Canadian Geotechnical Journal
Revue canadienne de géotechnique

Simplified analysis of chord and brace effects on jackup leg penetration for preloading in soft clay

Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2017-0434.R1
Manuscript Type:	Note
Date Submitted by the Author:	03-Mar-2018
Complete List of Authors:	Aagesen, Ron; Capital Signal de Mexico S.de R.L. de C.V Dean, E.T.Richard; Caribbean Geotechnical Design Limited, Lee, Fook Hou; National University of Singapore Faculty of Engineering, Civil & Environmental Engineering Li, Yuping; Hohai University, Civil Engineering
Is the invited manuscript for consideration in a Special Issue? :	N/A
Keyword:	jackup, spudcan, preloading, soft clay

SCHOLARONE™
Manuscripts

Simplified analysis of chord and brace effects on jackup leg penetration for preloading in soft clay

Rev.1, by R.Aagesen¹, E.T.R.Dean², F.H.Lee³, and Y.P.Li⁴, February 2018

- 1 Capital Signal de México S.de R.L. de C.V., Mexico, aagesenr@capitalsignal.com,
- 2 Corresponding Author, Caribbean Geotechnical Design Limited, Trinidad and UK, richard.dean@caribgeo.com. Address for physical correspondence: c/Goya 18, L'Escala, Alt Emporda, Girona 17130, Spain, tel: (34) 97277 3467
- 3 National University of Singapore, Faculty of Engineering, Civil and Environmental Engineering, leefookhou@nus.edu.sg
- 4 Geotechnical Engineering Research Institute, Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China, Juliya-li@hotmail.com

Abstract

The main codes of practice governing jackup preloading presently do not consider the possibility of beneficial effects of soil resistance generated by leg chord and leg brace members as they move downwards through disturbed soil that has been squeezed past the spudcan to form part of the backfill. This paper argues that these effects can be significant for the special case of deep penetrations in soft clay. An approximate method of estimating the effects is proposed and discussed. Results are found to be broadly consistent with recent centrifuge model tests and numerical analyses. Further work is recommended to explore these potentially important and certainly complex effects.

Keywords

Jackup, spudcan, preloading, punch-through, soft clay

Statistics

No. of words in main text 3850
No. of Figures 4
No. of Tables 1
No. of Appendices 1 (with 830 words)

Notation

Basic SI units are quoted below. M=meters, N=Newtons, Pa=Pascals. Where appropriate in the text, powers of ten are used, so that for example stresses may be expressed in kPa and forces may be expressed in kilonewtons [kN] or megaNewtons (MN).

b, b_{eff}	diameter of tubular, actual and effective [m]
B	spudcan diameter [m]
B_{leg}	horizontal distance between leg chords [m]
C	equivalent circumference for leg truss elements [m]
dP'	infinitesimal increment of P' along tangent to yield envelope [N]
D	embedment depth (equals z_b for geometry of Figure 1) [m]
F'_b	component of F'_{net} due to absence of soil from cavity and spudcan volume [N]
$F'_{b,leg}$	component of resistance due to absence of soil from volume of leg, see also F'_{net} [N]
F'_{leg}	force resisting motion of leg chords and braces through soil [N]
F'_{net}	net soil resistance force, equation 2 [N]
$F'_{weightless}$	resistance force accounting for bearing capacity of spudcan assuming weightless soil [N]
h_s	equivalent spudcan height; embedded spudcan volume divided by bearing area [m]
H_{bay}	bay height [m]
L_i	length of an i^{th} tubular in a bay [m]
$N_c s_c d_c$	combination of bearing capacity factor and modifiers for clay [-]
N_{lat}	lateral capacity factor for tubular moving through clay [-]
P'_n, P'_s	soil resistances per unit length normal and parallel to centreline of tubular [Nm^{-1}]
P'_v, P'_x	soil resistances per unit length parallel and normal to motion of tubular relative to soil [N]
s_u	undrained shear strength of undisturbed clay [Pa]
$s_{u,dist}$	undrained shear strength of disturbed clay [Pa]
s_{um}	undisturbed undrained shear strength at mudline [Pa]
S_{dist}	ratio of undisturbed strength divided by disturbed strength [-]
v	displacement or velocity of tubular relative to soil [m or ms^{-1}]
v_n, v_s	displacement or velocity of soil in normal and axial directions of tubular [m or ms^{-1}]

V	volume of soil displaced by spudcan [m^3]
$V_{leg,bay}$	Volume of soil displaced by the chords and braces in one leg bay [m^3]
W_{back}^I	submerged weight of backflow [N]
z_1	depth to top of cavity [m]
z_2	depth to lowest level of effective interaction between lattice leg and soil [m]
z_b	depth to bearing surface [m]
z_{tip}	depth to spudcan tip [m]
β	cone apex angle (see Figure 4). A flat-based spudcan has $\beta = 180^\circ$
γ_1^I	average submerged unit weight of soil displaced from cavity [N.m^{-3}]
γ_s^I	average submerged unit weight of soil displaced from volume occupied by spudcan [N.m^{-3}]
θ	angle of tubular centreline to horizontal (or to the normal the direction of motion)
ρ	rate of increase of undisturbed undrained shear strength with depth [N.m^{-1}]
σ_v^I	vertical effective stress at the level of the bearing area [Pa]
ψ_{lat}	lateral capacity coefficient (N_{lat}) divided by axial shear capacity coefficient (π) [-]

Introduction

Geotechnical aspects and operations of large jackups used in the offshore oil and gas sector are described by Cassidy et al (2004), Dier et al (2004), Vasquez et al (2005), Dean (2009), Randolph and Gourvenec (2011), Koole (2015) and others. After the unit has been towed to site with legs elevated, the legs are set down on the seafloor and the hull is jacked a short distance out of the water. The legs are then preloaded, usually individually. This causes the spudcans to penetrate into the seafloor to a depth at which a required factored ultimate bearing capacity is achieved. The hull is then jacked up further to achieve an adequate air gap for subsequent operations.

Prior to these operations, a prediction is typically made for the relation between leg penetration and leg load during preloading. The SNAME (2008) and ISO (2012) standards provide guidance on these calculations, as discussed by Wong et al (2012). A “wished-in place” methodology is used, pioneered by Endley et al (1980), Young et al (1984) and others. Subsequent research led to improvements to the basic methodologies, particularly through the use of centrifuge model testing (Murff 1996; Gaudin et al. 2010).

More recently, centrifuge model testing has been combined with finite element analyses to provide greater understanding of deformation mechanisms, and to allow the inevitable inaccuracies of the wished-in place assumptions to be assessed and possibly overcome (Hossain et al. 2006; Randolph 2013). One such combined study, by Li (2014) and Li et al (2012, 2017, 2018), looked at issues associated with the lattice leg, including the one considered herein and outlined below.

Field studies have been carried out to verify and calibrate the SNAME and ISO methodologies. Menzies and Roper (2008) compared several calculation methods with field data for normally consolidated clays. Bienen and Cassidy (2013) explored effects of consolidation in soft clays. Several authors suggest improved methods for the case of sand overlying clay, which is one cause of occasional punch-through failures (Brennan et al. 2006; Hu et al. 2014; Mahanta 2016).

Problem definition

Modern “spudcan” footings at the bottom of each leg are typically conical in shape (Figure 1). They may be up to 20 meters or more in diameter, and may penetrate 40 meters or so into normally consolidated clay. The legs are often lattice frames. The leg chords include the racks that are used by the jacking systems. The braces are typically constructed from tubulars.

As the spudcan penetrates the soil during preloading, a cavity develops above the spudcan. On further penetration, the clay flows around the spudcan in a “flow-around” mechanism (Hossain et al. 2004, 2005, 2006, 2014). Disturbed clay thus moves into place above the spudcan, and can comprise the major part of “backfill”. As the penetration increases, a column of disturbed soil develops above the spudcan. Siciliano et al (1990) found that piles placed at more than one-half the spudcan diameter away from the edge of the spudcan were relatively undisturbed by this process, so the column of disturbed soil probably has a diameter of less than two spudcan diameters. Detailed analyses by Li (2014) reveal a complex pattern of soil movements in the disturbed zone.

The problem addressed herein is as follows. If chord and brace members move downwards through the disturbed clay, some resistance may be expected from the clay, because the downwards movement forces clay to flow around some leg truss elements and to flow past others. This is not accounted for in the standards, but is expected to increase the vertical loading that is needed to penetrate the leg further into the seafloor. The effect is shown below to be small for shallow spudcan penetrations, but significant for deeper spudcan penetrations.

The problem has been addressed by Li (2014) and Li et al (2012, 2017, 2018) in a combined centrifuge model testing and numerical study. Their study found effects of the order of 10% for lattice legs with similar geometric characteristics to realistic jackups, and much larger effects with extra leg steel. They concluded that the lattice leg affects leg loads during penetration in at least three ways (1) it restricts soil backflow into the region of the spudcan footprint, altering the size and shape of the cavity (2) it induces some sleeve (leg chord) friction resistance, and (3) it increases the extent of the influence zone beneath the spudcan footing. Based on the bound theorems of

plasticity theory (eg. Davis and Selvadurai 2005), the blocking effects on kinematics are consistent with an increase the net soil resistance to spudcan penetration.

Li et al (2017) presented a detailed suggested methodology for calculating the effect of lattice leg obstruction on cavity depth. The present paper proposes a simplified method for calculating the different effect of a lattice leg on penetration resistance.

Proposed simplified analysis

The component of penetration resistance of interest herein comes from shear on the leg chords and combined shear and normal forces on the braces. A simple method to account for this might be to define an equivalent circumference C for the leg, such that the sum F'_{leg} of all the vertical resistances experienced by the leg chords and braces, would be:

$$(1) \quad F'_{leg} = \int_{z_1}^{z_2} s_{u,dist} C dz$$

where $s_{u,dist}$ represents the disturbed shear strength of the soil as a function of depth z below the seafloor, z_1 is the shallowest depth at which there is effective contact between the disturbed soil and the leg elements, and z_2 is the depth to the lowest level of interaction between the lattice leg and the soil.

Taking account of this soil resistance on leg truss elements, the ultimate soil resistance F'_{net} in clay would be expressed in the following way:

$$(2) \quad F'_{net} = F'_{weightless} + F'_b + F'_{leg}$$

$$(3) \quad F'_{weightless} = \frac{\pi B^2}{4} N_c s_c d_c s_u$$

$F'_{weightless}$ is due to the bearing capacity of weightless clay, ignoring the surcharge effect. Houlsby and Martin (2003) give bearing capacity factors for this, as described in SNAME (2008) and ISO (2012). For clay soils the second term, F'_b , can be expressed conveniently as follows:

$$(4) \quad F'_b = \frac{\pi B^2}{4} (\gamma'_1 z_1 + \gamma'_s h_s)$$

The first part is the extra soil resistance that is available because of the absence of soil in the cavity of depth z_1 at the top of the soil column (Figure 1). The second is due to the absence of clay from the volume $V = \pi B^2 h_s$ occupied by the spudcan, where h_s is an equivalent spudcan height. In a “wished in place” approach, γ'_1 and γ'_s are average submerged unit weights of the soil that previously occupied the cavity and volume V respectively.

F'_b includes the effects that are modelled in SNAME (2008) and ISO (2012) as a combination of surcharge and “soil buoyancy” or “spudcan buoyancy” effects. The equations in the standards allow for an N_q value different from 1, whereas the concept of equivalent height herein assumes that $N_q=1$, which is appropriate for clay but not sand. A small additional effect can be associated with the displacement of soil by the leg chord and braces. However, the Appendix of this paper shows this is typically very small, and it has been neglected in the calculations below.

Initial estimate of the leg resistance effect

An initial estimate of the potential effect of leg resistance can be obtained by considering the case of an undrained shear strength that varies linearly with depth, from an initial value of zero at the mudline (in reality zero strength does not occur because the material would be eroded, instead the lowest mudline strengths are typically of the order of one or a few kPa).

In this simplified scenario, taking $z_1 = 0$ and z_2 equal to the depth D of the spudcan bearing area, the leg resistance evaluates to CD times the average disturbed shear strength over the embedded depth. The relative magnitude of the clay buoyancy term F'_b will reduce with increasing penetration once the spudcan has passed below the seafloor and the full cavity depth has been achieved. A convenient estimate of the significance of the leg resistance at deep penetrations can therefore be obtained as the following ratio:

$$(5) \quad \frac{F'_{leg}}{F'_{weightless}} \approx \frac{2}{\pi N_c s_c d_c S_{dist}} \frac{CD}{B^2}$$

where S_{dist} is the ratio of undisturbed shear strength divided by disturbed shear strength. In the present application, the clay through which the legs move is likely to be only partially remoulded, so an appropriate value of sensitivity might be less than the value measured using full remoulding.

The equation shows that $F'_{leg} / F'_{weightless}$ increases with depth ratio D/B , and with equivalent circumference ratio C/B . This is expected, because the comparison is similar to one between the side friction and end bearing for a pile. The side friction increases approximately with the square of depth if the undrained shear strength increases linearly with depth, while the end bearing increases approximately linearly in this kind of soil.

Calculating the equivalent circumference

A typical lattice leg consists of a number of identical lattice segments or “bays”. A bay will include leg chords, horizontal braces, and shear braces in the horizontal and vertical planes. To calculate the equivalent circumference, it is convenient to start by considering a general tubular in clay (Figure 2a). The tubular has length L and diameter b , at angle θ to the relative direction of flow of cohesive soil past it. The angle is zero for a horizontal brace and for a horizontal span breaker, but positive for diagonal braces. The following calculation assumes the tubular is fully rough, so that the maximum shear stress on its surface is the shear strength $s_{u,dist}$ of the partially disturbed clay.

The soil resistance forces per unit length of tubular are P'_v parallel to the relative motion and P'_x at right angles to this motion. These can be calculated from the resistances P'_n and P'_s in the directions normal and axially to the tubular (Figure 2b) as follows:

$$(6) \quad P'_v = P'_n \cos \theta + P'_s \sin \theta$$

$$(7) \quad P'_x = P'_n \sin \theta - P'_s \cos \theta$$

To calculate P'_n and P'_s , it is convenient to use a combined loading approach for a pile moving through clay (Achmus and Thieken 2011). An elliptical yield envelope is postulated (Figure 2c). For a flow direction that is parallel to the tubular ($\theta=90^\circ$), the shear resistance $P'_{s,max}$ per unit length

would be computed in the normal way for a pile penetrating clay, but using the relevant disturbed strength:

$$(8) \quad P'_{s,\max} = \pi b s_{u,dist}$$

An additional factor may be appropriate to account for over-consolidation ratio, perhaps similar to that used in pile capacity calculations in undisturbed soil (eg.API, 2012, Section 6.4.2), but this is not included herein. For soil flow perpendicular to the tubular, a formula for lateral loading of a pile or pipeline would be appropriate, so that:

$$(9) \quad P'_{n,\max} = N_{lat} b s_{u,dist} = \psi_{lat} P'_{s,\max}$$

where $\psi_{lat} = N_{lat} / \pi$. Fleming et al (1985) describe a flow mechanism for lateral loading of a pile which gives capacity factors N_{lat} of 9.14 for a smooth circular pile and 10.5 for a perfectly rough pile. API (2012) Section 6.8.2 gives a limiting value of 9 for a pile. Hence ψ_{lat} would be about 3.

There is contact between the tubular and the soil even in the absence of normal load. If the shear resistance is assumed to be largest when there is no lateral force, and vice versa, then the elliptical yield envelope might have the following equation:

$$(10) \quad \left(\frac{P'_n}{P'_{n,\max}} \right)^2 + \left(\frac{P'_s}{P'_{s,\max}} \right)^2 = 1$$

which is similar to that proposed by Achmus and Thieken (2011). In Figure 2c, point N represents a state of pure normal loading of the tubular, while point C represents pure shear. The tangent to the yield envelope at a general point can be obtained by differentiating this with respect to P'_n and P'_s . The following applies for a vector (dP'_n, dP'_s) along the tangent:

$$(11) \quad \frac{P'_n}{P'^{1/2}_{n,\max}} dP'_n + \frac{P'_s}{P'^{1/2}_{s,\max}} dP'_s = 0$$

Let v be the relative velocity of the tubular relative to the soil. The relative velocities in normal and shear directions are $v_n = v \cos \theta$ and $v_s = v \sin \theta$. If the normality rule of associated flow plasticity holds (eg.Davis and Selvadurai 2005), the flow vector will be normal to the above tangent, so that:

$$(12) \quad \tan \theta = \frac{v_s}{v_n} = -\frac{dP'_n}{dP'_s}$$

where (dP'_n, dP'_s) are incremental changes along the tangent. Note that normality is intuitively correct at the point C (shear load only, and shear displacement only) and at point N (normal force only, and displacement normal to the tubular in physical space). Using equation 11 to substitute for the tangent vector in the above equation, then re-arranging the result, gives:

$$(13) \quad \frac{P'_s}{P'_{s,\max}} = \left(\frac{P'_n}{P'_{n,\max}} \right) \frac{\tan \theta}{\psi_{lat}}$$

Using the envelope equation 10 to solve for the normal resistance per unit length, gives:

$$(14) \quad \frac{P'_n}{P'_{n,\max}} = \frac{\psi_{lat}}{\sqrt{\psi_{lat}^2 + \tan^2 \theta}}$$

Using these results in equation 6 to calculate the soil resistance in the direction of the motion of the tubular, and using the equations 8-9 to substitute for the maxima, gives:

$$(15) \quad P'_v = \pi b_{eff} s_{u,dist}$$

$$(16) \quad \frac{b_{eff}}{b} = \sqrt{\psi_{lat}^2 \cos^2 \theta + \sin^2 \theta}$$

b_{eff} might be interpreted as the effective diameter of the tubular for the purposes of a calculation for soil resistance to the given motion.

Figure 3 shows the variations of the factors with θ . For $\theta=0^\circ$, the ratio equals $b_{eff}/b = \psi_{lat}$, as expected. When $\theta=90^\circ$, $b_{eff}/b = 1$, as expected.

In a leg bay of height H_{bay} (Figure 1), there will be a number of tubulars. Let the i^{th} have length L_i and effective diameter $b_{eff,i}$. If there are no shielding or interference effects, net soil resistance will be the sum of resistances from all the tubulars, and average resistance per length of leg will be this divided by the bay height. Hence using equations 1 and 15:

$$(17) \quad C = \frac{\pi}{H_{bay}} \sum_{element} b_{eff,i} L_i$$

where C is the equivalent circumference. C/π would be an equivalent diameter.

Example calculations

Equivalent circumference C

Table 1 gives a calculation for the equivalent circumference for a 4-chorded leg with K-bracing on a large jackup (see also Figure 1). The spudcan diameter has been taken as $B=15$ meters, the leg width has been taken as $B_{\text{leg}}=10$ meters, and the bay height has been taken as $H_{\text{bay}}=5$ meters.

The leg chords are typically constructed around the rack that is used for jacking, and are far from circular in section (SNAME 2008; ISO 2012). The present calculations assume an equivalent diameter of 0.75 meters. The chords are vertical, so the angle θ (Figure 2(a)) for a chord is 90° . Equation 16 then gives $b/b_{\text{eff}}=1$, and the product of the chord length per bay, the number of chords, and the effective diameter comes out as 15 meters. For a horizontal brace, $\theta=45^\circ$, and the effective diameter evaluates as larger than for a chord, even though the actual diameter is smaller. The product of length, number, and effective diameter is greater than for the chords. The product for the diagonal braces is also greater. Even the relatively thin span breakers are more important than the chords in these calculations, as regards soil resistance to vertical leg motions.

The result is that the sum of the products of the factored diameters is 114.3 m^2 , equivalent to an effective area of $114.3 \times \pi = 359 \text{ m}^2$ for a bay of height 5 meters, or an equivalent circumference of $359 / 5 \approx 72$ meters. The C/B ratio is 4.8, and the $C/(\pi B)$ ratio is 1.5.

Leg resistance calculations

Figure 4 shows an example of the effect of leg resistance on the net ultimate leg load as a function of the depth of the spudcan bearing area below the mudline. Spudcan diameter has been taken as 15 meters. The cone angle is taken as 150° , giving a single cone base of height $7.5 \times \tan 15^\circ \approx 2$ meters. The maximum bearing area occurs at a tip penetration of 2 meters. Equivalent spudcan height for the shape shown is $h_s=3$ meters. Equivalent circumference for the leg has been assumed to be as 72 meters, as calculated above.

Clay submerged unit weight has been taken as uniform 7 kN/m^3 . This is a simplification, as actual values can typically vary from around 4 kN/m^3 at the seafloor in a normally consolidated deposit, to a little more than 7 kN/m^3 at depth. Undrained shear strength has been assumed to vary linearly from 3.6 kPa at the surface, increasing at 1.2 kPa per meter depth. Using Hossain and Randolph's (2009) method as described in ISO (2012), the maximum cavity depth is 3 meters.

The leftmost curve in Figure 4 is for the sum $F_{weightless}^I + F_b^I$, without leg resistance effects. Houlsby and Martin's (2003) method has been used to determine the end bearing due to the spudcan, with a surface roughness coefficient of 0.4 for the spudcan, as recommended as a default value in the standards. For the first 6 meters of penetration, F_b^I is increasing. At this point, the full cavity depth has formed above the spudcan, and subsequent penetration involves clay squeezing around the spudcan in a way that keeps the cavity depth constant. (In practice the cavity may exhibit instability, or may be deeper if the leg bracing is sufficient to provide support, see Menzies and Roper 2008; Li et al (2012, 2017) and Li (2014). However this is ignored in the present calculation).

The rightmost curve represents the largest possible effect of leg resistance, calculated for a sensitivity of 1, equivalent to no reduction of soil strength in the region above the spudcan. As expected, the difference between this and the curve without leg resistance increases approximately as the square of the depth. At 40 meters depth, the leg resistance is almost equal to the bearing resistance, so the total resistance is almost twice the value from end bearing capacity alone.

In practice, an operative sensitivity of around 2 might be more usual. Typical laboratory values can often be larger than this, but as noted earlier, the operative value for the present calculation is expected to be less than laboratory value. The curve drawn for $S_{dis}=2$ shows a leg resistance that is about 20% of the uncorrected resistance at 20 meters penetration, and 50% at 40 meters depth. This would represent an important effect in practice.

For a very sensitive soil, the operative sensitivity for the present analysis might perhaps reach 5. The curve for this shows a leg resistance effect of about 10% at a depth of 20 meters, and 20% at 40 meters.

Discussion

Practical achievements of this paper

The calculations proposed above are for an extra component of soil resistance that does not appear to have been accounted for in the present SNAME (2008) or ISO (2012) standards. The example calculations confirm that the extra component can be small if spudcan penetrations are much less than a spudcan diameter. The extra component can be significant for larger penetrations.

These results are in broad agreement with centrifuge model tests and numerical work by Li et al. (2017, 2018), in which model tests showed similar leg resistance effects. That work also shows that a more complex kinematics can occur in some instances, and some effects of this are discussed in the Appendix to the present paper.

It is unclear whether previous calibration and validation exercises have accounted for the soil resistance along the legs. Menzies and Roper (2008) found that predictions using Houlsby and Martin's (2003) factors $N_{cs}d_c$ were almost always less than measured leg loads. It seems feasible that the difference may have been due to soil resistance on the leg truss members.

The geometric information needed to calculate leg resistance effects is readily available in jackup as-built drawings, so there would be no difficulty in implementing the present method immediately. In addition to the problem of penetration during preloading, resistance effects during spudcan extraction may also occur, for which a similar calculation method may apply.

Validation

The previous field and model tests and numerical analyses mentioned above were not designed to validate the present method. Specific field and model tests to do so in future would be recommended, with a jackup leg instrumented to measure the contribution of soil resistance along the leg separately from the end bearing contribution of the spudcan. The field data by Menzies and Roper (2008) also revealed small increases in spudcan penetration over time at constant load. They suggested that this might be due to cavity collapse, water void effects, or time-dependent clay strength. A simple calculation model for the latter is proposed by Li et al (2018) and Yi et al (2018).

A key parameter for the analysis of the leg resistance is the disturbed shear strength in the “backfill” clay above the spudcan, or equivalently the operative value of sensitivity. As noted earlier, the operative sensitivity value is likely to be less than the value measured in the laboratory using full remoulding. Model and field tests may help to clarify this.

Caveats and limitations

The proposed methodology has involved relatively simple assumptions about the relative motions of the leg elements and soil. Possible shielding effects of one leg element on another have not been considered. No material or load factors have been included in the analysis, but may be appropriate for design or assessment purposes. The present calculations have not accounted for effects of different surface roughnesses of leg chords and braces, or for effects of over-consolidation ratio on available strength. Results by Li (2014) suggest there may be an additional friction fatigue effect that reduces the extra resistance (equivalent to increasing S_{dist}).

A more complex assessment might be needed if a leg is installed in a footprint from a previous jackup deployment. Borings performed in old footprints typically show disturbed strengths that are a little larger than the fully remoulded strengths measured in the laboratory. A further complication will arise if water jetting has been used previously to free a spudcan during extraction. Jetting can introduce irregular water voids, and can lead to softening of the surrounding soil over time, typically producing extra penetration for a subsequent rig at the same site (Kohan et al. 2015).

The calculations herein were for a uniform soft clay soil profile. Sand seams and layers would be expected to complicate the picture, including by altering the kinematics and so altering the leg resistance forces. Punch-through typically involves a plug of sand being pushed downwards as the spudcan enters a thin sand layer (Hossain et al. 2004). The flow-around mechanism (Figure 1) might be expected to switch off as this happens, being blocked by the sand. One effect could be to reduce the leg resistance, thereby contributing to the severity of the punch-through.

Concluding remarks

This paper explored a contribution to soil resistance that does not appear to be accounted for in the present SNAME (2008) and ISO (2012) standards for jackup site specific assessment.

A simplified calculation methodology was presented, based on familiar geomechanics of soil resistance and flow around tubulars. The analysis suggested that the contribution can be significant for spudcan penetrations of one spudcan diameter or more into soft, essentially normally consolidated clay. The contribution will be less important for stronger soils where penetrations are typically less than one spudcan radius.

The calculation results are broadly consistent with the combined centrifuge and numerical study by Li (2014) and Li et al. (2017, 2018). However the centrifuge tests were not designed specifically to validate the proposed method. Specific tests to do this would be recommended. Field tests with instrumented legs may also be useful.

The present proposals are limited by the assumption of simplified kinematics in the disturbed zone, whereas centrifuge and numerical studies tend to confirm a more complex picture (Li 2014). There is also a need to determine an appropriate value for sensitivity for the purpose of the leg resistance analysis. Other complications that are not well understood can also occur in the field, including time-dependent penetration at constant load, and strength reductions in previous jackup footprints, and future research in these areas could also be useful.

Acknowledgments

The fourth author would like to acknowledge scholarship funding from the National University of Singapore and post-doctorate funding from Hohai University. The valuable comments of the reviewers of the first draft are also gratefully acknowledged.

References

- Achmus, M., and Thieken, K. 2011. Behaviour of piles in combined axial and lateral loading. *Proc Frontiers in Offshore Geotechnics II*, eds S.Gourvenec and DJ White, CRC Press
- API. 2000. *Recommended Practice for Planning, Designing and Installing Fixed Offshore Platforms – Working Stress Design*, API RP2A, 21st edition, and subsequent updates, American Petroleum Institute
- Bennett Associates 2010. *LeT 116C Jack-Up, KFELS B-Class Jack-Up. Phase 2 benchmarking of ISO 19905-1*. Report No: 709-J-IO-RPT-001 prepared for the ISO Benchmark Panel
- Bienen, B., and Cassidy, M.J. 2013. Set Up and Resulting Punch-Through Risk of Jack-Up Spudcans during Installation. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 139(12)
- Brennan, R., Diana, H., Stonor, R.W.P., Hoyle, M.J.R., Cheng, C.-P., and Roper, R. 2006. Installing jackups in punchthrough-sensitive clays. Paper OTC 18268, *Offshore Technology Conference*, Houston
- Cassidy, M.J., Martin, C.M., and Houlsby, G.T. 2004. Development and application of force resultant models describing jack-up foundation behaviour. *Marine Structures*, 17(3-4), 165-193
- Davis, R.O., and Selvadurai, A.P.S. 2005. *Plasticity and Geomechanics*. Cambridge University Press
- Dean, E.T.R. 2009. *Offshore Geotechnical Engineering – Principles and Practice*. Thomas Telford.
- Dier, A., Carroll, B., and Abolfathi, S. 2004. *Guidelines for jack-up rigs with particular reference to foundation integrity*. UK HSE Research Report 289, HSE Books
- Endley, S.N., Rapaport, V., Thomson, P.J., and Baglioni, V.P. 1981. Prediction of jackup rig footing penetration. Paper OTC 4144, *Offshore Technology Conference*, Houston
- Fleming, W.G.K., Weltman, A.J., Randolph, M.F., and Elson, W.K. 1985. *Piling Engineering*. Blackie Academic & Professional
- Frieze, T. 2001. *SNAME 5-5B WSD 0: Comparison with SNAME 5-5A LRFD and the SNAME 5-5A North Sea Annex*. Offshore Technology Report 2001/001 prepared by PAFA Consulting Limited for the UK Health & Safety Executive, HSE Books
- Gaudin, C., Clukey, E., Garnier, J., and Phillips, R. 2010. New frontiers for centrifuge modelling in offshore geotechnics. *Frontiers in Offshore Geotechnics II*, eds S Gourvenec and DJ White, CRC Press, 155-188

- GL Noble Denton. 2010. *ISO Phase 3 Benchmarking, ISO 19905-1 (DIS), Validity Check, KFELS B class*. Report No.25316
- Hossain, M.S., Hu, Y., and Randolph, M.F. 2004. Bearing behaviour of spudcan foundation on uniform clay during deep penetration. Paper 51153, *Proc Int Conf Offshore Mechanics and Arctic Engineering*, OMAE 2004, Vancouver
- Hossain, M.S., Hu, Y., Randolph, M.F., and White, D.J. 2005. Limiting cavity depth for spudcan foundations penetrating clay. *Geotechnique* 55(9), 679-690
- Hossain, M.S., Randolph, M.F., Hu, Y., and White, D.J. 2006. Cavity stability and bearing capacity of spudcan foundations on clay. Paper OTC 17770, *Offshore Technology Conference*, Houston
- Hossain, M.S., and Randolph, M.F. 2009. New mechanism-based design approach for spudcan foundations on single layer clay, *ASCE Journal of Geotechnical and Geoenvironmental Engineering*. Vol. 135, No. 9, pp. 1264-1274
- Hossain, M.S., Zheng, J., Menzies, D., Meyer, L., and Randolph, M.F. 2014. Spudcan Penetration Analysis for Case Histories in Clay. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 140 (7)
- Houlsby, G.T., and Martin, C.M. 2003. Undrained bearing capacity factors for conical footings on clay. *Geotechnique* 53 (5), 513–520
- Hu P., Stanier S.A., Cassidy M.J., and Wang, D. 2014. Predicting Peak Resistance of Spudcan Penetrating Sand Overlying Clay. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 140(2)
- ISO. 2012. International Standard ISO 19905-1. *Petroleum and natural gas industries - Site-specific assessment of mobile offshore units - Part 1: Jack-Ups*. International Standards Organization
- Kohan, O., Bienen, B., Gaudin, C., and Cassidy, M.J. 2015. The effect of water jetting on spudcan extraction from deep embedment in soft clay. *Ocean Engineering* 97, 90-99
- Koole, T. 2015. *Modern Jack-Ups and their Dynamic Behaviour - Investigating the trends and limits of moving into deeper waters*. MSc thesis, Delft University of Technology
- Li, Y.P. 2014. Lattice leg effects on the penetration and bearing behaviour of spudcan foundation. PhD thesis, National University of Singapore

- Li, Y.P., Lee, F.H., Goh, S.H., Yi, Y.T., and Zhang, X.Y. 2012. Centrifuge Study of the Effects of Lattice Leg on Penetration Resistance and Bearing Behavior of Spudcan Foundations in NC Clay. Paper OMAE2012-83137, *ASME International Conference on Offshore Mechanics and Arctic Engineering*, Volume 4: Offshore Geotechnics; Ronald W. Yeung Honoring Symposium on Offshore and Ship Hydrodynamics, 79-86
- Li, Y.P., Yi, J.T., Lee, F.H., Goh, S.H., Liu, Y., Yang, Y., Zhang, X.Y., and Wu, J.F. 2017. Effects of the lattice leg on cavities and bearing capacity of deeply embedded spudcans in clay. *Geotechnique* 67 (1), 1-17
- Li, Y.P., Yi, J.T., Lee, F.H., Goh, S.H., and Hu, J. 2018. Effect of lattice leg and sleeve on the transient vertical bearing capacity of deeply penetrating spudcans in clay. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 144(5).
- Mahanta, R. 2016. Punch-through analysis of jack-up rig at a site off the East coast of India – a case study. *Indian Geotechnical Conference IGC2016*, IIT Madras, Chennai India
- Menzies, D., and Roper, R. 2008. Comparison of Jackup Rig Spudcan Penetration Methods in Clay. Paper 19545, *Offshore Technology Conference*, Houston
- Murff, J.D. 1996. The geotechnical centrifuge in offshore engineering. Paper OTC 8265, *Offshore Technology Conference*, Houston
- Randolph, M.F. 2013. Analytical contributions to offshore geotechnical engineering. 2nd McClelland Lecture: *Proc. 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering*, Paris
- Randolph, M.F., and Gourvenec, S. 2011. *Offshore Geotechnical Engineering*. Spon Press
- Siciliano, R.J., Hamilton, J.M., Murff, J.D., and Phillips, R.J. 1990. Effect of Jackup Spud Cans on Piles. Paper OTC 6467, *Offshore Technology Conference*, Houston
- SNAME. 2008. *Recommended Practice for Site Specific Assessment of Mobile Jackup Units*. Technical and Research Bulletin 5-5A, Society of Naval Architects and Marine Engineers
- Vasquez, J.H., Michel, R.P., Alford, J.H., Quah, M., and Foo, K.S. 2005. *Jack up units - a technical primer for the offshore industry professional*. Bennett & Associates
- Wong, P.C., Templeton, J.S., Purwana, O.A., Hofstede, H., Cassidy, M.J., and Martin, C.M. 2012. Foundation Modeling and Assessment in the New ISO Standard 19905-1. Paper OTC 23521, *Offshore Technology Conference*

Yi, J.T., Li, Y.P., Bai, S., Fu, Y., Lee, F.H., and Zhang, X.Y. 2018. A simple effective stress approach for modelling reate-dependent strength of soft clay. Paper OMAE-16-1074, *Journal of Offshore Mechanics and Arctic Engineering*, 140(4)

Young, A.G., Remmes, B.D., and Meyer, B.J. 1984. Foundation performance of offshore jack-up drilling rigs. *ASCE Journal of Geotechnical Engineering* 110(7), 841-859.

Figure Captions

Figure 1. Spudcan and leg with deep penetration into soft clay: (a) plan cross-section and (b) elevation. Soil deformation mechanisms sketched based on Siciliano et al (1990) and Hossain et al (2004, 2006).

Figure 2. Proposed calculation for soil resistance against translation of an inclined tube (a) forces parallel and normal to motion (b) forces normal and axial to tube (c) yield envelope and flow vector.

Figure 3. Variations of factors with angle θ .

Figure 4. Results for example calculations.

Appendix

Alternative mechanisms

The calculation presented in the main text produce an upper bound estimate of the resistance that comes from material that is above the spudcan. It is therefore appropriate to consider whether there may be other feasible mechanisms that might produce lower upper bounds.

One such alternative would be a mechanism in which a cylindrical soil plug with the same diameter as the spudcan slides downwards at the same rate as the spudcan. In this mechanism, the spudcan and soil plug act like a large-diameter pile, and the relative movements between the truss elements and the soil that are considered in the main text would not occur. There would be shear resistance on the boundary between the plug and the disturbed soil surrounding it. The calculation of this resistance, denoted here as F_1' , would be similar to equation 1 but with C replaced by the plug circumference πB :

$$(18) \quad F_1' = \int_{z_1}^{z_2} s_{u,dist} \pi B dz$$

The downwards motion of the plug would inhibit soil from flowing around the spudcan from below it to above it. One possibility is that this volume movement would instead create an upwards motion of disturbed soil in an annulus of external radius nB , where n is some number likely to be a little greater than 1.

Let v_s be the downwards velocity of the soil plug and spudcan. Then compatibility indicates that the average upwards velocity of the soil in the annulus would be $v_s / (n^2 - 1)$. This will then induce a shear force F_2' between the outside of the annulus and the surrounding intact soil. Assuming that the disturbed strength dominates this, and noting that the annulus diameter would be n times the plug diameter, gives $F_2' = nF_1'$. The work equation for the mechanism would then be as follows:

$$(19) \quad F'_{net} v_s = (F'_{weightless} + F'_b) v_s + F'_1 \left(v_s + \frac{v_s}{n^2 - 1} \right) + F'_2 \frac{v_s}{n^2 - 1}$$

where the second brackets gives the relative velocity of the soil plug relative to the soil in the annulus. Cancelling v_s , substituting for F'_1 and F'_2 , and using equation 1 to simplify, gives:

$$(20) \quad F'_{net} = F'_{weightless} + F'_b + F'_{leg} \frac{nB}{(n-1)C}$$

Comparing this with equation 2 shows that this plugging mechanism will provide a lower upper bound if the equivalent circumference is greater than $n/(n-1)$ times the spudcan diameter. Work by Siciliano et al (1991) and others suggests that n will typically be less than 2. Hence the plugging mechanism would be expected to occur preferentially only if the truss elements are relatively large.

In practice, there may be a more complicated interaction between leg elements and soil, and the actual mechanism that applies may be in between the plugging mechanism described above and the mechanism discussed in the main text, which might be regarded as a coring mechanism analogous to a coring pile.

Li et al (2014, 2017) show that it can be possible for a mixture of the plugged and coring mechanisms to occur. In some analyses, the cavity above the spudcan footing became stable at a depth of 1.2 times the spudcan diameter. For the upper part of the lattice leg, soil movements outside the lattice leg were inclined (close to the ground surface), flowing towards the lattice leg. At larger depths, soil movement outside lattice leg was generally downward, indicating that the lattice was dragging soil downwards. In the lower part of the lattice leg, the soil beneath spudcan footing back-flowed towards the lattice leg, giving elements of the coring mechanism just above the spudcan. In some analyses, plug movement was confined only to a central core within the lattice, allowing relative motion of the chords and braces through the disturbed soil as in the mechanism described in the main text. These effects depend very much on the relative sizes of the leg truss elements and core, and on the over-consolidation ratio of the original soil.

For these reasons, it is suggested that the coring mechanism described in the main text gives one limiting case, and the plugged mechanism described above gives another. These cases are readily calculable in practice without detailed finite element work. The limiting case giving the lowest leg load would be an effective lower bound. The actual mechanism that occurs will typically have characteristics of both of the limiting cases, and further work may be possible to determine practical criteria and formulae which can provide more accurate estimates of this.

Clay buoyancy effect due to leg in soil

As noted in the main text, there is a small buoyancy effect from the volume of clay displaced by leg chords and braces. The effect arises if the effective weight W'_{back} of backfill is computed ignoring the displaced volume of these elements. If the volume of the elements is $V_{leg,bay}$ per bay height, then the buoyancy force $F'_{b,leg}$ would be estimated as:

$$(21) \quad F'_{b,leg} = \frac{V_{leg,bay}}{H_{bay}} \int_{z_1}^{z_2} \gamma' dz$$

For the dimensions given in Table 1, $V_{leg,bay} / H_{bay}$ is about 4 m². So, for a bearing area penetration of 7.5 meters, this force is about (6.5 – 3.0) x 7 x 4 kN ≈ 0.1 MN. For a penetration to 37.5 meters, the force is about (37.5 – 3.0) x 7 x 4 kN ≈ 1 MN. These values are significantly smaller than the corrections due to soil resistance.

Table 1. Example calculations for equivalent circumference C

Assumed lateral coefficient N_{lat} 9				Bay height H_{bay} 5 meters			
Item	Diameter b , mm	Angle θ degrees	b_{eff}/b	b_{eff} mm	Length L , m	No, N	$N \cdot L \cdot b_{eff}$ m^2
Leg chord	750	90	1.00	750	5	4	15.0
Horizontal brace	350	0	2.86	1003	10	4	40.1
Diagonal brace	350	45	2.15	751	7	8	42.1
Span breaker	250	0	2.86	716	6	4	17.2
Sum, m^2							114.3
Equivalent diameter (sum divided by bay height), meters							22.9
Equivalent circumference, meters							71.8

Figure 1. Spudcan and leg with deep penetration into soft clay: (a) plan cross-section and (b) elevation. Soil deformation mechanisms sketched based on Siciliano et al (1990) and Hossain et al (2004, 2006)

Figure 2. Proposed calculation for soil resistance against translation of an inclined tube (a) forces parallel and normal to motion (b) forces normal and axial to tube (c) yield envelope and flow vector

Figure 3. Variations of factors with angle θ

Figure 4. Results for example calculations