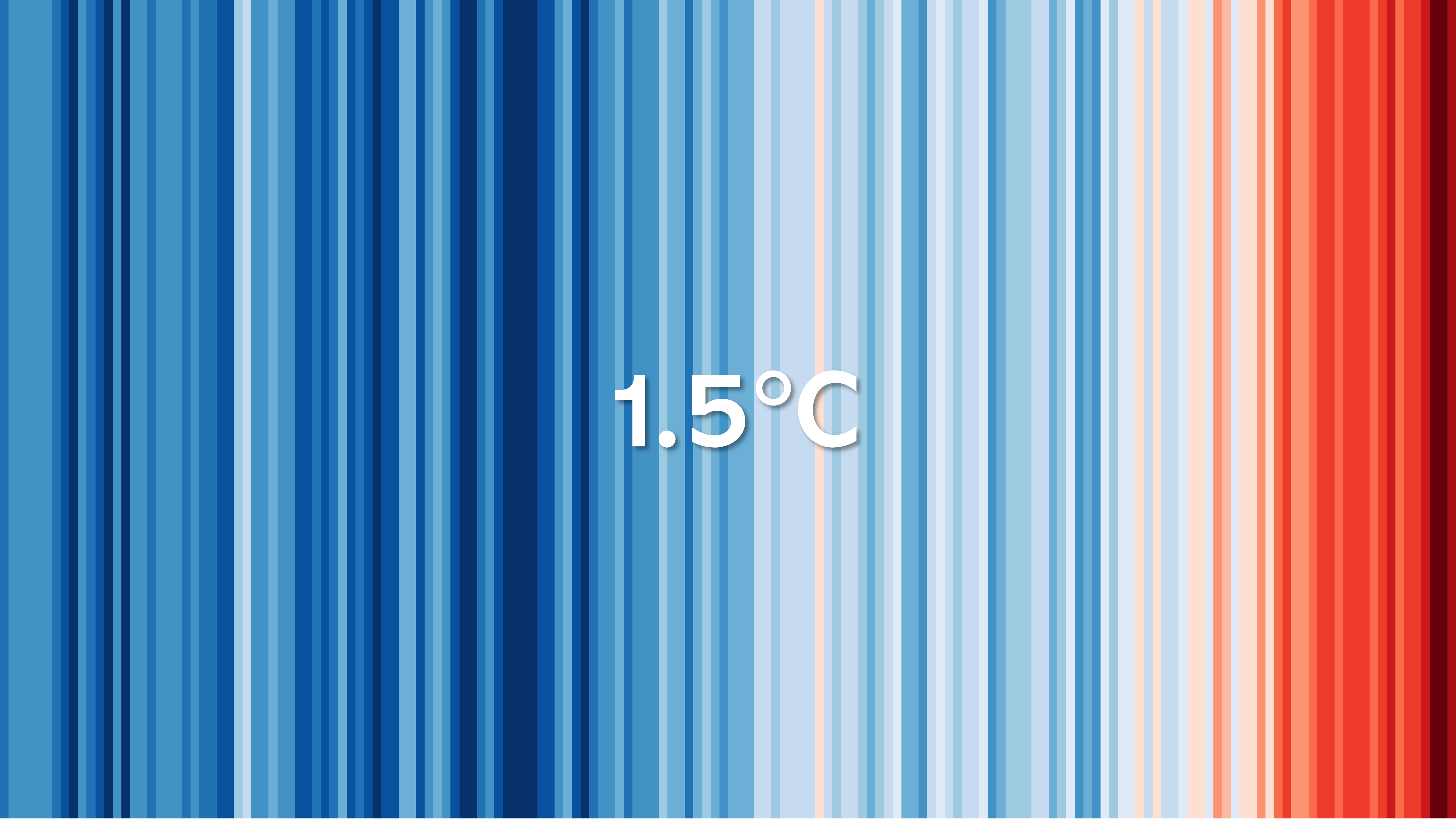
State-of-the-art lecture
Geotechnics for offshore wind developments

Ana Page[1)], **Britta Bienen**[2)]

[1)] Norwegian Geotechnical Institute (NGI), Norway

[2)] University of Western Australia, Australia

Why offshore wind?


1.5°C

The first generation

To scale

Hornsea 1 (2019, operational), 2 (2022, operational), 3 (2027, under construction)

200 m

11 turbines rated 450 kW each

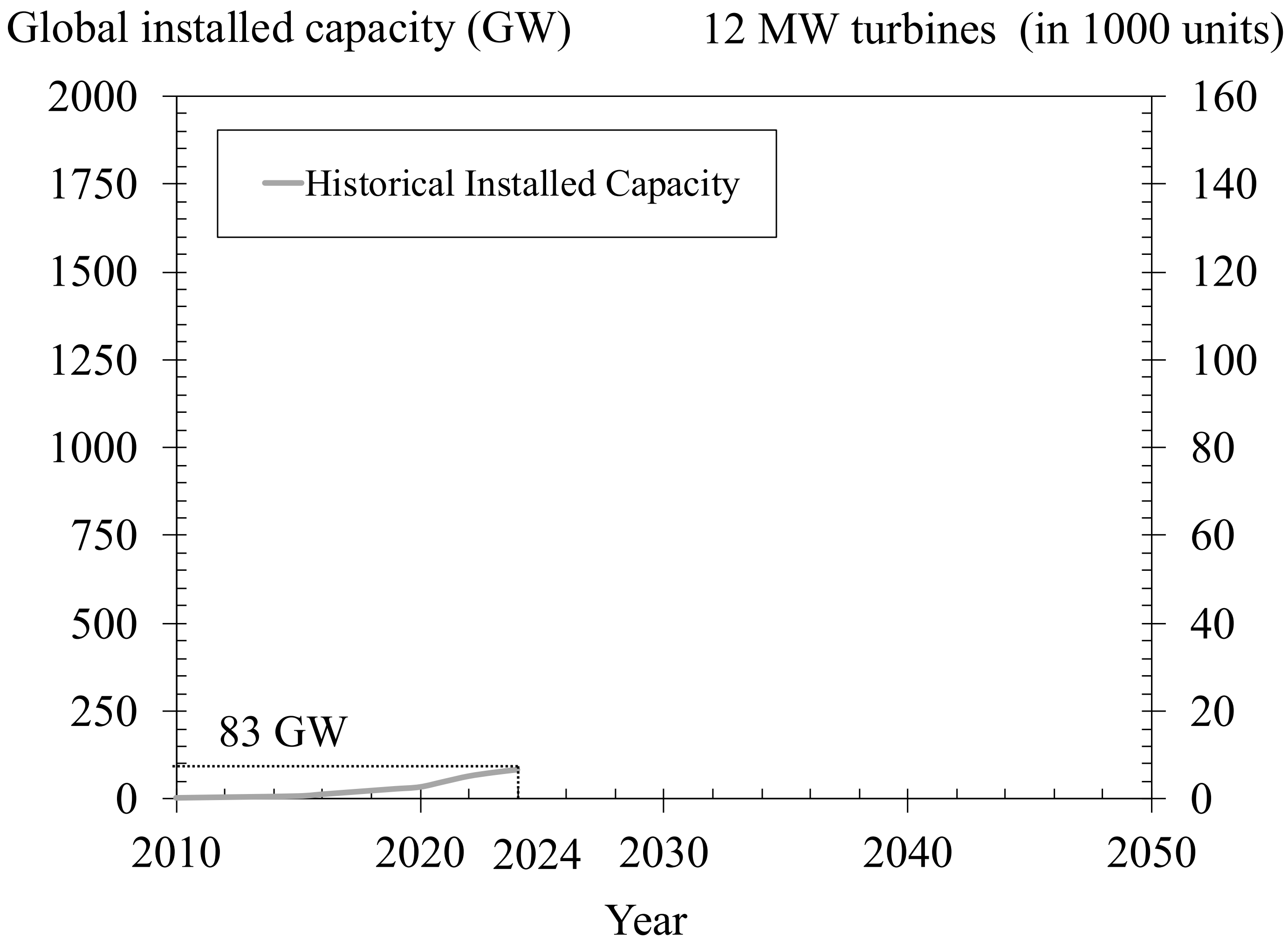
~1.5 km offshore, a few m water depth

Powered 2,200 homes

Vindeby, 1991

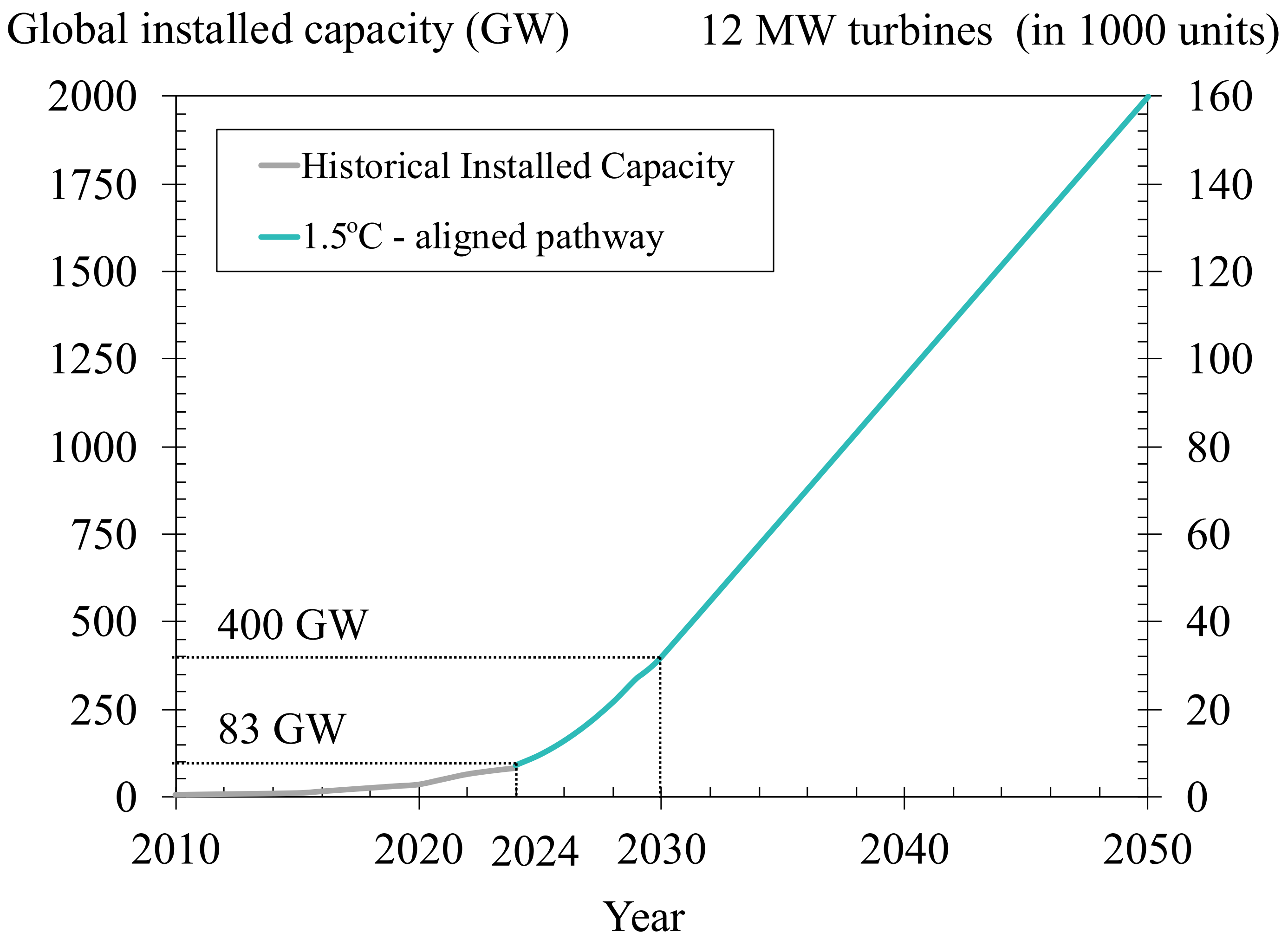
54 m

From 83 GW to 2000 GW in 25 years



Source: IRENA (2024) and Gourvenec (2024)

From 83 GW to 2000 GW in 25 years



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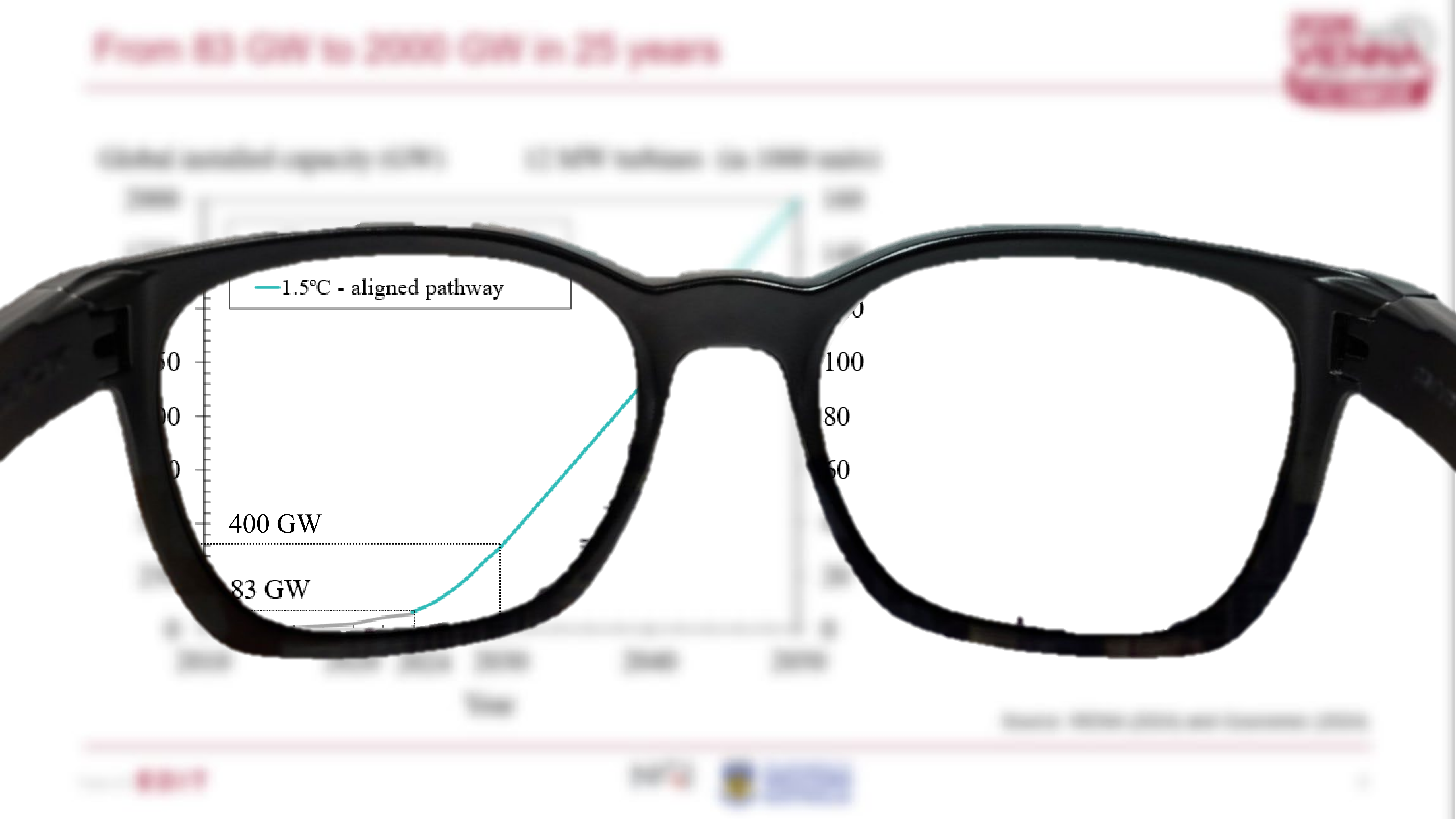
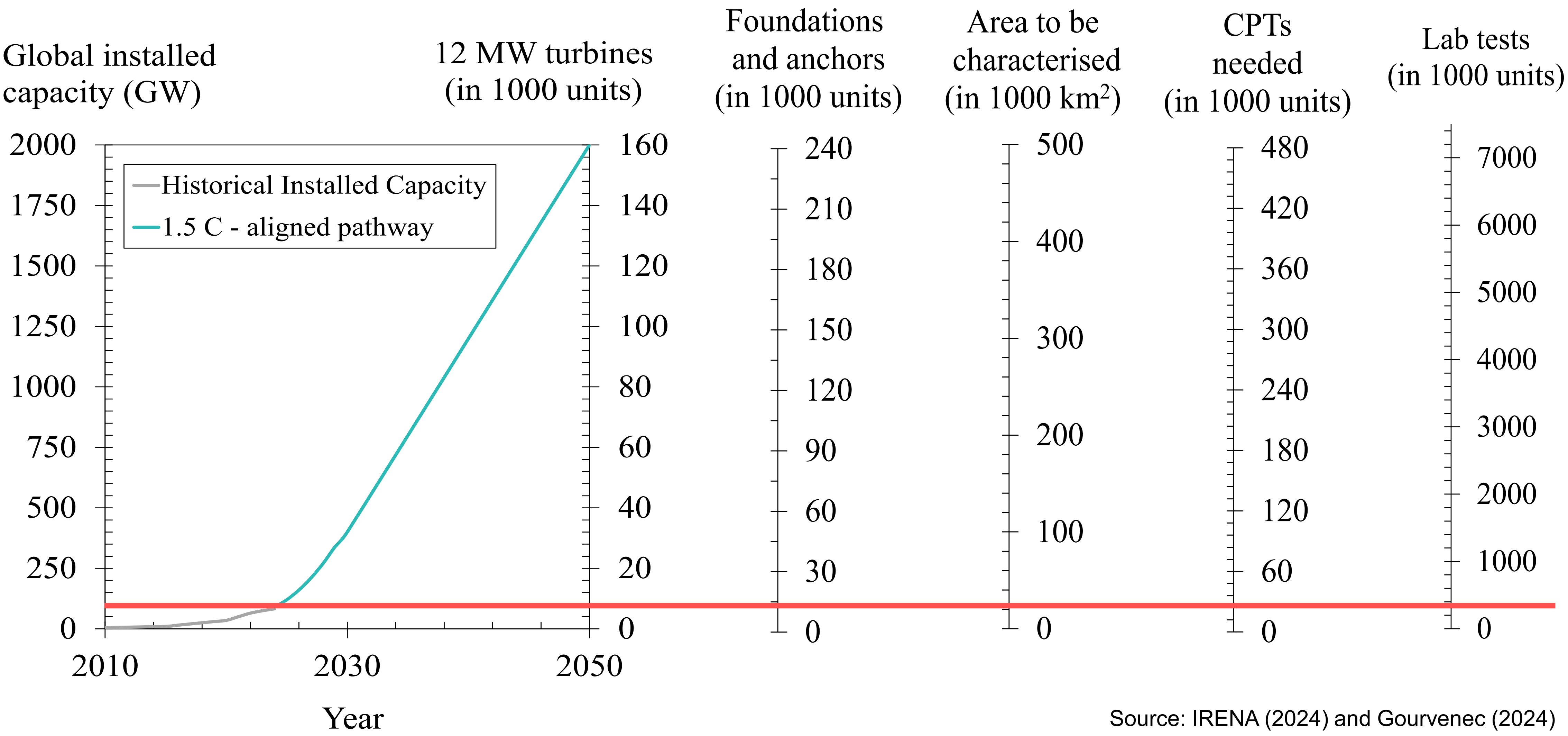

1.5℃ - aligned pathway
100
80
400 GW
83 GW

From 83 GW to 2000 GW in 25 years



Source: IRENA (2024) and Gourvenec (2024)

Challenging geotechnics across the full lifecycle

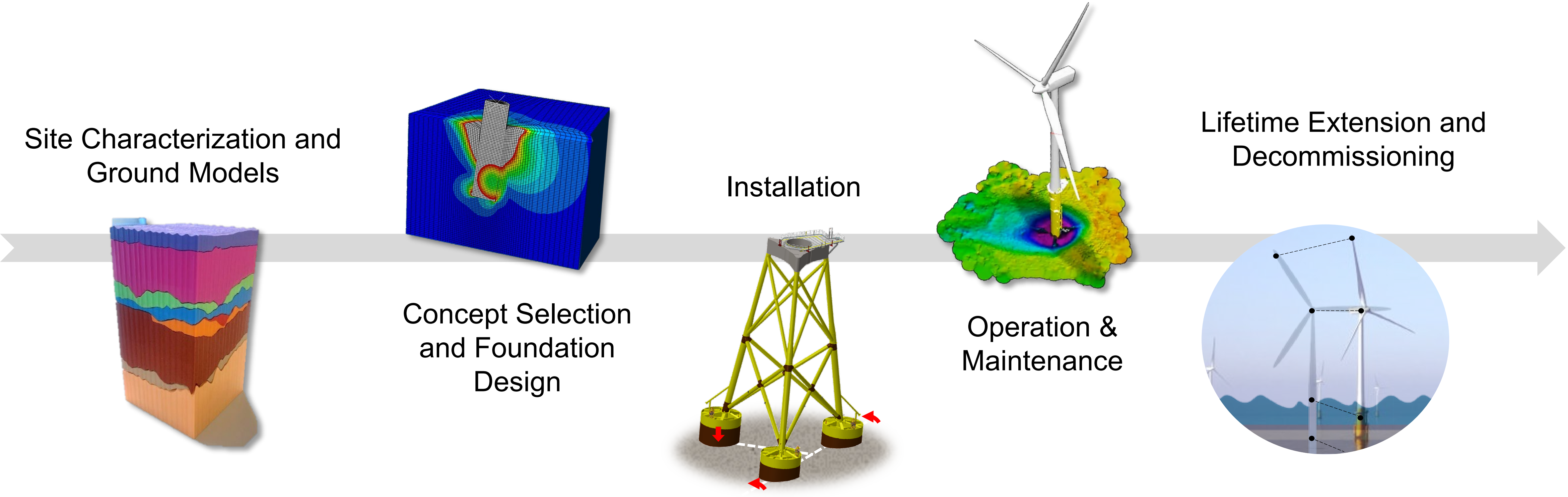
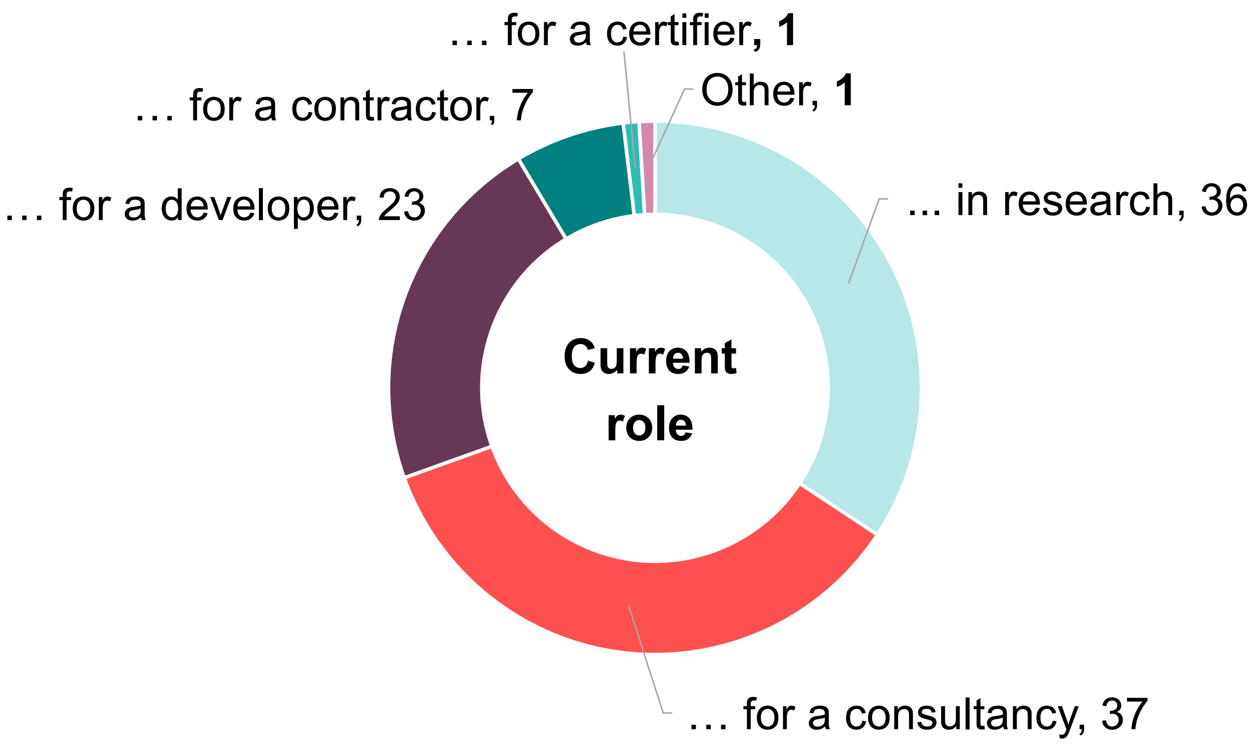


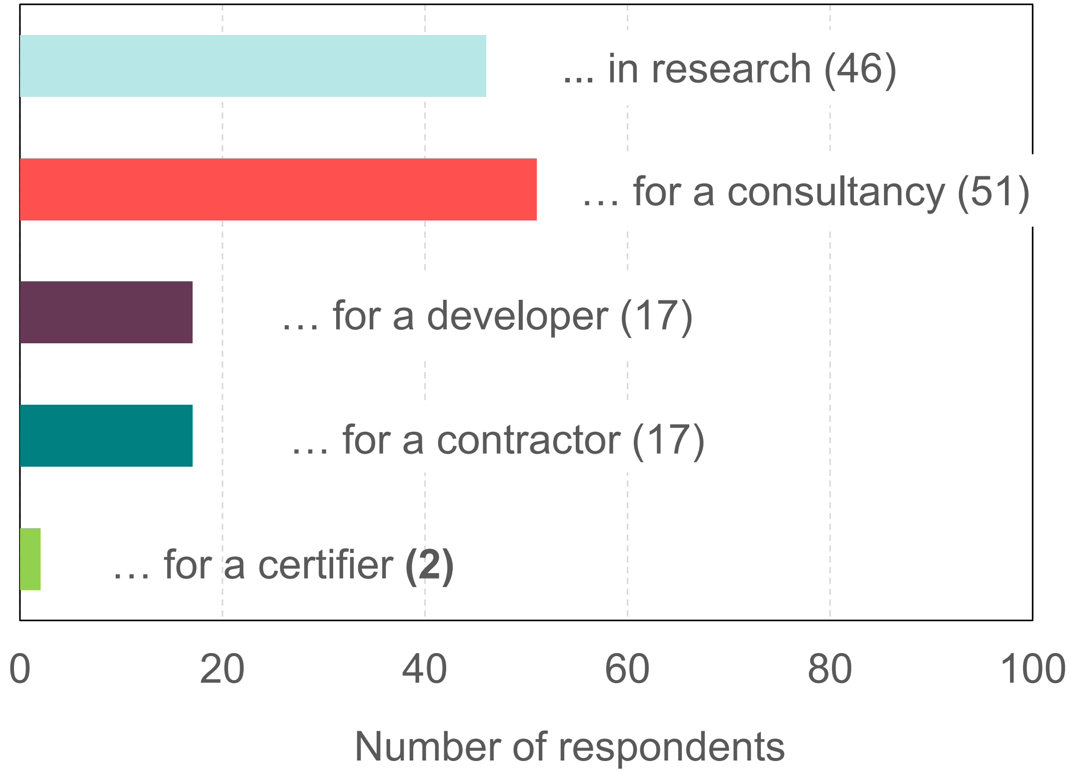
Image Source: NGI and Sparrevik (2019)

How we captured the state-of-the-art

Three sources: **literature**, 92 **survey** responses and 16 **interviews**



I have previous work experience…



Site Characterization and Ground Models

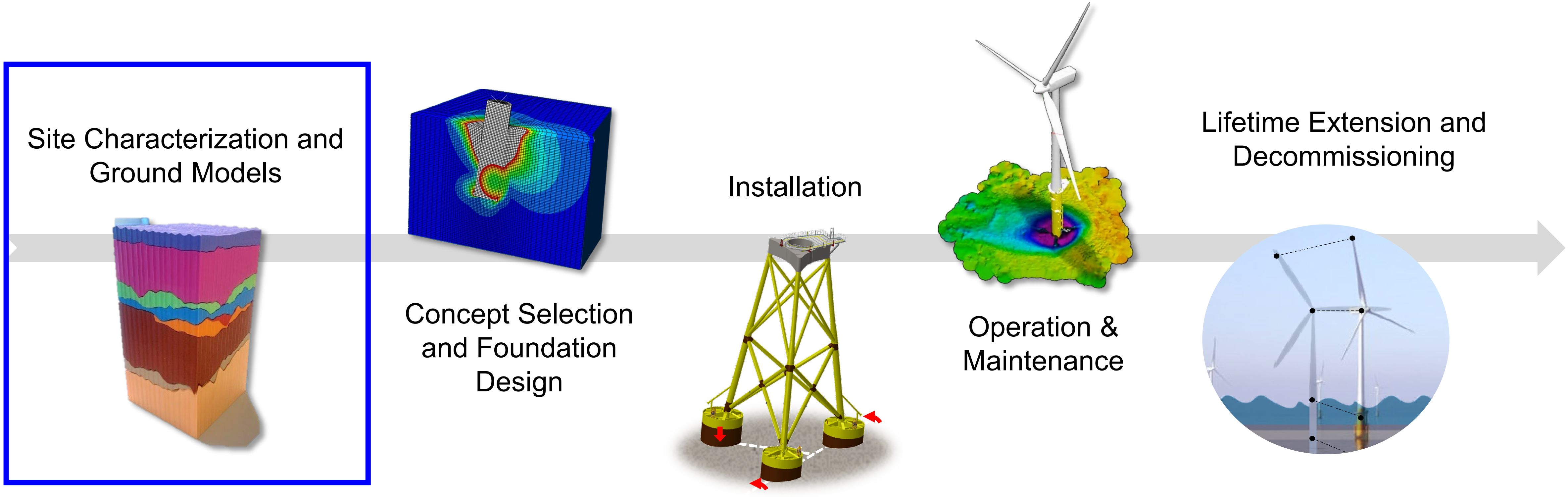
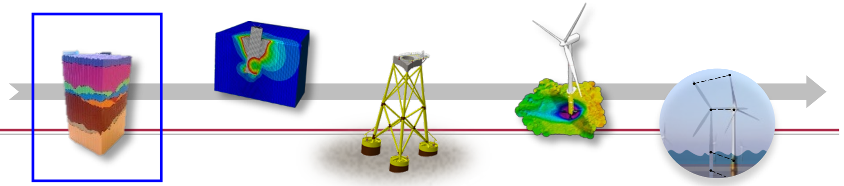


Image Source: NGI and Sparrevik (2019)

Offshore wind starts with site conditions



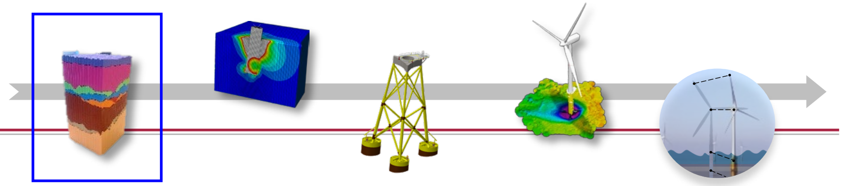
- Metocean: wind, waves and currents
- Ground conditions: soil type, properties and spatial variability
- Sparse direct measurements in complex stratigraphy

415 km² footprint over Vienna

Turbine scale compared with the DC Tower (250 m) and the Danube tower (252 m)

Large areas + complex stratigraphy + sparse direct measurements → ground model

What is a ground model?

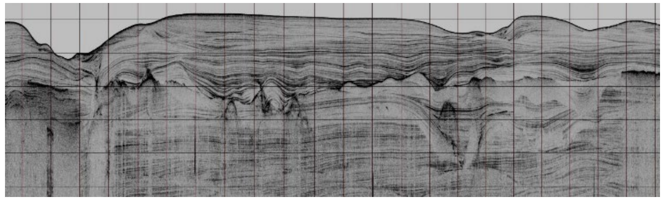


- A ground model is a 3D representation of seafloor and subsurface, developed to support decisions:
  - It helps predict conditions where we have not measured directly
  - Supports decisions on layout, design, geohazards, and investigation planning
  - Evolves as new data become available

Geology

Geotechnics

Geophysics



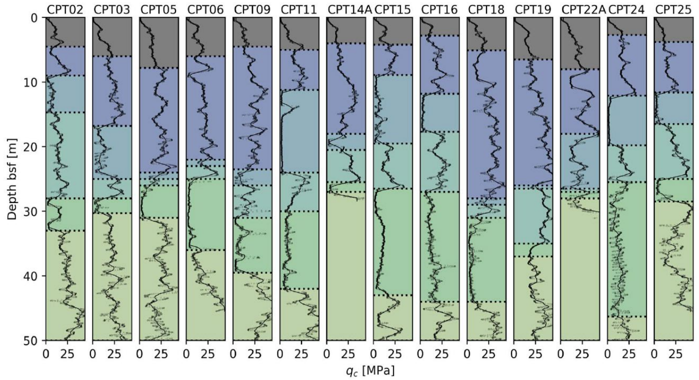
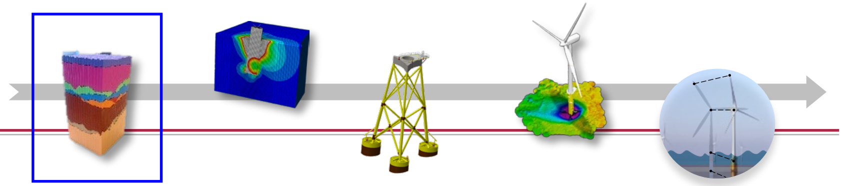


Image Source: Vardy et al. (2022), Sauvin et al. (2022), Klinkvort et al. (2020)

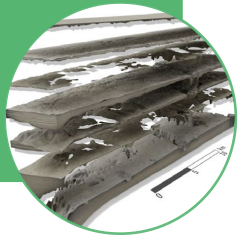
Why integration matters



Each dataset sees something different

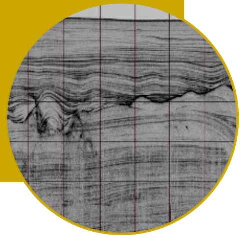
- Consistent regional context
- Depositional and erosional history
- Explains spatial variability
- Often qualitative and interpretation-dependent

Geology



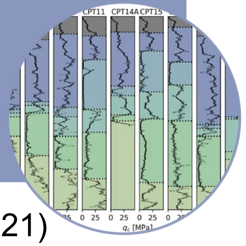
- Non-invasive site-wide coverage
- 2D / 3D spatial continuity
- Resolution in dm, decreasing with depth
- Affected by time-depth conversions, noise and resolution

Geophysics



- Invasive and sparse
- 1D: Samples + CPTs
- Resolution in cm
- Affected by empirical correlations and sample quality

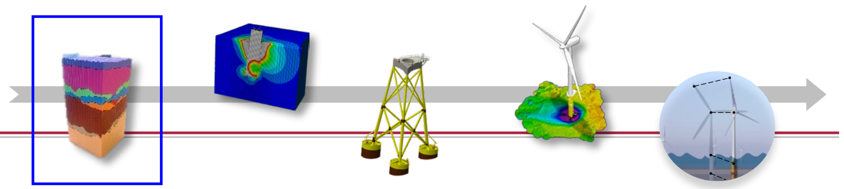
Geotechnics



Adapted from Vanneste at al. (2021)

Integration reduces blind spots and makes uncertainty visible

Developing integrated ground models



What limits implementation?

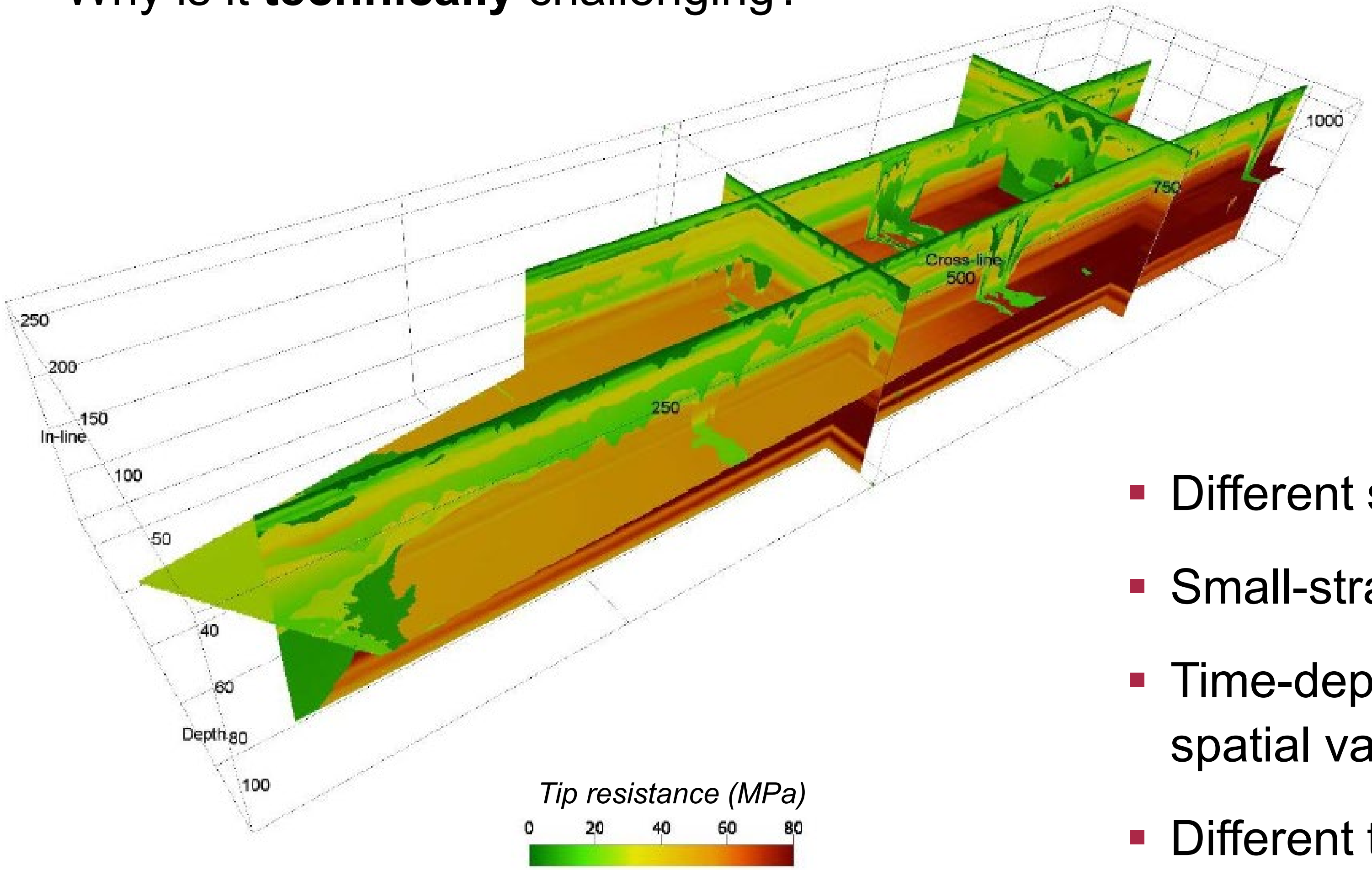
Main barrier	Respondents (%)
Early financial commitment	55%
Integration of different datasets	16%
Technical / in-situ measurements	16%
Language barriers between disciplines	13%

The main barrier: early financial commitment

- Value clearer after problems occur
- Compressed timelines limit model sophistication
- Vessels, labs and experienced resources can constrain quality
- Regional differences in early site investigations:
  - developer-led vs centralised models

Developing integrated ground models

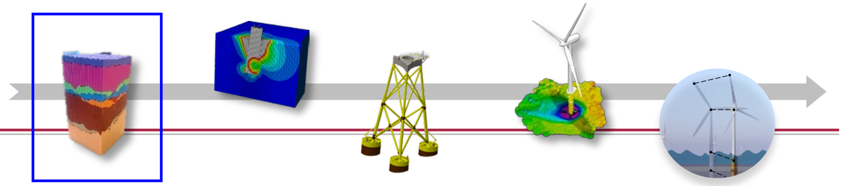
Why is it **technically** challenging?

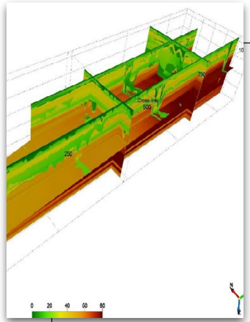


- Different scales and resolutions
- Small-strain vs large-strain properties
- Time-depth conversion and layer boundaries, spatial variability and seabed mobility
- Different terminology across disciplines

Image Source: Sauvin et al. (2022)

Research and innovation



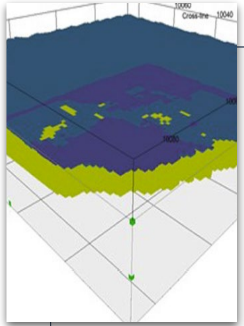


Site-wide geotechnical properties

Sparse CPT and boreholes

Link seismic data to geotech. parameters

Seismic inversion · ML · Predictive CPTs

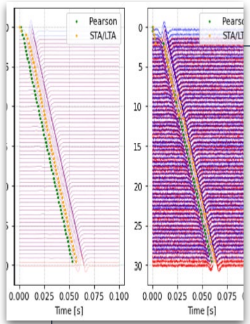


Uncertainty propagation

Uncertainty accumulates through workflow

Propagate uncertainty to design inputs

Velocity models · layer boundaries · soil units · sample quality · empirical relations

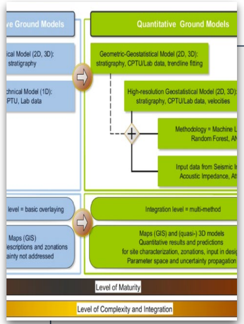


Earlier design input

Need faster site characterisation

More design-relevant in-situ tools

SCPT · cyclic CPT · T-CPT · MR-CPT



Scalable workflows

Ground models are often project-specific

Digital, repeatable workflows

Automation · updating · data management

Image sources: Sauvin et al. (2022), Vanneste et al. (2021), Santos et al. (2023)

Concept selection

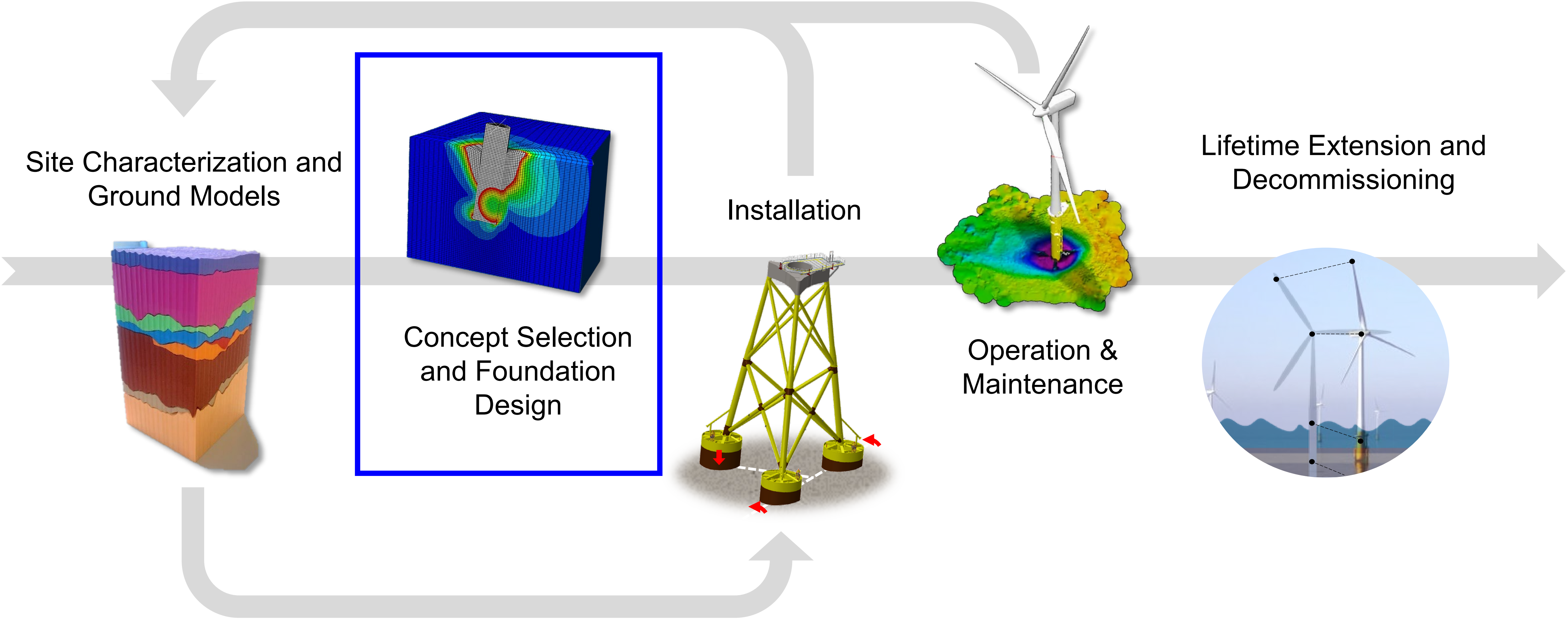
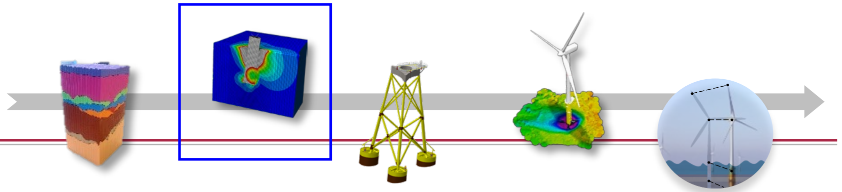


Image Source: NGI and Sparrevik (2019)

Concept selection



What drives it?

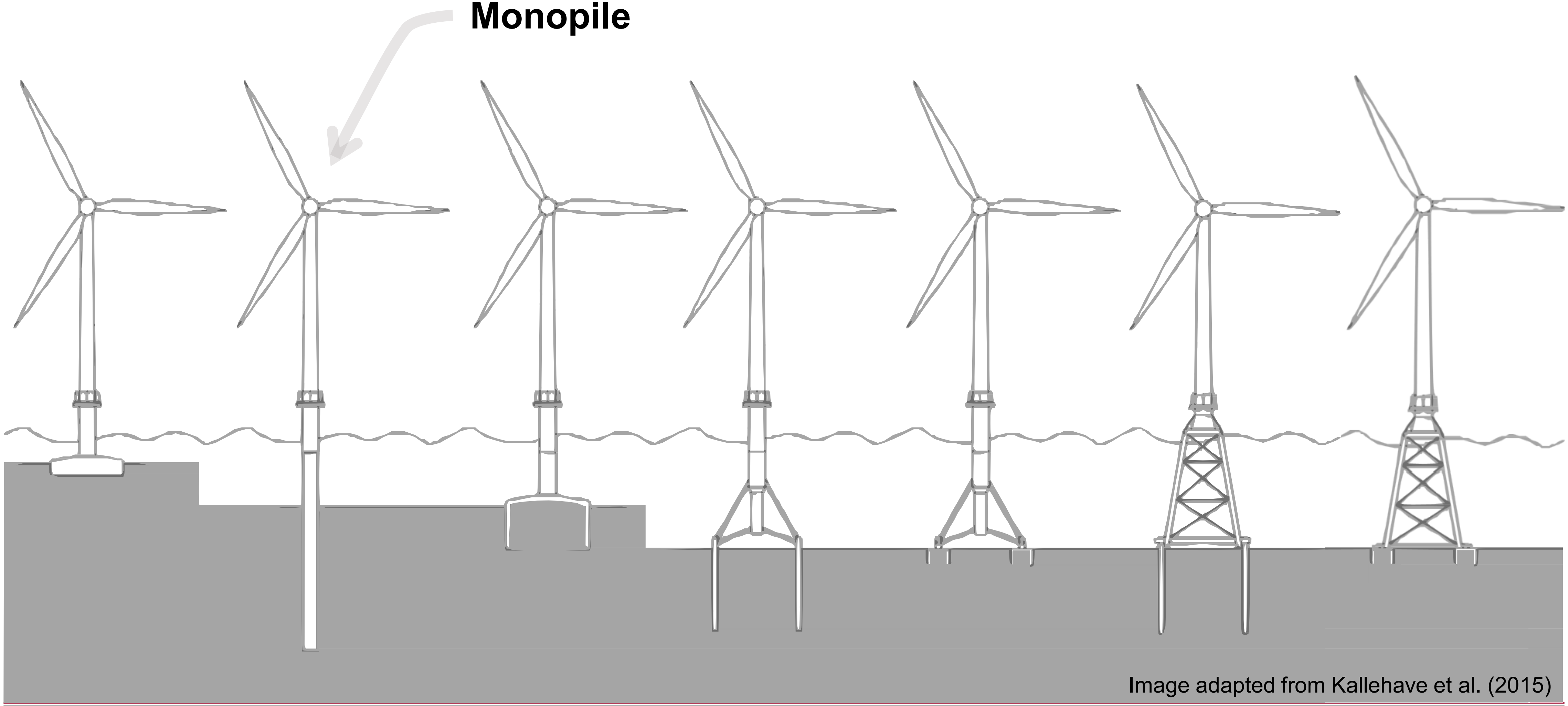
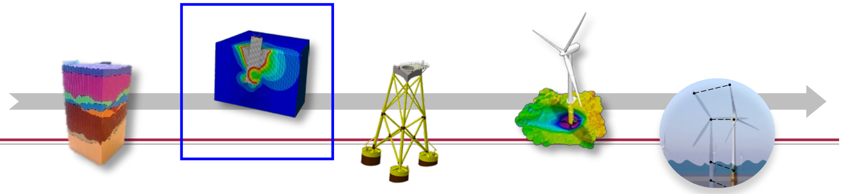


Image adapted from Kallehave et al. (2015)

Concept selection

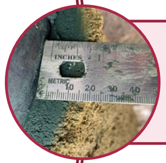


Choosing a concept with an acceptable overall risk profile for the project

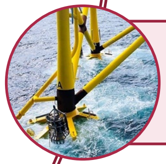
Key factors

Ground conditions: soil type · variability · boulders · shallow rock · seismicity

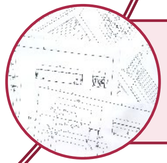
Water depth & turbine size: dimensions · dynamic response · vessel limits



Installability: refusal · pile run · installation method (noiseless)



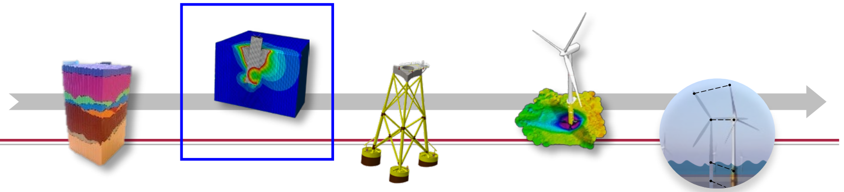
Supply chain: fabrication · vessels · local content · track record



Schedule & certification: schedule risk · certification confidence · approval

Image Source: Vinck et al. (2025), Ørsted, PIGS JIP, NGI

Concept selection



Evolution up to now

Data Source: NREL

Concept selection

Why monopiles dominate

Industrialised fabrication

automated production · parallel production capacity

Mature supply chain

vessels · yards · installation experience

Large operating track record

established design and installation experience

Cost competitiveness

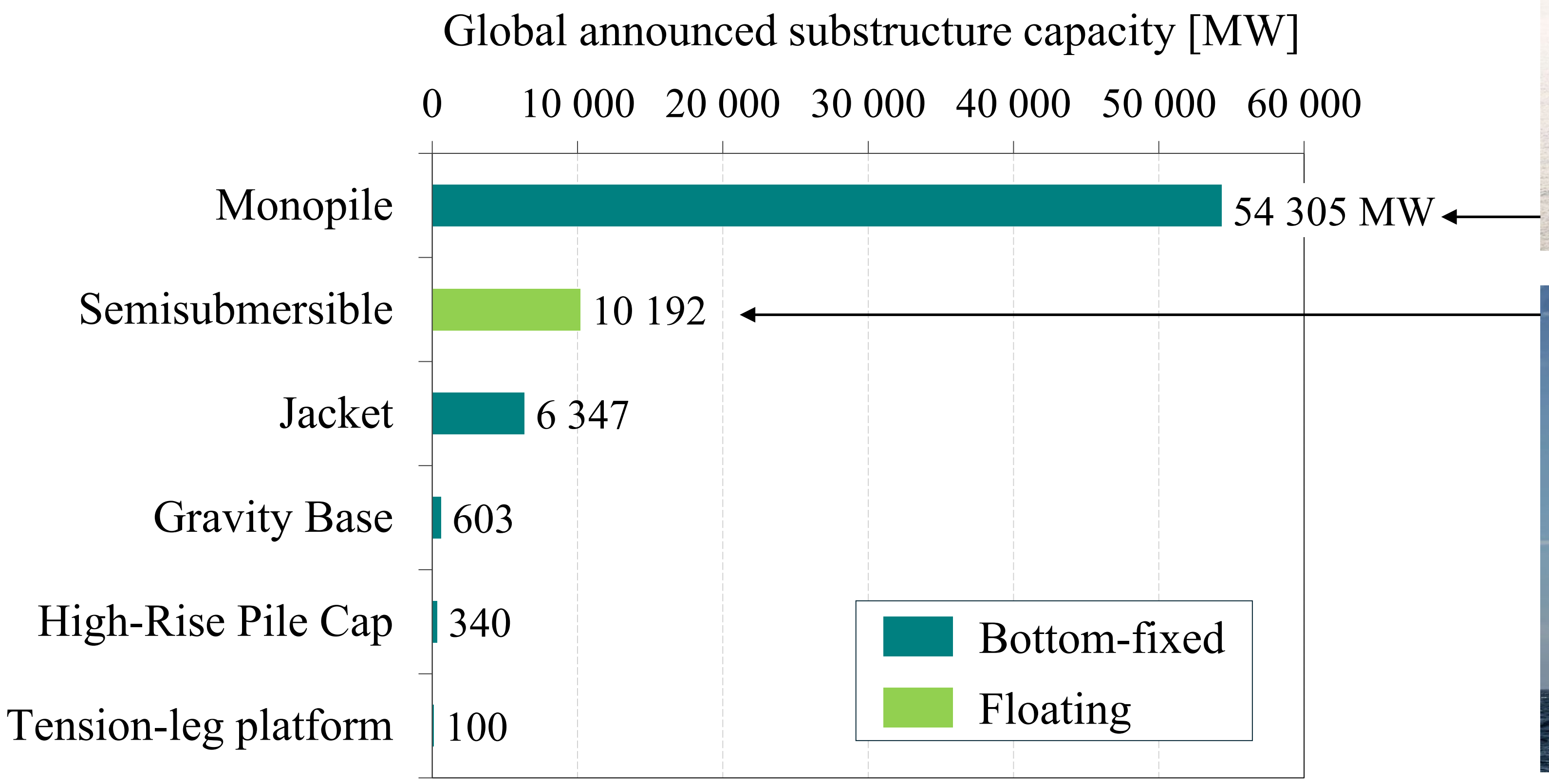
comparatively low perceived cost

Drivers for alternative concepts:

difficult ground · seismicity · installation constraints · local content · deeper water

Image Source: NGI

Concept space is widening



Data Source: NREL; Image Source: DEME Offshore, Flotation Energy

Foundation design

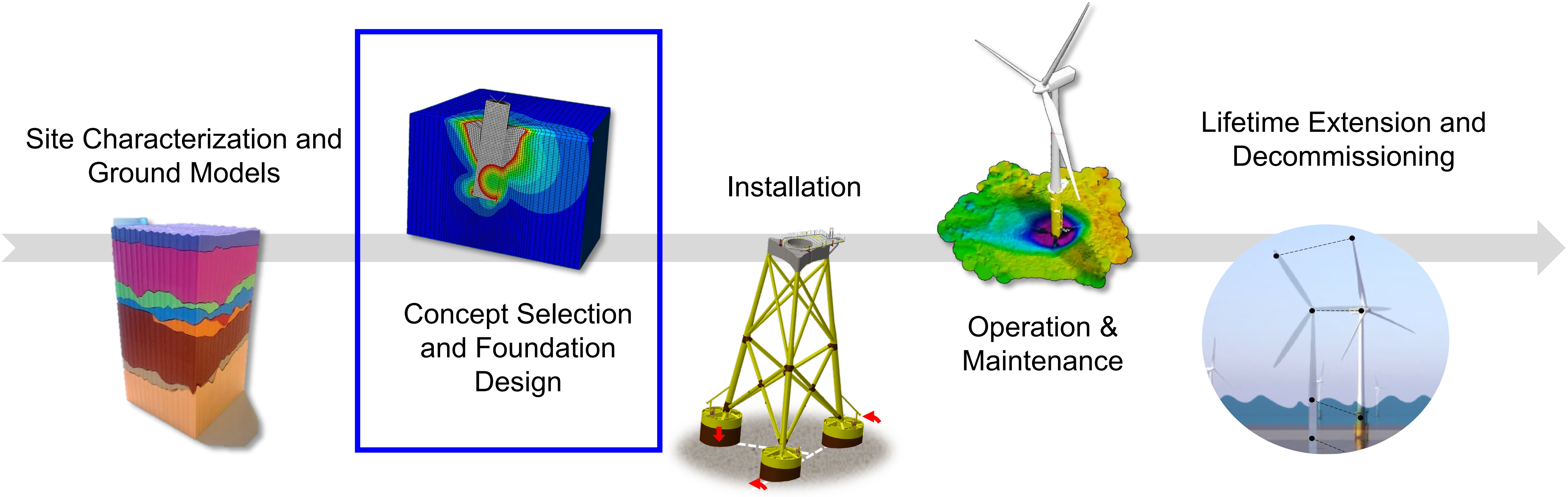
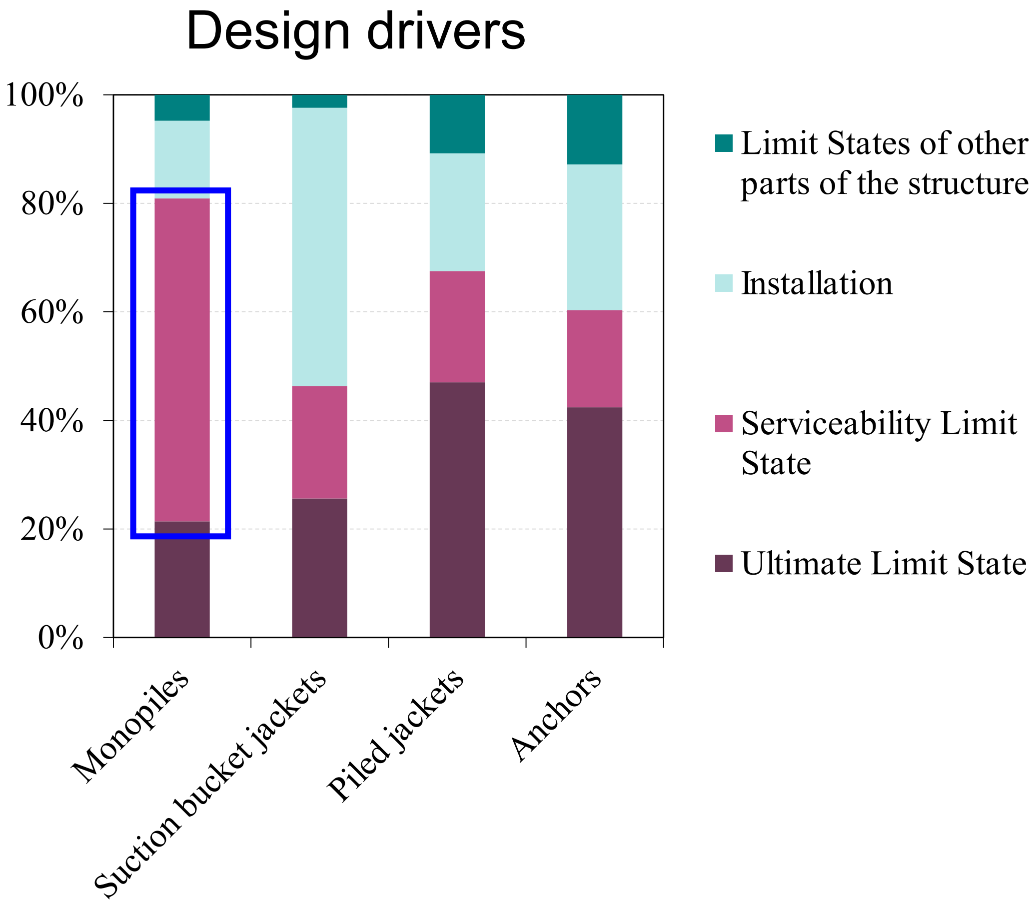


Image Source: NGI and Sparrevik (2019)

Foundation design

- Needs to meet requirements for Ultimate Limit State (ULS), Serviceability Limit State (SLS)



Foundation design

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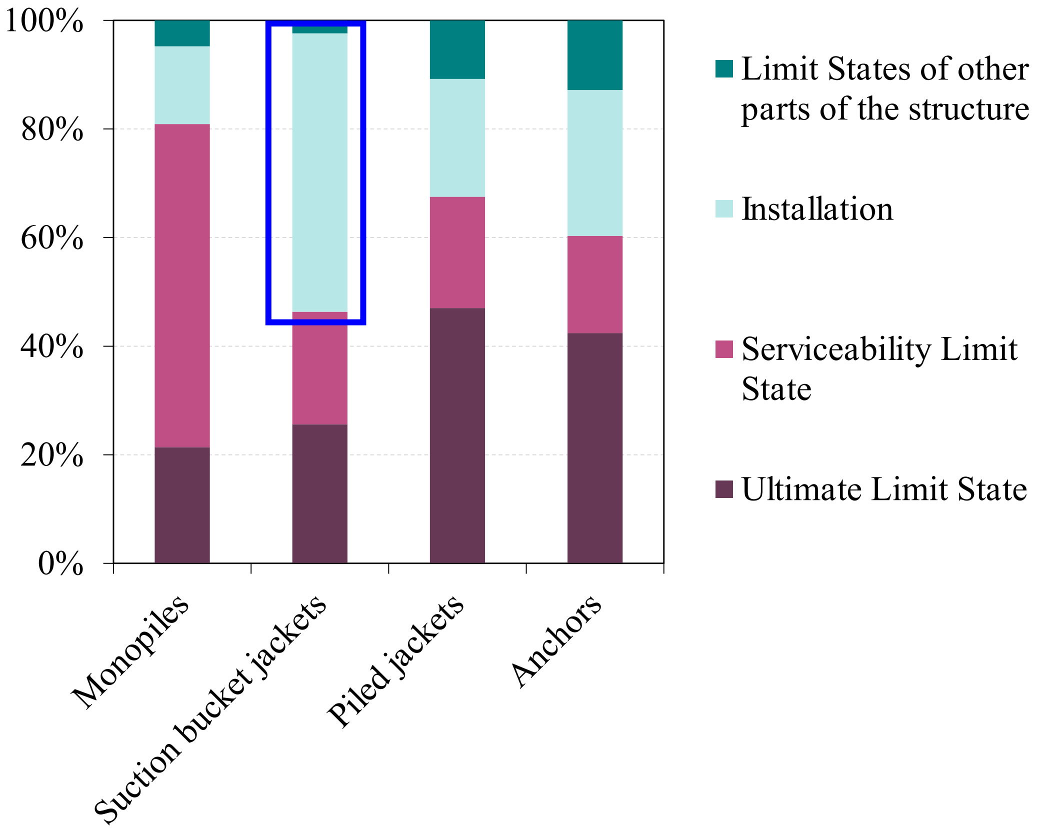
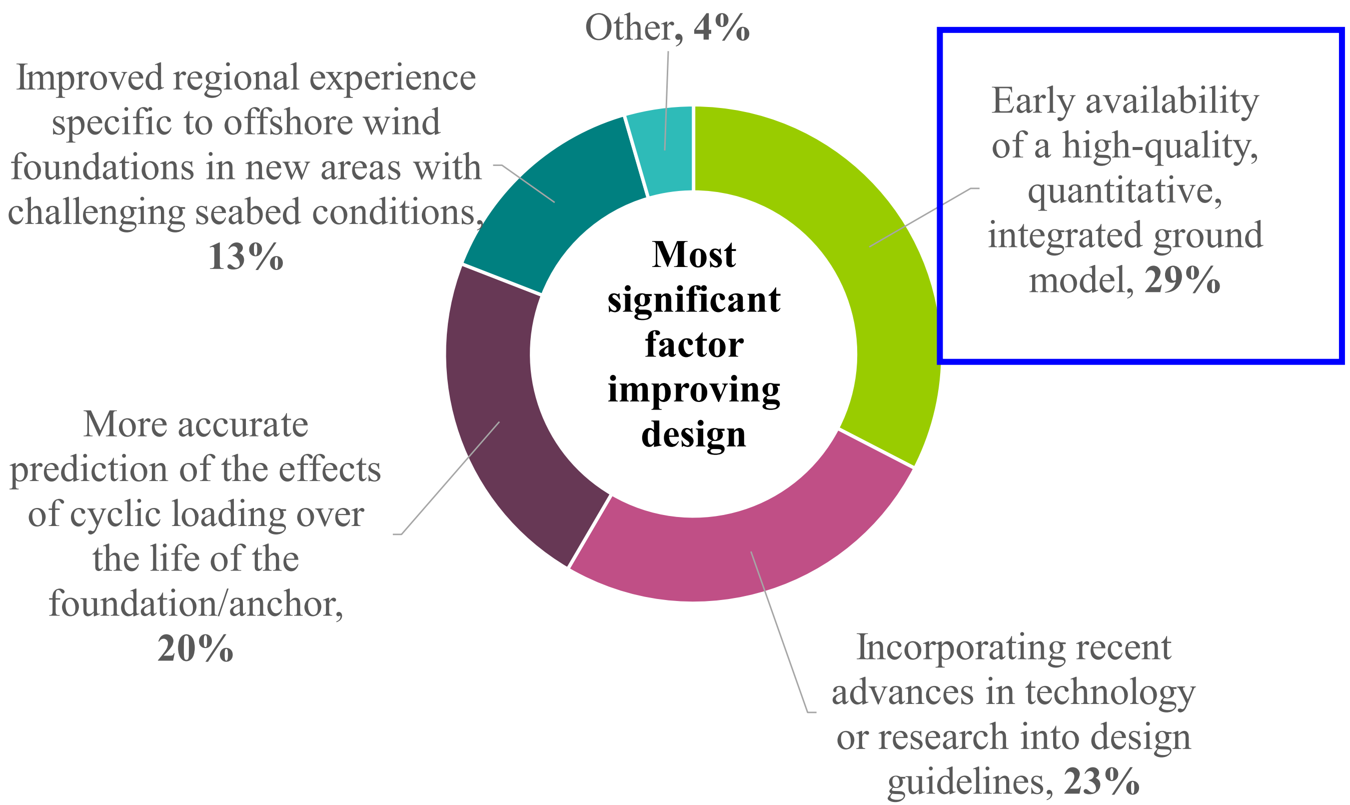
Design drivers



Factors that could result in significant improvements



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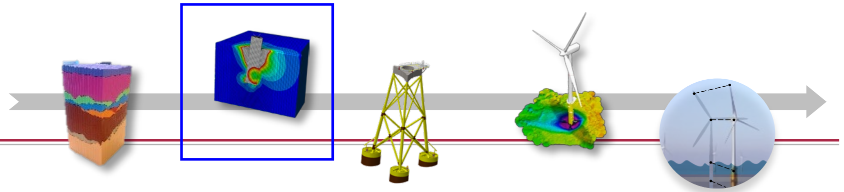

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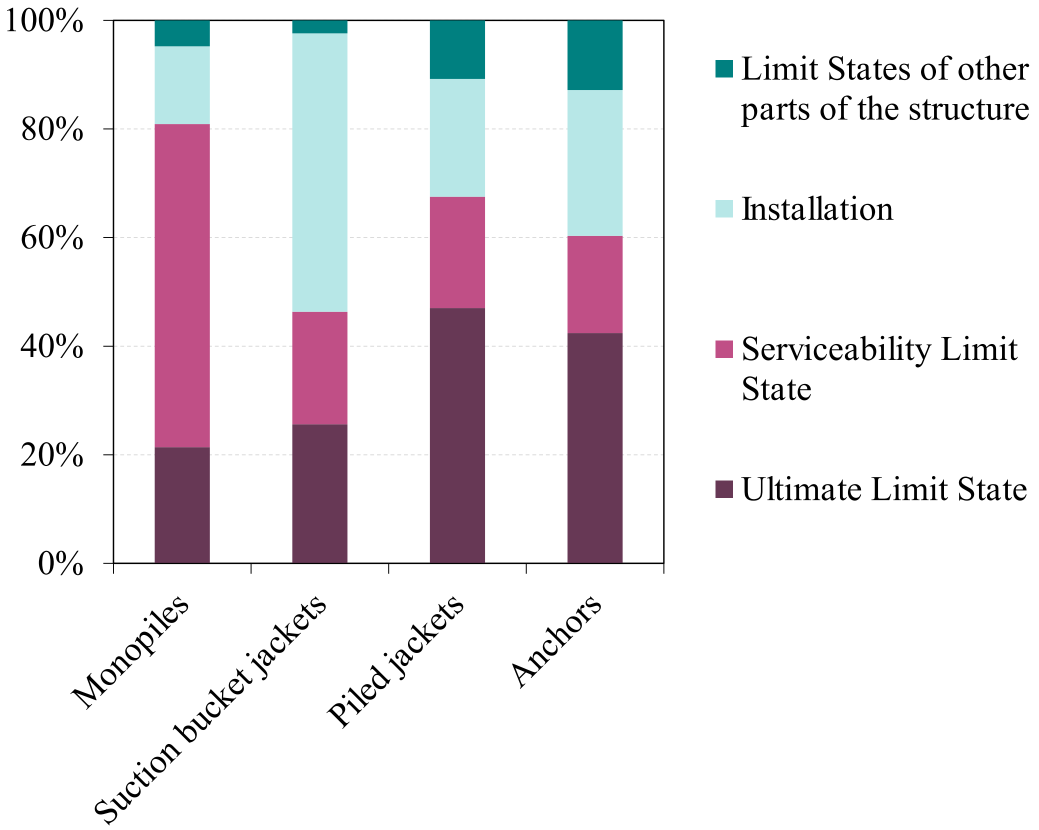

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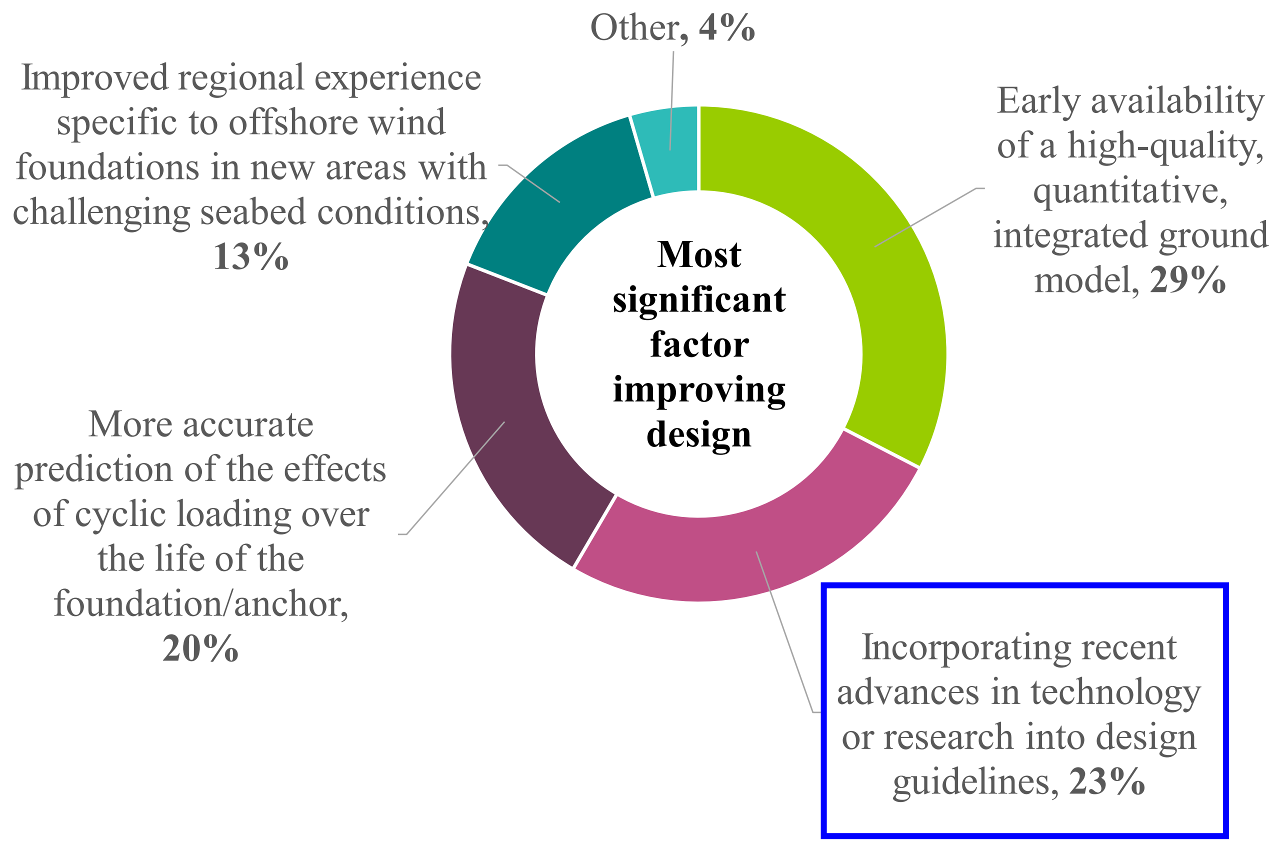

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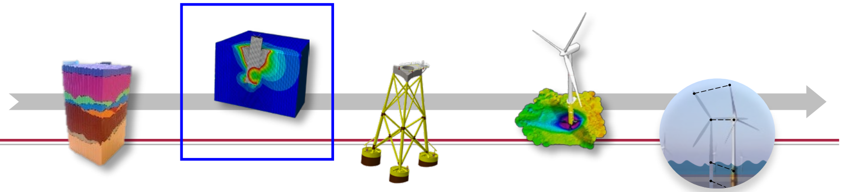

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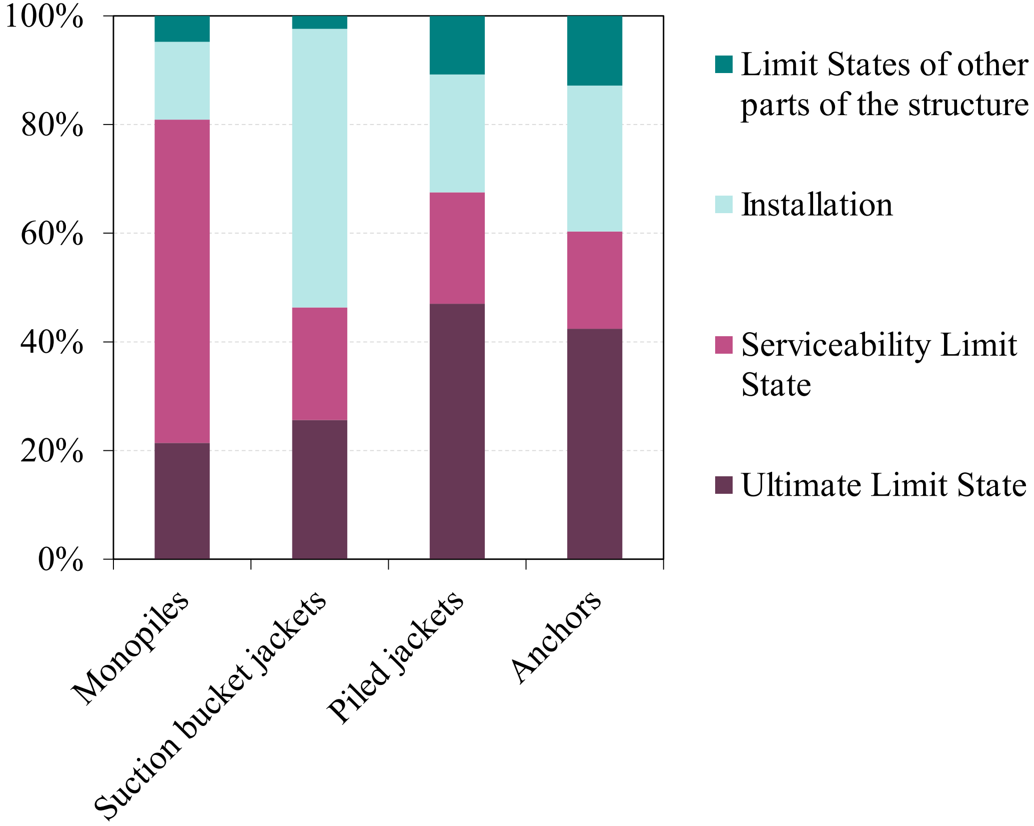

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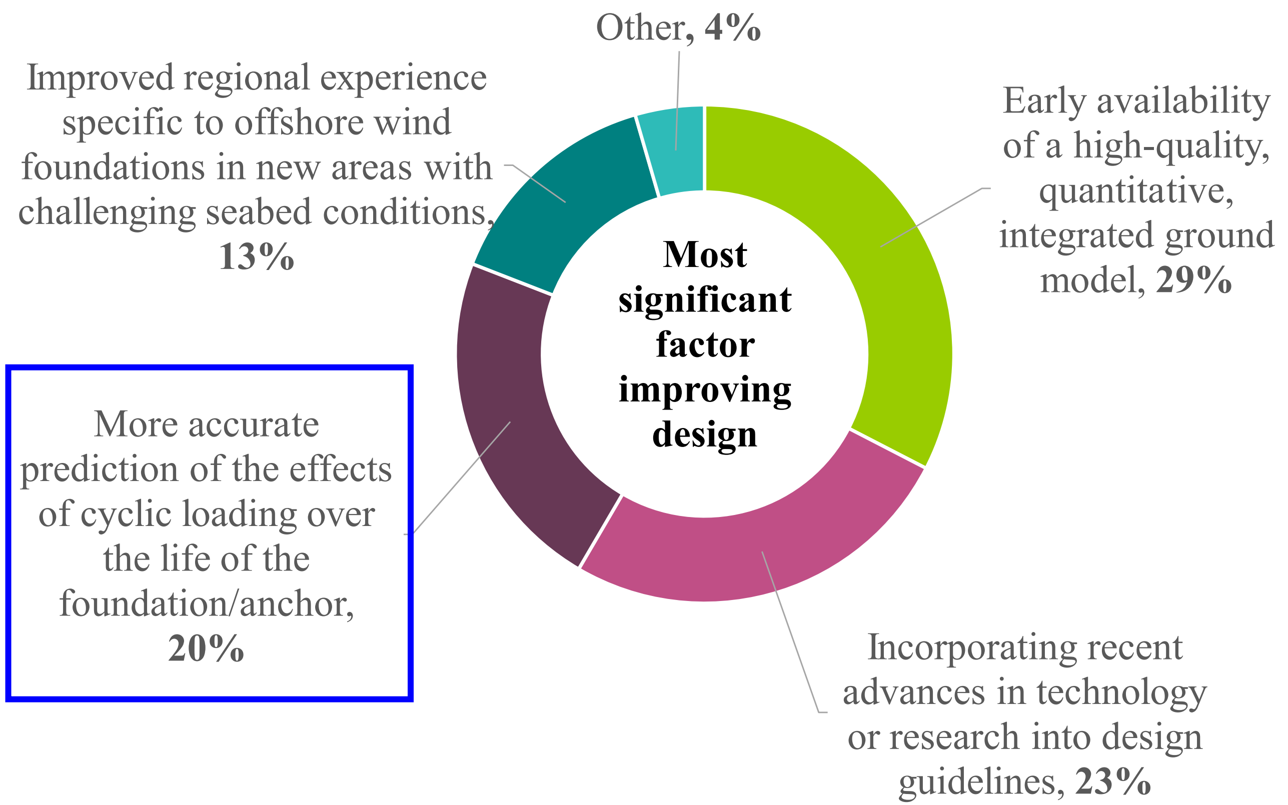

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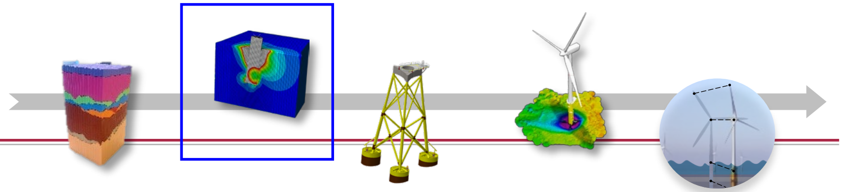
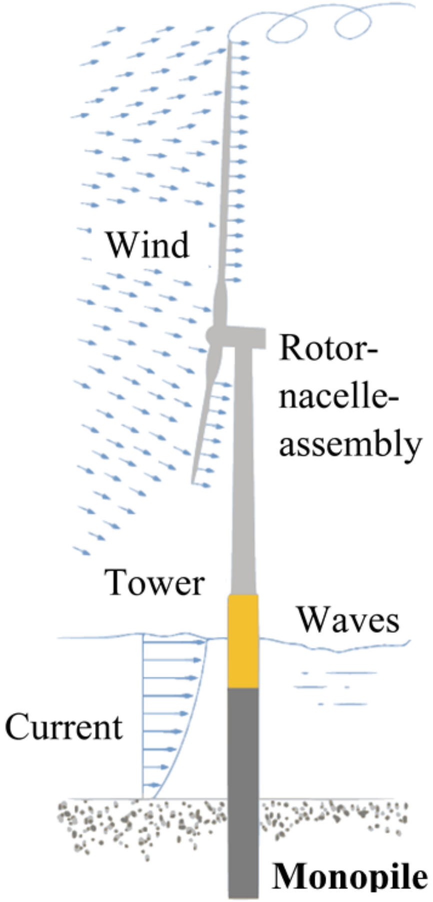
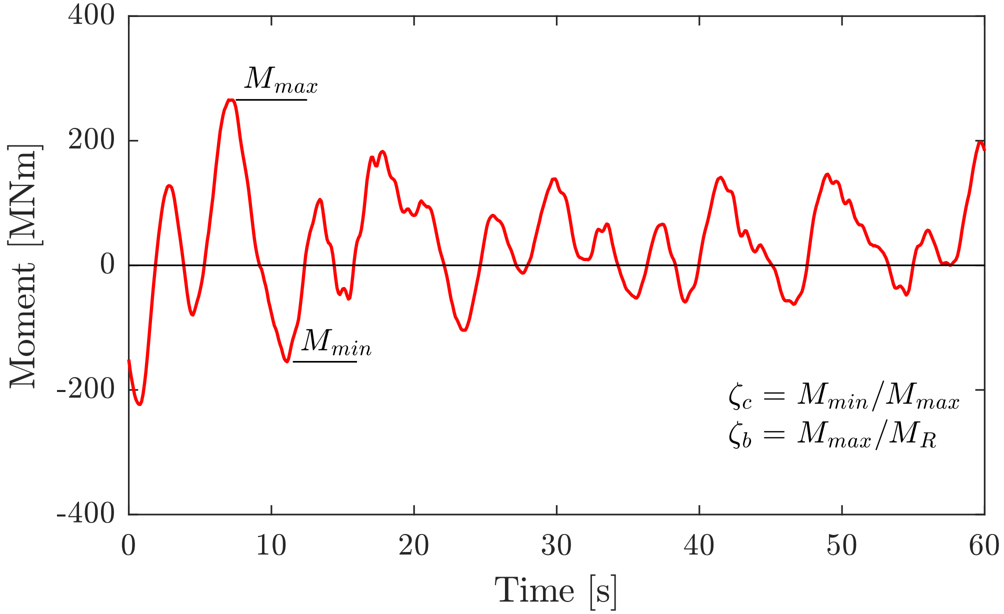
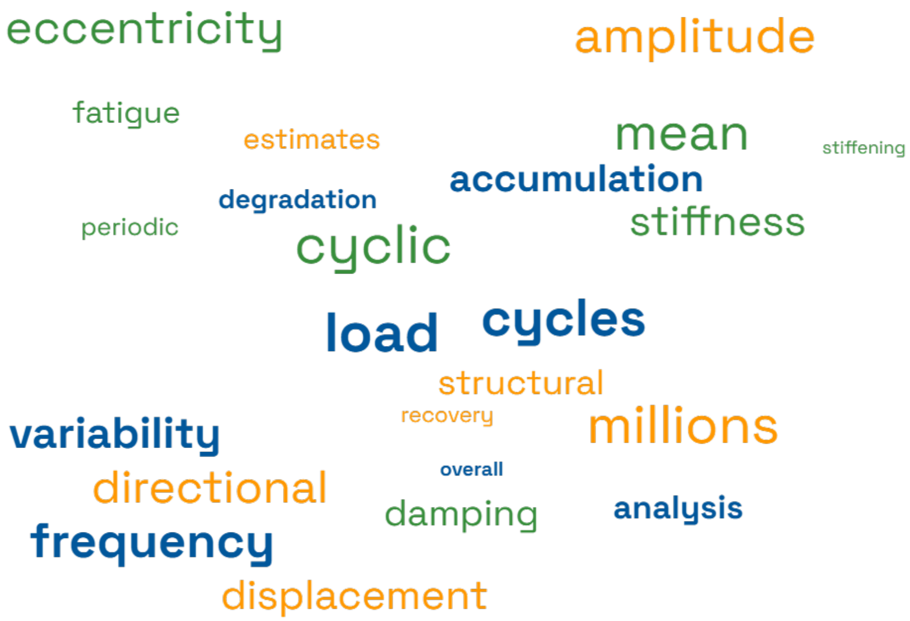


- for cyclic loading over a lifetime
- avoiding resonance and ensuring serviceability

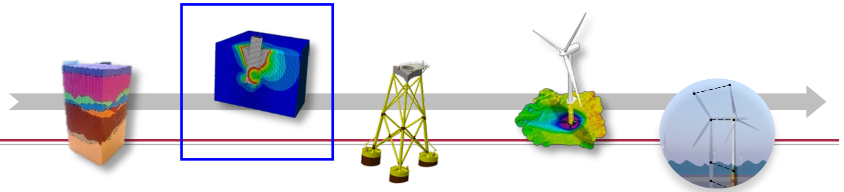






Irregular time-domain history

Foundation design



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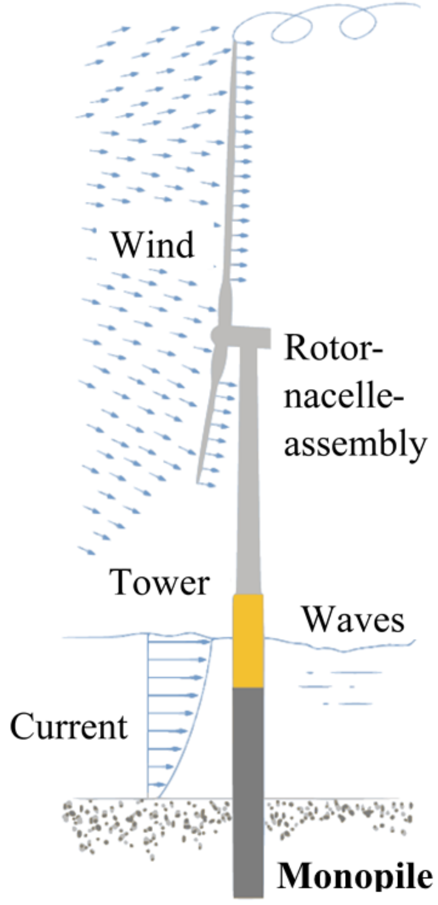
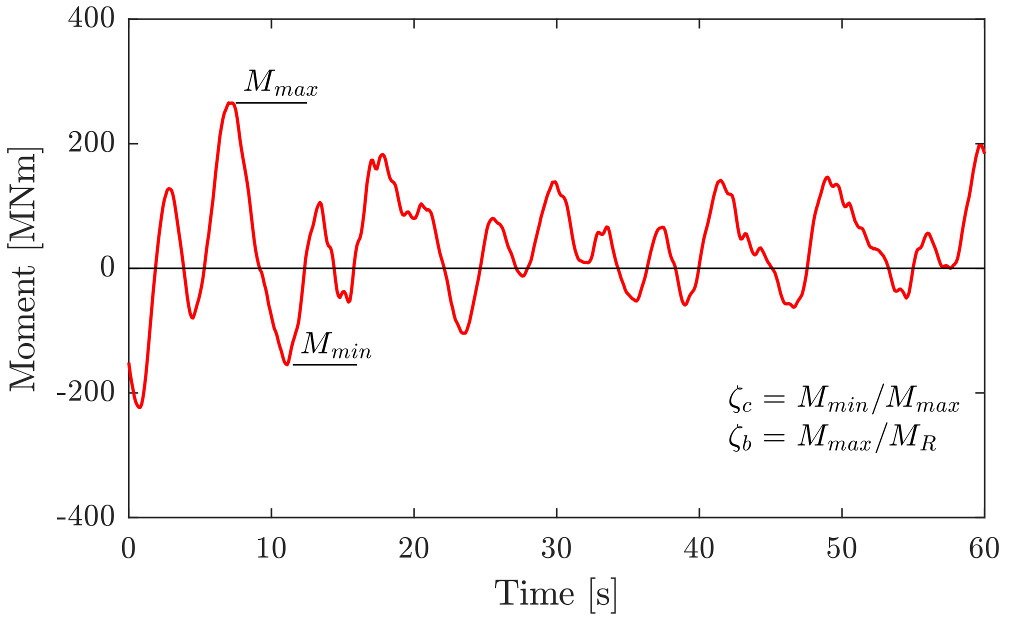
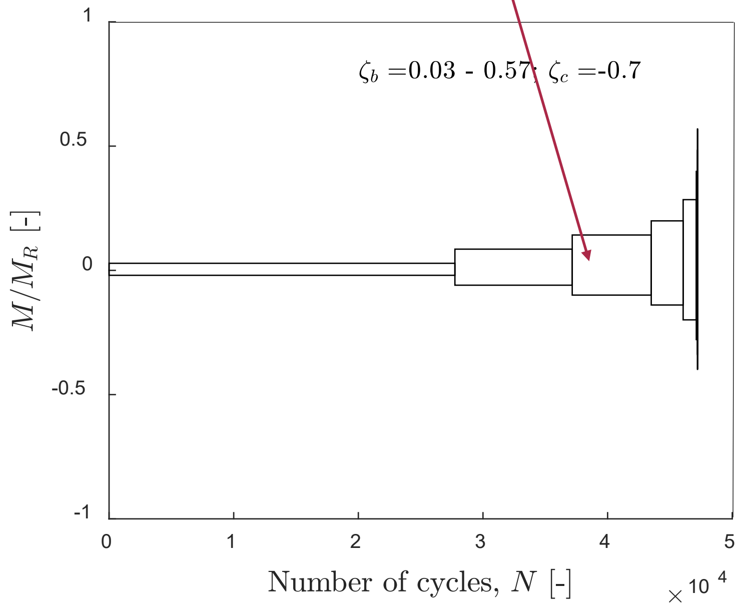




Irregular time-domain history

Cycle counting method (e.g. Rainflow counting)

Constant average and cyclic loads and constant period

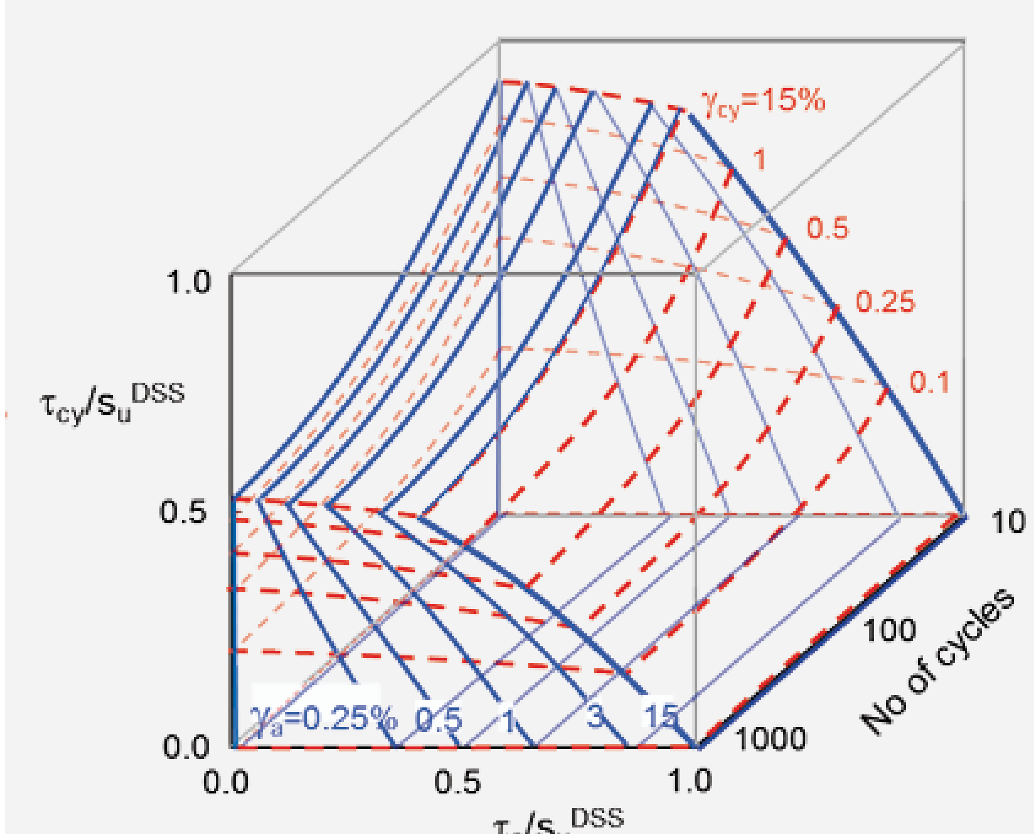


Sorted packages of regular cycles

Page et al. (2020)

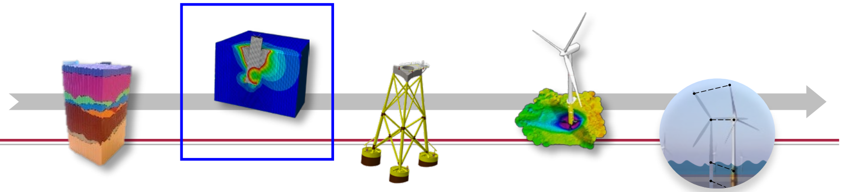
Foundation design

- for cyclic loading over a lifetime
- Prediction approaches include
  - **Cyclic contour diagrams**
  - 3D FE with Sanisand-MS, HCA
  - Macro-elements
  - p-y curves, CPT-based
- Certification?



Andersen (2015)

Foundation design



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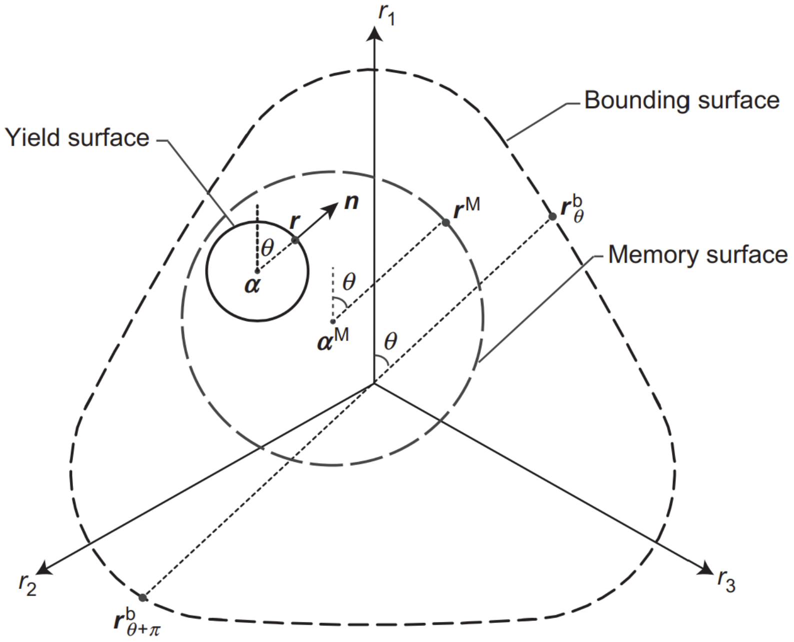
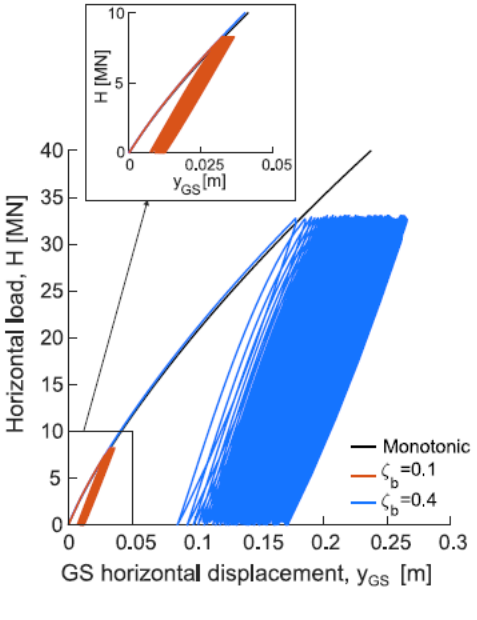


Liu et al. (2019)



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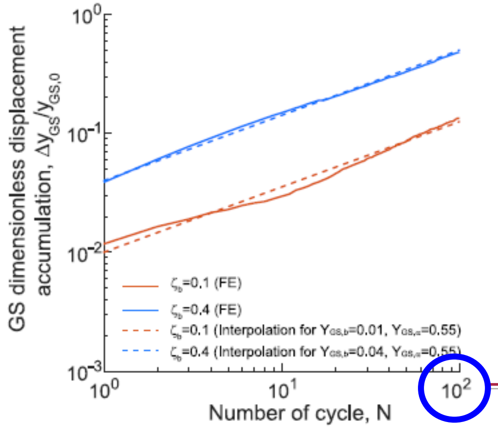
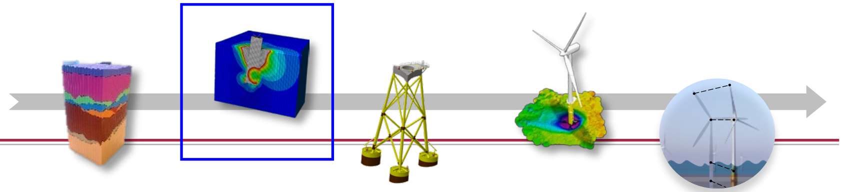


Flessati et al. (2026)

Foundation design



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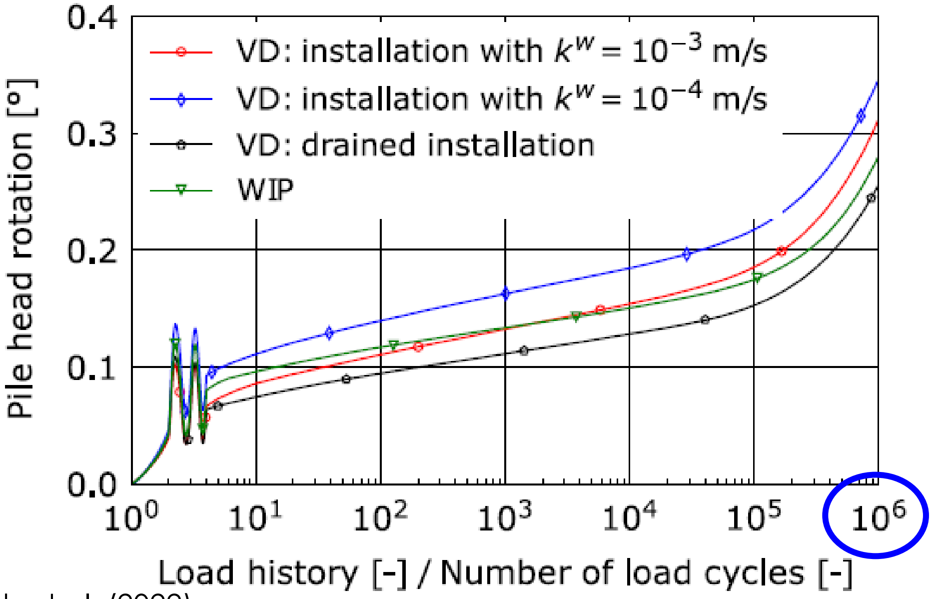
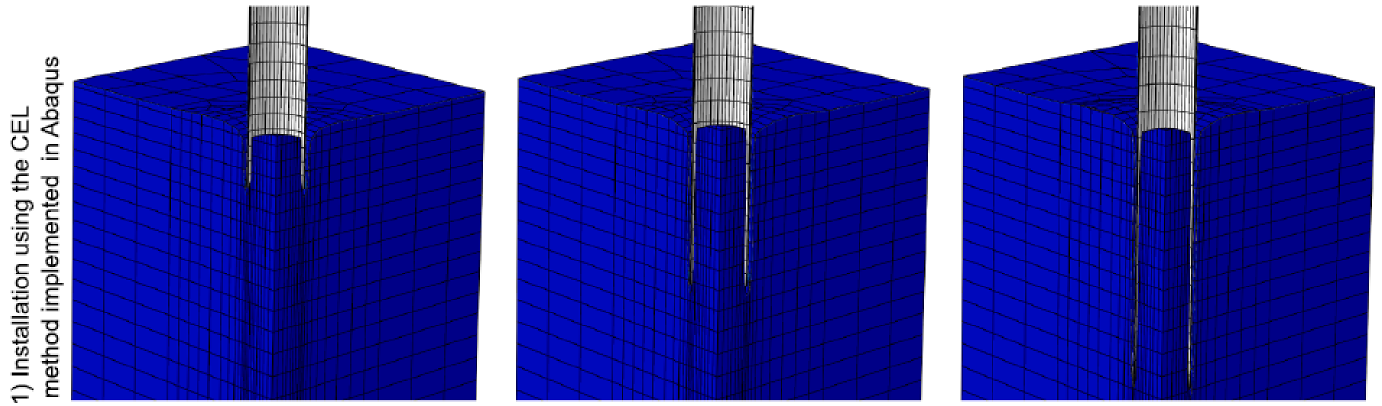
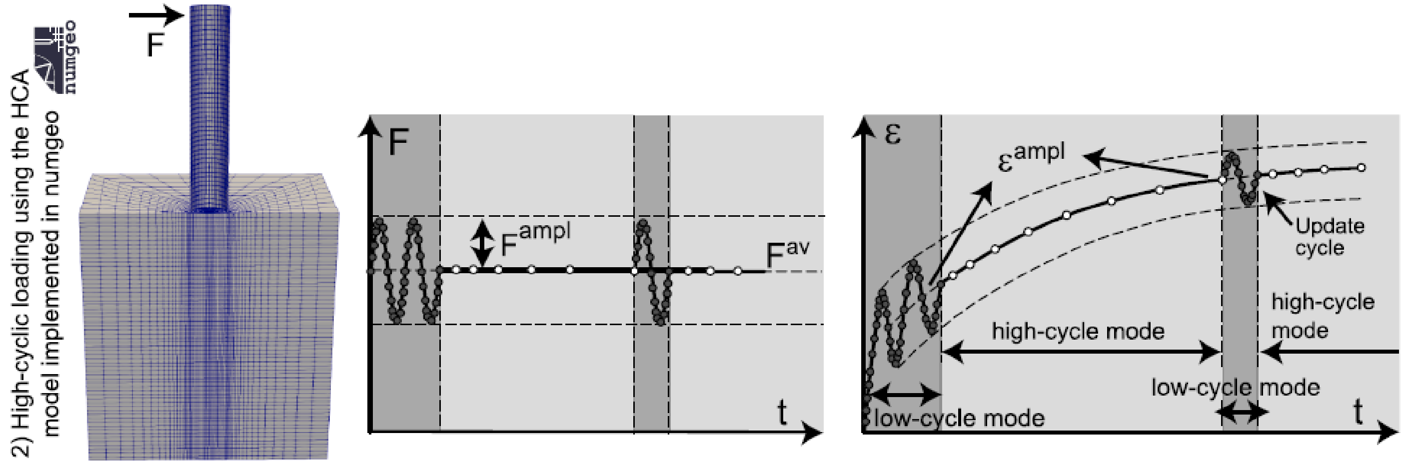


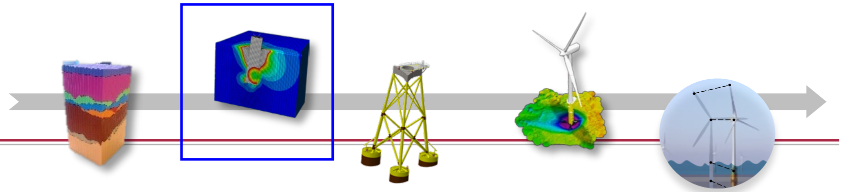
Staubach et al. (2022)



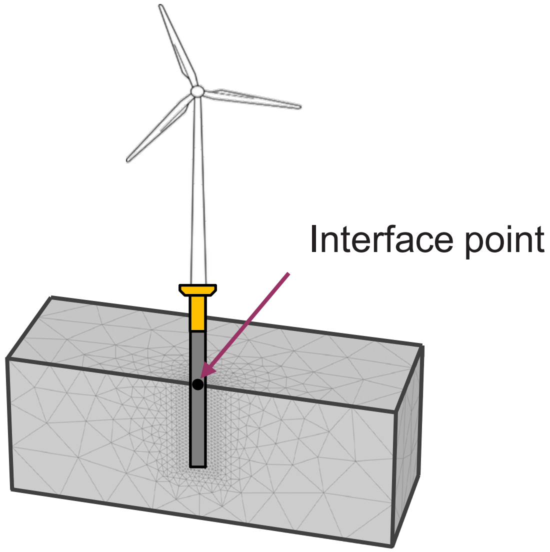


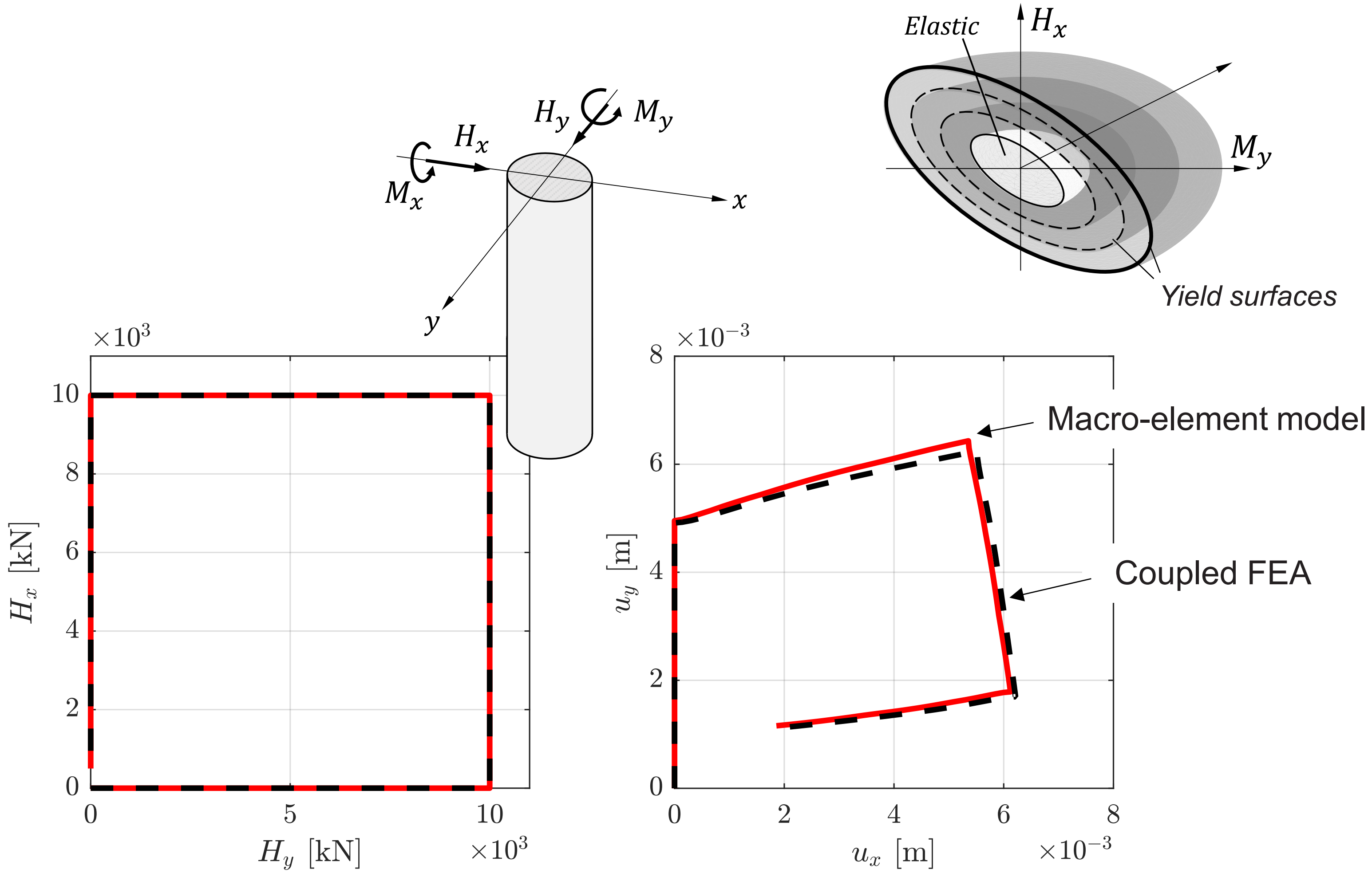
Machaček et al. (2021)

Foundation design



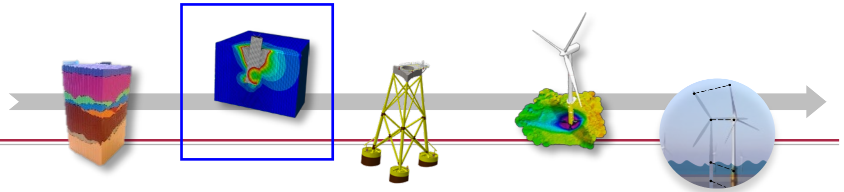
- for cyclic loading over a lifetime
- Prediction approaches include
  - Cyclic contour diagrams
  - 3D FE with Sanisand-MS, HCA
  - **Macro-elements**
  - p-y curves, CPT-based



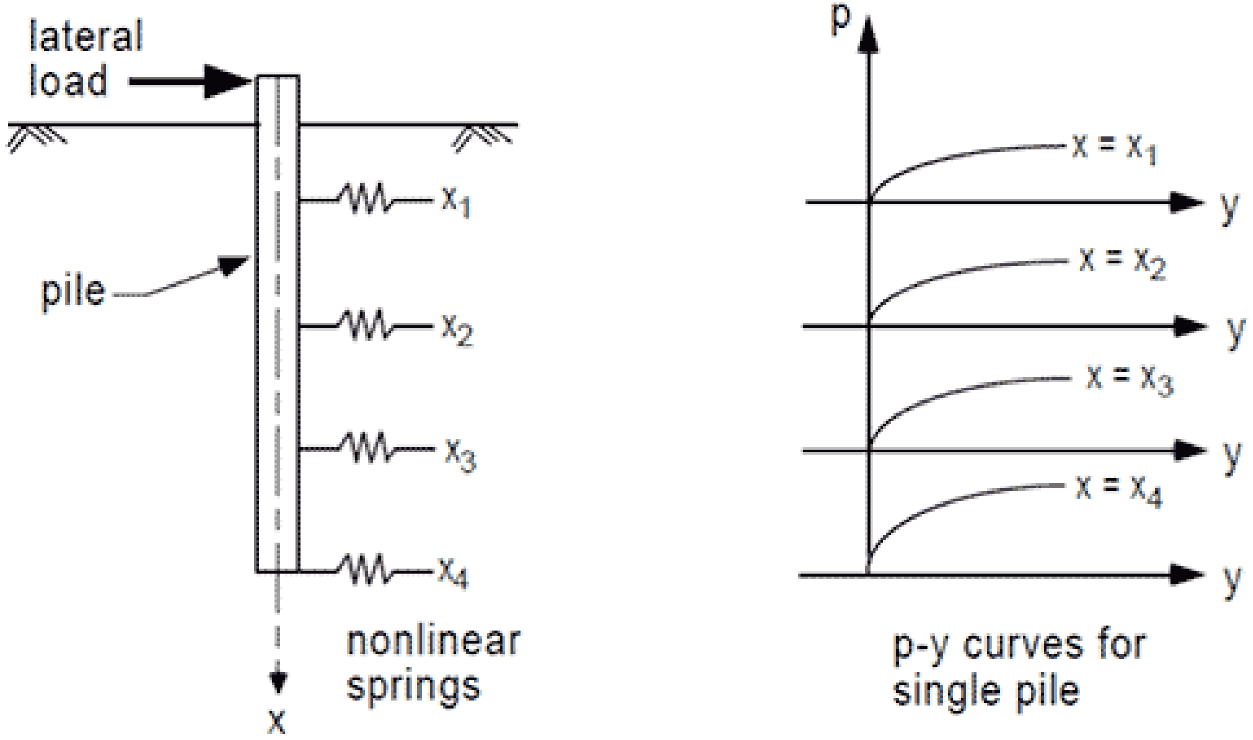


Page et al. (2019)

Foundation design



- for cyclic loading over a lifetime
- Prediction approaches include
  - Cyclic contour diagrams
  - 3D FE with Sanisand-MS, HCA
  - Macro-elements
  - **p-y curves**, CPT-based
- Certification?

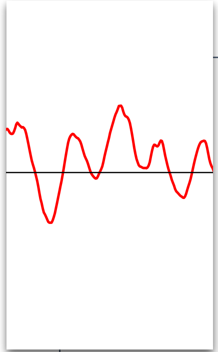


Foundation design

- for cyclic loading over a lifetime

- Experience since 1991, data?

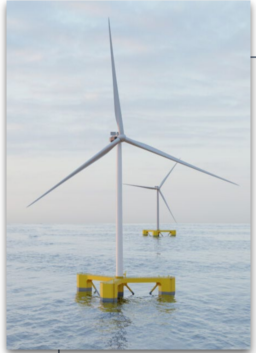
Research and innovation



Global benchmark exercise

Industry-wide consensus

- Insights into variability of approaches and results
- Inform improvements
- Enhance uniformity across industry



Shared anchors/moorings

- Interaction of different cyclic loading histories
- *Scalable workflows · whole life design*

Installation

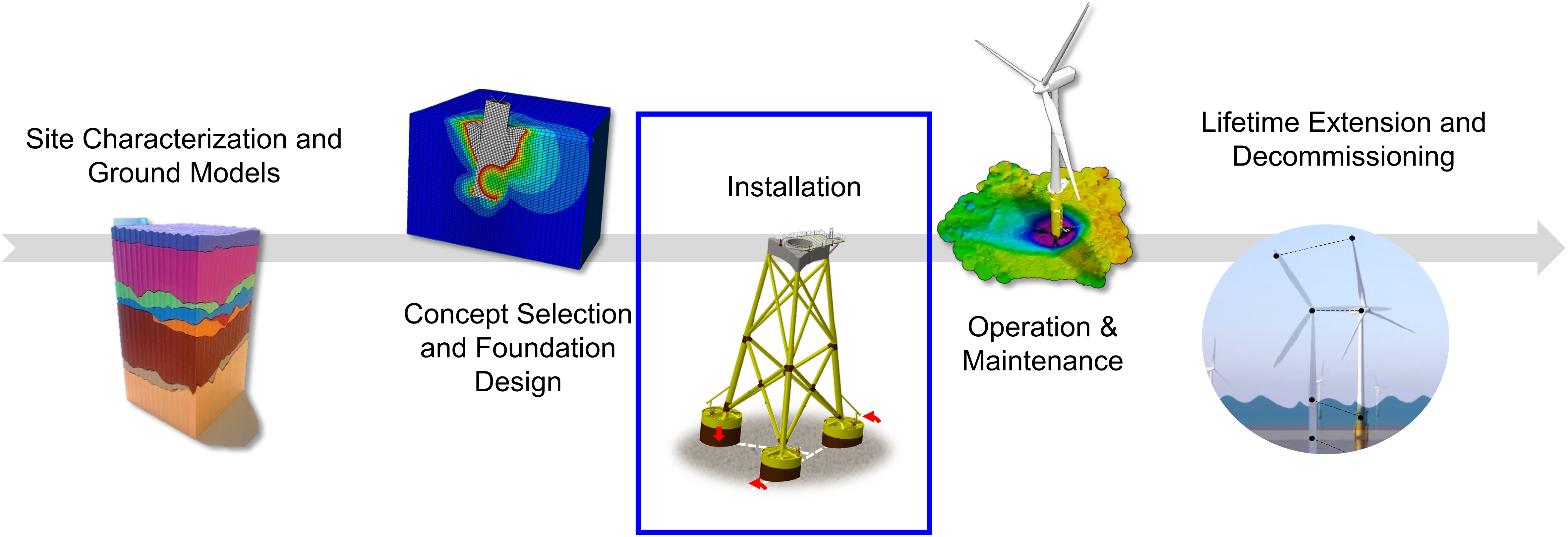


Image Source: NGI and Sparrevik (2019)

Installation

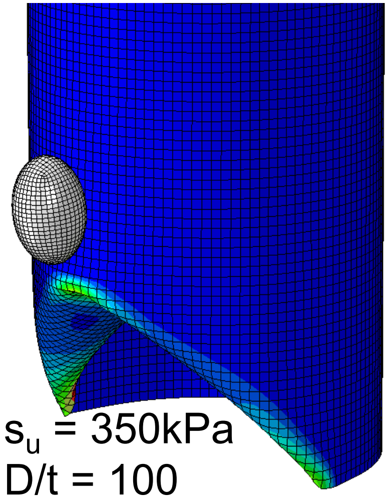
- Traditionally a check, design based on capacity and stiffness
- Monopile, impact-driven


Source: DEME Offshore

Installation

- Increasingly in focus (noise, challenging seabed conditions not only in new regions, foundation types)

Source: Vattenfall,Kriegers Flak



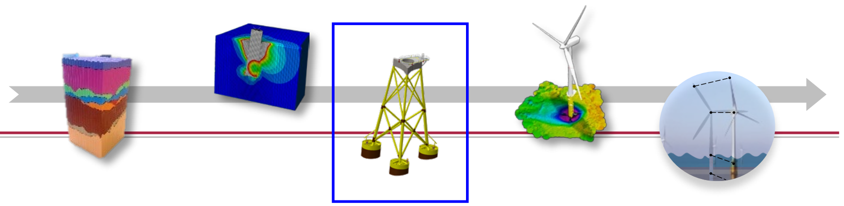
“ ”

Vinck et al., 2025

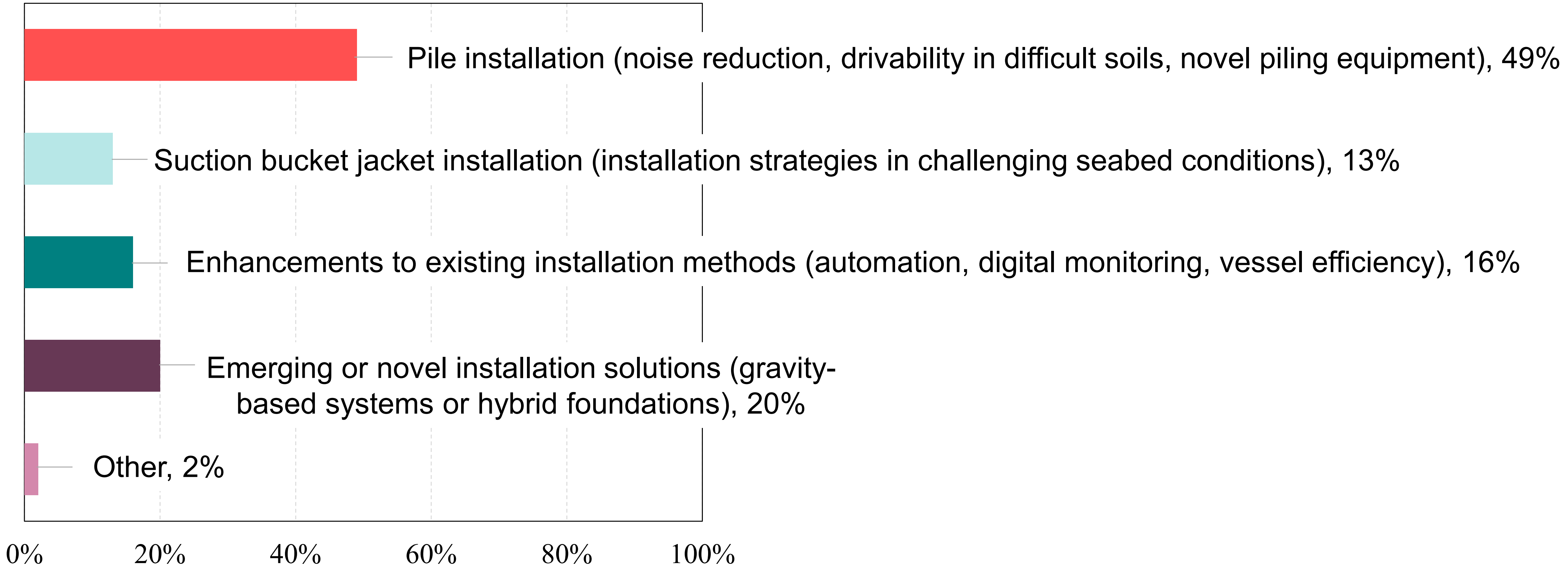
Source: Orsted

- Incidents very expensive (tens of millions of $$)
- Uncertainty of expected response (refusal, pile run) → risk

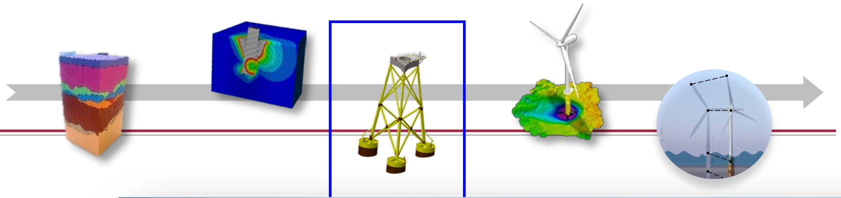
Installation



- Traditionally a check, design based on capacity and stiffness
- Increasingly in focus, survey results:



Installation



- Innovative methods and strategies in complex soils

- <u>Pressure cycling</u> of suction buckets:

Periodic reversal of pumping and displacement

Most effective

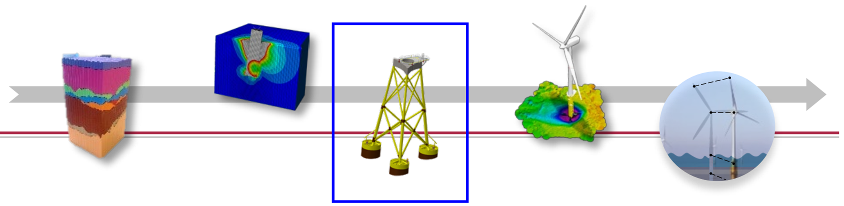
  - at depth (friction)
  - in clay layers
  - when pressure below plug uplift

Findings from centrifuge testing and field experience agree

National Geotechnical Centrifuge Facility, University of Western Australia

Mani et al. (2024)

Installation



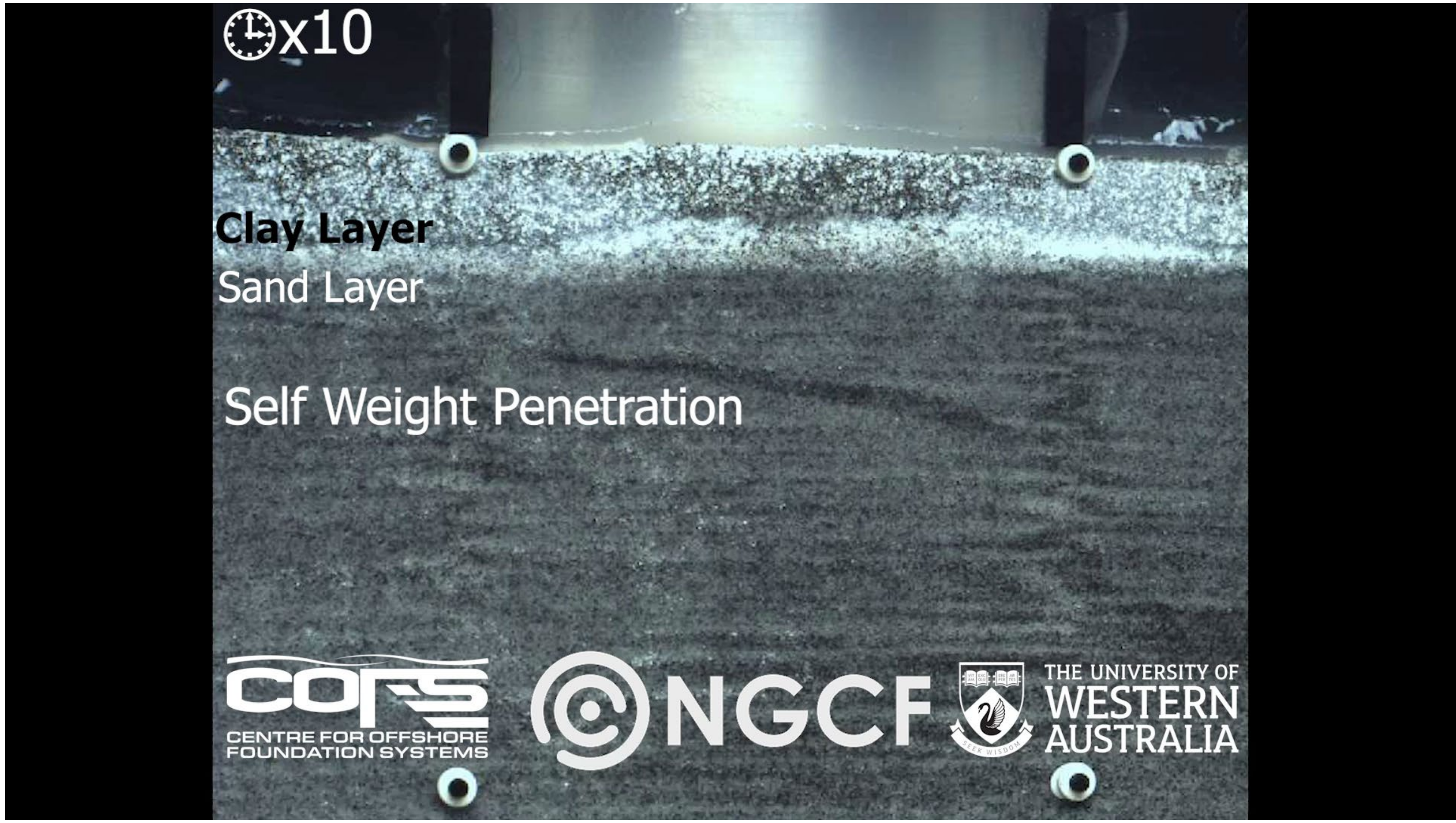
- Pressure cycling of suction buckets:

Periodic reversal of pumping and displacement

Most effective
  - at depth (friction)
  - in clay layers
  - when pressure below plug uplift

Findings from centrifuge testing and field experience agree

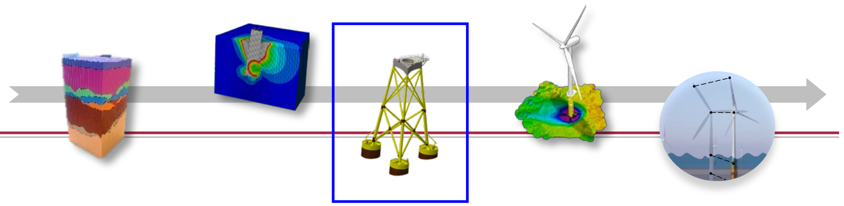
Plug uplift in suction installation



2026 AUSTRIA VIENNA WHERE IT ALL BEGAN 21st ICSMGE

NGI THE UNIVERSITY OF WESTERN AUSTRALIA

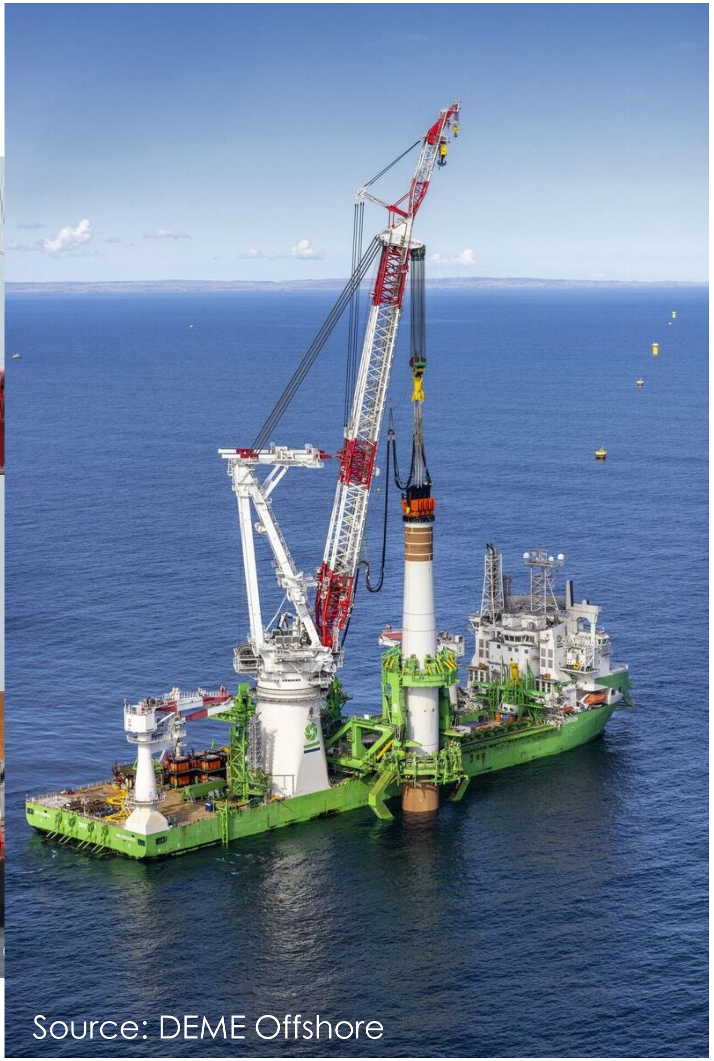
Installation



- Innovative methods and strategies → paper
- Vibro-driven monopile installation (lower acoustic emissions, no pile run)
- Anholt, Riffgat, Kaskasi, Moray West, Hai Long, Coastal Virginia Offshore Wind
- Prediction methods (room for improvement, accuracy refusal more than pile penetration velocity, low confidence in fatigue life estimate)

Source: Cape Holland

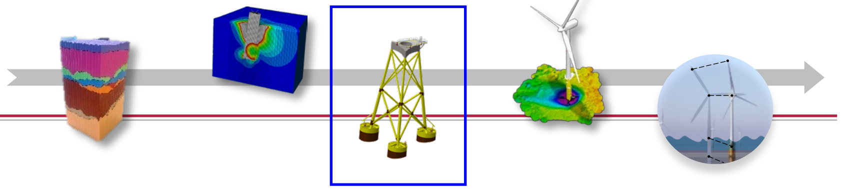
Source:



Source: DEME Offshore

- Effect of installation process on foundation stiffness, performance?

Installation



- Innovative methods and strategies
- Vibro-driven monopile installation with water jetting

- 3 monopiles installed at Hollandse Kust West wind farm in the Dutch North Sea
- first time at commercial scale

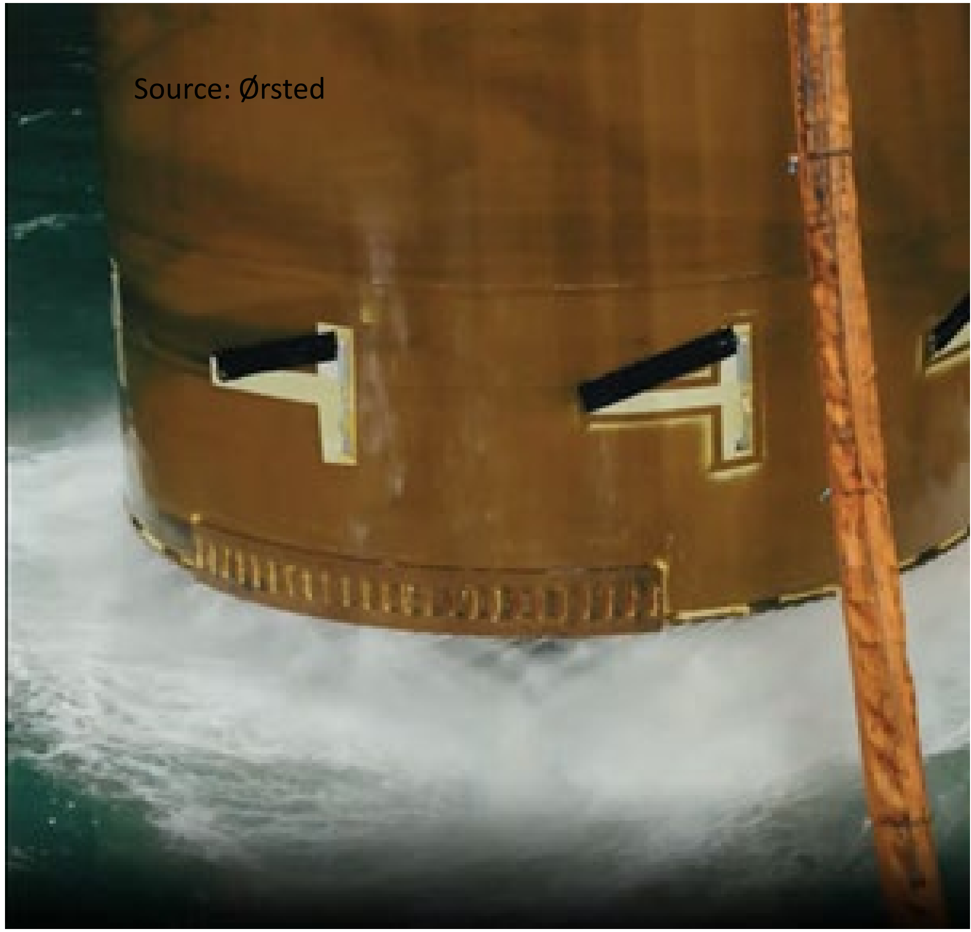
- Effect of installation process on foundation stiffness, performance?

Installation

- Innovative methods and strategies
- Monopile installation with water jetting

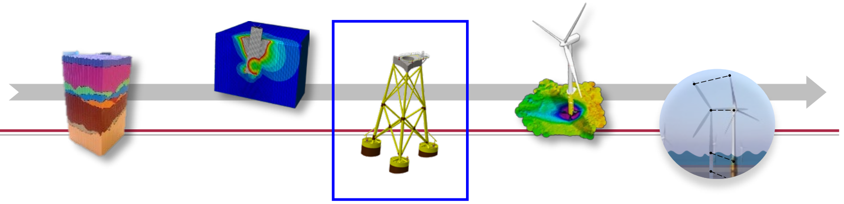
- 3 monopiles installed at Gode wind 3, German North Sea, sandy site
- Underwater noise levels marginally above ambient

- 11 MW turbines



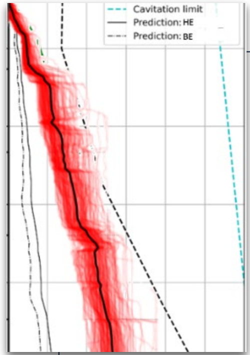
- Effect of installation process on foundation stiffness, performance?

Research and innovation



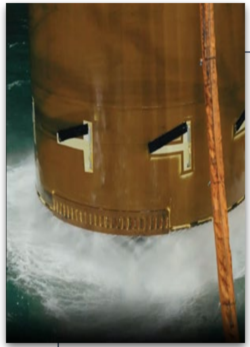
Complex soils

- Adapt prediction methods
- *Soil characterisation · Models*



Closing the loop, installation pred.

- Back-analysis of wider datasets
- Consideration of all contributions
- *Predictive methods· Field data*



Innovative installation methods

- Understand mechanisms
- Develop models
- *Small-scale testing · Numerical modelling ·Trial installations · Field data*

Innovation driven by

- Environmental constraints
- Logistical efficiency
- Adaptation to complex geotechnics

Operation and maintenance

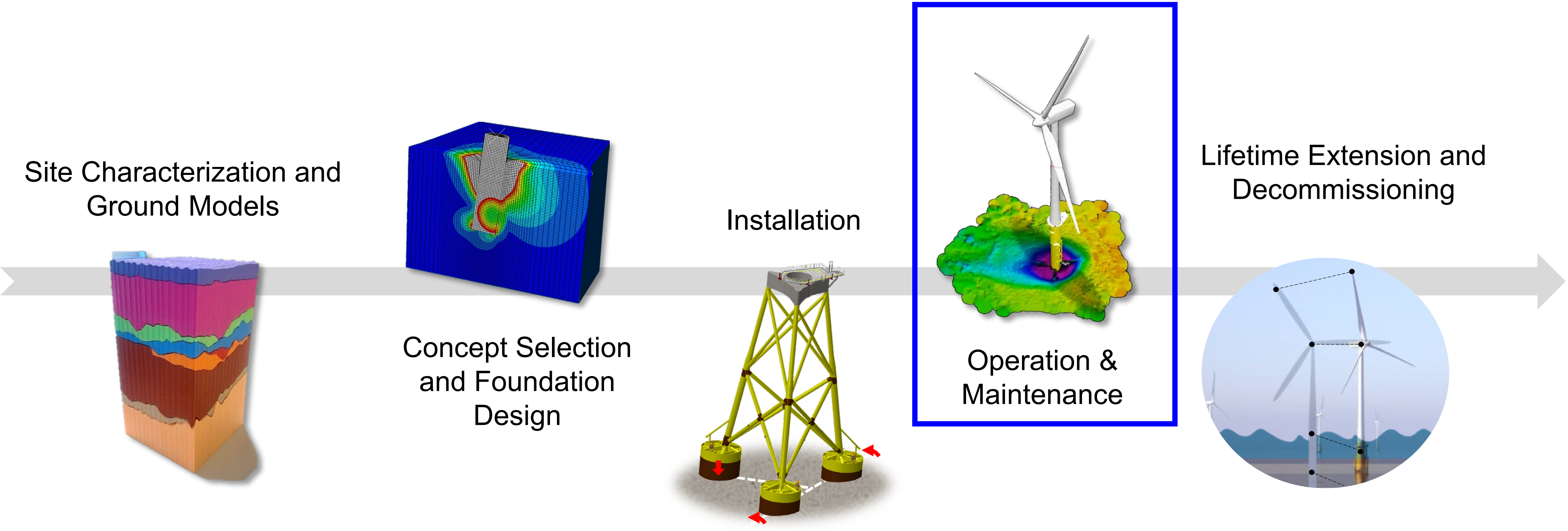


Image Source: NGI and Sparrevik (2019)

Operation and maintenance

Activities needed to ensure performance and safety during operation

Inspection & condition monitoring:

corrosion · scour

Maintenance of critical systems:

grout connections · mooring-line tension

Structural health monitoring (SHM):

loads · deformations · vibrations · environmental conditions

Image source: NGI and Empire Enginering

The situation today

State of practice: not uniform

Survey: O&M aspects of foundations and anchors are at a similar state of the art across industry

Agree 27%	Disagree 73%

Interviews:

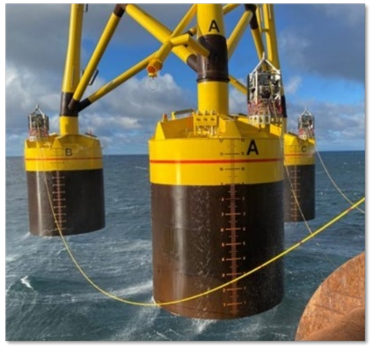
- Monitoring practices vary between developers
- Approaches differ by foundation type and project maturity
- Data are often not shared beyond the project team:
  - confidentiality
  - incomplete datasets

SHM system for a SBJ. Photo: NGI

Operational data for cyclic design

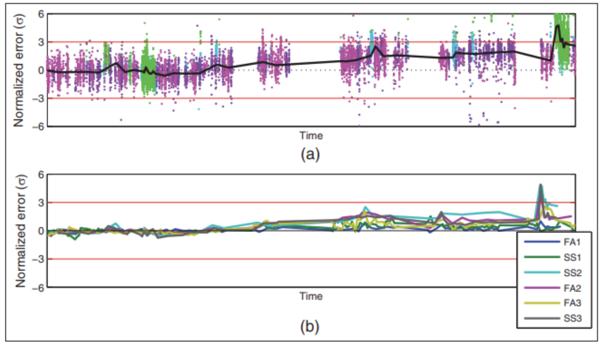
Real load histories:

SBJ (Photo: NGI)



Vestas V80 (Video: YouTube)

Weijtjens et al. (2015)



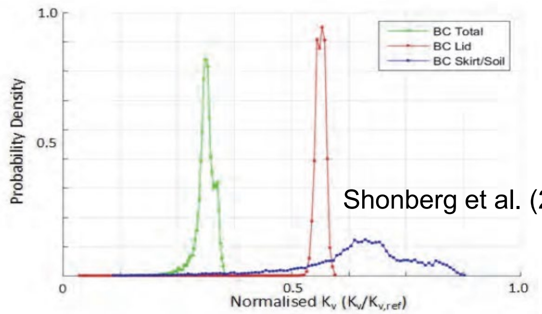
Installation

Shutdown / idling

Changes in the system

25 – 30 years

Normal operation



Shonberg et al. (2017)

Rare events

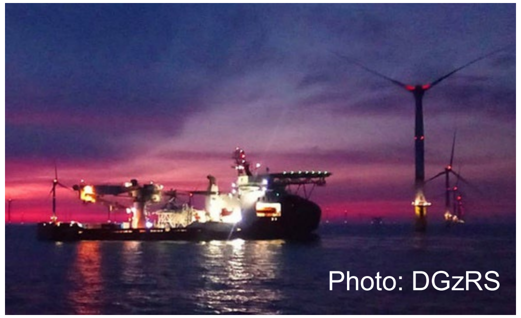
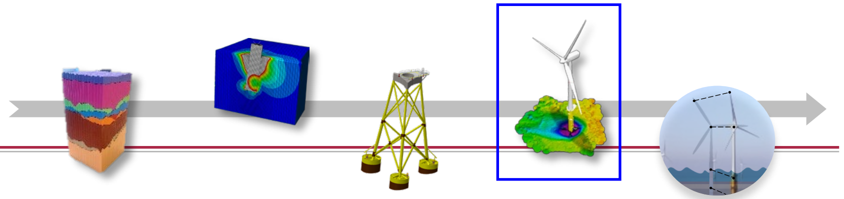
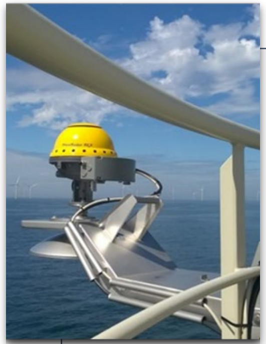


Photo: DGzRS

Research and innovation

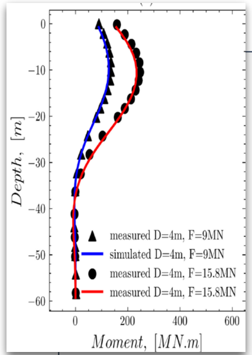




Measure long-term loads histories

Understand the composition of long-term (25-30 years) load histories

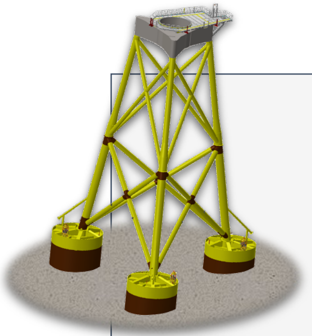
Sequence · Direction · Retrofit instrum.



Verify design assumptions

Back-analysis of wider datasets

Align on cyclic design of OWTs



Long-term performance (foundation)

Identify mechanisms & their importance

Pore pressure build-up · Degradation · Stiffening · Permanent rotations

Long-term performance (anchor)

Identify mechanisms & their importance

Shared moorings · Trenching · Gapping · Permanent displacements

Image Source: NGI and Kheffache et al. (2024)

Structure of the lecture

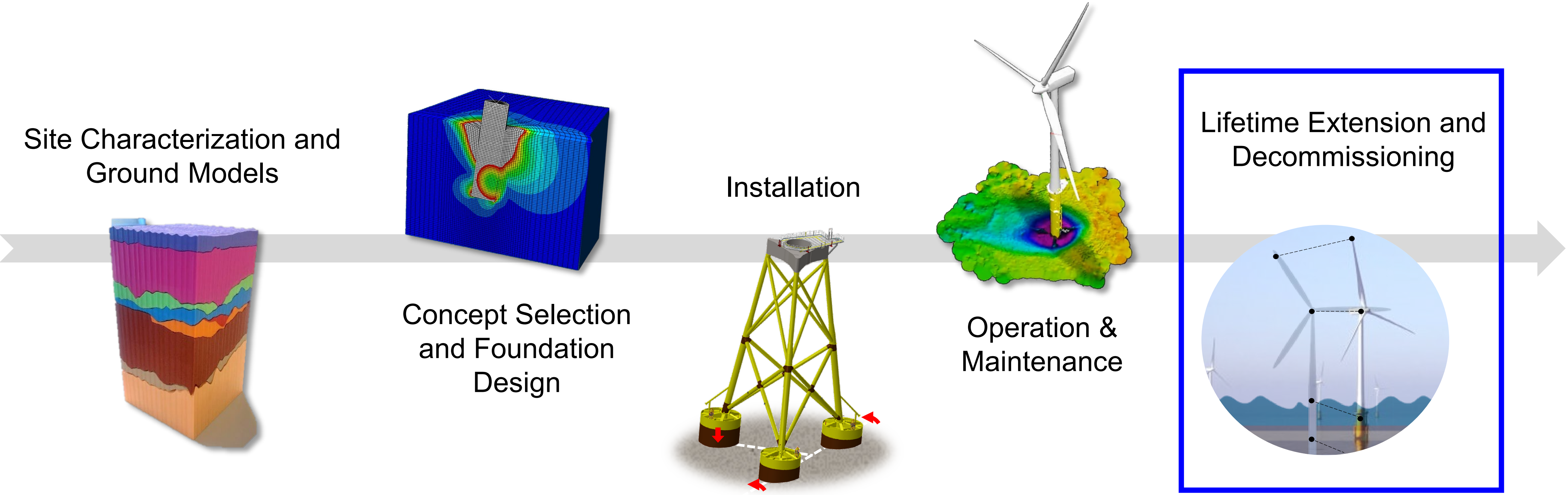
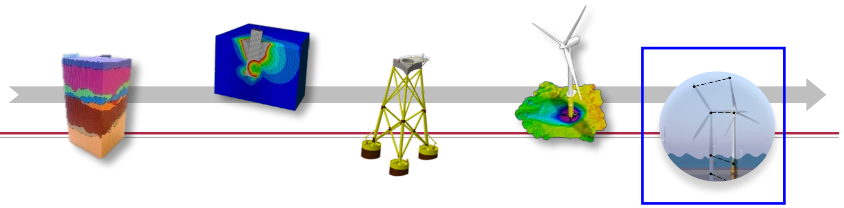


Image Source: NGI and Sparrevik (2019)

Lifetime extension, decommissioning



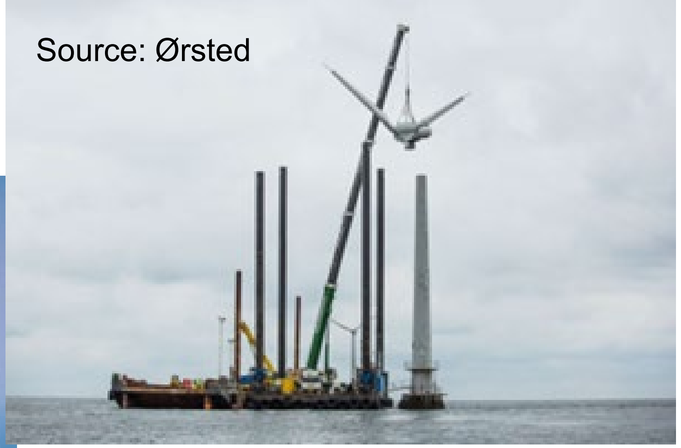
- Decommissioning of <u>onshore</u> wind turbines well established – what about offshore?
- Requirements in most countries currently: full removal at end-of-life

? Current practice, challenges

Vindeby, commissioned 1991

decommissioned 2017

Source: Ørsted



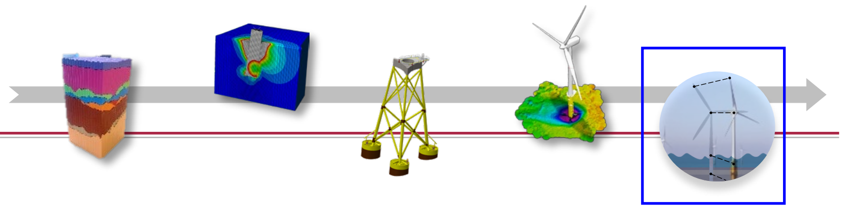
Source: Ørsted

11 turbines,

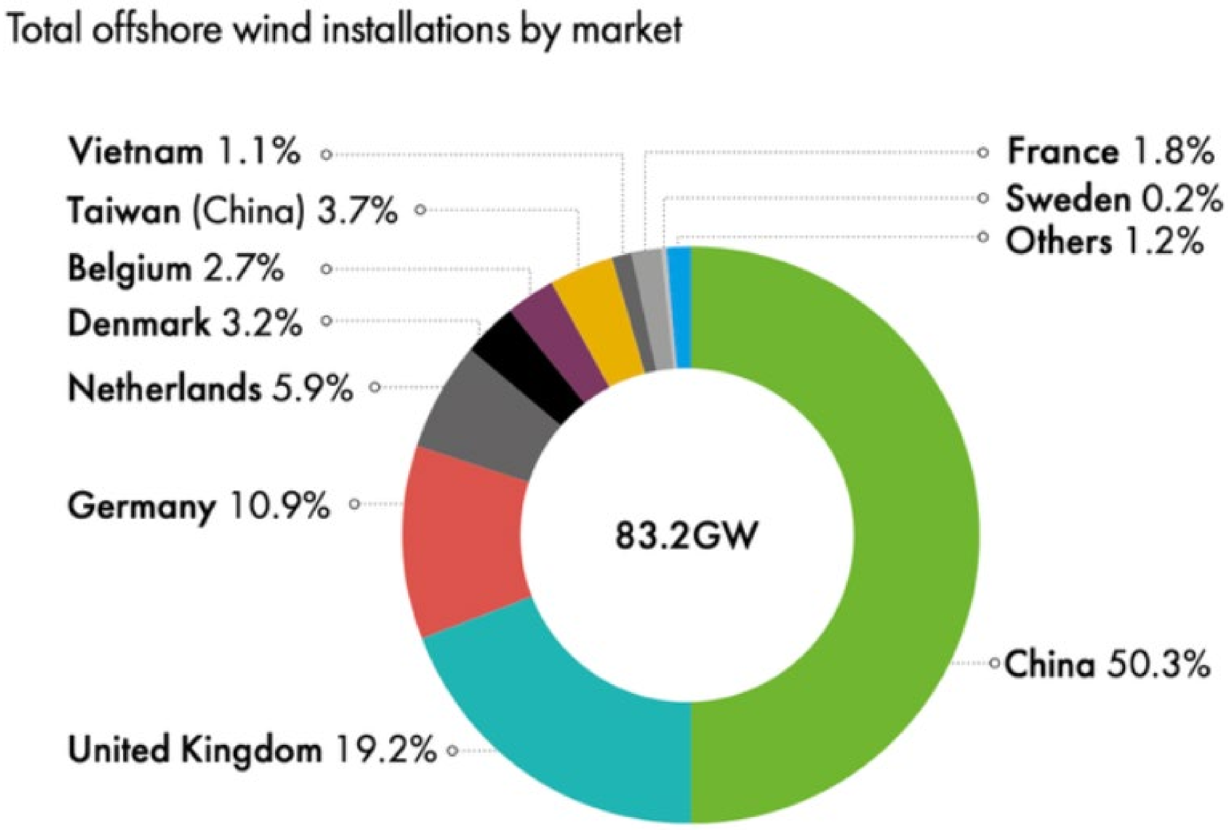
3 km array, 3 km export cable

- Few offshore wind farms decommissioned to date
- Close to shore, ~1.5 km
- Shallow water
- Bespoke decommissioning
- End of 2024: 83 GW installed capacity globally
- End of life of 3.5 GW by 2035

Lifetime extension, decommissioning

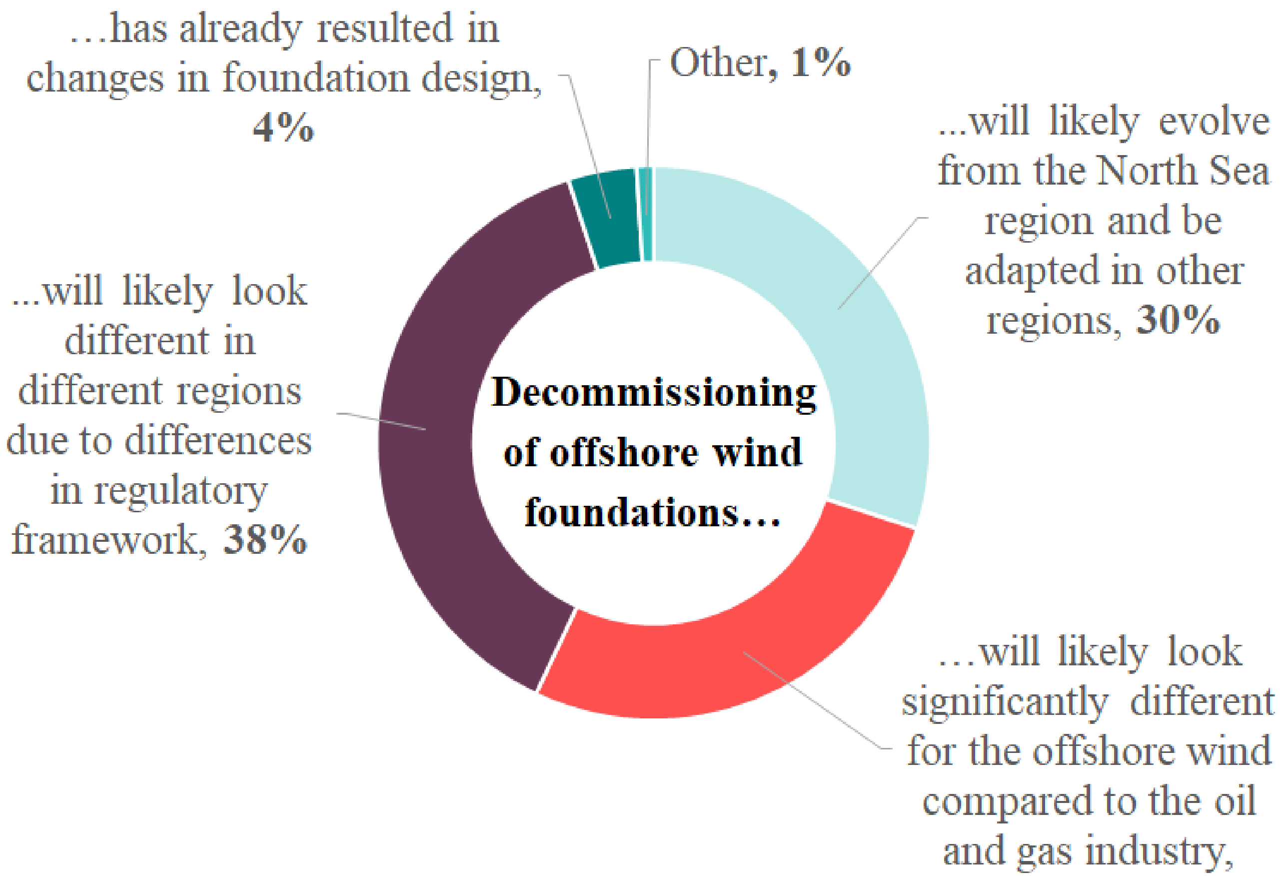


- End of life of 3.5 GW by 2035
- Hundreds of turbines, mostly on monopiles → scale up
- Further from shore, in deeper water
- Where?
- Evolution of end-of-life strategies required



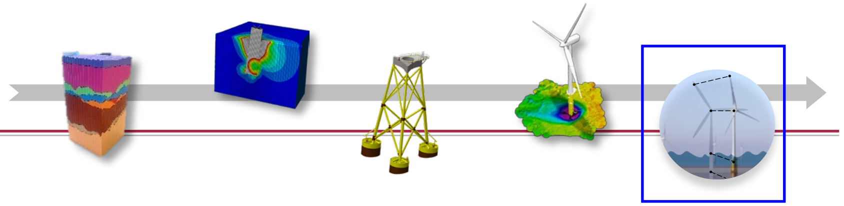
Lifetime extension, decommissioning

- Evolution of end-of-life strategies required



- When does an offshore wind farm need to be decommissioned?
  - Regulatory, e.g. seabed lease expiry
  - Technical: how has the system aged?
  - …
- Delaying can have financial and environmental benefits

Lifetime extension



- What is the remaining life of the structure?
- Installation, long-term loading and changes

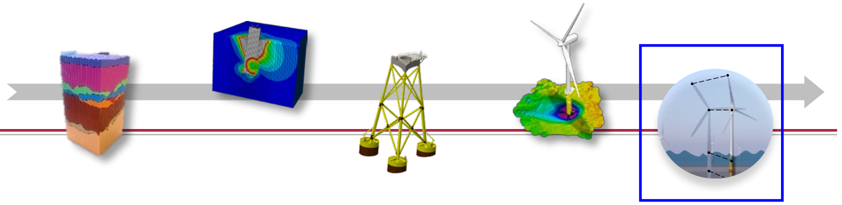
to predicting:

Accurate reliable models… and

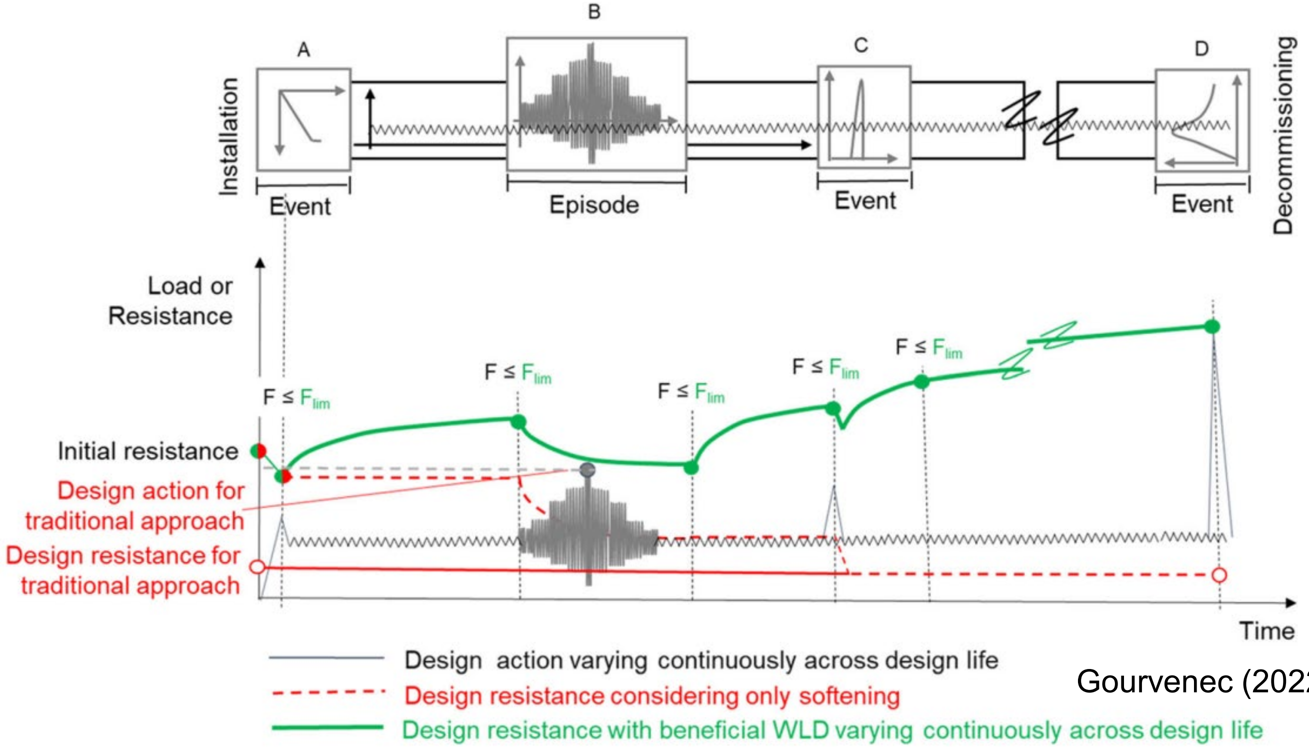
- End-of-life decision making process requires planning
- Informed evaluation of risk and costs

- Current data paucity, paired with low confidence in prediction methods (timeframe: decades)
- Multi-faceted challenges (incomplete datasets, longevity of instrumentation, cost of monitoring, big data, separate systems, separation between teams and companies as well as temporal…)

Decommissioning



- Decommissioning requires planning
- Installation reversible? Extraction resistance?



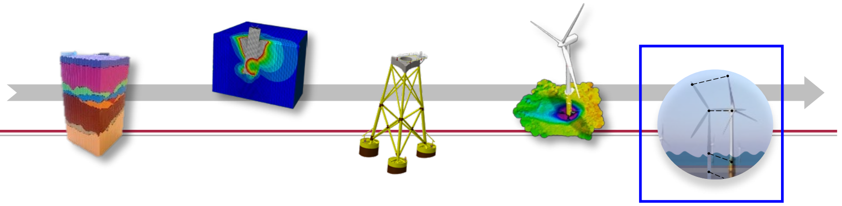
Gourvenec (2022)

Dogger Bank Met Mast Removal 2017 after 4 years operation (photos: SPT)

Bittar et al. (2024)

- **Multi-faceted challenges** (incomplete datasets, longevity of instrumentation, cost of monitoring, big data, separate systems, separation: teams/companies as well as temporal…)
- Uncertainty impairs evaluation of decommissioning options

Research and innovation



Long-term foundation resistance

- Understand the governing processes
- Validate prediction methods
- *Whole life design· Field data*

Digital twins

- Monitoring over long periods of time
- Consideration of all contributions
- *Big data· cross-disciplinary*

Design for decommissioning

- Retrieval part of the design
- Anticipate decades in advance
- *Cross-disciplinary*

Not all critical aspects are geotechnical

- Regulatory
- Logistical
- Cross-disciplinary integration
- …

We’ve come full circle

- … and there is so much more to discuss – anchors, cables…

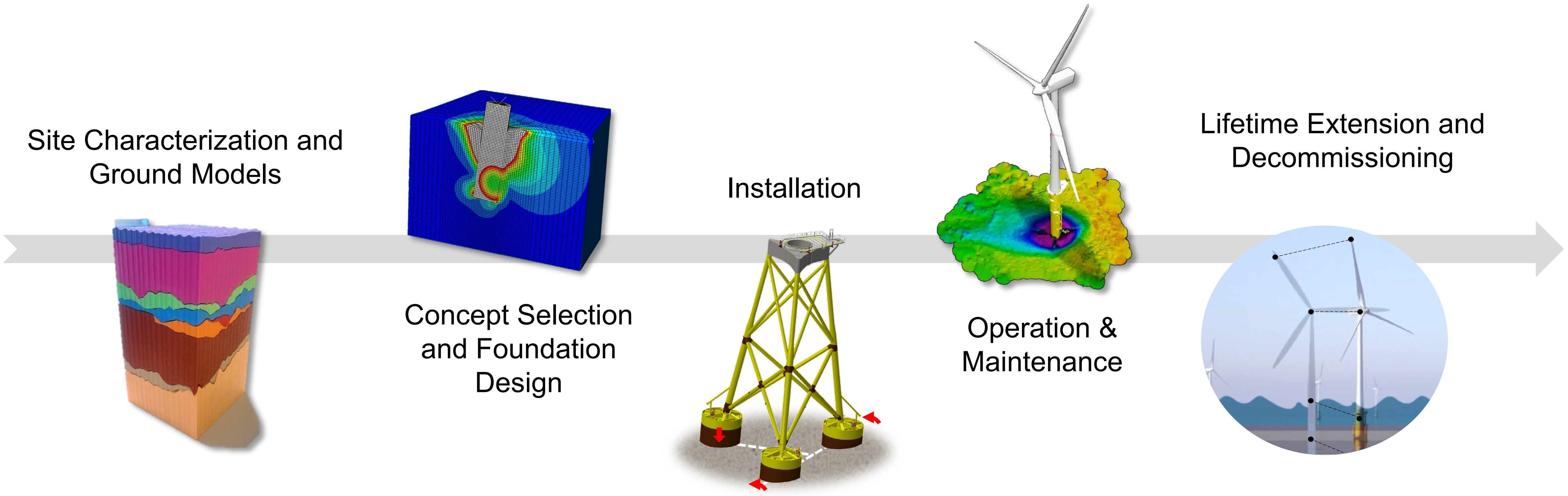


Image Source: NGI and Sparrevik (2019)

Concluding remarks

- State-of-the-art/industry: a snapshot in time

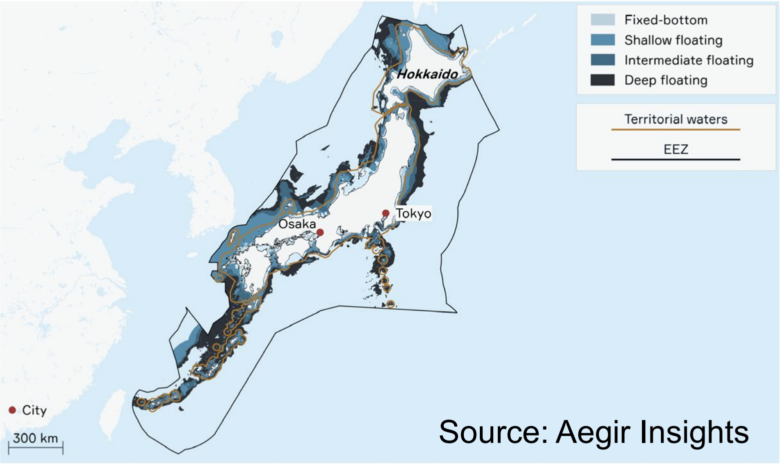
- Example: changes in Japan from April 2026

  government now conducts environmental and site investigations before auction

  ➔ no more parallel assessments by multiple developers

  shifting early-stage risk from developers to government

  enabling faster and more coordinated site development

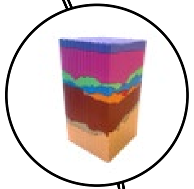


Source: Aegir Insights

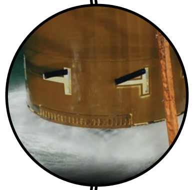
Concluding remarks

What does this snapshot show?

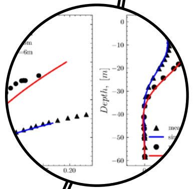
Industrialisation remains important beyond monopiles



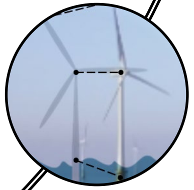
Standardisation is needed where practice is project-specific



Innovation often addresses several constraints at once



Existing data are underused

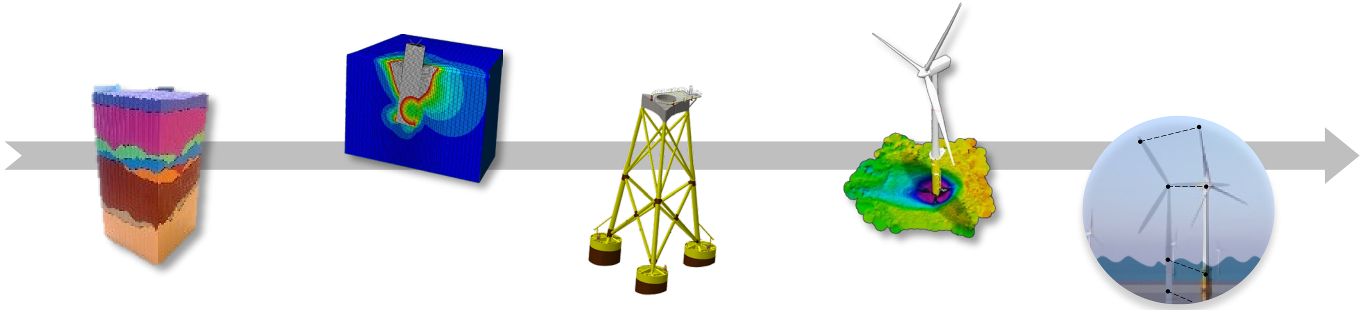


Risk management links the lifecycle

Concluding remarks

- A snapshot based on literature, 92 survey responses and 16 interviews

- Research and innovation areas across the project lifecycle



- Offshore wind geotechnics is a field where research and practice are closely linked
    - Field experience feeds research questions, and
    - Research-driven solutions quickly move into guidance and accepted practice

This interaction is a strength as offshore wind deployment accelerates

Acknowledgements

- ICSMGE
- NGI and COFS/UWA
- All 92 survey respondents
- Thank you for insightful conversations and feedback to:

Maarten Vanneste, Rasmus Klinkvort, Mark Randolph, Hendrik Sturm, Jan Dührkop, Christian LeBlanc Thilsted, Neil Morgan, Pauline Suzuki, Sylvie Raymackers, Avi Shonberg, Yiorgos Perikleous, Youhu Zhang, Sarah Elkhatib, Tim Pucker, Luís Berenguer Todo Bom, Volker Herwig, Iona Richards, François Bertrand, Santiago Quinteros, Per Sparrevik, Thomas Langford, Phil Watson

Thank you!