rentel
OFFSHORE ENERGY

seamade
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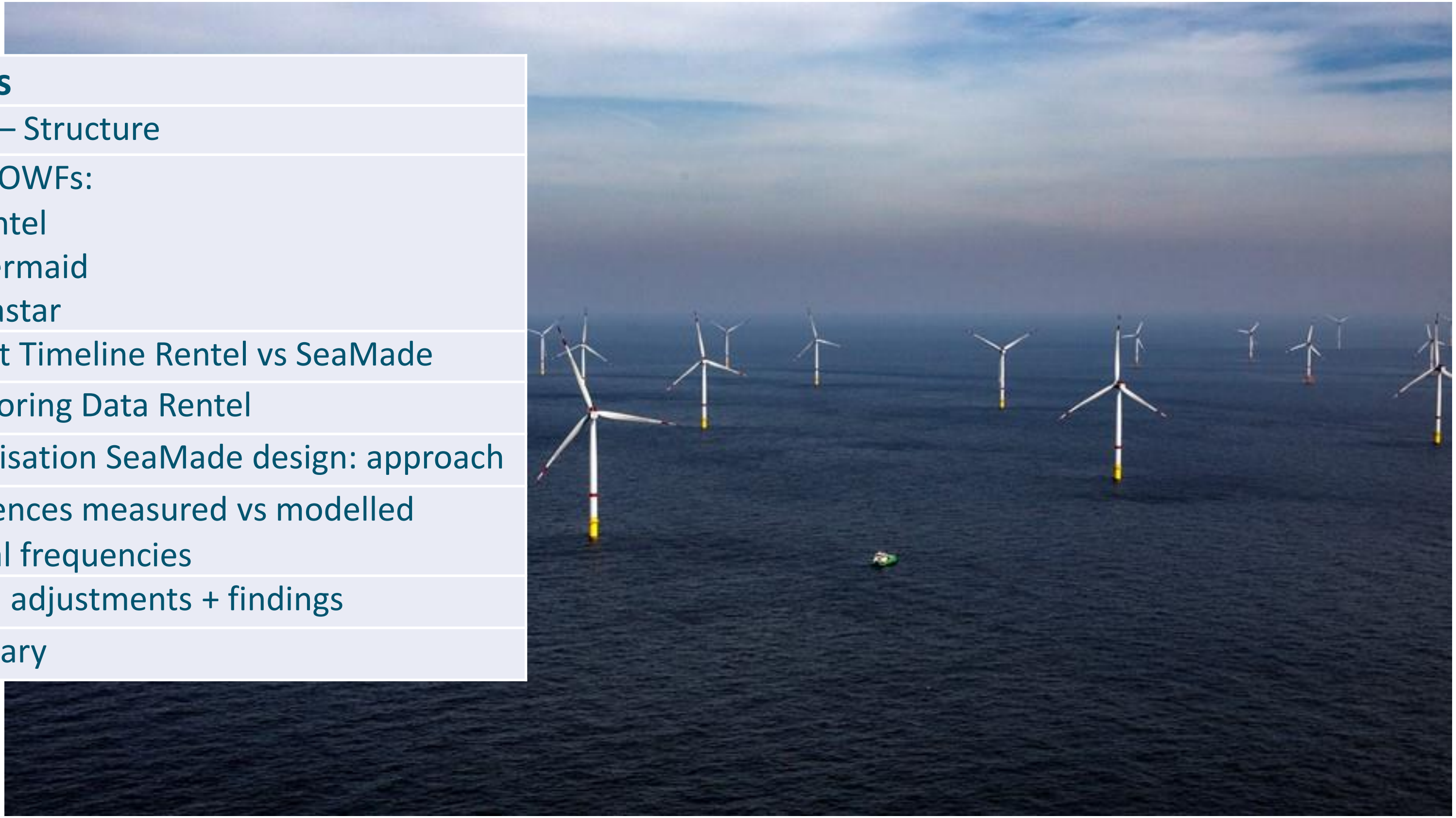
Use of Monitoring data to optimise detailed design

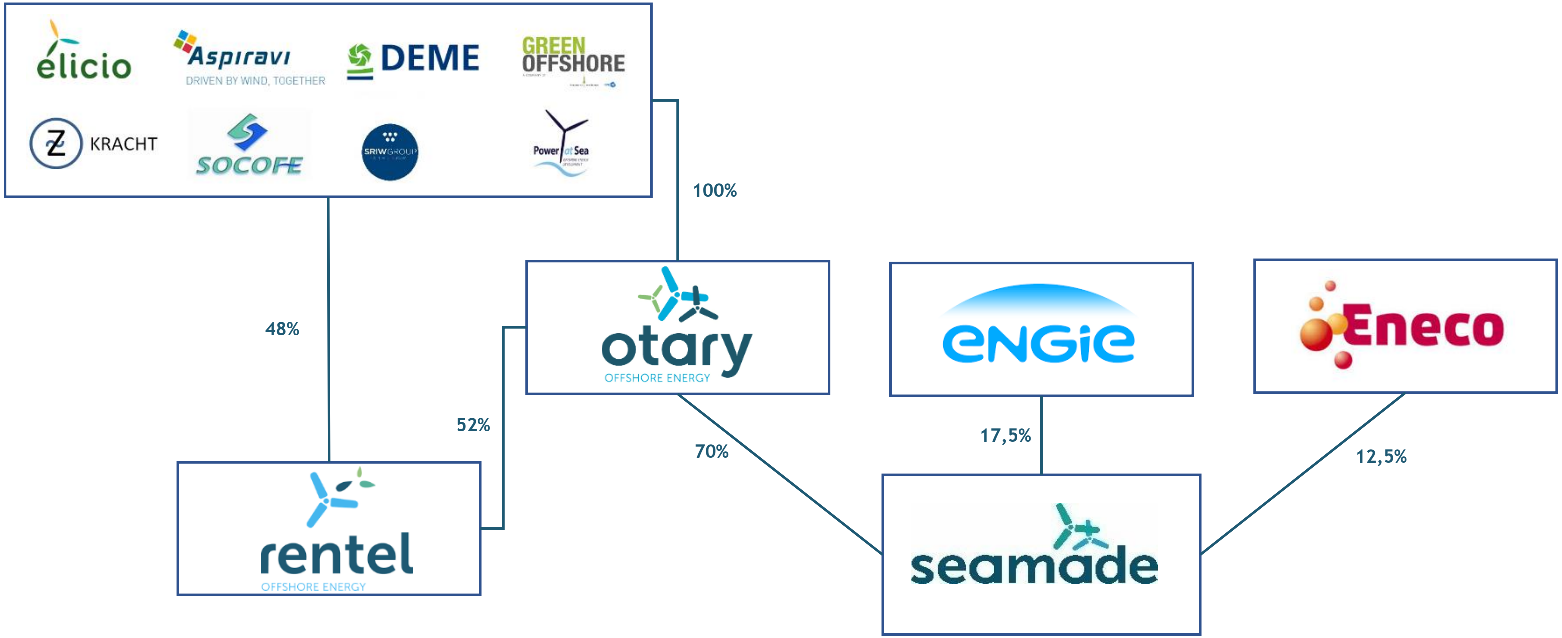
1 October 2019

Agenda

	Topics
1	Otary – Structure
2	Otary OWFs: a) Rentel b) Mermaid c) Seastar
3	Project Timeline Rentel vs SeaMade
4	Monitoring Data Rentel
5	Optimisation SeaMade design: approach
6	Differences measured vs modelled natural frequencies
7	Model adjustments + findings
8	Summary

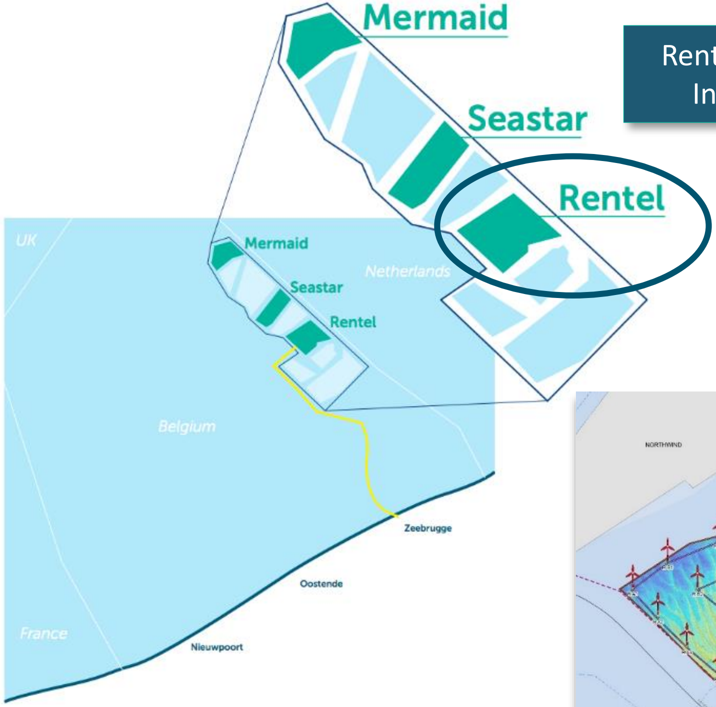


1. Shareholding Structure Otary

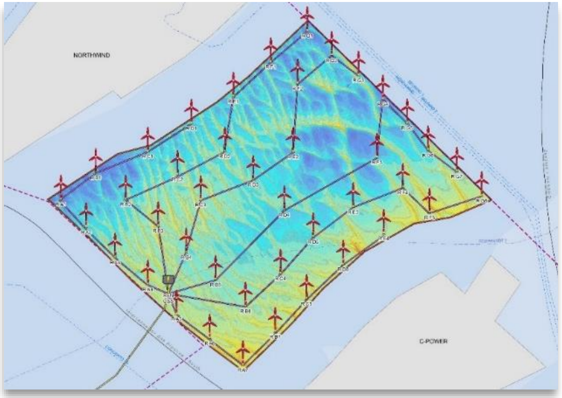


The Mermaid and Seastar projects are jointly developped, financed and constructed as SeaMade in order to maximize synergies and meet the 2020 targets.

2. Otary OWFs
a) Rentel Concession

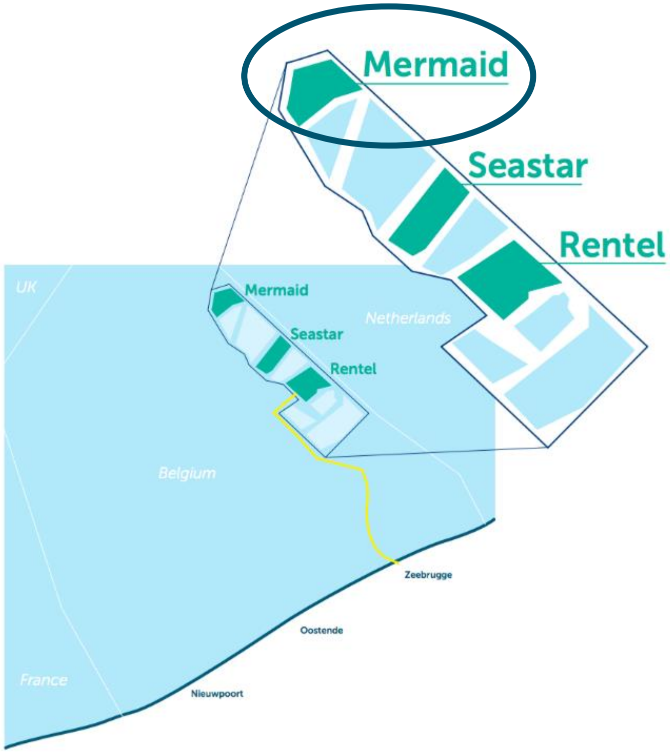


Rentel = 309 MW
In Operation



- **42 SG 7.0-154 windturbines & 1 OSS**
- **Capacity:**
  ± 309 MW
- **Estimated production:**
  1.0-1.1 Twh/year
- **Surface:**
  22,72 km²
- **Average water depth:**
  22 – 36 m
- **Distance to shore:**
  34 km off Zeebruges & 40 km off Ostend.
- **2D length export cable to shore**: 39,7 km (ASL)
- **OSY- OSS Rentel connecting cable length:**
  4,26 km

b) Mermaid Concession



28 WTG SG-8.0-167 (PB to 8.4MW)

Capacity:
235,2 MW

Surface:
17 km²

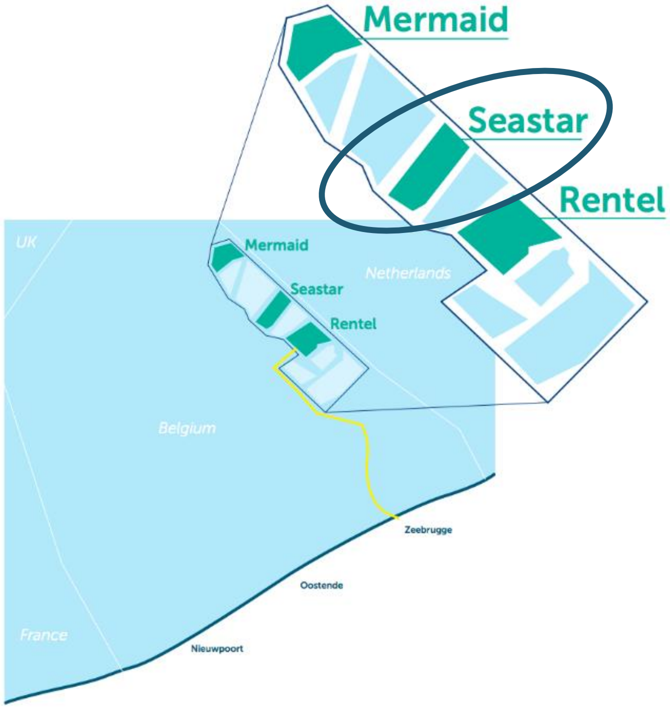
Average water depth:
22 – 42 m

Average wind speed:
9,7 m/s

Export cable length connection to MOG:
20,6 km

Distance to shore:
50 km

c) Seastar concession



30 WTG SG-8.4-167 (PB to 8.4MW)

Capacity:
252 MW

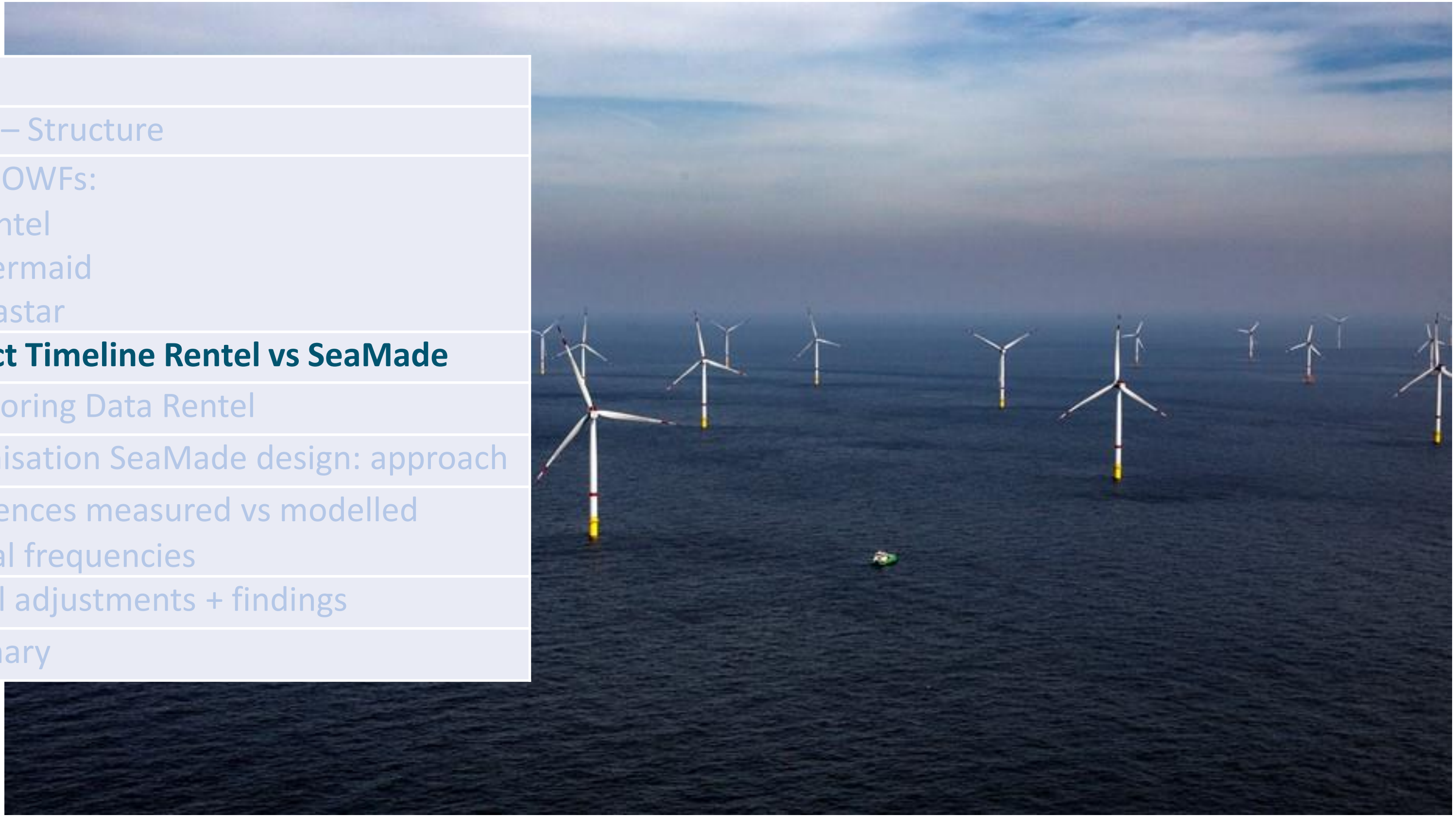
Surface:
19,54 km²

Average water depth:
20 – 38 m

Average wind speed:
9,6 m/s

Export cable length connection to MOG
6,74 km

Distance to shore:
38 km



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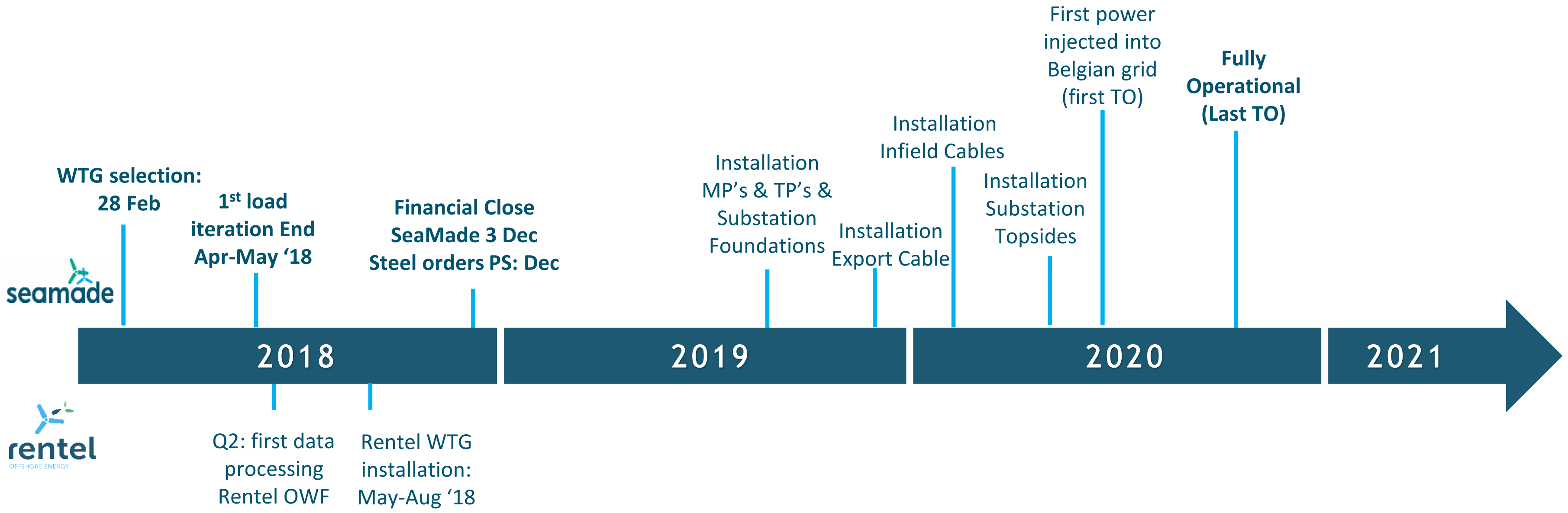
3. Project Timeline Rentel vs SeaMade



Aim: Taking benefit of available data 1st OWF for detailed design next OWFs: not only factual geotech data (same soil layers) but also

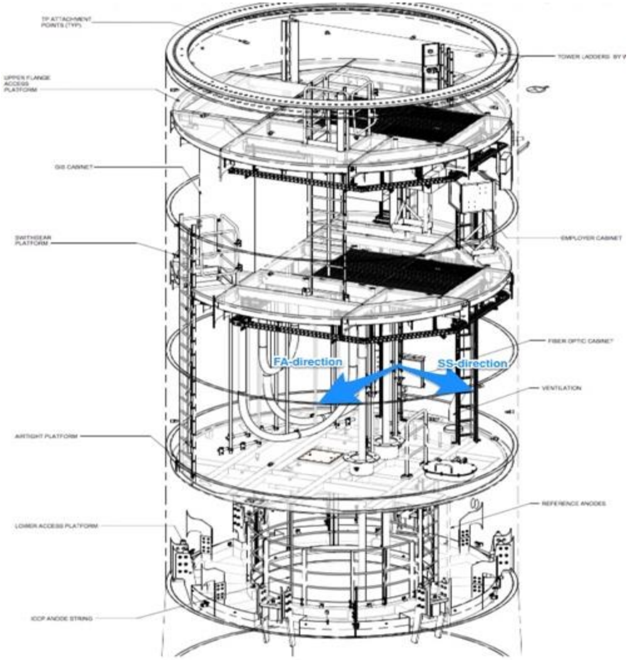
- **processed SHM data**
- **Driving logs**

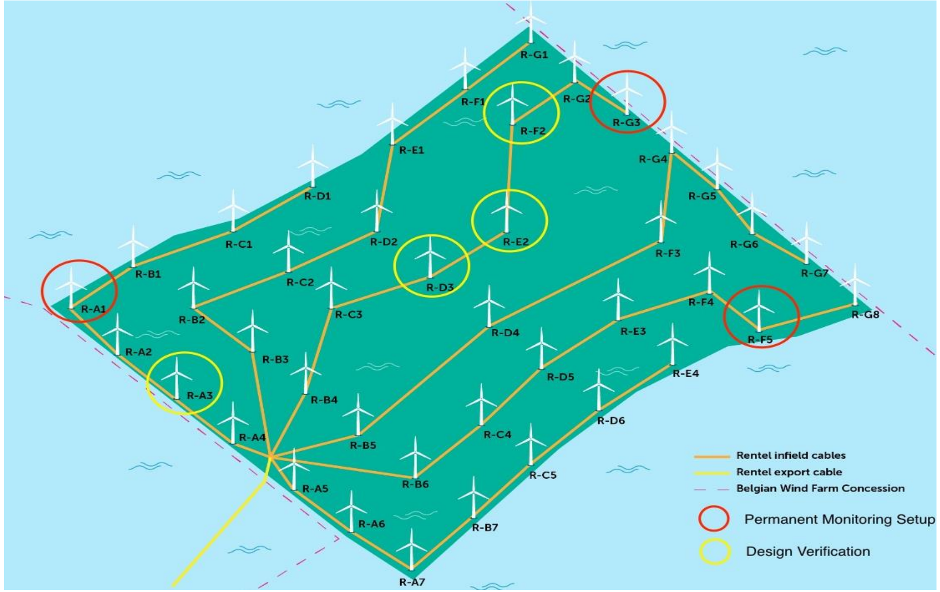
Whilst still respecting timeline towards FC

4. Monitoring Data Rentel (1)

- Q2 2018: processed OMA measurement data (operational modal analysis) from 3 foundations on Rentel OWF with permanent monitoring set-up :

  Single biaxial accelerometer at R-A1, R-F5, R-G3





4. Monitoring Data Rentel (2)

- That time, **MP+TP** installed (grouted connection).
  No tower or nacelle installed yet

- A1 + G3 : **only filter** layer installed for duration of measurement period

- F5 **full scour** protection (incl. rock armour)

- Measurement periods:

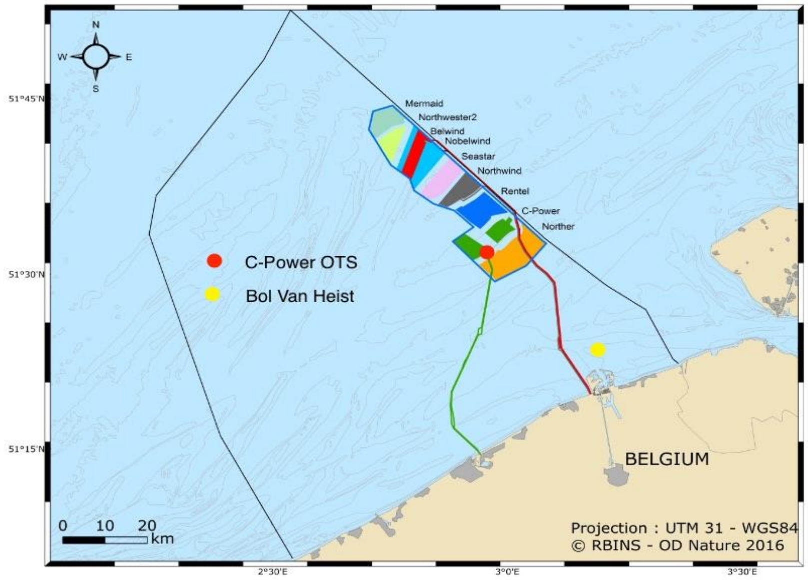
Measurement Period R-A1:	18/01/2018-27/05/2018 (Average of 55% monthly data availability)
Measurement Period R-F5	12/02/2018-19/05/2018 (Average of 75% monthly data availability)
Measurement Period R-G3	03/01/2018 -25/05/2018 (Average of 85% monthly data availability)

Data collected via solar powered data acquisition system, hence no 100% data availability

4. Monitoring Data Rentel (3)

- Tidal level & wave height data: via wave radar on transformer station of nearby OWF C-Power
- OMA (24Sea) for accurate estimates of natural frequencies, damping ratios (*) and mode shapes

(*) sensitive to both user-settings as the choice of algorithm



4. Monitoring Data Rentel (4)

- large variations on estimated frequencies due to changing environmental conditions (eg tidal level, wave parameters)
- Reference frequency for each location calculated
- Established **reference state** :
  - Tidal level: LAT (0 cm)
  - Significant wave height: 1 m

Resonance Frequency	A1	F5	G3
Prior Rock Armour	1,240Hz	-	1,340Hz
Post Rock Armour		1,513Hz	

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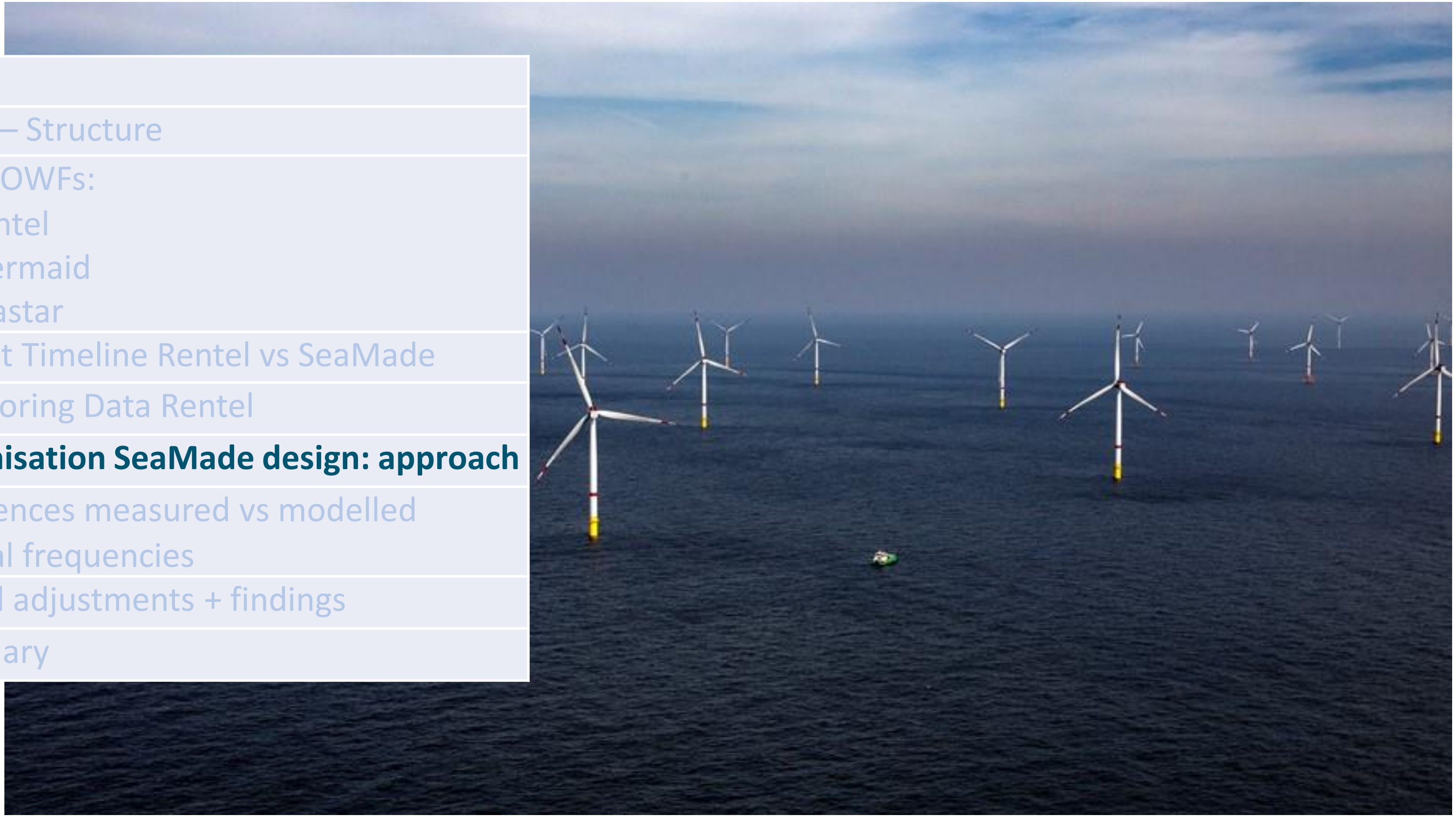

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5. Optimisations for SeaMade design

General approach for all 3 assessed Rentel locations,

considering conditions present at time of measured natural frequencies:

- Set up as-built model of the Rentel foundations
  Soil profiles : same methodology as agreed for Mermaid and Seastar OWFs (≠ designers Rentel vs SeaMade)
- Tuning of the soil stiffness to reduce gap with measured modal parameters by different adjustments
- Setup FE model to check that modifications are physically realistic

Final aim: Implement optimization in (ongoing) detailed design phase of

SeaMade (input 2nd load iteration, subject to timely approval CB)

6. Rentel design natural frequencies vs modelled

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Calculated 1st natural frequency in simulation model for SeaMade (foundation only) prior to model optimisation

Measured 1st natural frequency: higher than the modelled

Position	Seabed level	Water level	Pile diameter mudline	Pile penetration	1st natural frequency	Measured 1st natural frequency	Difference in 1st NF between design & measurements
	[mLAT]	[mLAT]	[m]	[m]	[Hz]	[Hz]	[%]
A1	-35.2	0.0	8.00	40.53	1.008	1.240*	-18.7
F5	-32.3	0.0	7.50	32.44	1.199	1.513	-20.8
G3	-27.9	0.0	7.80	34.30	1.001	1.340*	-25.3

Design conditions:

- MP + TP only, A1 + G3: only filter
- No corrosion allowance and marine growth (Rentel OWF under construction when measured)
- No cyclic degradation of the soil taken place yet -> static p-y curves applied
- Soil of position **A1**: mainly consisting of **clay** layers
- Positions **F5 and G3**: mostly consisting of **sand** layers

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	a) Determine soil layer sensitivity
	b) Include scour protection in model
	c) Tune initial soil stiffness
8	Summary

7. Model adjustments (1)

Aim: reduce gap between simulated and measured 1st natural eigen frequency to increase the modelled eigen frequencies via realistically tuned parameters

a) **Soil layer sensitivity**

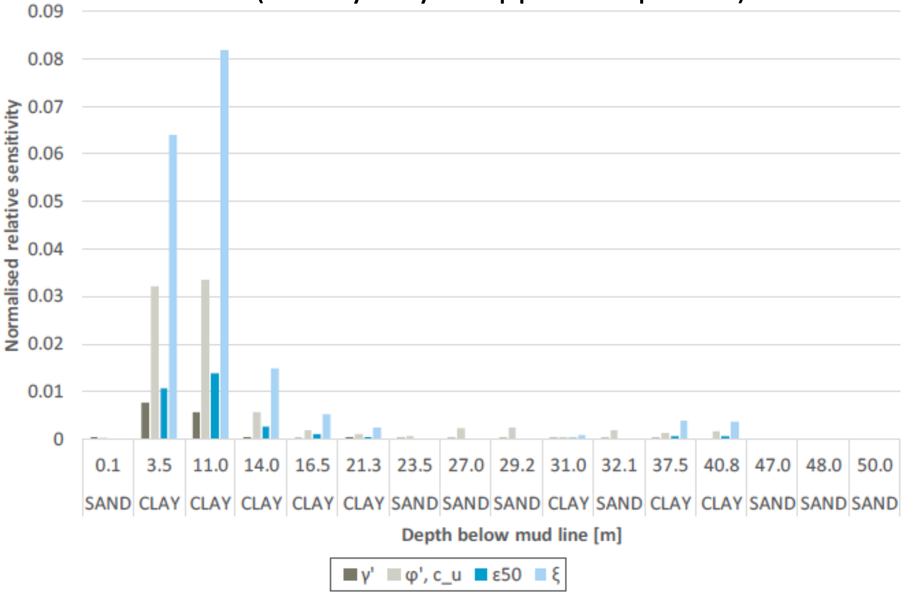
- Determine most sensitive soil layers and their influence on the natural frequency of the system (which is approx. 5x higher than for a fully assembled turbine)
- Tune / Alter the soil parameters within realistic boundaries :
  - γ' – submerged unit weight
  - Characteristic soil strength parameters
    - φ' – angle of internal friction for sand (frictional soils)
    - c_u – undrained shear strength for clay (cohesive soils)
  - For clays only:
    - ε_{50} – the strain at half the maximum stress
    - ξ – empirical coefficient for stiff clay (Modified Matlock)

7. Model adjustments (2)

Findings soil layer sensitivity:

- Upper soil layers (first 15m below mudline) most sensitive to influence the 1st eigenfrequency of MP-TP:
  missing masses of tower and nacelle in the model (inducing larger lateral pile deformations at depth, mobilizing soil reactions from deep soil layers)
- Modifications to underlying soil layers:
  almost no influence on 1st eigenfrequency of the structure
- Addition of scour protection layer:
  slight decrease of all sensitivities, more influence of 1st sand layer

A1 (mainly clay in upper soil profile)



Normalised relative sensitivity of the soil parameters (consistent units to allow comparison)

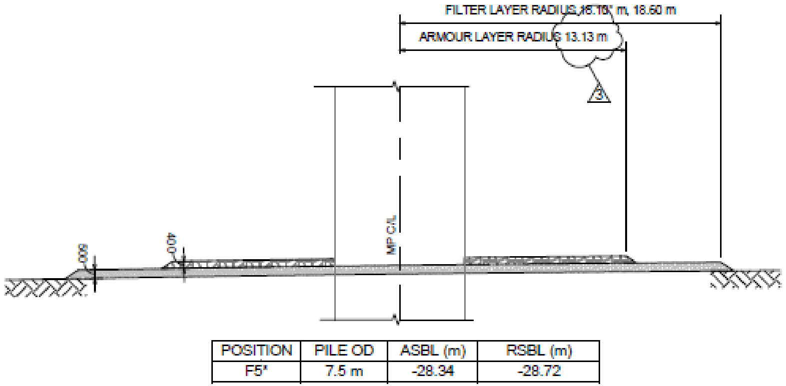
7. Model adjustments (3)

b) Include scour protection

Consider as-built dimensions of scour protection in the calculations
Total thickness filter & armour layer approx. 0.2 m higher than design

Findings:

- natural frequency ↗ with addition of a filter/armour layer (impact of additional scour protection weight on the effective stresses of the soil layers)
- Upper soil layers most sensitive
- Armour layer installed at F5 : further increase of modelled eigenfrequency
- Scour layer thickness ↗ : also first eigenfrequency ↗



POSITION F5

Position	Filter layer height	Armour layer height	1st natural frequency	Difference in 1st NF between design & measurements	
	[m]	[m]	[Hz]	[%]	
A1	0.6	-	1.015	-18.1	(+0.6)
F5	0.6	0.5	1.249	-17.4	(+3.4)
G3	0.6	-	1.030	-23.2	(+2.1)

7. Model adjustments (4)

c) Include initial soil stiffness enhancements

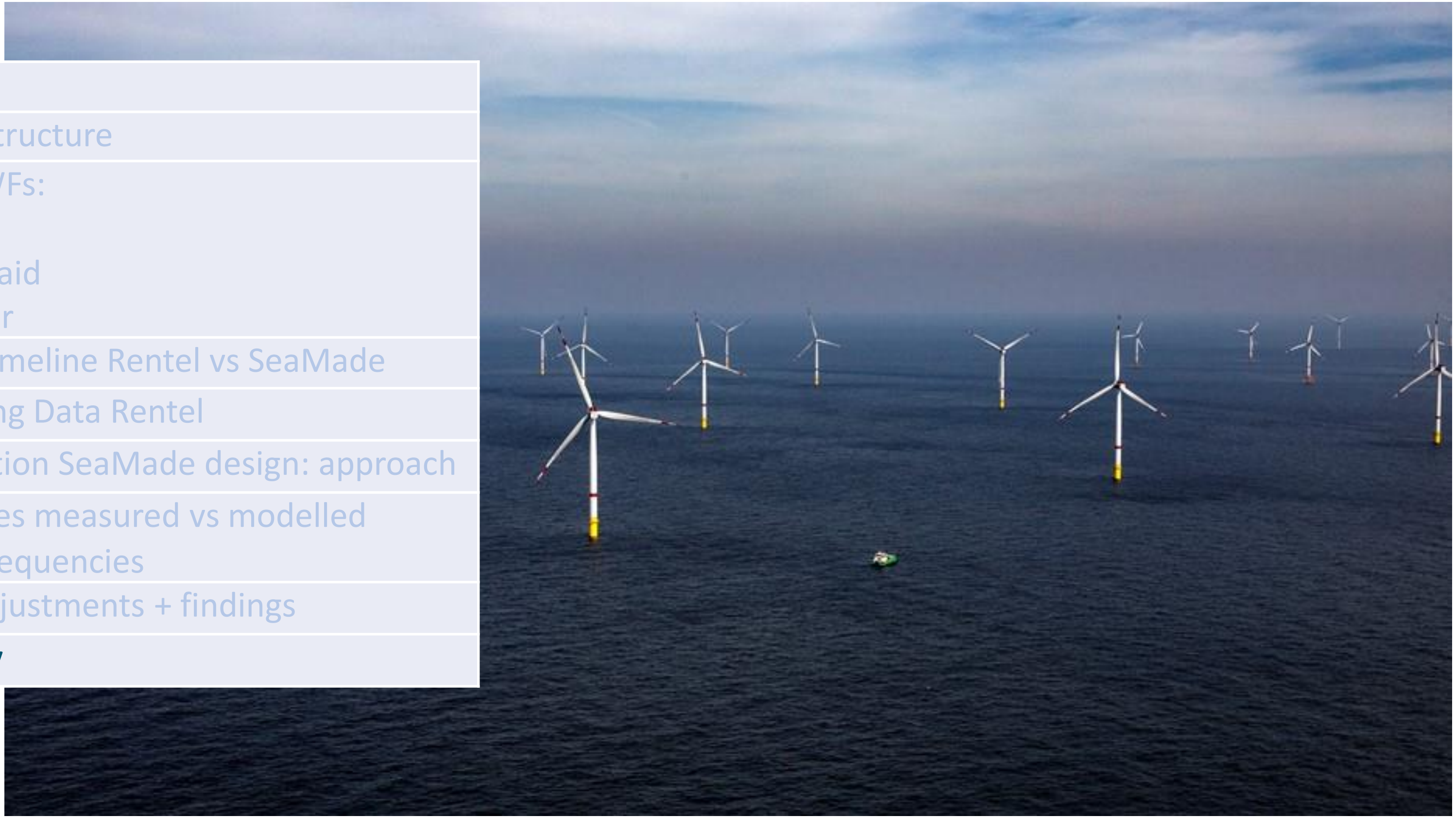
- Extensive FE calculations performed on the clay layers in original SeaMade geotech design -> no justification for initial stiffness increase for the clay layers
- Kallehave method to determine soil stiffness of sands for large-diameter MPs by modifying the initial stiffness of the API p-y:
  - Increase of initial stiffness of the sand p-y curve model by introducing a dependency on the MP O.D.
  - Stress and strain level correction
  - Tested against measurements from other OWF
- More accurate determination of total soil stiffness while still being conservative

7. Model adjustments (5)

Findings:

- ➢ Increase of up to 12.4% for location G3 (sand dominated upper layers, similar for F5).
- ➢ A1: small sand proportion in upper soil profile, only very small influence

Position	1st natural frequency	Difference in 1st NF between design & measurements	
	[Hz]	[%]	
A1	1.009	-18.6	(+0.1)
F5	1.377	-9.0	(+11.8)
G3	1.168	-12.9	(+12.4)



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8. Summary (1)

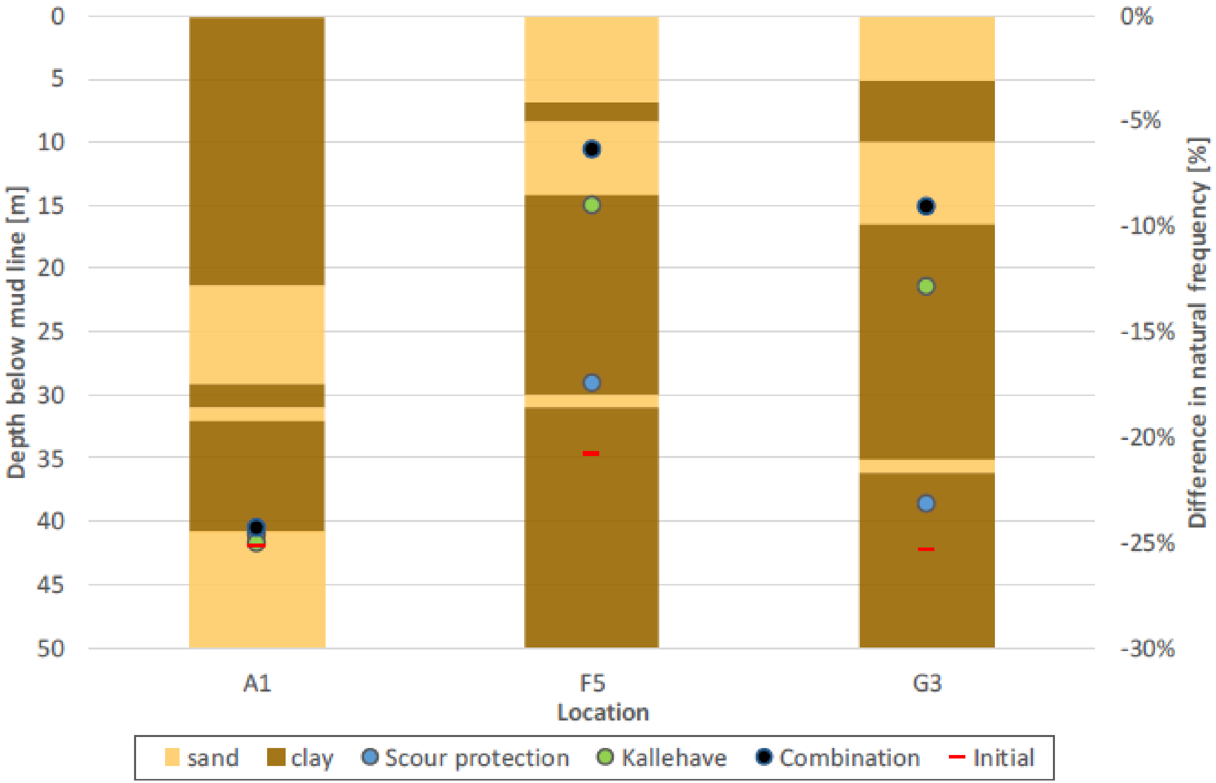
Simultaneous application of scour protection & optimized initial soil stiffness for sand :

- Main increase of locations G3 & F5 (sand dominated upper layers) reducing the gap with the measured frequency to 6%.
- A1: small sand proportion in upper soil profile, limited increase only of the eigenfrequency

Position	1st natural frequency	Difference in 1st NF between design & measurements	
	[Hz]	[%]	
A1	1.019	-17.9	(+0.8)
F5	1.420	**-6.3**	(+14.4)
G3	1.241	-9.0	(+16.3)

8. Summary (2)

Corresponding results of the modification iro soil profiles for 3 locations



8. Summary (3)

- Exact match with the measured frequencies will/ cannot be reached due to additional structural ≠ between the model and the as-built structure
- Risk for too many parallel modifications on input of 2nd iteration iro convergence (e.g. also Δ LCT, Δ tower design introduced that time)
- Timeline design prevailing, no timely conclusion between CB + designer on further optimizations (damping) given upcoming FC & steel order dates
- Hard to quantify steel savings (cfr above, various changes in input)

Overall positively experienced to apply existing data along the design without jeopardizing timeline:

Geotech data, structural health monitoring, pile driving records, …