CASE STUDY OF A JACK-UP GOING ON LOCATION IN A MULTI-MODAL SEA STATE

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ABSTRACT
Going-on-location of jack-ups is a critical operation typically limited by wave-induced vessel motions. Making an educated go / no-go decision based upon all available information is paramount to safe and effective Wind Turbine Generator installation campaigns. The available information has two parts: 1) the knowledge of the vessel and planned operation and 2) the knowledge of the (forecasted) environment. Part 1) should be site-specific and is obtained from dedicated simulations using a sophisticated model [1]. Part 2) is the topic of this paper.

Available information regarding the current and upcoming sea state is available, in order of level of detail, as: 1) total sea state parameters (H_s, T_p, Dir), 2) sea state parameters per wave system e.g. wind sea and swell, and 3) a full 2D wave spectrum. For each of these, a decision-making method is available. These decision-making methods are compared and verified to real cases.

The Vole au vent jack-up vessel has successfully performed a significant number of field moves over the last 10 years on various Offshore Wind Farms in Europe and North America. Jan De Nul has developed a culture of continuous logging of performance of its offshore assets. The resulting data are continually used to increase understanding of assets and their behavior. This understanding is used to increase both safety and efficiency of operations. The resulting historical database is tapped into for this study.

It is concluded that total sea state parameters alone should not be used for decision-making. Using sea state parameters for individual wave systems (e.g. wind sea and swell) has high accuracy, but is elaborate and the optimal vessel heading is not evident. Calculation aides support the crew to optimize the vessel heading and enable straightforward determination of workability. Dedicated on-board consoles do the same, but use the 2D wave spectrum directly for highest accuracy.

KEY WORDS: jack-up, installation, decision-making support, motion measurement

Figure 1: Wind turbine installation vessel

INTRODUCTION

Vole au vent, Figure 1, is a four-legged jack-up, owned and operated by Jan De Nul. Built in 2013, she has a DWT of 8,000 t and a crane with 1,500 t lifting capacity. She is over 140 m long and over 40 m wide. The legs are tubular, at 4.8 m diameter and over 90 m length.

The hydraulic jacking system, Figure 2, consists of dual working rings, allowing continuous jacking at high-speed, or at high load.

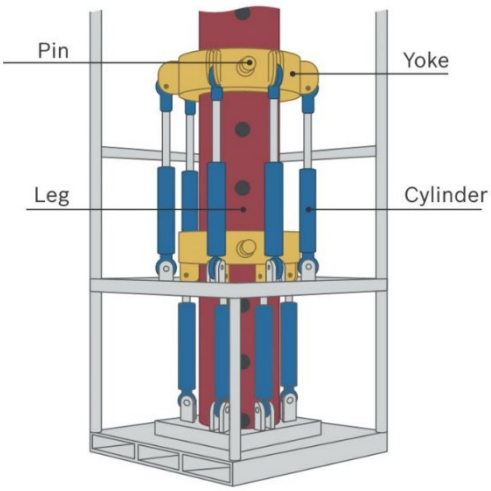

Figure 2: typical hydraulic jacking system

Going-on-location, or installation of the jack-up, is a weather restricted operation where wave-induced vessel motions play an important role in the overall workability. The structural capacity of the jacking system and legs is not to be exceeded in the process. Proper tools and procedures must be in place on board to make an educated go / no-go decision to start the installation of the jack-up.

Such tools and methods are the topic of this paper.

Three decision-making methods are applied and verified w.r.t as-measured behavior. One method takes into account the forecasted *total sea state* only. This is the simplest method, as only one parameter needs to be evaluated. This simplicity is also the main drawback, as it does not consider relevant information about the potential existence of multiple wave systems and it neglects the spectral and directional shape of the energy distribution. This method was the first to be adopted by the industry.

The second method takes into account the parameters of individual wind wave and swell systems, which adds significant relevant information. The accuracy of this method is significantly higher than the previous one, but adds complexity to the decision-making process, increasing the need for tools and calculators.

The third method is most sophisticated and takes into account the entire forecasted 2D wave spectrum and combines this with a frequency domain method to determine the stochastic maximum response. The amount of data involved cannot be processed by hand and the method necessitates a dedicated console on-board, such as the MO4 system.

Vessel motions, jacking system loads, forecasted wave parameters and 2D wave spectra were logged and used to compare values as predicted by each of the three decision-making methods in order to make a quantified comparison.

Numerical simulation of going-on-location is used throughout this paper. The actual method of simulation is summarized, but is not the topic of this paper. For those interested, ref [1] of 2023 presents this method in detail.

To make an educated go / no-go decision, real-time information regarding the current and upcoming sea state is required. This first ingredient to decision making is the topic of the next section.

REAL-TIME SEA STATE INFORMATION

Real-time (or nowcast) and forecasted sea state information is provided by metocean bureaus. This metocean forecast typically comes at a six-hour interval and is used on-board to plan operations accordingly. This section starts by diving a little deeper in the mechanics of the metocean forecast / nowcast.

Nowcast sea state information is best taken from global forecasting models such as ERA5 or WAVEWATCH III, which is blended with observations and aided by a specialized metocean bureau's expertise. Often high resolution local nested (SWAN) models, e.g. [2], [3], which contain more information on the bathymetry are created. These are being fed on the boundaries by global model data. For marine operations relatively close to shore it is typically advised to make use of high-resolution models as they are able to capture local effects. The SWAN model considers discretized patches of sea. Wave energy inside a patch is recorded in discrete bins of direction and frequency. i.e. each part of the total wave energy within a patch has a direction and a frequency. The total wave energy is represented as the total significant wave height H_s. The wave frequency, through the dispersion relation, is used together with wave direction to determine the energy flux exiting the patch into neighboring patches. Similarly, the influx from neighboring patches is determined. In addition, wave energy is locally dissipated (wave breaking) and created (wind).

The above provides a (overly) simplified view of how wave energy is forecasted. The wave energy, discretized per direction and frequency, is a 2D wave spectrum and can be visualized as in Figure 3. This is the raw output, i.e. without further processing, of a SWAN model.

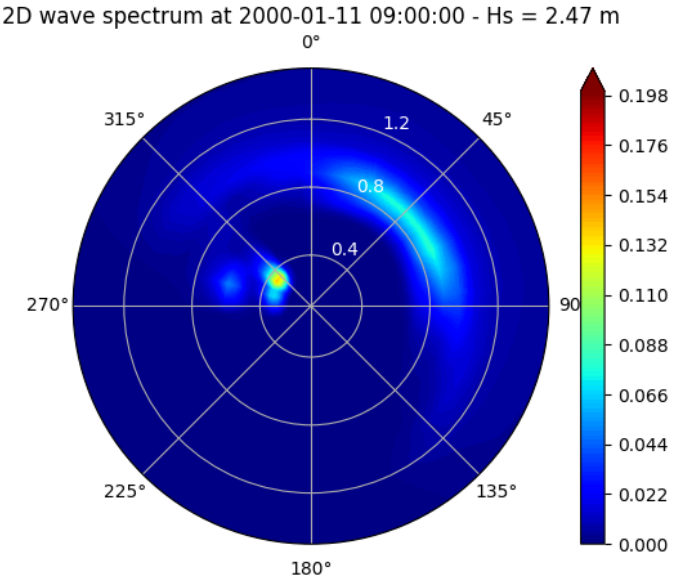

Figure 3 Example of a 2D wave spectrum (radial axis is frequency in [rad/s])

The 2D wave spectrum is the most complete, most detailed view of a sea state that can be obtained. The amount of data contained in it is very large and requires tools to process. Therefore, the metocean bureau assigns comprehensible parameters to describe the sea state. A forecaster may decide to change and update the parameters based on experience and observations, an intervention that is not as straightforward to perform with a 2D wave spectrum.

Typically, several wave systems that make up the sea state are identified, see e.g. [4]. This is a multi-modal sea state. Wave parameter identification is not straight-forward and often utilizes complex algorithms to distinguish between wave systems, especially if these systems share energy in the same directional or spectral bin. The first identified wave system is a *wind sea* system, which is typically of short period and choppy i.e. high directional spreading. See, for instance, the system coming from NE in Figure 3. The second and following wave systems are typically *swell* systems. These have longer periods and low directional spreading. See for instance the system coming from NW in Figure 3.

Each wave system is characterized by three parameters. These are significant wave height H_s, mean period T or peak period T_p and mean direction D.

In addition to these sea state parameters assigned to each wave system, the total sea state is characterized by similar parameters: $H_{s;total}$, $T_{p;total}$ and D_{total}. The definition of $T_{p;total}$ and D_{total} differ per metocean bureau, as will be exemplified in the final sections of this paper. The definition of $H_{s;total}$ is unambiguous. It represents the total wave energy. It relates to the $H_{s;i}$ of individual wave systems like so:

$$H_{s;total} = \sqrt{\sum {H_{s;i}}^2}$$

Summarizing, there are three ways to view a sea state (in order from most simplified to most complete):

1.) Total sea state, represented by parameters $H_{s;total}$, $T_{p;total}$ and D_{total}.
2.) Multiple wave systems, each represented by parameters H_s, T and D.
3.) Full 2D wave spectrum, representing wave energy in discrete bins of T and D

A decision-making method exists for each of these three views into the sea state. This paper attempts to show the accuracy of each method through application and verification w.r.t measurements and simulations. First however, the simulation method is summarized.

SIMULATION MODEL FOR GOING-ON-LOCATION

A model of the vessel suitable for simulation of going-on-location is performed in accordance with the framework as outlined by Holland, 2023[1]. This framework elaborates on work by Chakrabarti, 2012 [5], and by Vazquez et at. 2016 [6] and 2017 [7], endorsing that only non-stationary models with moving legs are suitable. The framework enables fully independent modelling hydrodynamics, structural behavior and soil-spudcan interaction through introduction of a multi-body model.

The soil-spudcan interaction model accounts for different behavior in virgin loading, unloading and reloading. The horizontal load is modelled through a stick-slip model, with maximum resistance being dependent upon instantaneous vertical loading. Doing so, it applies aspects of kinematic hardening behavior as per Houlsby and Puzrin, 2016 [2].

This simulation model was used to determine the allowable H_s for a range of wave directions and a range of spectral peak periods. To do so, multiple simulations are performed for each wave direction D, for each spectral peak period T_p, for several significant wave heights H_s. In all cases, the waves are long-crested and the frequency distribution of wave energy is according to JONSWAP. For each simulation, the results in terms of loads and accelerations are compared to capacities and limits to determine if the operation was within acceptable limits. A realistic example outcome of allowable H_s, to some extent fictionalized, is presented in Table 1. This workability is used throughout the paper.

The sea state used in the simulations is thus characterized by the very same three parameters that are used to characterize the forecasted sea state. However, to perform a simulation, further assumptions need to be made to create, or synthesize, a wave train. Typically, it is assumed that the frequency distribution of wave energy is determined by the JONSWAP spectrum. The directional distribution is commonly assumed to be unidirectional, i.e. the waves are long-crested.

This is a key point of this paper. A *parameterized* version of a real-world sea state, that may hold any number of wave systems, is very different from a *synthesized* wave spectrum used in simulations. Yet, terms like significant wave height are frequently used indiscriminately of context or meaning. The allowable H_s found through simulation using a synthesized sea state is often compared directly to the $H_{s;total}$ representing a complex real world sea state to make a go / no-go decision. This is the topic of the following section, methods to make a (more) educated go / no-go decision.

Table 1 Allowable significant wave height Hs [m] (fictionalized)

Wave heading [deg]	Spectral wave period [s]							
	4	**6**	**8**	**10**	**12**	**14**	**16**	**18**
0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
30	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9
60	2.0	2.0	2.0	1.6	1.5	1.4	1.5	1.6
90	2.0	2.0	1.5	1.3	1.1	1.1	1.2	1.2
120	2.0	2.0	2.0	1.6	1.6	1.4	1.5	1.6
150	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.0
180	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

DECISION-MAKING METHODS

This section presents the three decision making methods, each related to one of the three methods of representing a sea state as introduced above. A fourth method is introduced for the sake of verification, but cannot be used in day-to-day decision-making so is excluded from further comparison.

1.) Single parameter sea state

Decision making method 1. is most simple and most frequently used. For the forecasted total sea state, Peak period Tp and Mean direction D are noted. The mean direction is compared to the vessel heading to find the relative wave heading. For this Tp and relative heading, the allowable significant wave height $H_{s;allowable}$ is found from a table e.g. Table 1. If the total sea state $H_{s;total} < H_{s;allowable}$, the operation may go ahead.

2.) Multi-parameter sea state

Decision making method 2. is similar to method 1., but instead of using the total sea state, the individual wave systems are considered. For each wave system *i* (e.g. wind waves and swell), $T_{p;i}$ and direction D_i are used to find $H_{s;allowable;i}$. Now a unity check is introduced for each wave system i:

$$UC_i = \frac{H_{s;i}}{H_{s;allowable;i}}$$

The total unity check is found by summation of the squares of the components, which is analogous to the summation of H_s of sea state components as presented in a previous section:

$$UC_{total} = \sqrt{\sum {UC_i}^2} < 1.0$$

If $UC_{total} < 1.0$, the operation may go ahead.

Decision making method 2. is often endorsed by the engineering consultant that determines the allowable sea state through simulation. It is noted that the method is elaborate as it requires multiple operations and the optimal vessel heading is not evident. Dedicated calculation aides are a welcome support for on-board application of this method. Such aides make the optimal heading visually evident and enable straightforward determination of UC_{total}.

3.) 2D wave spectra using transfer functions

A transfer function can be found that relates the wave energy in the 2D spectrum, thus specified per direction and frequency, to a limiting result. For instance, a transfer function can be found between wave energy and the maximum unity check in the jacking system occurring *at any time* during going-on-location. Determination of this transfer function requires a large number of simulations of variable sea states.

The transfer function necessarily assumes a linear relation between wave energy and result. Such relation is not present. Therefore, the relation can be correct at one value of outcome (unity check in this case) but must be incorrect for others. The point of linearization is chosen at the point of interest, a unity check of UC = 1.0.

The thus found transfer function can be directly applied to the forecasted 2D wave spectrum. Integration of all contributions will yield a total unity check UC per limiting factor. If for all unity checks UC < 1.0, the operation may go ahead.

MO4 has developed onboard decision support systems that combine 2D spectral weather forecasts with transfer functions in the frequency. The specific transfer functions for going on location have been integrated into the application. The flow is presented in Figure 4.

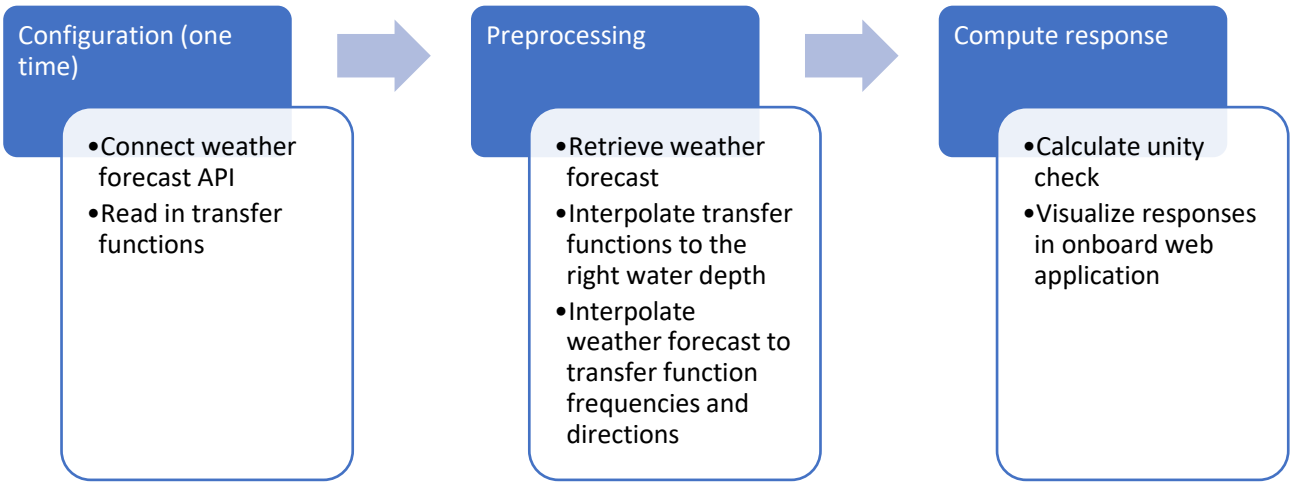

Figure 4 Flow diagram presenting the MO4 system

The maximum response is calculated as follows:

$$UC_{total} = \sqrt{\iint |TF(\omega,\theta)|^2 S_\eta(\omega,\theta) d\omega d\theta} < 1.0$$

If $UC_{total} < 1.0$, the operation may go ahead.

2D wave spectra used directly in simulation (A fourth method)

The actual (forecasted) 2D wave spectra could be used directly in the time-domain simulation model. The waves in the model represent the actual sea state, including all details. No assumptions about distribution of wave energy over direction or frequency need be made. This is the most accurate method available. Using this method for decision making would be overly cumbersome and prone to errors. It is used in this paper for the purpose of verifying the accuracy of the methods 1 – 3 as introduced above and is not considered as an alternative to these.

CASE STUDY

Introduction

In order to demonstrate the three different decision-making methods, two examples are worked out using realistic weather forecasts and wave spectra and logged data. Interest goes out mainly to vessel motions and bottom impact during going-on-location.

Jan De Nul has developed a culture of continuous logging of performance of its offshore assets. The resulting data are continually used to increase understanding of assets and their behavior. This understanding is used to increase both safety and efficiency of operations. The resulting historical database is tapped into for this study.

The motion behavior of Vole au vent is measured using an Xsense MTi-30 IMU recording with a sampling frequency of 40Hz. This dedicated device is preferred over regular onboard IMUs as they are often recording at lower sampling frequencies or are used for critical vessel systems such as the dynamic positioning (DP) system.

The loads in the jacking system are logged using the hydraulic pressure measurements.

Sea state information from a WaveRider buoy and from forecasts by two metocean bureaus (#1 and #2) that were actually used for on-board decision making are presented. Three decision making methods are applied and compared.

The sea state is obtained from hindcast by a model based upon the global ERA5 model. This sea state is expressed as a 2D wave spectrum. In addition, a Waverider buoy is used to measure real-time wave elevation. This is considered to be the most accurate source to determine the total wave energy present at the time of going-on-location. The 2D wave spectrum is therefore scaled so as to match the total wave energy as measured by the Waverider buoy.

The hindcast 2D wave spectrum representation of the sea state is applied directly to the simulation model, see Figure 5. As-measured and as-simulated motions and loads are compared.

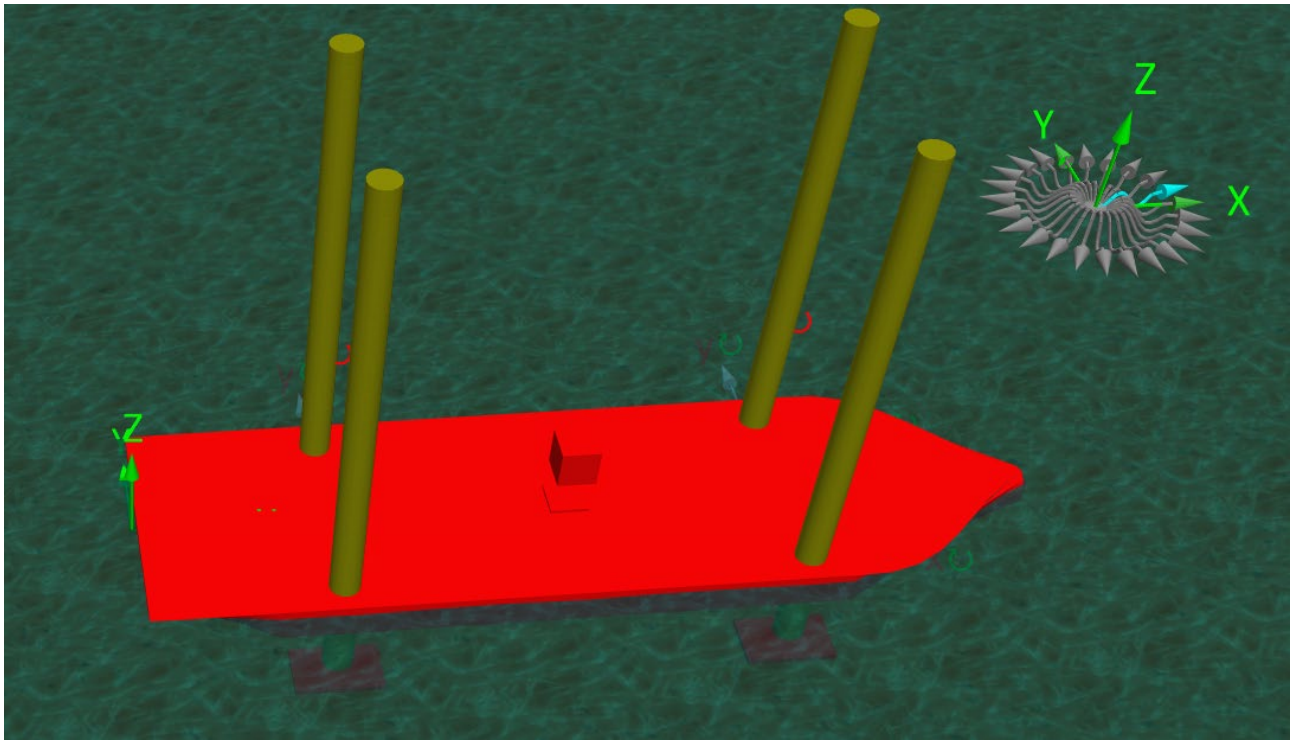

Figure 5 Simulation model with wave trains implementing 2D wave spectrum

Case 1 – Sea state with single energy peak

The first case considers Vole au vent going on location in a unimodal sea state. The as-measured and forecasted sea state data is presented in Table 2. In addition, from hindcast, the 2D spectrum is presented in Figure 7.

All sources are in agreement; the sea state is fully governed by a swell incoming from West. Both metocean bureaus, per convention, do report a wind waves system, but the wave height for this is negligible. Both parameter-based decision-making methods indicate a unity check of 0.6, thus workable. The allowable Hs is limited to 2.0 m and does not necessarily reflect the actual expected limiting capacities. Method 3, taking into account the 2D spectrum, indicates a slightly lower unity check, possibly due to the relatively high directional spreading of the swell.

Table 2 Sea state information for case 1 from four sources. UCs for all three decision-making methods are presented per source where applicable.

	Total sea state			Wind waves			Swell			Workability [UC] Per method ##		
	H_s[m]	T_p[s]	Dir[deg]	H_s	T_p	Dir	H_s	T_p	Dir	#1	#2	#3
WaveRider	0.9	9	278	-	-	-	-	-	-	0.5	-	-
Metocean #1	1.17	9.4	284	0.12	2.6	293	1.17	9.5	284	0.6	0.6	-
Metocean #2	1.1	10.3	282	0.3	2.2	283	1.1	8.8	280	0.6	0.6	-
Hindcast 2D	1.25	-	-	-	-	-	-	-	-	-	-	0.5

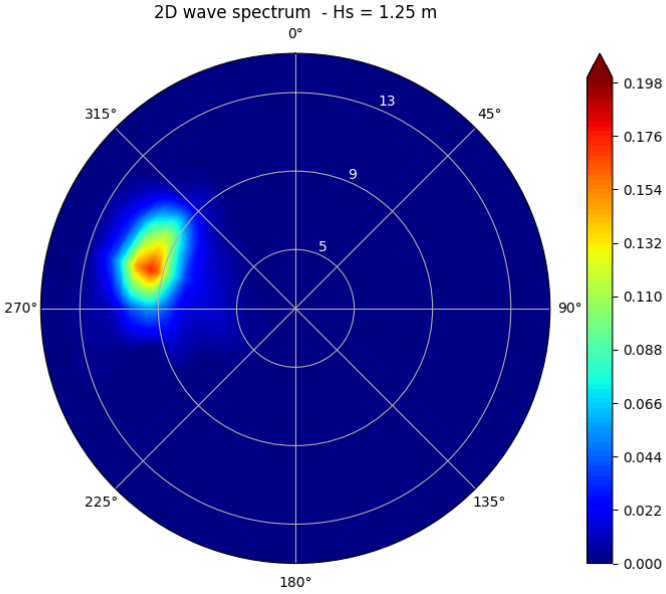

Figure 6 2D wave spectrum for case 1 (radial axis is period in [s])

The 2D spectrum is also applied directly to the time-domain simulation model (the fourth method). The motion behavior is compared to the as-measured motions in Figure 9, bottom graph. It can be seen that the motion behavior before impact is equal. It can also be seen that the impact phase lasts about 40 seconds in the measurements and in the simulation.

The measured impact loads are smaller than the leg weight and only appear for one leg. The simulated impact loads appear for two legs. This could indicate a difference in trim / heel between the vessel and the model. The order of magnitude of the measured peaks is similar, but the simulated peaks are significantly higher. Due to the load peaks being relatively small (smaller than the leg weight), the difference may be attributed to a number of causes, including friction. The measured and simulated impact loads are not significant enough to determine a meaningful unity check.

Case 2: Sea state with double energy peak

The second case considers Vole au vent going on location in a bi-modal sea state. The as-measured and forecasted sea state data is presented in Table 3. In addition, from hindcast, the 2D spectrum is presented in Figure 8.

It is clear from that a bi-modal sea state is active. There is a swell visible from West and a wind sea from North. The wind sea is choppy, with its energy ranging between NW and NE. Metocean bureau #1 estimates the dominant direction be NNE, metocean bureau #2 estimates the dominant direction at NNW. This, together with differences in swell heading, carries over into the total wave heading, which ranges from NW to N between the two bureaus. This translates to quartering seas to full beam seas.

Table 3 Sea state information for case 2 from four sources. UCs for all three decision-making methods are presented per source where applicable.

	Total sea state			Wind waves			Swell			Workability [UC] Per method ##		
	H_s[m]	T_p[s]	Dir[deg]	H_s	T_p	Dir	H_s	T_p	Dir	#1	#2	#3
WaveRider	0.8	4	293	-	-	-	-	-	-	0.4	-	-
Metocean #1	0.95	7.7	358	0.82	3.7	34	0.53	15	309	0.6	0.4	-
Metocean #2	0.8	9.2	293	0.5	2.9	339	0.5	9.2	273	0.5	0.3	-
Hindcast 2D	1.0	-	-	-	-	-	-	-	-	-	-	0.3

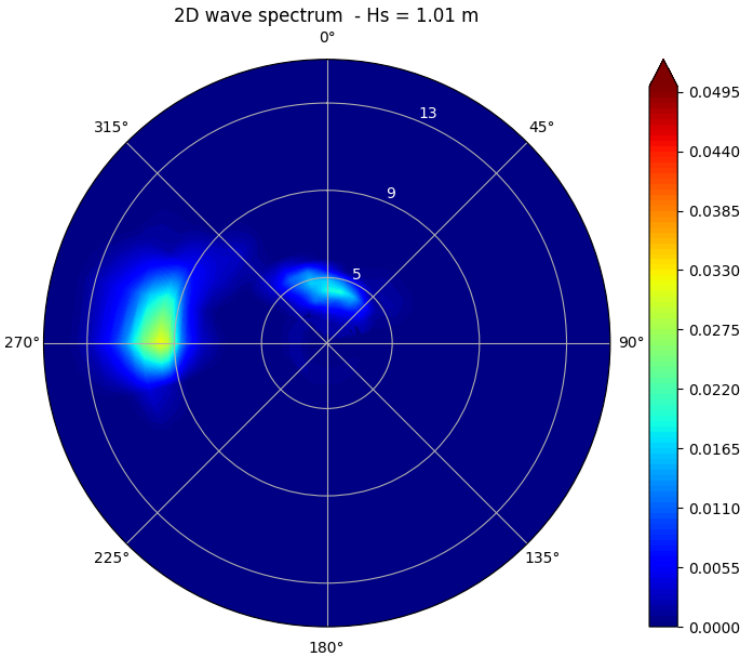

Figure 7 2D wave spectrum for case 2 (radial axis is period in [s])

Decision making method #1, taking into account total sea state parameters, yields UC 0.4 to 0.6. This shows that the uncertainty is of O(1), i.e. -50% to + 100%, which is not acceptable. In the face of such uncertainty, it is well advised to make conservative decisions.

The reason for this uncertainty is that the allowable wave height in beam seas is significantly lower than for following seas. It differs per metocean bureau which direction is chosen as representative.

Decision making method #2, taking into account individual wave systems, yields UC 0.3 to 0.4.

Method #3, which applies the full 2D spectrum to a transfer function indicates a unity check of 0.3.

The 2D spectrum is also applied directly to the time-domain simulation model. The motion behavior is compared to the as-measured motions in Figure 10, bottom graph. It can be seen that the motion behavior before impact is equal. It can also be seen that the impact phase lasts about 20 seconds in the measurements and in the simulation.

The measured impact load peaks, like for case 1, are smaller than the leg weight. Again, the vessel is stabilized before the entire leg weight is resting on the seabed. The same behavior is seen in the simulated loads. However, where the simulated loads do show peaks due to seabed interaction, this is not observed in the measured loads. It is likely that the force peaks were not sufficiently high to overcome friction. It could be the case that the force peak must be higher than the leg weight to become sufficiently significant.

The measured and simulated loads on the jacking system are too insignificant to determine a meaningful unity check. Therefore, quantitative conclusions with respect to the accuracy of the decision-making methods cannot be made. Comparative conclusions between the methods however remain valid.

Case selection and justification

The presented cases were selected based upon the sea state parameters from the metocean bureaus indicating a unimodal and bi-modal sea state. After this selection, all other information was gathered. Some of the comparisons between measurements and simulated data, such as the duration of the impact phase, worked nicely and were repeatable. Other, more quantitative comparisons were necessarily influenced by aleatoric uncertainty. It is noted here that all three decision making methods are designed to perform best at the limits of acceptability, i.e. around UC = 1. Far away from this, linearization choices may have significant influence on the outcome. The selected cases are both well within acceptable limits. Therefore, quantitative conclusions based on the comparison between measurements, simulations and decision-making methods for the two selected cases should not be drawn.

Further details regarding the cases are known by the authors but may not be shared in the public domain.

CONCLUSION

Three decision making methods are presented to provide a go / no-go decision regarding going-on-location of a jack-up. Method 1) takes into account total sea state parameters only, method 2) takes into account parameters of all present wave systems (e.g. wind sea and swell) and method 3) takes into account the full 2D wave spectrum.

It was shown that all three methods are suitable for sea states governed by a single wave system of minor directional spreading. For multi-modal sea states it is shown that a higher level of sophistication of the method reduces uncertainty. Reduced uncertainty simultaneously increases both safety and workability. These two observations are backed by simulations and limited measurement data.

It is tentatively concluded that basing a go / no-go decision based on total sea state parameters alone is bad practice if the sea state consists of multiple significant components such as wind sea and swell. The choice of dominant direction and mean period of the total sea state, made by a metocean specialist interpreting the data, may obfuscate wave energy with a direction and / or period to which the vessel is sensitive. Using total sea state parameters alone therefore comes with high uncertainty in the assessment without a bias to the conservative side.

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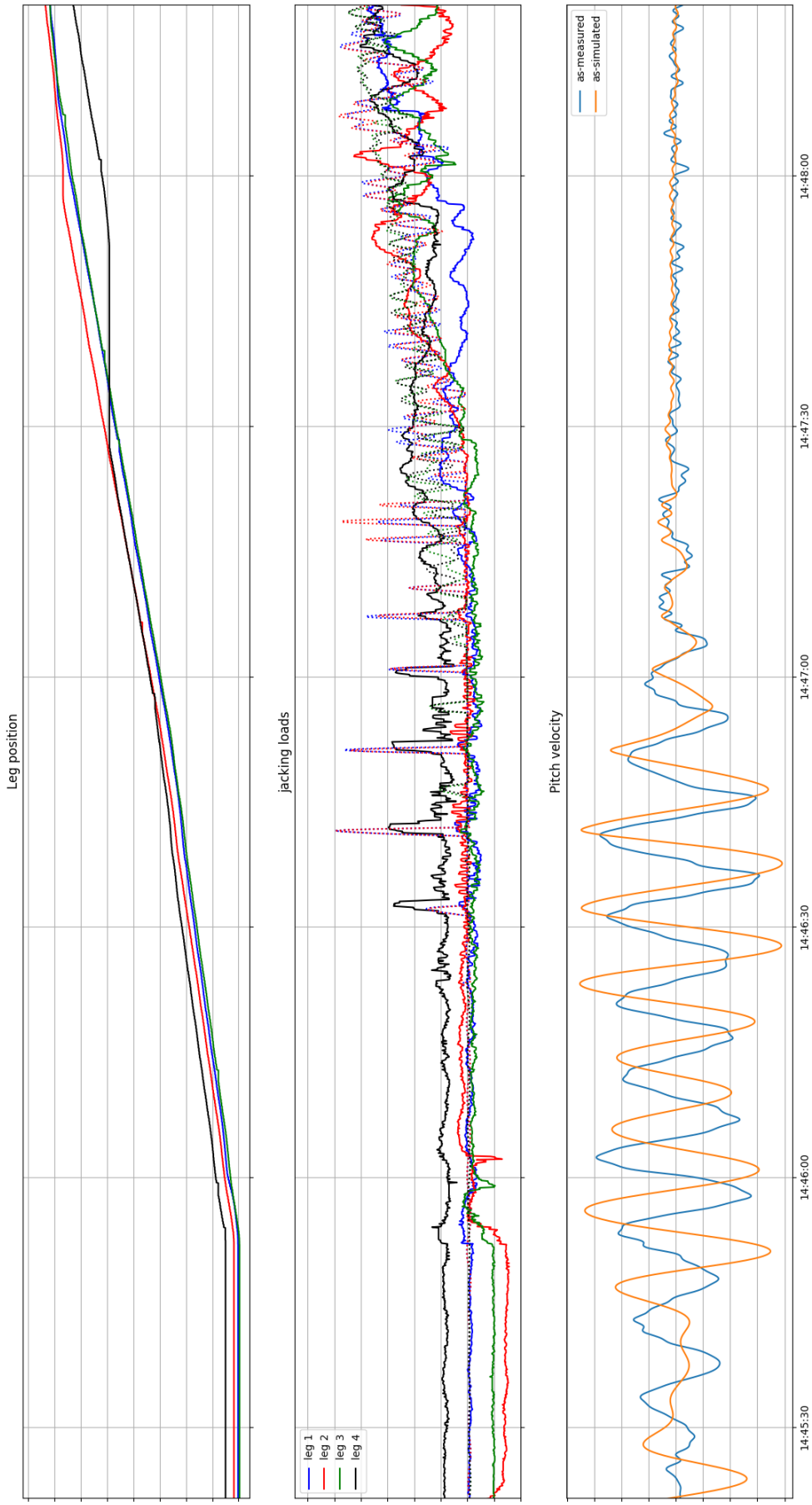

Figure 8 Measurements and simulation results for case 1 (dotted lines represent simulated loads)

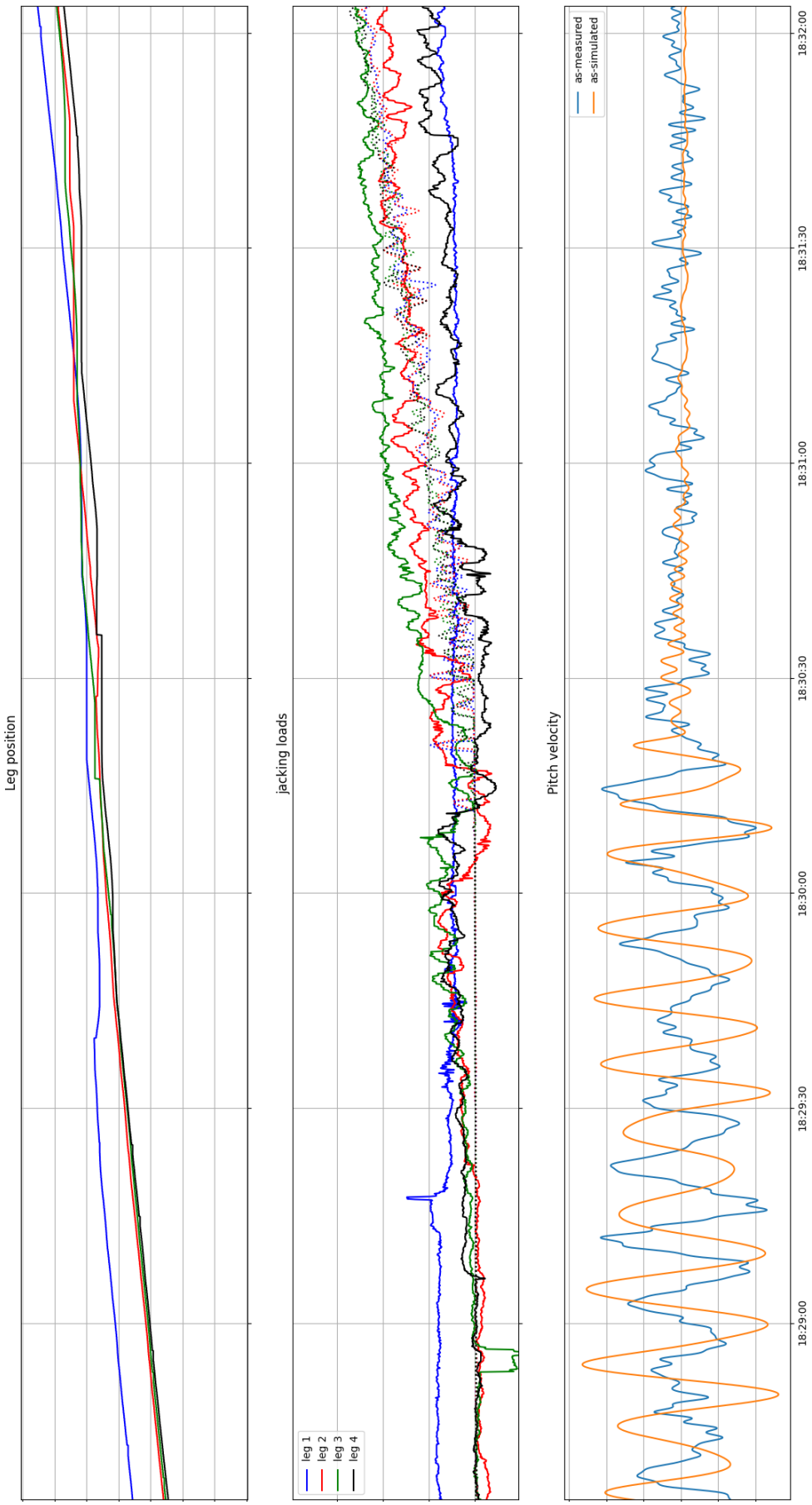

Figure 9 Measurements and simulation results for case 2 (dotted lines represent simulated loads)