REPORT

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

ADAPTATION FOR PRACTITIONERS

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Client:	The Research Council of Norway (NFR)
Client contact person:	Harald Rikheim
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for NGI

Project manager:	Amir M. Kaynia
Prepared by:	Arnkjell Løkke
Reviewed by:	Ana M. Page, Amir M. Kaynia

Summary

An important attribute of the recently developed REDWIN foundation models – developed to be used for integrated analyses of offshore wind turbines (OWTs) – is that they are flexible in how their input can be obtained. Presented in this report are several possible ways to obtain such input, ranging from very simple procedures requiring only a minimum of basic soil input parameters, to more sophisticated nonlinear FEA that requires detailed site investigations and corresponding laboratory testing. Because many of these methods are standard procedures commonly used in OWT foundation design, they facilitate the adaptation of the REDWIN model by practitioners in all phases of actual engineering projects.

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1 Introduction

The design of offshore wind turbines (OWTs) and their support structures (such as the foundation) is a multi-disciplinary task that requires input from the geotechnical engineer, structural engineer, metocean experts, installation contractor, and the turbine manufacturer. Each of these have their own set of tools and procedures on how to do their respective parts of the design. To bridge this inter-disciplinary gap, designs are often conducted using specialized integrated dynamic analysis software that, in addition to the structural model itself, incorporate models for representing waves, wind and the control system of the turbine, as well as the foundation and soil response. Of these, the analysis models representing the soil response are often the simplest and based on highly idealized assumptions that do not necessarily capture realistically the soil and foundation behaviour. As part of the REDWIN (Reducing the Cost of Offshore Wind by Integrated Structural and Geotechnical Design) research project, a library of new foundation models have been developed to address this lack of accurate and robust models for representing the foundation and soil response in integrated analyses.

This report briefly outlines practical recommendations on how the REDWIN models can be used in various parts of OWT design analyses. Different methods for obtaining the required input to the models for the different phases of the design are presented, and techniques for better understanding the characteristic behaviour of the models (e.g. material damping from hysteresis loops) are outlined.

2 Design of offshore wind turbine foundations

The design of offshore wind turbine foundations goes through several stages, starting with a preliminary design that may include a feasibility study and FEED (front end engineering design), through to detailed design. In the preliminary design, the main objectives are to identify feasible foundation concepts, obtain sufficient confidence in the design for the financial investment decision (FID) to be made, and to lay the ground work for the detailed design phase. Typically, only basic information is available about the site, soil properties and expected loading conditions. Preliminary design calculations are therefore often based on simplified methods (e.g. using static loads on the turbine and support structure and empirical formulas to estimate foundation stiffness) to screen and evaluate different foundation designs.

An offshore wind farm may consist of as many as 50-100 OWT foundations, each of which has to be designed separately. In order to optimize the workflow and reduce the number of analyses, the wind farm is often *clustered* by grouping together locations with similar design drivers, for example similar soil profiles and/or loading conditions. Depending on the design method used, the geotechnical input can then be normalized for each cluster, or upper and lower estimates of stiffness and foundation response may be developed to assist in preliminary design of the foundation.

As the design process matures, more information becomes available for example via new site investigations and additional laboratory testing to determine soil properties. Load calculations are also refined, as these are inherently interconnected to the properties of the foundation. The design work in this phase primarily consists of checking and verifying the initial design assumptions using more sophisticated analysis methods (e.g. integrated OWT simulations) and if possible, optimize the design, in addition to providing documentation that the proposed design meet relevant standards and design guidelines.

Throughout these phases, the geotechnical foundation design are often conducted based on three main analysis criteria:

- ULS (Ultimate Limit State) design, where the foundation capacity is assessed, typically considering extreme load events (e.g. storms) that are analysed using cyclic load histories and consideration of the potential for cyclic soil degradation due to accumulation of pore pressures.
- FLS (Fatigue Limit State) design, where the foundation design is evaluated with regards to its fatigue lifetime. From the geotechnical side this typically involves providing estimates on the foundation stiffness and global foundation damping as input to integrated load simulations conducted by the structural engineer.
- SLS (Serviceability Limit State) design, where rotations and deformations (both peak values and long-term accumulated values) are evaluated with respects to operability criteria for the turbine.

The REDWIN foundation models, illustrated in Figure 1, can be used in all stages of design and for all types of design analyses (ULS, FLS, SLS) because of the inherent flexibility in how their model input is obtained. This flexibility allows the level of detail and sophistication in the model input to be adapted to the phase the project is currently in. The use of the models as part of the OWT design workflow is illustrated in Figure 2.

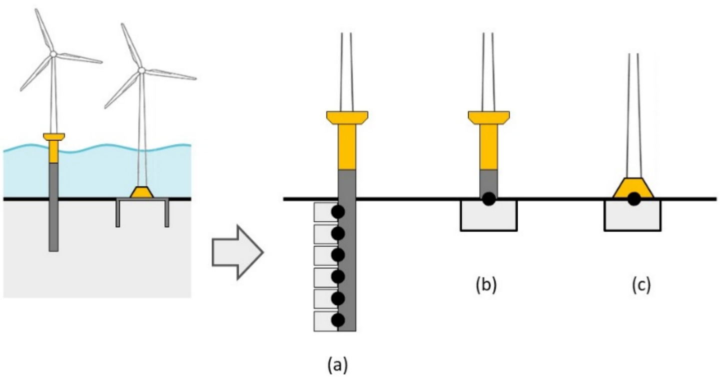


Figure 1 The three types of REDWIN foundation models: (a) REDWIN model 1, a distributed soil reaction model for monopiles; (b) REDWIN model 2, a macro-element model for monopiles; (c) REDWIN model 3, a macro-element model for shallow foundations.

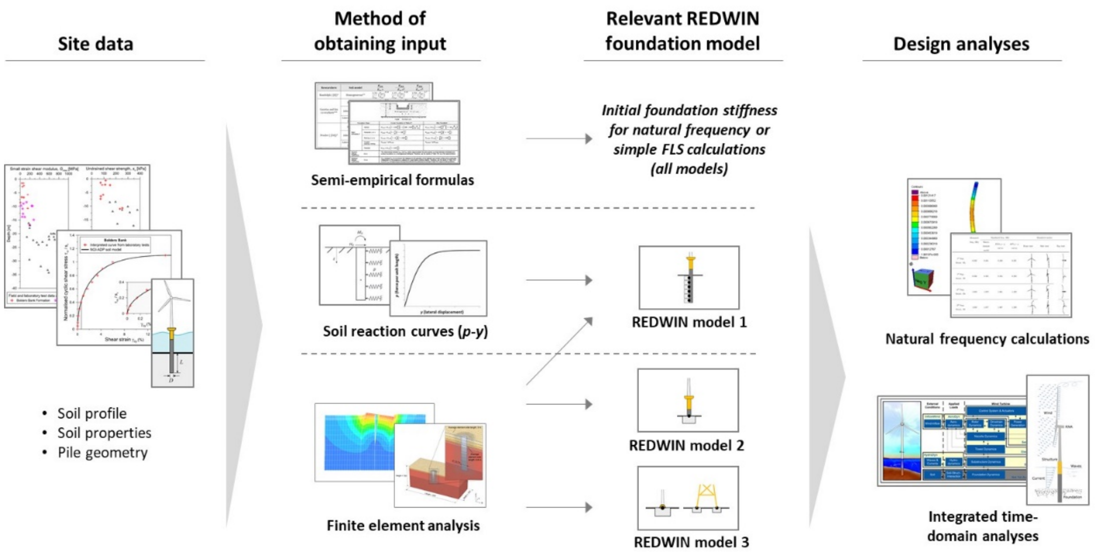


Figure 2 Use of REDWIN foundation models in OWT design.

3 Generating input to REDWIN foundation models

The primary input to the REDWIN foundation models are load-displacement (and moment-rotation) curves that describe the soil and foundation response to monotonic loading. REDWIN model 1 can make use of "*p*-*y* type" soil reaction curves at locations distributed along a monopile as input; REDWIN models 2 and 3 on the other hand require the initial stiffness and nonlinear load-displacement curves for the "total" foundation response of monopiles (model 2) or caisson foundations (model 3). Defining the model input in the form of load-displacement response curves (or soil-reaction curves for REDWIN model 1) offers several advantages:

- The model input have a direct physical interpretation.
- The models are not limited to idealized cases, but can handle arbitrary soil profiles and material types found at actual offshore sites.
- The calibration process is flexible because there are several ways to obtain the required input, with varying degree of complexity and accuracy.

These characteristics greatly increase the usefulness and accessibility of the REDWIN models for actual engineering projects. For example, the use of finite element analysis (FEA) to obtain load-displacement input curves ensures that site-specific soil input and state-of-the-art numerical models can be directly utilized, and that the models can make use of future advances in FEA, e.g. improved constitutive models for clays and sands.

Another useful feature is that while FEA *can* be used to obtain the input, it does not necessarily *have* to be used. This enables the designer to streamline the design process for an overall offshore wind farm by adapting the level of detail in the model input to the phase the project is currently in. For example, simplified methods or normalized calibration methods can be used in the early phase design (e.g. feasibility studies), while more comprehensive and detailed FEA can be applied in the FEED and/or detailed design phase when more site-specific soil data is available.

Some alternative methods to obtain the model input are illustrated in Figure 3. Each of these methods are described in more detail in the following sections, starting from the simplest to the most advanced.

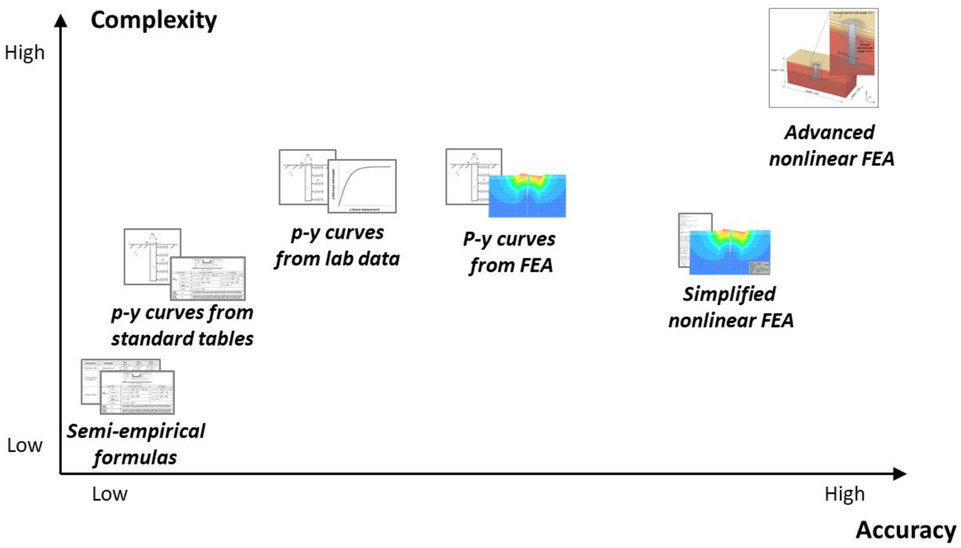


Figure 3 Methods for obtaining input to REDWIN foundation models.

3.1 Semi-empirical formulas

For analyses in the early design stages, such as determining the first natural frequency and performing initial FLS analyses (at low load levels), it may be sufficient to adopt a linear elastic foundation model where the initial foundation stiffness and foundation damping are the primary inputs. The foundation is then modelled using linear translational and/or rotational springs applied at mudline or another decoupling point.

To compute the initial foundation stiffness, there exists several semi-empirical relationships for different types of foundations embedded in idealized soil profiles, a few of which are mentioned herein. Randolph (1981) presented dimensionless flexibility functions for lateral displacement and rotation of flexible piles (i.e. piles with a length that is longer than their "active length") floating in a homogeneous or linearly increasing soil profile subjected to horizontal and moment loading at the pile head. Gazetas (1991, 1983) presented tables with standardized formulas for static stiffness coefficients and dynamic stiffness and damping coefficients for swaying (horizontal movement), rocking (rotational movement) and coupled swaying-rocking movements. Tables are presented for homogeneous, linearly increasing, and parabolic soil profiles, and for both shallow foundations and flexible piles. For shallow foundations, Doherty and Deeks (2003) used a semi-analytical technique to develop dimensionless elastic stiffness coefficients for vertical, horizontal, moment and torsional response of rigid circular footings of several geometries embedded in an elastic halfspace. The variation of shear modulus with depth may correspond to normally consolidated sand or clay.

Common for these formulae is that no results were presented for the types of geometries – in particular L/D ratios – that are most relevant for large-diameter monopiles. The more recent paper by Shadlou and Bhattacharya (2016) presented such data for monopiles with $L/D > 2$ embedded in homogeneous or inhomogeneous ground profiles. For each round profile, static and dynamic impedance functions were proposed for piles exhibiting rigid and flexible behaviour.

No standardized (or normalized) formulas currently exist for determining the complete nonlinear load-displacement curves for the overall response of OWT foundations. Work on developing such normalized curves for monopile response is in progress at NGI.

3.2 Distributed soil reaction springs (*p-y* approach)

Analysis of monopile foundation by modelling the pile as a beam and the soil as a series of nonlinear elastic springs distributed along the pile (*p-y* curves) have long been industry practice in monopile design. Previous design standards for OWT foundations typically referred to the standardized API *p-y* curves (API 2014) which have long been used in the oil and gas industry; however, research have highlighted the limitations of applying these curves for monopile design (Page et al. 2016; Kallehave et al. 2015). Newer design standards have moved away from the API method and towards more refined methods for obtaining lateral *p-y* springs (DNV-GL 2016).

The recent PISA (Pile Soil Reaction) joint industry research project has developed a 1D framework for design of monopile foundations subjected to lateral loading (Byrne et al. 2017). An important finding of the project is the inclusion of three additional soil reaction components in addition to the conventional lateral *p-y* distributed springs along the pile: (1) distributed moment-rotation springs along the pile, (2) a horizontal force-displacement spring at the base, and (3) a moment-rotation spring at the base. The PISA projects refers to each of these nonlinear elastic functions that relate reactions (forces or moments) to deformations (displacements or rotations) as "soil reaction curves". Generic curves are scaled by relevant pile geometries and soil data to obtain site-specific curves to be used in analyses.

These frameworks (lateral *p-y* and PISA) are both compatible with REDWIN foundation model 1 which can be used in a "distributed" form along the monopile. The model can be used both to model distributed lateral force-displacement and moment-rotation springs along the pile, as well as model the horizontal force and moment reaction springs at the base of the pile. Using REDWIN model 1 in this configuration has the advantage that it includes the effects of stiffness change during load reversals and hysteresis damping during cyclic loading; both of these are mechanisms that have been observed in the field.

Three different ways of obtaining soil-reaction curves for the REDWIN model 1 are outlines in the next sections.

3.2.1 Using available rule-based methods

Part of the recent PISA project has been to develop rule-based methods for establishing soil reaction curves for large-diameter monopiles (Byrne et al. 2017). The shape of the dimensionless curves are represented by a four parameter model: $\bar{x}$ is a normalized displacement variable, $\bar{y}$ is a normalized reaction variable, k is the initial stiffness, and n is a curvature parameter.

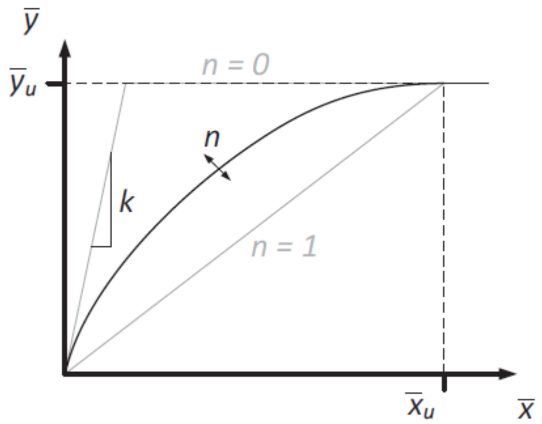


Figure 4 Normalized generic soil reaction curve for the PISA rule-based method. Figure from Byrne et al. (2017).

These generic soil-reaction curves are scaled using relevant pile geometries and basic soil strength and stiffness parameters obtained from site investigations to obtain site-specific curves. Required for the soil is the variation with depth of (1) the small-strain shear modulus G_0, and (2) the undrained shear strength s_u (for clays). Values of G_0 can be measured using seismic cone test; undrained shear strength can be obtained from CPT-tests, laboratory testing on high quality samples, or ideally, a combination of these two. Because only basic soil information is required, this approach can be applied in the preliminary concept design stage where detailed soil parameters and results from laboratory testing are still unavailable.

It would also be possible to obtain lateral *p-y* curves for REDWIN model 1 using the API methodology. However, this is not recommended because the API curves have been shown to give inaccurate results when applied to monopile analyses (Page et al. 2016).

3.2.2 Scaling of results from cyclic DSS tests

Methods have been developed to derive site-specific soil response curves for slender piles from direct simple shear (DSS) stress-strain curves obtained from laboratory testing (Zhang and Andersen 2017). This framework has also been extended to account for the effects of cyclic loading by making use of cyclic interaction diagrams based on soil testing (Zhang et al. 2017).

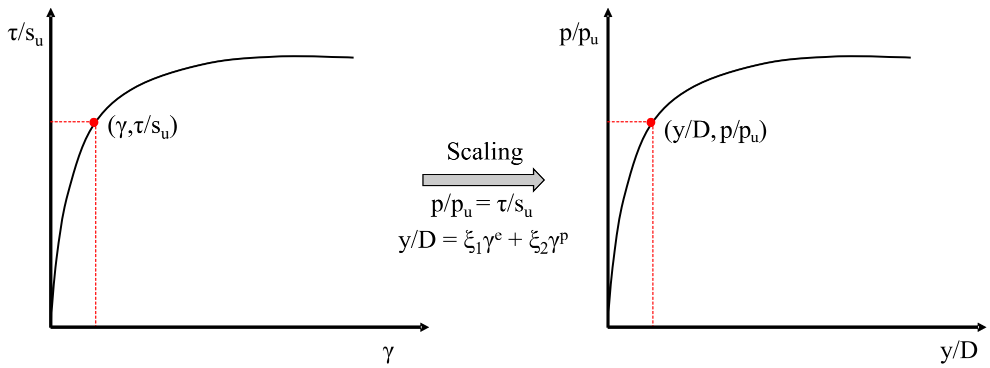


Figure 5 Conceptual model for deriving monotonic p-y curves from stress-strain response for slender piles. Figure from Zhang and Andersen (2017).

This method has been adapted to large diameter monopiles (Zhang and Andersen 2018), which experience different soil failure mechanisms than slender piles and therefore requires modifications to the formulation. Formulated based on results from nonlinear FEA, the method divides the nonlinear soil response into three different mechanisms (Figure 6): (1) a wedge failure mode in the upper part of the pile above the rotational point, (2) a flow around failure mode in the lower part of the pile, and (3) a shear-displacement mode at the pile tip.

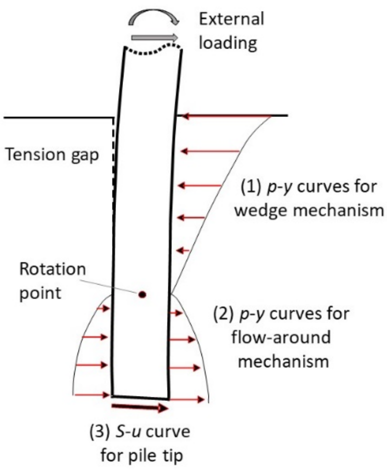


Figure 6 Conceptual model for monopile analysis. Figure from Zhang and Andersen (2018).

A set of standardized equations have been developed to obtain soil reaction curves for each of these three mechanisms. Detailed descriptions of these equations and instructions on how the method can be applied to monopile analysis and design can be found in Zhang and Andersen (2018).

3.2.3 Using numerical-based methods (FEA)

Alternatively to using rule-based equations or results from DSS tests to obtain soil reaction curves, they can also be derived directly from the results of FEA. Procedures for applying such methods are outlined in (Byrne et al. 2015, 2017). Nonlinear FEA using representative models for the soil behaviour are then conducted for a range of relevant design cases (e.g. for different monopile geometries), and soil-reaction curves are extracted from the results and adapted to being incorporated into the 1D soil-reaction curve modelling framework. This approach requires the same detailed soil input parameters, determined from site investigations and laboratory testing as the FEA described in Section 3.3, and is therefore primarily useful in the later stages of design when such data is available.

3.3 Nonlinear finite element analysis (FEA)

The results of FEA can be used directly to obtain the load-displacement response curves at mudline for REDWIN models 2 and 3. This direct approach avoids several of the the limitations that are inherent in using soil-reaction curves based on a 1D modelling framework, which are especially prominent for layered soils (Page 2018).

3.3.1 Advanced nonlinear FEA

The most advanced way to obtain the required input for the REDWIN foundation models is to perform three-dimensional nonlinear FEA of the foundation and surrounding soil volume using a general FEA program (e.g. PLAXIS3D) with constitutive models that accurately represent the nonlinear cyclic stress-strain behaviour of soils observed in laboratory tests. The effects of cyclic behaviour of the soil can for example be described using the undrained cyclic contour diagrams established on the basis of DSS test results.

These types of nonlinear FEA can fully account for different soil types, layering, etc., as well as arbitrary foundation types (piles, caissons, gravity based, etc.) and geometries. However, because the analyses require detailed information about parameters to calibrate the soil constitutive model, they are mostly applicable for the later stages of design when such information is available. In addition, it is rarely practical to conduct detailed nonlinear FEA for every foundation in a large wind farm; instead, locations that are representative for a certain cluster of foundations can be analysed and the results interpolated/extrapolated to cover monopiles other locations.

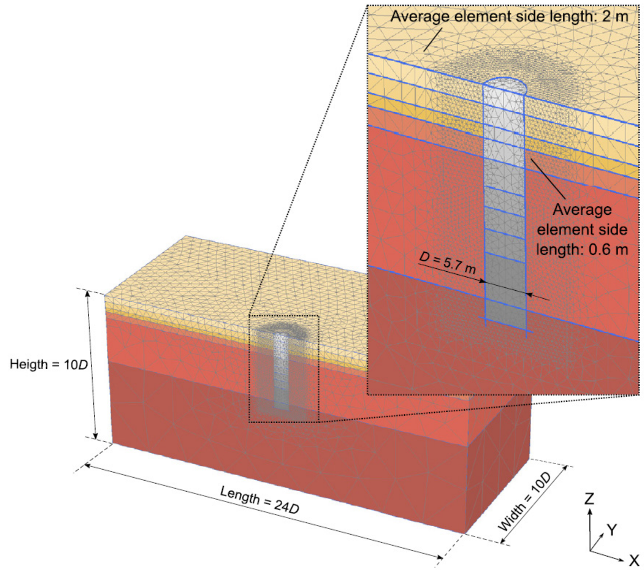


Figure 7 PLAXIS3D finite element model for monopile response. Figure from Page et al. (2018).

3.3.2 Simplified nonlinear FEA

As part of the REDWIN project, an alternative, simplified workflow has been developed to obtain initial foundation stiffness and nonlinear load-displacement curves for OWT foundation response. Using a modified version of the nonlinear FE program INFIDEP, internally developed at NGI in the 1980s-90s, as the main computational engine, a set of pre- and post-processing modules have been developed to facilitate generating input data for REDWIN models 2 and 3.

The workflow of using this nonlinear FE program to generate input data for REDWIN models 2 and 3 is described as follows. First, the user specifies some basic input (soil layering, basic soil properties, pile geometry, etc.). Then, the program runs in batch mode in the background to compute the initial stiffness and load-displacement curves, and finally the output is converted to the correct format required for the REDWIN models. This workflow is illustrated in Figure 8.

The advantage of this tool is that it is very fast (typically each analyses takes a minutes or less), and that it requires only basic inputs to characterize the soil and foundation response, so that a number of geometries and soil conditions can be assessed in very short time. Automation of these analyses allow streamlining of the design process with only a marginal increase in the time required for the overall design process. Thus, the use of this program represents an attractive way to obtain REDWIN model input with sufficient accuracy for most applications. An example of the use of the program, as well as a numerical example validating its accuracy for monopile analyses, is included in Appendix A.

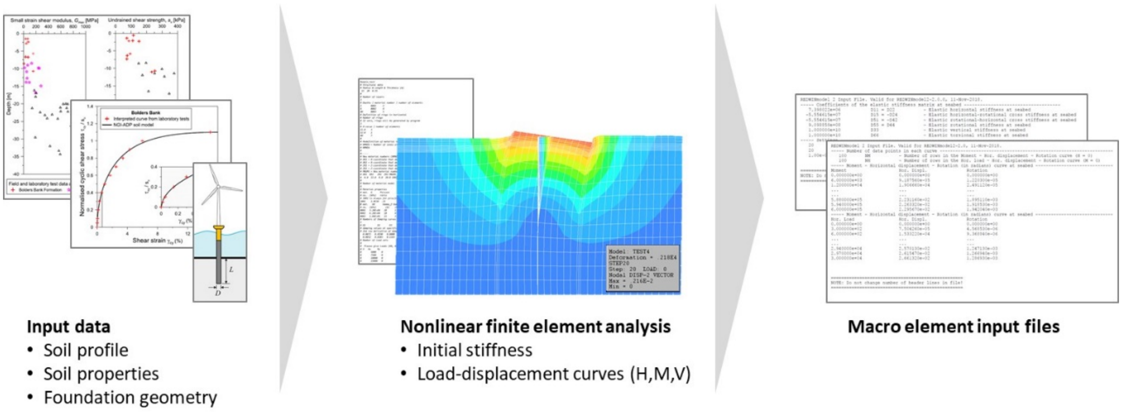


Figure 8 Workflow for simplified FEA with INFIDEP to obtain REDWIN model input.

4 Interpretation of macro-element behaviour

The REDWIN foundation models differ from the "conventional" foundation models that are often used for OWT design in several ways, most importantly they represent more accurately the stiffness change during load reversals, and include the effects of foundation hysteresis damping.

The latter of these, foundation hysteresis damping, has several characteristics that are potentially advantageous for OWT design, such as higher damping at higher load levels. However, due to its amplitude-dependency, this mechanism has the disadvantage that the overall level of damping cannot be directly specified or easily determined. In the next section, a method for how to estimate the level of overall damping in a FE model of the foundation is presented.

4.1 Foundation hysteresis damping

The REDWIN foundations models are formulated in a mathematical framework that ensures that foundation hysteresis damping is "automatically" included in the model. Hysteresis damping is a form of internal material damping in which energy is dissipated via internal friction and slipping and sliding of internal planes within the material during cyclic loading. Mathematically, the damping ratio for hysteresis damping is defined as

$$D = \frac{1}{4\pi} \cdot \frac{E_h}{E_p} \tag{1}$$

where D is the damping ratio, E_h is the area of the of the stress-strain loop in a cycle and E_p is the maximum potential energy in the same cycle (Figure 9).

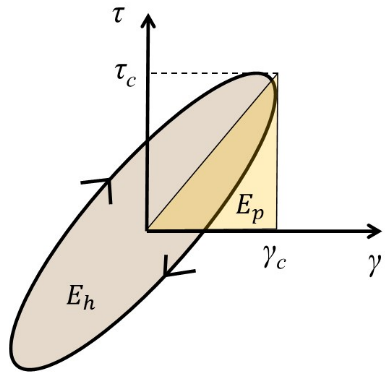


Figure 9 Illustration of energy loss E_h in a closed hysteresis loop. The definition of the maximum potential energy E_p in the cycle is also shown.

This mechanism depends on the loading amplitude, that is, it will generate higher damping values at higher load levels. This differs from traditional Rayleigh damping methods for specifying structural damping. Compared to Rayleigh damping, hysteretic damping will reduce the amplification of the structural response during periods when aerodynamic damping is not present (e.g. during idling conditions). This, in turn, may have a significant impact on the estimated fatigue lifetime of the foundation and tower.

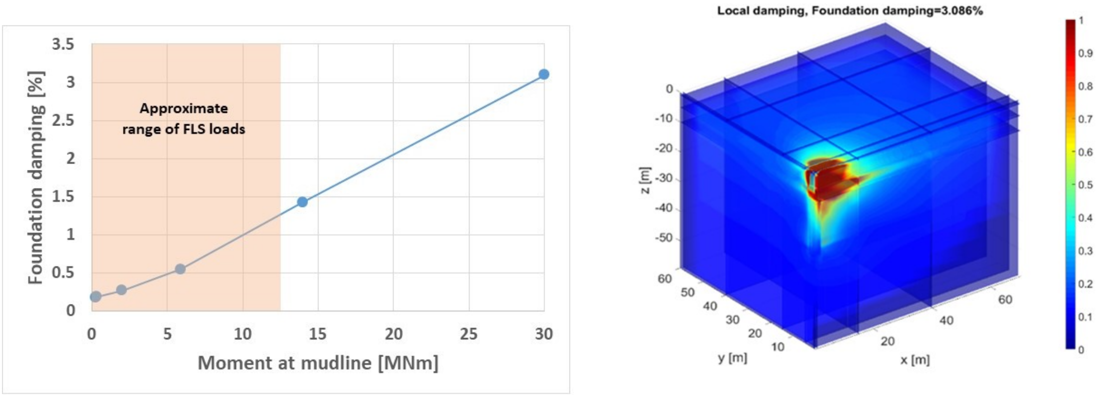
Because of this load-dependency, it is difficult to estimate a-priori the overall amount of hysteresis damping in the foundation. To address this issue, a procedure has been developed as part of the REDWIN project to quantifying foundation damping at different load levels directly from FEA models (NGI 2017). The procedure integrates stresses and strains in every element in the FEA model to compute the individual contribution from each element, and sums these up to determine the overall foundation damping ratio[1].

The tool can provide output in the form of a curve for the overall foundation damping at different load levels (Figure 10a), and can also visualize the spatial variation of damping in the model at a given load level (Figure 10b). The tool has been validation against measured damping in a DSS test, as well as example simulations for an actual OWT monopile foundation at an offshore wind park located in the North Sea.

The FEA program INFIDEP, described in Section 3.3.2, is also capable of providing an estimate of the overall foundation damping at different load levels, using a set of pre-defined material damping curves as input. Such curves can be estimated using standard functions for damping in different materials (Darendeli 2001), or directly from the results of laboratory DSS or Triaxial tests.

The use of such tools to estimate the overall foundation damping allows the structural engineer to get a better understanding of the contribution from foundation hysteresis damping to the overall energy dissipation in the OWT-foundation system.

[1] The term "overall foundation damping", as defined herein, refers to the energy dissipation taking place in the foundation and the surrounding soil, not the overall damping in the entire OWT-system which also includes structural damping in the tower and turbine, aerodynamic damping, and hydrodynamic damping.



(a) (b)

Figure 10 Example output from damping tool for an OWT in the North Sea: (a) foundation damping as a function of moment load, (b) spatial variation of location damping at 60MNm moment load.

5 Conclusions

An important attribute of the recently developed REDWIN foundation models – developed for integrated analyses of OWTs – is that they are flexible in how their input can be obtained. This report has presented several possible ways to obtain such input, ranging from very simple procedures requiring only a minimum of basic soil input parameters, to more advanced nonlinear FEA that requires detailed site investigations and corresponding laboratory testing.

Because many of these methods are standard procedures commonly used in OWT foundation design, they facilitate the adaptation of the REDWIN model by practitioners in all phases of actual engineering projects.

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Appendix A

USING INFIDEP TO OBTAIN REDWIN INPUT

Contents

A1 Introduction

To facilitate the use of the REDWIN foundation models, the internal NGI finite-element program INFIDEP has been modified and compiled in a form that streamlines the process of generating input to the foundation models.

The 3D finite element program INFIDEP (NGI 1999) was originally developed at NGI in the late eighties to be used for calculation of gravity base structures (GBS) for offshore oil and gas developments. Due to limited computer capacities at that time, it was essential to develop a very efficient code. Therefore, a special "pineapple slice" ring element is used, which drastically reduces the required number of degrees-of-freedom for axisymmetric problems where the displacement field around the foundation has high gradients primarily in the radial and vertical directions.

As part of the REDWIN project, this program has been modified and specialized for monopile analyses. The required user input has been streamlined, a new and more user-friendly soil-model has been implemented, and the program has been compiled to run in a batch setup that facilitates its use for obtaining the REDWIN model input. The new pre-processor requires basic information about the pile geometry, FE discretization, soil layering, soil material properties and load cases; information which is relatively easy to obtain, even early in the design process. A post-processor has also been developed to reformat the analysis output in a way so that it is ready for use with the REDWIN foundation models.

This appendix presents how the modified INFIDEP program can be used to calibrate the input for the REDWIN foundation models for an offshore wind turbine (OWT). First, the program is verified numerically by computing the response of a 9m diameter monopile foundation in an idealized reference soil profile and comparing with results obtained using the 3D FEA program PLAXIS3D (Brinkgreve et al., 2016). Then, the program is used to obtain the required input for REDWIN model 2.

A2 Verification of INFIDEP for monopile analyses

To verify the INFIDEP program for monopile analysis, a 9m diameter monopile foundation in an idealized reference soil profile is analysed and the results are compared with results obtained by modelling the same system in the commercial FEA program PLAXIS3D.

A2.1 Soil parameters and pile properties

The idealized soil profile considered consists of a homogeneous, isotropic, clay with a shear strength profile (s_u^{DSS}) that increases linearly with depth down 3m, and is then kept constant with depth at a value s_u^{DSS} = 100 kPa. The failure strain for the soil is selected to be γ_f = 15% and the strain at 50% mobilization is γ_{50} = 1.5%. The resulting stress-strain curve is used directly without modification to account for possible effects of strain-rate or cyclic soil degradation. The ratio $G_{max}/s_u^{DSS} = 1000$ is kept constant with depth. The DSS shear strength and G_{max} profiles are shown in Figure A1, and the resulting INFIDEP material parameters are shown in Table A1. All analyses are run undrained.

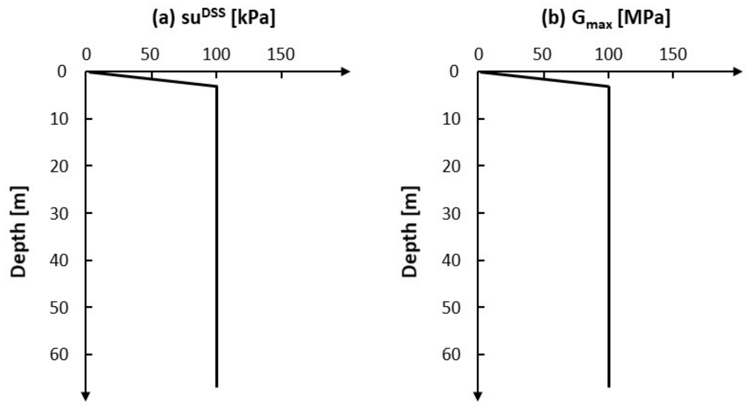

Figure A1 Soil profiles used in FEA: (a) DSS shear strength profile, (b) G_{max} profile.

Table A1 Material parameters for soil layers in the INFIDEP model.

Parameter	Unit	Layer 1	Layer 2
Start depth	[m]	0	3.0
End depth	[m]	3.0	60
su^{DSS}_top	[kPa]	1	100
s_u^A/s_u^{DSS}	[]	1.0	1.0
s_u^P/s_u^{DSS}	[]	1.0	1.0
ds_u^{DSS}/dz	[kPa/m]	33.3	0
G_{max}_top	[MPa]	1	100
γ_{50}	[%]	1.5%	1.5%
γ_f	[%]	15 %	15 %

To model the potentially weaker zone between the pile and the soil, a separate thin interface layer is included in the model. This interface is given properties that correspond to half the stiffness (G_{max}) and half the shear strength (s_u^{DSS}) of the surrounding soil outside the pile.

A2.2 Pile properties

The pile is modelled as a linear elastic thin-walled cylinder with length L = 36m, diameter D = 9 m (i.e. L/D = 4), and a constant wall thickness t = 80 mm. The steel in the pile has a modulus of elasticity E_{steel} = 210 GPa and Poisson's ratio of 0.3.

A2.3 Mesh and boundary conditions

The finite element mesh follows an axisymmetric discretization. The pile is discretized using shell element in the shape of a vertical circular cylinders with constant wall thickness, which are given beam and shear flexibility properties. The soil volume is separated into a near-field region and a far-field region by a cylindrical boundary. The near-field soil elements are "pineapple slice" ring elements, with upper and lower faces that are horizontal, and inner and outer faces that are vertical in the shape of circular cylinders. The far-field soil elements are layer elements with linear elastic material behaviour that extends from the cylindrical boundary to infinity in the horizontal direction.

The mesh, shown in Figure A2, consists of 1170 elements and 1240 nodal points. The mesh is refined in the areas near the pile and close to the surface where the largest deformations are expected.

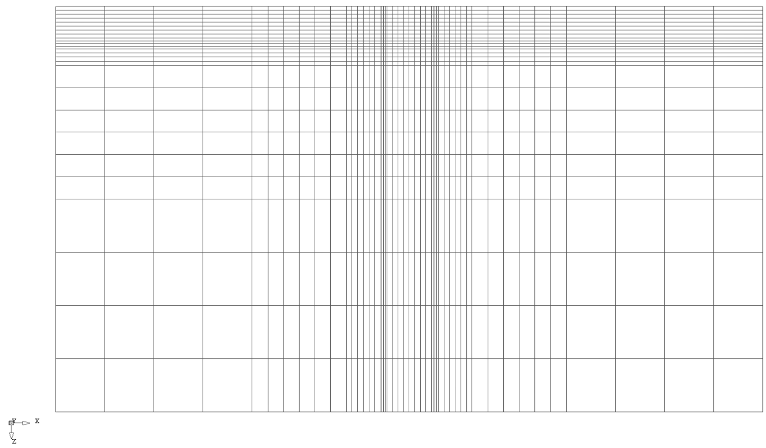

Figure A2 Axisymmetric finite element mesh for INFIDEP model.

A2.4 Loads

A single analysis with a "ULS type" load is conducted. The loads applied at the pile head at mudline are a horizontal force H = 45 MN and an overturning moment M = 1500 MNm, corresponding to a load eccentricity for the horizontal force of 33.33 m. Note that this combined H-M load case does not correspond to the two load cases used for determining the REDWIN model input, which requires separate analyses for horizontal load (with M = 0) and moment load (with H = 0) at mudline; see Section A3.

A2.5 PLAXIS3D analysis model

To obtain a benchmark to which the INFIDEP results can be compared, the same system is analysed using the commercial FEA program PLAXIS3D. The isotropic clay is modelled in PLAXIS3D using the NGI-ADP material model (Grimstad, Andresen, and Jostad 2012). Input to the NGI-ADP material model consists of the undrained shear strength s_u, the G_{max}/s_u ratio, and the failure strain, these are selected based on the values in Table A1. The interface between the pile and the soil is modelled using the same properties as the INFIDEP model, i.e. half the stiffness and strength of the surrounding soil. The PLAXIS3D model and with approximately 26 000 finite elements is shown in Figure A3.

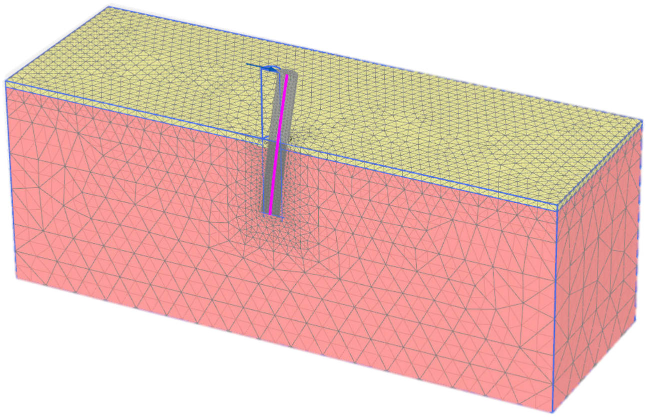

Figure A3 PLAXIS3D analysis model.

A2.6 Results

Figure A4 shows the deformed monopile and surrounding soil under the combined horizontal-moment loading conditions.

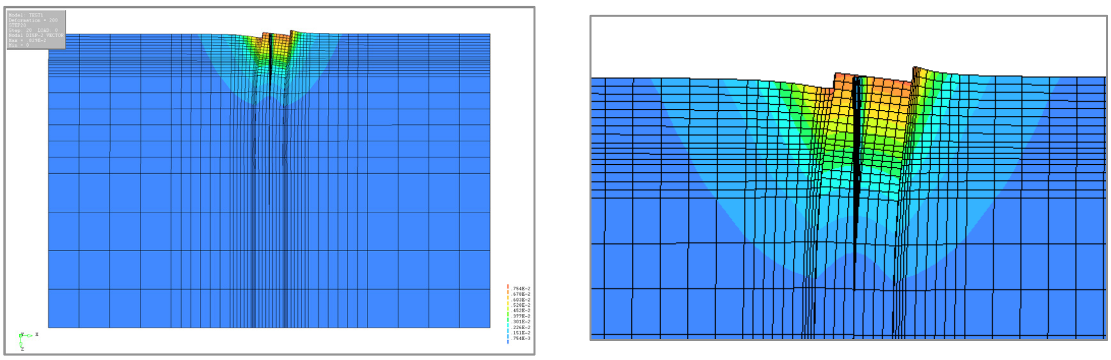

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Figure A4 Deformed mesh for last load step of INFIDEP analysis. Response of entire domain (left), and close-up near the surface (right).

Presented in Figure A5 is the foundation response in terms of load-displacement (left) and moment-rotation (right) curves, where results obtained using INFIDEP is compared with the results from PLAXIS3D. The results from INFIDEP closely matches the results from the PLAXIS3D analysis: the initial stiffness for both curves are very close, the overall shape of the nonlinear response curves are close, and the maximum discrepancies are around 10% for the load-displacement and moment-rotation responses. These discrepancies can be attributed to slight differences in the two FEA models, the soil constitutive models used, and formulation for the interface between the pile and the soil.

The distribution of shear forces and moments along the embedded part of the monopile with are shown in Figure A6, where the results computed by INFIDEP are compared to PLAXIS3D results. The agreement is very good for both the shear forces and the moments along the pile, thus demonstrating the ability of INFIDEP to accurately compute the foundation and pile response for this system.

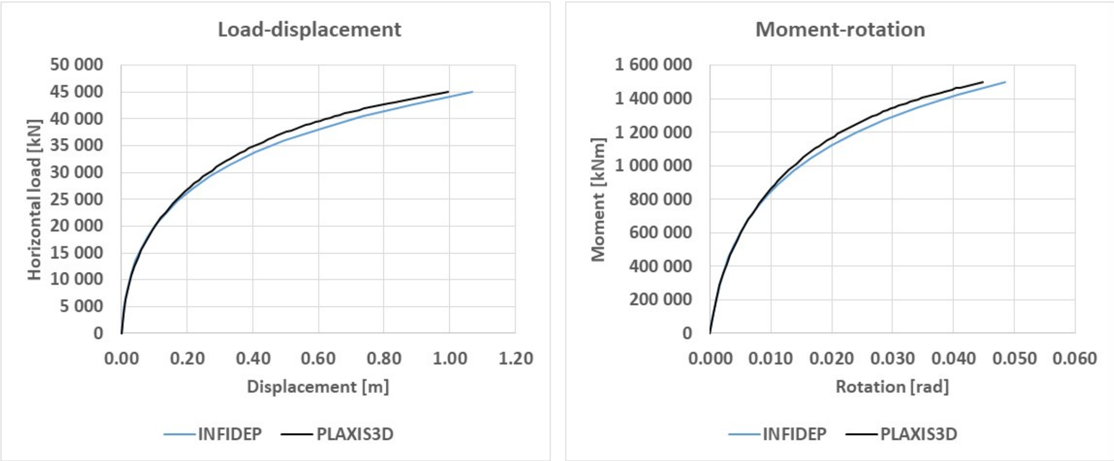

Figure A5 Nonlinear response for combined horizontal load and moment applied at mudline computed by INFIDEP and compared to results obtained using PLAXIS3D.

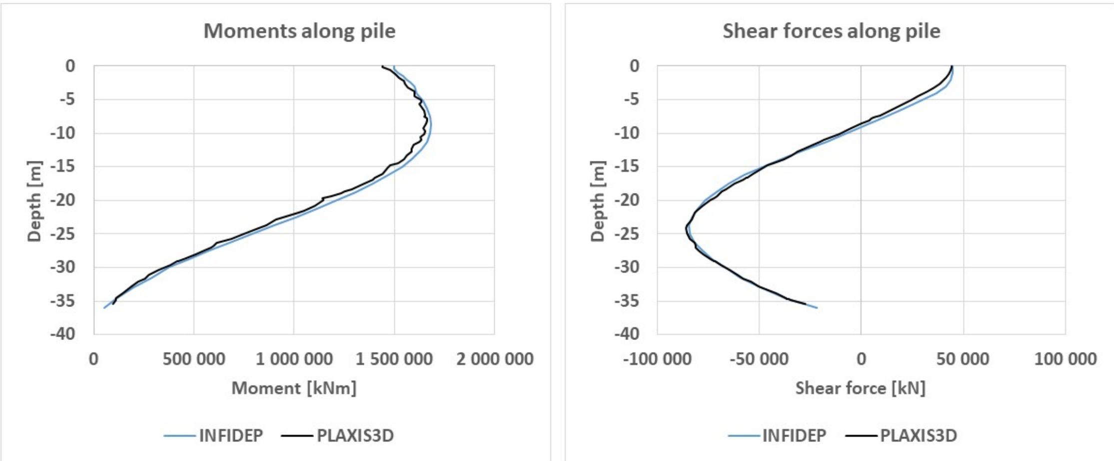

Figure A6 Shear forces and moments along monopile computed by INFIDEP and compared to results obtained using PLAXIS3D.

A3 Generating input for REDWIN foundation model

Presented in the following section is an example of how INFIDEP can be used to obtain the required input for REDWIN model 2. The analysis model (soil profile, pile geometry, FE mesh) considered is the same as the one described in Section A2; however, the load cases considered are different. In addition, results are presented for three different pile lengths: L = 36m (L/D = 4), L = 27m (L/D = 3), and L = 18m (L/D = 2).

A3.1 Loads

Two static pushover analyses are run to obtain the required load-displacement and moment-rotation input curves: (1) a pure horizontal force applied at the pile head at mudline, and (2) a pure moment load applied at the pile head at mudline. In both cases, the resulting displacements and rotations at mudline are recorded to form the input to the REDWIN macro-element model. In addition, two analyses are run with unit amplitude load and moment applied at mudline (separately) to obtain the coefficients of the small deformation monopile foundation stiffness matrix.

A3.2 Results

A3.2.1 Small deformation stiffness matrix

Presented in Table A2 are the coefficients of the elastic small deformation monopile foundation stiffness matrix for three different length monopiles. The coefficients are determined by first computing the coefficients of the flexibility matrix **F** based on the unit-amplitude horizontal load and moment, and then inverting this matrix to obtain the stiffness matrix **K**.

Table A2 Comparison of monopile foundations stiffness computed by INFIDEP.

Stiffness term		L = 36m	L = 27m	L = 18m
Horizontal, K_{xx}	[kN/m]	5.54E+06	5.51E+06	5.47E+06
Coupling, K_{xr}	[kN/rad]	-2.90E+07	-2.92E+07	-2.96E+07
Rotational, K_{rr}	[kNm/rad]	5.52E+08	5.49E+08	5.13E+08

A3.2.2 Nonlinear load-displacement curves

Nonlinear curves with load-displacement response and moment-rotation response are shown in Figure A5 for three different monopile lengths. These curves represent, together with the coefficients in Table A2, the complete set of input to define the macro-element behaviour for REDWIN model 2.

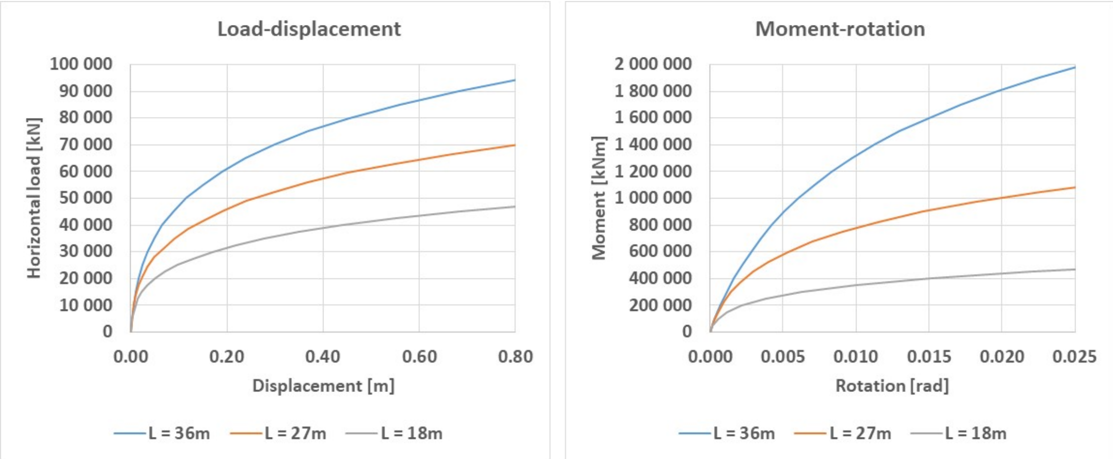

Figure A7 Nonlinear load-displacement and moment-rotation response computed by INFIDEP for monopile with three different lengths in idealized soil profile.

A4 Discussion and conclusions

This appendix has numerically verified the use of INFIDEP to compute the nonlinear response of monopiles in clay, and shown an example of how INFIDEP can be utilized to obtain the required input for the REDWIN macro-element models. The verification example demonstrates that INFIDEP is capable of computing monopile response that is in good agreement with results from a much more sophisticated nonlinear FEA using PLAXIS3D, and that the program is able to consider the combination of horizontal force and moment loading in a sufficiently accurate way.

The good level of accuracy obtained in these analysis is noteworthy considering how much simpler and faster the INFIDEP model is compared to the full nonlinear analysis in PLAXIS3D. For example, the INFIDEP analysis model only has a few hundred elements vs. several tens of thousands of elements in the PLAXIS3D model, and runs in about 20 seconds vs. about one hour for the PLAXIS3D model.

The efficiency gain this program represents is very advantageous for situations that require a large number of analyses to be conducted in a short time, e.g. design optimizations, parameters studies, or early phase screening analyses where many sites and/or designs must be quickly evaluated. By enabling the REDWIN model input to be obtained in such an effective way, the INFIDEP program facilitates the adaptation of the REDWIN foundation models for all phases of design.

A5 References

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NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

Main office
PO Box 3930 Ullevaal St.
NO-0806 Oslo
Norway

Trondheim office
PO Box 5687 Torgarden
NO-7485 Trondheim
Norway

T (+47)22 02 30 00
F (+47)22 23 04 48
NGI@ngi.no

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