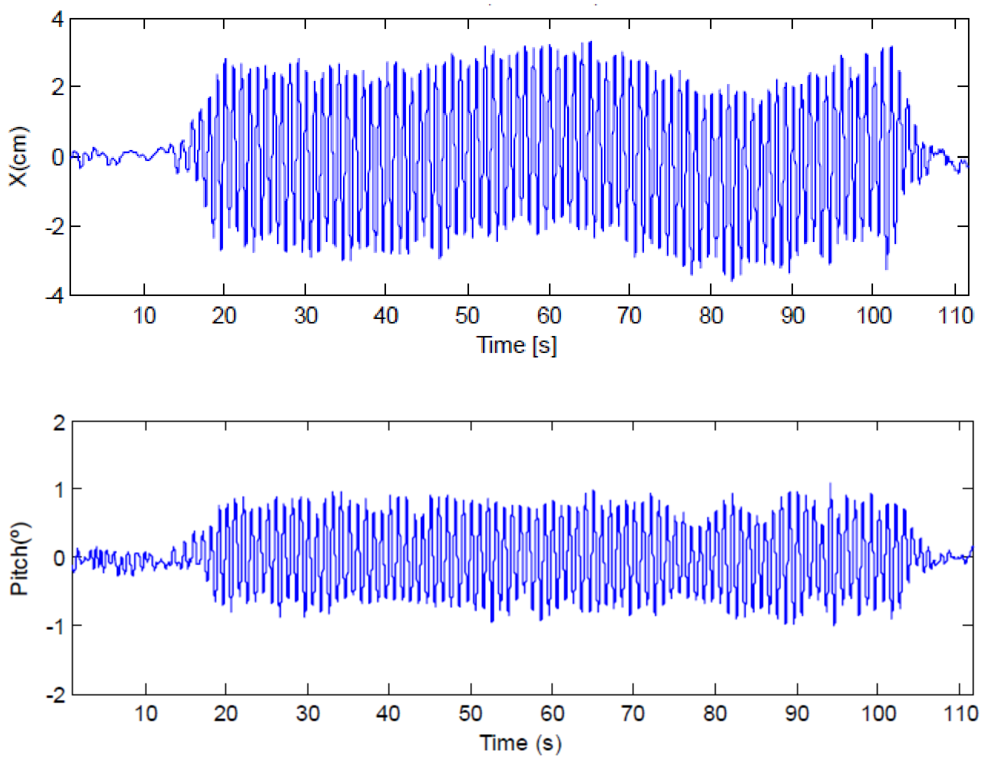


Scale testing: *Mooring system test*

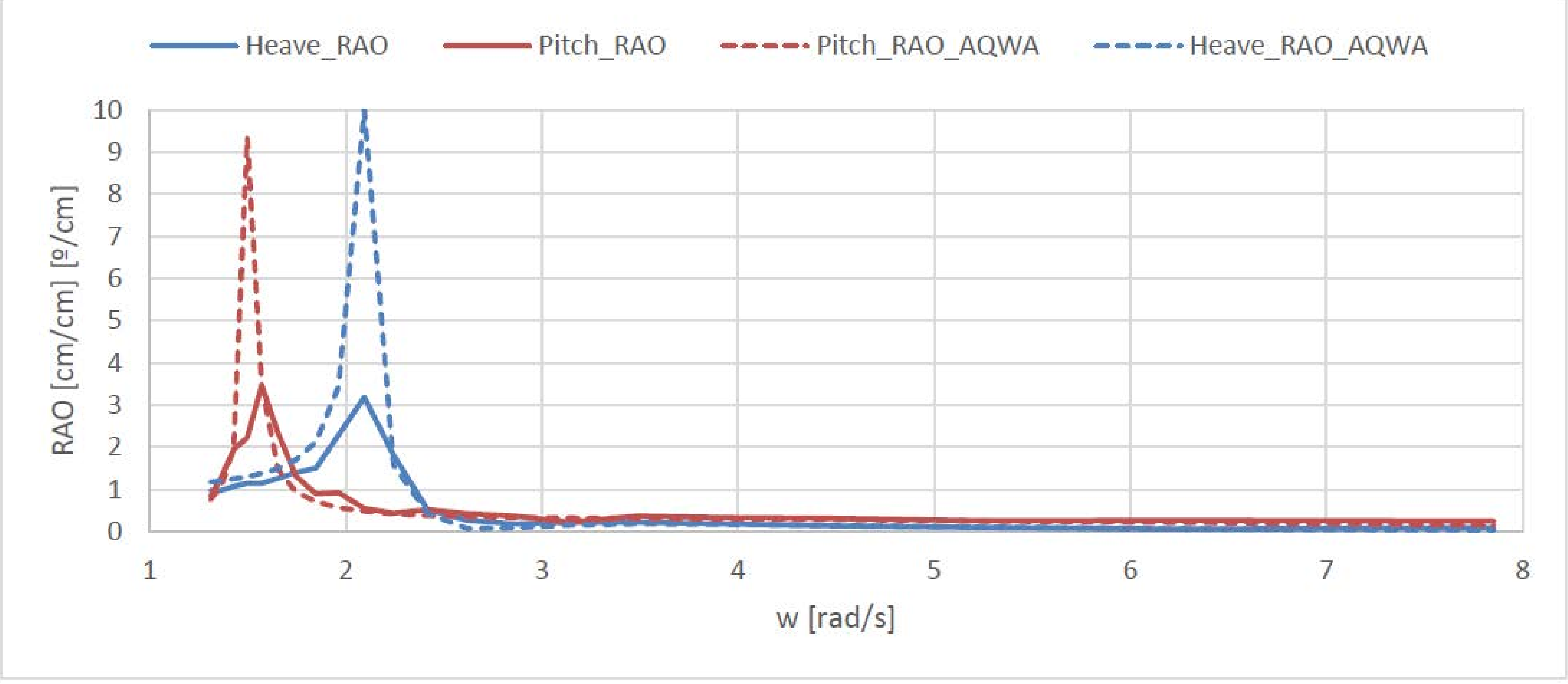




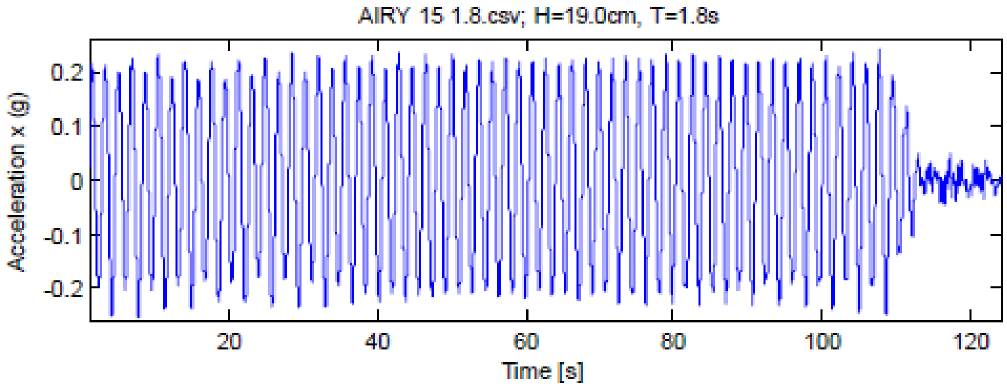
Scale testing: *Experimental RAO's*

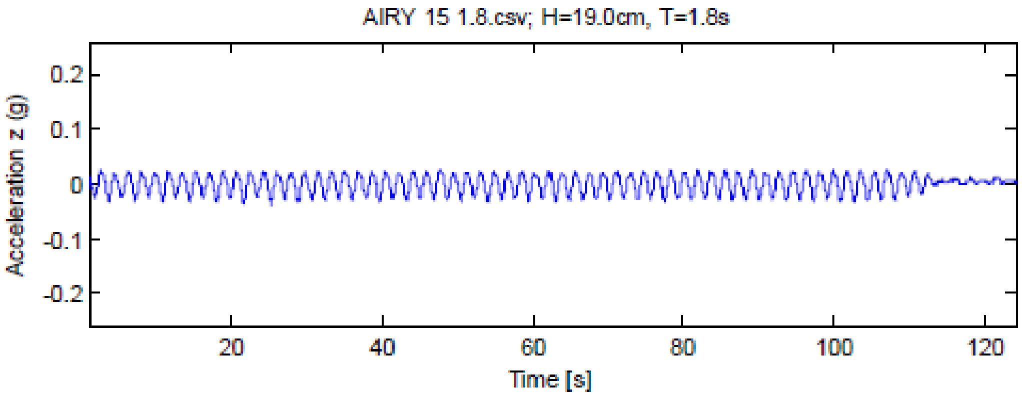


Scale testing: *Experimental RAO's*



Scale testing: *Wind* + *waves*





www.youtube.com/watch?x-yt-cl=85114404&v=WLMVEfj3Ozc&x-yt-ts=1422579428

Scale testing: *Wind + waves*

AIRY TESTS

Mooring Dir.[1]	Wind dir. [º]	T [s]	H [cm]	Heave max [cm]	Pitch [º]	Roll [º]	Nacelle Max Acc. X [g]
1	83.9	1.2	9.1	0.4	-0.2 ± 1.3	2.5 ± 0.3	0.128
	83.4	1.8	18.5	1.9	-0.2 ± 3.1	2.5 ± 0.7	0.169
	178.6	0.9	7.2	0.2	-3.0 ± 0.6	-0.2 ± 0.7	0.082
	179.0	1.2	9.6	0.5	-3.0 ± 1.2	-0.1 ± 1.0	0.119
	179.0	1.5	14.0	1.5	-3.0 ± 2.4	-0.1 ± 0.9	0.153
	179.1	1.8	18.7	2.2	-3.0 ± 3.2	-0.1 ± 0.6	0.166
2	1.2	1.2	9.3	0.5	2.8 ± 1.2	0.7 ± 1.0	0.109
	1.1	1.5	14.5	1.2	2.8 ± 2.0	0.7 ± 0.9	0.150
	1.1	1.8	18.8	2.0	2.9 ± 3.0	0.6 ± 1.0	0.170
	0.9	2.3	28.5	3.0	2.9 ± 5.2	0.5 ± 1.4	0.183
	25.4	0.9	6.6	0.2	3.0 ± 0.9	0.5 ± 0.8	0.075
	25.6	1.2	9.5	0.5	2.9 ± 1.1	0.5 ± 0.8	0.115
	25.6	1.5	14.1	1.2	2.9 ± 2.0	0.4 ± 1.0	0.157
	25.7	1.8	18.7	2.0	2.9 ± 2.9	0.4 ± 1.2	0.172

IRREGULAR TESTS

Mooring Dir.[1]	Wind Dir. [º]	T_p [s]	H_S [cm]	Heave max [cm]	Pitch [º]	Roll [º]	Nacelle Max Acc. X [g]
1	84.2	0.9	5.1	0.6	-0.3 ± 1.2	-2.5 ± 09	0.156
	179.0	0.9	4.9	0.6	-3.0 ± 0.9	-0.2 ± 1.0	0.159
	179.0	1.8	21.4	3.6	-2.9 ± 5.2	-0.1 ± 1.5	0.399
2	1.4	0.9	5.1	0.7	2.9 ± 1.2	0.5 ± 1.7	0.167
	1.4	1.8	21.2	3.7	2.8 ± 7.2	0.6 ± 1.6	0.363
	25.6	0.9	5.2	0.5	3.0 ± 1.8	0.5 ± 1.9	0.158
	25.5	1.8	15.9	3.7	3.0 ± 6.1	0.4 ± 2.5	0.362

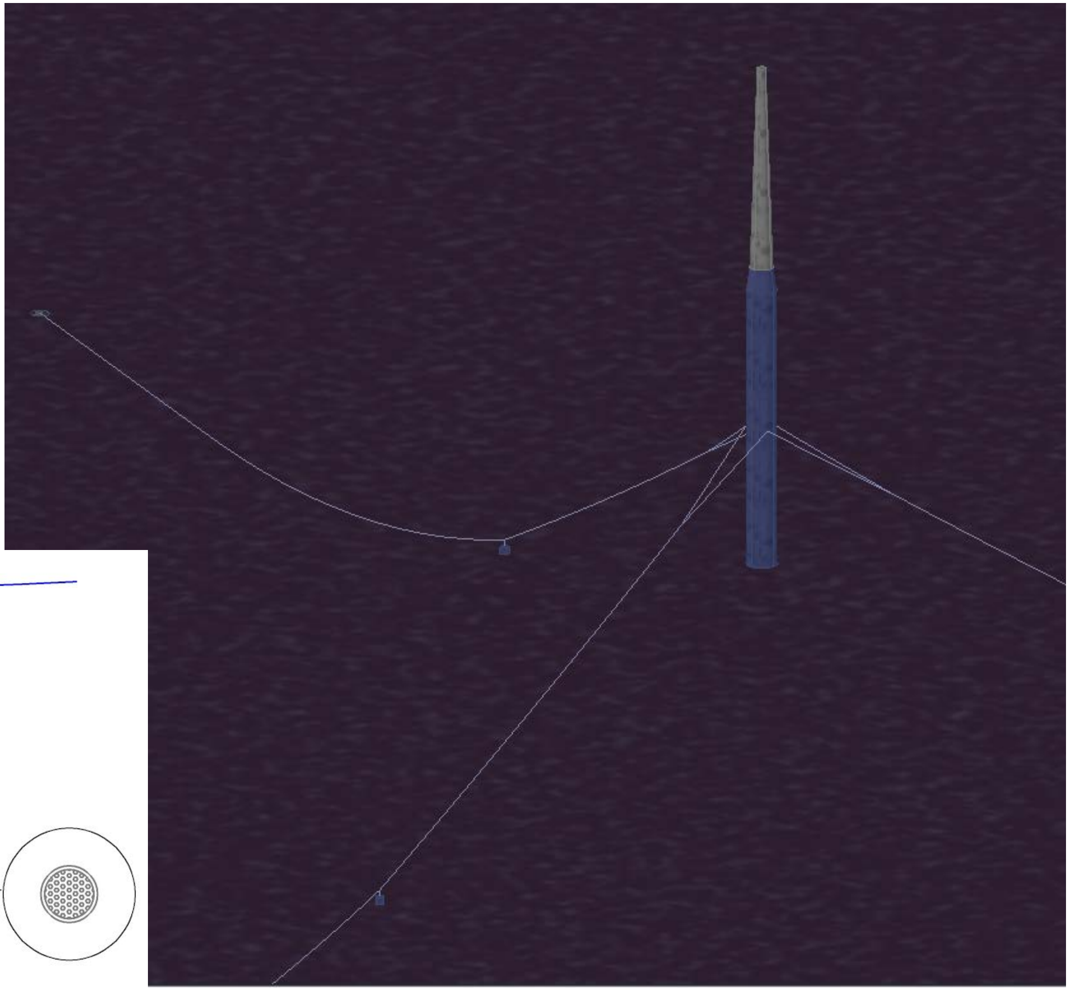
REFINED CONCEPT, after experiments and verification

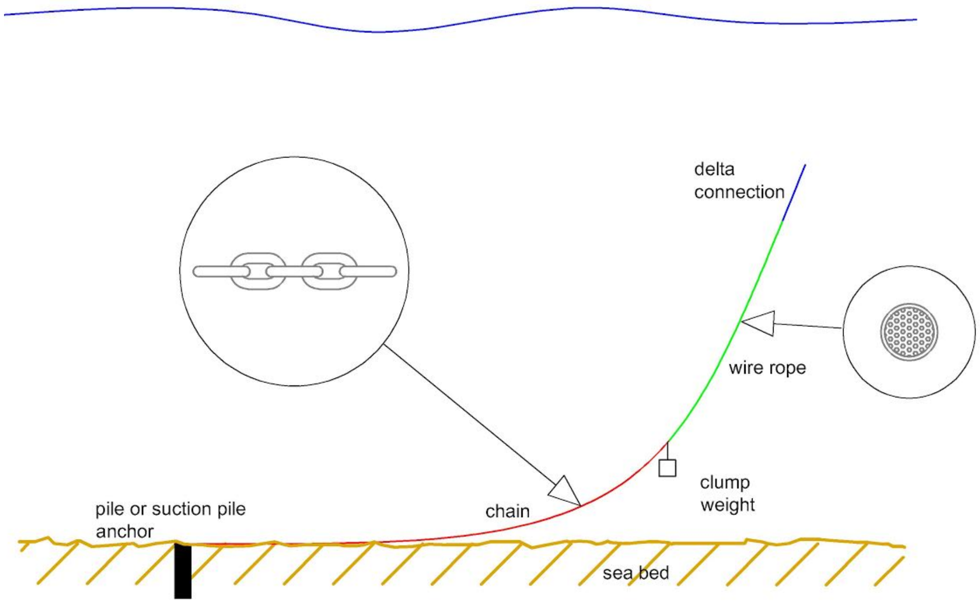
- Experiments show a good behavior: RAO’s, free decay, coupled wind and wave (regular and irregular) for the selected cases.
- Detailed simulations detected a need for a larger yaw stiffness for some accidental cases.

- Design of the mooring system has been revised in order to fulfill the required yaw stiffness.
- New system requires the use of suction piles, larger diameter moorings, intermediate weights and delta connection to the platform.

REFINED CONCEPT

Anchor radius [m]	750
Line length [m]	782
Chain length [m]	472
Wire rope length [m]	250
Delta line length [m]	60
Chain mass per unit length [kg/m]	275
Wire rope mass per unit length [kg/m]	67
Clump Weight mass [T]	63





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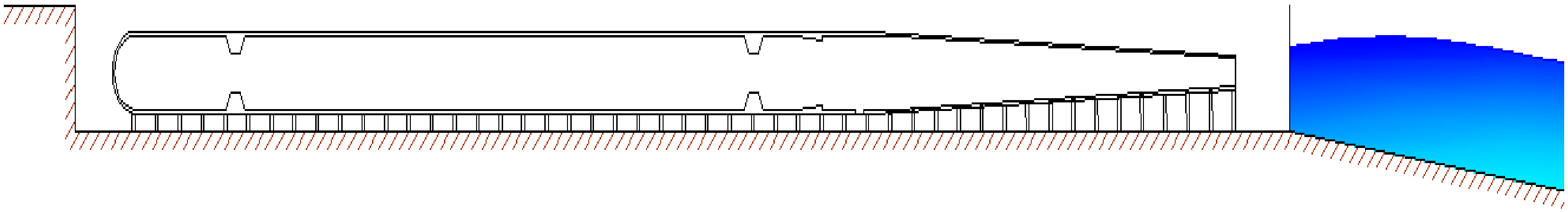
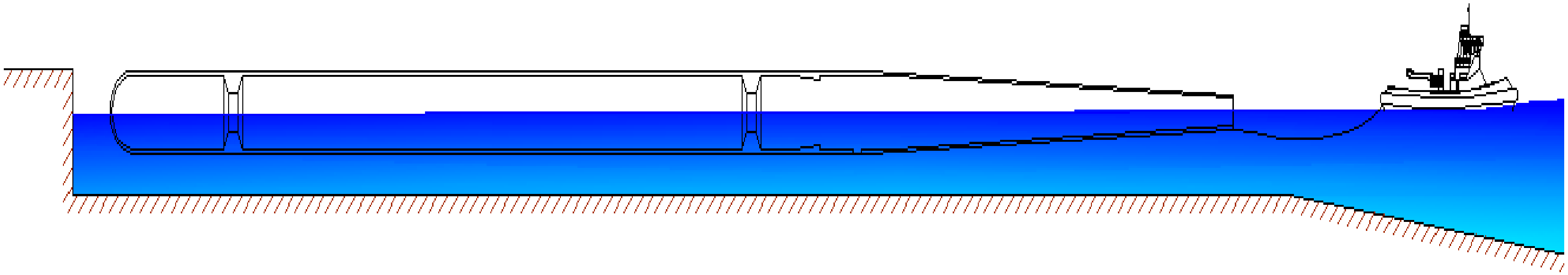
4.- Q&A

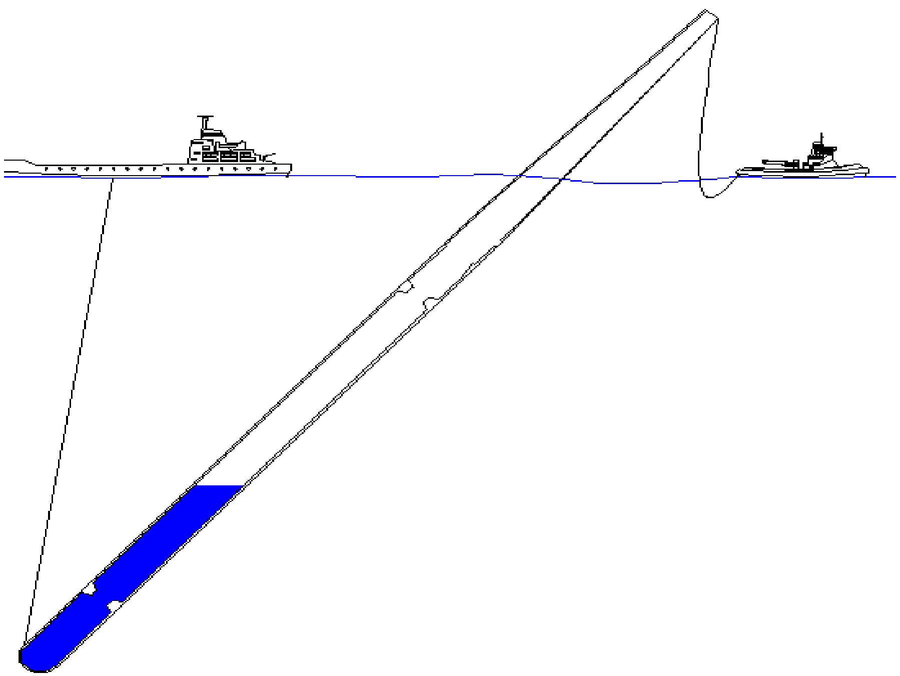
The structure is built horizontally in a dry dock to be towed out to the installation site

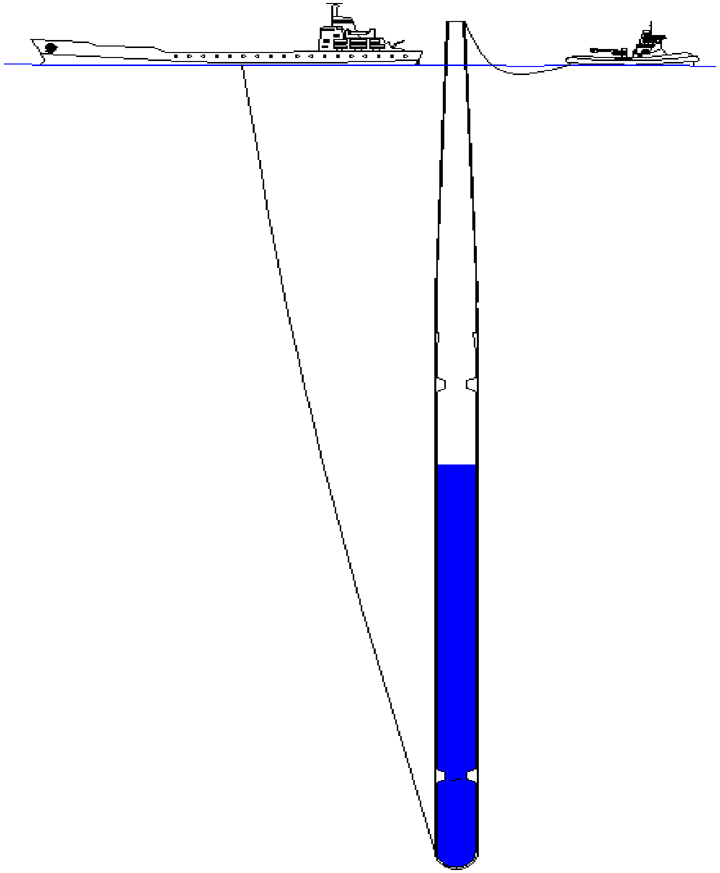




Construction & Installation

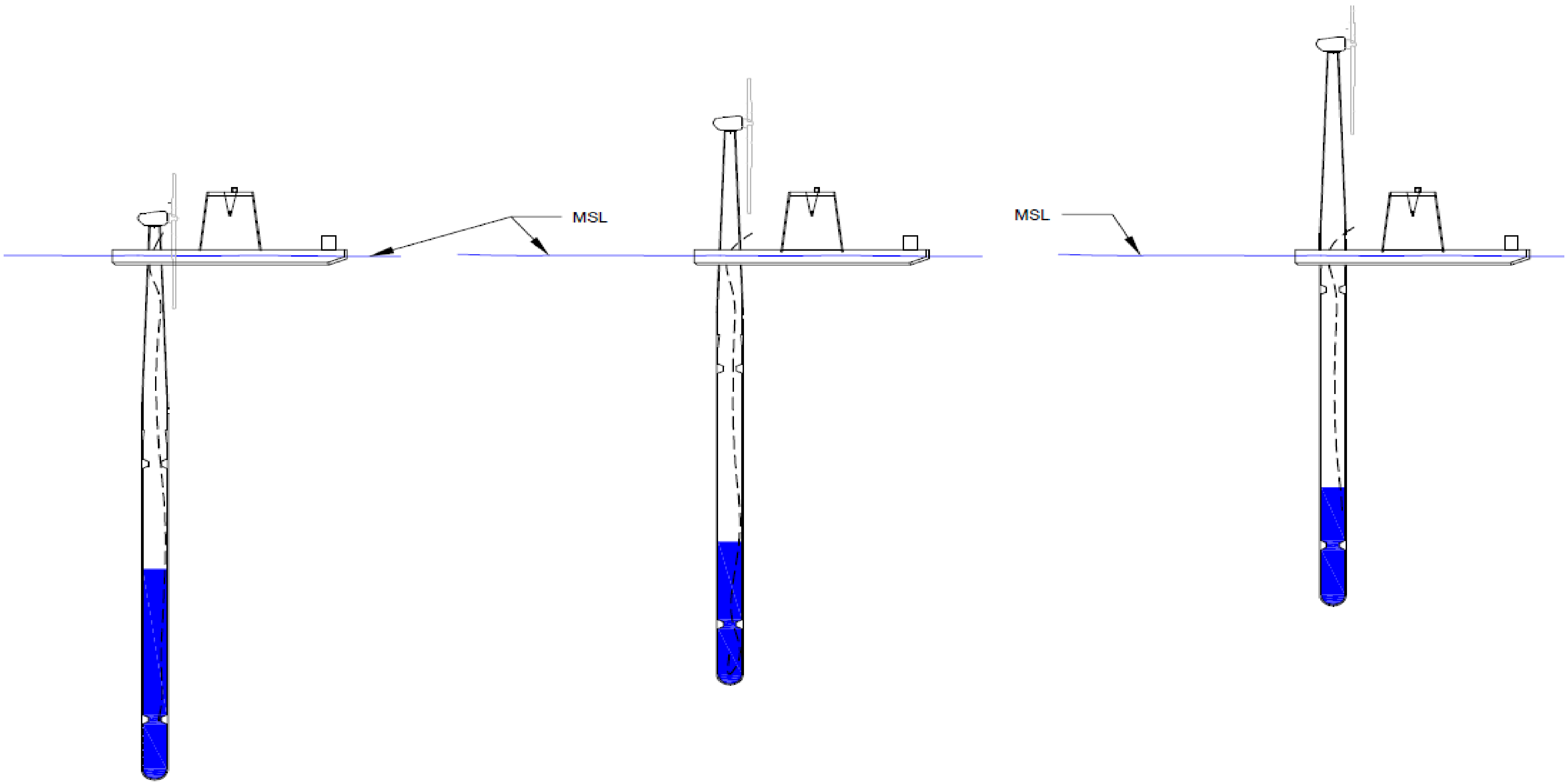
The structure is partially sunk while starts to erect. The erection is controlled by using a cable attached to a boat.



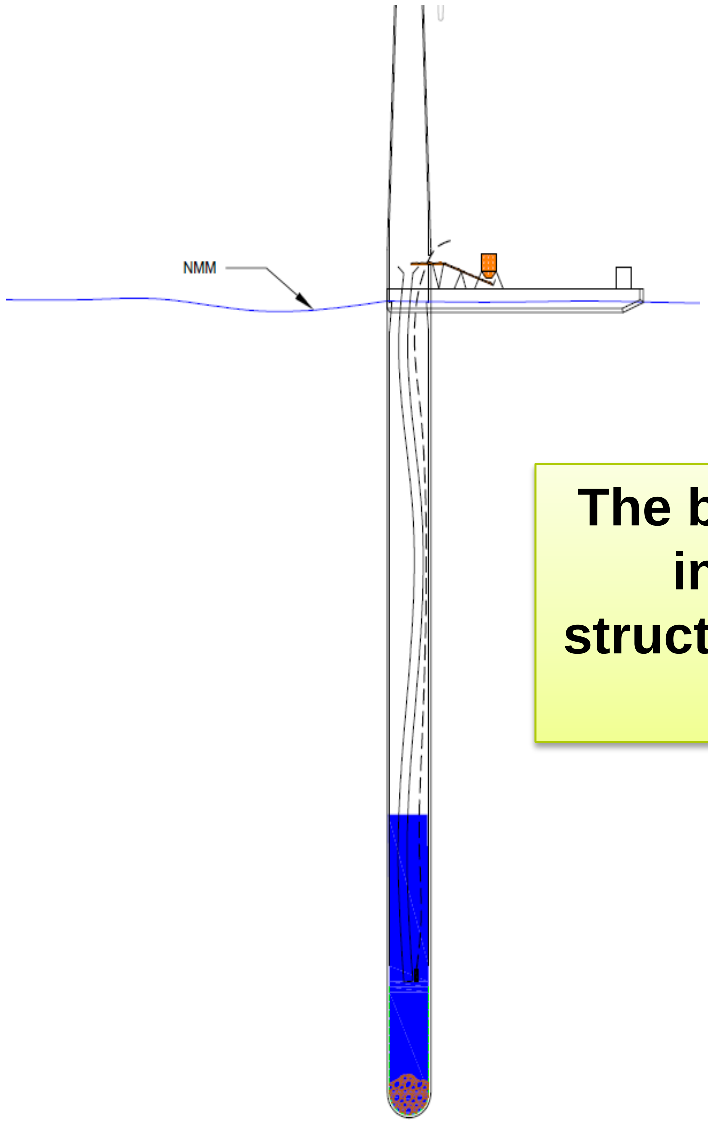


Construction & Installation

FOWT installed avoiding heavy cranes, being emerged after the installation.



Construction & Installation



The ballast aggregates are introduced into the structure while the water is pumped out

1.- Project overview

1.1 Why a floating platform?
1.2 Goal of the project
1.3 Project Consortium and Tasks Allocation
1.4 Main results

2.- Technical approach

2.1 Why concrete
2.2 Design process
2.3 Verification: Experiments & Simulation
2.4 Construction & Installation

3.- Conclusions

4.- Q&A

Conclusions

•The Afosp project has proven the **technical feasibility and viability** of the developed design by experiment and numerical simulations.

•The design was **adjusted and optimized** according to findings from simulations and tests.

•LCOE for Afosp is **25% lower** than LCOE for floating solutions.

•AFOSP solution main **advantages** regarding LCOE:

- **Cost of support structure**
- **O&M of the support structure**
- **Lifetime of the support structure (40/50 years)**