EERA DeepWind Conference 2024

Wind farm optimization
Paper number: 72

Assessing the influence of nonlinear mooring restoring forces in the optimization and design of FOWT

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Universidade de São Paulo
TECHNOMAR ENGENHARIA OCEÂNICA

Agenda

1) Introduction
2) Methodology
3) Case Study
4) Conclusions

1) Introduction

2) Methodology

3) Case Study

4) Conclusions

Introduction

- Early-stage design often defaults to equivalent linear stiffness models, despite the inherent nonlinearity of mooring systems
- Assessment on linear assumptions can significantly misrepresent mooring restoring forces
- This simplification leads to a critical gap in mooring line optimization, potentially compromising the entire mooring system's performance and costs.
- **Objective:** Investigate and underscore the limitations of the equivalent linear model during FOWT optimization processes

1) Introduction
2) **Methodology**
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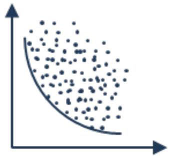
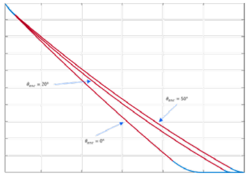
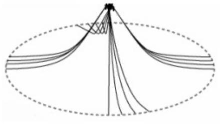
Methodology



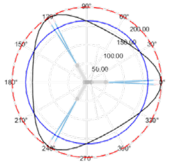
Different FOWT mooring system were designed using an optimization framework based on the Genetic Algorithm strategy – Mas-Soler et al. (2022)



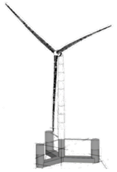
Consideration of intermediate to large water depths (500, 1000 and 2000) and three different mooring configurations: catenary, semi-taut, and taut lines



Evaluation of final systems responses comparing equivalent linear and nonlinear mooring models



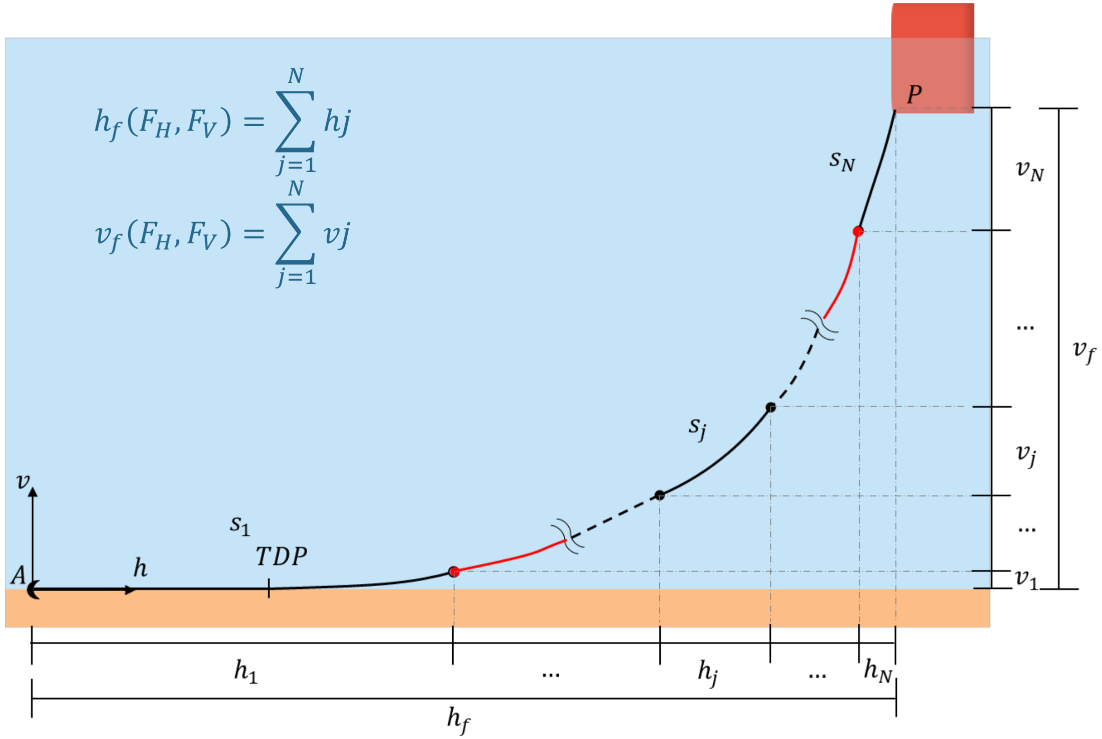
System responses are investigated by means of offsets and anchor tensions



Case study using the reference semi-submersible platform VolturnUS-S

Linear model vs. Nonlinear model

$$\mathrm{K}(\mathbf{q}^*) = \sum_{i=1}^{N} \begin{array}{c} \mathrm{K}_{TT}^{(i)} \qquad\qquad\qquad \mathrm{K}_{TR}^{(i)} \\ \left[\begin{array}{ccc:ccc} K_{11}^{(i)} & K_{12}^{(i)} & K_{13}^{(i)} & K_{14}^{(i)} & K_{15}^{(i)} & K_{16}^{(i)} \\ K_{21}^{(i)} & K_{22}^{(i)} & K_{23}^{(i)} & K_{24}^{(i)} & K_{25}^{(i)} & K_{26}^{(i)} \\ K_{31}^{(i)} & K_{32}^{(i)} & K_{33}^{(i)} & K_{34}^{(i)} & K_{35}^{(i)} & K_{36}^{(i)} \\ \hdashline K_{41}^{(i)} & K_{42}^{(i)} & K_{43}^{(i)} & K_{44}^{(i)} & K_{45}^{(i)} & K_{46}^{(i)} \\ K_{51}^{(i)} & K_{52}^{(i)} & K_{53}^{(i)} & K_{54}^{(i)} & K_{55}^{(i)} & K_{56}^{(i)} \\ K_{61}^{(i)} & K_{62}^{(i)} & K_{63}^{(i)} & K_{64}^{(i)} & K_{65}^{(i)} & K_{66}^{(i)} \end{array}\right] \\ \mathrm{K}_{RT}^{(i)} \qquad\qquad\qquad \mathrm{K}_{RR}^{(i)} \end{array}$$



Pesce, Amaral and Franzini (2018)
Amaral, Pesce and Franzini (2022)

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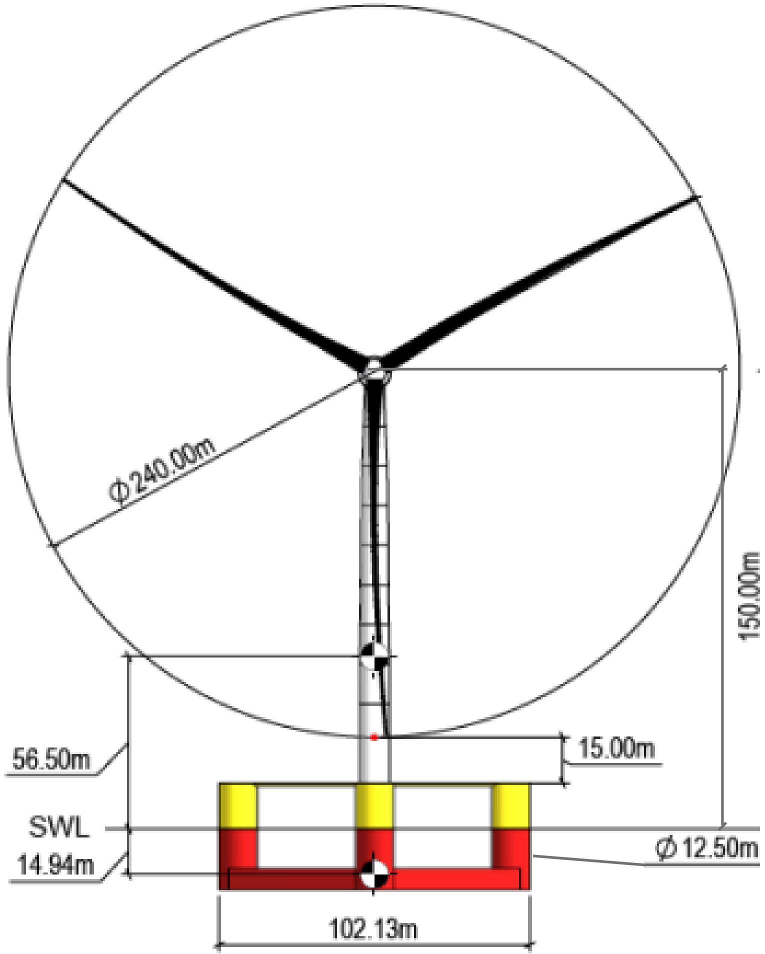
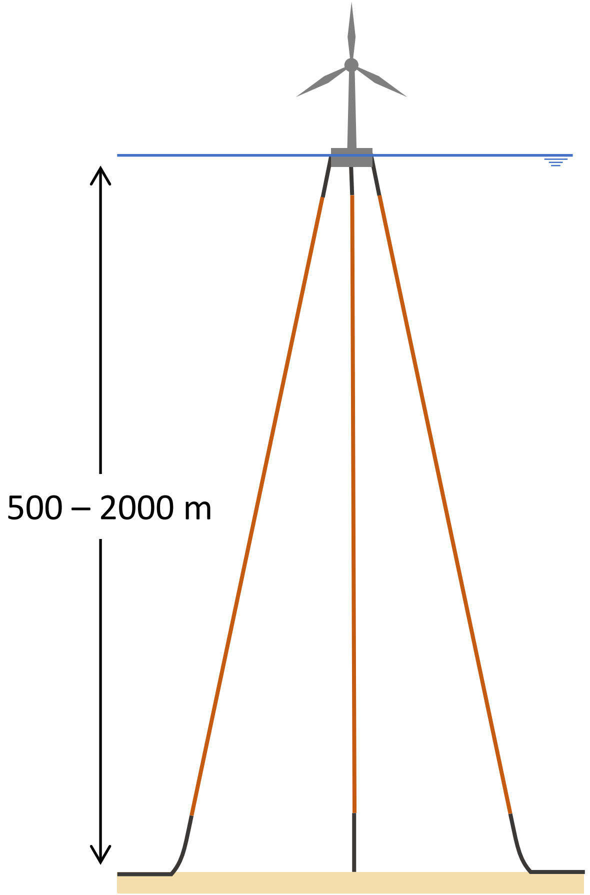
Case study: Wind turbine and water depth

Rated power	15 MW
Rated wind speed	10.59 m/s

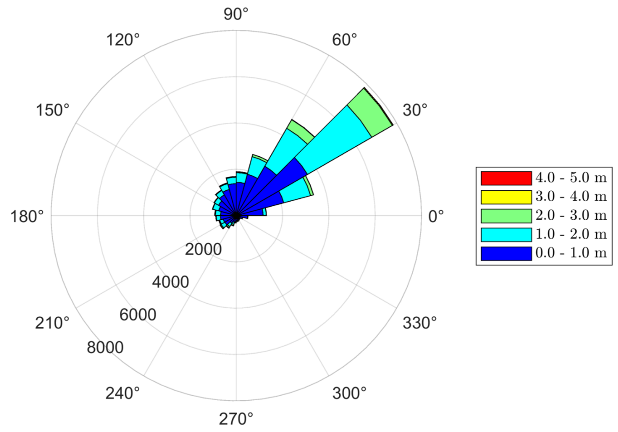
Specifications of the IEA 15MW Wind Turbine



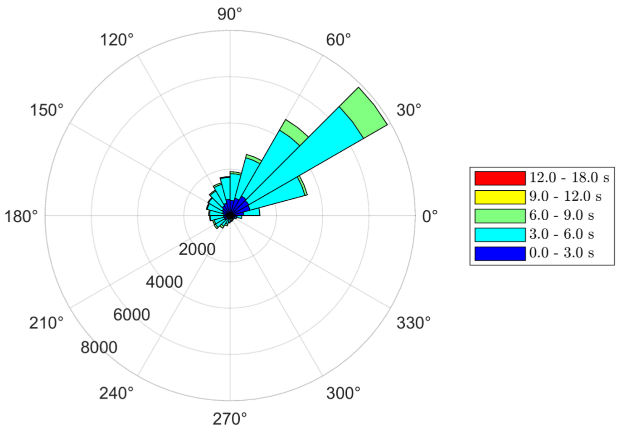


Case study: Metocean – ERA5 database

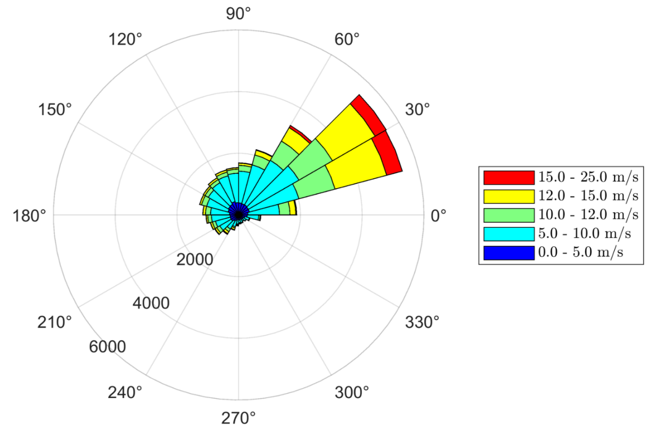
Local sea wave Hs



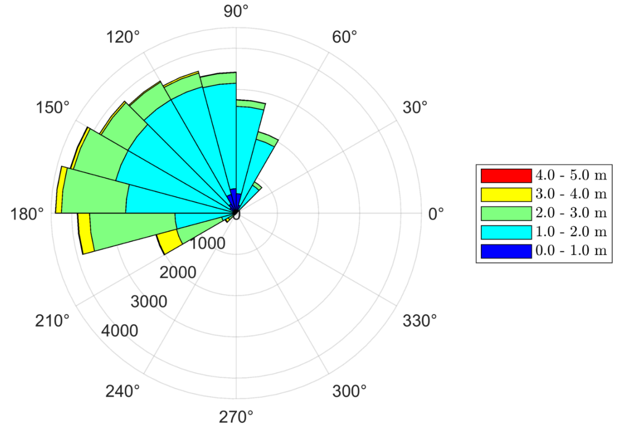
Local sea wave Tp



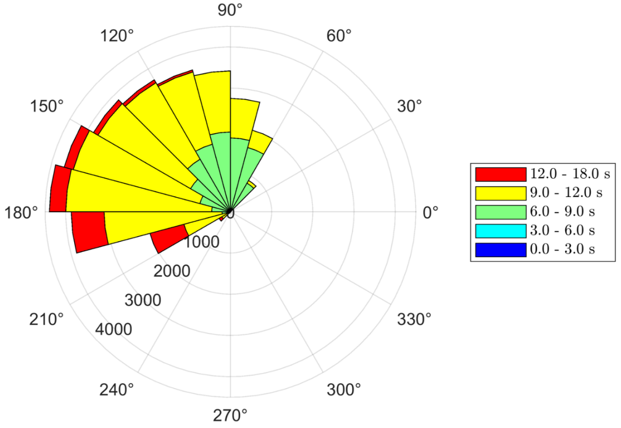
Wind speed at hub



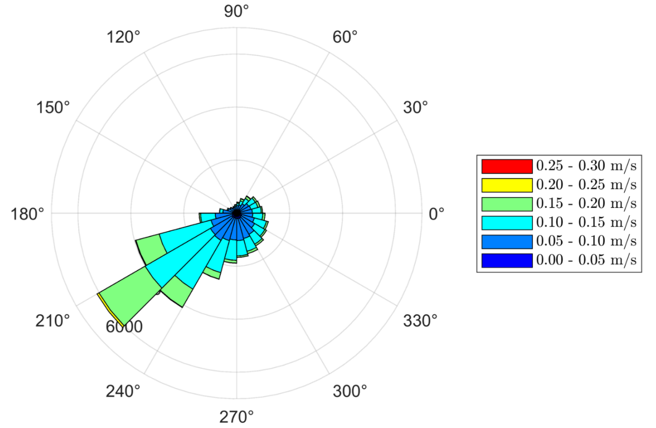
Swell wave Hs



Swell wave Tp



Sea current speed

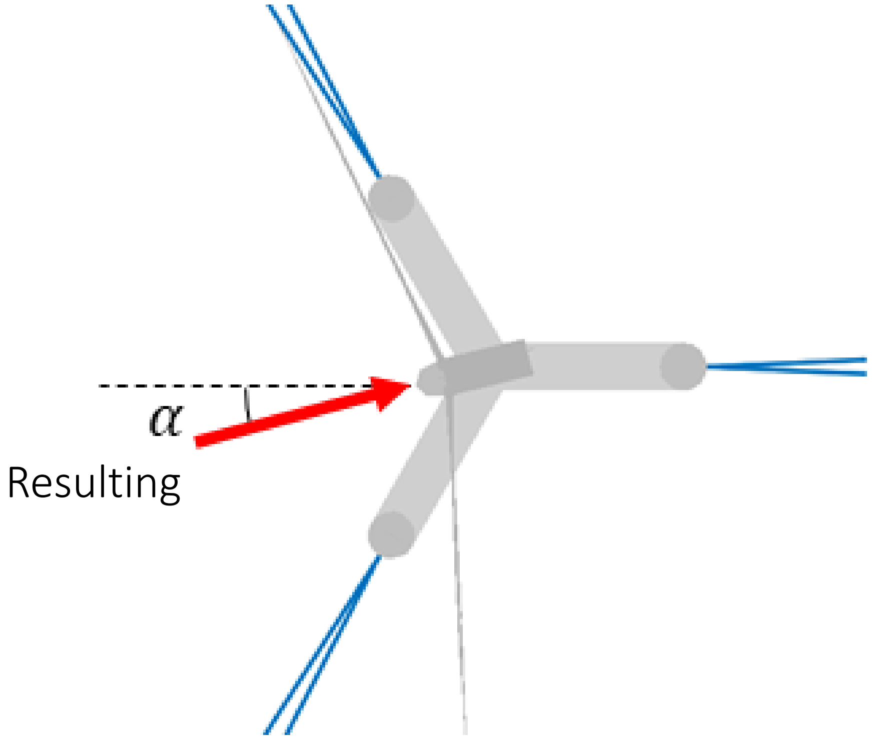


35,065 environmental conditions (12 years/3h-long)

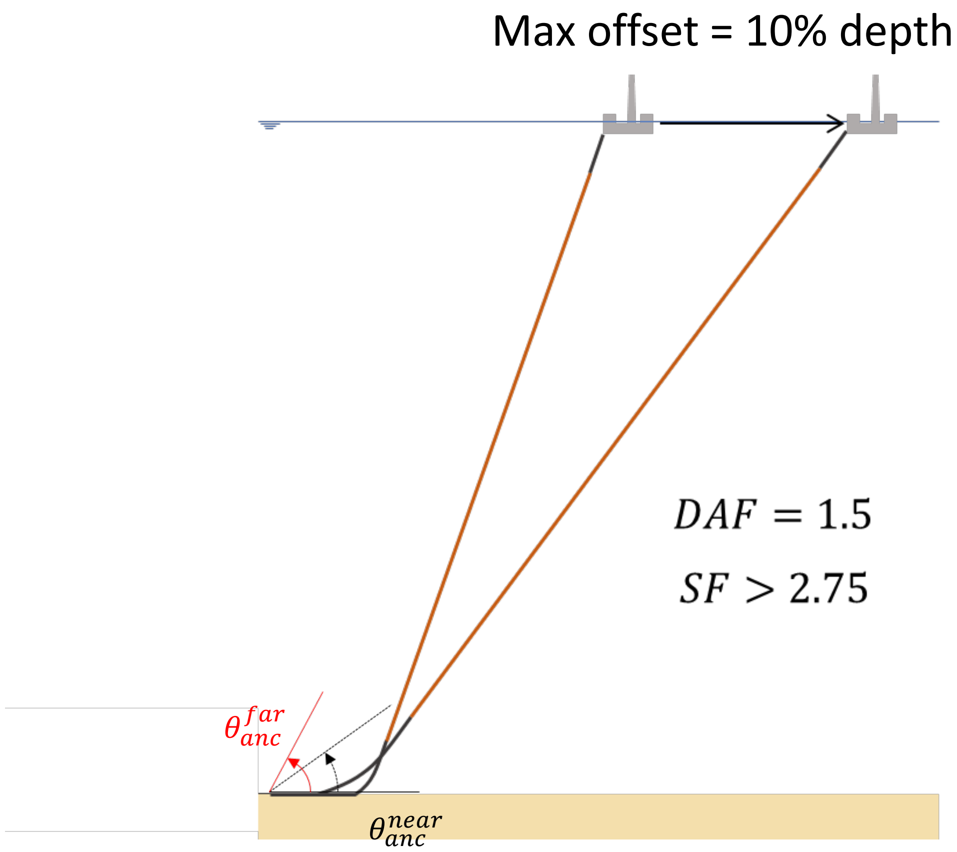
Case study: Steady (mean) force

Maximum estimated values for wind, current and wave forces for all environmental conditions
Analysis for different incidences (0 to 180°)

Component	Magnitude [kN]	Magnitude [%]
Wind (structure)	116.85	3.54
Wind (thrust)	2375.43	72.12
Wave mean	109.65	3.34
Current drag	691.82	21.00
Resulting	3293.75	100



Optimization restrictions and equilibrium calculation



Far equilibrium position ($\overline{\boldsymbol{q}}$) calculation

Total mean force at $\overline{\boldsymbol{q}}$*:*

$$\boldsymbol{F} = \boldsymbol{F}_{ext} + \boldsymbol{Q}(\overline{\boldsymbol{q}}) = 0$$

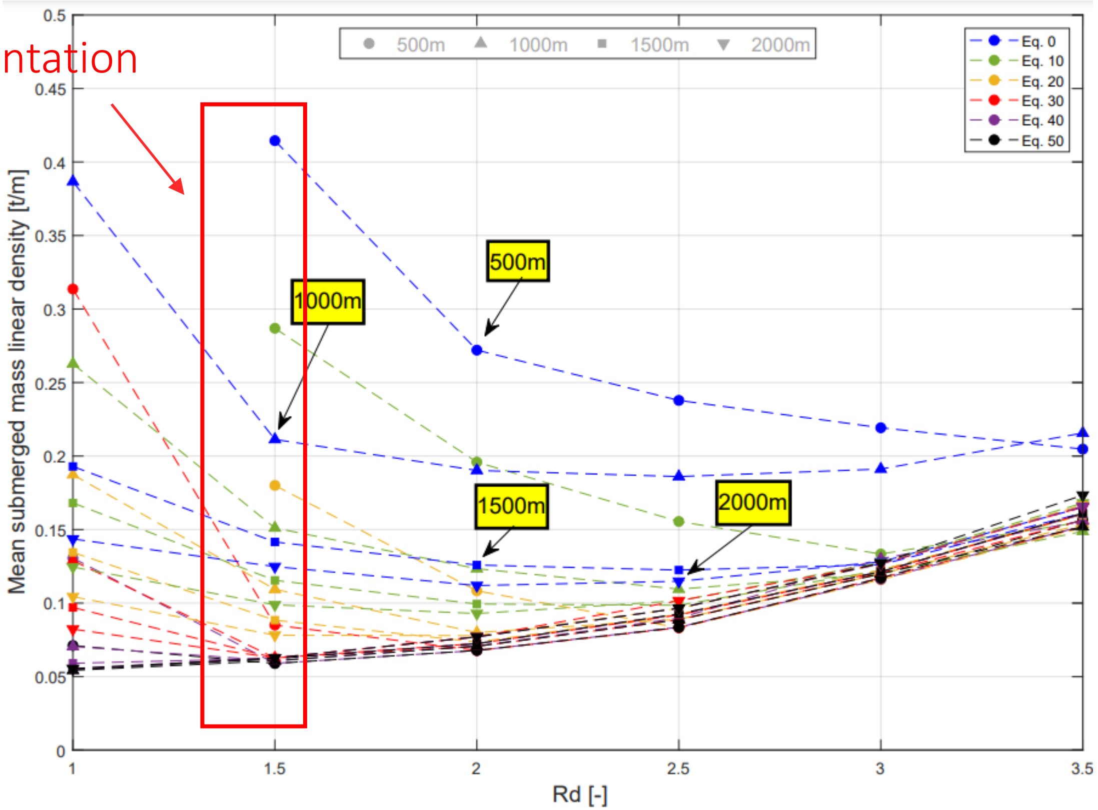
Root-finding problem → Newton-Raphson method:

$$\boldsymbol{q}_{i+1} = \boldsymbol{q}_i + \mathbf{K}(\boldsymbol{q}_i)^{-1}(\boldsymbol{F}_{ext} + \boldsymbol{Q}(\boldsymbol{q}_i))$$

Where $\mathbf{K}(\boldsymbol{q}_i)$ is the stiffness matrix computed at $\boldsymbol{q}_i$

Pool of optimized mooring system

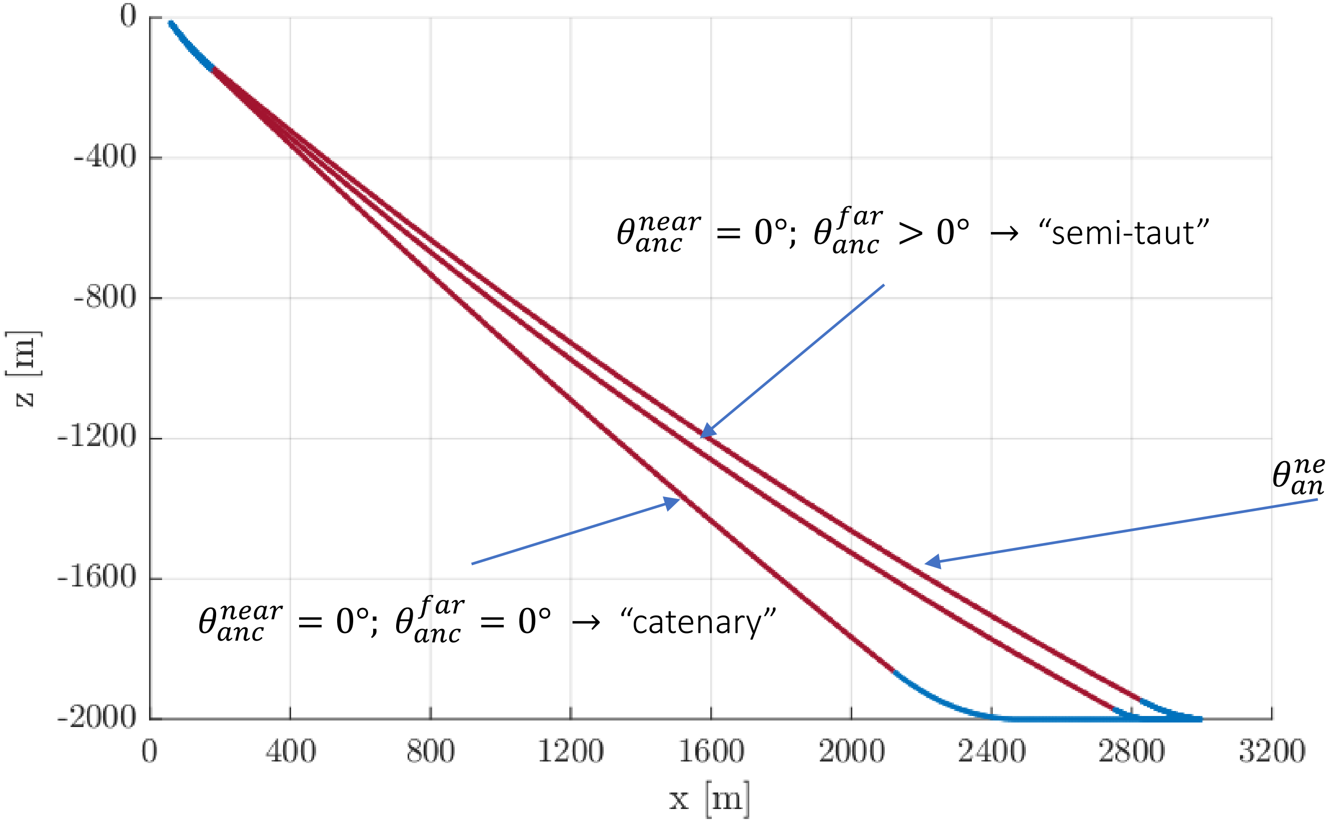
- Different water depths and different restrictions for anchor angle limits



Focus of this presentation

Selected concept

Water depth = 2000 m



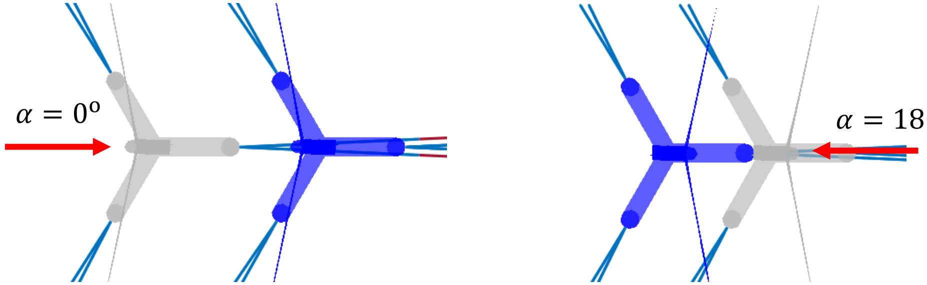
$\theta_{anc}^{near} = 0°;\ \theta_{anc}^{far} > 0°$ → “semi-taut”

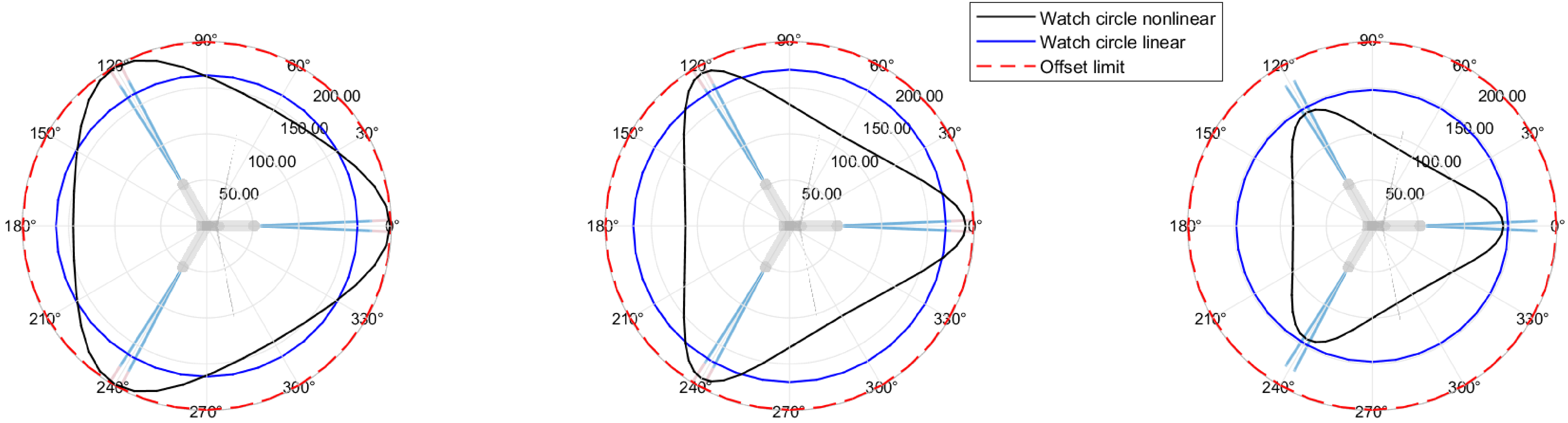
$\theta_{anc}^{near} > 0°;\ \theta_{anc}^{far} > 0°$ → “taut-leg”

$\theta_{anc}^{near} = 0°;\ \theta_{anc}^{far} = 0°$ → “catenary”

Offset watch circles [m]

Water depth = 2000 m





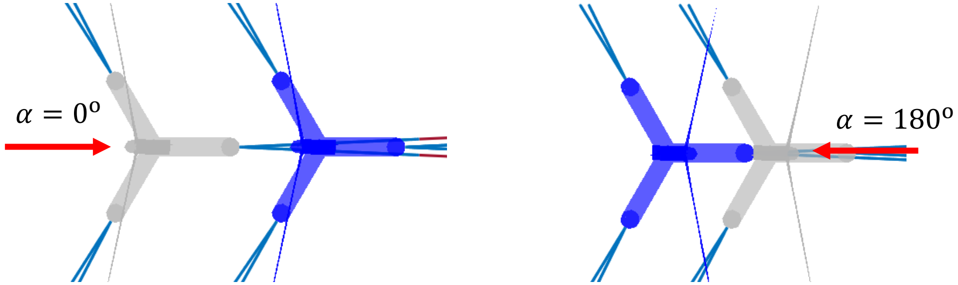
$(a)\ \theta_{anc} = 0°$
("catenary")

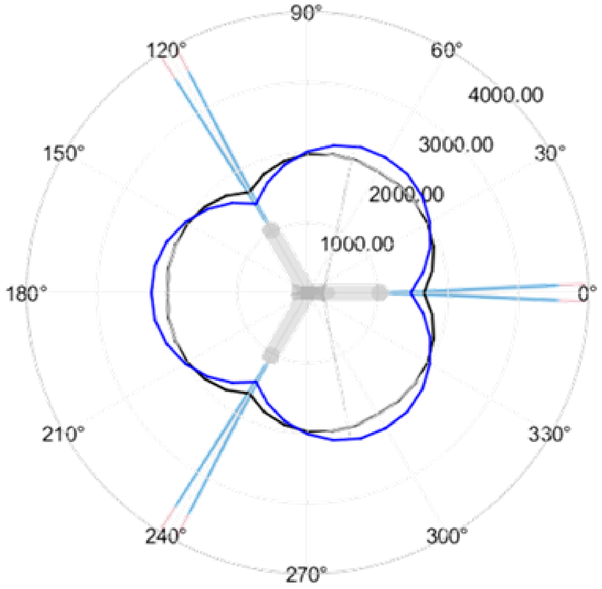
$(b)\ \theta_{anc} = 20°$
("semi-taut")

$(c)\ \theta_{anc} = 50°$
("taut-leg")

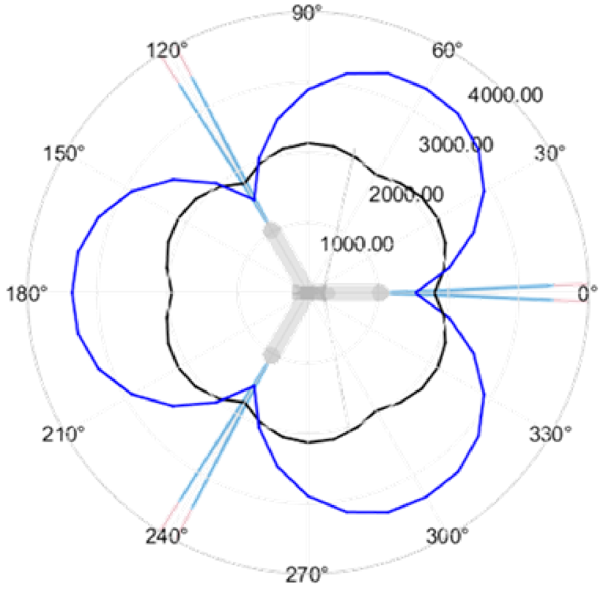
Anchor tension [kN]

Water depth = 2000 m

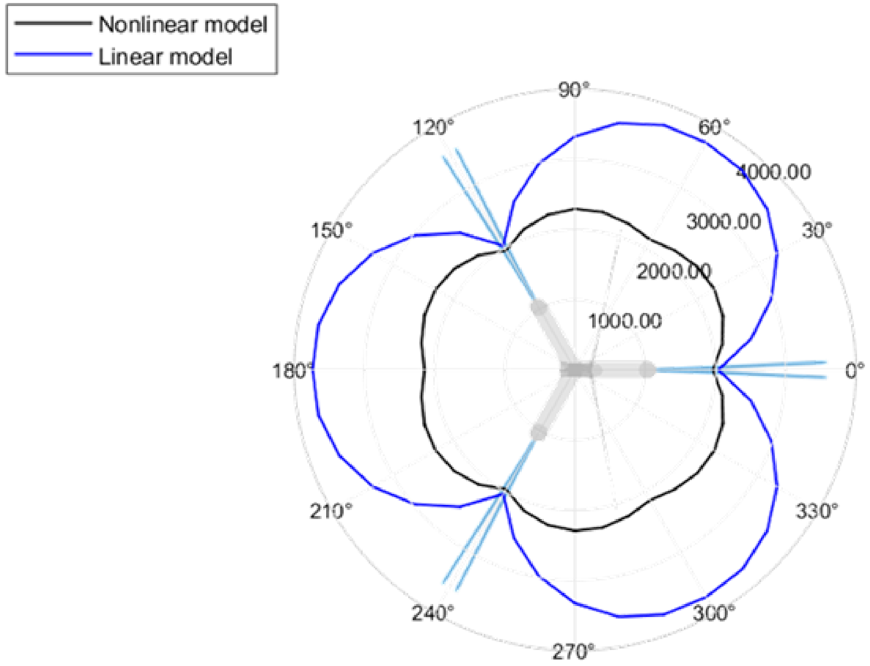




$(a)\ \theta_{anc} = 0°$
(“catenary”)



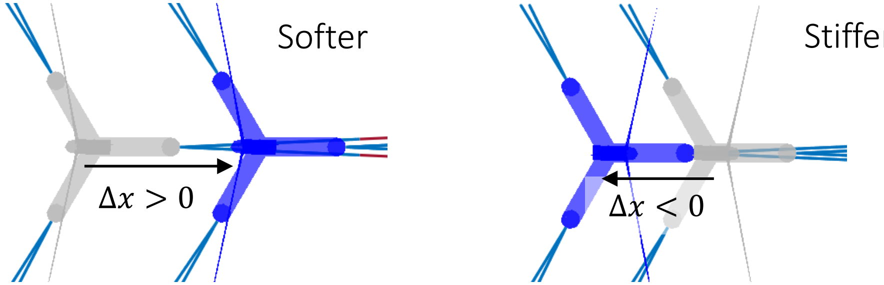
$(b)\ \theta_{anc} = 20°$
(“semi-taut”)



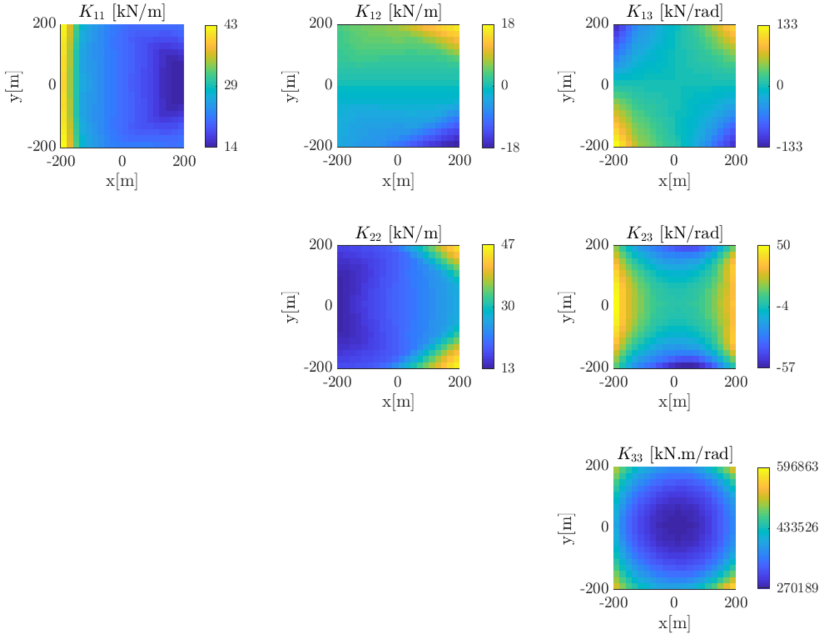
$(c)\ \theta_{anc} = 50°$
(“taut-leg”)

Stiffness Maps

Water depth = 2000 m



See Pesce, Amaral and Franzini (2018) – 3x3 or Amaral, Pesce and Franzini (2022) – 6x6



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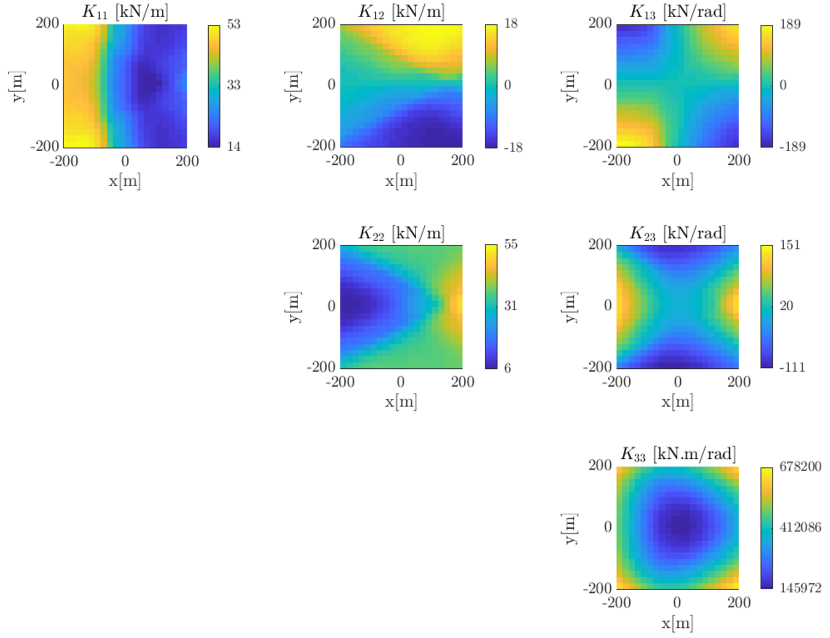
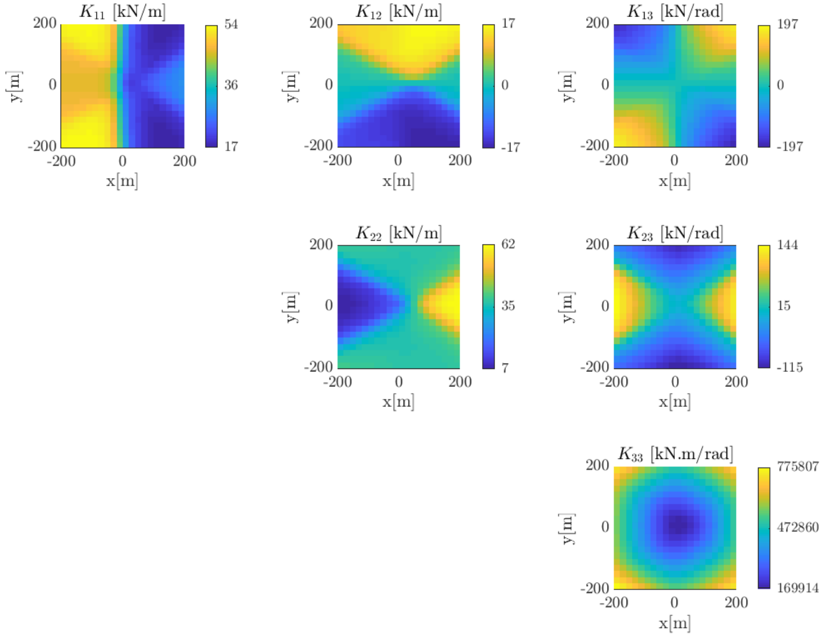
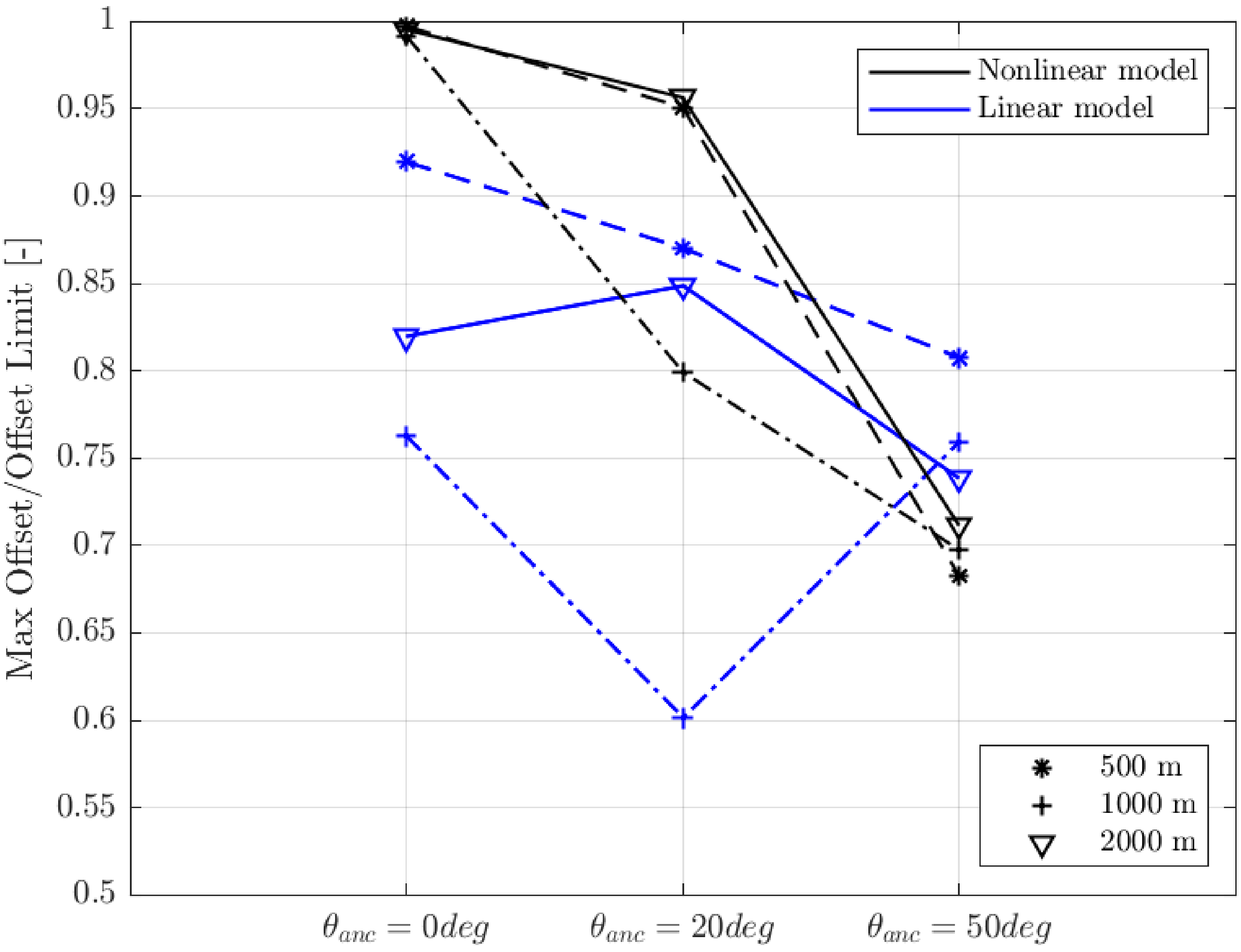


$(b)\ \theta_{anc} = 20°$
("semi-taut")

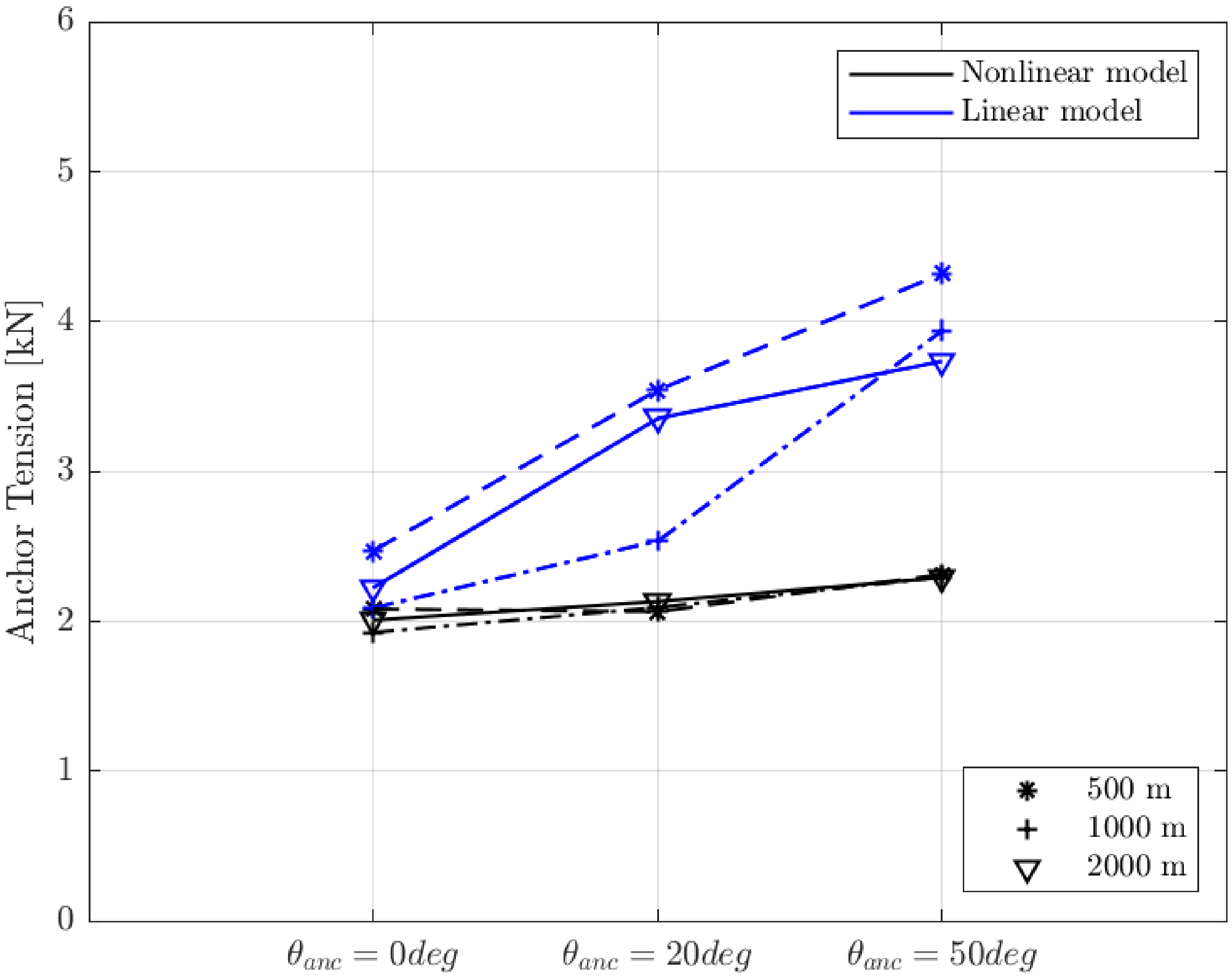


$(c)\ \theta_{anc} = 50°$
("taut-leg")

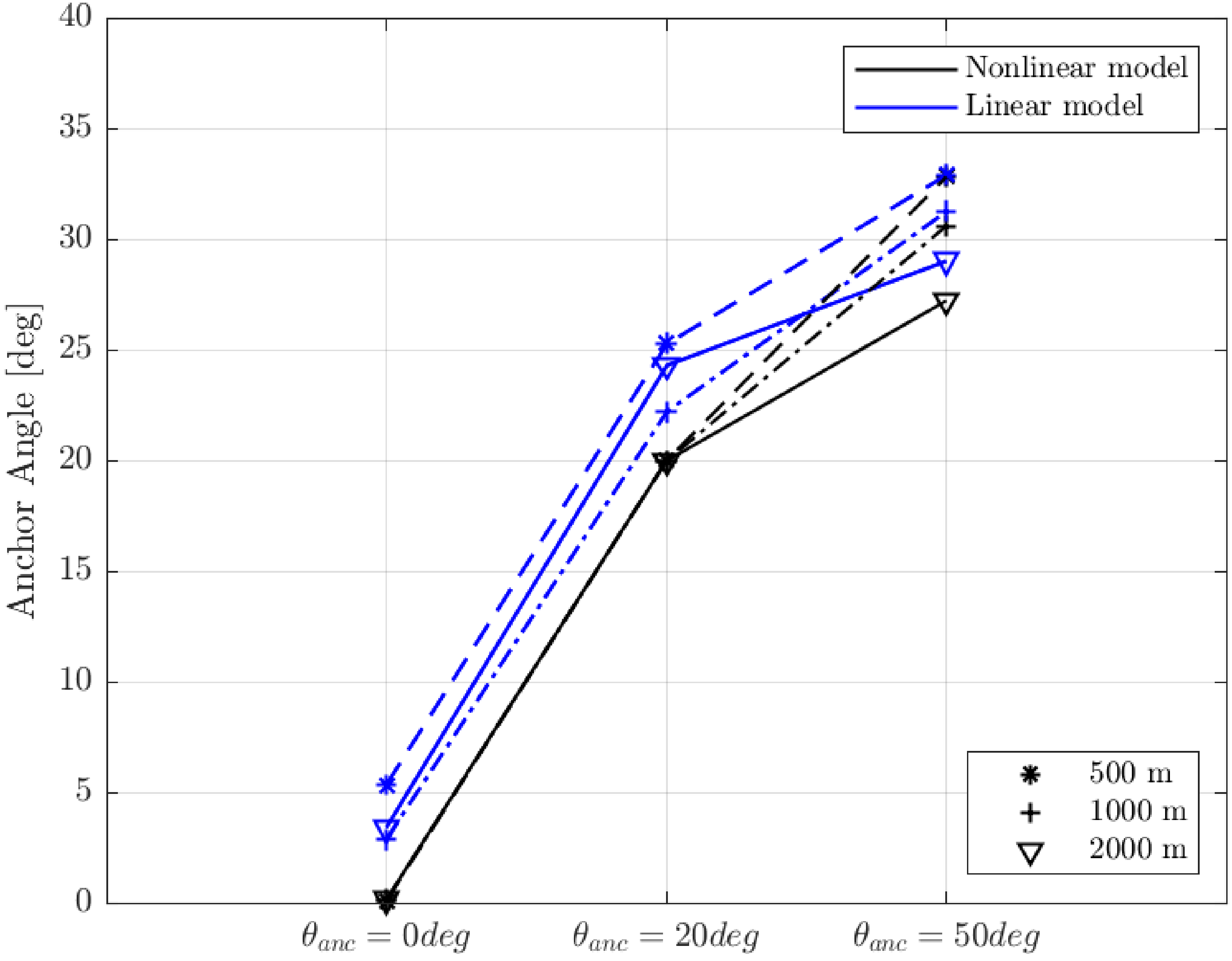
Maximum offset



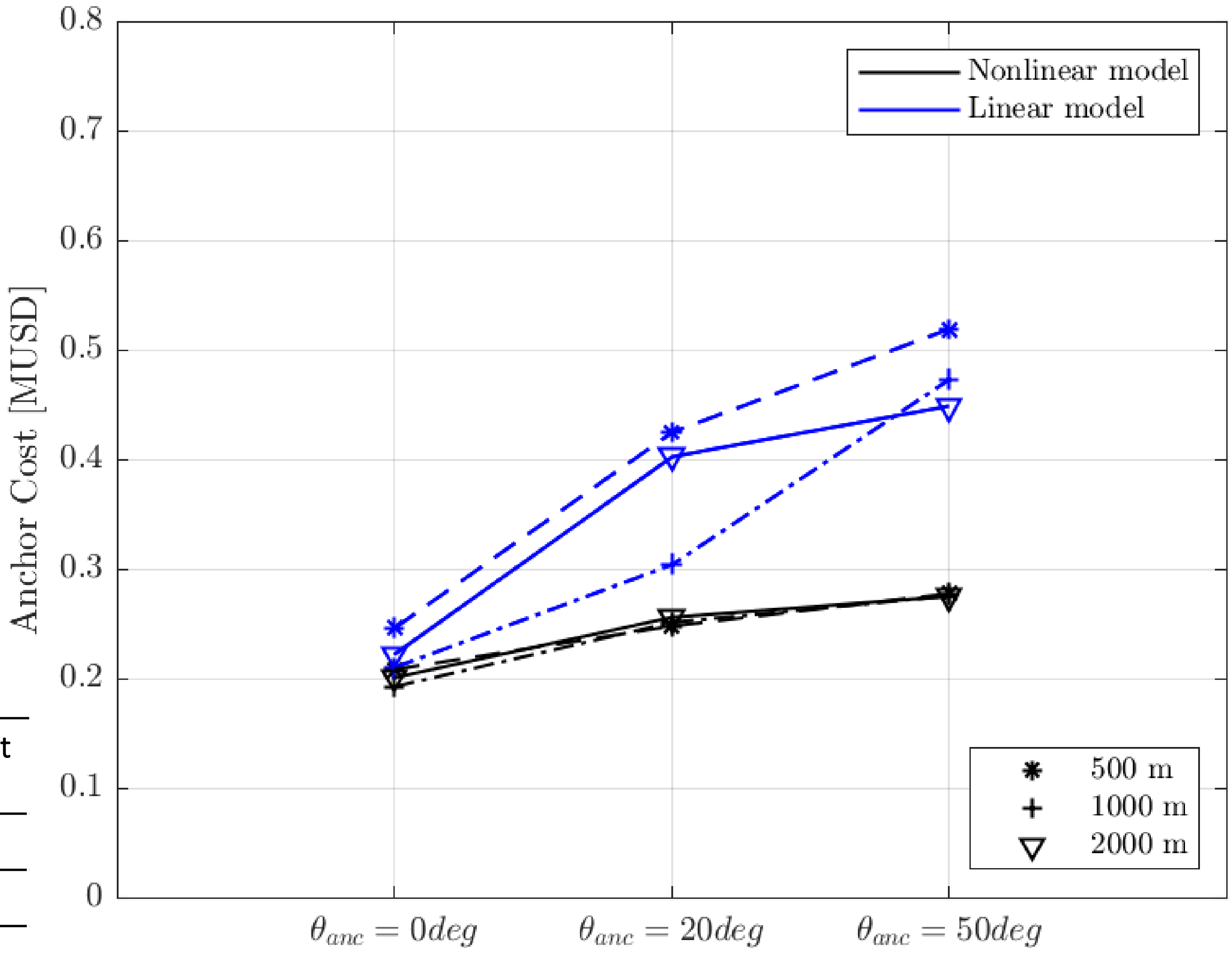
Anchor tension



Anchor angle (far)



Anchor aquisition cost



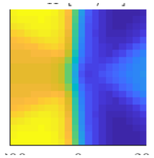
Anchor type	Aquisition cost [MUSD/kN]	Angle limit [deg]
DEA	100	<10
VLA	120	45
SPA	150	>45

Conclusions

Nonlinear optimization reveals minimal difference for catenary lines, but significant discrepancies in semi-taut and taut-leg configurations compared to linear models

In main restoring directions, linear models significantly overestimate offsets, particularly in tauter mooring systems

Linear models tend to overestimate anchor tensions, leading to more costly anchor designs. This overestimation biases the optimization process in favor of catenary systems over tauter configurations

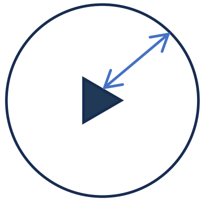


The stiffness maps highlight the pronounced nonlinearity in stiffer mooring systems and their variability with offset changes

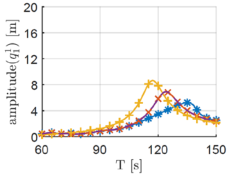
Similar nonlinear trends are observed at water depths ranging between from 500 – 2000 m, with the greatest discrepancies noted at depths of 500 m

Utilizing a nonlinear model tends to stabilize cost estimates across different water depths, suggesting more predictable budgeting for mooring systems.

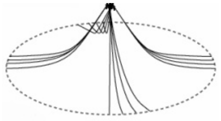
Further work



Continue the investigation, considering other anchor radius/water depth ratios, to generalize optimization strategies



Conduct a comparative study in the frequency domain to understand how different mooring models respond to dynamic loading conditions



Numerical simulations with higher-order mooring models (e.g. using FAST and Orcaflex), to evaluate the optimized design errors from the model choice

Thank you!

(And let’s collaborate!)

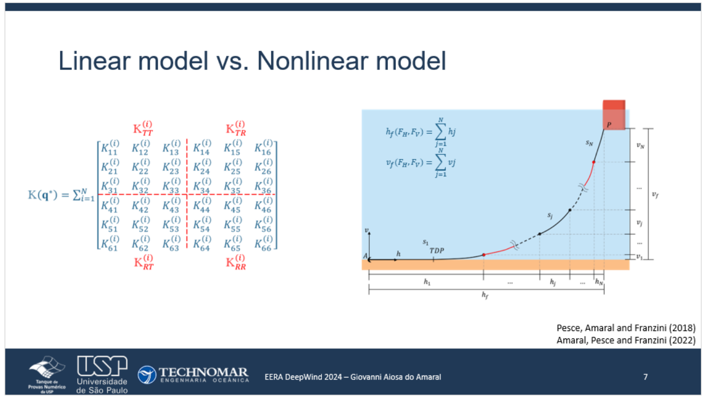
Acknowledgments

BR
PETROBRAS

anp
Agência
Nacional do
Petróleo

Tanque de
Provas Numérico da USP
Numerical Offshore Tank

USP
Universidade
de São Paulo



Linear model vs. Nonlinear model

Pesce, Amaral and Franzini (2018)
Amaral, Pesce and Franzini (2022)

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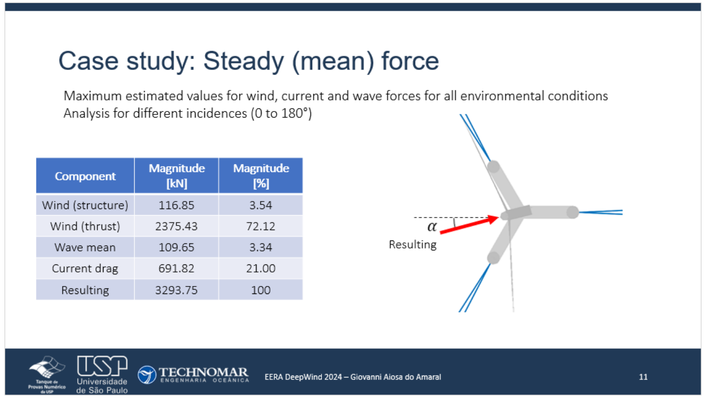

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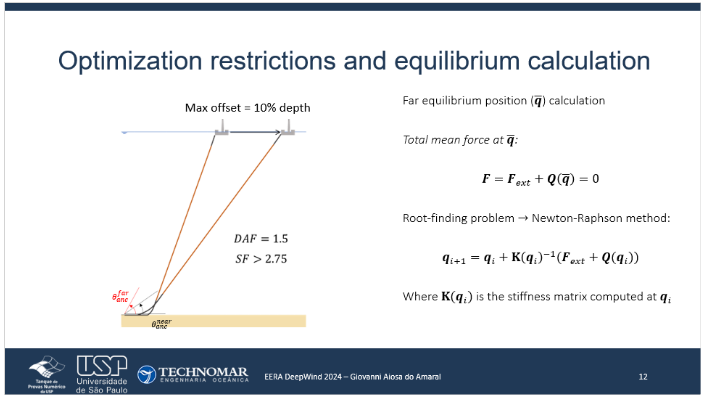

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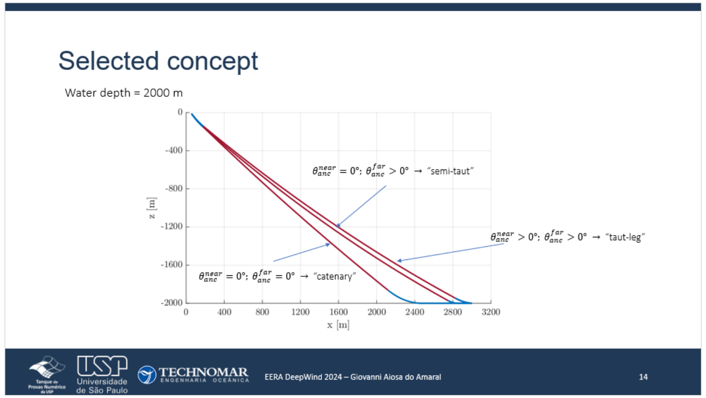

Selected concept

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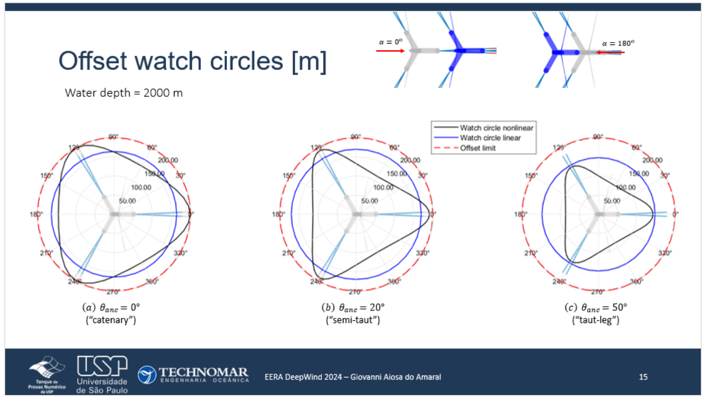

Offset watch circles [m]

Water depth = 2000 m

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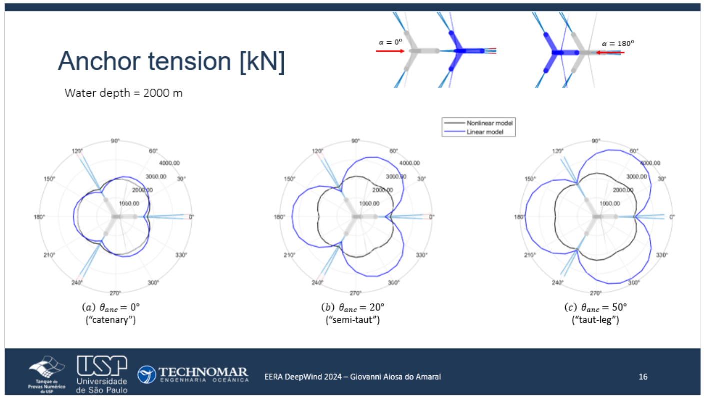

Anchor tension [kN]

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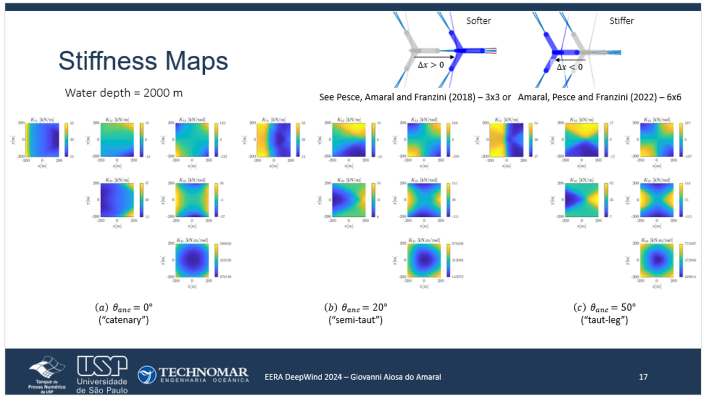

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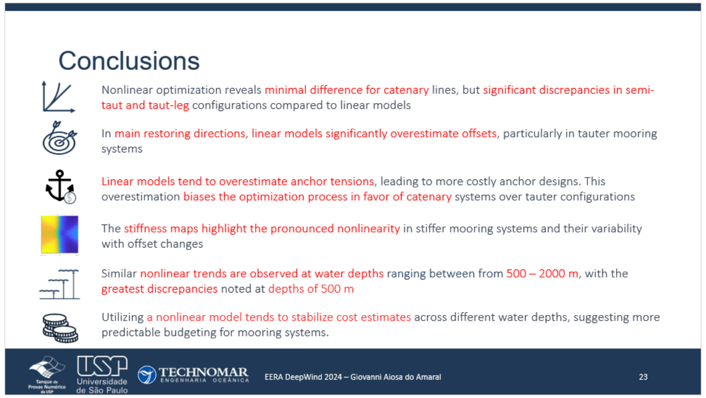

Conclusions

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- In main restoring directions, linear models significantly overestimate offsets, particularly in tauter mooring systems
- Linear models tend to overestimate anchor tensions, leading to more costly anchor designs. This overestimation biases the optimization process in favor of catenary systems over tauter configurations
- The stiffness maps highlight the pronounced nonlinearity in stiffer mooring systems and their variability with offset changes
- Similar nonlinear trends are observed at water depths ranging between from 500 – 2000 m, with the greatest discrepancies noted at depths of 500 m
- Utilizing a nonlinear model tends to stabilize cost estimates across different water depths, suggesting more predictable budgeting for mooring systems.

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Contact me!

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gamaral@technomar.com.br