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A probabilistic approach to the ultimate capacity of skirted foundations in spatially variable clay

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ABSTRACT

Skirted foundations are used in offshore applications to resist the large horizontal and moment loads that are characteristic of the ocean environment. The combination of vertical–horizontal-moment (VHM) loading results in complicated stress conditions in the seabed and design is often based on VHM failure envelopes. These have generally been constructed by numerical analysis using a deterministic characterisation of soil properties and disregard the natural spatial variability of marine sediments. In this study, spatial variability is taken into account by coupling a random field model with finite element analysis. The paper presents a probabilistic analysis of the ultimate capacity of skirted foundations in spatially variable undrained clay. The increase of strength with depth typical of a marine clay is included in the modelling framework. Probabilistic failure envelopes are constructed to analyse the effect of spatial variability when skirted foundations are subjected to different combinations of VHM loading. The results show that the probability of failure increases under high vertical loads and at peak moment capacity in the HM plane, suggesting that care should be taken in design at these areas of the failure envelope. The methodology demonstrates a straightforward and effective way of quantifying uncertainty in the ultimate limit state design of offshore geotechnical structures and the results presented provide specific guidance for the design of skirted foundations.

1. Introduction

In offshore applications, shallow foundations are often equipped with peripheral vertical skirts which penetrate into the seabed. The skirts improve the ability of the foundation to resist the large horizontal and moment loads that are imposed by environmental factors such as wind and waves. In undrained conditions, capacity may be enhanced by the development of suction within the enclosed soil plug which provides short term tensile resistance [11].

The interaction of vertical–horizontal-moment (VHM) loading, shown in Fig. 1, is a critical design issue. It has been shown that classical bearing capacity solutions are inadequate for describing the capacity of foundations in complex soil conditions subject to combined VHM loading, and often lead to under prediction of capacity [26,14]. A far more versatile approach to assessing the ultimate limit state is to construct failure envelopes in VHM load space and compare design loads to those which would lead to failure of the foundation [25].

Numerical investigations of the shape of the undrained VHM failure envelope for skirted foundations with various embedment ratios and in uniform and normally consolidated clays have been undertaken by Yun and Bransby [7] and Gourvenec and Barnett [13]. These studies have considered the soil to be described by deterministic parameters following a defined trend. However, due to complex physical and chemical formation processes, soil is inherently a highly variable material and the values of engineering parameters can be observed to fluctuate through the soil mass [21]. Spatial variability is difficult to characterise in a deterministic model as knowledge of ground conditions is limited by constraints on site investigations, a particular factor offshore. Dealing with uncertainty is therefore a central component of geotechnical design.

Probabilistic studies using random fields to represent soil parameters have shown that spatial variability can affect both the failure mechanism and bearing capacity of surface footings [15,24,1]. VHM failure envelopes for a surface footing on spatially variable clay have also been constructed by Cassidy et al. [8]. Footing embedment has been considered in a recent study by Pieczyńska-Kozłowska et al. [22] of bearing capacity on a spatially variable drained soil. However, for skirted foundations the relatively low embedment ratio, defined by the ratio D/B as shown in

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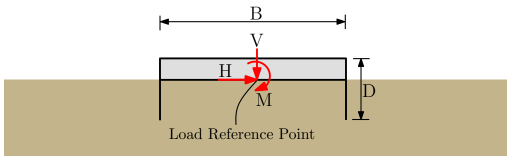

Fig. 1. VHM loading of a skirted foundation.

Fig. 1, means that the soil plug must be taken into account in the determination of the VHM failure envelope and substitution of a solid embedded foundation at the same depth may be inappropriate [7]. In addition, marine clays are characterised by an increasing strength with depth [25], the gradient of which can significantly influence footing behaviour [14]. In general, previous probabilistic investigations of surface footings have considered a uniform soil mass with strength constant with depth, which may not be applicable in the offshore environment.

In this paper, the ultimate capacity of skirted foundations in spatially variable undrained clay is assessed under both uniaxial loading and combinations of VHM loads. Probabilistic failure envelopes are constructed to illustrate the effect of combined loading on the probability distribution of bearing capacity under different load combinations. The probabilistic envelopes are based upon cumulative distribution functions (CDFs), and enable a better understanding of the level of risk associated with this appealing design methodology. In addition, this study incorporates the increase of strength with depth that is typical of marine clays and an important consideration in offshore applications.

2. Computational framework

The effect of spatial variability on the undrained VHM capacity of skirted foundations is assessed by coupling a random field model with finite element (FE) analysis. Monte Carlo simulation is used to characterise the stochastic response, i.e. the probability density function (PDF) of ultimate capacity. The implementation is non-intrusive, meaning the FE code is not modified and proceeds in the usual deterministic manner. In each simulation, a random field is generated and passed to the FE solver, where the VHM capacity is obtained.

2.1. Simulation of spatial variability

The undrained shear strength, s_u, is generally used to determine bearing capacity in undrained conditions. A correlated random field of s_u will therefore be considered in order to simulate the spatial variability that would likely occur in the field.

Marine sediments are often normally consolidated and exhibit an increasing strength with depth. This creates an additional challenge for simulating spatial variability as the random field can no longer be homogeneous, whereby the joint PDF of the random field is constant across the domain [27]. An assumption of homogeneity greatly simplifies the treatment of random fields; in the case of a Gaussian random field, only the mean and variance are needed to define the entire field. However, the undrained shear strength may be related to the overconsolidation ratio (OCR) and effective vertical stress, σ'_v, as follows [28]:

$$\frac{s_u}{\sigma'_v} = rOCR^m \tag{1}$$

where r and m are constants. In a normally consolidated marine clay, OCR is equal to 1. If a limited mudline strength, $s_{u,m}$, is accounted for, the profile of s_u increasing with depth may be expressed as:

$$s_u = r\sigma'_v + s_{u,m} = r\gamma' z + s_{u,m} \tag{2}$$

where z is the depth below the mudline and γ' the effective unit weight of the clay. Spatial variability may therefore be taken into account by considering r as a homogeneous random field [19]. Here, both γ' and $s_{u,m}$ are taken as deterministic quantities.

The mean (μ_{s_u}) and standard deviation (σ_{s_u}) of s_u are:

$$\mu_{s_u} = s_{u,m} + \gamma' z \mu_r \tag{3}$$

$$\sigma_{s_u} = \gamma' z \sigma_r \tag{4}$$

where μ_r and σ_r are the mean and standard deviation of r, respectively. Both μ_{s_u} and σ_{s_u} are dependent upon the vertical effective stress. The increase in variability of s_u with depth has been observed by Lumb [20] in a normally consolidated marine clay and so can be considered to represent a typical offshore scenario.

It is clear that s_u should not be a negative value and a Gaussian distribution would therefore be unsuitable for r. A lognormal distribution takes only positive values, making it an appropriate choice. If $\mathbf{x}$ denotes spatial position, the lognormal random fields $r(\mathbf{x})$ and $s_u(\mathbf{x})$ can be generated by:

$$r(\mathbf{x}) = \exp\left[\mu_{L,r} + \sigma_{L,r} G(\mathbf{x})\right] \tag{5}$$

$$s_u(\mathbf{x}) = s_{u,m} + \gamma' z r(\mathbf{x}) \tag{6}$$

where $G(\mathbf{x})$ is a standard homogeneous Gaussian random field of zero mean and unit variance and $\mu_{L,r}$ and $\sigma_{L,r}$ are, respectively, the mean and standard deviation of $\ln(r)$.

The standard Gaussian random field $G(\mathbf{x})$ is generated using the Karhunen–Loeve (KL) expansion. Keaveny et al. [17] analysed the correlation structure of s_u at several offshore sites and found that an exponential autocorrelation function can provide a suitable fit. This is convenient from a numerical perspective as analytical solutions of the KL eigenvalue problem are available for this type of autocorrelation function [10]. Here, an anisotropic exponential autocorrelation function is used. The autocorrelation distances in x- and y-directions (L_x, L_y) of the transformed field $s_u(\mathbf{x})$ are comparable to those of $r(\mathbf{x})$ [29]. The values of L_x and L_y of $\ln(r)$ are taken to be 10 m (2.5 × B) and 1 m (0.25 × B) respectively, consistent with reported values in literature (e.g. [18,21]).

The random field is discretised on a rectangular grid, referred to as the stochastic mesh, which is separate from the FE mesh but defined on the same geometry. The coupling between the random field and FE model is achieved by interpolating the values of the random field on the stochastic mesh to the Gauss points of the FE mesh using shape functions. Note that this means that while $s_{u,m}$ is deterministic when generating the random field, in the finite element model the mudline strength will be random due to interpolation from the stochastic mesh.

2.2. Finite element model

The deterministic simulations are carried out using the commercial FE code Plaxis 2D [23]. A range of embedment ratios between 0 and 1 were considered in order to observe the effect of skirt length on the ultimate capacity of the foundation. Plane strain analysis was used to minimise computation time and allow comparison with previous FE studies. It has also been found that the VHM failure envelope of plane strain and circular surface footings is very similar [11], but further investigation would be required to generalise the results presented here.

The clay is assumed to be undrained and obeys a linear elastic-perfectly plastic Mohr–Coulomb constitutive law, which is equivalent to the Tresca criterion in undrained conditions. In the deterministic case the undrained shear strength of the clay increases