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Bearing capacity on sand overlying clay: An analytical model for predicting post peak behaviour

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ABSTRACT

New analytical models have recently been presented for evaluating the peak bearing capacity of circular footings penetrating sand-over-clay and the subsequent capacity once embedded in the underlying clay. However, in lieu of any analytical model, current methods of analysis use an inaccurate linear interpolation for the bearing capacity between the peak and the clay surface. This paper proposes an analytical model for calculating the bearing capacity of circular footings after the peak failure in sand-over-clay soils and before the footing enters the clay. Based on observations from visualisation experiments conducted in a geotechnical centrifuge, and consistent with the silo analysis approach used in predicting the peak capacity, the failure mechanism is a vertical frustum of sand progressively being forced into the underlying clay. Analysis of the capability of the new model to retrospectively simulate a database of 66 geotechnical centrifuge tests is provided. Motivation for improved prediction methods comes from the offshore mobile jack-up industry where concerns remain over the punch-through of large 20 m diameter spudcan footings in sand-over-clay. Accurate prediction of not just the peak bearing capacity but the subsequent load-displacement behaviour is required in order to assess the effectiveness of operational methods used to mitigate punch-through incidents.

1. Introduction

Jack-ups are mobile self-elevating platforms consisting of a hull and three or more retractable legs. Each leg is supported by an independent circular 'spudcan' footing that can be over 20 m in diameter (with example shapes provided by Cassidy et al. [1]; Dean [2]). Once on location, the legs of a jack-up are jacked down into the seabed, and eventually the hull is raised above sea level, with the weight of the rig carried by the spudcans.

This installation procedure remains problematic for the offshore industry (Osborne and Paisley [3]; Hunt and Marsh [4]; Osborne et al. [5,6]; Jack et al. [7]). In seabeds comprising sands overlying weaker clays a 'punch-through' event can cause a rapid vertical penetration of the spudcan. Uncontrolled punch-through of the sand into the clay, as illustrated in Fig. 1, poses a threat to the jack-up's structure, stability and onboard personnel. Accurate pre-installation assessment of the vertical load-penetration curve remains an industry priority in predicting occurrence of punch-through events, with new analytical methods recently published (e.g. Okamura et al. [8]; Teh et al. [9]; Teh, [10]; Teh et al. [11]; Lee et al. [12]; Hu et al. [13]) aiming to improve the accuracy of industry guideline ISO 19905-1 (ISO) [14]. Cautiously installing the jack-up with the hull at positive draft or as close to the water as possible is an operational method currently used to mitigate the effects of a punch-through event. This allows any rapid leg penetration to cause

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Notation

d	penetration depth of footing
d_{peak}	footing depth at peak penetration resistance
$d_{post,\ peak}$	footing depth at local minimum of the post peak penetration resistance
D	diameter of the footing
D_F	distribution factor
E	parameter to simplify the algebra
H_s	sand thickness
I_D	relative density
N_c	bearing capacity factor
q	penetration resistance
q_0	surcharge at sand surface
q_{clay}	penetration resistance in the clay layer
q_{peak}	peak penetration resistance
$q_{post,\ peak}$	local minimum of the post peak penetration resistance
s_{um}	shear strength of clay at sand-clay interface
s_u	local undrained shear strength of clay
z	depth of the disc element
γ'_c	effective unit weight of clay
γ'_s	effective unit weight of sand in the disc element
ϕ'	friction angle of sand
ϕ^*	reduced friction angle due to non-associated flow rule
ϕ_{cv}	critical state friction angle of sand
Ψ	dilation angle of sand
$\bar{\sigma}'_z$	mean vertical effective stress
τ	shear stress
σ'_n	normal stress

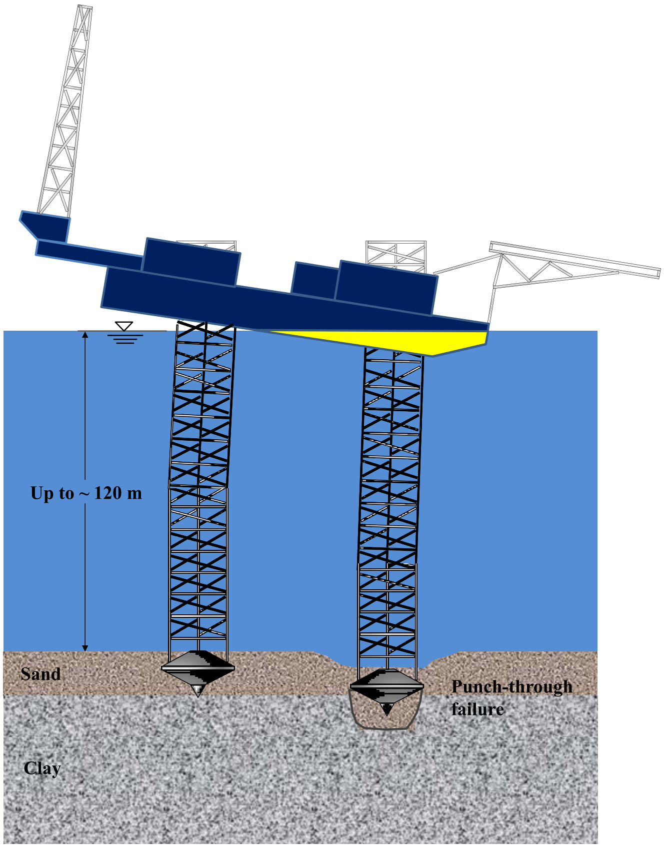

Fig. 1. Depiction of a punch-through event of a jack-up.

hull immersion with the beneficial reduction of spudcan load due to buoyancy. However, to predict what will happen in such an event requires not just an accurate prediction method for the peak bearing capacity but all of the subsequent post-peak load-displacement behaviour.

This paper proposes an analytical model for calculating the bearing capacity of a spudcan after the peak failure in sand-over-clay soils and before the spudcan enters the clay. It is consistent with failure mechanisms observed through centrifuge tests (incl. Teh et al. [15], Hu et al. [16]). It is based within the analytical framework for calculating peak capacity by Lee et al. [12] and Hu et al. [13], and is calibrated against the database of 66 centrifuge tests reported by Teh et al. [17], Lee et al. [18] and Hu et al. [13,16]). All test results are provided in the supplementary material. This paper provides additional detail and accuracy to the method to calculate a full penetration resistance profile of Hu et al. [19,20].