RELIABILITY ANALYSIS OF JACKUP STRUCTURES

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ABSTRACT

In designing structures to resist environmental loading, decisions are made under a great deal of uncertainty that may lead to a finite risk of exceeding limit states of the structures. Classically, in order to minimize the risks, conventional safety factors based on deterministic analyses are commonly used in the design. Recently, codes of practice employed reliability methods to calibrate the load and resistant factors (the partial safety factors).

The application of probabilistic analysis in structural engineering is still an emerging technology. The appropriate form and shape of probability distributions for the relevant parameters are not completely known with certainty, and also procedures are too complex for a reasonable size structure. Consequently, the methods should not be expected to provide "true" or "absolute" probability-of-failure values but can provide consistent measures of *relative reliability* when reasonable assumptions are employed. Such comparative measures can be used to indicate, for example, which alternative design may be more reliable than another.

The purpose of research effort leading to this paper was to develop, test, and illustrate procedures that can be used by structural engineers to assign conditional probabilities of failure to structural elements as functions of Metocean loads. Such probabilities are in turn can be used by economists when estimating benefits to be derived from proposed structural improvements. In this paper, a reliability-based design (RBD) procedure for determining reliability of independent leg jack up subjected to the overturning effect of environmental loads.

1. INTRODUCTION

Jack-ups are mainly used for drilling (Figures 1 and 2), and are not designed for a specific site. Therefore, footing (Figure 3) must penetrate into the seabed until a safe condition is achieved. If the stabilising effect of gravity loads (and the foundation fixity) is not adequate for the wave loading, then collapse of the rig under severe storm condition is a possibility. Wave action causes the footing to penetrate deeper. However, the sum of air gap, the water depth and the footing penetration can not exceed the leg length.

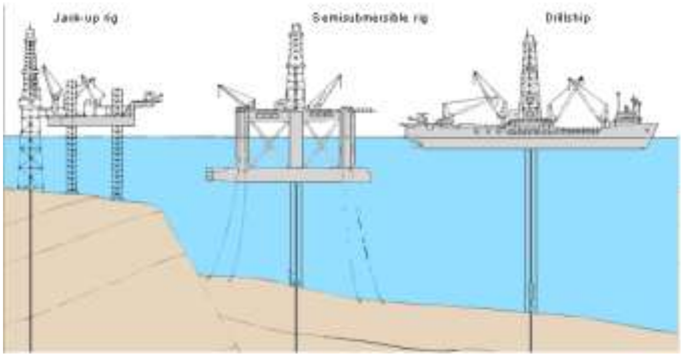


Figure 1 Jack-up and other drilling platforms

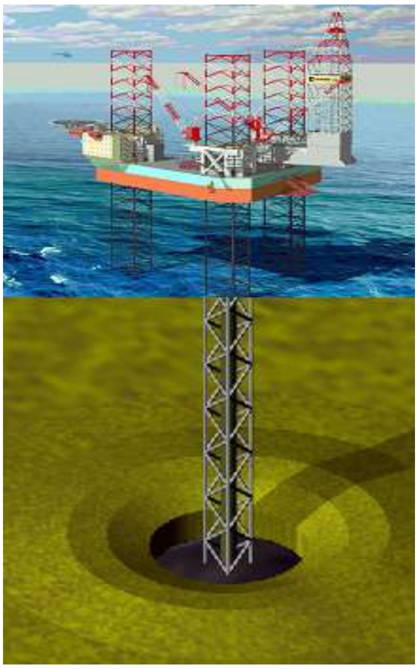


Figure 2 A three-legged Jack-up in drilling mode
(www3.imperial.ac.uk/)

In addition to the problem concerning the stability and penetration of spud-can, the foundation fixity requires attention. Foundation fixity is defined as the ability of soil to restrain the rotational movement of the footing under the lateral loads.

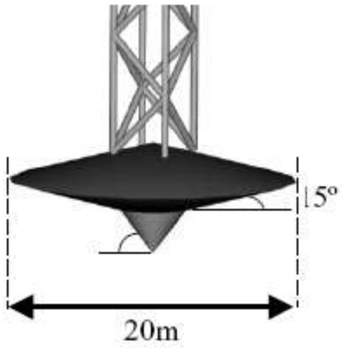


Figure 3 Typical Spud-can for a modern Jack-up

Jack-ups are used for drilling as well as for accommodation (Figure 4).

Figure 4 A jack-up positioned for drilling
(www3.imperial.ac.uk/)

After arriving at site, legs are lowered down and the jack-up is pre-loaded (Figure 5). Then the hull is raised to the full air-gap. Preloading ensures that some level of fixity is achieved, and further penetration would not cause problems. Topside loads, as well as the foundation fixity, provide the required stability against overturning during operation.

Reliability methods are used when intervention for remediation becomes too complex and expensive for an existing structure. Applying reliability method to a structure of reasonable size is a formidable task and hence simple approximate approaches are gaining popularity with structural designers. This paper describes an approximate method for determining the reliability of jack-ups against overturning. The methods described should not be expected to provide “true” or "absolute" probability-of-failure values but can provide consistent measures of *relative reliability* when reasonable assumptions are employed. Such comparative measures can be used to indicate, for example, which remediation may be more beneficial.

Generally a simple balancing load is performed to make sure the minimum factor of safety (usually 1.25) is achieved against overturning.

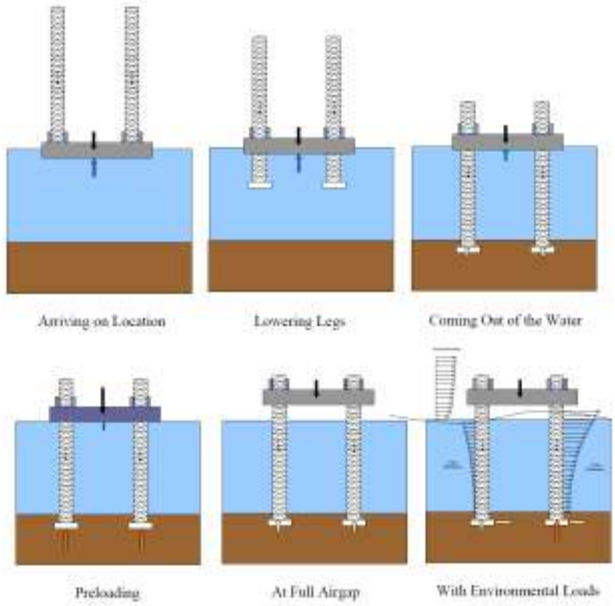


Figure 5 Installing and preloading
(www.bbengr.com)

Designs developed using different reliability methods will still retain some inherent uncertainty in the absolute sense. Nevertheless, they also provide more information than deterministic approaches to the same problem. The use of a consistent probabilistic framework, with reasonable engineering judgment checks for reasonableness, should have the advantage and appeal of consistency when compared to the alternative method of trying to identify a single environmental condition at which a jack-up changes from being reliable to unreliable.

2. FAILURE MODES

The environmental (wave, wind and current) loads (Figure 6), which are essentially horizontal during operation, create overturning moment (Figure 7). The restoring moment which stabilizes a jack-up unit is provided by weight (and the foundation fixity). Classifying societies require the ratio between the overturning and restoring moments not be less than 1 (most require 1.25). Verification of soil failure is also a design condition.

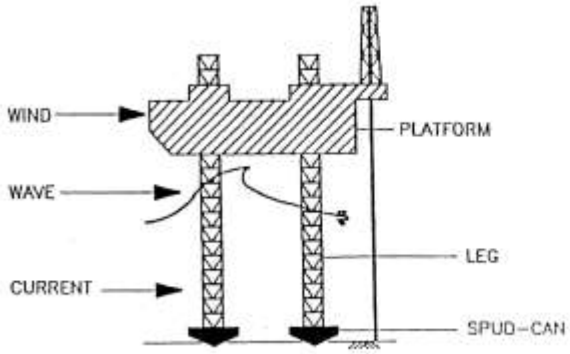


Figure 6 Environmental loads

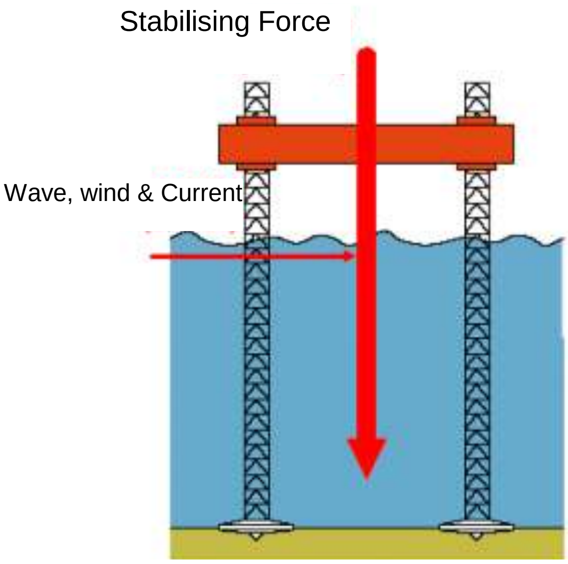


Figure 7 Stabilising and destabilising

When the load distribution is different from required for operation or survival condition (especially in cantilever mode) it is vital to check the safety against overturning (Figures 7 and 8). If the environmental conditions reach or exceed the allowable conditions, the rig operators need advance warning as it takes a few hours to bring a jack-up rig into a safe condition, i.e. bringing the rig to its survival condition. The operation and survival conditions are normally clearly identified in the Operating Manual. In hurricane, a jack-up may lose all its leg and float on its hull (Figure 9).

Figure 8 A failed jack-up

Figure 9 A jack-up overturning under the environmental actions

Figure 10 Total lose of all legs (Ensco 64 after Hurricane Ivan)

During initial preloading, and in calm weather, the footings of a jack up are essentially subjected to purely vertical loading. During drilling operation and in a storm, the spud-cans must also resists overturning moments, horizontal loads and changes in vertical load arising from wave action.

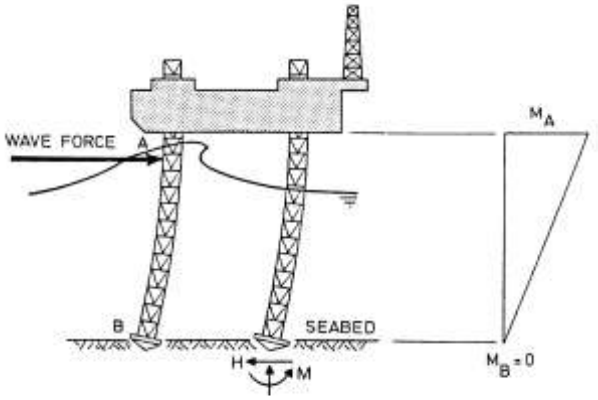


Figure 11 No foundation fixity

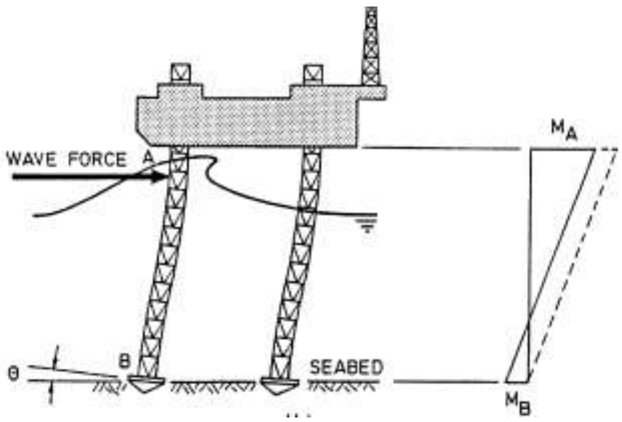


Figure 13 Partial foundation fixity

Under storm condition footing experiences a combination of vertical and horizontal loads and moments. The conventional procedure is to assume the footing offers no resistance to moment loading, i.e. behaving like a pin. Under this assumption the maximum bending moment occurs at the top of the leg, which proves to be critical in design. If the footings offer some rotational restraint, the ultimate capacity of the rig would enable it to work under more severe wave loading than the simplified assumption allows. Spud-cans are often embedded to a significant depth below the seabed, typically up to two times their diameters in soft clay (Figure 14). If such fixity can be achieved the natural period of the rig reduces and hence the stress level drops and the fatigue life increases.

Foundation Failures are generally of the following types:

- Punch trough during preload due to a soil profile which includes a strong layer overlaying a weak layer
- Excessive storm damage- penetration due to the maximum preload did not exceed the maximum storm loads; preload is primarily vertical while the storm load is a combination of vertical and horizontal laud
- Footing instability initiated by scour which reduces the bearing area
- Slope instability of the seabed triggered by mass movement of sediment
- Instability caused by force used to extract footing when the pullout resistance of the footing exceeds the available uplift force.

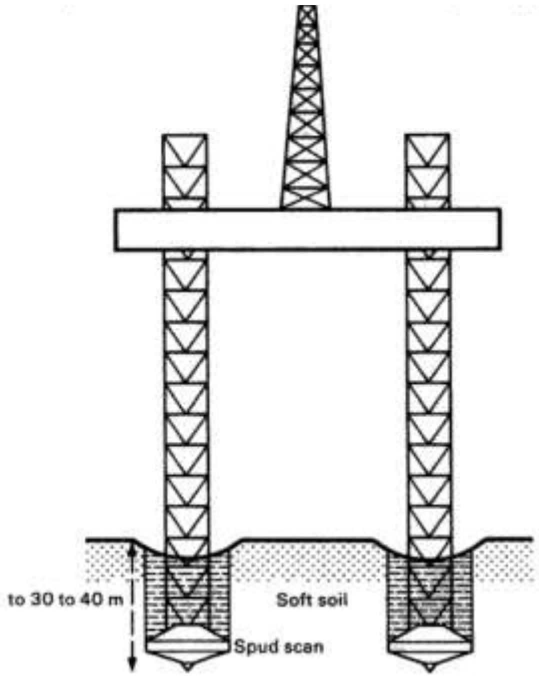


Figure 14 Footing penetrations into the seabed

3. RELIABILTIY INDEX

For an existing structure, the probability of failure P_f can be expressed as a function of the overturning moment and other factors including duration, structural strength, weld strength & quality, general workmanship, etc. The conditional probability of failure can be written as:

$$P_f = P\left(failure \middle| OT\right) = f\left(OT, X_1, X_2, \cdots, X_n\right)$$
(1)

In the above expression, the first term (denoting probability of failure) will be used as a shorthand version of the second term. In the second term, the symbol "|" is read *given* and the variable *OT* is the *Overturning Moment*. In the third term, the random variables X_1 through X_n denote relevant parameters such as material strength, P-Delta effect, environmental loads, dynamic effect, section sizes etc. Equation (1) can be restated as follows: "The probability of failure, given an overpressure, is a function of the overpressure, its duration and other random variables." This study will focus on developing the *conditional* probability of failure function for the overturning moment, which will be constructed using engineering estimates of the probability functions or moments of the relevant variables.

In the capacity-demand model, the probability of failure or unsatisfactory performance is defined as the probability that the demand on a system or component exceeds the capacity of the system or component. The capacity and demand can be combined into a single function (*the performance function),* and the event that the capacity equals the demand taken as the *limit state*. *Reliability* is the probability that the limit state will not be reached or crossed. The performance measure is taken as the factor of safety against overturning.

The likelihood that a structure will meet or exceed a specified level of damage for a given level of overpressure is:

$$\text{Probablity of Failure} = P\left[R > LS \mid IM = y\right] \qquad (2)$$

where R is the response measure of the system response or the demand of environmental condition on the structure, LS is the limit state or damage level, IM the intensity measure and y is the realization of the chosen environmental intensity measure. This probability of failure is represented by:

$$P_f = P\left[\frac{E(R)}{E(C)} \geq 1\right] \qquad (3)$$

where P_f the probability of is exceeding a specific damage-state, $E(R)$ is the expectation of environmental demand on the structure and $E(C)$ is the structural capacity or damage state.

Assuming a lognormal distribution

$$P_f = \Phi\left[\frac{\ln(E(R)/E(C))}{\sqrt{V_R^2 + V_C^2}}\right] = \Phi(Z) \qquad (4)$$

Here $E(C)$ is the median value of the structural capacity defined for the damage state, V_c is the dispersion or lognormal standard deviation of the structural capacity, $E(R)$ is the environmental demand as a function of a chosen environmental intensity parameter, V_R is the logarithmic standard deviation for the demand and $\Phi(*)$ is the standard normal distribution function.

The maximum overturning moment is designated by R . According to this definition R is a utilization ratio, and $E(C)$ act as the maximum available capacity with a maximum value of 1.. The reliability index is then determined from R and V_R obtained from multiple runs as described later in this paper.

The reliability index β is a measure of the reliability of an engineering system that reflects both the mechanics of the problem and the uncertainty in the input variables. This index provides a measure of comparative reliability without having to assume or determine the shape of the probability distribution necessary to calculate an exact value of the probability of failure. The reliability index is defined in terms of the expected value and standard deviation of the performance function, and permits comparison of reliability among different designs without having to calculate absolute probability values.

The probability of failure associated with the reliability index is a *probability per structure*; it has no time-frequency basis. Once a structure is constructed or loaded as modelled, it either performs satisfactorily or not. Nevertheless, the β value calculated for an existing structure provides a rational comparative measure.

Reliability indices are a relative measure of the current condition and provide a qualitative estimate of the expected performance. Structures with relatively high reliability indices will be expected to perform their function well. Structures with low reliability indices will be expected to perform poorly and present major rehabilitation problems.

4. RELIABILITY ANALYSIS

A simplified reliability analysis includes the following steps [12]:

1. A deterministic model (e.g., an analysis procedure to determine the overturning of the system). In this study we use a simple manual calculation.

2. Important variables considered to have sufficient inherent uncertainty are taken as random variables and characterized by their expected values, standard deviations- correlations are neglected in this paper. In concept, every variable in an analysis can be modelled as a random variable as most properties and parameters have some inherent variability and uncertainty. However, a few specific random variables will usually dominate the analysis. Including additional random variables may unnecessarily increase in computational effort without significantly improving results. When in doubt, a few analyses with and without certain random variables will quickly illustrate which are significant, as will the examination of variance terms in a Taylor's series analysis. Significant random variables typically include material strengths, structural dimension, mass distribution, load distribution, support conditions.

3. A performance measure, or a limit state, $E(R)/E(C) \geq 1.0$ (where $E(R)$ is e.g. the maximum tolerable deformation, or a given ductility factor μ , minimum acceptable OT etc.).

4. The expected value and standard deviation of the performance function are next calculated. In concept, this involves integrating the performance function over the probability density functions of the random variables. In practice, approximate values are obtained using the expected value, standard deviation, and correlation coefficients of the random variables in the Taylor's series method or the point estimate method.

5. The reliability index β is calculated from the expected and standard deviation of the performance function. The reliability index is a measure of the distance between the expected value of $\ln(E(R))$ and the limit state $\ln(E(C))$.

6. If a probability of failure value is desired, a distribution is assumed and $P(f)$ is calculated.

For step 4 the moments of the performance function are estimated from the moments of the random variables. Methods such as direct integration, Taylor’s series, point estimate methods, and Monte Carlo Simulation [Vose] can be used to determine the mean and standard deviation of the performance function. In direct integration, the mean value of the function is obtained by integrating over the probability density function of the random variables [12].

In order to estimate the variability of design results in terms of their mean and standard deviations, the First Order Second Moment (FOSM) method that involves approximation based on Taylor expansion are employed in this paper.

$E(R)$ can be expressed as:

$$E[R] = R(E[X_1], E[X_2], \cdots, E[X_n]) \quad (5)$$

where $X_i (i = 1,2,3...)$ represents the random variables such as material yield strength, post yield hardening, masses and their distribution and damping and so on.

If Taylor series expansion for a performance function of several random variables, $E(R)$, is performed about the mean values of the random variables and only first order terms are retained, approximate variance of the function can be expressed as:

$$VarR = \sum \left(\frac{\partial R}{\partial X_i} \right)^2 \sigma_{X_i}^2 + 2 \sum \left(\frac{\partial R}{\partial X_i} \times \frac{\partial R}{\partial X_j} \right) \rho_{X_i, X_j} \sigma_{X_i} \sigma_{X_j} \quad (6)$$

When the random variables in function R are assumed uncorrelated, Equation (6) can be presented in a simpler form as follows:

$$Var[E(R)] = \sum \left(\frac{\partial E(R)}{\partial X_i} \right)^2 \sigma_{X_i}^2 \quad (7)$$

It is quite common in engineering to encounter non-closed form of the performance functions.

When R is a non-closed form function, the partial derivatives of R can be estimated numerically using the finite difference method, i.e.:

$$\frac{\partial R}{\partial X_i} \approx \frac{R[X_{i+}] - R[X_{i-}]}{X_{i+} - X_{i-}} \tag{8}$$

where X_{i-} and X_{i+} represents the random variable X_i taken at some increment above and below its expected values (e.g. $\pm 1\sigma$ or $\pm 2\sigma$). Theoretically, an extremely small increment gives the most accurate value of the derivative at the expected value. This FOSM method allows the engineer to see the contribution of each random variable to the total uncertain in the function R.

$$Var[R] \approx \sum_{i=1}^{n} \left(\frac{R[X_{i+}] - R[X_{i+}]}{2} \right)^2 \tag{9}$$

5. DESCRIBING VARIABLES

5.1 WAVE, WIND & CUREENT

A major component in this process is determining the environmental loads. The simplest analysis is a deterministic static or dynamic analysis, which accounts for soil-wave-structure interactions. The static analysis is generally inadequate when the structure's natural period exceeds 3 seconds. However, jack-ups in water depth of 70 t0 90 meters have a natural period 5 to 6 seconds. For 100 to 110 meter deep the natural period raises to 6 to 8 seconds.

5.2 AIR GAP

RP 95J describes two means of calculating a minimum air gap. The preferred method is site specific and the alternative is the use of the generic air gap curve.

A site specific minimum air gap should be derived from 100-year hurricane wave crest data plus an uncertainty allowance of 3 to 5 %. Additionally, an appropriate settling allowance applicable to the involved unit and soil conditions should be calculated and added to the wave crest and uncertainty allowance computation. The wave crest data should be derived from the site specific metocean data described under Part I. Potential storm settlement calculations should be based on a 100-year return period event or greater.

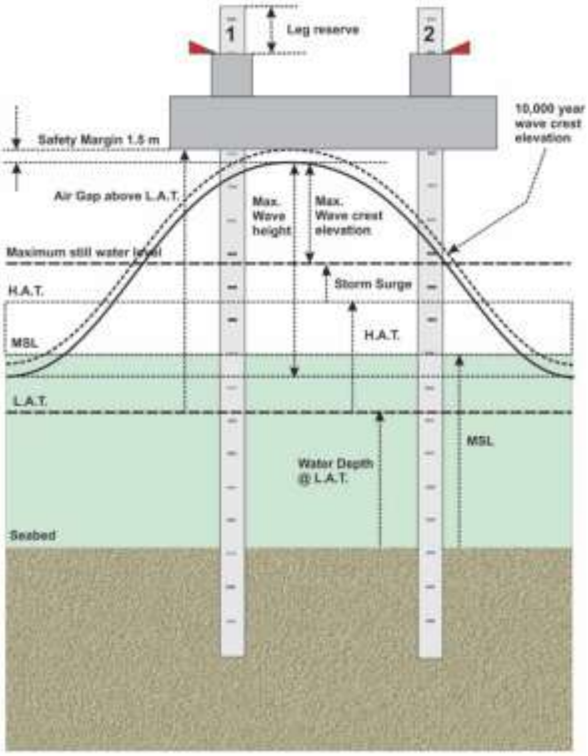


Figure 15 Design parameters (3)

An alternative to the site specific method of air gap calculation is the use of the generic air gap curve located on Appendix A of the RP and depicted in Figure 2. This curve was derived from new metocean calculations and includes a crest uncertainty factor as well as a settlement factor of 4 feet.

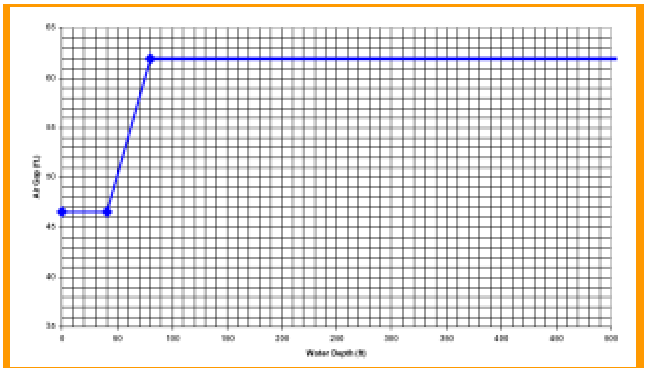


Figure 16– Generic Air Gap Curve [2]

6. OVERTURNING OF A JACK-UP

For impendent leg jack-ups, the axis of rotation is assumed to be horizontal connecting the axes of two legs at the bottom of spud-cans, as shown in Figure 17.

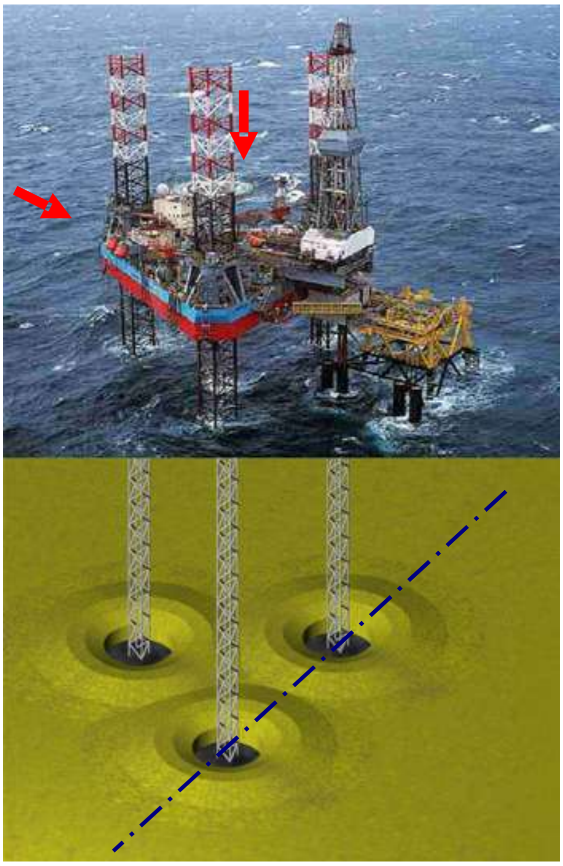
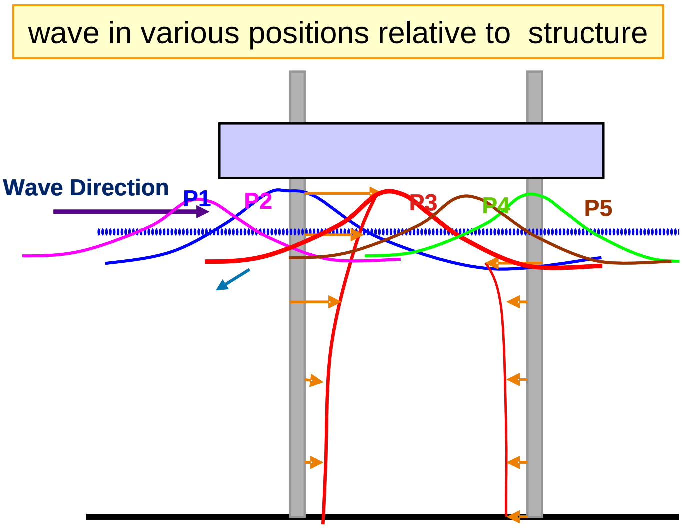


Figure 17 Axis of rotation on an independent leg jack-up (7)

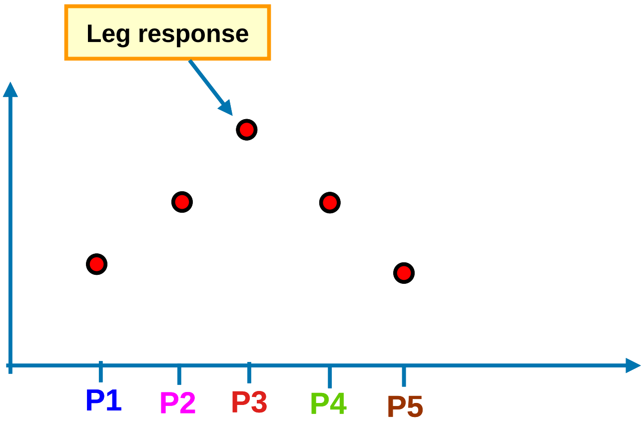
If partial embedment of the spud-cans can be assumed, the position of the axis of rotation is eccentric on the most loaded side of spud-cans. If the spud-cans and the lower part of the legs are embedded, the axis of rotation passes through the resultant pressure. DNV (1990) assumes that the axis of rotation is located mid-way between the centre and the outer edge of the spud-cans.

6.1 OVERTURNING MOMEMENT

Overturning moment is calculated by assuming all environmental loads are acting in unison. The overturning moment is calculated with respect to the axis of rotation assuming that wave, current and wind acting in the same direction. This calculation must account for the dynamic amplification factor and the P-D effect. In practice the P-D effect is accounted for by reducing the capacity of the system.



(a) Position of wave at different location



(b) Resulting leg load

Figure 18 Positioning of wave crest

The overturning moment is given by (Figure 19):
The overturning moment including the dynamic amplification component is calculated by:

$$M_{OT} = M_{mean} + DAF \times A_H$$

M_{OT} =total overturning moment

M_{mean} =mean value of overturning moment for one wave cycle

DAF = dynamic amplification factor

A_H =Amplitude of moment due to wave and current

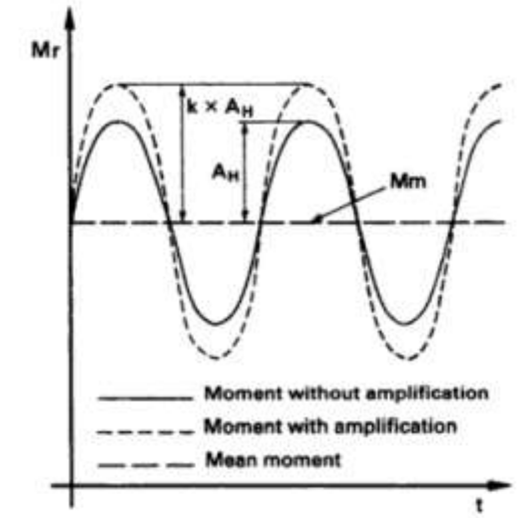


Figure 19 Overturning moment (1)

$$DAF = \frac{1}{\left(\sqrt{(1-(T_0/T)^2)^2 + (2cT_0/T)^2}\right)}$$

T_0 =natural period of the jack-up
T =wave period
c =total damping due to soil, structure and hydrodynamic; about 6 to 8% of the critical damping)

If damping is very small, the above equation reduces to:

$$DAF = \frac{1}{(1-(T_0/T)^2)}$$

6.2 RESTORING MOMENTS

Naturally realistic variable onboard loads should be used for evaluation of restring moments. If no details are available half of the total allowable variable loads in survival condition can be assumed to be as a “realistic” load level.
Buoyancy of submerged parts (legs, spud can...) is taken into account in calculation of restoring moment.

Restoring moment is reduced to take into account the actual deformation of the jack up, the clearance between the leg and the hull, the overall dimension and horizontal tolerances, as well as the P-D effect; this is given by:

The following equation is used to determine the restoring moments:

$$M_{res} = M_{r0} - \frac{nP(e_0 + e)}{1 - \frac{P}{P_E}}$$

or, $M_{res} \approx M_{r0} - nP(e_0 + e)$

M_{res} =restoring moment
M_{r0} =restoring moment assuming structure is rigid
P =average axial for in the leg
P_E =critical Euler buckling load
e_0 =horizontal static displacement of the jack up ($e_0 = e_1 + e_2 + e_3$; Figure 20)
e = horizontal displacement of the jack-up under the total environmental loads
n =number of legs

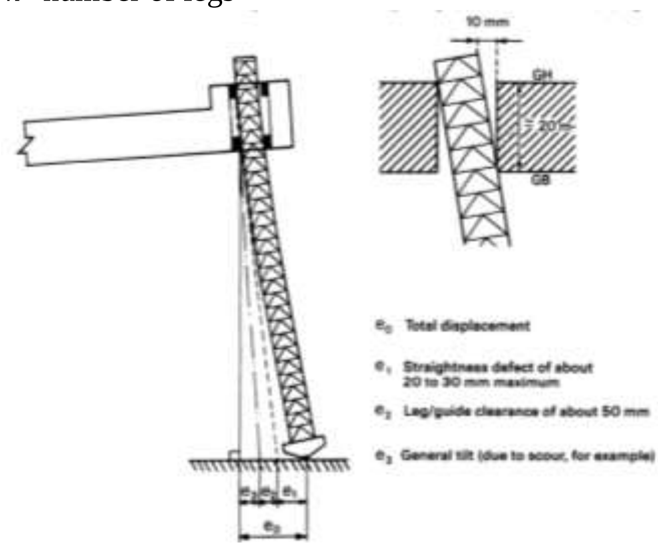


Figure 20 Horizontal static displacements (1)

6.4 SAFETY FACTOR

During initial preloading, and in calm weather, the footings of a jack up are essentially subjected to purely vertical loading. During drilling operation and in a storm, the spud-cans must also resists overturning moments, horizontal loads and changes in vertical load arising from wave action. Under storm condition footing experiences a combination of vertical and horizontal loads and moments. The conventional procedure is to assume the footing offers no resistance to moment loading. i.e. behaving like a pin. Under this assumption the maximum bending moment occurs at the top of the leg, which proves to be critical in design. If the footings offer some rotational restraint, the ultimate capacity of the rig would enable to work under severe wave loading than the simplified assumption allows. Spud-cans are often embedded to a significant depth below the seabed, typically up to two time diameter in soft clay. If such fixity can be archived the natural period of the rig reduces and hence the stress level drops and the fatigue life increases.

This starts with the determination of the most unfavourable sea states namely wave period & direction and loading conditions.

The most unfavourable crest position is determined by passing a wave through the structure. For independent leg jack ups, the vertical wave loads are negligible. The maximum overturning moment is determined when the total horizontal load is at its maximum.

For independent leg jack up the axis of rotation for evaluating the overturning moment and restoring moments, is assumed to be the axes of two legs at the bottom level of the spud can (Figure 1). If partial embedment of the spud can be ascertained, the position of the axis of rotation is eccentric on the most loaded side of the spud cans. If the spud-can and the lower part of the legs support this embedment the axis of rotation passes through the resultant of the pressures. DNV assumes that the axis of rotation is located mid-way between the centre and the outer edge of the spud cans.

If the safety factor is less than 1.25, a number of checks are necessary; e.g. possibility of mobilizing some level of spud can fixity and the ability of the can-leg connection to resist this moment.

Provided such possibility can be ascertained, it can be assumed that the axis of rotation is eccentric and located at distance M/Q from the centre of spud cans towards the most heavily loaded edges (M is the moment under the foundation and Q is the normal load under the foundation)

7. EXAMPLE

7.1 BASIC DATA

The basic data for the case study are given in Figure 21:
Reactions due to self-weight and on board variable loads at the jacking system level are:

- Aft legs : 32 MN each
- Bow leg: 30 MN
- Apparent leg weight 6MN each
- Natural Period $t_0 = 7s$,
- Cross-sectional area $0.4m^2$
- Leg Moment of inertia $5m4$
- Equivalent E 200,000 MPa
- Distance between spud-can and bottom hull 105m
- Distance between bow leg to axis of rotation 55m
- Wave period $T = 14s$

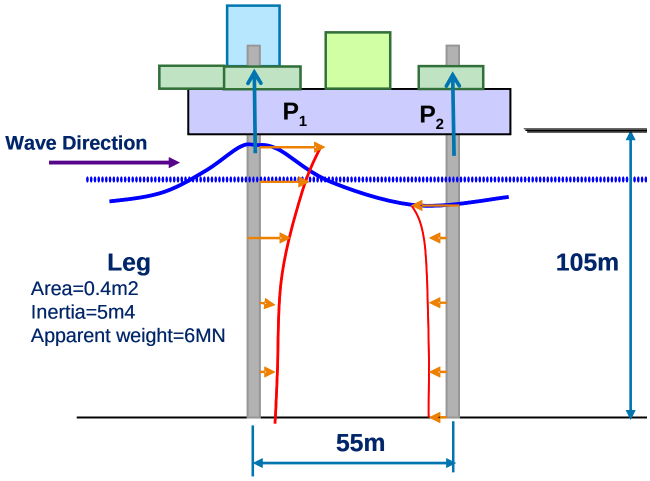


Figure 21 Basic data for the example problem

The above data gives 1.2m displacement at top of platform, including clearance.

7.2 Environmental Loads

Table 1 gives overturning moment due to wave, current and wind on the installation. These are calculated for the mean values of the parameters and hence an uncertainty associated with them. It is assumed that the coefficient of variation (COV) for this loads are 0.25. It should be noted that for some depth, where the air gap is not adequate, wave in deck causes additional overturning moment.

Water Depth	**Wave** MNm	**Current** MNm	**Wind** MNm	**Air Gap** m
50	246	34	88	20
55	286	39	102	20
60	333	45	119	20
65	387	52	138	20
70	450	61	160	20
75	520	71	186	20
80	610	83	216	20
85	705	96	250	20

90	820	112	292	15
95	**950**	**130**	**339**	**10**
100	1120	150	394	5
105	1315	175	457	0
110	1690	229	599	0

Table 1

7.3 Calculation of restoring moment, M_{res}

Though the restoring moment remains the same for all water depths, all calculations in this section relates to 95 water depth.

(a) Ignoring deformations, restoring moment is calculated by the product of reaction under the least loaded leg multiplied by the distance from this leg to the axis of ration

$$M_{res} = (30+6)\times 55 = 1980 MNm$$

(b) The critical buckling load, P_E

The average load per leg P , is:

$$P = (32+32+30)/3 + 6/2 = 34.33 MN$$

The radius of gyration of the leg:

$$r = \sqrt{I/S} = \sqrt{5/0.4} = 3.536m$$

The leg's slenderness ratio is:

$$\lambda = (2l)/r = (2\times 105)/3.536 = 59.4$$

The critical Euler stress:

$$\sigma_E = \frac{\pi^2 E}{\lambda^2} = \frac{\pi^2 \times 200{,}000}{59.4^2} = 447.6\,\mathrm{MPa}$$

Hence:

$$P_E = 0.4m^2 \times 447.6\,\mathrm{MPa} = 179\,\mathrm{MN}$$

The reduction of the restoring moment due to excursion (1.2m) of the platform (P.D effect) and the buckling risk of the leg is determined by:

$$\frac{nP(e_0+e)}{1-\dfrac{P}{P_E}} = \frac{3\times 34.4\times 1.2}{1-\dfrac{34.4}{179}} = 152.9 MNm$$

The effective restoring moment, taking account of the excursion of the platform and the buckling of the leg is:

$$M_{res} = 1980 - 152.9 = 1827.1 MNm$$

7.3 Calculation of Overturning Moment

Dynamic amplification factor is:

$$DAF = \frac{1}{(1-(7/14)^2)} = 1.33$$

The average moment due to wave and current is:

$$\frac{950-130}{2} = 410 MNm$$

The amplitude of moment due to wave and current is

$$A_H = \frac{950+130}{2} = 540 MNm$$

The total overturning moment to be considered is hence:

Moment due to wind=339MNm

Average moment due to wave and current=410MNm

Dynamic amplitude of moment du to wave and current: 540x1.33=719.83MNm

Hence total =1468.82MNm

The overturning safety factor is:

$$SF = \frac{M_{res}}{M_{OT}} = \frac{1827.1}{1468.82} = 1.24$$

7.4 Conditional Probability of Failure

Six random variables are considered, the Wave, current, wind, Wave-period, Leg-load and excursion. The assigned mean probabilistic moments for the Metocean loads are given in Table 1 and also in the Appendix. The minimum acceptable overturning safety factor is taken to be 1.0.

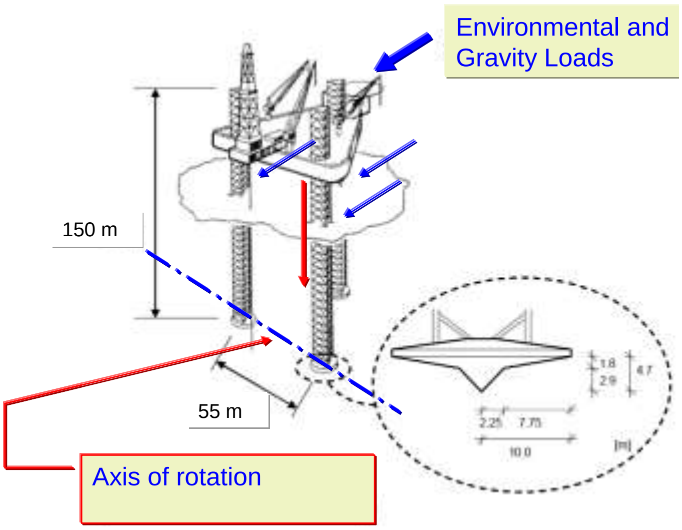


Figure 22 Rotation axis of the example problem

For the first analysis (RUN1), the six random variables are taken at their expected values. The utilisation factor is 0.78 (3.9/5).

For the second, third and fourth analyses, one variable is taken at a time and its value is assumed to be the expected value plus and minus one standard deviation, while other three variables are kept at their expected values. Results obtained from these analyses are used to calculate the total variance related to the Utilisation Ratio. For instance:

$$Var[R] \approx \left(\frac{R[X_{i+}] - R[X_{i-}]}{2} \right)^2 = \left(\frac{0.48 - 1.5}{2} \right)^2 = 0.023$$

When the variance components are summed, the total variance will be: 0.046591. Taking the square root of the variance gives the standard deviation of 0.21585.

The Utilisation Ratio, R, is assumed to be log-normally distributed random variable with the expected vale (first moment) $E(R) = 0.8040$ and $\sigma_R = 0.21585$. Using the properties of the lognormal distribution, the equivalent normally distributed random variable has the following parameters:

$$E(\ln R) = \ln E[R] - \frac{1}{2}\sigma^2_{\ln R} = \text{-}0.25293$$

and

$$\sigma_{\ln R} = \sqrt{\ln\left[1 + V_R^2\right]} = 0.26846$$

The maximum allowable R is assumed to be 1.00

$$\beta = \frac{\ln(E(R)/E(C))}{\sqrt{V_R^2 + V_C^2}} = \frac{0.26381 - (\text{-}0.25293)}{\sqrt{(0.26856)^2 + (0.0)^2}} = 0.9588$$

For this value, the cumulative distribution function $F(\beta) = 0.8312$, this represents the probability that the R is below the critical value. The probability that the UR is above the critical value is

$$P_f = 1 - F(\beta) = 1 - 0.8312 = 0.1688$$

These analyses were repeated for a number of water depths from 70m to 120m. The resulting conditional probability of failure function is shown in Figure 23.

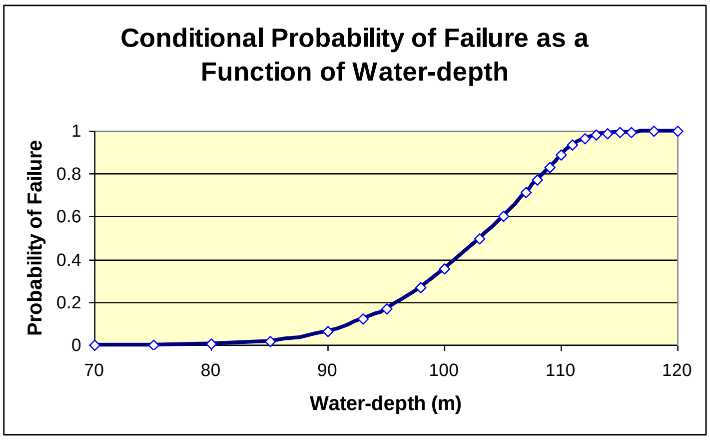


Figure 23 Conditional probability of failure

7. CONCLUSIONS

The conditional probability of failure was determined for given levels of environmental loads on an example jack-up. This curve can be used to carry out detailed safety assessments of jack-up failure due to overturning moment. This approach identifies the load carrying margin for stability of jack-ups.

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Table 2 Summary of inputs and results for the case study (95 m water depth)

		1	2	3	4	5	6	7	8	9	10	11
1		Varaible	Level of parameter	Wave (kN)	Current (kN)	Wind (kN)	Wave Period (S)	Average restoring weight(kN)	Excursion (m)	Ave Deck Height (m)	Mso	Slenderness
2	Run1		Mean	950	130	339	14	36	1.2	105	1980	59.40
3	Run2	Wave	Mean-б	712.5	130	339	14	36	1.2	105	1980	59.40
4	Run3		Mean+б	1187.5	130	339	14	36	1.2	105	1980	59.40
5	Run4	Current	Mean-б	950	97.5	339	14	36	1.2	105	1980	59.40
6	Run5		Mean+б	950	162.5	339	14	36	1.2	105	1980	59.40
7	Run6	Wind	Mean-б	950	130	254.25	14	36	1.2	105	1980	59.40
8	Run7		Mean+б	950	130	423.75	14	36	1.2	105	1980	59.40
9	Run8	Wave Period	Mean-б	950	130	339	10	36	1.2	105	1980	59.40
10	Run9		Mean+б	950	130	339	18	36	1.2	105	1980	59.40
11	Run10	Leg_weight	Mean-б	950	130	339	14	32.4	1.2	105	1782	59.40
12	Run11		Mean+б	950	130	339	14	39.6	1.2	105	2178	59.40
13	Run12	Excursion	Mean-б	950	130	339	14	36	0.9	105	1980	59.40
14	Run13		Mean+б	950	130	339	14	36	1.5	105	1980	59.40

	12	13	14	15	16	17	18	19	20	21	22
1	Pe	Reduction	Ms	DAF	Average Moment	Amp	OTM	Safety Factor (F.O.S)	Utilisation Ratio Required(=1.0)/ F.O.S	Varaince component	Variance component %
2	179.040	152.925	1827.075	1.333	410.000	540.000	1469.000	1.244	0.8040		
3	179.040	152.925	1827.075	1.333	291.250	421.250	1191.917	1.533	0.6524		
4	179.040	152.925	1827.075	1.333	528.750	658.750	1746.083	1.046	0.9557	0.02300	49.36335
5	179.040	152.925	1827.075	1.333	426.250	523.750	1463.583	1.248	0.8011		
6	179.040	152.925	1827.075	1.333	393.750	556.250	1474.417	1.239	0.8070	0.00001	0.01886
7	179.040	152.925	1827.075	1.333	410.000	540.000	1384.250	1.320	0.7576		
8	179.040	152.925	1827.075	1.333	410.000	540.000	1553.750	1.176	0.8504	0.00215	4.61810
9	179.040	152.925	1827.075	1.961	410.000	540.000	1807.824	1.011	0.9895		
10	179.040	152.925	1827.075	1.178	410.000	540.000	1385.218	1.319	0.7582	0.01338	28.70740
11	179.040	152.925	1629.075	1.333	410.000	540.000	1469.000	1.109	0.9017		
12	179.040	152.925	2025.075	1.333	410.000	540.000	1469.000	1.379	0.7254	0.00777	16.68424
13	179.040	114.694	1865.306	1.333	410.000	540.000	1469.000	1.270	0.7875		
14	179.040	191.157	1788.843	1.333	410.000	540.000	1469.000	1.218	0.8212	0.00028	0.60804
15									SUM	0.04659	
16	E(i)=	0.8040		E(ln)=	-0.25293		z=	0.9588			
17	Var(R)=	0.04659									
18	Sigma(i)=	0.21585		Sigm(ln R)	0.26381						
19	V(R)=	0.26846									
20							Pr(f)= F(z)	0.8312			
21	I(crit)	1.00		Ln(I crit)=	0.0000						
22							Pf=1-F(z)	0.1688			