REPORT

REDWIN - Reducing cost of offshore wind by integrated structural and geotechnical design

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Summary

The REDWIN project (REDucing cost of offshore WINd by integrated structural and geotechnical design) is a 4-year research project, funded primarily by the Research Council of Norway (NFR) through the ENERGIX program, with the objective of reducing the cost in offshore wind turbine (OWT) design by developing new engineering tools that enable more accurate representation of soil and foundation behaviour in integrated analysis of these structures. One of the main outputs of the 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. The input to the foundation models are simple and intuitive nonlinear load-displacement curves that represent the foundation (pile or caisson) and soil response. The new models overcome several of the limitations inherent in existing foundation design tools and allow designers to adopt accurate, advanced, and validated foundation models in all phases of OWT design.

This report presents an overview of the development and main features of the new soil-foundation models, outlines the required input to the models and how to obtain this input, and describes how the models can be implemented with software for integrated analyses of OWTs. The details of the mathematical formulation of the foundation models have been published in a series of journal papers (available on the REDWIN project website) and are therefore not included in this report.

The new foundation models described in this report are freely available for use in research and engineering projects with proper reference, and can be obtained via the REDWIN project website: https://www.ngi.no/eng/Projects/REDWIN

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Review and reference page

1 Introduction

1.1 Offshore wind turbine foundations

Offshore wind turbines (OWTs) are dynamically sensitive structures that are exposed to irregular cyclic loads caused by wind, waves, ocean currents, and operation of the turbine itself. The interaction between loads, the structural dynamics, and turbine behaviour are strongly coupled and nonlinear. For this reason, design of OWTs is based on integrated dynamic nonlinear time domain analyses that incorporate all significant factors affecting the structural response into one global model for the OWT. Advanced models are used for representing waves, wind and the control system of the turbine; however, highly simplified models are usually used to represent the foundation and soil response. These foundation models consistently underestimate the foundation stiffness, as demonstrated by the poor agreement between measured and predicted natural frequencies of OWTs in operation (Kallehave et al. 2015), and ignores foundation damping, which may result in a underestimation of fatigue lifetime (Aasen et al. 2017).

There are several types of foundations used for OWTs (Figure 1). Large diameter monopiles (now approaching 10m) have to date been the dominant foundation date comprising more than 80% of installed foundations (Wind Europe 2018). However, other foundations concepts such as gravity based foundations and suction caisson foundations (suction buckets) may become preferred in the future due to increasing turbine size, development in deeper waters, and environmental restrictions on noise emissions from pile driving.

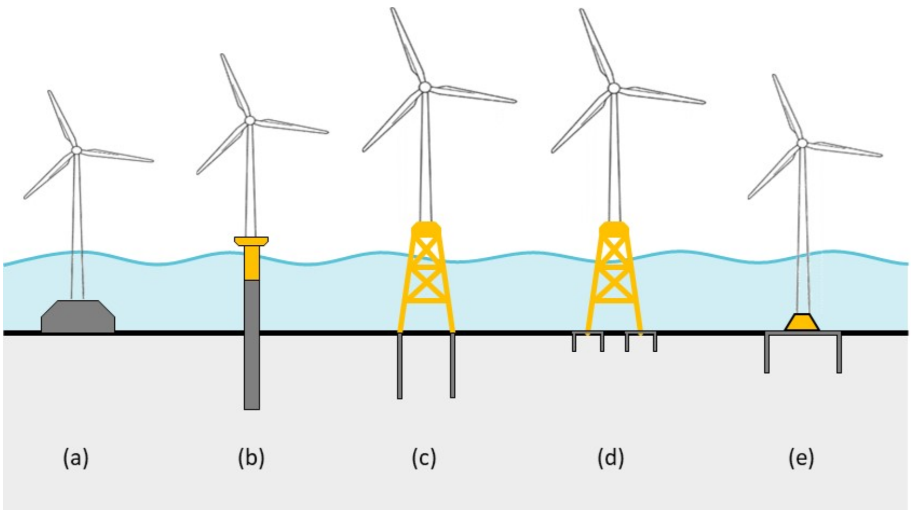


Figure 1 Types of OWT foundations: (a) gravity based, (b) monopile, (c) piled jacket, (d) suction caisson jacket, (e) mono caisson.

Gravity based foundations and suction caisson foundations rest on the seabed with skirts that penetrate into the soil, and can be used in two structural configurations: a monopod with a single column connecting the tower and foundation, or multi-leg configurations such as jackets or tripods with suction caissons supporting each leg. These concepts have already been applied in full scale developments (Houlsby and Byrne 2005; Peire et al. 2009; Shonberg et al. 2017), but no standardized method exists for modelling of these foundations in design.

1.2 Traditional design procedures for OWT foundation

The foundation models traditionally used in integrated analyses of OWT foundations are simplistic and based on several assumptions. For monopiles, the soil and foundation response is commonly represented by simple *p-y* springs distributed along the length of the pile. These springs relate the local resultant lateral resistance, *p*, to the local lateral displacement of the pile, *y*, and the relationship between these is commonly specified as semi-empirical functions based on only a few experimental tests. The current industry practice follows the DNV standard (DNVGL 2016), which recommends the use of API p-y formulation (API 2014) for monopile design if validated, e.g. by finite element analyses.

While the API *p-y* curve methodology has been successfully applied for pile design in the oil and gas industry for decades (Arshad and O'Kelly 2016), it is based on a set of assumptions that seem less appropriate for OWT foundations (Page et al. 2016), as the method was primarily developed to provide conservative ultimate capacity rather than accurate foundation stiffness and damping. Consequently, the applicability of the API *p-y* curves to predict pile behaviour in integrated analyses of OWTs has been questioned. Comparison between predicted and measured fundamental frequencies of monopile-based OWTs indicate that API *p-y* formulation for piles in sand consistently under-estimates the soil stiffness (Kallehave et al. 2015). Moreover, because the API *p-y* response generally follow a nonlinear elastic backbone curve, it is incapable of reproducing foundation hysteresis damping. This damping mechanism has been observed in actual field measurements, and typical foundation damping values have been estimated based on monitoring data from existing OWTs (Versteijlen et al. 2011; Shirzadeh et al. 2013; Damgaard et al. 2013).

Recognizing the well-known limitations of the API *p-y* curves, several authors have proposed alternative *p-y* models (Jeanjean 2009). Most recently, the PISA project (Byrne et al. 2015) has developed more accurate models of *p-y* combined with rocking springs for static lateral loading for large diameter piles. This improvement of the *p-y* methodology has the advantage of being tailored to large-diameter support structures and is easy to implement in simulation tools; however, the important effects of cyclic loading and hysteretic damping are not included in the current PISA formulation.

The representation of shallow foundation response (gravity based and suction bucket foundations) is typically modelled even simpler, often with distributed linear elastic springs to represent the soil and foundation response. Distributed springs (similar to the *p-y* approach) could potentially be computed by FEA, but determining spring coefficients based on only a few load cases may fail to capture the changing stress distribution mechanisms (soil reactions) for varying load combinations. It is therefore considered to be more accurate to describe the global foundation stiffness directly as a lumped overall response. The foundation stiffness can then be represented by a spring in each degree-of-freedom (DOF) or by a stiffness matrix with coupling terms. Analytical solutions for computing such elastic stiffness coefficients for shallow foundations exist in the literature (e.g. Bordón, Aznárez, and Maeso 2016; Doherty and Deeks 2003; Gazetas 1983; Suryasentana et al. 2017; Vabbersgaard et al. 2009)

A viable alternative to the *p*-*y* curves for piled foundations and linear elastic models for bucket foundations is the so called macro-element approach, which reduces the soil–foundation system to a single "element" located at the interface between the foundation and the rest of the structure. Macro-element foundation models are however rarely employed for design of OWTs, for several reasons. First, even though the theoretical formulations of existing models are well described in the research literature, documentation on their usage and application to actual case studies is limited. Secondly, input parameters for the models are usually predefined based on idealized model test conditions, which makes adaptation to actual sites in the field challenging. The new macro-element foundations models presented later in this report will overcome these limitations.

1.3 The REDWIN project

Several geotechnical disciplines are required to accurately model the soil/foundation response for OWTs. Site investigations have to be planned and accompanied by laboratory testing; interpretation of soil parameters and soil characteristics has to be carried out; and finally, the foundation response has to be described in a mathematical model so that it can be implemented in integrated analyses, which are often carried out by specialized aero-hydro-servo-elastic codes. Figure 2 illustrates this chain of activities.

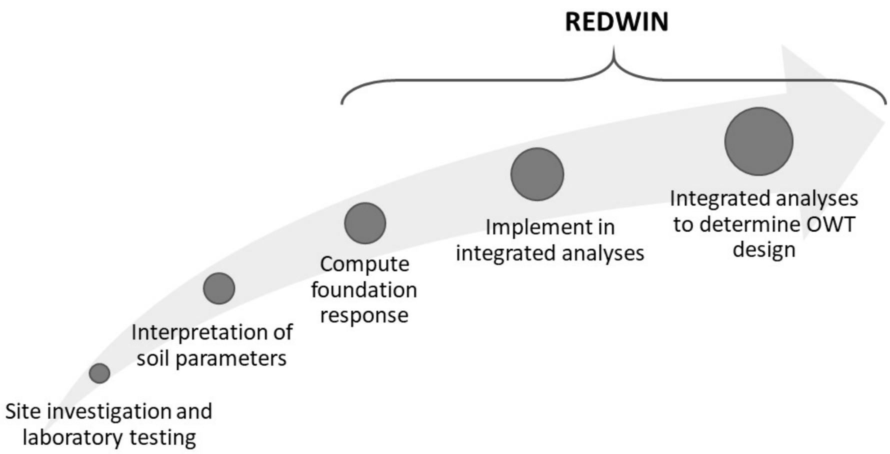


Figure 2 Design chain for determining foundation response of OWTs in dynamic structural analyses: from site investigation to time-domain integrated load analyses.

In order to improve OWT designs, a significant knowledge gap that exists in the design chain in Figure 2 must be addressed, namely, the lack of accurate numerical models describing the foundation and soil response in integrated dynamic analyses. Without such models, it is difficult to justify conducting expensive site investigations and thorough interpretation of soil parameters when the same level of accuracy cannot be attained in the integrated dynamic analyses.

Recognizing the shortcomings of current foundation models used for OWT design, the goal of the REDWIN (REDucing cost of offshore WINd by integrated structural and geotechnical design) project has been to develop new engineering tools for accurate representation of the soil and foundation behaviour in integrated OWT analyses. The project, funded primarily by the Research Council of Norway (NFR), consists of a consortium of six partners with demonstrated industry and research experience in offshore wind technology (Figure 3).

Figure 3 REDWIN project partners: The Norwegian Geotechnical Institute (NGI), The Norwegian University of Science and Technology (NTNU), Institute for Energy Technology (IFE), The Research Council of Norway, Equinor, Vattenfall[1] and Dr. Techn. Olav Olsen.

The primary objective of the REDWIN project is to contribute to reduction of costs in OWT design by developing a library of improved soil-foundation models for shallow (e.g. bucket foundations) and deep foundations (e.g. monopiles), that can be implemented in integrated analysis tools through standardized interfaces. The input to the foundation models are simple and intuitive nonlinear load-displacement curves that represent the foundation (pile or caisson) and soil response to monotonic loading. The improved models overcome the aforementioned limitations of existing foundation design tools and will allow designers to adopt accurate, advanced, and validated foundation models in all phases of design.

[1] Vattenfall replaced Statkraft as project partner in 2016.

1.4 Organization of this report

This report consists of 5 chapters. In Chapter 2, the main principles and framework used to develop the REDWIN foundation models are presented, and implementation of the foundation models in integrated analysis tools is outlined. Chapters 3 – 5 contain brief "user's manuals" for each of the three soil-foundation models developed in the REDWIN project. This include descriptions of their main features, instructions on how to obtain the required user inputs, and examples that demonstrate the accuracy of the foundation models applied to actual cases.

The details of the mathematical formulation of the models is purposefully excluded from this report because it can be found in several peer-reviewed journal papers, that also contain additional validation examples using actual case-histories. The papers can be downloaded from the REDWIN website: https://www.ngi.no/eng/Projects/REDWIN

This report also contains two appendices. Appendix A presents instructions of how to implement and use the REDWIN models in integrated simulation tools through the DLL interface. Appendix B contains examples of input files and outlines the possible error messages produced by the models.

2 REDWIN foundation models

2.1 Principles of model development

The REDWIN foundation models were developed to overcome the shortcomings of existing models, while still being simple enough to be easily implemented and used with the types of integrated simulation tools applied in OWT design. This overall objective led to some general principles guiding the model development:

1. Application-oriented models, so that a suitable model can be intuitively selected for the foundation type being considered.
2. User interfaces that are understandable to practitioners.
3. General models that can capture different soil conditions found at offshore sites.
4. The models should exhibit realistic response though a load cycle, e.g. reduction in stiffness for high load levels and generation of hysteretic damping.

To ensure applicability for different foundation types, a library of three soil-foundations models was developed. To facilitate its practical application in integrated simulation tools, where the response of the OWT has to be computed in the time domain for thousands of load cases, simplifications in the macro-element model formulation leading to fast, simple and more robust implementation were favoured. The user interface is intuitive since the model input is specified by one or several physically interpretable load-displacement response curves. This response is typically computed in design, often by FEA, and the method used to establish these curves is independent of the specific model. This way, any type of soil conditions can be considered when establishing the input load-displacement curves.

2.1.1 Macro-element concept

The REDWIN foundation models are developed as macro elements. A macro element (Figure 4) condenses the soil–foundation system to a single "element" located at the interface between the foundation and the rest of the structure (or alternatively, a series of "elements" distributed along the foundation, Figure 4b), and captures the nonlinear soil–foundation response through force-displacement relationships for this interface point. The nonlinear behaviour of the surrounding soil is embedded in the macro-element formulation through its input parameters. This represents an attractive way to model foundations in integrated structural analyses of OWTs, where the structure itself is the main focus of the analysis.

The REDWIN macro-element foundation models have several advantages over traditional foundation models (e.g. *p*-y curves) used in integrated analyses of OWTs:

- They are capable of accurately representing the nonlinear load-displacement response observed in experimental tests and in the field, including realistic foundation stiffness and hysteretic damping, coupled response between lateral loads (the model for suction caisson foundations also includes coupling between

lateral and vertical responses), multi-directional loading, and nonlinear stiffness reduction at higher load levels.
- They are computationally very efficient because only 6 DOFs (i.e., 3 translational and 3 rotational), are required to model the entire foundation and surrounding soil. This ensures that the macro element operates as efficiently as distributed *p*–*y* curves in integrated analyses of OWTs.
- Calibration of the load-displacement input curves for the model, which can be based on finite element analysis (FEA) or directly from laboratory tests, is simple, flexible, has a direct physical interpretation, and can handle different types of soil conditions (homogeneous or layered, clay- or sand-dominated soil profiles, etc.)

In addition to the macro-element foundation models, a separate software has been developed to assist in the structural design of the pile itself. This software extracts output from the macro element and compute forces, displacements, stresses and fatigue damage for various locations along the pile and various points in each cross section.

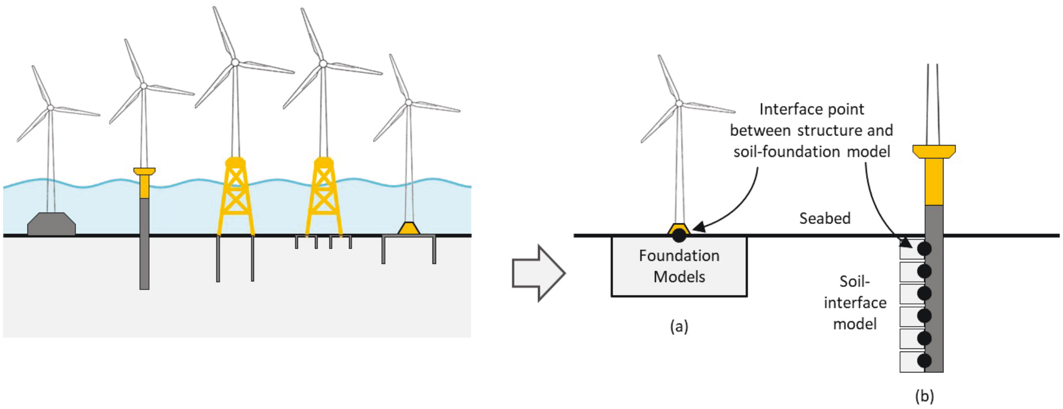


Figure 4 Illustration of the macro-element concept: (a) foundation model, (b) distributed soil-interface model.

2.1.2 Multi-surface plasticity framework

The REDWIN foundation models are formulated within the theoretical framework of multi-surface plasticity (Mróz 1967; Iwan 1967). In this framework, the plastic displacement depends on how a series of nested surfaces move in the load space, and the hardening is defined by piecewise linear curves (Figure 5). In its simplest (one-dimensional) form, this corresponds to a rheological model with springs in parallel with different stiffness and yield forces (Figure 5a). This framework is capable of capturing the type of nonlinear hysteretic behaviour observed for OWT foundations, illustrated in Figure 5b and 5c for 1D and 2D coupled response, respectively.

Multi-surface plasticity models have the advantage that they are conceptually simple and robust, easy to implement, and allow for flexible calibration of the input parameters.

The following main assumptions and considerations were used for developing the mathematical formulation of the REDWIN models:

- A set of finite element analyses of the foundation and surrounding soil were performed to establish the basis of the model formulations. A numerical approach was selected over physical model testing because such tests are costly and time consuming, can only consider a few load paths, and have difficulties reproducing the layered soil conditions found at most offshore sites, especially when it involves clay.
- The yield criterion is formulated based on results from the FEA, supported by symmetry considerations. Associative flow and kinematic hardening is assumed.
- The yield surfaces are allowed to intersect to avoid multiaxial numerical ratcheting (Montáns and Caminero 2007). This differs from the formulation of most other multi-surface plasticity models (Mróz 1967) which include a non-intersection condition.

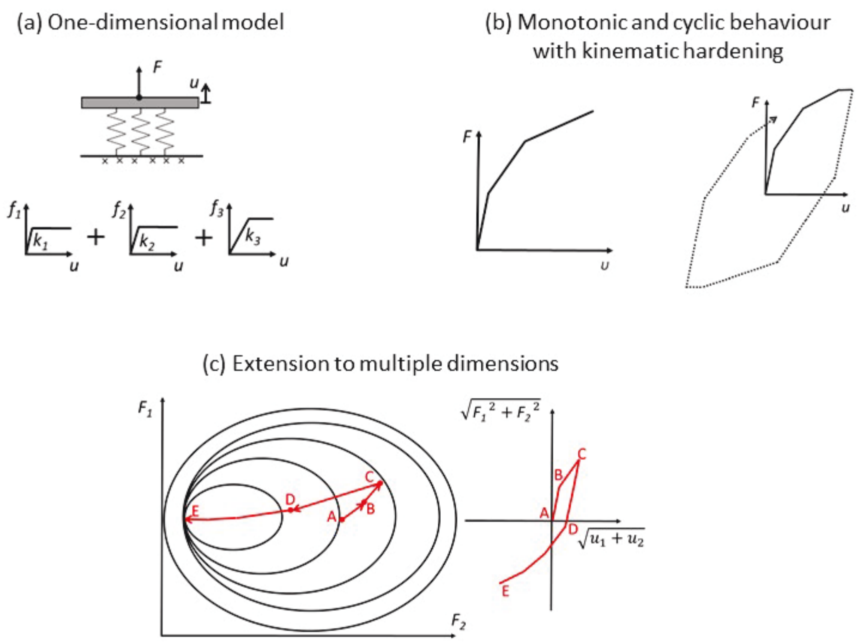


Figure 5 Illustration of the multi-surface plasticity concept: (a) one-dimensional model illustrating the parallel spring principle, (b) resulting monotonic and cyclic behaviour of 1D model, (c) extension to multiple dimensions with multi-surface translation in load space.

2.2 Which REDWIN model to use?

To ensure applicability of the REDWIN models to different foundation types and structural analysis codes, a library of three foundation models, covering the most common foundation types for OWTs, was developed (Figure 6).

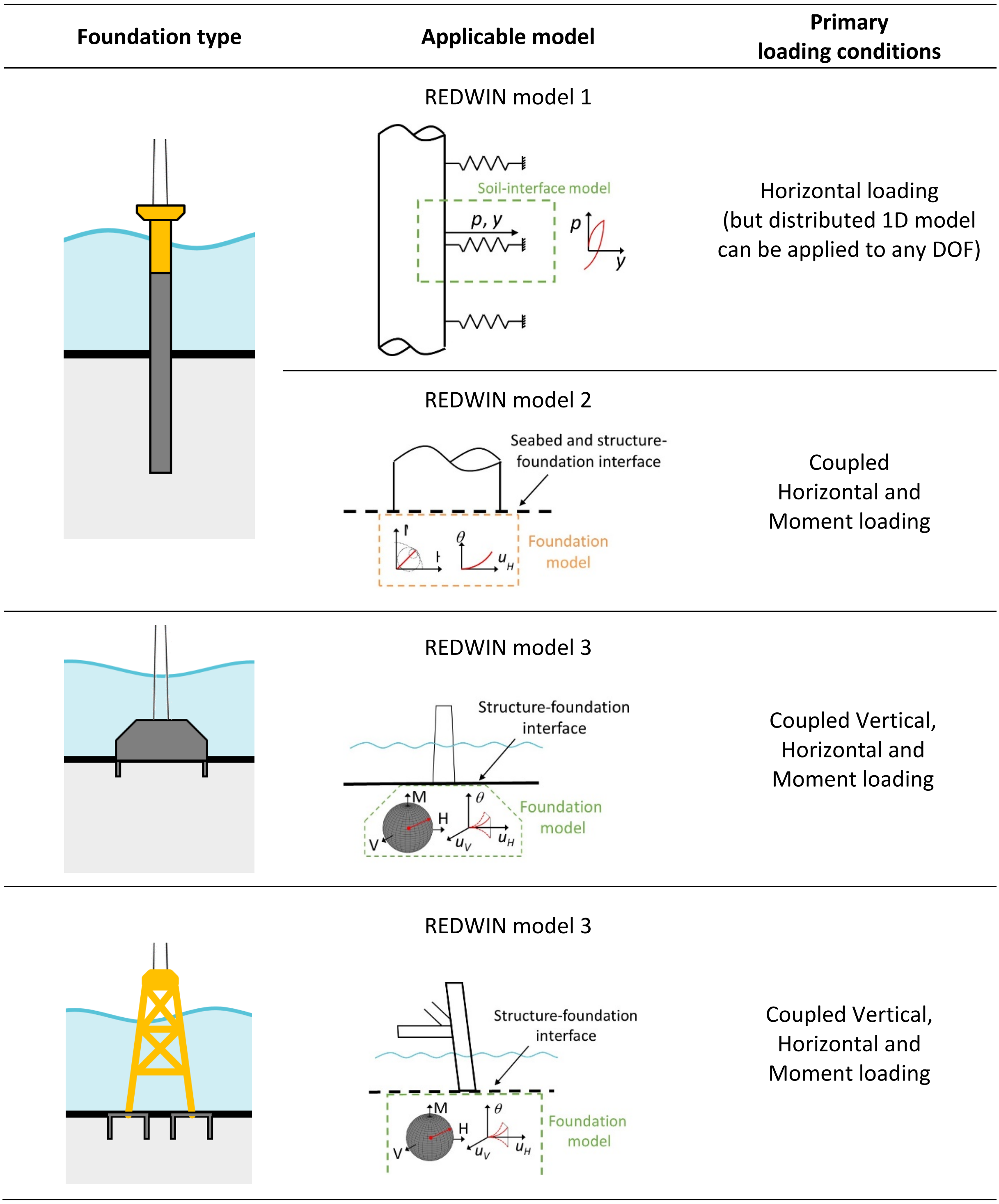


Figure 6 Overview of REDWIN foundation models.

REDWIN model 1, developed primarily for piles that are intended to be analysed by the traditional *p-y* approach, is a simple, one-dimensional macro element that uses springs in parallel to describe the nonlinear response to cyclic loading including hysteretic damping. This model can be employed as distributed springs along the monopile when the foundation is explicitly included in the integrated analyses. REDWIN model 2 represents the monopile and surrounding soil by a single macro-element located at seabed. The third model, REDWIN model 3, is a macro-element developed for shallow foundations such as gravity based foundations with or without skirts and caisson foundations. Each of the three models and their use is described in more detail in Chapters 3–5.

The models have been developed with the purpose of being simple and practical. If used for design analyses, it is recommended to compare the response of the models to some general load paths computed by FEA to ensure that an acceptable level of accuracy is achieved for the particular application.

2.3 Implementation of models in integrated analysis software

The REDWIN foundation models have been written in Fortran and compiled as Dynamic Link Libraries (DLLs) for integration in time-domain simulation codes for OWTs. All the foundation models have been compiled to DLLs in a Windows environment using Microsoft Visual Studio and the Intel Fortran compiler. Two versions have been compiled for each model: x86 (32 bit) and x64 (64 bit).

The models have been tested and verified in a Windows environment with Microsoft Visual Studio and Intel Fortan. Brief descriptions of how to implement the DLLs in integrated simulations software can be found in Appendix A. It is expected that other system setups will require minor modifications to these procedures for successful implementation of the DLLs.

As of October 2018, the REDWIN foundation models have been incorporated in two integrated simulation software: 3DFloat (Nygaard et al. 2016) and SIMA (Marintek 2015). It is further planned that the models will be implemented in the simulation program FAST (Jonkman and Buhl Jr. 2005) and used in the upcoming code-to-code comparison OC6 facilitated by the National Renewable Energy Laboratory (Robertson 2018).

2.3.1 Main functionality

The REDWIN foundation models are called by the integrated analysis software via the subroutine `InterfaceFoundation`:

```
InterfaceFoundation (PROPSFILE, LDISPFILE, IDTask, nErrorCode,
ErrorCode, Props, StVar, StVarPrint, Disp, Force, D)
```

This subroutine is exported from the DLL of the relevant foundation model and loaded into the integrated analysis software.

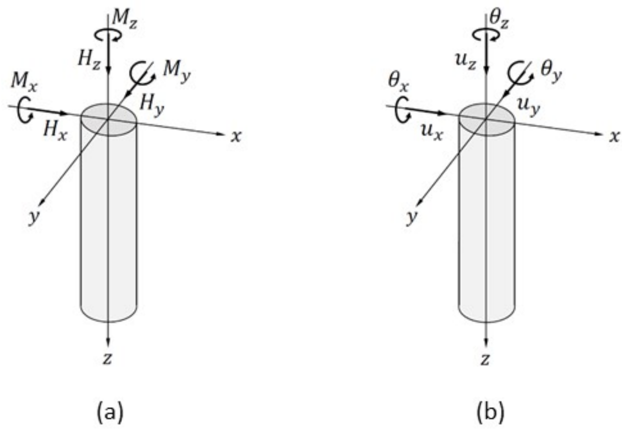


Figure 7 Sign convention for the REDWIN macro-element models (after Butterfield, et al., 1997): (a) forces and moments, (b) displacements and rotations.

The subroutine `InterfaceFoundation` takes in a 6 x 1 vector of displacements and rotations (Disp), defined at the structure-foundation interface (SFI) point, and returns a 6 x 1 vector of forces and moments (Force) consistent with the received displacements. These follow the sign convention proposed by Butterfield et al. (1997), shown in Figure 7. The actual nonlinear force-displacement relation is computed internally in the different REDWIN models. The set of arguments passed to and from the subroutine is standardized for all three foundation models and described in Table 1.

Three tasks can be performed by the foundation models, these are identified using the 'IDTask' flag.

Initialize model (IDTask = 1)
This task reads the model input files PROPSFILE and MDISPFILE, initializes the model input/output arrays (Disp, Force, D) and state variables (StVar) to zero, and performs the internal calibration required to set up the parameters for the multi-surface plasticity model based on the discretization parameters and load-displacement input curves. This task must be completed before any other tasks can be performed, but only needs to be performed once per run.

Calculate internal foundation forces (IDTask = 2)
This task constitutes the main part of the macro element: foundation forces and moments (Force) are calculated based on the vector of received displacements and rotations (Disp) at the SFI. The calculations are performed internally in the REDWIN models using iterative predictor-corrector procedures to achieve convergence in the multi-surface plasticity model. The models include automatic sub-stepping, which is activated if the global displacement increment is too large to achieve convergence directly.

Return elastic macro-element stiffness matrix (IDTask = 3)
IDTask = 3 returns the 6 x 6 elastic macro-element stiffness matrix, *D*, at the SFI which can be used to assemble the global stiffness matrix for the OWT system. Note that for

REDWIN model 1, which uses only one or two DOFs (depending on the mode in which it is run), only the relevant non-zero components of the elastic stiffness matrix will be returned. For models 2 and 3, the full 6 x 6 stiffness matrix is computed and returned.

Table 1 Description of arguments for 'InterfaceFoundation' subroutine in the DLLs.

Argument name	Description	Type and dimension
PROPSFILE	Name of input text file number 1 (model parameter input). The file name is specified in the calling software. The content and syntax of the input file depends on the model and is explained for each model in the relevant chapters 3-5.	Character
LDISPFILE	Name of input text file number 2 (load-displacement input curves). The file name is specified in the calling software. The content and syntax of the input file depends on the model and is explained for each model in the relevant chapters 3-5.	Character
IDTask	Integer that specifies the required action for the foundation model. The flag is assigned by the calling software. The following alternatives are supported: IDTask = 1: Read input properties, initialize and calibrate model IDTask = 2: Calculate forces based on displacement at end of step IDTask = 3: Calculate elastic macro-element stiffness matrix	Integer (1)
Disp	Array containing six displacements and rotations (u_x, u_y, u_z, θ_x, θ_y, θ_z) at the structure-foundation interface (SFI) the end of the step (or iteration step). The sign convention of displacements follows the right-hand rule illustrated in Figure 7.	Real (6)
Force	Array containing six forces and moments (F_x, F_y, F_z, M_x, M_y, M_z) at the structure-foundation interface (SFI) at the end of the step (or iteration step). The sign convention of forces follows the right-hand rule illustrated in Figure 7.	Real (6)
D	The 6 x 6 elastic macro-element stiffness matrix at the SFI.	Real (6,6)
ErrorCode	Array containing one or more error codes. These are specific to each model and explained for each model in Appendix B.	Real (100)
nErrorCode	Variable counting the number of error codes	Integer (1)
Props	Array containing foundation model properties (used internally by the REDWIN models). Specific to each model.	Real (100,200)
StVar	Array containing the state variables at the end of the step (used internally by the REDWIN models). Specific to each model.	Real (12,100)
StVarPrint	Array indicating which state variables should be printed to the screen. This feature is currently not supported.	Integer (12, 100)

3 REDWIN model 1

3.1 Main features

REDWIN model 1 is a simple, nonlinear multi-surface plasticity model with a single degree-of-freedom that can be used to model the distributed soil response along a monopile structure (Figure 8a), e.g. the load-deflection response at discrete locations along a monopile (the *p-y* concept). Alternatively, the model can be used as a simplified 1D foundation model describing the global moment-rotation response of a monopile or caisson foundation (Figure 8b). An example of the first application can be found in Markou and Kaynia (2018) and examples of the second application (global moment-rotation response of a monopile) in Aasen et al. (2017) and Krathe and Kaynia (2017).

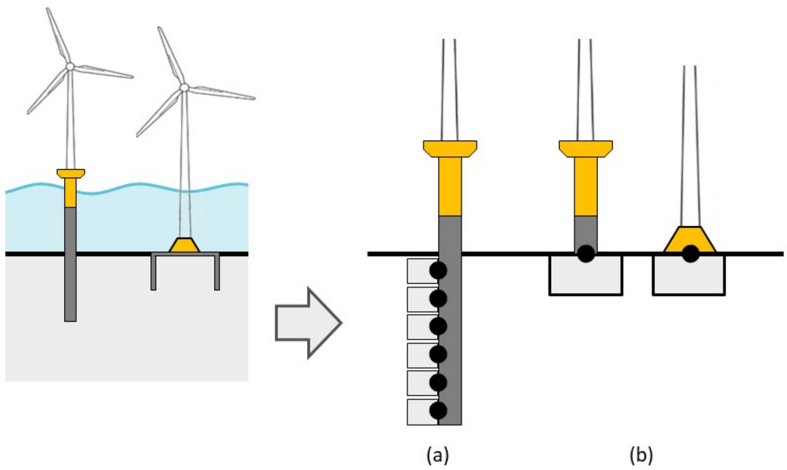


Figure 8 Illustration of use of REDWIN model 1: (a) distributed 1D macro elements describing lateral load-deflection response along monopile (similar to p-y concept), (b) simplified 1D macro element describing moment-rotation response of a monopile of caisson foundation.

The macro-element model consists of several springs in parallel, hereafter denoted sub-springs, each of them exhibiting linear elastic perfectly plastic behaviour (Figure 9a). This concept of using coupled springs to mimic a smooth overall load-displacement response was first suggested by Iwan (1967), and is sometimes referred to as the IWAN-model after the author. Each sub-spring has individual stiffness and yield load, but all sub-springs are constrained to have the same displacement. Thus, when the displacement increases, an increasing number of sub-springs will yield, resulting in a multi-linear behaviour with stepwise reduction in the total stiffness. This relatively simple rheological model is capable of generating the type of hysteretic behaviour with kinematic hardening observed in actual OWT foundation systems. Furthermore, the model is attractive in the way it responds to load reversals: since the yield load is equal in compression and extension (Figure 9a), each sub-spring will obey Masing's rule during cyclic loading. Thus, the total response will also obey Masing's rule, as illustrated in Figure 9b. Additional details of the model formulation can be found in Page et al. (2017).

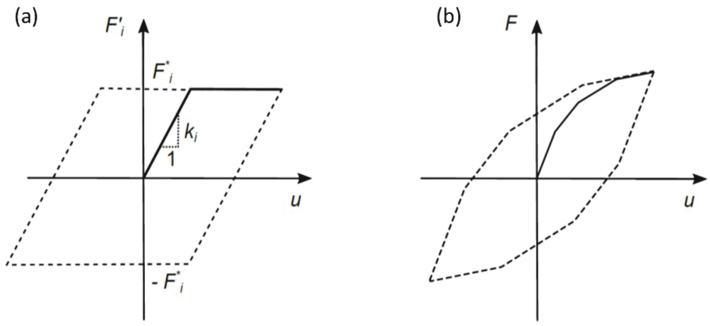


Figure 9 Illustration of REDWIN model 1 nonlinear behaviour: (a) elastic-perfectly plastic behaviour of each individual spring, (b) resulting hysteretic behaviour of macro element.

The simple macro-element model has several features and assumptions that has been adopted to ensure an effective and robust model formulation:

- The model only considers the response in one (or two uncoupled) degrees-of-freedom.
- The model provides a stepwise variable stiffness so that the stiffness and hardening is not restricted to any single predefined function.
- The model exhibits overall kinematic hardening behaviour when subjected to cyclic loading.
- Input to the model can be any type of monotonically increasing force-displacement or moment-rotation curve.
- The model gives a realistic stiffness during load reversals, which is of particular importance for operational load cases that combines cyclic loading with a large average load component.

If the model unexpectedly stops, e.g. if there is an issue with the internal calibration, the model will produce an error code. An overview of possible error codes and suggested actions are provided in Appendix B.

3.2 Required user input

The main input to REDWIN model 1 is a nonlinear load-displacement (or moment-rotation) curve for the specified degree-of-freedom. In addition, a few numerical parameters must be specified. The user specifies these data in two input files, PROPSFILE and LDISPFILE (Tables 2 and 3); the full path, name and file extension of these two files should be specified in the calling software. Examples of correctly formatted input files are included in Appendix B.

Table 2 Content of PROPSFILE input file for REDWIN model 1.

Input	Description
runmode	Type of configuration to run the macro element in. 1 = moment-rotation (uses global DOF5) 2 = two (uncoupled) horizontal load-displacements (uses global DOF1 and DOF2)
Nk	Number of springs used to calibrate the 1D model.

Table 3 Content of LDISPFILE input file for REDWIN model 1.

Input	Description
N	Number of lines (rows) with tabulated force-displacement values in LDISPFILE.
data	N pairs of load-displacement values. The first column contains loads (or moments), second column contains displacements (or rotations).

During model initialization (IDTask = 1), the model reads the input from PROPSFILE and LDISPFILE and performs an internal calibration to define the parameters (stiffness and yield force) for each sub-spring in the model. The model parameters are calculated as follows: first, the load-displacement curve is read and discretized into N load points F_N, with highest resolution near the initial part of the curve. Then, the stiffness of each sub-spring is determined from softest (the one that yields last) to stiffest, and the corresponding yield loads for each sub-spring are defined to reproduce the total load points F_N. The resulting parametrization is illustrated in Figure 10.

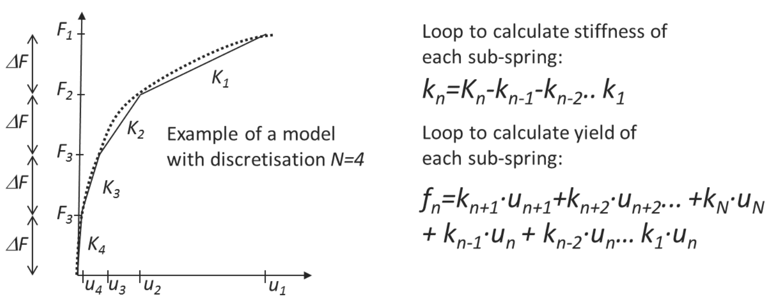


Figure 10 Illustration of the internal calibration to generate model parameters for REDWIN model 1 based on an input load-displacement curve.

3.2.1 How to obtain the user input

Load-displacement curves
For use of REDWIN model 1 as distributed macro-elements along the length of the pile (Figure 8a), the tabulated load-displacement curves containing forces and horizontal displacements at discrete points along the pile can be specified directly from *p*-*y* curves. These *p*-*y* curves can be obtained, for instance, from finite element analyses of the soil volume and the pile. Methods also exist to generate *p*-*y* curves directly from the results of direct simple shear (DSS) tests, which are commonly used to characterize soils at offshore sites (Zhang and Andersen 2017).

For use of REDWIN model 1 as a simple macro-element model at seabed, the tabulated moment-rotation curve containing moments and rotations at seabed can be obtained from nonlinear static pushover analyses of the pile with a soil model that represents the relevant nonlinear cyclic response.

4 REDWIN model 2

4.1 Main features

REDWIN model 2 is a macro element used to describe the response of a pile foundation supporting a monopile-based OWT including the effects of multi-directional loading on the foundation, e.g. from waves hitting the tower in different directions, or misalignment between wind and wave forces. The model captures the complete response of the foundation and surrounding soil: horizontal forces and moments are related to displacements and rotations using the nonlinear framework of multi-surface plasticity, whereas the vertical and torsional cyclic response, known to be less significant for monopiles, is modelled linearly elastic and uncoupled from the horizontal and moment response. The model formulation is based on results from 3D finite element analyses of the soil and foundation, where pile geometry and soil conditions were selected from the site of a real offshore wind farm. The model has been demonstrated to give very good agreement with results from cyclic FEA, results from large-scale pile tests, and results full-scale field measurements of an OWT installed on the North Sea (Page et al. 2018; Page, Grimstad, et al. 2019; Page, Næss, et al. 2019).

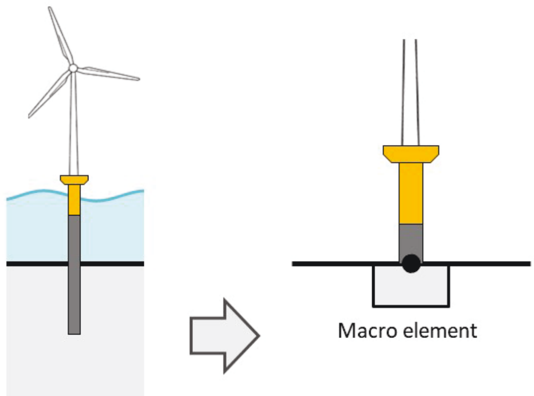


Figure 11 Illustration of REDWIN model 2: a macro element describing the multi-directional response of a monopile.

The model is formulated based on the results of 3D FEA. The following assumptions and main features are included in the formulation:

- The accuracy of the model directly depends on the ability of the FEA (or model tests) used in the calibration to accurately represent the pile behaviour.
- The response to vertical and torsional loading are modelled as linearly elastic and are assumed to be uncoupled from the other DOFs.
- The effect of vertical loads on the lateral response is not explicitly considered in the formulation. If considered necessary, this effect can be included indirectly by calibrating the model at the relevant vertical load level.

- The model is rate-independent and provides foundation stiffness and damping that is independent of the applied loading frequency.
- The model is formulated based on the assumptions that the yield surfaces are homothetic to each other and that the kinematic hardening rule follows Masing's rule. These assumptions have been demonstrated to be appropriate for low to moderate load levels, but may be less accurate for load levels close to the ultimate capacity of the foundation.
- The model does not accumulate displacements during cyclic loading. This is consistent with the premise that significant displacement accumulation is not expected for the low load levels and number of cycles in the 10–60 minutes long time windows in integrated load simulations.

If the model unexpectedly stops, e.g. if convergence is not achieved or there is an issue with the calibration, the model will produce an error code. An overview of possible error codes and suggested actions are provided in Appendix B.

4.2 Required user input

REDWIN model 2 requires two main types of user input: (1) the coefficients of the elastic stiffness matrix, D, at seabed, and (2) two load-displacement curves from nonlinear pushover analyses. In addition, a few numerical parameters must be specified. The elastic stiffness matrix is used to predict the elastic foundation response, and the nonlinear load-displacement curves are employed to derive the shape and size of the yield surfaces and the hardening law in the multi-surface plasticity model. This last derivation is performed internally by the model.

The user specifies these data in two input files, PROPSFILE and LDISPFILE, that are read during the initialization of the models (IDTask = 1). The contents of the two input files are shown in Tables 4 and 5, and examples of correctly formatted input files are included in Appendix B.

Table 4 Content of PROPSFILE input file for REDWIN model 2.

Input	Description
Coefficients of the elastic stiffness matrix *D* at seabed	In total, six coefficients of the elastic stiffness matrix *D* at mudline. Numbering refers to degree-of-freedom defined in Table 1: D11 (= D22) Elastic horizontal stiffness D15 (= -D24) Elastic horizontal-rotational coupling stiffness D51 (= -D42) Elastic rotational-horizontal coupling stiffness D55 (= D44) Elastic rotational stiffness D33 Elastic vertical stiffness D66 Elastic torsional stiffness
Ns	Number of yield surfaces used for calibration, recommended value = 15-25.
iMax	Maximum number of iterations before sub-stepping routine is called, recommended value = 10-20.
tol	Convergence tolerance, recommended value = 1.0e-06.

Table 5 Content of LDISPFILE input file for REDWIN model 2

Input	Description
NM	Number of lines (rows) with tabulated values for pure moment load. Maximum value supported = 200.
NH	Number of lines (rows) with tabulated values for pure horizontal load. Maximum value supported = 200.
data	Tabulated values for load-displacement-rotation input. The first NM rows contain moments (first column), horizontal displacements (second column), and rotations (third column). The next NH rows contain horizontal force (first column), horizontal displacement (second column), and rotations (third column).

4.2.1 How to obtain the user input

Elastic stiffness matrix
For homogeneous soil profiles, the elastic stiffness matrix coefficients can be obtained from semi-empirical formulas, see for instance Randolph (1981), Gazetas (1991) or Doherty et al. (2005). For layered soil profiles, or for changes in soil stiffness with depth not considered in these semi-empirical formulas, the coefficients can be obtained from FEA, or from boundary element analyses, see for instance Kaynia (1982).

Nonlinear load-displacement curves
These can be obtained from static pushover FEA with a soil model that represents the relevant nonlinear cyclic response. Alternatively, data from model tests can be directly employed; however, the load-displacement curves must be monotonically increasing.

Two analyses (or tests) are required to establish the load-displacement input curves (Figure 12): (1) a pushover analyses where a moment is applied at the pile head at seabed, from which the $M - u_M - \theta_M$ curves are obtained, and (2) a pushover analyses where a horizontal load is applied at the pile head at seabed, from which $H - u_H - \theta_H$ curves are obtained. Rotations should be specified in "units" of radians; and forces and displacements should follow a consistent unit system (specified by the simulation tool calling the foundation model). It is assumed in the multi-directional model that the response is the same in the two horizontal (x and y) directions, as in any radial direction.

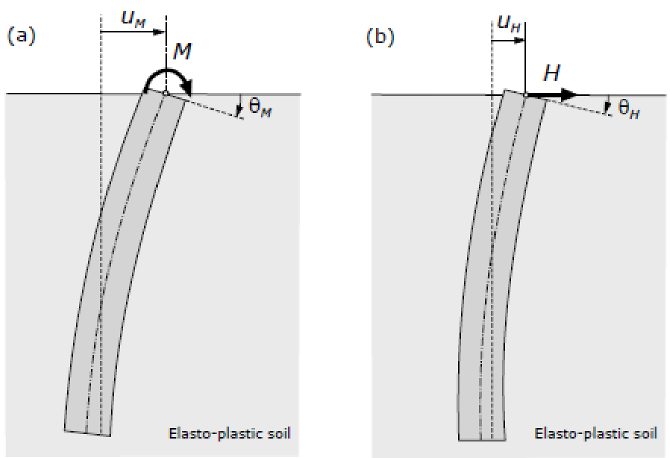


Figure 12 Load cases in FEA to determine load-displacement curves at seabed for REDWIN model 2: (a) overturning moment, (b) horizontal load.

4.3 Examples of model application

This section presents two examples that demonstrate the accuracy of REDWIN model 2 applied to analyse monopiles in different soil conditions. Additional validation examples are available in Page et al. (2018) and Page, Grimstad, et al. (2019)

4.3.1 Example A: Monopile embedded in a layered soil profile

Example A, presented in full in Page et al. (2018), demonstrates the performance of REDWIN model 2 and verifies its response against the FEA used as a basis for the model formulation. The example (Table 6) is based on one of the monopiles in the Sheringham Shoal wind farm located in the North Sea off the coast of Norfolk, following information available in the research literature (Hamre et al. 2011; Arany et al. 2017; Le et al. 2014). A steel monopile with a diameter of 5.7 m and a wall thickness of 0.06 m, penetrating 28.5 m into the soil, is considered.

Three of the main soil layers found at the site (Le et al. 2014), the Bolders Bank clay, the Egmond Ground sand, and the Swarte Bank clay, are included in the soil profile. Maximum shear modulus and undrained shear strengths (from UU and CAU) measurements for these layers are plotted in Figure 13a, and shear stress-strain curve interpreted from direct simple shear (DSS) laboratory tests are compared with the NGI-ADP soil model for the Bolders Bank soil layer in Figure 13b.

Table 6 Soil and pile input data for Example A.

Name	Example A
Comparison against	Monotonic Finite Element Analyses
Site description	Layered soil profile at the Sheringham Shoal offshore wind farm, United Kingdom
Soil layering	Bolders Bank Formation: firm to stiff clay; Egmond Ground Formation: dense to very dense sand; Swarte Bank Formation: stiff to hard sandy-gravelly clay
Main soil properties	
Unit Weight, γ (kN/m^3)	19.0–21.3
Average shear modulus at very small strains, G_{max} (MN/m^2)	200
Average undrained shear strength, s_u (kPa)	150
Shear strain at failure, γ_f (%)	16–20
Pile dimensions	
Diameter, D (m)	5.7
Length, L (m)	28.5
Wall thickness, t (m)	0.060
L/D (−)	5
D/t (−)	95

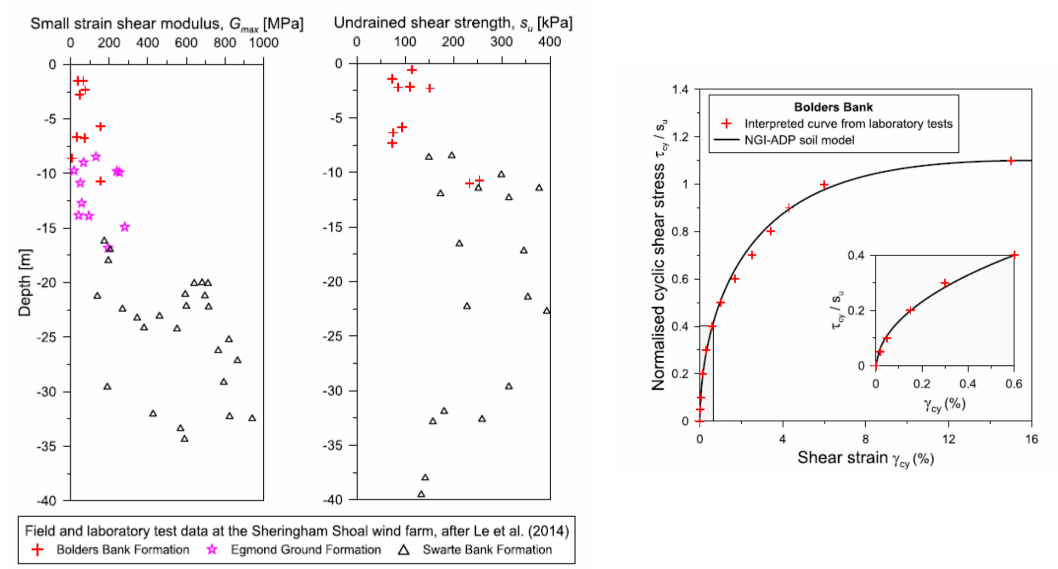


Figure 13 (a) Small strain shear modulus (G_{max}) and undrained shear strength (s_u) with depth from laboratory tests, modified after Le et al. (2014); (b) Comparison of NGI-ADP model with DSS laboratory tests of the Bolders Bank clay.

The commercial software PLAXIS 3D (Brinkgreve, et al. 2015) is used to perform the 3D FEA, the analysis model is shown in Figure 14. The model is calibrated from two load-displacement curves (pure moment and pure horizontal force) computed by the 3D FEA. Additional details on the material properties and analysis model can be found in Page et al. (2018).

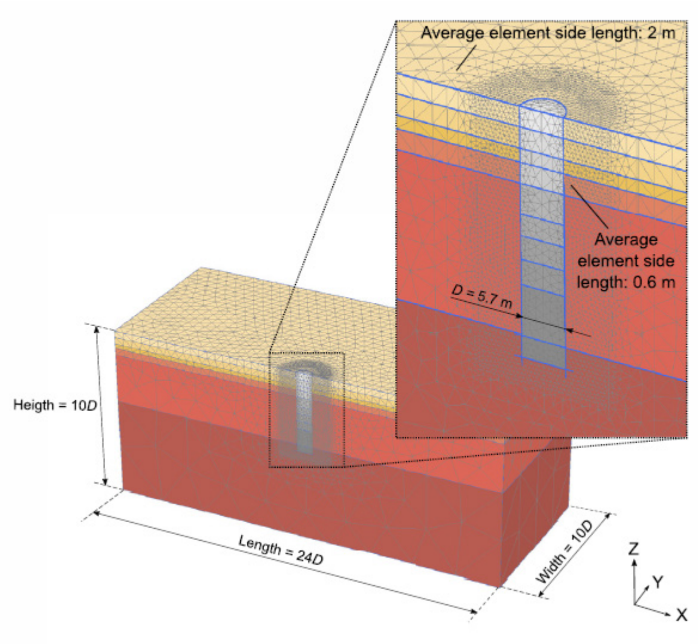


Figure 14 Plaxis 3D finite element model of the Sheringham Shoal reference case.

Presented in Figure 15 are comparisons between the model and the monotonic FEA. In the comparison, displacement controlled radial paths, where the ratio between horizontal displacements and rotations at the pile head is kept constant, are applied at the pile head. Good agreement can be seen for all the load paths considered, demonstrating that the model captures well the load-displacement response for various load paths (Figure 15a), and that it is also capable of correctly reproducing the coupling between moment and horizontal displacement seen in the FEA (Figure 15b).

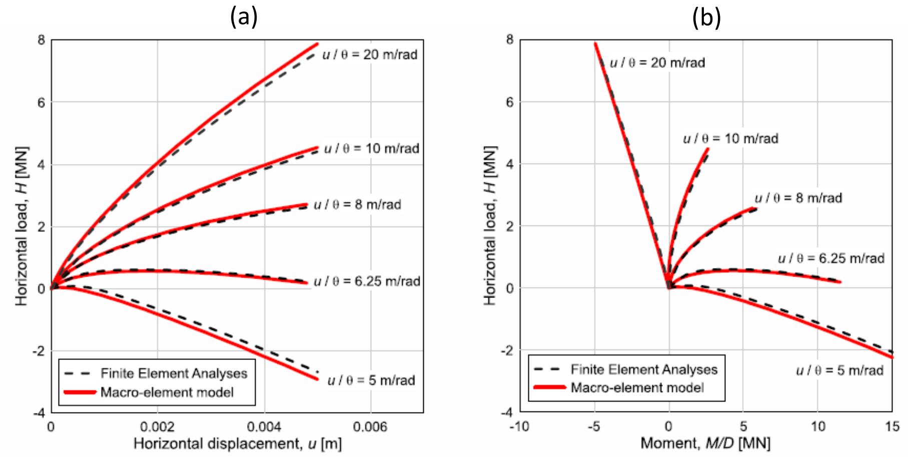


Figure 15 Comparison of results from REDWIN model 2 and FEA in displacement-controlled tests with constant u/θ-ratios: (a) H-u_H response, (b) H-M response

4.3.2 Example B: Monopile embedded in a homogeneous clay profile

Example B, presented in full in Page, Grimstad, et al. (2019), is based on the WAS-XL monopile in clay (Velarde and Bachynski 2017), a reference design for large diameter monopile foundations. The pile considered is a tubular steel pile with 9 m diameter and constant wall thickness 0.1125 m, embedded 36 m into the soil. This corresponds to a length-to-diameter ratio of 4 and a diameter-to-wall thickness of 80, which is representative for monopiles supporting OWTs.

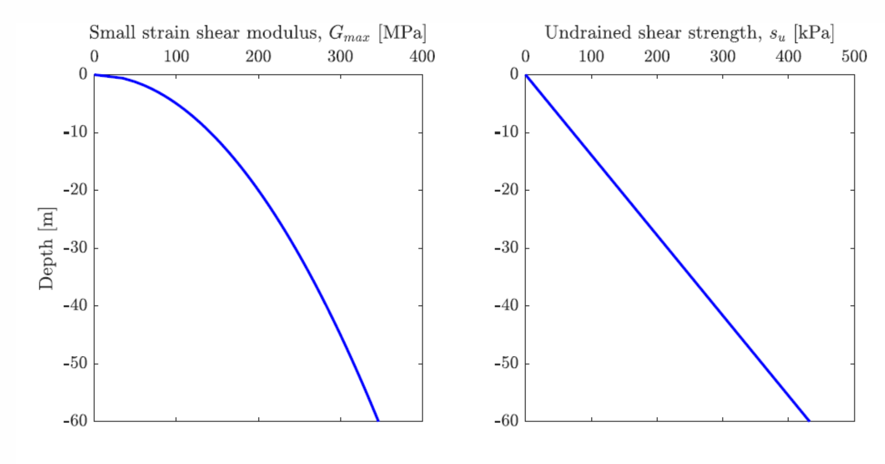


Figure 16 Variation of small strain shear modulus and undrained shear strength with depth.

The soil considered is an idealized, homogeneous stiff clay with plasticity index 30% and over consolidation ratio (OCR) of 4. Figure 16 shows the variation of undrained shear strength and maximum shear modulus of the soil with depth. A constant ratio between the undrained shear strength and the initial effective vertical stress of 1.0 was selected based on correlations from Andersen (2015). Additional details on the material properties and analysis model can be found in (Page, Grimstad, et al. 2019).

The model is calibrated using monotonic load-displacement curves from nonlinear FEA as input. Then, the performance of the model is evaluated by comparing against FEA results for radial load paths in Figure 17. The macro-element model captures well the load-displacement response and therefore the reduction in stiffness as a consequence of the coupling between in-plane and out-of-plane loads.

Also compared (in Figure 18) are dynamic response results computed by REDWIN model 2 and FEA for the most intense 10 sec part of a ULS load history for an actual OWT. Again, the results from REDWIN model 2 closely matches the FEA results. These results demonstrate that the yield surface, flow rule and hardening law in the model are suitable to describe the nonlinear, multi-directional dynamic response of OWT monopile foundations during ULS events.

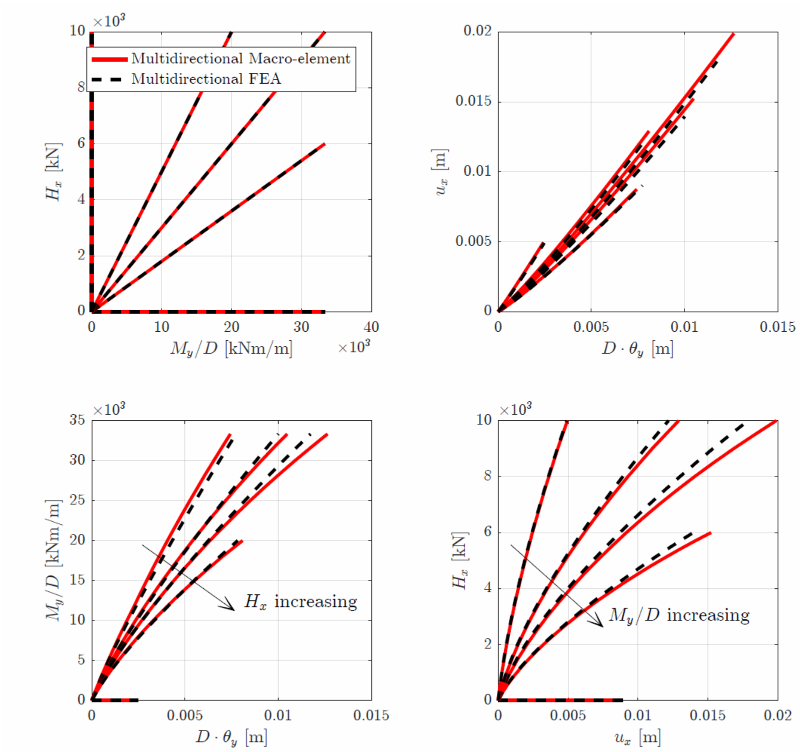


Figure 17 Comparison of response results from REDWIN model 2 and FEA for radial load paths. $H_x = 0$ and $M_y/D = 0$ are the load paths used in the internal model calibration.

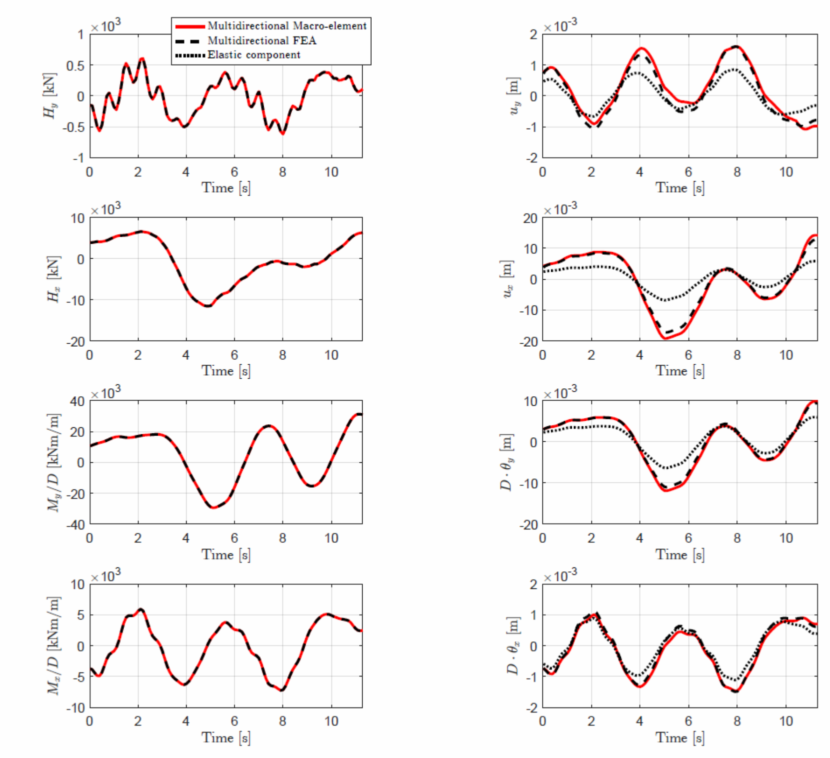


Figure 18 (a) Applied loads from the most intense 10 sec part of a ULS simulations of an OWT, (b) comparison of REDWIN model 2 response and FEA response.

4.4 Tool to compute forces, stresses and fatigue along pile

The macro elements compute the response of the pile and the soil at an interface point connecting the foundation with the rest of the structure, typically located at seabed. In order to compute the forces, stresses and fatigue along the part of the pile embedded in the soil, a separate tool was developed and implemented in MATLAB as a two-step procedure. First, the bending moments and shear forces along the pile are computed from force-histories at seabed. Then, the stresses and fatigue damage along the pile is calculated. The tool can be used both for REDWIN models 1 and 2.

The tool, and its user manual, can be delivered with the REDWIN foundation models upon request.

5 REDWIN model 3

5.1 Main features

REDWIN model 3 addresses the two different structural configurations of bucket foundations for OWTs (Figure 19): (1) three or four buckets that supports a jacket structure, where the jacket transfers the large overturning moment from the OWT to the buckets through vertical load pairs, and (2) a mono-bucket or gravity based foundation supporting a single tower, where the large overturning moment from the OWT is transferred directly to the bucket as a moment load. The model is capable of accurately describing the stiffness and hysteric damping characteristics of bucket foundations, including the effects of multi-directional loading.

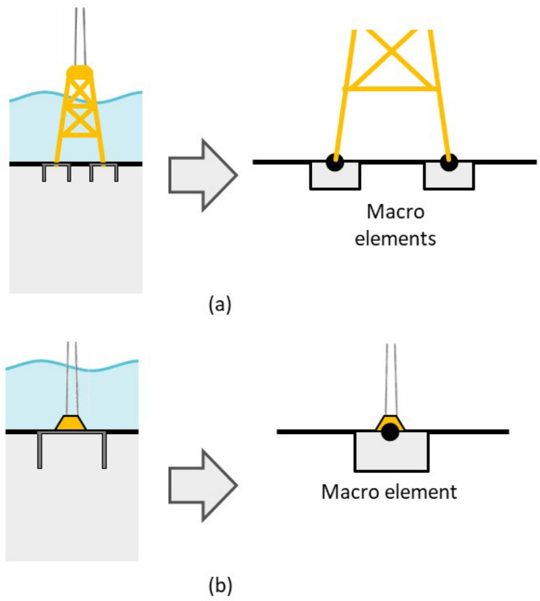


Figure 19 Illustration of REDWIN model 3 for two configurations of caisson foundations: (a) multiple buckets supporting a jacket structure, (b) mono-bucket supporting single tower.

The macro-element formulation is based on results from FEA of skirted foundations with different geometries and clay soil profiles, that considers combined vertical, horizontal and moment loads, and combined static and cyclic loading. An important finding from this numerical study was the attractiveness of identifying a representative decoupling point (Figure 20) and using the foundation response from pure vertical, horizontal, and moment loading at this load reference point to describe the response to combined load paths. This principle has been used to formulate the model in the multi-surface plasticity framework, which is well-suited to model response to irregular cyclic loading. The formulation also includes internal flexibility of the foundation, which addresses the recent finding indicating that caisson flexibility can contribute significantly to the total response of the foundation (Skau et al. 2019).

The uniaxial load-displacement curves that comprise the model input makes the model behaviour site-specific and able to capture the variations in response in inhomogeneous soil profiles, thereby greatly increasing the attractiveness of the model for practical use. Comparisons with finite element analyses and field test data have demonstrated that the model is capable of accurately modelling the response of the bucket foundations, including effects of caisson flexibility (Skau et al. 2018, 2019).

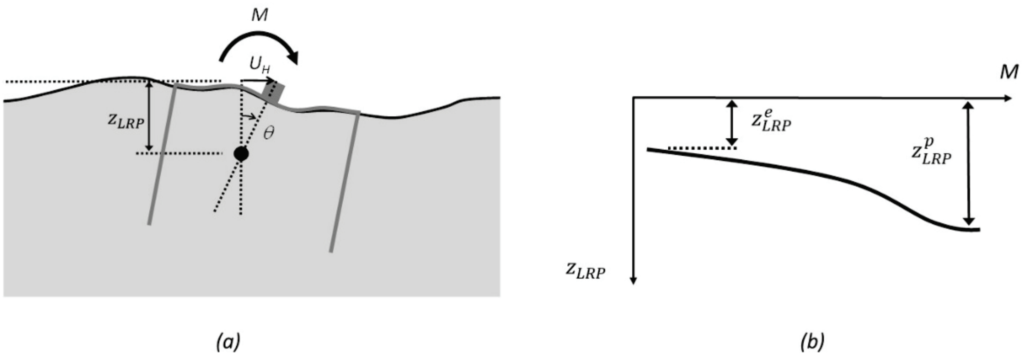


Figure 20 (a) Illustration the load reference point, the decoupling point where zero horizontal displacement occurs when a moment load is applied at the SFI, (b) variation of the load reference point for increasing load levels.

The following assumptions and main features has been adopted the model formulation:

- The model uses elliptic yield surfaces. This simplifies the basic model equations, but has the disadvantage that it may cause inaccurate response close to failure, possibly underestimating the ultimate capacity.
- The effect of caisson flexibility is included as a linear elastic contribution that is added to the overall foundation stiffness.
- The model uses a load reference point at a depth z_{LRP} as an input parameter, which is different from seabed. This brings convenience to the macro-element formulation by simplifying the mathematical functions that describe the multiple yield surfaces.
- The implementation of bi-directional horizontal loading assumes that the force and moment resultants $H = \sqrt{H_x^2 + H_y^2}$ and $= \sqrt{M_x^2 + M_y^2}$, respectively, remain in the same plane.
- The response to torsional loading is assumed to be uncoupled from the other load-response components, and modelled simply by a linear elastic stiffness coefficient specified by the user.

If the model unexpectedly stops, e.g. if convergence is not achieved or there is an issue with the calibration, the model will produce an error code. An overview of possible error codes and suggested actions are provided in Appendix B.

5.2 Required user input

REDWIN model 3 requires two types of user input: (1) the load reference points, z^{e}_{LRP} and z^{p}_{LRP} , which are the depths to the decoupling points where zero horizontal displacement occurs when a moment load is applied at mudline (see Figure 20) for elastic and plastic response, respectively; and (2) three load-displacement curves from nonlinear pushover analyses for loads (V, H, M) applied at the structure-foundation interface (SFI). In addition, a few numerical discretization parameters must be specified.

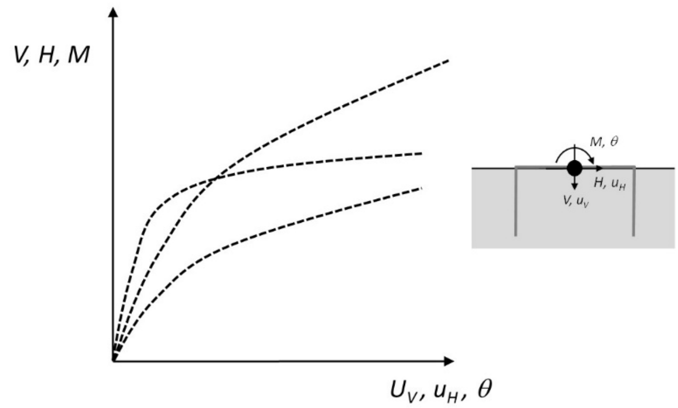


Figure 21 Illustration of input load-displacement curves at SFI for vertical (V), horizontal (H) and moment (M) loading.

The model does not use the uniaxial input response curves directly, but instead transfers them to a set of parameters for the multi-surface plasticity model. These parameters are determined by an automatic internal discretization of the load-displacement curves, followed by determination of the shape and size of the elliptic yield surfaces and corresponding hardening parameters.

The user specifies the input data in two input files (PROPSFILE and LDISPFILE) that are read during the initialization of the models (IDTask = 1). The contents of the two input files are shown in Tables 7 and 8, and examples of correctly formatted input files are included in Appendix B.

Table 7 Contents of PROPSFILE input file for REDWIN model 3.

Input	Description
zLRP_e	Depth to the elastic decoupling point, see Figure 20.
zLRP_p	Depth to the plastic decoupling point, see Figure 20.
D66	The coefficient of the elastic torsional stiffness (component D66 in the elastic stiffness matrix *D*). This can be set to a high value if torsional response is not important.
Ns	Number of yield surfaces used in calibration, recommended value = 15-20, maximum value supported = 30).
nsub	Number of substeps in the iterative procedure, recommended value = 100).
tol	Convergence tolerance, recommended value = 1.0e-03.
dDOF	Which input curve to use for surface discretization in the calibration tool. 1 = vertical load, 2 = horizontal load, 3 = moment. If one load direction (V, H, or M) is expected to dominate the response, it is recommended to use this as the basis for the discretization.

Table 8 Contents of LDISPFILE input file for REDWIN model 3.

Input	Description
NV	Number of lines (rows) with tabulated values for the vertical load – vertical displacement input curve.
NH	Number of lines (rows) with tabulated values for the horizontal load – horizontal displacement input curve.
NM	Number of lines (rows) with tabulated values for the moment – rotation input curve.
data	Tabulated values for load-displacement and moment-rotation. The next NV rows contain vertical force (first column) and vertical displacement (second column). The next NH rows contain horizontal force (first column) and horizontal displacement (second column). The next NM rows contain moments (first column) and rotations (second column).

5.2.1 How to obtain the user input

Load reference point

The physical interpretation of the load reference point is illustrated in Figure 20. By applying a pure moment load to the foundation at the SFI point, z_{LRP} can be determined by the following equation:

$$z_{LRP} = \frac{u_{H,SFI}}{\theta_{SFI}} \quad (1)$$

where $u_{H,SFI}$ and θ_{SFI} are the horizontal displacement and rotation, respectively, at the SFI when a pure moment load is applied at SFI.

Because z_{LRP} depends on the soil mobilization, two points need to be specified: one for initial mobilization to determine the depth to the elastic decoupling point, z^e_{LRP}, and one near "failure" to determine the depth to the plastic decoupling point z^p_{LRP}. Additional details regarding the load reference point and its physical interpretation can be found in Skau et al. (2018, 2019).

Nonlinear load-displacement curves

Three pushover analyses are required to establish the load-displacement input curves (Figure 21): (1) pure vertical loading applied at the SFI, from which the $V - u_V$ input curve is obtained; and (2) pure horizontal load applied at the SFI[2], from which the $H - u_H$ input curve is obtained; and (3) pure moment load applied at the SFI, from which the $M - \theta$ input curve is obtained. Rotations should be specified in "units" of radians; and forces and displacements should follow a consistent unit system (specified by the simulation tool calling the foundation model).

It is recommended to use FEA to establish these uniaxial response curves. The analyses can be run as quasi-static analyses, however, the soil's stress-strain curve should reflect a cyclic backbone curve. If laboratory data from cyclic tests are available, these can be used directly to extract cyclic behaviour. If only monotonic soil data is available, the effect of cyclic degradation on foundation level can be approximated by the procedure in Skau et al. (2017). The model is however not restricted to any single procedure for establishing the uniaxial load-displacement input data. For example, if relevant model test data is available, these can be used directly to specify the input instead of FEA.

5.3 Examples of model application

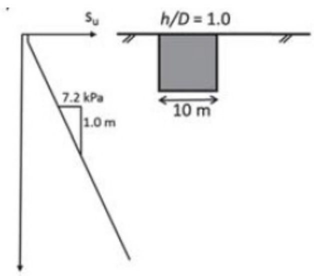
This section presents two examples that demonstrate the accuracy of REDWIN model 3 applied to analyse skirted foundations subjected to monotonic and irregular load histories. Additional examples, including validation of the model against results from large-scale field tests, are available in Skau et al. (2018) and Skau et al. (2019).

5.3.1 Example A: Skirted foundation in homogeneous clay profile

This example demonstrates the performance of the macro-element model applied to skirted foundations and verifies its response against FEA results. The case considered consists of a skirted foundation with diameter D = 10 m and h = 10 m skirt penetration

[2] In this analysis, the lid should be assumed rigid and constrained to move purely horizontally (i.e with zero vertical displacements or rotations) to ensure that the load-displacement response reflects horizontal translation only.

depth (Figure 22), with the foundation and the soil inside the skirt modelled as perfectly rigid. The NGI-ADP soil model (Grimstad, Andresen, and Jostad 2012) is used to describe the soil behaviour. The static undrained shear strength is assumed to increase linearly with depth, expressed in terms of the direct simple shear (DSS) strength s_u^{DSS}, this linear increase is assumed to be 7 KPa / m. The stress-strain behaviour, obtained from the NGI-database on cyclic behaviour of clays, represents an over-consolidated clay typical for North Sea offshore wind farm sites (OCR = 4, average load F_a = 0, and number of equivalent cycles, N_{eq} = 10). The loads and displacements from these analyses are evaluated in the load reference point (LRP) at a depth, $z_{LRP} = 2h/3$. Additional details on the material properties and FEA model can be found in Skau et al. (2018)



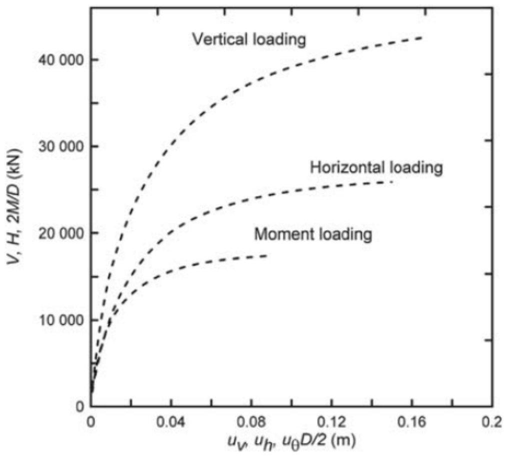


Figure 22 (a) Site profile and foundation geometry, (b) uniaxial load-displacement response used as input to macro element.

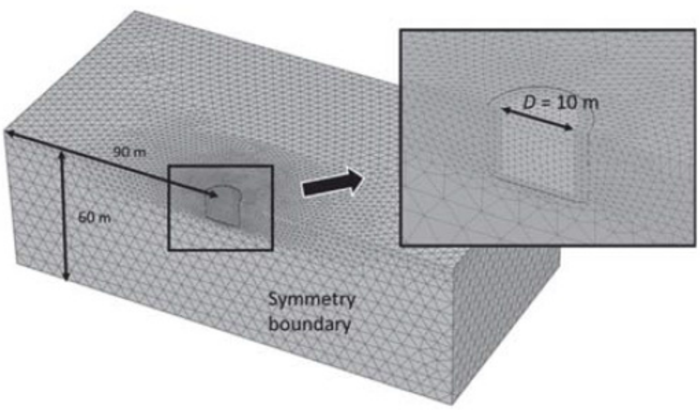


Figure 23 Plaxis 3D finite element model.

The input for the macro-element model is established by the procedure described in Section 5.2.1, with results from FEA (analysis model shown in Figure 23) used to calculate the uniaxial load-displacement curves (Figure 22b) and z_{LRP}. Because the skirt is assumed to be rigid in this analysis, the elastic and plastic decoupling points were assumed to coincide at a depth of 6.7m.

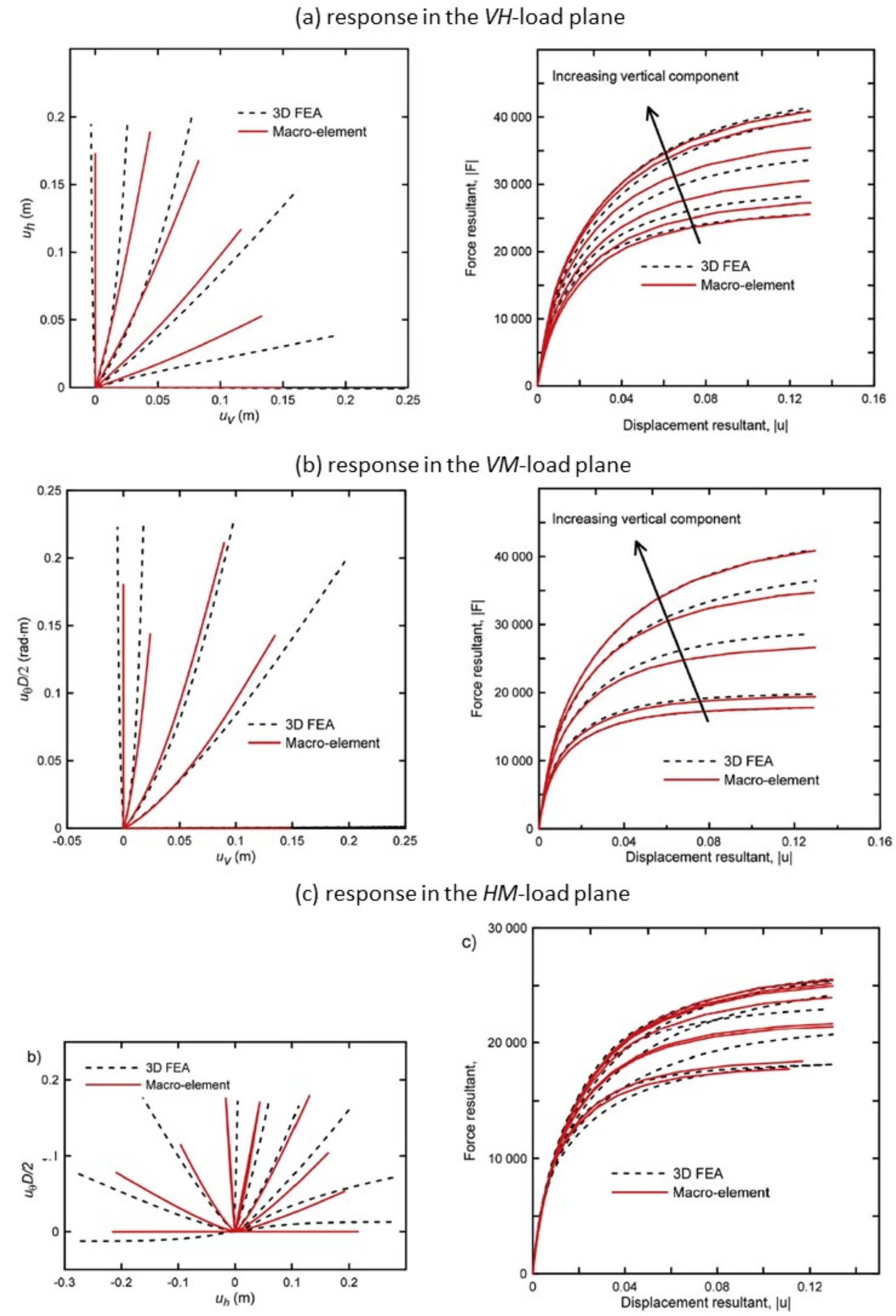


Figure 24 Comparison of results from FEA and macro element: (a) response in the VH-load plane with M = 0; (b) response in the VM-load plane with H=0; (c) response in the HM-load plane with V=0.

The responses computed by REDWIN model 3 are compared to FEA results for various radial load paths in Figure 24. Both resultant values ($|F| = \sqrt{V^2 + H^2 + (2M/D)^2}$ and $|u| = \sqrt{u_v^2 + u_h^2 + \theta^2 D/2}$), and individual components, e.g. $u_v - u_h$ are compared. The agreement between the results from REDWIN model 3 and the FEA is generally good. It is observed that the discrepancies are most prominent in the *HM*-plane. This occurs because of the simplifications in the yield and potential function in the model formulation, which are less accurate in the *HM*-load plane compared to the other load planes (Skau et al. 2018).

5.3.2 Example B: Response to irregular cyclic loading

The ability of REDWIN model 3 to compute the response to irregular cyclic loading is demonstrated by applying a cyclic load history to a foundation with diameter D = 10 m and h = 5 m skirt penetration depth. The soil profile is identical to that in Example A, except for the inclusion of a 10m thick stiffer layer from 7.5m to 17.5m depth where the shear strength and stiffness is increased by a factor of 2. The FE model used to establish the input load-displacement curves is the same as that in Figure 23, except for the inclusion of the stiffer layer, the updated bucket geometry, and that the soil plug inside the skirts are assigned the actual soil properties.

The skirted foundation is subjected to combined horizontal and moment loading in the form of a 10-min irregular load history that is representative for a monopod foundation during idling of the turbine in high wind and wave conditions. The load history is scaled so that the typical cyclic amplitude is approximately half the foundation capacity.

Presented in Figure 24 are the resulting moment and rotation computed by REDWIN model 3. Note that rotations did not accumulate during the simulation. The increase in rotations around 25 s and 340 s may be interpreted as such accumulation since the average rotation does not return to its previous average level, however, this change is in agreement with kinematic hardening behaviour, and the surfaces have only temporarily been taken to a new average level. At the end of the load history, the load is increased further making it comparable to the virgin monotonic load response (Figure 24c). These results show that the two curves again coincide, demonstrating that the model does not cause numerical ratcheting.

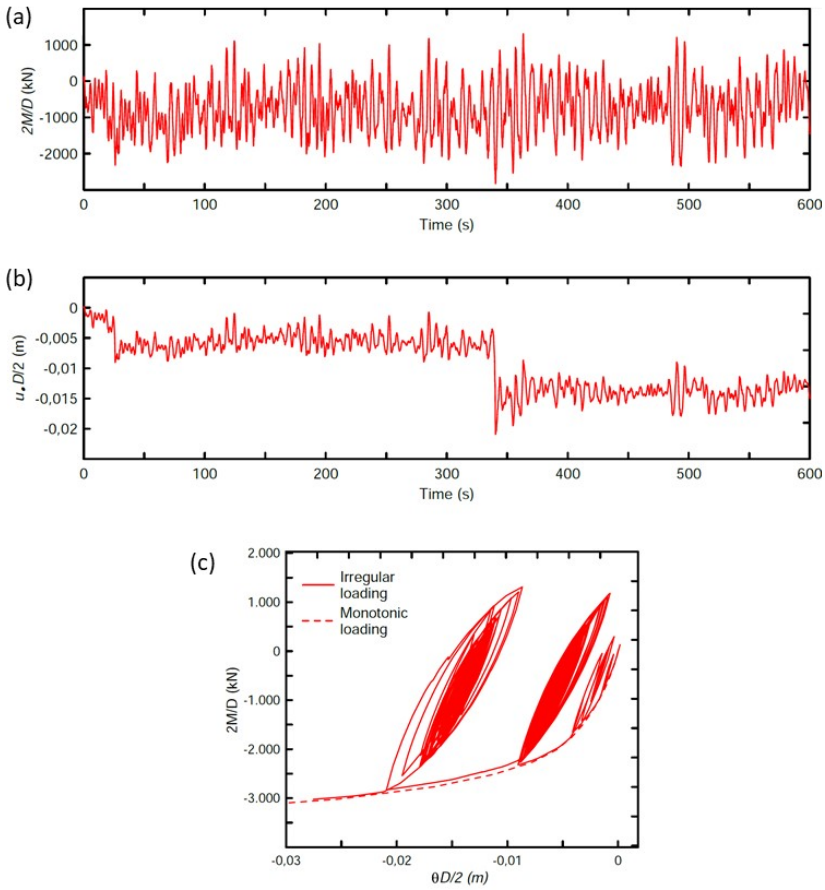


Figure 25 Irregular cyclic response computed by REDWIN model 3 for example B case: (a) moment-time response, b) rotation-time response, (c) rotation-moment response.

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Appendix A

IMPLEMENTATION OF DLL FILES

Contents

Implementation of DLL files

The DLLs (and .lib files) for each of the REDWIN models have been compiled in a Windows environment using Microsoft Visual Studio and Intel Fortran compiler. The DLLs have been compiled in two versions: x86 (32 bit) and x64 (64 bit). Other system configurations might require modifications to the implementations described below to implement the DLLs.

A1 Compiling DLL together with simulation software

If Intel Fortran is available, the easiest way to include the DLL models in the source code is to use the intrinsic `ATTRIBUTES DLLIMPORT` functionality and reference the relevant REDWIN library file (.lib) when compiling the calling program (the simulation software). This loads the `InterfaceFoundation` subroutine from the DLL, which can then be called in the main program as if it was any other locally defined subroutine. Specifically, the following line should be included in the source code:

```
!DEC$ ATTRIBUTES DLLIMPORT :: InterfaceFoundation
```

An example of such implementation in a Windows environment is included with the example files provided with the REDWIN foundation models.

While this approach is straightforward, it requires that the name of the DLL file remains the same and that the file is present in the directory from which the main program is run. A more flexible approach that avoids this restriction is presented next.

A2 DLL not compiled together with simulation software

Calling the REDWIN DLLs when they have not been compiled directly together with the simulation software will differ depending on the compiler and system environment. While this approach requires some additional lines of code relative to the procedure in Section A1, it has the advantage of being more flexible because the file name and path of the DLL is specified and can be changed without having to recompile the main program.

In general, it consists of the following four steps[1] (for Fortran code):

1. Declare a 'procedure' type variable with a 'pointer' attribute. The target of the pointer will be the subroutine `InterfaceFoundation` in the DLL. In the 'procedure', an 'abstract interface' is defined, and under this, the subroutine is defined, including the name and type of all arguments. These arguments should

[1] The advice and suggestions from Jacobus de Vaal and Tor Anders Nyggard at IFE on their experience implementing the DLLs in 3DFloat is gratefully acknowledged.

be identical to the arguments in the actual `InterfaceFoundation` routine, see Table 1 in Section 2.3.

2. Define the target of the procedure pointer, that is: (1) determine where the DLL is located and load it, and (2) get the address of the subroutine inside the DLL. For example, with Intel Fortran the intrinsic `ifwin` functions `LoadLibrary` and `GetProcAddress` can be used. In other environments, similar functionality should be available.
3. Transfer the DLL subroutine's address (generated in Step 2) to a procedure pointer and make it the target for the 'procedure' type variable from Step 1. This can be done with the intrinsic Fortran `transfer` function, and the intrinsic `iso_c_binding` and `c_f_procpointer` functions.
4. Call the subroutine using the name of the 'procedure' type variable.

Steps 1-3 only need to be performed once, and then the subroutine can be used as many times as needed. They can for example be nested in an 'IF' statement to avoid repeating the steps constantly. An example of this implementation in a Windows environment is included with the example files provided with the REDWIN models.

Appendix B

DETAILS ON INPUT FILES AND ERROR CODES

Contents

Details on input files and error codes

This appendix presents additional details regarding the possible warnings and error messages generated by the foundation models, as well as examples of correctly formatted input files for each model.

B1 Description of error codes for REDWIN models

The models have several built-in warning messages and errors if problems are found. Below is a brief description of the possible warning messages and error messages. A warning message will trigger an error code, but will not stop the model execution, whereas an error message will stop the model execution.

Table B1 ErrorCodes for REDWIN model 1.

ErrorCode	Description	Suggested action
1	Warning: The number of rows in LDISDPFILE exceed the maximum number supported (200). The calibration will proceed using the first 200 values.	Reduce the number of data points in the input file.
2	Error in the interpolation tool used in the model calibration. The value you are trying to interpolate is outside the interpolation curve.	Please inspect LDISPFILE to make sure that it covers a wide enough range and that all values are positive. Try to extend the input load-displacement curves in LDISPFILE.

Table B2 ErrorCodes for REDWIN model 2.

ErrorCode	Description	Suggested action
1	Warning: The plastic force-displacement calibration curve has several zero-rows. The solution does not stop, but the results may be inaccurate or erroneous.	Check that the provided coefficients of the elastic stiffness matrix are consistent with the load-displacement input curves.
2	Error. The iteration to find the plastic rotation increment and the plastic displacement increment did not converge.	The force you are trying to apply might be outside the calibrated range. Please extend the input load-displacement curves in LDISPFILE. Alternatively, increase the number of iterations in PROPSFILE.
3	Error in the interpolation tool used in the model calibration. The value you are trying to interpolate is outside the interpolation curve.	Please inspect LDISPFILE to make sure that it covers a wide enough range and that all values are positive. Try to extend the input load-displacement curves in LDISPFILE.
4	Error in the calibration tool. The contours of plastic horizontal displacement and the contours of plastic rotation are parallel.	The input might be non-physical. Please check that LDISPFILE is in the correct format and that the units are consistent.
5	Error in the calibration tool. The calculation of the orientation of the yield surfaces might be wrong.	The input might be non-physical. Please check that LDISPFILE is in the correct format and that the units are consistent.
6	Error in the calibration tool. The contours of plastic horizontal displacement are stepper than the contours of plastic rotation.	The input might be non-physical. Please check that LDISPFILE is in the correct format and that the units are consistent.

Table B3 ErrorCodes for REDWIN model 3.

ErrorCode	Description	Suggested action
1	Warning. The solution in the current sub-step seems to be diverging. Will attempt to reduce the step size.	The step size may be too large for convergence to be reached. The model will attempt to try again with a smaller step size.
2	Error. The sub-stepping algorithm in the multi-surface plasticity model did not converge.	The cause of divergence is usually that the applied loads exceed the calibration range, or that there are several identical spring stiffness for low load levels. Possible solutions are: reduce the number of yield surfaces (Ns), increase the number of substeps (nsub), increase the range of the input load-displacement files.
3	Error in the calibration tool. The input file cannot be found.	Check that the file name and path of the input files PROPSFILE and LDISPFILE are correctly specified.
4	Error in the calibration tool during read of PROPSFILE or LDISPFILE.	Check that the format of the input files are correct.

B2 Example of correctly formatted input files

The REDWIN foundation models read the required model input (model parameters and load-displacement curves) from two text files: PROPSFILE and LDISPFILE. The file name and path of these two files are specified by the calling program (the simulation software) using the modes. Examples of correctly formatted input files for each model are presented on the following pages.

Input files for REDWIN model 1

PROPSFILE

```
REDWINmodel 1 Input File. Valid for REDWINmodel1-2.0, 1-Nov-2018.
----- Model coefficients --------------------------------------------------------------------------------
   1         runmode             - Depth to elastic decoupling point
   15        Nk                  - Number of springs to calibrate model (recommended value = 15-20, max. value = 30)


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NOTE: Do not change number of header lines in file!
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```

LDISPFILE

```
REDWINmodel 1 Input File. Valid for REDWINmodel1-2.0, 1-Nov-2018.
----- Number of data points in each curve ---------------------------------------------------------------
   200       N                   - Number of rows in the load - displacement curve
----- Data points for load-displacement curve -----------------------------------------------------------
Load         Displacement
0            0
2452000      0.000919
4437000      0.001844
7822000      0.003703
...          ...
...          ...
47691000     0.60081
47749000     0.617334
47773000     0.625588


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NOTE: Do not change number of header lines in file!
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```

Input files for REDWIN model 2

PROPSFILE

```
REDWINmodel 2 Input File. Valid for REDWINmodel2-2.0.0, 26-Oct-2018.
----- Coefficients of the elastic stiffness matrix at seabed ----------------------------------
   7.398022e+06           D11 = D22           - Elastic horizontal stiffness at seabed
  -5.554615e+07           D15 = -D24          - Elastic horizontal-rotational cross stiffness at seabed
  -5.554615e+07           D51 = -D42          - Elastic rotational-horizontal cross stiffness at seabed
   9.098858e+08           D55 = D44           - Elastic rotational stiffness at seabed
   1.000000e+10           D33                 - Elastic vertical stiffness at seabed
   1.000000e+10           D66                 - Elastic torsional stiffness at seabed
----- Settings --------------------------------------------------------------------------------
   20                     Ns                  - Number of yield surfaces (recommended value = 15-25)
   20                     iMax                - Num. of iterations before activating sub-stepping (recommended = 10-20)
   1.00e-06               tol                 - Convergence tolerance (recommended value = 1.0e-06)


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```

LDISPFILE

```
REDWINmodel 2 Input File. Valid for REDWINmodel2-2.0, 26-Oct-2018.
----- Number of data points in each curve ------------------------------------------------------------------
   100       NM            - Number of rows in the Moment - Hor. displacement - Rotation curve (H = 0)
   100       NH            - Number of rows in the Hor. load - Hor. displacement - Rotation curve (M = 0)
----- Moment - Horizontal displacement - Rotation (in radians) curve at seabed ------------------------------
Moment                    Hor. Displ.               Rotation
0.000000e+00              0.000000e+00              0.000000e+00
6.000000e+03              9.187560e-05              1.220300e-05
1.200000e+04              1.906660e-04              2.491120e-05
...                       ...                       ...
...                       ...                       ...
5.880000e+05              2.231160e-02              1.895110e-03
5.940000e+05              2.263320e-02              1.918530e-03
6.000000e+05              2.295670e-02              1.942040e-03
----- Moment - Horizontal displacement - Rotation (in radians) curve at seabed ------------------------------
Hor. Load                 Hor. Displ.               Rotation
0.000000e+00              0.000000e+00              0.000000e+00
3.000000e+02              7.504260e-05              4.568530e-06
6.000000e+02              1.533220e-04              9.368840e-06
...                       ...                       ...
...                       ...                       ...
2.940000e+04              2.570130e-02              1.247130e-03
2.970000e+04              2.615470e-02              1.266940e-03
3.000000e+04              2.661320e-02              1.286930e-03



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NOTE: Do not change number of header lines in file!
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```

Input files for REDWIN model 3

PROPSFILE

```
REDWINmodel 3 Input File. Valid for REDWINmodel3-2.0, 1-Nov-2018.
----- Model coefficients -------------------------------------------------------------------------------
   6.7       zLRP_elastic       - Depth to elastic decoupling point
   6.7       zLRP_plastic       - Depth to plastic decoupling point
   1.00e+10  D66                - Elastic torsional stiffness at SFI
----- Numerical settings -------------------------------------------------------------------------------
   15        Ns                 - Number of yield surfaces (recommended value = 15-20, max. value = 30)
   100       nSubsteps          - Number of substeps in iterative procedure (recommended value = 100)
   1.0e-03   tol                - Convergence tolerance (recommended value = 1.0e-03)
   1         dDOF               - Curve used for surface discretization (1 = ver. load, 2 = hor. load, 3 = moment)


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```

LDISPFILE

```
REDWINmodel 3 Input File. Valid for REDWINmodel3-2.0, 1-Nov-2018.
----- Number of data points in each curve -----------------------------------------------------------------
   220       NV                  - Number of data points in the vertical load - vertical displacement curve at SFI
   200       NH                  - Number of data points in the Horizontal load - horizontal displacement curve at SFI
   150       NM                  - Number of data points in the Moment - rotation curve at SFI
----- Vertical load-displacement curve at SFI -------------------------------------------------------------
Ver. Load    Ver. Displ.
0            0
2452000      0.000919
4437000      0.001844
...          ...
...          ...
47749000     0.617334
47773000     0.625588
----- Horizontal load-displacement curve at SFI -----------------------------------------------------------
Hor. Load    Hor. Displ.
0            0
1496000      0.00075
3654000      0.002261
...          ...
...          ...
27031000     1.391732
27033000     1.405681
----- Moment - Rotation curve at SFI -----------------------------------------------------------------------
Moment       Rotation (in radians)
0            0
8660000      0.000148
16510000     0.000343
...          ...
...          ...
90913000     0.056991
90961000     0.058552


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