REDWIN – REDucing cost in offshore WINd by integrated structural and geotechnical design

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Abstract. The cost of offshore wind energy production has to be reduced continuously to improve its competitiveness compared to other energy sources. To contribute to this goal, a 4-year research project *REDWIN – REDucing cost of offshore WINd by structural and geotechnical integrated design* – is currently ongoing, addressing the challenge of integrating the geotechnical discipline in the design process. The project aims to develop foundation and soil models to be used in dynamic time-domain analyses of offshore wind turbine structures. A library of models has been developed for representation of the most common foundation types. The models can be applied to different ground conditions by site-specific model input. To make the models applicable for practical usage, it has been important to balance the need for computational effectiveness against the need for accuracy. Studies so far indicate that the foundation models improve the accuracy in the integrated analyses.

1. Introduction

Due to slenderness and dynamic sensitivity of offshore wind turbines (OWT), as well as complex loading environment, integrated analyses are required in design. The integrated analyses include loads from wind, waves, current, turbine controller performance and soil or foundation support. The soil/foundation models are often overly simplified. Linear and nonlinear uncoupled springs (p-y curves) is standard practise for monopiles, and linear elastic lumped stiffness models are often used for shallow foundations such as gravity based foundations and buckets. Comparison between the computed natural frequency of OWT used in design and the natural frequency measured on site indicate that the foundation stiffness is not satisfactorily modelled. This may affect the fatigue life of the structure and the maximum loads. The lack of good soil/foundation models also prevents the design from benefitting from the investment in soil investigation and accurate interpretation of soil behaviour and site condition.

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More elaborate foundation models are required to improve the accuracy of integrated analyses. The ongoing research project REDWIN – *REDucing cost of offshore WINd by integrated structural and geotechnical analyses* which started in 2015, addresses this issue. The title points to the key aspects in the project: Reducing cost by integration of the geotechnical properties in the structural design process. The NGI-led research program is sponsored by the Research Council, Statoil and Vattenfall. The geotechnical department at the Norwegian University of Science and Technology (NTNU), Institute for Energy Technology (IFE) and Dr. Techn. Olav Olsen take part within the project as research collaborators. This paper explains why the wind industry should focus on the aspect soil and foundation response in OWT design analyses, and it summarize briefly some results and outcomes of the project at the time of writing this paper. The project aims at developing foundation and soil models to be used in integrated structural analyses under wind and wave loads. These models should address fundamental soil and foundation characteristics, such as soil nonlinearity, soil damping, site specific soil variability and coupling effect between load components.

2. Dynamics of offshore wind turbines

2.1. Loads and eigenfrequencies

OWTs are slender structures, exposed to a complicated load regime with various frequencies. The excitation loads from the blade passing, the so called 1P frequency, and from the full turbine rotation at 3P frequency, affect the steel structure in fatigue, which is design driving for the OWT. Because of this, the OWT has to be designed with a natural frequency separated from these excitation frequencies. Figure 1 illustrates the power spectrum density of the loads from wind and waves and the 1P and 3P frequency range of some selected turbines. Typically, OWT are designed with a natural frequency between 1P and 3P, denoted soft-stiff design, indicated in Figure 1.

2.2. The importance of foundation behaviour

The narrow frequency band makes the prediction of foundation stiffness important, since it influences the overall dynamic behaviour of the OWT. The extent of influence depends on the relative stiffness of the foundation and the tower. It is up to designers to choose how to balance the tower and foundation flexibility. Two extreme designs are illustrated in Figure 2a, where one of the parts (either the tower or the foundation) is assumed perfectly rigid. The extreme designs make the dynamic response of the OWT governed by the foundation stiffness or by the tower stiffness.

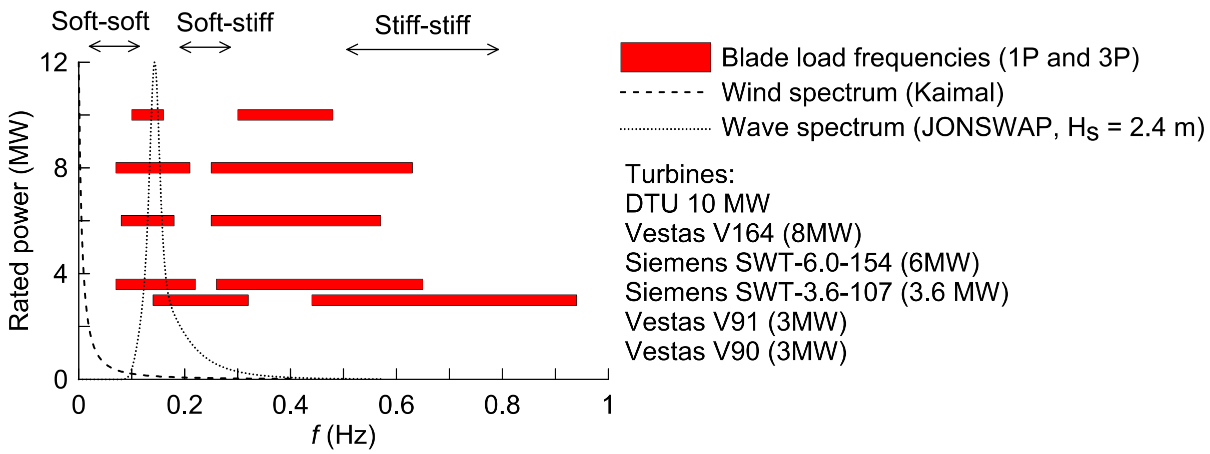
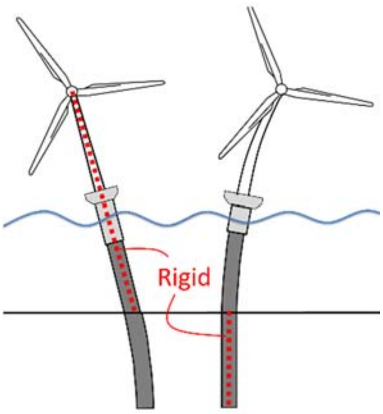


Figure 1 Load frequencies from wind, waves and blade rotation for some selected turbines (after Bak et al., 2013; Arany et al., 2016).

Soil properties have inherent uncertainties compared to steel and this must be reflected in the design practice. To reduce the importance of this uncertainty, the OWT is designed such that the overall dynamic behaviour is most influenced by the tower flexibility and less by the foundation flexibility. However, this may not be the most cost effective solution. Figure 2b illustrates this point by results from a sensitivity study considering the effect of foundation and tower stiffness ratio on the natural system frequency. The study is based on an OWT installed in a North Sea wind farm. The figure shows the first natural frequency normalized by the natural frequency of a fully clamped tower at mudline. The natural frequency decreases as the foundation stiffness reduces. The measured natural frequency and the back-calculated normalized stiffness of the real design of the OWT is also included as an example of how a specific foundation-tower stiffness is balanced. In the actual construction, referred to "as built", the dynamic behaviour is mainly controlled by the tower stiffness. However, the frequency target in the Design Basis was lower, giving a foundation-to-tower stiffness ratio less than 6. In this range, the tower stiffness governs the natural frequency of the whole system. It is useful to future design if similar plots based on other turbine designs are made available in the public domain to reveal typical design practice.



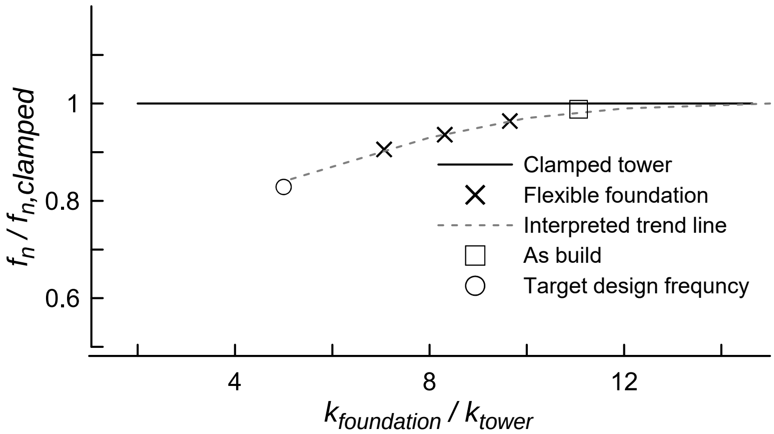


Figure 2 Dependence of OWT natural frequency on foundation stiffness a) Fully clamped foundation and fully rigid tower above mudline, b) OWT natural frequency as function foundation and tower stiffness ratio.

Improving the understanding of the OWT dynamics is of great importance for two reasons. Firstly, measurements suggest that stiffness of OWTs are systematically under predicted [3,4]. Figure 3 summarize findings from [4] which assessed natural frequency measurements from over 400 wind turbines and compared them with design predictions. The deviation varied from 0 – 20 %. Secondly, any change in the natural frequency has an impact on the fatigue damage of the structural components. Schafhirt *et al.* [5] investigated the effect of foundation stiffness on the fatigue damage using the OC3 code comparison turbine from NREL [6]. Figure 4 illustrates the fatigue damage sensitivity to natural frequency changes. The figure gives the accumulated fatigue damage in the pile at mudline as function of changes in natural frequency [5].

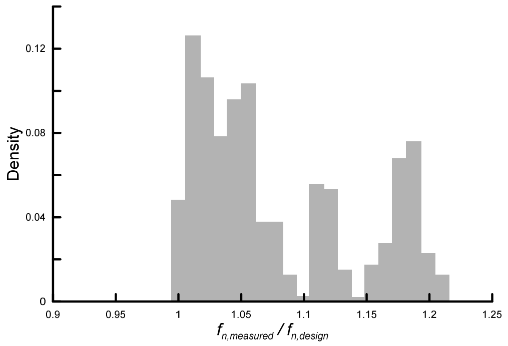


Figure 3 Measured natural frequencies versus frequency predicted in design for more 400 OWT (after [4]*).*

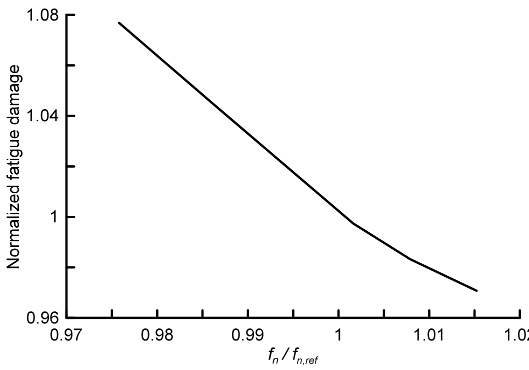


Figure 4 Effect of change in natural frequency on the accumulated fatigue damage (adapted from [5]*).*

3. REDWIN research project

The impact of the foundation behaviour on the OWT dynamics give a strong incentive to accurately model the dynamic behaviour of the foundation of the OWT in the design. DNV [7] recommend to carry out so called *integrated analyses* in the time domain to ensure a good dynamic representation. These analyses include: wind and wave loads, blade pitch controller, structural dynamics and soil/foundation response. The integrated approach is motivated by the observation that the loads and the reactions are strongly coupled. The time domain analyses are motivated by the fact that the load and reactions are strongly nonlinear. State of the art of integrated analyses today include foundation behaviour, hydrodynamics, aerodynamics, structural dynamics and the blade pitch controller system. In the REDWIN project, the program 3DFloat [8] developed at IFE was used to carry out such aero-hydro-elasto-dynamic analyses. Figure 5 illustrates loads and reactions included in integrated analyses. Figure 6 shows foundation types considered in the REDWIN.

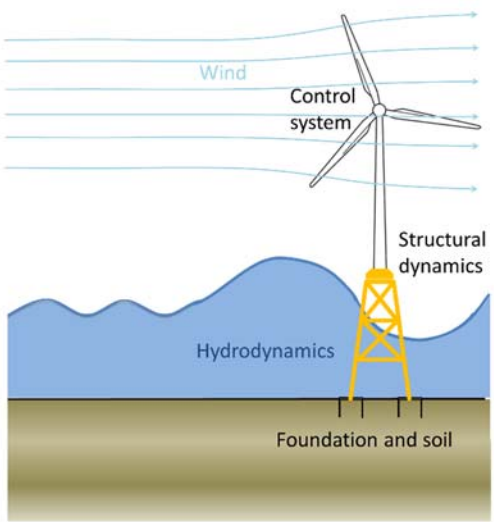


Figure 5 Loads and reaction included in integrated analyses.

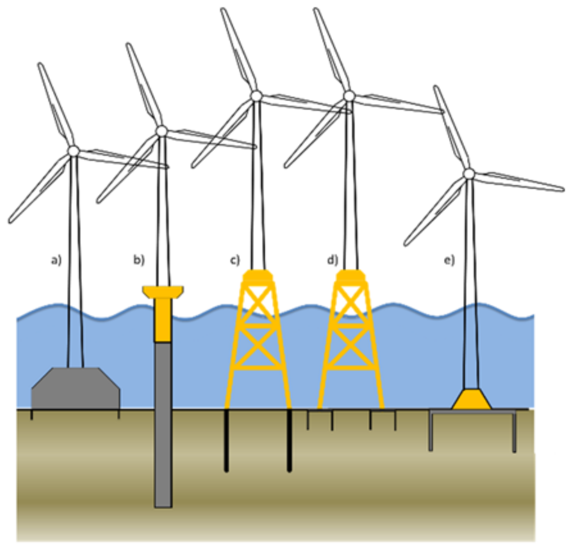


Figure 6 Foundation type considered in REDWIN project (OWTs not in scale).

Several geotechnical disciplines are required to accurately model the soil and the foundation response. Site investigations have to be planned and closely followed accompanied by laboratory testing. Interpretation of soil parameters and soil characteristics has to carried out prior to computation of the foundation response. Finally, the foundation response has to be described in a mathematical form such that it can be implemented in the integrated analyses. Figure 7 illustrates this chain of activities influencing the foundation stiffness as it finally appears in the integrated structural analyses. The REDWIN project aims to address three of the aspects mentioned below: The computation of the relevant foundation and soil response, their implementation in integrated analyses, and finally assessing the effect of the foundation and soil response by integrated analyses. To improve the geotechnical accuracy in the integrated analyses it was clear that a significant gap existed in the chain in Figure 7; namely the lack of numerical models for the foundation and the soil available for integrated analyses. Thorough work on interpretation of soil parameters and advanced geotechnical analyses are difficult to justify if the same accuracy cannot be implemented in the integrated dynamic analyses.

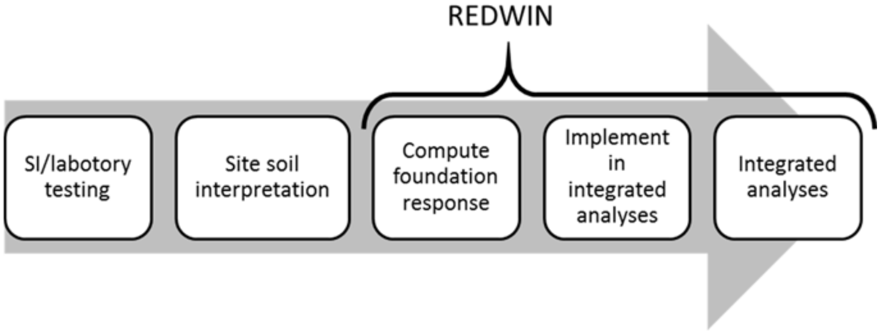


Figure 7 Design chain from soil investigations to response representation in integrated analyses

4. Soil and foundation models for integrated analyses

4.1. Present industry practice

The numerical models of foundation response that are used in design work today are overly simplified. It is not within the scope of this paper to give a detailed review of the different models available; reference is made to [9] for a thorough discussion on the topic. However, some comments are included in the following. The models used are mainly simple 1D springs. For shallow and skirted foundations, these are typically linear elastic and defined according to the load level of interest. The soil response is obviously not linear and iterations between structural and geotechnical analyses are often required. This process, which is illustrated in Figure 9, is time consuming, hence costly for developers. In addition, the iterative approach is questionable when the load histories are strongly irregular, as discussed in [10].

For monopiles, the design approach is more standardized by the use of the *p*-*y* approach where the pile is modelled as a beam and the soil is represented as a series of discrete, uncoupled, non-linear springs. The springs relate the local lateral resistance, *p*, to the local lateral displacement of the pile, *y*. Different formulations are proposed depending on the type of soil (sand or clay) and the type of loading (static or cyclic). A detailed description of the approach is given by e.g. Reese and Van Impe [11]. The current API *p*-y curve formulations, originally developed for slender piles are also used for design of monopiles. The formulations are primarily based on the work of Matlock [12] for laterally loaded piles in clay and Reese et al. [13] for laterally loaded piles in sand. The shape of the API curve for clay is defined by ε_{50}, the soil strain at 50 % shear stress mobilization ($\tau/\tau_f = 0.5$). The shortcomings of such a simple formulation can be illustrated by comparing the response of two clays from an offshore wind farm in the North-Sea. Zhang and Andersen [14] have shown that the stress-strain DSS curve of a clay has the same shape as the *p*-*y* curve for a monopile in the same material. Thus, the shape of the DSS-response is directly comparable to the *p*-*y* curve shape. Figure 8 shows the stress-strain curves from static DSS tests of two over-consolidated North Sea clays. The shear stress is normalized by the maximum shear stress and the shear strain are normalized such that the shear strain at 50% mobilization (γ_{50}) is similar for both curves. However, the curves are still very different. The difference in the example may appear obvious for geotechnical engineers, but it challenge the pile design practice in the offshore wind industry. The REDWIN models which are presented later address this challenge by a flexible formulation that can capture greater variety of soil response. Several modified *p-y* curves for monopiles have been suggested the last decade. Most significant is the recent PISA project, which revised the *p-y* curves and suggested improved functions based on large scale testing and FEA [15,16].

An alternative modelling approach, frequently suggested by researchers to represent shallow foundations, is the macro-element approach. Macro-element models reduce the foundation and the surrounding soil to a force–displacement relation at one point at the interface of the foundation and the structure. The term macro-element, first used in the early 1990s [17], has roots back to the pioneering work of Roscoe [18] and later Butterfield [19,20]. The concept of macro-elements has been further developed for earthquake and offshore applications, e.g. bridge piers and spudcans for jack-ups. The theoretical framework behind macro-element models has been adapted from soil modelling. The early models were developed for static loading within the elasto-plastic framework [17,21]. Later, models accounting for cyclic loading were developed in the framework of hyperplasticity [22], hypoplasticity [23] and multi-surface plasticity [24]. Unfortunately, the models have to a limited degree entered in design practice. There may be several reasons for this. However, two reasons appear prominent. While the theoretical formulations of existing models are well documented in multiple papers, the available literature describing usage and case studies is very limited. Secondly, the input parameters are predefined for idealized conditions from model tests. This makes adaption to complicated sites in the field more difficult.

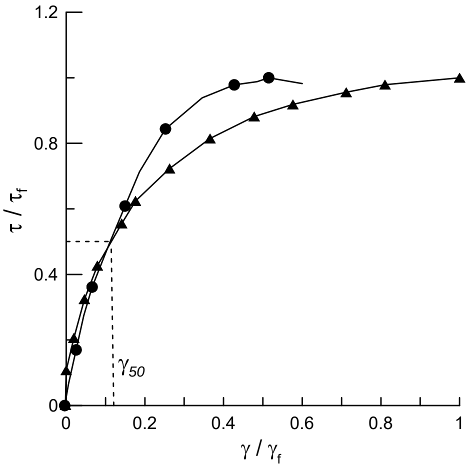


Figure 8 Stress-strian curves from two DSS tests on over consolidated North-sea clay

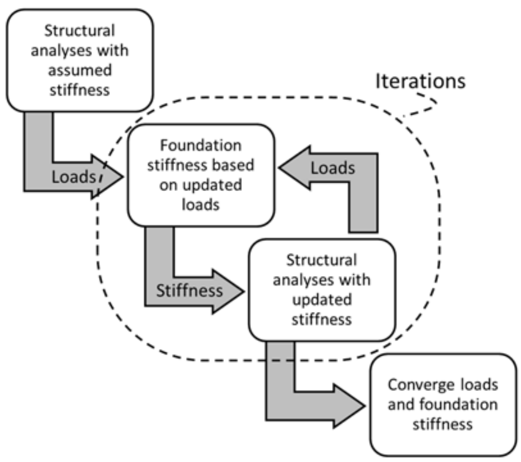


Figure 9 Iteration flow in computation of foundation stiffness

5. REDWIN foundation models

The models developed in REDWIN aim to answer the issues raised above. This has led to some general principles for model development:

1. Application oriented models such that it is intuitive to choose a suitable model for the problem and foundation type of considerations.
2. User interface understandable to practitioners.
3. General models to capture different soil conditions.
4. The models should work in time-domain, which means they should exhibit realistic response though a load cycle, e.g. reduction in stiffness as function of load level and generation of material damping.

To ensure applicability to different structures, a library of soil/foundations models was developed. The models developed so far have focused on monopiles and shallow skirted foundations. The model developed for shallow skirted foundations is applicable both to gravity based foundations and to bucket foundations. For monopile foundations, two models are developed. One model follows the traditional distributed *p-y* curve approach where the monopile foundation is explicitly included in the integrated analyses. The second model for monopiles is a macro-element where the monopile is represented as a structural boundary at seabed.

The user interface is intuitive since the model input is physically interpretable. Typically, one or several load-displacement response curves have to be specified as model input. This response is typically computed in any design case, often by FEA, and the method used to establish the curves are independent of the specific models. It also means that potential degradation effects from cyclic loading can be included in the load – displacement curves specified as input.

The flexibility is obtained by avoiding specific hardening functions and avoiding hardcoded relations between the response in different directions. In practice, this means that the model can fit very different response curves, e.g. the two stress-strain curves shown in Figure 8.

5.1. Mathematical formulation

The models are formulated within the theoretical framework of multi-surface plasticity [25,26]. In this framework, the plastic component, which gradually increases as function of mobilization, is the sum of several plastic contributions. Mathematically this is expressed as:

$$d\boldsymbol{u} = d\boldsymbol{u}^e + d\boldsymbol{u}^p = d\boldsymbol{u}^e + \sum_{i=1}^{n} d\boldsymbol{u}_i^p(\boldsymbol{F}, \boldsymbol{a}) \qquad (1)$$

The displacement increment $d\boldsymbol{u}$ caused by a load increment can be divided up into an elastic part, $d\boldsymbol{u}^e$, and a plastic part $d\boldsymbol{u}^p$. The plastic part is the sum of n contributions. Each contribution is a function of the total loads and the state parameter, which keeps track of the recent load history. The state parameters in the REDWIN models are related to kinematic hardening such that the model produces damping but no accumulation of displacement. The plastic contributions can be formulated in different ways. For REDWIN model 1 (1D), the contribution is defined by a set of internal elasto-plastic springs in parallel as shown in Figure 10a. The principle is illustrated by 3 springs in parallel, each with its own stiffness (k) and yield load (f). The displacement is similar in all the springs and the total stiffness will be stepwise reduced as the springs yield one after the other during the loading. For the models with 2-6 DOFs, the plastic contributions are given by surface translation forced by the movement of the total load position in the load space. The figure shows how surface translation leads to additional plastic displacement. Every new surface translation adds more plastic displacements giving a stepwise reduction in stiffness. The figure also shows how the models respond to both monotonic loading and cyclic loading with load reversals. The principles of both models are built on the models suggested by [27] and are illustrated in Figure 10. *Table 1* summarizes the developed models and the foundation type they are intended for.

5.2. Model input

The model behaviour depends on the computed load-displacement curve. This is more extensive than e.g. the API *p-y* requirements, but the input ensures adaptability to different site conditions, and the load-displacement curves have a clear physical interpretation. Facing layered and varying ground conditions offshore, FEA is the most accurate and flexible method for establishing response curves assuming the soil model is suitable and its parameters are properly defined. A thorough discussion on the advantage of using FEA for determining foundation response is given by Page et al [28].

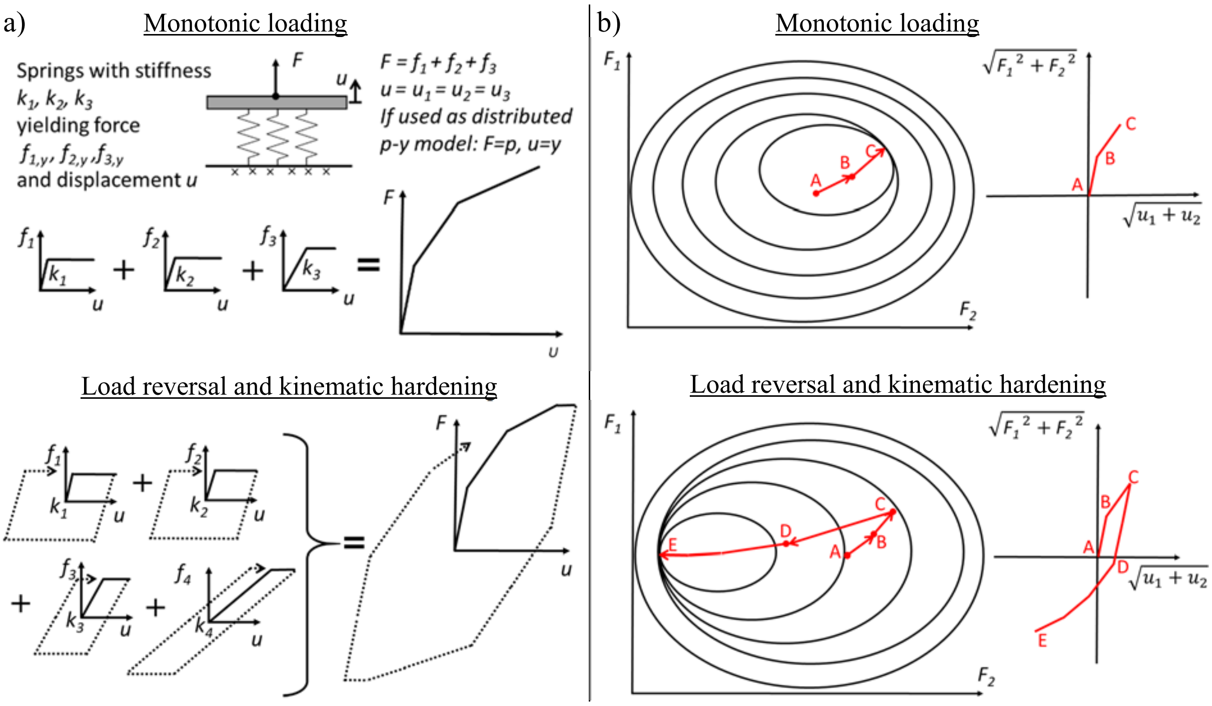


Figure 10 Illustration of the multi-surface plasticity concept a) 1D- parallel coupled principle, b) 2D-multi-surface translation in load space

Geotechnical engineers are used to delivering load-displacement curves interpreted as a load dependent stiffness input. It should be noted that the foundation models in *Table 1* will also produce damping through a load cycle. Carswell *et al.* (2015) and Aasen *et al.* (2017) have demonstrated that the foundation/soil damping may influence the design, in particular the fatigue damage. However, up to now, it has not been common to compute foundation damping in design, partly due to lack of available analyses tools. As explained in the next section, tools has been developed in the REDWIN project to address this.

5.3. *Assessment of foundation damping*

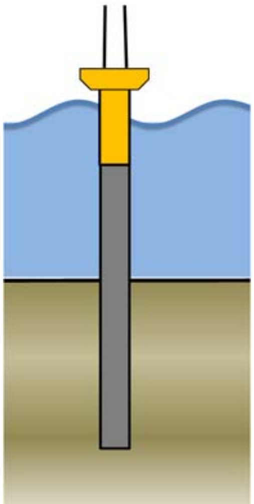
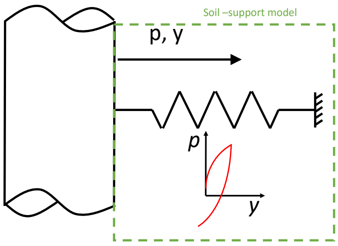
The type of foundation damping of greatest relevance to the OWT is the material or hysteretic damping. The radiation damping is less relevant as it mainly influences the dynamics at higher frequencies. A procedure was therefore established in the REDWIN project to estimate damping from the soil. The procedure involves the steps from extraction of damping at soil element level to computation of a global foundation damping. Figure 11 illustrates the steps in the calculation of foundation damping based on the material damping measured in laboratory test. These steps are a) Cyclic laboratory testing. b) Soil damping extracted from the tests in the form of damping as function of cyclic strain levels. c) Overall foundation damping computed in FEA for the relevant load level by integration of strain and dissipated energies on soil element level. This can be written:

$$D_{found} = \frac{\sum(V \cdot E_h)}{4\pi \sum(V \cdot E_p)} \tag{2}$$

where E_h is the energy loss and E_p potential energy of the soil elements. d) By computing the damping at different loads levels, a damping – load curve for the foundation is established.

The damping produced by the macro-element model, which is based on the load-displacement curve input, can be compared with the computed damping. Experience shows that the curves agree reasonably well for the load levels critical to OWT. However, the models obey Masing's rule, which may overestimate the damping at high load levels. The procedure suggested by Kaynia and Andersen (2015) may then be applied to find a reasonable approximation.

Table 1 Foundation types and available soil/foundation models

<table>
<tr><th>Foundation and substructre</th><th>Model applicable</th><th>Loading regime</th></tr>
<tr><td rowspan="2"></td><td>Redwin model 1

</td><td>Distributed 1D model to be applied to any DOF.</td></tr>
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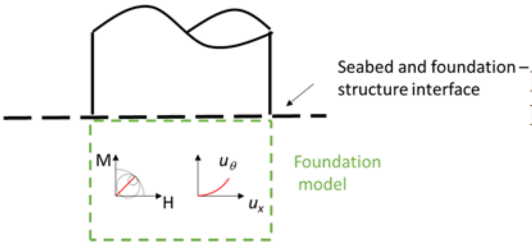
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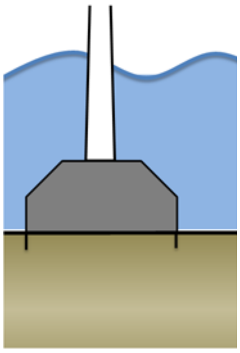
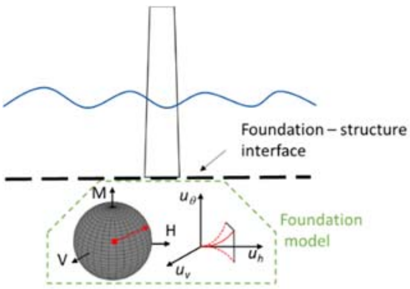
<tr><td></td><td>Redwin model 3

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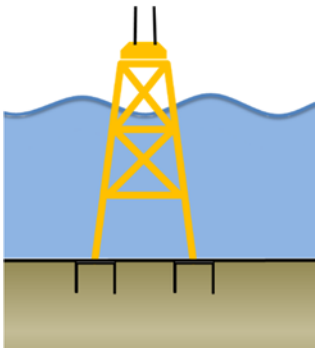
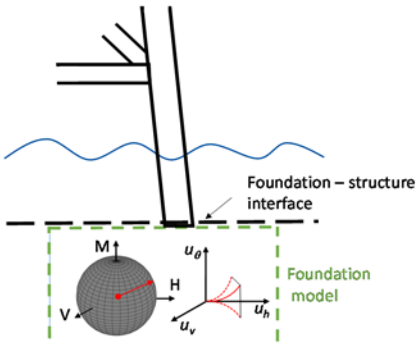
<tr><td></td><td>Redwin model 3

</td><td>Vertical-Horizontal-Moment-loading</td></tr>
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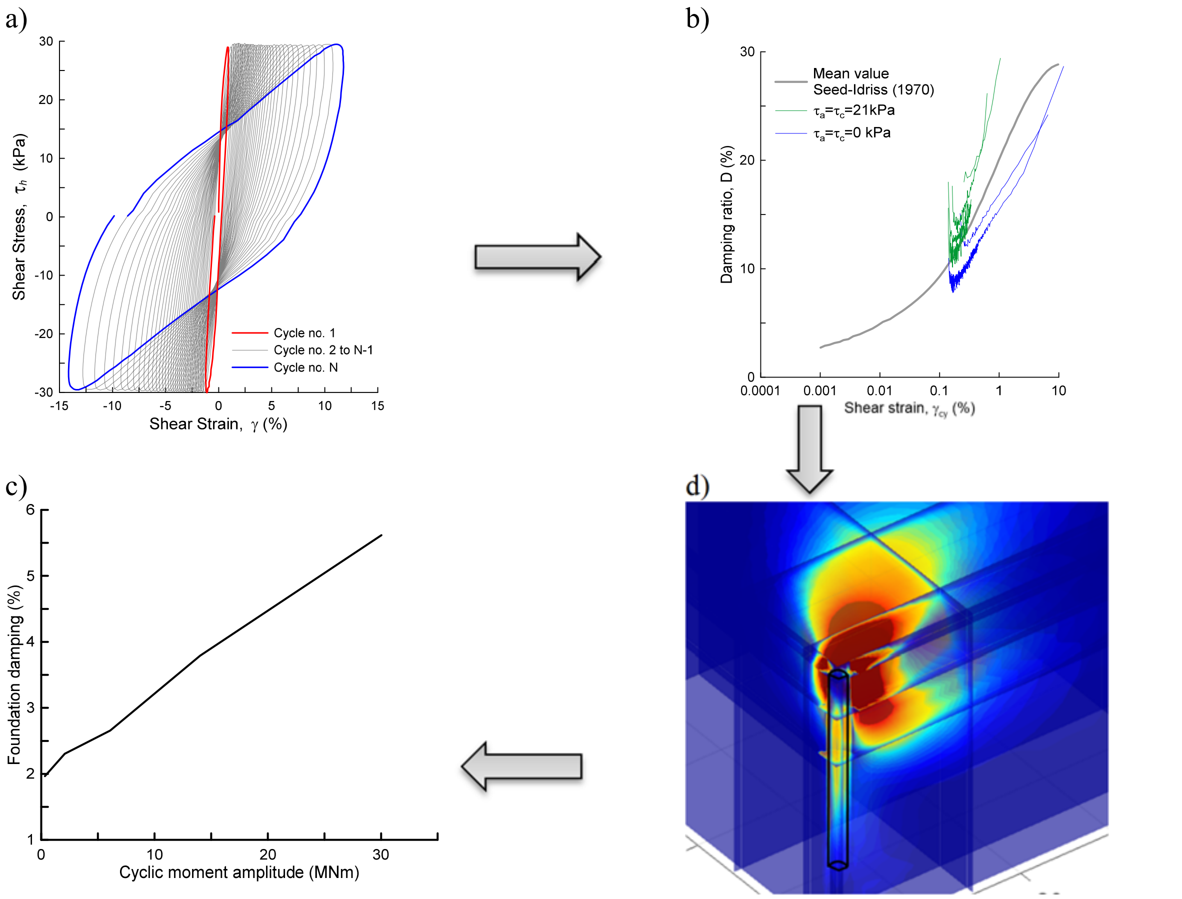

Figure 11 Computation of foundation damping. A) Laboratory sample testing, b) Extraction of damping for the soil element, c) Integration of the damping in soil volume d) Foundation damping as function of cyclic moment amplitude.

6. Model demonstration

The performance of one of the REDWIN models is demonstrated for a layered site with a gravity based foundation supporting a monotower. The REDWIN model 3 is suitable for such a foundation and loading regime. A thorough description of the model is given in [32]. However, Figure 12 summarizes some key steps in the process of defining input and producing model response. Figure 12a shows the FEA used to compute the responses in three directions of loading, which are shown in Figure 12b. The response of the macro-element model will then reflect the soil response modelled in the FEA. For dynamic OWT analyses, the response should reflect the cyclic behaviour. Figure 12c shows an example of computed moment and rotation response through a 10 min time history.

7. Impact of foundation models

Studies of the impact of the foundation models will be one of the most important tasks in the project's final year. The studies will reveal insight into how the models influence OWT design compared to conventional models expressing the effects on quantities such as steel utilization and cost. Some studies, have already been carried out, with useful and informative conclusions. They indicate that REDWIN models are more accurate than existing ones and have a positive effect on cost reduction. Two studies are briefly summarized herein.

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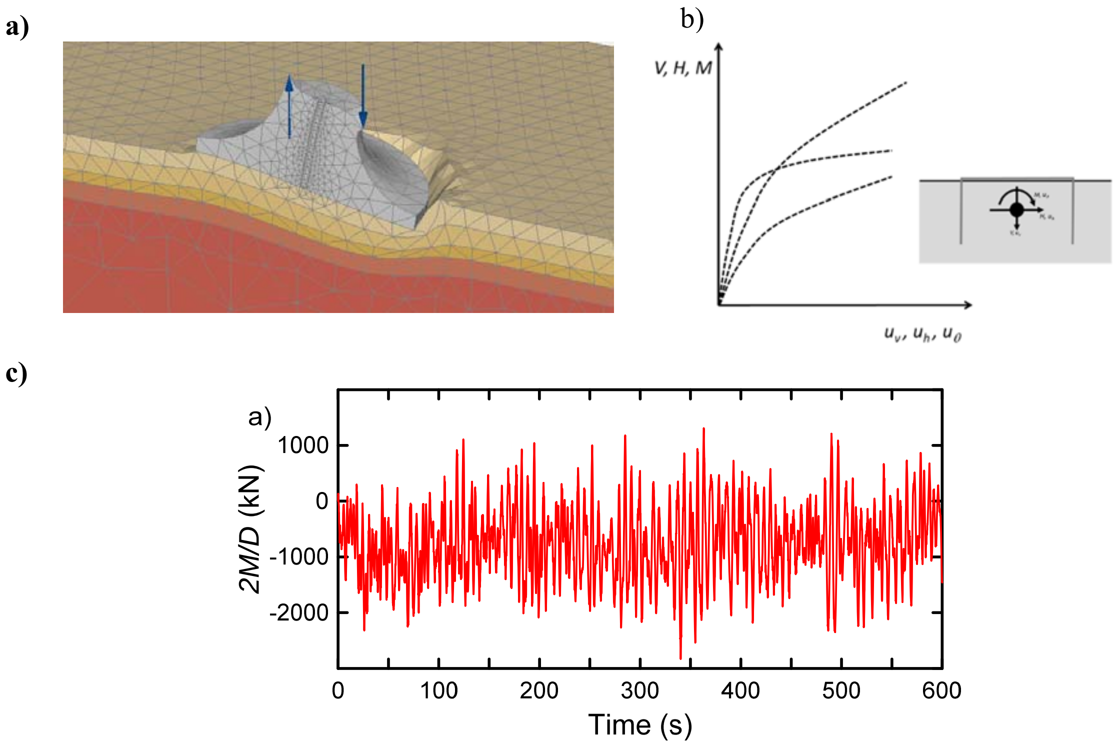

Figure 12 Demonstration of model response. a) FEA of foundation with site spesific data, b) Uniaxial load response as input to model, c) Macro-element response - Moment and rotation through a 10 min time history.

7.1. Foundation effect on monopile fatigue damage

The study by Aasen *et al.* [30] considered the 5MW wind turbine from the National Renewable Energy Laboratory (NREL) according to the OC3 Phase II [6]. The turbine is supported by a 6m diameter, 36m long monopile installed in medium dense sand. The study investigated the influence of different foundation models on the fatigue damage. The fatigue damage was computed based on time domain analyses in the software 3Dfloat [8]. The modes were all relatively simple but the study revealed important information about the impact the of foundation behaviour on the overall design. The following recap include results from four foundation models:

A. API *p-y* distributed elements.
B. Linear elastic model at mudline
C. Linear elastic spring at mudline with viscous damper (ca. 1.5 % foundation damping)
D. REDWIN model 1 from *Table 1* used as a lumped foundation model applied to the rotational degree of freedom in the depth of the rotation centre.

The computed normalized fatigue damage for the monopile is shown in Figure 13. The most important observation is that the relative difference on fatigue damage is significant, thus the foundation behaviour has an impact on fatigue – a design driver in monopile design. A closer look also reveals that both stiffness and damping influence the fatigue damage. The stiffness influence can be seen from the difference between model A and B, which has different stiffness and no damping. The damping influence can be seen from the difference between model B and C, which has the same stiffness but 0 and 1.5 % foundation damping respectively. Finally, it is encouraging to see that model D (REDWIN model 1), which is considered to be the most accurate model, gives less fatigue damage than the other models.

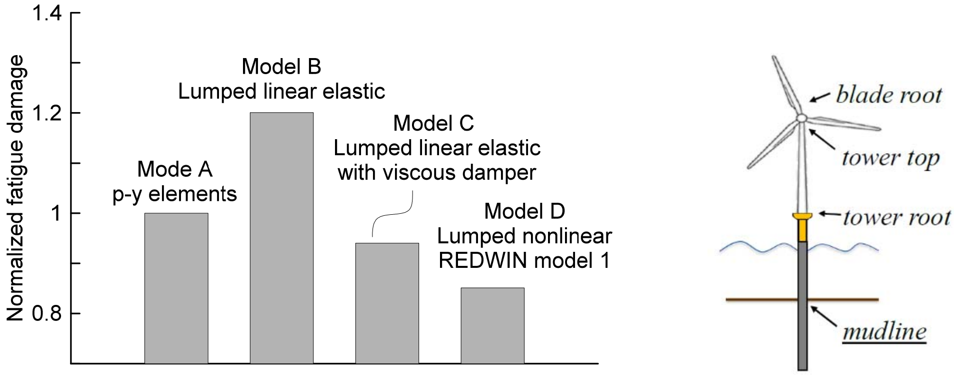

Figure 13 Foundation model influence on fatigue damage at tower root after [30].

7.2. *Prediction of foundation stiffness and natural frequency*

The second study considered an offshore wind turbine on a monopile installed in the North Sea. Measured accelerometer data from the turbine were collected over several years of operation and post-processed in the Redwin project. The idling periods are of great interest for the foundation performance as this response is more affected by the foundation stiffness than the response during production. The natural frequency of the first mode was identified for these periods. The post-processing of the measured data contained sample periods with shifting wind and wave direction. The peak spectral density from one of these periods are shown in Figure 14. The natural frequency range predicted in the original design using the *p-y* approach are also indicated on the figure. The natural frequency of the turbine was revised in the REDWIN project by using the REDWIN model 2 fromTable *1*. A geotechnical 3D FEA was carried out prior to the analyses to establish a moment – rotation curve to be used as input to the model. The 3D FEA used the NGI-ADP soil model [33] and site specific soil data including cyclic testing. The substructure and tower was modelled in detail in 3Dfloat and REDWIN model 2 implemented with the monopile stiffness and damping characteristics. The natural frequency computed by this revised model is also included in Figure 14 for comparison with the measured and original design values. It is evident that the revised model agrees significantly better than the original design. It should be noted that the result was obtained without any tuning of input parameters to bring the computed natural frequency close to the measured. The importance of the results are emphasized by the fatigue damage sensitivity to natural frequency shown in Figure 3.

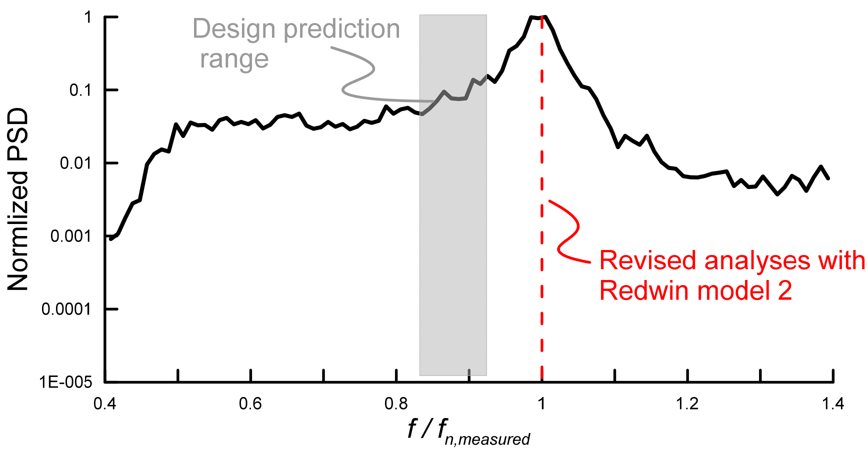

Figure 14 Peak spectral density from measurements showing natural frequency f_n of the first mode compared with original design natural frequency and natural frequency for analyses with Redwin model 2.

8. Conclusions

The foundation and soil support models developed in the REDWIN project offer effective, practical and accurate representation of foundation and soil behaviour. The models can be used in time domain analyses and are application-oriented, linking different foundation types to specific models. The models benefit from being calibrated using FEA, which can also compute damping and capture location-specific properties more accurately compared to e.g. API *p-y* curves or other closed form solutions. Comparisons with measured data from the field suggest that the models are more accurate. Numerical parametric studies have been carried out to investigate the effect of the models. These studies indicate that the foundation models significantly influence the design, and that the REDWIN models are beneficial since they include soil damping. More studies have to be carried out to investigate the extension of these conclusions for a greater range of foundation types and conditions.

The project has helped remove barriers between structural and geotechnical engineers and made it possible to solve design problems with an improved integration.

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