ASSESSING SEISMIC RISK AND TARGET RELIABILITY FOR JACK-UPS USING CONTINUOUS-TIME MARKOV CHAINS

D. Rabaut
Engineering, Design & Technology DEME Offshore
DEME
** corresponding author: rabaut.dieter@deme-group.com*

ABSTRACT
This article examines the definition of target reliability for different operational modes of a Jack-up using a Continuous-Time Markov Chain (CTMC) model to evaluate seismic risk. The CTMC framework captures the stochastic transitions between various operational states of the Jack-up, offering a method for evaluating reliability under seismic conditions. The findings emphasize the importance of state-dependent reliability in assessing the performance and structural integrity of Jack-ups during seismic events.

Reliability in seismic design focuses on the ability of structures to perform their intended functions during and after an earthquake. It involves assessing the probability that a structure will not fail under seismic loads over its expected lifetime. Probability assesses the likelihood of seismic events and their intensities, while reliability evaluates the performance and safety of structures under those seismic events.

KEY WORDS: seismic, continuous-time Markov chain, Jack-up, reliability, recurrent state

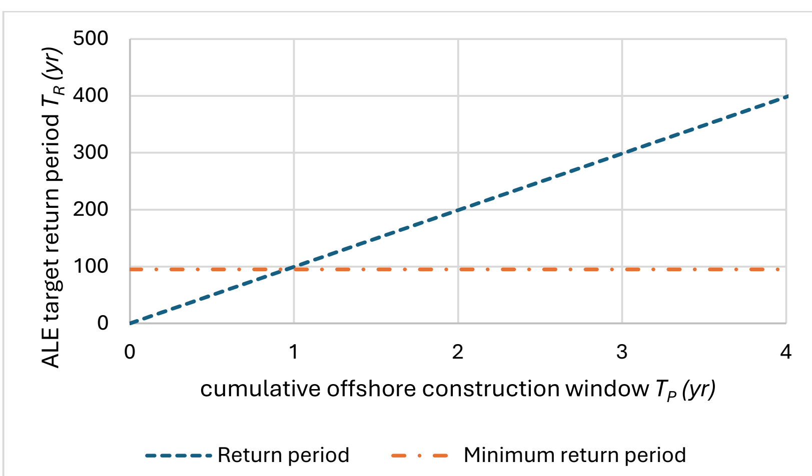
INTRODUCTION
In recent years, the offshore renewables industry has geographically expanded into seismically active regions like Taiwan and Japan. A body of standards and guidelines exists for the seismic assessment of Jack-up platforms for the exploration and operation of offshore oil and gas fields. [6] [7] For Jack-up vessels used for installing and servicing wind farms such standards and guidelines are yet to be developed. The article examines the question whether target reliability needs to be approached differently given the different nature of the operations, long-term deployments in oil and gas and very short-term deployments in the renewable sectors.
The section **Probability of Seismic Events** addresses how time of exposure is taken into account and how this is addressed in the current state of the art guideline. The section **Modelling Jack-up Operations as a Markov Chain** explains how the different operational states of a Jack-up can be modelled as a Continuous-Time Markov Chain (CTMC) with recurrent states. In **Target Reliability**, the irreducible CTMC is expanded with an absorbing state, failure due to a seismic event. The target reliability is made function of the operational state the Jack-up is in, its vulnerability and the ratio of time it is in that state. The CTMC framework is used to capture the stochastic nature of the Jack-up's operational transitions, providing a method to quantify reliability under seismic conditions. In the **Conclusion** it is demonstrated how assessing seismic risk and target reliability for Jack-ups using continuous-time Markov chains leads to a better understanding of that risk further leading to more reliable operations in wind farm installation and servicing.

PROBABILITY OF SEISMIC EVENTS
In seismic design, a lifetime target reliability is referenced as a non-exceedance requirement. Non-exceedance requirements in seismic design are criteria that ensure certain performance levels are not surpassed during a seismic event of a certain intensity level. The performance level can be expressed in different ways, from no damage, over limited structural and non-structural damage, to resistance against collapse and maintaining integrity to allow for safe evacuation.
Seismic events are modelled as a Poisson process, where the occurrence of each event is independent of the previous events. This means that the probability of an earthquake occurring in a given time period is constant. The Poisson process is characterized by a rate parameter λ, which represents the average number of events per unit time of a specified ground motion level. The non-exceedance probability P_{NE} is the probability that a certain level of ground shaking or seismic intensity will not be exceeded during the lifetime of a structure. The probability that the seismic intensity will not exceed the threshold level during the lifetime (T_L) is given by:

$$P_{NE} = P(\text{non-exceedance in } T_L \text{ years}) = e^{-\lambda T_L}$$

The longer a structure is exposed to seismic risk, the greater the likelihood it will experience the specified ground motion. In high seismic regions, small earthquakes tend to occur frequently (high λ), while large, damaging earthquakes are much rarer, typically occurring only once every several hundred or even thousands of years (low λ). As a result, structures or conditions that exist only for a short duration are less likely to be subjected to a major seismic event.
Depending on the practice or industry target reliability can be expressed in two ways: Annual Probability of Exceedance (APE) or Annual Frequency of Exceedance (AFE). [1]
Building codes assume an appropriate duration of seismic exposure for structures corresponding to the design lifetime (typically 50 years) and define an Annual Probability of Exceedance over that lifetime depending on the use or criticality of the infrastructure. General purpose buildings require a 10% Probability of Exceedance ($P_E = 1\text{-}P_{NE}$) over the lifetime (T_L), essential building 5%. [2] Based on formula for P_{NE} the APE can be derived: $P_E = 1 - e^{-\lambda T_L}$, $APE = 1 - e^{-\lambda}$, for small values of λ, APE ≈ λ.
In offshore standards seismic risk is defined as a design earthquake with a given Return Period (T_R), a Maximum Considered Earthquake (MCE) that is expected to occur over a given period of time. [3] The associated seismic risk, the Annual Frequency of Exceedance (AFE), is the inverse of the return period, AFE = $\lambda = 1/T_R$. By changing the duration of exposure, the former method allows for changing the APE. This is for example done in EN 1998-2, the European building code for bridges, where the duration of the construction phase of a bridge is used instead of the design lifetime.[4] The latter method does not allow for changing the AFE, as it does not depend on a lifetime.

In August 2021 DNV published Recommended Practice, DNV-RP-0585, which provides comprehensive principles and technical recommendations for the seismic design of wind power plants. [5] Although primarily aimed at wind power plants, chapter 2.7 is dedicated to installation vessels. It is the first specific provision for earthquake assessment aimed at Jack-up wind farm installation vessels. The Recommended Practice states that in order to reduce over-conservatism, it allows for the performance-based seismic design of installation vessels. The design principles may follow the ISO 19901-2 framework, assuming exposure level L1, but use the maximum envisaged cumulative offshore construction window within the project (T_P) instead of the vessel's service life (Δt) to derive the applicable Abnormal Level Earthquake (ALE) and Extreme Level Earthquake (ELE) return periods. However, the resulting ELE return period shall not fall below 95 years or the design Serviceability Limit State (SLS) return period of other key wind power plant assets, whichever is lower.
The RP states that based on a target annual probability of failure AFE = $4\times10^{-4} = 1/2500 = \lambda$ and an effective in-service life of approximately 25 years (Δt): $P_E = P(\mathit{at\ least\ one\ event\ in\ time}\ \Delta t) = 1 - e^{-\lambda \cdot \Delta t}$. Leading to lifetime probability of exceedance of P_E = 10%. This probability of exceedance is then used to calculate an APE, using the above P_E and the construction window T_P: $P_E = 1 - e^{-\lambda' T_P}$.
Where λ' is the value of the APE, APE = $\lambda' \approx AFE \times \Delta t / T_P = \lambda \times \Delta t / T_P$. However, the resulting ELE return period ($T_R = 1/\lambda'$) shall not be lower than 95 years.

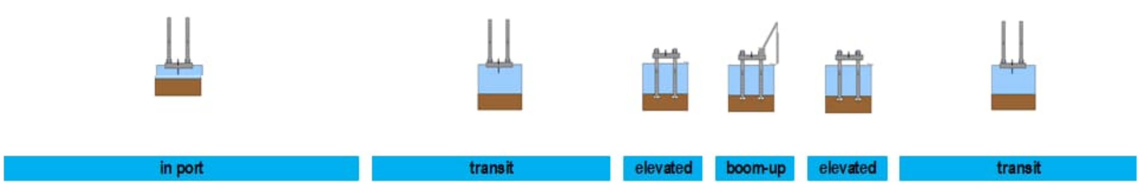


Graph showing the required ALE target return period [years] in function of the maximum envisaged cumulative offshore construction window [years].

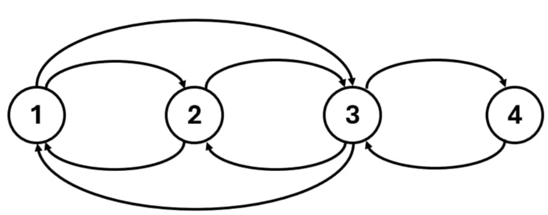
The approach proposed gives considerably lower return periods to be considered. Typically, the cumulative offshore construction window T_P would range between ½ year and 2 years, leading to return periods TR between 95 years and 200 years.
This approach has several drawbacks. As it is based on only one individual project, disregarding the lifetime, it leads to degrading reliability over the lifetime. The probability of exceedance over the construction window $P_E(T_P)$ is the same as the target probability of exceedance over the effective in-service life $P_E(\Delta t)$. Considering there will be m projects over the lifetime, the resulting lifetime probability of exceedance of $P_E(mT_P) = 1 – [1–P_E(T_P)]^m$. If, for example, 10 projects, with a $P_E(T_P) = 10\%$, are executed over the lifetime of the vessel than the resulting probability of exceedance $P_E(10\times T_P) = 1 – [1–10\%]^{10} = 65\%$. A second drawback is that the assessment does not consider the vulnerability the Jack-up is in. It does not differentiate between a Jack-up being floating (low vulnerability for seismic events), jacked-up or having the boom up (high vulnerability for seismic events). It does not motivate the operator to reduce the time spent in more vulnerable mode and to return to less seismic vulnerable modes when possible.

MODELING JACK-UP OPERATIONS AS A MARKOV CHAIN

Operating a Jack-up can be modelled as a random process having a discrete state space, that can change state with jumps that occur at continuous times. The discrete states are the different modes the Jack-up can be in: floating, jacked-up on operating airgap, jacked-up on survival airgap, jacked-up with boom up, etc.
The operational dynamics of Jack-up vessels can be represented using a Continuous-Time Markov Chain (CTMC). This method is particularly well-suited for modelling the inherent stochastic nature of offshore operations, wherein the durations and transitions between various phases are probabilistic by nature.
A CTMC is characterised by a finite set of discrete states and a transition rate matrix that specifies the likelihood of transitioning between states over continuous time. For Jack-up vessel operations, each operational phase—such as being in port, transiting to site, jacking up, operational mode (lifting or installation), adopting survival mode during adverse weather, or relocating to subsequent sites—can be mapped to a distinct state within the CTMC.
State transitions occur according to transition probabilities determined by factors such as task completion, environmental conditions, and logistical constraints. The sojourn time in each state is typically assumed to follow an exponential distribution, consistent with the memoryless property characteristic of CTMCs. This assumption is generally justified, as the likelihood of leaving a given state does not depend on the duration already spent in that state.
The transition rate matrix (also referred to as the generator matrix) governs the rates at which transitions between states occur. For instance, the transition rate from the "Transit" state to the "Elevated" state quantifies the frequency at which the process moves from “Transit” to “Elevated”.



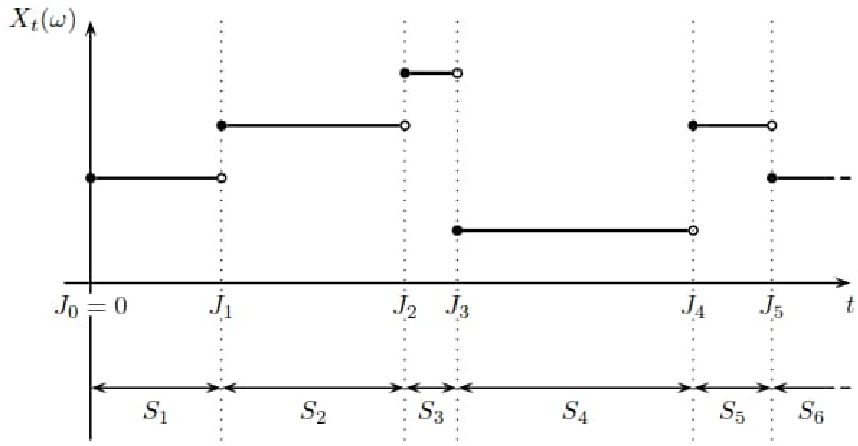
Example of an operational cycle with different operating modes.



The different operating modes of a Jack-up can be modelled as a Markov chain.
Nodes represent operational phases (states), directed edges indicate possible transitions between phases.

Let X_n represent the time that the Jack-up is in state n. X_n is a random variable that can have a discrete, continuous, or mixed distribution. The Jack-up process satisfies a continuous version of the Markov property.

The chain can jump between states at any time, not just at integer times. Hence the Jack-up process can be modelled as a Continuous-Time Markov Chain (CTMC).



An illustration of the jump times and holding times of a discrete-state taken from [8]

Let $X = (X_t)_{t\geq 0}$ be a stochastic process taking values in a finite or countable state space S, a subset of the integers. X is a CTMC if it satisfies the Markov property:

$$P(X_{t_n} = i_n | X_{t_1} = i_1, \dots, X_{t_{n-1}} = i_{n-1}) = P(X_{t_n} = i_n | X_{t_{n-1}} = i_{n-1})$$

for all $i_1,\dots,i_n \in S$ and any sequence $0 \leq t_1 < t_2 < \cdots < t_n$ of times.
The Markov property states that the distribution of the chain at some time in the future, only depends on the current state of the chain, and not its history.
The process is time-homogeneous, the conditional probability does not depend on the current time, so that:

$$P(X_{s+t} = j | X_s = i) = P(X_t = j | X_0 = i), \qquad s \geq 0$$

We can define a (stochastic) matrix of transition probabilities $P(t) = (P_{ij}(t))_{i,j\in S}$ at time t. The transition probability for a time-homogeneous chain is

$$P_{ij}(t) = P(X_t = j | X_s = i), \qquad s, t \geq 0$$

The transition probability characterizes the evolution of probability for a CTMC, but it requires a lot of information. There is no interest to know $P(t)$ for all times t to understand the dynamics of the chain. We can characterize the dynamics of a CTMC in two equivalent ways:

1. By the times at which the chain jumps, and the states that it jumps to.
2. Through the generator Q, which is an infinitesimal version of P.

A Continuous-Time Markov Chain stays in a state for a certain amount of time, then jumps immediately to another state where it stays for another amount of time, etc. The process can be characterized by the times at which it jumps, and the distributions of the states it jumps to.

The jump time J_m is the time of m^{th} jump. The holding time S_m is the length of time a CTMC stays in its state, before jumping for the m^{th} time. It is calculated from the jump times as $S_m = J_m - J_{m-1}$. The jump time J_m is a stopping time of $(X_t)_t \geq 0$ for all m. A random variable T with values in $[0,\infty]$ is a stopping time for a continuous-time process X, if, for each $t \in [0,\infty)$, the event $\{T \leq t\}$ depends only on $(X_s : s \leq t)$.
The discrete-time process $(Y_n)_{n=0}^{\infty}$ given by $Y_n = X_{J_n}$ is called the jump process, jump chain, or embedded chain.

In a Continuous-Time Markov Chain (CTMC), the generator matrix (also known as the rate matrix or Q-matrix) and the transition matrix play crucial roles in describing the behaviour of the process.
The generator matrix (Q) defines the rates at which transitions occur between states. It is an n x n matrix where each entry (q_{ij}) represents the rate of transitioning from state (i) to state (j). The key properties of the generator matrix are:

- Off-Diagonal Entries: For $i \neq j$, q_{ij} represents the rate of transitioning from state (i) to state (j).
- Diagonal Entries: for $i = j, q_{ii} = -\sum_{i\neq j}^{n} q_{ij}$. This ensures that the rows of the matrix sum to zero, reflecting the total rate of leaving state (i).

The transition matrix $P(t)$ describes the probabilities of transitioning between states over a time interval t. Each entry $p_{ij}(t)$ in the transition matrix represents the probability of being in state j at time t given that the process started in state i at time 0. The transition matrix is related to the generator matrix through the matrix exponential:

$$P(t) = e^{Qt}$$

where e^{Qt} is the matrix exponential of Qt. This relationship shows how the transition probabilities evolve over time based on the rates specified in the generator matrix.

In the long run, a Continuous-Time Markov Chain (CTMC) with finite recurrent states is generally not time-dependent. This is because such a chain tends to reach a steady-state distribution or equilibrium, where the probabilities of being in each state stabilize and no longer change over time.
A CTMC has a stationary distribution if there exists a probability distribution π over the states such that:

$$\pi Q = 0$$

This means that the distribution π remains unchanged over time when the system is in equilibrium. For a stationary distribution to exist, the CTMC must be **irreducible** (every state can be reached from any other state) and **positive recurrent** (the expected return time to any state is finite).
The limiting probabilities P_j for the CTMC are defined (when they exist, independent of initial condition $X(0) = i$) as the long-run proportion of time the chain spends in each state $j \in S$:

$$P_j = \lim_{t\to\infty} \frac{1}{t}\int_0^t I\{X(s) = j|X(0) = 1\}\, ds$$

which after taking expected values yields

$$P_j = \lim_{t\to\infty} \frac{1}{t}\int_0^t P_{ij}(s)\, ds$$

When each P_j exists and $\sum_j P_j = 1$, then $\vec{P} = \{P_j\}$ (as a row vector) is called the limiting (or stationary) distribution for the Markov chain. Letting

$$P^* = \begin{pmatrix} \vec{P} \\ \vec{P} \\ \vdots \end{pmatrix}$$

denote the matrix in which each row is the limiting probability distribution $\vec{P}$ can be expressed nicely in matrix form as

$$\lim_{t\to\infty} \frac{1}{t}\int_0^t P(s) ds = P^*$$

If $X(t)$ is a positive recurrent CTMC, then the limiting probability distribution $\vec{P} = (P_{i,j})$ exists, is unique, and is given by

$$P_j = \frac{E(H_j)}{E(T_{jj})} > 0, j \in S$$

The steady-state probability P_j is the ratio of $E(H_j)$, the expected time the process spend in state j during a cycle over $E(T_{jj})$, the expected time it takes for the process to return to state j after leaving it.
The stationary distribution and the limiting distribution of a Continuous-Time Markov Chain (CTMC) are the same when the CTMC is ergodic. A CTMC is ergodic if it is:

- Irreducible: Every state can be reached from any other state.
- Positive Recurrent: The expected return time to each state is finite.
- Aperiodic: The system does not cycle through states in a fixed period.

For an ergodic CTMC, the chain will converge to a unique stationary distribution regardless of the initial state. This stationary distribution is also the limiting distribution.
The long-term behaviour of a Jack-up process can be described by a unique stationary distribution which is also the limiting distribution. For a Jack-up process with n discrete states, and the ratio of expected time spent in each state j over the total expected cycle time is π_j, the transition matrix P can be written as:

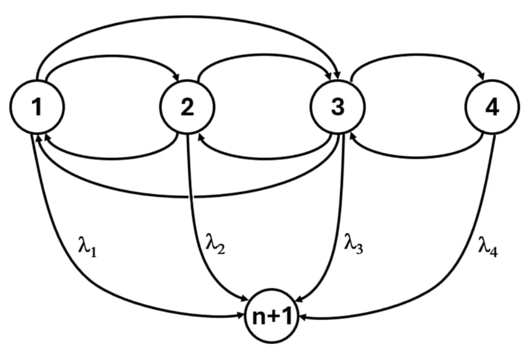
$$P = \pi = \begin{pmatrix} \pi_1 & \pi_2 & \cdots & \pi_n \\ \pi_1 & \pi_2 & \ddots & \pi_n \\ \vdots & \vdots & & \dots \\ \pi_1 & \pi_2 & \cdots & \pi_n \end{pmatrix}$$

DIFFERENTIATING TARGET RELIABILITY

An absorbing state in a Continuous-Time Markov Chain (CTMC) is a special type of state with the property that once entered in the state, the process remains indefinitely in that state. This means that the rate of leaving the state is zero and there are no transitions out of the state. A state i is absorbing if: $q_{ii} = 0$ and $q_{ij} = 0$ for all $j \neq i$.

In seismic design, lifetime target reliability is often framed as a non-exceedance requirement, ensuring that specific performance thresholds are not surpassed during seismic events of defined intensity (characterized by rate parameter λ). These thresholds range from no damage, through limited structural and non-structural damage, to full structural integrity that allows safe evacuation. When modelled as a Continuous-Time Markov Chain, a seismic event of a certain intensity level that leads to a critical performance threshold—such as collapse or loss of structural integrity—can be represented as an absorbing state. Once this state is reached, the system cannot transition to any other state, reflecting the irreversible nature of such failure in the context of structural performance. The non-exceedance requirement can be added to the Jack-up process as an absorbing state. Once the chain enters the absorbing state (go beyond the non-exceedance requirement), it stays there indefinitely.

Different states have different seismic vulnerability. The probability that a system or component will perform its required functions under stated conditions for a specified period of time can be expressed as a reliability function, $P_{NE} = e^{-\lambda_i t}$. The chain will have specific probabilities of being absorbed into the absorbing state from each transient state. The non-exceedance seismic event will be state dependent, for each state *i*, there will be a rate parameter λ_i.



The different operating modes of a Jack-up as a Markov chain with absorbing state n+1.

Adding an absorbing state to a Continuous-Time Markov Chain (CTMC) significantly changes its long-term behaviour. All other states, that where irreducible become transient, meaning that the chain will eventually leave these states and be absorbed. The probability of being in any transient state goes to zero as time goes to infinite. Unlike the case without an absorbing state, the steady-state distribution will be concentrated entirely on the absorbing state. The probability of being in any transient state will be zero in the long run.

$$(\pi') = \begin{pmatrix} \pi & 0 \\ 0 & 1 \end{pmatrix}$$

$$(\pi')(E') = \begin{pmatrix} \pi_1 & \pi_2 & \cdots & \pi_n & 0 \\ \vdots & & \ddots & & \vdots \\ \pi_1 & \pi_2 & \cdots & \pi_n & 0 \\ 0 & 0 & & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-\lambda_1 t} & 0 & \cdots & 0 & 1-e^{-\lambda_1 t} \\ 0 & e^{-\lambda_2 t} & \cdots & 0 & 1-e^{-\lambda_2 t} \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & e^{-\lambda_n t} & 1-e^{-\lambda_n t} \\ 0 & 0 & & 0 & 1 \end{pmatrix}$$

$$(\pi')(E') = \begin{pmatrix} \pi_1 e^{-\lambda_1 t} & \pi_2 e^{-\lambda_2 t} & \cdots & \pi_n e^{-\lambda_n t} & \pi_1(1-e^{-\lambda_1 t}) + \pi_2(1-e^{-\lambda_2 t}) + \dots + \pi_n(1-e^{-\lambda_n t}) \\ \pi_1 e^{-\lambda_1 t} & \pi_2 e^{-\lambda_2 t} & & \pi_n e^{-\lambda_n t} & \pi_1(1-e^{-\lambda_1 t}) + \pi_2(1-e^{-\lambda_2 t}) + \dots + \pi_n(1-e^{-\lambda_n t}) \\ \vdots & & \ddots & & \vdots \\ \pi_1 e^{-\lambda_1 t} & \pi_2 e^{-\lambda_2 t} & \cdots & \pi_n e^{-\lambda_n t} & \pi_1(1-e^{-\lambda_1 t}) + \pi_2(1-e^{-\lambda_2 t}) + \dots + \pi_n(1-e^{-\lambda_n t}) \\ 0 & 0 & & 0 & 1 \end{pmatrix}$$

In the long run, the transition matrix of a Continuous-Time Markov Chain (CTMC) becomes

$$\{(\pi')(E')\}^m = \begin{pmatrix} \pi_1 e^{-\lambda_1 t}(\pi_1 e^{-\lambda_1 t} + \pi_2 e^{-\lambda_2 t} + \dots + \pi_n e^{-\lambda_n t})^{m-1} & \cdots & 1-(\pi_1 e^{-\lambda_1 t} + \dots + \pi_n e^{-\lambda_n t})^m \\ \pi_1 e^{-\lambda_1 t}(\pi_1 e^{-\lambda_1 t} + \pi_2 e^{-\lambda_2 t} + \dots + \pi_n e^{-\lambda_n t})^{m-1} & & 1-(\pi_1 e^{-\lambda_1 t} + \dots + \pi_n e^{-\lambda_n t})^m \\ \vdots & \ddots & \vdots \\ \pi_1 e^{-\lambda_1 t}(\pi_1 e^{-\lambda_1 t} + \pi_2 e^{-\lambda_2 t} + \dots + \pi_n e^{-\lambda_n t})^{m-1} & \cdots & 1-(\pi_1 e^{-\lambda_1 t} + \dots + \pi_n e^{-\lambda_n t})^m \\ 0 & & 1 \end{pmatrix}$$

The last column is the long-run probability of exceedance.

Seismic design assessment is a time-variant reliability problem, where reliability is usually expressed in terms of first-passage probability or probability of time to first failure. The occurrence of earthquakes is a stochastic process. The reliability problem can be approached as a time-invariant assuming that the earthquake occurrences follow a Poisson process, so that the distribution of demand in any unit time-interval is the same, and the deterioration of resistance is neglected, which is acceptable for a well-maintained structure, not exposed to previous damaging earthquakes during its lifetime. Under these conditions, probability of failure in a reference period can then be found by comparing the maximum demand in the reference period, function of the rate of earthquakes, with the time-invariant resistance.
For seismic design, target reliability is referenced to the non-exceedance requirement. The corresponding target probability over the lifetime is denoted as P_{NE}.
The probability is defined as

$$P_{NE} = e^{-\lambda T_L}$$

With λ the annual rate of exceedance, which is the average number of times per year that a certain level of ground shaking is expected to be exceeded.
If t_p is the project duration, then m is the ratio of the project duration t_p over the design lifetime T_L.

$$P_{NE} = e^{-\lambda T_L} = e^{-\lambda \mathrm{m} t_p}$$

We can differentiate the seismic vulnerability by making the reliability function of the operational state the Jack-up is in and its vulnerability when in that specific state. The long-run probability of exceedance should be minimum the lifetime target reliability required.

$$1 - e^{-\lambda \mathrm{m} t_p} \geq 1 - \left(\pi_1 e^{-\lambda_1 t_p} + \dots + \pi_n e^{-\lambda_n t_p}\right)^m$$

$$e^{-\lambda} \leq \pi_1 e^{-\lambda_1} + \dots + \pi_n e^{-\lambda_n}$$

The vulnerability has not only become a function of the vulnerability of the operational state the Jack-up is in, but also of the ratio of time it is in that specific state. States with high vulnerability are balanced by states with low vulnerability, the ratio of time with high vulnerability can be balanced by ratio of time with low vulnerability.

CONCLUSION

Assessing seismic risk and target reliability for Jack-ups using continuous-time Markov chains leads to a better understanding of that risk during a project lifecycle. If allows to identify the vulnerability to seismic events or its probability of (non)-exceedance and its associated ratio of time in the different operational states, the Jack-up vessel can be in. The method allows for differentiation between different modes and their associate seismic vulnerability. This incentivises operators to reduce the time a Jack-up is in a vulnerable state to a minimum. Weather downtime and out of service time can be modelled as well. By modelling the operation of a Jack-up vessel as a Markov chain, we can analyse and optimize its performance, ensuring efficient and reliable operations in the wind farm with due account for seismic events.
Further discussion and industry research is needed to define the required target reliability taking into account the specific nature of Jack-up vessels used for installing and servicing wind farms.

REFERENCES

[1] Sampson, Mark. Seismic Loading for Short-Term Duration Exposures and Temporary Structures. , Jan. 2022. https://doi.org/10.2172/1860669

[2] Minimum Design Loads and Associated Criteria for Buildings and Other structures. Reston, VA: American Society of Civil Engineers, 2017, https://doi.org/10.1061/9780784414248

[3] Leyendecker, Edgar & Hunt, R. & Frankel, Arthur & Rukstales, Kenneth. (2000). Development of Maximum Considered Earthquake Ground Motion Maps. Earthquake Spectra. 16. 21-40. https://doi.org/10.1193/1.1586081

[4] Eurocode 8: Design of Structures for Earthquake Resistance—Part 2: Bridges, European Standard EN 1998-2 (2005). European Committee for Standardization, Brussels.

[5] DNV-RP-0585 Edition August 2021, Seismic design of wind power plants

[6] ISO 19905-1:2012 — Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups 1.

[7] ISO 19901-2:2017 — Petroleum and natural gas industries — Specific requirements for offshore structures — Part 2: Seismic design procedures and criteria.

[8] J.R. Norris. Markov Chains. Cambridge Series in Statistical and Probabilistic Mathematics. Cambridge: Cambridge University Press, 1997. https://doi.org/10.1017/CBO9780511810633