AKER ARCTIC TECHNOLOGY

# Extreme and fatigue-driven load analysis for floating offshore wind turbine foundations in ice

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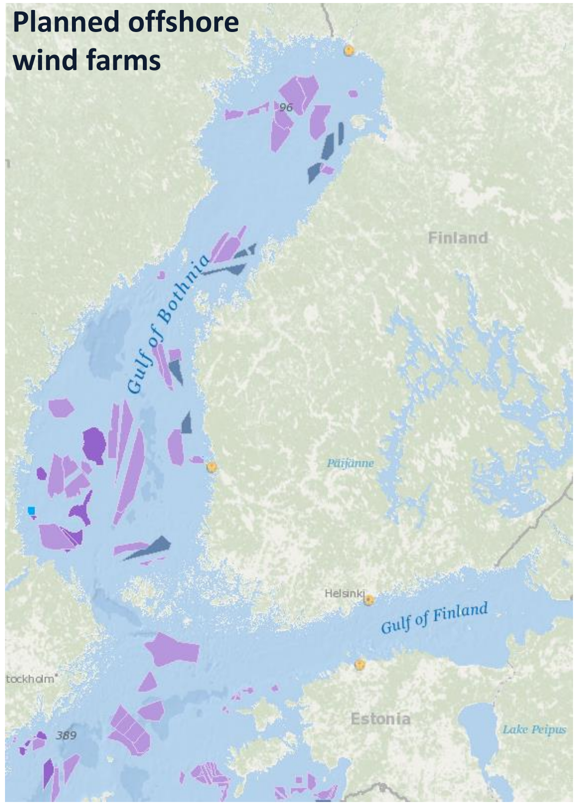
# Ice loads on offshore wind foundations

- Why do we care?
- What is the problem?
- How to get it right?
- How can we use the results?
- Conclusions

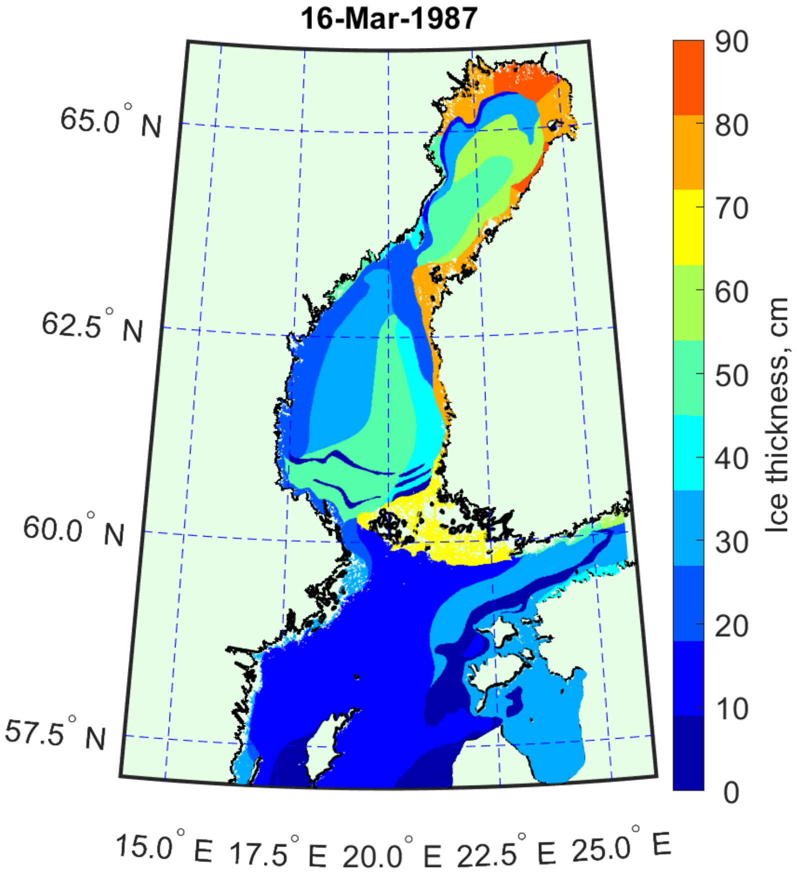
# Why do we care?

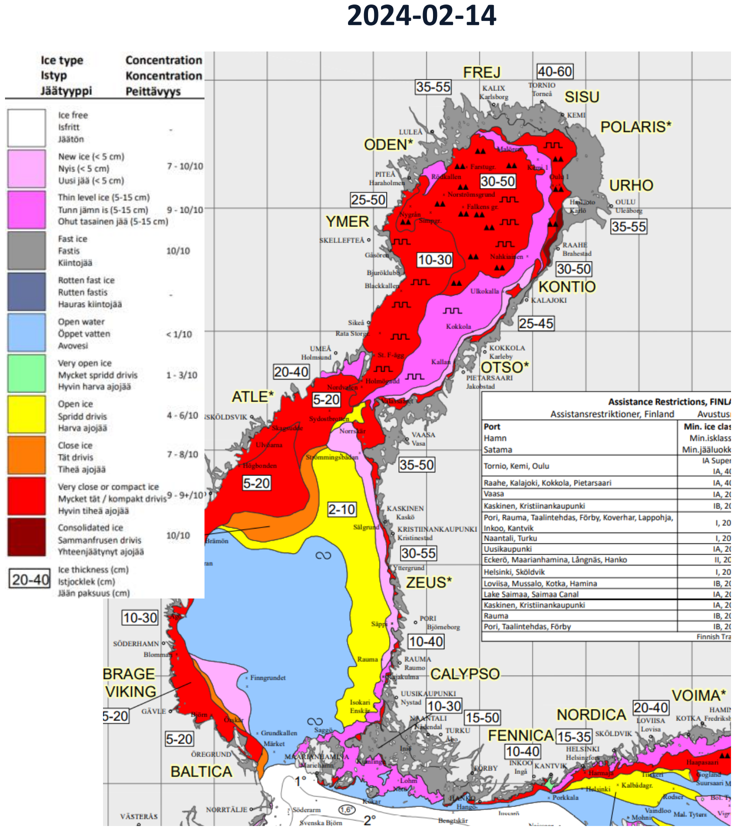
# Offshore wind farms in the Baltic Sea: demand for analysis

- Designing a wind turbine foundation is inherently **site-specific**, requiring careful consideration of wind and wave loading, and the same principle applies to assessing **various types of ice loading**.
- As for today, the effect of ice on the future offshore wind farms in the Baltic Sea is unknown and uncertain.



https://map.4coffshore.com/offshorewind/





https://en.ilmatieteenlaitos.fi/ice-conditions

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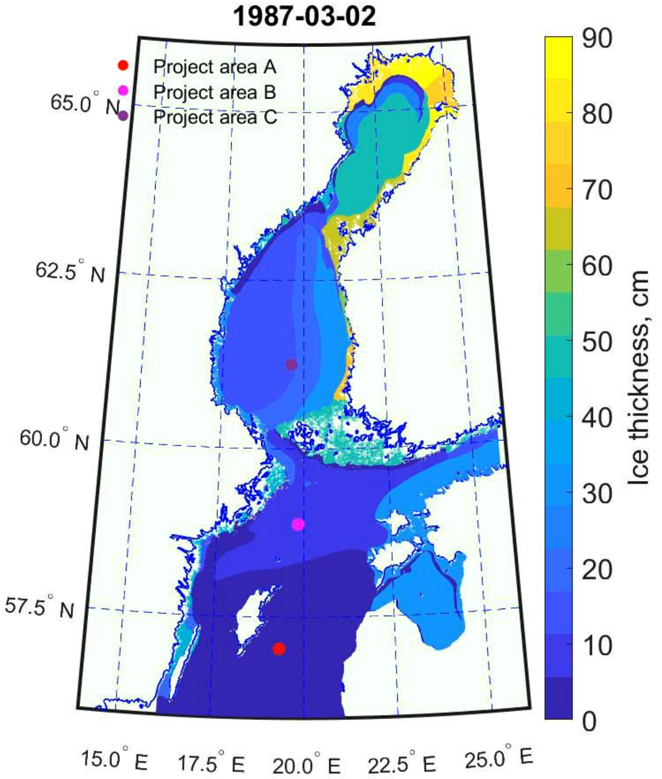
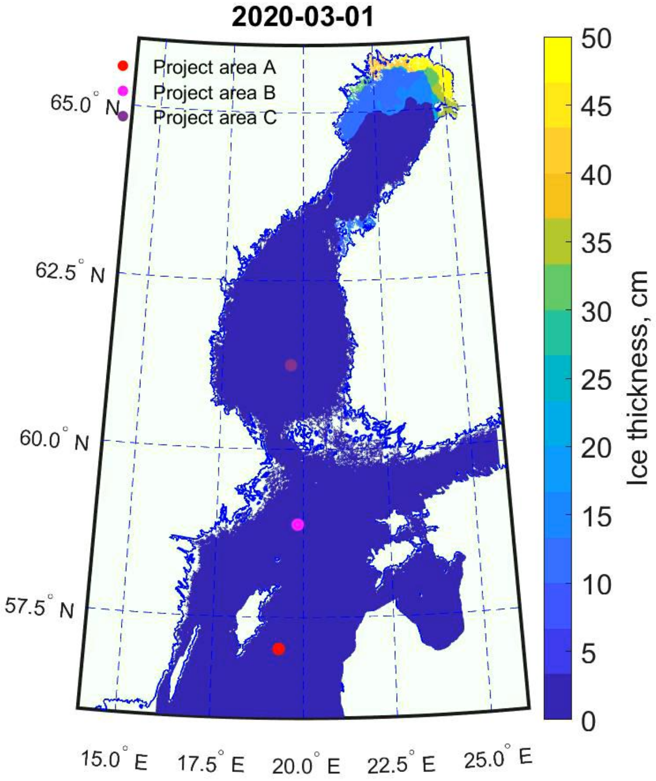
# Site-specific environmental data: ice conditions

| Parameter / Project area (over the past 50 years of observations) | Wind farm area 1 | Wind farm area 2 | Wind farm area 3 |
|---|---|---|---|
| The longest duration of ice present at the site, approx. | 4 months | 1.5 months | 1 week |
| Maximum level ice thickness | 0.5 m | 0.25 | 0.15 m |
| Height of ice ridge keel | 10 m | 7 | 3 m |

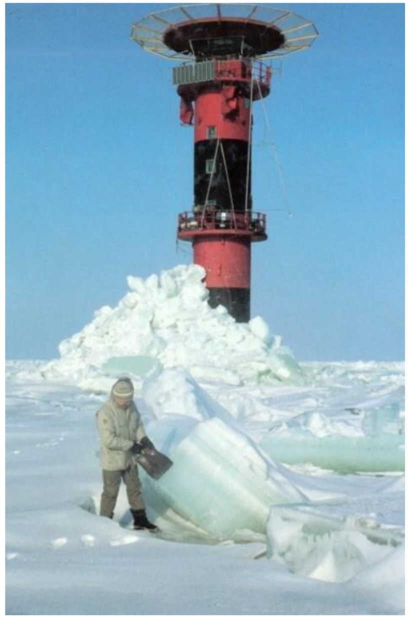


It is crucial to address the variability of ice conditions on the specific site correctly to obtain realistic ice loads estimates



# Lessons learned from the bottom-fixed structures

Lighthouse Bjørnklack after overloading event on 4th April 1985
(Engelbrektson et al., 1987)



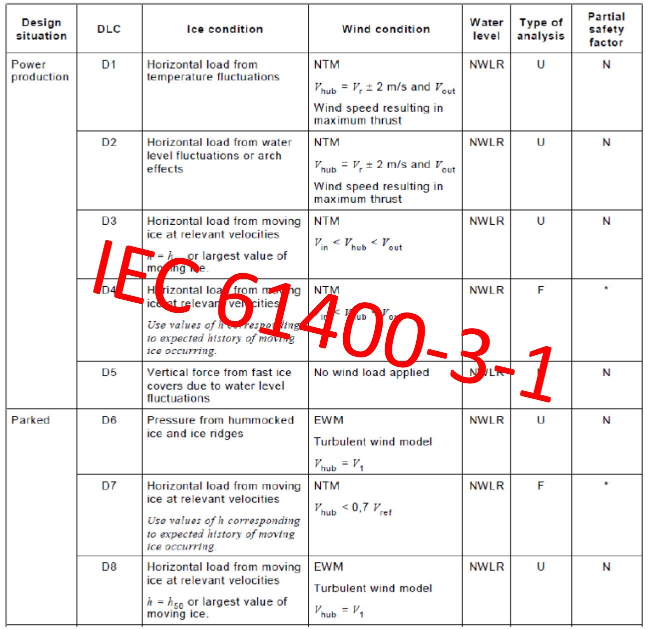
Kemi-1 lighthouse (Aker Arctic, 1995)

- Overturning and sliding failures in 70s-80s
- Sometimes the collapse was associated with a significant vibration – fatigue failure?
- Understanding of ice-structure interaction and ice failure mechanisms are of utmost importance for efficient design of offshore structures
- Floating structures are more complex, where the interaction between ice features and the moored floating structure is largely not known and represents a rather novel scientific field

# What is the problem?

# Design requirements for offshore wind turbines: need for more detailed methodology

In design load cases for ice loads coupled with other environmental loads, IEC 61400-3-1 and DNV-ST-0437 refer to ISO 19906

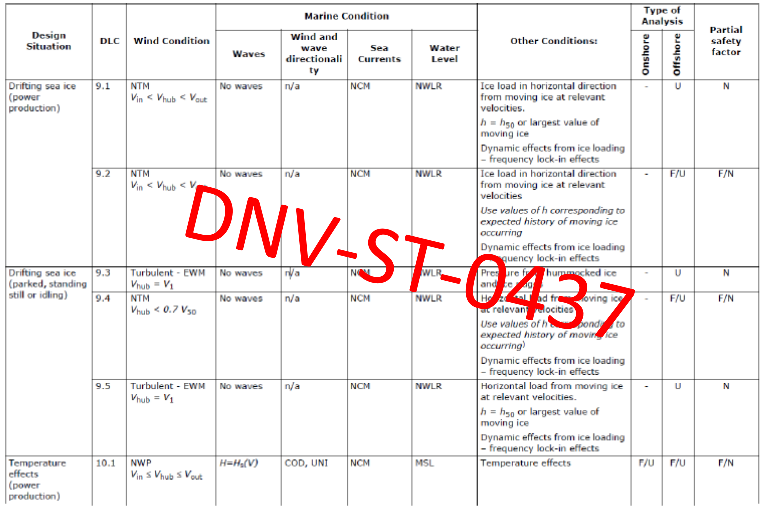


| Design situation | DLC | Ice condition | Wind condition | Water level | Type of analysis | Partial safety factor |
|---|---|---|---|---|---|---|
| Power production | D1 | Horizontal load from temperature fluctuations | NTM<br>$V_{hub} = V_r \pm 2$ m/s and $V_{out}$<br>Wind speed resulting in maximum thrust | NWLR | U | N |
| | D2 | Horizontal load from water level fluctuations or arch effects | NTM<br>$V_{hub} = V_r \pm 2$ m/s and $V_{out}$<br>Wind speed resulting in maximum thrust | NWLR | U | N |
| | D3 | Horizontal load from moving ice at relevant velocities<br>$h = h_{50}$ or largest value of moving ice. | NTM<br>$V_{in} < V_{hub} < V_{out}$ | NWLR | U | N |
| | D4 | Horizontal load from moving ice at relevant velocities<br>*Use values of h corresponding to expected history of moving ice occurring.* | NTM<br>$V_{in} < V_{hub} < V_{out}$ | NWLR | F | * |
| | D5 | Vertical force from fast ice covers due to water level fluctuations | No wind load applied | NWLR | [illegible] | N |
| Parked | D6 | Pressure from hummocked ice and ice ridges | EWM<br>Turbulent wind model<br>$V_{hub} = V_1$ | NWLR | U | N |
| | D7 | Horizontal load from moving ice at relevant velocities<br>*Use values of h corresponding to expected history of moving ice occurring.* | NTM<br>$V_{hub} < 0{,}7\ V_{ref}$ | NWLR | F | * |
| | D8 | Horizontal load from moving ice at relevant velocities<br>$h = h_{50}$ or largest value of moving ice. | EWM<br>Turbulent wind model<br>$V_{hub} = V_1$ | NWLR | U | N |

Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines.

**SFS-EN ISO 19906:2019:en**

**Petroleum and natural gas industries. Arctic offshore structures (ISO 19906:2019)**



| Design Situation | DLC | Wind Condition | Marine Condition | | | | Other Conditions: | Type of Analysis | | Partial safety factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Waves | Wind and wave directionality | Sea Currents | Water Level | | Onshore | Offshore | |
| Drifting sea ice (power production) | 9.1 | NTM<br>$V_{in} < V_{hub} < V_{out}$ | No waves | n/a | NCM | NWLR | Ice load in horizontal direction from moving ice at relevant velocities.<br>$h = h_{50}$ or largest value of moving ice<br>Dynamic effects from ice loading – frequency lock-in effects | - | U | N |
| | 9.2 | NTM<br>$V_{in} < V_{hub} < V_{out}$ | No waves | n/a | NCM | NWLR | Ice load in horizontal direction from moving ice at relevant velocities<br>*Use values of h corresponding to expected history of moving ice occurring*<br>Dynamic effects from ice loading – frequency lock-in effects | - | F/U | F/N |
| Drifting sea ice (parked, standing still or idling) | 9.3 | Turbulent - EWM<br>$V_{hub} = V_1$ | No waves | n/a | NCM | NWLR | Pressure from hummocked ice and ice ridges | - | U | N |
| | 9.4 | NTM<br>$V_{hub} < 0.7\ V_{50}$ | No waves | n/a | NCM | NWLR | Horizontal load from moving ice at relevant velocities<br>*Use values of h corresponding to expected history of moving ice occurring)*<br>Dynamic effects from ice loading – frequency lock-in effects | - | F/U | F/N |
| | 9.5 | Turbulent - EWM<br>$V_{hub} = V_1$ | No waves | n/a | NCM | NWLR | Horizontal load from moving ice at relevant velocities.<br>$h = h_{50}$ or largest value of moving ice<br>Dynamic effects from ice loading – frequency lock-in effects | - | U | N |
| Temperature effects (power production) | 10.1 | NWP<br>$V_{in} \le V_{hub} \le V_{out}$ | $H=H_s(V)$ | COD, UNI | NCM | MSL | Temperature effects | F/U | F/U | F/N |

Loads and site conditions for wind turbines

# ISO 19906: suitable as a starting point

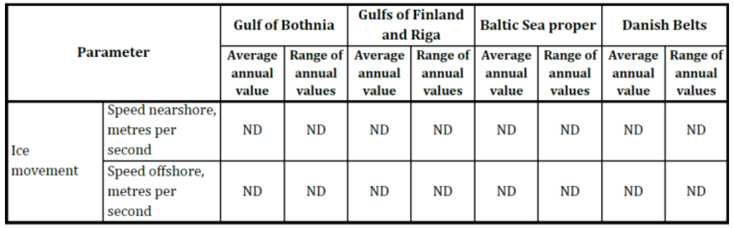
ISO 19906 is a useful baseline for addressing ice load considerations. However, it has several limitations:

- Lack of definition for the ice property values.
- Lack of explicit guidance for fatigue loads definition.
- Questionable relevance for some structures.
- Absence of a detailed methodology for floating structures.
- Suggests the use of both model and full-scale data.
- Open for interpretation for coupled modelling of environmental loads.

*As per ISO 19906:*

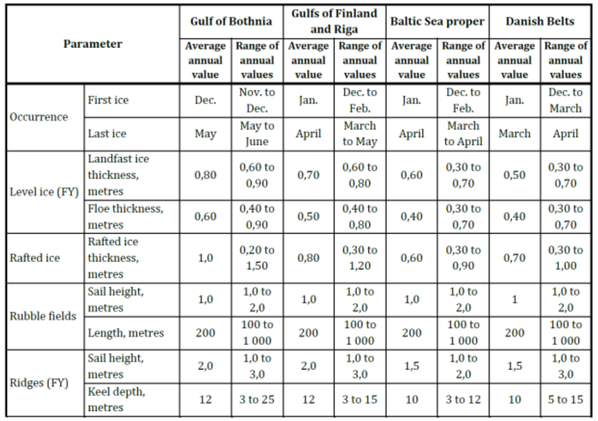
*"Where possible, data from full-scale measurements of ice actions shall be used to verify new designs. Physical models and mathematical models may also be used to determine the response of structures to ice actions, in combination with ocean current, wind and wave actions".*

As per ISO 19906



| Parameter | | Gulf of Bothnia | | Gulfs of Finland and Riga | | Baltic Sea proper | | Danish Belts | |
|---|---|---|---|---|---|---|---|---|---|
| | | Average annual value | Range of annual values | Average annual value | Range of annual values | Average annual value | Range of annual values | Average annual value | Range of annual values |
| Ice movement | Speed nearshore, metres per second | ND | ND | ND | ND | ND | ND | ND | ND |
| | Speed offshore, metres per second | ND | ND | ND | ND | ND | ND | ND | ND |

ND – No data



| Parameter | | Gulf of Bothnia | | Gulfs of Finland and Riga | | Baltic Sea proper | | Danish Belts | |
|---|---|---|---|---|---|---|---|---|---|
| | | Average annual value | Range of annual values | Average annual value | Range of annual values | Average annual value | Range of annual values | Average annual value | Range of annual values |
| Occurrence | First ice | Dec. | Nov. to Dec. | Jan. | Dec. to Feb. | Jan. | Dec. to Feb. | Jan. | Dec. to March |
| | Last ice | May | May to June | April | March to May | April | March to April | March | April |
| Level ice (FY) | Landfast ice thickness, metres | 0,80 | 0,60 to 0,90 | 0,70 | 0,60 to 0,80 | 0,60 | 0,30 to 0,70 | 0,50 | 0,30 to 0,70 |
| | Floe thickness, metres | 0,60 | 0,40 to 0,90 | 0,50 | 0,40 to 0,80 | 0,40 | 0,30 to 0,70 | 0,40 | 0,30 to 0,70 |
| Rafted ice | Rafted ice thickness, metres | 1,0 | 0,20 to 1,50 | 0,80 | 0,30 to 1,20 | 0,60 | 0,30 to 0,90 | 0,70 | 0,30 to 1,00 |
| Rubble fields | Sail height, metres | 1,0 | 1,0 to 2,0 | 1,0 | 1,0 to 2,0 | 1,0 | 1,0 to 2,0 | 1 | 1,0 to 2,0 |
| | Length, metres | 200 | 100 to 1 000 | 200 | 100 to 1 000 | 200 | 100 to 1 000 | 200 | 100 to 1 000 |
| Ridges (FY) | Sail height, metres | 2,0 | 1,0 to 3,0 | 2,0 | 1,0 to 3,0 | 1,5 | 1,0 to 2,0 | 1,5 | 1,0 to 3,0 |
| | Keel depth, metres | 12 | 3 to 25 | 12 | 3 to 15 | 10 | 3 to 12 | 10 | 5 to 15 |

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# Ice-related challenges for offshore wind turbine foundations

**Variability of environmental conditions**

- Season
- Location
- Types of sea ice
- Effect of wind and waves

**Limited real-life experience of floating wind turbines in ice-covered waters**

- Impact of ice loads on turbine performance and energy output
- Ice effect on hydrodynamics and vice versa
- Structure's behaviour in floating conditions
- Challenges for the mooring arrangements

**ISO 19906, IEC 61400-3-1 and DNV-ST-0437**

- Require experience and engineering judgement
- No explicit method for coupled modelling of environmental loads

## Solutions

- Detailed study of the project area
- Selection of prevailing conditions and ice actions
- Collection of available full-scale data
- Modelling of the loads on foundation: case studies
- Analysis of the requirements and design practices
- Generation of the relevant design load cases

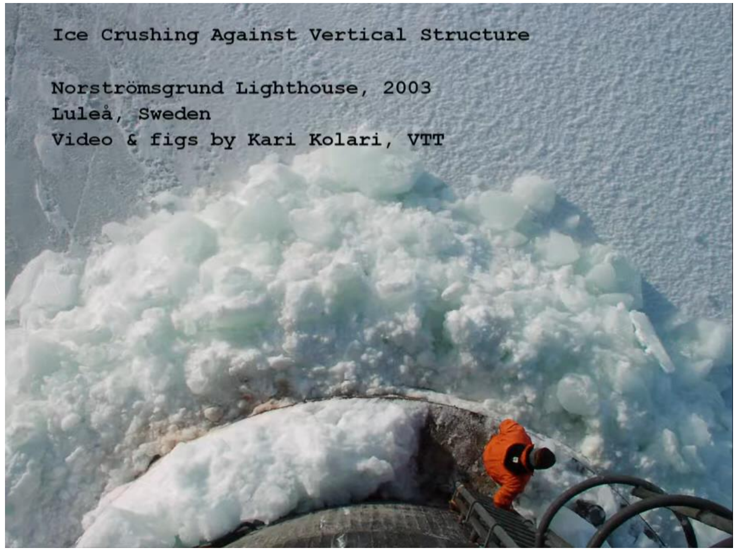
# How to get it right?

# Establishing ice load scenarios

- Actions from level ice crushing
- Actions from ridges
- Impact from discrete ice features
- Actions from features lodged against the structure
- Adfreeze effects
- Thermal effects
- …

**The most adverse load cases need to be carefully selected out of the variety of scenarios !**

Kemi I: Aker Arctic Archives

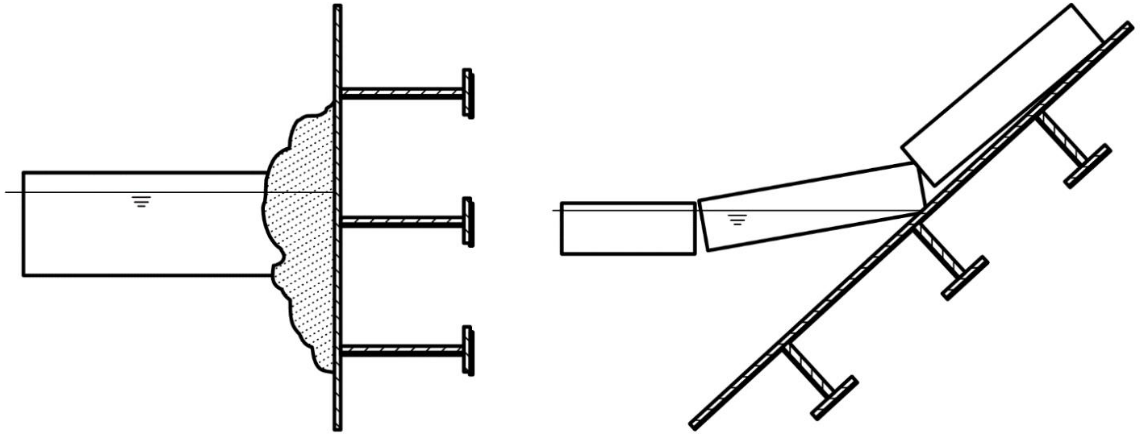


Level ice crushing at Nordströmgrund (from Kari Kolari, VTT)

# Ice loads scenario also depends on the structure!

- Vertical or inclined
- Cylindrical or flat
- Wide or narrow
- Rigid or compliant
- Single-leg or multi-leg

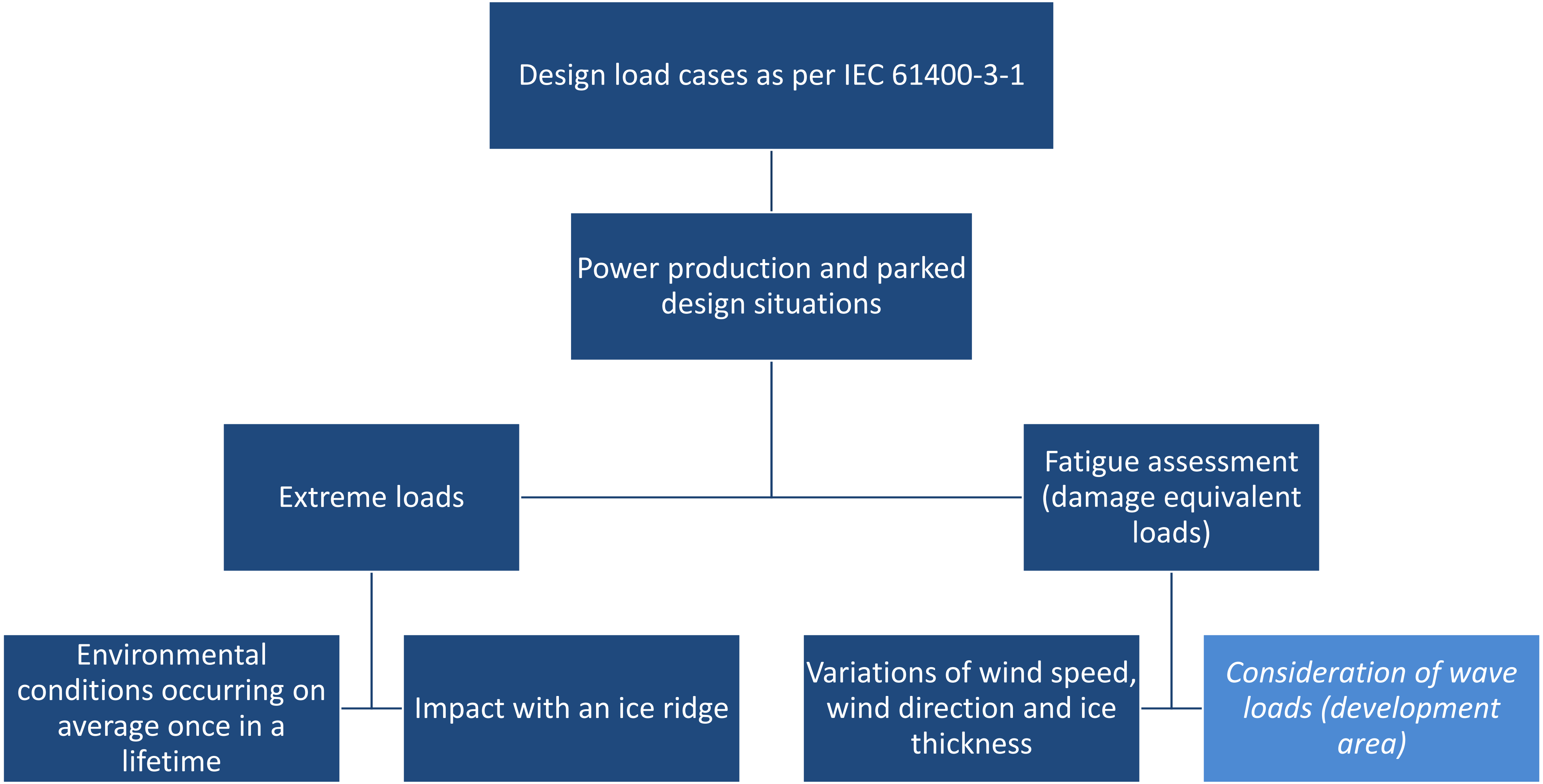
…



**a) Crushing failure (vertical structure)** **b) Bending failure (sloping structure)**

Crushing and bending failure (ISO 19906)

# Design load cases for offshore wind turbines in ice



Design load cases as per IEC 61400-3-1

Power production and parked design situations

Extreme loads

Fatigue assessment (damage equivalent loads)

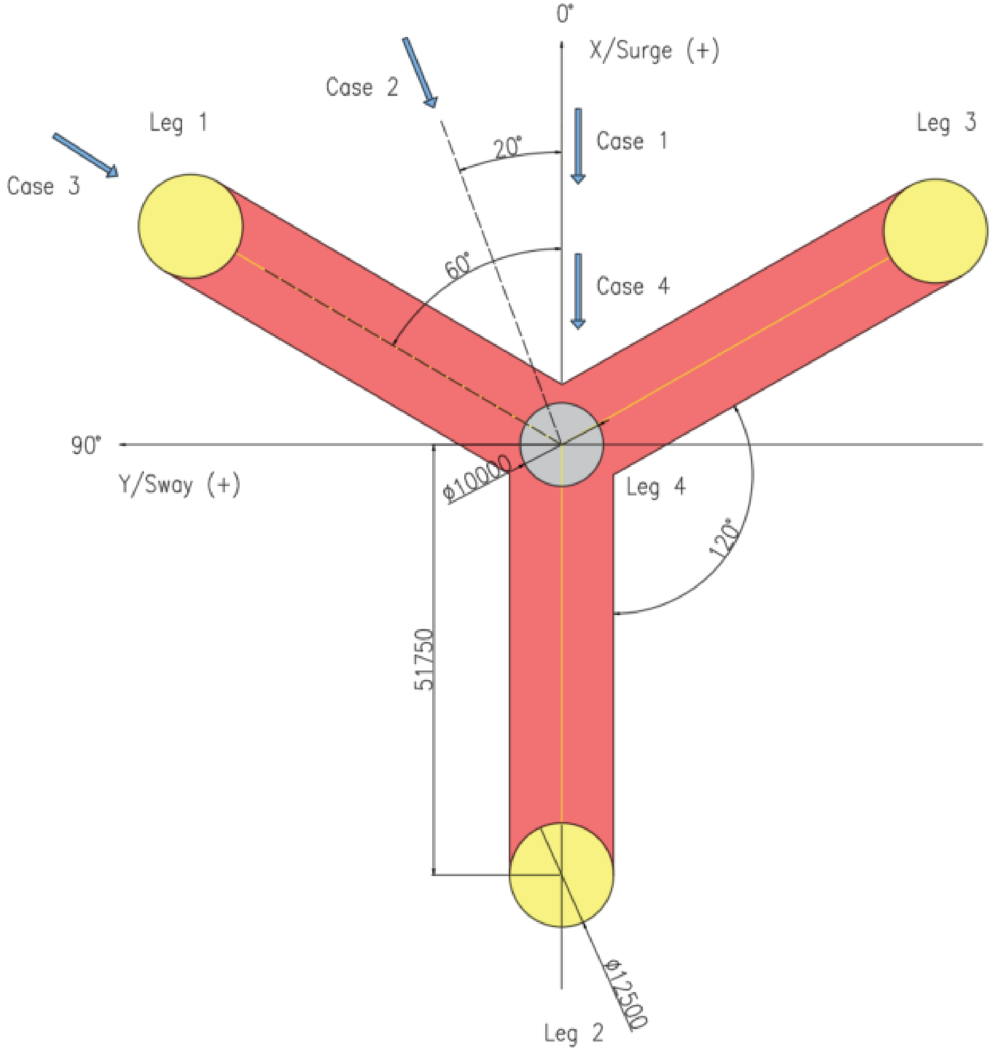
Environmental conditions occurring on average once in a lifetime

Impact with an ice ridge

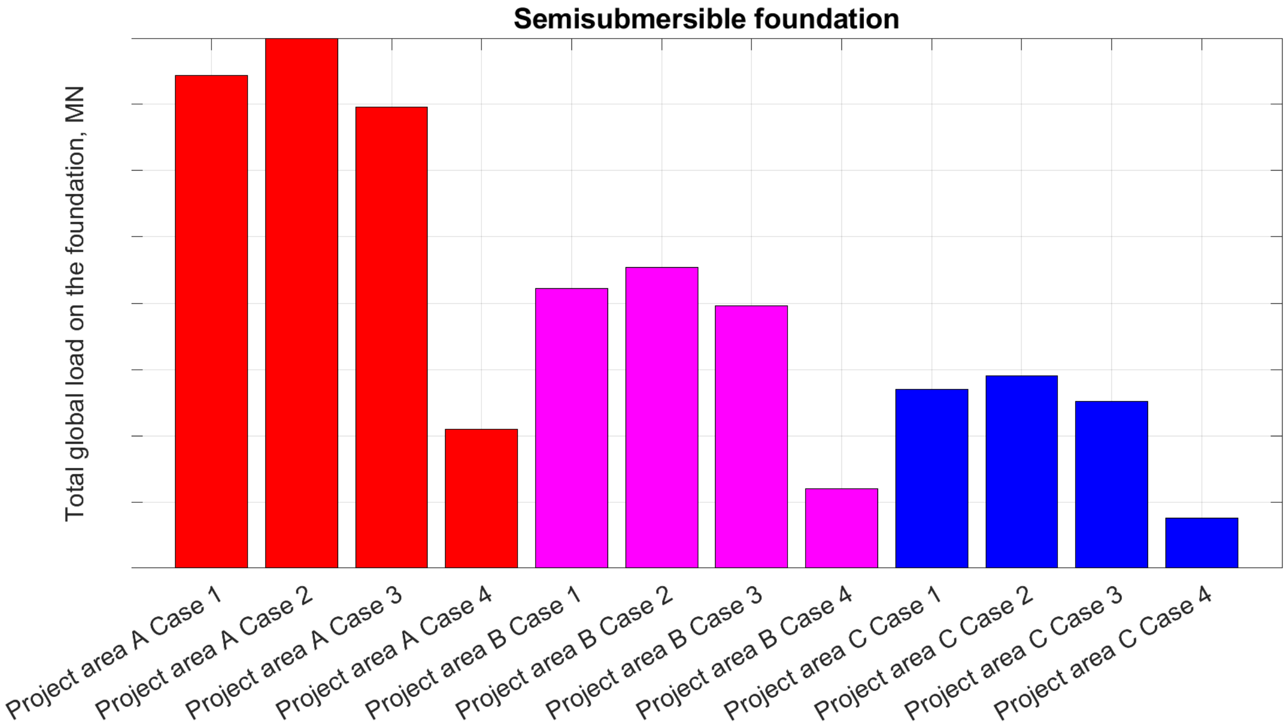
Variations of wind speed, wind direction and ice thickness

*Consideration of wave loads (development area)*

# Example of extreme ice load scenarios

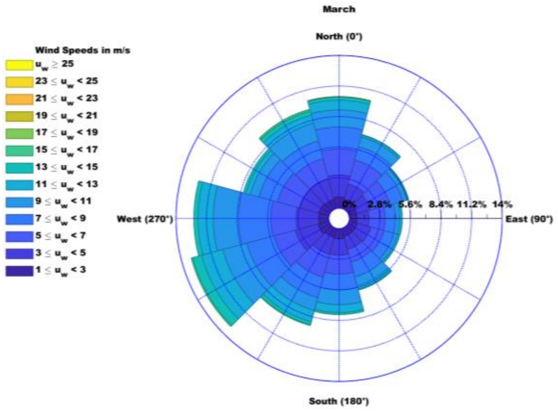


- Level ice crushing
- Ridge interaction
- Most adverse ice loading parameters in terms of the response of the structure
- The load values vary significantly across the sites

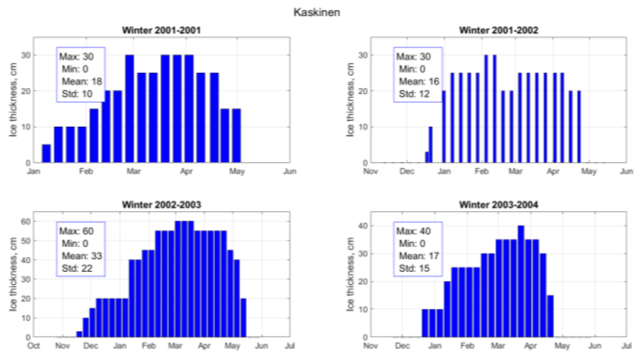


# Example of fatigue assessment

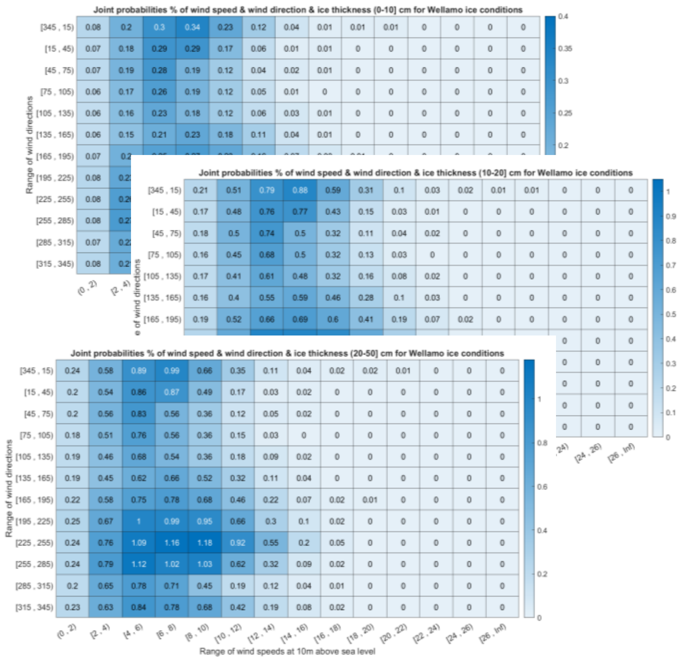
## Wind data



## Ice conditions data



## Combination of environmental data

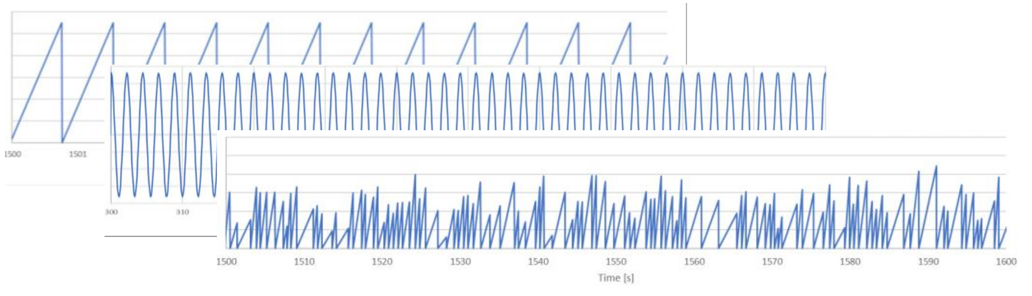


Joint probabilities % of wind speed & wind direction & ice thickness (20-50] cm for Wellamo ice conditions

| Range of wind directions | (0 , 2) | [2 , 4) | [4 , 6) | [6 , 8) | [8 , 10) | [10 , 12) | [12 , 14) | [14 , 16) | [16 , 18) | [18 , 20) | [20 , 22) | [22 , 24) | [24 , 26) | [26 , Inf) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [345 , 15) | 0.24 | 0.58 | 0.89 | 0.99 | 0.66 | 0.35 | 0.11 | 0.04 | 0.02 | 0.02 | 0.01 | 0 | 0 | 0 |
| [15 , 45) | 0.2 | 0.54 | 0.86 | 0.87 | 0.49 | 0.17 | 0.03 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 |
| [45 , 75) | 0.2 | 0.56 | 0.83 | 0.56 | 0.36 | 0.12 | 0.05 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 |
| [75 , 105) | 0.18 | 0.51 | 0.76 | 0.56 | 0.36 | 0.15 | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| [105 , 135) | 0.19 | 0.46 | 0.68 | 0.54 | 0.36 | 0.18 | 0.09 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 |
| [135 , 165) | 0.19 | 0.45 | 0.62 | 0.66 | 0.52 | 0.32 | 0.11 | 0.04 | 0 | 0 | 0 | 0 | 0 | 0 |
| [165 , 195) | 0.22 | 0.58 | 0.75 | 0.78 | 0.68 | 0.46 | 0.22 | 0.07 | 0.02 | 0.01 | 0 | 0 | 0 | 0 |
| [195 , 225) | 0.25 | 0.67 | 1 | 0.99 | 0.95 | 0.66 | 0.3 | 0.1 | 0.02 | 0 | 0 | 0 | 0 | 0 |
| [225 , 255) | 0.24 | 0.76 | 1.09 | 1.16 | 1.18 | 0.92 | 0.55 | 0.2 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| [255 , 285) | 0.24 | 0.79 | 1.12 | 1.02 | 1.03 | 0.62 | 0.32 | 0.09 | 0.02 | 0 | 0 | 0 | 0 | 0 |
| [285 , 315) | 0.2 | 0.65 | 0.78 | 0.71 | 0.45 | 0.19 | 0.12 | 0.04 | 0.01 | 0 | 0 | 0 | 0 | 0 |
| [315 , 345) | 0.23 | 0.63 | 0.84 | 0.78 | 0.68 | 0.42 | 0.19 | 0.08 | 0.02 | 0 | 0 | 0 | 0 | 0 |

Range of wind speeds at 10m above sea level

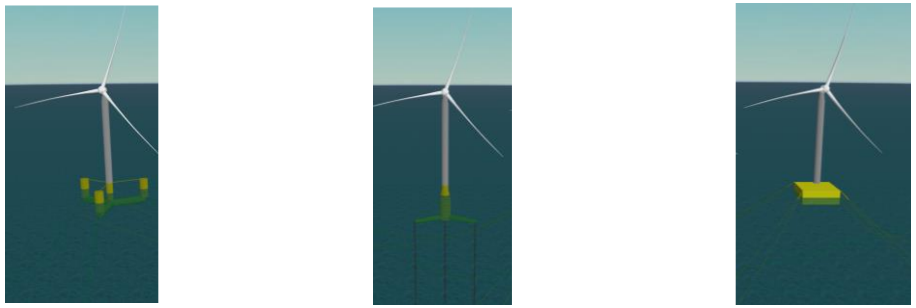
## Modelling of design load cases for the foundation



Design load cases: IEC 61400-3-1 /DNV-ST-0437

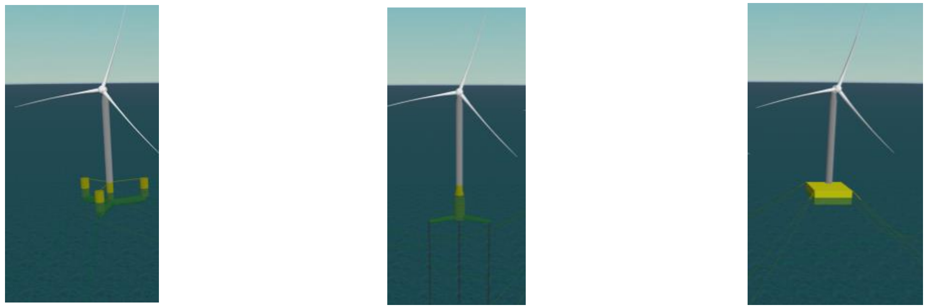
# How can we use the results?

# Outcomes of the analysis: comparison of concepts



| Increase due to ice loads compared to open water | | Semi-submersible | TLP | Barge |
|---|---|---|---|---|
| **Motions** | Extreme load case:  Maximum surge/sway motion | Moderate | High | Low |
| | Extreme load case: Maximum roll/pitch motion | Insignificant | Low | Very high |
| **Loads** | Extreme load case: load at tower base | Low | Low | Very high |
| | Extreme load case: highest increase in floater | Very high | Low | - |
| | Fatigue: fatigue load at tower base | Insignificant | Insignificant | Insignificant |
| | Fatigue: highest increase in floater | Very high | - | - |
| **Mooring** | Mooring maximum tension | Very high | Insignificant | Very high |
| | Anchor maximum tension | Very high | Insignificant | Very high |
| **RNA** | Annual energy production | Insignificant | Insignificant | Insignificant |

# Outcomes of the analysis: risks and costs

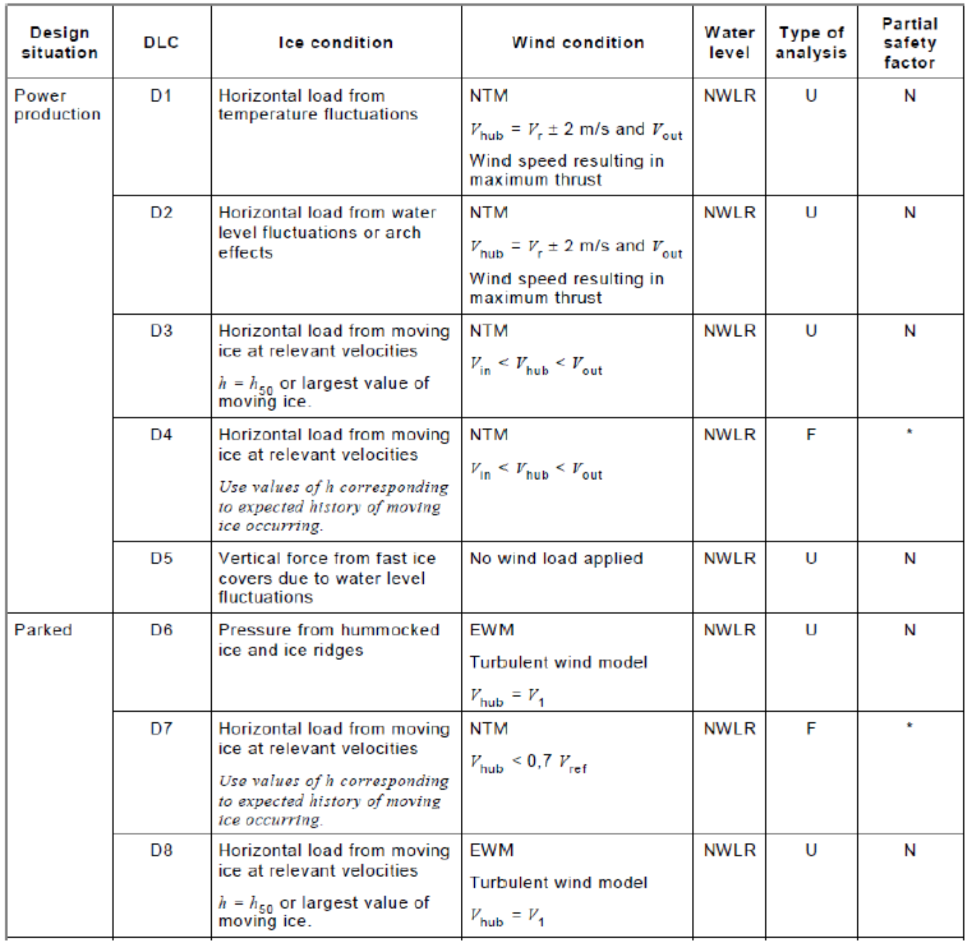


Example of the risk and cost matrix

| | | Semi-submersible | | TLP | | Barge | |
|---|---|---|---|---|---|---|---|
| **Series** | **Item description** | **NO ICE** | **ICE** | **NO ICE** | **ICE** | **NO ICE** | **ICE** |
| 100 | EPCI Project Management | Very low | Very low | Very low | Very low | Very low | Very low |
| 200 | Engineering | Low | Low | Low | Low | Low | Low |
| 250 | Ancillary Services | Low | Moderate | Moderate | High | Moderate | High |
| 300 | Fabrication and Assembly | Low | Moderate | Moderate | High | Moderate | High |
| 400 | Mooring Systems | Low | Moderate | Moderate | High | Moderate | High |
| 500 | Cables | Moderate | Moderate | Moderate | Moderate | Moderate | Moderate |
| 600 | Wind Turbine Integration | Low | Low | Moderate | Moderate | Moderate | Moderate |
| 700 | Mooring System Pre-Lay Operations | Low | Moderate | Moderate | High | Moderate | High |
| 800 | Cables Pre-Lay Operations | Low | Low | Moderate | Moderate | Moderate | Moderate |
| 900 | Tow and Hook-up | Low | Low | Moderate | Moderate | Moderate | Moderate |
| 1000 | Decommissioning | High | High | High | High | High | High |
| **Total** | **Total Weighted Risk** | **Low** | **Moderate** | **Moderate** | **High** | **Moderate** | **High** |

# Outcomes of the analysis: Design Load Cases

IEC 61400-3-1



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| | D4 | Horizontal load from moving ice at relevant velocities<br>*Use values of h corresponding to expected history of moving ice occurring.* | NTM<br>$V_{in} < V_{hub} < V_{out}$ | NWLR | F | * | ✓ |
| | D5 | Vertical force from fast ice covers due to water level fluctuations | No wind load applied | NWLR | U | N | |
| Parked | D6 | Pressure from hummocked ice and ice ridges | EWM<br>Turbulent wind model<br>$V_{hub} = V_1$ | NWLR | U | N | ✓ |
| | D7 | Horizontal load from moving ice at relevant velocities<br>*Use values of h corresponding to expected history of moving ice occurring.* | NTM<br>$V_{hub} < 0{,}7\ V_{ref}$ | NWLR | F | * | ✓ |
| | D8 | Horizontal load from moving ice at relevant velocities<br>$h = h_{50}$ or largest value of moving ice. | EWM<br>Turbulent wind model<br>$V_{hub} = V_1$ | NWLR | U | N | ✓ |

1. Design load cases can now be taken forward as a basis for design
2. Iterations to optimize the structure for anticipated ice conditions using the loads determined
3. Identification of critical areas within the structure in relation to ice actions

# Conclusions

- Offshore structures are known to be susceptible to overloading and fatigue failure.
- Existing standards do not provide comprehensive guidelines and ready-made solutions for the structural analysis of OWT foundations. Apart from that, the prescribed methodology cannot be applied directly to the floating and moored structures. Aker Arctic in cooperation with partners and in compliance with the existing guidelines, have developed the methodology to assess the ice loads on offshore wind turbines foundations for various scenarios.
- Site-specific environmental data must be analyzed to obtain the realistic value of the ice loads.
- Extreme and fatigue-related scenarios pose the largest challenge for the foundations. Most importantly, mooring arrangements must be adjusted accordingly.
- Enhancing the structural elements to withstand ice conditions effectively promises a considerable reduction in both weight and associated costs. This leaves room for further optimization and search for mitigation solutions.

# Acknowledgements

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# THANK YOU

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