Conceptual Design of a Time-Efficient Method for the Installation of Mono-piles exceeding crane Capacity

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in co-operation with Van Oord

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Abstract

The offshore wind energy industry is growing rapidly. Parks and turbines grow in size and capacity. Contractors are hereby forced to develop installation methods, capable of handling large size and weight substructures. These new methods are preferably executed with already existing installation equipment. This research develops a new mono-pile installation method for existing equipment, in which the pile to be installed exceeds the crane capacity. The method is designed for Offshore Installation vessel Aeolus, owned by Van Oord. By means of a four step approach a new installation concept will be generated and evaluated. The static load of a crane capacity exceeding pile *in the crane is analysed and the largest uncertainties of the method will be discussed. The largest knowledge gap is identified in the upending phase of the operation and a dynamic motions analysis of that phase is consequently executed. This paper is a summary of a confidential Master's thesis and discusses the calculations. However, the results of the analysis are not provided.*

1. Introduction

In Aeolus' current mono-pile installation method, piles are horizontally stacked on main deck where they are upended by the main crane. The tailing crane supports the operation by managing the other side of the pile. Once upended, the pile is lifted out of the tailing crane and moved to the other side of the vessel. There, it is slowly lowered through the gripper into seabed. The gripper controls the lateral motions of the pile during lowering and later, also during installation. Once the pile is lowered into the soil, the lifting tool of the crane is changed for a hammering tool. The pile is subsequently hammered into the seabed, while small corrections to the pile position can be made by the gripper.

This paper proposes an installation concept for the installation of mono-piles exceeding crane capacity for a vessel like Aeolus. Where the use of a gripper and time-efficient supply of piles are taken into account.

To design a feasible installation method, a four phase approach is adopted. In the first phase, existing mono-pile installation methods are studied. The most important design criteria are identified and are consequently used to evaluate the currently available installation techniques. The identified criteria and possible solutions are combined in phase 2 to generate a feasible concept.

The feasibility and practicability of the designed concept will be evaluated in Phase 3. The largest uncertainty or show stopper to actually execute this operation will finally be analysed in Phase 4.

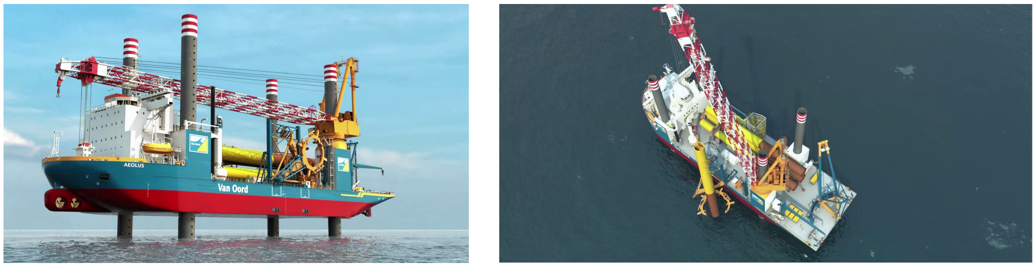

Figure 1: *Pile installation by Aeolus*

2. Phase 1: Existing method study

In the literature study of this thesis, existing mono-pile installation methods were analysed to indicate the most important design aspects regarding mono-pile installations.

The most important criteria to evaluate a mono-pile installation method on, are workability, safety and duration. Costs are considered a measure to reach a certain level of score on the criteria. Van Oord is a for-profit company and consequently needs to deliver results. Cost management is therefore important to reach set goals. Most work is tendered to off-shore contractors. Offerings, economically attractive with high safety levels, short duration and high workability, have the best chance to survive the tendering process. However, to reach a high level of criteria, the costs rise. The challenge therefore is to find the optimal balance in cost versus criteria.

2.1. Workability

According to van der Wal and de Boer (2004) [5] workability is the percentage of time that the environmental conditions at a given location meet the operational limits for a certain procedure. The operational conditions are the maximum environmental conditions whereby the procedure can be satisfactory executed. The operational conditions follow from the design limits. The design limits are the maximum allowable forces, motions, accelerations, etc. of an operation prescribed by equipment, regulations or other parties. The environmental conditions which ensure these limits are the maximum operational conditions of the operation.

Workability is in general statistical determined by use of wave scatter diagrams. These diagrams are based on historical data and show the probability of a certain wave height to occur as a function of direction and period. By comparing these diagrams with the operational limits the workability can be determined.

However, according to Verwey, Serraris and Huijsmans [2]there is a significant influence of the duration of the procedure and the duration of the environmental conditions on the workability of the procedure. A procedure with a short duration needs a smaller time gap then a procedure with a long duration. To investigate the workable time gaps of a large procedure, the procedure is split up into small procedure steps with their own operation criteria. Combining all these steps into one procedure, will lead to the time domain operation criteria for the total of the procedure. With these time domain operation criteria, the persistency workability can be determined.

2.2. Safety

To describe or determine the level of safety, the level of risk is analysed. Risk is a function of probability and consequence. The consequences can be expressed in different occurrences like injuries, material damage or environmental harm. Probability of an undesired event is often described in terms of frequency per year.

Suddle (2003) [4] states that consequences, and therefore also risks, can be expressed in terms of costs. To lower the risk, investments for safety measures should be made. He states that the higher the investments, the lower the level of risk will be. However, there will always be a residual risk, since not all risks can be eliminated. An optimum of investments costs and risk reduction should therefore be dedtermined. Norms and regulations limit the acceptable risk. By engineers choice, this risk can be eliminated even more. In practice, this risk assessment is often done following the ALARP principle, As Low As Reasonably Practicable.

2.3. Time

"Remember that time is money" is a popular business quote once written by the famous statesman and scientist, Benjamin Franklin. He illustrates that when no work is carried out, time is wasted, and therefore money is wasted in two ways: by not earning money and by spending money at the same time. A procedure which is short in duration compared to others saves money. Less people have to get paid, less fuel is used and there is less devaluation of the equipment. Of course all these aspects are dependent on the used equipment and material. However, generally seen, a procedure which takes less time is lower on cost then a procedure with a longer duration, under the same conditions.

Also, a short procedure has a lower probability of incidents. There is less time that the procedure is exposed to eventual hazards. On top of that, a short procedure has a higher workability in terms of persistency. Since the procedure is shorter, a smaller gap in the time analyses has to be found to do the installation, and there will consequently be more of these suitable gaps.

3. Phase 2: Concept Generation

The objective of this phase is to generate a concept to install crane capacity exceeding piles with the Aeolus. First, a number of concepts are generated which satisfy the stated objective. Then, the concepts are guided through different elimination gates where they will be evaluated on the gate associated criteria. At the end of this phase, one suitable concept remains and will be specified and analysed into depth in Phase 3.

The four step approach is embodied as follows:

1. **Ideation or brainstorming.** Identifying as many as possible solutions for the given problem. During this phase, the only criteria that have to be met are the thesis objectives. Objectives are mandatory for the concepts, they define the goal of this thesis. All solutions which meet the objectives are permitted. It is after this phase where the undesired concepts are eliminated.

2. **Gate 1: Safety and costs.** The concepts generated in step one are evaluated on the first set of criteria: safety and cost-efficiency. The concepts are evaluated on their achievability with regard to safety. Concepts with high risks or high risk mitigation costs are eliminated. The concepts that are fundamentally unsafe or unfeasible are eliminated here.

   Main question: can the method be safely executed in a cost efficient way?

3. **Gate 2: practicability and costs.** The residual concepts are evaluated on their operational efficiency and costs. The concepts are detailed to operational level and the non-efficient ones are separated from the efficient ones. Concepts will for instance be evaluated on operational

limits, time and simplicity. The guidelines for the elimination in gate two is provided in chapter 3.

Main question: Is the method operational efficient?

4. **Gate 3: Multi Criteria Analysis.** The detailed concepts are evaluated on criteria by means of a multi-criteria analysis. If required, concepts are even more detailed. The methods are evaluated on safety, costs, workability and time.

   Main question: Which concept is the most suitable concept for a time-efficient XL mono-pile installation with Aeolus?

   After the multi-criteria analysis, one concept will arise as the final design. A sensitivity analysis is executed to determine the probability that, due to small mistakes or misjudgements, the currently second best concept is actually the best concept.

It came forward that the most suitable concept to time-efficiently install mono-piles exceeding crane capacity is by 'Floating Upending Trapped Air'.

4. Phase 3

The feasibility and practicability of the defined concept will be discussed in this section. This design step aims at identifying gaps in current knowledge to execute this operation. Which aspects of the 'Floating Upending Trapped Air' installation concept require more research in order to calculate the feasibility of this method? First, the concept is detailed to a higher level. Then, the concept is assessed on the main criteria of this thesis, workability, time, safety and costs. The largest show stopper identified will be analysed in phase 4 of this thesis.

4.1. The operation

The floating pile is supplied by tugs, upended in water by Aeolus' main crane and subsequently positioned in the gripper. The pile remains partly in the water whereby the total pile weight is split over the crane and the buoyancy force. Then, the pressure inside the pile is increased so that the bottom plug can be removed. Due to the pressurized air, the water can not flow into the pile. The pile remains its floating capacity. In this way, the weight in the crane can be controlled and does not exceeds its capacity. Before pressurizing, water can be inserted to decrease the probability on air escape on the bottom of the pile. After bottom plug removal, the pile is lowered to seabed whereby the pressure in the pile is maintained. Since the volume decreases, a valve needs to be applied which regulates the pressure and volume within the pile. Once the pile is lowered on the bottom, water is inserted to reduce the probability of soil parts to flow in when pressure is decreased. When the water level and pressure inside correspond to outside values, the top plug can be removed.

Figure 2: *Hook on-, upend - and positioning of pile*

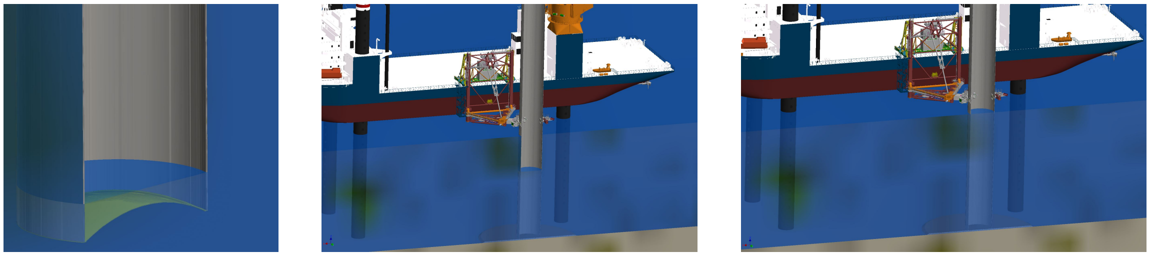

Figure 3: *Insert water, lower pile, insert water and simultaneously lower pressure*

4.2. Statics of the upending process

This section provides the static calculations of the crane loads for the upending process for a specific project. Since the piles mass exceeds the crane capacity it is important to understand what the loads are during pile installation.

4.2.1. Pile specifications

Based on market developments, the pile in this research contains the parameters shown in Table 1. These data will be used in the first analysis of the different loads on the pile.

Parameter	value
Mass Pile [t]	1219
Max OD pile [mm]	7700
Max thickness Pile [mm]	85
Length pile [m]	82.72
Water Depth [m]	35

Table 1: *Chosen project parameters*

4.2.2. Pile Upending Phases

The load on the crane in the upending process can be divided into four stages. First, the pile is upended until the top leaves the water. Then, the pile is further upended until the bottom is totally under water. In these two phases of upending, the load in the crane builds up quickly. In the third phase, the pile inclination angle increases further while the load in the crane remains constant. This is due to the fact that the volume under water remains constant. Only the angle of pile inclination changes. Finally, the load on the crane increases a little since the pile is slightly pulled out of the water. A summary of the upending process is shown in Table 2. The total course of the load on the crane and inclination of the pile is undefined, due to non-linear rotation. Section **??** discusses the crane load in combination with inclination angles as defined by OrcaFlex.

Phase	movement	crane tension (t)	inclination (deg)
1	Pile rotates linear until topplug leaves water surface	0-410	0-2.65
2	Pile rotates non linear to last moment equilibrium	410-550	2.65-15.4
3	Pile rotates further on moment equilibrium	550	14.4-85
4	Last rotation angles to equal load distribution	600	85-90

Table 2: *Summary of inclination phases of pile*

Phase 1 The first phase is short and contains the first heeling angles, where both ends of the pile remain in the water. These movements can be approached by the Scribanti formula for wall sided structures. When the depth of the pile decreases as the tension in the crane line builds up, simultaneously, the pile starts to incline. When the top of the pile leaves the water surface, the Scribanti formula does not apply any more.

During the first angles of upending, the force on the structure increases linear with the inclination angle phi. The under water volume of the mono-pile decreases together with the pile depth. The moment the inclination angle multiplied by the top plug distance to the COG becomes larger than the depth of the pile, is at a crane pull force of 420t and an inclination angle of 2.65 degrees. This is shown in Figure 4.

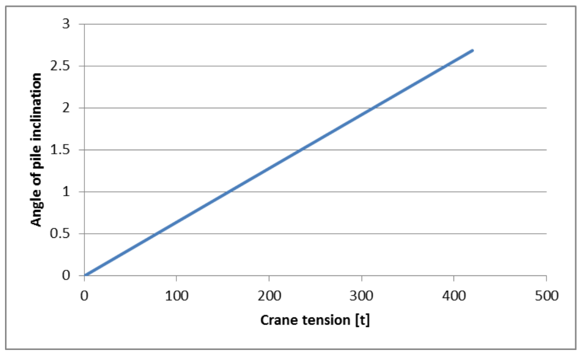

Figure 4: *Inclination angle due to crane line tension in Phase 1*

Phase 2 In the second phase of upending, the inclination of the pile angle increases with the crane pull force. The crane pull force applies a momentum to the pile. The maximum stability moment is the largest moment before the momentum equilibrium becomes unstable. In the case of a floating mono-pile this is when the inclination of the pile due to an applied heeling moment is large enough that the topplug leaves the water surface.

This maximum stability moment is a different one than described earlier. This stability moment arised from an applied heeling moment, instead of a pulling force. For the pulling force, the stability moment is at a force of 420t and 2.65 degrees. For the heeling moment, the stability moment is set by the maximum inclination angel before the topplug leaves the water. This is for an angle of 3.5 degrees. If the scribanti formula is continued, and the fact that the top plug leaves the water surface is neglected, the applied pull force to reach an inclination angle of 3.5 degrees is 550t. So the maximum stability moment of the pile is is reached by a crane pull force of 550t. From that moment, the tension in the crane line does not increase further and the pile lowers into the water.

The only difference here, is that the topplug has already left the water surface. So, the inclination angle and crane load have a non linear connection. But, due to the maximum inclination angle corresponding to the maximum stability moment, the crane force is determined. The bottom plug lowers consequently at a crane pull force of 550 t in the water.

Upending: Phase 3 In the third phase the tension in the crane remains constant while the inclination angle increases. In the previous section a tension of 550 t was derived for the maximum momentum equilibrium. This would imply that the force in phase 3 is 550t as well. This can be checked by taking the sum of moments around hook point T. The momentum of the buoyancy force and mass should be in equilibrium. The buoyancy force is dependent on the immersed volume of the structure due to Archimedes Law. In the system of a mono-pile, the volume is dependent on area A and submerge depth D. The mass dictating the depth can be described as the piles dry weight F_z and the crane's pull force in tonnes, F_{crane}.

$$F_z - F_{crane} = \rho \times g \times A \times D \tag{1}$$

In this equation, there are 2 dependent unknowns, crane force F_{crane} (t) and submerged depth D. An overview of the static situation during upending is provided in Figure 5. By taking the sum of the moments around the lifting point (see Figure 6), D ,F_b and consequently F_{crane} can be determined.

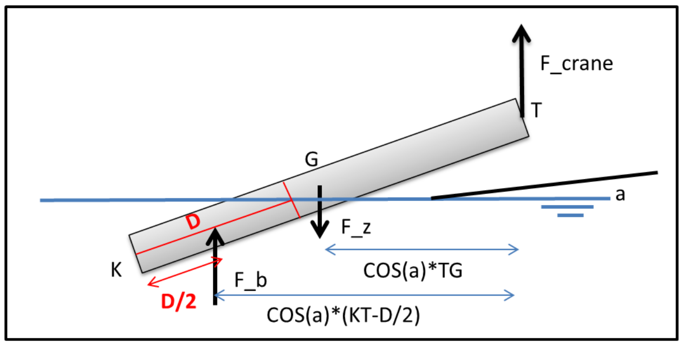

Figure 5: *Sum of moments around hook point*

$$F_z = m \times g \tag{2}$$
$$F_b = \rho \times g \times \nabla \tag{3}$$
$$F_z \times GT - F_b \times (KT - 0.5 \times D) = 0 \tag{4}$$
$$F_z \times GT = \rho \times g \times A \times D \times (KT - \frac{D}{2}) \tag{5}$$
$$\tag{6}$$

This leads to a draft D=13.95m and a crane load of 553.4 tonnes for the selected data. This is 0.6 percent more than the crane load determined earlier and consequently confirms the assumption that the maximum momentum equilibrium prescribes the upending force.

The minimum inclination angle belonging to a depth of 13.95m where the bottom plug is under the water surface is 15.43 degrees. So from an angle of 15.43 degrees, the crane pull tension does not change any more until phase 4. A summation of the approach for the non-linear development of the crane load is given below.

1. The maximum moment equilibrium prescribes the crane pull force when the bottom plug lowers into the water. The crane load stays equal after this moment equilibrium since there is no extra force required to upend the pile.

2. This is checked by taking the moment equilibrium around the top point of the pile. The crane pull force calculated by the moment equilibrium is equal to the crane pull force determined by the sum of moments.

3. The minimum inclination angle for the start of phase 3 can consequently be determined by the underwater length of the pile and the radius of the pile.

4. The non linear progress of the inclination and crane load in phase 2 can consequently be approximated by the end of phase 1 (F=410t, angle =2.65 deg.)and the start of phase 3 (F=550t, angle=15.4 deg.).

Upending: Phase 4 During the last phase of the upending procedure, the crane tension increases a little bit more. In this last phase of upending, the crane pull force and buoyancy force need to align with each other to overcome the last angles of inclination. The angles of inclination are very small in this phase and the effect of arm length of the overturning moment is therefore almost 0. To reach a moment equilibrium, the forces in the couple, crane force and buoyancy force, need to be equal. The crane load increases, while the buoyancy force decreases until they are in equilibrium. This equilibrium is determined by the formula in equation 7 and is the maximum static load in the crane to totally upend a floating pile.

$$\frac{F_{crane} + F_b}{F_{total}} = 609.5t = 5979KN \tag{7}$$

The load of the pile in the crane is a dynamic load due to wind, current and waves. Regulations prescribe a multiplication of the static load to encounter the dynamic component of the load. This factor is called the dynamic amplification factor (DAF). The DAF factors varies from 1.1 to 1.5. DNV GL [1], one of the leading independent technical advisors to energy industry operators across the world, provides guidelines with regard to these operations. The DAF factor for offshore lifts into sea for structures between 500 and 100 tonnes is 1.2. The maximum dynamic crane load during upending according to DNV is 731.4 tons. This implies that the upending process would be executable with the defined parameters. However, one has to keep in mind that this DAF factor is for lifting objects in air with a floating vessel. In this method, the vessel is jacked up and the load is floating. The DAF factor is consequently probably larger than 1.2. To determine the DAF factor of this operation, a dynamic load analysis should be executed.

This would imply that the load in the crane of the mono-pile can be described by equation 4.2.2.

$$\frac{\text{Pile weight}}{2} \cdot \text{DAF}_{\text{crane load}} < \text{Crane capacity} \tag{8}$$

4.2.3. Pressure development

The pressure in water is dependent on the considered location in the water. When the pressure in the pile is larger than the outside water pressure, the plug can be removed from the pile. For an estimation of the duration to pressurize the pile, a 7 bar, 30 $\frac{m^3}{min}$ normal industrial compressor is used. The duration is calculated by means of the ideal gas law and the specific gas constant. The mass flow per minute for such a compressor is 249 kg/min. The total time to reach a pressure of 2.4 bar is consequently 26 minutes. This is quiet a long duration, where the pile is floating in the gripper. This raises some questions about the dynamic behaviour of the pile in the gripper which will be discussed in Section 4.3.1.

4.3. Feasibility

This section discusses the feasibility of the designed method. The feasibility of the concept will be evaluated on the three criteria which influence the costs of the installation: Safety, Time and Workability. The goal of this section is to determine what extra research should be executed to make a proper estimation of the feasibility.

4.3.1. Safety

A Risk Assesment (RA) is often executed to determine the safety level and riskful aspects of an operation. The specification of the RA depends on the phase of the design process. When the design is rather high level, the RA can not be very detailed. The focus of the RA should then consequently lay upon identifying the required information to specify the RA. At this moment in the design process of the installation method for XL mono-piles, the focus of the RA lays upon the required research. What aspects of the procedure require more information to evaluate the likelihood and severities? When all research has been done, and the risks are well identified, the severity and likelihood of a certain event can more easily be determined. Besides this, mitigation measures can be established.

The three largest risks identified in the RA are: failure of one of the plugs, motions of the pile in gripper and pile motions during upending. The design criteria and possibilities to develop the top and bottom plug should be investigated. The safety and applicability of these plugs determines for a large part the practicability of the method. Special attention should go to the top plug design, since failure of the trapped air mechanism can lead to quick crane overload.

The second aspect are the motions of the pile in the gripper. It is not clear how the motions of the pile react in combination with the gripper. The gripper has an operational limit of 2m, based on open-ended piles. It is currently unclear what the operational limits of a closed pile in a gripper are.

The final aspect in which additional research is required, are the dynamical motions during upending. There is a potential risk on side lead and large dynamic crane loads. When pile motions are large during the upending process, the operational limits should be low to control the motions and forces. This can have a big influence on the workability of the method. The motions of the pile, and belonging side and crane loads are the largest show stopper of the method. When pile upending requires very low sea states to ensure a safe operation, the total installation process can be infeasible.

4.3.2. Time

The duration of the operation influences its workability. Operations with long durations require a large time gap with the limiting operational environmental conditions. When the duration is short, this time gap occurs more frequently and the workability is consequently higher.

The duration of the installation operation is shown in Table 3 and is based on installation data of Van Oords Aeolus and Svanen. The new installation method is just one hour and five minutes longer mainly due to connection testing and pile pressurizing.

A delay and learning curve duration of half an hour is encountered in the operation. After that moment, water is inserted in the pile and there is consequently no point of return. The crane can after the start of that operational step, not lift the pile any more. This half an hour is encountered to check and reposition the pile when required. When the operation is executed more often, this step might decrease or totally vanish.

4.3.3. Workability

As discussed in section 2, the workability is determined by the operational limiting conditions and the occurring environmental conditions at the installation location. There are generally two approaches to determine the workability of an operation. The first is by comparing the governing wave scatter data with the operational limits. In the second method, the duration of the operational phases together with the operational limits are compared to the governing environmental conditions.

The operational limits of all installation phases need to be known in order to determine the workability. The operational limits with regard to the different installation steps are shown in Table

	Activity	Duration	Total time	Hs max (m)
1	Hook on Upending Tools to MP topplug	00:45:00	00:45:00	1
2	Upending MP	00:15:00	01:00:00	U
3	position pile in gripper and close gripper	00:50:00	01:50:00	U
4	Connect and test compressed air supply to pile	00:30:00	02:20:00	U
5	Pressurizing	00:25:00	02:45:00	U
6	Remove bottom plug	00:10:00	02:55:00	U
7	Lower pile to seabed and remain pressure	00:15:00	03:10:00	U
8	Delay and learning curve time	00:30:00	03:40:00	U
9	Insert water and simultaneously lower pressure	00:22:00	04:02:00	2
10	Hook off Upending Tools and Top plug	00:35:00	04:37:00	2

Table 3: *Duration of installation activities*

3. The abbreviation U stands for undefined. Installation step 2 to 8 have undefined operational limits. This means that the workability of the total process can not be defined because of the undefined operational limits of some individual steps.

The maximum significant wave height in step 3, hooking on, is now the governing criterion. In a wave scatter workability analyses, this wave height of Hs=1m is the prescribing wave height of the operation. Before the workability of the method can be established, the operational limits of installation step 4 to 9 should be determined. As discussed in Section 4.3.1, the upending phase encounters some large risks which are dependent on the dynamic motions during upending. However, the motions of the floating pile in the gripper can also cause some difficulties regarding air/water supply hose connecting and loads in the gripper.

4.3.4. Feasibility conclusion

In a first assesment, the concept is considered to be feasible. The static analysis shows that crane loads are maximum half of the pile weight. There is consequently probably enough space left for the dynamic load factor.

With regard to safety there are generally 2 riskful factors in the procedure: pile upending and water/air supply. The water/air supply design encounters difficulties since the supply hoses need to be connected and tested offshore. Furthermore, the plug system should have a very low risk on failure because the crane can consequently be overloaded when one of the plug fails. The loads of the floating pile on the gripper are also an important factor which should be investigated.

The largest show stopper of the installation procedure is the upending procedure. There is currently not enough knowledge about the dynamics of the pile hanging in the crane. Side lead- and overload on the crane are a potential risk. To study these risks and operational limits, a dynamic analyses needs to be executed. The workability of the method can in this way be determined and the feasibility of the concept can be assessed.

The majority of the research performed during this thesis is therefore aimed at determining the operational limits of the upending procedure. This way, the workability, and so the feasibility of the concept can be determined. The following sections will therefore focus on the dynamics of upending a mono-pile in order to determine the operational limits.

5. Phase 4

The largest uncertainty identified in the established method are the dynamics of upending a floating pile. Unfortunately, this thesis is confidential and the foundings of the dynamic analysis are therefore not public. This paper discusses the executed calculations. However, the specific input and results are not provided.

5.1. Natural modes

There are two natural modes that influence the motions of the pile during upending. The magnitude of the fundamental periods of the modes change through the upending process. There is a certain time span during upending where the fundamental period of one of the modes approaches the wave periods. This ensures resonance motions. The magnitude and severity of this resonance is analysed in the thesis.

5.2. Design limits

The motions of the pile are researched on basis of 4 design limits: crane load, side-lead, off-lead and pile position. Maximum crane load and side lead angle are prescribed by the crane manufacturer. Off-lead is a function of crane capacity, and crane load. The crane capacity decreases when the offlead angle becomes larger. This is because the distance from crane base to force vector is larger. So, when the load in the crane is high, the off-lead angle has a smaller limit than when the crane load is small. The maximum pile position is prescribed by the crane radius. The maximum pile position is assumed by means of regulations and off-lead expectation. The crane radius is chosen based on that maximum position. The pile position limit follows from that radius. Whether this limit is exceeded, is checked in the dynamic analysis. If the limit is not exceeded the crane radius might become smaller, whereby the crane capacity increases. If the limit is exceeded, the crane radius should increase. This means that the capacity decreases, maximum off-lead angle decreases. One has to keep in mind that the total dynamic system changes when the radius changes. The dynamic analysis should be executed again when the crane radius changes.

5.3. Calculation

Fully 3D non-linear time domain finite element program OrcaFlex is used to model the upending operation. The motions of one position influences the motions of the next position. The dynamic upending operation can therefore not be discretized but has to be executed in one total simulation. So, a number of simulations of the same environmental condition have to be executed to withdraw conclusions. Since the real time simulation time duration is long and requires a large amount of computer memory, this number is taken not too high, on 100 simulation pieces. So, the upending operation procedure, is executed a hundred times with the same environmental condition but with different wave configurations.

The most probable maximum (MPM) of these maxima is consequently determined by formula 9 given by Journe and Massie [3]. The most probable maximum is the the largest magnitude of the designed limit with the highest expectation.

$$[H]\mathbf{MPM} = \mu + \sigma\sqrt{2ln(n)} \tag{9}$$

In which,

μ	=	The mean value of the 100 maxima for the considered criteria
σ	=	The standard deviation of the 100 maxima for the considered criteria
n	=	Number of simulation, 100

Load Case	Environmental condition
1	Waves approach from 90 and 135 degrees
2	Waves approach from 90 degrees and current direction changes
4	Waves approach from 135 degrees and current direction changes

Table 4: *Summation of Load cases*

5.4. Load cases

Fully 3D non-linear time domain finite element program OrcaFlex is used to model the upending operation. Three different environmental load cases where studied. One with only waves, two with waves and current. A summation of all load cases is shown in Table 4. A visualisation of the load cases is given in Figure 6.

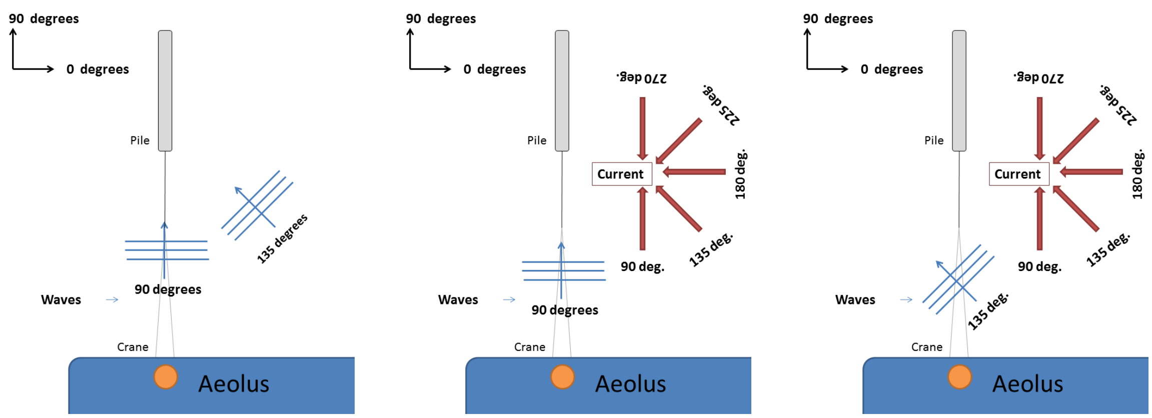

Figure 6: *Load case 1, 2 and 3*

5.4.1. Waves

The pile has the smallest motions in head waves. The area on which the waves can apply their forces is than the smallest. So, the pile should be positioned with top or bottom plug in the wave direction. Since Aeolus is a Jack-up vessel it can position itself in the most suitable direction with regard to wave direction. Approaching waves execute horizontal forces on the pile so Aeolus should be positioned in such a way that the waves travel away from the vessel in the direction of the pile. In this way the pile can never hit the vessel. Aeolus main crane can also rotate. So, if the vessel is not positioned totally perfect the crane can just easily rotate until it is in line with the pile. Alignment of the pile and crane should as much as possible be remained since the side-lead angle on the crane is than consequently as small as possible.

There is always a possibility that the pile is not corrected positioned and that the alignment is not perfect. To study the behaviour of the pile and crane in such a situation a wave approach angle of 45 degrees offside of the crane is analysed. The first load case is therefore waves approaching from an angle of 90 degrees and 135 degrees.

5.4.2. Current

Wind turbines with mono-pile foundations are always built in shallow water (up to 45m). Due to tidal changes in these shallow waters, currents can occur. Peak current velocities of the North Sea are 1 to 1.2 m/s. The maximum current velocity of the project used as basis of this research is 1.2 m/s. This current peak is governing for about 30 minutes of the total tide duration. It is therefore not unusual that offshore installation operations are postponed until current velocities are lower than the peak velocity. The current influence is therefore not studied at its maximum peak velocity but at 0.8 m/s. Reaction forces will in this way not be too large. However, the possible waiting time for the current velocity to decrease is also short.

The current direction variates every six hours due to the tides. There are consequently two force directions, one of the waves and one of the current. Current is a steady force, wave force variates due to wave height and period. To limit pile motions it is wise to chose the wave direction as the pile direction and to let the current direction variate. The second environmental case is waves in 90 degrees direction and a current direction change from 90 to 270 degrees.

The piles optimum position is in head or stern waves. It is almost always possible to position the pile in that way. However, when the waves are approaching in line with the vessel, the crane can not be positioned in line with the waves. It should therefore be researched how the pile reacts in waves approaching in an angle of 45 degrees with the crane combined with current.

5.5. Workability

By means of MPM of the the design limits: crane load, side-lead, off-lead and pile position, the maximum operational conditions for upending are determined. Since operational steps 3 to 8 are not modelled, their operational condition is assumed with knowledge of the conventional upending procedure and HLV Svanen. The scatter workability and persistency workability are determined for the total installation operation for a specified location.

6. Conclusion

The 'Floating Upending Trapped Air Concept' can be considered feasible to install mono-piles exceeding crane capacity with regard to first hand calculations. The maximum static crane load during installation of such a mono-pile is exactly half of the weight of the pile. To get an insight in the feasibility and practicability of the concept, the concept was specified to a higher level. The feasibility of the concept was evaluated on the three main criteria of this thesis. Safety was examined by a Risk Assessment and the largest risks were identified in plug design, pile-gripper motions and, the dynamic motions of the pile during upending. A time schedule for one cycle of pile installation was established and it appeared that the mean installation time was only 1 hour and 5 minutes longer than the conventional method. For all installation steps the main operational limits were determined. However, it occurred that there was currently not enough insight in the dynamic motions of the pile during upending to establish the operational limits of this operation. For this reason, a dynamic motion analysis on the upending process has been executed.

In the dynamic analysis it came forward that there are two natural modes that influence the motions of the pile during upending. One of the natural frequencies of these modes approaches to the wave frequencies. The dynamic load on the crane was not expected to exceed the crane capacity due to buoyancy forces working on the pile. It was on the other hand expected that side lead angles of the crane line exceed their limits.

Non linear time domain software OrcaFlex was used to model the upending process in different environmental conditions. In the model, the mono-pile is upended from horizontal to vertical position. Three load cases were studied to establish the operational limits of the upending procedure in which wave heights, periods, and approach angles are varying. The operational limits were subsequently established and a scatter workability- and persistency workability analyses was executed for one specific location.

7. Recommandations

In the calculation of the operational conditions of the upending procedure, one added mass, and one damping coefficient are used for the total operation. However, these coefficient do actually change with the angle on inclination of the pile. By discretization of the operation, different coefficient can be used. However, the effect of the motions in different upend positions is hereby neglected. It should be determined what the magnitude of that effect is so that an extra damping can be applied in the discretized operation.

The upending procedure is modelled and operational conditions are for this step determined. To get a total perspective on the concepts feasibility, motions and forces with regard to pile and gripper should be researched. The forces and motions when the gripper is closing and when the gripper is closed should be investigated and analysed. In this way, the operational conditions for the residual installation steps can be determined and the exact workability of the method can be established.

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