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Comparative study on two deployment methods for large subsea spools

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ABSTRACT

The demand for subsea spool deployment is increasing with the expansion of offshore projects. For a project to install multiple spools, different deployment methods can be used. The choice of method may influence the safety and the total cost of the project. Thus, it is important to evaluate different deployment methods in the planning phase. This study addresses weather window analysis of two deployment methods for large subsea spools. The purpose is to compare the efficiency of the two methods in terms of total installation time for projects with different numbers of spools. Numerical modeling and time-domain simulations of the critical activities are carried out. The simulations together with the operational criteria provide the allowable sea states, which are the key input for weather window analysis. Hindcast data from a site in the Barents Sea are used for weather window analysis. The total installation time is compared for various months, different total numbers of spools and transportation durations. The influence of the possible increase of the allowable sea states for the critical activity on the total installation time is also evaluated. Through the comparative studies, recommendations to select the proper deployment method for different situations are provided.

1. Introduction

There are increasing challenges in the installation of subsea structures in recent years. Larger and heavier subsea structures are being installed in harsh environments and in deep waters. Deployment of subsea structures using offshore cranes is a weather-sensitive operation and may account for significant downtime in the whole installation project (DNVGL, 2016). These operations affect the installation costs for a subsea field development, and thus can directly impact the overall capital expenditure. Careful planning with sophisticated analysis is an important prerequisite for safe execution of the installations.

Lifting operations are weather restricted operations, for which operational limits need to be established during the planning phase (DNVGL, 2014). For practical use, the operational limits are often expressed in terms of environmental conditions or motions that can be monitored on-board the installation vessel. Li (2016) and Guachamin Acero et al. (2016) described a general methodology to establish the operational limits using response-based criteria. The operational limits in terms of allowable sea states are obtained by fulfilling the criteria that the characteristic value of the governing response is less than the design capacity. The methodology is composed of the following six main steps: 1) Identification of potentially critical events; 2) Numerical modeling of operational activities; 3) Identification of critical events and limiting parameters; 4) Calculation of characteristic dynamic responses; 5) Evaluation of the allowable limits; 6) Assessment of the operational limits. Examples of application of this methodology and assessment of operational limits can be found in the published literature (Li et al., 2016; Gao et al., 2016; Guachamin Acero, 2016; Verma et al., 2019).

Among the steps to establish operational limits, numerical modelling and analysis are of great importance to estimate the critical dynamic responses. Many studies have been performed to estimate the characteristic responses of various lifting activities, including lift-off operations (Graczyk and Sandvik, 2012; Karatas, 2020), over-boarding (Li et al., 2020), lifting through the splash zone (Bunnik et al., 2006; Sarkar and Gudmestad, 2010; Næss et al., 2014; Amer, 2020), heavy lift operations (Cha et al., 2010; Zhu et al., 2017; Acero et al., 2017) and mating operations (Jiang et al., 2018; Verma et al., 2019). Due to the complex environmental loading with transient dynamic effects of the lifting system during the operation, the prediction of the motions and loads is a challenging task. The state-of-the-art approach is to perform time-domain simulations of the installation system including the vessel, the lifted object structure, the hoisting system, and other coupling

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elements between these components. For different critical phases of the lifting operation, the focus on the analysis also varies. For example, accurate implementation of the hydrodynamic coefficients is essential for structures that experience high slamming loads during the splash zone crossing (Molin, 2011), such as subsea template and GRP covers (Solaas et al., 2017). On the other hand, the control of the crane winch and the tugger lines may dominate the motions for lift-off and mating operations (Ren et al., 2018). Thus, different methods should be considered when establishing the operational limits for complex operations.

For operations dominated by wave motions, the allowable sea states can be obtained in terms of significant wave height (H_s) and spectral wave period (T_p). Uncertainties in the allowable sea states also need to be evaluated to provide safety margins (Natskår et al., 2015; Guachamin-Acero and Li, 2018). The allowable sea states and weather forecasts provide the basis for the decision-making during the execution of the operation. In the planning phase, the installation procedure, allowable sea states and site conditions serve as input for operability and weather window analysis. The operability and weather window analysis are useful to size equipment, select installation vessel and optimize the installation method. Examples of operability and weather window analysis of various operations can be found (O'Connor et al., 2013; Wu, 2014; Yang et al., 2017; Gintautas and Sørensen, 2017).

Subsea spool structures are important components in the subsea production systems to connect the pipe ends and the interconnecting facilities (Bai and Bai, 2005). Spools must be designed to meet functional requirements including pressure, temperature, thermal expansion, environmental loads, and installation loads, etc. There are many studies in the literature focusing on different design aspects, such as seismic design (Yasseri, 2020), flow-induced vibrations (Lu et al., 2016), and tuned mass damper for vibration control (Zhang et al., 2015), etc. The design of the spools is not the emphasis of this study. Instead, this study focuses on the deployment of subsea spools, which refers to the phase to lift the spools from the deck of a vessel and lower them to the seabed. The spools are normally deployed by offshore construction vessels with onboard cranes. The whole installation can be in general divided into several phases (Parra, 2018). The spool is firstly transported by a construction vessel or a feeding barge. After lifted-off from the deck of the vessel or the barge, the spool is lowered through the splash zone. The spool is then deeply submerged until it reaches the seabed. Finally, the connections between the spool and the subsea equipment are carried out by remotely operated underwater vehicle (ROV). The main critical activities are the lift-off phase and the lowering through the splash zone, which require careful numerical modeling and analysis. Because spools are getting larger and heavier, lifting operations become more challenging and are often carried out in relatively low sea states in the summer seasons (Cosson et al., 2018; Aarset et al., 2011). Moreover, with the expansion of offshore projects, the number of spools that need to be installed in one project is also increasing due to increasing number of wells (and redundant wells for production assurance) (Yasseri and Bahai, 2018). To improve the safety and efficiency of spool installation, a robust installation strategy needs to be established in the planning phase.

This study aims to tackle one of the challenges faced by marine contractors on the choice of deployment method for large subsea spools. Two deployment methods are compared by weather window analysis. The analysis is based on the installation procedure, the allowable sea states and the hindcast data at the reference site. The total installation time using the two deployment methods is compared for various practical installation situations. This paper first describes the two deployment methods, followed by numerical methods to derive allowable sea states. Then, weather window analysis, results and discussions on the comparative studies are presented. Finally, the conclusions and recommendations from this study are given.

Table 1
Main activities for deployment method 1.

Spool No.	Activity group	Main activities
1	1	Load-out and transportation to site
	2	Preparation and deployment from the construction vessel
	3	ROV survey
	4	Sailing back to harbor
2 to N	5 to 4N	Repeat activities No. 1–4 for each spool

2. Description of two deployment methods

2.1. Deployment method 1 – transportation and deployment with construction vessel

A common method for installation of subsea spools involves only one construction vessel. This method is considered efficient when the number of spools to be installed is small (for example, less than 5). The main activities for the whole installation are summarized in Table 1. Four main activity groups are required to install one spool. Here, one activity group refers to a series of activities that cannot be split or interrupted once the weather condition deteriorates. Activity group No. 2 (summarized as preparation and deployment) includes cutting sea fastening, lift-off the spool from its own deck, over-boarding and lowering the spool through the splash zone until it is landed on the target location on the seabed. The lowest allowable limits of sea states among these activities should be used as the operational limits for this activity group. Once the deployment is finished and the lifting gear has been recovered, a final survey will be carried out by an ROV.

The most critical activity that determines the allowable sea states for activity group No. 2 is lowering the spool through the splash zone, where the hydrodynamic loads on the spool may cause unacceptable responses. Due to large non-linearities of the lowering process, time-domain simulations are required, which will be detailed in Sec. 3.

After the first spool is installed, the activity groups No. 1–4 need to be repeated to install N spools. In this case, the construction vessel needs to sail back and forth to pick up new spools and deploy them one by one. The number of trips back and forth between the harbor and the offshore site is the same as the number of spools, which is denoted as N.

2.2. Deployment method 2 – transportation with feeding barge and deployment with construction vessel

If the number of spools to be installed is large (for example, over 10 spools) and the distance between the harbor and the offshore site is long, then deployment method 1 may not be efficient. This is because a large amount of time is spent on transportation. An offshore construction vessel is equipped with specialized equipment onboard to perform complex installation tasks, and the day rate for such a vessel is much more costly than feeding barges with similar size. Therefore, it may be more beneficial to employ feeding barges to transport the spools, while the construction vessel stays at the offshore site to perform the deployment activities. Thus, this deployment method 2 employs one construction vessel and at least one feeding barge.

It should be mentioned that this study deals with installation of large spools, whose shape is usually complex with large horizontal dimensions (see Fig. 1). Thus, it is only possible to transport one spool using conventional offshore construction vessels or feeding barges per trip.

The main activities for the whole installation using deployment method 2 are summarized in Table 2. The transportation and installation of the first spool is carried out by the construction vessel. For the second and the remaining spools, the transportation is carried out by one or more feeding barges while the construction vessel is positioned at the offshore site to continue the deployment. Table 2 only shows the activities that involve the construction vessel. The transportation of spools

Table 2
Main activities for deployment method 2.

Spool No.	Activity group	Main activities
1	1	Load-out and transportation to site
	2	Preparation and deployment from the construction vessel
	3	ROV survey
2	4	Preparation, **lift-off from barge** and deployment from the vessel
	5	ROV survey
3 to *N*	6 to (1+2*N*)	Repeat activities No. 4–5 for each spool
–	Last	Sailing back to harbor

using a feeding barge is carried out in parallel to the activities at the offshore site. For example, while installing the first spool, the barge is transporting the second spool. The second spool should arrive at the offshore site by the time the ROV survey for the first spool is completed. Once the weather permits, the preparation for lift-off of the second spool from the barge will initiate. After the lift-off, the construction vessel will continue with the deployment while the barge sails back to the harbor to pick up a new spool. In this way, this method avoids mobilization of the construction vessel going back and forth between the harbor and the offshore site when many spools are required to be installed.

The most critical activity for deployment method 2 is the lift-off from barge, which is included in activity group No. 4. Compared to lift-off from the own deck of the construction vessel using deployment method 1, the installation system experiences more dynamics due to the relative motions between the barge and the vessel, reducing the allowable sea states for lift-off from barge. Moreover, the allowable sea states for lift-off from barge are lower than lowering the spool through the splash zone (see Sec.3.3), which is the critical activity for deployment method 1. This indicates that long waiting on weather time may be expected for lift-off activity using deployment method 2.

Although the deployment method 2 seems to be more efficient, the current industrial projects hesitate to apply this method due to two main reasons. First, the number of spools to be installed in one project in the past was often relatively low. Second, the allowable sea states for lift-off from barge are too low, which results in the waiting time for deployment method 2 even longer than the transportation time in most seasons. These two aspects may limit the application of deployment method 2 for many marine contractors. However, with the expansion of offshore industry, there is a need for installing more spools within a project. The location of some offshore sites is moving further away from the shore, increasing the transportation time. Moreover, new measures can be implemented to potentially increase the allowable sea states for the lift-off from barge. The above aspects will be considered later when comparing the efficiency of the two deployment methods.

3. Numerical methods and assessment of operational limits

Because of the complexity of the multi-body dynamic systems experiencing hydrodynamic loadings, simplified frequency-domain analysis can hardly be used to predict the motion responses under irregular waves. Thus, numerical analyses using time-domain methods are required to estimate the motions of the system for critical activities. As discussed in Sec. 2, the critical activities for the two deployment methods are lowering the spool through the splash zone and lift-off from barge. This section will discuss the numerical models used to estimate the responses and the methods to assess the allowable seas states for these two activities.

Table 3
Main features of the construction vessel and the feeding barge (Li et al., 2020a).

Specification	Construction vessel	Feeding barge
Length overall	156.7 m	100 m
Breadth	27 m	25.6 m
Maximum draft	8.5 m	4 m
Freeboard	3.5 m	4.5 m
Displacement	1.70E4 tons	1.04E4 tons

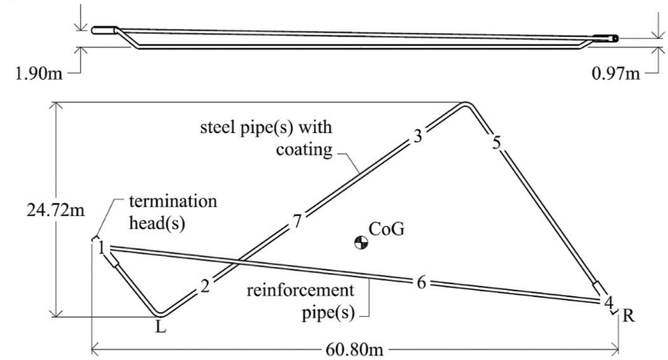


Fig. 1. Side and top views of the example subsea spool (connection points for seven slings are shown with numbers 1–7) (Li et al., 2020a).

3.1. System description

The installation system contains the construction vessel, the feeding barge (for deployment method 2 only), the subsea spool, and the hoisting system. The construction vessel is equipped with a crane with a maximum lift capacity of 400 tons. The feeding barge is a conventional barge capable to operate in the North Sea. The barge has a sufficient deck area to transport large subsea spools. The main dimensions of the construction vessel and the feeding barge are given in Table 3.

The subsea spool has a large horizontal dimension and is composed of different sections of tubular members. Fig. 1 presents the side and top views of the spool piece, where the horizontal position of the center of gravity (CoG) is highlighted. The large horizontal dimension of the spool makes it challenging for the lifting operation. A reinforcement pipe is attached to limit compression of the spool, and thus the structural failure during the deployment can be avoided. The reinforcement pipe is assumed rigidly connected to the termination heads. The total mass of the spool and the reinforcement pipe is 45.2 tons.

The hoisting system for the spool lifting operation includes the slings, the lifting wire, and the winch. The slings connect the spool to the hook, and the lifting wire connects the hook and the crane. Due to the large

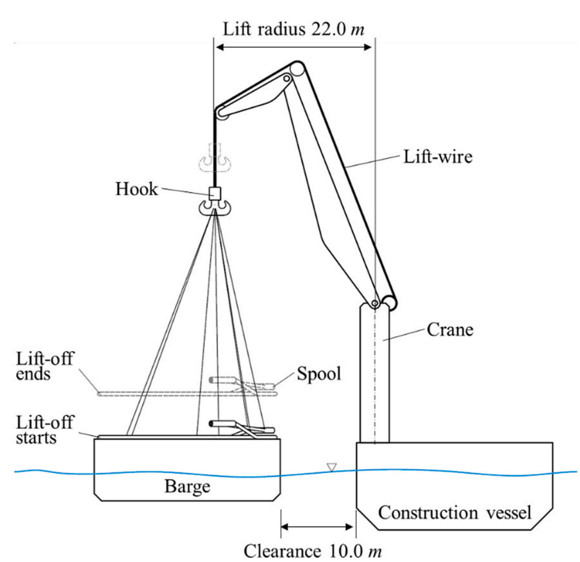


Fig. 2. Layout of the installation system for the lift-off from barge.

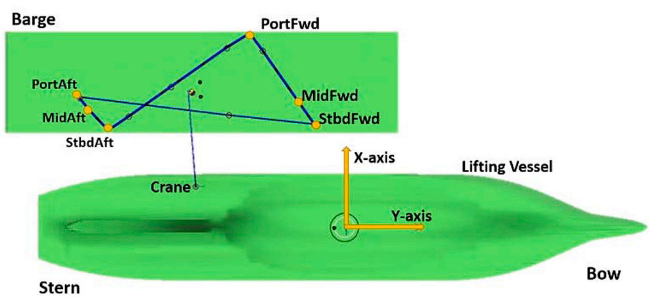


Fig. 3. Numerical model for lift-off from barge in SIMA-SIMO Software (Li et al., 2020a).

horizontal dimension of the spool structure, seven slings are arranged to distribute the loads on the spool. The locations of the seven slings on the spool are shown in Fig. 1.

3.2. Numerical methods

The detailed numerical models and methods for the two critical activities, i.e., the lowering through the splash zone and the lift-off from barge, have been studied in detail and published in Li et al. (2020a, 2020b). Given that the objective of this study is to compare the efficiency of two deployment methods, the numerical methods are briefly discussed here.

3.2.1. Lift-off from barge

When using deployment method 2, the spool is initially resting on the feeding barge. During lift-off, the hoisting system lifts the spool off from the deck of the barge before lowering it through the splash zone. The configuration of the installation system for the lift-off operation is illustrated in Fig. 2.

For this activity, hydrodynamic loads on the vessel and the feeding barge need to be calculated. It should be noted that hydrodynamic interactions between the barge and vessel are considered in the numerical analysis because they are in close vicinity during the lift-off operation. The hydrodynamic coefficients are obtained using the panel method program (DNV, 2010) in the frequency domain. In comparison with a single vessel standalone, the interactions are found to mainly influence the hydrodynamic coefficients of the feeding barge in roll, sway, and yaw directions (Parra, 2018).

The wire couplings through the seven slings and the lifting wire are modeled as linear springs. The flexibility of the spool is considered and distributed among the flexibility of the seven slings. Moreover, tugger lines are often used in the spool lifting operation to constrain the horizontal motions of the spool. In the current model, yaw stiffness has been added to the spool for simplicity, to represent the restoring forces from tugger lines.

The spools are often supported directly on the deck of the barge during transportation. Thus, the contact between the spool and the deck is steel to steel contact. During lift-off, if re-hit happens between the deck and the spool, the re-hit forces may be substantial due to the high stiffness of the deck contact (Karatas, 2020). As an alternative, retractable supporting units can be incorporated to support the spool. Once the spool is lifted, the supports will be retracted to avoid re-hit. However, these retractable supporting units need to be designed for this particular purpose, and thus the installation cost may be increased.

In the numerical model, the deck fenders are modeled using fender couplings. Each fender coupling includes a fender point and a fender plane, which provides friction force and compression forces when the two bodies have contact, see Li et al. (2020a) for details. Stiffness and damping properties based on the steel to steel contact are specified. In this study, six fender points are modeled. The forces on those fender points during lift-off are calculated to assess the operational limits. The numerical model was established in SIMA-SIMO software (SINTEF Ocean, 2020), and the top view of the model is shown in Fig. 3.

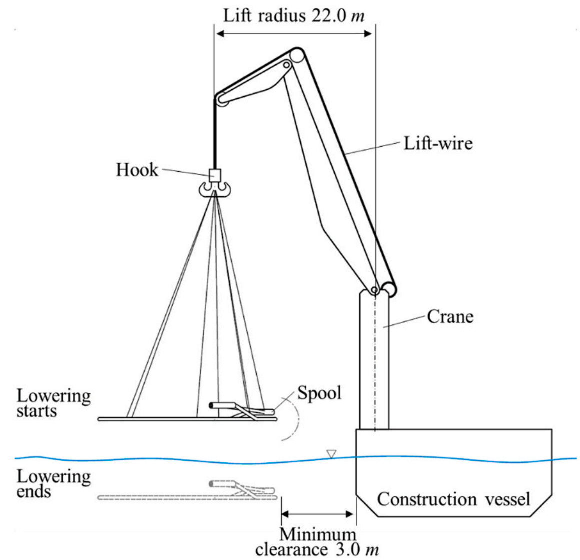


Fig. 4. Layout of the installation system for the lowering through the splash zone.

3.2.2. Splash zone lowering

The second critical activity is the lowering of the spool through the splash zone. For deployment method 1, this activity is performed after lift-off from own deck and over-boarding of the spool to the side of the construction vessel. For deployment method 2, the barge will move away from the construction vessel after the lift-off from barge, followed by the lowering through the splash zone. Fig. 4 shows the layout of the system for the lowering activity.

In this case, the hydrodynamic properties of the vessel alone should be used without interaction with the barge. The modeling of the hoisting system is the same as for the lift-off operation. The challenge in the numerical modeling of the lowering activity is to properly estimate the hydrodynamic forces on the spool when it crosses the splash zone. Depth-dependent added mass and damping coefficients need to be considered for the spool sections experiencing changing positions with respect to the instantaneous free surface. Moreover, the kinematics of the fluid where the spool sections are lowered are disturbed by the vessel motions. This is denominated as shielding effects from the vessel when the lifted object is close to the vessel. The response amplitude operators (RAOs) of the disturbed wave kinematics with respect to undisturbed wave elevation in the frequency domain can be obtained. These RAOs depend on the wave periods, and wave direction and vary with locations. They are implemented in the time-domain to calculate the instantaneous fluid kinematics, which are applied to obtain the wave loads on the spool sections using Morison's formula. A detailed implementation of the shielding effects and sensitivity studies refers to Li et al. (2020b).

3.2.3. Time-domain simulations

Responses analyses are performed for the established numerical models to solve the corresponding equations of the motion. The model for lift-off from barge consists of 21 degrees of freedom (DOFs) in total (the construction vessel, the barge, and the spool are modeled with 6 DOFs, whereas the hook is modeled with 3 DOFs). The model for the lowering operation consists of 15 DOFs. Step-by-step integration method is applied to solve the coupled equations of motion using Newmark-beta numerical integration with a time step of 0.02 s. The lifting wire is paid-in with a speed of 0.5 m/s during lift-off and is paid-out with a speed of 0.1 m/s during lowering operation.

Both the lift-off and the lowering operations are transient processes with nonlinear dynamic loads. Simulations using different irregular wave realizations are required to account for the variability of waves. Thus, enough wave seeds for the time-domain simulations are important to provide statistics to assess operational limits. The influences of the seed number on the allowable sea states using different total wave seed numbers were studied in Li et al. (2020b). Moreover, for lift-off operation, the wave seeds must be selected to exclude the unreasonable wave seeds that do not fulfill the judgement of the crane operators in the real operation before assessing the operational limits. This is done by checking the relative motion between the crane tip and the deck of the barge shortly after lift-off. This relative motion should increase within a defined short period after the activation of the winch (Li et al., 2020a). The wave seeds that do not fulfill such requirement are excluded. The wave realizations for the time-domain simulations are generated based on JONSWAP (Joint North Sea Wave Project) spectrum considering short-crested seas (DNVGL, 2017).

3.3. Assessment of operational limits

3.3.1. Operational criterion

Based on the recommended practice (DNVGL, 2016), the potential critical events that limit the lift-off from barge and the corresponding criteria are as follows:

1) Potential snap loads in the slings. The dynamic load capacity (DLC) of the sling should not be exceeded. Based on practical sling properties, the DLC of the sling is 318.8 kN.
2) Slack wire condition for slings. The criterion for the slack-sling condition is that the minimum dynamic tension in any of the slings during the operation should be larger than zero.
3) Re-hit of the spool against the supporting deck. Here, re-hit shall mean the event in which the object hits the supporting deck after any lift attempt. The static fender force on the spool is 145.2 kN for the initial condition when the spool is rested on the deck. Thus, this criterion requires that the re-hit force on the spool at any fender locations should be lower than the static force.

For the lowering operation, the above criteria 1) and 2) on snap loads and slack wire condition should also be fulfilled. Besides, the lowering operation also requires considering the following critical event and criterion:

4) Collision between the spool and the vessel. Minimum clearance between the spool and the vessel should be maintained during the lowering process. According to DNVGL (2016), 3m is used as the minimum clearance criterion in the assessment of allowable sea states for the spool lowering process.

Due to the large horizontal dimensions of the spool, a small rotational motion of the spool may cause large vertical displacements at the end of the spool. This can lead to possible high re-hit forces during lift-off, and possible slack wire and snap loads in the slings during both lift-off and lowering processes. Thus, the activities studied here are very sensitive to wave conditions. When searching for the allowable sea states, the above criteria should be fulfilled simultaneously for the corresponding activity. The assessment is carried out by comparing the selected statistical values of dynamic responses obtained from each wave condition with the limiting values from the criteria. The sea states that fulfill these criteria are considered as allowable sea states.

3.3.2. Allowable sea states

Based on the numerical analysis and the operational criteria, the operational limits in terms of allowable sea state parameters (H_S and T_p) have been obtained for the two critical activities. The allowable sea states are sensitive to different parameters, including sea state descriptions (such as wave spectral type, wave direction, wave spreading and wave components), numerical methods (such as the method to calculate hydrodynamic forces and inclusion of shielding effects) and statistical methods (the fitted distribution model of critical responses and the percentile to choose the extreme responses). Other factors, such as time-domain integration methods, time step, and seed numbers will also introduce uncertainties to the dynamic responses and thus the derived allowable sea states. Many studies have been devoted to quantifying uncertainties in the allowable sea state assessment for various operations (Guachamin-Acero and Li, 2018; Li et al., 2021). For complex operations relying on time-domain simulations, the quantification of the uncertainties requires comprehensive sensitivity studies. The uncertainties of the lowering operation of the spool were studied in Li et al. (2020b). Fig. 5 presents one example of the comparisons on the allowable sea states with and without shielding effects. It can be seen that the allowable sea states are sensitive to the shielding effects and the spreading index for short-crested waves. A detailed discussion on the comparison of sea states with and without shielding effects refers to Li et al. (2020b).

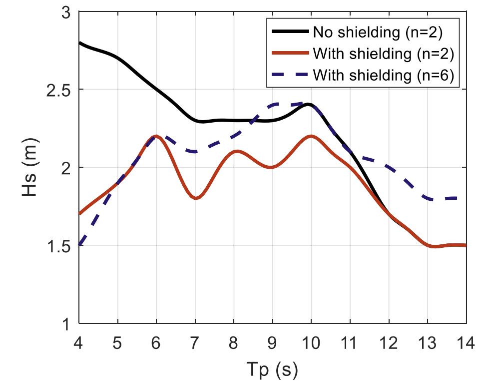


Fig. 5. Comparison of allowable sea states for the lowering through the splash zone (wave direction is 165 deg, 50 wave seeds, n is the index of the cosine spreading function for short-crested waves) (Li et al., 2020b).

Table 4
Allowable H_s values for different T_p for the two critical activities (wave direction is 165 deg, JONSWAP spectrum with spreading index $n = 6$, shielding effects included).

Critical operation	T_p = 4s	T_p = 6s	T_p = 8 s	T_p = 10 s	T_p = 12 s	T_p = 14 s
Lift-off from barge	1.1 m	1.1 m	1.0 m	1.2 m	1.2 m	1.0 m
Splash zone lowering	1.5 m	2.2 m	2.2 m	2.4 m	2 m	1.6 m

In this paper, the study on uncertainties in the allowable sea states will not be discussed in detail here. The allowable sea states corresponding to the most realistic cases are chosen based on the previous work by Li et al. (2020a, 2020b) and applied in the weather window analysis, see Table 4. As shown in the table, the allowable H_s for lift-off from barge are substantially lower than those for the lowering operation. As mentioned in Sec. 2.2, the low allowable sea states for lift-off from barge may result in long waiting on weather for deployment method 2.

4. Weather window analysis

Weather window analysis is performed to evaluate the operability and efficiency of the two deployment methods. It is important to choose the potential months with minimum total installation time to reduce the costs. Often, the project duration lasts for weeks to months, and the

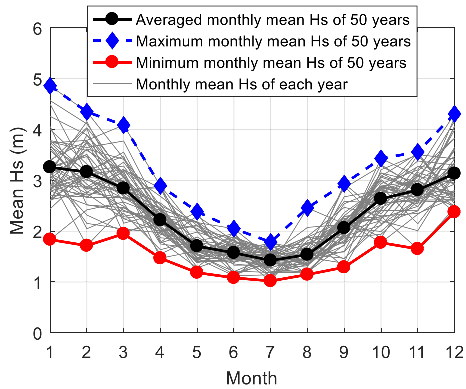


Fig. 6. Monthly mean H_s values from the 50 years' hindcast data.

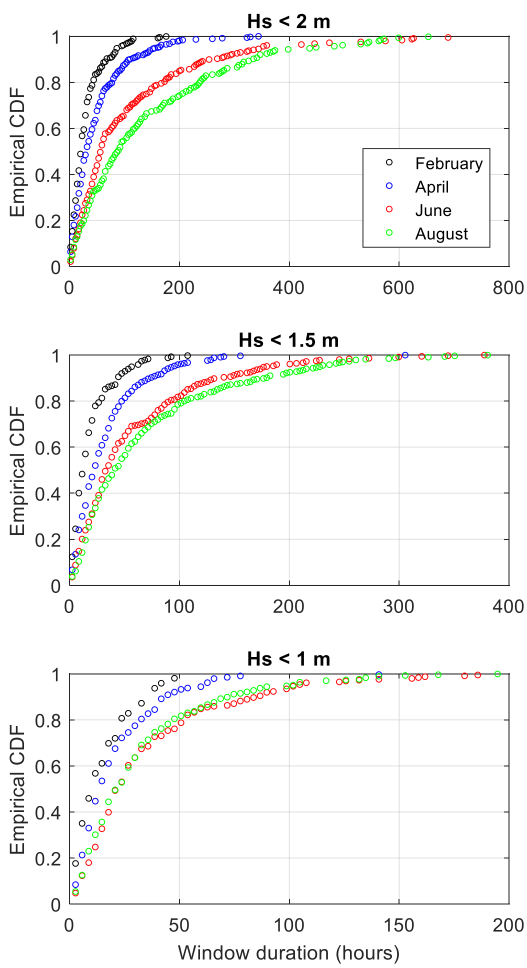


Fig. 7. Empirical CDF of the weather window durations for different H_s limits based on 50 years' hindcast data.

weather conditions for the planned project period are unpredictable. Thus, weather window analysis using hindcast data from the past years is often adopted to estimate the total installation time.

4.1. Wave conditions

The hindcast wave data of one reference site at the Barents Sea is chosen for the weather window analysis in this study. The coordinate of this site is [72.02°N, 22.1°E] with water depth of around 350 m, and it is southeast of the Johan Carlsberg field. The hindcast data are from the Norwegian Reanalysis Archive 10 km (NORA10) database, providing wind and sea states characteristics every 3 h from September 1957 to the present (Reistad et al., 2011). The NORA10 hindcast data have been widely used in the planning phase of different offshore activities and were validated against offshore measurement data (Bruserud and Haver, 2016). 50-year wave data from 1961 to 2010 are applied in this study. The hindcast data provide H_s, T_p and wave direction for the total sea, the wind sea, and the swell sea.

Table 5
Average number of the weather windows per year (and the average duration) for different H_s limits and different months.

Number (Duration)	$H_s < 2\,m$	$H_s < 1.5\,m$	$H_s < 1.0\,m$
February	5.8 (31.2 h)	4.1 (19.6 h)	0.9 (15.5 h)
April	7.4 (50.5 h)	6.8 (33.6 h)	3.4 (21.3 h)
June	5.2 (109.7 h)	7.2 (58.3 h)	5.3 (36.0 h)
August	4.4 (138.9 h)	6.7 (69.1 h)	6.1 (32.9 h)

The yearly and seasonal variations of the wave heights for this site are firstly investigated. Fig. 6 presents the averaged, maximum, and minimum monthly mean H_s. The mean H_s values for individual years are also presented. In general, higher mean H_s values occur in the winter months from October to March than those in the summer season from April to September. Often, it is preferable to perform offshore installations in the summer months for weather-sensitive operations to reduce the risks and installation costs. However, for many occasions due to challenges of the project schedule, vessel availability and other practical issues, the installations may need to be carried out in winter. In this case, the planning of the installation activities must be devised to ensure the safety of the operations by considering measures to increase the operational sea states and to make robust contingency plans.

From Fig. 6, a large yearly variation of the mean monthly H_s values is also observed. The variabilities are also larger in the winter months than those in the summer months. Even in the summer months, the differences between maximum and minimum mean H_s are larger than 0.8 m, representing large uncertainties. This indicates the importance to perform weather window analysis based on a large database of wave conditions to provide reliable statistics of the installation time for a given site.

For an operation with sequential activities, waiting on weather often happens before executing the weather-sensitive activities with low operational limits. The lowering operation for deployment method 1 and the lift-off operation for deployment method 2 have the lowest allowable sea states with H_s limits between 1 m to 2.5 m, as shown in Table 4. Three H_s limits based on the averaged allowable H_s values from Table 4 are used to study the weather windows by simply comparing the hindcast total H_s values with these selected limits. Fig. 7 presents the empirical cumulative distribution functions (CDF) of the weather window durations for selected H_s limits based on 50 years' data.

As expected, the duration of the weather windows reduce significantly as the H_s limit decreases. The duration of the weather window is in general shorter in February and longer in June or August. Moreover, it is seen that the number of available windows for $H_s < 2\,m$ is higher than those for lower H_s limits. Table 5 lists the average number of the weather windows per year and the average duration in hours (shown in parentheses). When H_s limit is 1 m, both the number of windows and the duration are in general lower than those with higher H_s limits, even in the summer months. This low operability calls attention to the challenges of installing many spools using deployment method 2. When H_s limit is 2 m, the average duration of the weather windows in summer is longer than 100 h (more than 4 days). With around 4–5 windows of over 100 h on average each month, potential operability of over 60% can be expected. Thus, based on the site condition, some preliminary results can be already obtained by only studying the hindcast data. However, to provide more extensive results, weather window analysis based on both the hindcast data and operational limits for all activities should be

Table 6
Input of deployment method 1 for weather window analysis.

Spool No.	Activity group	Activities	Reference period (hours)	Allowable sea states
1	1	Transportation to site	6	$H_s = 3\,m$ for all T_p
	2	Preparation and deployment	3	Allowable seas states for **lowering operation** in Table 4.
	3	ROV survey	3	$H_s = 3\,m$ for all T_p
	4	Sailing back to harbor	6	$H_s = 3\,m$ for all T_p
2 to N	Repeat the activities No. 1–4 and corresponding input for each spool			

Note: total duration of installing N spools (excluding waiting time) is $(18 \times N)$ hours.

Table 7
Input of deployment method 2 for weather window analysis.

Spool No.	Activity group	Activities	Reference period (hours)	Allowable sea states
1	1	Transportation to site	6	$H_s = 3\,m$ for all T_p
	2	Preparation and deployment	3	Allowable seas states for **lowering operation** in Table 4.
	3	ROV survey	3	$H_s = 3\,m$ for all T_p
2	4	Preparation, lift-off from barge and deployment	3	Allowable seas states for **lift-off from barge** in Table 4.
	5	ROV survey	3	$H_s = 3\,m$ for all T_p
3 to N	Repeat activities No. 4–5 and corresponding input for each spool			
–	Last	Sailing back to harbor	6	$H_s = 3\,m$ for all T_p

Note: total duration of installing N spools (excluding waiting time) is $(6 \times N + 12)$ hours.

carried out.

4.2. Input for two deployment methods

The two deployment methods have been discussed in Sec. 2. Here the key input for the two methods that will be used for the weather window analysis are summarized in Table 6 and Table 7, respectively. The input includes activities, reference period and allowable sea states for each activity group. The reference period (duration) of each activity is based on the operational procedure of similar projects and includes contingency time. The allowable sea states for the critical activities (lowering operation for method 1 and lift-off from barge for method 2) refer to the results given in Table 4. For less sensitive operations, including transportation and ROV survey, a constant H_s limit of 3 m is used based on practical experiences. For a total number of N spools, the net installation time without any waiting on weather is also given in the tables. It is seen that the net installation time is lower using method 2 (for $N > 1$) because feeding barges are used to transport the spools instead of the construction vessel.

4.3. Estimating the total installation time

Weather window analysis using hindcast data can estimate the total installation time for different total number of spools using two deployment methods. Here, the total installation time for the defined installation task corresponds to the duration of installing all spools, including the time for all activities listed in Table 6 (and Table 7) and the time of waiting on weather. Normally, during the planning phase, the starting time of the project is decided, and the vessel will be rented from the predetermined date until the completion of the whole project. If the weather condition is not suitable, waiting time before and between the activities is expected and should be accounted for in the total time, which reflects the total cost for renting the vessels.

The weather windows for each activity group can be identified based on the hindcast wave data time history. For activities that are only limited by H_s, a direct comparison of the allowable H_s with hindcasted total H_s is performed. For the critical activities with allowable limits in terms of both H_s and T_p, the allowable H_s for each hindcasted T_p is firstly calculated and then compared with the hindcasted H_s. A detailed description of the weather window analysis can refer to Guachamin Acero et al. (2016). It should be mentioned that the required weather window for each activity must be identified in sequence based on the installation procedure and their respective duration.

With the identified weather windows for each activity group, the waiting time between these windows is also found. By counting the hours from the starting time to the completion of all the activities to install N spools, the total installation time is thus obtained. Such analysis is repeated for changing N using two deployment methods, and the results are discussed in the next section.

4.4. Results and discussions

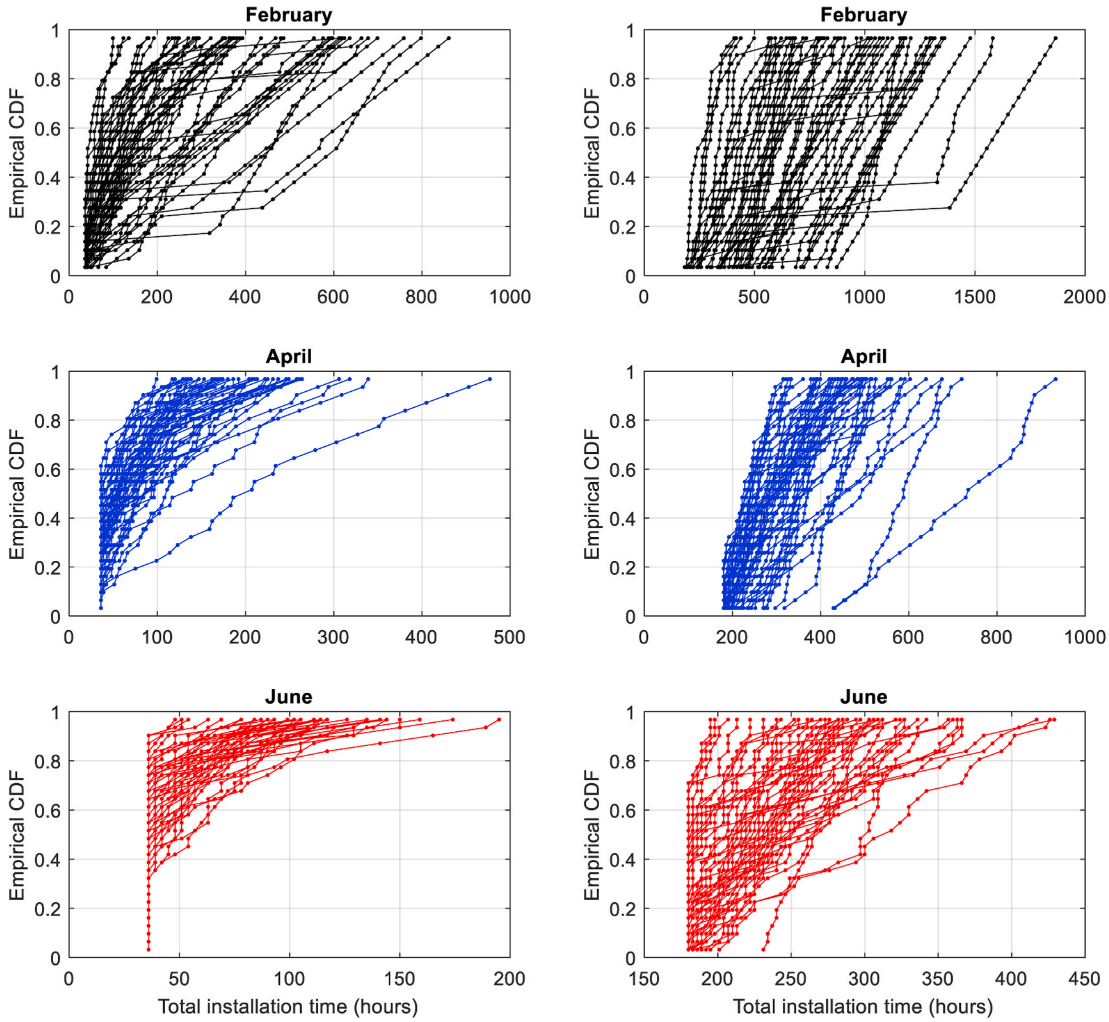
To obtain sufficient sample data of the total installation time for different months, weather window analysis for each installation case is repeated daily assuming that the starting time for the installation is at 0 h each day. This setup ensures a 24-h difference between the starting time of each analysis, and thus reduces the correlation between the sample data of the total installation time. Take April as an example. If the operation is planned to start in April, a sample size of 30 (by assuming the installation starts at each day in April) for the total installation time can be obtained using the hindcast data for a given year. Based on this sample data, an empirical CDF function for this year can be established. By repeating the weather window analysis using 50 years' hindcast data, a total sample of 1500 total installation time for this month can be generated.

4.4.1. Comparison of total installation time

Fig. 8 compares the empirical CDF of the total installation time starting at three different months. For each subfigure, the empirical CDF functions based on yearly data are displayed together. Strong yearly variations of the distributions are observed for all selected three months, which are consistent with the variation of the wave conditions as illustrated in Fig. 6.

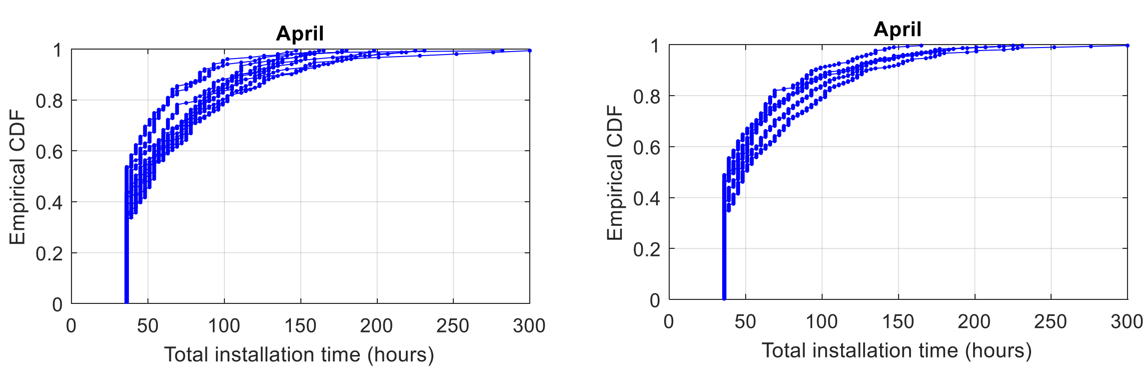
The scattering of the distributions in Fig. 8 reduces from February to June with reduced total installation time. This is because the waves become less severe in the summer months. Two total numbers of spools ($N = 2$ and 10) are compared in Fig. 8. When the spool number increases from 2 to 10, the spread of the yearly empirical distribution increases greatly for all three months. More activities need to be carried out to complete the installation task when N increases, which demands more weather windows. Meanwhile, the waiting time between the weather windows also increases and introduces larger yearly deviations. Moreover, the limited sample size of each month annually (for example 30 data in April each year) also introduces large uncertainties in the empirical CDF, which contributes to the large spread of the results.

To further illustrate the statistical uncertainties due to the size of the sample data, Fig. 9 presents the empirical CDF of the total installation time for deployment method 1 in April (for $N = 2$) using 5 years' and 10 years' hindcast data as input, respectively. When using 5 years' hindcast as input, the total 50 years' data are divided into 10 sets of 5 years. The same applies when using 10 years' input data. The empirical CDF using different sets are presented together to show the spreading of the



(a) Deployment method 1 ($N = 2$). (b) Deployment method 1 ($N = 10$).

Fig. 8. Yearly empirical CDF of the total installation time using deployment method 1.

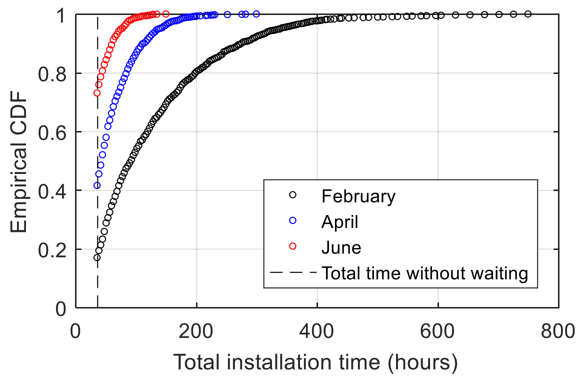


(a) Using 5-year hindcast data. (b) Using 10 years' hindcast data.

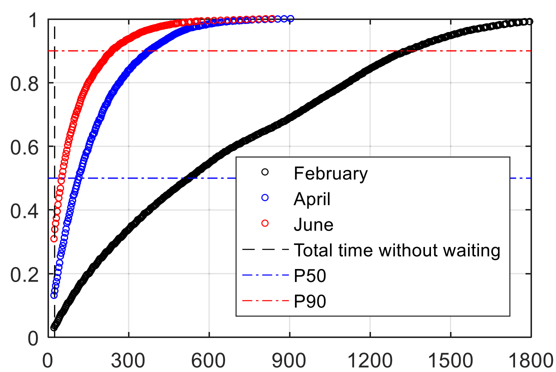
Fig. 9. Empirical CDF of the total installation time for April (deployment method 1, $N = 2$).

distributions. Compared to Fig. 8 (a), the scattering of the empirical CDF narrows down significantly with the increasing length of the input data. Taking the values corresponding to 50% of the CDF as an example, the range of the values reduces from [36, 208] hours based on yearly PDF to [36, 54] and [39, 51] hours based on 5 years' and 10 years' PDF, respectively. Thus, it is evident that a longer input hindcast data provides more reliable estimate of the statistic values. However, it is difficult to suggest a minimum requirement of data because the problems are case-dependent. If limited hindcast data are available, it is recommended to evaluate the uncertainties by statistical methods, such as Monte Carlo simulations.

In this study, to reduce the statistical uncertainties, all 50 years'



(a) Deployment method 1 ($N = 2$).



(b) Deployment method 2 ($N = 2$).

Fig. 10. Empirical CDF of the total installation time for 2 spools based on 50 years' data.

hindcast data for each month are used for further analysis. The empirical CDF using all hindcast data for three selected months are shown in Fig. 10 for $N = 2$ case. The repeated sample data with the same installation time are removed in the figure. Compared with the monthly empirical distributions in Figs. 8 and 9, a larger sample by including all 50 years' results provides a more reliable and smoother distribution.

Based on the installation procedure, the installation time for two spools without any waiting time are 36 h and 24 h, respectively, for two deployment methods. As shown in Fig. 10 (a), the probability of installing 2 spools without any waiting time is around 75% using deployment method 1 if the operation starts in June. This probability drops to around 40% and 18% if the operation starts in April and February, respectively. The whole empirical distribution moves noticeably to the right-hand side from June to February, indicating a significant increase of the waiting time in the winter months.

A similar trend is observed for deployment method 2, as shown in Fig. 10 (b). However, for the same target total installation time in the same month, the probability of completing the operation using deployment method 2 is much less than that using method 1. This indicates a much longer waiting time using method 2 due to the lower allowable sea states of the lift-off activity. Moreover, the probabilities of completing the installation without any waiting time are also lower using method 2, and they are around 30%, 12% and 3% for June, April, and February, respectively. To discuss how the total installation time changes with the starting months, the number of spools and the deployment methods, the total installation time corresponding to the probability of 50% (P50) and 90% (P90) in the empirical distribution, as indicated in Fig. 10 (b), are used for further comparison.

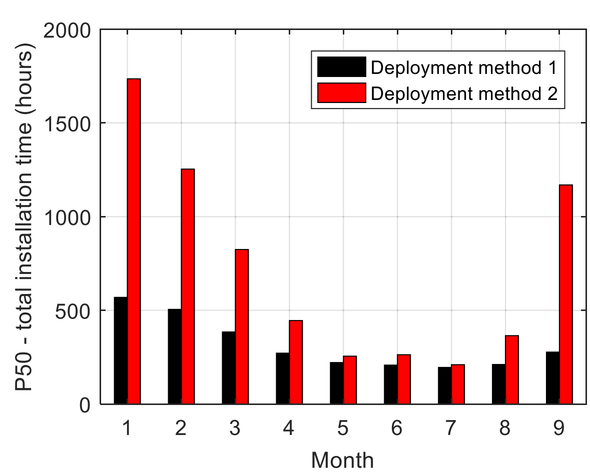
The monthly variation of the P50 total installation time for two deployment methods are compared in Fig. 11. As mentioned, weather-sensitive operations are often performed in the summer seasons (from May to August) to reduce waiting time and the installation costs. Here, the results for January to April are also included to provide a wider overview on the monthly change of the installation duration. As expected, the installation time is much lower when the operation starts in May to August than in January to April for all presented cases in Fig. 11.

When spool number $N = 2$, deployment method 2 consumes much more hours compared to method 1 for all months. However, when the total number of spools increases to 10, a similar total installation time from May to July is observed among the two deployment methods. This indicates that the extra waiting time due to the low allowable sea states of the lift-off from barge using deployment method 2 is comparable to the transportation time of the construction vessel using deployment method 1. It is expected that if N or the transportation duration increases, deployment method 2 may consume less installation time than method 1 in the summer months.

4.4.2. Sensitivity study on the total number of spools and transportation time

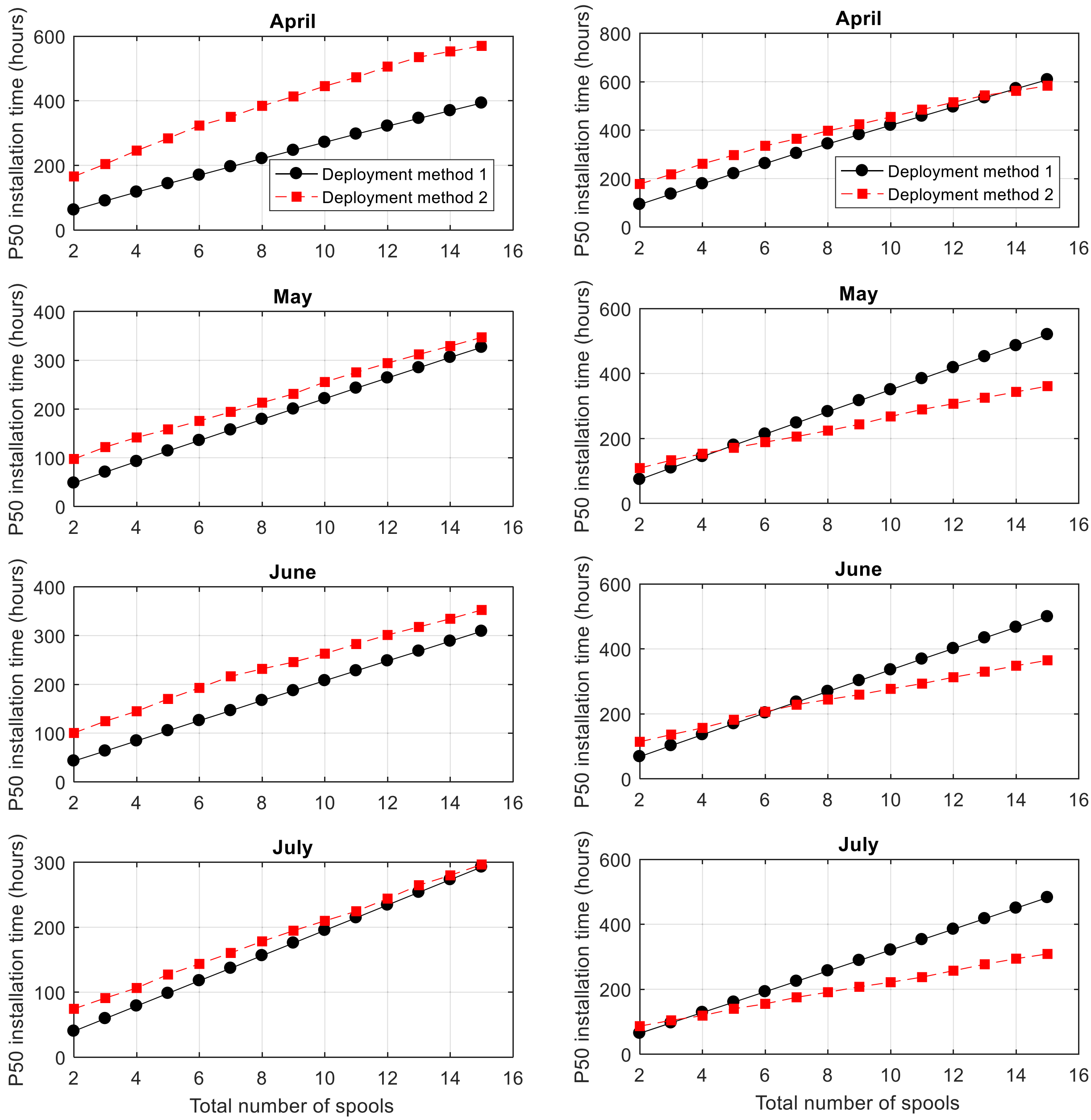
Weather window analysis for different N and different transportation durations has been carried out. The P50 total installation time for $N = 2$ to 15 with transportation time of 6 h and 12 h is compared in Fig. 12. Four starting months from April to July are chosen for the comparisons. When the transportation time is 6 h, using deployment method 1 is more efficient for different N. However, the differences in time are very small

(a) Total spool number $N = 2$.



(b) Total spool number $N = 10$.

Fig. 11. P50 total installation time for operations starting at different months.



(a) Transportation time of 6 hours . (b) Transportation time of 12 hours.

Fig. 12. Comparison of P50 total installation time for different total number of spools.

for $N > 12$ in May and July.

If the installation site is further away and longer transportation time is required, deployment method 2 using feeding barge for transportation shows a great advantage. When the transportation time per single trip is 12 h, the total installation time using deployment method 2 is less than using method 1 for $N > 6$ when installing from May to July. Despite the lift-off from barge is riskier with lower allowable sea states than the lowering operation, the waiting time for lift-off from barge using method 2 in the summer months may be shorter than the transportation time using deployment method 1 when the transportation distance is long. With increasing N, the accumulated transportation time dominates the total installation time for method 1, making this deployment method less preferable.

4.4.3. Influence of lift-off allowable sea states on deployment method 2

It is observed from Fig. 12 that if 10 spools need to be installed in July, the P50 total installation time is around 200 h when the transportation time is 6 h using both deployment methods. For deployment method 1, the net installation time without waiting time is 180 h. Thus, the potential to increase the installation efficiency using method 1 is limited since only a very short time (around 10%) is used for waiting on weather. On the other hand, the net installation time is only 72 h using deployment method 2, and more than 60% of the total installation time is for waiting on weather based on the current input. Therefore, there is great potential to increase the efficiency if the waiting time using deployment method 2 can be reduced. As discussed, the waiting time is mainly caused by the low allowable sea states for the lift-off from barge.

To increase the allowable sea states for the lift-off from barge, both passive and active methods have been proposed by Karatas (2020). The active methods can incorporate winch control during lift-off operation to prevent the occurrence of the re-hit between the spool and the deck of the barge. The active control requires the development of a reliable

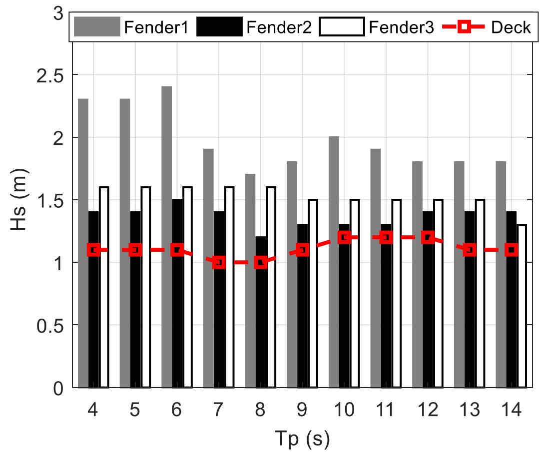


Fig. 13. Allowable sea states for lift-off from barge using different fender models.

control algorithm. The passive method, on the other hand, is proposed to use fenders between the spool and the deck during the operation. The intention is to absorb the impact energy and reduce the potential re-hit forces during lift-off. Sensitivity studies were carried out to compare the influence of different fender properties on the allowable sea states by Li et al. (2020a). Fig. 13 presents the allowable sea states for the lift-off from barge including three different soft fender models in the previous study. The allowable sea states for 'Deck' corresponds to the case directly lift-off from the deck of the barge (as listed in Table 4), which are used in the weather window analysis in the previous sections.

As shown, all three soft fender models can increase the allowable sea state for the critical lift-off operation compared to the 'Deck', indicating the potential to reduce total installation time for deployment method 2. However, the application of these fenders was only studied numerically and has not been validated in offshore operations so far. Thus, for a conservative comparison, the allowable sea states based on 'Soft fender 2' are applied in the weather window analysis.

Based on the results in Fig. 12 for transportation time of 6 h, the total installation time using deployment method 2 with the selected soft fender is obtained and presented in Fig. 14. Significant reductions in the total installation time using method 2 are observed, especially for large N. Take $N = 10$ as an example. The total installation time using deployment method 2 in July reduces from around 200 h–120 h when using the soft fender instead of the deck fender. Among the total time, the waiting time reduces from around 64%–40%. This proves the significant importance of increasing the allowable sea states for the lift-off from barge operation. If this improvement of allowable sea states can be applied in practice, deployment method 2 is preferable especially when the project requires to install many spools in the same campaign.

4.5. Summary on the weather window analysis

The comparison and sensitivity studies performed in this section reveal that the total installation time of the project depends on many parameters, including the total number of spools, the planned seasons, the distance from harbor to the offshore site, and the allowable sea states of the critical activities. These parameters, in turn, are relevant to choosing the deployment method.

The deployment method 1 shows a great advantage compared to deployment method 2 when the transportation distance is short, or when the total number of spools is less than 10 with increased distance. This advantage is more noticeable when the project is planned to be carried out in non-summer months. The long waiting time for deployment method 2 due to very low allowable sea states for lift-off from barge results in much longer total installation. However, for longer transportation distance, deployment method 2 becomes more beneficial

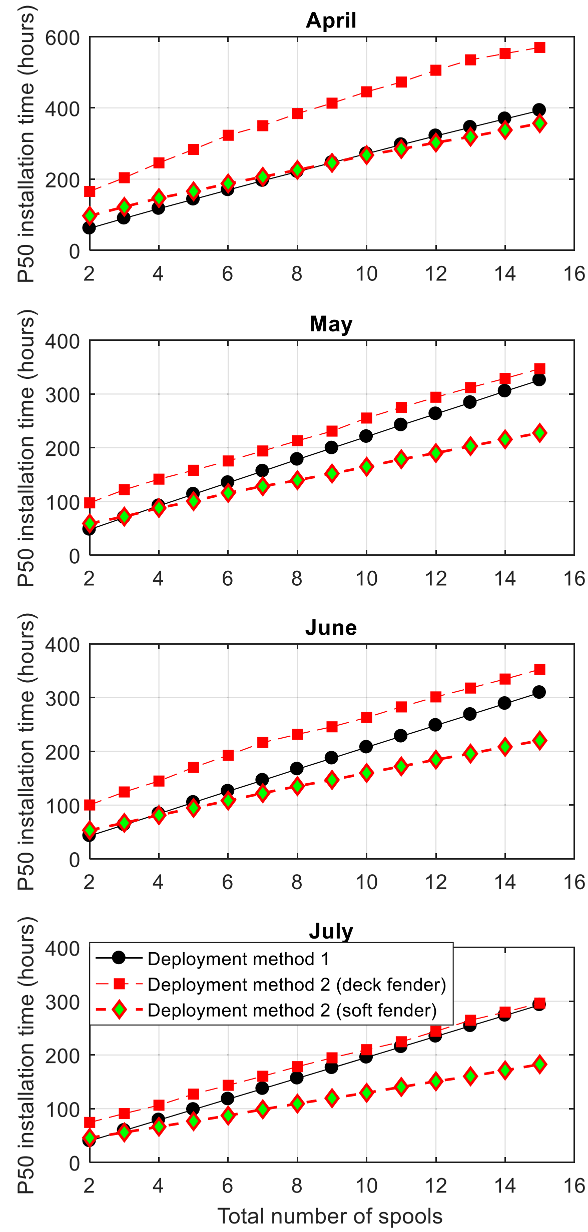


Fig. 14. P50 total installation time for different total number of spools (transportation time 6 h).

given that the use of feeding barges increases the availability of the construction vessel at the offshore location compared to method 1.

Moreover, it is also observed that for both methods the waiting on weather time accounts for a large percentage of the total installation time. This is because of the low allowable sea states for the critical activities, i.e., the lift-off from barge and the lowering through splash zone. It is crucial to increase the allowable sea states by improving the installation method or equipment. One possible way to increase the allowable sea states for the lift-off from barge using fenders is discussed. The use of the soft fender can increase the averaged allowable H_s from around 1.11 m–1.35 m, resulting in around 24% decrease of the waiting time for a whole project to install 10 spools in July. Thus, to further reduce the installation total time, efforts should be made to increase the operational limits for the critical activities.

This study is focused on the comparison of the total installation time, which determines the renting cost of the construction vessel. The cost of the barges in this case is assumed secondary. However, if the project needs to install many spools (for example 15 spools) with long transportation distance, multiple barges may be needed. This is to ensure that the construction vessel performs the deployment task whenever weather permits without waiting for the feeding barge. In this case, the renting cost of multiple barges for deployment method 2 should be considered when comparing with deployment method 1. Therefore, in the real engineering projects, the choice of deployment methods should consider all these aspects in the planning phase.

5. Concluding remarks

This paper studies and compares two deployment methods for multiple spool installations. The objective is to provide suggestions for the selection of installation methods in the planning phase. The main approach applied is to perform comprehensive weather window analysis to quantify the total installation time for the two methods using 50 years' hindcast data. The input for the weather window analysis is based on practical installation procedure, whereas the allowable sea states for critical activities are obtained from numerical methods using time-domain simulations. It is found that the allowable sea states for the critical activities are in general low for the large spool deployment.

The chosen offshore site for the weather window analysis is close to an existing offshore field in the Barents Sea. The wave condition shows large yearly and seasonal variations, indicating the uncertainties in the weather window analysis. Statistical values of the total installation time corresponding to 50% non-exceedance are used for comparison of different installation cases. The influences of the total number of spools, the transportation time, and the allowable sea states of critical activities on the total installation time are discussed in detail. It is concluded that deployment method 1 gives lower installation time when the transportation distance is short, or when the total number of spools is less than 10 for a longer distance. When the transportation distance doubles, deployment method 2 becomes more beneficial in the summer months for a large number of spools. The use of the soft fender for lift-off from barge can increase the averaged allowable H_s, and thus significantly decrease the waiting time for deployment method 2.

However, the choice of deployment method also depends on other factors, such as vessel availability, project schedule, and other practical issues. The results from this study can be used as a reference for decision-making in the early planning phase of the project. Moreover, the methodology applied in this study, including numerical methods, weather window analysis, and sensitivity studies can also be applied for similar types of marine operations.

CRediT authorship contribution statement

Lin Li: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Xinying Zhu:** Conceptualization, Methodology, Resources, Writing – review & editing. **Carlos Parra:** Methodology, Formal analysis, Writing – review & editing. **Muk Chen Ong:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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