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Predicting jack-up spudcan installation in sand overlying stiff clay

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ABSTRACT

There has been a constant trend towards larger mobile jack-ups capable of operating for extended periods in deeper water and in harsher environmental conditions. This is increasing both the size of their spudcan footings and the operational bearing pressures. Though some new analytical methods to predict the load-penetration profile have been proposed, and shown to fit centrifuge experiments well, these methods were calibrated mainly using experimental and numerical data for sand overlying soft clay. This paper reports six centrifuge tests simulating spudcan installation in sand overlying a stiff clay. These are complemented with large-deformation finite element analyses, simulating the continuous penetration of the spudcan in sand over stiff clay. Modified Mohr-Coulomb and Tresca models were used to describe the sand and clay behaviour, accounting for the effects of strain softening on the response of the soil. These results provide confidence that a recently published analytical method to predict the peak capacity can indeed be extended to high bearing resistances and stronger underlying clays. Bearing capacity factors used to predict capacity in the underlying clay have, however, been updated to reflect the new database of results. A new formulae that explicitly accounts for increasing strength with depth profiles is provided.

1. Introduction

In water up to a depth of approximately 150 m, mobile independent leg jack-up rigs are widely used to perform most offshore drilling. The jack-up units are designed for more onerous conditions leading to increased spudcan bearing pressures. Although the popular rig classes exhibited maximum vertical installation bearing pressure in the range of 200–600 kPa, some of the reported field cases have indicated higher bearing pressures (see Fig. 1). Are the calculation methods used to predict the vertical installation of spudcans appropriate for these pressures and all offshore conditions?

For instance, the punch-through of a spudcan through a layer of sand into underlying clay has been intensively investigated in a geotechnical centrifuge by Craig and Chua (1990), Teh (2007), Lee (2009), Teh et al. (2010), Lee et al. (2013a), Hossain et al. (2016) and Hu et al. (2014a, 2016). Table 1 summarises the testing database, with the shear strength of the clay at the sand-clay interface s_{um} ranging from 7.2 to 25.8 kPa and the shear strength gradient in the range of 0–2.1 kPa/m. Because it is easier to lay in a centrifuge this database consists of soft clays. However, for many of the punch-through locations of greatest concern, such as in the South Baltic and the North Sea, layered sand over stiff clay stratigraphy with $s_u > 40$ kPa are common (Werno et al., 1987; Kellezi et al., 2005; Kellezi and Stadsgaard, 2012). There is a need to confirm the applicability of analytical methods in these stronger soil profiles. It is noted that the term “stiff clay” is used somewhat generically in this paper to describe clays of strength greater than those previously used in the centrifuge testing and numerical analysis on the sand-over-clay problem. These are clays greater than 40 kPa, though this is slightly different to that defined in ISO (2012).

Load spread and punching shear are the ‘standard’ methods included to estimate the peak spudcan bearing pressure in sand overlying clay in the ISO 19905-1 guidelines (ISO, 2012). There is mounting evidence that these methods produce low estimates of the spudcan bearing pressure during punch-through failure when the undrained shear strength of the clay is low (Teh et al., 2010; Lee et al., 2013a; Hu et al., 2015b). However, whether such underestimation of the spudcan bearing pressure also occurs for the higher underlying undrained shear strengths often encountered offshore requires further validation.

Recently, a new analytical penetration resistance-depth profile prediction method (hereinafter called the Hu et al. method) was proposed (Lee et al., 2013b; Hu et al., 2014b, 2015a). It was calibrated using a testing and numerical database with soft clay strength of 10–40 kPa at the sand-clay interface and strength gradient of 1.5–2.5 kPa/m (Lee et al., 2013a; Hu et al., 2014a, 2015a, 2016). In the prediction of the peak

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penetration resistance in the upper sand layer, the stress level and dilatant response, as well as the embedment depth, are taken into account using a discretised silo approach. In the prediction of spudcan capacity in the underlying clay, both the thickness of the trapped sand beneath the spudcan and the clay's undrained shear strength increment with depth are accounted for.

The motivation for this paper emanates from the need to characterise spudcan installation in sand over stiff clay and to validate analytical methods used to calculate load-penetration profiles. The term “stiff clay” is used for the clays with strength greater than 40 kPa in the following analyses. The main objectives of the testing and numerical programme are: (a) to model experimentally the penetration resistance of a spudcan of generalised geometry penetrating medium-dense sand overlying stiff clay in a beam centrifuge and to extend the existing testing database to incorporate clay of higher undrained shear strength; (b) to evaluate the performance of the guideline methods in estimating the spudcan penetration resistance in sand over stiff clay soils; and (c) to validate the Hu et al. method to predict spudcan penetration resistance-depth profiles. This will provide confidence for use of these methods in typical offshore conditions faced by practitioners.

2. Testing programme

Physical modelling of spudcan penetration in medium-dense sand overlying stiff clay was conducted using the beam centrifuge at the University of Western Australia (UWA). The centrifuge has a swinging platform with a standard rectangular strongbox. It has internal dimensions of 650 mm (length) × 390 mm (width) × 325 mm (depth), representing a prototype testing area of 130 m × 78 m × 65 m respectively when testing at 200*g*. Tests were performed using four model spudcans of the same shape, but with dimensions scaled according to Fig. 2. The diameter of the model spudcan, D, ranged from 30 mm to 60 mm. The models were made from duraluminium and included a 13° shallow conical underside profile (included angle of 154°) and a 76° protruding spigot. These spudcans were the same shape as those used in the tests of sand overlying soft clay by Teh et al. (2010), Lee et al. (2013a) and Hu et al. (2014a) and in previous combined loading experiments of Martin and Houlsby (2000), Cassidy et al. (2004) and Vlahos et al. (2011).

2.1. Sample preparation

Commercially available super-fine silica sand and kaolin clay were adopted in all the centrifuge tests to form the sand and clay layers, respectively. Both materials have been well characterised and used extensively in the geotechnical centrifuges at UWA. The key properties of the sand and clay are summarised in Table 2.

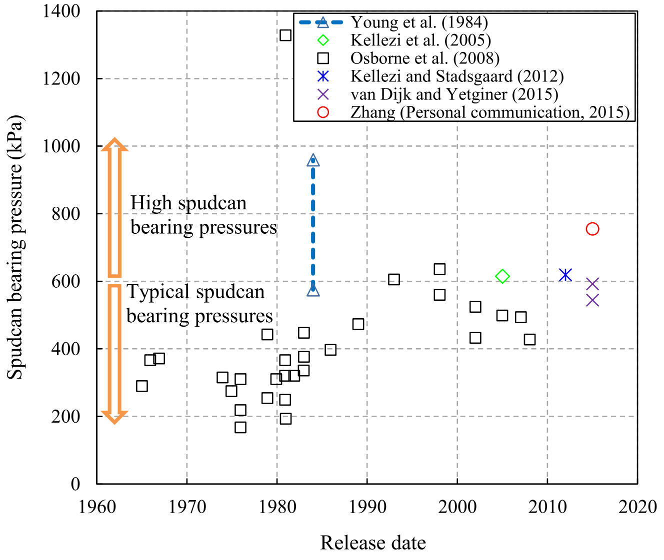

Fig. 1. Record of jack-up spudcan bearing pressures.

Initially, sand was laid at the base of a strongbox in a layer ~10 mm thick and saturated to form a drainage layer. The kaolin clay was mixed with water under vacuum to form a clay slurry to about two times the liquid limit of clay. The kaolin clay slurry was then transferred into the strongbox and consolidated overnight. Seven specially designed steel beams (50 mm × 50 mm cross-section) were placed along the curvature of the strongbox to surcharge the clay. A brass mesh together with a geofabric were used as a flexible barrier between the kaolin clay and the overburden, which was strong enough to support the steel beams but flexible and porous so as not to point load the sample or alter the pore-pressure dissipation (see Fig. 3). The underlying clay was then over-consolidated at an acceleration of 300*g* until no further displacement of the clay was recorded, indicating the clay was fully consolidated. All tests were conducted at 200*g*, and the over-consolidation ratio, OCR, for the underlying clay was at least 1.5. After consolidation, the clay was scraped to form a smooth surface. The top sand layer was formed by pluviating fine sand particles. The sand drop height, hopper travel speed and opening were controlled to create medium-dense sand. The soil sample was then saturated and subjected to an acceleration of 200*g*, with the effective centrifuge radius being set at two-thirds from the bottom of the clay. The clay thickness was measured to be 193 mm, with a sample thickness of 213 mm and 223 mm, depending on the thickness of the top sand.

2.2. Testing procedure

A total of six spudcan penetration tests were performed in medium-dense sand overlying stiff clay with sand thickness H_s of 20 and 30 mm, for which the ratio H_s/D was between 0.33 and 1.0. All the tests were spaced at least 1.5D edge-to-edge and with a clear minimum 1.5D between the spudcan edge and the sidewall of the strongbox. A free layer of water was maintained above the sample being tested. As detailed in Table 3, three tests of varying spudcan diameter were performed with the initial sand thickness of 30 mm. Following these tests the sand was further scraped back to 20 mm, allowing three tests to be performed at different H_s/D ratios. The bottom clay was re-consolidated at 200*g* overnight after the scraping process.

Table 1
Summary of sand-over-clay centrifuge tests reported in the literature.

Investigation	Centrifuge type	Number of tests	Clay property		
			s_{um} (kPa)	k (kPa/m)	kD/s_{um}
Lee (2009) UWA Tests	beam	5	13.2	1.9	1.1–2.0
Teh et al. (2010) NUS Tests	beam	7	7.8–25.8	1.6	0.6–2.0
Teh et al. (2010) UWA Tests	beam	3	7.2–14.6	1.2	0.7–1.0
Lee et al. (2013a) UWA Tests	drum	30	16.3–19.1	2.1	0.6–2.0
Hu et al. (2014a) UWA Tests	drum	15	11.0–13.0	1.5–1.6	0.7–2.8
Hu et al. (2016) UWA Tests	drum	11	11.3–22.2	1.5–2.1	0.8–1.1
Hossain et al. (2016) UWA Tests	drum	6	23.5	0	0
Summary	beam/ drum	77	7.2–25.8	0–2.1	0–2.8