Design, Analysis and Wave Tank Testing of a Semi-Submersible Braceless Concrete Offshore Wind Turbine Platform

EERA DeepWind'2015 Deep Sea Offshore Wind R&D Conference, Trondheim 4 – 6 February 2015

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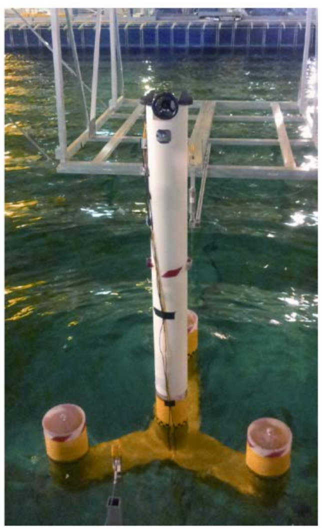

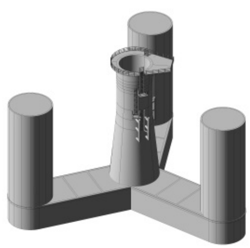

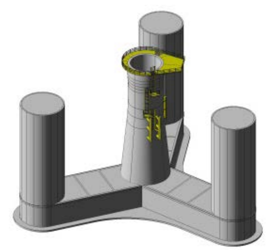

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acciona

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Statoil

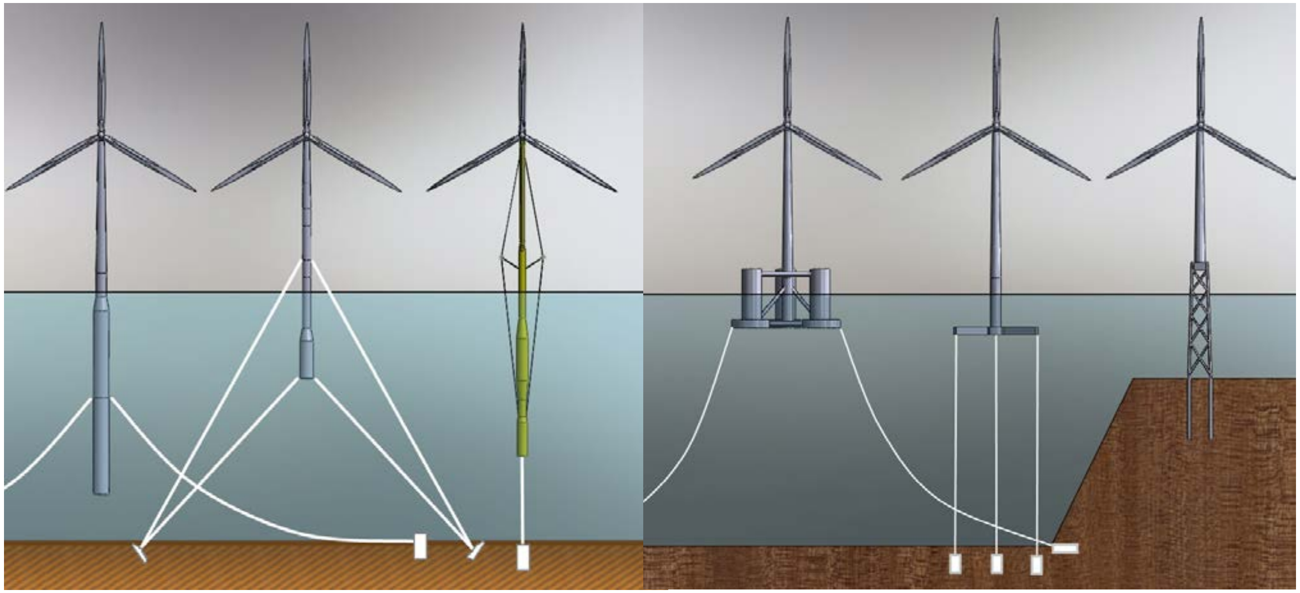
Outline

- Background
- Why concrete and braceless ?
- Goals
- Partners and roles
- Results
  - Wave tank test
  - Platform and mooring system design
  - Loads analysis
  - Fabrication and installation
  - Cost distributions
- Conclusions

Background

- By volume, Dr.techn Olav Olsen AS (OO) has designed more than 60% of the offshore concrete platforms in the world.
- First sketch of braceless floater in 2010.
- Patent application in 2011. Approved patent for Norway 2012.
- Funding from the Norwegian Research Council and Statoil 2012.
- In-kind contribution from Acciona Infraestructuras S.A
- Feasibility study finished January 2015.

Floating Wind Turbines:
Did we explore the whole design space yet ?

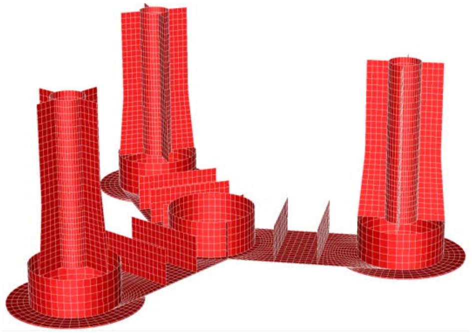


Emphasis in this project:

- Fabrication
- Installation
- Maintenance
- Long life/retrofitting

Why Concrete and Braceless?

- Concrete can be designed for 100 years operation
  - A site will not run out of wind
  - Retrofit of Rotor/Nacelle Assembly
  - Concrete is not sensitive to fatigue
- No maintenance or inspections required
- Robust and rigid structure
  - Resistant to impact loads
  - Less need for complicated braces and joints
  - Concrete very competitive for large scale structures – ideal for future large wind turbines (10 MW+)



RCN Project no. 225946/E20
Concrete Substructure for Floating OWTs

Organization

NFR/RCN

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Project Owner
Olav Olsen

Trond Landbø, Project Manager
Dagfinn Sveen, Structural Design
Håkon S. Andersen, Analyses
John Meling, Senior Advisor

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Gunther Auer, Technical Coordinator

Project Partner
Statoil ASA

Viviane Simonsen, Contract Coordinator
Tor D. Hanson, Technical Coordinator

Goals

- Phase 1:Define “frozen” floater configuration. Concept design suitable for a feasibility study.
- Phase 2:Design drawings and load calculations with sufficient detail to document feasibility of the conceptual design
  - Wave tank test/validation of simulation models
  - Design of mooring system
  - Loads analysis
  - Fabrication, access systems
  - Installation
  - Costs and risks

Partner roles

- Dr.techn. Olav Olsen AS (OO)
  - Project management
  - Concept, Structural Design, Loads analysis, Construction and Installation
- Institute for Energy Technology (IFE)
  - Integrated simulation tool 3DFloat development and support,
  - Modeling of rotor/nacelle, full scale configuration
  - Modeling of wave tank scale model floater
  - Tuning of pitch controller
  - Loads analysis
  - Wave tank test in cooperation with CENER
- Acciona Infraestructuras S.A.
  - Access systems, construction, costs, risk analysis
- Statoil ASA
  - Definition of generic rotor and metocean conditions
  - Review and discussions
  - Funding

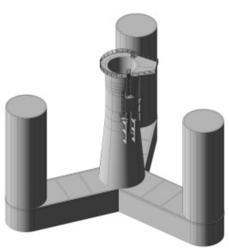
Design basis and philosophy

- General
  - North Sea harsh environmental conditions and intermediate water depth
  - Inshore assembly and installation of turbine in shallow, protected waters
  - Offshore installation without the use of expensive heavy lifting vessels
- Safety philosophy/redundancy
  - Damage stability for accidental flooding
  - Mooring system without redundancy combined with normal safety class in accordance with DNV-OS-J103 (floating foundation structure normally unmanned)

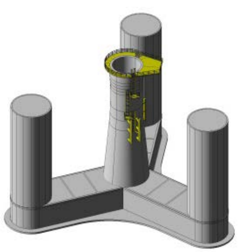
Design basis	Karmøy	North Sea
Water depth [m]	200	95
Hs [m] (max 50 year)	12.9	10.5
Current [m/s] (max 50 year)	1.70	1.35
Wind [m/s] (max 50 year)	48	43.2
Turbine diameter [m]	120	154
RNA mass [t]	310	365
Tower height [m]	64.00	81.76
Tower mass [t]	350	650
Rated thrust [kN]	660	850
Hub height wrt. SWL [m]	81.0	97.8

Platform

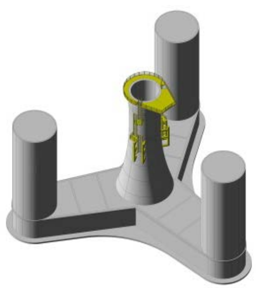
- More than 20 concept configurations developed
  - Heave period ~ 20 s
  - Pitch period > 28 s
  - Max. static heel 6 deg
  - Minimum draft with WTG < 10 m
  - Stable in all temporary conditions without solid ballast
  - Positive air gap at all times
  - Damage stability



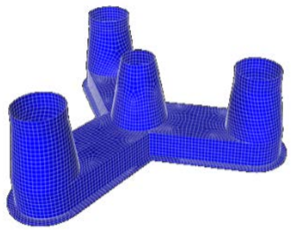
Original



Bilge keel



Wide pontoon



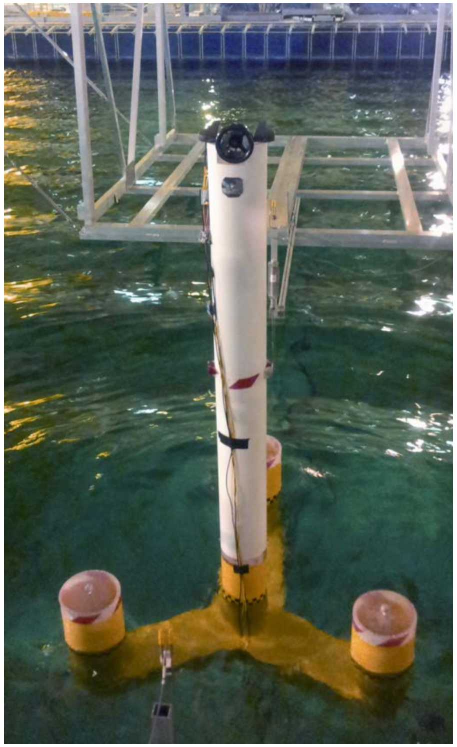
Coned columns

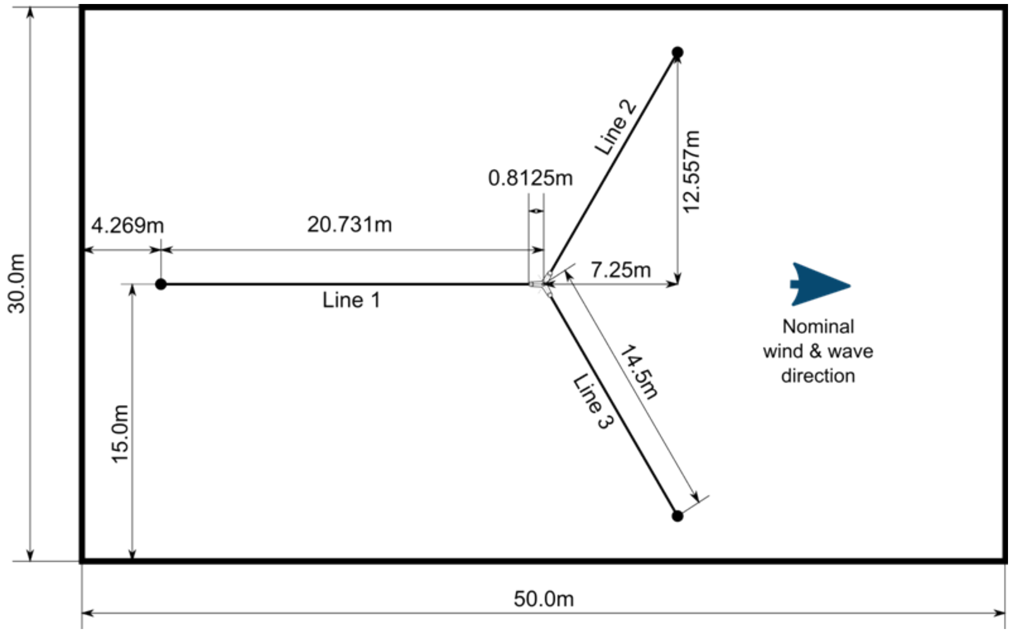
Large corner damper plates

Mooring system

- Water depth of 100m makes design of catenary mooring systems challenging.
- Initial screening of 5 conceptual designs
- Comprehensive sensitivity analyses
- 2 designs analyzed in detail for extreme loads (ULS) and fatigue (FLS)
- Baseline chosen as 147mm chain, 500 kN pretension and anchor radius of 750m
- The baseline mooring system has a fatigue life of more than 20 years, and excess capacity during a 50-year storm.
- Several innovative mooring systems designed in the project show potential for cost reductions.

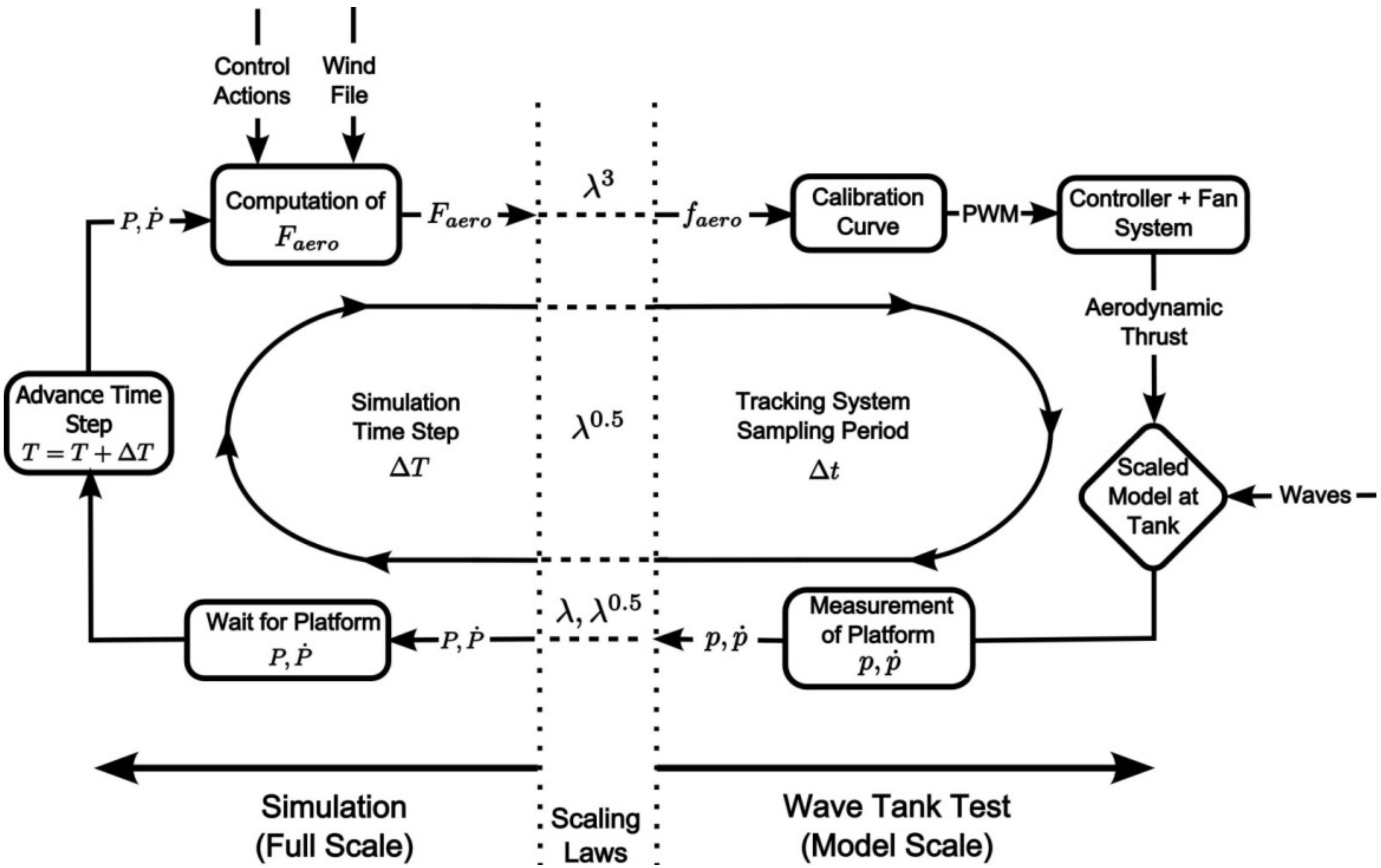
MARINET Wave Tank Test, ECN Nantes, France



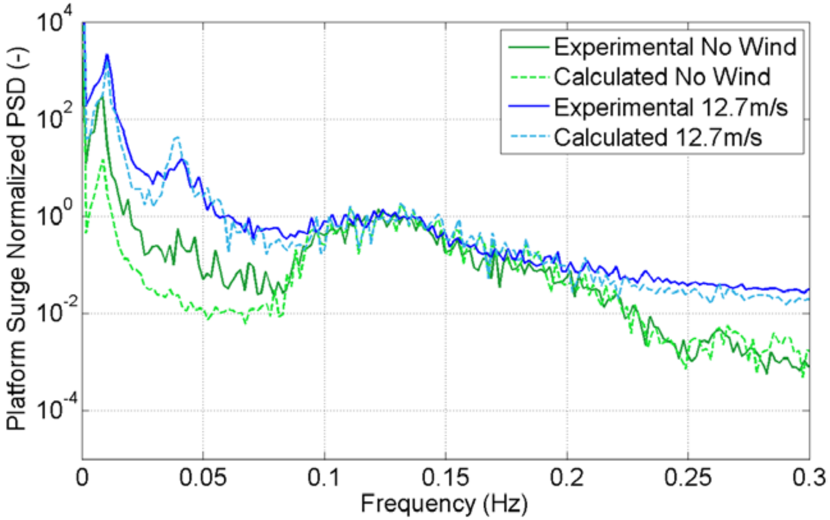


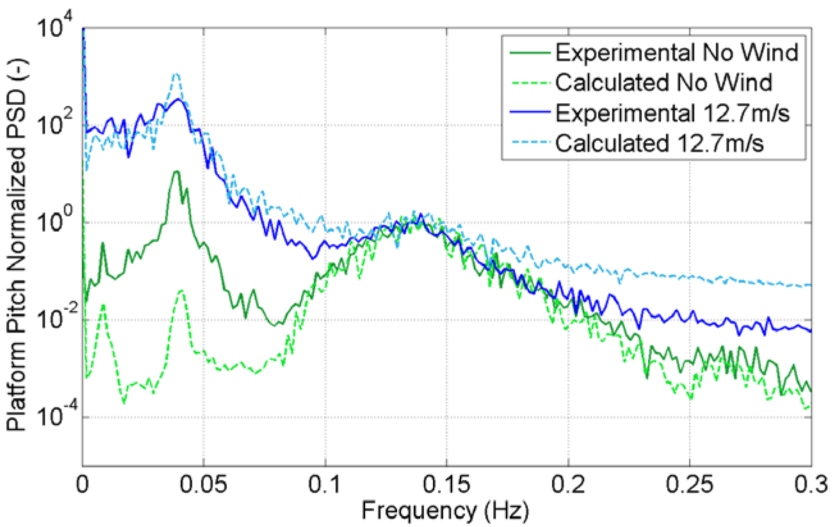
Azcona, J., Bouchotrouch, F., González, M., Garciand, J., Munduate, X., Kelberlau, F. and Nygaard, T.A. (2014). *Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines Using a Ducted Fan*. Journal of Physics: Conference Series 524 (2014) 012089.

Software-in-the-loop system



Hs=2.64m Tp=7.3s (full scale) U=12 m/s
FAST + CENER Mooring Line Model





Generic wave tank model has peak at pitch eigen frequency and wave frequency, also with little excitation (no wind case). This is not captured by the linear FAST model. Updated full scale model has higher pitch eigen period, further away from the heave period, and pitch damper plates. Pitch motions are small during normal operation.

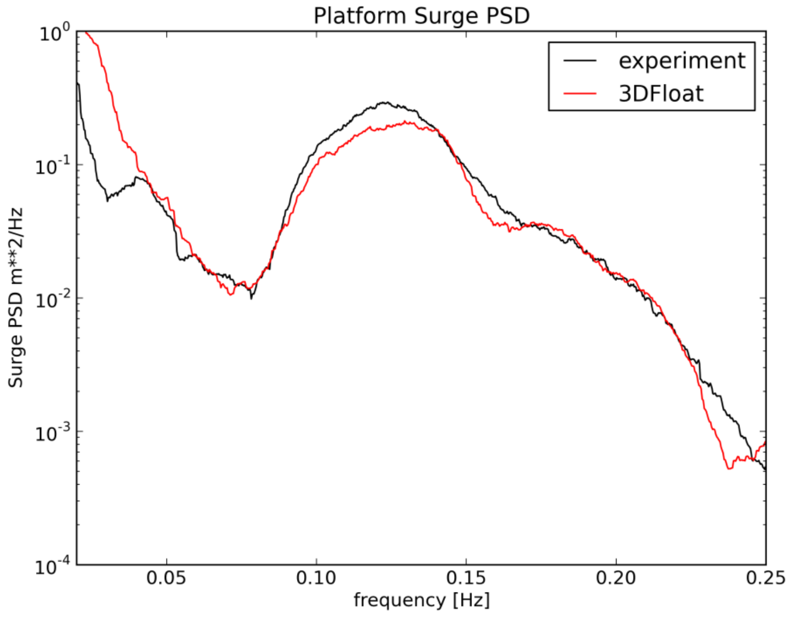
Adjustment of coefficients

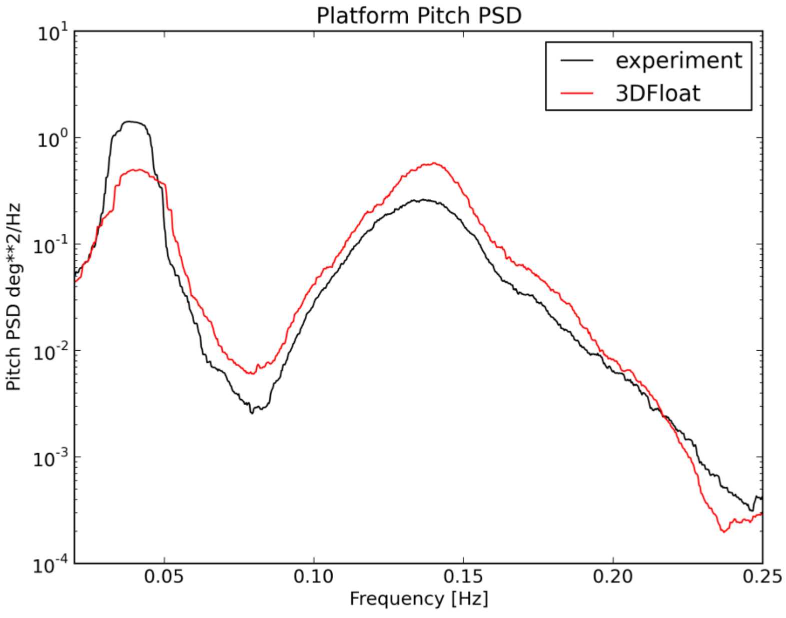
- Added mass coefficients are adjusted by comparing simulations with wave tank forced motion and free decay tests.

- Quadratic drag terms are adjusted by looking at first part of free decay test.

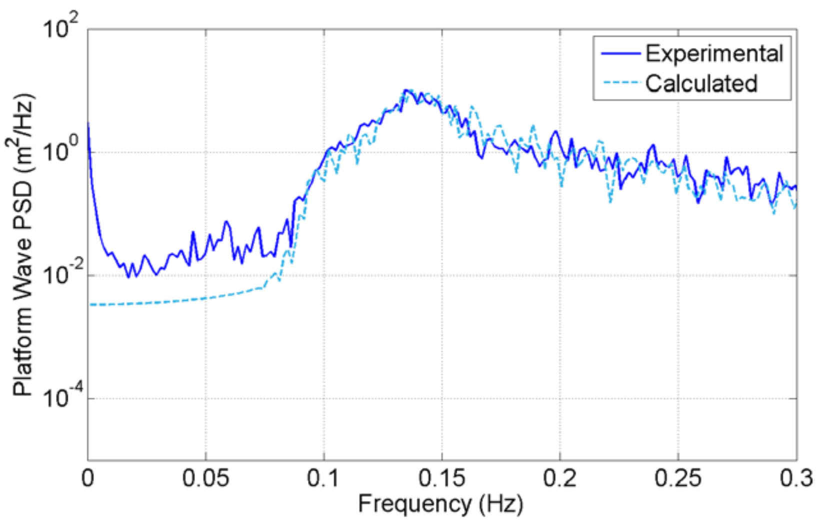
- Linear damping terms are adjusted by looking at last part of free decay test.

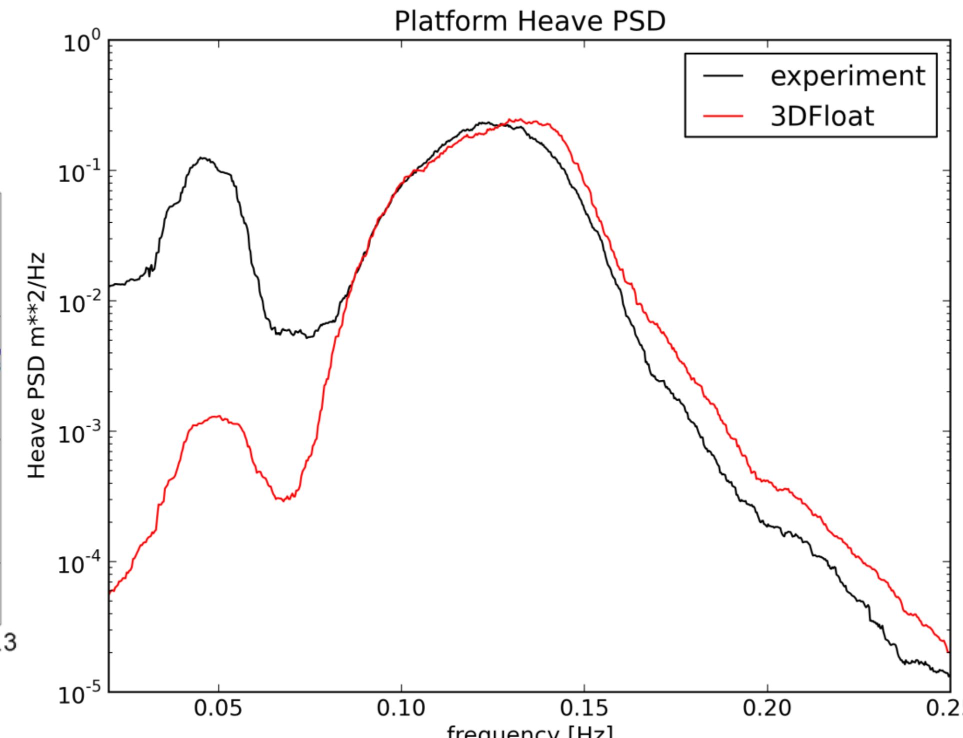
Hs=2.64m Tp=7.3s (full scale) No Wind 3DFloat vs. experiment





Hs=2.64m Tp=7.3s (full scale) No Wind 3DFloat vs. experiment





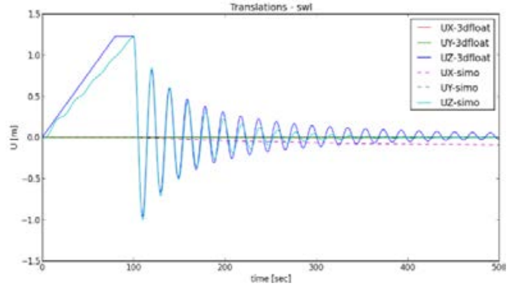
The fitted wave spectrum has lower low-frequency energy. This can partly explain the lower response at heave eigen-frequency in the model

Loads Analysis

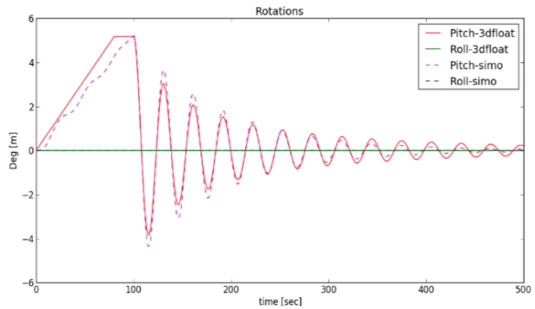
- SIMO (MARINTEK): Rigid floater, Linear Potential Theory and Morison elements, Quasi-steady mooring line model
  - Fast assessment of global motion characteristics
  - Screening of mooring line configurations
- 3DFloat (IFE): Finite-Element-Model of flexible structure including mooring lines. Morisons equation provides loads distributed on the structure
  - Detailed analysis of mooring line dynamics
  - Detailed information on load transfer, input to stress calculations in pontoons and mooring lines
- Despite the modeling differences, very similar results for the platform motions

3DFloat vs. Simo response for free decay and regular waves with linear spring mooring

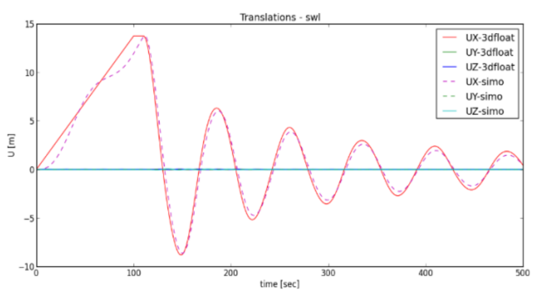
Heave

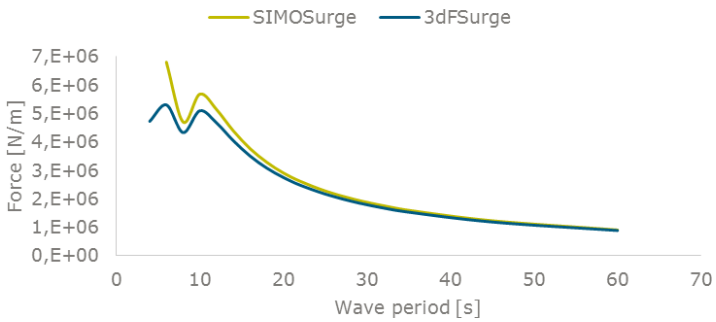


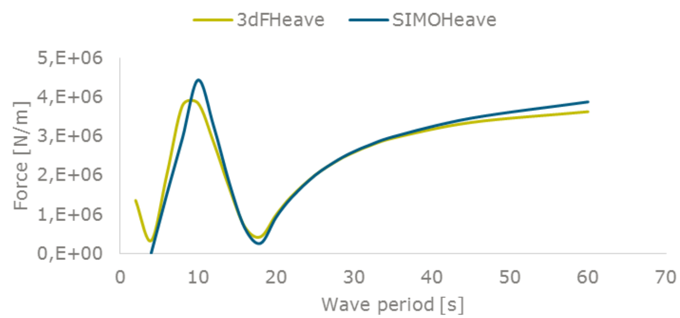
Pitch



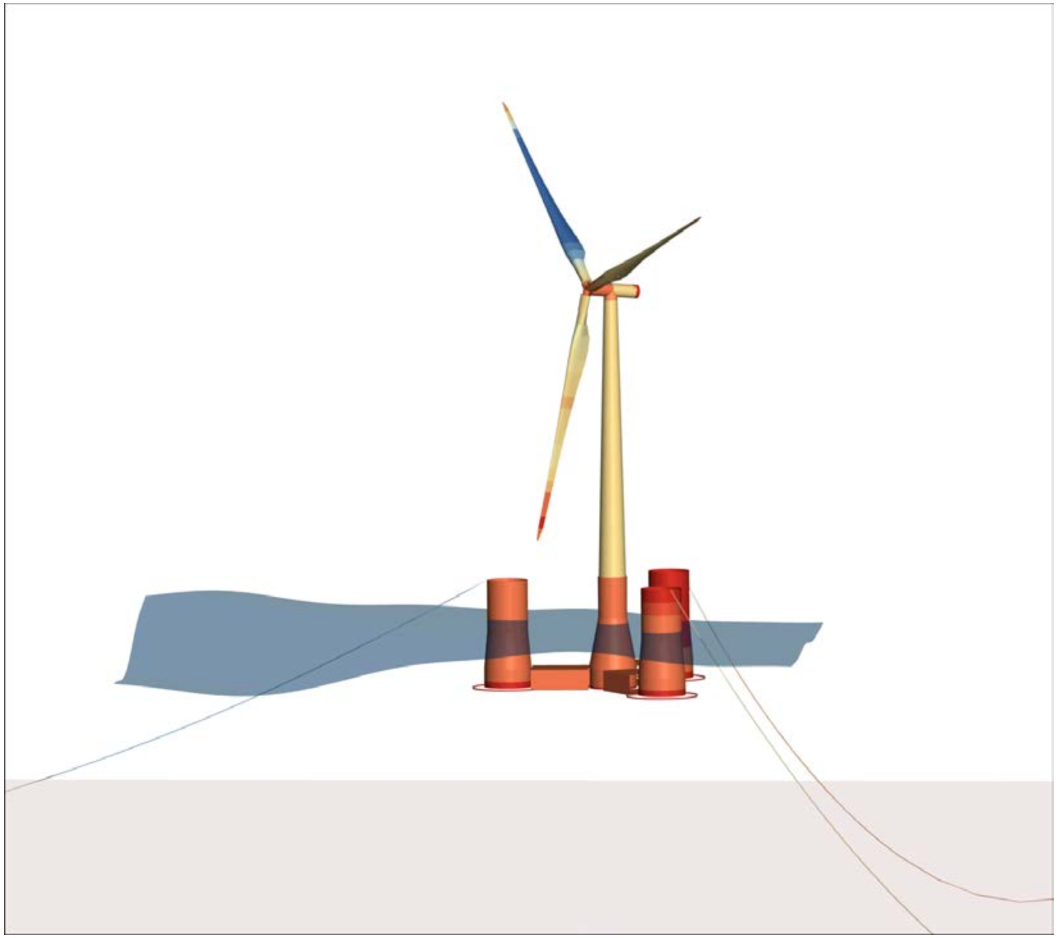
Surge







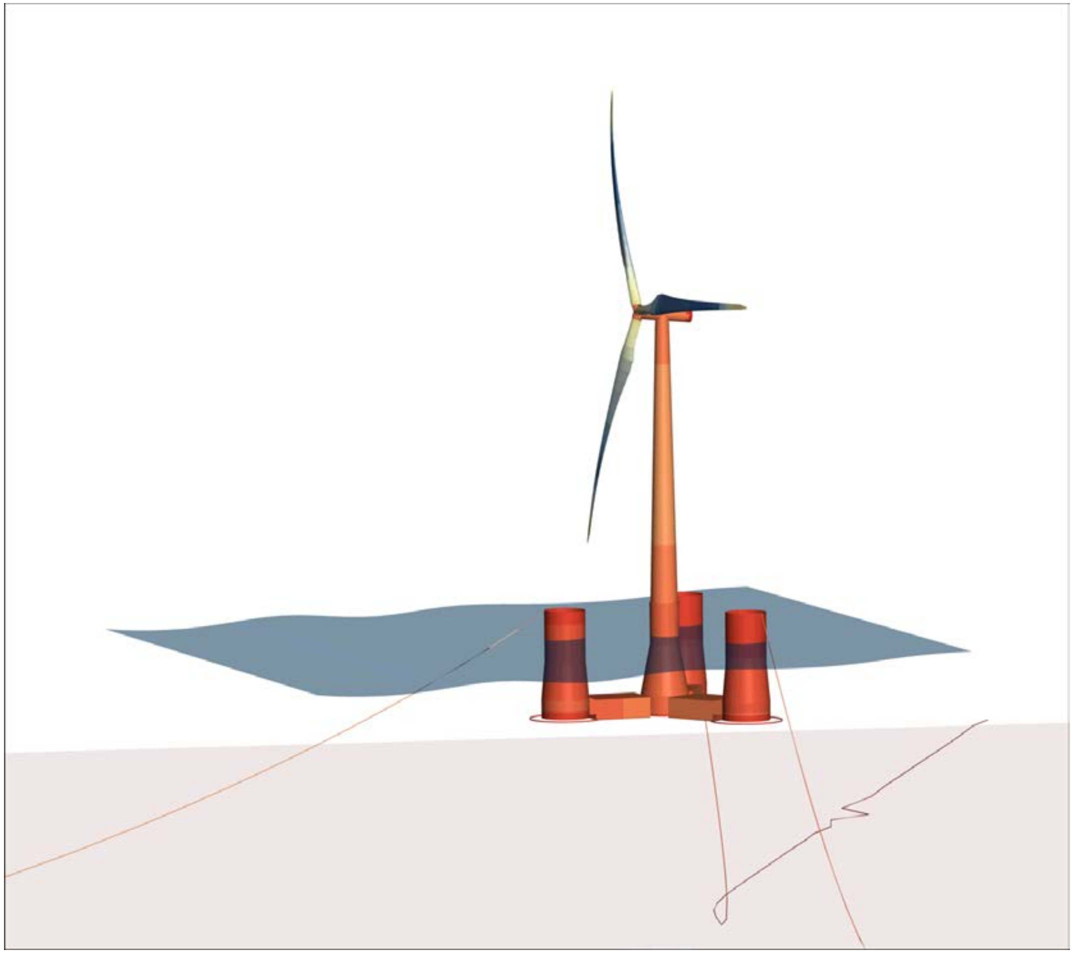
Extreme Loads in Mooring Lines



- 7 load cases, upwind mooring line aligned with wind and waves
- 3 hours, 4 seeds
- Low utlization through 50 year storms
- Expect no surprises from complete LC matrix and more seeds

3DFloat animation: Jacobus Bernardus De Vaal, IFE

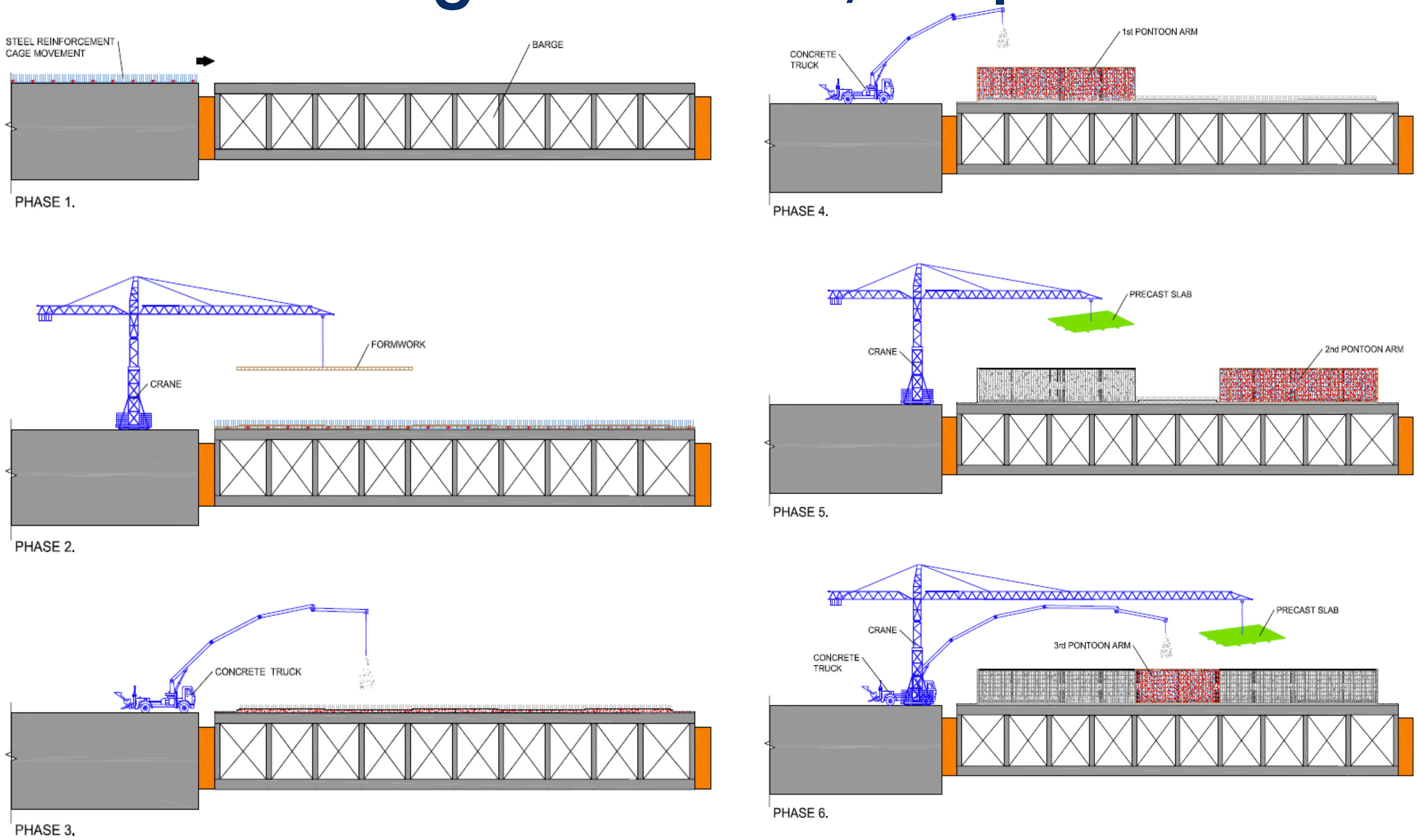
Fatigue in Mooring Lines



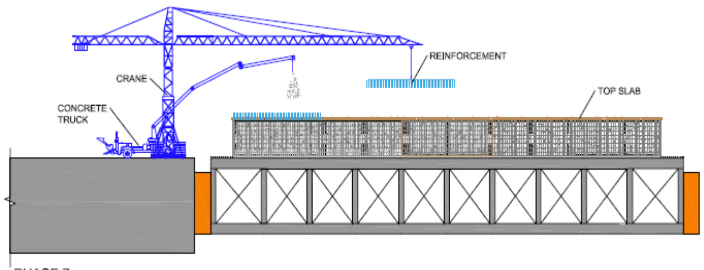
- 81 load cases
- 30 min, 1 seed each
- DNV OS-E301
- Fatigue life of 27 years
- More detailed analysis could allow reduction in chain diameter

3DFloat animation: Jacobus Bernardus De Vaal, IFE

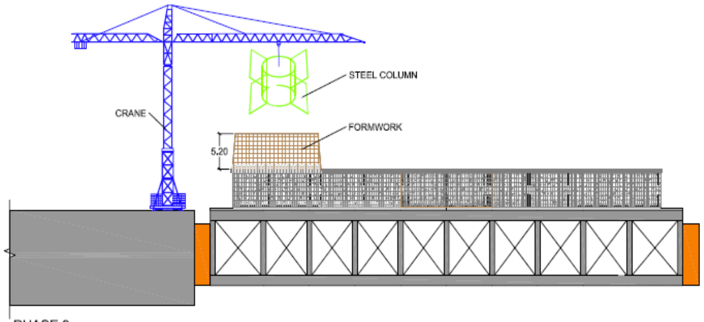
Fabrication of concrete prototype with climbing formwork, step 1 - 6



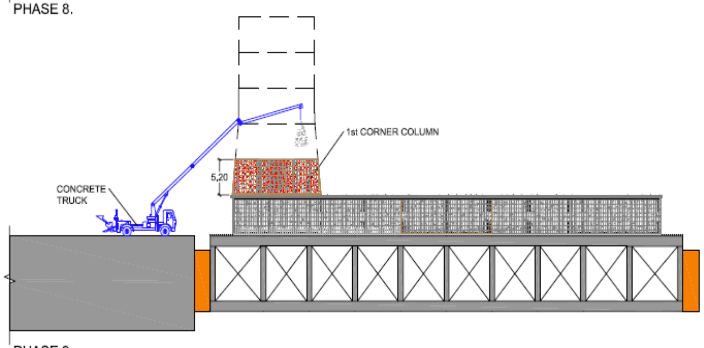
Fabrication of concrete prototype with climbing formwork, step 7 - 12



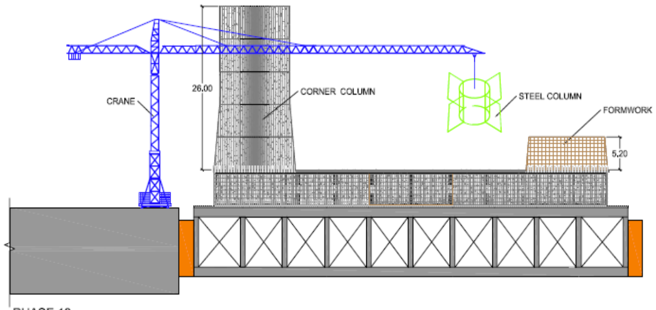
PHASE 7.



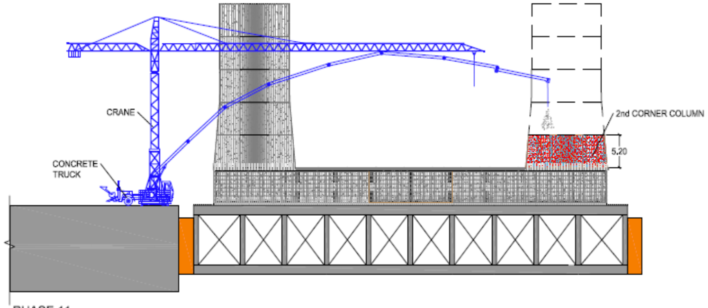
PHASE 8.



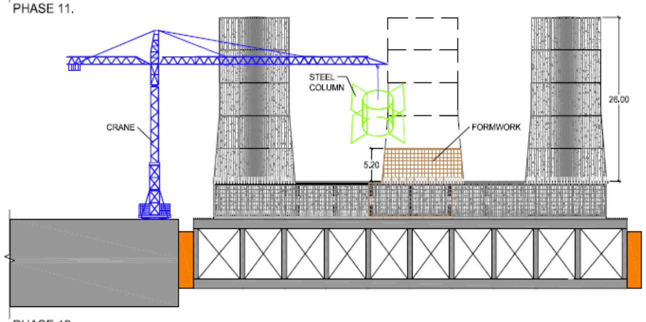
PHASE 9.



PHASE 10.

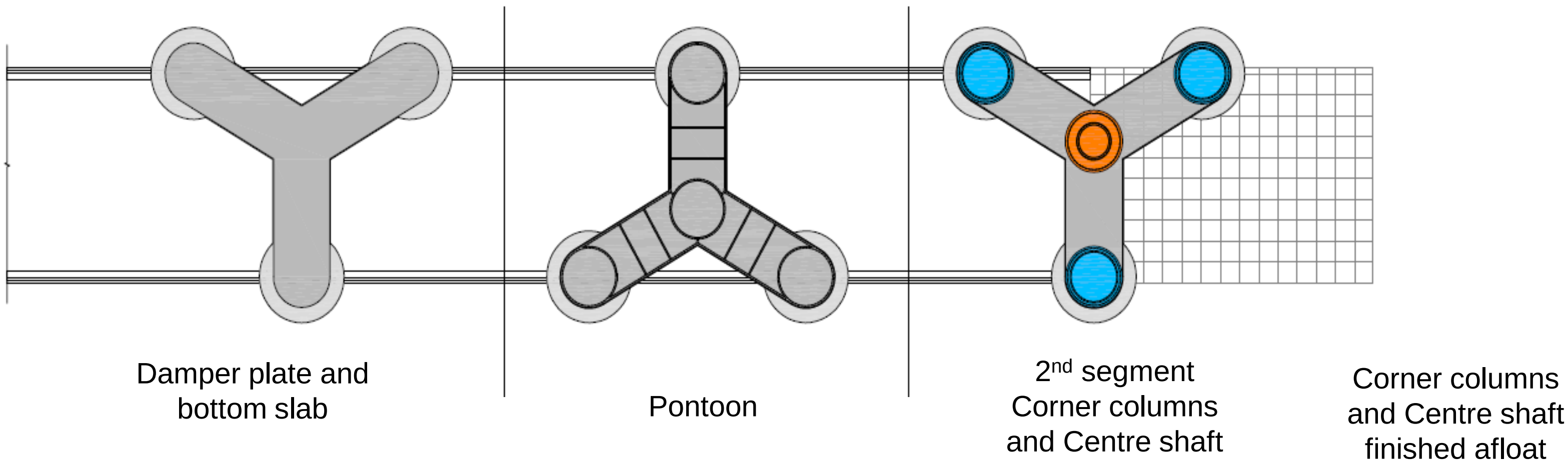


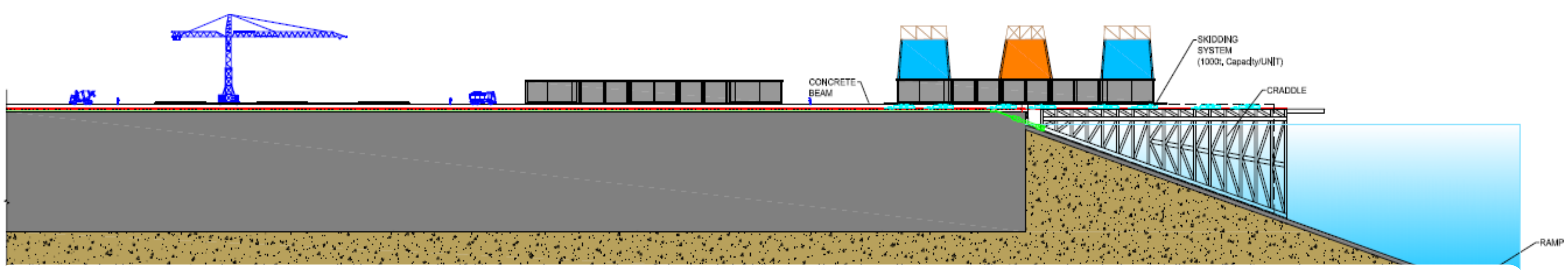
PHASE 11.



PHASE 12.

Skidding Assembly line with parallell work allows efficient OO-star mass production

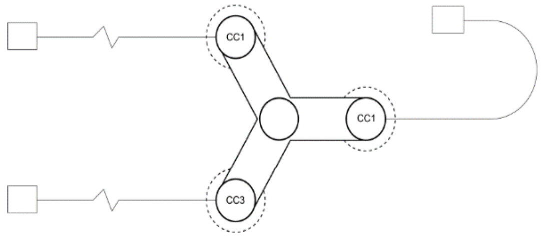




Longitudinal cross section – Construction stages

Vessels and equipment

- Desired case for towing, two AHTS towing in parallel at a draft of 16.7 m. Emergency towing configuration on last corner column. This draft show a more stable tow, and the orientation of the tow ensures minimal drag resistance.



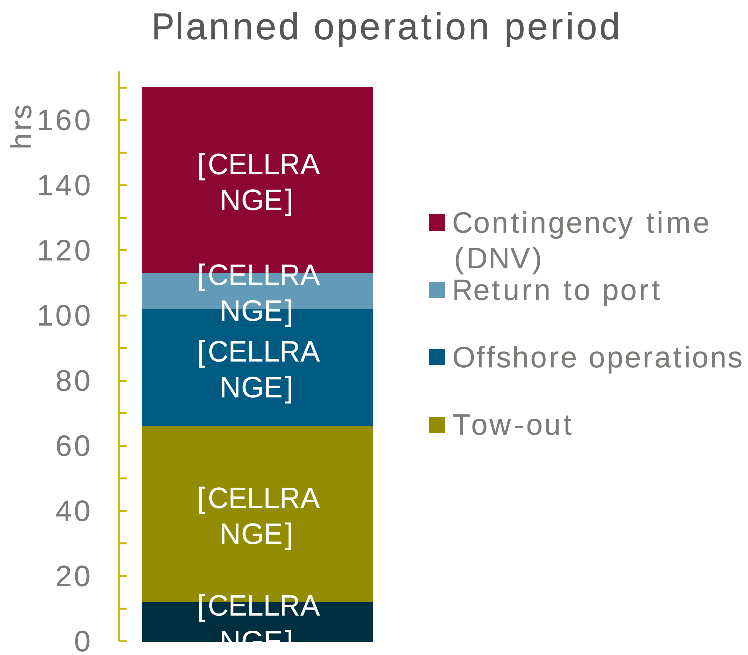
- Rated BP required greater than 131 t each, efficiency factor of 0.75 included
- Pre-laid mooring around installation point, pick up line and buoy from mooring used for connection
- Towline as fibre core rope
- ROV for connecting mooring, and survey
- Towing wire connected to floater over bridles from each corner column
- Metocean data for the North Sea

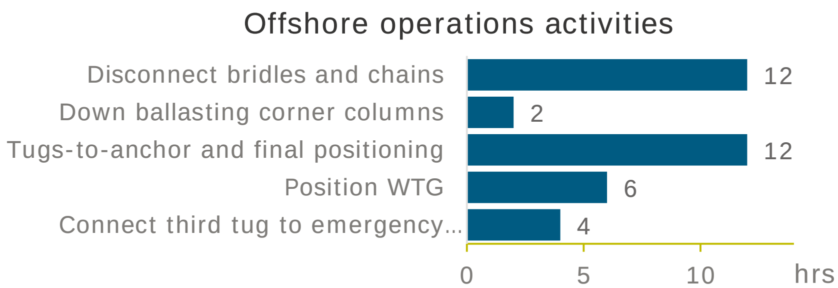
Property for each AHTS	Rough Sea
Required BP	131 t
Towline length	910 m
Towline diameter	68 mm
MBL of towing line	298 t
Towline weight	18 t
MBLBRIDLE	1.3 x MBLTOWLINE

Bridle components
ROV shackle for connection of bridles to floater
Intermediate chain between shackles and plate connection
Shackles for connection of intermediate wires to ROV shackle and plate connection
Shackles for connecting plate connection to towing wire or mooring leg
Plate connection

Design condition	Rough Sea
Hs	4 m
Tp	9 s
Wind speed at 10 m	15 m/s
Current	0.8 m/s

Typical Marine Operations schedule (project dependent)

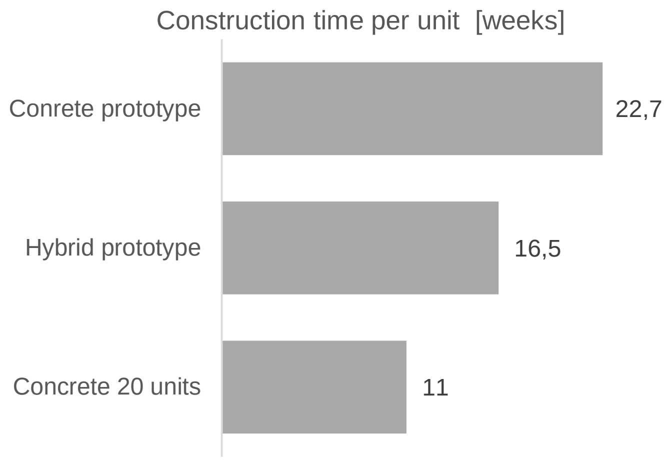


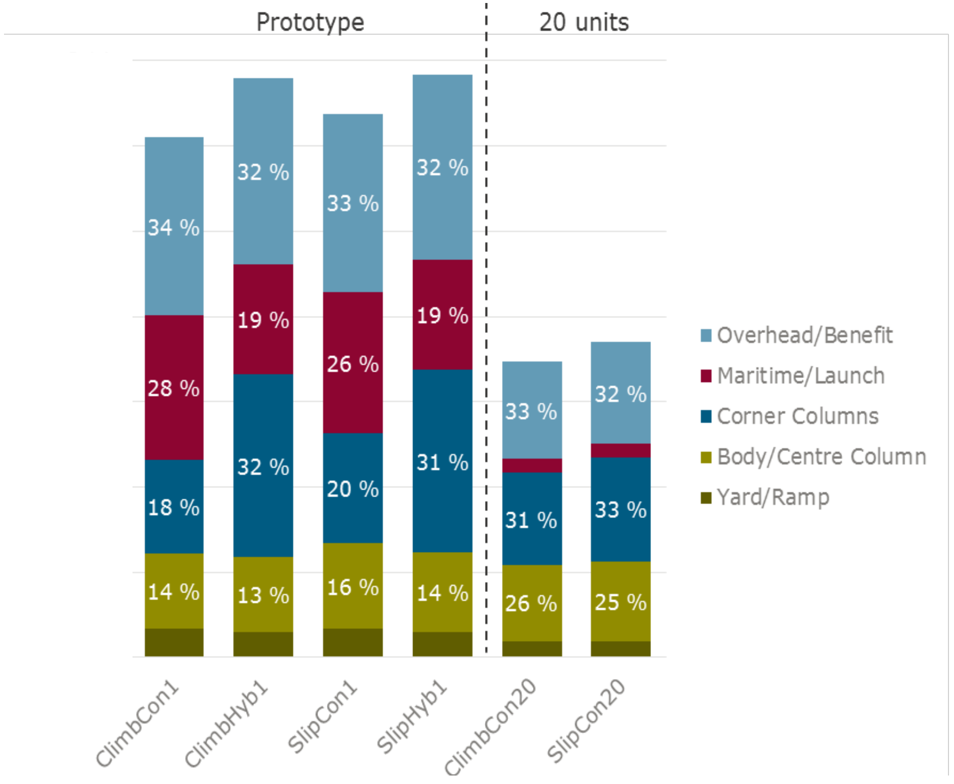


Prerequisites

- Weather forecast every 12 h
- Aborting/reverting operations at any stage within 12 h. Weather restricted operation according to DNV
- Towing at 2-4 knots speed
- 50 % contingency according to DNV, less contingency upon approval
- Mooring and electrical grid pre-laid. Connection to mooring is performed from winch on board of the AHTS.
- Third tug to be included during installation, to restrain movement, and assist during placement around the installation point

Mass production offers ~50% reduction in construction time and substructure cost





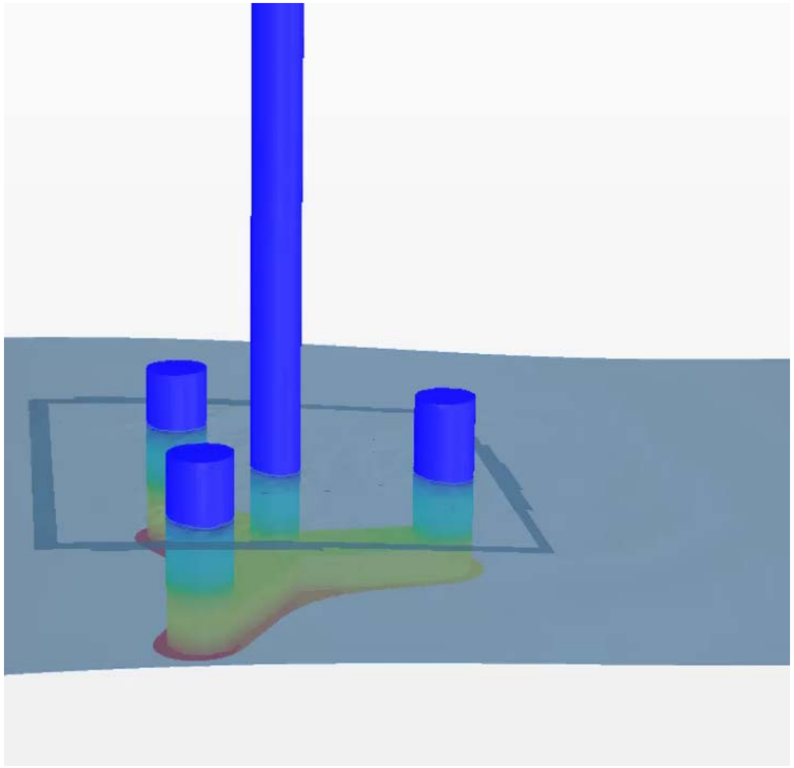
The components relative contribution to the cost of each concept are shown in percentages.

Conclusions

- Analyses confirm feasible construction and deployment of OO-star wind floater
- Substructure is optimized and found suitable for a North Sea site
- Mooring analyses confirmed excess capacity in both Ultimate and Fatigue Limit State for a catenary system with 147 mm diameter (optimization potential)
- Concrete design concluded with a moderate amount of normal reinforcement, in addition to post-tensioning cables and shear reinforcement, which achieved 50 years fatigue life
- Transport to site can be done with two medium size AHTSs. Hook-up at the site using three vessels can be done within 24 hours.
- Mass production offers ~50% reduction in construction time and substructure cost, compared to one-off.
- The overall installed cost of the OO-Star Wind Floater (excl. tower, RNA and electrical) can be reduced by 30% going from prototype to fabrication of 20 units.

Next steps

- Fatigue assesment in tower and rotor
- Upscaling (10MW ?)
- Wave tank test of updated configuration/CFD
- Detail design
- Prototype



Acknowledgements

- The project was funded by the Norwegian Research Council and Statoil, contract 225946/E20
- The wave tank test at ECN, Nantes was in part funded by the EU MARINET project, NOWITECH, IFE, Acciona and CENER.

Thank you for your attention !

Extra slides are available in the conference proceedings

Phase 2 delivery consists of 10 reports and 11 drawings

Phase 1	Doc.no.	Document name
	11802-OO-R-000	Document List
	11802-OO-R-001	Design Basis
	11802-OO-R-002	Substructure Configuration
	11802-OO-R-003	Hydrodynamic Analysis and Simulations
	11802-OO-R-004	Mooring Analyses
	11802-OO-R-005	Structural Design – Preliminary
	11802-ACC-R-006	Construction Procedures
	11802-OO-D-001	General View
	11802-OO-D-002	Construction Sequences
	11802-OO-D-003	Post Tensioning

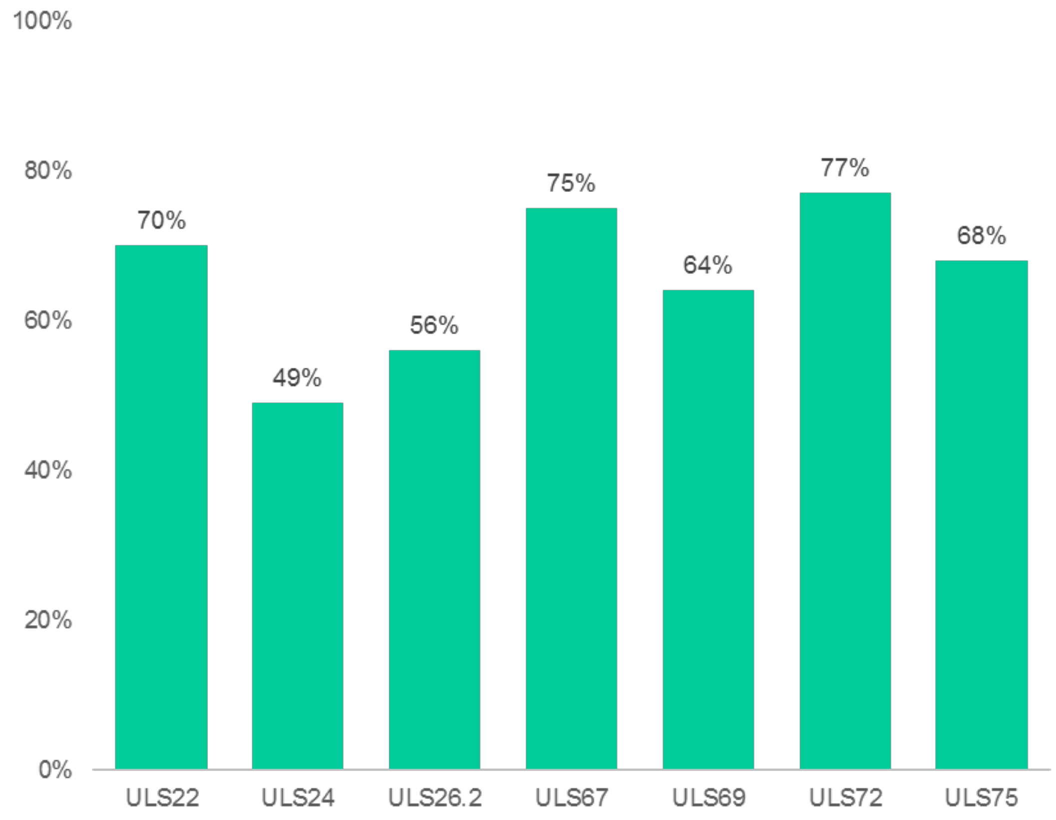
Phase 2	Doc.no.	Document name
	11802-OO-R-201	Design Basis – phase II
	11802-OO-R-203	Hydrodynamic Analysis and Simulations – phase II
	11802-OO-R-204	Mooring Analyses – phase II
	11802-OO-R-205	Structural Design – phase II
	11802-OO-R-207	Marine Operations
	11802-OO-R-208	Cost estimate
	11802-ACC-R-201	Access System
	11802-ACC-R-202	Risk Management General Presentation
	11802-ACC-R-203	Fabrication Assessment Prototype
	11802-ACC-R-204	Fabrication Assessment 20 Units
	11802-OO-D-001	General View
	11802-OO-D-002	Construction Sequences
	11802-OO-D-003	Post Tensioning
	11802-OO-D-004	Hybrid General View
	11802-OO-D-005	Hybrid Construction Sequences
	11802-OO-D-006	Nomenclature
	11802-ACC-D-201	Construction Drawings
	11802-ACC-D-202	Concrete Prototype Sequence
	11802-ACC-D-203	Hybrid Prototype Drawings
	11802-ACC-D-204	20 Units Construction Sequence Drawing
	11802-ACC-D-205	Access System Drawings

ULS analysis based on Line 1 inline load cases demonstrated adequate capacity

Analysis based on selected ULS load cases (only worst inline cases considered) demonstrates more than sufficient capacity for the 147 mm catenary system

> **Potential for reducing chain diameter**

For a detail engineering study, the full ULS load case matrix should be applied, with more than the 4 seeds run for each case in this study. Regarding the relatively low utilizations more seeds would most likely not imply overutilization.



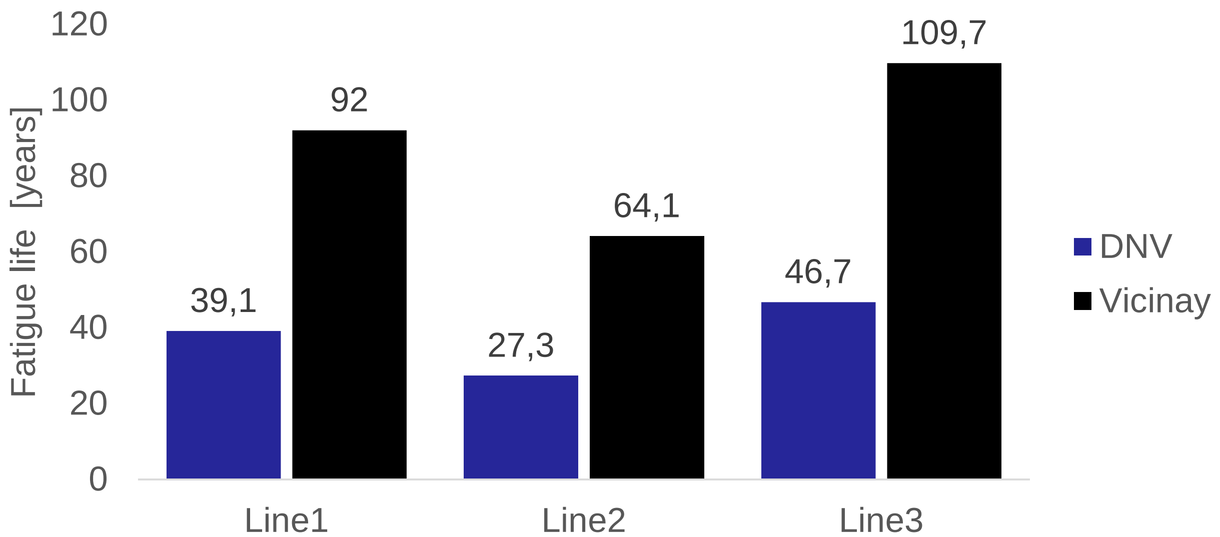
Utilisation found from “average-max”-method for the four seeds run for each load case combined with load static (1.3) and dynamic (1.75) load factor

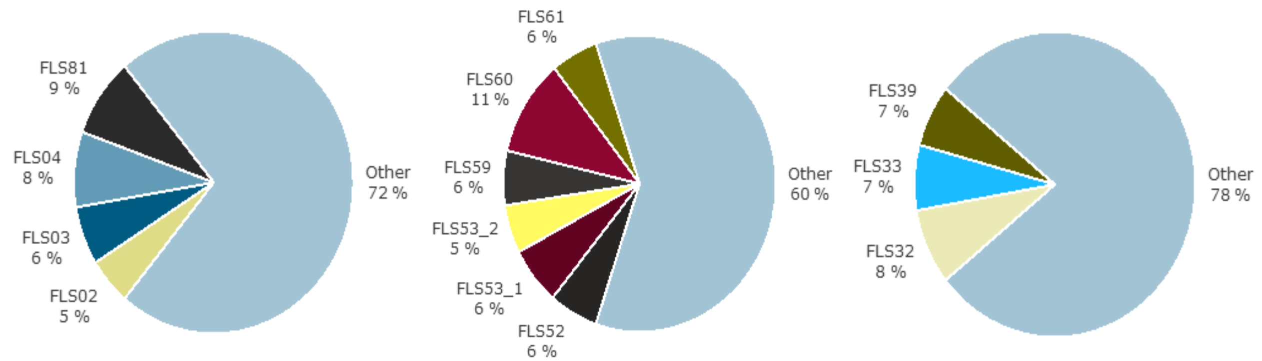
FLS analyses proved line 2 governing with fatiuge life of 27.3 Years

Design fatigue factor of 6 is applied in the FLS analyses.

Vicinay's S-N-curve increases fatigue life by more than 130 %.

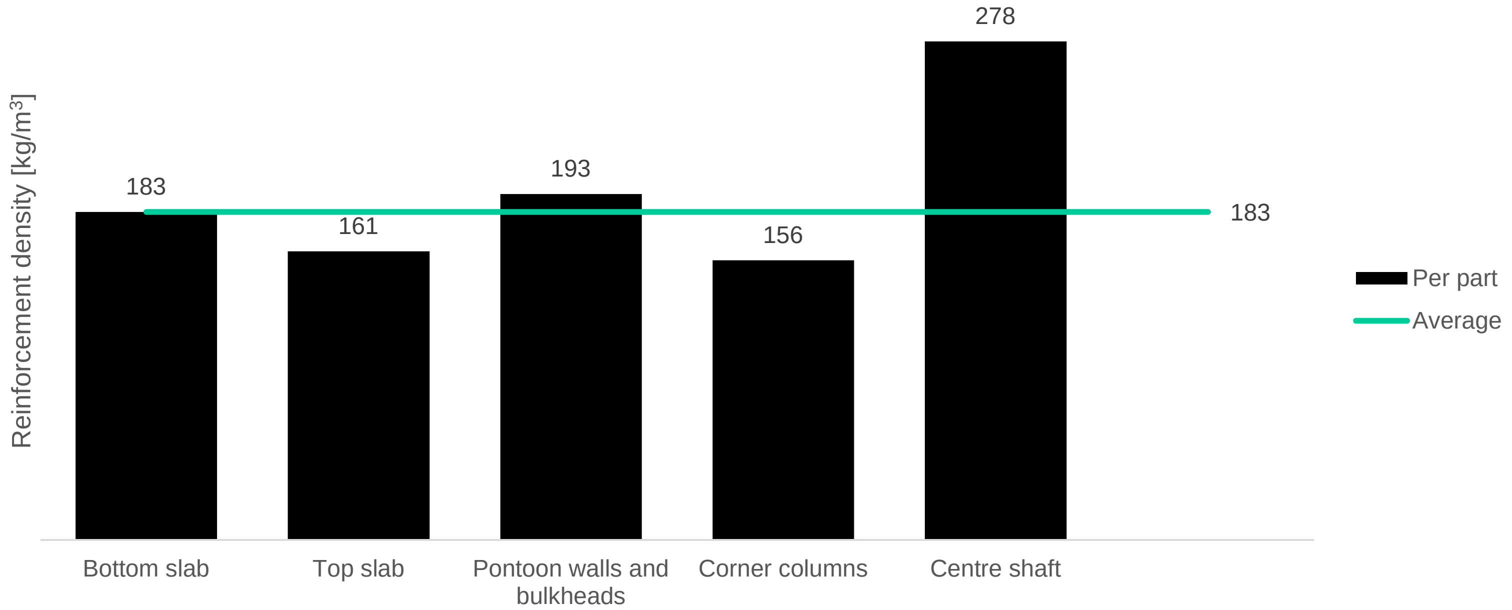
It is recommended that each load case should not account for more than 5-10 % of the total damage. The only load case that exceeds this condition is FLS60.





Normal reinforcement density of ~200* kg/m3, cs need 80% more reinforcement than cc

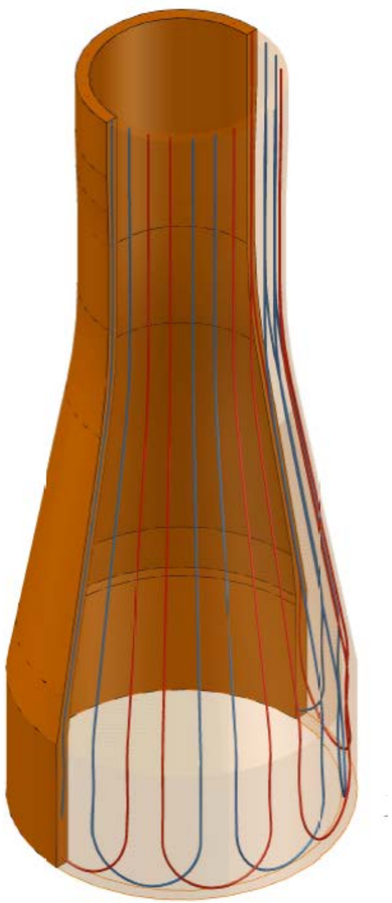
(* Excluding splicing and shear reinforcement)



Part	Reinforcement	Governing loads/limit state
All, except centre shaft	Shear	FLS wave loads
Centre shaft	All	FLS combined loads
Top slab	Normal	ULS mooring loads
Bottom slab, pontoon walls, bulkheads	Normal	Wave loads, varying limit states
Corner columns	Normal	Mooring loads in ULS and crack width calculations

Post-tensioning System

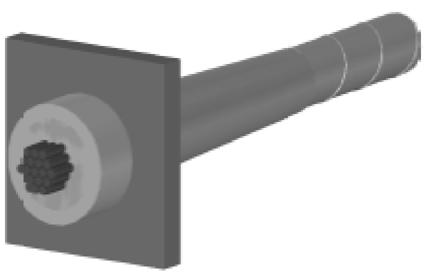
Centre shaft,
(6-19)-cables



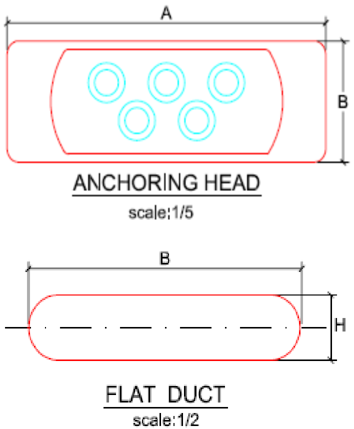
Part	Direction	Tendons
Bottom slab	Radial	$(6\text{-}5)_A$c330
Top slab	Radial	$(6\text{-}5)_A$c260
	Hoop	1*(6-19)
Centre shaft	Vertical	29*(6-19) (c900 in top of shaft)

Post-tensioning of each strand: 150 kN

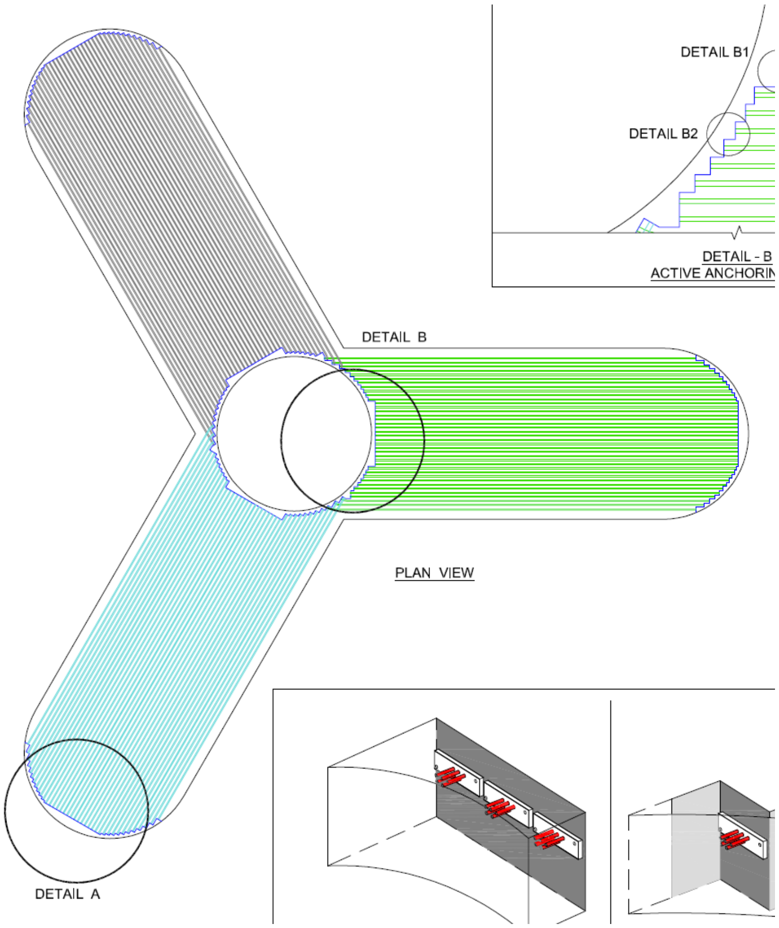
(6-19)-cables:

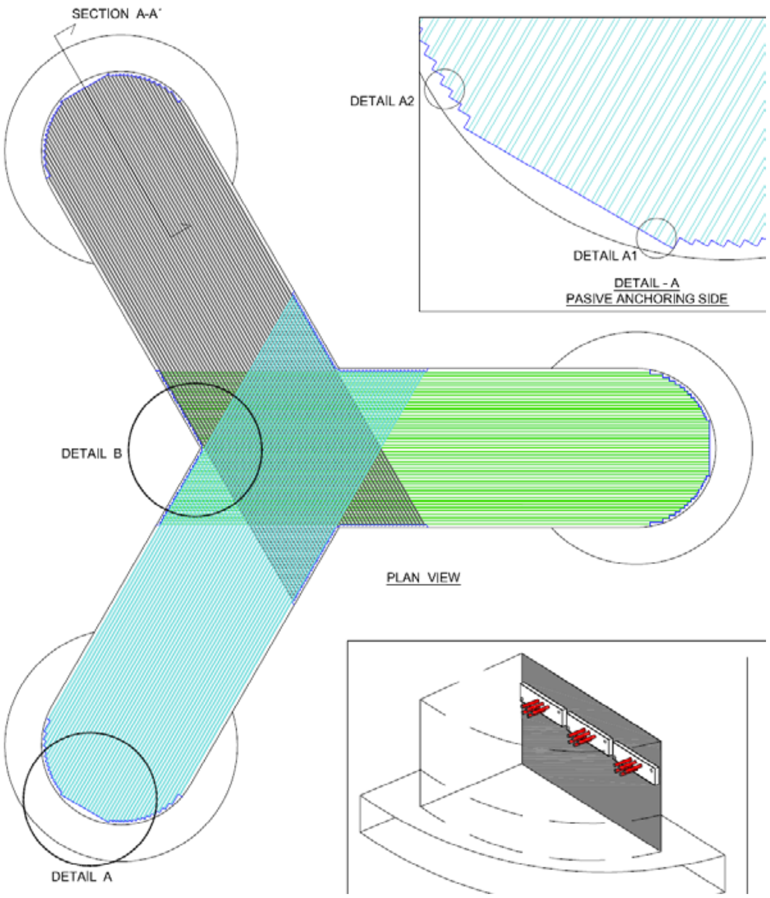


$(6\text{-}5)_A$-cables:



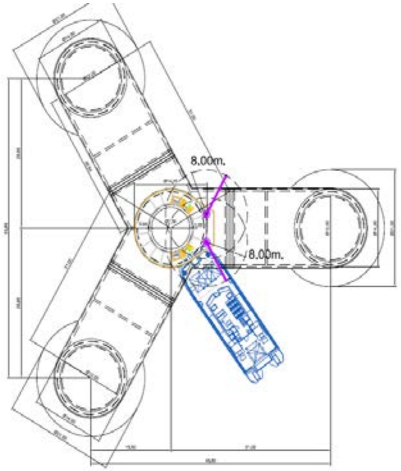
Post-tensioning System

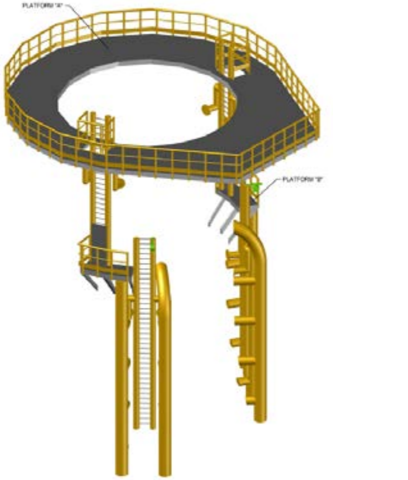


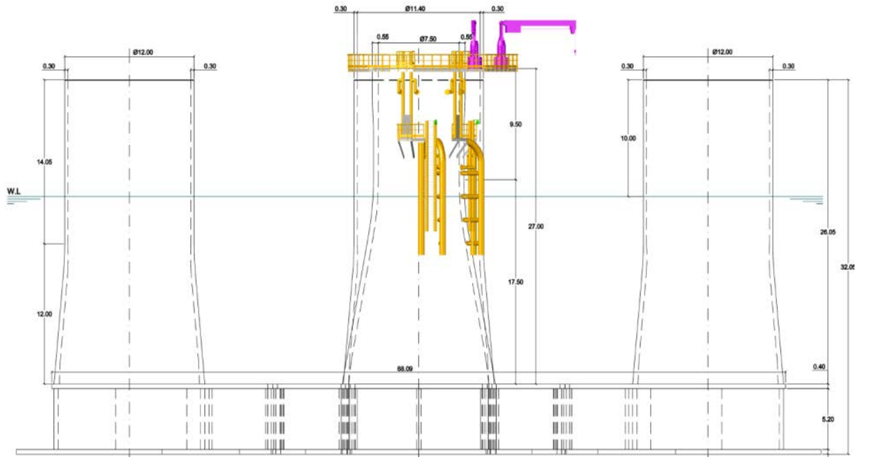


Redundant access from vessel permitted by double landing tubes at centre shaft

- Two boat landings offer increased redundancy
- Access to corner columns disregarded
- Intermediate resting platform, blocking door and fall arrest system on ladders
- Access to nacelle through elevator or emergency ladder inside WTG mast
- Double cranes increase lifting redundancy







Moderate risk associated with both prototype and serial construction

- Risk assessment based on Acciona Risk Identifiaction Workshop, September 9th
- Risks identified and grouped
- Most critical identified risks:
  - Permits and environmental authorizations might take longer than expected
  - Floater efforts during transportation and loading
  - Difficulty to get aggregates (rock materials) supply form adequate quarries

acciona Infraestructuras		Consequence 1 Insignificant	2 Low	3 Medium	4 Major	5 Catastrophic
Likelihood	A Almost certain	Moderate	Significant	High	High	High
	B Likely	Moderate	Moderate	Significant	High	High
	C Moderate	Low	Moderate	Moderate	Significant	High
	D Unlikely	Low	Low	Moderate	Moderate	Significant
	E Rare	Low	Low	Low	Moderate	Moderate

Construction of prototype

	HIGH nº	HIGH valor	SIGNIFICANT nº	SIGNIFICANT valor	MODERATE nº	MODERATE valor	LOW nº	LOW valor
Economic	3	52	3	36	10	74	3	10
Scheduling	4	81	2	24	11	76	2	6
Environment & Community					2	14	1	3
Reputation			1	12	1	8	1	3
HS & Security					2	12		
libre								
	9	165	8	96	39	270	9	29

	HIGH	SIGNIFICANT	MODERATE	LOW	Total
Total Consequences:	9	8	39	9	65
Consequences' value:	165	96	270	29	560
Total percentage:	29,5%	17,1%	48,2%	5,2%	

CONSTRUCTION: 34,5% — MODERATE

Serial construction of 20 units

	HIGH nº	HIGH valor	SIGNIFICANT nº	SIGNIFICANT valor	MODERATE nº	MODERATE valor	LOW nº	LOW valor
Economic	4	72	5	60	10	70	3	10
Scheduling	5	91	4	48	10	67	2	6
Environment & Community					2	14	1	3
Reputation			1	12	1	8	1	3
HS & Security					3	17		
Conformity	3	47	5	60	12	79	2	7
	12	210	15	180	38	255	9	29

	HIGH	SIGNIFICANT	MODERATE	LOW	Total
Total Consequences:	12	15	38	9	74
Consequences' value:	210	180	255	29	674
Total percentage:	31,2%	26,7%	37,8%	4,3%	

CONSTRUCTION: 36,4% — MODERATE