Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

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SECTION 1: PROJECT DETAILS

Project Title	Developing Damping Parameters for Irish Offshore Wind Farms
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Project Summary

In order to achieve the greenhouse gas emissions targets set out in the Paris agreement, Ireland will need to significantly decarbonise its energy supply. Due to reducing costs, offshore wind now offers a viable means for large scale decarbonisation of Ireland's electricity supply. It is predicted that the offshore wind installation rate in Europe will continue to increase resulting in an industry worth more than €20 Billion per year in Europe alone [1]. One of the key challenges in the engineering design of an Offshore Wind Turbine (OWT) relates to choosing appropriate values for damping of the OWT structure. Choosing more realistic values of damping in design can lead to significant reductions in the calculated loads acting on the structure as well as large reductions in fatigue damage, which can lead to savings of up to 10% in steel weight across the structure [2]. The primary goal of this project is to advance the scientific knowledge of OWT damping and provide accurate and realistic damping values for use in the design of Irish offshore wind farms, specific to soil types and conditions relevant for potential offshore wind development zones around Ireland. This work in this project has been divided into 5 main work packages. The research combined numerical modelling, experimental soil testing, and dynamic analysis to *enhance the understanding of soil-structure interaction effects on turbine stability and fatigue life. A desk study established environmental conditions, followed by preliminary 3D finite element (FE) modelling to assess monopile behaviour (WP1). Advanced laboratory tests quantified soil damping properties (WP2), which were then used to calibrate numerical models, particularly the HSsmall constitutive model, ensuring accurate representation of soil behaviour. Full-scale 3D FE simulations provided insights into foundation damping mechanisms (WP3), while load assessments and multi-body dynamic (MBD) modelling evaluated turbine responses under extreme environmental conditions (WP4). The findings are summarised in a guidance document (WP5) which highlights the significant role of soil damping in offshore wind turbine performance and provides critical data to optimize monopile design, improving cost efficiency and structural resilience for future offshore wind developments in Ireland.*

Keywords	Offshore wind, Damping, Soil-Structure Interaction

SECTION 2: FINAL TECHNICAL REPORT

2.1 Executive Summary

This project aimed to enhance the understanding of foundation damping in offshore wind turbine (OWT) monopiles, a critical factor in the structural integrity and long-term performance of wind farms. The project was led by Trinity College Dublin (TCD) in collaboration with industry partners Gavin and Doherty Geosolutions Ltd. (GDG) and Dublin Offshore Consultants. The study focused primarily on quantifying soil-structure interaction damping, which is essential for optimizing fatigue life predictions and structural stability of OWTs. The project comprised five key work packages:

WP1. Desk Study & Preliminary Modelling:
A comprehensive desk study analyzed metocean conditions, soil profiles, and wind turbine loading scenarios to define the basis for offshore monopile design. Preliminary 3D finite element (3DFE) models were developed to assess monopile-soil interactions under Irish offshore conditions.

WP2. Experimental Soil Element Testing:
Laboratory testing was conducted using advanced cyclic soil triaxial testing to characterize hysteretic soil damping and establish a robust soil test database. The results enabled calibration of advanced constitutive models used in WP3.

WP3. Numerical Model Calibration & 3DFE Foundation Modelling:
The numerical soil models were calibrated using laboratory test results from WP2, allowing accurate simulation of soil response under dynamic loads. Dynamic 3D finite element simulations of monopile foundations with different geometries and soil conditions were performed and the foundation damping parameters were extracted.

WP4. Load Assessment & Structural Analysis:
This WP involved developing a full aerodynamic OWT model for dynamic analysis of the structural response under various wind and wave loading scenarios. The model was used to assess the effects of foundation damping on a 15MW wind turbine. The OWT models demonstrated that foundation damping significantly influences fatigue performance, potentially leading to improved design efficiencies and cost reductions.

WP5. Guidance Document:
This WP involved developing a guidance document on how foundation damping can be estimated for use in OWT design. Three different approaches for estimating foundation damping were proposed depending on the available information and stage of engineering design The document highlights that foundation damping significantly influences structural performance and fatigue design, which can lead to improved design efficiency and cost reductions. An estimate of the potential cost reductions are described in WP5.

2.2 Introduction to Project

The development of offshore wind energy is critical to Ireland's transition towards a sustainable, low-carbon future. With its vast wind resources, the Irish offshore sector presents a significant opportunity for large-scale renewable energy generation. A key challenge in offshore wind turbine (OWT) design is the soil-structure interaction (SSI) of monopile foundations, particularly the influence of damping effects on turbine dynamics. Damping plays a crucial role in mitigating vibrations induced by wind, waves, and operational loads, directly affecting fatigue performance and structural longevity. Current industry design methods tend to oversimplify damping parameters, leading to over-conservative fatigue life estimates and potentially higher construction and maintenance costs. This research project was formed with the aim of improving design methods for offshore wind turbines, particularly with regard to monopile damping.

2.3 Project Objectives

The primary goal of this study was to develop a set of damping parameters that accurately reflect the behaviour of monopile-supported offshore wind turbines under Irish offshore conditions. The research aimed to:

- Characterize damping mechanisms in offshore wind monopiles, particularly hysteretic soil damping.
- Develop and calibrate numerical soil models using high-quality laboratory test data.
- Assess foundation damping through 3D finite element (FE) analysis, improving current design methodologies.
- Evaluate offshore wind turbine (OWT) loads and structural response, incorporating damping effects.
- Develop a set of design recommendations which can be used by Engineers designing offshore wind turbines.

2.4 Summary of Key Findings/Outcomes

Describe how your project has furthered the current state-of-the-art, current knowledge or current practice. Clearly highlight the degree of novelty and innovation demonstrated by your project.

Address each innovation in a bullet point below. Add as many bullet points as you need:

- Innovation 1: Review of design conditions relevant for Irish offshore wind farms (WP1)

  As part of this work, a detailed study was undertaken to assess the conditions relevant for Irish offshore wind farms and to define a basis for the coupled design analysis of fixed base offshore wind turbines. The report D1.1 was produced based on site specific knowledge as a result of GDGs involvement in a number of offshore wind projects around Ireland. This report offers a valuable reference for geotechnical or meteorological research for Irish offshore wind farms.

- Innovation 2: Review of soil-structure interaction damping for monopiles (WP1)

  A comprehensive review of the methodologies used to assess foundation damping for offshore wind turbines was undertaken. A detailed review of the existing research in this area resulted in a journal publication entitled "Foundation damping for monopile supported offshore wind turbines: A review" in the international journal Marine Structures which has been highly cited since publication.

- Innovation 3: Review of industry methods for applying damping in offshore design (WP1)

  A comprehensive review of methods currently being used in industry for the estimation of foundation damping for offshore monopiles was undertaken, with input for the industry partners.

A critical assessment of current industry practice was performed to help define how new methods developed in this project could fit into the industry monopile design workflow

- Innovation 4: Advanced experimental lab testing of Irish soils (WP2)

  A comprehensive laboratory testing campaign was conducted using Advanced Dynamic Triaxial Testing apparatus (DYNTTS) to quantify the damping behavior of irish soils. This dataset forms a critical reference for offshore wind developers lacking high-quality site-specific soil data. The programme focussed on samples of Blessington and Kilmuckridge sands which were reconstituted at different relative densities. A comprehensive test matrix which covers the range of stress conditions likely to be relevant for offshore monopiles was explored.

- Innovation 5: Developed 3DFE Plaxis model of monopile cyclic field tests for comparison of damping parameters (WP3)

  3DFE models of the monopile field tests from the literature, undertaken as part of the PISA project in Dunkirk, France, were modelled in Plaxis 3D software using advanced constitutive soil model calibrated using an approach developed by the PI. The model showed comparable levels of damping when compared to the field tests results indicating the constitutive soil model is capable of capturing the damping response. The results from this were published in the CPT22 conference which will be held in Bologna in June 2022.

- Innovation 6: Calibration of constitutive soil models for modelling monopile damping (WP3)

  The project successfully calibrated advanced constitutive models (e.g., HSsmall) against laboratory test data developed in WP2. These models improve predictions of monopile-soil interaction, ensuring that OWT foundation damping is accurately simulated for different seabed conditions.

- Innovation 7: Developed calibrated 3DFE model monopile models to assess foundation damping (WP3)

  Calibrated 3DFE models were used to assess the effects of hysteretic soil damping in monopile design. The study was able to demonstrate negligible radiation damping (geometric wave effects) and seperate the effects of soil hysteretic damping (material energy dissipation). Curves of damping ratio vs pile displacement were developed to enable

- Innovation 8: Developed finite element model of 15MW turbine structure in Abaqus (WP4)

  This innovation relates to WP4. In addition to development of a dynamic aeroelastic model, a detailed 3D finite element model of the NREL 15MW offshore wind turbine was also developed. This model has been benchmarked against NREL's OpenFAST code using available data from the International Energy Agency (IEA). This finite element model is the first of its kind for the 15MW offshore wind turbine.

- Innovation 9: Developed finite element model of 15MW turbine structure in Abaqus (WP4)

  A multi-body dynamic (MBD) model was developed to simulate the real-time operational behaviour of an OWT, incorporating aerodynamic, hydrodynamic, and soil-structure interaction effects. This provides an improved methodology for assessing wind-wave misalignment impacts on OWT stability. The foundation stiffness and damping parameters from WP3 were incorporated.

- Innovation 10: Guidance document for OWT damping

  A guidance document for estimating offshore wind turbine monopile foundation damping was produced. Three different approaches for estimating foundation damping were proposed depending on the available information and stage of engineering design.

2.5 Project Impact

This project has made significant contributions to the Irish energy sector, aligning with national and international policy objectives and supporting the Sustainable Energy Authority of Ireland (SEAI)'s remit. The project addresses critical challenges in offshore wind energy development by improving the methods for calculating foundation damping parameters, leading to improved structural performance and cost reductions for offshore wind turbines. The key societal, economic, and technological impacts of this project are outlined below.

Ireland has set ambitious targets for offshore wind energy deployment as part of its commitment to net-zero emissions by 2050 and the Climate Action Plan 2023, which aims for at least 7 GW of offshore wind capacity by 2030. The success of these initiatives depends on optimizing foundation design for Irish offshore wind farms, reducing installation costs, operational risks, and long-term maintenance requirements. This project directly supports these objectives by improving the accuracy of offshore wind turbine foundation models, ensuring more efficient monopile designs that reduce over-conservatism in fatigue assessments. This project facilitates large-scale offshore wind deployment by enhancing the reliability of site-specific soil damping parameters, reducing uncertainty in geotechnical design.

This research aligns with key national and EU-level policies, supporting renewable energy integration, climate action, and sustainable economic growth including Ireland's Climate Action Plan & Offshore Renewable Energy (ORE) Policy. By improving foundation performance modelling, this research directly contributes to reducing the levelized cost of energy (LCOE) for offshore wind, making projects more viable.

This project has significantly advanced offshore wind technology in Ireland by developing a dataset of damping parameters, improving numerical modelling accuracy for soil-structure interaction for offshore monopiles and improving load assessment methodologies for large-scale offshore wind turbines (e.g., 15MW turbines). These advancements contribute to reducing offshore wind project risks and uncertainties, facilitating more reliable and cost-effective wind farm developments.

The findings of this project have direct economic benefits for Ireland's offshore wind sector by reducing offshore wind project costs through improved monopile design efficiency, lowering material and installation expenses and minimizing conservatism in foundation design, allowing developers to optimize turbine spacing, foundation depth, and fabrication costs. Ultimately, this will support job creation in Ireland's renewable energy sector, engineering, and construction. By refining offshore wind foundation design methodologies, the project supports Ireland's ambition to become a global leader in offshore wind technology and innovation.

This project contributes to societal and environmental benefits by accelerating the deployment of clean energy infrastructure, reducing reliance on fossil fuels and lowering carbon emissions and enhancing public confidence in offshore wind developments by ensuring that projects are designed with maximum efficiency and reliability. By optimizing foundation designs, the environmental impact of constructing these offshore wind farms is also reduced.

2.6 Recommendations

A guidance document was developed to assist in estimating foundation damping for offshore wind turbine monopiles. The document outlines three distinct methodologies for damping estimation, tailored to the available data and the specific stage of the engineering design process. A detailed set of recommendations have been provided in the D5 Report (WP5) which provides guidance on how to calculate damping parameters for offshore monopiles.

2.7 Conclusions and Next Steps

This project has enabled key new insights into foundation damping for offshore wind turbines. Future project work should focus on expanding the database of soil tests and calibrated numerical models to include cohesive soils and glacial tills. Greater focus should be placed on cyclic accumulation properties and developing cyclic contour diagrams for different soil types, which would be very beneficial to the industry. Previous experimental testing undertaken in this project only considered small numbers of load cycles (typically <100). Future projects should focus on the effects of large numbers of cycles up to 10,000 per test. Further research could also examine the effects of asymmetric cyclic loading with non-zero average cyclic stress. There is an urgent requirement for new research in soil cyclic loading and integrated foundation models which include cyclic loading, specifically tailored for Ireland's offshore wind industry to improve engineering approaches. This could potentially lead to significant cost savings for offshore wind developers which would result in reduced costs for clean renewable offshore wind energy, provide further economic incentives for offshore wind developers and ultimately increase the rate of offshore wind development around Ireland.