STRUCTURAL RELIABILITY ANALYSIS FOR CRANE OPERABILITY CONDITIONS OF OFFSHORE WIND FARM JACK-UPS

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ABSTRACT

A structural reliability analysis has been performed as part of the Jack-up Renewable Energy Guidelines (J-REG) Joint Industry Program (JIP) which aimed to produce guidance specific to Offshore Wind Farm (OWF) jack-ups that is lacking in the current ISO Standard (ISO 19905-1) developed for the Oil and Gas Industry. One of the aspects for which no guidance exists currently is related to load and resistance factors for site-specific assessment of crane lift operating conditions of OWF jack-ups.

A gap was identified in the existing ISO 19905-1 standard for operational foundation safety since this standard considers extreme storm conditions that rarely happen whereas OWF jack-ups use their main crane to lift heavy wind turbine components into place. These operations are performed during mild (restricted) weather conditions and on a frequent basis.

In the structural reliability analysis that has been performed several typical OWF jack-ups, varying in leg and jacking system type as well as size, have been analyzed for three defined soil conditions assumed to represent soil risk profiles ranging from low to medium to high. The study has been a collaboration between ABS, GustoMSC and DNV. ABS has focused on the spudcan foundation load-displacement behaviour, GustoMSC on the structural load and strength accounting for both crane load (effects) as well as a non-linear foundation model and DNV on the reliability analysis and calibration of safety factors. The initial phase of determining the spudcan foundation behaviour has been presented in an earlier paper. The present paper focuses on the load and reliability analyses.

A target reliability level was agreed with participants in the J-REG JIP and for that load and resistance factors have been derived that were recommended for site-specific assessment of crane operational conditions for OWF jack-ups. The aim of this reliability analysis was to provide input to the J-REG JIP participants and to support them in preparing guidance text to include in the J-REG Guideline.

KEY WORDS:
Jack-up, SNAME, offshore wind farm, crane operation, Structural Reliability Analysis (SRA), foundation safety.

INTRODUCTION

A structural reliability analysis has been performed as part of the Jack-up Renewable Energy Guidelines (J-REG) Joint Industry Program which aimed to produce guidance specific to Offshore Wind Farm (OWF) jack-ups that is lacking in the current ISO Standard (ISO 19905-1) developed for the Oil and Gas Industry. One of the aspects for which no guidance exists currently is related to load and resistance factors for the site-specific assessment of crane lift operating conditions of OWF jack-ups.

The main reason for this study is a gap in the standard ISO 19905-1 for operational foundation safety in comparison with jack-ups for the oil and gas industry, which are designed for extreme storm conditions that happen rarely. OWF jack-ups use their offshore crane to lift heavy wind turbine components into place. These operations are performed frequently during mild weather (restricted) conditions.

Typically, OWF jack-ups have four legs and perform the preloading by applying the weight on two legs over one diagonal while unloading the two legs on the other diagonal. When a jack-up performs a heavy lifting operation using its crane, the foundation loads may approach the foundation capacity as established by preloading. The consequence of exceeding the preload capacity is considered to be an additional penetration and load redistribution to other legs, which again affect the loads on the jack-up and crane, which can result in structural overload of legs, holding systems, hull structure, or the crane, with an associated probability of failure.

In the structural reliability analysis that has been performed several typical OWF jack-ups, varying in leg and jacking system type as well as size, have been analyzed for three defined soil conditions assumed to represent soil risk profiles ranging from low to medium to high. At the time of writing of this paper, analyses and discussions are still on-going with respect to soil profiles that pose a possible high risk to the operation. Therefore, the present paper presents the work for low/medium soil risk profiles only.

The study has been a collaboration between ABS, GustoMSC and DNV. ABS has focused on the spudcan foundation load-displacement behaviour, GustoMSC on the structural load and strength accounting for both crane load (effects) as well as a non-linear foundation model, and DNV on the reliability analysis and calibration of safety factors. The initial phase of determining the spudcan foundation behaviour has been presented in an earlier paper [1]. The present paper focuses on the load and reliability analysis.

This work is intended to provide recommendations for practice, and as such to be considered by the J-REG JIP participants to develop guidance text on crane operational conditions for OWF jack-ups that can be included and published in the SNAME Bulletin.

STRUCTURAL RELIABILITY ANALYSIS APPROACH

An extreme event for a crane lift operation is defined as follows: starting from where the crane picks up a load, then slewing outward, thereby increasing the crane leg axial load and approaching the preload of the footing foundation, as shown in Figure 1. In Figure 2, the load and resistance are represented by random variables with their associated probability density functions (PDFs), which consider the stochastic nature of the underlying variables, such as weight, operating loads, metocean conditions, foundation resistance and capacity of the leg and holding system. The probability that the load (or load effect) L exceeds the structural capacity (or resistance) R, which is associated with the overlapping region of the load and resistance PDFs, is equal to the probability of failure P_f. This probability of failure during an extreme event should be associated with an acceptable level of reliability. The subtraction of the random variable for the load L from the random variable for the resistance R results in what is known as a limit state function (or safety margin M), as shown in Figure 2. The probability of failure P_f is the same as the probability of limit state violation (i.e., $P[R - L \leq 0]$). The PDF of the limit state function is used to calculate the probability of failure in a structural reliability analysis.

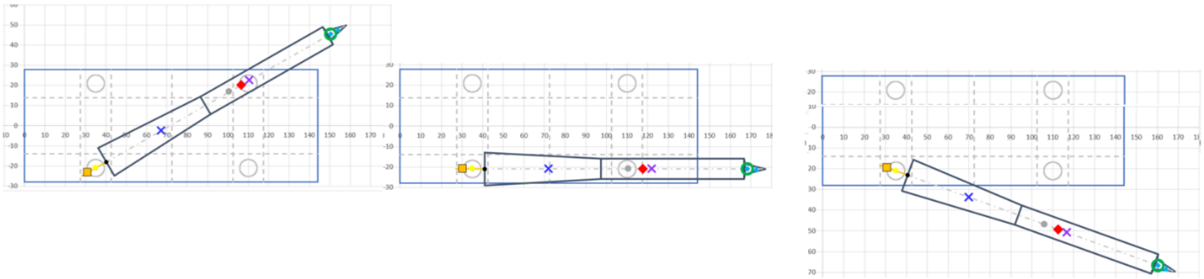

Figure 1 - Example of a crane operation with the crane at the starboard-aft leg

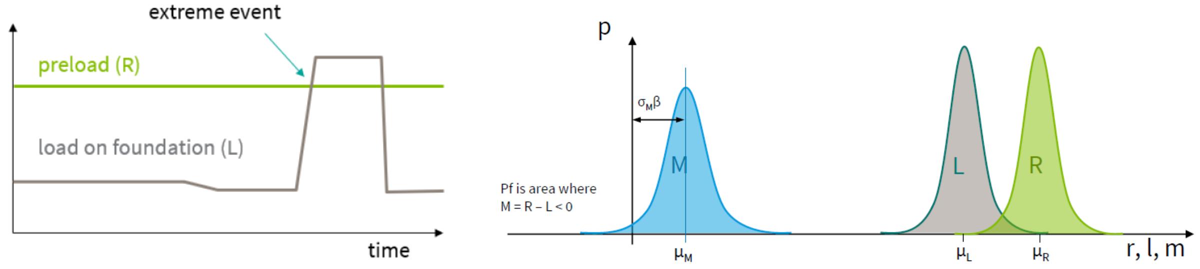

Figure 2 - Extreme event and PDFs for load L, resistance R and safety margin M

The primary input to a structural reliability analysis comprises the PDFs for the main random variables associated with load and resistance. In practice this necessitates the specification of characteristic values of actions and resistance based on a prescribed probability of not being exceeded. Characteristic values of loads and other actions should rarely be exceeded, whilst those of resistance should normally be exceeded. The probabilities of exceedance should not be so large or so small that the characteristic values are not occasionally encountered [2]. PDFs that are appropriate for the types of random variables are then selected and calibrated to match the characteristic values at their prescribed probabilities. The tails of these PDFs are then used within the structural reliability analysis to extrapolate beyond the characteristic values to the very low probabilities of structural failure that are to be expected within the realm of acceptable levels of safety.

A probability of failure of 10^{-4} per annum is considered acceptable when safeguarding redundant offshore structures against the consequence of serious failure [3]. With the frequent deployment of OWF jack-ups at many different locations this necessitates an assumption to be made for the number of turbine installation operations and a simplified characterisation of the separate sites that are to be expected in a typical year of operation. In the absence of comprehensive historical data and complete knowledge of future projects, it is evident that considerable engineering judgement is required when selecting characteristic values of the main random variables and the types of PDFs, and when also assessing the number of annual crane operations and the range of sites.

JACK-UP DATA AND SITE CONDITIONS

Five units were defined representing jack-ups presently active in the Offshore Renewable Industry, with main particulars as presented in Table 1.

Table 1 - Five typical OWF jack-up units considered representative.

		Unit 1	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**
Number of legs	#	6	4	4	4	4
Leg	Type	Closed	Tubular	Truss	Tubular	truss
Jacking system	Type	Double cylinder	Pin-in-hole	Rack-and-pinion	Pin-in-hole	Rack-and-pinion
Preload	t	7,500	2,500	2,500	9,000	16,000
Crane WLL*)	t	1,000	600	600	1,600	2,500
Crane type	Type	Pedestal	Pedestal	Pedestal	Leg encircling	Leg encircling

Three soil risk profiles were defined where risk is related to the consequence of a preload overload scenario:

1. Low risk profile - a strongly increasing spudcan resistance curve as a function of penetration, such that an increase of spudcan load beyond preload only results in a small additional penetration.
2. Medium risk profile - a weakly increasing spudcan resistance curve as function of penetration, such that an increase of vertical footing load beyond preload results in a moderate amount of additional penetration.

3. High risk profile (typically punch-through represented by sand over clay) - spudcan resistance as function of penetration depth decreases beyond a penetration depth with peak resistance in the vicinity of the preload level. The additional leg penetration resulting from a preload overload scenario could be excessive and result in progressive collapse.

In this study, the low-risk soil profile is assumed to be reasonably represented by a seabed comprising homogeneous sand, the medium risk profile by a seabed comprising a homogeneous (medium) stiff clay and the high-risk profile of a sand overlying soft clay. The present paper presents the work for low to medium soil risk profiles only as the analyses and discussions related to the high-risk soil profile are on-going.

Crane lifting operations are by default performed in weather-restricted conditions. The conditions in which jack-ups operate (i.e., elevated weight and eccentricity, water depth, and foundation properties) tend to vary even within a single OWF project. These aspects are the cause of differences in behaviour and loads. One design operational condition that is intended to be a reasonable and robust design case for crane lift operations for each of the different types of units is considered.

ANALYSIS MODEL, INPUTS AND ASSUMPTIONS

Analyses of crane-lift operational conditions were performed taking into consideration the specific actions and non-linear large displacement foundation behaviour associated with operating conditions. Actions are related to weight and crane (operating) loads and metocean conditions. Loads were determined by a quasi-static, geometrically non-linear, FE model of the jack-up including foundation. This overall model consists of a jack-up model of hull and legs, a crane model, and a non-linear foundation model. Specific emphasis in the model is given to:

- Modelling of the hull such that relevant hull deformations resulting in increased loads on the most heavily loaded leg are included.
- Modelling of the loads resulting from the crane lift in various stages of the lift such that the governing phase is included (from load pick-up to target location).
- Modelling of load-displacement behaviour of a spudcan foundation representing crane operation by considering loads from still water reaction approaching preload and beyond. The P-Δ effect is implicitly accounted for using geometrically non-linear analysis models and associated tools. The non-linear geometric effect on overturning crane moment due to tilting of the jack-up from differential displacements of its foundations is explicitly accounted for in the analysis. The structural integrity of the crane is not verified.

A Coupled Eulerian-Lagrangian (CEL) FE soil analyses was performed by ABS [1] to assess the large-deformation foundation performance associated with crane operations. ABS's numerical model was calibrated with the help of available centrifugal test data, matching soil flow mechanism, cavity depth, and bearing capacity at different soil depths. CEL analyses were performed only for unit 5, providing load-displacement graphs in vertical (see for example Figure 3), horizontal, and rotational directions with the load history representative of crane operations. Displacements due to foundation resistance exceedance are incorporated in the analysis model. The load-displacement graphs for the other units are based on the load-displacement graphs of unit 5 by scaling based on spudcan area and preload. This was considered reasonable since the spudcan bearing pressures for the units 2 to 5 inclusive are similar.

For the clay medium risk soil profile, load dependent fixity and horizontal stiffness were considered. Inside the yield surface the foundation is assumed to behave as non-linear elastic, and non-linear elastic-plastic with potentially large strains beyond the yield surface. The two ranges are illustrated in Figure 3. Outside the yield surface the fixity model is based on the curves from ABS. Fixity within the yield surface is calculated using the failure ratio defined by ISO-19905-1 Formula A 9.3-57 [4] (as no stiffness values could be derived from the finite element analysis results for this regime).

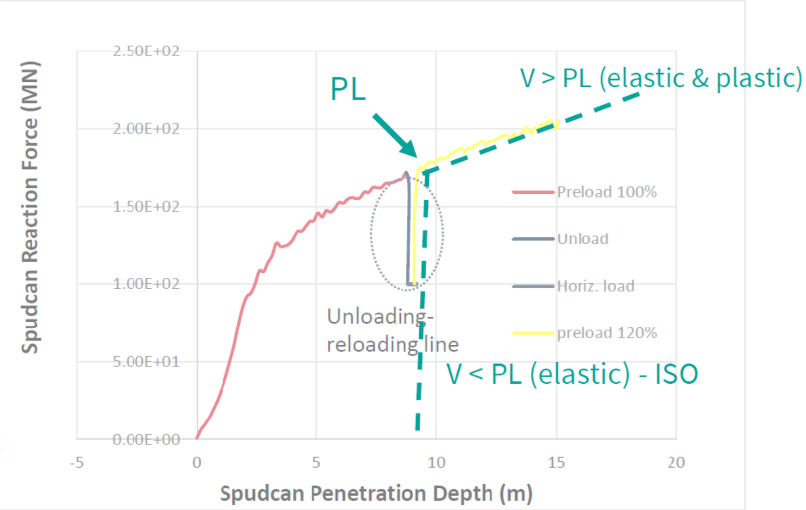

Figure 3 - Example of the elastic and elastic-plastic ranges on the load-displacement graph of medium risk profile (clay) for unit 5. PL is the preload at footing level.

The jack-up structure is verified for global structural integrity using the assessment criteria of ISO 19905-1 [4], with all load and resistance factors set to 1.0 and assumed representative of an Accidental Limit State. The structural integrity is represented by leg strength, holding capacity and leg-hull design load. As a measure for the utilization of the preloaded spudcan foundation, the preload check is used as a representative value, with the Unity Check (UC) calculated as follows:

$$\text{UC Preload } [-] = \frac{\text{Vertical load @ foot [MN]}}{\text{Preload @ foot [MN]}}$$

The governing failure mode in the structural reliability analysis is found to be holding system failure. It is emphasized that, in the present analyses, exceedance of the preload by itself is not a failure mode. This is because the consequences of exceedance of the preload are implicitly considered in the analyses by the defined load-displacement behaviour of the spudcan foundation. The consequences of exceeding the structural limits are assumed to be onset of damage. Redundancy of the holding system is not considered. It is assumed that onset of damage may lead to functionality losses with a risk of harming the environment and potentially risking safety of personnel on board. The consequence of leg or holding system failure are therefore considered serious.

A parameter sensitivity study associated with uncertainty was performed to investigate the effect of individual parameters on the limit state functions. The sensitivity analyses were performed by varying one parameter at a time with an upper-bound “high” and a lower-bound “low” value in relation to the corresponding base case value. The base case value is the value that applies in the deterministic design analysis. In the base case all model parameters are equal to their base case, or characteristic values. For many of the input parameters initially considered, the influence in terms of relative unity check was determined to be negligible. Based on the results of the initial sensitivity study, the most significant input parameters were determined, and several related parameters were combined into groups, where each group is represented by a single stochastically distributed variable. The lumped groups were defined as follows:

- Lump environment (Env): wave height, wave period, current velocity, wind velocity
- Weight (EW): elevated weight
- Lump LCG/TCG (CG): eccentricity and weight distribution to legs
- Lump crane load (Crane): hook load, boom weight, crane weight, boom COG, pick-up location LCG & TCG, Target location TCG
- Lump foundation (Found): penetration, backflow, backfill, shear modulus

Non-exceedance probabilities for the upper-bound and lower-bound values were determined by expert judgement and were agreed upon in JIP meetings between participants. The sensitivity of a model parameter is represented by the fraction of change relative to the base case defined as ΔUC. In addition to the lumped group cases, two more distributions were considered: applied preload and holding capacity, and both were aimed to be conservative.

The holding capacity is assumed to be correlated to the yield strength. As such it is reasonable to assume a steel yield strength distribution for uncertainty in holding capacity. The coefficient of variation is set to 10%, which is somewhat higher than normally applied for the yield strength when applied to steel structures, and this is assumed to cover some model uncertainty. The distribution and corresponding relationship to the characteristic normalized holding capacity is shown in Figure 4.

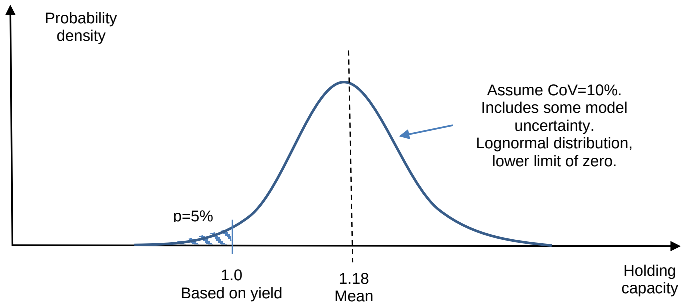

Figure 4 - Assumed probability distribution of the holding capacity relative to the holding system rated capacity.

In consultation with the JIP participants, it was decided to assume 20 critical lifts per soil risk profile, with a target probability of failure of 10^{-4} per annum.

PARAMETER SENSITIVITY – INPUT TO STRUCTURAL RELIABILITY ANALYSIS

With all the jack-ups investigated having four legs, there is significant redistribution of vertical footing reactions to other legs in case the spudcan foundation under the crane leg becomes overloaded. It was justified not to perform calculations for unit 1 because it provides more room for load redistribution due to its six legs such that this type of unit is not governing in determining the required load and resistance factors.

Given the importance of non-linear foundation behaviour, the analyses for the base case crane operations have been carried out for scenarios where the preload utilization would be close to unity when safety factors have been applied. With the low and medium risk soil profiles, the maximum vertical footing reaction under the crane leg in the base case is 90% of the corresponding preload value.

The highest utilization checks (UCs) throughout the sensitivity study have been found to be mainly associated with preload and leg holding, and as such are the focus of the tabulated results. Table 2 shows the sensitivity results for the low risk profile in terms of percentage variation from the utilization checks to the base case. Due to the small penetration in sand, the spudcans are treated as being pinned (i.e., no rotational stiffness is provided by the seabed) and as such the UCs are insensitive to soil properties. Of most significance, we see only small variations for leg holding utilization even when there is a substantial reduction in the achieved preload. These analysis findings are consistent with the expectation that preload exceedance during crane operations is not a major concern with a low risk profile such as homogeneous sand. Since preload exceedance is not critical, the limit state for leg holding is the relevant criterion.

Table 2 - Summary of analysis sensitivity results, low risk profile, preload and holding.

Case	Specification	Change in preload utilization relative to base case				Change in holding utilization relative to base case			
		Unit 2	**Unit 3**	**Unit 4**	**Unit 5**	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**
0	Base case	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1	Lump env low	-4.4%	-10.2%	-12.4%	-4.8%	-21.6%	-11.6%	-13.2%	-17.3%
2	Lump env high	1.5%	0.8%	1.6%	0.2%	5.7%	1.0%	1.7%	1.5%
3	EW low	-5.4%	-4.3%	-4.8%	-5.6%	-5.4%	-4.8%	-5.1%	-2.7%
4	EW high	1.9%	1.4%	1.4%	1.7%	1.6%	1.6%	1.5%	0.6%
5	Lump LCG/TCG low	2.6%	1.7%	2.8%	2.4%	1.7%	1.9%	3.0%	0.5%
6	Lump LCG/TCG high	-2.1%	-1.7%	-2.8%	-2.5%	-1.8%	-1.9%	-3.0%	-0.8%
7	Lump crane load low	-5.7%	-4.6%	-2.9%	-1.9%	-3.0%	-5.2%	-3.1%	-1.7%
8	Lump crane load high	7.2%	5.8%	5.8%	1.5%	4.0%	6.6%	6.2%	0.9%
9	Lump foundation low	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10	Lump foundation high	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
11	Preload -5%	5.2%	5.0%	4.5%	4.7%	-1.2%	-0.3%	-0.8%	-2.3%
12	Preload -10%	11.1%	11.9%	11.8%	9.8%	-2.9%	0.8%	0.6%	-3.9%
13	Preload -15%	17.4%	20.8%	21.0%	16.4%	-3.3%	3.1%	3.0%	-5.1%

Table 3 shows the sensitivity results for the medium risk profile. The deeper penetrations in clay offer increased contact area with the spudcans, thereby leading to rotational stiffness being provided by the seabed [1]. Thus, the removal of environmental load (i.e., Lump env low) has a smaller effect when compared with the pinned foundations associated with Table 2. Again, we see only small variations for leg holding utilization when there is a substantial reduction in the achieved preload. The analysis findings are consistent with the expectation that preload exceedance during crane operations is also not a major concern with a medium risk profile such as homogeneous clay.

Table 3 - Summary of analysis sensitivity results, medium risk profile, preload and holding.

Case	Specification	Change in preload utilization relative to base case				Change in holding utilization relative to base case			
		Unit 2	**Unit 3**	**Unit 4**	**Unit 5**	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**
0	Base case	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1	Lump env low	-2.7%	-9.5%	-5.9%	-2.1%	-15.1%	-10.9%	-6.6%	-10.0%
2	Lump env high	0.3%	3.1%	1.2%	0.2%	4.9%	3.6%	1.4%	1.2%
3	EW low	-5.8%	-5.1%	-4.5%	-5.8%	-6.1%	-5.9%	-5.1%	-5.1%
4	EW high	1.8%	1.6%	1.4%	1.8%	1.9%	1.8%	1.5%	1.6%
5	Lump LCG/TCG low	2.4%	2.2%	3.2%	2.7%	2.5%	2.5%	3.6%	2.4%
6	Lump LCG/TCG high	-2.4%	-2.2%	-2.6%	-2.7%	-2.5%	-2.5%	-2.9%	-2.4%
7	Lump crane load low	-5.6%	-5.6%	-4.0%	-2.2%	-3.7%	-6.5%	-4.5%	-5.3%
8	Lump crane load high	6.6%	6.7%	4.4%	2.0%	6.9%	7.8%	4.9%	4.8%
9	Lump foundation low	5.3%	5.5%	6.3%	1.3%	1.2%	0.7%	0.7%	0.5%
10	Lump foundation high	-2.0%	-2.3%	-5.0%	-4.7%	-1.6%	-0.9%	-0.8%	-0.7%
11	Preload -5%	5.3%	5.3%	5.4%	5.3%	0.0%	0.0%	0.1%	0.0%
12	Preload -10%	11.1%	10.9%	10.4%	11.4%	0.0%	-0.2%	-0.7%	0.0%
13	Preload -15%	12.9%	11.8%	11.7%	12.6%	-4.6%	-5.8%	-5.6%	-5.8%

The fractional changes in utilization shown in the above tables are associated with estimated characteristic values of the parameters considered in the sensitivity study. The results have been used to provide inputs to the PDFs for the structural reliability analysis: normal distributions have been assumed for the elevated weight, centres of gravity, crane loads and soil parameters; a log-normal distribution has been assumed for the leg holding capacity, based on similarities with distributions for yield strength of steel; a long-term distribution has been used for the significant wave height with truncation above operational limits for environmental loading; Hermite polynomials have been used to provide a fitted curve for the negatively skewed distribution of preload.[1] The PDFs are then used to combine the effects of the included random variables to form the limit state functions for leg holding and preload and to compute probabilities of limit state violation in the structural reliability analysis.

The formulation of the limit state function for the holding system as a function of the random variables $\boldsymbol{X}$ may be expressed as follows:

$$G_{holding}(\boldsymbol{X}) = HC - UC(\boldsymbol{X})$$

or stated more explicitly as,

$$G_{holding}(\boldsymbol{X}) = HC - UC_{BC-holding}\big(1 + \Delta UC(Env) + \Delta UC(EW) + \Delta UC(CG) + \Delta UC(Crane) + \Delta UC(Found) + \Delta UC(Preload)\big)$$

where HC is the random variable for the holding capacity, normalized such that the unity check at the characteristic holding capacity is 1.0. UC_{BC} refers to the base case utilization. ΔUC is the fraction of change relative to the base case utilization as a function of the random variables including the environmental conditions Env, elevated weight EW, centre of gravity CG, crane load $Crane$, foundation $Found$ and preload $Preload$. The probability distributions for the different random variables are all assumed to be independent.

A limit state function for preload exceedance has also been defined for the low and medium risk profiles:

$$G_{preload}(\boldsymbol{X}) = 1 - UC_{BC-preload}\big(1 + \Delta UC(Env) + \Delta UC(EW) + \Delta UC(CG) + \Delta UC(Crane) + \Delta UC(Found) + \Delta UC(Preload)\big)$$

The authors have sought to consider the possibility that a consequence of the preload/pre-drive procedures typical for OWF jack-ups (preloading over diagonals of statically indeterminate 4-legged units) is that the achieved preload value may be less accurately known than when using water ballast for preloading as is the case for 3-legged units in oil and gas practice. Estimates of the uncertainty in the achieved preload have been made whilst keeping in mind the principal differences in procedure and in the determinacy of leg reactions. In Figure 5, the fractional change in preload utilization is shown for the medium risk profile together with the associated cumulative probability distribution that has been assumed for the achieved preload. The table at the right side of the figure shows that there is an assumed 1.4% probability of the achieved preload being less than 90% of the target value. This level of probability represents an occasional event that is expected to be encountered. The changes in utilization shown by the blue dots are taken from the quasi-static non-linear analysis results for the associated values of achieved preload. In the reliability analysis, a linear relationship between the achieved preload and preload utilization is used, without taking any benefit from apparently decreasing sensitivity for 85% preload. It is assumed that the uncertainty in the preload is independent between the installations at different locations.

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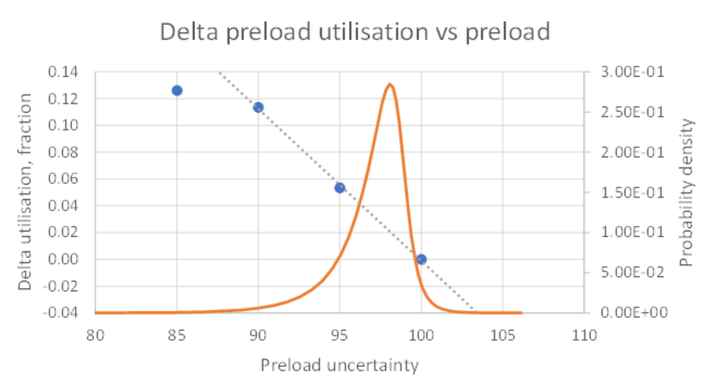
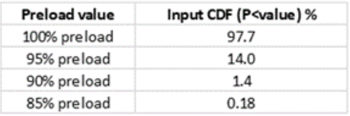
[1] The Hermite polynomials used in probability theory are orthogonal to the standard normal distribution and provide a convenient way of introducing departures from the normal distribution, such as skewness and kurtosis.





Preload value	Input CDF (P<value) %
100% preload	97.7
95% preload	14.0
90% preload	1.4
85% preload	0.18

Figure 5 - Change as fraction preload utilization versus the achieved preload together with the associated probability distribution of the achieved preload, unit 5, medium risk profile.

The results that provide an input for the structural reliability analysis are in terms of the fractional change in the utilization ratio for different variations in the parameter uncertainties. Hence, the base case utilization can be varied under the assumptions that the fractional change to the parameter variations in the sensitivity study remains the same. This enables the calculation of the annual probability of failure as a function of the base case utilization ratio or as a function of the total safety factor on load. This assumption is reasonably accurate when the base case utilization is near that required at the target probability of failure.

RESULTS OF STRUCTURAL RELIABILITY ANALYSIS

All structural reliability analyses have been carried out using Proban [5]. The main results are given in terms of the annual probability for violation of the different limit states analysed. It is assumed that there are 20 critical installations in each soil profile per year. From the quasi-static analyses, it is seen that the consequences of exceeding the preload in both the low risk and medium risk profiles are considered not to be serious. What is most important for the low and medium risk profiles is that the foundation bearing capacity increases with increasing penetration. For a low risk profile, increased bearing capacity is achieved for small amounts of additional penetration. In medium risk profiles, the additional penetration might be larger, but it allows also for increased spudcan rotational fixity and more redistribution of load to the other legs. An important aspect is that the base case preload utilization for the analysis is set to 0.9 (safety factor of 1.1), and that preload exceedance is allowed for and accounted for when analyzing the holding capacity. Figure 6 and Figure 7 show that a relatively high annual probability of preload exceedance is predicted, i.e., almost up to 0.1 for a safety factor of 1.1.

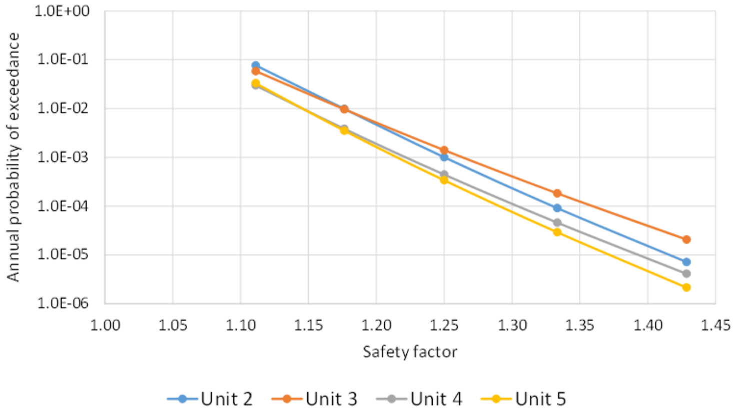


Figure 6 - Annual probability of exceedance versus partial resistance factor on preload, low risk profile.

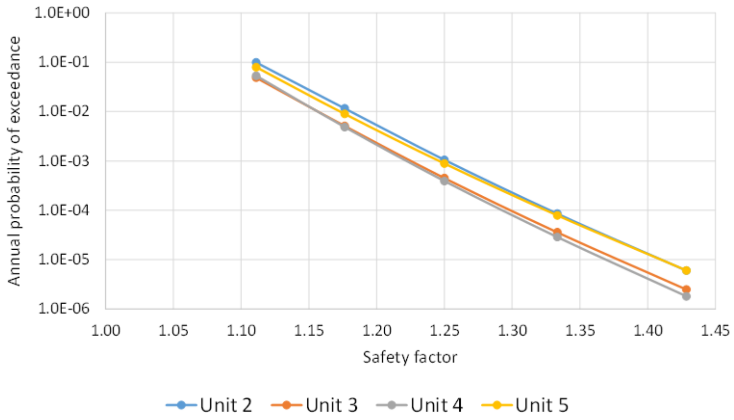


Figure 7 - Annual probability of exceedance versus partial resistance factor on preload, medium risk profile.

The results for limit state violation of the holding system are included in Figure 8 and Figure 9 for low risk and medium risk profiles respectively. It is observed that a safety factor of 1.25 provides an annual probability of holding failure of 10^{-4} or below for all the four units in the low risk profile, whereas a slightly higher safety factor of 1.27 is needed in the medium risk profile at this probability level for units 2 and 3.

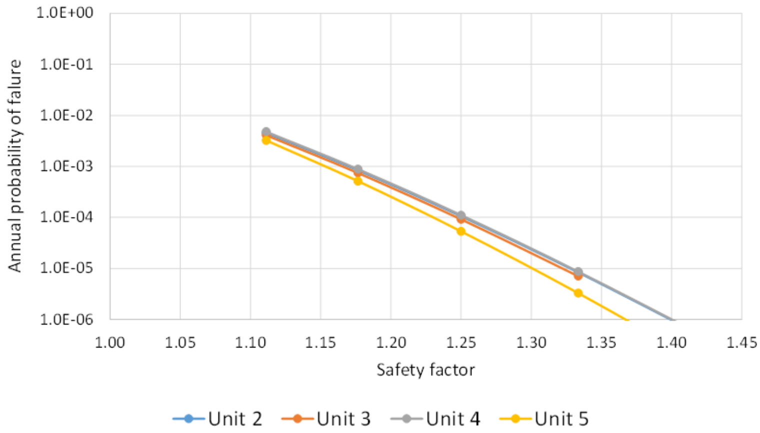


Figure 8 - Annual probability of exceedance versus partial resistance factor on holding capacity, low risk profile.

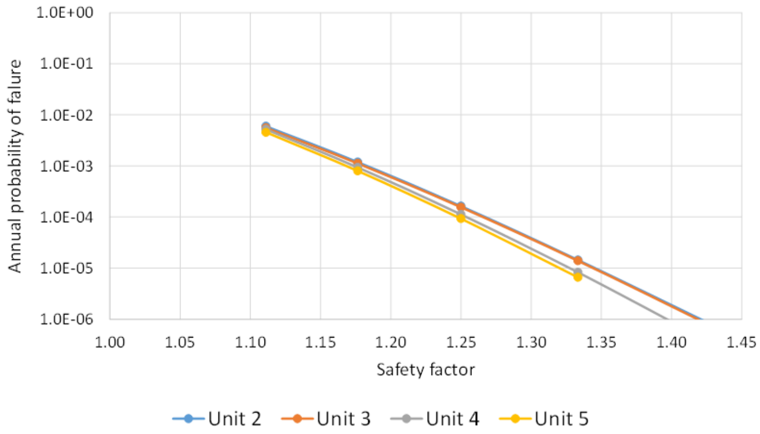


Figure 9 - Annual probability of exceedance versus partial resistance factor on holding capacity, medium risk profile.

DISCUSSION AND RECOMMENDATIONS

Based on the analyses performed, assumptions made and to meet the target reliability level of 10^{-4}, for low/medium risk soil profiles the resulting required partial action and resistance factors from this study are:

- a partial resistance factor of 1.10 on the foundation capacity defined by applied preload;
- a partial resistance factor of 1.25 on steel strength, such as holding strength and leg strength;
- a partial action factor of 1.0 on all actions.

With the design crane lift operational condition satisfying these requirements it is found that the probability of structural collapse of the jack-up meets the defined target reliability level. These factors may not be applicable to conditions where a risk of punch-through in the elevated operating condition may remain after installation. The consequence of exceeding the preload then becomes critical since large displacements due to a punch-through (of two legs) can result in structural failure (full system collapse). In these circumstances, it is therefore recommended to determine the safety factor on preload that is needed to obtain the target annual probability of punch-through induced failure.

The holding capacity check is the governing limit state which includes the effects of a potential exceedance of the preload by the load-displacement spudcan behaviour. The latter was explicitly accounted for in the analysis model. An important assumption is that the base case preload utilization is set to 0.90 and that preload exceedance is allowed for and accounted for when analyzing the holding capacity. Therefore, a relatively high annual probability of preload exceedance is acceptable, i.e., almost up to 0.1 for a safety factor of 1.1. Exceeding preload during crane operations is not a major concern with a low or medium risk soil profile.

It is observed (Table 2 and Table 3) that the change in utilization ΔUC between “high” (upper bound) and “low” (lower bound) values of parameters is mostly marginal, i.e., a few percent. It is also observed that parameter sensitivities tend to be larger towards the variations that result in a lower unity check. This seems reasonable as the leg and crane loads are mostly driven by static weight; thus, it is conservative to define weight related variables in the design analysis toward the high end. The base case for the environmental conditions is close to the “high” estimate but with some sensitivity for the holding utilization for truss leg jack-ups. The utilizations also show some sensitivity to the crane load and elevated weight.

It is noted that for this study the risks are associated with the situation during elevated operation, not during preloading. The risk to the operation may be critically dependent on the risks associated with the foundation of the jack-up. The identification of risks is a subject of the assessment and may be strongly dependent on the uncertainties related to the exact soil profile (layering and properties) at the site.

It is noted that a structural reliability analysis is not intended to allow for “gross errors” which include human errors. Gross errors do occur and should be considered by the designer and avoided by safeguards in the design, fabrication, installation, and operation processes. Particular attention should be made towards the crane operation being performed according to the operational manual and specified (site-specific) limitations.

The safety during crane operations may be dependent on the pre-driving methods, procedures to perform the preloading, and accuracy of monitoring the actual preload applied to the foundation as well as during the crane operation, such as discussed in [1], [6], [7], [8]. Further investigation into these factors is recommended.

Foundation safety under maximum vertical load has been the focus of the present study, however other factors should be considered in a site-specific assessment of crane operations to ensure structural integrity of the jack-up during crane operations, such as to avoid uplift and sliding of a leg.

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