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Random finite element method for spudcan foundations in spatially variable soils

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ABSTRACT

Spudcans are large diameter (~20 m) conical foundations holding up mobile jack-up platforms for offshore oil and gas developments in shallow to moderate water depths. During self-installation the spudcan often penetrates several tens of meters into seabed soils, where large variations often occur in the shear strength of the soils. Although the failure mechanisms and bearing capacity of spudcan foundations have been studied in homogeneous soil and layered uniform soil, the effect of the spatial variability in soil strength on the spudcan response is still unclear. This study presents a random finite element method (RFEM) for assessing the failure mechanisms and the bearing capacity of a spudcan foundation embedded in spatially varied seabed soils. A comprehensive review of seabed soils discusses typical ranges of the mean, the coefficient of variation and the scale of fluctuation of the undrained shear strength. Random fields are generated and mapped into a non-linear finite element analysis to reveal the failure mechanisms of the spudcan in spatially varied soils. The influence of the scale of fluctuation in different directions is investigated. The results indicate that ignoring the spatial variability of soil strength leads to an overestimation of the bearing capacity. It is unconservative for the foundation design to assume an isotropic random field model in the RFEM analysis.

1. Introduction

Mobile jack-up platforms are key contributors to the development of offshore oil and gas reservoirs in shallow to moderate water depths. A typical modern jack-up consists of a buoyant triangular hull, three independent truss-work legs and inverted conical spudcan foundations (Young et al., 1984). A jack-up is self-installed by lifting the hull from the water and pushing the large spudcans (approximately 20 m in diameter) into the seabed. In soft soils, the foundation may penetrate up to 3 diameters to achieve the adequate bearing capacity for the jack-ups during an extreme storm event (Hossain and Randolph, 2009).

The failure mechanisms of spudcan foundations in uniform soils or homogenous soils with linearly increasing strength with depth, have been studied over the past decades (e.g., Young et al., 1984; Martin and Houlsby, 2001; Cassidy et al., 2004; Erbrich, 2005; Menzies and Roper, 2008; Osborne et al., 2009; Hossain and Randolph, 2010). However, under typical conditions, the seabed soils in many offshore areas are made up of interbedded layers of clay and sand with large variations in the shear strength (Hossain and Randolph, 2009; DNV, 2012; Lee et al., 2013a,b). This variation in soil strength has often been ignored in previous studies due to the complexity of the spatially variability of the seabed soils. The influence of the spatially varied properties of soils on the bearing capacity of the embedded spudcan foundation remains unclear.

This study aims to present the failure mechanisms and bearing capacity of a spudcan foundation embedded in spatially varied seabed soils using a random finite element method. The spatial variation of seabed soils is first reviewed and characterised based on random field theory. Then, the spatially varied soils are modelled by numerically generated random fields which are further mapped into a non-linear finite element analysis to investigate the failure mechanisms and the bearing capacity of the spudcan foundation. Finally, Monte Carlo simulations are performed to explore the possible failure modes of the spudcan foundation in the spatially varied seabed. This study explores the possible failure mechanisms of a spudcan foundation considering the complex soil conditions and shed light on the reliability of foundation designs (Khoshnevisan et al., 2014).

2. Spatial variability in seabed soils

Soil properties may vary in space both vertically and horizontally due to sedimentational, physical or chemical changes in the

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Table 1
Scales of fluctuation for offshore soils.

Soil	Location	Property	Scale of fluctuation (m)		Reference
			Horizontal	Vertical	
Offshore soils	North sea	Cone penetration resistance	35.4–62	–	Tang (1979)
Sand	North sea	Cone penetration resistance	26	0.4	Wu et al. (1987)
Offshore soils	–	Cone penetration resistance	24.6–66.5	–	Keaveny et al. (1989)
Offshore soils	–	Undrained shear strength	–	0.48–7.14	Keaveny et al. (1989)
Silty clay	North sea	Cone penetration resistance	7–24	1.4–2.0	Lacasse and de Lamballerie (1995)
Clay	Norwegian trench	Undrained shear strength	–	0.05–0.08	Uzielli et al. (2006)
Offshore soils	Gulf of Mexico	Undrained shear strength	9000	14	Cheon and Gilbert (2014)
Clay	Timor sea	Cone penetration resistance	317	–	Li et al. (2015b)

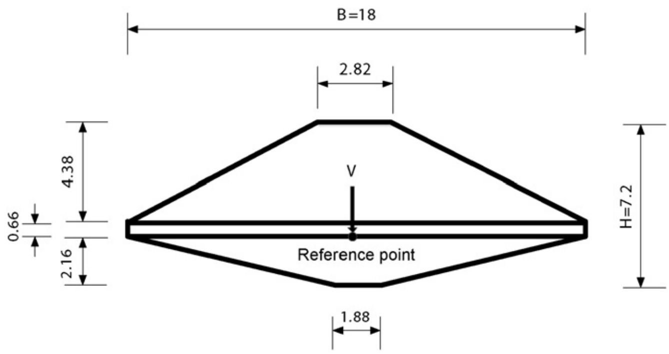

Fig. 1. Geometry of the spudcan foundation (Unit: m).

environment. The variability of the soil property is often described by the mean, variance (or standard deviation) and probability density function. If the spatial correlation of a soil property among different locations is incorporated, a trend that represents the mean value and the residuals that reflect the variability around the trend are employed (Phoon and Kulhawy, 1999; Lacasse et al., 2014). The residuals at nearby locations are statistically correlated to one another in space and are a function of their separation distances. The function is commonly referred to as the autocorrelation function. The integral of the autocorrelation function leads to the scale of fluctuation (Baecher and Christian, 2003; Lloret-Cabot et al., 2014). The correlation between soil property values at two locations within the scale of fluctuation is strong.

The spatial variability of seabed soils has been reported for the North Sea (Høeg and Tang, 1976; Tang, 1979; Wu et al., 1987; Nadim, 1988; Keaveny et al., 1989; Lacasse and de Lamballerie, 1995; Uzielli et al., 2006), the Gulf of Mexico (Cheon and Gilbert, 2014), and offshore Australia (Randolph et al., 1998; Bienen et al., 2011; Li et al., 2015b). Lacasse and Nadim (1996) reviewed offshore soils and found that the undrained shear strength (s_u) of clay followed a normal or lognormal distribution with its coefficient of variation (COV) ranging between 5% and 35%. Uzielli et al. (2006) analysed the cone resistance of Troll clay off the shore of Norway and reported that the undrained shear strength increased with depth. The mean value of the Troll clay increased from 12.7 kPa to 36.3 kPa with its standard deviation increasing from 2.0 kPa to 5.3 kPa. For offshore clays in Timor Sea, north-west of Australia, Randolph et al. (1998) found that the undrained shear

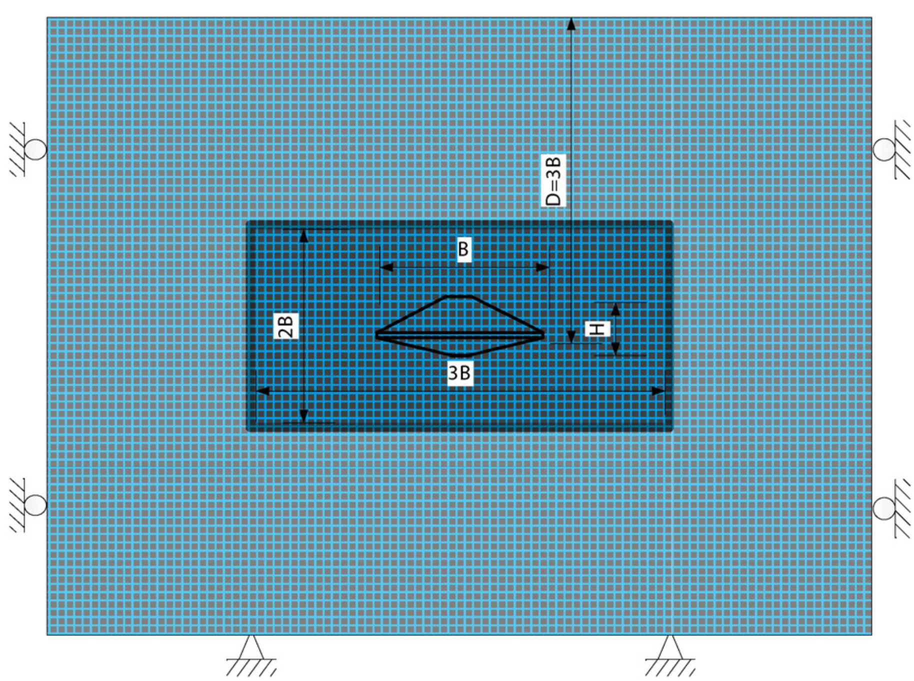

Fig. 2. Finite element model and boundary conditions.