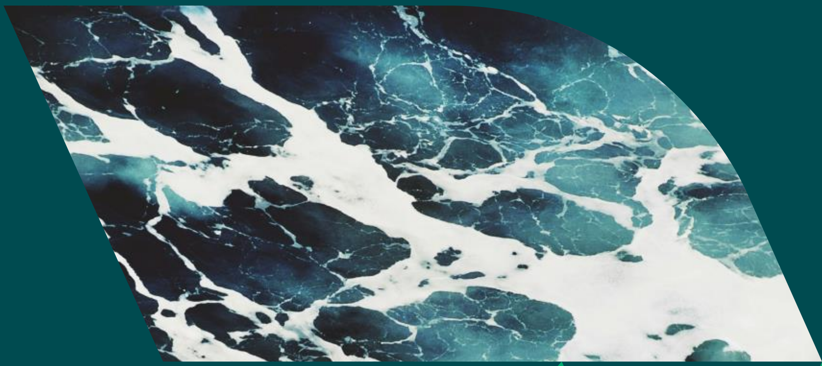

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The impact of geotechnical spatial variability on the installation of suction caisson anchors

L'impact de la variabilité spatiale géotechnique sur la conception des ancrages de caissons d'aspiration

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ABSTRACT: Over the past decade, the offshore wind industry has evolved with significant technological advances. These have been driven by the need for offshore wind energy to provide cost-competitive renewable energy. The economics of offshore wind necessitates lean and efficient designs and nowhere is this more prevalent than in anchors for floating wind turbines. This paper examines the impact of geotechnical spatial variability on the installation of suction caisson anchors for floating offshore wind turbines (FOWTs). Monte Carlo simulations are used to examine the probability of failure of the suction caissons to reach its target depth during installation.

RÉSUMÉ: Au cours de la dernière décennie, l'industrie éolienne offshore a évolué grâce à des avancées technologiques significatives. Celles-ci ont été motivées par la nécessité de l'énergie éolienne offshore pour fournir une énergie renouvelable à un coût compétitif. L'aspect économique de l'éolien offshore nécessite des conceptions simples et efficaces, et cela n'est nulle part plus répandu que dans les ancrages des éoliennes flottantes. Cet article examine l'impact de la variabilité spatiale géotechnique sur l'installation d'ancrages à caissons à succion pour les éoliennes offshore flottantes (FOWT). Les simulations Monte Carlo sont utilisées pour examiner la probabilité de défaillance des caissons d'aspiration pour atteindre leur profondeur cible lors de l'installation.

Keywords: Suction caisson anchor; offshore geotechnics; suction installation; floating offshore wind turbine; Monte-Carlo simulations.

1 INTRODUCTION

The offshore wind sector has undergone significant advancements in recent years, and there is now particular focus on the development of floating offshore wind turbines (FOWTs) for deep water. Better understanding of the uncertainty in their design, can help reduce the cost of suction caisson anchors (SCAs) for FOWTs. One aspect of uncertainty can be related to geotechnical variability and the complexity of the soil across a wind farm site. Moreover, the high costs associated with offshore geotechnical surveys can lead to overly cautious SCA designs, primarily due to the lack of detailed, site-specific geotechnical data. This paper aims to outline an approach for addressing this issue using Monte-Carlo simulations to examine the probability of failure to achieve the target penetration of a SCA during installation.

2 SUCTION CAISSON INSTALLATION DESIGN

The installation of a SCA takes places over two stages: (1) touchdown and self-weight penetration followed by (2) suction penetration. The penetration resistance, R, of a SCA can be calculated using two standard approaches: the bearing capacity (alpha/beta) or Cone

Penetration Test (CPT) based approach. This paper will focus on the latter.

Penetration resistance is determined using equation 1 (DNV, 2017):

$$R = A_p k_p q_{c,L} + A_{si} \int k_f q_{c,z} dz + A_{so} \int k_f q_{c,z} dz \quad (1)$$

where A_p (m^2) is the anchor skirt tip area, k_p(-) is an empirical coefficient relating the CPT tip resistance to the unit-end bearing resistance, $q_{c,L}$is the CPT cone tip resistance at the anchor embedded length, L (m), A_{si} (m) is the caisson inner perimeter, k_f (-) is an empirical coefficient relating the CPT tip resistance to the unit skin friction resistance, $q_{c,z}$ is the CPT cone tip resistance at depth z (m) and A_{so}(m) is the caisson outer perimeter.

3 ANALYSIS INPUTS

A simple suction caisson anchor model was developed to assess the probability of failure during installation due to geotechnical variability in the soil. A diameter of 10m, skirt wall thickness of 50mm and a range of lengths from 10-20m (in 1m increments) were assumed for the anchor geometry. To estimate the anchor weight, padeye dimensions of 1m x 1m with a thickness equal to twice the wall thickness of the skirt were assumed. The thickness of the top plate was assumed equal to that of the padeye. To maintain model simplicity, the mass contributions of internal or external stiffeners were omitted.

3.1 Maximum installation force

The maximum available installation force was defined as the sum of the force due to the maximum pump pressure and the weight of the caisson for each length considered. The maximum pump pressure was assumed to be 500kPa, or 5bar, and was transformed to a force by multiplying it across the area of the anchor lid. The weight of the caisson was computed by multiplying the sum of the volume of the skirt, top plate and padeye by the submerged density of steel, taken to be 6,850 kg/m^3.

3.2 Soil parameters

In the calculation of penetration resistance, this study adopted a lognormal distribution of the k_p and k_f parameters to account for the model uncertainty in these empirical coefficients. The mean and 95th percentile parameters of the resulting lognormal distributions were adopted as the 'Most probable' and 'Highest expected' values, respectively, as reported in DNV (2017) and shown in Table 1.

Table 1. Values of k_f and k_p for SAND from (DNV, 2017).

Coefficient	Most Probable (R_{prob})	Highest Expected (R_{max})
k_f	0.001	0.003
k_p	0.3	0.6

Firstly, the underlying normal distribution parameters, mean and standard deviation, were derived, and these were exponentiated to obtain a lognormal distribution dataset. The standard deviation (SD) of the lognormal distribution can be determined from equation 2:

$$SD = \sqrt{(e^{\sigma^2} - 1)(e^{2\mu + \sigma^2})} \quad (2)$$

where σ and μ are the standard deviation and mean of the underlying normal distribution, respectively. The lognormal distribution had a standard deviation of 0.0639 for k_p and 0.000344 for k_f.

For each Monte Carlo realisation, a unique value for k_p and k_f was sampled from a lognormal distribution of 10,000 values. Local seepage effects in sand during installation were ignored.

3.3 Monte-Carlo simulation inputs

In the study, geotechnical spatial variability was examined using spatially varying CPT cone resistance profiles, generated using the random field approach. The method used to develop these profiles is outlined in Igoe and Reale (2023). A summary of the procedure is provided in this section.

The CPT profiles were assumed to be normally distributed, and the random field was defined using three parameters: mean, standard deviation, and scale of fluctuation (θ). At first a mean CPT profile is derived to which noise can then be added. The mean CPT cone resistance profile, $\bar{q}_t$ (corrected for pore pressure effects), was derived based on a constant relative density of 70% using correlations proposed by Kulhawy and Mayne (1990). A scale of fluctuation value of θ = 5m was assumed in this analysis. Using the Markov correlation structure, a correlation matrix can be developed from equation 3:

$$\rho(\tau_j) = exp\left(\frac{-2|\tau_j|}{\theta}\right) \quad (3)$$

where j = 0, 1,…, n-1 with n being the number of data points, $\tau_j = j\Delta\tau$ is the lag distance between the two data points and ρ is the correlation matrix. Given that the correlation matrix is positive definite, it can be decomposed into upper (L^T) and lower (L) triangular forms via Cholesky decomposition:

$$\rho = LL^T \quad (4)$$

Subsequently, the spatially correlation normal random field, G, is derived by multiplying the lower triangular matrix with a matrix of independent normal random numbers with a mean of zero and a standard deviation of one, denoted as U, as per equation 5:

$$G = LU \quad (5)$$

Finally, by adjusting the normal random field, G, using the mean and standard deviation, stochastic CPT profiles are produced using equation 6:

$$q_t = \bar{q}_t + \sigma G \quad (6)$$

For the corrected cone resistance in this paper, a coefficient of variation of 30% was assumed meaning $\sigma = 0.3\bar{q}_t$.

4 RESULTS AND DISCUSSION

Firstly, an acceptable probability of failure (p_f) was defined at 5%. 10,000 CPT profiles were developed to represent the geotechnical variability across a site. The result of this analysis is shown in Figure 1.

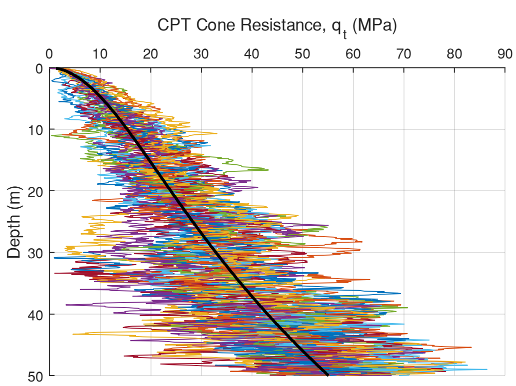

Figure 1. Cone resistance versus depth below seabed (mean profile represented by black line).

For each CPT profile, values of kf and kp were sampled from their distribution and the penetation resistance of the SCA was computed using equation 1. No uncertainty in the geometrical properties of the caisson was considered. Figure 2 shows the total soil installation resistance of the anchor with respect to depth below seabed for a range of pile embedded lengths. The weight of the anchor (black line), maximum installation force including self weight (red line) and total resistance using the mean CPT profile and 'Most probable' (dashed blue line) and 'Highest expected' (dashed black line) k_f and k_p parameters are also included in Figure 2.

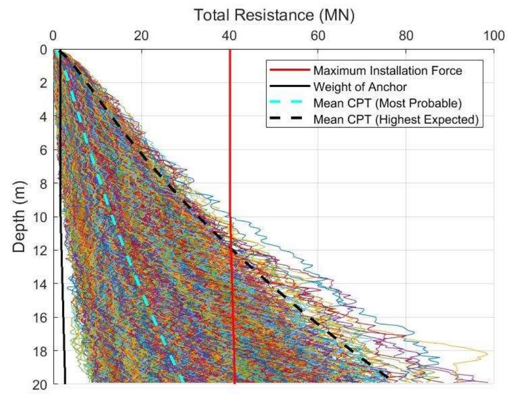

Figure 2. Total installation resistance versus depth below seabed.

Figure 3 shows a box plot of the total resistances across for a range of anchor lengths from 10 – 20m. The mean is shown as a horizontal red line across the centre of each box, with the top and bottom of each box representing +/- one standard deviation from this mean. The whiskers extending from the box show the minimum and maximum values of total resistance at each anchor length. The horizontal stepped green line above each box represents the maximum installation force for that anchor length.

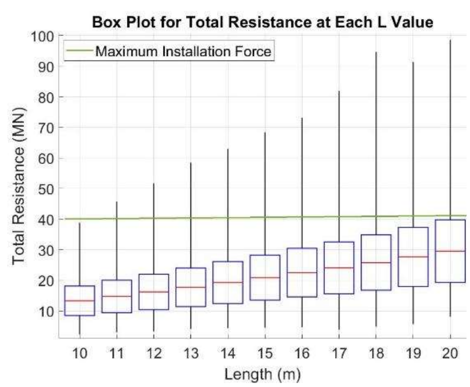

Figure 3. Box plot of total resistance for each anchor length.

The probability of failure in this paper is estimated using Monte-Carlo simulation. The failure criterion was defined using the inequality shown in equation 7:

$$R > maximum\ installation\ force \quad (7)$$

This failure included any instance up to and including the length increment, as the anchor may fail during installation prior to reaching the target penetration depth.

The probability of failure across all CPT profiles for each length can be determined as N_f/N where N_f is the number of realisations which fail and N is the total number of realisations. A sensitivity analysis was conducted to confirm that 10,000 realisations was adequate to maintain a stable probability of failure for each iteration. Figure 5 shows this analysis for each increment in length. A summary of the maximum installation force and percentage failure for each anchor length is provided in Table 2.

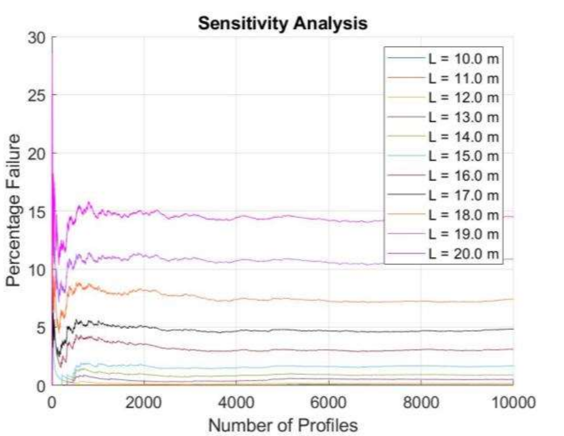

Figure 5. Sensitivity analysis for each anchor length, L.

Table 2. Summary of results.

Length (m)	Maximum Installation Force (MN)	Percentage Failure (%)	Mean Resistance (MN)
10	40.08	0.00	13.30
11	40.18	0.07	14.72
12	40.29	0.19	16.19
13	40.40	0.51	17.70
14	40.50	0.95	19.28
15	40.61	1.91	20.87
16	40.71	3.29	22.52
17	40.82	5.05	24.06
18	40.92	7.57	25.80
19	41.03	10.97	27.64
20	41.13	14.47	29.52

5 CONCLUSIONS

This paper explores the potential impact of geotechnical spatial variability on the installation of suction caisson anchors for floating offshore wind turbines. The probability of failure of a range of anchor lengths was investigated using Monte-Carlo simulation with 10,000 realisations. This paper presented an approach to the preliminary installation design of suction caisson anchors from CPT data to account for site-specific variations in ground conditions. This study has shown that Monte-Carlo simulations can be used effectively to enhance quantitative understanding of the impact of geotechnical variability on the suction installation failure/success rate. This work will be developed to incorporate the in-place capacity of an anchor to include an estimation of the site-specific operational probability of failure of suction caisson anchors.

ACKNOWLEDGEMENTS

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