Influence of the rotor nacelle assembly mass on the design of monopile foundations

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In light of the developments of the offshore wind industry in terms of water depth and turbine size, the objective of the research presented in this paper is to gain insight in the applicability limits of the monopile support structure for large offshore wind turbines. This is done by demonstrating how the mass of the rotor nacelle assembly (RNA) of a turbine influences the design of monopile support structures. A fictitious 5MW class wind turbine with 126 m rotor diameter is used as reference case. The typical RNA mass of existing turbines in this class is around 400 tons. Here, the RNA mass is varied between 100 and 750 tons. For each variation, a design of the monopile is created with a first natural frequency of 0.29 Hz.

The results are given in terms of mass, pile diameter and soil penetration depth for water depths of 30m and 50m. These are projected against the current industry limits for the production of monopiles and hoisting capacity on installation vessels. Furthermore, it is shown above which prestress of the RNA mass the size of the support structure is significantly influenced. The combined results substantiate that the monopile will remain the choice support structure type in coming years and that RNA mass reduction leads to significant economic gain for wind farm developers. Additionally, a solution which offers further perspective to the application of the monopile is briefly discussed.

1 Introduction

1.1 *Background and motivation*

Since the introduction of (offshore) wind energy the size of the turbines has continued to grow. Anno 2014, the average installed capacity of wind turbines offshore lies above the 4.0 MW [1]. Sieros *et al.* [2] investigated upscaling of turbines and showed that 20 MW turbines are technically feasible. They showed that future turbines of 10 MW would require a rotor of 174 m in diameter. It was also pointed out that upscaling comes at the

price of unfavorable mass increase of the rotor nacelle assembly (RNA). The exponential growth of the RNA mass with respect to the rotor diameter size of existing turbine designs is illustrated by figure 1a. The trend line shows that upscaling a rotor to 150 m in diameter can result in a RNA mass around 750 tons.

Next to the increase in size and mass of the wind turbines, offshore wind farms are placed further offshore and in deeper waters [1]. At the end of 2013 over 75% of all turbines offshore were supported by a monopile support structure [1]. The simplicity of the monopile design made it a preferable support structure option. However, the turbine size and water depth developments will at a certain point limit this preference. These developments lead to monopiles that are longer, have larger diameters and are heavier. Figure 1b depicts the water depth records of the monopile (MP) over time. The most recent data point represents the monopile foundation of the Greater Gabberd offshore wind farm [3]. The trend line illustrates that in the future the monopile might be used in even deeper waters. The question remains where the limit lies of the applicability of the monopile foundation.

Schaumann and Böker [5] and de Vries and Krolis [6] investigated the influence of increasing water depths on the mass of support structures. Both studies demonstrate that deeper water results in a monopile that is longer, has a larger diameter and has a strong increase of mass. However, both papers do not state a limit for its applicability. Seidel [7]
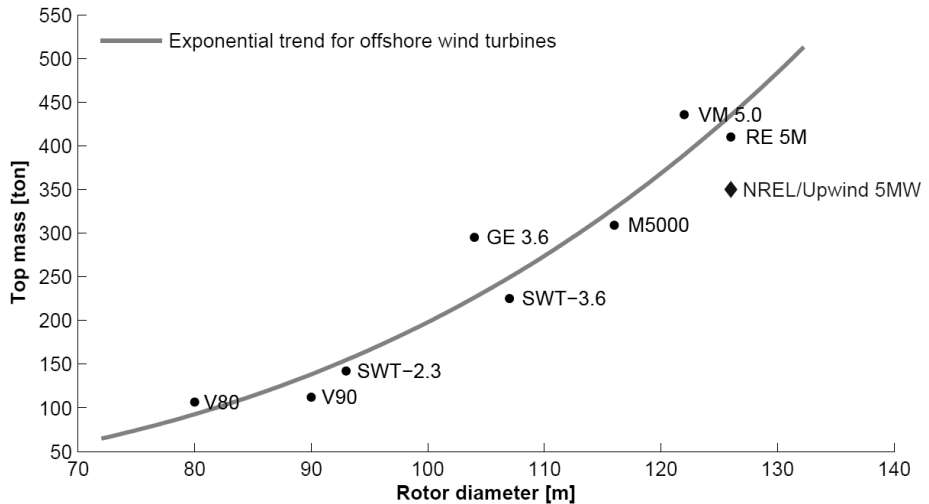

Figure 1a. Developments of turbines and monopiles over years.

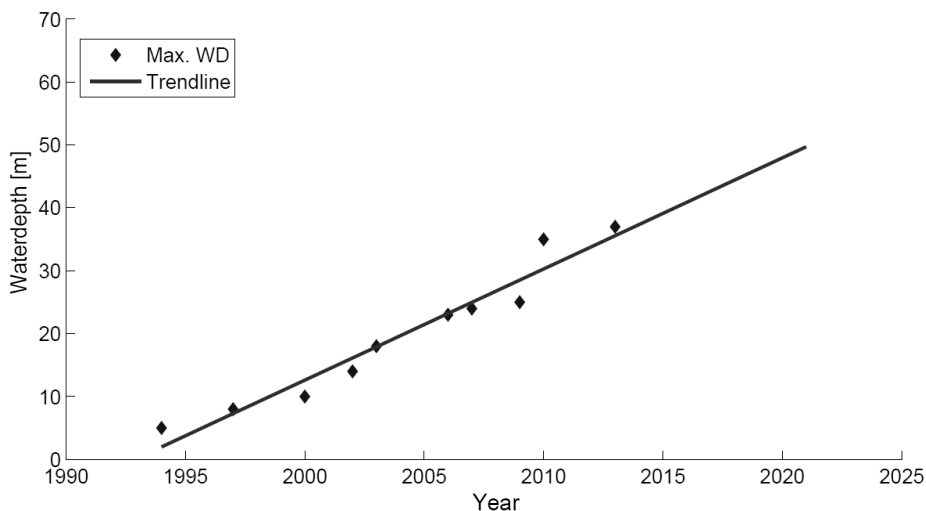*RNA trend as function of the rotor diameter [4]*

Figure 1b. Developments of turbines and monopiles over years.

Water depth record of applied monopiles

states that monopiles can be used for turbines larger than 5 WM and up to 40m water depth, provided that the soil is sufficiently stiff.

Taking the current status of the industry into account, some limits of the applicability of the monopile can be established. The largest pile diameter that is installed up to date is the one at the Baltic II wind farm, measuring 6.5 m [8]. The SIF group, one of the main manufacturers of monopiles in Europe, recently announced that it can produce monopiles with diameters of 9m (series) and 12m (one-offs) [9, 10]. Hence, in terms of production the monopile diameter can exceed current records.

Next to the manufacturing limit, the current installation limit focuses on the lifting capacities of the industry. A limit on the lift capacity of offshore wind vessels is not easy to determine, as the largest installation vessels, like the Thialf of Heerema with a crane hoisting capacity of 14200 tons [11], can easily install the current monopiles. However, the downside of using such vessels that were built to lift heavy offshore oil platforms is the price of the vessel. Therefore, this vessel has only been used once for the installation of a wind demonstration project. To determine a lifting limit of offshore wind installation vessels, the crane hoisting capacities of purpose built vessels is considered. Using the vessel data of the 4c-offshore website [12], a lifting limit of the purpose built vessels for offshore wind installation can be set around 1000 tons. An example of such a vessel is the

new built Aeolus of marine contractor Van Oord with a crane hoisting capacity of 900 tons [13, 14].

1.2 *Objective*

This paper demonstrates how the RNA mass of a reference turbine influences the design of monopile support structures. The results are used to consider the applicability of the monopile in future wind farms that are placed in deeper water and with heavier turbines. Furthermore, this study provides turbine developers with insight on the potential to reduce the required amount of support structure steel as a result of the RNA mass reduction for a 5 MW turbine. Additionally, the results support the selection of the support structure type in early design stages of future wind farms for similar turbines.

1.3 *Approach*

The NREL 5.0MW turbine, the corresponding turbine tower and the environmental conditions of the Ijmuiden shallow water depth site of the UPWIND project are used in this study [15]. The turbine mass is varied from 100-750 tons in steps of 50 tons. For each of the RNA masses a finite element (FE) model of the monopile, transition piece (TP) and turbine is made in Ansys. This FE model consists out of pipe elements for the monopile, transition piece and turbine tower. De Vries and Krolis [6] concluded that buckling checks for ULS conditions are fulfilled with a diameter D over wall thickness t ratio of 80 at locations around the mudline of the monopile designs. In this paper a fixed D/t ratio of 75 is used for the design of the monopile and transition piece. This is done to account for the effect of fatigue on the required wall thickness. The effect of this choice is also be investigated in this paper. The RNA of the turbine is taken into account as a lumped mass on top of the turbine tower. The overlap between the monopile and the transition piece is taken into account as one cylinder with a wall thickness equal to the sum of the thicknesses of both cylinders. The soil is taken into account as discrete soil springs equal to Zaaijer [16] representation of discrete soil springs. These springs are determined with the method presented in the API standard [17]. For the natural frequency calculation in this analysis the stiffnesses of the non-linear soil springs are linearized around the unloaded situation.

Each of the resulting monopile designs is checked on the requirements on strength for the ultimate limit state (ULS) load case and natural frequency. The monopile designs are made for 30 and 50m of water depth for two reasons. Firstly, this is done to show the influence of the water depth on the resulting weight of the monopiles as function of the turbine RNA

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mass. Secondly, a water depth of 30m is comparable to current activities and 50m water depth is the maximum in the Dutch sector of the North Sea. Fatigue calculations and optimization of the monopile design are not performed within this analysis. In figure 2 a flow diagram of the used approach is given.
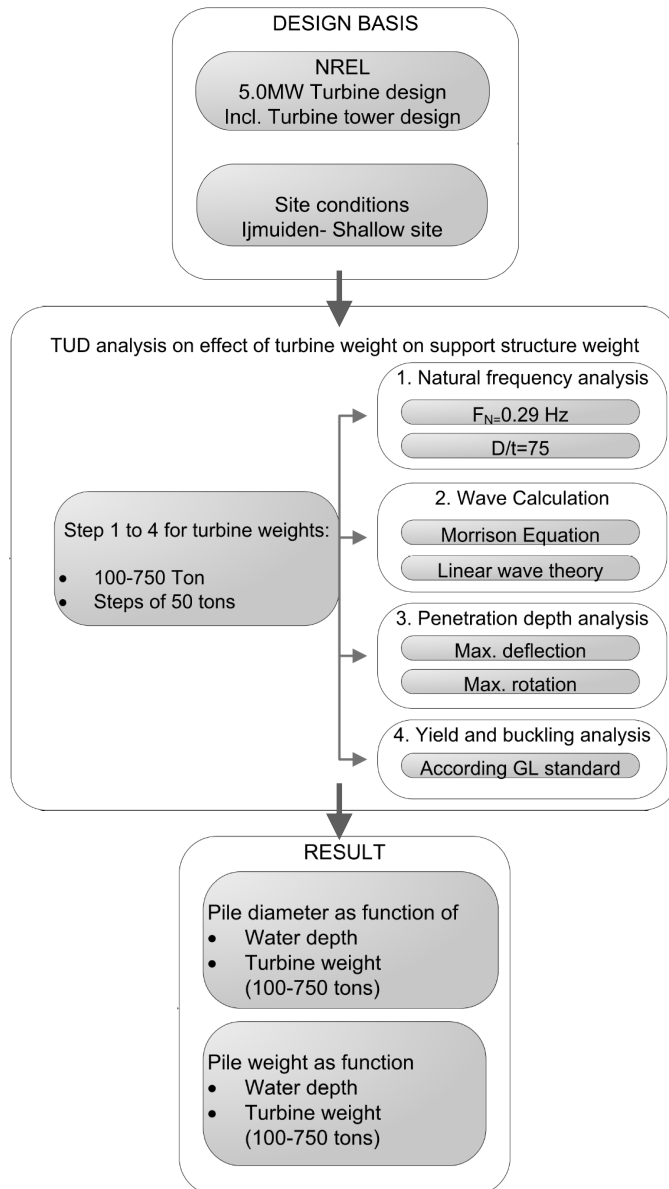

Figure 2. Approach of the analysis

2 Definition of the case study

2.1 Reference turbine design parameters

In this analysis the design basis of the UPWIND project [15] is used. The environmental conditions and turbine details are kept constant with the exception of the water depth and RNA mass. Table 1 gives these parameters and the bottom and top diameter of the turbine tower of NREL 5.0MW turbine. The mass of the flanges are taken into account as lumped masses. In figure 3 an overview of the base cases is given for the 30m and 50m water depth case, respectively.

Table 1. Turbine design parameters of the case study [15]

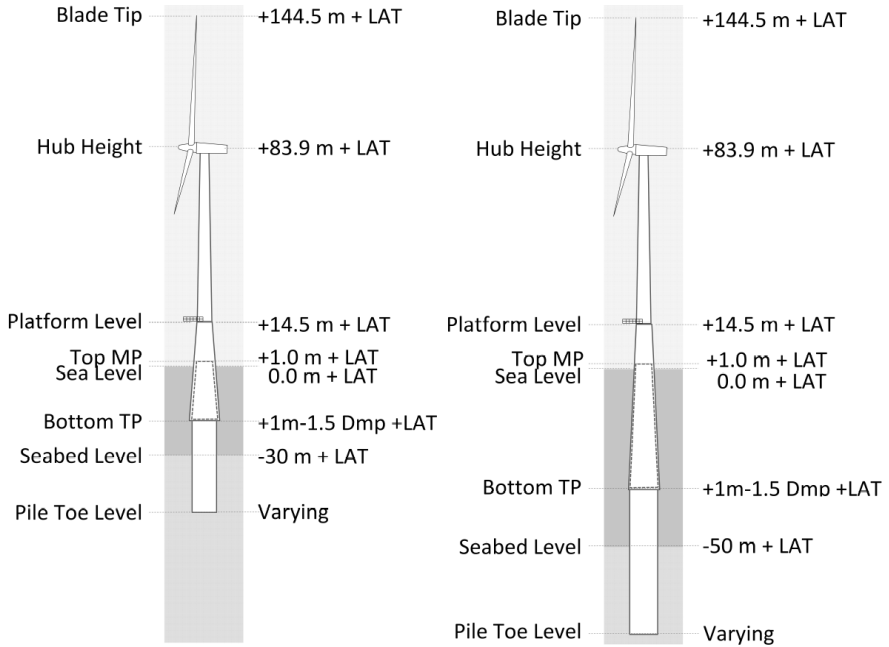| Parameter	Value	Unit
Rotor diameter	126	m
Operational rotor speed	6.9 - 12.1	rpm
Allowable f_1 range	0.22 - 0.31	Hz
Turbine tower bottom/top diameter	5.6 / 4	m

Figure 3. Overview of the base cases of 30m and 50m water depth

2.2 *Input for the ultimate limit state load case*

The ultimate limit state (ULS) load case is load combination number 3 of the basic load cases (table F1) in the DNV design standard [18], repeated here in table 2. Wave loads are calculated with the Morison equation using the linear airy wave theory and Wheeler stretching. The wave conditions, coming from the Upwind design basis, are repeated in table 3 for convenience. Other design parameters that are given in table 3 are taken from [19] and the table gives the loads of the NREL turbine for the DLC 1.3 of the IEC standard [20].

Table 2. ULS wave load combination and return period

Wind	Waves	Current	Ice	Water level
5 years	50 years	5 years	-	50 years

2.3 *Monopile support structure design procedure*

A MP design is made for each variation of the RNA mass for 30m and 50m water depth using the design procedure as shown in figure 4. This design procedure is similar to the procedure that is used by de Vries and Krolis [6]. With the fixed D/t ratio, the diameter of the monopile is varied until the desired natural frequency is obtained. In this process the top diameter of the transition piece is equal to the turbine tower bottom diameter. The

Table 3. Design parameters [15]

Parameter	Value	Unit
Turbine overturning moment (DLC 1.3) at interface	84230	kNm
Turbine lateral force (DLC 1.3) at interface	1400	Nm
H_{max}	15.01	m
$T(H_{max})$	10.06	s
$U_{current,50y}$	1.2	m/s
Marine growth (MSL -2m to (-WD+10)m)	100	mm
Soil profile	hard/stiff profile	
Steel type MP	355	MPa
Material factor	1.1	

bottom diameter of the transition piece is determined by the monopile diameter and a fixed grout thickness of 50mm. The transition piece is a conical cylinder with an overlap with the monopile from +1m LAT to -1.5 D_{MP} + 0.5m LAT. Once the preliminary dimensions are obtained the extreme loads are calculated. Combinations of the extreme wave height, current and wind loads are used for the lateral stability and strength checks. If one of the check is not satisfied the dimensions are increased. Each of the resulting designs fulfils the following requirements:

- 1st natural frequency = 0.29 Hz $\pm$ 1%
- Unity check of buckling and yield check $\leq$ 0.9 for the ULS case
- Deflections of the pile under ULS are within the requirements :
  Maximum deflection at mudline $\leq$ 3 D_{MP} /100 m
  Maximum deflection at pile toe $\leq$ 0.02 m
  Maximum influence of the penetration depth on natural frequency -0.1%
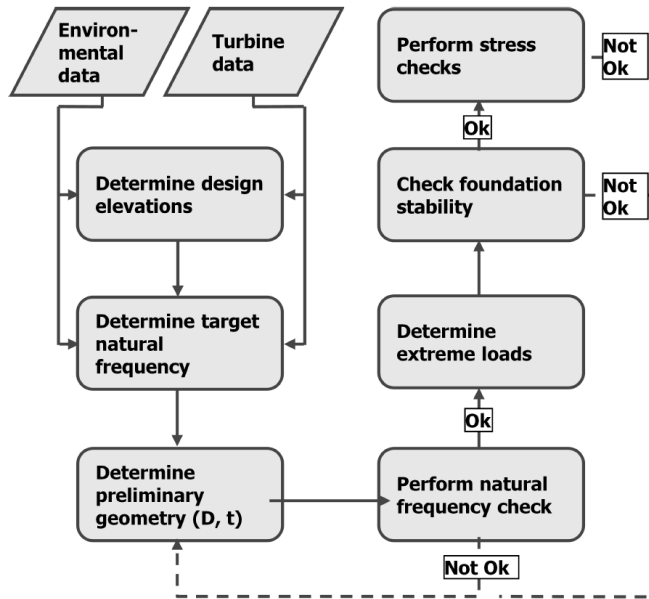

Figure 4. Approach of the monopile design

3   Results

3.1   Results after natural frequency check

Figure 5 gives the results of the resulting diameter of the support structure for the 30m and 50m case and the variation of the RNA weight after the natural frequency check with a D/t of 75. The figure shows that for the RNA masses between 100 tons and 500 tons the relation between the RNA mass and diameter mass is linear but above the 500 tons the diameter increases exponentially. The same figure plots the fabrication limits of pile diameters of SIF group and the diameter of monopile of the Baltic II. On basis of the manufacturing limit of SIF for serial production, the figure shows that the manufacturing limit of a monopile is reached for RNA masses around 500 and 600 tons in 50m and 30m of water depth, respectively. If the maximum diameter that can be manufactured by SIF is considered, the monopile support structure can still be applied for a turbine with a rotor diameter of 126m and RNA masses up to 650 tons for both 30m and 50m of water depth.

The influence of the D/t ratio on the results is checked using the same design procedure as given in figure 4 except that a D/t ratio of 100 is used. Figure 6 gives the results of a D/t = 75 and D/t = 100. It shows that the diameter increases for a reduced wall thickness ratio. The spread in diameter also increases with larger RNA masses of the turbine.
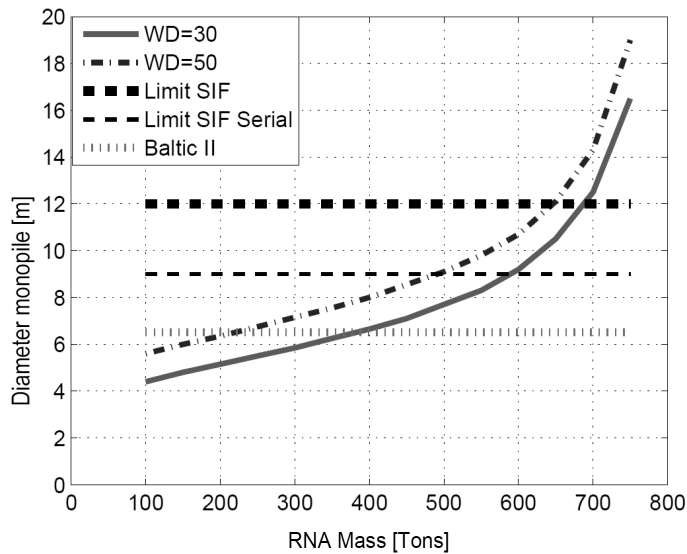

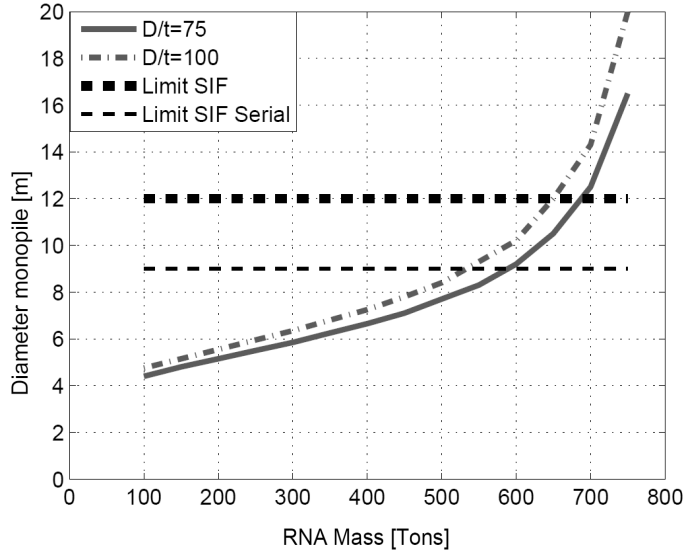*Figure 5. Resulting diameter after the natural frequency check for D/t = 75*

Figure 6. Resulting diameter after the natural frequency check for WD = 30m

3.2 *Wave load, penetration depth and strength check results*

In figure 7 the total lateral wave force and moment at mudline, *F* and *M* respectively, are given as function of the RNA mass of the turbine. The wave force increases significantly with increasing RNA masses. Figures 7a and 7b have a similar trend lines as figure 5. The
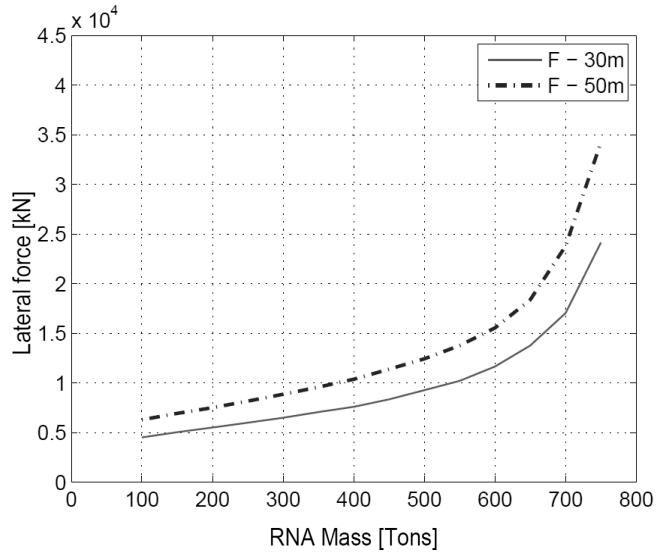

Figure 7a. Wave loads development for designs in 30 and 50m water depth for D/t = 75.

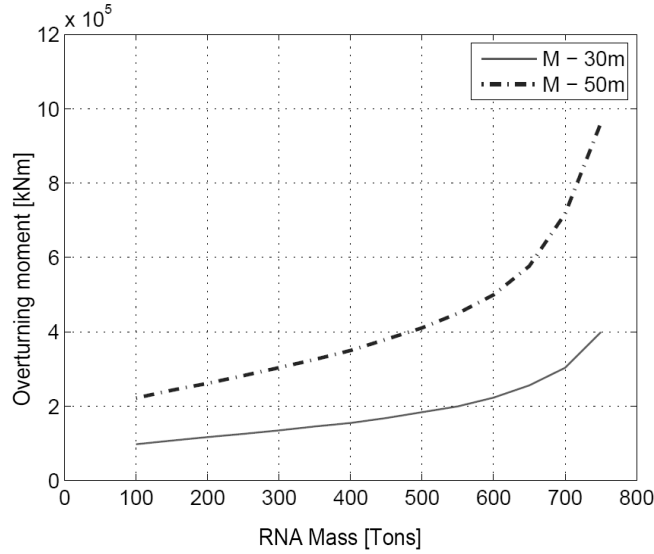*Lateral force as function of the RNA mass of the turbine*

Figure 7b. Wave loads development for designs in 30 and 50m water depth for D/t = 75.
Overturning moment as function of the RNA mass of the turbine

same resulting wave loads as function of the pile diameter instead of RNA mass show a linear relation. This shows that heavy turbines cause larger wave loads as an effect of the necessity of larger diameter foundation piles to keep the natural frequency constant. The influence of the D/t ratio on the wave loads is limited and an increase in diameter as a result of a higher D/t ratio leads to a small increase in wave loads for an equal target natural frequency and turbine weights.

In order to calculate the correct penetration depths, the piles are subjected to the combined wind and waves loads at mudline location. The pile penetration depth is subsequently decreased with steps of 1m until it either starts influencing the natural frequency or meets one of the requirements presented in section 2.3. Figure 8 gives the resulting penetration depths as function of the RNA mass of the turbine. It illustrates that the penetration depth is increasing almost linear with the increase of the RNA mass. It should be noted that all penetration depths were limited by the natural frequency influence, which is attributed to the effect of the stiff soil profile.

Figures 9 to 11 give the result of the yield (stress reserve factor) and global buckling checks for water depths of 30m and 50m as function of RNA mass and diameter, respectively. Only the design for 100 and 150 ton RNA mass and in 30m water depth do not meet the set buckling limit for a D/t ratio of 75. The figure also shows that the yield limits are not
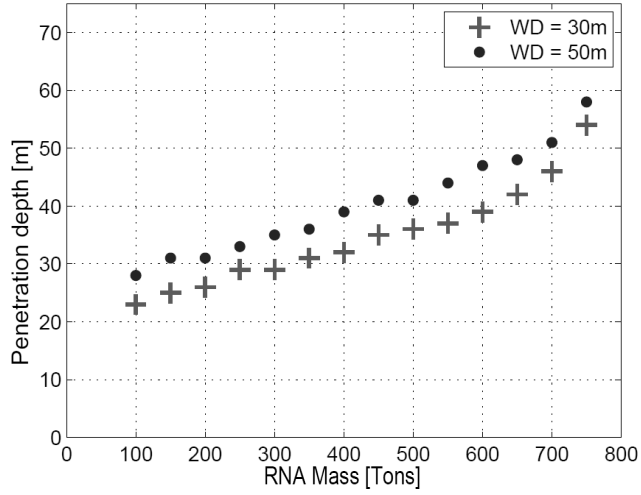
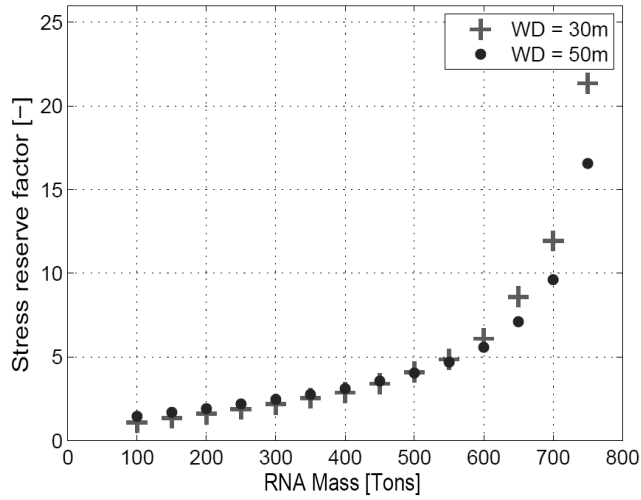*Figure 8. Penetration depth as function of the turbine RNA mass and water depth for D/t = 75*

Figure 9. Yield check for designs in 30 and 50m water depth for D/t = 75

reached for these designs. Furthermore, the figures illustrate that with increasing mass of the RNA the checks are fulfilled with big reserves, which is an effect of the increasing diameter and moment of inertia. Increasing the D/t ratio to 100 for the 30m water depth leads to a slight increase in the global buckling ratios. This implies that the use of thinner walled piles require larger diameters to fulfil the natural frequency requirements. For these cases the larger diameter resulted in larger wave loads and buckling ratios.

3.3 Mass comparison after the design cycle

For each of the monopile designs the mass of the foundation plus the transition piece is calculated. Figure 12a gives the total mass of the support structure (MP + TP) as function of the RNA mass of the turbine. The increase of the monopile and transition piece shows an exponential development for the increasing mass for both water depths. Figure 12b shows
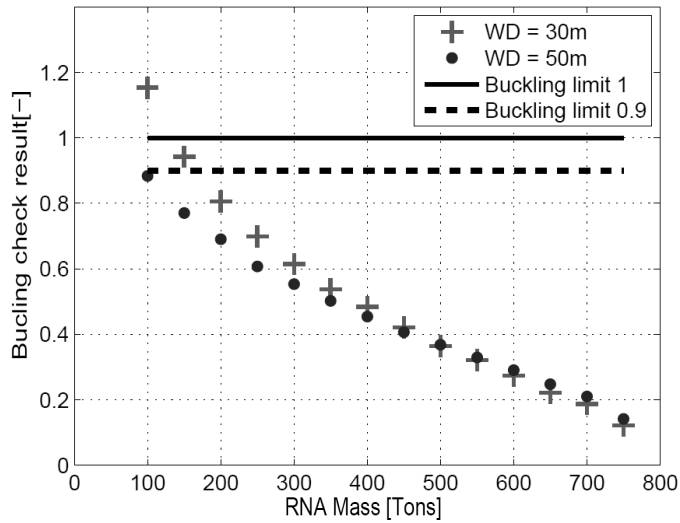

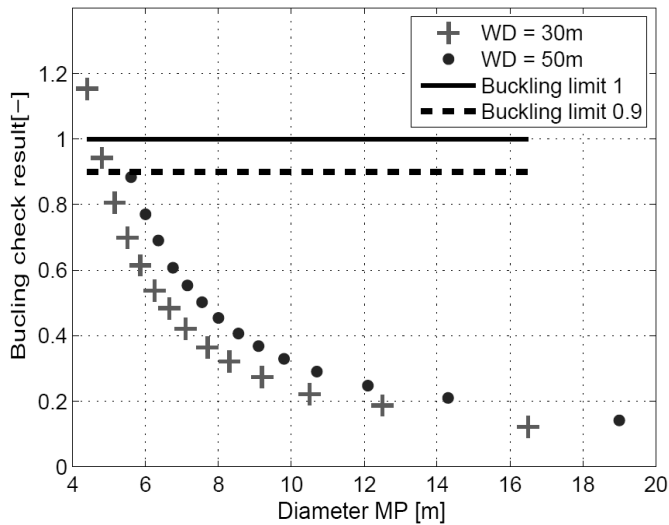Figure 10. Buckling check as function of the RNA mass for 30 and 50m water depth and D/t = 75

Figure 11. Buckling check as function of MP diameter for 30 and 50m water depth and D/t = 75

the mass of the monopile only and the assumed installation limit of 1000 tons. It shows that for 50m of water depth the mass of the monopile rapidly exceeds the typical hoisting capacity of purpose built wind installation vessels. For 30m of water depth the monopiles exceed the installation limit for corresponding RNA masses of 400 tons.
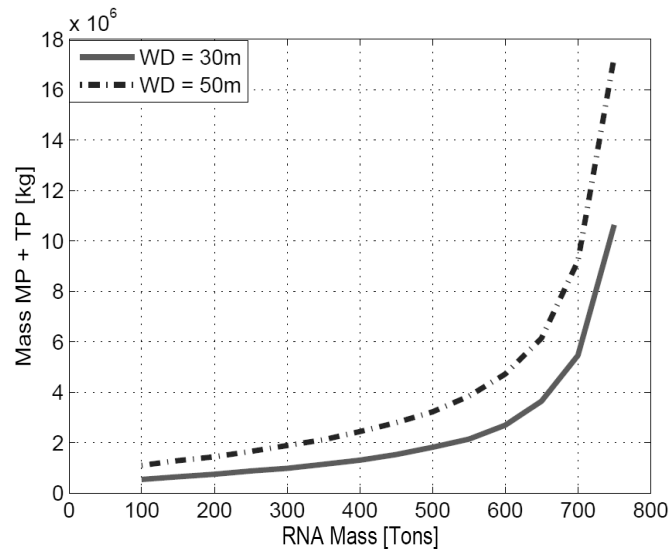

Figure 12a. Mass of the support structure as function of the RNA mass of the turbine for D/t = 75. Total mass MP and TP
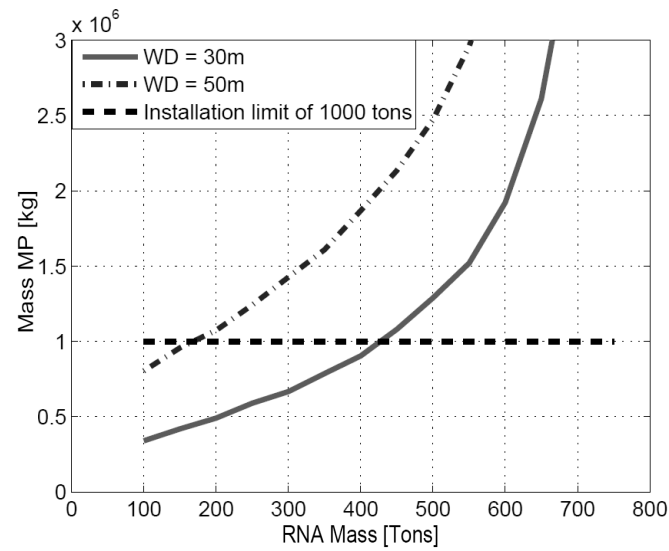

Figure 12b. Mass of the support structure as function of the RNA mass of the turbine for D/t = 75. Total mass MP

3.4   *Results including the prestress effect on the natural frequency*

The previous sections confirm that with an increasing mass of the RNA, the 1st natural frequency of an offshore wind turbine can only be kept constant with the increase of stiffness/diameter. The gravity that is working on the mass of the RNA also introduces an axial compression on the support structure.

Bokaian [21] demonstrated that axial compression of a clamped-free beam has a lowering effect on the natural frequencies for certain ratios between axial stiffness and axial compression. This effect of axial compression, also known as prestress, is taken into account for a natural frequency analysis similar to the one described in section 3.1. Figures 13a and 13b illustrate the effect of prestress on the resulting designs by comparing it with the results without prestress. The effect of the prestress on the diameter and mass of the monopile are small up to an RNA mass of 500 tons. Above RNA masses of 500 tons the prestress produces an increase of pile diameter in order to keep the natural frequency constant. Prestress thus has a marginal effect on the design of monopiles for turbines with RNA masses below 500 tons. For an RNA mass above 500 tons the prestress can no longer be neglected. For example, an RNA mass of 700 tons requires an increase in diameter and mass of the monopile of 25% and 50% respectively as a result of prestress.
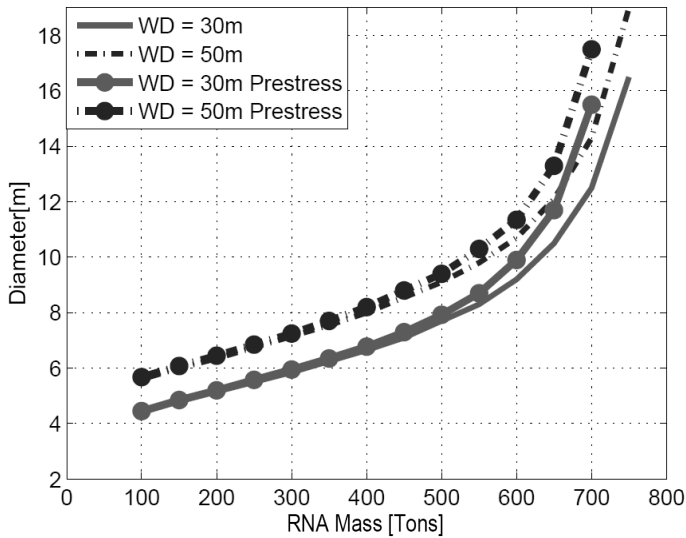

Figure 13a. Effect of the prestress on the diameter and mass of the support structure as function of the RNA mass of the turbine. Diameter MP with and without prestress

The results demonstrate that the RNA mass of a turbine to a large extend determines the size and mass of a monopile foundation. They also illustrate the potential to reduce the required amount of support structure steel as a result of the RNA mass reduction for a 5 MW turbine.

4   Future of the monopile as support structure for offshore wind turbines

It is shown that for turbines with an RNA above the 400 tons a monopile needs to be installed with vessels with crane hoisting capacities above the 1000 tons. Considering the manufacturing limit and the resulting diameter of this analysis, one can see that for the near future the monopile still can be used for heavier turbines and deeper water.
The heavy monopiles however need to be installed with bigger vessels that are more expensive and it would be desirable to work with smaller installation vessels. In order to do this and have a monopile foundation for future (heavier) offshore turbines a solution needs to be found.
Using the monopile as foundation in deeper waters and/or heavier turbines will either lead to the need of more installation vessel with larger crane hoisting capacities or to
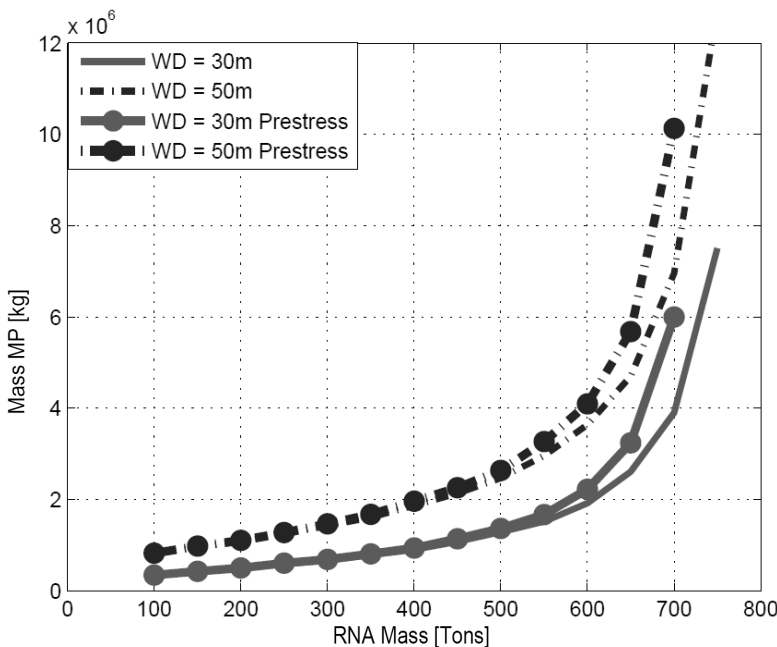

Figure 13b. Effect of the prestress on the diameter and mass of the support structure as function of the RNA mass of the turbine. Total mass MP with and without prestress

monopiles made out of multiple sections. The slip joint, given in figure 14, for example can be used to realize further use of current lift vessels. This conical connection is based on friction and uses the principle of two cups sliding in each other [22]. It has been used onshore in Windmaster turbines in the Netherlands and recently got renewed attention as a result of the grout related issues. In turbine towers it is common to use multiple sections which is a method that is not applied in support structures. A monopile is driven into the soil and then connected to the bottom of the turbine tower using a transition piece with either a grouted connection or an alternative connection such as a slip joint. Using one or multiple slip joint(s) a connection can be made to the turbine tower with the advantage that a monopile can be manufactured out of shorter and lighter sections. Lighter sections require smaller crane capacities for the installation of the support structure and enable the use of smaller installation vessels, which may result in reduction of the cost of installation. The slip joint thus offers an perspective to extend the applicability of the monopile.
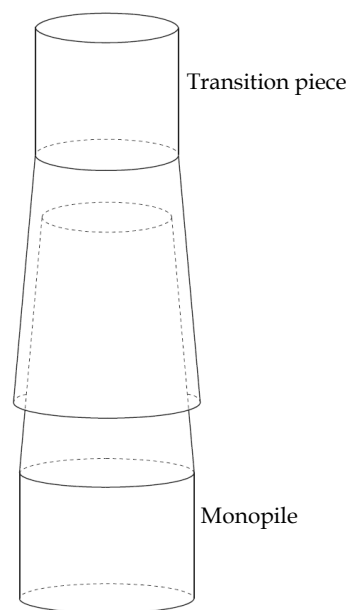
Transition piece

Monopile

Figure 14: Slip joint concept

5   Summary and discussion

The current trend of the increase in mass and size of the offshore wind turbines will have an effect on the future use of the monopile. Therefore, the effect of the mass of the rotor nacelle assembly of a turbine with a rotor diameter of 126m on the monopile support structure was investigated in this paper for 30m and 50m of water depth. For each water depth and turbine mass variation, ranging from 100 - 750 tons, a monopile design was made with a natural frequency of 0.29 Hz. Following checks on natural frequency and strength the resulting designs show that the diameter increases linear with increasing RNA masses up to 450 tons. Above the 450 tons the diameter of the monopile increases exponentially. The mass of the resulting monopiles and transition pieces show a similar growth pattern. According to SIF, the maximum pile diameter that can be manufactured in series is 9m. In 30m of water depth the corresponding limit for the RNA mass is around

600 tons. In 50m of water depth the corresponding limit for the RNA mass is around 500 tons. SIF's manufacturing limit of one off's piles at its site is 12m. With this diameter of 12m the monopile support structure can still be applied for turbines with RNA masses up to 650 tons for both 30m and 50m of water depth. Furthermore, it is shown that the masses of monopiles designed for turbines with an RNA mass above 400 tons are too large for installation vessels with a crane capacity of 1000 tons or less. The applicability limit of the monopile will thus be determined by either the manufacturing limit or the crane capacity of the installation vessel. The inclusion of prestress effects of the RNA mass on the design of the monopile is significant for RNA masses larger than 500 tons. For example, the increase in diameter and mass of the monopile as a result of the prestress for an RNA mass of 700 tons is 25% for 30m water depth and 50% for 50m water depth.

The results demonstrate that the RNA mass of a turbine to a large extend determines the size and mass of the monopile foundation. They also illustrate the potential to reduce the required amount of support structure steel as a result of the RNA mass reduction. It is shown that to continue to use the monopile as foundation in deeper waters and/or (very) heavy turbines, there is a need for more installation vessels with larger crane hoisting capacities or monopiles that are made out of multiple sections. Considering the current top masses and applied diameters the near future of the monopile still looks promising. The use of a slip joint will make this future look even brighter.

The resulting monopile designs presented in this paper are meant to be used for indications and insight. Fatigue calculations and optimization of the monopile designs were not performed within this analysis. Fatigue calculations tend to result in a larger required wall thickness compared to the required thickness after ULS calculations. To take the effect of fatigue on the resulting wall thickness in account a D/t ratio of 75 was used in comparison to the suggested 80 of de Vries and Krolis [6]. Optimization of the designs could result in a smaller wall thicknesses and a reduction of monopile mass. It should be noted that optimization should be done considering all requirements. If overall the wall thickness is decreased/optimized on basis of the strength checks, it will result in a diameter increase as result of the natural frequency requirement. This increase in diameter can cancel (a part of) the envisioned weight decrease of the pile and result in larger wave loads and buckling ratios.

It should be noted that the used soil profile, turbine and turbine tower design influence the results presented in this paper. The used soil profile represents stiff soil conditions in the Dutch North Sea. For softer soil the resulting diameter and mass would increase as larger diameters are needed to compensate for the softener stiffness of the soil.

The rotor diameter of the turbine determines the total height of the offshore turbine and was kept constant in this analysis. Turbines with larger rotors than 126m will result an increase in length of the total structure. This increase in length will result in monopile designs with larger diameters for similar RNA masses and natural frequency requirements. Turbines with smaller rotors will have the opposite effect on the designs. The turbine loads increase with a larger rotor which on its turn may result in a larger required wall thickness to pass FLS and ULS checks. The choice of keeping the rotor diameter constant may therefore underestimate the size and weight of resulting designs. However, in the same analysis the turbine tower is kept constant. This is done as in most cases the turbine tower is a part of the turbine and not to be altered by the marine contractor. If the turbine tower would be optimized for each RNA mass and monopile designs, the results will be less conservative. The presented masses of the monopiles are therefore to be used for the purpose of insight.

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