

# Floating installation of offshore wind turbine foundations

“An Engineering Assessment on Ship – Monopile Interaction during Pile Driving”

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## THESIS COMMITTEE

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## ABSTRACT

Offshore wind turbines are growing significantly to become a cost-effective alternative for the offshore oil and gas market. This causes rapid growth of offshore wind turbine foundations (monopiles). Currently, monopiles are installed using jack-up vessels like Aeolus. However operations will be limited by crane capacity and its cost-effectiveness is subject to discussion. Therefore floating vessels are preferred for future monopile installation; although little is known about the interaction between ship and monopile during the pile driving process. This research focusses on the multi-body behaviour of a floating structure connected to a monopile which is partly penetrated in the seabed. Frequency domain calculations are performed in combination with spectral analyses to investigate floating monopile installation with HLV Svanen and a monohull concept. It is shown that the natural period of the multi-body system shifts towards the working conditions (wave period) of HLV Svanen. Therefore pile release is advised to avoid resonance during monopile installation. It is concluded that increasing scale of monopiles hardly affects the performance of HLV Svanen, while a monohull concept does not significantly improve the performance of floating monopile installation. However a new gripper design should be introduced to ensure structural integrity of the upscaling monopiles.

**Keywords:** Monopile installation, Multi-body dynamics, Frequency domain analysis

## 1. INTRODUCTION

### OFFSHORE WIND MARKET

Growing demand for energy and concern for global warming have initiated research into green energy solutions. Wind energy of which is currently the main source of green energy generated offshore, especially in the North Sea where strong and steady winds blow throughout the year. Since the offshore wind market is relatively new and continuously changing to become a cost-effective alternative for the oil and gas market, wind turbines and supporting structures are significantly growing, see Table 1.

Table 1 Development of offshore wind market

Wind Turbine Particulars					
		2015	2017	2020	
Turbine capacity	$P_E$	4	8	12	MW
Rotor diameter	$D_R$	130	165	200	m
Water depth	$WD$	32	40	50	m
Monopile dimensions					
Length	$L_P$	65	80	90	m
Diameter	$D_P$	7	8	10	m
Weight	$W_P$	800	1300	2200	ton

Up until several years ago, monopiles were found to be feasible up to 30 – 40 meters of water depth [1]. However practice has shown that the monopiles are still preferred over Gravity-Based Structures (GBS) and jacket foundations. Mainly due to their manufacturing simplicity and proven-track record, still 70% of all supporting structures consist of monopiles.

The challenge for Van Oord is to determine how monopiles are installed in the (near-) future. Currently two fundamentally different vessels are used for monopile installation: Jack-up vessel Aeolus, and Heavy Lifting Vessel (HLV) Svanen.

### JACK-UP METHODOLOGY

Jack-up vessel Aeolus installs monopiles in elevated condition. After lifting the monopile from deck, the monopile is positioned in the gripper and lowered to the seabed. The main advantage of the jack-up methodology is that the inclination of the monopile can be controlled to guarantee the upright position of the pile during hammering. Installation of one monopile (incl. transition piece) takes 19 hours. Pile driving of which takes approximately 4 hours (21%).

Although the jack-up methodology is a proven concept, questions have been raised about its cost-efficiency. Especially the crane capacity (900t) is limiting operations with jack-up vessel Aeolus in the future. However limited deck-space, deadweight and jacking duration (18%) are subjects for discussion.

### FLOATING METHODOLOGY

HLV Svanen is a catamaran-shaped crane vessel, which can lift up to 8000 tonnes. Sufficient to keep up with wind market developments. The operations with HLV Svanen are similar to the one of jack-up vessel Aeolus. Instead of the jacking system, HLV Svanen uses mooring lines for station-keeping. Therefore the vessel is subjected to environmental influences of waves, wind and currents. Motions of

the vessel thus limits the operations. Current practice reveals that especially the hammering phase is complex, since the monopile is continuously oscillating about its upright condition. Additionally there is concern about the structural integrity of the monopile, especially when the monopile is penetrated deeper into the soil. Effectively, the monopile will start acting as an additional mooring to HLV Svanen. Since knowledge on this topic is scarce, the research will focus on the hammering phase of the operation for floating structures. Although HLV Svanen is not limited by the current developments in the offshore wind market, it is expected that the floater is approaching its limits.

Ideally, operations are performed by a dedicated floater (monohull-shaped) with Dynamic Positioning (DP) capabilities. In this way, the operations can be shortened with respect to jack-up vessel Aeolus and HLV Svanen (jacking procedure and anchor handling). Additionally a monohull can carry multiple monopiles and motion behaviour characteristics are assumed to be better than that of HLV Svanen. This research includes both HLV Svanen and a monohull concept to compare floating operations.

## 2. RESEARCH FOCUS

### SCOPE OF WORK

This research focusses on the floating installation of offshore wind turbine foundations (monopiles). Pile driving is found to be limiting the operations of HLV Svanen. Pile handling and lowering are thus not incorporated in this research. The hammering process is observed up to a soil penetration equal to two times the pile diameter. At this soil penetration the monopile is assumed to be fixed in the soil.

This thesis focusses on the multi-body dynamics of the floater coupled to a monopile founded in the seabed. Focus is on hydrodynamic behaviour of the floater with monopile rather than design and operational issues.

### MAIN OBJECTIVES

The main objective of this research is:

*“Determine feasibility of future monopile installation by floating structures based on ship-monopile interaction during pile driving.”*

To investigate the main objective, the research is split into three different parts:

1. Define representative modelling method to calculate ship – monopile interaction during pile driving.
2. Describe governing effects of interaction between floater and monopile founded to the seabed.
3. Determine the feasibility of future pile installation from floating structures by comparing upscaling monopiles and different floaters.

## METHODOLOGY

A computational model is set-up to describe the effects of ship – monopile interaction. The outcomes of the model are examined based on current Svanen practice. After validation of the model, governing effects of interaction are discussed. Especially the motion behaviour of the system is compared for increasing soil penetration of the monopile.

Thereafter the model is used to simulate the system behaviour of HLV Svanen under influence of upscaling monopiles, see Table 1. Additionally a concept is derived for a dedicated floater, based on the hull geometry of jack-up vessel Aeolus. The performance of both HLV Svanen and the monohull concept is derived and compared.

## 3. COMPUTATIONAL MODEL

### MODEL SET-UP

In Figure 1, an overview of the computational model is given. Initially frequency domain calculations are desired to model the coupled system for their low computational effort and provided insight. Main particulars of HLV Svanen are shown in Table 2.

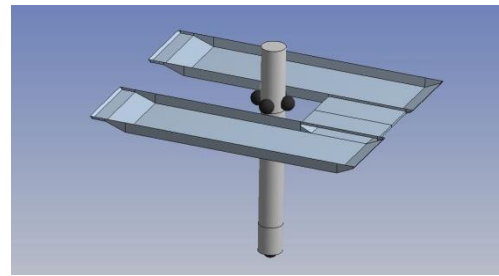


Figure 1 Model set-up of HLV Svanen with Monopile

Table 2 Main particulars of HLV Svanen

HLV Svanen	
Length	102,8 m
Breadth	71,8 m
Depth	6,0 m
Draft	3,3 m
Displacement	13960 t

### HYDRODYNAMIC ANALYSES

In ANSYS AQWA, both floater and monopile are modelled. Diffraction/radiation analyses are performed to calculate the hydrodynamic contribution of the vessel to the equation of motion: Added mass, added damping and wave excitation.

Both floaters, HLV Svanen and the monohull concept are subjected to frequency and mesh resolution tests to undermine inaccurate results of the diffraction/radiation analysis of Svanen. For HLV Svanen, an external lid was placed on top of the underwater hull connection (Figure 1) to suppress instable water motions.

The monopile is modelled up until the soil pivot (see following section), which is located below the seabed. Therefore non-diffracting elements are introduced between the soil pivot and the seabed (Figure 2). Effectively, the water depth is increased but the water depth is considered as deep, thus not affecting the results of the analyses with ANSYS AQWA.

### SOIL MODEL

The soil model is handled as input in this research. The stiffness model is derived according to P-y method [2] and simplified to a rotational pivot including rotational stiffness, see Figure 2. Stiffness calculations are performed at Van Oord's Offshore Wind Department.

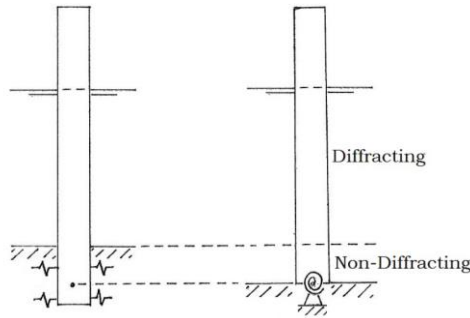


Figure 2 Approximation of soil model

### GRIPPER MODEL

The original gripper frame, including support arms, is shown in Figure 3. The support arms connect the monopile with the vessel during pile driving.

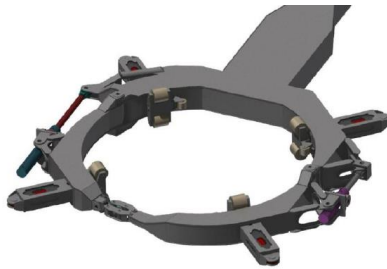


Figure 3 Gripper frame and support arms

The only option for modelling contact in ANSYS AQWA is by using fenders [3]. Fenders are able to model the gripper representatively, but the calculations can only be performed for one wave condition ( $H_s$ ,  $T_p$ ,  $\mu$ ) at a time in ANSYS AQWA. Therefore coupling the equation of motion is performed with MATLAB.

The gripper is able to transfer both forces and moments to the monopile, see Figure 4. Time domain analyses with ANSYS AQWA show that local moments are introduced for wave periods above 10 seconds. In this thesis, wave periods of 6,0 to 8,0 seconds are governing. Therefore local moments subjected to the monopile are not modelled.

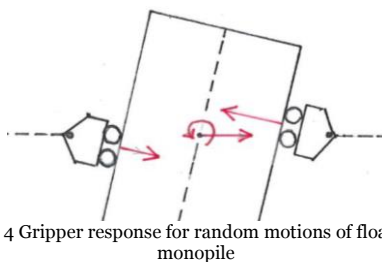


Figure 4 Gripper response for random motions of floater and monopile

### CALCULATIONS WITH MATLAB

The coupled system is schematically shown in Figure 5. The equation of motion can be coupled in two separate ways: a coupling stiffness or a rigid connection. In this thesis, the coupling is made by a rigid connection between ship and monopile, since it provides better insight in the stiffness contributions.

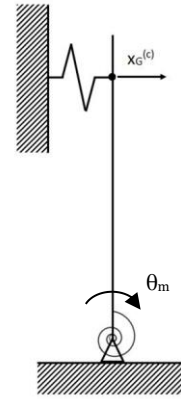


Figure 5 Schematic overview of coupled system (2DOF example)

The equation of motion for the coupled system are given by:

$$-\omega^2 \begin{pmatrix} M_g & 0 \\ 0 & I_p \end{pmatrix} \cdot \begin{pmatrix} x_g \\ \theta_m \end{pmatrix} + \begin{pmatrix} k_m & 0 \\ 0 & k_{p,RB} \end{pmatrix} \cdot \begin{pmatrix} x_g \\ \theta_m \end{pmatrix} = \begin{pmatrix} F_{w,x_g} \\ M_{w,\theta_m} \end{pmatrix} + \begin{pmatrix} -F_{gr} \\ F_{gr} \cdot l \end{pmatrix} \quad (3.1)$$

In which:	$\omega$	Wave frequency
	$M_g$	Mass + Added mass gripper motion
	$I_p$	Inertia + Added mass of pile at soil pivot
	$k_m$	Mooring line stiffness
	$k_{p,RB}$	Stiffness in soil pivot (hyd + soil)
	$F_{w,x_g}$	Wave excitation on vessel
	$M_{w,\theta_m}$	Wave excitation on monopile
	$l$	Distance between pivot and gripper
	$x_g$	Uncoupled gripper motion
	$\theta_m$	Pile motion
	$F_{gr}$	Interaction force between ship and monopile

Although not shown in the equations, damping is added to the calculations. Equation 3.1 is comprised of two equations, with three unknown parameters ( $x_g$ ,  $\theta_m$  &  $F_{gr}$ ). This issue is tackled by the kinematic condition that is introduced by the rigid connection between ship and monopile:

$$\begin{pmatrix} x_g \\ \theta_m \end{pmatrix} = \begin{pmatrix} 1 \\ 1/l \end{pmatrix} \cdot x_g^{(c)} \quad (3.2)$$

In which:  $x_g^{(c)}$  Coupled gripper motion

It essentially states that the motion of the system consists of the motion of the gripper and corresponding motion of the monopile. Therefore the degrees of freedom (DOF) can be reduced from 2 to 1 DOF.

The equation of motion for the coupled system is given by:

$$-\omega^2 (M_g + I_p / l^2) \cdot x_g^{(c)} + (k_m + k_{p,RB} / l^2) \cdot x_g^{(c)} = F_{w,x_g} + M_{w,\theta_m} / l \quad (3.3)$$

Thereafter the motions of the system are calculated as standard ship motions [4]. Therefore motion Response Amplitude Operators (RAO) are calculated of the coupled system. After solving the motion RAO, the pile motions can be derived from equation 3.2.

The forces between the ship and monopile can be calculated from equation 3.1. Both equation of motion will give the same results. In this case, the moment equilibrium on the monopile is used to solve the gripper forces according to:

$$-\omega^2 I_p \cdot \theta_m + k_{p,RB} \cdot \theta_m = M_{w,\theta_m} + F_{gr} \cdot l \quad (3.4)$$

### STIFFNESS CONTRIBUTIONS

Several stiffness contributions are identified for the monopile: hydrostatic, soil and structural stiffness. In Table 3, the different contributions are compared.

Table 3 Stiffness contributions of monopile only

Monopile stiffness contributions					
Penetration depth		5 m	10 m	15 m	20 m
Hydro + Soil	$k_{p,RB}$	100%	99%	93%	81%
Structural	$k_{p,str}$	0%	1%	7%	19%
Total	$k_{p,t}$	100%	100%	100%	100%

For calculations, only the “rigid-body” stiffness are incorporated, since structural stiffness is found to be sufficiently low up to 15 meters of soil penetration. Both hydrostatic and soil stiffness are important. The hydrostatic stiffness of the monopile is negative for all situations. At 5 meters of soil penetration, the soil stiffness is not able to overcome the negative hydrostatic stiffness.

The total stiffness in the system is determined by the mooring lines and hydrostatic & soil stiffness of the monopile (see eq. 3.3), as shown in Table 4.

Table 4 Stiffness contributions of the system

System stiffness contributions					
Penetration depth		5 m	10 m	15 m	20 m
Hydro + Soil	$k_{p,RB}$	-28%	34%	73%	90%
Mooring	$k_m$	128%	66%	27%	10%
Total	$k_t$	100%	100%	100%	100%

At shallow penetration, the mooring line stiffness is of major importance, while stiffness contributions of the monopile become important for higher soil penetration.

### ENVIRONMENTAL CONDITIONS

The behaviour of the system (read: RAO) is described in Chapter 5. However wave conditions have to be incorporated for comparison with the limiting criteria. Therefore spectral analysis is performed based on the JONSWAP wave spectrum [5]. Spectral analysis is based on the superposition principle of waves, which states that an irregular wave can be observed as a summation of different

linear waves. The response spectrum can be calculated according to:

$$S_z(\omega) \cdot d\omega = |RAO|^2 \cdot S_{jonswap}(\omega) \cdot d\omega \quad (3.5)$$

In which:  $S_z$  Response spectrum  
 $S_\zeta$  Wave spectrum (JONSWAP)  
 RAO RAO of pile motion or gripper forces

The response spectrum essentially represents the irregular response of the system in irregular waves. The (expected) maximum response in a certain time frame can be described by the Rayleigh distribution [5]. The probability that the motions of the monopile (example) exceed a certain threshold value can be described by:

$$P(\theta_m < \theta_{max}) = 1 - \exp\left(\frac{-\theta_{max}^2}{2 \cdot m_0}\right) = 1 - \frac{1}{N} \quad (3.6)$$

In which:  $\theta_{max}$  Most probable maximum (pile motion)  
 $m_0$  Area beneath the response spectrum  
 N Number of oscillations in time frame

For the hammering phase, the most probable maximum is based on a 20 hour operation in high frequent waves ( $T_p = 6$  s):

$$\theta_{max} = 2,17 \cdot 2\sqrt{m_0} \quad (3.6)$$

The most probable maximum is used to compare the response of the system with the operational conditions set for the operation (following section).

Calculations with ANSYS AQWA (time domain) are performed to investigate second order drift forces. Drift forces are found to be of minor importance, since the system (especially at 15 meters of soil penetration) is relatively stiff. The probability of resonant motions at difference frequencies is therefore low [5]. Additionally the wave height is relatively low ( $H_s = 1,25$  m), while drift forces are proportional to the wave height squared [5].

Swell waves are not taken into account in this thesis, since operations are not realistic in these wave conditions ( $T = 12 - 16$  s). For reference see Chapter 5.

### LIMIT CRITERIA

Several limit criteria are set for the floating installation of monopiles. The pile motions are firstly limited by the plasticity of the soil. Once the monopile exceeds the inclination limit, the soil will deform plastically and the monopile will not return to its upright position.

Additionally the pile should be delivered within  $0,25^\circ - 0,50^\circ$ , to ensure the upright condition of the transition piece and thus the wind turbine.

The interaction forces are limited by the forces in the gripper. Gripper interaction forces should be sufficiently low to prevent structural failure of the monopile.

Table 5 Limit criteria for Svanen with monopile ( $D_p = 8,0$  m)

Limit criteria					
Penetration depth		5 m	10 m	15 m	20 m
Plastic soil deformation		1,10°	0,63°	0,45°	0,35°
Pile inclination at delivery	Bolted		0,25°		
	Grouted		0,50°		
Gripper failure			200 t		
Monopile failure			150 t		

## VALIDATION

From current Svanen practice is known that operations are practical up to the following wave conditions:

$$H_s = 1,25 \text{ m}, T_p = 6,0 \text{ s}, \mu = 180^\circ$$

Which is the only practical reference available. The computational model is found representative since both pile motion and gripper forces are well below the limit criteria in these wave conditions. See Table 6.

Table 6 Validation of computational model with current Svanen practice

Validation of computational model		
Svanen with $D_p = 8,0$ m monopile		
Soil penetration of 15 meters		
	$\theta_m$	$F_{gr}$
MPM response	0,33°	133 t
Limit criteria	0,45°	150 t

The operations are limited at 15 meters of soil penetration, see following chapter.

## 5. SHIP-MONOPILE INTERACTION

All calculations in this chapter are performed for the 8 meter diameter monopile, see Table 1.

### PILE MOTION RESPONSE

The coupled motions of the system are calculated, by equation 3.3, for increasing soil penetration. Essentially only the soil stiffness is increased and therefore the change in response is governed by shifting natural periods. In Table 7, the shifting natural period are shown.

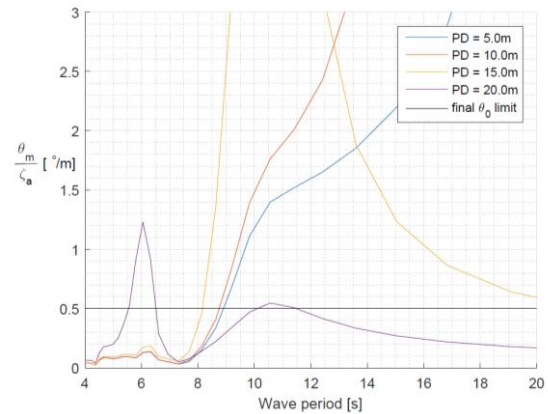
Table 7 Shifting natural periods of coupled system for increasing soil penetration

Shifting natural periods of coupled system				
Penetration depth	5 m	10 m	15 m	20 m
Natural period ( $T_N$ )	23,5 s	16,7 s	10,5 s	6,4 s

In Figure 6, the pile motion response is shown for increasing soil penetration. As mentioned in the previous chapter, Svanen typically operates in 6 second waves. Up until 15 meters of soil penetration, pile motions are relatively low for these wave periods. However resonance is expected, if the Svanen holds on to the monopile up to 20 meters of soil penetration.

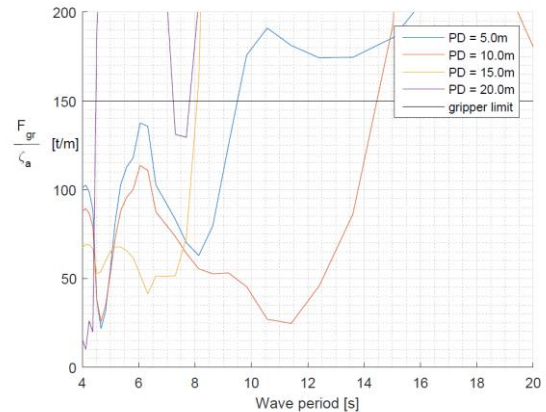
Current Svanen practice shows that the monopile can be assumed safe and sound at  $PD = 2D_p$ . Therefore the monopile can be released safely at 15 meters of soil penetration. Monopile release is

thus a necessity for successful operations with floating structures.

Figure 6 Comparison of system response for increasing soil penetration (RAO:  $T = 4 - 20$  s,  $\mu = 180^\circ$ )

### GRIPPER FORCE RESPONSE

Similar calculations are performed for the gripper forces, as shown in Figure 7. Gripper forces are calculated from equation 3.4, by inserting the calculated motions shown in Figure 6.

Figure 7 Comparison of interaction forces for increasing soil penetration (RAO:  $T = 4 - 20$  s,  $\mu = 180^\circ$ )

Unlike the motions of the system, gripper forces decrease from 5 to 10 meters of soil penetration. After which, the gripper forces increase significantly for higher soil penetration.

This is caused by the shifting natural period of the monopile itself, see Table 8.

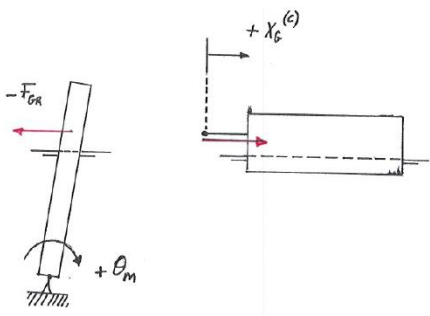
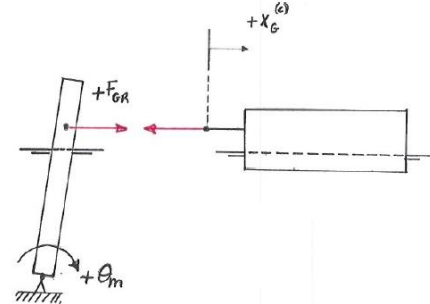
Table 8 Shifting natural periods of the monopile for increasing soil penetration

Shifting natural periods of monopile				
Penetration depth	5 m	10 m	15 m	20 m
Natural period ( $T_N$ )	21,6 s	13,1 s	5,4 s	2,8 s

At the natural period of the system, the left-hand side of equation 3.4 will go to zero and the gripper forces will be governed by damping and wave excitation only (damping is small). Additionally a phase shift will occur between the pile motions and gripper forces [6].

This phase shift is responsible for a change in gripper interaction mechanism, shown in Table 9.

Table 9 Change of gripper interaction by shifted natural period of the monopile

Ship restricts monopile motion		$T \ll T_N$
if $\theta_m > 0$ and $F_{gr} < 0$ than:		$\varepsilon_{\theta_m} = \varepsilon_{F_{gr}} \pm 180^\circ$
		
Monopile restricts ship motion		$T \gg T_N$
if $\theta_m > 0$ and $F_{gr} > 0$ than:		$\varepsilon_{\theta_m} = \pm \varepsilon_{F_{gr}}$
		

It is shown that the interaction forces between ship and monopile increase significantly, if the monopile restricts the motion of the vessel ( $T \gg 13,1$  s for PD = 10 m &  $T \gg 5,4$  s for PD = 15 m).

Since the floater should hold on to the monopile up to 15 meters of soil penetration. Mooring effects of the monopile are inevitable and will influence the gripper forces experienced with the Svanen. All results shown after this chapter are based on 15 meters of soil penetration.

## 6. FUTURE PERFORMANCE SVANEN

### CHANGE OF LIMIT CRITERIA

Pile inclination at delivery will remain the same for increasing monopiles. However soil limits will change significantly for increasing pile diameter. In Table 10, changing limit criteria are listed.

Table 10 Changing limit criteria for upscaling monopiles

Limit criteria for upscaling monopiles		5 m	10 m	15 m	20 m
Plastic soil deformation	$D_p = 8$ m	$1,10^\circ$	$0,63^\circ$	$0,45^\circ$	$0,35^\circ$
	$D_p = 9$ m	$0,37^\circ$	$0,32^\circ$	$0,25^\circ$	$0,22^\circ$
	$D_p = 10$ m	$0,34^\circ$	$0,31^\circ$	$0,24^\circ$	$0,21^\circ$
Pile inclination at delivery	Bolted		$0,25^\circ$		
	Grouted		$0,50^\circ$		

### PERFORMANCE OF SVANEN

As shown in Figure 6, the response of the coupled system (and thus the performance) is governed by the natural period of the pile motions. In Table 11, the natural periods of the system are given for different monopile sizes.

Table 11 Change of natural periods of coupled system by monopile growth

Natural periods with upscaling monopiles					
Monopile	Diameter	8 m	9 m	10 m	10 m
	Water depth	40 m	40 m	40 m	50 m
	Weight	1344 t	1582 t	1953 t	2198 t
Natural period ( $T_N$ )		10,5 s	8,7 s	8,7 s	10,1 s

Increasing monopile diameter without changing the water depth, will decrease the natural period of the system. This is caused by the fact that the soil stiffness increases more rapidly than the pile inertia. Increasing water depth has positive effects on the natural period of the system.

In Figure 8, the change of pile motions (MPM) are shown for upscaling monopiles. Spectral analyses are performed for increasing peak period, to find the environmental limits of the operation.

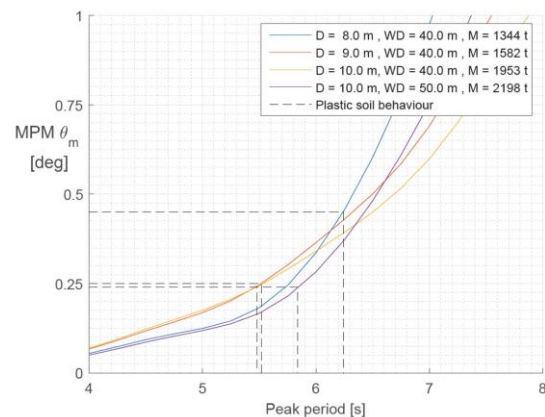


Figure 8 Development of pile motions for upscaling monopiles (MPM:  $H_s = 1,25$  m,  $T_p = 4,0 - 8,0$  s,  $\mu = 180^\circ$ )

The pile motion increase significantly for increasing monopile diameter, due to the shifted natural period of the system (for similar water depths). Additionally the pile inclination criteria (plastic soil deformation) become stricter, decreasing the environmental limits of the Svanen.

However both water depth and monopile diameter will increase correspondingly. Therefore the 10 meter diameter monopile in 40 meters of water depth is out of proportion. For increasing water depth (WD = 50 m), the natural period of the system is positively changed and therefore the pile motions decrease as shown in the figure.

Effectively, one can conclude that for the realistically shaped monopiles, the environmental limits hardly change. Which means that the performance of the Svanen is hardly changed for upscaling monopiles (up to 2200 tonnes).

## CHANGE OF INTERACTION FORCES

In Figure 9, the (MPM) gripper forces are calculated for a range of different peak periods.

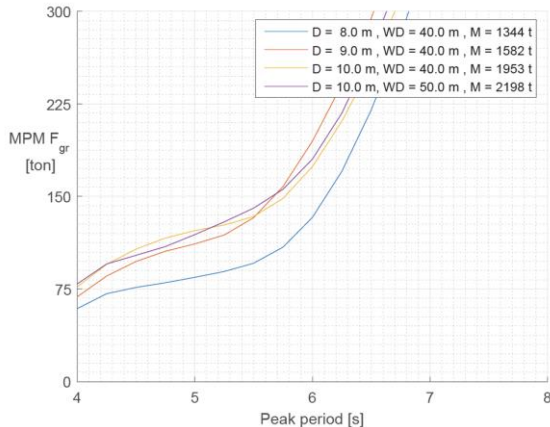


Figure 9 Development of gripper forces for upscaling monopiles (MPM:  $H_s = 1,25$  m,  $T_p = 4,0 - 8,0$  s,  $\mu = 180^\circ$ )

As indicated in Chapter 5, gripper forces are governed by wave excitation for wave periods near the natural period ( $T_N = 5$  s for  $D_p = 8,0$  m). For increasing monopiles, the wave excitation will increase quadratically [5]. This cannot be retrieved from the figure directly, since natural periods and damping effects influence the gripper interaction forces. The wave excitation on the monopile will hardly increase for increasing water depth, since the dynamic pressure (on the monopile) decreases exponentially with water depth.

For higher peak periods, the interaction forces are governed by the motions of the monopile. Since the interaction forces are significantly increased, a new gripper design is required to prevent structural failure of the monopiles.

## 7. FUTURE PERFORMANCE MONOHULL

### CONCEPT GENERATION

In Chapter 1 is mentioned that installation by means of a monohull-shaped structure is preferred over the jack-up vessel Aeolus and HLV Svanen. However a monohull concept is not available within Van Oord and therefore a concept is generated based on the main particulars of jack-up vessel Aeolus. The weight of the vessel is corrected for the jacking system and the main particulars are varied to transport five large monopiles, see Table 12.

Table 12 Concept generation based on Aeolus hull shape

	Jack-up vessel Aeolus	Monohull concept
Length	137,2 m	160,0 m
Breadth	38,0 m	35,0 m
Depth	9,1 m	13,0 m
Draft	6,0 m	7,8 m
Lightweight	16954 t	20838 t
Deadweight	7250 t	16959 t
Displacement	24204 t	37797 t

The vessel is able to transport the five largest monopiles at hand in this research:  $L_p = 90$  m,  $D_p = 10$  m,  $W_p = 2200$  ton.

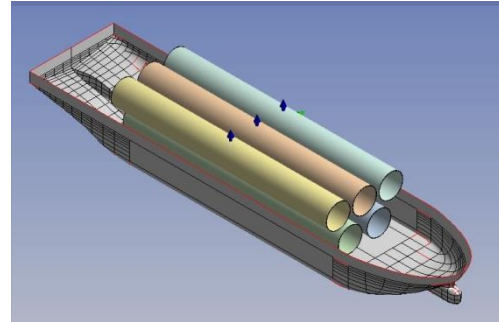


Figure 10 Monohull concept transporting five  $D_p = 10$  m monopiles

### POINTS OF ATTENTION

The monohull concept will install the monopiles one by one, which means that when installing the last monopile the displacement of the vessel has decreased, see Table 13. Motion behaviour of the monohull itself is slightly better, when fully loaded.

Table 13 Loading conditions during time offshore

	Installing first monopile	Installing last monopile
Piles on board	4	0
Draft	7,4 m	5,8 m
Displacement	35591 t	26780 t

Additionally, wave spreading will have significant effects on the performance of the monohull. While HLV Svanen performs similar in uni-directional and multi-directional waves. Wave spreading is taken into account in the spectral analysis by adjusting the wave spectrum [5]:

$$S_{\zeta}(\omega, \mu) = \left( \frac{2}{\pi} \cos^n(\mu - \bar{\mu}) \right) \cdot S_{\zeta}(\omega) \quad (7.1)$$

In which: $S_{\zeta}(\omega, \mu)$	Wave spectrum as function of wave frequency and direction
$n$	Spreading factor ( $n = 2$ )
$S_{\zeta}(\omega)$	Wave spectrum as function of wave frequency only
$\bar{\mu}$	Main wave direction

Effects of wave spreading are shown in Table 14, in which the performance of the Svanen and monohull is compared.

### COMPARISON OF INSTALLATION TECHNIQUES

In this section, the jack-up vessel Aeolus, HLV Svanen and the monohull concept will be compared. Both pile motions and gripper forces are calculated for several wave conditions and workability analyses are performed on a typical North-Sea wave scatter diagram. This all-year scatter diagram is cut-off at  $H_s = 2,0$  m, to represent the summer season.

In Figure 11, the pile motion response is compared for the different installation techniques.

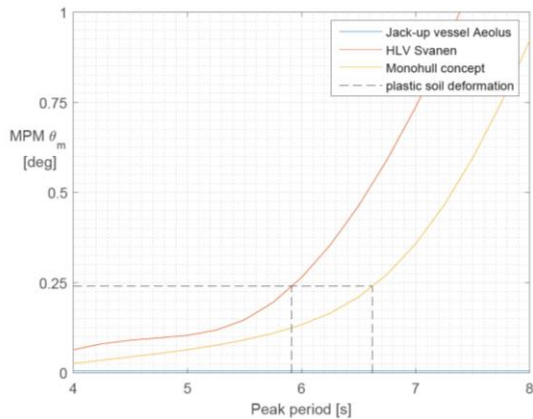


Figure 11 Pile motion comparison between different installation techniques  
(MPM:  $H_s = 1,25$  m,  $T_p = 4,0 - 8,0$  s,  $\mu = 180$  incl. spreading)

The monohull concept is able to install monopiles in more severe sea states than HLV Svanen. This is especially caused by the increased inertia (positive effect on natural periods) and decreased wave excitation in bow wave conditions. However the performance of the operation is hardly increased by changing the floater itself, as shown in Table 14.

Table 14 Workability of HLV Svanen and monohull concept  
( $\mu = 180^\circ$ )

	HLV Svanen	Monohull concept
Uni-directional waves	57,6 %	79,1 %
Multi-directional waves	59,8 %	70,7 %

Additionally the gripper forces are calculated for the different installation techniques, see Figure 12. Currently the gripper is designed based on wave excitation on the monopile (jack-up vessel Aeolus). However for floating operations, mooring effects will significantly increase the expected gripper forces. Therefore the design philosophy of the gripper has to be altered for floating monopile installation.

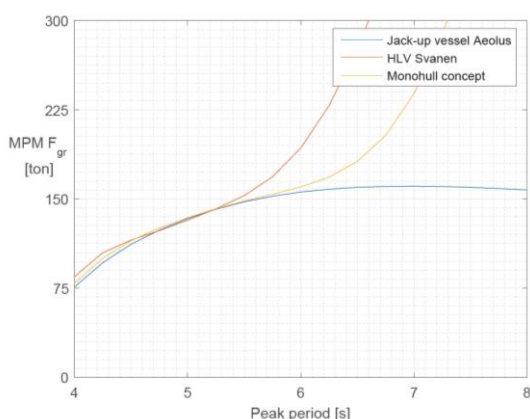


Figure 12 Gripper force comparison between different installation techniques  
(MPM:  $H_s = 1,25$  m,  $T_p = 4,0 - 8,0$  s,  $\mu = 180$  incl. spreading)

## 8. CONCLUSIONS & RECOMMENDATIONS

### OPERATIONS

In this research is shown that HLV Svanen is able to install upscaling monopiles (up to 2200t). The monopile should be released prematurely, if the natural periods of the system coincide with the typical working conditions of the coupled system. These requirements will be hard to meet for large monopiles that are installed in shallow water.

### EQUIPMENT

Although HLV Svanen is able to install upscaling monopiles without significant loss of performance, the gripper design should be altered to cope with the mooring effects which significantly increase the interaction forces between ship and monopile.

Additionally was found that a monohull concept could not significantly increase floating monopile installation with respect to HLV Svanen. Especially due to wave spreading effects, the monohull concept disappointed.

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