1 Summary

The main idea behind the REDWIN project (REDucing cost of offshore WINd by integrated structural and geotechnical design), which was initiated in 2014, is to close the gap between the structural and geotechnical disciplines that has hampered optimal design of offshore structures for years. The dynamics of these structures is heavily influenced by the stiffness of the foundation. However, this stiffness is not constant, but depends on the response of the structure. In conventional industry practice, it has been widely accepted that the behaviour of foundations cannot be included in structural analyses in a realistic way – no matter how detailed and accurate it is described by geotechnical engineers – because good foundations have not existed in any structural software. This problem has been present in dynamic analyses of buildings and offshore oil & gas structures for years, but has received renewed focus in design of offshore wind turbines, which are more slender and dynamically sensitive structures. In the REDWIN project, a library of soil-foundation models has been developed to address this need. The models capture almost all foundation types, and will make structural engineers capable of analysing and designing offshore wind turbines more reliably. Fundamental foundation behaviour such as non-linear stiffness, coupling between load components, material damping, and effects of cyclic loading are included in the developed models. The improved reliability in the analyses make it possible to optimize the structures, which ultimately results in better designs that will reduce the cost of energy. This is reflected in the title of the project, namely *Reducing cost of offshore wind by integrated structural and geotechnical design*. The library of soil-foundation models can be used for free, and will be shared with interested users upon request.

2 Project objectives and background

The cost of offshore wind energy production must be continuously reduced to improve its competitiveness compared to other energy sources. The 4-year research project *REDWIN – Reducing cost of offshore wind by structural and geotechnical integrated design* – was initiated with the primary objective of contributing to such cost reduction by enabling better integration of the geotechnical discipline into the design process of offshore wind turbines (OWTs). To achieve this goal, several secondary objectives were defined:

- Development of a library of OWT foundation models suitable for implementation in integrated analyses tools through standardized interfaces. Calibration and validation of these models.
- Implementation of the new foundation models into the integrated simulation tool 3DFloat.
- Development of computational tools for estimating soil and foundation damping.
- Processing and analysis of measurements from full-scale OWT structures to quantify stiffness and damping properties.

- Identifying the key parameters driving the design of OWT structures, and quantify the potential cost savings by integrated design through re-design.
- Dissemination and communication of the project results.

3 Most important R&D tasks performed, and groups that have played a key role in the project.

The REDWIN project consortium consisted of actors with long research and industry experience within offshore wind energy. The project's four research partners (NGI, IFE, NTNU and Dr. Techn. Olav Olsen) have conducted the majority of the research and development activities, the most significant of which are listed herein:

- NGI (Norwegian Geotechnical Institute) has carried out the R&D work related to soil and foundation modelling, model development and validation, signal processing and data analysis. This has included the development of a library of new foundation models for shallow and deep foundation suitable for use in integrated analyses of OWTs, formulation of practical procedures for practitioners on how to use the new foundation models, development of computational tools for determining soil damping properties in Direct Simple Shear (DSS) laboratory tests and tools for estimating the overall damping in OWT foundations, processing and analysis of full-scale measurement data, and comparison of calculated OWT response with full-scale measurements.
- IFE (Institute for Energy Technology) has led the development of the integrated simulation tool 3DFloat, in particular the implementation and testing of the new REDWIN foundation models. An important part of this work has been to investigate the impact of the models by studying the sensitivity of foundation behaviour on the structural response of typical OWT designs. In addition, IFE has conducted sensitivity studies investigating the driving design parameters for both ULS and FLS load cases, and quantified the potential benefits of using the REDWIN foundation models for OWT analysis and design.
- NTNU has hosted the two PhDs that have been completed during the project, Ana M. Page (project doctoral research fellow) and Kristoffer S. Skau (NGI doctoral research fellow associated with the project in-kind). Both PhDs have been focusing on formulating, implementing and validating the library of new foundation models.
- Dr. Techn. Olav Olsen has led the activities related to OWT re-design and cost analysis. This has included an evaluation of the cost savings potential by using the newly developed REDWIN foundation models in design instead of the conventional *p-y* curve approach.

The project's industry partners, Equinor and Vattenfall, have provided partial financial assistance and have contributed with essential full-scale measurement data from operating offshore wind farms. They have also given valuable input and recommendations to the conducted research activities to ensure that the output of these meet industry requirements and can be implemented for actual projects.

4 Project's implementation and use of resources.

The project's activities consisted of several modules that were conducted independently by the research partners together with several joint research activities to link the individual studies. For example, while the advanced foundation models were being developed at NGI and NTNU, a simple model provided by NGI was implemented by IFE in their 3DFloat code in order to find out the challenges and requirement for model implementation and identify the requirements for the final models for a seamless integration. A schedule was defined at the beginning of the project and was monitored/adjusted during the bi-annual meetings of the research partners. In addition, a Technical Advisory Team (TAG) was established that participated in the annual meetings and gave suggestions for improvements and new ideas.

With the above planning, the resources at the participating institutions were effectively utilized without any unnecessary overlapping or loss of time due to un-coordinated work. In addition, the industrial partners were extremely helpful technically and in providing unique data that enhanced the value of the developed tools.

5 Results achieved in the project

One of the most significant outputs of the REDWIN project is a library of new soil-foundation models for shallow (e.g. bucket foundations) and deep foundations (e.g. monopiles) for time-domain dynamic analysis of OWTs, that can be implemented in integrated analysis tools through standardized interfaces. These new foundation models overcome several of the limitations inherent in existing foundation design tools, and allow designers to adopt advanced, accurate, and validated foundation models in all phases of OWT design. An important attribute of these foundation models is that they are flexible in how the user input is obtained. The project has documented several methods to obtain this input, ranging from very simple procedures requiring only basic soil input parameters, to more advanced non-linear FEA that can make use of detailed site investigations and corresponding laboratory testing.

Another important output of the project is the improved understanding of soil and foundation damping. A procedure was established to estimate damping arising from the soil at various levels by first extracting damping at a soil element level and then utilize these results to compute an overall global foundation damping relevant for the integrated analysis. Such tools allow the structural engineer to get a better understanding of the contribution from foundation hysteresis damping to the overall energy dissipation in the OWT-foundation system.

Studies of the impact of the new foundation models have been an important task in the project's final year. These studies have demonstrated how the REDWIN models can benefit future OWT design compared to conventional models by reducing steel tonnage and thereby cost. Comparisons between calculated and measured responses at an actual OWT installed in the North Sea have also demonstrated that the REDWIN models are much more accurate than existing models in predicting the fundamental vibration properties of OWTs. These results have contributed to improving the understanding of OWT behaviour and the factors that govern OWT design.

6 Significance/benefits of the results

The REDWIN project has contributed to a significant improvement of state-of-the-art geotechnical modelling capabilities for the soil and foundations for OWTs. The new foundation models offer effective, practical and accurate representation of foundation and soil behaviour, which can be used in integrated dynamic time domain analyses. A maintained focus on practicality and flexibility in the calibration of the model input have ensured that they are suitable for use by practicing engineers in all phases of OWT design. This is evident by the fact that several large industry actors are now implementing the models in their own design programs.

In sum, the project has helped remove barriers between structural and geotechnical engineers, and represents an important step towards integrating the geotechnical discipline into a streamlined design process for OWT structures. It is expected that the project results will enable lowering of the cost for future generations of OWT foundations, and that it will be an important tool for evaluating the potential for lifetime extension of existing offshore wind farms.

7 Disseminating and utilising of results

From the start of the REWDIN project there has been high emphasis for the project to publish its results in peer-reviewed international journals. This has resulted in more than 20 publications in international peer-reviewed journals and at internationally recognized conferences. Focus was also given to disseminate outcomes of the project to practitioners in the offshore wind energy industry. This was – for example – achieved through the REDWIN final workshop in Oslo in November 2018 which gathered more than 100 participants from across the offshore wind industry and academia. This successful workshop had keynote speakers sharing their views on future opportunities and challenges the offshore wind energy industry will be facing, and brought practitioners and researchers together to discuss the future needs for research and development in the industry.

Several of the results of the project will go beyond the completion of the project. For example, the REDWIN foundation models will be used as part of the upcoming code-to-code comparison study OC6 hosted by the National Renewable Energy Laboratory (NREL). Additionally, several of the largest actors in the offshore wind energy industry (e.g. Equinor, Siemens Gamesa Renewable Energy) are working on implementing and making use of the new foundation models.

The results of the project have also given the partners ideas to launch new research proposals. For example, new initiatives have been taken for proposals within both NFR's ENERGIX program and EC's H2020 program. Therefore, while enhancing the knowledge and expertise of the partners and serving the industry with new design tools, REDWIN has enabled the partners to achieve higher positions in the research community and step to other challenging domains.