An approach for time-dependent reliability analysis of Jackup structures

Ahmad Idris1*, Indra Sati Hamonangan Harahap1 and Montasir Osman Ahmed Ali1

Abstract: This paper proposes an approach for evaluation of time dependent reliability of Jackup structures. An approach for signal processing using prolate spheroidal wave functions is combined with stochastic field representation method to represent ocean waves with least number of independent sources of uncertainty. First passage probability for dynamical systems subject to stochastic loading was then used in the formulation of the reliability approach. A simplified Jackup was modelled and used to demonstrate the time dependent reliability approach by propagating the uncertain wave load on the unit. In-house computer codes were developed for the analysis of the stochastic response in time-domain to obtain time dependent failure probabilities. The results were compared with those of a similar model in which the statistical method is used.

Keywords: reliability analysis; offshore structures; time dependent probability

1. Introduction
Jackup is a mobile structure used for oil exploration and production in various offshore locations. Its suitability for use at a specific location is checked using different levels of safety assessment methods. Based on the guideline for site specific assessment (SSA) of Jackup (International Standardization Organization, 2009; SNAME, 2008), when the unit fails to satisfy the criteria of a given assessment level, it is not simply disqualified for use in the location, rather, it is further assessed by increasing the assumptions of the analysis method until a decision can be made. For example, dynamic response can be considered when the unit fails an assessment in which static response was used. One of such recommended safety assessment approach is the analysis of the structural response which is

ABOUT THE AUTHORS
The authors of this manuscript are members of the Offshore and Geotechnical Engineering research cluster at the Department of Civil and Environmental Engineering of Universiti Teknologi Petronas, Malaysia. The research project from which this article was derived is aimed at improvement of the current Site Specific Assessment (SSA) procedures as given in the guidelines for jack-up SSA. It is a project aimed at developing more accurate structural, geotechnical and response analysis methods for jack-up by considering soil-structure interactions. Ahmad Idris, born in Pindiga, Gombe-Nigeria, is currently a PhD student under the supervision of Indra Sati Hamonangan Harahap and Montasir Osman Ahmed Ali.

PUBLIC INTEREST STATEMENT
The efficiency of a reliability analysis methods depends on how much information about the given problem the method has utilised. By using time-dependent reliability analysis methods in jack-up reliability, more information about the uncertain loading as well as the dynamic response is utilised. This enables more in-depth analysis of the stochastic response by studying the transitions from the safe to unsafe regions of failure. This results in a more accurate estimate of the failure probability for the jack-up due to the random behaviour of the wave loading. Accurate estimate of these failure probabilities enables a safer and accurate assessment of the jack-up before being offered for use in a given offshore location.
usually accomplished by the use of reliability theories whereby a reliability criterion is used to assess the suitability of the units. Such reliability analysis methods are divided into time dependent and time independent methods. In time independent methods, statistical properties (mean and standard deviation) of the extreme response are used to evaluate the probability that a given response threshold value is not exceeded during the period of excitation. When the unit fails the criteria of time independent approach, appropriate time dependent methods are recommended to be used in the response analysis.

Jackup reliability analysis using statistical distribution methods (Cassidy, Taylor, Taylor, & Houlsby, 2002; Guedri, Cogan, & Bouhaddi, 2012; Mirzadeh, Kimiae, & Cassidy, 2016a) is accomplished by selecting appropriate environmental parameters describing a given design state. Structural dynamic analysis is performed on a simplified model (Cassidy, Taylor, & Houlsby, 2001; Jensen & Capul, 2006) or a full model (Mirzadeh, Kimiae, & Cassidy, 2015, 2016b) in accordance with the SSA guidelines. The statistical distribution function of the extreme response is then used to evaluate the probability that a given response value is not exceeded.

Time dependent reliability analysis approach in Jackup reliability studies is absent in the literature. Presently, the methods used in the response analysis of Jackup units cannot evaluate the evolution of the failure probabilities in time domain as recommended in International Standardization Organization (2009), and SNAME (2008). In time dependent reliability analysis, rather than using extreme response values, failure probabilities are evaluated by considering time histories of the structural response due to random stochastic loading. In a fully correlated time dependent problem, failure probabilities are defined over a time interval that consist of a finite number of instants where the variables and failure events between time instants are interdependent (Hu & Du, 2013).

This study aims to propose a methodology for time dependent reliability analysis of Jackup. The method is based on the representation of the sea state using Karhunen-Loève series (KLS expansion (Ghanem & Spanos, 1991; Phoon, Huang, & Quek, 2002, 2004). Eigenfunctions of Prolate spheroidal wave functions (PSWF) (Osipov & Rokhlin, 2014) will be used as the orthogonal basis functions of the KLS expansion. Time dependent reliability solution methods will be used in the determination of the failure probabilities of a simplified Jackup model during operation. The results of this study will constitute another level of Jackup SSA in which more complex assumptions are incorporated in to the reliability analysis as recommended in the guidelines.

2. Time dependent reliability analysis
When some of the design random variables in reliability analysis are subject to change in properties with due course of time, then the effect of time will have to be featured in the analysis. In such cases, the interest lies in the determination of the probability that the magnitude of the response history of a system will exceed a prescribed threshold level within a given time interval. This is given as (Andrieu-Renaud, Sudret, & Lemaire, 2004):

\[ P_f(T) = P(\exists t \in [0, T]; \{ Y(t) \} \geq b) \]

Equation (1) represents the first passage (also known as first excursion) problem with type D barrier whose complexity is related to the interaction of excursion events of the response (He, 2009). During excitation by a stochastic input, the structural response continuously makes transitions from safe to unsafe regions (up crossings) of limit state (Figure 1).

The general approach for the solution of first passage problems is the use of integral equation method based on out crossing theories (Madsen & Krenk, 1984) and Simulation techniques (Dubourg, Sudret, & Deheeger, 2013; Rubinstein & Kroese, 2008).

Simulations techniques involve random simulation of the stochastic input and solving the structural system a number (large) of times (N) to obtain population of structural response (\( Y(t) \)). Response variability can then be studied using simple statistical relations as (Sakata, Okuda, & Ikeda, 2015):
Other variants of the simulation techniques that aim to reduce the computational cost involved are also employed. For example, methods such as the importance sampling (Papaioannou, Papadimitriou, & Straub, 2016), subset simulation (Schneider, Thöns, & Straub, 2017) and line sampling (Lu, Song, Yue, & Wang, 2008) were proposed whereby instead of solving the system a large number of times, the simulation of the random input is controlled in such a way that only representative random variables are used without significant loss in accuracy. On the other hand, metamodeling techniques such as the use of Polynomial response surface (Zhao, Fan, & Wang, 2017), gradient-enhanced Kriging (Ulaganathan, Couckuyt, Dhaene, Degroote, & Laermans, 2016) and Artificial Neural Networks (ANN) (Chojaczyk, Teixeira, Neves, Cardoso, & Soares, 2015) are used to develop a model that describe the relationship between the structural input and the resulting output in such a way that when the stochastic input is simulated, the desired population of the response can be obtained without recourse to the structure. For large systems such as Jackup structures, the computational cost required in simulation techniques made its application nearly infeasible.

In the integral equation method, the general form of the first passage probability of failure is given as:

\[ P_f(t) = 1 - \left[ 1 - P_f(t_a) \right] e^{-\int_{t_a}^{t} \nu^+ \text{d}t} \]  

(4)

\( P_f(t) \) is the probability of starting below the threshold level of the response and \( \nu^+ \) is the up crossing rate.

Various analytical procedures exist for the determination of the up crossing rate for a general random process. For example, an analytical approach to compute the crossing rates was derived for a stationary Gaussian process (Lutes & Sarkani, 2004) and for general stochastic process (Sudret, 2008). In problems where the up crossing events rarely occur over a longer period of time, it is assumed that the up crossings are independent and follows a Poisson distribution and the approach
for their evaluation is proposed in Schrupp and Rackwitz (1988), Lutes and Sarkani (2004). Whereas the Poisson assumption is shown to be efficient in the evaluation of first excursion probabilities Andrieu-Renaud et al. (2004), Hu and Du (2012) the assumption of independence between crossing events does not hold for many engineering applications in which correlations between failure events exist. In order to improve the accuracy of the Poisson assumption, a method of joint up crossing rates was proposed by Hu and Du (2013) in which the time instant are considered to be interdependent. The modification of the Poisson assumption for stationary Gaussian process is given in the study of VanMarcke (1975) in which up crossings are assumed to be interdependent and the rate of their decay obtained by considering the clumping effect of the response envelop.

In this study therefore, the integral equation and the VanMarckes approximation methods will be used to evaluate the failure probability of Jackup unit.

2.1. Poisson assumption of up-crossing method

In the Poisson assumption, the first excursion probability is obtained by assuming that crossing events are independent and follows the Poisson distribution and the up crossing rates \( \nu^+ \) is obtained using the Rice formula (Rice, 1944) by linearizing the limit-state function at the most probable point for each time instant:

\[
\nu^+(t) = \alpha(t) \phi(\beta(t)) \psi \left[ \frac{\beta(t)}{\alpha(t)} \right]
\]

where:

\[
\omega = \sqrt{\eta(t) \eta^*(t) + \eta(t) \bar{C}(t,t) \eta^*(t)}
\]

and

\[
\psi(x) = \phi(x) - x \phi(-x)
\]

The reliability index \( \beta(t) \) and the design point vector \( \eta(t) \) at each time instant are evaluated as (Valdebenito, Jensen, & Labarca, 2014):

\[
\beta(t) = \frac{r^*}{\|\kappa(t)\|}
\]

\[
\eta(t) = -r^* \frac{\alpha(t)}{\|\kappa(t)\|^2}
\]

Here, \( r^* \) is the response threshold value and \( \kappa(t) = [\kappa_1(t), \kappa_2(t) \ldots \kappa_{Nt}(t)] \) is the vector whose dimensions \( Nt \) is equal to the number of terms in the expansion of the stochastic input and the approach for its determination is given in the next section.

2.2. VanMarckes approximation

In the VanMarckes modification of the Poisson assumption for stationary Gaussian process (VanMarcke, 1975) in which crossings are assumed to be interdependent. The first excursion probability is given as:

\[
P_f(t_a, t_b) = 1 - [1 - P_f(t_a)] e^{-\frac{\omega(t_b)}{\omega(t_a)}}
\]

where \( \omega(t) \) is the decay rates obtained by modifying the rate of crossings. The VanMarckes approximation of the decay rates can be calculated from:
Here, $\beta(t)$ is the instantaneous reliability index at time $t$ as given in Equation (8). The parameter $q(t)$ is the bandwidth parameter that describes the bandwidth of the structural response and $\nu_b(t)$ is the VanMarckes up crossing rate at time $t$ and are given as (He, 2009):

$$q(t) = \sqrt{1 - \frac{a_1(t)^2}{a_0(t)a_2(t)}}$$  \hspace{1cm} (12)$$

$$\nu_b(t) = \frac{1}{2\pi} \sqrt{\frac{a_1}{a_0}} e^{-0.5\beta(t)^2}$$  \hspace{1cm} (13)$$

3. Modeling of variations in ocean surface elevation

The first stage of uncertainty treatment of systems is the representation of the stochastic fields which is the mathematical description of the uncertain input of the structural system. As it will be seen in the next section, uncertainty analysis of systems subject to stochastic excitation requires the number of dynamic analysis equal to the number of stochastic expansion terms. The Karhunen-Loeve expansion (KLE) method have been shown to be more efficient approach for the representation of a stochastic process with minimal number of independent sources of uncertainty (Idris, Harahap, & Ali, 2017; Phoon et al., 2004). In this study therefore, a method based on KLE that uses orthogonal functions derived from the properties of Prolate Spheroidal Wave Functions (PSWF) will be used in the representation of the wave. The general expression of a stochastic field $u(x, t)$ using KLE is given as:

$$u(x) = \bar{u}(x) + \sum_{n=1}^{N} \sqrt{\lambda_n} \xi_n \phi_n(x)$$  \hspace{1cm} (14)$$

The function $\bar{u}(x, t)$ is the mean value of the field and for a Gaussian process, it is assumed to be equals to zero. The eigenvalues $\lambda_n$ and the eigenfunctions $\phi_n$ are obtained from the solution of the integral equation cast with the auto correlation function $R(t-t')$ of the field as the kernel as:

$$\int_0^1 R(t-t')\phi_n(t)dt = \lambda_n \phi_n(t)$$  \hspace{1cm} (15)$$

A scheme by Sclavounos (2012) in which a sea state can be represented based on the KLE decomposition of the wave signal introduced a method that uses the eigenfunctions of PSWF with tuneable band width parameter. The method which allows ocean wave loading to be represented with minimal number of terms provides a means by which state of the art reliability solution methods can be used in the evaluation of time dependent probability of failure for large offshore structures.

3.1. Evaluation of prolate spheroidal wave functions (PSWFs)

PSWFs plays a significant role in signal processing due to the fact that they have been natural tools for the analysis of band limited functions (Senay, Chaparro, & Durak, 2009). For a sea state in which the spectral energy density of the location is known, the Karhunen-Loeve expansion method with PSWFs can be used to express the surface elevation of the wave to develop wave kinematics and subsequently obtain the wave loading within the duration of the sea state (Sclavounos, 2012).

PSWFs are those functions originally discovered as the eigenvectors of the Sturm-Liouville differential Equation problem (Karoui & Mounni, 2008; Rokhlin & Xiao, 2007):
They are also the Eigen vectors of the integral:

$$F_{π}(ψ)(x) = \int_{-1}^{1} e^{iπt}ψ(t)dt$$

### 3.2. Evaluating Eigen functions of the KLE

By obtaining the eigenvalues and eigenfunctions of PSWFs from the solution of Equations (16) and (17), the corresponding eigenvalues and eigenfunctions of KLE in Equation (14) can be obtained using the spectral energy density model by casting the integral equation:

$$M_{ij} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \psi_{i}^{c*}\psi_{j}^{c*}S(ω)dω$$

This lead to the formulation of the symmetric matrix of form (Sclavounos, 2012):

$$Q_{ij} = Q_{ji} = χ_{i}A_{j}CP_{ij}$$

By solving the above matrix eigenvalue problem, the eigenvalues $χ_{i}$ and the eigenvectors $\beta_{ij}^{p}$ provides the means for the solution of KLE integral equation. They are used to calculate the eigenfunctions of the KLE as:

$$ϕ_{n}(t) = \sum_{j=0}^{∞} β_{qj}^{p}\psi_{j}^{lc}$$

By obtaining the eigenfunctions in Equation (20), the wave surface elevation can be represented as the linear superposition of these eigenfunctions as in Equation (14) with the coefficients $ξ_{n}$ taken as independent identically distributed random variables. The decay of the eigenvalues from the solution of Equation (19) shows the required number of terms to keep in the expansion.

Detailed procedure for the KLE representation of a sea state in which the PSWF are used can be found in Sclavounos (2012). The properties of the PSWFs are discussed in Osipov and Rokhlin (2014), their application in signal processing have been discussed in Moore and Cada (2004) while detailed procedure for their evaluation is outlined in Xiao, Rokhlin, and Yarvin (2001).

### 4. Structural analysis

A linear structural system is usually represented by an appropriate finite element model with n-degree of freedom. Such systems’ structural response due to an input excitation is described by differential equation of the form (Paultre, 2013):

$$M \ddot{x}(t, z) + C \dot{x}(t, z) + Kx(t, z) = g( t, z)$$

Here, $\dot{x}$ and $x$ stands for the acceleration and velocity vectors of the response vector $x$ respectively. $M$, $C$ and $K$ are respectively the mass, damping and stiffness matrices which depends on the structural parameters that, for a relatively shorter duration, are assumed to be deterministic and $g$ is the vector associating the random input $f(t,z)$ with the structural degree of freedom. The structural response of interest can be evaluated as (Paultre, 2013; Valdebenito et al., 2014):

$$Y(t, z) = \int_{0}^{t} h(t-τ)f(τ, z)dτ$$
where $h(t)$ is the unit response function due to unit pulse at time $t = 0$. Consequently, based on the representation of the ocean surface elevation using KLE method in the previous section, the dynamic response at each time $t$ can be given as:

$$Y(t, z) = \Delta t \sum_{s=1}^{Nt} (h(t - \tau) f_s(t)\zeta_s$$  \hspace{1cm} (23)

Here also, $Nt$ stands for the number of terms in the representation of the stochastic input which corresponds to the number of the dominant eigenvalues from the solution of KLE eigenvalue problem. This can alternatively be written as (Valdebenito et al., 2014):

$$Y(t, z) = \kappa(t)^T \tilde{Z}$$ \hspace{1cm} (24)

where the vector $\tilde{Z}$ represents the standard Gaussian random variables in the stochastic expansion and $\kappa$ is a vector given by:

$$(\kappa(t))_s = \sum_{i=0}^{t} h(t - t_i) f_s(t) \hspace{1cm} s = 1 \ldots Nt$$ \hspace{1cm} (25)

Consequently, the solution of Equation (25) requires the solution of the system at discretised time intervals and for each of the standard Gaussian random variables which corresponds to the number of terms in the input representation (Figure 2).

5. Implementation of framework on idealized Jackup unit

To demonstrate the application of the framework, a simple Jackup model used in the study in Cassidy (1999) was selected and used. The structural and environmental conditions are taken as the same to enable comparison. The model consists of three legs and hull with uniform properties. The legs and hull are considered as beam elements with two legs up-wave and single leg down-wave. The structural material properties of the jack up model can be found in Jensen and Capul (2006), Cassidy et al. (2002) and the effect of marine growth is neglected.
Stationary stochastic ocean condition specified by Pierson-Markowitz (P-M) spectrum model is assumed. Three design conditions specified by wave return period and described by significant wave height \( H_s \) and zero crossing period \( T_z \) is considered as given in Table 1.

In-house computer codes were developed based on the mathematical models for the evaluation of PSWFs and the eigenfunctions of KLE. Full dynamic analysis was performed using numerical schemes in commercial software to obtain response of the structure due to stochastic wave loading. The pinned foundation type was selected and the response in deck displacement was obtained (Figure 3).

5.1. Reliability evaluation
In uncertainty treatment of stochastic systems, the interest is in the comparison of the response of interest \( Y(t, z) \) against the allowable maximum value \( r^* \) within the period of the excitation. In this study, the response in deck displacement is selected and failure is said to have occurred when the response exceeds the threshold value. The occurrence of such failure is defined in terms of performance function given as:

\[
g(t, z) = 1 - \max \left( \frac{\|Y(t, z)\|}{r^*} \right)
\]

where the performance function is less than or equals to zero at any time the response surpasses the threshold limit.

6. Results and discussions
In Figures 4–6, the surface elevation of a wave from a sea state simulated for each given return period with KLE expansion using PSWFs by superposition of 8 terms as given in Equation (9) is shown. This is achieved by using the eigenvalues and eigenfunctions of the PSWFs in the expansion as discussed in previous sections.

<table>
<thead>
<tr>
<th>Return period (Years)</th>
<th>( H_s ) (m)</th>
<th>( T_z ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>12.00</td>
<td>10.81</td>
</tr>
<tr>
<td>1000</td>
<td>13.25</td>
<td>11.36</td>
</tr>
<tr>
<td>106</td>
<td>16.45</td>
<td>12.66</td>
</tr>
</tbody>
</table>
Figure 4. Surface elevation of a wave with P-M spectral energy density described by significant wave height $H_s = 12$ m and wave period $T_z = 10.81$ m ($10^2$ years return period).

Figure 5. Surface elevation of a wave with P-M spectral energy density described by significant wave height $H_s = 13.25$ m and wave period $T_z = 11.36$ m ($10^3$ years return period).

Figure 6. Surface elevation of a wave with P-M spectral energy density described by significant wave height $H_s = 16.45$ m and wave period $T_z = 12.66$ m ($10^6$ years return period).
The simulated surface elevation was compared with the surface elevation record of a wave obtained under the same environmental conditions and simulated by superposition of 512 terms using New wave theory in the study of Cassidy (1999) as well as using Fourier sine and cosine terms in (Chokrabarti, 1987) with 2000 terms. This is multiple times more than the 8 terms in the PSWFs-KLE method of this study. Consequently, only 8 number of structural analysis runs corresponding to the independent random variables in the KLE representation are required instead of 512 or even 2000 runs if the wavelet superposition method as in the new wave and Fourier method were used. The computer cost required to simulate the wave using the three different methods is shown in (Idris et al., 2017) to be approximately the same.

Time dependent reliability analysis using the two methods described in previous sections was evaluated. Figures 7 and 8 show the mean crossings rates for each of the methods and return periods. It can be seen that as the failure criteria is increased, the crossing rates decays to zero, indicating a wider safe operational region in which crossing may not likely occur.

Figures 9–11 show the cumulative probability of failure computed using the time dependent reliability methods in this study and the method using statistical distribution function of the extreme values in the study of Cassidy et al. (2002). It can be seen that the probabilities of failure increases (showing continuous reduction in chances of failure) as the failure criteria is increased. The comparison shows that the time dependent reliability framework gives higher values of the safe probability.
Figure 9. Time dependent probability of failure for 100 years return period.

Figure 10. Time dependent probability of failure for 1000 years return period.

Figure 11. Time dependent probability of failure for $10^6$ years return period.
than the traditional approach in which the statistical distribution functions of the extreme conditions were used. In Figure 7, the failure probability is plotted as a function of the ratio of allowable displacement to the actual displacement and it can also be seen that in the time dependent reliability approach, the failure probability values are lower than those computed using the traditional method.

7. Conclusions
As stated in the SSA guidelines (International Standardization Organization, 2009; SNAME, 2008), Jackup suitability for use in a given offshore location is assessed in stages. In the assessment process, one of the methods of the assessment is the use of reliability theories. Time dependent reliability methods are recommended by the guidelines to be used in the assessment. In conclusion, this study has:

- Represented the ocean wave using Karhunen-Loeve expansion with eigenfunctions of prolate spheroidal wave functions in which fewer numbers of independent sources of uncertainty are used.
- Propagated the ocean wave loading on a simplified Jackup model in the framework of finite element analysis to obtain dynamic response in deck horizontal displacement.
- Performed time dependent reliability analysis using outcrossing theory and evaluated time dependent probabilities of failure of Jackup unit. The results obtained from the two different time dependent reliability analysis methods have shown that different values of failure probability can be obtained. The comparison made with the results of reliability analysis using extreme response statistics (mean standard deviation) have shown a significant difference in values which increases with the increase in the severity of the sea state.

By evaluating the failure probabilities using time dependent reliability analysis methods, this study has shown that if a jack up failed the reliability criteria when analysed using statistical methods, then it can be further analysed using the time dependent reliability methods presented in this study. This therefore constitute a further stage of the Jackup SSA using reliability theories as recommended in the guideline. In a similar fashion, failure probability in other criteria such as overturning or bearing capacity can be evaluated using the same approach. By solving the system using any acceptable numerical scheme, the response quantity in any of the criteria can be obtained. The statistical parameters for the response quantity can be evaluated in the same way as those evaluated for the deck displacement in this study, and the reliability analysis can be performed using the same approach.

Notations

- $a_0, a_1, a_2$: Zero, First and second order spectral moments
- $\alpha$: Rates of decay of crossings
- $\beta_e$: Eigenvectors from the solution of $Q$
- $\beta$: Instantaneous Reliability Index
- $b$: Threshold value of allowable displacement
- $\phi$: Eigenfunctions from the solution of $Q$
- $C$: Slepian frequency
- $\eta$: Most probable point (MPP)
- $\phi(\cdot)$: Cumulative density function (CDF)
- $\chi$: Eigenvalues from the solution of $Q$
- $f$: Function
- $F_c$: Integral operator
- $\phi(\cdot)$: Probability density function (PDF)
κ  Response vector
λ  Eigenvalues of PSWFs
M  Karhunen-Loeve Integral equation
Nmc  number of simulation samples
Ω  cut-off frequency of spectral energy density
Pc  differential operator
P  probability
Pr  probability of failure
ψ  eigenfunctions of PSWFs
q  band width parameter of response
Q  matrix eigenvalue problem
r*  response allowable threshold
σ  standard deviation
t  time instant
τ  time lag
T  duration
ν  poisson assumption crossing rate
Vb  VanMarckes up-crossings rates
x  random variable
X  distance along x-direction
Y(t)  structural response at time t
ξ  independent identically distributed variables
z  standard Gaussian random variables

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