Framework for Reliability Assessment of Offshore Wind Support Structures

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Executive summary

Design for Reliable Power Performance (D4REL) is an R&D project to improve the reliability and controllability of offshore wind farms to reduce the operational uncertainty of future offshore wind farms.

Work package 3 of the D4REL project investigates where cost reductions in the support structure are possible while keeping a sound and safe design. Probabilistic design methods (structural reliability methods) are used to study whether there is any conservatism in the design of support structures.

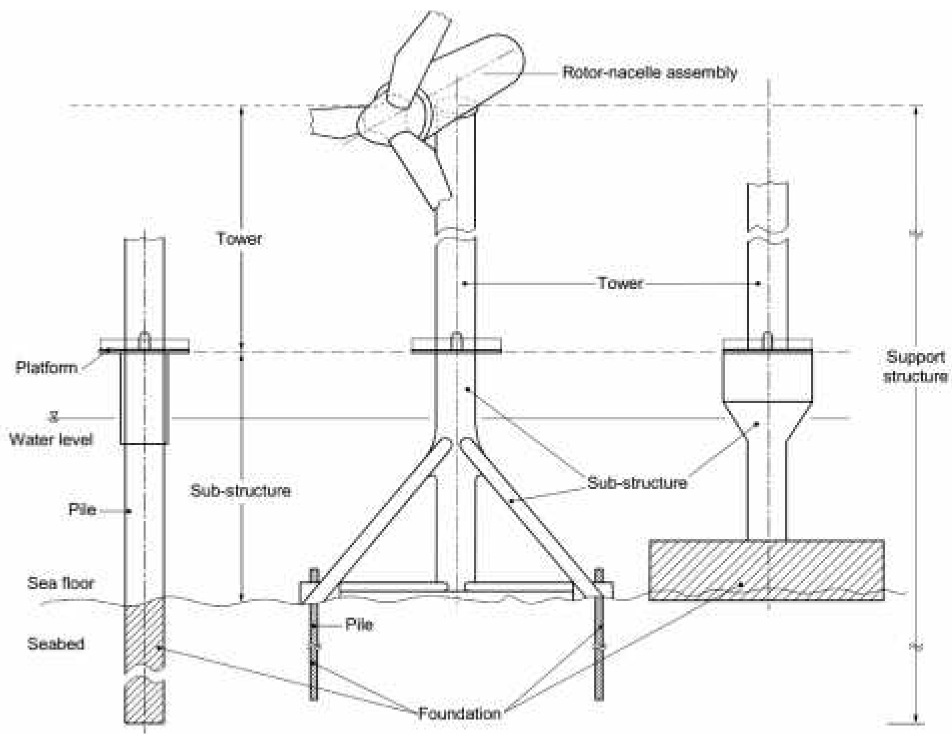
In this report a general framework for reliability assessment of existing monopile design is given. As an introduction design requirements for offshore wind support structures as recommended in guidelines and standards are briefly explained. Next a general framework for reliability assessment of offshore wind support structures is outlined. Finally, the outlined approach is illustrated using a simple case study.

1 Introduction

In order to reduce the cost of energy produced by offshore wind, wind farm components such as support structures should be designed to have a sufficient reliability level, but not more. This report is intended to describe a framework for reliability assessment of existing design of support structures using probabilistic concepts.

The IEC 61400-3 [1] (hereinafter referred to as IEC) defines *support structure* as part of an offshore wind turbine consisting of the tower, sub-structure and foundation as illustrated in **Figure 1**.

Figure 1: Parts of an offshore wind turbine [1]

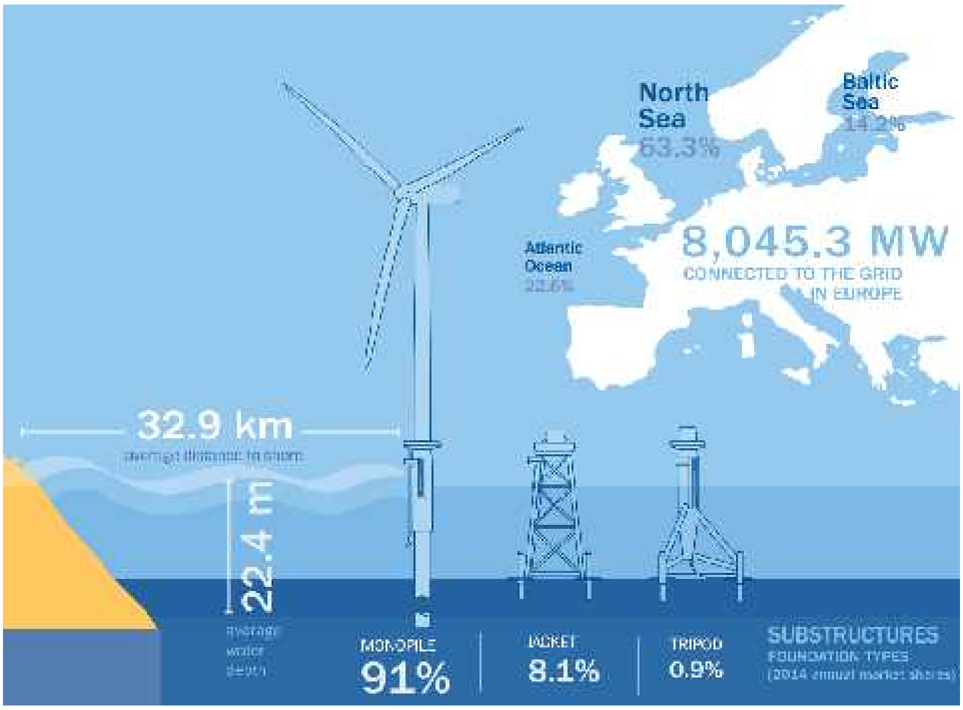


The structural configuration of support structures can be categorised as:

1. Monopile structures
2. Tripod structures
3. Lattice Structures
4. Gravity structures
5. Floating structures

By the end of 2014 about 2500 offshore wind turbines were installed in Europe [5]. The majority of installed turbines were supported by monopile structures (91%). Market share of different support structures in European offshore wind farms up to the end of 2014 is shown In **Figure 2**.

Figure 2: The statistics of European offshore wind development in 2013 [5]



Additionally, based on the trends and outlook, it is anticipated that monopile structures will be the favourable support structure for the next five years. Therefore, in this document only reliability assessment of monopile structures is considered.

A typical monopile structure is shown on the left side of **Figure 1** and **Figure 2**.

2

Design Requirements

The IEC outlines the minimum design requirements for all components of offshore wind turbines and recommends the ISO 2394 [2] (hereinafter referred to as ISO) and DNV-OS-J101 [3] (hereinafter referred to as DNV) specifically for design and structural analysis of offshore wind support structures. In the following some of IEC and DNV design requirements are briefly explained.

2.1 IEC Design Requirements

The IEC states that the safety level of a structure or a structural component is considered to be satisfactory when the design load **S**trength S_d doesn't exceed the design material **R**esistance R_d as shown in equation (1).

(1) $S_d \leq R_d$

In equation (1), S_d is the design value for the aggregated internal load or load response to multiple simultaneous load components from various sources for the given design load case and R_d are design values for materials.
In the IEC equation (1) is called as *design criterion* or *design inequality*. Moreover, the corresponding equation $S_d = R_d$ forms the *design equation*. The requirement in the equation (1) should be verified for several different load cases.

2.1.1 IEC Design Situations

The IEC states that for design purposes, the life of an offshore wind turbine can be represented by a set of design situations covering the most significant conditions that an offshore wind turbine may experience. The IEC defines eight design situations to be considered for an offshore wind turbine:

1. Power production

2. Power production plus occurrence of fault
3. Start-up
4. Normal shutdown
5. Emergency shutdown
6. Parked (standing still or idling)
7. Parked and fault conditions
8. Transport assembly, maintenance and repair

Within each design situation several design load cases should be considered and the requirement in equation (1) should be verified. Each load case has a different design situation and wind, wave and current climate.

2.1.2 IEC Design Analysis

IEC states that when relevant the following analysis should be done for defined load cases:

1. Analysis of ultimate strength (U)
    - Normal design load cases (N)
    - Abnormal design load cases (A)
    - Transport and erection (T)
2. Analysis of fatigue failure (F)
3. Analysis of stability analysis (buckling, etc)
4. Critical deflection analysis (mechanical interference between blade and tower, etc)

Each type of analysis requires a different formulation of the design equation and deals with different sources of uncertainties.

2.1.3 IEC Design Uncertainty

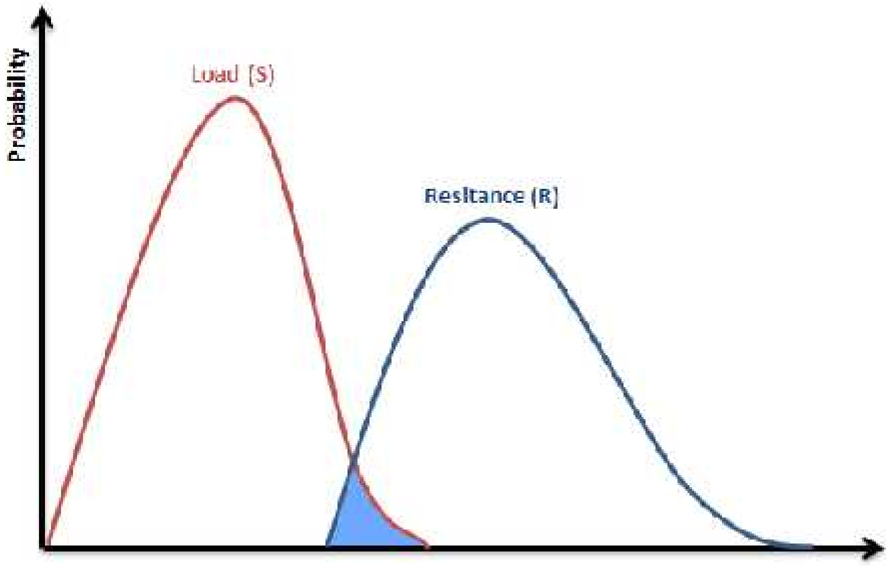
In order to account for uncertainties and variability in load strength and material resistance, *partial safety factors* (PSF) are used in the IEC. Partial safety factors are parameters defined by IEC to apply to characteristic values and calculate the design values. The partial safety factor for loads is denoted by γ_f and partial safety factor for materials in denoted by γ_m as shown in equations (2) and (3).

(2) $S_d = S_k \gamma_f$

(3) $R_d = R_k / \gamma_m$

In equations (2) and (3), S_k is the characteristic value for the load and R_k is the characteristic value of material properties. In order to demonstrate the worst case scenario in the design, lower quantile of resistance distribution and higher quantile of load distribution is used to calculate the characteristic values. An example is shown in **Figure 3**.

Figure 3: The characteristic value of load and resistance using high and low quantiles of their distribution function (marked by blue)



The partial safety factors for loads used in the IEC take account of possible unfavourable deviations/uncertainties of the load from the characteristic value and uncertainties in the loading model .

The partial safety factors for materials used in this standard, as in the ISO, take account of:

- possible unfavourable deviations/uncertainties of the strength of material from the characteristic value
- possible inaccurate assessment of the resistance of sections or load-carrying capacity of parts of the structure
- uncertainties in the geometrical parameters
- uncertainties in the relation between the material properties in the structure and those measured by tests on control specimens
- uncertainties in conversion factors

These different uncertainties are sometimes accounted for by means of individual partial safety factors but in the IEC the load related factors are combined into one factor.

Based on the type of analysis (ultimate or fatigue) IEC defines different partial safety factor for loads and materials. In the followings the PSF values for ultimate and fatigue analyses are discussed.

Partial Safety Factor for Ultimate Analysis

The IEC states that for ultimate analysis of design situations, the partial safety factor for loads should be at least the values in **Table 1**.

Table 1: IEC partial safety factors for loads (γ_f)

Unfavourable Loads			Favourable Loads
Type of Design Situation			All Design Situations
Normal (N)	Abnormal (A)	Transport & Erection (T)	
1.35[1]	1.1	1.5	0.9

In absence of recognised design codes, IEC states that the partial safety factor for materials should be:

- 1.1 for components with ductile behaviour
- 1.2 for components with non-ductile behaviour (for global buckling of curved shells such as tubular towers and blades)
- 1.3 for components with non-ductile behaviour (for rupture from exceeding tensile or compression strength)

The mentioned values for PSF of materials are considered as minimum in presence of recognised design codes.

Partial Safety Factor for Fatigue Analysis

The IEC states that for fatigue analysis the partial safety factor for loads should be 1.0 for all normal and abnormal design situations.

In absence of recognised design codes, the IEC states that the partial safety factor of material for fatigue analysis should be:

- 0.9 for welded and structural steel which S-N curve is based on 97.7% survival probability and where it is possible to detect critical crack development by periodic inspections
- 1.1 for welded and structural steel which S-N curve is based on 97.7% survival probability and where no inspection is done to detect the cracks
- 1.2 for fibre composites with 95% survival probability and confidence level of 95% as the basis for S-N curve
- 1.5 for S-N curve based on 50% survival probability and coefficient of variation less than 15%
- 1.7 for S-N curve based on 50% survival probability and coefficient of variation of 15% to 20% such as components made of composites

1 For "power production" design situation for normal turbulence model (NTM), normal sea state (NSS) and normal current model (NCM) the partial safety factor for loads should be 1.25.

The mentioned values for PSF of materials are considered as minimum values in presence of recognised design codes.

2.2 DNV Design Requirements

As stated before, the IEC outlines the minimum design requirements for offshore wind turbines and recommends ISO and DNV for specific design requirements. According to DNV, offshore wind support structures should be designed to the normal safety class, which is an annual probability of failure in the range 10^{-4} for unmanned structures. For offshore wind turbines where personnel are planned to be present during severe loading conditions, DNV recommends the design to high safety class with nominal annual probability of failure of 10^{-5}.

The DNV categorise four design methods for offshore wind support structures, which are briefly explained in the followings. The four design methods defined by DNV are:

1. Design by partial safety factor method with linear combination of loads and load effects, also called load resistance factor design (LRFD)
2. Design by partial safety factor method with direct simulation of combined load effect of simultaneous load processes
3. Experimental based design
4. Probability based design

2.2.1 PSF Design Method with Linear Combination

The partial safety factor design method with linear combination of loads and load effects is separate assessment of the load effect in the structure due to each applied load process and is used in both IEC and DNV guidelines for design of offshore wind turbine support structures. As explained for equation (1) the design resistance R_d has to be larger than the design load effect S_d for the structural component considered.

In the DNV guideline, the IEC design criterion is called *limit state*. The DNV defines limit state as a condition beyond which a structure component will no longer satisfy the design requirements. Moreover, the DNV defines the IEC design equation as *limit state function.* In equation (4) the limit state function is denoted as g $(x_1,x_2,\ldots)$ where x_i are the state variables.

$$g\,(x_1,x_2,\ldots) = R_d - S_d = 0 \qquad (1)$$

The state variables are stochastic variables defined with their distribution function representing all stochastic variables of R_d and S_d.

Similar to the analysis types of the IEC, the DNV defines four relevant limit states for offshore wind support structures:

1. Ultimate limit states (ULS)
2. Fatigue limit states (FLS)
3. Accidental limit states (ALS)
4. Serviceability limit states (SLS)

Similar to the IEC, the DNV defines the uncertainty associated with each analysis method by means of partial safety factor (PSF) for loads and materials. In the followings the DNV PSF values for ultimate and fatigue analyses are discussed.

Partial Safety Factor for Loads

The DNV defines the partial safety factor with respect to different load categories[2]:

1. Ultimate limit states (ULS): based on **Table 2**
1. Fatigue limit states (FLS): 1.0 for all load categories
2. Accidental limit states (ALS): 1.0 for all load categories
3. Serviceability limit states (SLS): 1.0

Table 2: DNV partial safety factor for loads for ultimate limit states

Load Factor Set	Limit State	Load Categories			
		G	Q	E	D
(a)	ULS	1.25	1.25	0.7*	1.0
(b)	ULS	ψ**	ψ**	1.35	1.0
(c)	ULS for abnormal wind load cases	ψ**	ψ**	1.1	1.0

* When environmental loads are to be combined with functional loads from ship impacts, the environmental load factor shall be increased from 0.7 to 1.0 to reflect that ship impacts are correlated with the wave conditions.

** For permanent loads (G) and variable functional loads (Q), the load factor in the ULS shall normally be taken as ψ = 1.0 for load combinations (b) and (c). When a permanent load (G) or a variable functional load (Q) is a favourable load, then a load factor ψ = 0.9 shall be applied for this load in combinations (b) and (c) of Table 2 instead of the value of 1.0 otherwise required. The only exception from this applies to favourable loads from foundation soils in geotechnical engineering problems, for which a load factor ψ =1.0 shall be applied. A load is a favourable load when a reduced value of the load leads to an increased load effect in the structure.

For analysis of the ULS, the sets denoted as (a) and (b) shall be used when the characteristic environmental load or load effect is established as the 98% quantile in the distribution of the annual maximum load or load effect. For analyses of the ULS for abnormal wind load cases, the set denoted (c) shall be used.

2 DNV load categories are G = permanent load, Q = variable functional load, normally relevant only for design against ship impacts and for local design of platforms, E = environmental load and D = deformation load.

Partial Safety Factor for Materials

Based on the DNV, the partial safety factor for materials for buckling of steel materials should be based on **Table 3**, where λ is the reduced slenderness parameter equal to square root of specified minimum yield stress, f_y, divided by elastic buckling stress, σ_e.

$$\lambda = \sqrt{\frac{f_y}{\sigma_E}}$$

Table 3: DNV material partial safety factor for buckling

Type of Structure	λ ≤ 0.5	0.5 < λ <1.0	λ ≥ 1.0
Girder, beams stiffeners on shells	1.1	1.1	1.1
Shells of single curvature (cylindrical shells, conical shells)	1.1	0.8 + 0.6λ	1.4

In the DNV the material safety factor for ultimate limit state of tubular steel structures and non-tubular beams, columns and frames is defined as 1.1.

The DNV material safety factor for concrete structures is given in **Table 4**.

Table 4: DNV material safety factor for concrete and reinforcement

	ULS	FLS	ALS	SLS
Reinforced concrete/grout	1.45/1.30	1.50/1.35	1.20/1.10	1.0
Steel reinforcement *	1.10/1.05	1.10/1.00	1.10/1.00	1.0
Plain concrete/grout, fibre reinforced concrete/grout	1.45	1.50	1.20	1.0

* more description could be found in DNV guideline, Table 8-1

More information about material safety factor of grouted connections is given in section 9 of the DNV guideline.

2.2.2 PSF Design Method with Direct Simulation

The second PSF design method is similar to design by the first method with linear combination of loads and load effects. The first method is based on a linear combination of individual characteristic load effects determined separately for each of the applied load processes, whereas the second method is based on a direct simulation of the characteristic combined load effect from the simultaneously applied load processes.

2.2.3 Experimental based Design

The third design method is experimental based. In this method load effects, structural resistance and resistance against material degradation is established by means of testing or observation of the actual performance of full-scale structures.

2.2.4 Probability based Design

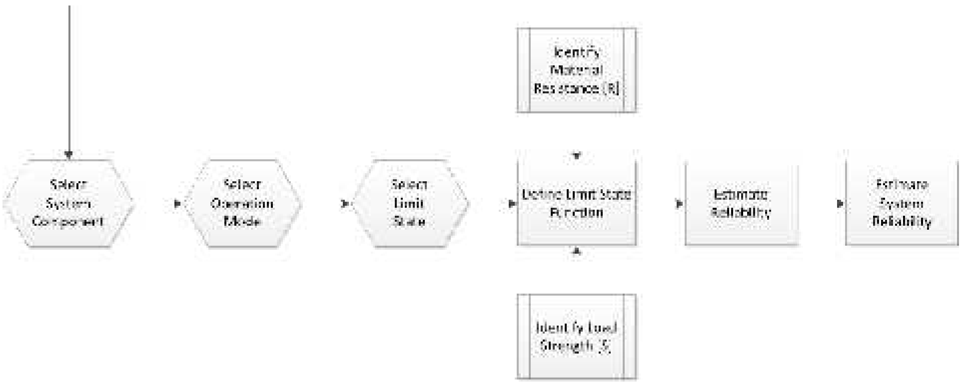
The last design method, probability based design, can be used as calibration of deterministic analysis methods like LRFD method.

In the next chapter load strength and material resistance as inputs for the limit state functions are described.

3 Reliability Assessment

In **Figure 4** a general framework for probabilistic assessment of monopile structures is illustrated. The depicted process should be repeated for each component, operation mode and limit state.

Figure 4: Framework for probabilistic reliability assessment of monopile structures



3.1 System Components

The first step in reliability assessment of support structures using probabilistic approaches is to identify system components. Since in this report monopile structures are considered, the system components are:

1. Tower
2. Monopile

For simplicity reasons the transition piece is not included in this assessment.

3.2 Operation Modes

In the IEC eight different operation mode or design situations are described. In order to limit the scope of the reliability assessment in this report only four operation modes representing extreme situations during the lifetime of an offshore wind farm are considered:

1. Power production
2. Start-up
3. Emergency shutdown
4. Parked (Idling)

3.3 Limit States

As described in the previous section, the DNV describes four limit states for offshore wind support structures. In this report the first two limit states are considered and other parameters such as eigenfrequencies will be included as boundary condition in the limit state functions. The two considered limit states in this reports are:

1. Ultimate & Buckling limit state
2. Fatigue limit state

Once the limit state function is defined, stochastic variables, their distribution type and statistical parameters should be identified. The uncertainty of stochastic variables could be categorised as:

- Physical or inherent uncertainty
- Measurement uncertainty due to the imperfect measurements
- Statistical uncertainty due to limited sample size of measurements
- Model uncertainty due to imperfect knowledge or simplified models

3.4 Structural Resistance

Structural resistance are modelled using data from handbooks or codes for different limit states like fatigue or ultimate/buckling.

3.5 Load Strength

Loads on offshore wind turbine support structure is mostly environmental loads. Environmental loads are loads that vary in magnitude, position and direction. In the DNV the following environmental loads are discussed:

1. Wind loads
2. Hydrodynamic loads induced by waves and current, including drag forces and inertia forces
3. Earthquake loads
4. Current-induced loads
5. Tidal effects
6. Marine growth
7. Snow and ice loads

In this study only a limited number of scatter climate data are available:

1. Significant wave height vs. peak wave period
2. Significant wave height vs. wind speed 10m
3. Significant wave height vs. wind speed hub height
4. Significant wave height vs. total water level
5. Significant wave height vs. mean wave direction
6. Significant wave height vs. zero-crossing wave period
7. Wind direction vs. mean wave direction

Based on the available scatter data only a few environmental loads are considered in the limit state functions and the rest of environmental loads are not considered. The considered environmental loads are:

1. Significant wave height (H_s)
2. Peak wave period ($T_p|H_s$)
3. Wind speed ($U_{10}|H_s$)
4. Wind direction ($\sigma_U|\ U_{10}$)

The distribution function and statistical parameters of the mentioned climate data are used in the limit state functions as stochastic variables. The turbulence intensity as described in the IEC is considered as a deterministic parameter to decrease the level of complexity of the limit state functions.

In order to simulate the structural response to environmental loads, an aeroelastic analysis is performed. First, the selected wind turbine and support structure are modelled using an aeroelastic tool. Second the aeroelastic forces and moments are calculated. At ECN two aeroelastic tools are available:

1. PHATAS, which is a nonlinear aeroelastic tool
2. TURBU, which is a linear aeroelastic tool

3.6 Reliability Assessment

After defining the limit state functions and their stochastic variables, the reliability of the component can be analysed. There are four different reliability methods to handle the stochastic variables [4]:

- Level I methods, where stochastic variables are modelled by one characteristic value, such as partial safety factor in LRFD design method.
- Level II methods, where stochastic variables are modelled by mean value and standard deviation.
- **Level III methods, where stochastic variables are modelled by their distribution functions.**
- Level IV methods, where consequences of failure are also taken into account and the risk (consequence multiplied by the probability of failure) is used as a measure of the reliability.

In this report the stochastic variables are modelled using their distribution function. Therefore, the reliability methods level III are applicable. There are several techniques to estimate the reliability for level III methods, such as [4]:

- Simulation techniques, where samples of the stochastic variables are generated and the relative number of samples is used to estimate the probability of failure. The simulation techniques like Monte Carlo can be used as validation for more complex techniques like FORM and SORM (see below).
- **First Order Reliability Method (FORM) techniques, where limit state function is linearized and the reliability is estimated using level III methods.**
- Second Order Reliability Method (SORM) techniques, where a quadratic approximation to limit state function is determined and probability of failure for the quadratic failure surface is estimated.

The FORM techniques are a suitable option for reliability assessment of monopile structures. The advantage of FORM is the information on the importance of the selected stochastic variables to the total variance of the limit state function. Therefore, a FORM based reliability tool will be used in this report. Tools based on the FORM method result in a reliability index β, which is a measure of the reliability of a component. The reliability index β is defined in the equation (5), where ϕ() is the standardised normal distribution function and $P_F(t)$ is the cumulative probability of failure in time interval t.

(5) $$\beta(t) = -\phi^{-1}(P_F(t))$$

After the reliability assessment and calculation of the reliability index β, the associated safety factors can be calculated. The calculated safety factors can later on be compared to the target reliability level defined in the IEC and DNV standards. This part is discussed in the next chapter.

4

Case Study

In order to illustrate the approach explained in chapter 3, a simple reliability assessment example is given in this chapter. This example doesn't represent an offshore wind turbine support structure.

4.1 Limit State

A simple limit state function is considered:

(6) $$g = z \times R - G - Q$$

where
g is the limit state function
z is the design parameter (deterministic)
R is the resistance (stochastic)
G is a permanent load (stochastic)
Q is a variable load (stochastic)

The limit state function given in equation (6) can be considered as limit state function of a pile and z can be considered as cross section area of the pile. The stochastic variables in equation (6) are defined with their distribution function as shown in **Table 5**.

Table 5: Distribution parameters of the limit state function

Stochastic Variable	Distribution Type	Expected Value	Coefficient of Variation
R	Lognormal	1 kN/m^2	0.15
G	Normal	2 kN	0.1
Q	Gumbel	3 kN	0.4

4.2 Reliability Assessment

In this example, the goal of the reliability assessment is to find the design parameter (z) for the target reliability index of 3.8 which corresponds to annual probability of failure of 7.2E-5:

(7) $P_f = \phi(-\beta) = \phi(-3.8) = 7.2348E\text{-}05$

The reliability assessment of this case study is done using FERUM[3] assuming the initial design parameter (z) equal to 10 m^2. The result of the first FERUM reliability assessment is:

1	z=1.000000e+01	beta=2.429822e+00

As seen above, for z equal to 10 m^2 the reliability index is 2.4 and much lower than the target reliability index of 3.8. Therefore, the initial design parameter (z) should be changed and the FERUM assessment should be repeated to reached the target reliability index. The results are:

2	z=1.010000e+01	beta =2.460882e+00
3	z=1.020000e+01	beta =2.491601e+00
4	z=1.030000e+01	beta=2.521990e+00
5	z=1.040000e+01	beta=2.552055e+00
…		
54	z=1.530000e+01	beta=3.743606e+00
55	z=1.540000e+01	beta=3.763760e+00
56	z=1.550000e+01	beta=3.783791e+00
57	**z=1.560000e+01**	**beta=3.803701e+00**

As seen above, after 57 iterations of FERUM reliability assessment, the target reliability index of 3.8 with an acceptable precision is reached. The design parameter corresponding to this target index is 15.6 m^2. The design values of stochastic variables corresponding to this reliability index are also calculated by FERUM:

Table 6: Reliability assessment results done by FERUM for β=3.8

Parameter		FERUM results (design values)
Reliability Index	β	3.8037
Design parameter	z	**15.6 m^2**
Resistance	R	0.7609 kN/m^2
Permanent load	G	2.0396 kN
Variable load	Q	9.8309 kN

Furthermore, the partial safety factors corresponding to this reliability assessment can be calculated.

3 Finite Element Reliability Using Matlab (FERUM); http://www.ifma.fr/ferum

4.3 Partial Safety Factors

In order to calculate the partial safety factors, characteristic values of stochastic variables should be calculated. The characteristic values are shown in **Table 7**.

Table 7: Characteristic values of stochastic variables

Variable	Expected value	Characteristic value	
Resistance (R)	1 kN/m^2	5% quantile	0.7737 kN/m^2
Permanent load (G)	2 kN	50% quantile	2 kN
Variable load (Q)	3 kN	98% quantile	6.1107 kN

Therefore, based on the equation (2) and (3) in chapter 2 for load and resistance safety factors we have:

(2) $S_d = S_k \gamma_f$ → for permanent load (G) and variable load (Q)

(3) $R_d = R_k / \gamma_m$ → for resistance (R)

Table 8: Partial safety factors

Variable	Characteristic value	Design value	Partial safety factor
Resistance (R)	0.7737 kN/m^2	0.7609 kN/m^2	**1.0168**
Permanent load (G)	2 kN	2.0396 kN	**1.0198**
Variable load (Q)	6.1107 kN	9.8309 kN	**1.6087**

The calculated results of this reliability assessment can be used to calibrate the partial safety factor of LRFD design method.

This case study is only intended to demonstrate the general approach. A more relevant case study should be done based on the approach explained in chapter 3 for offshore wind support structures.

References

[1] International Electrotechnical Commission (IEC); Design Requirements for Offshore Wind Turbines (IEC 61400-3:2009); Geneva, Switzerland.

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