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Assessment of marine operations for offshore wind turbine installation with emphasis on response-based operational limits

Thesis for the degree of philosophiae doctor

Trondheim, December 2016

Norwegian University of Science and Technology
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Abstract

This thesis addresses methodologies for assessment of response-based operational limits in terms of allowable vessel responses or sea state parameters, and numerical analyses of current and novel offshore wind turbine (OWT) installation activities.

A generic and systematic approach that allows for identification of critical events, limiting (response) parameters and assessment of response-based operational limits of marine operations was developed. The approach is based on numerical simulations of the actual operations. Frequency and time domain techniques or operation-specific numerical analysis methods may be applied. An efficient method for assessment of the operational limits of mating operations has been proposed. The method relies on a number of crossings that a mating pin is allowed to perform out of a circular boundary (docking cone circular perimeter) in a given period of time. By carrying out a quantitative assessment of the system dynamic responses, the critical events and corresponding limiting parameters are identified. A characteristic value of a limiting parameter needs to be determined based on extreme value distributions for a target exceedance probability. This depends on the type of operation and consequences of failure events. The characteristic value is compared with the allowable limit of the limiting parameter, so the environmental conditions can be identified. The limits of these environmental parameters represent the operational limits of an installation activity. In this thesis only the effect of wave actions are considered, while current and wind actions are not included.

The OWT installation activities studied in this thesis are executed with a floating heavy lift vessel (HLV). Three main activities were considered: the monopile (MP) initial hammering process, the transition piece (TP) mating operation, and the entire installation of the tower and rotor nacelle assembly (RNA). For the installation of the MP and TP, standard operational procedures were employed, while for the tower and RNA, a novel and efficient single lift installation concept was developed. This novel concept is based on the principle of the inverted pendulum and requires a cargo barge, a medium-size HLV and a specially designed upending frame. The need for huge (in terms of lifting height and capacity) offshore crane vessels is eliminated. Moreover, it has been shown that the novel concept is a feasible and valid alternative for current installation procedures. The current procedures employ jack-up vessels for sequential installation of wind turbine components; however, these activities are not studied in this thesis.

The generic approach was applied to the MP, TP and tower and RNA

installation activities. For the MP initial hammering process, it was found that the critical events are failure of the hydraulic system and out-of-tolerance inclination of the MP. For the TP mating operation, the critical events are the failure of the bracket supports and the failed mating attempt between the TP bottom tip and the MP. During the tower and RNA installation, structural failure of the hoist wire, structural damage of the hinged supports, and a failed mating attempt of the upending frame are identified to be critical events. For various limiting parameters, the operational limits were established in terms of allowable limits of sea states, which are a basis for assessment of the operatiblity.

A methodology for weather window analysis and assessment of operability of marine operations was also developed. This methodology includes the response-based operational limits and accounts for sequence, continuity and duration of the activities, which are shown to be important in the analyses. The operational limits of the MP and TP installation were used for weather window analysis and assessment of the operability during the planning phase. Moreover, it is shown that weather forecasts can be used to identify workable weather windows and support on-board decision making during the execution phase.

The methodologies provided in this thesis are systematic and efficient for modeling of current and novel OWT installation activities with the aim of establishing response-based operational limits. These are necessary for planning and safe execution of OWT installation activities.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of philosophiae doctor.

This work has been performed at the Department of Marine Technology from the Norwegian University of Science and Technology in Trondheim, with Professor Torgeir Moan as the main supervisor and Professor Zhen Gao as co-supervisor.

The thesis was financially supported by the Research Council of Norway through the Centre for Ships and Ocean Structures (CeSOS) and the Centre of Autonomous Marine Operations and Systems (AMOS). This support is greatly appreciated.

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Last but not least, I want to express my gratitude to God and my family. To my parents José and Elvia, my sister Carola and my brother Victorino for their love and support, and for being my source of motivation. To all my relatives who were always supportive when we needed help from each other, especially to my comadre Lidia, who has been my other source of inspiration.

Wilson Ivan

December 2016
Trondheim, Norway

List of Appended Papers

This thesis consists of an introductory part and a summary of the papers.

Methodology for assessment of operational limits

Paper 1:

Methodology for assessment of the operational limits and operability of marine operations.
Authors: Wilson Guachamin Acero, Lin Li, Zhen Gao, Torgeir Moan
Published in *Ocean Engineering*, Vol. 125, October 2016

OWT monopile installation

Paper 2:

Assessment of Allowable Sea States During Installation of Offshore Wind Turbine Monopiles With Shallow Penetrations in the Seabed.
Authors: Lin Li, Wilson Guachamin Acero, Zhen Gao, Torgeir Moan
Published in *Journal of Offshore Mechanics and Arctic Engineering*, Vol.138, August 2016

OWT transition piece installation

Paper 3:

Steady state motion analysis of an offshore wind turbine transition piece during installation based on outcrossing of the motion limit state
Authors: Wilson Guachamin Acero, Torgeir Moan, Zhen Gao
Published in *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*, St. John's, Newfoundland, Canada, May 31 - June 5, 2015

Paper 4:

Methodology for assessment of the allowable sea states during installation of an offshore wind turbine transition piece structure onto a monopile foundation
Authors: Wilson Guachamin Acero, Zhen Gao, Torgeir Moan
Under review in *Journal of Offshore Mechanics and Arctic Engineering*, 2016

OWT tower and RNA installation

Paper 5:

Numerical Study of a Novel Procedure for Installing the Tower and Rotor Nacelle Assembly of Offshore Wind Turbines based on the Inverted Pendu-

lum Principle
Authors: Wilson Guachamin Acero, Zhen Gao, Torgeir Moan
Under review in *Journal of Marine Science and Application*, 2016

Paper 6:
Assessment of the dynamic responses and allowable sea states for a novel offshore wind turbine tower and rotor nacelle assembly installation concept based on the inverted pendulum principle
Authors: Wilson Guachamin Acero, Zhen Gao, Torgeir Moan
Published in *Energy Procedia*, Vol. 94, September 2016

Declaration of Authorship

This thesis is composed of six papers. I have been the first author in *papers 1, 3, 4 ,5 and 6*, in which I developed the ideas, performed the analyses and reported the results.

Dr. Lin Li is co-author in *paper 1.* She has contributed with constructive ideas for systematic development of the methodologies and provided numerical analysis results for monopile installation. She is also the first author in *paper 2*, in which I assisted on the development of a procedure for numerical analysis and assessment of operational limits, and provided practical input based on current industry practice.

In all papers, Professor Torgeir Moan and Professor Zhen Gao have contributed with suggestions, comments and revisions that increased the scientific quality of the articles.

Abbreviations

ν^+	Upcrossing rate
Φ	Gaussian cumulative distribution function
σ	Standard deviation
A	Added mass matrix
B	Damping matrix
b	Damping coefficient
b_{cr}	Critical damping
E	Young Modulus
F^{ext}	External force vector
F_{shear}	Soil-monopile base shear force
h	Retardation function
K	Stiffness matrix
k	Elastic spring coefficient
M	Structural mass matrix
m, μ	Mean value
r	Mating gap or docking cone radius
S_c	Characteristic response value
S_{allow}	Allowable limit including a safety factor
T_R	Reference period or duration of an activity

v	Velocity
x, $\dot{x}$, $\ddot{x}$	Motion, velocity and acceleration vectors
CDF	Cumulative distribution function
DAF	Dynamic amplification factor
FD	Frequency domain
FEM	Finite Element Modeling
GBF	Gravity based foundation
Hs	Significant wave height
MBL	Minimum breaking load
MP	Monopile
OWT	Offshore wind turbine
P-y	Soil-monopile lateral force-displacement curve
PDF	Probability density function
Q-z	Soil-monopile end tip force-displacement curve
RAO	Response Amplitude Operator
RNA	Rotor Nacelle Assembly
T-z	Soil-monopile axial friction force-displacement curve
TD	Time domain
TP	Transition piece
Tp	Wave spectrum peak period
VMO	Veritas Marine Operations
WOWW	Workable weather window

Glossary of terms

The definitions of the terms provided in this thesis are necessary for analysis of marine operations.

Activity sequence and continuity

Offshore installation activities are sequential, which means that some activities cannot start if any one of the preceding activities is not finished. Additionally, some activities are continuous and cannot be interrupted if bad weather approaches or motion responses are beyond acceptable limits. This is because in this load condition the system structural integrity may be compromised and the operation can be irreversible.

Allowable limits

Allowable limits are the maximum values that response parameters limiting the operations may reach to remain within acceptable safety margins. The allowable limits need to include safety factors to account for various sources of uncertainty. For the sea state parameters, the allowable limits are known as "allowable limits of sea states". Similarly, for the vessel responses that can be measured on-board, for instance, motions, velocities and accelerations, the allowable limits are known as allowable limits of responses.

Allowable responses

Allowable responses refer to a response of a vessel in a monitoring loading condition (e.g., crane tip motion or acceleration) prior to execution which is equal to or less than the allowable limits of the responses.

Allowable sea states

Allowable sea states are all Hs (for corresponding Tp) with values less than or equal to the allowable limits of sea states. For a group of sequential and continuous activities, the combined lower envelope will provide the allowable limits of the sea states.

Characteristic value of a limiting parameter

According to design codes, see e.g., Det Norske Veritas (2013a), the load effects can be represented by a characteristic value as far as possible derived from statistical data for a specified target percentile. The percentile is selected based on the type of operation and the risks associated with failure events.

Critical and restrictive events

A critical event is an occurrence that could endanger the integrity of an infrastructure, risk lives or pollute the environment, for instance the structural failure of a crane. This event is normally irreversible. On the other hand, a restrictive event does not lead to catastrophic consequences and could be reversible. For example, a failed attempt of a mating operation can be tried again, and is reversible.

Governing limiting parameters

This term refers to one or more parameters limiting the entire operation, i.e. resulting in the lowest allowable limits of sea states.

Governing activities

From a sequence of continuous offshore activities, the governing activities have the lowest allowable limits of the sea states.

Limiting (response) parameters

They are parameters that allow the quantification of a critical event and limit the operations. If the characteristic value of a limiting parameter exceeds its allowable limit, the safety margins are reduced and failure may occur.

Marine operations

According to Det Norske Veritas (2011a), marine operations are non-routine operations of limited duration to handle objects and vessels in the marine environment during temporary phases.

A marine operation is a process involving interaction among the dynamic systems, operational procedures, environmental actions and human intervention.

Methodology for assessment of operational limits

This term refers to a sequential set of steps that are required for identification of limiting parameters and derivation of operational limits.

Monitoring phase prior to execution of marine operations

This phase refers to a loading condition "prior" to execution of an offshore activity, in which the motions of the vessels can be monitored. Notice that monitoring motion responses in this phase is different from monitoring a limiting parameter such as the wire tension "during" the execution phase.

Numerical methods and numerical analysis methodologies

Numerical methods are frequency and time domain techniques used to find approximate solutions for equations of motion of dynamic coupled models. Numerical analysis methodologies refer to procedures developed for accurate and efficient numerical modeling of specific offshore installation activities.

Operability of marine operations

Operability refers to the available time for execution of a marine operation during a reference period that normally is given in terms of months or seasons.

Operational limits

They are allowable limits of sea states and allowable limits of vessel responses for the monitoring loading conditions prior to execution.

Operational procedures

The operational procedures are sets of systematic actions that provide information on the activities, sequence, duration and required sub-operations.

Workable weather windows (WOWW)

These are sets of continuous allowable sea states with a duration longer than the minimum required to complete a marine operation.

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Chapter 1

Introduction

1.1 Background and motivation

The need for alternative energy sources others than fossil fuels has recently increased. The depletion of oil reservoirs, environmental pollution and global warming are leading into a transition from fossil fuels into renewable alternatives such as wind energy. In recent years, wind energy has grown fast due to its potential and increasing demand. Figure 1.1 shows that by the end of 2015 the cumulative installed capacity was approximately 432 GW. This amount includes 12.11 GW installed offshore, from which 3.019 GW were added in 2015. The European Wind Energy Association (2015b) has forecasted that by 2030, the offshore wind energy installed capacity in the European Union (EU) countries can be 66.5 GW.

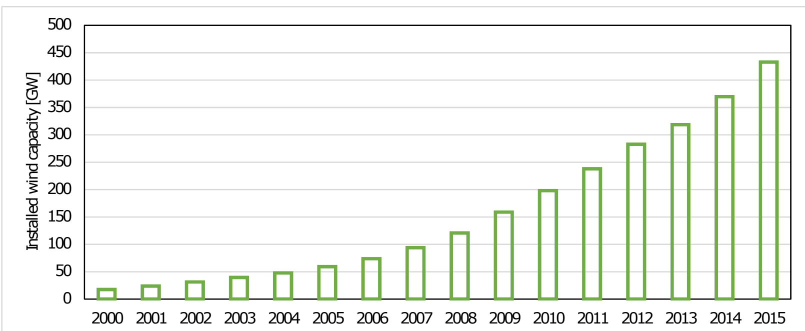


Figure 1.1: Global wind energy installed capacity (Global Wind Energy Council, 2015)

To satisfy the future energy demands, more offshore wind turbines will be installed. The current tendency is to move towards offshore locations, because the wind velocity is more steady and higher, larger offshore wind turbines (OWTs) can be installed when compared with onshore wind turbines, and there is less impact on people, e.g., noise.

Offshore wind turbines are structures installed in open waters with the aim of generating electricity from the energy in the wind. Depending on the water depth, several concepts for OWT foundations exist. Figure 1.2 shows that the main components of an OWT are the foundation, the turbine tower, the nacelle and the blades. The foundation is composed of the bottom-fixed or floating substructure and a transition piece (TP) connecting the foundation and the turbine tower. Bottom-fixed foundations such as tripods and jackets are fastened to the seabed by means of piles. Floating concepts are connected to the seafloor using mooring lines and tendons.

By the end of 2015, 3230 OWTs with bottom-fixed foundations were grid-connected in the EU countries. From these foundations, 80 % were monopiles (MPs), 9.1 % gravity-based, 5.4 % jackets, 3.6 % tripods and 1.7 % were tripiles (European Wind Energy Association, 2015a). The reason for the preference of MPs over other foundations is because of their construction and installation simplicity, and lower associated costs. As the water depth, size, and number of the wind turbines increase, the trend is to use larger diameter monopiles and shift from MPs to jackets and tripods, see Fig. 1.2. According to the European Wind Energy Association (2015a), during 2015, 419 offshore wind turbines with an average capacity of 4.2 MW were installed in an average water depth of 27.1 m. Furthermore, it is expected that the average capacity of new wind turbines will increase to 8 MW by 2018.

During the life cycle of an OWT, the installation phase is important. This is because some structural components can experience the largest loads in their lifetime. In addition, the cost of the installation phase is significant, and would correspond to approximately 20% of the total capital expenditure (CAPEX) (Moné et al., 2013).

Since the profit margins in the wind energy sector are low, it is necessary to reduce these costs by improving the current installation procedures, developing more efficient installation concepts, using more accurate and systematic methodologies for analysis of marine operations, and increasing the operational limits of the installation activities while maintaining sufficient safety margins.

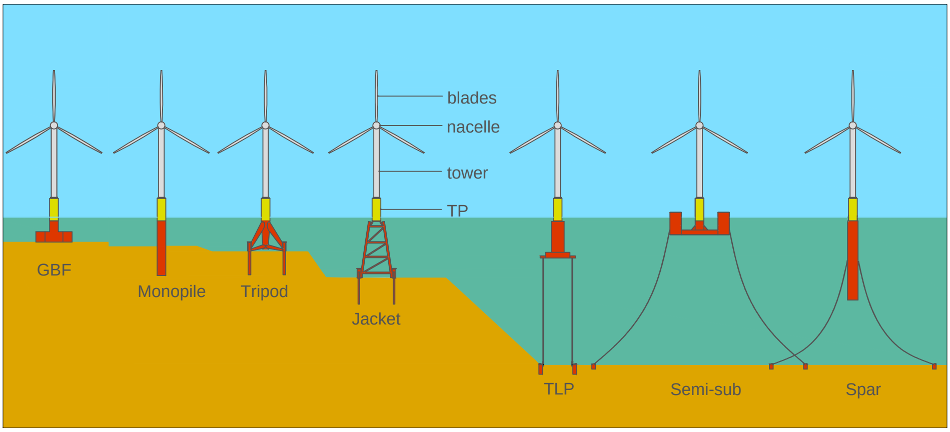


Figure 1.2: Offshore wind turbine foundations and main turbine components

1.2 Standards and guidelines for analysis of offshore wind turbine installation activities

Planning and execution of OWT installation activities are carried out according to recommendations provided by regulatory authorities. To date, the modeling and execution of OWT installation activities are mainly based on guidelines that have been developed for the oil and gas offshore industry. Recommended practices and guidelines such as International Organization for Standardization (2015a) and Det Norske Veritas (2010) are suitable for modeling environmental conditions and loads. Some recommendations and simplified formulations for analyses of typical lifting operations are provided by Det Norske Veritas (2011b). Based on these analyses, the response parameters of the dynamic systems can be studied and used to establish operational limits. These operational limits and other relevant parameters such as duration of the operations, forecast lead time, etc., are required for planning of marine operations. General requirements for these parameters are provided by Det Norske Veritas (2011a), GL Noble Denton (2015), London Offshore Consultants Limited (1997) and International Organization for Standardization (2009, 2015b). Among them, the last one provides guidelines and requirements for modeling and analysis of marine operations for offshore wind turbine installation during planning phases, and operational aspects for execution phases.

An important parameter for analysis of marine operations is the duration of the operation. This duration is referred to as reference period T_R by Det Norske Veritas (2011a), and is defined as: $T_R = T_{POP} + T_C$ where T_{POP} is a planned operational period and T_C is a contingency time. If the reference period is less than 72 hours, the marine operation is weather-restricted, and weather forecasts can be used for decision-making prior to execution of marine operations. The focus of this thesis is on offshore wind turbine MP, TP, and tower and RNA installation activities, which are normally weather-restricted.

1.3 State-of-the-art OWT installation procedures

This section describes the most commonly used and novel procedures for installing offshore wind turbine components and assemblies of these components.

1.3.1 Installation of foundations

Installation procedures for OWT bottom-fixed foundations are similar to the ones used in the offshore oil and gas industry.

Gravity based foundations (GBFs) are suitable for shallow water. The mass can be over 2500 tons (Thomsen, 2014), and thus, large heavy lift crane vessels are needed for a single lift operation. However, the normal procedure is to tow them to the site, and ballast and lower them in a controlled sequence onto the specially prepared seabed.

The most common type of bottom-fixed foundation is the monopile, which can be employed in water depths up to approximately 40 m (Thomsen, 2014). The MP is normally transported on the deck of the HLV which can be a floating platform or a jack-up barge. It is also common to transport the MPs in dry condition using feeder cargo barges. Once at the offshore site, the crane lifts-off, upends, and lowers the MP to the seabed. Then, a hydraulic hammer is used to drive the MP to final penetration.

Tripods and jacket structures are normally transported on the deck of the installation vessels or transportation barges. The foundations are lifted-off, positioned, and lowered to the seabed using an on-board crane. A hydraulic hammer is used to drive small diameter piles and fasten the foundations to the seabed. Then, a grouting mixture is poured in the annular gap between the piles and foundation leg sleeves. Because of the size of the tripod and tower structures, large HLVs in terms of height and lifting capacity are required, see Fig. 1.3.

In addition, a transition piece (TP), which connects the MP and sometimes the tripod foundations with the turbine tower, needs to be installed. The TP is normally lifted-off from the own deck of the installation vessel, aligned, lowered onto the MP foundation, leveled and finally grouted. Leveling the TP is required to adjust the final inclination of the OWT tower.

(a) Tripod installation using a jack-up vessel. Source: `http://worldmaritimenews.com`

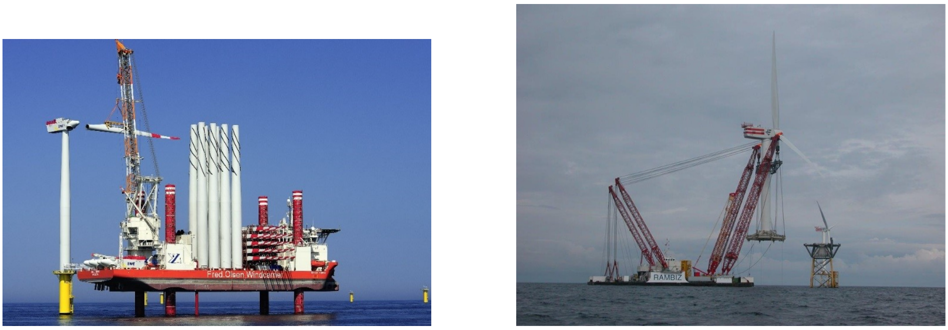
(b) Jacket installation using a floating HLV. Source: `https://www.boskalis.com`

Figure 1.3: Installation of OWT foundations

1.3.2 Installation of turbine tower, nacelle and rotor

The installation of the turbine tower components is new compared to the oil and gas industry practices. Nowadays, the *split* installation procedure as shown by Wang and Bai (2010), is commonly used to install the tower, nacelle and each blade separately and in sequence. The operations are executed with jack-up crane vessels, see e.g., Fig. 1.4 (a). There are also variations of this procedure with the aim of reducing the number of lifts, and thus, the installation time. The drawback of the split method is that it is weather-sensitive during the standard jack-up leg lowering and retrieval process. The allowable limit for the significant wave height (Hs) is between 1.2 and 1.5 m (Thomsen, 2014). Moreover, the operational water depths are between 30 to 60 m (El-Reedy, 2012).

Alternatively, a fully assembled tower and RNA has been installed by a single lift procedure using a huge floating crane vessel, see Fig. 1.4 (b). This operation was found to be very challenging and unattractive (Sarkar, 2013). A numerical analysis of this operation was performed by Ku and Roh (2015) by applying time domain simulations.



(a) OWT balde installation using a jack-up vessel. Source: `https://media.licdn.com/mpr/mpr/shrinknp_800_800/p/6/005/0b7/104/353401b.jpg`

(b) Single lift OWT and RNA installation using a floating HLV. Source: `http://www.scaldis-smc.com/en-GB/rambiz-3000/31/`

Figure 1.4: Installation of turbine tower components

1.3.3 Installation of substations

In addition to the foundations and turbine towers, another important wind farm component is the substation. It is a cluster infrastructure designed to collect the energy generated by every wind turbine and convert it into high voltage current before transporting it to shore using power transmission cables. The installation of this module is normally carried out by the single lift or the float-over method, see Fig. 1.5. The choice of the method depends on the available capacity of the HLVs and the mass of the module. The single lift method is normally used when the module is not too heavy for the available HLVs, see Fig. 1.5 (a). The installation procedure consists of the following steps: lifting the module from the deck of the HLV or from a transportation barge, positioning it a few meters above the foundation, aligning the mating pins, monitoring the motion responses of the pins, lowering, mating and landing. For topsides with large mass and size, the float-over method is commonly applied, see Fig. 1.5 (b). In this method, a cargo barge that transports the module in dry condition, floats over the specially designed jacket. After that, the barge is moored to the jacket, ballasted, and the mating phase occurs. Next, the barge is ballasted further to achieve enough clearance between the structures, and finally the barge sails away.

It is observed that the installation of a substation and a transition piece (see Subsec. 1.3.1) share some similarities in the execution procedure. There is a phase where the mating points are aligned and the motions are monitored. If the motions are too large when compared to the allowable mating gaps, the subsequent operations may not be possible. This is an important criterion for making a decision on-board vessels during execution of installation activities.

(a) Substation installation using an HLV. Source: `http://www.offshorewind.biz`

(b) Substation installation using the float-over method. Source: `https://www.overdick.com/projects/offshore-wind/hvdc_sylwin_alpha`

Figure 1.5: Installation of substations

1.3.4 Novel OWT installation concepts and specialized vessels

New installation vessels and concepts have also been proposed. Huisman Equipment B.V. (2015) presented a concept of a new twin hull installation vessel which uses an active heave compensation system during landing of the tower on the foundation. Seok (2013) proposed a method to install an OWT tower using a specially modified jack-up vessel. This vessel has an opening that allows the OWT foundation to get into it. This is done by varying the tension and length of the mooring lines followed by a standard leg lowering procedure. A frame on the deck allows for vertical positioning and lowering of the OWT tower. However, this installation vessel and procedure have not been applied. Sarkar and Gudmestad (2013) proposed a novel concept for the installation of an OWT tower and RNA. The procedure requires a patented system for keeping the blades out of the water during the tower transportation. The technical feasibility of this concept was based on some preliminary design considerations and operational aspects carried out by Korovkin (2012); however, the method has not been applied in practice. A self installing concept of a fully integrated tower and gravity based foundation was proposed by Wåsjø et al. (2013). In this concept, the assembly is transported on two cargo barges and is installed using a controlled lowering process. Model tests and numerical analyses have been conducted to assess its feasibility (Bense, 2014).

Furthermore, Jin and Jo (2014) suggested the use of a stabilizing frame to constrain the pendulum motions of a fully assembled tower that is lifted from a cargo barge. Finally, Graham (2010) developed a concept that consists of a cargo barge transporting the OWT in horizontal position to the site and a mechanism to rotate the tower to the vertical position. The rotation is carried out using hydraulic systems located on the deck of the cargo barge. After that, pins located at the bottom of the tower mate with the docking cones of a specially designed foundation. Next, the stern of the barge is pulled backwards using winches and anchors on the seabed. Then, a clamping system on the foundation receives the tower in a vertical position. However, this method has not been shown to be feasible and has not been applied in practice.

Based on the above-given literature review, it appears that there are not many alternative concepts for OWT tower installation; the proposed novel solutions require new vessels and procedures for which very limited information exists regarding numerical analyses and feasibility. Thus, alternative installation methods which are feasible, efficient, and use available equipment are required.

1.4 Methods for numerical analysis

Analysis of marine operations requires a synergy between various disciplines such as structural mechanics, hydrodynamics, stochastic methods and probabilistic design. This is necessary to develop numerical modeling procedures and computer codes that allow for representing the actual marine operations. In addition, the theory implemented in each computer code varies depending on the application, and in general a combination of various computer codes is necessary to numerically model marine operations.

Computer codes such as OFFPIPE (Malahy, 2013) and OrcaFlex (Orcina Ltd, 2006) are commonly used for analysis of pipeline, cable and umbilical installation. These codes can provide reaction forces and stresses on the pipeline; however the motion response amplitude operators (RAOs) of the installation vessel are normally computed in other codes such as Wamit (Lee, 1995), Wadam (Det Norske Veritas, 2013b) or AQWA-LINE (Century Dynamics-Ansys Inc., 2011). The computer code SACS (Structural Analysis and Design Software) has modules to analyze structural responses during offshore transportation and jacket launching, but the RAOs need to be input as well. For offshore heavy lifting operations, there are computer codes that perform well with motion response analysis but offer limited number of mechanical couplings and structural analysis capabilities. Some examples are: OrcaFlex, the Ansys-AQWA suite of programs, SIMO and Riflex (MARINTEK, 2012) and aNySIM (MARIN, 2009). The dynamic responses obtained from these codes can serve as input into other more specialized structural or fluid dynamics' codes. Thus, a number of computer codes are necessary to build even simplified numerical models and assess the dynamic responses of structures during planning of marine operations.

Dynamic responses need to be assessed by numerical modeling of the "actual" marine operation. Depending of the type of marine operations, this can be done by applying frequency domain (FD) and time domain (TD) methods. In general, TD are applied to study dynamic responses of non-linear systems and systems with time-variant dynamic properties. Taking as an example the float-over operation, the dynamic system needs to include non-linear contact elements, because contact between mating structural elements will occur during the entire mating operation. Moreover, the dynamic properties such as natural periods of the system may change during the installation, because the cargo barge is ballasted. Thus, the mating process is non-stationary, and as a result of this process, the mean vertical position of the barge changes with time. Due to the complexity that involves modeling the actual float-over operation and the limited number of features of existing computer codes, the current practice is to conduct TD simulations of float-over operations with the barge at specific draughts or percentages of load transfer (Jung et al., 2009; He et al., 2011). Thus, the actual non-stationary float-over operations are not simulated, so the dynamic responses can be expected to be different from cases when the actual operations are modeled numerically.

Non-stationary lifting and landing operations have been studied by Sandvik (2012). It was found that the response statistics resulting from numerical analyses of non-stationary processes are significantly different from cases where operations were modeled using simplified stationary process TD simulations. This is because in a non-stationary lifting or lowering process, the dynamic properties of the system change with time, the dynamic responses do not build-up as in a stationary case, and in the stationary case the actual duration of the operation is not modeled. Thus, numerical modeling of actual operations is necessary.

As it was shown above, modeling marine operations is challenging, and numerical models are only approximate representations of actual dynamic systems. In addition, important features cannot be captured with existing modeling techniques and computational tools. Thus, more accurate numerical analysis methodologies are needed. Li et al. (2014b, 2015b) developed a methodology to account for shielding effects of installation crane vessels on monopile foundations and the radiation damping of the monopile during non-stationary lowering process. In addition, efficient numerical analysis methodologies are required for quick assessment of the dynamic responses. Fylling (1994) proposed a methodology that is suitable for estimation of initial impact velocities of drifting vessels. This methodology was applied by Sandvik (2012) to study lift-off and landing operations of dynamic systems with time-invariant dynamic properties. This method is suitable for assessment of snap and impact velocities by imposing a winch speed on time histories of displacements obtained from stationary process TD simulations. Moreover, a simplified method to assess snatch loads during OWT monopile lift-off has been proposed by Zhao et al. (2016).

Based on the literature review, few efficient and accurate methodologies for numerical modeling of marine operations have been developed. In addition, these methodologies are operation-specific and are not applicable for other marine operations. Moreover, the features and tools available in the state-of-the-art codes are not sufficient to model entire marine operations. Instead, the operation is divided into several activities and some of them may not correspond to the actual operations. Thus, further development of methodologies and tools is required.

1.5 Operational limits

During execution of a marine operation, the basic safety criterion is that any response of the dynamic system (e.g., the wire tension) should not exceed its allowable limit (including safety factors). However it is practical to transform these limits into limits in terms of sea state parameters or motion responses of vessels that can be monitored before and during the execution of marine operations. These are operational limits that can be established during the planning phase and should be derived systematically. Moreover, these limits need to account for uncertainties in material mechanical properties, statistical uncertainty, model uncertainty, forecast uncertainty, etc. Depending on the type of operation and consequences of failure events, safety factors need to be established and calibrated to ensure enough safety margins.

Det Norske Veritas (2011a), International Organization for Standardization (2015b) and GL Noble Denton (2015) provide recommendations on the operational criteria for planning and execution of marine operations. The criteria are mainly expressed in terms of significant wave height (Hs), while the wave spectrum peak period (Tp) is not considered. The Hs parameter is reduced by alpha factors that account for uncertainties in the weather forecast methods and leading times, and the reference period (duration) T_R of the activities. However, floating units are highly sensitive to Tp, and thus, Tp also needs to be included.

Clauss and Riekert (1990a,b) presented a summary of operational limits in terms floating crane vessel motion responses. These limits were given based on experience from projects executed in the North Sea. Some of these vessel motion criteria were also expressed in terms of sea state parameters. Likewise, Smith et al. (1996) provided the operational limits in terms of allowable impact velocities for a jack-up vessel during the standard leg lowering procedure. The limits were derived from structural damage criteria based on structural analyses of leg members. Similarly, Clauss et al. (1998) proposed a methodology for assessment of the allowable sea states during offshore pipelaying based on maximum permissible stresses on the pipe. The methodology accounts for wave and vessel motion induced stresses. In addition, Cozijn et al. (2008) assessed the operational limits for installing a module using a floating crane semi-submersible platform onto a floating vessel. The limits were derived based on numerical analysis, model tests, and offshore site measurements. Moreover, Graczyk and Sandvik (2012) established the allowable sea states for the lift-off and landing of an offshore wind turbine component on the deck of a ship. The dynamic response of the lifted object was estimated based on formulations given by Det Norske Veritas (2011b) and the allowable acceleration on the lifted object was simply assumed.

An approach to derive the operational limits in terms of Hs and Tp for a drilling jack-up unit during the deployment and retrieval of its legs was given by Matter et al. (2005). The allowable stresses in the spud cans, legs, and pinions were established based on structural analyses. These allowable stresses were expressed in terms of allowable vessel motions, and by using the response amplitude operators (RAOs) in a free floating condition, these motions were given in terms of allowable sea states. Similarly, Ringsberg et al. (2015) presented the allowable sea states for a jack-up vessel during deployment of its legs. The sea states were identified by comparing the allowable forces on the spud can, which were derived from finite element modeling (FEM), with the characteristic values of the impact forces, which were computed from a coupled spud can and soil interaction model.

The literature cited above shows that the operational limits for marine operations have been assessed considering different approaches, which vary and are not clearly indicated.

1.6 Operability and weather window analysis

The operability is a measure of the available time for executing an operation in a given reference period and in a safe manner. It is normally assessed using the operational limits (in terms of sea state parameters) and scatter diagrams of the offshore site.

Human comfort criteria for operability analysis have been established in the past (NORDFORSK, 1987; Lawther and Griffin, 1987; Werenskiold et al., 1999). These criteria have been used to assess the operability of ships. For instance, Fonseca and Guedes Soares (2002) studied the operability of a container ship and a fishing vessel. Several criteria such as vessel roll and deck accelerations were considered, and a sensitivity study on the most relevant parameters was carried out. In addition, Tezdogan et al. (2014) assessed the operability of a high speed catamaran vessel based on passenger comfort criteria. A comparative study by applying various sea-keeping theories was conducted, and the effect of seasonality was also investigated.

The operability of OWT service vessels has also been assessed. For instance, Wu (2014) assessed the operability for the docking operation between service vessels and OWT foundations. This was done for the current access method that relies on the friction force between the vessel and the foundation. Dynamic responses computed using the frequency domain method and scatter diagrams were employed.

The operability should preferably be assessed from weather window analysis, where the sequence, duration, and continuity of each activity can be included. Nielsen (2007) provided a procedure to estimate the available time for execution of a marine operation. The procedure is based on the conditional distribution function of Hs on the duration of weather windows, so the time histories of hindcast wave data are employed. This method is suitable for planning of marine operations; however, the peak period Tp is not included. Bergøe (2015) provided the operability of jack-up and floating units. Although the allowable sea states were simply assumed, the sequence and duration of the activities were incorporated in the analyses. In addition, Velema and Bokhorst (2015) identified the weather windows for installation of a subsea storage module. The heading providing the best responses was selected based on directional wave spectra from updated weather forecast and on-board numerical simulations. Moreover, Gintautas et al. (2016) proposed a methodology for identification of weather windows with the aim to support on-board decision-making during offshore wind turbine installation.

This is done by on-board numerical simulation of the operations and probabilistic assessment of the dynamic responses, which are computed using updated forecast wave data. In the analyses, the sequence and duration of the activities were included; however, the operational limits were simply assumed.

Based on the aforementioned literature, it appears that no methodologies that link practical and systematically derived response-based operational limits and weather window analysis have been published. These operational limits should be used to assess the operability of different OWT installation procedures while considering the duration, sequence and continuity of the activities.

1.7 Aim and scope

In view of the lack of published methods for establishing transparent and practical operational criteria for marine operations, and the need for feasible alternative OWT installation procedures, important objectives of this thesis are:

- Establish a general and systematic methodology for identification of critical events and assessment of the operational limits for marine operations.
- Establish practical operational limits in terms of Hs, Tp, and vessel response parameters that can be monitored on-board and used for decision-making.
- Develop a methodology for operability assessment of marine operations that accounts for response-based operational limits, duration, sequence and continuity of the activities.
- Develop procedures for numerical modeling of current OWT installation activities.
- Develop methodologies for numerical analysis of critical OWT installation activities, e.g. the mating operation of a transition piece.
- Develop alternative and feasible OWT installation concepts or procedures.

This thesis is written as a paper collection, including five journal papers and one conference paper, which are attached in the Appendix. The scope of the thesis is shown in a matrix in Fig. 1.6, where the main topics and the interconnection between appended papers are illustrated.

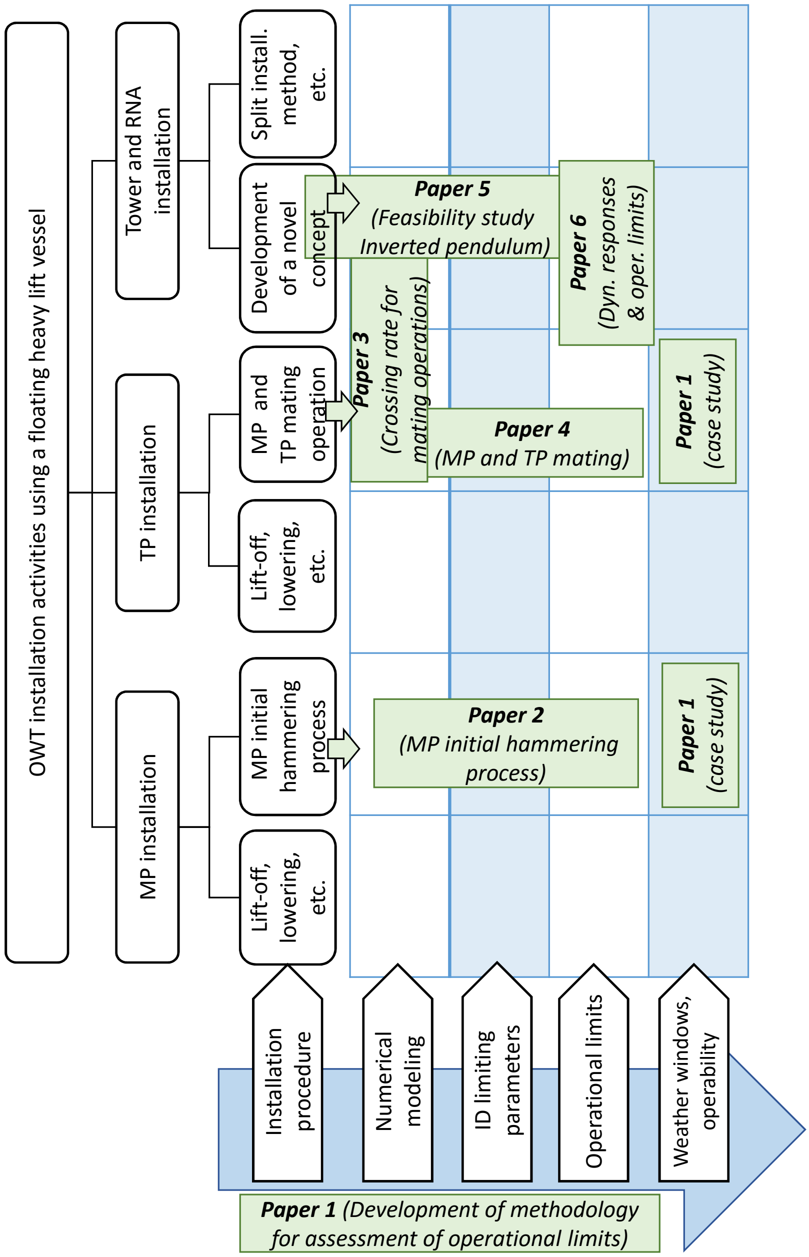


Figure 1.6: Scope of the thesis and its interconnection with the papers

Figure 1.6 shows the research approach that is followed in this thesis. A generic methodology for systematic derivation of operational limits for marine operations is developed (*paper 1*). The generic methodology is based on numerical modeling of *actual* (in general) non-stationary operations and quantitative assessment of dynamic responses. By comparing characteristic values of dynamic responses with their allowable limits, a backward derivation of limits of sea state parameters is possible. This methodology is applied to MP, TP and OWT and RNA installation activities. For the MP and TP (*papers 2 and 4*), standard installation procedures are considered , while for the OWT tower and RNA (*paper 5*), a novel installation concept is developed. Numerical models and methods are developed for the installation activities. A numerical method suitable for mating operations is addressed in *paper 3*. The numerical models are established based on information available in literature and assumptions. Meanwhile, the allowable limits of some response parameters are estimated based on specifications of the equipment and reasonable assumptions. Contact-impact problems are only addressed in terms of representative global motion responses, e.g. initial relative impact velocities, so the structural damage criteria which need to be established based on FEM are not included. For some installation phases, sensitivity studies on modeling parameters are carried out (*paper 6*). Only wave load actions are considered, while wind and current load actions are not included.

1.8 Thesis outline

This thesis is composed of seven chapters. The content of each chapter including the reference papers is briefly summarized below.

Chapter 1:
This chapter provides an introduction including the background and motivation, a brief review of current guidelines and standards, an overview of current OWT installation methods, some methodologies for accurate and efficient numerical analysis of marine operations, current developments in operational limits, the aim and scope, and the outline of the thesis.

Chapter 2:
This chapter deals with a general methodology for the assessment of the operational limits and operability of marine operations, especially for offshore heavy lifting. This is a summary of *paper 1*.

Chapter 3:

This chapter addresses the installation procedures and system components used for numerical modeling of the MP, TP and OWT tower and RNA installation activities. This chapter is a summary of *papers 2, 4 and 5*.

Chapter 4:
This chapter provides the numerical methods and models that were used for analysis of various OWT installation activities. The numerical methods are provided as a summary of *papers 3 and 4*, while the numerical models are a summary of *papers 2, 4 and 5*.

Chapter 5:
In this chapter, the operational limits for the installation activities are established. They are assessed by applying the methodology provided in Ch. 2. Numerical models given in Ch. 4 are employed. The results are a summary of *papers 2, 4, 5 and 6*.

Chapter 6:
In this chapter, the operability for installation of the MP foundation and the TP using a floating crane vessel is provided. This chapter is a summary of a case study in *paper 1*

Chapter 7:
Conclusions, highlight of original contributions and recommendations for future work are provided.

Chapter 2

Methodology for assessment of operational limits and operability of marine operations

2.1 General

For any marine operation, the feasibility of its execution needs to be evaluated based on the characteristics of the vessels, equipment and environmental conditions of the offshore site. If it is feasible, the equipment and installation season need to be selected well in advance. This is achieved by assessing the performance of the installation system during execution of these activities. Numerical simulations, documentation, guidelines and experience from related past projects are normally employed to establish the operational limits, which can be used for assessment of the operability during the planning phase or for decision-making during the execution phase of marine operations.

The current industry practice for planning and execution of marine operations, is to express the operational limits in terms of Hs "design limits". These limits are mainly based on experience from past projects. Moreover, offshore standards provide guidelines to account for forecast uncertainties in the Hs parameter. This is done for instance by means of alpha factors, which are reduction factors (applied on Hs) that depend on the forecast methods and duration of the operations (Det Norske Veritas, 2011a). However, the approach that is followed to establish these Hs design limits is not clear, and the following questions may be asked:

- How should the operational limits be established?
- Are the Hs limits sufficient?
- Which installation activities should be chosen for numerical analyses?
- How should numerical simulations be conducted?
- Which response parameters should be analyzed?
- How should response statistics be assessed?

The above questions have not been properly addressed in the literature and scientific papers. Thus, a systematic methodology for assessing the operational limits and operability of marine operations is required.

Guachamin Acero et al. (2016d) (*paper 1*) developed a general approach that is suitable for identification of critical events and corresponding limiting (response) parameters of critical operations, and assessment of the operational limits in terms of allowable limits of sea states. Moreover, a general procedure for assessment of the operability of marine operations based on weather window analysis was proposed. A brief description of these procedures is provided in this chapter.

2.2 Marine operation execution phases and loading conditions

Figure 2.1 shows two phases during the execution of a marine operation. First, there is a "monitoring phase" prior to the (actual) execution of marine operations (DYNAMIC SYSTEM 1), in which the responses of the vessel e.g., motions, velocities, accelerations are monitored and compared with the operational limits given in the operational manual. This is done to make a decision on whether or not to start an operation. In this loading condition, the system is weakly non-linear, it has time-invariant properties, and the resulting processes are stationary, see section 4.2. Thus, frequency domain (FD) methods can be applied. This is suitable for computations using on-board systems.

Second, there is an execution phase with different loading conditions in which critical events can occur (DYNAMIC SYSTEM 2). These loading conditions are necessary for numerical analysis and assessment of the operational limits. Moreover, during the execution of the activities, some

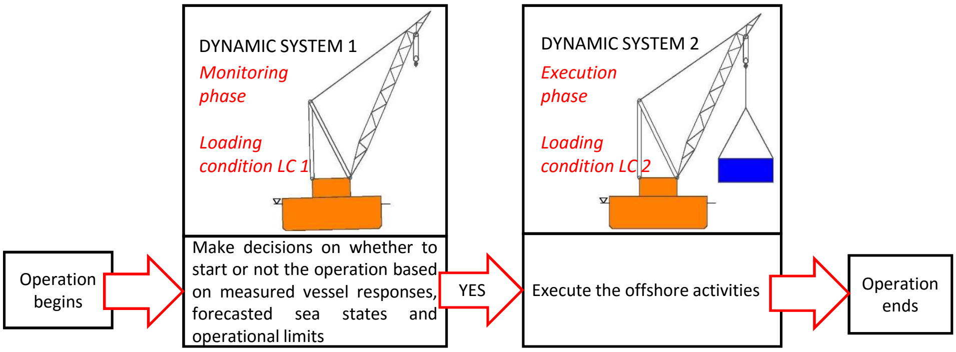


Figure 2.1: Phases and loading conditions for execution of a marine operation (Guachamin Acero et al., 2016d)

dynamic responses can be monitored, for instance, the wire tension. This parameter can be used to take mitigation actions (if the tension reaches dangerous levels), but not to make decisions before executing an offshore activity.

2.3 Assessment of the operational limits of marine operations

This section deals with a methodology for assessment of the response-based operational limits of a marine operation. The operational limits are derived from numerical analysis of the actual execution phase. These limits can be used in the monitoring phase prior to execution to support on-board decision-making, and during the planning phase for operability analysis.

2.3.1 Operational limits of a single activity

The methodology for assessment of the operational limits is shown in Fig. 2.2. Based on typical installation procedures, the first objective is to narrow down the number of cases for numerical analyses. Preliminary identification of potential critical events and their corresponding activities is commonly done by applying qualitative risk assessment techniques together with technical discussions form past projects and reports, see step 2 in Fig. 2.2. These activities are selected to build numerical coupled models and carry out global dynamic response analyses of the system under “typical” sea states (steps 3 and 4). Quantitative assessment of the dynamic responses is conducted (step 5), and the parameters that may reach dangerous levels (limiting parameters) when compared with their allowable limits (including safety factors) are identified (step 6). For contact-impact problems, the allowable limits need to be established based on structural damage criteria, see e.g., Li et al. (2014a).

For time domain simulations conducted in step 4, the number of seeds required for assessment of the dynamic responses does not need to be large, because these responses are only used for screening of limiting (response) parameters and are not used for assessment of the operational limits. Note that the actual operations need to be simulated numerically, i.e. the stationarity, linearity and time-variant properties of the dynamic system need to be considered. Time domain and frequency domain methods are normally applied. Moreover, more accurate and efficient methodologies for numerical analysis of specific marine operations have been developed by Li et al. (2014b, 2015b) and Sandvik (2012). Some methods used in this thesis are addressed in Sec. 4.2.

For the identified limiting (response) parameters, the corresponding dynamic coupled models (step 7) are used to carry out numerical simulations, and build response statistics and extreme value distributions. This is done for "all" possible Hs and Tp combinations. The characteristic value of a limiting parameter is selected, e.g., for a target probability of non-exceedance based on extreme value distributions (step 8). This probability depends on the type of operation, duration and consequences of the failure events, see Sec. 2.5.

For the time domain simulations carried out in step 8, normally a large number of seeds is required to achieve convergence on the response statistics. In equation (2.1), the characteristic values $S_c(Hs, Tp)$ are compared with the allowable limit S_{allow} (including a safety factor γ_s) of a limiting (response) parameter, and thus, the allowable limits of sea states are established, see step 9. Finally, the allowable limits of sea states can be expressed in terms of allowable limits for responses of the system in a loading condition prior to execution, see monitoring phase in Fig. 2.1. These limits are useful because they can be compared with responses that are measured on-board. Figure 2.2 shows that allowable limits of both, sea states and responses in monitoring phases are known as "operational limits", and they should to be provided in the operational manuals.

$$S_c(Hs, Tp) = \frac{1}{\gamma_s} S_{allow} \tag{2.1}$$

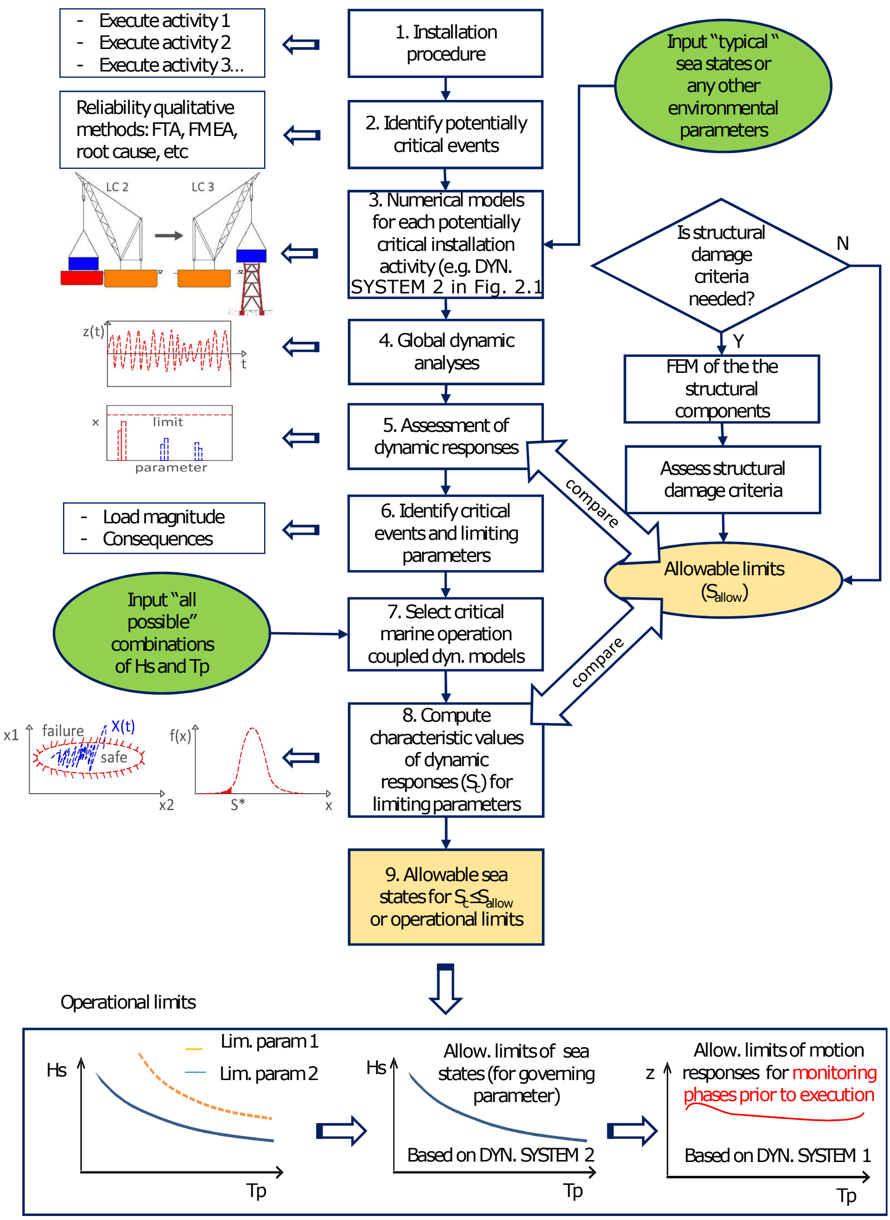


Figure 2.2: General methodology to establish the operational limits (Guachamin Acero et al., 2016d)

2.3.2 Operational limits for groups of continuous activities

The installation of an OWT normally requires the execution of several sequential activities. These activities can be continuous, and thus, they can be grouped, e.g., MP lift-off and lowering. By following the procedure given in the previous subsection, the allowable limits of sea states for each activity can be established. Figure 2.3 shows two groups of continuous activities: "G1" and "G2", for which the lower envelopes of the allowable limits of sea states are the operational limits of the combined group of activities. The envelopes also allow to identify the limiting parameters governing the execution of the marine operation.

By following the aforementioned procedure, it is possible to systematically establish the allowable limits of the sea states for each group of continuous activities in the entire marine operation.

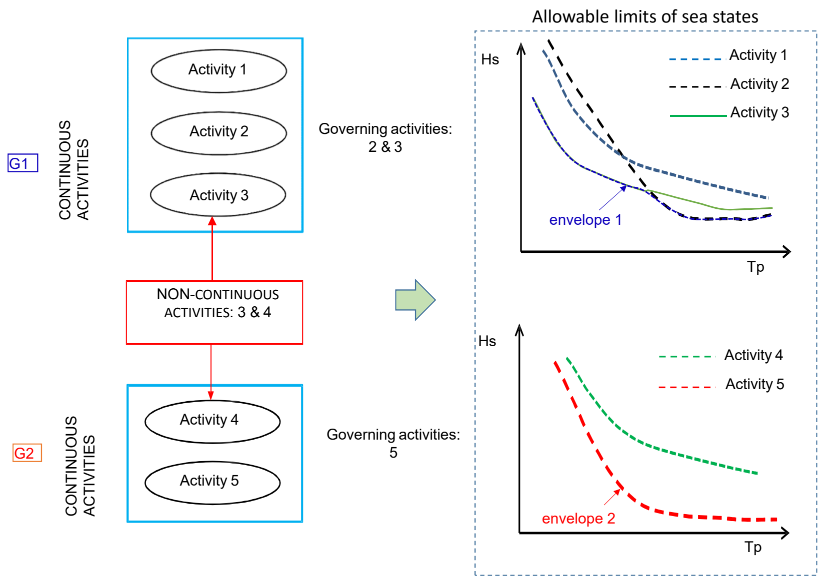


Figure 2.3: Allowable limits of sea states for groups of continuous activities (Guachamin Acero et al., 2016d)

2.4 Weather window analysis and operability

Weather windows are necessary for assessment of the operability of a marine operation during the planning phase, and to make decisions on whether to start or to stop the execution of an activity. For these purposes, hindcast and forecasted wave data are required.

For the planning phase, the weather windows can be identified and used to assess the operability of a marine operation. The time histories of Hs and Tp based on hindcast wave data are required, see Fig. 2.4 (a). For every time step, the corresponding Tp_i is used to identify the allowable Hs_i for every group of activities, see Fig. 2.4 (b). By comparing the time histories of hindcast Hs and their allowable limits (for corresponding Tp), the workable weather windows of each group of activities can be identified, see Fig. 2.4 (c). Then, the weather windows of each activity group are put in sequence and including their respective duration. An example for two groups is shown in Fig. 2.4 (e), where t_{R1} and t_{R2} are their duration. The parameter t_R is denoted as reference period by Det Norske Veritas (2011a). A starting time for activity group G1 is first identified. After G1 is finished, G2 starts. Since G1 and G2 are not continuous, they can be split. Following this procedure, the workable weather windows of the complete operation can be identified, and by counting them during the total period of analysis, the operability can be assessed.

For the execution phase, the weather windows can be identified by following the same procedure as for the planning phase; however, the forecasted wave data need to be used, see Fig. 2.4 (a).

The procedure outlined above is ideal and systematic, but does not account for the fact that the starting and stopping times for the activities are uncertain, and thus, it can be conservative or unconservative. However, this topic is not addressed in this thesis.

2.5 Assessment of characteristic values of limiting parameters

It was stated earlier that a characteristic value of a limiting (response) parameter needs to be calculated for a target percentile or a non-exceedance probability of an extreme value distribution. This distribution needs to be fitted using the extreme responses, which are calculated by numerically modeling the actual marine operations. The number of seeds for the TD simulations should be sufficient to achieve convergence of the statistical properties (response statistics), and thus, reduce the statistical uncertainty. However, this is only one source of uncertainty and several other sources have to be considered as discussed below.

Other sources of uncertainties include numerical models (model uncertainty), wave models (wave model uncertainty), forecasted wave data (fore-

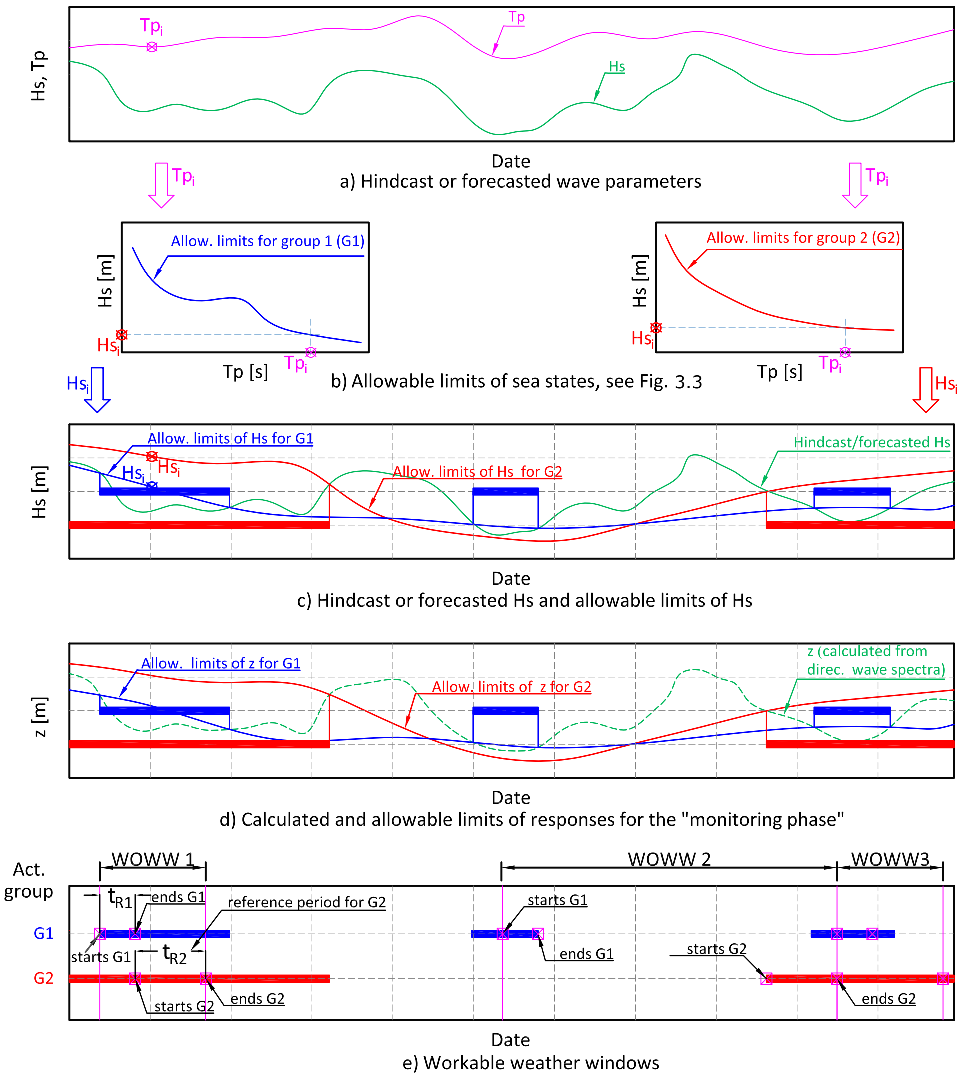


Figure 2.4: Weather windows analysis including continuity and duration of offshore activities. (a) Hindcast or forecasted Hs and Tp; (b) Allowable limits of Hs for corresponding Tp; (c) Hindcast or forecasted and allowable limits of Hs; (d) Dynamic responses based on forecasted wave data and allowable limits of responses for the monitoring phase; (e) Workable weather windows (Guachamin Acero et al., 2016d)

cast uncertainty), human decisions, etc. In all these uncertainty sources, there are modeling parameters for which the probability density functions (PDFs) can be established, for instance, the forecasted Hs. The influence factors of each of these uncertainty modeling parameters on characteristic values of the limiting (response) parameters can be assessed from probabilistic models, and the most important ones can be considered. Then, the characteristic value of a limiting parameter can be computed for a target non-exceedance probability.

The target non-exceedance probability should be chosen based on the consequences of failure events and reversibility of the operation. For instance, the non-exceedance probability of the allowable tension of a wire rope during a lifting operation should be low enough to guarantee safety, because consequences of a structural failure can be catastrophic. In contrast, the mating attempt of a transition piece with a monopile foundation should be designed for a higher exceedance probability because this operation can be tried again in the case of a failed attempt (reversible operation) and the consequences are not catastrophic. Thus, the target non-exceedance probability depends on the type of operation. Moreover, it is noted that the responses need to be assessed by modeling the actual operations, so the duration of simulations should be applied according to the operational manuals.

Some offshore standards and papers dealing with sources of uncertainty and target non-exceedance probability are briefly discussed below. Det Norske Veritas (2014b) recommends that characteristic values of loads for some marine operations such as loadout, transport, and installation of subsea objects, correspond to a 10 % probability of exceeding the allowable limits (design loads) of limiting parameters. In addition, Det Norske Veritas (2014a) provides load factors for heavy lifting operations. These factors account for failure event consequences and uncertainties in several material and geometric parameters that affect the load and the capacity of the structural components. The intention of these factors is to ensure a probability for structural failure less than 1×10^{-4} per operation.

Furthermore, statistical models given by Natskår et al. (2015) or alpha factors provided by Det Norske Veritas (2011a) can be used to account for uncertainties in forecasted Hs as function of forecast lead times. The alpha factors are reduction factors that can be applied on the Hs design limits (operational limits). In fact, Det Norske Veritas (2011a) states that the alpha factors should be calibrated to ensure that the probability of exceeding the operational limits (in terms of Hs) with more than 50% is less than 10^{-4}. Based on this statement, it is demonstrated that these factors are considered to be independent of the type of operation and consequences of failure events. Moreover, Tp needs to be included because it is an important parameter for floating vessels. Thus, distribution functions that account for uncertainties in both Hs and Tp parameters are required.

In this thesis, the probabilistic assessment of the operational limits including all sources of uncertainty is not addressed. The effects of the statistical uncertainty and consequences of failure events are in some extent included when assessing the characteristic values and allowable limits of limiting (response) parameters, i.e., assuming percentiles for extreme value distributions and safety factors for the capacity.

Chapter 3

Installation systems and procedures

3.1 General

The installation of foundations, transition pieces and turbine tower components is normally executed with jack-up and floating crane vessels. Jack-up vessels offer a stable platform for crane lifting operations, so the lifting operations do not depend on wave conditions. As it was mentioned earlier, some disadvantages of these platforms are the water depth limitations, mobilization time, and low sea states in which the legs can be deployed and retrieved. Alternatively, floating HLVs are known to be competitive for marginal wind farms and offer fast transit speed between wind turbines. A downside of floating vessels is that the dynamic responses are sensitive to wave actions, so the installation of OWT components is more challenging. The installation activities studied in this thesis are executed using floating HLVs.

This chapter deals with the system components and procedures for the MP initial hammering process, TP mating operation, and the entire installation of the tower and RNA. The procedures for the MP and TP installation are commonly applied by offshore installation contractors, while a novel procedure developed by Guachamin Acero et al. (2016c) (*paper 5*) is used to assess the installation of the OWT and RNA. The installation procedures are required for identification of potential critical activities, which is carried out in Ch. 5.

3.2 Monopile initial hammering process

A MP is normally installed using a jack-up or a floating HLV. Monopile foundations are normally transported on the deck of crane vessels, from which they are lifted-off, relocated, upended, lowered and driven into the soil.

A potential critical operation for MP installation is the initial phase of the MP hammering process, which starts when a hydraulic hammer is put on the top of the MP and finishes when the MP is able to stand on its own under wave actions.

The system components and installation procedure are given by Li et al. (2016b) (*paper 2*) and are summarized below.

3.2.1 System components

The main system components for the MP initial hammering process are shown in Fig. 3.1. A HLV is rigidly connected to a gripper device. The gripper is composed of hydraulic cylinders and piston rods that are radially distributed, see Fig. 4.2 (a). The gripper holds the MP in the vertical position during the initial part of the hammering process.

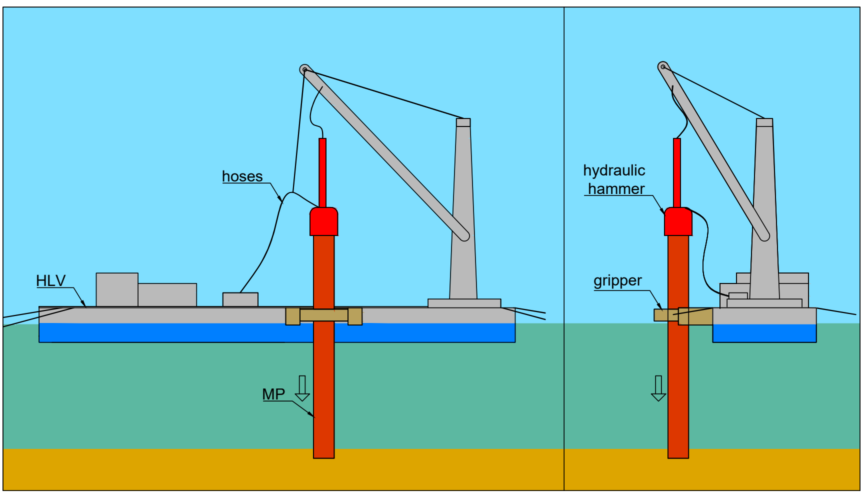


Figure 3.1: System components for the MP initial hammering process

The main particulars of the structures are given in Table 3.1. A HLV with an eight point mooring line system and a MP structure are the main structural components.

Table 3.1: Main particulars of the structures for the MP initial hammering process (Li et al., 2016b)

Parameter	*Notation*	*Value*	*Units*
- HLV			
Displacement	$\bigtriangledown$	5.12×10^4	tons
Length	L	183	m
Breadth	B	47	m
Draught	T	10.2	m
- Monopile			
Mass	M_{MP}	500	tons
Diameter	D_{MP}	5.7	m
Thickness	th_{TP}	60	mm
- Hydraulic hammer			
Mass	M_{HAM}	300	tons

3.2.2 Installation procedure for MP initial hammering process

A summary of the installation procedure is given below.

1. The gripper is used to hold the MP after its landing on the seabed. The gaps between the hydraulic pistons rods and the MP are closed to avoid impact loads. The MP and the gripper move in the horizontal plane due to first and second order wave forces.

2. A hydraulic hammer is placed on top of the monopile using the HLV crane.

3. The mooring lines of the HLV are adjusted to position the MP vertically.

4. The mean inclination of the MP is measured at various quadrants of the monopile using a handhold inclinometer.

5. The MP inclination is corrected to a zero mean value by varying the stroke of the piston rods of the hydraulic cylinders. A pre-compression force is applied.

6. To drive the MP into the soil, a few blows are applied using the hydraulic hammer. The MP inclination, which is caused by wave actions, is measured and corrected by varying the stroke of the piston rods.

7. The previous step is repeated until the hydraulic cylinders are not able to correct the MP inclination.

8. Correct the MP inclination by varying the length of the mooring lines and by applying thruster forces.

9. Retract the hydraulic piston rods and drive the MP to final penetration.

3.3 TP mating operation using a floating crane vessel

The TP is a cylindrical structure that is used to connect the MP foundation with the tower lower section. The TP is normally transported on the deck of an installation vessel. Once the MP is installed, the TP will be lifted off, aligned with the MP and lowered until it lands on the MP foundation. A critical activity is normally the mating operation. It starts when the TP bottom tip is located a couple of meters above the MP, and ends when the TP bracket supports land on the MP tip, see Fig. 4.8.

Guachamin Acero et al. (2016b) (*paper 4*) studied the mating operation between a TP structure and a MP foundation. The main particulars of the system components and the installation procedure are summarized below.

3.3.1 System components

Figure 3.2 shows that the system is composed of a HLV, a TP structure with a rigging system connected to the crane tip, and a MP foundation fixed to the seabed.

The main particulars of the HLV and TP are shown in Table 3.2. The MP was modeled according to Table 3.1.

3.3.2 Installation procedure for the TP mating operation

The installation procedure for the TP mating operation is summarized as follows:

1. The TP structure is aligned with the MP structure and positioned a couple of meters above the MP.

2. The motions of the TP bottom tip are monitored to decide whether or not the mating operation is possible.

3. If the motions of the TP bottom tip are acceptable, the TP is slowly lowered towards the MP.

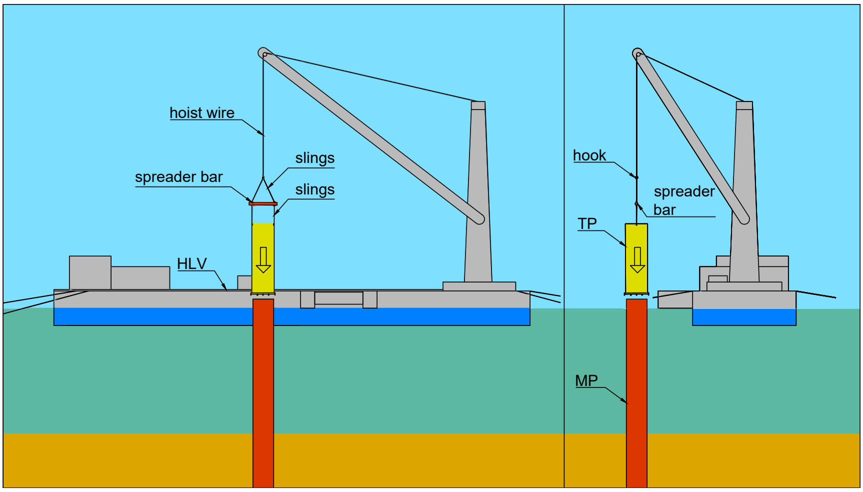


Figure 3.2: System components for the TP mating operation

Table 3.2: Main particulars of the structures for the TP mating operation (Guachamin Acero et al., 2016b)

Parameter	*Notation*	*Value*	*Units*
- *HLV*			
Displacement	∇	2.55×10^4	tons
Length	L	140	m
Breadth	B	30	m
Draught	T	6	m
- *Transition piece*			
Mass	M_{TP}	200	tons
Diameter	D_{TP}	6.4	m
Thickness	th_{TP}	60	mm
Length	L_{TP}	20	m

4. The initial part of the mating operation occurs.

5. The lowering process continues until the bracket supports of the TP land on the MP tip.

3.4 Novel concept for OWT tower and RNA installation

Guachamin Acero et al. (2016c) (*paper 5*) developed a novel concept and procedure for installation of the fully assembled OWT tower and RNA.

This concept is based on the inverted pendulum principle and was shown to be a feasible alternative for jack-up crane vessels. Moreover, this concept eliminates the necessity of huge floating crane vessels in terms of lifting capacity and height. Typical OWT foundations can be monopiles, tripods and jackets (under specific modifications).

3.4.1 System components

Figure 3.3 shows the main components of the installation system. A medium size HLV is required for upending of the OWT. In addition, a cargo barge is needed for transportation of the OWT to the site in an horizontal position, which is assumed to be feasible. Moreover, a specially designed upending frame is also required to upend the tower. This upending frame has two grippers. The grippers provide a pair of supports that are able to transfer the bending moments and shear forces. The foundations need to be installed with an specific heading based on wave spectra statistics. This is because of the benefits of shielding effects provided by the HLV on the motions of the cargo barge.

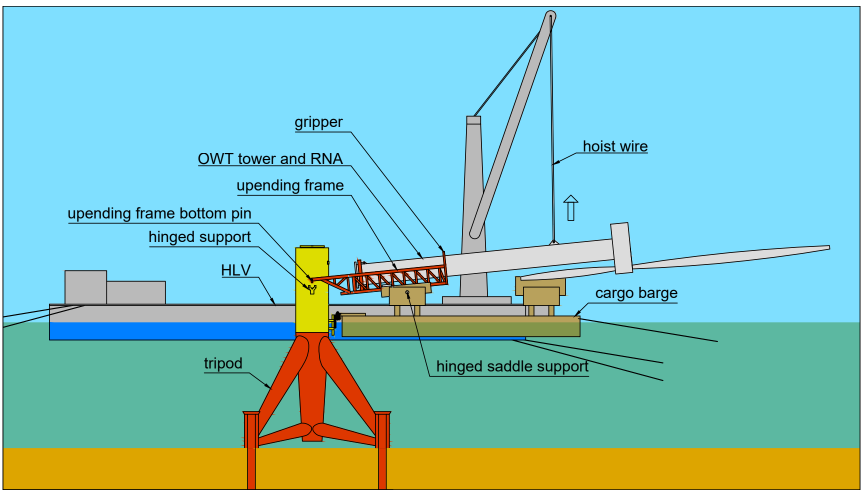


Figure 3.3: System components during lift-off of the OWT tower and RNA

The main particulars of the system components are given in Table 3.3.

3.4.2 Installation procedure

A summary of the procedure for installation of the OWT tower and RNA is given below.

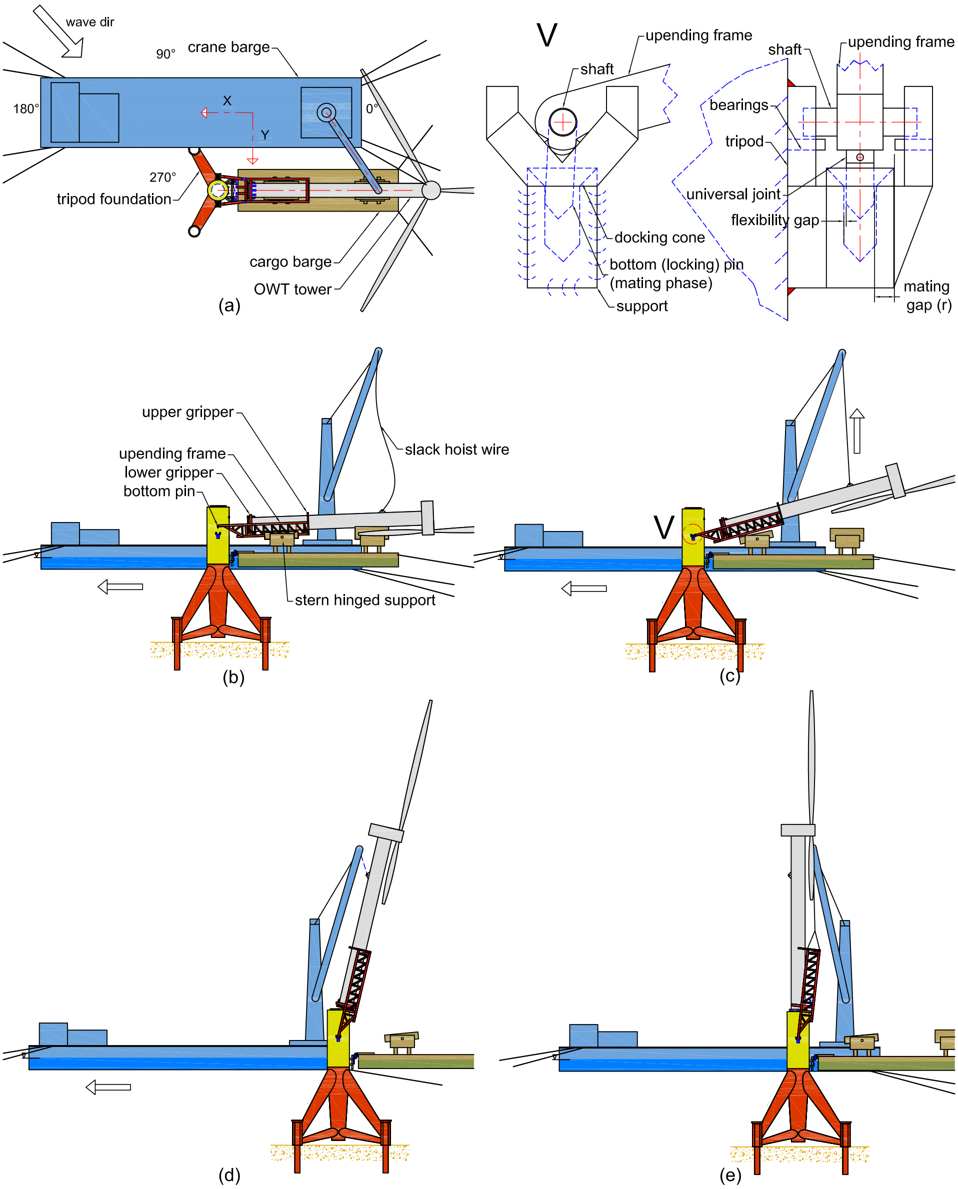


Figure 3.4: Installation procedure for OWT tower and RNA. (a,b) Motion monitoring phase; (c) Mating between the upending frame and the foundation supports; (d) Upending of the OWT tower in the final stage; (e) Completion and upending frame removal

Table 3.3: Main particulars of the structures for OWT and RNA installation (Guachamin Acero et al., 2016c)

Parameter	*Notation*	*Value*	*Units*
- *HLV* (see Table 3.2)			
- *Cargo barge*			
Displacement	∇	5.09×10^3	tons
Length	L	69	m
Breadth	B	18	m
Draught	T	4	m
Metacentric height	GM	3.75	m
Vertical position of COG above keel	VCG	5.0	m
- *Tower components* (Jonkman et al., 2009)			
Tower mass	M_{tower}	348	tons
Nacelle mass	$M_{nacelle}$	240	tons
Blades mass	M_{blades}	110	tons

1. The stern of the cargo barge is moored to the foundation using mooring lines and fenders. The bow of the barge is moored to the seabed using typical catenary lines, see Fig. 3.4 (a).

2. A HLV is moored to the seabed using a pipelaying mooring arrangement. This is because the vessel has to move forward during the OWT installation.

3. The separation between the stern of the barge and the foundation is adjusted using cantilevered beams. This allows for alignment between the upending frame bottom pins and the supports on the foundation (docking cones).

4. The motions of the upending frame bottom pins are monitored to decide whether or not to start the operations.

5. The crane tip or the lifting block and the lifting point on the OWT tower are aligned and connected with lifting wires in slack condition, see Fig. 3.4 (b).

6. The lift-off operation starts and continues until the bow saddle support on the cargo barge is cleared, see Fig. 3.3.

7. The mating process between the bottom pins of the upending frame and the foundation supports starts. This operation is finished when

there is enough clearance between the OWT and the stern saddle support on the cargo barge, see Fig. 3.4 (c).

8. The lifting points are aligned by gradually moving the crane vessel forward. This is done by pulling-in mooring lines connected to the seabed. This is a well-known procedure employed by pipelay vessels in shallow water.

9. The OWT upending process continues by moving the HLV in small increments.

10. By the final stage of the upending phase, the lifting points do not need to be aligned, because an horizontal force is required to bring the OWT to vertical position and avoid a possible crane interference, see Fig. 3.4 (d).

11. The OWT is lowered using hydraulic jacks provided in the upending frame, the turbine tower lands on the foundation, where it is finally bolted.

12. The upending frame is removed and placed onto the cargo barge. The frame can be used for another OWT tower and RNA, see Fig. 3.4 (e).

Guachamin Acero et al. (2016c) showed that the total installation time can be less than 16 hours, which could be reduced to 8 hours if a DP vessel is employed, because the mooring activity for the HLV would not be required. In contrast, the installation time using jack-up vessels is approximately 3 days (Herman, 2002). Moreover, jack-up vessels can normally operate between 30 to 60 m water depths (El-Reedy, 2012). Thus, this novel concept can offer a higher installation rate and is less water depth-sensitive than the current installation practice.

Chapter 4

Numerical modeling of offshore wind turbine installation activities

4.1 General

The installation procedures for MP, TP and tower and RNA were summarized in Ch. 3. The operational limits of potential critical installation activities will be addressed in Ch. 5. These limits can be established based on quantitative assessment of the dynamic responses. To study these responses, numerical methods and models of the installation systems are required.

This chapter deals with numerical methods and models, which are required to study dynamic responses of potential critical OWT installation activities.

4.2 Numerical methods for analysis of marine operations

It was shown in Subsec. 2.3.1 that the allowable limits of sea states are established based on the allowable limits and characteristic values of the limiting (response) parameters. The characteristic values are obtained by numerically modeling the various marine operations. This is done by applying numerical methods and models. In general, frequency and time domain methods are employed; however, more accurate and efficient operation-specific numerical analysis methodologies can be applied. This section deals with numerical methods that were employed for analysis of OWT turbine installation activities.

4.2.1 Time and frequency domain methods

For a dynamic coupled model of an installation system, the equations of motion can be solved in the frequency or time domain. The frequency domain method can be applied to weakly non-linear systems and for analysis of responses resulting from a stationary process, see e.g. dynamic system 1 in Fig. 2.1. In contrast, if the dynamic systems are non-linear and the resulting processes are non-stationary, time domain methods need to be applied.

There are various computer codes for analysis of marine operations. In this thesis, the state-of-the-art programs ANSYS-AQWA and SIMO developed by Century Dynamics-Ansys Inc. (2011) and MARINTEK (2012) were employed. The codes are widely used in the offshore industry and academia, see e.g., Oosterlaak (2011), and are capable of representing multi-body dynamic systems, hydrodynamic interaction between diffracting structures, joints with different types of constraints, mooring lines and winches for lifting operations, and fenders. Moreover, external forces can be added into the time domain solver by using an external dynamic library which is suitable for modeling DP and steering systems. Based on these features, the codes are suitable for modeling OWT installation activities.

The frequency domain method

In the frequency domain, the equations of motion of a rigid body dynamic system can be written as follows:

$$-\omega^2\left[\boldsymbol{M}+\boldsymbol{A}(\omega)\right]\boldsymbol{X}(\omega)+i\omega\boldsymbol{B}(\omega)\boldsymbol{X}(\omega)+\boldsymbol{K}\boldsymbol{X}(\omega)=\boldsymbol{F}^{ext}(\omega) \tag{4.1}$$

Where, **M** is the multi-body structural mass matrix, **A** and **B** are the frequency dependent added mass and damping matrices. The coefficients of these matrices are normally calculated by diffraction analysis using the panel method. **K** is the stiffness matrix, which accounts for the hydrostatic, mooring and coupling restoring terms. **X** is the vector of the motion of the system and $\mathbf{F}^{ext}$ is the vector of external forces acting on the system. As stated earlier, in this thesis only the first and second order wave actions are considered. The equations of motions can be solved for a response parameter under regular wave actions. The result is a transfer function or response amplitude operator (RAO) which can be used to carry out spectral analyses and assess the system dynamic responses in irregular seas.

The time domain method

In the time domain, the equations of motion of a dynamic system can be written as follows:

$$[\boldsymbol{M} + \boldsymbol{A}^{\infty}]\,\ddot{\boldsymbol{x}}(t) + \int_0^t \boldsymbol{h}(t-\tau)\,\dot{\boldsymbol{x}}(\tau)\,d\tau + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{F}^{ext}(\boldsymbol{x}, \dot{\boldsymbol{x}}, t) \tag{4.2}$$

Where $\boldsymbol{A}^{\infty}$ is the infinite frequency added mass matrix, $\boldsymbol{x}$, $\dot{\boldsymbol{x}}$, $\ddot{\boldsymbol{x}}$ are the position, velocity and acceleration of the system, and the added mass and damping coefficients are incorporated in the equations of motion via the retardation function $\mathbf{h}$. The various coupling forces due to lifting wires and fender elements are included in the stiffness matrix. The equations of motion are solved in every time step increment by applying numerical techniques, e.g., Newmark-beta methods.

4.2.2 Dynamic systems and numerical methods for analysis of OWT installation activities

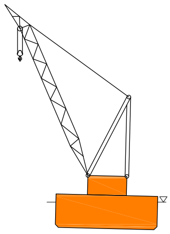
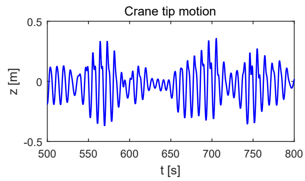
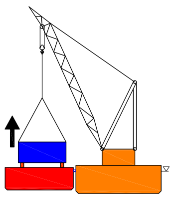
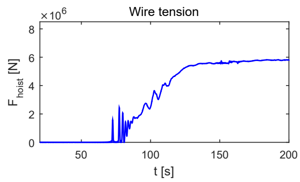
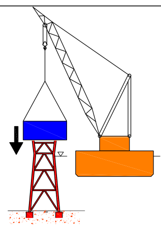
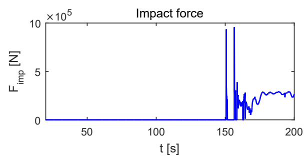
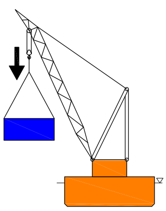
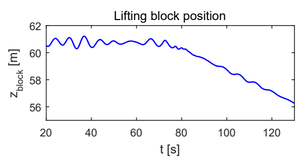
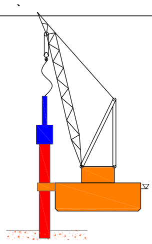
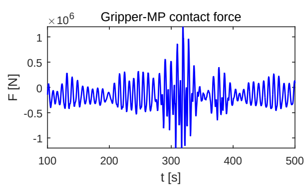
Marine operations need to be analyzed by modeling numerically the actual operations. In addition, a dynamic system can be non-linear and the response can be a result of a non-stationary process. Furthermore, since marine operations require moving objects from one place to another, changes such as winch speed need to be imposed into a dynamic system. As a consequence of these changes, the dynamic properties of a system may change. This subsection addresses typical dynamic systems and standard numerical methods required for analysis of OWT installation activities.

Weakly non-linear and non-linear dynamic systems

Some phases of an offshore operation correspond to weakly non-linear systems. A typical example is the monitoring phase prior to execution of a lifting operation, see the dynamic system (a) in Table 4.1. Another example is the motion monitoring phase of a vessel prior to a mating operation, see Subsec. 4.2.3.2. These installation phases can be solved in the frequency domain, because the motions are small, the dynamic properties of the system do not change in time, and the system is weakly non-linear.

There are also non-linear systems in which the output does not vary linearly with the input. For these systems, the stochastic responses need to be computed by applying the time domain method. The dynamic systems (b,c,e) in Table 4.1 are typical examples of OWT installation activities where the time domain method is normally applied.

Table 4.1: Dynamic systems, stochastic dynamic responses and numerical methods for analysis of typical OWT installation activities. Mean value (μ) and standard deviation (σ) are statistical properties of dynamic responses

	Dynamic system	Stochastic dynamic responses	Numerical method
Time-invariant	(a) Pre-lift  weakly non-linear	 *Stationary process*: $d\sigma/dt = 0$; $d\mu/dt = 0$	Frequency or time domain
Time-variant	(b) Lift-off  non-linear	 *Non-stationary process*: varying module position	Time domain
	(c) Mating  non-linear	 *Non-stationary process*: varying module position	Time domain
	(d) Lowering  weakly non-linear	 *Non-stationary process*: $d\sigma/dt \neq 0$; $d\mu/dt \neq 0$,varying block position	Time domain
	(e) MP-hammering  non-linear	 *Non-stationary process*: varying MP penetration	Time domain

Stationary and non-stationary processes

The wave elevation is said to be a stationary process if the statistical properties such as the mean value and standard deviation of a realization of that process (e.g., registration of the wave elevation) are independent of time. These statistical parameters are used to represent the sea state by means of a wave spectrum. For analyses of marine operations, this wave spectrum is normally assumed to be invariant for a period of 3 hours.

During offshore lifting operations, the dynamic system always experiences changes imposed by an external action. For example, a winch is required to slew the crane, to lower a payload or to move the vessel to a new position. By taking the installation of a topside module as an example, an imposed winch speed makes the lowering process non-stationary. As a result, the statistical properties of the position of the topside module vary with time. Thus, imposed changes on a system under stationary wave conditions can make the output of the system a non-stationary process, see the responses of the dynamic system (d) in Table 4.1. If the imposed changes significantly affect the dynamic properties of the system (e.g., natural periods), the system is time-variant. In general, offshore lifting and lowering operations need to be solved in the time domain even if the system is weakly non-linear. However, if the the winch speed is applied very slowly, so that the dynamic properties of the system do not change significantly and the system is weakly non-linear, the operations can be studied using stationary process TD simulations (condition when the system has reached the steady state). Imposed changes such as winch speed, can be added separately to the time histories of the dynamic response. This method is addressed below.

4.2.3 Methodologies for analysis of lift-off and mating operations

As it was stated earlier, it is important to develop efficient methodologies that allow a quick assessment of the dynamic responses. In this subsection, two methodologies: one for lift-off and landing, and another one for mating operations are addressed. These methodologies are general and relevant for OWT installation activities.

4.2.3.1 Lift-off and landing operations using floating heavy lift vessels

In offshore installation, most of the dynamic systems have time-variant dynamic properties. As stated earlier, external actions (e.g., winch speed) change the state of a dynamic response. In these cases, the system dynamic properties are greatly influenced by these external actions, so the dynamic responses need to be assessed by simulating the actual operations. In contrast, there are systems in which these changes happen so slowly that they can be analyzed by applying stationary process TD simulations.

Systems with time-invariant dynamic properties

The numerical methods given here are suitable for dynamic systems on which a change has been imposed (e.g. winch speed) on the dynamic response computed from a system in steady state condition, and the dynamic properties of the system are not significantly affected.

It has been shown that limiting (response) parameters such as snap and landing velocities are suitable for characterizing lift-off and landing operations (Det Norske Veritas, 2011b; Guachamin Acero et al., 2016b,c). This is because these parameters are directly related to the snap and impact forces. A suitable numerical method (collision method) for assessment of the first snap or impact velocities was proposed by Sandvik (2012). This method was originally developed by Fylling (1994) where it was applied to estimate collision velocities of drifting ships. Guachamin Acero et al. (2016b) (*paper 4*) applied the method for assessment of the landing and wire snap velocities during a TP installation onto a MP foundation.

Figure 4.1 shows the basis for estimating impact velocities. It requires TD histories of the relative displacement z_{rel} and velocity v_{rel} of the mating points (from coupled models and stationary process TD simulations). The lowering speed is imposed into the relative displacement time history, and only points having a negative relative displacement (z_{imp}) are considered, see Fig. 4.1 (a) red color points. The corresponding velocities v_{imp} without winch speed are shown in Fig. 4.1 (b).

Note that snap loads can occur after landing of the structure if the crane tip is moving upwards and the slack length of the wire is short. This is possible when the distance paid-out by the crane wire is smaller than the displacement of the crane tip. Figure 4.1 (a) shows the points z_{snap} complying with this condition (black color). The snap velocities v_{snap} (without including winch speed) are shown in Fig. 4.1 (b). For lift-off operations, the same reasoning is applied. The winch has to pay-in and the crane tip has to move upwards. The total snap velocity is the sum of a characteristic value of the dynamic snap velocity and the winch speed.

Because lift-off and landing activities last only a few minutes, the time history of the velocity can be divided into several short duration intervals. Then, extreme value response statistics and distributions can be established.

The number of samples should ensure that statistical properties such as mean value and standard deviation have converged. Based on the extreme value response statistics or distributions, a characteristic (response) value corresponding to a target probability of non-exceedance or percentile is selected. This target probability depends on the type of operation and associated failure events, see Sec. 2.5. This numerical method has been applied to identify heave impact and snap velocities during the TP installation, see Subsec. 5.3.2.3.

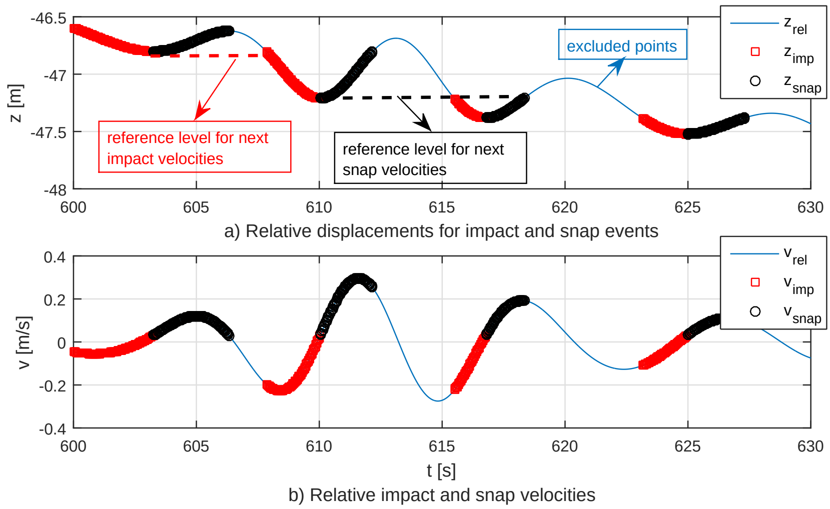


Figure 4.1: Determination of impact and snap velocities based on TP bottom tip displacement and velocity TD histories. (a) TP bottom tip relative heave displacements (respect to the crane tip) for constant lowering speed; (b) Possible impact and snap velocities (no winch speed included) (Guachamin Acero et al., 2016b)

Systems with time-variant dynamic properties

During installation of OWT components, the MP, TP and tower structures may not be considered to be light weight, because the installation vessels are normally smaller than the ones used for the oil and gas industry and their responses can be affected. If this is the case, lift-off operations need to be analyzed by imposing the winch speed in the equations of motion and solving them in the time domain. In other words, it is necessary to model the actual operations. Typical examples are the lift-off of a module from a cargo barge and the mating of heavy topside modules. In these activities, the dynamic properties of the structures are different before, during and after the load transfer. In addition to the non-linear system, changes in stability parameters may occur, and these effects need to be included. Thus, several TD simulations of the actual operations using random seeds are required for assessing extreme value distributions, and thus, estimating characteristic values, see Sec. 2.5.

4.2.3.2 Mating operations

Mating operations are standard activities within the oil and gas, and wind energy industries. Mating requires a docking pin to be inserted into a female receptacle or docking cone. The available mating gap is given by the annular space between the mating structures. The current practice is to calculate the significant or 3-hour maximum responses by applying stationary process TD simulations. Then, these response parameters are compared with the allowable mating gap to decide whether a sea state is acceptable or not. However, the actual monitoring phase prior to mating operations only lasts a few minutes and the surge and sway motions are correlated. A practical criterion to decide whether or not a mating operation is possible was proposed by Guachamin Acero et al. (2015) (*paper 3*). This method is based on the number of crossings that a mating pin is allowed to cross circular boundary of radius r in a time interval. This criterion is practical and has been adopted in this thesis. Furthermore, the magnitude of the mating gaps and allowable crossing rates depend on how well the structures are aligned and the criterion of the operators. These are sources of uncertainties that are not addressed in this thesis, but are discussed in Sec. 2.5.

The numerical solution for the crossing rate is obtained from spectral analyses of response parameters that are computed by applying the frequency domain method. An alternative solution has also been proposed by Low (2009) using another approach, and it was applied to a different problem. It was found that both 1^{st} and 2^{nd} order motion contributions of the TP should be included. Both contributions were assumed to be independent, so their covariance matrices can be added. By considering that the allowable crossing rates required for mating operations are relatively high (1 or 2 crossings per minute), the Gaussian approximation for the second order wave motions will provide acceptable results when compared with a more sophisticated method such as the time domain. The numerical solution is fast and accurate, which makes it suitable for quick assessment of the allowable sea states.

Out-crossing rate from a circular boundary

The limit state function defined by a circle could be written in the following form:

$$D(\boldsymbol{X}) = \left(\frac{x_1}{r}\right)^2 + \left(\frac{x_2}{r}\right)^2 = 1 \tag{4.3}$$

Where, x_1 and x_2 are the stochastic responses in surge and sway. Naess (1983) proposed a general methodology to evaluate the out-crossing rate of a vector process based on the properties of the conditional probability. This methodology was applied to equation (4.3) and the following solution was obtained (Guachamin Acero et al., 2015).

$$\nu_{S_D}^{+} = \int_{x_2} E\left(\dot{x}_n | \boldsymbol{X} = \boldsymbol{x}\right) f_{\boldsymbol{X}}\left(x_1 = f(x_2, d), x_2\right) |J| dx_2 \tag{4.4}$$

$$E\left(\dot{x}_n | \boldsymbol{X} = \boldsymbol{x}\right) = \int_0^{\infty} \dot{x}_n f_{\dot{X}_n} d\dot{x}_n = \sigma_{\dot{x}_n} exp\left[-\frac{1}{2}\left(\frac{m_{\dot{x}_n}}{\sigma_{\dot{x}_n}}\right)^2\right] + m_{\dot{x}_n} \Phi\left(\frac{m_{\dot{x}_n}}{\sigma_{\dot{x}_n}}\right) \tag{4.5}$$

$$J = \frac{2r}{\left[d - (x_2/r)^2\right]^{0.5}} \tag{4.6}$$

Expression (4.4) can be evaluated numerically, $\nu_{S_D}^{+}$ is the outcrossing rate, $|J|$ is the Jacobian of the transformation of x_1 in the bivariate probability density function (PDF), which needs to be evaluated for $d = 1$ following the definition of the limit state function, r is the radius of the circle, Φ is the Gaussian cumulative distribution function (CDF) and $\sigma_{\dot{x}_n}$ & $m_{\dot{x}_n}$ are the standard deviation and mean values of the normal velocities when solved for their conditional PDF. Alternatively, TD simulations of the stationary process can be applied. The numerical solution was applied for assessment of the allowable limits of sea states during the TP and OWT tower and RNA mating activities, see Subsecs. 5.3.2.1 and 5.4.3.

4.3 Numerical modeling of the MP initial hammering process

The (actual) MP driving and correction of the inclination require modeling of the following parameters: the hammer blow impact force, the hydrodynamic forces acting on the MP and HLV, the gripper contact forces, the soil-MP reaction forces and the correction forces. As stated in the installation procedure, the MP-gripper system moves in the horizontal plane due to the first and second order wave actions. The problem is simplified by assuming that the hammer blows do not affect the inclination of the MP and by decomposing the total gripper contact force into a dynamic part resulting from wave actions acting on the HLV-MP system, and MP inclination correction force required to bring the MP to a zero mean inclination. The dynamic component is obtained from global dynamic analysis while the correction force is calculated from quasi-static analyses (Li et al., 2016b) (*paper 2*).

The dynamic coupled models were built in the SIMO program (MARINTEK, 2012). The dynamic responses including the gripper contact force were studied by conducting stationary process TD simulations at 2 m stepwise incremental penetrations between 2 and 10 m. The coupled equation of motions were solved in the time domain for incremental steps of $1 \times 10^{-2}\, s$. The added mass and damping coefficients were calculated from WAMIT using the panel method and incorporated in the time domain via retardation functions. The external actions on the system are the first and second order wave forces. Coupling and mooring forces were included in the stiffness and damping matrices.

The hydraulic system of the gripper device was modeled using spring and damper elements. The spring coefficient for the MP-gripper contact elements $k_{grip} = 3 \times 10^7$ N/m was estimated based on guidelines given by Albers (2010) for typical hydraulic cylinder specifications (IHC Merwede, 2016). The damping coefficient was chosen as $b_{grip} = 0.2b_{cr}$. The elastic contact model is shown in Fig. 4.2 (a).

The soil-MP interaction of large diameter piles at shallow penetration depths is different from slender piles at large penetration depths. For the former one, it has been shown that the skin friction and base shear provide large contributions to the overall soil reaction forces (Byrne et al., 2015; Lesny and Wiemann, 2006). For the dynamic coupled system, the Winkler model was applied; therefore, the soil-MP interaction was modeled with non-linear springs and dampers. The contributions from the lateral load-deflection P-y, friction T-z, base shear F_{shear}, and MP end tip load-displacement Q-z curves were applied. These curves were derived based on recommendations given by the American Petroleum Institute (2000) for typical sandy soils. The spring-damper models are shown in Fig. 4.2 (b). Since the soil-MP skin friction was included, some elastic energy will be dissipated during the loading and unloading phases. An example of an hysteretic loop for MP inclination under cyclic loading is shown in Fig. 4.3. The hammer was modeled as a point mass on top of the monopile.

For the correction phase, quasi-static analyses of the correction force were conducted. This force is due to the intact soil reaction when moving the MP back to a zero mean inclination, and was calculated for the expected

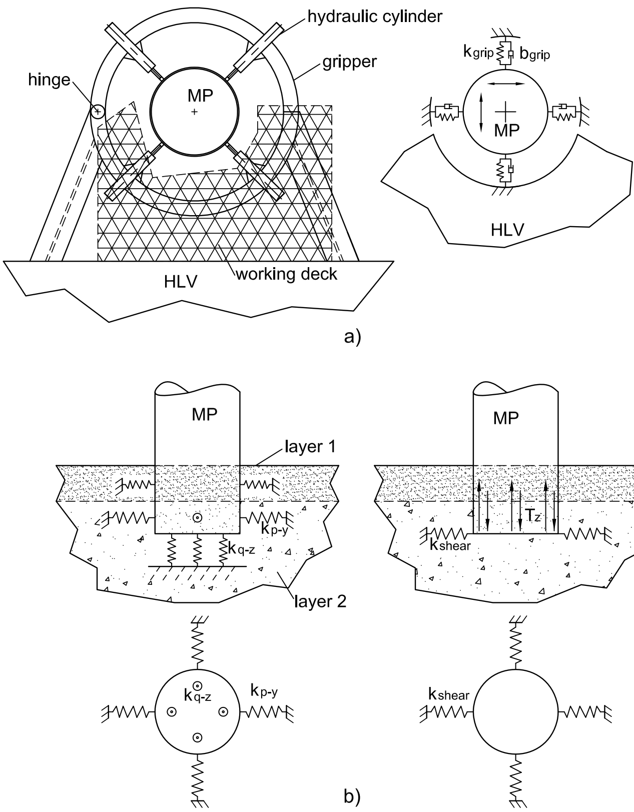


Figure 4.2: Spring-damper models. (a) Gripper-MP physical and contact models; (b) Soil-MP interaction model (Li et al., 2016b)

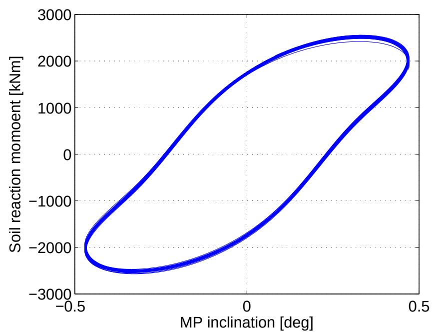


Figure 4.3: Typical soil reaction moment vs MP inclination due to cyclic loading with a period of 6 *s (Li et al., 2016b)*

maximum MP inclination (obtained from global response dynamic analysis) during a 10 min duration of the operation, which corresponds to the elapsed time between a correction phase and a hammering event. A schematic outline of a dynamic coupled model is shown in Fig. 4.4.

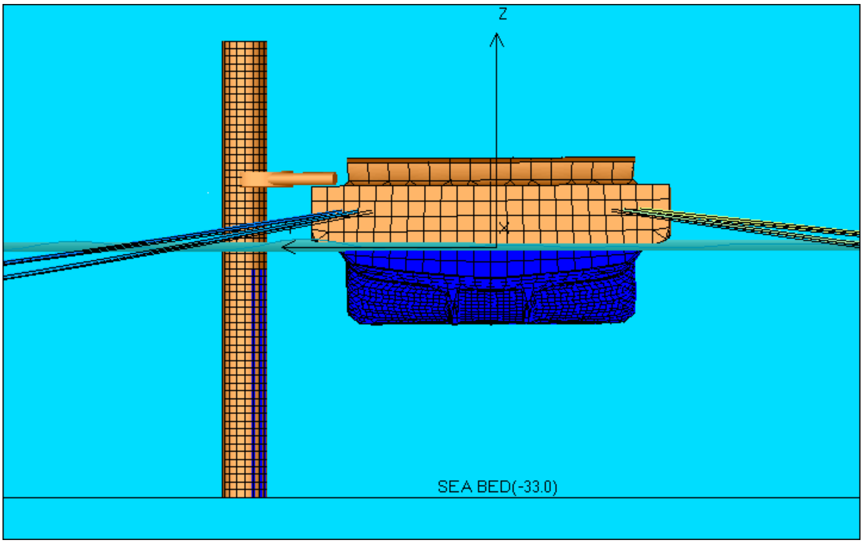


Figure 4.4: Schematic outline of a dynamic coupled model for the MP initial hammering process (Guachamin Acero et al., 2016d)

4.4 Numerical modeling of the TP mating operation

The TP mating operation is divided into several activities, which were modeled numerically according to the methodology proposed by Guachamin Acero et al. (2016b) (*paper 4*). A summary of the methodologies for numerical analysis of potential critical TP installation activities, numerical methods and modeling parameters that were used to model the various activities is given in Table 4.2. The dynamic coupled models were built in the AQWA suite of computer codes developed by Century Dynamics-Ansys Inc. (2011). A schematic outline of a dynamic coupled model is shown in Fig. 4.5. For analyses of TP installation activities using the TD method, a time step of 2×10^{-2} s was applied.

The potential critical installation activities provided in Table 4.2 are identified in Subsec. 5.3.1. A brief description of the numerical methods and elastic contact models used to model these activities is provided below.

Activity 1: The TP bottom tip motion monitoring phase is studied by applying the crossing rate method given in Subsec. 4.2.3.2. This is possible

Table 4.2: Numerical methods and modeling parameters for the TP mating activities (Guachamin Acero et al., 2016b)

No.	*Activity*	*Methodology*	*Numerical method*	*Modeling parameters*
1	Monitor TP's bottom motions prior to mating	Crossing rate method, Subsec. 4.2.3.2	FD	annular gap r = 0.30 m (Assumed)
2	Mating operation	Collision method, Subsec. 4.2.3.1	TD	winch lower. speed = 2 m/min, duration $\leq$ 1 min
3	Lowering	N. A.	TD	winch lower. speed = 2m/min, duration $\leq$ 5 min
4	Landing	Collision method, Subsec. 4.2.3.1	TD	winch lower. speed = 2m/min, duration $\leq$ 1 min

because the motion responses of the TP bottom tip are small and they are the result of a stationary process.

Activity 2: During the initial phase of the mating operation, axial and lateral impact of the finger guides can occur. The axial impact is studied by applying the collision method described in subsection 4.2.3.1. Note that in this method, the impact events are not modeled, and thus, only characteristic values of impact velocities can be assessed. The physical and contact models as well as the possible contact-impact points are shown in Fig. 4.6. The lateral impact was studied by applying stationary process TD simulations. The contact model shown in Fig. 4.7 was applied.

Activity 3: For analysis of the TP lowering phase, non-stationary process TD simulation were carried out. The elastic contact model shown in Fig. 4.7 was applied as well.

Activity 4: For the landing phase, the collision method given in subsection 4.2.3.1 was applied. For comparison, non-stationary process TD simulations were conducted, see Subsec 5.3.2.5. The physical and contact models are shown in Figure 4.8.

The rigging configuration was chosen according to Fig. 4.6 (a). The elastic wires and contact elements were modeled according to Table 4.3. Contact elements were required for non-linear global dynamic analyses of installation activities. The stiffness coefficient for the contact elements k_{con} was reasonably estimated based on the pile head load-displacement curves given by Hoit et al. (2007) and the T-z curves provided by the American Petroleum Institute (2000). For a pile with a diameter of 6 m and a penetration depth of 40 m in soft clay, the secant axial stiffness can be inferred

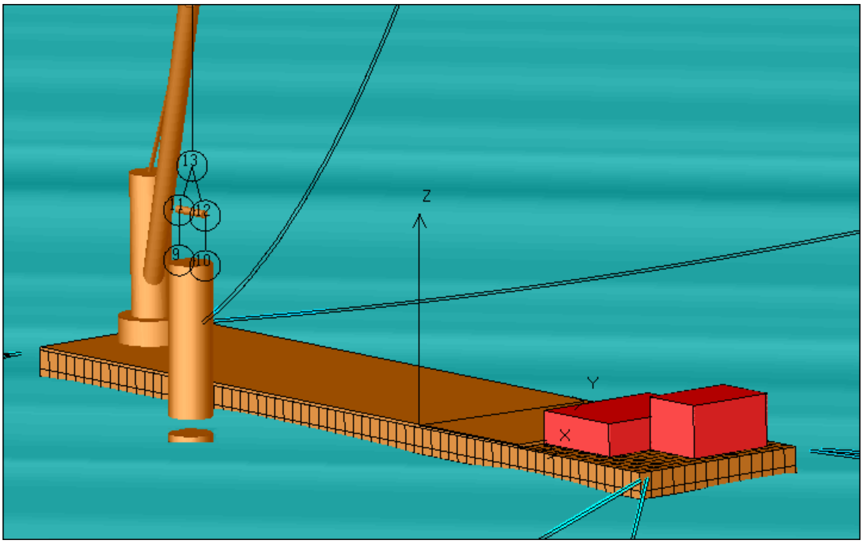


Figure 4.5: Schematic outline of a dynamic coupled model for TP landing (Guachamin Acero et al., 2016b)

to be approximately 3×10^4 kN/m for load levels of 6000 kN. For sandy soils it can be between 1 and 2×10^6 kN/m.

Table 4.3: Summary of spring and damper coefficients for numerical analyses of the TP installation activities (Guachamin Acero et al., 2016b)

Parameter	*Notation*	*Value*	*Units*	*Properties*	*Source*
Hoist wire rope stiffness	k_{wire}	3×10^4	kN/m	D=60mm, L=40m, N=4, MBL=3.5MN, E=210 GPa	$k_{wire} = N \times EA/L$, (Lankhorst ropes, 2015)
Wire rope sling stiffness	k_{sling}	5×10^4	kN/m	D=60mm, L=10m, N=1, MBL=3.5MN, E=210 GPa	
Contact elem. spring coeff.	k_{con}	1×10^5	kN/m		(American Petroleum Institute, 2000; Hoit et al., 2007)
Contact elem. damping coeff.	b_{con}	$0.05b_{cr}$	-		Assumed
TP surge, sway damping coeff.	$b_{11,22}$	$0.03b_{cr}$	-		Assumed

4.5 Numerical modeling of the OWT tower and RNA installation activities

Guachamin Acero et al. (2016c) (*paper 5*) provided modeling parameters

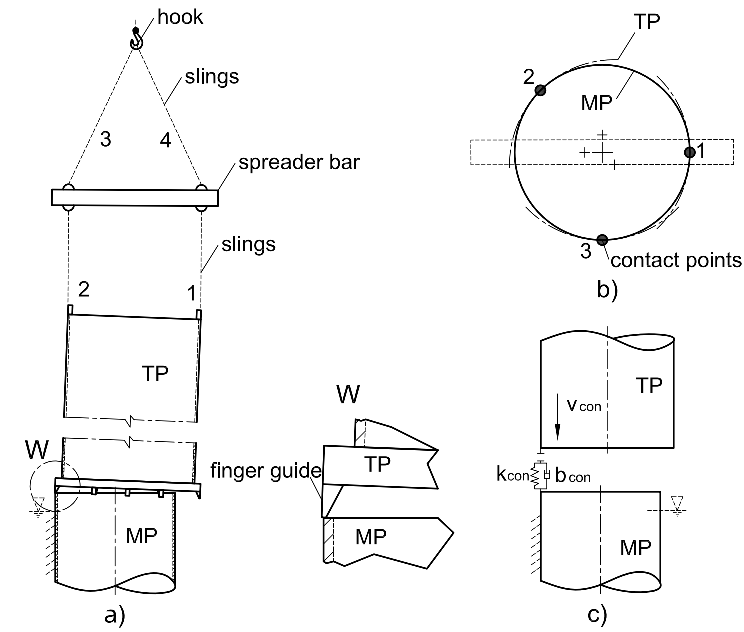


Figure 4.6: Models for TP-MP axial contact-impact prior to mating. (a) Physical model; (b) Contact points; (c) Spring-damper model (for Activity 2) (Guachamin Acero et al., 2016b)

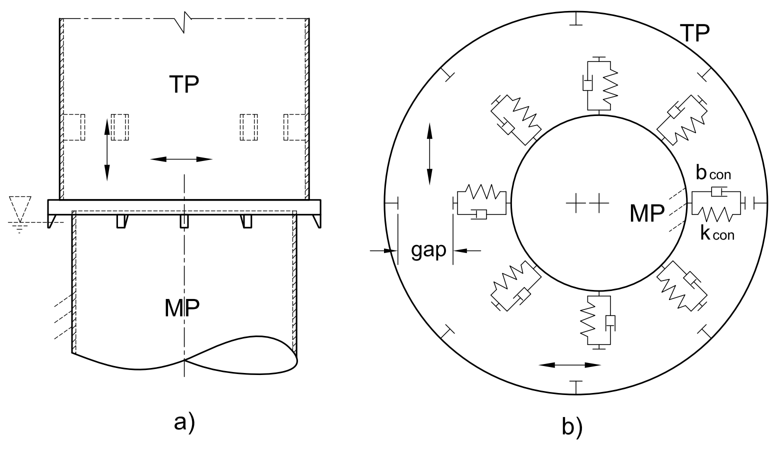


Figure 4.7: Lateral contact during TP mating operation (a) Physical model; (b) Spring-damper model (for Activities 2, 3) (Guachamin Acero et al., 2016b)

for the various installation activities. The entire installation procedure was

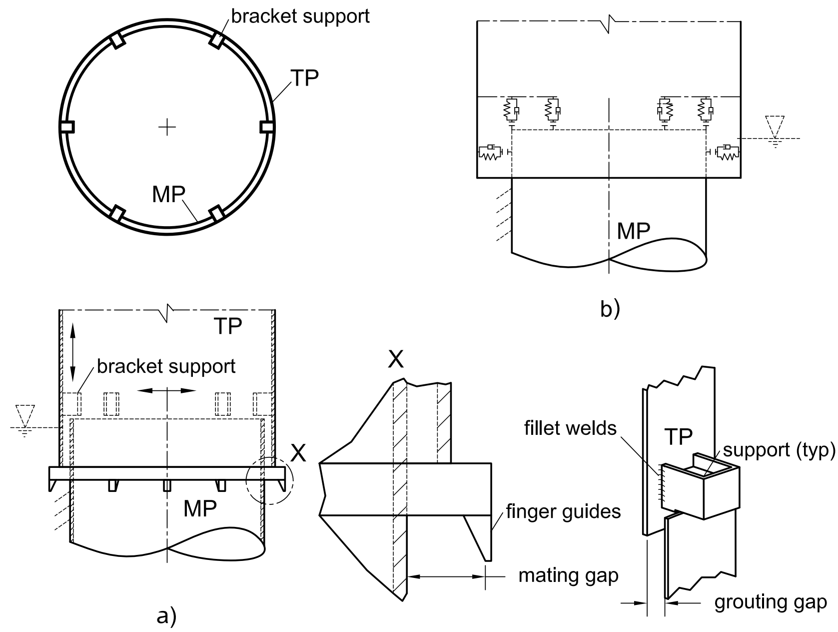


Figure 4.8: Contact-impact during TP landing (a) Physical model; (b) Spring-damper model (for Activity 4) (Guachamin Acero et al., 2016b)

divided into several potential critical activities, see Subsec. 5.4.1. This is normally done to facilitate the modeling of complex marine operations. The OWT tower and RNA installation activities are analyzed in the AQWA suite of computer codes. A summary of these activities, methodologies, numerical methods and some numerical modeling parameters are given in Table 4.4 and described in more detail below. A schematic outline of the dynamic coupled model during frame mating is shown in Fig. 4.9.

Activity 1: Prior to the lift-off operation, the total weight of the tower and the upending frame is taken by two saddle supports on the cargo barge, see Fig. 3.4 (b). These supports were modeled using springs and dampers to restrict vertical and lateral motions and rotations with respect to the cargo barge, see Fig. 4.10 (a). For the OWT tower lifting operation, a winch speed of 5 m/min was assumed. Once the lift-off operation is completed, the winch stops, the saddle support located at the bow of the cargo barge clears the tower, and the hinged saddle support located at the stern of the cargo barge is still loaded. The activity was simulated by applying the time domain method.

Activity 2: There exist a phase where the upending frame pins are aligned and the motions are monitored. This process is stationary, so the

Table 4.4: Activities, numerical methods and modeling parameters for the OWT tower and RNA installation (Guachamin Acero et al., 2016c)

No.	*Activity*	*Methodology*	*Numerical method*	*Modeling parameters*
1	OWT tower lift-off	N. A.	TD	hoist winch speed = 5 m/min, duration ≤ 1 min
2	Monitor upending frame bottom pin motions	Crossing rate method, Subsec. 4.2.3.2	FD	docking cone radius r = 0.35 m
3	Upending frame and foundation support mating	N. A.	TD	hoist winch speed = 5 m/min, duration ≤ 1 min
4	OWT upending	N. A.	TD	variable HLV forward speed ≤ 3 m/min, hoist winch speed = 3 m/min, duration ≤ 30 min

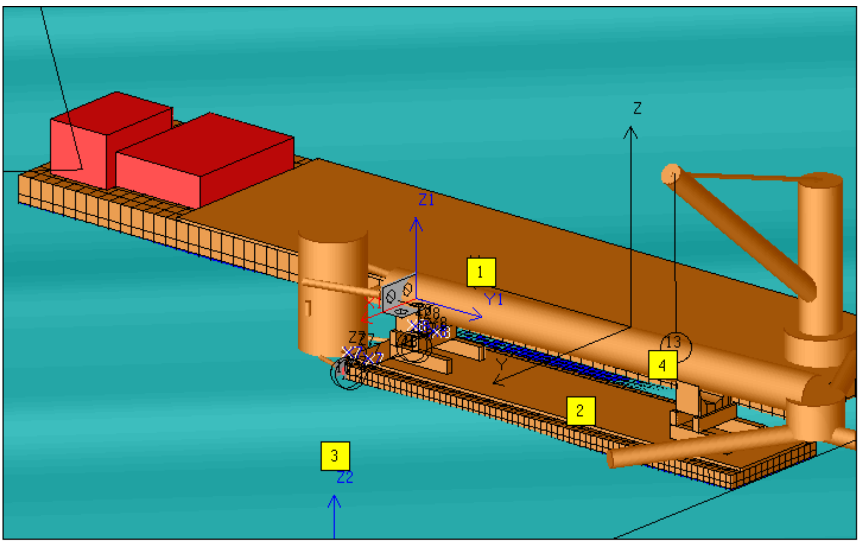


Figure 4.9: Schematic outline of a dynamic coupled model for the tower lift-off and upending frame mating operations (Guachamin Acero et al., 2016c)

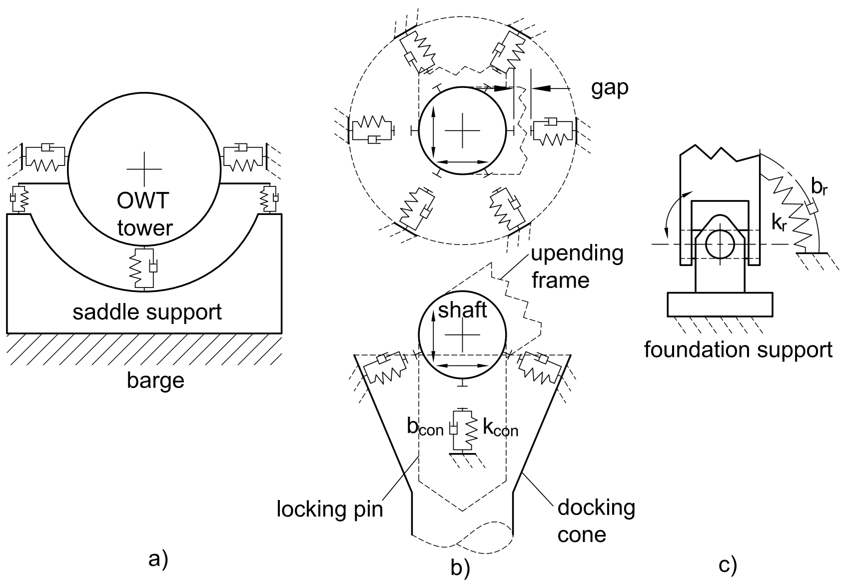


Figure 4.10: Elastic contact models. (a) OWT tower-cargo barge interaction model for lift-off and mating (Activities 1, 2 and 3); (b) Spring-damper model for the mating phase (Activity 3); (c) Tower upending articulation model (Activity 4) (Guachamin Acero et al., 2016c)

crossing rate method given in Subsec. 4.2.3.2 can be applied. Note that in this initial part of the mating phase, no impact of the foundation supports has occurred yet and part of the weight of the OWT tower is taken by the stern saddle support, see Fig. 3.3.

Activity 3: The HLV continues lifting the tower; a winch speed of 5 m/min is assumed. Consequently, mating between the upending frame bottom pins and the tripod supports occurs. The elastic contact model shown in Fig. 4.10 (b) was employed. This contact model is simply composed of a point (docking pin and shaft) which is allowed to dock into a receptacle modeled with conically arranged springs and dampers. This activity was simulated by applying the time domain method.

Activity 4: For the upending phase, a universal articulated joint is used to connect the upending frame and the supports on the foundation. The elastic model shown in Fig. 4.10 (c) was applied. A rotational spring is used to limit the roll responses of the OWT tower and to provide some flexibility to the system. This is necessary to reduce the magnitude of the hoist wire tension and the reaction forces on the foundation supports. This activity is studied by applying the time domain method.

For the lift-off and mating activities a time step of 1×10^{-3} s was applied, while for the upending activity a time equal to 5×10^{-2} s was used.

Table 4.5: Summary of spring and damper coefficients for the numerical analyses of the OWT and RNA installation activities (Guachamin Acero et al., 2016c)

Parameter	*Notation*	*Value*	*Units*	*Properties*	*Source*
Hoist wire rope stiffness	k_{wire}	5×10^4	kN/m	D=60mm, L=40m, N=8, MBL=3.5MN, E=210 GPa	$k_{wire} = N \times EA/L$, (Lankhorst ropes, 2015)
Contact elem. spring coeff.	k_{con}	7×10^4	kN/m		(Hamilton et al., 2008)
Universal joint spring coeff.	k_r	5×10^6	kNm/rad		Assumed
Contact elem. damping coeff.	b_{con}	$0.10 b_{cr}$	-		Assumed
Fender spring coeff.	k_{fen}	5×10^2	kN/m		Assumed
Barge-tripod mooring rope spring coeff.	k_{rope}	2×10^2	kN/m		Assumed

The properties of the wire ropes, contact elements, mooring ropes and fenders are shown in Table 4.5. The spring coefficient of the contact elements for the mating operation k_{con} is chosen based on specifications from equipment used in float-over operations (Hamilton et al., 2008). For a universal joint used to model the upending phase, the stiffness in the out-of plane direction k_r is estimated by assuming that a 250 kN horizontal force acting on the lifting point of the OWT causes a maximum static deflection of 1 deg.

Chapter 5

Assessment of the operational limits

5.1 General

The installation procedures for a MP foundation, a TP structure and a novel OWT and RNA concept were provided in Ch. 3. These procedures contain many sequential activities, some of which are critical for the installation and can lead to critical events. A critical event such as a structural failure of a rigging system can occur if the allowable limits (including safety factors) of the structural components are exceeded. This event can lead to catastrophic consequences, and thus, it has to be avoided. As stated earlier, the tension in the lifting wires is a parameter that limit a lifting operation. This parameter is suitable for taking mitigation actions during execution of the operation when the monitored tension reaches dangerous levels. However, the tension is not suitable for making a decision on whether to start or not the lifting operation because there is no tension to be measured. Thus, it is practical and convenient to express the "physical" limits such as wire tension in terms of allowable limits of sea state parameters or vessel responses in monitoring phases prior to execution, see Sec. 2.2.

In this chapter, the potential critical OWT installation activities, critical events, and corresponding limiting (response) parameters are identified. Numerical methods given in Sec. 4.2 together with numerical modeling aspects given in Secs. 4.3-4.5 are applied for quantitative assessment of the dynamic responses. A summary of this assessment is provided in this chapter and in more detail in the reference papers given in each section. By comparing the characteristic values of limiting (response) parameters and their allowable limits, the operational limits (in terms of allowable limits of sea states) of installation activities are provided. The general methodology developed by Guachamin Acero et al. (2016d) (*paper 1*) is applied, see Sec. 2.3.

5.2 MP initial hammering process

Li et al. (2016b) (*paper 2*) identified the critical events and limiting parameters, and proposed a methodology for assessment of the allowable limits of sea states. A summary of these results is provided in this section.

5.2.1 Identification of potential critical events and limiting parameters

Based on the installation procedure (for MP initial hammering) given in Ch. 3, a preliminary identification of critical events and corresponding limiting parameters follows:

Failure of the hydraulic system: The contact force on the gripper device may exceed the allowable limit of the hydraulic system. This force includes the dynamic component due to HLV-MP dynamic motions and the quasi-static mean MP inclination correction force. A hydraulic system failure event is critical because it can stop the operation and pollute the environment. The corresponding limiting parameter is the total gripper contact force. The allowable limit for the contact force was chosen as 491 kN, which corresponds to the allowable axial force (including a safety factor) for a hydraulic cylinder with a piston rod diameter of 140 mm and a maximum working pressure of 100 bar (IHC Merwede, 2016).

Insufficient thruster and mooring line correction force: The thrusters and mooring system are required to move the MP back to a zero mean inclination. If the capacity is insufficient, the MP inclination may not be corrected. The limiting parameter is the correction force. In this thesis, it was assumed that sufficient correction force is available.

Unacceptable MP inclination: At the end of the MP initial hammering process, the MP inclination can exceed its allowable limits, resulting in an unsuccessful MP installation. The event is not critical but restrictive and the limiting parameter is the MP inclination. An allowable limit of 0.5 deg was chosen. This limit is normally between 0.5 and 1 deg, so that shim plates can be used to level the TP. This is because the turbine tower inclination has to be less than 0.1 deg (Strandgaard and Vandenbulcke, 2002).

A summary of the potential critical events, limiting parameters and allowable limits is shown in Table 5.1.

Table 5.1: Potential critical events, limiting parameters and allowable limits for the MP initial hammering process

No.	*Critical event*	*Limiting parameter*	*Allowable limit*
1	Failure of hydraulic system	Gripper contact force	491 kN (IHC Merwede, 2016)
2	Insufficient mooring and thruster force	Correction force	Assumed sufficient in this thesis
3	Unacceptable MP inclination	MP inclination	0.5 deg (Strandgaard and Vandenbulcke, 2002)

5.2.2 Assessment of dynamic responses

Based on the numerical methods described in Ch. 4, dynamic analyses using stationary process TD simulations at various penetration depths were conducted. A quantitative assessment of the system dynamic responses (including the limiting parameters shown in Table 5.1), under typical sea states was carried out to identify response parameters that may reach dangerous levels. The sea states were modeled by applying the JONSWAP wave spectrum model provided by Det Norske Veritas (2010). Figure 5.1 shows that under typical installation sea states, the gripper contact force and the MP inclination can reach unacceptable levels, and thus, they are limiting parameters.

5.2.3 Assessment of the MP inclination correction force

As it was stated earlier, the total MP-gripper contact force has contributions from the dynamic force caused by HLV-MP coupled motions and wave actions, and the quasi-static force from the MP inclination correction phase. The correction force depends on the soil reaction, the mooring line tension, and the inclination of the MP (Li et al., 2016b). The maximum MP inclination is calculated as the expected maximum during a period of 10 min, which is an approximate duration between the hammering event and the correction phase of the MP inclination. The required force to bring the MP to zero mean inclination for a typical sandy soil is shown in Fig. 5.2.

5.2.4 Assessment of the allowable sea states for the MP initial hammering process

Figure 5.3 shows that characteristic values of the dynamic gripper contact force and MP inclination can be calculated for any sea state, while the MP inclination correction force can be estimated for any soil condition and

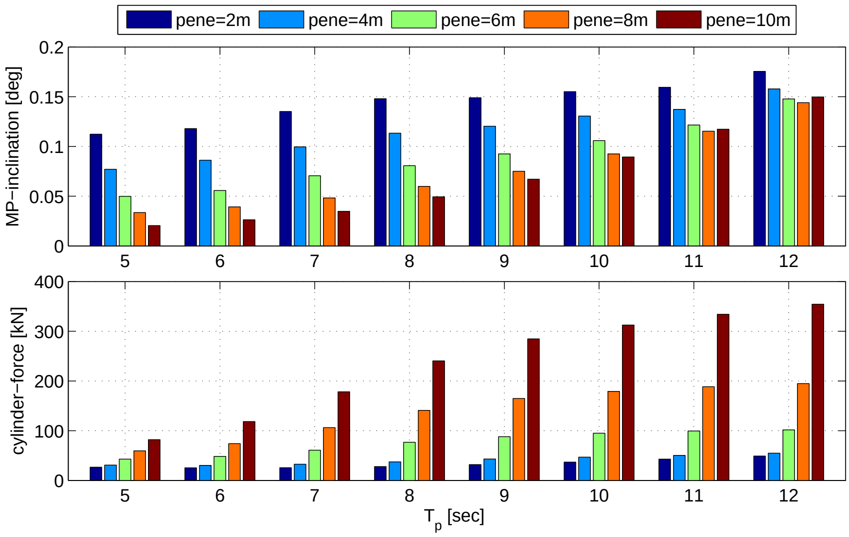


Figure 5.1: Standard deviation of MP inclinations and contact forces on one hydraulic cylinder at different MP penetration depths (pene) and wave condition from 3 hour time domain simulations, Hs= 1.5 m, wave dir= 150 deg (Li et al., 2016b)

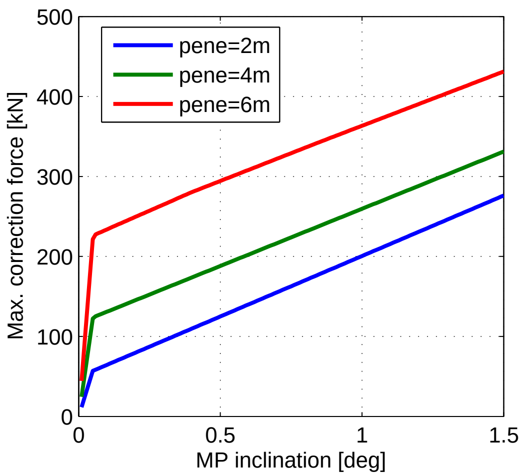


Figure 5.2: Correction force vs maximum inclination (over 10 min) of the MP for various penetration depths (pene) (Li et al., 2016b)

penetration depth, see Fig. 5.2. The characteristic values of the contact forces were calculated for an exceedance probability of 10^{-4} based on 3 hours stationary process TD simulations. This probability level was chosen based on the recommendation given by Det Norske Veritas (2011a) Sec. A 200. On the other hand, the characteristic value of the MP inclination is calculated by averaging the maximum inclination from several 10 min TD simulations. The expected maximum is assumed to be sufficient because the out-of-tolerance criterion for MP inclination does not lead to catastrophic consequences.

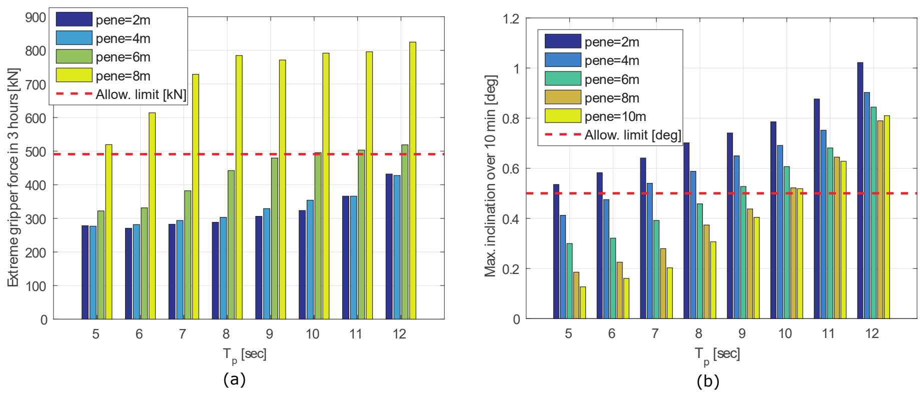


Figure 5.3: Allowable limits and extreme responses, Hs= 1.5 m, wave dir= 150 deg. (a) MP-gripper contact forces, exceedance probability 10^{-4} *based on* 3 *hours TD simulation; (b) MP inclination over 10 min simulations (Li et al., 2016b)*

Li et al. (2016b) (*paper 2*) developed a methodology to find the allowable limits of sea states for the MP initial hammering process. The methodology allows for combining both limiting parameters: MP inclination and gripper contact force. In addition, an extra parameter, i.e. a critical penetration depth d_{c1} at which the gripper can be released given the fact that the MP can stand alone in waves, was included. This critical penetration depth can be calculated following the guidelines given by American Petroleum Institute (2000) for any sea state, MP, and soil property. The methodology was applied for every possible Hs and Tp combination and some relevant headings, and thus, the allowable limits of sea states were established, see Fig. 5.4.

5.3 TP mating operation

After completion of the MP installation, if the weather conditions are acceptable, the TP lifting operations can begin. Among the various TP in-

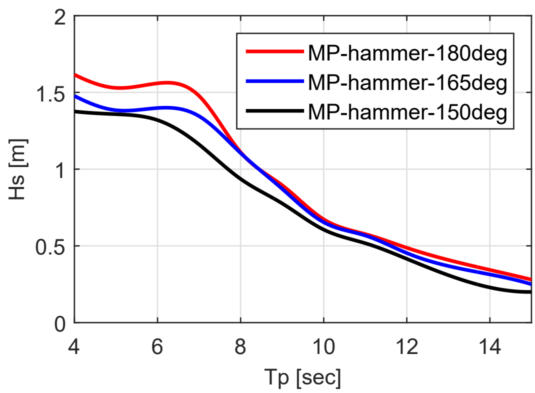


Figure 5.4: Allowable limits of sea states for the initial phase of the MP hammering process (Li et al., 2016b)

stallation activities, the TP docking (mating) is normally considered to be critical. Guachamin Acero et al. (2016b) (*paper 4*) identified the critical events and limiting parameters of the TP mating operation. These parameters were used to establish the allowable limits of sea states based on global dynamic analyses of the installation activities.

5.3.1 Identification of potential critical events and limiting parameters

A preliminary screening of the potential critical events and corresponding limiting parameters is shown in Table 5.2. Some possible criteria for setting the allowable limits are provided as well. For these activities, numerical analyses were performed by applying the methodologies and numerical methods proposed in Table 4.2. The results are summarized in the following subsections.

5.3.2 Assessment of dynamic responses for the TP mating activities

5.3.2.1 Motion monitoring phase prior to mating

This activity is not critical but restrictive for the TP mating operation. The purpose of this phase is to align the TP and decide whether or not the mating operation is possible. If the TP bottom tip motions are large, the mating operation cannot occur. The limiting parameter is chosen to be the rate of crossing of the TP bottom tip out of a circular boundary equivalent

Table 5.2: Potential critical events, limiting parameters and allowable limits for the mating operation of a TP onto a MP foundation (Guachamin Acero et al., 2016b)

No.	*Activity*	*Sub-activities*	*Critical event*	*Limiting parameter*	*Allowable limit*
1	Motion monitoring	Align TP, Monitor TP bottom tip motions	Failed mating attempt	Crossing rate of a circular boundary	1-2 crossings per minute. Assumed
			Structural damage	Impact velocity	Not available
2	TP-MP mating	Lower TP (winch at constant speed), TP initial mating phase occurs	Structural damage of finger guides	Impact velocity	Not available
			Structural failure of the rigging system	Wire tension	DAF= 1.3, crane capacity (Det Norske Veritas, 2011b)
3	TP lowering	Lower TP, monitor wire tension, correct TP heading	Structural failure of the rigging system	Wire tension	DAF= 1.3, crane capacity
			TP gets stuck	Friction force	TP inclination
4	TP landing	Lower TP, slack lifting wires	Structural failure of the TP bracket supports	Heave impact velocity	approx. 0.14 m/s, see Subsec. 5.3.2.5
			Structural failure of the rigging system	Snap load	DAF= 1.3, crane capacity

to the TP and MP annular gap. This criterion is practical and convenient for planning of mating operations.

The numerical analysis methodology given in Subsec. 4.2.3.2 is used to calculate the rate of crossing for all possible Hs and Tp combinations. An annular gap of 0.3 m and an allowable limit of the crossing rate $\nu^+_{allow} =$ 0.0167 Hz (i.e. 1 outcrossing per minute) were assumed. The method is efficient because the problem is solved in the frequency domain. For typical installation headings, the allowable limits of sea states are provided in Fig. 5.5.

5.3.2.2 Typical installation sea states for numerical analysis of TP mating activities

To identify the limiting parameters of the subsequent mating activities, typical installation sea states are needed. The allowable limits of sea states of the motion monitoring phase (see Fig. 5.5) are assumed to be representative for these operations, and they are provided in Table 5.3.

The potential critical events and limiting parameters listed in Table 5.2 were assessed quantitatively by applying the numerical methods proposed

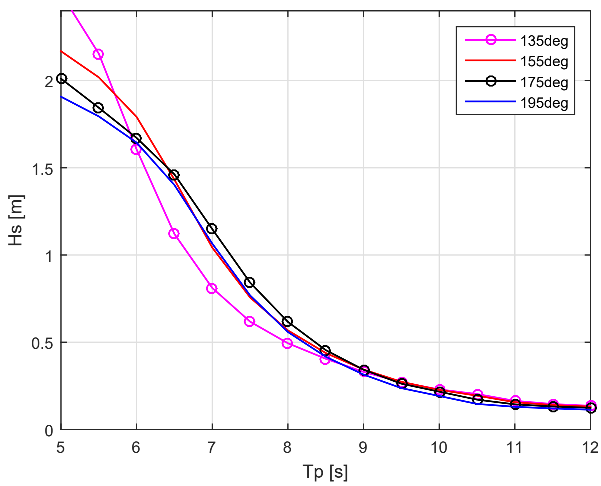


Figure 5.5: Allowable limits of sea states for the monitoring phase of the TP's bottom tip. Limiting parameter: TP's bottom tip motions, allowable crossing rate limit: $\nu^{+}_{allow} = 0.0167$ Hz and mating gap: $r = 0.3$ m (Guachamin Acero et al., 2016b)

Table 5.3: Typical sea states for analysis of subsequent mating activities

Parameter	*Units*	Values			
Hs	[m]	1.6	0.81	0.49	0.35
Tp	[s]	6.0	7.0	8.0	9.0

in Table 4.2, the results are shown below.

5.3.2.3 Axial impact between the finger guides and the MP tip

If the motions of the TP bottom tip in the monitoring phase are acceptable, the decision to lower the TP and execute the mating operation is made. The possible axial impact between the TP finger guides (see Fig. 4.6) and the tip of the MP was investigated. The characteristic heave impact velocity was computed by applying the collision method described in Subsec. 4.2.3.1 for typical installation sea states given in Table 5.3. Some statistical parameters of this axial impact velocity are shown in Fig. 5.6. The expected maximum impact velocity including the winch speed is approximately 0.14 m/s, and was obtained after averaging the maximum value over several 5 min interval time histories.

The dynamic effect of these possible impact events on the sling and wire

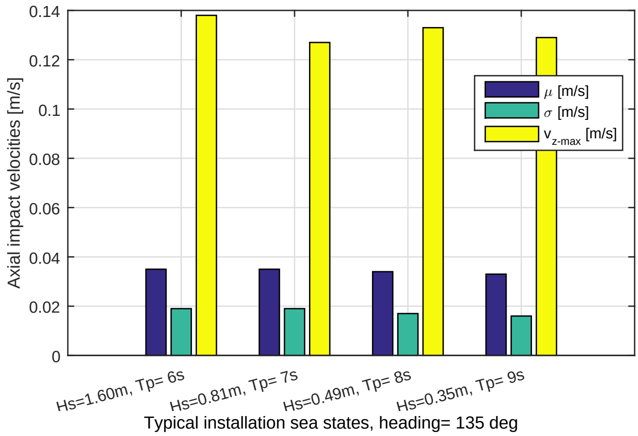


Figure 5.6: Response statistics of the axial impact velocities prior to the mating phase (Guachamin Acero et al., 2016b). Based on the collision approach method (Sandvik, 2012)

ropes was also investigated. This is done by applying a regular wave with an amplitude of 1 m and a period of 7 s for a wave direction of 135 deg. This wave condition was chosen because it produces a similar maximum amplitude of the TP bottom tip heave velocity. This was not done to replace the stochastic irregular waves with a regular wave, but to conveniently study the dynamic effects due to impact events on the system responses. A realistic winch speed of $v_{winch} = 2$ m/min was chosen. It was found that during and after impact, the tension in the slings decreases and no slack lines occur. Therefore no critical events were identified in this installation phase (Guachamin Acero et al., 2016b).

5.3.2.4 Lateral impact between the finger guides and the MP outer wall

During the initial phase of the MP-TP mating activity, stationary process TD simulations were carried out to study the dynamic effects on the slings. The sea states given in Table 5.3 were applied to the system using the contact models shown in Fig. 4.7. It was found that the dynamic amplification factor was always below 1.3 and no slack lines were observed. Thus, no critical events are identified in this phase (Guachamin Acero et al., 2016b).

5.3.2.5 Lowering and landing of the TP structure

Based on Fig. 5.6, the expected maximum axial impact velocity was approximately 0.14 m/s. This is also a characteristic value of the landing velocity, and thus, it can be used to assess the impact force and the stress in the TP bracket connections.

Since impact events occur at low speeds (quasi-statically), equation (5.1) can be applied (Det Norske Veritas, 2011b; Hamilton and Ramzan, 1991). The parameters $F_{imp-snap}$ and $v_{imp-snap}$ are the snap force and velocity, k_{con} is the stiffness of the contact elements, and M is the impact contributing mass. Assuming that the spring coefficient for a typical sandy soil is approximately 1×10^6 kN/m (see Sec. 4.3), the maximum impact force is $F_{z-max} = 1.95 \times 10^3$ kN, which is large when compared with the static weight of the TP, which is 2×10^3 kN (see Table 3.2). Additionally, it is reasonable to assume that only one bracket support can take the initial impact load. For the case of a TP's bracket with fillet welds (see Fig. 4.8) having a length of 25 cm and width of 2.5 cm, the shear stress is 167 MPa, while the allowable shear strength for a mild steel is approximately 125 MPa. Based on these results and assumptions, it can be stated that structural failure of the bracket supports may constitute a critical event and its limiting parameter is the axial impact velocity. Moreover, the TP mating can be attempted at a higher lowering speed and sea states; especially when a motion compensation system and larger mating gaps are employed. Thus, larger impact forces than the ones predicted above can occur.

$$F_{imp-snap} = v_{imp-snap} \sqrt{k_{con} M} \tag{5.1}$$

The TP lowering and landing activities have also been investigated by TD analysis of the non-stationary lowering process. An example of dynamic response time histories is shown in Fig. 5.7, where it is observed that a wire rope failure event is unlikely to occur. Moreover, response statistics confirmed that the expected maximum landing impact velocity is approximately 0.14 m/s (Guachamin Acero et al., 2016b).

5.3.3 Assessment of the allowable sea states for the TP mating operation

Based on the results provided in the previous subsections, the TP installation is governed by the motion monitoring and the landing phases. The limiting (response) parameters are the crossing rate of the TP's bottom tip out of an annular mating gap and the landing velocity in heave. The characteristic values of the limiting parameters were assessed based on crossing

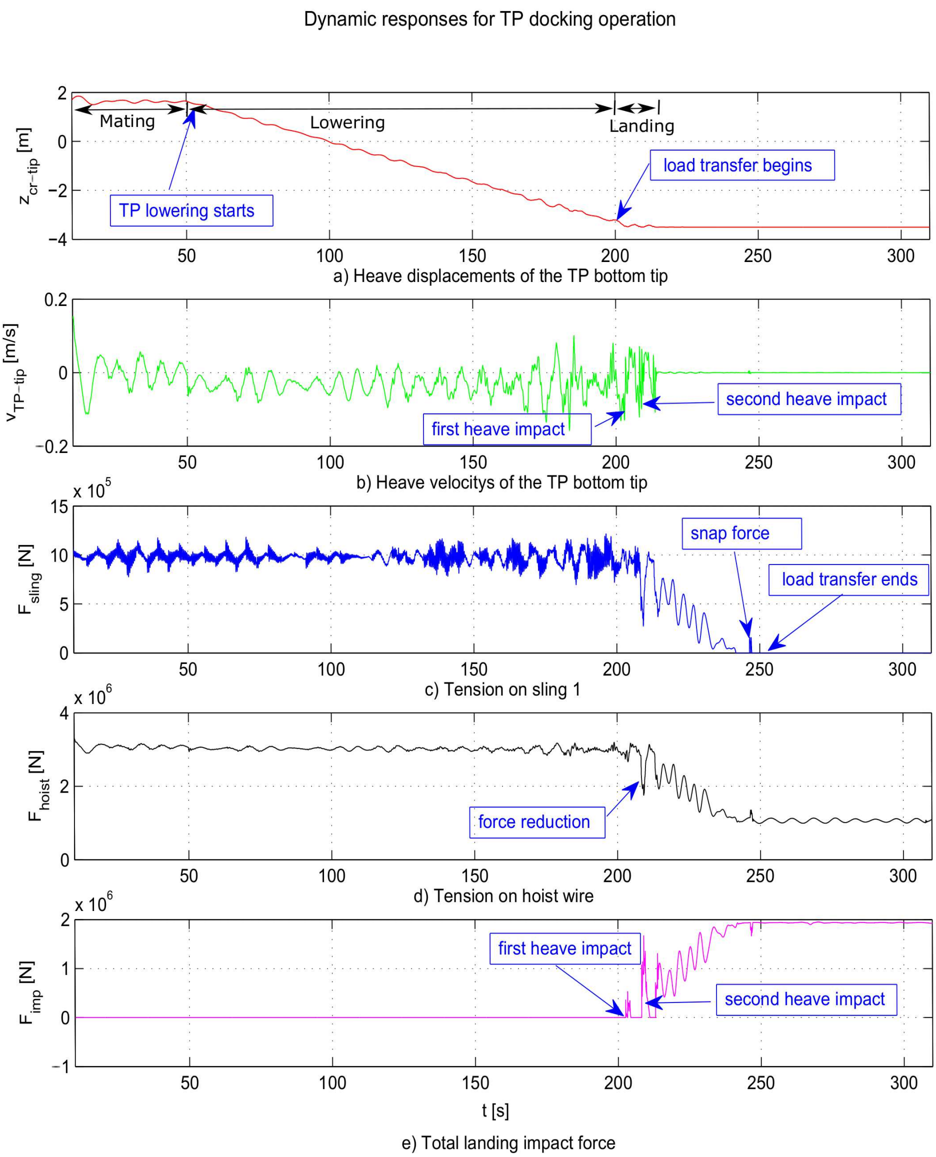


Figure 5.7: Example of dynamic responses from TD simulations of the lowering and landing phases. $Hs = 1.60$ *m,* $Tp = 6$ *s,* $\alpha = 135$ *deg (Guachamin Acero et al., 2016b)*

rates and extreme value response statistics. This was carried out for all possible Hs and Tp combinations by applying the numerical methods proposed in Table 4.2. Figure 5.8 shows examples of allowable limits of sea states for various limiting parameters and typical installation headings. The operational limits for the complete TP mating operation can be obtained by taking the lower envelope of the allowable limits of sea states.

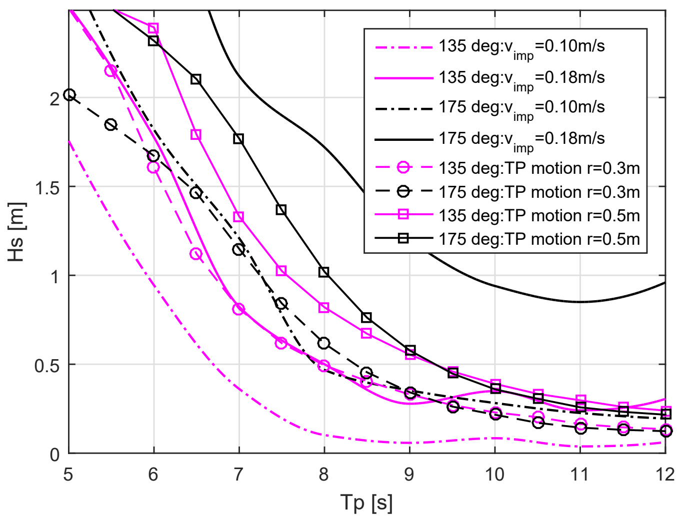


Figure 5.8: Allowable limits of sea states for TP-MP mating. Assumed allowable limit for the motion monitoring phase: crossing rate $\nu^+_{allow} = 0.0167$ *Hz for* $r = (0.3, 0.5)$ *m, arbitrary allowable limits for the landing phase:* $v_{imp} = (0.10, 0.18)$ *m/s (Guachamin Acero et al., 2016b)*

5.4 Tower and RNA installation

For the analysis of offshore wind turbine tower and RNA installation activities, the novel concept developed by Guachamin Acero et al. (2016c) was considered. This section deals with the identification of critical events and corresponding limiting parameters, and assessment of the operational limits for the various installation activities. Furthermore, response statistics and a sensitivity study on key modeling parameters are provided.

5.4.1 Identification of potential critical events and limiting parameters

Based on the installation procedure, the potential critical events and parameters limiting the operation were identified in a root cause diagram (Guachamin Acero et al., 2016c). A summary of potential critical installation activities and corresponding events is given in Table 5.4. A quantitative

Table 5.4: Potential critical installation activities and corresponding events considered for TD simulations

Activity	*Description*	*Critical events*	*Limiting parameter*	*Allowable limit*
1	Lift-off the OWT tower	Hoist wire breakage	Wire tension or crane capacity	5000 kN, see Subsec. 5.4.3
2	Mating of the upending frame bottom pins and foundation supports	Failed mating attempt, structural damage of the docking cones and pins	Allowable rate of crossing out of a circular boundary, allowable impact velocity	1-2 crossings per minute (assumed), r= 0.35 m, see Subsec. 5.4.3
3	OWT tower upending operation	Hoist wire breakage, structural failure of the pinned supports, and unacceptable OWT inclination	Allowable tension, reaction forces and inclination	5000 kN, Not available

assessment of the dynamic responses of the installation activities under typical installation sea states is provided below.

5.4.2 Assessment of dynamic responses for the OWT tower and RNA installation activities

5.4.2.1 Lift-off the OWT tower and RNA assembly

For a loading condition corresponding to Fig. 3.4 (b), a dynamic coupled model was built based on the structure's specifications given in Tables 3.3 and 4.5. The numerical methods and modeling parameters were selected according to Table 4.4. Figure 5.9 shows that snap loads on the hoist wire (at the beginning of the load transfer) will occur, and their magnitudes can be on the order of the mean tension after the load transfer. They can cause structural failure of crane or the rigging system, and thus, the tension is a limiting parameter.

5.4.2.2 Mating between the upending frame bottom pins and the foundation supports

Figure 3.3 shows a loading condition for this installation phase. The numerical methods and modeling parameters given in Tables 4.4 and 4.5 were applied. Figure 5.10 shows the impact forces on the tripod supports during the mating phase. They occur due to large initial impact velocities, which are caused by the first-order motions of the cargo barge, the crane tip motions, and the hoist winch speed. It is observed that the impact forces can be larger than the static weight of the tower, and thus, can cause

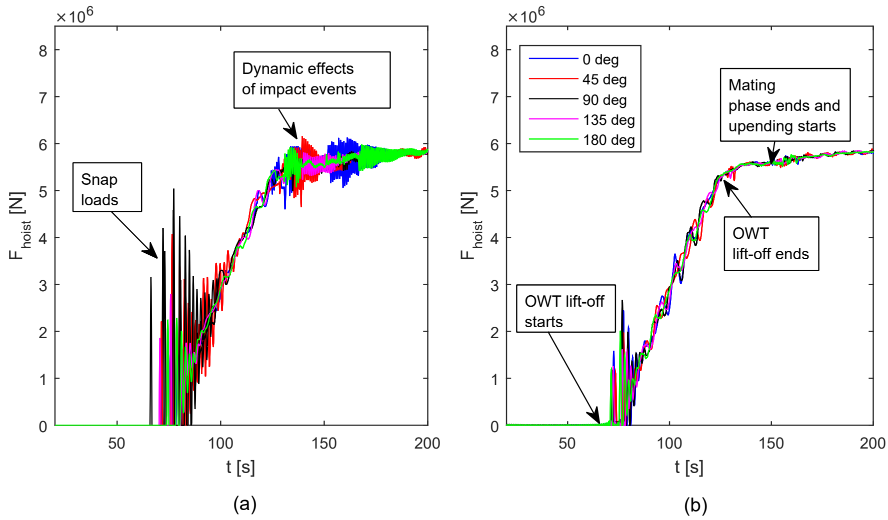


Figure 5.9: Hoist wire tension during tower lift-off. (a) Hs=1 m, Tp=8 s; (b) Hs=1 m, Tp=6 s (Guachamin Acero et al., 2016c)

local structural damage to the mating structural components shown in Fig. 3.4 detail V. The consequences can be delays in the project, and thus, the impact force is a limiting parameter.

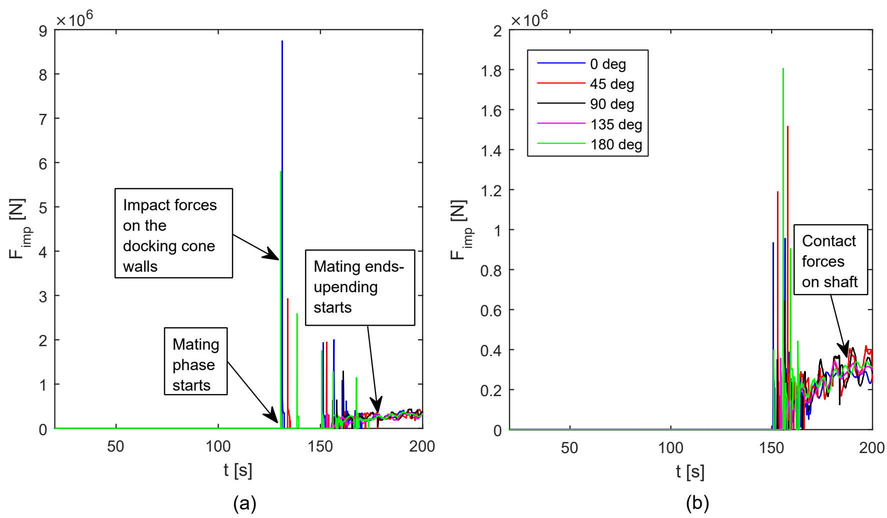


Figure 5.10: Impact forces on the foundation supports during the mating phase. (a) Hs=1 m, Tp=8 s; (b) Hs=1 m, Tp=6 s (Guachamin Acero et al., 2016c)

Based on the results shown in Figs. 5.9 and 5.10, it is observed that there is a time interval between the lift-off and mating phases (at approximately 120 s) in which no impact between the upending frame bottom pins and tripod supports has occurred yet. During this “initial mating phase”, there is a “restrictive” event (not critical), which is a failed mating attempt that occurs when the motions of the pins (limiting parameter) are too large. Moreover, the mating operation can be tried again if the motions of the pin are still acceptable.

5.4.2.3 Upending of the OWT tower and RNA assembly

Another dynamic coupled model was employed for numerical simulation of the upending of the OWT tower and RNA assembly. The loading condition corresponds to Fig. 3.4 (c). It starts when the mating operation is completed and ends when the OWT is in the upright position. Table 4.4 shows some parameters used to model the activity. The time histories of some relevant dynamic responses are shown in Fig. 5.11. It is observed that the reaction moments and inclination of the tower increase in the final upending stage, when the crane tip motions are large and the hoist wire shortens. A potential critical event is the structural failure of the hinged connection between the upending frame bottom pins and the foundation supports. The corresponding limiting parameter is the reaction out-of-plane bending moment. A restrictive event is the failed mating attempt of the OWT in the final upending stage. This occurs as consequence of the excessive inclination of the OWT which is the limiting parameter.

5.4.3 Assessment of the allowable sea states for the OWT tower and RNA installation

Guachamin Acero et al. (2016a) (*paper6*) assessed the allowable limits of sea states based on two limiting parameters. For the lift-off and initial mating phases, the wire tension and rate of crossing out of a circular boundary that the upending frame bottom pin performs with respect to the docking cones were considered. These two parameters were selected because their allowable limits can be reasonably estimated.

For the lift-off activity, the capacity of the HLV’s crane is assumed to be at least $7000\,kN$, so that, an allowable limit $F_{snap} = 5000$ kN (including a safety factor) for the snap force is considered. Based on the results shown in Fig. 5.9, it is observed that this limit is reasonable due to the uncertainty and large variation of the snap forces before the load transfer. It can be seen as if a larger safety factor is applied to the crane capacity before the

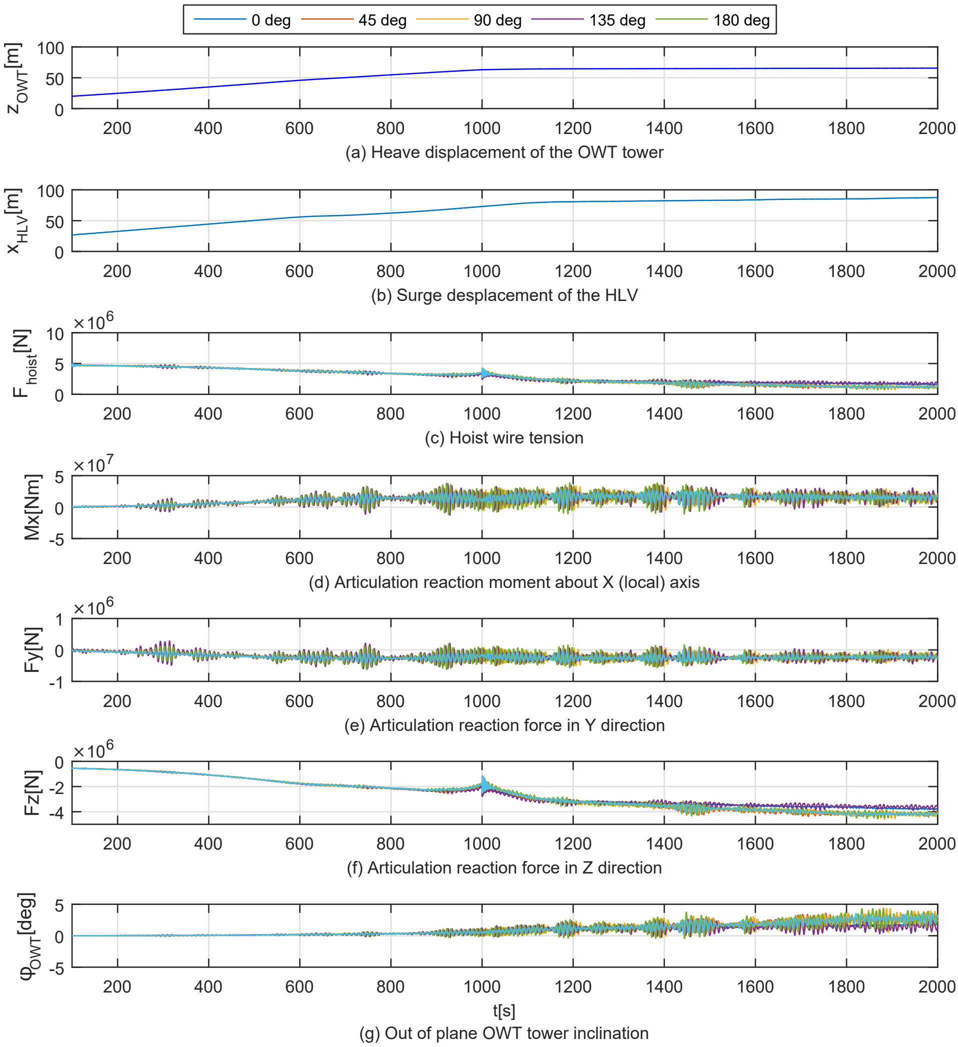


Figure 5.11: Dynamic responses during the OWT upending operation. PM wave spectrum Hs=1 m, Tp=8 s (Guachamin Acero et al., 2016c)

load transfer than after the load transfer, where the variation of the total tension is small.

Non-stationary process TD simulations were conducted. “All possible” combinations of Hs and Tp were considered, and a total of 60 seeds for each sea state were applied. The number of seeds was chosen to achieve convergence on the response statistics of the snap force. The maximum snap force of every 3 min time domain simulation was used to compute response statistics and fit the maxima to a Gumbel extreme value distribution. From this distribution, the characteristic value corresponding to a non-exceedance probability of 0.995 was selected. By comparing this characteristic value with the allowable limit of the snap force, the operational limits were established, see Fig. 5.12. The operational limits for a heading of 120 deg and an allowable tension of 7000 kN are provided as well.

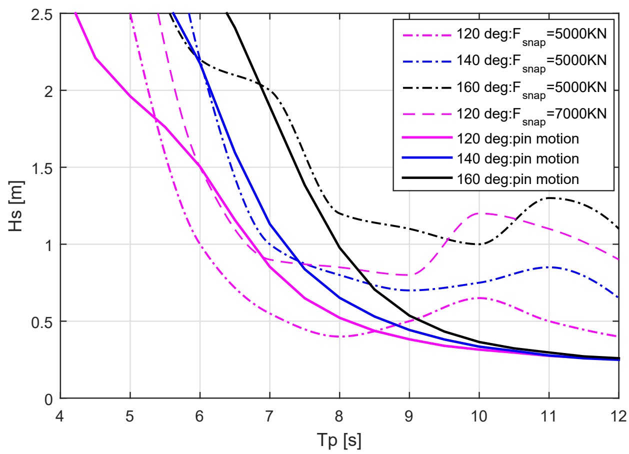


Figure 5.12: Allowable limits of sea states for the lift-off and mating operations, allowable limits: $F_{snap} = 5000\&7000$ *kN (Number of seeds= 60, simulations duration* ≤ 1 *min), pin motion (*$\nu^+ = 0.0167$ *Hz,* $r = 0.35$ *m) (Guachamin Acero et al., 2016a)*

Figure 5.13 (a) shows that approximately 45 seeds were necessary to achieve convergence on the response statistics (Guachamin Acero et al., 2016a). For the allowable limits of sea states given in Fig. 5.12, the response statistics of the snap forces are illustrated in Fig. 5.13 (b). It is verified that the maximum snap forces are in agreement with the allowable tension (5000 kN).

For the initial mating phase, a docking cone radius $r = 0.35$ m for the foundation support is assumed. The allowable limit can be expressed in terms of the rate of crossing of the upending frame bottom pin out of the docking cone radius, see the structural components in Fig. 3.4 detail V. A reasonable assumption is that the mating operation is possible if this crossing rate is less than one time per minute, i.e. $\nu^+ = 0.0167$ Hz. Based on this criterion, the allowable sea states can be established by applying the numerical solution proposed by Guachamin Acero et al. (2015), which is based on the frequency domain method and spectral analyses. The results are also shown in Fig. 5.12.

Note that there is a monitoring phase "prior" to the entire installation of the OWT tower and RNA. This phase is important to make a decision on whether to start or not the lifting operation. The allowable limits of sea states from Fig. 5.12 can be used to compute allowable limits of upending frame bottom pin motions for the monitoring phase prior to the lifting operation. For the monitoring phase loading condition shown in Fig. 3.4 (b), the process is stationary and the system is weakly non-linear as for the dynamic system 1 in Fig. 2.1 (Guachamin Acero et al., 2016d). Thus, the operational limits can be used on-board to compute responses using updated forecast directional wave spectra. Then, the responses can be compared with measurements from on-board systems such as OCTUPUS, and decisions can be made.

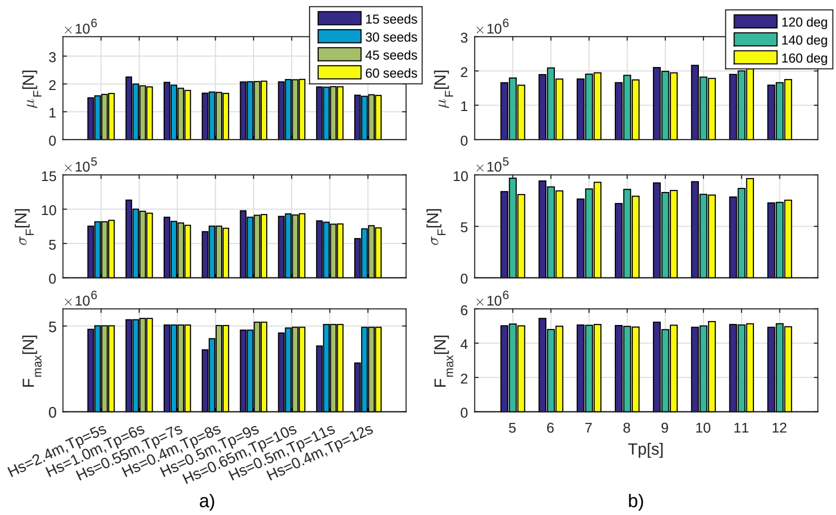


Figure 5.13: Statistical parameters of the snap forces during OWT tower lift-off. (a) Sensitivity study on seed numbers, wave dir= 120 deg; (b) Snap force statistical parameters for the allowable limits of sea states given in Fig. 5.12 for various wave dir., No. seeds= 60. Duration of TD simulations for the snap load events ≤ 1 min (Guachamin Acero et al., 2016a)

5.4.4 Response statistics and sensitivity study on key modeling parameters

It was shown in the previous subsection that the response statistics and extreme value distributions are necessary to establish characteristic values of the limiting parameters. Since the dynamic responses of the OWT tower and

RNA installation activities were analyzed using non-stationary process TD simulations (see Table 4.4), the number of seeds, duration of the activities and modeling parameters are important parameters. Moreover, assessment of the characteristic values of limiting parameters under representative sea states is important for future design of structural components of this novel installation concept. This subsection provides a sensitivity study on key modeling parameters (Guachamin Acero et al., 2016a) (*paper 6*).

5.4.4.1 Snap forces during lift-off

A sensitivity study on the hoist wire stiffness k_{wire} was carried out to assess the maximum snap forces, see Fig. 5.14 (a). As expected, a crane with larger wire stiffness gives larger snap forces. In contrast, softer spring coefficients yield smaller loads. However, the use of a more elastic wire rope can result in a heave natural period similar to the ones of the first order resonant modes, and this should be avoided.

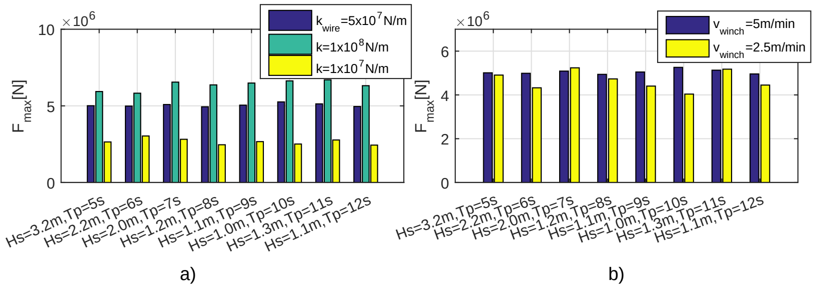


Figure 5.14: Maximum snap forces during OWT tower lift-off, wave dir=160 deg, No. seeds= 60. (a) Sensitivity on hoist wire stiffness; (b) Sensitivity on winch lifting speed. Duration of TD simulations for the snap load events ≤ 1 *min (Guachamin Acero et al., 2016a)*

Similarly, from Fig. 5.14 (b) it is observed that by decreasing the winch speed, the maximum snap forces may get reduced. However, at lower winch speeds, the number of snap events will increase, and thus, larger snap forces may occur.

5.4.4.2 Impact forces and velocities during the mating activity

Some results for various stiffness coefficients k_{con} of the contact elements in the foundation support (docking cone) are shown in Fig. 5.15. As expected, the contact stiffness has a large influence on the impact forces. However,

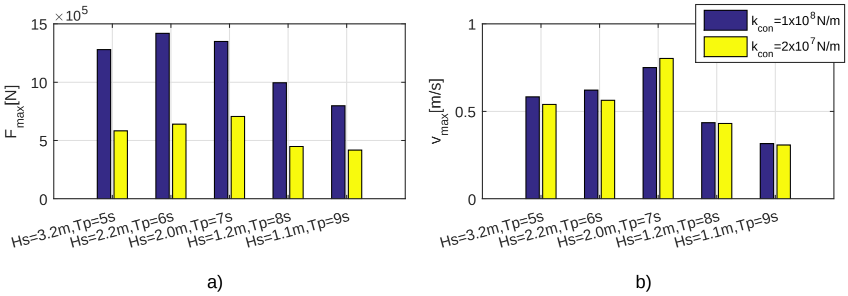


Figure 5.15: Sensitivity study on contact spring stiffness during the mating operation, wave dir=160 deg, No. seeds= 60. (a) Maximum impact forces; (b) Maximum impact velocities. Number of seeds= 60, duration of TD simulation for impact events ≤ 1 *min (Guachamin Acero et al., 2016a)*

it is observed that the initial impact velocities are similar. In other words, the system global dynamic responses are not affected by impact events.

5.4.4.3 OWT bending moment and roll during the final upending stage

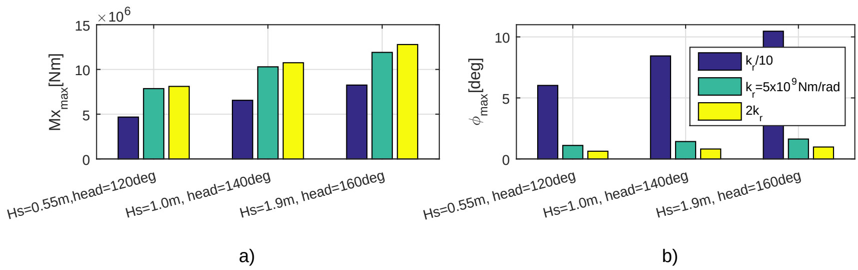


Figure 5.16: Sensitivity study on rotational spring coefficient k_r *during the final stage of the OWT upending operation, Tp= 7 s, various headings, No. seeds= 60. (a) Maximum articulation reaction moments; (b) Maximum out of plane OWT inclination. Duration of each simulation* ≤ 15 *min (Guachamin Acero et al., 2016a)*

Figure 5.16 shows that by increasing k_r, the reaction moments increase as well. In contrast, the out of plane OWT inclination is reduced. Proper selection of these coefficients will depend on the final design of the docking cone and locking pin (see e.g., Fig. 3.4 detail V), and should be set for acceptable OWT inclination angles during the final upending stage.

Chapter 6

Operability analysis

6.1 General

The installation procedures for the MP initial hammering process and the TP mating operation were briefly described in Ch. 3. Based on these procedures, the potential critical activities and corresponding limiting parameters were identified and the the allowable limits of sea states were established in Ch. 5. These limits were established for various MP and TP installation activities, and they can be used for weather window analysis. Workable weather windows can be identified by comparing the operational limits of each group of installation activities with the time histories of hindcast wave data. These groups of activities need to account for the sequence, duration and continuity of each activity. Based on the number of workable weather windows in a reference period of analysis, the operability of the entire marine operation can be calculated, see Sec. 2.4.

This chapter provides an assessment of the operability for installation of a MP and a TP using a floating HLV.

6.2 Allowable limits of sea states for MP and TP installation

The operational limits for the MP initial hammering process have been assessed in Subsec. 5.2.4. However, other activities such as MP lowering were not adressed. This is an important activity that needs to be executed before the MP hammering. The MP lowering activty was studied by Li et al. (2016a) and the operational limits are used in this thesis.

In practice, the same floating HLV is used to install the MP and TP structures. Once the MP is installed, the HLV is relocated at a safe distance and the TP lifting operation starts. Guachamin Acero et al. (2016d) (*paper 1*) assessed the operability of the entire operation based on the allowable limits of sea states of each operation. A summary of these limits is provided in this section.

Limiting parameters, corresponding activities, and operational limits are shown in Table 6.1. This information is required for weather window analysis.

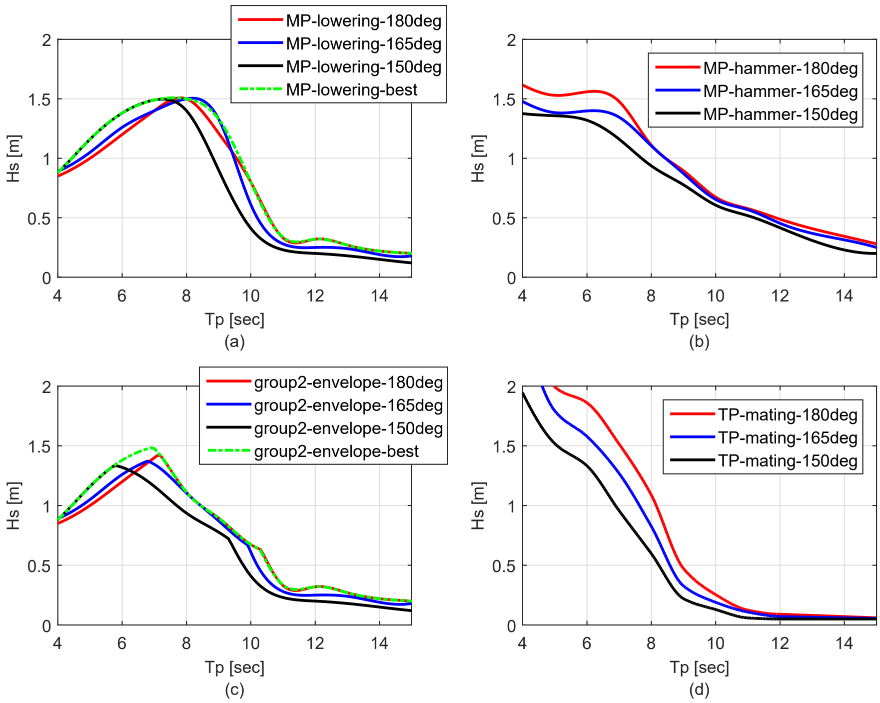


Figure 6.1: Allowable limits of sea states for single activities and activity groups (see. to Table 6.1) for various headings. (a) Allowable limits of sea states for the MP lowering operation; (b) Allowable limits of sea states for the MP initial hammering process; (c) Allowable limits of sea states for group G2; (d) Allowable limits of sea states for group G3 (Guachamin Acero et al., 2016d)

The allowable limits of sea states for the MP initial hammering process (Act. 3, group G2) were provided in Subsec. 5.2.4, and are shown in Fig. 6.1 (b). As stated earlier, another critical MP installation activity prior to MP hammering is the MP lowering (Act. 2, group G2) (Li et al., 2016a). A critical event was found to be the structural failure of the hydraulic cylinders. The limiting parameter is the horizontal motion of the MP at the gripper connection level, and the allowable limit is the available gap when the cylinders are retracted. The same HLV and MP as the ones given in Table 3.1 were used, and the allowable limit for the gap was assumed to be 1 m. The allowable limits of sea states are shown in Fig. 6.1 (a). Moreover, the combined allowable limits of sea states for the MP lowering and initial hammering process are provided in Fig. 6.1 (c). As will be shown, they can be combined because they are continuous activities and belong to the same group G2.

For the TP installation (Act. 4, group G3), the HLV used in the coupled model was also modeled according to Table 3.1. The TP bottom tip motion in the monitoring phase prior to mating was used as the only limiting parameter. By applying stationary process TD simulations, an allowable mating gap of 0.3 m and an allowable crossing rate of 0.0167 Hz, the allowable limits of sea states were established, see Fig. 6.1 (d).

6.3 Weather window analysis

Based on the operational limits established above, the weather windows could be identified. The allowable limits of sea states for the groups of activities given in Table 6.1 are used to identify the workable weather windows by following the procedure given in Sec. 2.4. The wave data from the Central North Sea (site 15) provided by Li et al. (2015a) were chosen for the weather window analysis of the MP and TP installation, see a sample of the time history in Fig. 6.2 (a). This site is suitable for MP foundations with an average water depth of 29 m, and the location is close to the Dogger bank wind farm. The hourly sampled hindcast 2D wave spectra from the period 2001 to 2007 were used.

Table 6.1: Installation activity groups for weather window analysis

Activity No.	*Group*	*Activity*	*Duration [hours]*	*Continuous*	*Allowable sea states*
1	1	Mooring the HLV	8	n	$H_s = 2.5$ m (assumed)
2	2	MP lowering	2	n	Fig. 6.1 (a) Ref. to (Li et al., 2016a)
3	2	MP hammering	1	y	Fig. 6.1 (b) Ref. to (Li et al., 2016b)
4	3	TP installation	1	n	Fig. 6.1 (d) Ref. to (Guachamin Acero et al., 2016b)

An example of workable weather windows is shown in Fig. 6.2 (b). This analysis can be done for all headings of the vessel. Then, the results can be sorted by month, so the best headings and seasons can be identified.

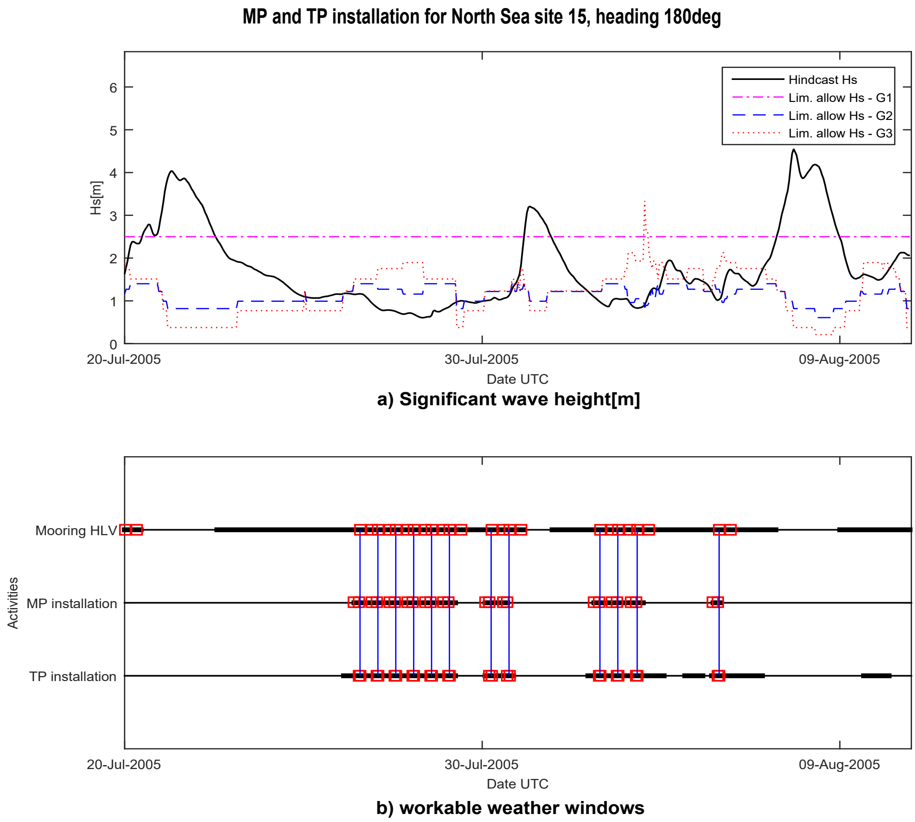


Figure 6.2: Typical weather window analysis based on hindcast wave data at universal time coordinate (UTC), and heading into the waves. a) Hindcast and allowable limits of Hs (for corresponding Tp); b) Workable weather windows (Guachamin Acero et al., 2016d)

6.4 Operability for MP and TP installation

The operability for the MP and TP installation is calculated by counting the number of available workable weather windows (WOWW) for completing the entire installation, and dividing it for the possible number of windows in the reference time period (2001-2007).

Figure 6.3 shows the operability for the installation of the MP and TP structure for various headings and months. Based on the operability , it is possible to select the season for the installation campaign. It is observed that the period June-August provides good operability and little downtime. Thus, operational limits derived systematically are very important for a realistic assessment of the operability of the MP and TP installation. It

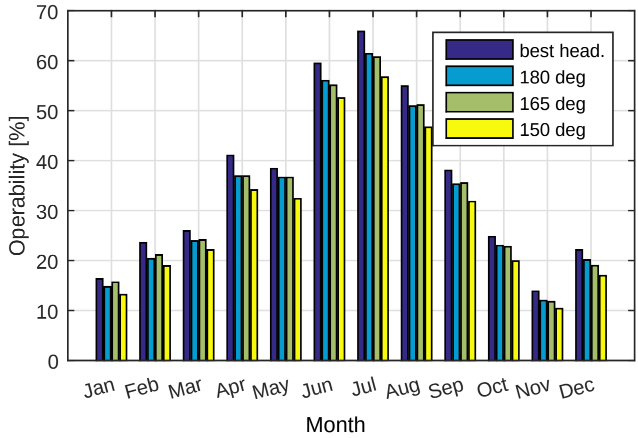


Figure 6.3: Operability for MP and TP installation for various headings and months (Guachamin Acero et al., 2016d)

is also observed that when the installation vessel is heading into the waves for each individual installation activity (best heading), the operability is increased (about 4.5%) for the month of July when compared to head seas (180 deg). This is possible if a DP vessel and updated weather forecasts are available.

Chapter 7

Conclusions and recommendations for future work

7.1 Conclusions

This thesis addresses many aspects related to the complete installation of an offshore wind turbine (OWT) monopile (MP), transition piece (TP), and tower and rotor nacelle assembly (RNA). It aims at providing researchers, industry and classification organizations a methodology for systematic analysis of marine operations, suitable numerical analysis methods, practical criteria for operational limits, and an alternative concept for single lift installation of an OWT tower and RNA.

A systematic methodology for establishing the operational limits of marine operations has been developed. This is a response-based approach where the operational limits are derived for actual parameters that limit the operations. These limiting (response) parameters and their corresponding critical events and activities are identified by numerical simulation of the actual operations and quantitative assessment of the dynamic responses. Non-linear features of the dynamic system, non-stationarity of the loads and responses, and actual duration of the operations need to be considered. Moreover, the characteristic values of limiting parameters should be selected for a target probability of non-exceedance that depends on the type of operation and associated failure consequences. These characteristic values can be compared with the corresponding allowable limits (including safety factors) to establish operational limits. For marine operations executed with floating vessels, especially for offshore heavy lifting, the methodology allows for assessment of operational limits in terms of allowable limits of sea states, which can be transformed into limits of vessel responses during monitoring phases prior to execution of activities. These limits are practical for on-board decision making and planning of marine operations.

The installation activities that were studied in this thesis include the MP initial hammering process, the TP mating operation, and the fully assembled OWT tower and RNA installation. For the installation of the OWT tower and RNA, a novel installation method was developed, and it has been shown to be feasible. This novel concept is based on the principle of the inverted pendulum and requires a medium size heavy lift vessel, a cargo barge, and an upending frame. This novel procedure aims to provide an efficient and valid alternative for current procedures employing large jack-up crane vessels.

Based on the systematic methodology, the potential critical OWT installation activities were modeled numerically. Numerical coupled models of actual operations were developed because they are necessary for accurate assessment of dynamic responses. The dynamic responses of the installation systems were computed considering external wave actions. Based on quantitative assessment of the dynamic responses, the critical events and limiting (response) parameters were identified.

For the MP installation, it was found that the critical event is the failure of the hydraulic system and the respective limiting parameter is the gripper contact force. This force has contributions from a dynamic force that occurs due to wave action and HLV-MP motions, and a correction force that is required to bring the MP back to zero mean inclination. The MP inclination occurs due to hammering of the MP during first- and second-order motions of the HLV-MP coupled system. These motions can be large, and thus, a failure installation event (not critical) is the unacceptable MP inclination (limiting parameter).

For the TP mating operation, the critical event is the failure of the bracket supports and a restrictive (not critical) event is found to be a failed mating attempt prior to the mating phase. For typical landing velocities and installation sea states, it was found that the impact force can cause structural failure of the bracket supports. Similarly, it was observed that large motions of the TP bottom can occur and exceed the annular gap between the MP and the TP. The limiting parameters are the TP landing velocity and horizontal motions of the bottom tip. These horizontal motions were addressed in terms of a rate of crossing of the bottom tip out of the annular mating gap.

With respect to the installation of the tower and RNA, the structural failure of the rigging components and structural damage of hinged supports are identified to be critical events; a failed mating attempt is a restrictive event. Large snap forces during the lift-off of the OWT tower occur due to large contributing masses and snap velocities. Similarly, large impact forces can be expected during mating of the upending frame and the foundation supports. Moreover, the initial phase of the mating operation may not be possible if the motions of the upending frame bottom pins are large. The limiting parameters are the total tension in the wire ropes, impact velocities on the foundation supports and horizontal motions of the upending frame pins.

For the lift-off and mating operations, efficient numerical analysis methodologies were proposed. The collision approach can be used for assessment of dynamic responses as result of a non-stationary process during lift-off and landing operations. This method is applicable to systems with time-invariant dynamic properties. Similarly the method of the rate of crossing of a mating pin out of a circular boundary is suitable for the initial phases of the mating operations. These numerical methods are suitable for both, screening of limiting parameters and systematic assessment of operational limits.

For various limiting parameters of the OWT installation activities, the operational limits were established in terms of allowable limits of sea states, which are a basis for assessment of the operatiblity.

An approach for weather window analysis of marine operations was proposed. This approach relies on the response-based operational limits derived for the actual limiting parameters. The sequence, duration, and continuity of the activities can be included. These weather windows can be used for operability analysis during planning phases and to make on-board decisions on starting times prior to the execution of activities. The methodology was applied to offshore wind turbine MP and TP installation using a floating HLV. For a given offshore site, it was found that installation seasons and headings can be selected in the planning phase.

7.2 Original contributions

The original contributions of this thesis are summarized below.

- *Development of a systematic methodology for identification of critical events, limiting parameters and assessment of operational limits in terms of allowable limits of sea states*

A general and systematic methodology for identification of critical events and corresponding limiting parameters based on quantitative assessment of the dynamic responses has been developed. For the identified limiting parameters, the methodology allows for assessment of the operational limits in terms of allowable limits of sea states or allowable limits of vessel responses in monitoring phases prior to execution of activities. These operational limits are response-based, and thus, are relevant for planning and execution of marine operations.

- *Development of a concept for installation of a fully assembled OWT tower and RNA*

  A novel method for installation of an OWT tower and RNA in a single lift has been developed and shown to be feasible. The method provides high installation rates, eliminates the need for huge installation vessels, requires few modifications to existing OWT structures and is an attractive alternative for current installation procedures.

- *Development of numerical models*

  Customized procedures for the numerical analysis of the MP initial hammering process, TP mating operation and OWT tower and RNA assembly installation were developed.

- *Development of a numerical solution and operational criteria for mating operations*

  An efficient numerical solution for the assessment of the rate of crossing of a mating pin out of circular boundary has been proposed. The rate of crossing of a mating pin out of a docking cone is a practical criterion that can be used for assessment of the allowable sea states of mating operations, e.g., float-over. The numerical solution is efficient because is based on the frequency domain method and spectral analysis, and thus, it can be implemented on-board vessels.

- *Development of a methodology for weather window analysis of marine operations*

  The methodology accounts for sequence, duration, continuity and the actual operational limits of the marine operations. It can be used for the planning and the execution phases.

7.3 Limitations and recommendations for future work

- *Assessment of the operational limits*

  This work has been limited to establishing the allowable limits of sea states based on characteristic values of limiting (response) parameters and semi-probabilistic based allowable limits where safety factors were assumed. In future, the various sources of uncertainties such as those associated with human decisions, environmental parameters, structural component mechanical properties, and numerical models need to be addressed. Thus, a reliability-based approach is needed, so the operational limits can include safety margins. This information is important for on-board decision-making systems. The methodology need to be customized for other marine operations such as towage, anchor handling, etc.

- *Allowable limits*

  The allowable limits of limiting parameters that require structural damage criteria based on FEM were not considered. These limits are required for problems involving contact-impact, and thus, they need to be established.

  The allowable limits for motion responses were assumed deterministic and selected arbitrarily. In practice, the limits will vary due to visual appreciation, construction tolerances, etc. Thus, uncertainties in the allowable limits need to be assessed.

  In this thesis, it was assumed that the horizontal transportation of a nacelle is possible. Structural damage criteria of the nacelle during installation in horizontal position need to be established based on finite element analysis. This criteria should be converted into an allowable limit of the acceleration. Moreover, issues regarding possible leakage of hydraulic fluids and oil need to be addressed.

- *Sensitivity study on modeling parameters*

  Various installation activities studied in this thesis were conducted for reasonably estimated modeling parameters. However, the choice of these parameters can influence the system dynamic responses. Sensitivity studies regarding key modeling parameters need to be carried out.

- *Operational limits of current OWT installation activities*

This thesis has been limited to global dynamic analyses of some activities including MP, TP and OWT tower and RNA installation. To date, the jack-up crane vessel is very often used for activities such as blade and nacelle installation. Thus, the operational limits of these activities need to be assessed. In addition, the operational limits for standard lowering procedures of jack-up legs need further research.

- *Further development of the novel OWT tower and RNA installation concept and comparative study*

  Further development of the novel concept in terms of structural design and validation is required. Moreover, a technical and economical comparison against existing procedures is necessary.

- *Alternative OWT installation concepts*

  Since the installation costs for OWT are high and the profit margins of offshore wind energy industry are low, more efficient alternative installation concepts and procedures are required. In addition, feasible concepts for offshore wind turbine access for repair and maintenance need to be developed.

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