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Reliability assessment of mooring lines for floating structures considering statistical parameter uncertainties

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ABSTRACT

This work focuses on the effect of parameter uncertainty on the reliability index and on the predictive reliability of mooring lines for floating structures under loading from extreme sea-states. A first-order analytic formulation is developed which takes into consideration uncertain parameters in the statistical models of the maximum dynamic tension and the breaking resistance of the mooring lines. Expressions are derived for the mean and the variance of the reliability index in terms of the mean values and the covariance matrix of the uncertain parameters, and of the sensitivity of the reliability index to the uncertain parameters. The predictive reliability index is expressed in terms of the mean and the variance of the reliability index. The formulation is applied to case studies of catenary and taut-leg mooring lines of an offshore structure and the relative effects of the sources of statistical uncertainty are assessed. The case studies demonstrated the applicability and capability of the formulation to capture and represent the relative contributions of the different sources of uncertainty on the predictive reliability and predictive failure probability, as well as on the statistics of the uncertain reliability index.

1. Introduction

Mooring lines are a critical component of the offshore floating structures used extensively, from shallow to ultra-deep waters, in the oil industry. Mooring lines of permanent production floating systems may be exposed to harsh environmental conditions that induce severe loads during their service life. Failure of mooring lines under extreme environmental loading may lead to production shutdown, damages of the floating structure and equipment, damages to nearby facilities and subsea systems, and rupture of risers. Thus, risk management strategies are normally implemented to assure safety and integrity during the service life of the structure, from the design to the operational phases. For probabilistic risk assessment of mooring lines, proper reliability assessment is a key issue.

The reliability assessment of mooring lines involves parameters in the probability distribution models of loading and resistance that are usually estimated from statistical inference using recorded environmental data and experimental, numerical, or field test data of resistance. Uncertainty is, therefore, involved in the parameters of the probabilistic modeling of loading as well as in the parameters of the idealized models used for mooring lines' resistance. Under parameter uncertainty, the reliability index and the failure probability become uncertain variables. Parameter uncertainties are in principle reducible if additional information or additional observational data is gathered. Therefore, it may be useful to assess the extent to which the uncertainty in the estimate of the reliability index, or in the failure probability, can possibly be reduced by gathering additional statistical data. The benefit of having additional information may then be compared against the cost of gathering it. Also, from the point of view of decision making on structural safety, it is desirable to quantify a measure of reliability that takes into account parameter uncertainties. Furthermore, the decision maker should have information on the level of uncertainty involved in the estimation of the reliability index and the probability of failure. A measure that takes into consideration parameter uncertainties is the so-called predictive reliability index [1].

In the case of mooring lines, structural reliability formulations have been developed and studies conducted on safety and design applications, see e.g. [2–9]. These works have advanced improved ways to deal with the probabilistic modeling of the mooring loading and line resistance. They have focused mainly on: (1) the characterization of maximum tension loads in the mooring lines under the combination of random extreme sea-states; (2) the use of response surfaces to express mooring loading as function of the metocean variables; (3) the numerical modeling of the floating system response under environmental loading; (4) the probabilistic modeling of mooring line resistance as a series system; and (5)

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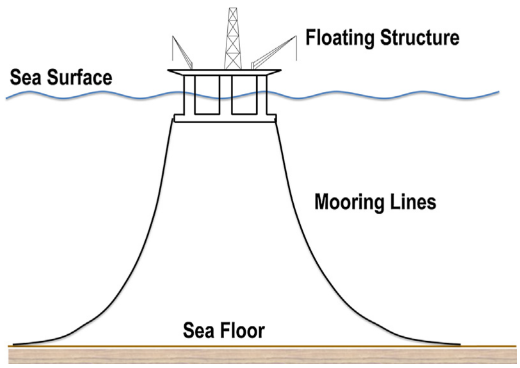

Fig. 1. Schematic depiction of mooring lines for floating structure.

the reliability-based calibration of partial safety factors for design purposes. None of these works have studied however the effect of parameter uncertainties on the uncertain reliability index. Montes-Iturrizaga et al. [10] carried an analysis of the predictive reliability of mooring lines for offshore floating structures. They considered the parameters of the distribution of the maximum dynamic tension of the mooring line to be functions of the random environmental variables describing the extreme sea states. Adopting a nested reliability approach, based on the use of an auxiliary limit state function [11], they were able to assess the predictive reliability index and applied it to the calibration of partial safety factors for design. Nevertheless, the assessment of the effects of parameter uncertainties on the statistics of the uncertain reliability index and on the predictive reliability was not considered in their study. In offshore geotechnical applications, formulations for reliability assessment under parameter uncertainty have been recently developed for suction caissons used as foundations for moored structures, which account for uncertainties in the statistical models of the tension loads in the mooring lines and in the model of the caisson capacity [12,13].

In this work, we focus on deriving an analytical formulation to quantify the effect of parameter uncertainties on the uncertainty of the reliability index of mooring lines for offshore floating structures under extreme sea-states. We address the probabilistic modeling of the maximum dynamic tension load and of the mooring line resistance in the limit state function, establishing the uncertain parameters in the corresponding statistical models. Next, using a first-order approach, expressions are derived for estimation of the mean and the variance of the reliability index. An expression is then used to estimate the predictive reliability index in terms of the mean and variance of the reliability index. The formulation is applied to case studies of catenary and taut-leg mooring line systems of a floating structure. Results are discussed, and final comments and conclusions are then given.

2. Limit state function

Consider a floating structure anchored to the sea bottom by means of a mooring line system, as schematically depicted in Fig. 1, and subjected to extreme sea states loading due to hurricane or storm conditions. The limit state function for ultimate tension failure of a line in the mooring system can be written as follows,

$$g(r, t_m, T_d) = r - t_m - T_d \tag{1}$$

where r denotes the mooring line resistance as defined by its breaking strength, t_m is the mean tension in the mooring line due to both pretension and mean environmental loads [14], and T_d is the maximum dynamic tension of the mooring line due to environmental loads (wind, wave, currents) during an extreme sea-state of duration s. We consider that sea surface elevation is modeled as a Gaussian process and assume that the dynamic tension load of mooring lines can be approximated as a Gaussian process. This approximate modeling is based on the work by Sarkar and Eatock Taylor [15] where response analyses of mooring lines, considering slowly varying second-order drift forces and first-order wave frequency vessel motions, indicated that the dynamic tension of mooring lines could be described as being Gaussian. It is also based on the work by Choi et al. [7], where statistical analysis of time-domain response computations of mooring systems under extreme sea states showed that using random vibration theory for Gaussian processes, the mean value of the maximum dynamic tension could be approximated in terms of a peak factor and the standard deviation of the dynamic tension. We thus assume here that the dynamic tension of a mooring line due to a stationary sea-state can be modeled approximately as a stationary Gaussian process. Let $\boldsymbol{\Theta}$ denote the vector of uncertain variables that define the loading under environmental conditions, such as significant or maximum wave height, peak spectral period, wind velocity, and surface current velocity. Based on Vanmarcke [16], the cumulative distribution function of the maximum value of the dynamic tension, over time interval s, can then be approximated as follows,

$$F_{T_d}(x|\boldsymbol{\Theta}) = \left[1 - \exp\left(\frac{-x^2}{2\sigma_{\boldsymbol{\Theta}}^2}\right)\right] \exp\left[-\nu_{\boldsymbol{\Theta}} s \frac{1 - \exp\left(-\sqrt{\frac{\pi}{2}} q_{\boldsymbol{\Theta}}^{1.2} \frac{x}{\sigma_{\boldsymbol{\Theta}}}\right)}{\exp\left(\frac{x^2}{2\sigma_{\boldsymbol{\Theta}}^2}\right) - 1}\right], x > 0 \tag{2}$$

where the standard deviation, $\sigma_{\boldsymbol{\Theta}} = \sigma(\boldsymbol{\Theta})$, and the mean cycle rate, $\nu_{\boldsymbol{\Theta}} = \nu(\boldsymbol{\Theta})$, of the dynamic tension of the mooring line, as well as the shape parameter of the dynamic tension power spectrum, $q_{\boldsymbol{\Theta}} = q(\boldsymbol{\Theta})$, are all expressed here as functions of the uncertain environmental variables $\boldsymbol{\Theta}$. The shape parameter $q_{\boldsymbol{\Theta}}$ is defined in terms of the first three moments of the dynamic tension power spectrum, λ_i $i = 1,2,3$, which also depend on $\boldsymbol{\Theta}$,

$$q_{\boldsymbol{\Theta}} = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}} \tag{3}$$

The probability distribution of T_d in (2) has been used in previous reliability studies [7,10,12].

For the mooring line resistance, as defined by its breaking strength, the probability distribution is based on the type I extreme value distribution model developed by Montes-Iturrizaga et al. [8,10]. It considers that a mooring line is a series system composed of M segments which commonly are a combination of chain, wire rope or polyester. Using extreme value theory it can be shown that the asymptotic probability distribution of the resistance of a line segment follows a Type I distribution for minima [17]. In this work, we consider that the mean value of line resistance, μ, is known and that the standard deviation of line resistance, Σ, is uncertain. Thus, uncertainty in the coefficient of variation of line resistance is introduced through uncertainty in the standard deviation of line resistance. The first order formulation shown next can be expanded to consider also the mean value of line resistance to be uncertain, but for the scope of this work, we will assume μ to be known and let Σ to be uncertain. The cumulative distribution of a mooring line's resistance is then written as follows,

$$F_R(r|\Sigma) = 1 - \exp[-\exp(\alpha_\Sigma(r - u_\Sigma))] \tag{4}$$

where parameters α_Σ, u_Σ, depend on the mean μ and uncertain standard deviation Σ of the line resistance,

$$\alpha_\Sigma = \frac{\pi}{\sqrt{6}\Sigma} \tag{5.a}$$