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Reliability analysis of suction caissons for moored structures under parameter uncertainties

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ABSTRACT

A study is performed to assess the effect of parameter uncertainties on the uncertainty of the reliability index of suction caissons for moored structures under extreme sea conditions. Uncertain parameters in the statistical model of the maximum dynamic tension of the mooring lines and in the suction caisson capacity model are considered. A first-order approach is used to express the mean and the variance of the reliability index of suction caissons in terms of the mean values of the uncertain parameters, and in terms of the sensitivity vector and the covariance matrix of the uncertain parameters, respectively. The predictive reliability of the suction caisson is estimated as a function of the mean and variance of the reliability index. Suction caissons in normally consolidated clay subjected to loading from catenary and taut-leg mooring lines of an FPSO structure under extreme sea conditions in the Gulf of Mexico are considered for the study. The results show the relative influence of parameter uncertainties on the uncertainty of the suction caisson reliability index.

1. Introduction

Suction caissons are used widely in the oil industry as foundations for different types of offshore floating structures from shallow to ultra-deep waters. Their main function is to anchor the mooring lines of a floating structure to the sea bottom under severe and normal environmental conditions. A suction caisson is a steel hollowed cylinder, embedded in the soil by a negative pressure that is created by pumping the seawater from the inside of the caisson, after an initial penetration due to self-weight. Suction caissons can be installed much faster than conventional piles and can be removed easier for decommissioning. They are a critical component of the mooring system for floating structures, and even more so since taut-leg moorings, which introduce a greater vertical component of loading, have become a preferred solution for ultra-deep waters.

Relatively few studies have been conducted on the reliability assessment of suction caissons for moored structures [1–4]. They have over time advanced improved ways to deal with the probabilistic modeling of the caisson capacity and the mooring loading. The reliability assessment of suction caissons involves parameters in the statistical and the physical models that may be estimated based on statistical inference, possibly using recorded environmental data, as well as experimental, numerical or field test data of capacity, which introduces uncertainty in their estimates. Parameter uncertainty may arise from the probabilistic modeling of the tension loads of the mooring lines, which depend on the uncertain metocean variables, as well as from the idealized models of the caisson capacity. Under parameter uncertainty, the reliability index becomes uncertain as well and a measure that takes into consideration parameter uncertainties is the so-called predictive reliability index. Rendón-Conde and Heredia-Zavoni [5] used a nested formulation to assess the predictive reliability of suction caissons, considering that the parameters of the probability distribution of the maximum dynamic tension of a mooring line are functions of uncertain metocean variables. In their study, the caisson capacity was modeled using the Plastic Limit method considering normally consolidated clays and response surfaces for capacity were generated in terms of the uncertain geotechnical variables. They studied the influence of the mean values of several geotechnical variables on the predictive reliability index and compared it against reliability estimates obtained using simplified formulations of the limit state function. However, parameter uncertainties in the caisson capacity model were not included and the effect of parameter uncertainties on the uncertainty of the reliability index were not considered in their study. Previous studies have not dealt with the issue of assessing explicitly the way in which parameter

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Nomenclature

CoV_{Hs}	coefficient of variation of Hs
CoV_{su_1}	coefficient of variation of Su_1
CoV_{Tp}	coefficient of variation of Tp
$C_{\Theta_f\Sigma}$	covariance matrix of $\mathbf{\Theta_f}$ and Σ
D	diameter of the suction caisson
E	caisson capacity model error or residual
$f_B(\beta)$	probability density function of B
$f_E(\varepsilon\vert\Sigma)$	probability density function of E
F_{T_d}	probability distribution function of T_d
$f_{\Gamma}(\gamma)$	probability density function of γ
Hs	significant wave height
L	length of the suction caisson
N_{ab}	reverse-end bearing factor
P	failure probability of caisson
$q_{\Theta_f} = q(\mathbf{\Theta_f})$	shape parameter of the dynamic tension power spectrum
$r(\gamma, \varepsilon)$	caisson capacity at the mudline
$\hat{r}(\gamma)$	deterministic model of caisson capacity
Su_1	undrained shear strength gradient
T_d	maximum dynamic tension in the mooring line during an extreme sea-state of duration s
T_D	design line tensions
t_m	mean tension in the mooring line
t_{m-C}	characteristic value of mean tension for 100 year return period sea states
Tp	peak spectral period
U	independent standard normal variable
u	sample value of U
α	side shear factor
β	reliability index of caisson
$\beta(\boldsymbol{\theta_f}, \sigma)$	conditional reliability index of the original problem
$B = \beta(\mathbf{\Theta_f}, \Sigma)$	conditional reliability index
$\boldsymbol{\gamma}$	geotechnical parameters
$\mathbf{\Gamma}$	vector of uncertain geotechnical variables
ε	sample value of E
θ_a	line tension angle at the padeye
θ_o	line angles at mudline
$\mathbf{\Theta_f}$	vector of uncertain metocean variables
μ_{Hs}	mean of Hs
μ_{Td-C}	characteristic value of the mean maximum dynamic tension for 100 year return period sea states
μ_{Tp}	mean of Tp
μ_B	mean of B
μ_ε	error mean in the capacity model
μ_{Θ_f}	mean vector of $\mathbf{\Theta_f}$
μ_Σ	mean of Σ
$\rho_{Hs,Tp}$	correlation coefficient between Hs and Tp
σ_B^2	variance of B
σ_{Hs}	standard deviation of Hs
σ_{Tp}	standard deviation of Tp
$\sigma_{\Theta_f} = \sigma(\mathbf{\Theta_f})$	standard deviation of the dynamic tension in the mooring line
σ_Σ	standard deviation of Σ
Σ	uncertain standard deviation of the capacity model
τ	ratio of CoV_{Hs} and CoV_{Tp}
$v_{\Theta_f} = v(\mathbf{\Theta_f})$	mean cycle rate of the dynamic tension in the mooring line
$\tilde{\beta}$	predictive reliability index
$\tilde{p}$	predictive failure probability
$(\nabla_{\Theta_f,\Sigma}\beta)_{\mu_{\Theta_f},\mu_\Sigma}$	sensitivity vector of B

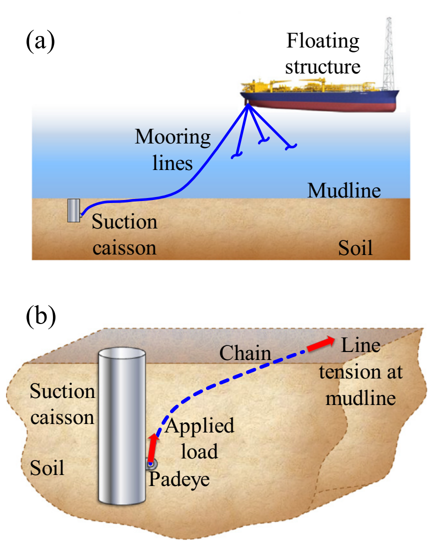

Fig. 1. (a) Moored structure; (b) suction caisson subjected to inclined loading at the padeye.

Table 1
Mooring line tensions and line angle at mudline.

Mooring system	t_{m-C} (kN)	μ_{Td-C} (kN)	T_D (kN)	θ_o (°)
Catenary	2871	2277	8801	1
Taut-leg	6200	2129	13152	36

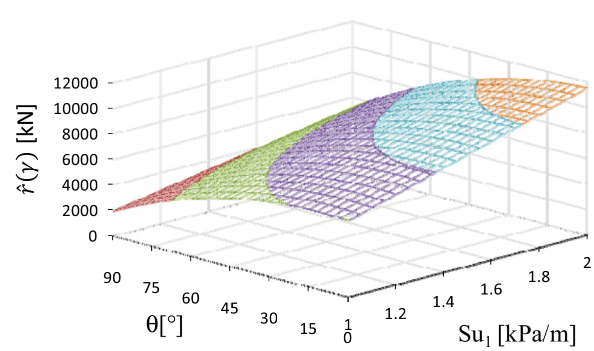

Fig. 2. Response surface for caisson capacity model at the mudline, $\hat{r}(\gamma)$.

uncertainties affect the uncertainty of the reliability index of suction caissons for offshore floating structures.

In this work, we use a first-order approximation to study the effect of parameter uncertainties on the uncertainty of the reliability index of suction caissons for moored floating structures. Parameter uncertainties in the statistical model of loading and in the physical model of capacity are considered. Expressions are derived for the mean and the variance of the reliability index of suction caissons in terms of the mean values and covariance matrix of the uncertain parameters, and of the sensitivity of the reliability index to the uncertain parameters. The mean and the variance of the reliability index are then used to estimate the predictive reliability and the predictive failure probability. The contributions of