COUPLED DYNAMIC EFFECTS OF LOWERING A LARGE MONOPILE THROUGH THE SPLASH ZONE FROM A JACK-UP

J. Bilbao*, H. Hofstede, V. Lit, O. van Ewijk
GUSTOMSC

C. Mollaibrahimoglu, Q. Meissonnier
CADELER

*Corresponding author: joaquin.bilbao@nov.com

1. ABSTRACT

As offshore wind turbines increase in size, so do their monopile foundations, with future designs reaching diameters of 12–15 meters and weights exceeding 2,500 tonnes. During installation, the hydrodynamic forces acting on a large monopile while it is being lifted through the splash zone can become significant. In case of jack-ups, the hydrodynamic loads induced by wave action on the monopile can become significantly higher than those induced on the legs. The effects of the suspended monopile in the water must therefore be carefully considered in site-specific assessments (SSA). This paper investigates the dynamic interaction between a jack-up and a monopile during lifting operations, focusing on how the coupled system's natural periods and wave conditions influence the total response. A realistic case study is presented to illustrate these effects and to demonstrate how certain wave conditions can amplify the response. The findings underline the importance of including the (hydrodynamic) effects of lifted monopiles in dynamic analyses to ensure safe and robust installation procedures for the growing size of monopiles.

2. KEYWORDS

Offshore wind, jack-up, monopile, splash zone, hydrodynamics, dynamic response, SSA

3. INTRODUCTION

Offshore wind energy has seen rapid growth in recent years, with turbines becoming larger, heavier, and installed in deeper waters [1]. These changes have pushed the limits of current installation technologies and brought new challenges for marine operations.

Monopiles remain one of the most common foundation types for bottom-fixed offshore wind turbines [2]. Their simplicity and cost-effectiveness make them suitable for large-scale deployment. These foundations are often installed using jack-ups, equipped with heavy cranes and gripper systems. During installation, the crane is used to lower the monopile through the splash zone, while the gripper provides lateral support to the monopile. Operational limits are defined by environmental conditions—primarily wind speeds that affect crane operations and wave conditions that affect jack-up stability.

The size and weight of monopiles have increased significantly. Recent designs feature diameters exceeding 10-12 meters and weights exceeding 1,500-2,500 tonnes. The increased size and weight place greater demands on lifting equipment and handling tools and cause larger structural responses during installation.

This paper investigates the dynamic interaction between a jack-up and a suspended monopile during the phase of lowering through the splash zone. The focus is on evaluating the resulting loads at the lower guide and at the leg foundation. A series of dynamic simulations and comparisons with simplified models are presented, and a bearing capacity checks is performed to assess the loading conditions against design limits following ISO 19905-1:2023 [3] and SNAME T&R 5-7 [4].

4. PROBLEM DEFINITION

Installing a monopile using a jack-up follows a specific sequence of operations. A typical sequence is described below. Figure 1 and Figure 2 visualizes some installation phases.

The sequence starts with transit, where the jack-up carries the monopile to the site. Once on location, the jack-up elevates and performs preloading to fix the legs in place on the seabed and then elevates to its operational airgap.

Next, the gripper system is deployed, extending outward from the hull. The monopile is then upended and lifted, moving from a horizontal position on deck to a vertical position using the crane and upending tool. It is then brought within reach of the gripper.

Once the gripper engages, the lowering phase begins. The monopile is lowered through the splash zone by the crane, with the gripper holding it steady. After it reaches the seabed, final adjustments are made to ensure it is positioned correctly.

Then, the hammer is lifted and aligned with the top of the monopile, followed by the piling operation, driving the monopile into the seabed.

This study focuses on the phase where the monopile is lowered through the splash zone. This is one of the most critical phases because the entire weight of the monopile is hanging from the crane while it is exposed to wave and current forces. The combination of suspended mass and hydrodynamic loads makes this phase sensitive to dynamic effects, and accurate modeling of the whole system comprising monopile, jack-up, gripper and crane is required to understand the forces on the jack-up structure during this part of the operation.

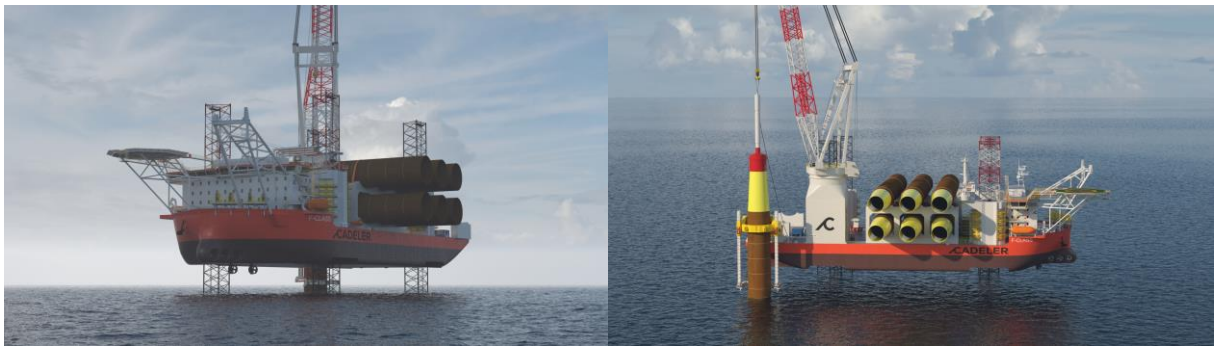


Figure 1 Cadeler A-Class, artist impressions.

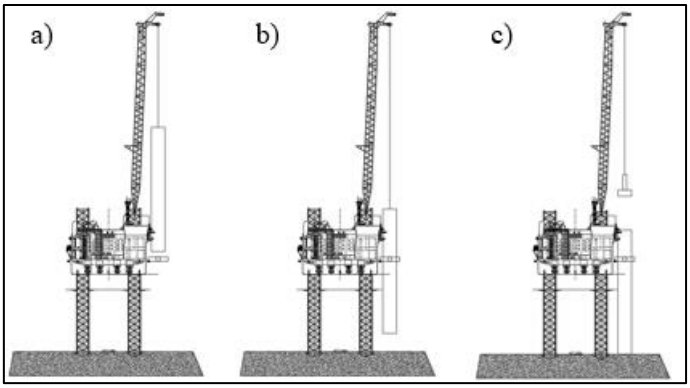


Figure 2 Installation phases visualized. a) Monopile lifted towards gripper. b) Monopile lowered through splash zone with gripper holding laterally. c) Monopile supported by seabed, crane lifting the hammer to begin piling operation.

5. MODELLING ASSUMPTIONS

This section outlines the modeling assumptions and physical components included in the analysis. The goal is to provide a transparent view of the simplified, yet representative, system model used to simulate the dynamic interaction between the jack-up and suspended monopile during the lowering operation. The hydrodynamic model focuses exclusively on effects due to lateral motions (jack-up surge/sway/yaw, monopile rotation around gripper) and the resulting inertial effects on the jack-up and monopile during the lowering operation. Vertical dynamics are explicitly excluded from the analysis.

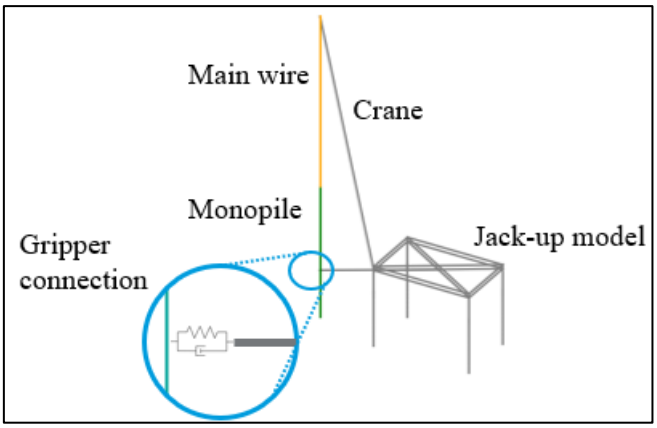


Figure 3 Simplified visualization of model and main elements.

5.1 Jack-up Structure

The jack-up used in the case study is a Cadeler A-Class unit, which is a GustoMSC NG-20000X-CA design. For the purposes of this study, a simplified finite element model is constructed using beam elements for both the hull and the legs. The model includes leg-to-hull connections represented as springs. P-Delta effects are incorporated. The foundation model assumes shallow spudcan penetration into uniform sand, with the spudcan-soil interface treated as a pinned support condition.

Hull flexibility is explicitly modeled, which is of particular importance during crane lift operations due to the sensitivity of load distribution.

5.2 Monopile

The monopile is modeled as a rigid body suspended from the crane tip and supported laterally by the gripper. The mass of lifting tools located at the top of the monopile is included. The monopile is free to rotate around the gripper point, which becomes the dominant degree of freedom in the dynamic response of the monopile. The restoring/overturning moment effect of the center of gravity of the monopile and lifting tool due to their displaced position as well as the effect of the crane main hoist wire under tension are included, assuming small displacements, resulting in linear stiffness components included in the system.

5.3 Gripper and Crane

The gripper is represented as a translational spring-damper system in the horizontal plane, connecting the hull and monopile through lateral stiffness and damping at gripper level. The crane is modeled as a rigid extension of the hull, and its structural mass is included in the model.

5.4 Static Loads

All non-hydrodynamic loads—elevated weight and center of gravity, crane load effects, monopile lift to gripper, leg weight, wind loading (assumed quasi-static), and gripper offset—are included explicitly. These loads are applied independently and are essential for capturing baseline system equilibrium, as well as secondary effects such as load redistribution under platform deformation. Static effects, including mass shifts, are also included in the P-Delta formulation and influence the mass and stiffness distribution used in the simulations.

5.5 Hydrodynamic Loading

Wave and current forces on the jack-up legs are computed using the Morison equation with constant hydrodynamic coefficients.

For the monopile, wave loading is based on precomputed diffraction results (for each submersion level), combined with time-domain drag forces It is highlighted that given the large diameter of the monopile, the use of Morison equation is prone to conservatism especially for short wave lengths, hence the choice for a diffraction model to account for hydrodynamic loadings. Drag forces are applied due to steady current; wave particle velocity is disregarded.

5.6 Damping contributions
A ratio of 5% of critical damping is assumed for the subsystem of the jack-up structure (excluding the monopile). Gripper damping is modelled separately.

Damping forces on the monopile comprise of two contributions i.e., damping from the diffraction analysis per submersion and a drag force component as a result of the monopile motion. The drag coefficient is selected as Cd = 0.25 considering the effect of the oscillatory nature of the flow around the moving cylinder (dependency of the Keulegan-Carpenter number).

6. METHODOLOGY

The overall methodology consists of a combination of static and dynamic analyses to assess the response of the combined jack-up and suspended monopile system during lifting operations. The approach captures both conventional static effects and time-domain hydrodynamic interactions.

6.1 Static Contributions
The static load contributions were calculated by accounting for all non-hydrodynamic effects. These include the elevated weight of the vessel including basic eccentricity, the load effect of moving the gripper outboard, the effect of lifting and moving the monopile into the gripper, the weight of the legs, and wind forces (assumed quasi-static). These components form the baseline system load condition.

Emphasis is given to the effect of hull flexibility on the static load effect from the crane lift as per SNAME T&R 5-7 [4]. In addition to the effect of shift of the load (crane boom, hook, monopile) from deck to gripper, the crane pedestal moment acting on the hull results in deformations of the hull. These deformations result in unevenly distributed vertical loads over the 4 legs with the larger portion over the 2 aft legs.

6.2 Dynamic Simulation Framework
Dynamic simulations were carried out using an in-house developed program that solves the coupled structural and hydrodynamic model. The program performs modal analysis to extract natural periods and damping ratios and executes time-domain simulations that account for wave- and motion-induced loads.

The model includes full structural representation of the jack-up, the gripper connection, and the suspended monopile. Hydrodynamic loads from irregular waves and steady current are incorporated via precomputed diffraction data and time-domain drag forces, as described earlier.

Each specific set of conditions, defined by monopile submersion, significant wave height, wave peak period, and wave heading, is processed to determine the values used in the assessment. For each case, thirty time-domain simulations are carried out. From each simulation, the extreme response (either maximum or minimum) is extracted. These thirty values are then fitted to a Weibull distribution, and the value with a 10% probability of exceedance is taken as the value for assessment, hereafter referred to as the P90 value

6.3 Parameter Basis
All geometry, mass properties, and hydrodynamic parameters for the jack-up and monopile system are defined according to the representative case as detailed in section 7. These include pile diameters, total weight, crane boom length, hull and leg configuration, and the position and properties of the gripper. No additional simplifications were introduced at the methodology stage beyond those already noted.

7. CASE STUDY

This case study evaluates a representative offshore monopile installation using a Cadeler A-Class jack-up, based on the GustoMSC NG-20000X-CA design. The analysis focuses on the coupled dynamic behavior of the jack-up and a suspended monopile during the lowering through the splash zone phase.

The relevant parameters defining the physical system, environmental conditions, and simulation setup are summarized below.

7.1 Main Dimensions and Capacities
- Legs: 4 triangular open-truss legs.

- Jacking system: opposed rack and pinion type.
- Main crane: Leg Encircling Crane.
- Deck space: 5,600m2
- Payload: more than 17,600 tonnes.

7.2 Elevated Conditions
- Water depth: 40 m.
- Foundation model: Pinned support at spudcan.
- Soil type: Uniform sand with shallow spudcan penetration.

7.3 Monopile Properties
- Normal 2XL Monopile
- Weight: 1,500-2,500 tonnes.
- Diameter: 10-12 m outer diameter.
- Hydrodynamic modeling: Based on diffraction model.
- Drag coefficients: C_d = 0.65 (current-induced), C_d = 0.25 (motion-induced).
- Submersion depths: Evaluated from 0 to 40 m in 5 m increments.

7.4 Crane Operation
- Initial monopile lift point: At centerline between legs, approximately mid-ship.
- Gripper location: Outboard at starboard side, aft of the legs.
- Operational path: The monopile is lifted from the initial position and moved laterally into the gripper location.

7.5 Gripper and Connection Model
- Lateral support: Gripper restrains lateral motion and transfers horizontal loads to the hull.
- Connection modeling: Spring-damper system with representative values.
- Rotational freedom: Monopile is free to pitch/roll at the gripper.

7.6 Environmental Conditions
- Wave spectrum: Pierson-Moskowitz, spreading coefficient n = 6.
- Wave parameters: H_s = 2.0 m; T_p = 4, 6, 8, 10, and 12 s.
- Current: Surface velocity 1.0 m/s.
- Wind: 20.0 m/s sustained at 10 m elevation.

7.7 Time-Domain Simulations
- Duration: 30-minute simulations.
- Random seeds: 30 seeds per submersion depth, Tp, and wave heading.
- Wave headings: Full circle (0° to 330° in 30° increments).
- Statistical treatment: P90 values (i.e., values with 10% probability of exceedance) obtained by fitting the peak responses of the 30 seeds to a Weibull distribution.

7.8 Foundation Capacity Assessment
- Preload: Maximum preload at Jacking System is applied.
- Safety factor: Partial resistance factor $\gamma_{R,VH}$ = 1.1 applied to capacity checks.

8. RESULTS

8.1 Static Loads

This section presents the breakdown of vertical static (weight, buoyancy, wind and static crane lift) loads at the starboard-aft (SB-Aft) leg foundation during the lifting operation. These loads represent the initial static

condition prior to any dynamic amplification from hydrodynamic effects and serve as a reference case for understanding the baseline system equilibrium.

Transfer of monopile from storage to gripper position is the static load effect of the change of vertical leg load due to the crane lift picking up the monopile from its position on deck, via upending, to the final gripper position. Reference is made to SNAME T&R 5-7 Appendix 18 [4]. Effects included are weight of the monopile, crane and effects from the crane pedestal moment. Flexibility of the hull increases the load effects from the pedestal moment on the aft legs. As the jack-up has 4 legs, Pretorque© [5] can be used to alleviate the static load on the crane leg.

Table 1 Load contributions at SB-Aft leg

Load Contribution	**Ratio to Total [%]**
Elevated weight	60%
Eccentricity	1%
Transfer of monopile from storage to gripper position	27%
Leg weight	6%
Wind	2%
Gripper moved to starboard	4%
Pretorque© (unloading)	-
Total	**100%**

8.2 Modal Analysis

Natural frequencies and damping ratios were calculated for varying monopile submersions. The dominant modes identified include two associated with monopile rotation (MP1, MP2) and three coupled modes associated with global jack-up motion (JUMP1–JUMP3). Table 2 summarizes the natural periods for each monopile submersion. It is noted that the 1st natural period of the coupled system increases from 6.7 s to 8.2 s with monopile submersion.

Table 2 Natural periods as a function of monopile submersion

Submersion [m]	**MP1 [s]**	**MP2 [s]**	**JUMP1 [s]**	**JUMP2 [s]**	**JUMP3 [s]**
0	10.9	10.6	6.7	6.6	6.4
5	10.7	10.5	7.1	6.7	6.4
10	10.7	10.6	7.5	6.9	6.4
15	11.1	11.1	8.0	7.0	6.5
20	12.2	12.1	8.2	7.0	6.5
25	13.9	13.6	8.1	7.0	6.5
30	15.9	15.5	7.9	7.0	6.5
35	18.4	17.9	7.8	7.0	6.5
40	21.6	21.0	7.7	6.9	6.5

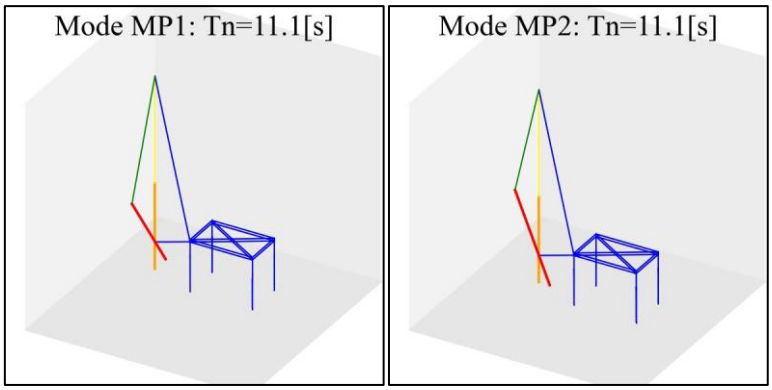


Figure 4 Modal analysis results. Mode shapes of MP1 and MP2 for 15m submersion.

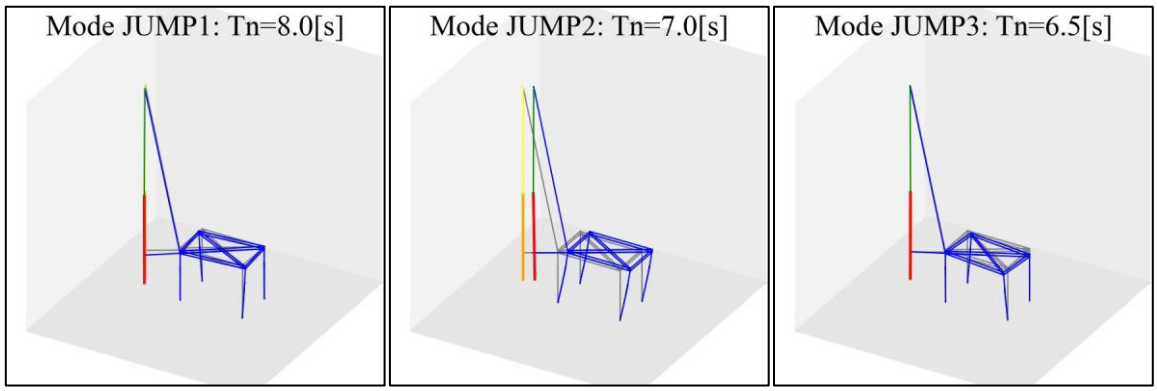
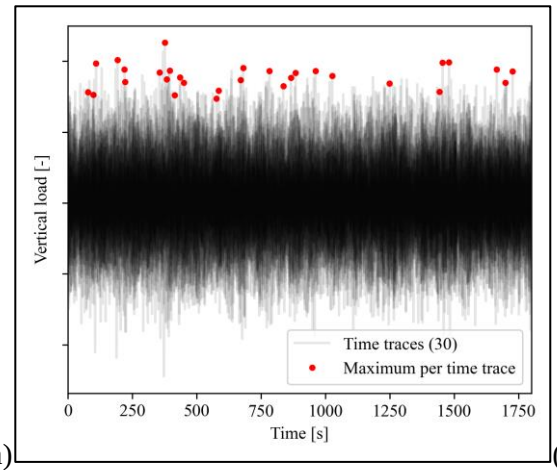


Figure 5 Modal analysis results. Mode shapes of JUMP1, JUMP2 and JUMP3 for 15m submersion.

8.3 Hydrodynamic response

The hydrodynamic response is measured by P90 values for the vertical and horizontal reaction at foundation, and the moment in the leg at lower guide. The methodology is visualized in Figure 6 for one of the conditions assessed. Figure 6(a) shows all thirty time traces obtained for the vertical load on the SB-Aft leg at foundation, for the particular case of Hs=2.0 m, Tp=8.0 s, wave heading 210 deg and monopile submersion of 10 m. The maximum of each simulations are shown by red dots. Figure 6 (b) shows the cumulative histogram and Weibull fit of these maxima along with the P90 value.

(a)



(b)

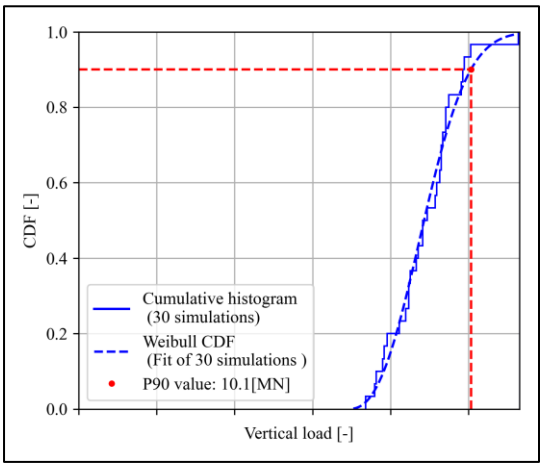


Figure 6 Vertical load on SB-Aft leg, Hs=2.0m, Tp=8.0s, wave heading: 210 deg, Pile submersion: 10 m.
(a) Time traces and maximum values of 30 simulations.
(b) Cumulative histogram and Weibull fit of 30 simulations along with P90 value.

8.3.1 Moment in SB-Aft leg at Lower Guide

Time-domain simulations were performed to extract the maximum moment in the SB-Aft leg at lower guide as a function of monopile submersion, wave period, and wave heading. In order to put the value in perspective, it is divided by the maximum moment found for associated 50-yr return period North Sea survival conditions. Maximum values are presented across wave headings and pile submersion levels.

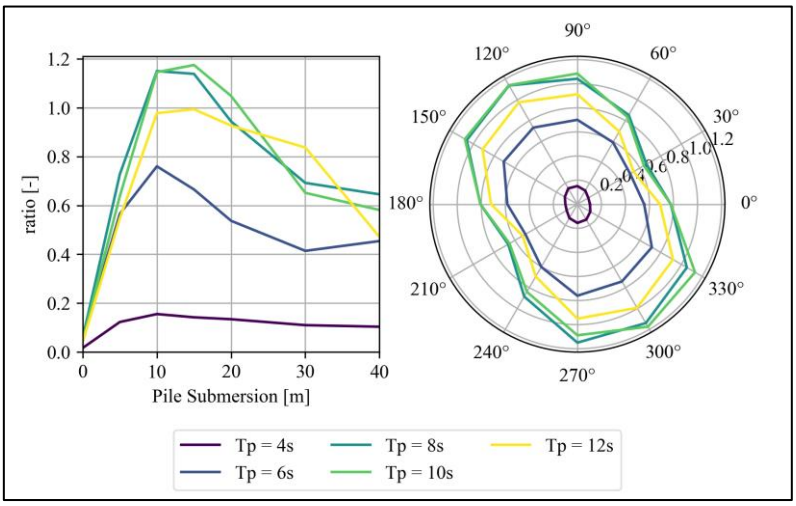


Figure 7 Max. Moment of SB-Aft leg at Lower Guide divided by Max. Moment found in survival conditions, by Pile Submersion and by Heading.

8.3.2 Loads in SB-Aft leg at Foundation

Foundation reactions were recorded in terms of vertical (Fv) and horizontal (Fh) loads at the SB-Aft leg. Maximum values are presented across wave headings and pile submersion levels.

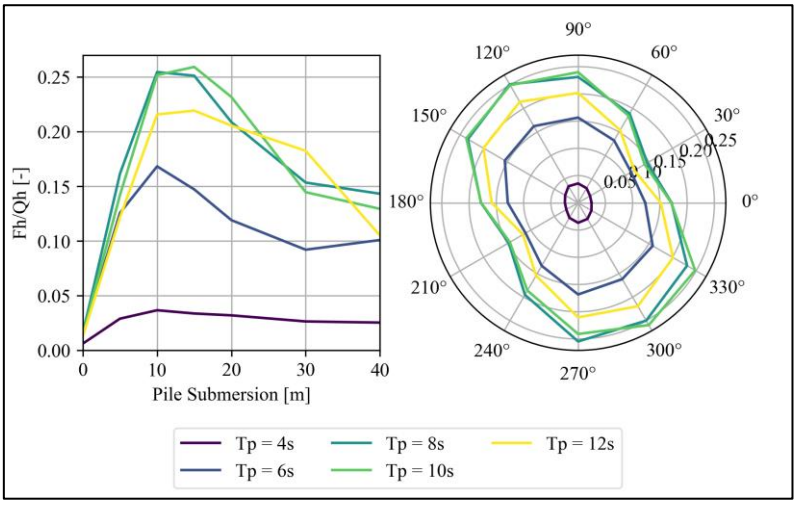


Figure 8 Max. Horizontal Load at Foundation by Pile Submersion and by Heading.

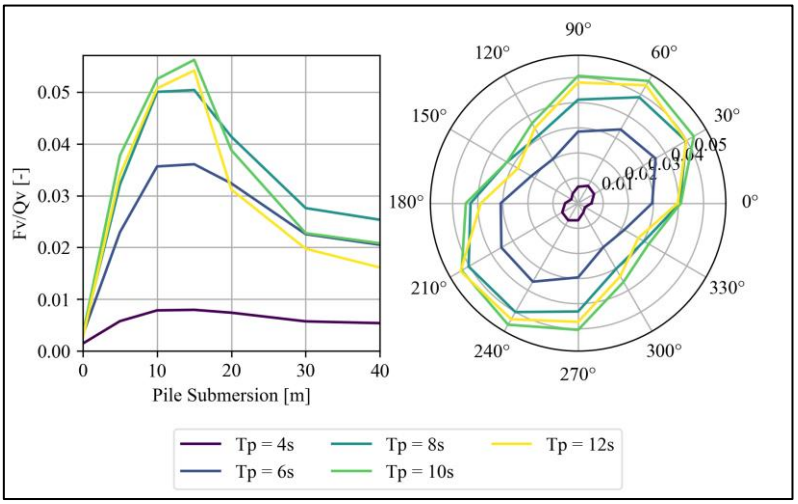


Figure 9 Max. Vertical Load at Foundation by Pile Submersion and by Heading.

8.4 Soil Bearing Capacity

A bearing capacity check was conducted using Fh–Fv load combinations and the foundation envelope defined as per ISO 19905-1:2023 [3]. Maximum P90 load combinations were conservatively used in the assessment.

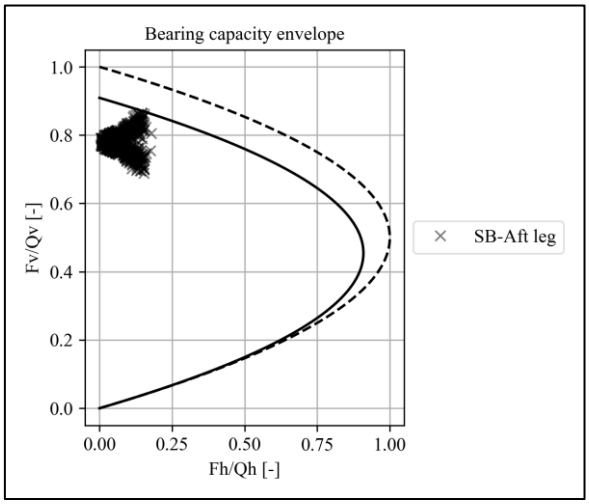


Figure 10 Bearing capacity envelope and Fh–Fv foundation loading at SB-Aft Leg.

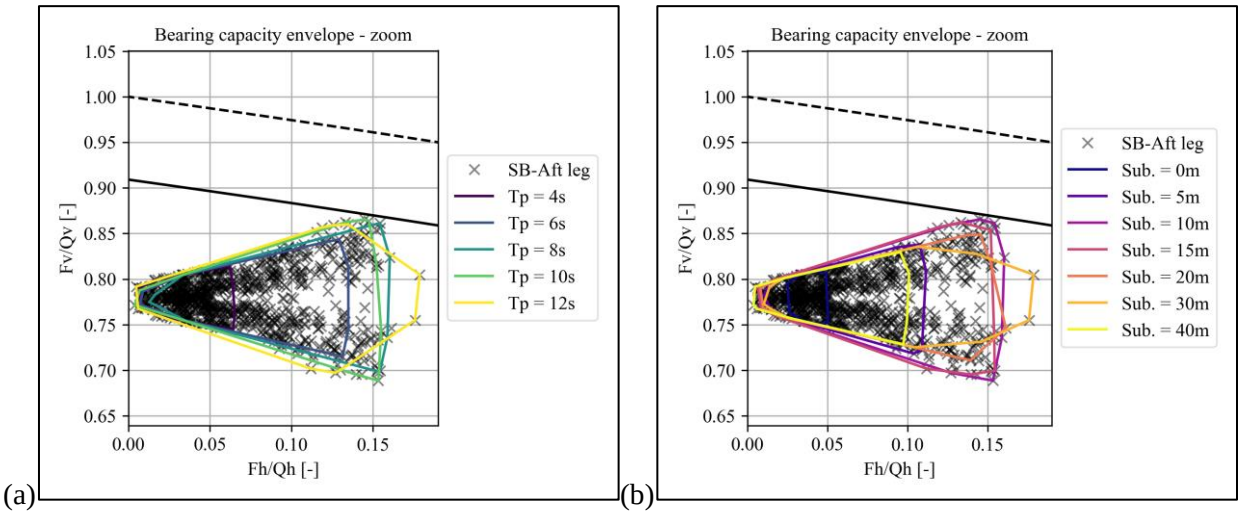


Figure 11 Bearing capacity envelope and Fh–Fv foundation loading at SB-Aft Leg.
(a) Zoom with Tp areas identified.
(b) Zoom with pile submersion areas identified.

9. DISCUSSION

The analysis shows that dynamic coupling between the suspended monopile and jack-up structure has a significant effect on the system response. This is observed in both the moment at the lower guide and the foundation loads. The increased moment in the leg at the lower guide can reach values up to approximately 1.2 times higher than those obtained under survival conditions, indicating the importance of considering hydrodynamic interaction effects during lifting operations.

Static load contributions are substantial. The main sources are the elevated jack-up weight and the crane operational loads, particularly the transfer of the monopile from storage to the gripper position. This transfer includes the effect of lifting the monopile, crane pedestal moment, and hull flexibility, all of which add to a substantial total vertical loading at the foundation. Pretorque© can be applied to alleviate the static vertical leg load.

Modal analysis of the coupled system reveals two dominant monopile modes and three coupled modes of the jack-up with monopile. The natural periods of the monopile modes increase with submersion, while the natural periods of the coupled modes initially increase up to around 20 meters of submersion and then begin to decrease. This trend suggests that coupling between the jack-up and monopile is strongest up to about 20 meters submersion, with interaction gradually diminishing at greater depths as the system decouples. This interaction shows the coupled nature of the system and highlights the consequences of resonance as the monopile is lowered through the splash zone.

The hydrodynamic response is assessed using P90 values, extracted from thirty 30-minute simulations per condition. In this context, the assumption of fixed submersion over 30 minutes is conservative, as actual operations involve continuous lowering. However, interruptions, either voluntary or involuntary, can occur, justifying the stationary assumption. More refined assessments can be performed using time-varying models, though these must also consider operational uncertainties.

The response is strongly dependent on both wave direction and monopile submersion. Peak loads are typically observed for headings around 120 and 300 degrees for the moment and horizontal load at the foundation, and around 210 and 30 degrees for the vertical load at the foundation. These main directions are a consequence of the gripper location relative to the jack-up. With respect to submersion, peak values are found between 10 and 15 meters, within the splash zone, particularly for wave periods around 8 to 10 seconds. These submersion levels correspond to the natural periods of the coupled monopile–jack-up system.

Bearing capacity checks indicate that the SB-Aft leg approaches the design envelope, driven by the combination of vertical static loads and significant lateral (horizontal and vertical) hydrodynamic forces. While

the static contribution from crane lifting operations is substantial, the lateral loads imposed by the monopile are equally important. In this case study, the monopile was found to generate wave-induced forces nearly nine times higher than those on the jack-up legs. These monopile loads are predominantly inertial in nature, contrasting with the more drag-dominated response of the truss legs. This highlights the importance of including monopile dynamics and hydrodynamic effects in assessments to properly check the foundation's capacity.

It should be noted that this analysis represents a specific operational scenario. Different jack-up configurations, monopile designs, soil and site conditions will alter the dynamics of the system. Soil support and damping affect the natural periods and dynamics and should be addressed. However, the findings illustrate the importance of accounting for dynamic interaction in such operations.

From an operational perspective, the use of coupled simulations gives better insight into critical phases of the lift. The results suggest that simplified uncoupled models may underpredict key load components, particularly in resonance-prone configurations. Incorporating hydrodynamic effects during monopile lift operational conditions in site-specific assessments is essential for ensuring safe and robust installation procedures.

Finally, the increasing diameter and mass of monopiles over recent years implies that dynamic effects during installation are becoming more pronounced. Current design guidelines, including ISO 19905-1:2023 and SNAME T&R 5-7, do not provide explicit guidance on how to address the interaction between a suspended monopile and the supporting jack-up structure. This highlights a gap in current standards and the need for further development to address this operational scenario. As the industry shifts toward larger monopile designs, simplified uncoupled analyses may no longer be sufficient to ensure that conditions remain within acceptable limits.

10. CONCLUSIONS

This study examined the dynamic interaction between a suspended monopile and a jack-up vessel during the lowering phase through the splash zone. Coupled time-domain simulations were carried out to evaluate the influence of hydrodynamic forces, structural flexibility, and monopile motion on system response. The analysis focused on the moment at the SB-Aft leg lower guide and on loads at the foundation, supported by modal analysis and bearing capacity checks.

The results demonstrate that dynamic coupling between the monopile and jack-up has a substantial impact on operational loads. Moment in the lower guide can reach up to 1.2 times the value from the associated 50-yr return period North Sea survival conditions. The response was found to be sensitive to monopile submersion and wave direction, with peak values occurring around 10 to 15 meters submersion and at headings aligned with the gripper position. Combined with the static loading, particularly from crane operations, lateral hydrodynamic loads from the monopile contribute significantly to foundation demand.

Current design standards, such as ISO 19905-1:2023 [3] and SNAME T&R 5-7 [4], do not explicitly address the dynamic interaction between suspended monopiles and jack-ups. This study highlights the need for improved assessment practices to ensure safety under evolving operational conditions.

Future work should explore transient lowering simulations and site-specific variations, as well as incorporate field measurements to validate model predictions. Additional sensitivity studies could investigate the influence of other parameters such as foundation stiffness, gripper, and crane position.

Overall, the findings highlight the relevance of monopile dynamics in the overall structural and foundation response. As monopile sizes continue to grow, these dynamic effects become increasingly important in ensuring safe and robust offshore installation operations.

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