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Research Paper

Probabilistic capacity analysis of suction caissons in spatially variable clay

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ABSTRACT

Suction caissons are increasingly used in offshore energy production to moor floating facilities in deep water. The holding capacity of a suction caisson is dependent on the angle of the mooring line and is often described in terms of a vertical-horizontal (VH) load interaction diagram, or failure envelope. These envelopes have commonly been defined by numerical methods using deterministic soil parameters, ignoring the natural spatial variability of seabed sediments. In this paper, spatial variability is modelled using a random field and coupled with finite element analysis to obtain a probabilistic characterisation of holding capacity. The increase of strength with depth that is characteristic of a marine clay is taken into account. A non-parametric approach using kernel density estimation is presented for constructing probabilistic VH failure envelopes that allow an appropriate envelope, associated with an acceptable level of risk, to be selected for design. A study of the autocorrelation distance, a quantity often difficult to obtain accurately in practice, has shown that the vertical autocorrelation distance has a much greater influence on the variability of holding capacity than the horizontal and should be carefully chosen in offshore applications.

1. Introduction

Development of offshore energy resources now regularly occurs in waters exceeding 1000 m in depth and the trend towards deep water production has led to much interest in the analysis of anchoring systems [1]. As water depths increase, structures that rest on the seabed and rely on traditional gravity or pile foundations become impractical and moored floating units make greater economic sense. Recently, suction caissons (also known as suction anchors) have received significant attention due to a low cost, accurate and environmentally-friendly installation process, which combines penetration by self-weight and by a pressure differential generated from pumping water out of the caisson.

Once installed, the direction of the load applied to a suction caisson is determined by the mooring arrangement. For catenary moorings, the load is at a shallow angle to the horizontal. In deep water, caissons are increasingly employed in taut-line mooring arrangements where the applied load is either inclined or close to vertical [2]. Knowledge of caisson response under combinations of vertical and horizontal load is therefore required to assess holding capacity.

Zdravkovic et al. [3] used a finite element (FE) method to describe the shape of the vertical-horizontal (VH) load interaction diagrams, or failure envelopes, under various caisson aspect ratios and soil anisotropy. A simple ellipsoidal expression for the VH failure envelopes was presented by Supachawarote et al. [4], again based on FE results. Plastic limit formulations have been developed by Randolph and House [5] and Aubeny et al. [6] to assess capacity under combined VH loading. More recent FE analyses have considered installation effects [7].

However, these studies have all considered a deterministic system in which the mechanical behaviour of the soil is described by parameters assigned a specific value. In reality soil is a naturally complex material, having been formed by a range of physical and chemical processes, and the values of engineering parameters are spatially variable. Uncertainty is therefore an integral part of geotechnical design.

A limited number of studies of the reliability of suction caissons subject to uncertainty in loads and capacity have been undertaken. Clukey et al. [8] considered catenary and taut-leg moorings in which system uncertainty was described in a simplified manner by including random variables, for example undrained shear strength s_u, in empirically-derived expressions for lateral and axial capacity. A First-Order Reliability Method (FORM) was used with a linear limit state function to define failure. A design code based on

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similar analyses has been produced by Dahlberg et al. [9]. A more detailed reliability study has recently been presented by Silva-González et al. [10], with a variety of sources of uncertainty included in a FORM analysis.

Whilst methods such as FORM are useful for quantifying the reliability of a suction caisson at a design point corresponding to a specified limit state function, the spatial variability of the soil is not modelled explicitly and mechanical behaviour is overlooked. Consideration of the spatial variation of soil properties has been shown to affect both capacity and failure mechanisms in a range of geotechnical scenarios such as simple bearing capacity problems and slope failures [e.g. 11,12].

In this paper, the holding capacity of a suction caisson in a spatially variable undrained clay subjected to combined VH loading is assessed. The increase of strength with depth typical of marine clays is taken into account. Spatial variability is modelled using a random field representation of soil strength parameters. This is coupled with an FE analysis, meaning that the failure mechanism and ultimate capacity is a direct and natural result of the spatial variation of soil parameters. A method for constructing probabilistic VH failure envelopes, allowing the results of the probabilistic capacity analysis to be easily used in design, is demonstrated. Finally a study of the effect of autocorrelation distance, a quantity often difficult to obtain accurately in practice, has been undertaken.

2. Computational framework

The computational framework consists of two parts: (a) generation of a random field and (b) an FE analysis of VH capacity. The method is non-intrusive, meaning that the FE solver is treated as a 'black-box' with no modifications to the code. The stochastic response is obtained by Monte Carlo simulation. This involves repeatedly generating a random field and passing the realisation to the deterministic FE solver to calculate the VH capacity.

The non-intrusive scheme is in contrast with intrusive formulations [e.g. 13], where stochastic terms are included in the stiffness matrix. As the FE code is unchanged, powerful commercial software may be used allowing complex geometries and constitutive models to be handled in a straightforward way. All that is required is a mapping of the random field to the FE program. In this paper a stochastic mesh, separate from the FE mesh, is used for this purpose. The random field is discretised into a collection of random variables at the nodes of the stochastic mesh, which consists of bilinear quadrilateral elements. Shape functions are then used to interpolate the values of the random field to the Gauss points of the FE mesh.

2.1. Spatial variability of undrained shear strength

The undrained shear strength, s_u, is generally used to determine suction caisson capacity in undrained conditions and therefore in this study the spatial variability of s_u will be considered. It is convenient to assume that the fluctuations in value of a parameter across a soil mass are randomly occurring. Spatial variability can then be modelled using a random field. To simplify the treatment of random fields an assumption of homogeneity is regularly made, whereby in the case of a Gaussian random the field the mean and variance are constant with depth [14].

In deep water locations, deposition occurs slowly and the typically fine-grained sediments have in general not been subjected to additional vertical stresses. These normally consolidated soils therefore commonly exhibit an increasing shear strength with depth [1]. This creates an additional challenge in simulating spatial variability because the mean, and often the variance, of s_u is not constant across the soil mass and so cannot be modelled using a homogeneous random field. However, the undrained shear strength can be related to the vertical effective stress (σ'_v) and overconsolidation ratio (OCR) as follows [15]:

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

where r and m are constants. In a normally consolidated soil the OCR is equal to 1, and in this case r is the undrained shear strength ratio $(r = s_u/\sigma'_v)$. Accounting for a limited strength at the mudline, $s_{u,m}$:

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

where γ' is the effective unit weight and z is the depth below the mudline. Phoon and Kulhawy [22] reported that the typical coefficient of variation (COV) of unit weight is very low, generally less than 0.1. Hence it is reasonable to consider γ' as deterministic. Given that σ'_v increases with z, the variation in the increase of undrained shear strength with depth may be simulated by considering r as a homogeneous random field [16]. Here, $s_{u,m}$ is taken as a deterministic value.

The mean (μ_{s_u}) and standard deviation (σ_{s_u}) of s_u may be written as follows:

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

$$\sigma_{s_u} = s_{u,m} + \gamma' z \sigma_r \tag{4}$$

where μ_r and σ_r are respectively the mean and standard deviation of r. From Eqs. (3) and (4), it is apparent that both μ_{s_u} and σ_{s_u} are dependent upon the vertical effective stress. The increase in standard deviation of s_u with depth has been observed by Lumb [17] in a normally consolidated marine clay.

2.2. Generation of random field

Physically, s_u cannot take a negative value. The ratio r therefore cannot be represented as a Gaussian random field. A lognormal PDF is defined only for values greater than zero and was identified by Lacasse and Nadim [18] as an appropriate distribution for the undrained shear strength ratio. If (x, y) denotes spatial position, a lognormal random field of r may be generated as follows:

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

And so,

$$s_u(x, y) = s_{u,m} + \gamma' z \exp\left[\mu_{L,r} + \sigma_{L,r} G(x, y)\right] \tag{6}$$

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

Here, the Karhunen-Loeve (KL) expansion is used to produce standard Gaussian random fields. The KL expansion of the zero mean random field $G(x, y)$ is:

$$G(x, y) = \sum_{i=1}^{\infty} \sqrt{\lambda_i} \xi_i \psi_i(x, y) \tag{7}$$

where $\{\psi_i\}_{i=1}^{\infty}$ and $\{\lambda_i\}_{i=1}^{\infty}$ are the eigenfunctions and eigenvalues from a spectral decomposition of a prescribed autocorrelation function, ρ_G, and $\{\xi_i\}_{i=1}^{\infty}$ is a set of independent standard Gaussian random variables. The infinite sum in Eq. (7) must be truncated in practice and in this study the number of retained terms is chosen