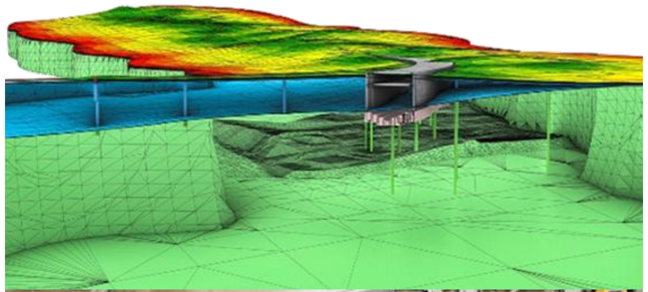
Anchor Selection and Whole-Life Performance for Offshore Floating Wind

• **Zefeng Zhou**
• *NGI - Norwegian Geotechnical Institute*

Organização
Comissão Portuguesa de Geotecnia nos Transportes

This is NGI

- Leading international centre for research and consultancy in engineering-related geosciences
- Develop solutions for industry and society, ensuring that we live and build on safe ground
- Independent foundation
- 403 employees which represent 39 nationalities
- Extensive exchanges and visits each year from both industry and academia from around the world

leading Geo lab and field test sites

NGTS

Market areas

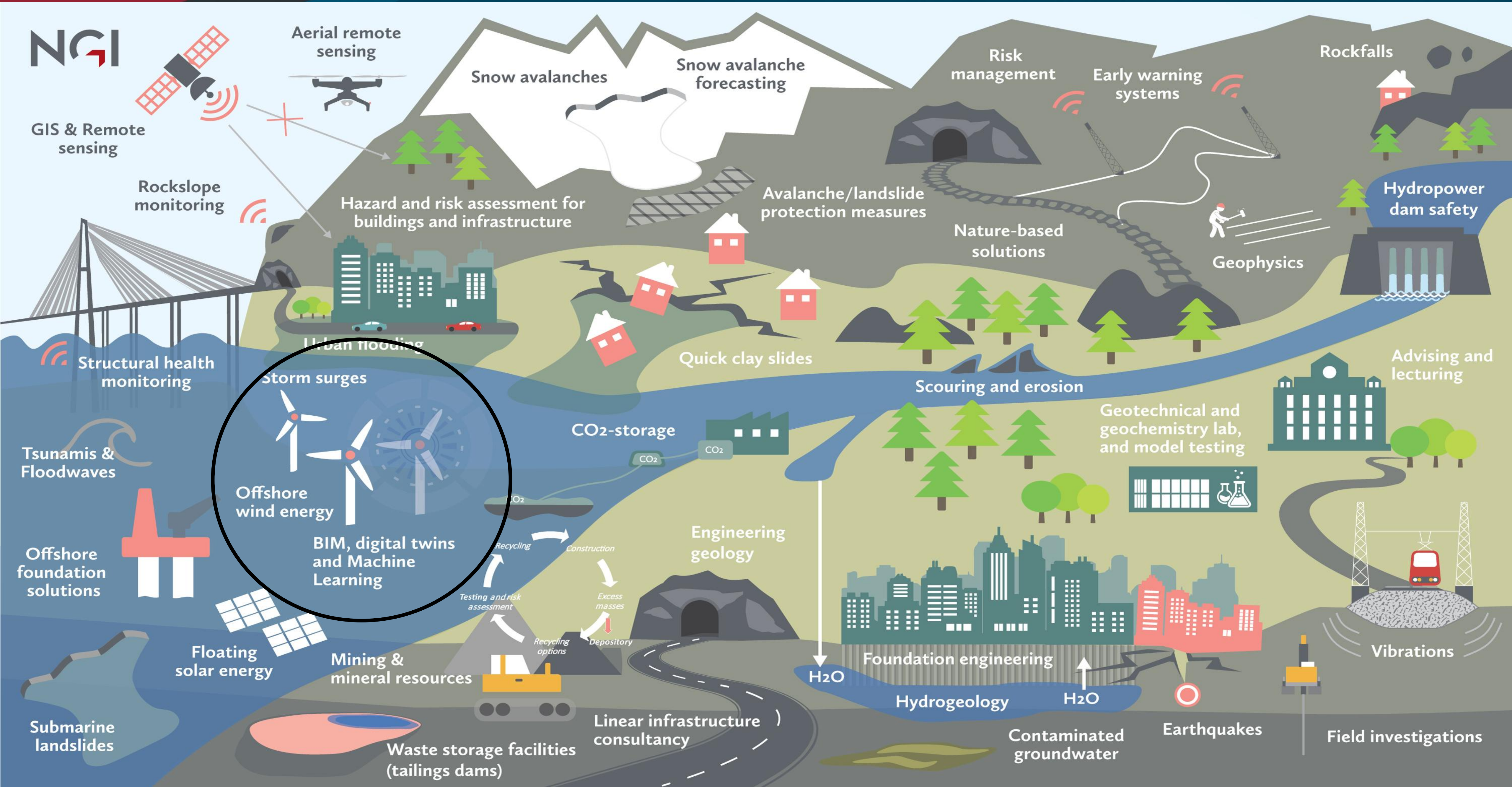
Offshore Energy

Natural Hazards

GeoData and Technology

Geotechnics and Environment

NGI


Aerial remote sensing
GIS & Remote sensing
Rockslope monitoring
Snow avalanches
Snow avalanche forecasting
Risk management
Early warning systems
Rockfalls
Hazard and risk assessment for buildings and infrastructure
Avalanche/landslide protection measures
Nature-based solutions
Geophysics
Hydropower dam safety
Urban flooding
Structural health monitoring
Storm surges
Quick clay slides
Scouring and erosion
Advising and lecturing
CO2-storage
Geotechnical and geochemistry lab, and model testing
Tsunamis & Floodwaves
Offshore wind energy
BIM, digital twins and Machine Learning
Offshore foundation solutions
Recycling
Construction
Testing and risk assessment
Excess masses
Recycling options
Depository
Engineering geology
Floating solar energy
Mining & mineral resources
Foundation engineering
H2O
Hydrogeology
Vibrations
Submarine landslides
Linear infrastructure consultancy
Waste storage facilities (tailings dams)
Contaminated groundwater
Earthquakes
Field investigations

Anchor Selection and Whole-Life Performance for Offshore Floating Wind

- Mooring system types
- Anchors for floating wind facilities
- Design of the anchoring system for offshore floating wind

BLUES

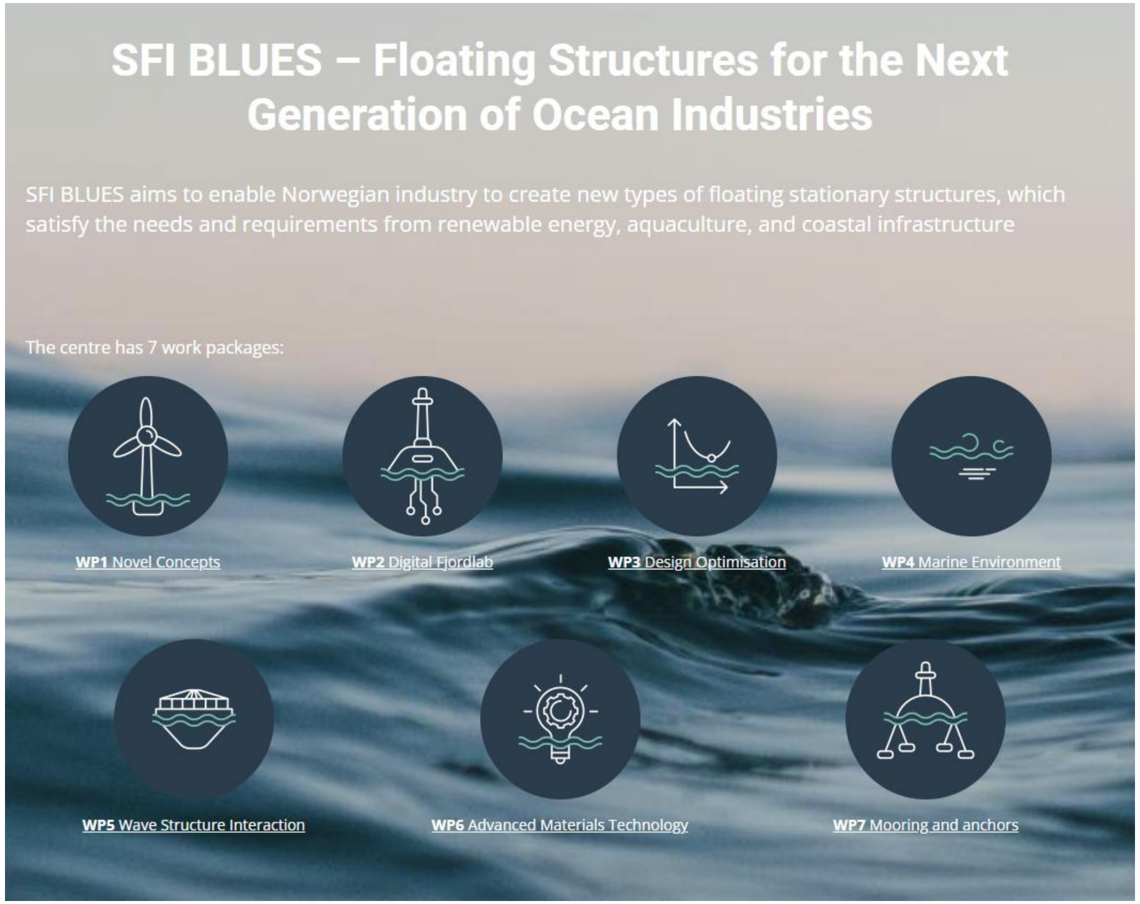
Floating structures for the next generation ocean industries

sfi Centre for Research-based Innovation

SINTEF NTNU NGI Norwegian Meteorological Institute

equinor Statens vegvesen Hydro Dr. techn. Olav Olsen AkerSolutions SEVAN SSP VRYHOF DNV·GL Ocean Sun APL | NOV Completion & Production Solutions

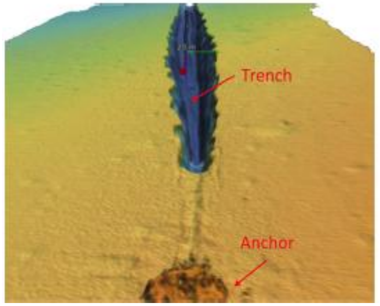
8-year research centre funded (182 MNOK)
Research Council of Norway

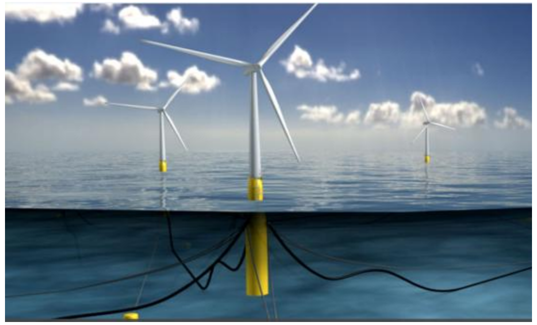


WP7 Mooring and anchors

- Cost optimalization
- Integrated analyses tools (DNV SIMA)
- Trench modelling
- Mooring line – soil interaction
- Digital test tank for new anchor concepts
- Anchors with multi-directional loading
- Monitoring and warnings, digital twin

Hans Petter Jostad





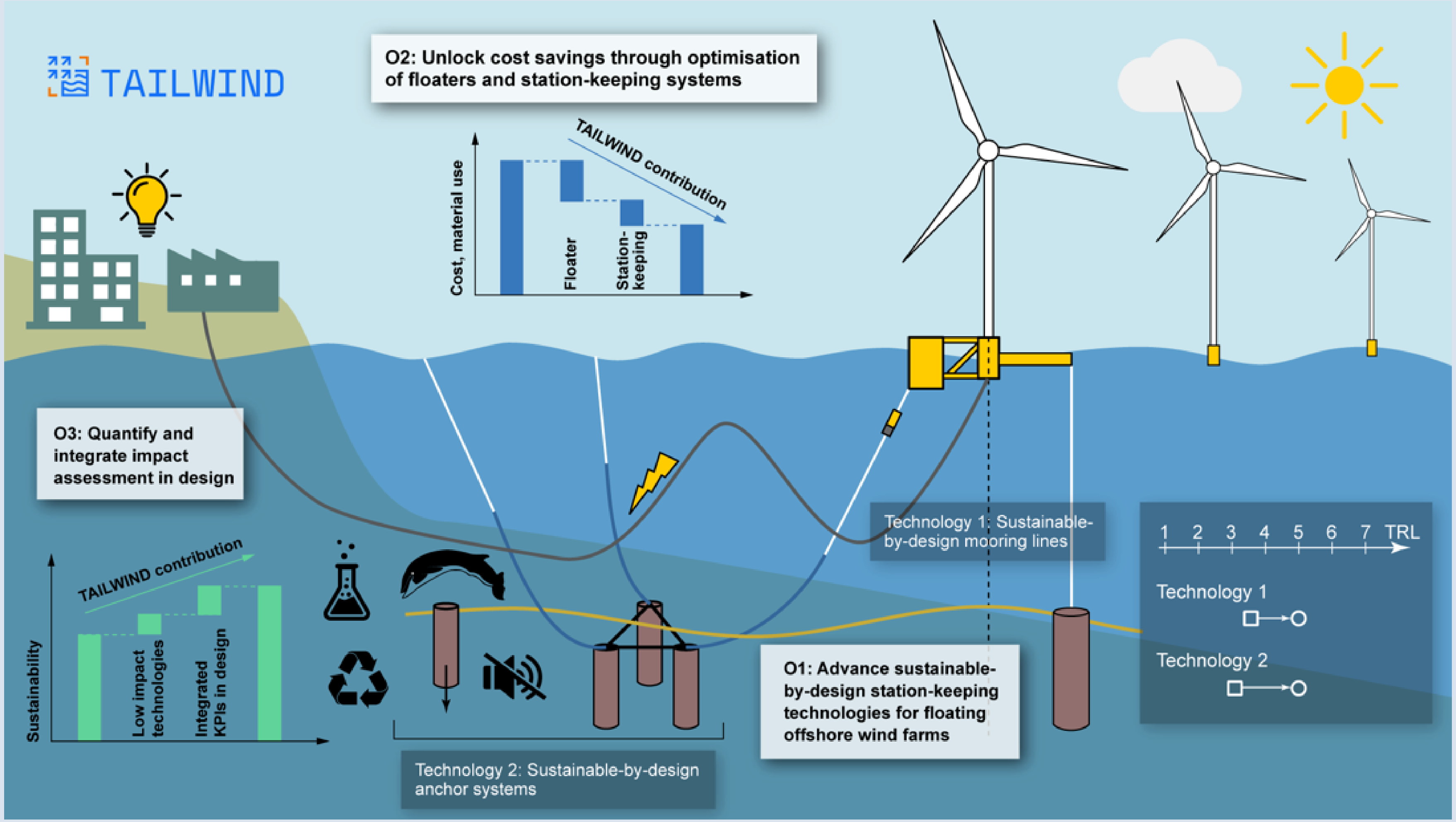
TAILWIND

PROJECT OVERVIEW

NGI

Coordinator:
Dr. Aligi Foglia
Dr. Zefeng Zhou

European Commission

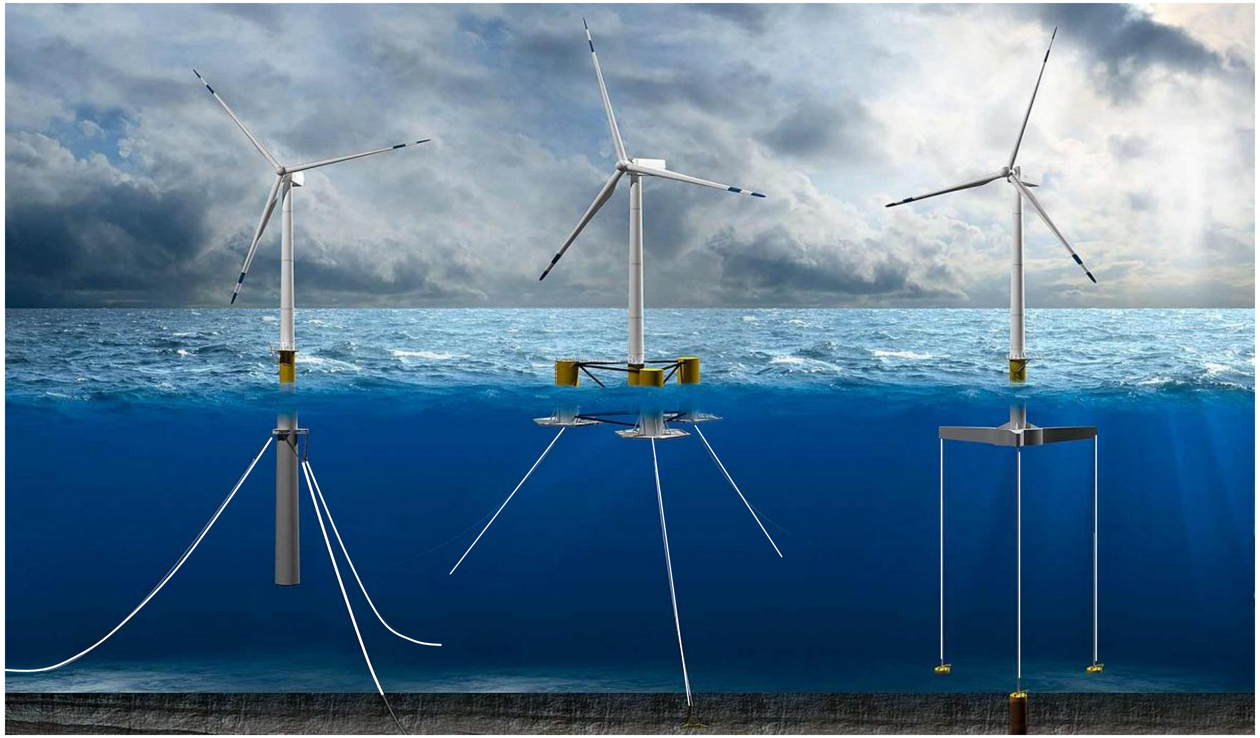


NGI, Clarke Modet, SINTEF, DTU, TU Delft, NKT, subsea 7, Bekaert, University of Southampton, Nautilus, ICONS, tecnalia

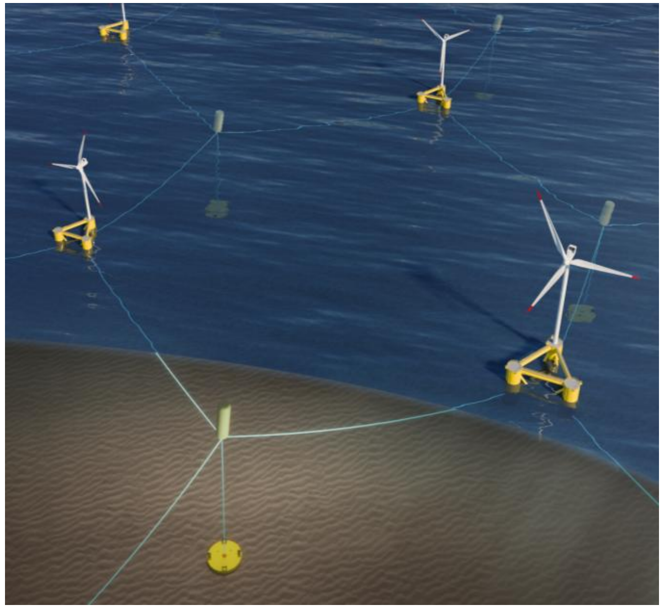
1. Mooring system types

- Environmental and operational loads - the mooring lines- anchor at the seabed

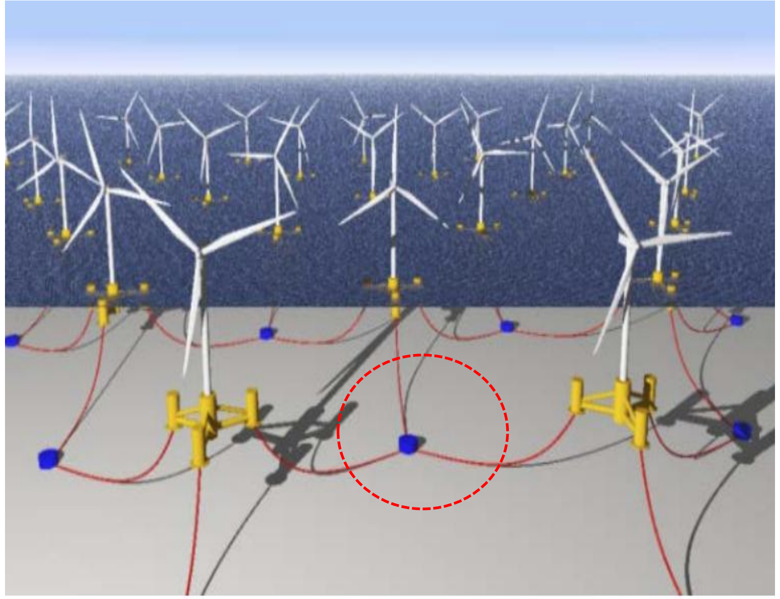
Caternary   Taut/semi taut   Tension leg



Novel Honeymooring system



Shared anchor system

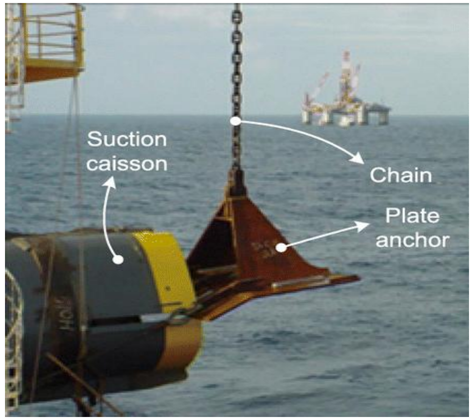


2. Anchors for offshore floating wind

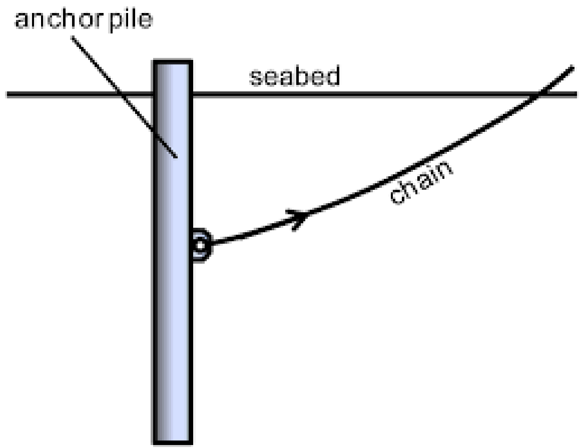
Anchors for floating wind facilities - Experience and knowledge gained from Oil & Gas

- Fluke anchors

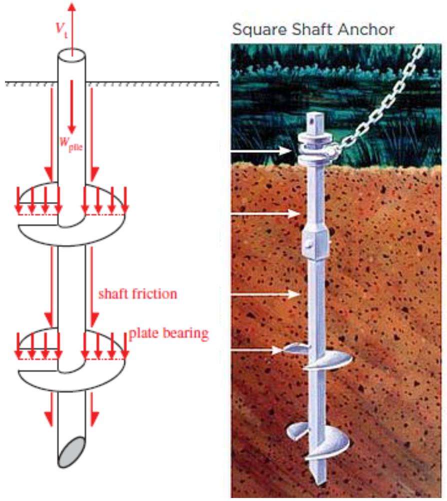
- Suction anchors



- Plate anchors



- Pile anchors



- Helical anchor

Design required site investigation

Anchor capacity

Fabrication and transportation

Installation

Soil types

Technology readiness level (TRL)

Long-term cyclic loading

Anchors for offshore floating wind

- Fluke anchors – widely used in oil & gas and floating wind demo projects

Caternary mooring
Semi-taut or taut mooring

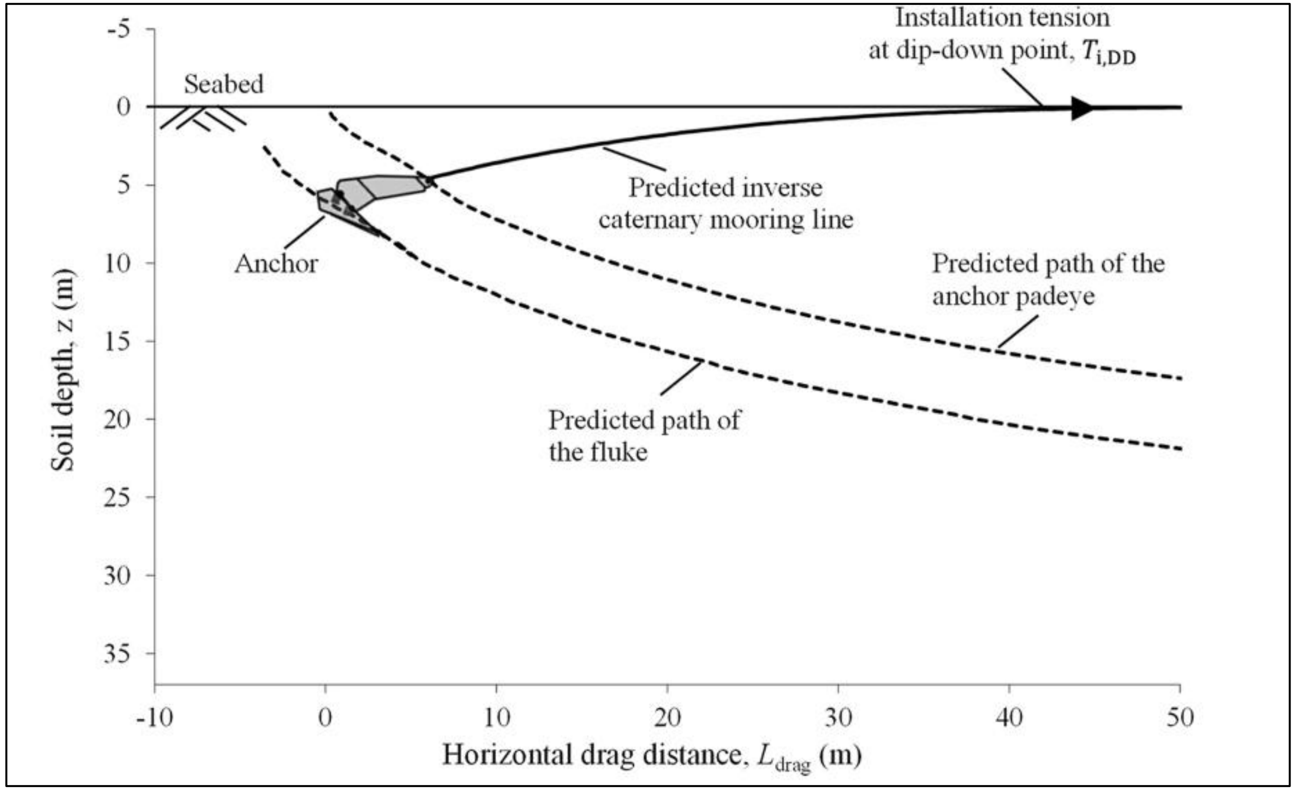
Pros	Cons
High anchor efficiency ratio (F_a/W)	High requirement for site invetigation and advanced element tests along the anchor drag path
Easy and noiseless installtion by AHV and low cost	Need to reply on additional drag to reach the max anchor capacity (due to limited AHV capacity)
Applicable for clay, silt, sand and weak rock*	Hard to determine the location of anchor
Extensive experience from oil&gas and current floating wind demo projects	Lack of prediction methods for sand and weak rock
Less sensitive to cyclic loading	Cannot be used for shared anchor point
Approved for long-term mooring	

Anchors for offshore floating wind

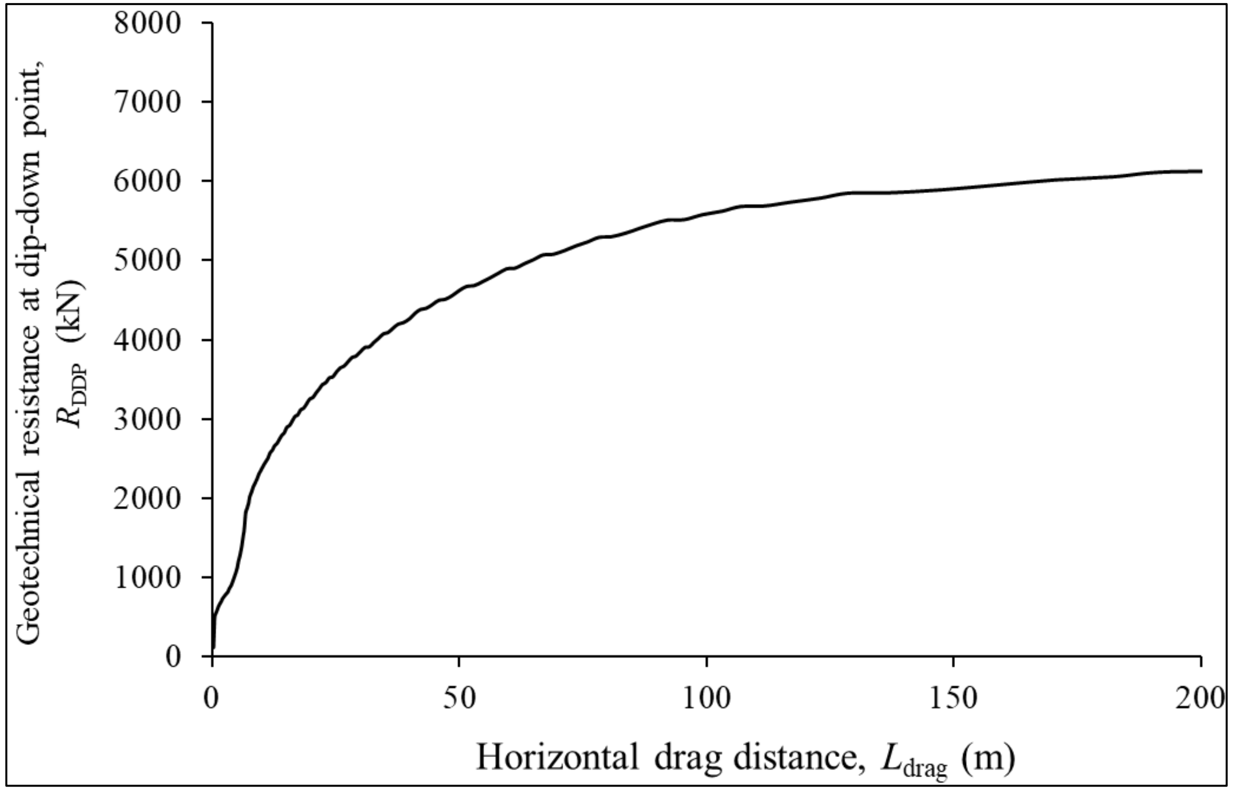
- Fluke anchors – widely used in oil & gas and floating wind demo projects

Most challenge task is to predict the trajectory of the anchor and capacity

<u>Anchor Trajectory</u> – depth v.s. horizontal drag



Anchor resistance v.s. horizontal drag



Anchors for offshore floating wind

- Suction anchors – widely used in oil & gas and floating wind demo projects

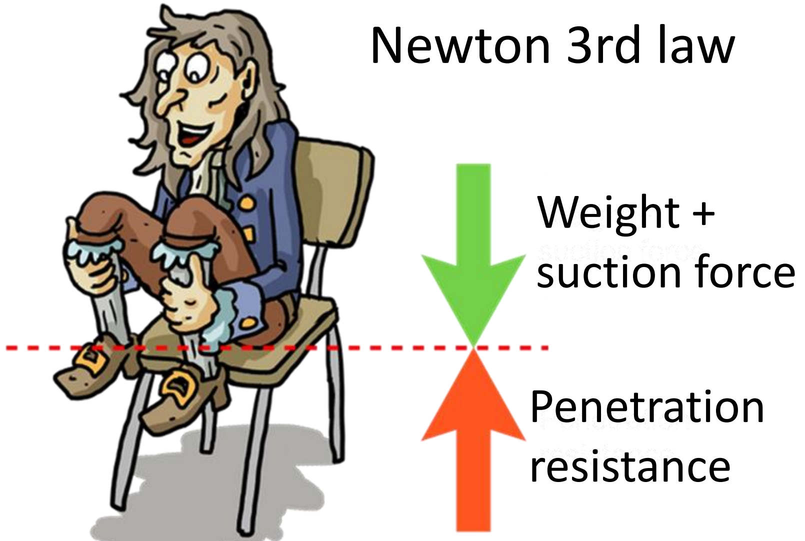
Caternary mooring
Taut/semi taut mooring
Honeymooring system
Novel shared anchor

Pros	Cons
High anchor efficiency ratio (F_a/W)	**High installation cost (especially for dense sand or layered soil)**
Noiseless installation for suction anchor	Need advanced element tests to evaluate the cyclic soil properties
Can well determine the location of anchor	**Sensitive to trench developed in front of anchor**
Applicable for clay, silt and sand	**Reduction in anchor capacity due to long-term tension load**
Extensive experience from oil&gas and current floating wind projects	
Can be used for shared anchor point	
Approved for long-term mooring	
CPTs tests and lab tests at each location are sufficient for design	

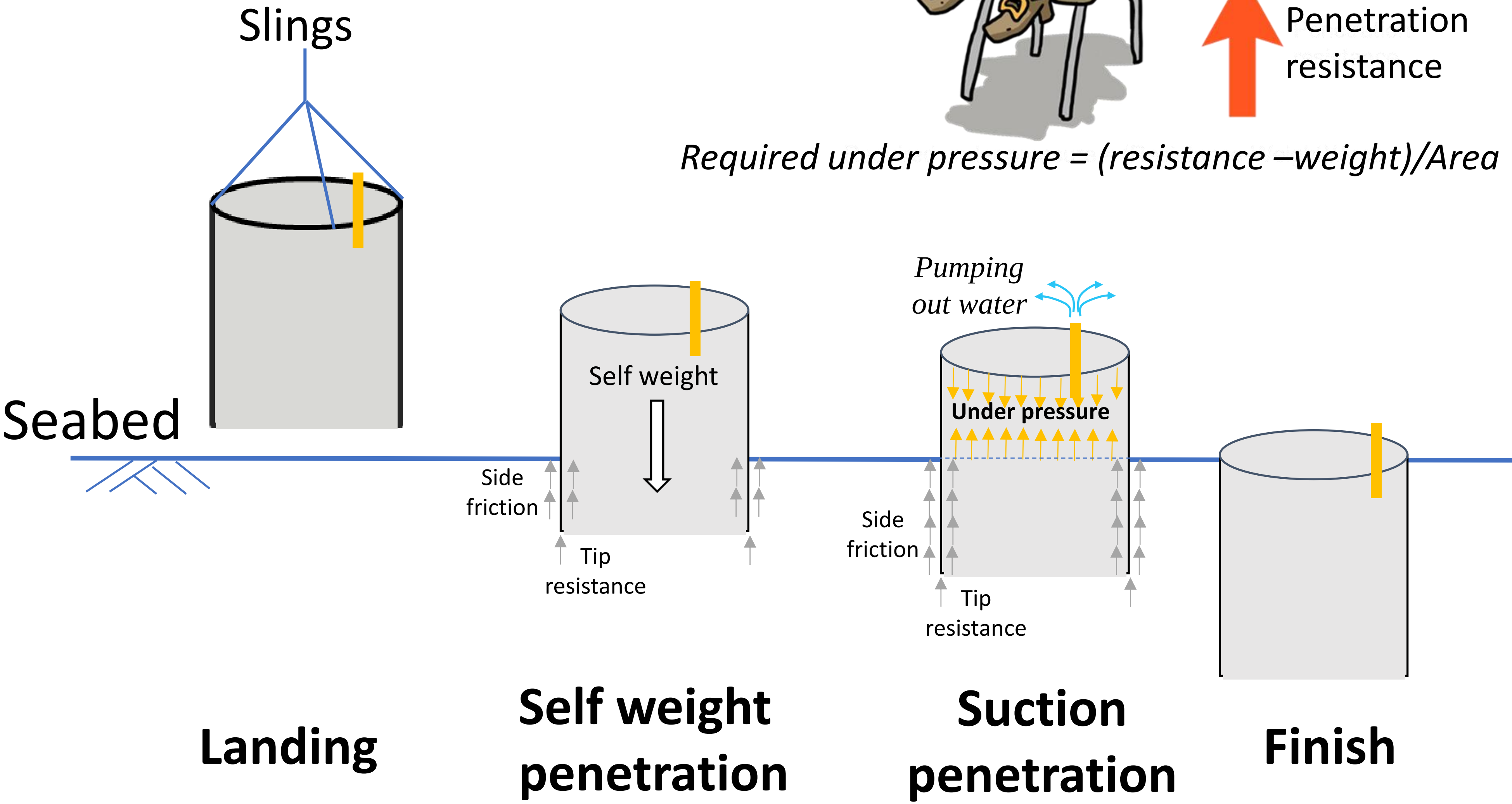
Anchors for offshore floating wind

- Suction anchors – Installation

Caternary mooring
Taut/semi taut mooring
Honeymooring system
Novel shared anchor
TLP



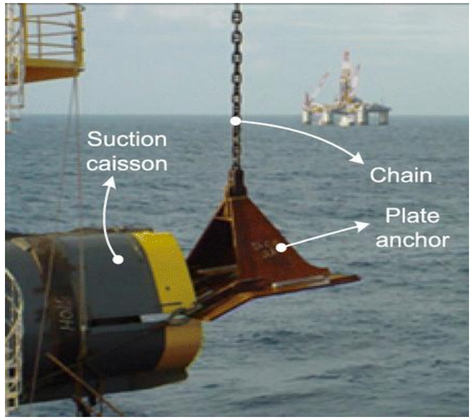
Required under pressure = (resistance –weight)/Area



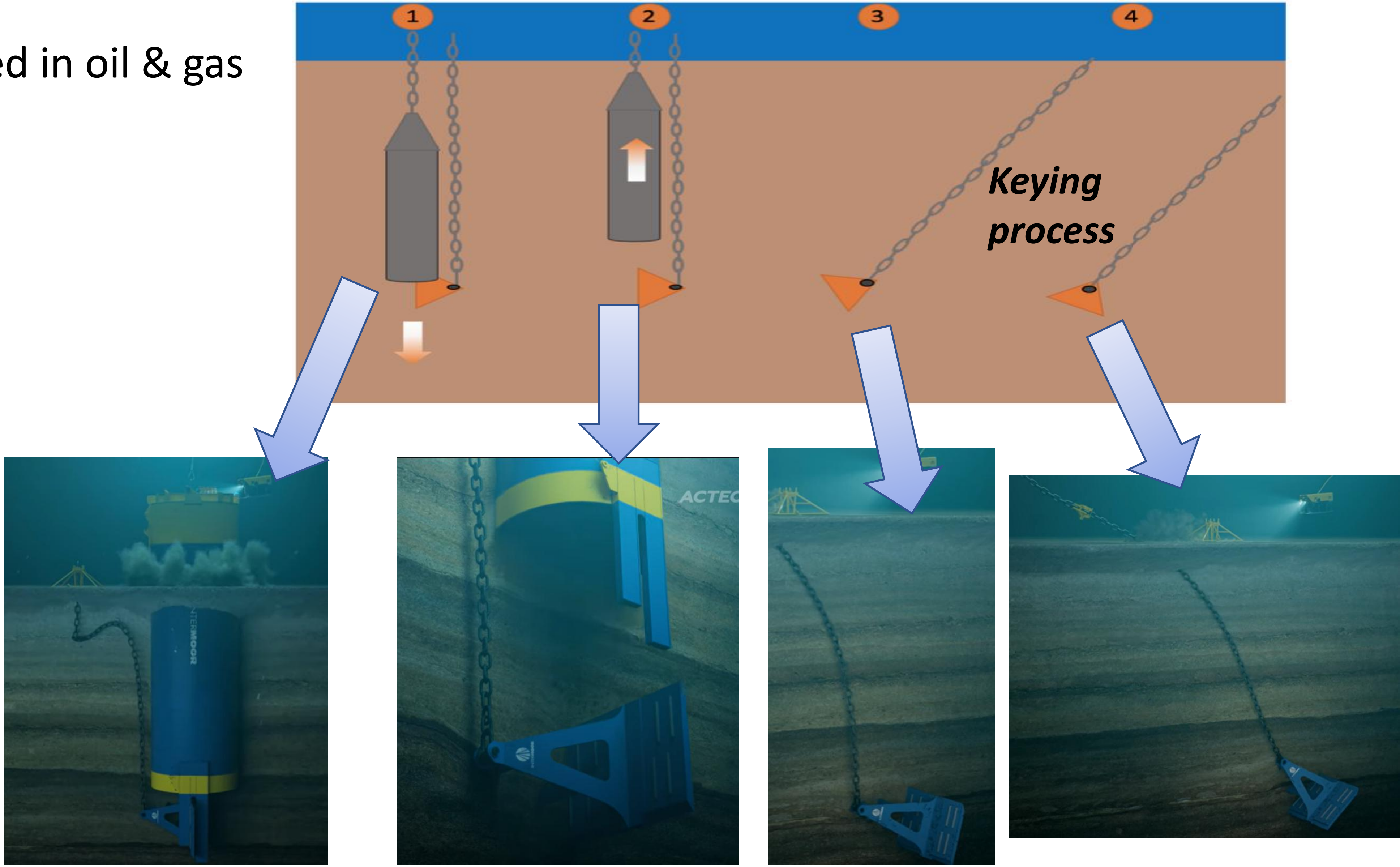
Anchors for offshore floating wind

- Plate anchors – used in oil & gas

Suction embeded plate anchor (SEPLA)



Caternary mooring
Taut/semi taut mooring
TLP

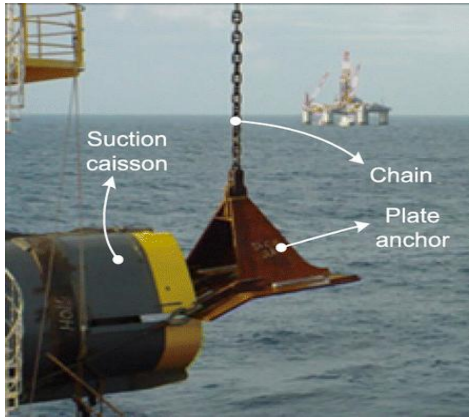


Suction embeded plate anchor (SEPLA) installation process

Anchors for offshore floating wind

- Plate anchors – used in oil & gas

Suction embeded plate anchor (SEPLA)

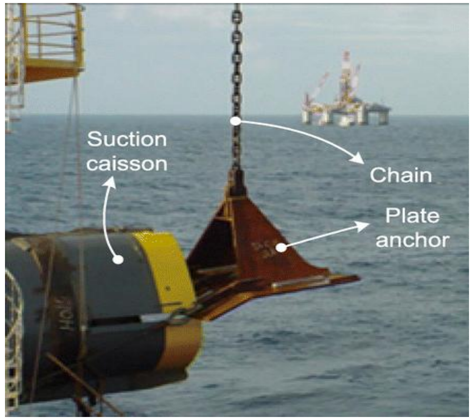


Caternary mooring
Taut/semi taut mooring
TLP

Pros	Cons
Highest anchor efficiency ratio (F_a/W)	**High installation cost (Only for SEPLA)**
Can well determine the location of anchor (SEPLA)	Need advanced element tests to evaluate the cyclic soil properties
Noiseless installation for suction anchor (SEPLA)	Cannot be used for shared anchor point
CPTs tests and lab tests at the location are sufficient for design (SEPLA)	**Loss in depth (& capacity) during anchor keying**

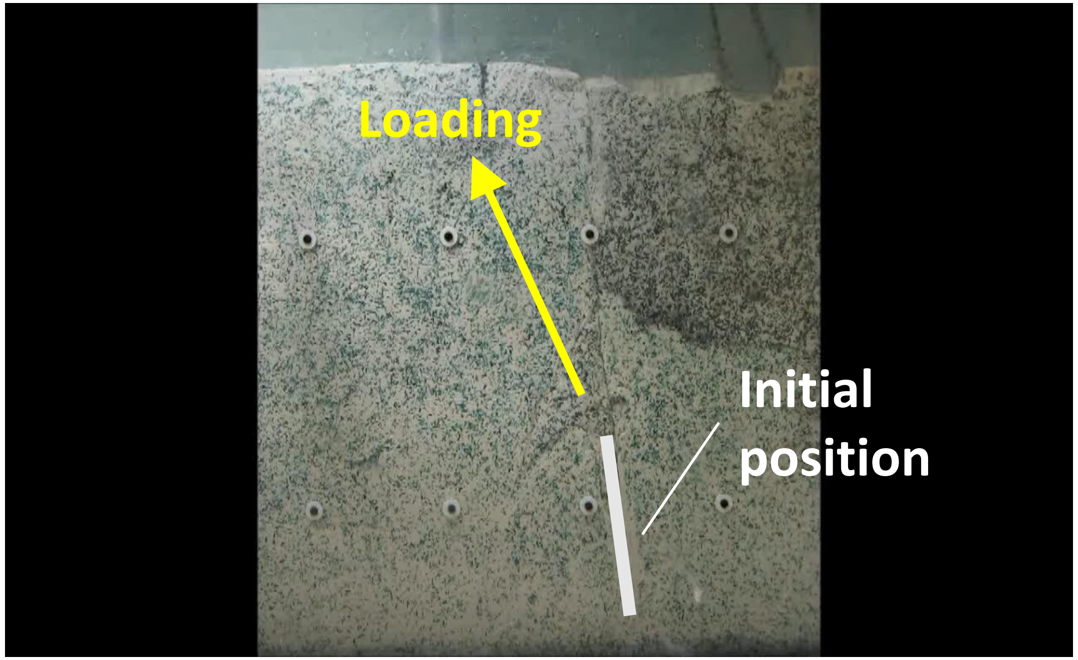
Anchors for offshore floating wind

- Plate anchors – used in oil & gas

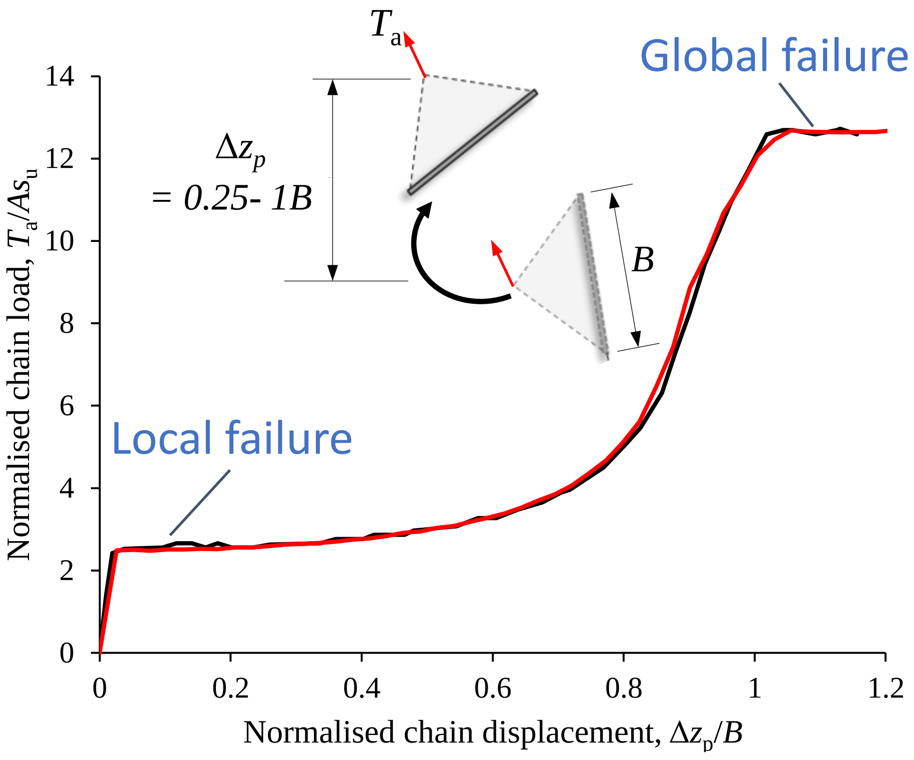


Caternary mooring
Taut/semi taut mooring
TLP

- The main issue associated with SEPLAs relates to the ***keying process***, as the anchor is first loaded, and the associated loss of embedment and reduction in capacity.

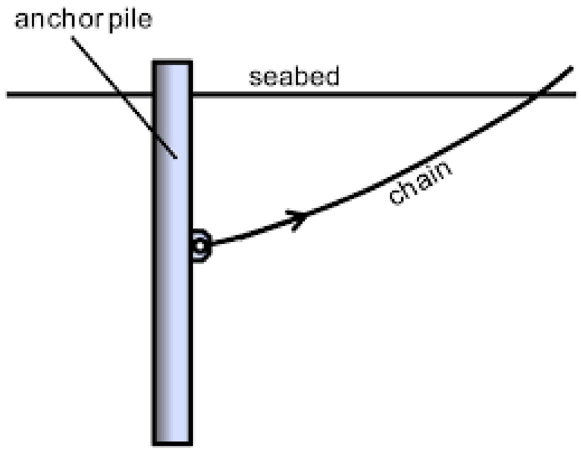


Anchor resistance v.s. chain displacement



Anchors for offshore floating wind

- Pile anchors

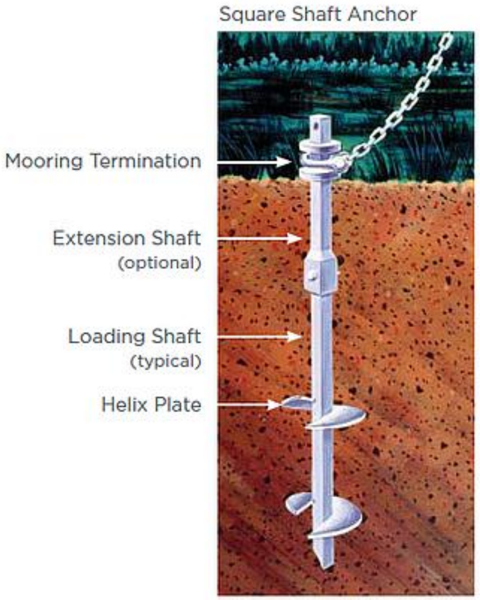


Caternary mooring
Taut/semi taut mooring
Honeymooring system
Novel shared anchor
TLP

Pros	Cons
High anchor efficiency (F_a/W)	**High installation cost in the deep water**
Can well determine the location of anchor	Need advanced element tests to evaluate the cyclic soil properties
Flexible with respect to soil type	**May have long construction time (for rock seabed)**
Can be installed in the rock by drilling and grouting	**Capacity is sensitive to location of the loading padeye**
Extensive experience from oil & gas	
CPTs tests and lab tests at the location are sufficient for design (SEPLA)	

Anchors for offshore floating wind

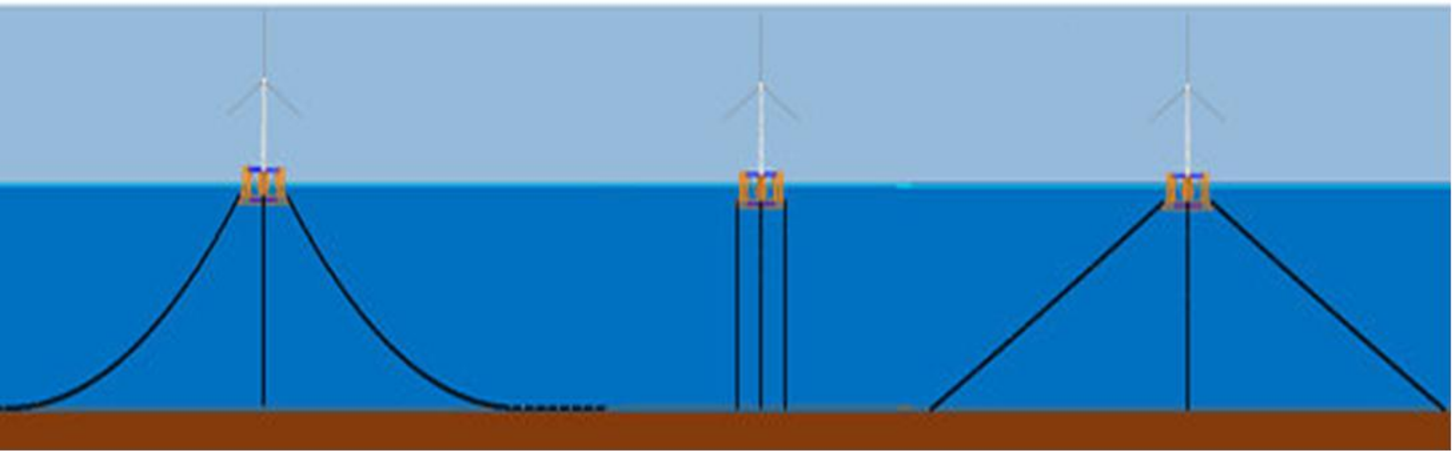
- Helical anchors



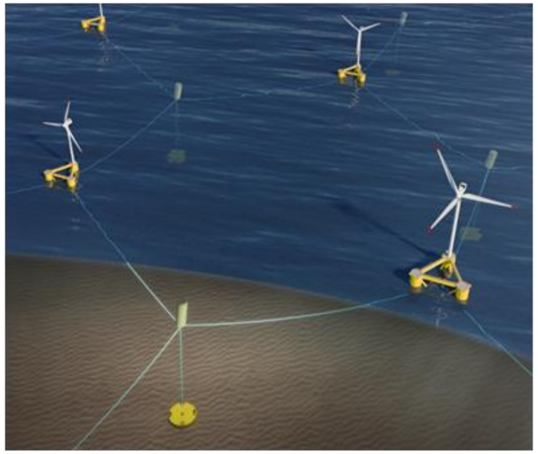
Pros	Cons
High anchor efficiency ratio (F_a/W)	**Limited experience gained**
Potentially applicable for clay, silt, sand and weak rock* (by drilling and grouting)	**May need new equipment for offshore installation and sizing of helical anchors can be limited by the installation equipment**
Minimal marine disturbance	**Lack of mature prediction methods**
Potential option for shared anchoring point	May have long construction time (for rock seabed)
CPTs tests and lab tests at the location are sufficient for design	Not proven for long-term offshore application
	Need advanced element tests to evaluate the cyclic soil properties

Anchors for offshore floating wind

Caternary Tension leg Taut



Novel Honeymooring



Caternary:
Suction anchor
Drag anchor
Pile anchor
Plate anchor

Tension leg:
Suction anchor
Pile anchor
Plate anchor

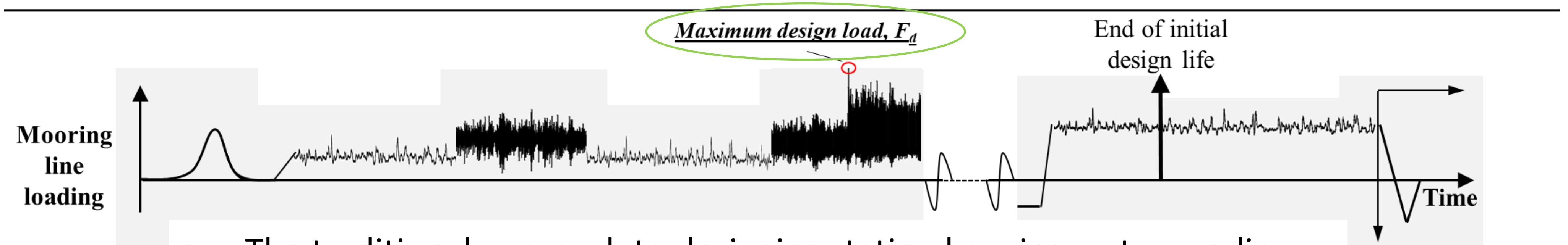
Taut:
Suction anchor
Drag anchor
Pile anchor
Plate anchor

Novel Honeymooring:
Suction anchor
Pile anchor
Plate anchor

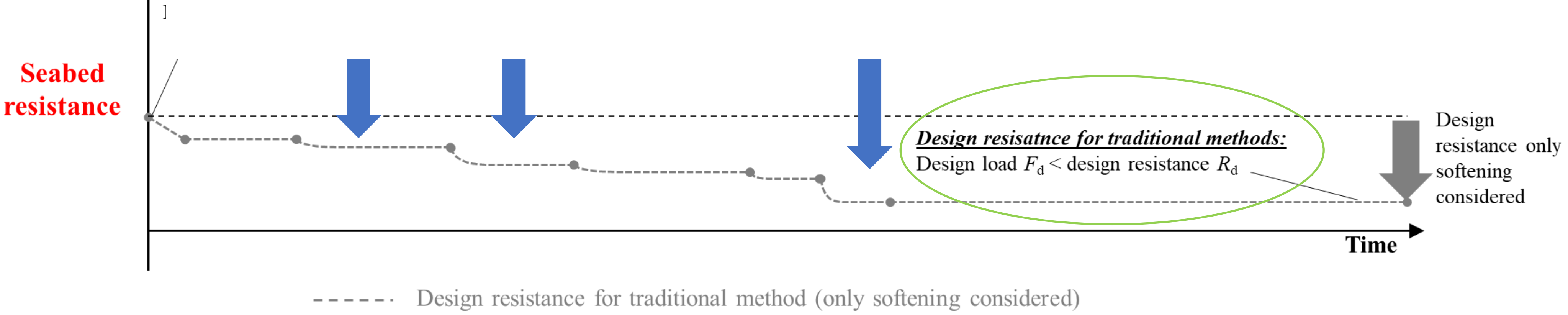
- Design required site investigation
- Anchor capacity
- Fabrication and transportation
- Installation
- Soil types
- Technology readiness level (TRL)
- Long-term cyclic loading

3. Design of the anchoring system for offshore floating wind

Traditional design concept



- The traditional approach to designing station keeping systems relies on a *conservative strategy*.
- Only the "worst-case" single values of minimum resistance and maximum action over the design life, ensuring that *the maximum design load does not surpass the minimum capacity* of the cyclic-softened anchors.



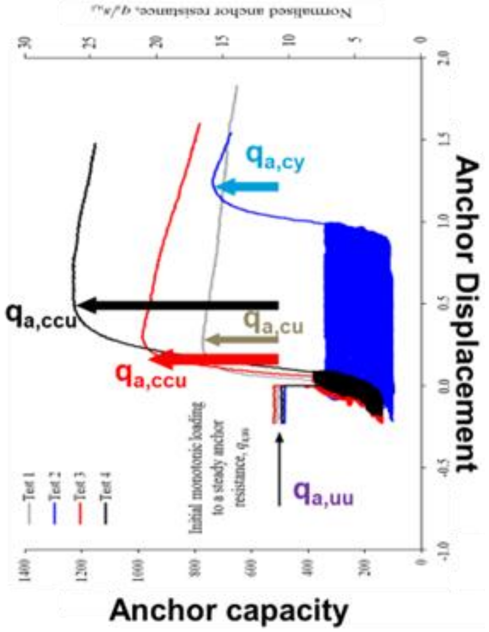
Does the strength of the seabed only decrease during cyclic loading?

3. Design of the anchoring system for offshore floating wind

- Long-term anchor capacity induced by cyclic loading and consolidation

Recent research indicates the anchor capacity can increase with long-term cyclic loading

Long-term anchor capacity



$q_{a,uu}$ → $q_{a,cu}$	**X1,5**	A contant maintained load + consolidation
$q_{a,uu}$ → $q_{a,cy}$	**X1,5**	Continuous long-term cyclic load
$q_{a,uu}$ → $q_{a,ccu}$	**X1,9**	One episode of short-term cyclic & maintained load + consolidation
$q_{a,uu}$ → $q_{a,ccu}$	**X2,5**	Five episodes of short-term cyclic & maintained load + consolidation

Unlocking points:

- ***'No pain no gain' soil behaviour***
- ***Maintained load with consolidation can increase anchor capacity by 50% of initial value***
- ***Long-term cyclic loading can enhance the beneficial effects***

→ ***Beneficial effects of long-term cyclic loading is ignored in current design method***

3. Design of the anchoring system for offshore floating wind

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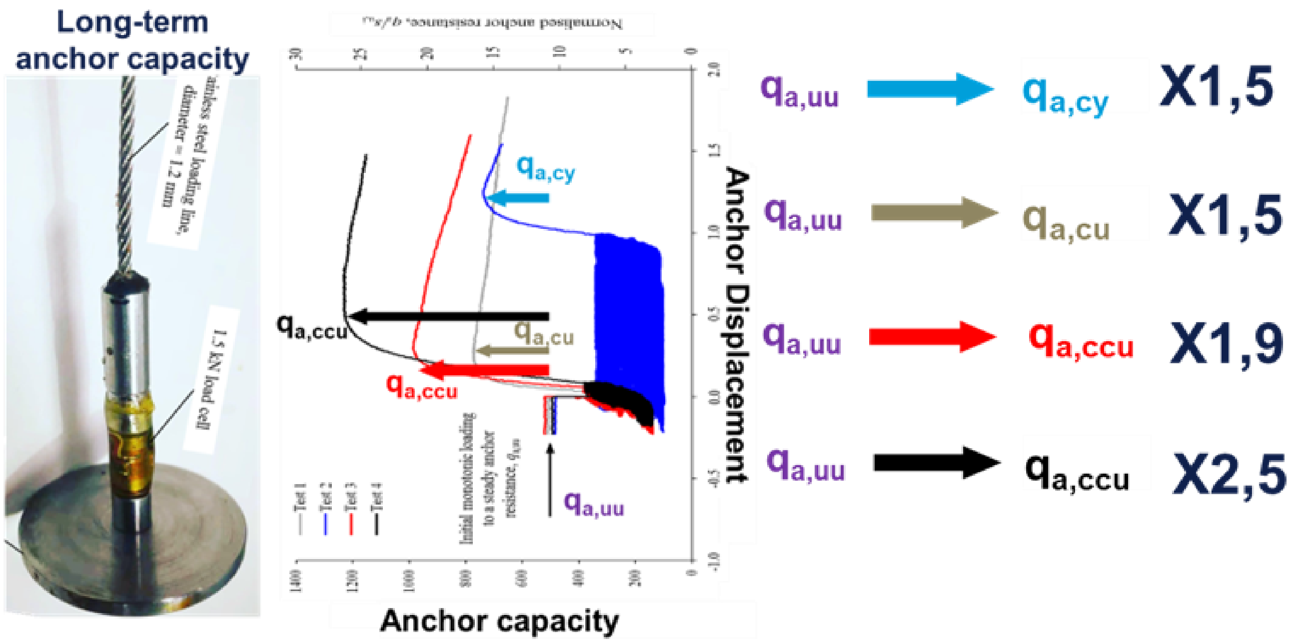

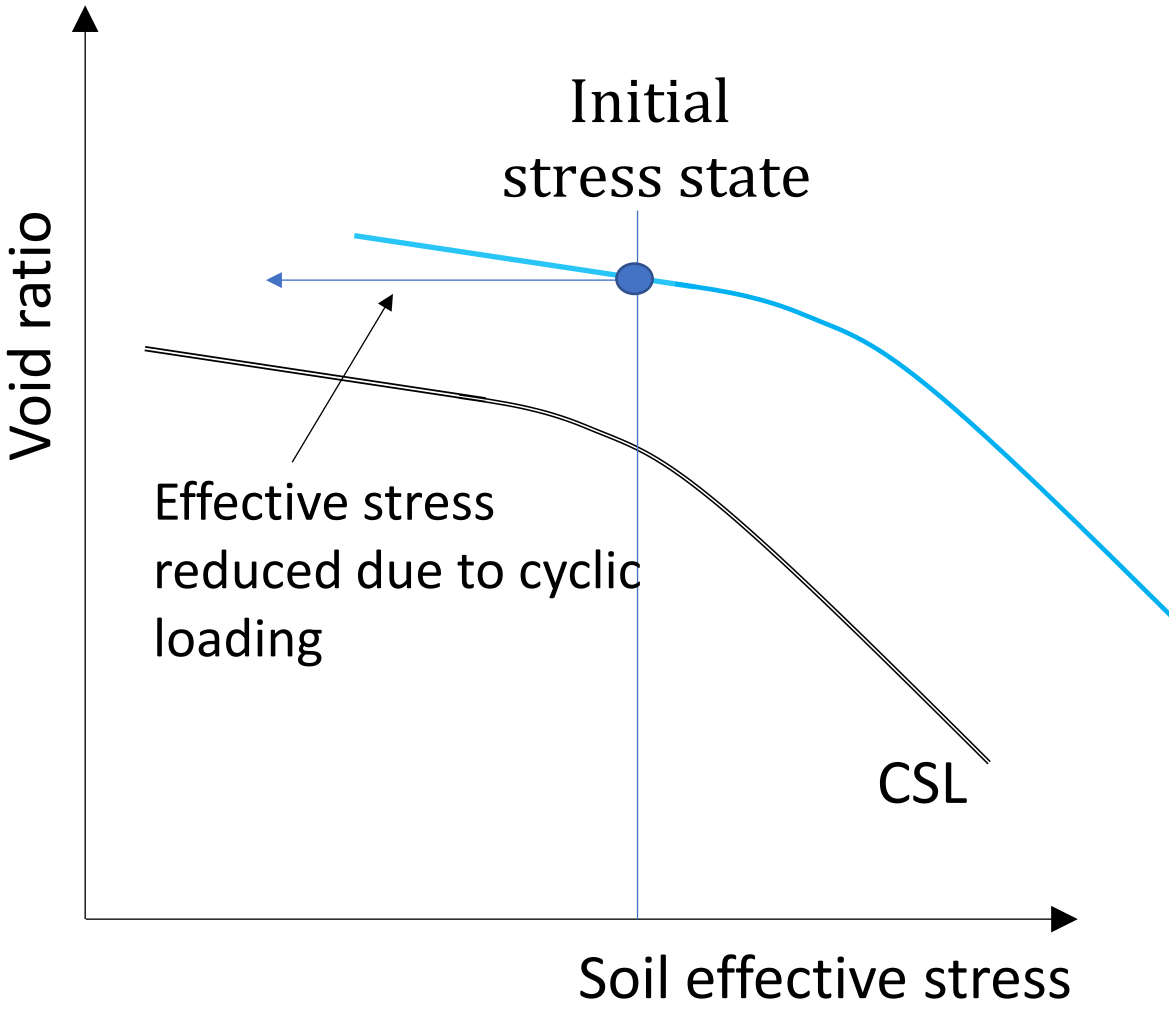

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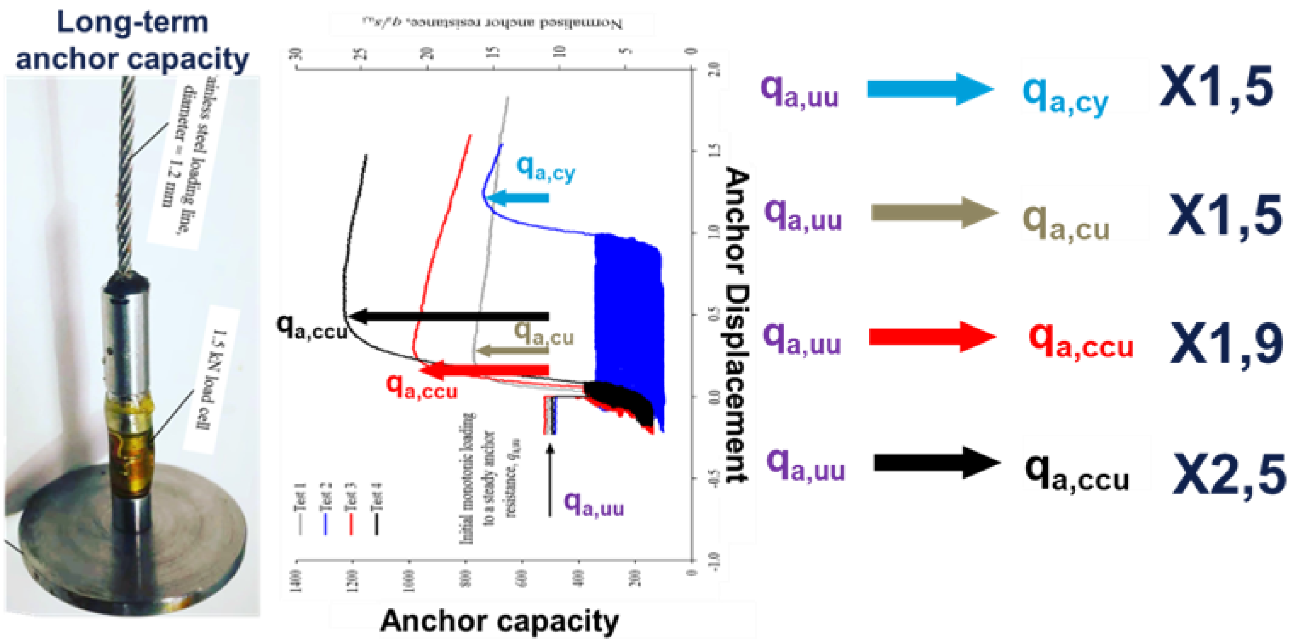

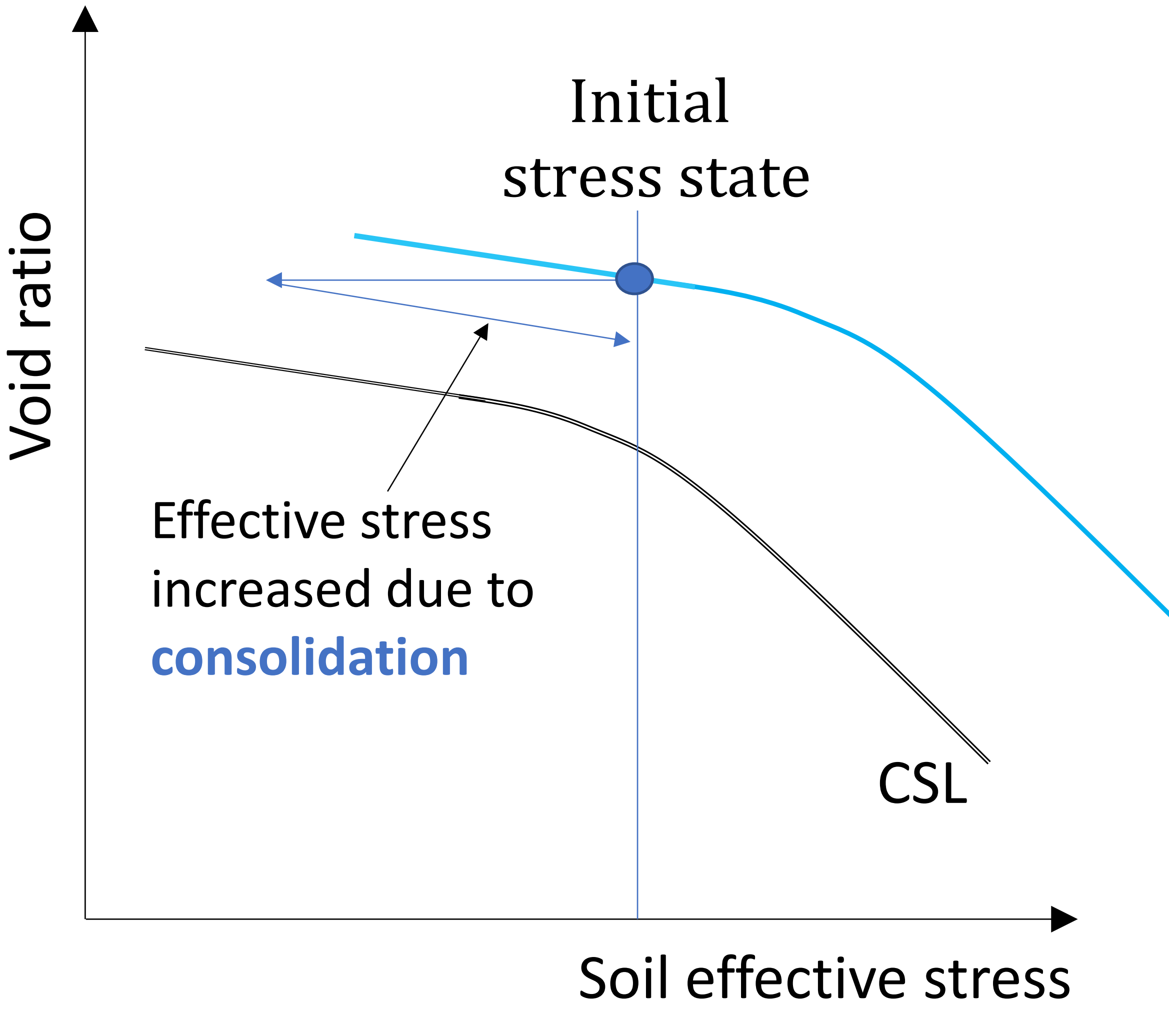

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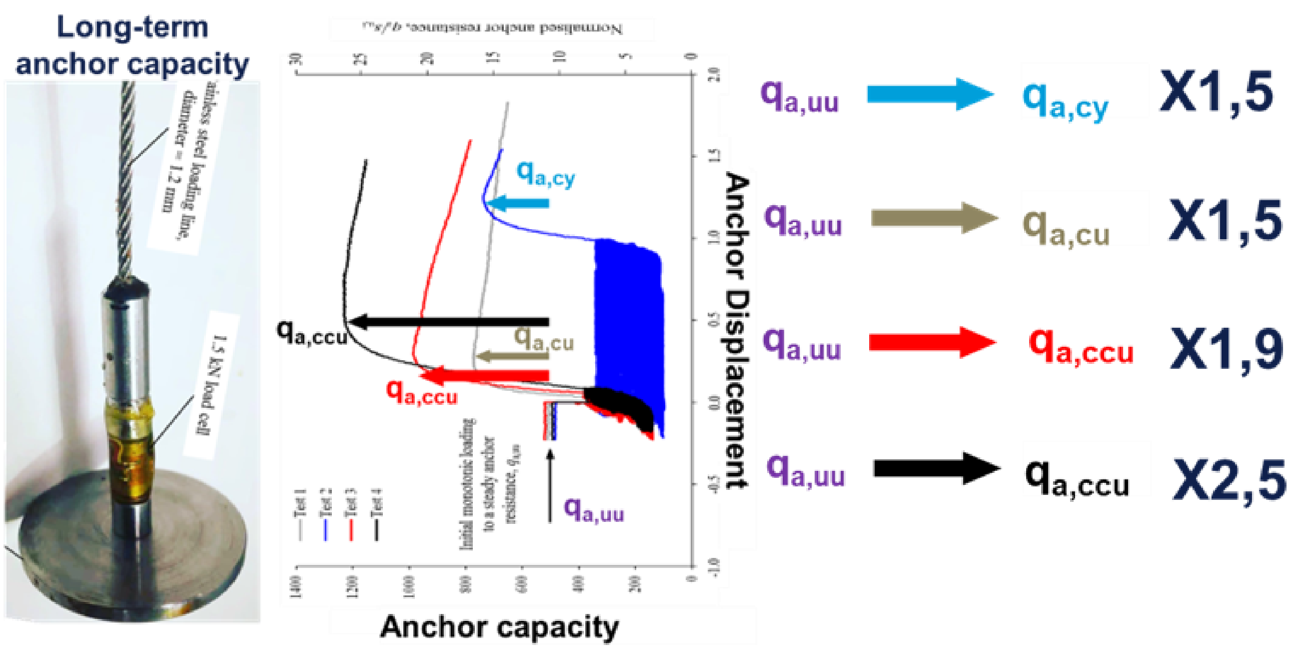

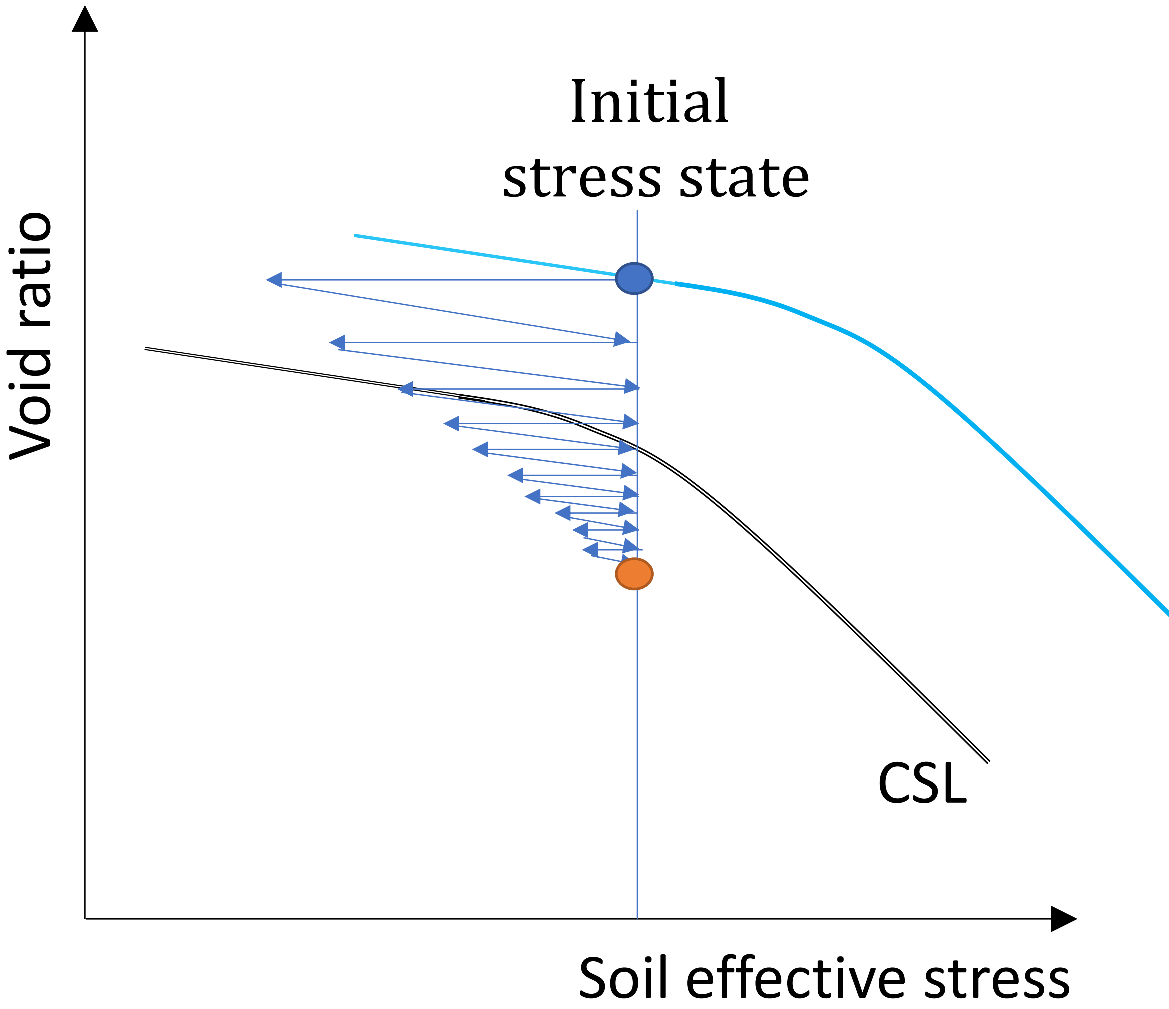

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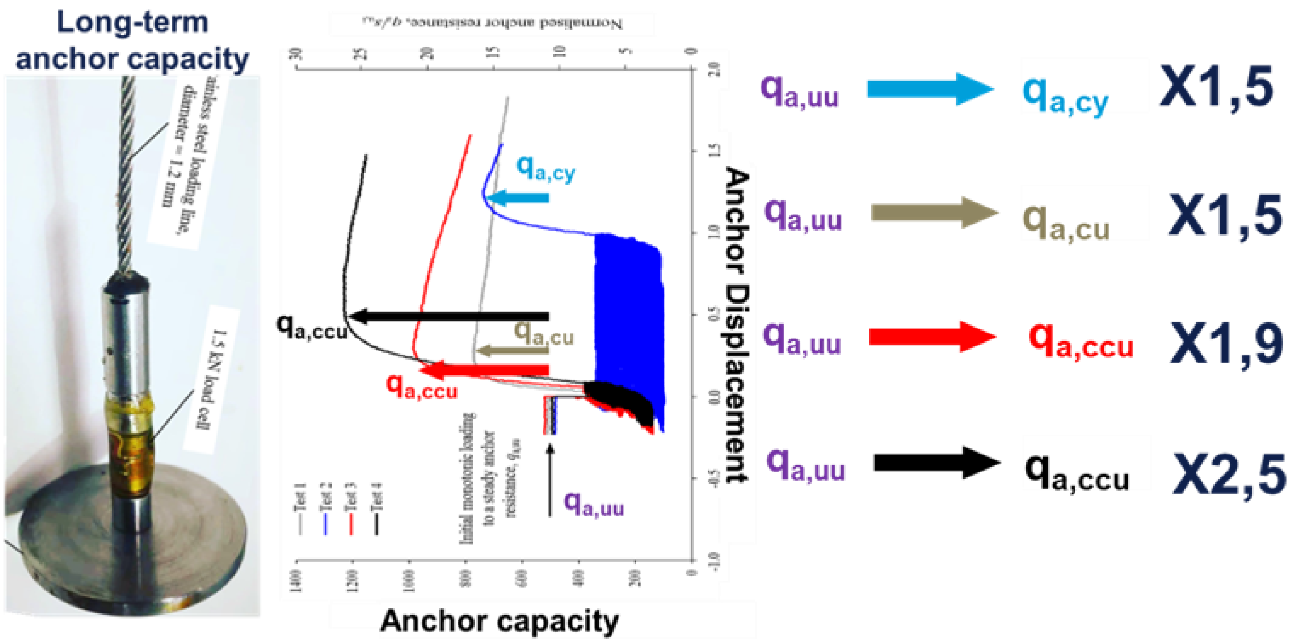
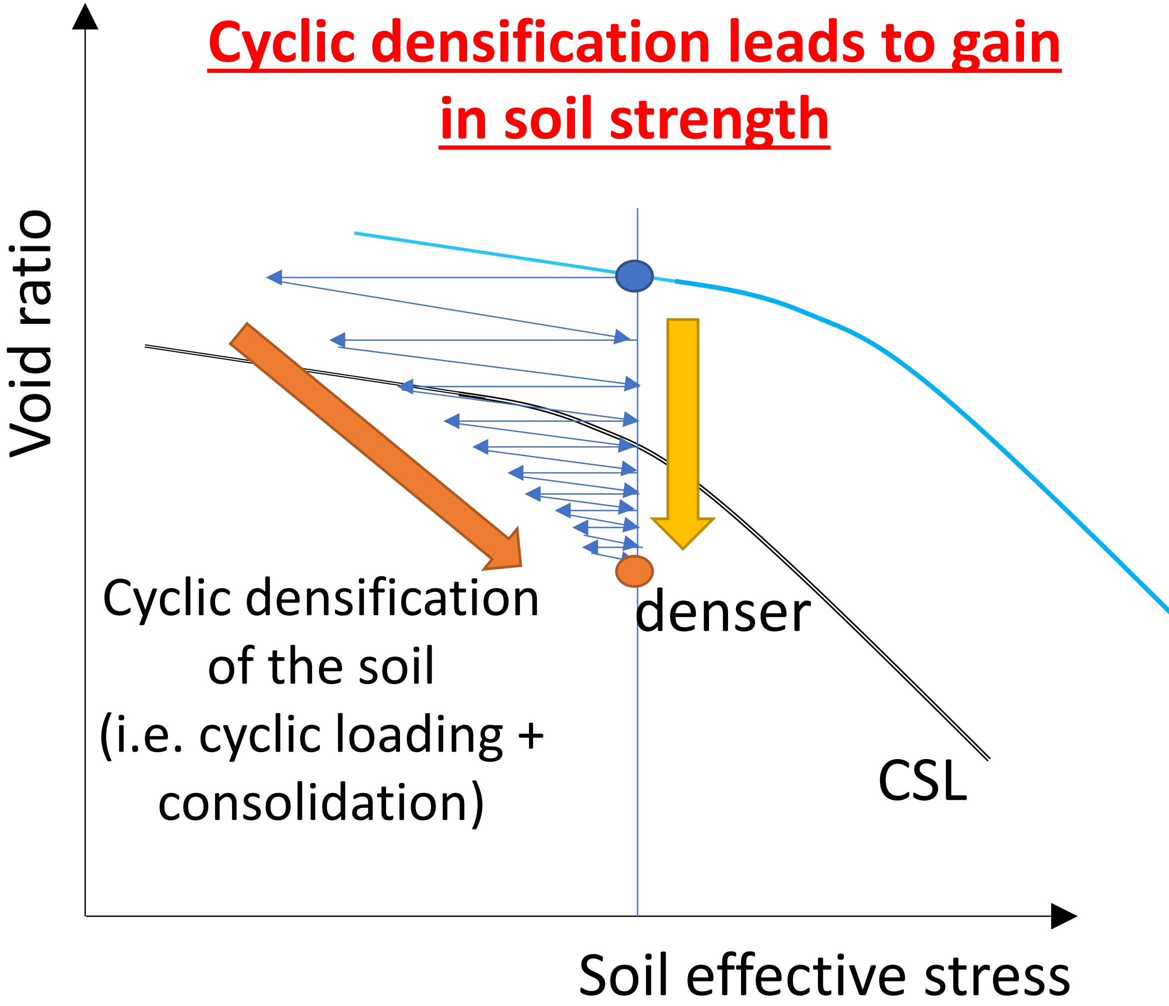


<u>**Cyclic densification leads to gain in soil strength**</u>



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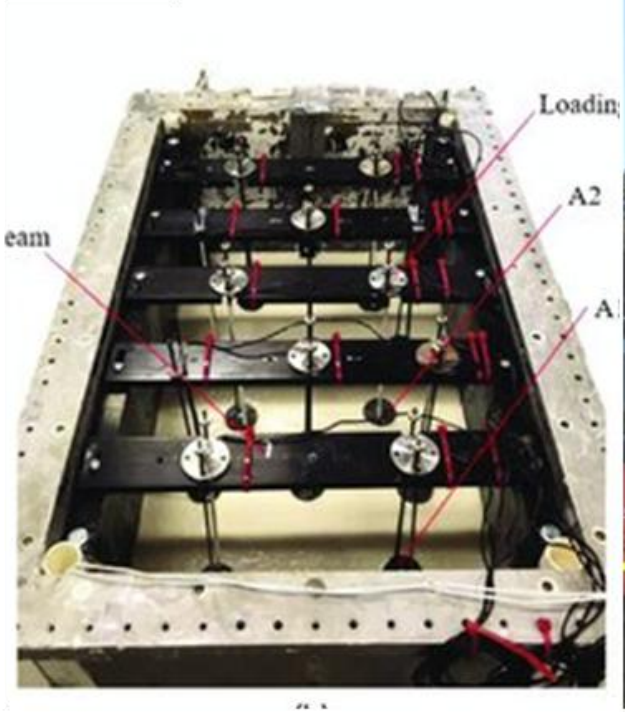


Centrifuge test at UWA

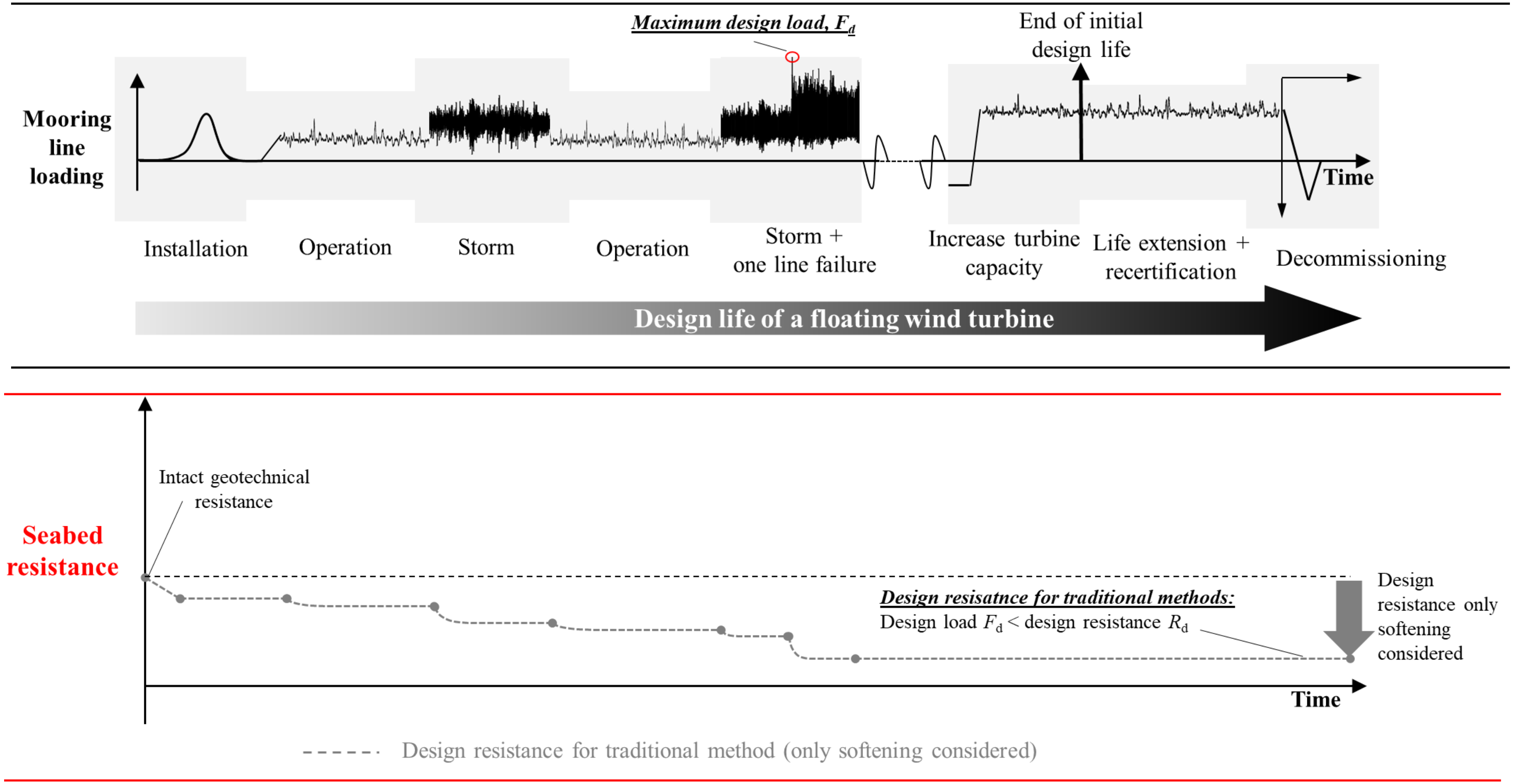
Field test at Perth WA

- Several centrifuge tests reveal changes in anchor capacity and its time-dependent failure mechanisms
- **The world's first long-term field test demonstrates the enhanced capacity of anchors over time.**
- Capable of banking the benefits of long-term loading in a short period

Publication is coming soon……

3. Design of the anchoring system for offshore floating wind

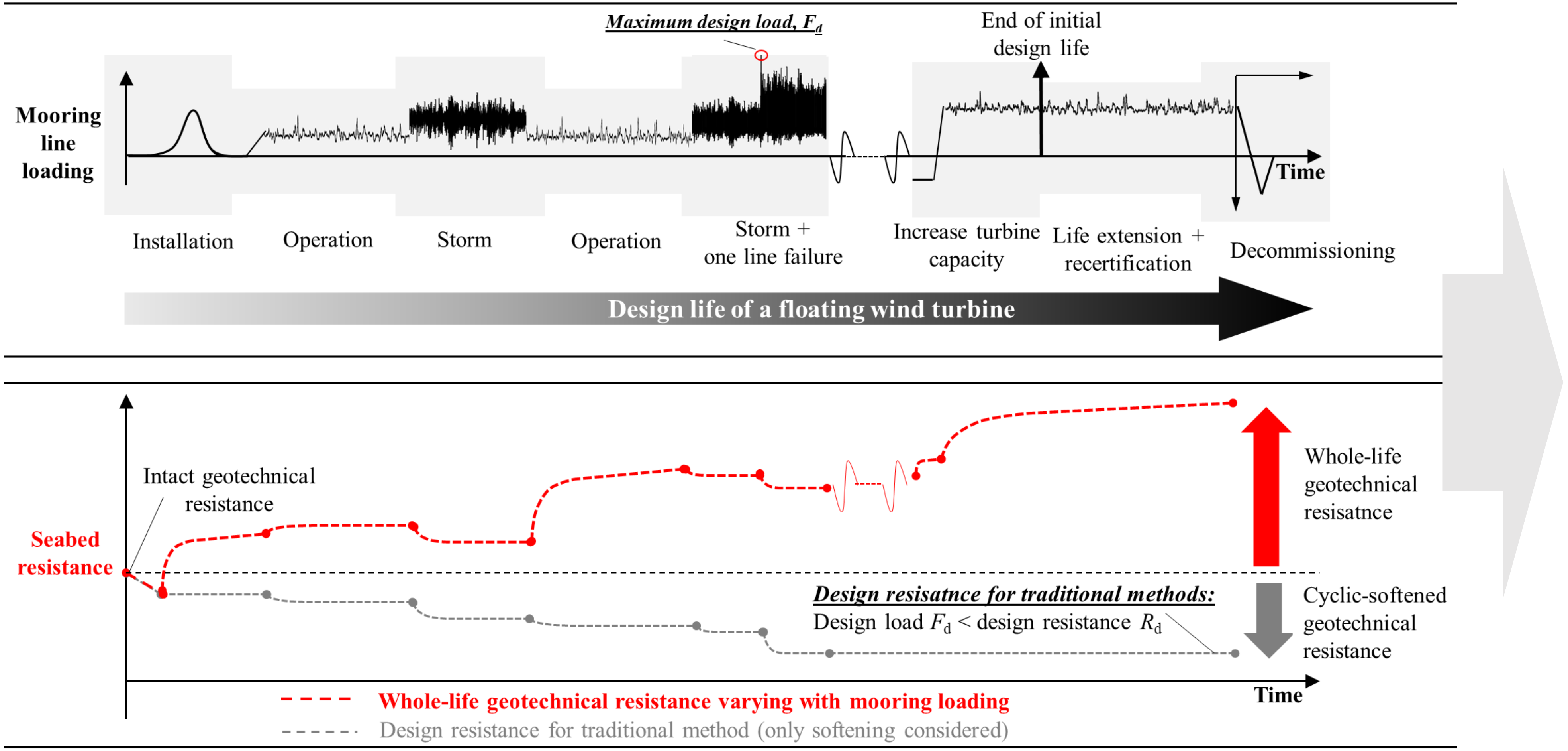
- Whole life geotechnical design concept for floating wind facilities



The principal for whole life geotechnical design: design result can be improved by considering whole life loading history and the resulting whole life seabed responses

3. Design of the anchoring system for offshore floating wind

Whole life geotechnical design concept for floating wind facilities



- Foundation sizing
- Safety margin
- Fabrication cost
- Transportation cost
- Installation cost
- Life extension analysis
- Decommissioning
- Digital twins

Reference:

[1] **Zefeng Zhou***, David J. White & Conleth D. O'Loughlin 2019, 'An effective stress framework for estimating penetration resistance accounting for changes in soil strength from maintained load, remoulding and reconsolidation', **Géotechnique**.

[2] **Zefeng Zhou***, Conleth D. O'Loughlin & David J. White 2020, 'An effective stress analysis for predicting the evolution of SCR–seabed stiffness accounting for consolidation', **Géotechnique**.

[3] **Zefeng Zhou***, Conleth D. O'Loughlin, David J. White & Sam A. Stanier 2020, 'Improvements in plate anchor capacity due to cyclic and maintained loads combined with consolidation', **Géotechnique**.

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[5] Ci Wang, Conleth D. O'Loughlin, Fraser Bransby, Phil Watson & **Zefeng Zhou***. Complex time-dependent processes influencing offshore foundations in clay: an experimental study on plate anchors, **Géotechnique**.

[6] **Zefeng Zhou***, David J. White & Conleth D. O'Loughlin 2019, 'The changing strength of carbonate silt: parallel penetrometer and foundation tests with cyclic loading and reconsolidation periods', **Canadian Geotechnical Journal**.

[7] Weiguo Zhang, **Zefeng Zhou***, Dhruba Pradham & Hao jin 2023, 'Design considerations of drag anchors in cohesive soil for floating facilities in the South China sea', **Marine Structures**.

[8] Ci Wang, Conleth D. O'Loughlin, Fraser Bransby, Phil Watson & **Zefeng Zhou***. Permeable Plate Anchors: Accelerating Capacity Gain in Soft Clay, **Journal of Geotechnical and Geoenvironmental Engineering**.

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[10] Shengjie Rui, Lizhong Wang, **Zefeng Zhou***, Hans Petter Jostad and Zhen Guo 2024, Bearing performance of a novel caisson-plate gravity anchor, **Géotechnique**.

Thank you!

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