Preliminary Insights from Foundations for Offshore Wind Turbines (FRONTIErS) Doctoral Network

Luke J Prendergast[1*], *Ken* Gavin[2], *Marcos* Arroyo[1] and *Gudmund* Eiksund

[1] *University of Nottingham, Department of Civil Engineering, Nottingham NG7 2RD, United Kingdom*
[2] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, 2628 CN, The Netherlands*
[3] *CIMNE–Universitat Politècnica de Catalunya, BarcelonaTech, Barcelona, Spain*
[4] *Norwegian University of Science and Technology, Department of Civil and Environmental Engineering, Norway*
[*] *Corresponding author: luke.prendergast@nottingham.ac.uk*

ABSTRACT. The European offshore wind sector has grown rapidly, with significant advances in turbine technologies, increased sizes, and construction locations further from the shore in deeper waters than ever before. A critical challenge has emerged relating to a growing lack of knowledge surrounding how to design foundations to support these new turbines, with the safety, life-span, cost, and environmental implications coming increasingly into question. To maintain Europe's stance as a World-leader in offshore wind, Foundations for Offshore Wind Turbines (FRONTIErS) Doctoral Network has been designed to bring together research-intensive universities and major industry stakeholders to train the next generation of graduates with the appropriate skills to tackle the emerging issues presenting as a barrier to continued development of the sector. Eleven Doctoral Candidates have been recruited to tackle significant challenges related to foundation design and performance. Projects focus on topics such as: understanding soil variability, effect of cyclic loading on axial capacity, pile aging, dynamic modelling informed from in-situ testing, time and spatial variation in soil properties, driveability modelling, gravity-base scour effects, multi-directional loading effects, centrifuge testing of cyclic loading response, and dynamic features of wind turbine foundations. This paper presents a preliminary overview of the various PhD projects ongoing as part of this network, which are in the early stages, as well as a summary of training conducted to date.

Keywords: FRONTIERS; MSCA; Doctoral Network; Marie-Curie; Offshore Wind.

1. Introduction

Foundations for Offshore Wind Turbines (FRONTIErS) Doctoral Network (DN) is a Marie Skłodowska-Curie Action, running from 2022 to 2026, which was funded under the MSCA 2021 Horizon Europe call. The focus of the network is on developing novel foundation technologies for Offshore Wind Turbines (OWTs) and solving critical issues acting as a barrier to the continued energy transition away from fossil-fuel reliance. FRONTIErS brings together leading industry stakeholders and academic experts in offshore geotechnics, structural engineering, and data-analytics, and is focussed on training 11 Doctoral Candidates (DCs). Participants in the network include leading European universities: University of Nottingham (UoN), Delft University of Technology (TU Delft), Universitat Politècnica de Catalunya (UPC) Barcelona, and Norwegian University of Science and Technology (NTNU); as well as globally-recognised experts in offshore wind engineering: Électricité de France (EDF), Esteyco, Norwegian Geotechnical Institute (NGI), and Sea and Land Project Engineering (SLPE). The wider network of Associated Partners includes Equinor, University of Western Australia (UWA), University of Texas (UT), Det Norske Veritas (DNV), Institut de Ciències del Mar-Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC), National Renewable Energy Laboratories (NREL), Denmark Technical University (DTU), National Yunlin University of Science and Technology (YUNTECH), InfraPlan Consulting, Klinkvort EURL, Offshore Wind 4 Kids, and Norconsult.

Wind energy is one of the most well-established and scientifically-mature renewable energy technologies, providing 44% of all new power installations in Europe in 2017 and supplying 12% of the EU-27 electricity demand in 2019 (EU, 2019). This is estimated to increase to 30% by 2030 (WindEurope, 2021). To date, it has mostly been onshore wind that has led this progress; however, focus has increasingly moved to offshore where these developments incur greater technical challenges and higher risks. In addition, since many near-shore sites have already been developed, new installations are taking place much further from the coast in ever deeper waters than previously attempted. Coupled with moving further offshore, OWTs have grown considerably in size (WindEurope, 2021), with the trend as shown in Fig. 1.

While progress in OWT technology is very positive, there is growing uncertainty in the behaviour of foundations, particularly as the structures evolve into systems not previously developed or tested. Unsafe or poorly designed foundations increase the likelihood of unsafe designs and the risk of early decommissioning. Uncertainty in foundation behaviour and limitations in design codes mean designers must act conservatively, leading to over-designed foundations to ensure safety, which has key cost and environmental implications. There is additionally growing uncertainty over how long these structures can withstand harsh offshore conditions, and the impact on structure fatigue lives. OWTs are dynamically sensitive and flexible systems, and minor inaccuracies in foundation stiffness can lead to resonant vibrations, leading to increased downtime and constrained operations, diminishing energy production potential. In newer geo-environments, these issues are compounded by geotechnical uncertainty, among other issues.

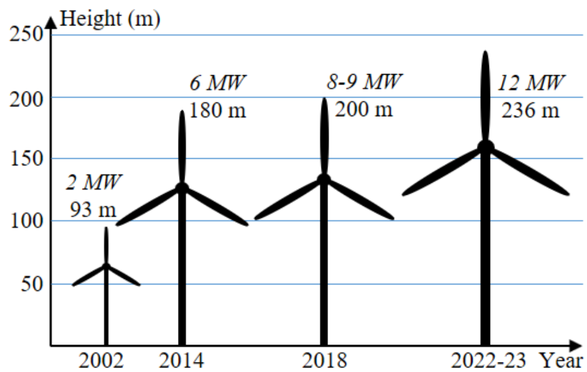

Figure 1. Evolution in turbine height since 2002

At the root of the engineering challenges described above are several technical challenges that need to be addressed:

- Large spatial footprint associated with Offshore Wind (OW) developments: Most oil and gas platforms are single, large structures. OW developments, on the other hand, consist of multiple structures arranged over a relatively large geographical area. This requires the statistical treatment of seabed variability.

- Serviceability-led design: In contrast to oil and gas structures, where capacity under extreme events has governed design, serviceability conditions such as cyclic settlement accumulation, dynamics and fatigue, are central to OWT design.

- Dynamic sensitivity: OWTs are long, flexible structures that are subjected to complex, multi-directional cyclic wind and wave loads. Dynamic soil-structure interaction and fatigue are not very well understood for systems of this nature.

- Installation effects: Installing OWT foundations (such as via pile driving) changes in-situ stress and stiffness conditions and alters properties such as strength, stiffness and permeability that govern the response.

- Limited track record: While the oil and gas sector has decades of precedent on which to build, the rapid pace of development in OW turbine technology implies a high degree of uncertainty persists regarding long-term performance of these new systems.

By leveraging decades of interdisciplinary experience in offshore oil and gas, FRONTIErS Doctoral Network has been customised to address the critical issue of providing safe, reliable, and economical foundations to sustain the offshore wind sector. FRONTIErS is addressing foundation engineering issues for emerging deep-water offshore wind developments in a dedicated research-led training environment, and is providing a pathway for 11 recruited DCs to gain valuable exposure to a rapidly developing and crucial industry. This paper presents a preliminary overview and summarises key actions of the network to date.

2. FRONTIErS PhD Projects

Eleven bespoke research projects have been hypothesised in order to help solve the most pressing issues for emerging deep-water OWTs. The projects and intended outcomes are discussed in the following subsections.

2.1. Project 1: "EXPLORE"

This project at NGI focuses on understanding the impact of soil variability (Prendergast et al., 2018) on foundation installation and performance. The impact of statistical variability on design parameters required for accurate estimation of the operating behaviour of pile and caisson foundations deployed to support offshore turbines will be investigated. The project will use site data to investigate the relationship between spatial variability in the surrounding soil volume of a foundation and the derivation of a shear strength profile from Cone Penetration Test (CPT) measurement, stiffness response, rate effects, and soil damping. The project will undertake parametric studies for both foundation types in the centrifuge at TU Delft.

2.2. Project 2: "CYCLIC-TENS"

This project at TU Delft will investigate the mechanical response of offshore foundations (monopiles and anchors for floating structures) under cyclic loads. A particular focus will be on cyclic tension loading, and the influence of mean cyclic load (and the cyclic amplitude) on the stiffness and axial capacity will be investigated. The potential beneficial effects of aging will be considered. The use of ground improvement techniques to increase the foundation performance will be assessed. The employment of these techniques is expected to increase the service life of both new and existing offshore structures. This is expected to reduce the costs and to improve the sustainability of offshore structures for renewable energy production, thus facilitating the energy transition. Particular attention will be given to the behaviour of the improved soil, potentially damaged by the application of a large number of load cycles. This project will include model tests in the centrifuge on a range of foundation geometries, full scale tests, and cyclic element testing on improved soils.

2.3. Project 3: "EXTEND"

This project at TU Delft will investigate the physical mechanisms influencing pile aging under vertical and lateral loading (Gavin and Igoe, 2019). A recent joint-industry project has shown that over a period between 100 and 1,000 days after installation by driving, pile capacities increase to double those estimated using industry standard CPT-based design approaches (Jardine et al., 2005; Lehane et al., 2005), which could influence the lateral behaviour through distributed moments on large-diameter monopiles. However, there are some notable outliers in the result, e.g. tests performed in the Port of Rotterdam suggest that the increase in pile capacity due to aging is very sensitive to the pile geometry. This project will include full-scale and centrifuge (laboratory) scale load tests on a range of pile geometries.

2.4. Project 4: "MONODYN"

This project at NGI will further develop a novel CPT-based multi-spring model (Tott-Buswell et al., 2024) for analysing the monotonic response of large-diameter monopiles and extend it to modelling dynamic soil-pile interaction under scour. The model comprising p-y, m-θ, base shear and moment springs will utilise CPT data to inform backbone curves for Masing-type hysteresis. A schematic of the model and how it differs from a flexible pile is as shown in Fig. 2. Further refinement of the small-strain regime will be provided by in-situ and laboratory measurements of G_0. The predicted dynamic behavior will be benchmarked/validated using centrifuge testing of long-run cyclic experiments. The model will then be extended to capture scour effects (Jawalageri et al., 2022; Prendergast et al., 2013), whereby the overburden reductions due to scour will be modelled as a change in the ultimate resistance of the respective backbone curves for each spring type (Chortis et al., 2020). This will then be validated using centrifuge modelling of scoured piles performed at the University of Nottingham. Supporting element laboratory testing will be incorporated through ongoing work at NGI in Oslo.

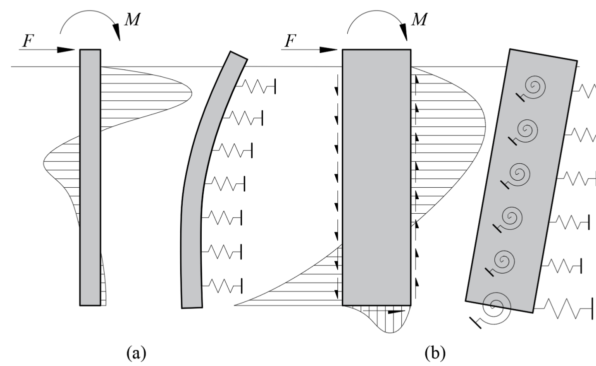

Figure 2. (a) Flexible pile resistance, (b) rigid pile resistance

2.5. Project 5: "MONO-JACK-3D"

This project at EDF will investigate the effect of temporal and spatial variability in ground conditions on the 3D structural behavior of jackets and monopiles. Two industrial cases will be explored, the first one deals with the uncertainty in the depth of different stratified layers which can lead (for jacket substructures) to differences in behavior of adjacent jacket legs and thus can increase fatigue damage. The second case deals with time-varying oscillations in seabed (global scour) which change the level of the mudline over the lifetime of a turbine exacerbating fatigue. The project will be achieved by developing a robust methodology to account for these two effects.

2.6. Project 6: "AX-RESIST"

Recent CPT-based design methods provide reliable estimates of the separate components of axial resistance, namely the shaft and base resistance of piles in either sand or clay. In the offshore environment, many piles are installed in mixed deposits. In the North Sea, high-strength sands are often interbedded with clay lenses, whilst at many locations offshore France, Scotland, and Ireland, superficial deposits are underlain by rock. The bearing capacity and stiffness of piles installed in these soils are highly uncertain. This project at TU Delft will focus on (i) interpretation of a series of instrumented pile load tests on piles installed in dense Pleistocene sands with interbedded stiff clay layers tested in the Maasvlakte 2 area of the North Sea, in the Port of Rotterdam, and (ii) advanced finite element analyses will be performed investigating the impact of stiff clay lenses embedded in sand, or fractured rock profiles on the axial resistance and stiffness of open-ended piles.

2.7. Project 7: "NU-PILE"

This project at UPC has the goal to develop and test a realistic modelling platform to represent the dynamic interaction during installation of monopiles in soils. Coupled hydro-mechanical behaviour will be considered for the soil, allowing for drained, undrained or partly drained installation. Installations by vibration and hammering will be considered. Representation of the monopile will aim to reproduce the dynamic driving signals recorded at installation. Being able to correctly reproduce installation will open new fundamental perspectives into monopile design for both lateral and axial loading. Model development will be based on the Geotechnical Particle Finite Element method (GPFEM), which at present has been applied mostly to quasi-static hydro-mechanical coupled problems, but has been already adapted to high frequency dynamic loading.

2.8. Project 8: "GB-SCOUR"

In this project at Esteyco, the aim is to analyse scour development around offshore Gravity Base System (GBS) in order to optimise design scour procedures. Foundation scour is well established in bridge engineering (Hamill, 1999), where scour depth is linked to the diameter/width of structural elements (May et al., 2002). This translates to offshore monopiles and jackets relatively easily, but leads to over-estimation in scour for GBS, which have variable cross-sections. This project will include computational fluid dynamic analyses to develop a scour design approach for GBS systems with varying sections and scaled model tests. Subsequently, an optimisation model for GBS scour protection will be developed that is optimised to the scour conditions established previously. The focus will be on material optimisation and type (rock-armour, concrete mattresses, synthetic weeds) as well as investigating pre-installation requirements prior to deployment.

2.9. Project 9: "MULTI-LOAD"

This project at NTNU will develop a 1:20 experimental model of a monopile in a 4 m $\times$ 4 m $\times$ 3 m test bed filled with dry sand. The pile will be monotonically loaded to failure with multi-directional loading applied to assess the influence on the stiffness and strength properties. The accumulation of deformation under one-way and multi-directional load cycling will also be tested for a range of load eccentricities. The project will additionally focus on load-interaction effects for a range of emerging monopile geometries (decreasing L/D ratios).

2.10. Project 10: "CENCYC"

This project at UoN will investigate the effect of long-term cyclic loading (1,000s of cycles) on the performance parameters (displacement/rotation) of foundations. The prediction of wind turbine foundation response to cyclic loading under complex loading regimes remains uncertain, particularly in light of forecasted extreme weather patterns due to climate change, therefore the long-term useability of foundations requires investigation. This project will make use of novel experimental developments at UoN centrifuge facility, which enable efficient actuation of hundreds of thousands of loading cycles on foundation systems, as well as in-flight variation of the cyclic load ratio (changing from one-way to two-way loading). The project will also consider the effect of installation method of the foundation systems (wished-in-place or driven) to ascertain the effect on the foundation response to loading.

2.11. Project 11: "SOIL-MASS-DAMP"

In this project at SLPE, recently developed Finite-Element model updating approaches that estimate soil mass contribution to dynamic motion of piles (Prendergast et al., 2019; Wu et al., 2018) will be extended to estimating mass and damping in the nonlinear response range. The influence of added soil mass is often ignored in simplified dynamic soil-structure interaction models, due to difficulties in estimating its contribution to the dynamic motion. Soil is often assumed to only provide a stiffness. Moreover, quantifying the damping behaviour of various geo-materials remains a challenge. The existing FE updating procedure can only be applied to data for small-strain (linear) vibrations and only focusses on mass and stiffness updating. The DC will expand the approach to the nonlinear (large-strain) range of cyclic motions and estimate mass, (operational) stiffness and damping using centrifuge modelling of piles subjected to dynamic loading and the development of representative numerical models of these systems. These models will be updated (mass, damping, stiffness) based on the response features from the test piles.

3. Training

Throughout the 36 month PhD program, DCs engage in Supervised Research, Thematic (Discipline-specific), and Transferable Skills training. The training regime has been customised to ensure that DCs excel in their careers in the highly competitive Research & Development environment whether based in Universities, public/private Research Institute, or in Industry. The training scheme is shown in Figure 3. As the network is still in the early phase, only a small amount of training has been conducted to date, elaborated in the following subsections.

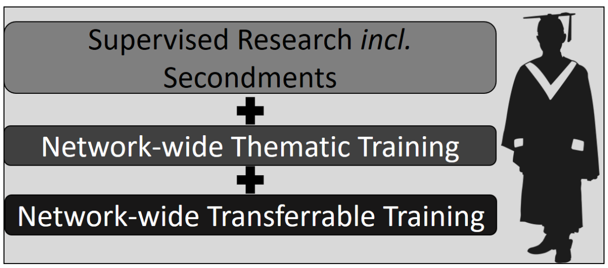

Figure 3. Integrated training plan

3.1. Geodynamics course

Between 6th and 9th November 2023, DCs had the opportunity to engage in a discipline-specific course in Geodynamics, at NTNU. The course provided the necessary background for estimating the dynamic response of foundations and vibrations in soils. Course content covered basic theory for dynamic systems with one or many degrees of freedom; wave propagation in elastic media; vibration of footings and foundations on soils; geotechnical earthquake engineering; among other topics.

3.2. Computational Analysis and Quantitative Research Methods for Engineers course

During a PhD Induction event at UoN in January 2024, DCs engaged in specialised Transferable Skills training in MATLAB and Quantitative Research Methods for Engineers. The MATLAB course covered a basic introduction to engineering computation, and was designed as an introductory course for the DCs. The Quantitative Research Methods course involved:

- An introduction to statistics for engineers,
- Understanding common statistical terms,
- Distinguishing between quantitative data types,
- Providing basic graphical and numerical summaries of data,
- Understanding hypothesis testing and p-values, and
- Interpreting simple regressions.

3.3. Future training

A range of training opportunities are in planning, including: PhD Summer Schools at UoN, UPC Barcelona, and TU Delft; discipline-specific training weeks across a range of topics; training in commercialisation, business development, communication, and presentation skills; as well as in-house training in bespoke topics related to each PhD project.

4. Conclusions

FRONTIErS Marie Skłodowska-Curie Action has been designed to constitute a best-practice model for cross-sectoral collaboration in offshore wind foundation engineering education, and its ethos can be translated to other sectors and disciplines. One of the core premises of the network is that there has recently been a growing trend of PhD graduates entering industry rather than obtaining academic posts, therefore it has become necessary to customise doctoral training schemes with an inherent industrial focus. PhDs are now seeing worth in challenges facing the industry, therefore newly formed structured programmes should encompass both academic and industrial viewpoints.

FRONTIErS has been strongly customised in this light. There are obvious benefits to having meaningful engagement between academic and industry stakeholders, such as:

a) There is a lack of available (and readily trained) graduates capable of tackling the emerging problems facing the OW sector, and

b) Often, research undertaken at universities does not translate into industrial practice.

Structured doctoral programmes are recommended to encompass joint training programmes that should be developed to better address future employer needs, and ensure that DCs are trained for potential careers in both sectors. FRONTIErS enables this, in that:

i) Individual research projects encompass both academic and industrial viewpoints in supervision, on-the-job training, and secondments,

ii) Network-wide thematic training embeds input from leading industrial experts, and

iii) Transferrable skills training comprises a cross-sectoral focus with industry and academic participants delivering the workshops/lecture series.

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