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Experimental investigation on the effect of spudcan shape on spudcan-footprint interaction

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ABSTRACT

The interaction between a spudcan and an existing footprint is one of the major concerns during jack-up rig installation. The influence of spudcan-footprint interaction has recently been well addressed by a number of researchers. A lack of investigation exists in mitigating spudcan-footprint interaction issues. In the field, stomping and successive repositioning is conventionally used in installing a rig adjacent to an existing footprint. Water jetting and perforation drilling are also sometimes suggested. This paper reports a measure for easing spudcan-footprint interaction issues, with the efficiency of a spudcan with 4 slots tested through model tests carried out at 1 g on the laboratory floor. The soil conditions tested simulate soft to moderate seabed strength profiles close to the mudline, varying the undrained shear strength. The most critical reinstallation locations of 0.5D and 1D (D = spudcan diameter) and existing footprint depths of 0.33D and 0.66D were investigated. By comparing with a conventional spudcan, the spudcan with slots reduced the induced maximum moment, horizontal force, and horizontal sliding distance by up to 80%, 40%, and 98% respectively. Critically, no additional operations, such as stomping/repositioning, perforation drilling, water jetting, are required to be performed offshore.

Introduction

1.1. 'Mobile' jack-up rig and spudcan-footprint interaction issues

Most offshore drilling in shallow to moderate water depths (<150 m) is performed from self-elevating jack-up rigs due to their proven flexibility, mobility and cost-effectiveness [1,2]. Today's jack-ups typically consist of a buoyant triangular platform supported by three independent truss legs, each attached to a large 10–20 m diameter spudcan. After the completion of the task, the legs are retracted from the seabed, leaving depressions (referred to as a crater or 'footprint') at the site. Jack-ups often return to sites where previous operations have left footprint in the seabed. This is, for examples, to drill additional wells or service existing wells; installing structures such as jackets, wind turbines [3–5]. Reinstallation on or adjacent to these footprints (as schematically shown in Fig. 1) is a problematic operation because the spudcan is subjected to eccentric and inclined loading conditions. The consequent adverse spudcan displacement could result in an inability to install the jack-up in the required position, leg splay, structural damage to the leg, and at worst, bumping or collapsing into the neighbouring operating platform [6]. The frequency of offshore incidents during installation near footprints has increased by a factor of four between the period 1979 ~ 1988 and 1996 ~ 2006 [7] and at an even higher rate over 2005 ~ 2012 [8]. Examples are noted by [9,10] and [11].

1.2. Spudcan footprint geometry

The depth and configuration of a footprint are a function of five main factors: (a) spudcan shape; (b) the soil type, strength and stratification; (c) operational period; (d) the depth of releasing suction at the base, i.e. detaching the spudcan base from the underlying soil, during extraction; (e) the degree of soil reverse backflow around the extracting spudcan. The effect of intact soil strength profile on the configuration of a footprint can be found from the results of half-spudcan tests carried out on clay deposits with various strength profiles [12]. The observed images showed that suction was sustained to a greater extraction depth in soft, lightly over-consolidated clay compared to that in stiff, heavily overconsolidated clay. This resulted in a conical footprint of depth

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Nomenclature

A	Spudcan plan area at largest section
b	Offset distance
c_v	Coefficient of consolidation
D	Foundation diameter at largest section
D_e	Object (area equivalent) diameter
d_{tip}	Penetration depth of spudcan tip
g	Earth's gravitational acceleration
H_0	Horizontal force at spudcan base level
h	Horizontal sliding distance
M_0	Moment at spudcan base level
s_u	Undrained shear strength
V	Vertical force
v	Object penetration velocity
x_F	Footprint diameter
z	Depth below soil surface
z_F	Footprint depth
β	Footprint angle
η	Ratio between footprint depth and spudcan diameter $= z_F/D$
γ'	Soil effective unit weight
κ	Ratio between footprint diameter and spudcan diameter $= x_F/D$
λ	Ratio between offset distance and spudcan diameter $= b/D$

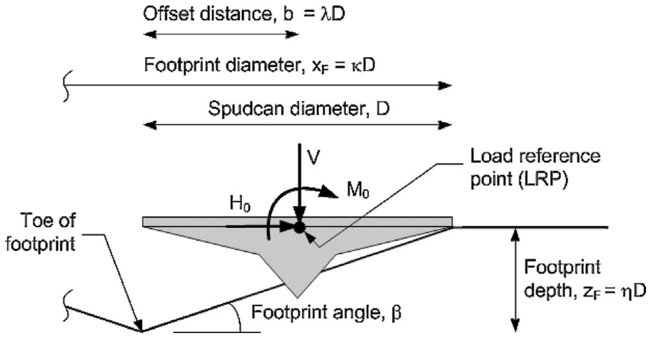
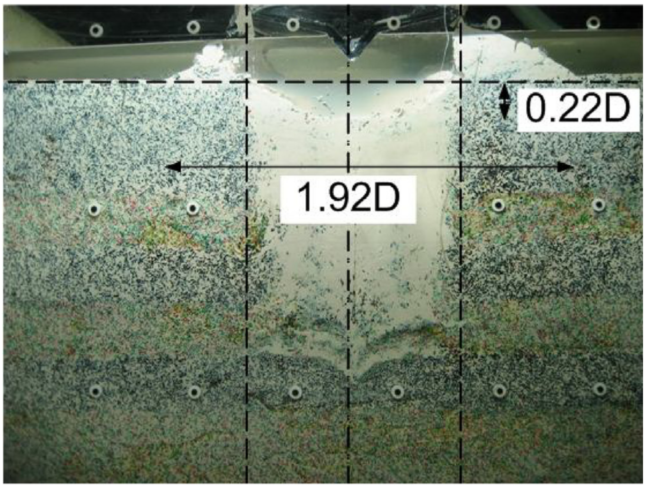
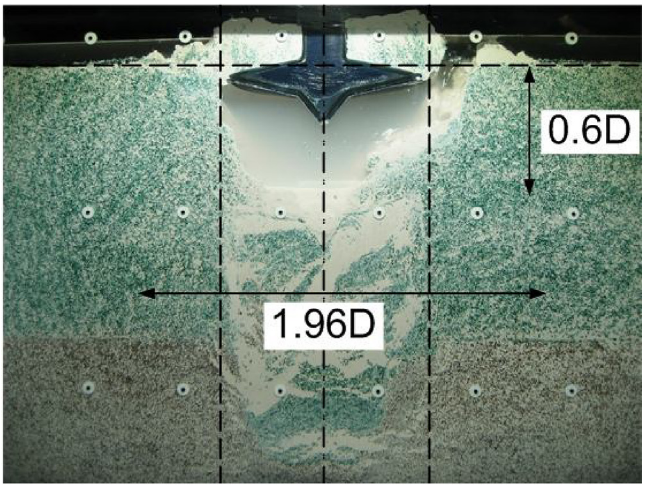


Fig. 1. Schematic diagram of spudcan-footprint interaction.



(a) Footprint in soft, lightly overconsolidated clay



(b) Footprint in stiff, heavily overconsolidated clay

Fig. 2. Geometry of spudcan footprints from centrifuge tests: (a) Footprint in soft, lightly overconsolidated clay; (b) Footprint in stiff, heavily overconsolidated clay.

$0.22 \sim 0.33D$ in soft clay (Fig. 2a) and cylindrical footprint of depth $0.5 \sim 0.66D$ in stiff clay (Fig. 2b). In addition, during initial penetration of the spudcan, the soil flows towards the surface, which led to surface heave over a wider area around the periphery. This was coupled with reverse backflow during extraction and dropping of backfilled soil around the periphery (and inside the crater), resulting in a soil hump around the periphery. The total width was $1.92 \sim 1.96D$. These findings are consistent with [13–16]. Critical footprint depth of $z_F = 0.33$ and $0.66D$ ($\eta = z_F/D = 0.33$ and 0.66) and width of $x_F = 2D$ ($\kappa = x_F/D = 2$) were considered in this study.

Clays soften as they are sheared and remoulded by a spudcan penetration-extraction sequence. The reduction in the undrained shear strength s_u decreases with the increase in radial distance from the footprint centre and along the depth. A zone of intensely remoulded soil was confined within 0.75D from the centre. However, the strength regains over the passing of time. After 1.5 years, the soil condition may found to be close to or even stronger than the undisturbed soil [14].

1.3. Previous work, existing measures for mitigating spudcan-footprint interaction issues, and objective of present study

Penetration of spudcan foundations next to footprints has been addressed by a number of researchers, with of particular interest being on spudcan-footprint interactions and consequent influence on jack-up legs with various fixity conditions (e.g. [17–19,14,15,20]. The critical offset ratio λ (defined as the ratio of the distance between the footprint centre and spudcan centre, b, and the spudcan diameter) was identified as $0.5 \sim 1$ for inducing maximum lateral displacement of $\sim 0.35D$. From case histories, Handidjaja et al. [10] found that if $\lambda > 1.5 \sim 1.7$, the effect of interaction can be neglected, while Teh et al. [13] reported a minor slip for $\lambda = 1$. ISO [6] expects minimal interaction between a spudcan and a footprint when the edge-to-edge distance exceeds one spudcan diameter. However, only minimum attention was paid on mitigating spudcan-footprint interaction issues. In the field, stomping and successive leg repositioning [11] and water jetting along with the spudcan preloading [10] have been used.