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JACK-UP INSTALLATION ON AN UNEVEN SEABED: RECOMMENDATIONS FROM MODEL TESTING IN OVERCONSOLIDATED CLAY

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ABSTRACT

This paper presents results of a laboratory testing program employing a reduced-scaled model of a three-legged jack-up to investigate the influence of an adjacent footprint on spudcan installation. This study focused on the installation of the full jack-up with a single leg located adjacent to a surface discontinuity. This contrasts previous studies that focused on the behavior of a single leg model and aims to account for the coupled interaction of the three legs and hull. The investigation was conducted using a 1:200 model scale jack-up designed to represent an average commonly used field jack-up. It was fully instrumented for leg bending and axial force measurement, and allowed unconstrained horizontal motion and rotation in the plane of foundation-footprint offset. Installation was performed at foundation-footprint centerline offsets of 0.75, 0.89, and 1.0 times the footprint diameter in overconsolidated kaolin clay adjacent to three different footprint types. The three footprint types - spudcan generated, a similarly shaped vertical walled auger generated, and shallow slope – were used to analyze separately the effect of shape and soil disturbance.

1 INTRODUCTION

Mobile jack-up rigs are increasingly being used in more challenging situations, such as in deeper water and at sites requiring multiple work-overs of fixed production platforms. Several notable jack-up failures in the last decade have substantially impacted project costs and human safety, especially at sites where installation and preloading have been affected by an uneven seabed and unexpected soil conditions (SNAME 2002). A situation encountered frequently by jack-up operators is the reinstallation of jack-up units near pre-existing footprints. Footprints in soft clay consist of a zone of heavily remolded soil extending up to 0.8 diameters from the centre of the spudcan. Footprint shape and depth depend on several factors, including spudcan geometry, soil strength characteristics, and the extraction method for the previous installation. Jack-up leg reinstallation near existing footprints having an uneven surface and soil strength heterogeneity across the spudcan diameter results in an eccentric reaction at the spudcan base, unknown bending and horizontal forces in the jack-up leg, and a tendency for the spudcan leg to slide towards the centre of the existing footprint. Such movements and forces may introduce imbalanced loading in the leg chords, producing a racking effect in the bracing (commonly referred to as RPD), which may subsequently cause their failure in compression.

In response to this issue, several laboratory and centrifuge testing programs using models of a single leg/spudcan system representative of commonly used field jack-ups have been conducted to investigate spudcan-footprint offsets that correlate with critical leg bending and displacement. The single leg behavior was investigated by monitoring: i) bending and horizontal force developed in the leg upon reinstallation assuming a rigid connection at the top of the leg (Cassidy et al. 2008; Gan et al. 2008), or ii) bending and the overall trajectory of the leg assuming free horizontal displacement at the top of the leg (Gaudin et al. 2007). These studies focused mainly on identifying the critical offset distance between the centre of the footprint and spudcan that generated maximum bending and horizontal force in the leg and which may compromise the structural integrity of the leg and the leg-hull connection.

In contrast, this paper presents a series of laboratory tests performed on a 1:200 reduced scale model of a typical jack-up unit, where the three legs were installed simultaneously in overconsolidated clay with the forward leg offset from a footprint formed by spudcan installation or artificially carved into virgin soil and the two rear legs installed in virgin soil. The goals of this study were to investigate: the i) effect of offset distance and ii) influence of footprint geometry and strength heterogeneity on development of bending and force in the leg interacting with the footprint while accounting for the coupled interaction of the three legs and hull.

2 MODEL JACK-UP

The model-scale jack-up used is described in detail by Byron-Brown (2004) and Bienen et al. (2008). The 1:200 model jack-up was scaled in stiffness and dimension to represent an average jack-up used in industry, with the objective of maintaining consistency in overall jack-up behavior during loading. The model is similar to a prototype field jack-up having a leg length of 89 m and spudcan diameter of 10 m when scaled by 200. Jack-up details, such as ballast tanks or drilling equipment, were not considered in the design.

A new hull was specifically created for this investigation to accommodate attachment of the dual loading and hull rotation measurement device. The 25 mm thick hull was machined from a solid block of aluminum into an equilateral triangle with truncated triangle corners. The jack-up legs are made of 25 mm diameter aluminum tubing having a 3 mm wall thickness and 445 mm length. The legs are rigidly threaded to both the hull and spudcan foundations creating fixed connections. The 50 mm (10 m prototype) diameter circular, aluminum spudcans are similar in shape to the MOD V "A" spudcan. They are threaded to the legs and have a smooth, untreated finish. Spudcan spacing (Table A) was slightly different from the original spacing reported by Bienen et al. (2008), which was replicated from an actual prototype jack-up, due to small modifications in the hull configuration for this testing series. Overall stiffness values for the jack-up hull and legs are presented in Table 1.

The overall height of the jack-up with the spudcans is 486 mm. With the hull rotation sensor and loading mechanism, the height is 574 mm. A portal frame was built to accommodate the height of the model jack-up over soil container. The setup of the actuator, model jack-up, portal frame, and sample container is shown in schematic form in Figure 1.

2.1 MOTION AND LOADING

A two-dimensional actuator enabling both vertical and horizontal displacement at a maximum rate of 3.1 mm/s was used to operate the model jack-up (and the soil characterization tools). Motion is provided by two DC servo-motors driving vertical and horizontal lead screws, where load or displacement control is achieved with LabView software.

Table 1. Jack-up properties (after Bienen et al 2008).

Characteristics	Jack-up Model
Hull length overall	167 mm
Hull width overall	193 mm
Depth of hull	25 mm
Total length of legs	445 mm
Ctr. of Fwd Leg to Ctrline of Aft Legs	117 mm
Ctr. to Ctr. of aft legs	135 mm
Spudcan Diameter (B)	50 mm
Cross Sectional Area of Leg, A_{leg}	207.3 mm^2
Second Moment of Area of Leg, I_{leg}	12777.6 mm^4
E_{leg} (aluminium 6060 tubing)	69000 N/mm^2
EI	8.82×10^8 N.mm^2
EA	14.3×10^6 N

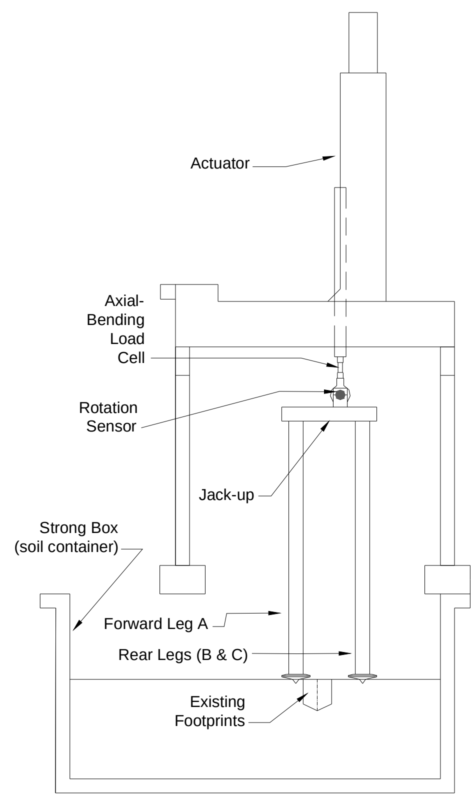

Figure 1. Schematic of jack-up with loading configuration.

2.2 JACK-UP INSTRUMENTATION

Axial load and bending were measured for each of the legs using full bridge strain gauges. Bending gauges were installed on the legs for measurement of bending in the plane of horizontal motion and rotation 40 mm below the hull and 27 mm above the spudcan levels. Horizontal and vertical displacements were measured at the hull level by encoders located on the two axis of the actuator, to monitor the displacement of the overall jack-up. Additionally, hull rotation (e.g., tilt) was measured by an optical incremental encoder located 20 mm above the hull. A data acquisition and accompanying control software programmed in LabView was used to collect instrument data and control displacements.

It is expected that the reinstallation of the forward leg nearby a footprint will result in a lateral motion of the overall jack-up. In order to ensure free horizontal displacement of the jack-up while applying vertical load, a specific axial-bending load cell, was designed 'in-house'. This load cell was installed above the hull rotation sensor (Figure 2) for the purpose of: i) cancelling the effect of bending caused by jack-up rotation, and ii) measuring bending in the overall jack-up. Measured axial loads from this load cell indicated the total load applied to the jack-up and were used only to validate measured leg loads using static equilibrium. Measured bending was used for servo control of horizontal motion of the actuator, where the actuator was controlled to move laterally in the plane of the footprint offset to maintain a constant bending moment of zero during jack-up penetration. This effectively induced a free lateral displacement condition for the jack-up during installation. Servo control of horizontal motion was activated only after achieving a total axial load of 5 N and touchdown of all three legs to ensure accurate footprint offset and prevent false motions. When rapid changes in the system led to failure of servo control of bending and horizontal motion, the actuator achieved maximum speed. At this time, the jack-up was considered unstable and the test terminated.

Axial-bending load cell

Rotation sensor

Figure 2. Jack-up loading and rotation mechanism.

2.3 DATA PROCESSING

All forces and displacements were translated to the spudcan level load reference point (L.R.P.), defined as the elevation of the maximum diameter of the spudcan first in contact with the soil during penetration (Figure 3). Displacement of the L.R.P. was determined from actuator motion, hull rotation, and jack-up geometry. Axial load (V) at the L.R.P. was determined as the measured axial load. Assuming cantilever leg behavior and bending theory, bending moments measured at the two locations on each leg were used to determine bending moments at both the L.R.P. and the connection with the hull. Resulting vertical (V) and horizontal (H) forces and moments (M) were normalized by a function of the intact undrained shear strength (s_u) at spudcan depth, spudcan area (A), and/or spudcan diameter (B).

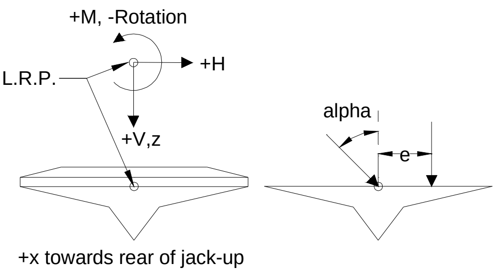

Figure 3. Adopted sign convention for data processing.

3 SOIL PROPERTIES

Testing was performed in overconsolidated kaolin clay, reconstituted from a slurry at an initial water content of 120%. The slurry was placed into a rectangular strongbox having 650 mm length, 390 mm width, and 325 mm height, over a 10 mm thick, saturated sand drainage layer. Each sample was consolidated with double drainage under a hydraulic press with pressures applied incrementally from 12.5 kPa to a final pressure of 100 kPa, resulting in an overconsolidated ratio ranging from 450 at 10 mm depth to 22 at the sample bottom. Samples remained covered with thin plastic film to prevent swelling except during testing. Each sample provided two testing lifts of 90-100 mm soil depth.

Prior to jack-up installation, undrained shear strength of the kaolin clay was determined from T-bar penetrometer tests (Stewart and Randolph, 1991). The T-bar, 5 mm in diameter and 20 mm long, was penetrated at 1 mm/s to ensure undrained behavior. Undrained shear strength, s_u, was determined by:

$$s_u = \frac{q_{T-bar}}{N_{T-bar}} \qquad (1)$$

where, $q_{T\text{-}bar}$ is the measured penetration bearing resistance and $N_{T\text{-}bar}$ is the T-bar bearing factor. $N_{T\text{-}bar}$ = 10.5 was adopted, which has been confirmed through experimental calibration on a range of material types, at various stresses and stress histories (Randolph et al., 2005). The resulting T-bar s_u profiles for the intact kaolin are presented in Figure 4.

Figure 5 illustrates the effect of spudcan installation on s_u, which influences the behavior of the jack-up during subsequent installation adjacent to the resulting footprints. The gray-scale contours illustrate $s_{u\text{-disturbed}}$ measured after spudcan penetration normalized by undisturbed s_u from the same depth at lateral distances of x/B = 2 from the footprint center (B = spudcan diameter). T-bar tests were spaced at 4 times the T-bar diameter to minimize the influence of testing on adjacent locations. The time between footprint generation and T-bar testing ranged from one to three days. It was assumed that retarded time-consolidation behavior at 1g resulted in little change in measured s_u during this time.

The most disturbed soil exists in areas directly affected by spudcan penetration. For shallow depths at direct penetration locations, $s_{u\text{-disturbed}}/s_{u\text{-intact}} < 0.3$. This is similar to $s_{u\text{-disturbed}}/s_{u\text{-intact}} = 0.26$ for completely remolded soil as determined from cyclic T-bar tests. Results show $s_{u\text{-disturbed}}/s_{u\text{-intact}}$ increases from 0.7 to nearly 1.0 for increasing depth greater than the maximum penetration depth. Generally, the greatest disturbance ($s_{u\text{-disturbed}}/s_{u\text{-intact}} < 0.7$) occurs laterally within a distance of x/B = 1.0 from the footprint centerline.

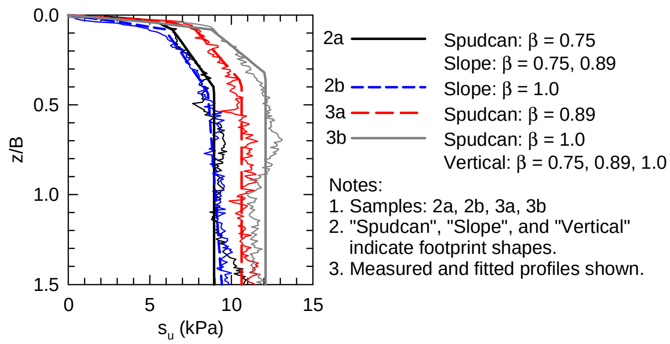

Figure 4. Undrained shear strength of kaolin samples.

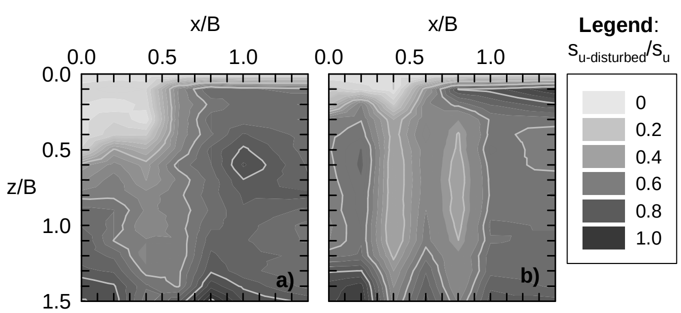

Figure 5. Depth contour plot from footprint center at the surface (0,0) of s_u measured after spudcan installation ($s_{u\text{-disturbed}}$) normalized by intact s_u for samples a) 2a and b) 3b.

4 FOOTPRINTS AND OFFSETS

Footprints were generated either by spudcans during full jack-up penetration or by using a sloped or vertical-walled auger. The sloped auger was designed to create a 14º slope footprint, which is similar to i) the 13º slope at the underside of the spudcan and ii) dimensions typically reported for in situ seabed footprints after spudcan installation and extraction in normally consolidated clay. Actual measurements made in situ and in centrifuge model tests typically have a diameter and depth up to twice and half that of the spudcan diameter, respectively. The vertical-walled auger was manufactured to create a footprint similar in shape and diameter (55 mm) to that created by the spudcans during full jack-up penetration in the study soil. Augered footprints have a depth of 12.5 mm (or 0.25 times B), which correlates with the average footprint depth upon extraction of the forward spudcan after full jack-up penetration in virgin soil and depths from Cassidy et al (2008).

Figure 6 presents a schematic of the offset ratios (β) employed in this investigation. β values were chosen based on the results of studies by Stewart and Finnie (2001) and Gaudin et al. (2007), which similarly provided for unrestrained horizontal motion during installation, albeit for single spudcan-leg systems at various offsets in clay during centrifuge testing. Stewart and Finnie (2001) determined β = 0.75 is the critical offset for overconsolidated clay. Gaudin et al. (2007) found the critical horizontal displacement ratio (x/B) occurred for offset installations between β = 0.75 and β = 1.0 in normally consolidated clay. Both confirm a change in behavior occurs for a single spudcan-leg system at offset installations between β = 0.75 and β = 1.0; where β ≤ 0.75 tests showed a reduction in leg bending moment to a negative maximum (bending away from the existing footprint) and β ≥ 1.0 tests showed a decrease followed by an increase to a positive maximum leg bending (bending into the existing footprint). For the purpose of this investigation using a full model jack-up, β values of 0.75, 0.89, and 1.0 were chosen to: i) bracket values shown to be critical in previous single leg investigations, and ii) investigate changing behavior between these two previously reported critical offsets.

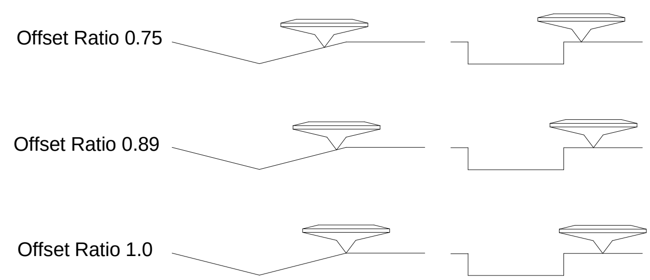

Figure 6. Schematic of spudcan-footprint offsets.

5 TEST PROGRAM

Installation was performed at a rate of 1 mm/s penetration with no more than one hour between footprint formation and installation of the jack-up at the various offset ratios. Reference installations of the full jack-up were performed in undisturbed soil, which created spudcan footprints for offset testing. Three tests each featured installation of the forward leg of the jack-up at the three β values forward of a footprint created i) by spudcan installation and ii) using the vertical-walled auger with rear legs penetrating virgin soil. These tests were performed to investigate jack-up response to a footprint of similar shape with and without the effect of s_u heterogeneity. Additionally testing was performed adjacent to the 14º slope footprint, with the β = 0.89 and 1.0 tests featuring forward leg installation forward of the footprint and the β = 0.75 test featuring forward leg installation with the footprint forward of the leg (i.e., the only footprint ahead of the jack-up).

6 EXPERIMENTAL RESULTS

The following sections discuss results of jack-up installation in intact overconsoliated kaolin and in the presence of footprints. Normalized forces and moments are denoted in boldface italic type, where axial load is $\boldsymbol{V} = V/s_u{\cdot}A$, horizontal force at the L.R.P. is $\boldsymbol{H} = H/s_u{\cdot}A$, moment in the leg at hull level is $\boldsymbol{M_H} = M_H/s_u{\cdot}A{\cdot}B$, and moment at the L.R.P. is $\boldsymbol{M_S} = M_H/s_u{\cdot}A{\cdot}B$. Behavior of the three legs is presented only for fully intact installation, while only behavior of the directly affected forward leg is presented for β offset tests. Angle of inclination from vertical, $\alpha = \tan^{-1}(H/V)$, and dimensionless eccentricity, $e/B = M/(V{\cdot}B)$ (Figure 3) are also given.

6.1 INTACT UNDISTURBED SOIL

For all reference penetrations into intact soil, the normalized behavior of the jack-up and its legs is generally similar. Results show $\boldsymbol{V}$ increases in the leg to a near constant value when the full spudcan diameter is engaged at approximately z/B = 0.25. After this, the jack-up experiences upward rotation of the forward leg corresponding to a slight overall lateral translation (x/B) of the legs towards the front of the jack-up. $\boldsymbol{H}$ and $\boldsymbol{M_H}$ indicate all leg experience bending away from the hull centroid in the plane of rotation. Positive $\boldsymbol{H}$ and $\boldsymbol{M_S}$ in the forward leg indicate leg bending towards the rear of the jack-up due to spudcan fixity to the soil that resists the trending forward motion caused by rotation. $\boldsymbol{M_S}$ values are similar and nearly constant with depth for the three legs throughout each test. The magnitude of $\boldsymbol{M_H}$ is also similar between the three legs, but differs in sign between the forward and rear legs due to geometry. As expected, $\boldsymbol{M_H}$ exceeds $\boldsymbol{M_S}$, as hull-leg fixity is greater than spudcan-soil fixity. Maximum α and eccentricity occur for all legs prior to engagement of the full spudcan diameter. Minor differences in behavior between the three legs were observed, and may be attributed to i) jack-up geometry, ii) location of the loading mechanism relative to the jack-up center of gravity, iii) minor geometric eccentricities parallel and perpendicular to the planes of rotation/translation, and iv) local s_u heterogeneity.

6.2 SPUDCAN FOOTPRINT

It is expected that installation of the jack-up with the forward leg adjacent a location having both a surface discontinuity and non-uniform strength profile will exhibit a large propensity for overturning and lateral translation, and experience greater bending in the legs. Figure 7 illustrates the behavior of the forward leg penetrating a footprint created by a spudcan for the three offsets during full jack-up installation.

Behavior of the jack-up during installation of the forward leg is similar for the three offsets: β = 0.75, 0.89, and 1.0. Full spudcan engagement results in downward rotation of the forward leg as it penetrates the footprint soil having a reduced, non-uniform s_u profile (see Figure 5), while the rear legs experience greater penetration resistance from the intact soil. Similarity between the β offset values indicates that the non-uniform, reduced s_u profile likely dominates the effect of footprint shape on jack-up installation behavior.

For spudcan generated footprints, $\boldsymbol{V}$ is less than the measured during intact installation due to reduction in s_u. Negative $\boldsymbol{H}$ and $\boldsymbol{M_H}$ developed in the forward leg during initial penetration indicate the leg bends forward due to hull rotation, and this trend continues with further penetration where $\boldsymbol{M_H}$ becomes more negative and the leg continues bending away from the footprint. Throughout penetration, $\boldsymbol{M_S}$ and x/B indicate the spudcan bends toward the footprint at the rear due to soil-spudcan fixity and the presence of the softer soil of the existing footprint. While it is expected that $\boldsymbol{H}$ and $\boldsymbol{M_H}$ would both be positive as the spudcan moves into the footprint, this is not the case as the actuator moves the opposite direction of the footprint. The β = 0.89 case is most critical for α, while the β = 0.75 offset experiences the greatest eccentricity. The behavior is caused by an overall overturning moment in the system caused by eccentricity between the deeply penetrated forward leg and the progressively smaller spudcan-soil interaction in the rear legs. While this behavior is common for the three offsets, the magnitude of forces, moments, displacement, and hull rotation differ. An offset of β = 0.89 resulted in the greatest $\boldsymbol{H}$, $\boldsymbol{M_H}$, and $\boldsymbol{M_S}$ values in the forward leg for spudcan generated footprints.

6.3 VERTICAL WALL FOOTPRINT IN INTACT SOIL

Unlike for the spudcan generated footprint, overall behavior of the jack-up and the forward leg is dependent on the offset distance of the forward leg from the vertical-wall footprint. Because the forward spudcan has a smaller bearing surface (i.e., the spudcan area engaged by the soil is less) in the presence of the footprint, $\boldsymbol{V}$ measured at the three offsets vary (Figure 8) and are less than measured for the reference case.

The behavior of the forward leg shown in Figure 8 is similar for the β = 0.75 and β = 0.89 tests. For β = 0.75, the forward leg rotates downwards at an early stage. This causes the rear legs to lose contact with the soil so all forces and moments in the jack-up are transferred to the forward leg. The forward leg experiences large negative $\boldsymbol{M_H}$ and $\boldsymbol{M_S}$ as the leg simultaneously bends away from the footprint in response to forward overturning of the hull and moves laterally away from the footprint. A hull rotation of nearly 15° at a jack-up penetration of z/B ~ 0.3 results in dramatic soil heave below the forward spudcan into the footprint, (Figure 9a). Following the rapid failure of the soil into the footprint, jack-up instability causes large horizontal displacements.

For β = 0.89, forward leg rotation into the footprint occurs at a later stage of the test. After full engagement of the rear spudcans, there is a rapid increase in $\boldsymbol{M_S}$ in all legs as bending occurs towards the rear of the jack-up and the existing footprint. Continued downward rotation of the forward leg into the footprint, large hull rotations (~15° at z/B ~ 0.6), and spudcan motion into the footprint cause the soil to also fail into the footprint. This causes a reduction in $\boldsymbol{M_S}$ in the forward leg.

Thereafter, the rear legs experience maximum M_S, M_H, and H, followed by a decrease to negative values as spudcan-soil fixity

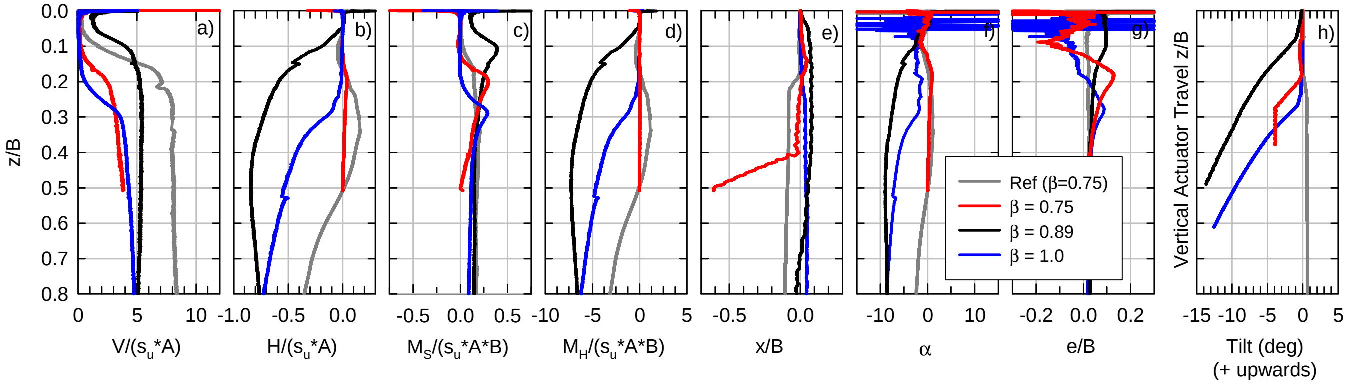

Figure 7. Comparison of measured and derived data obtained from the forward leg during penetration at three offset ratios from the center of a spudcan generated footprint during full jack-up installation.

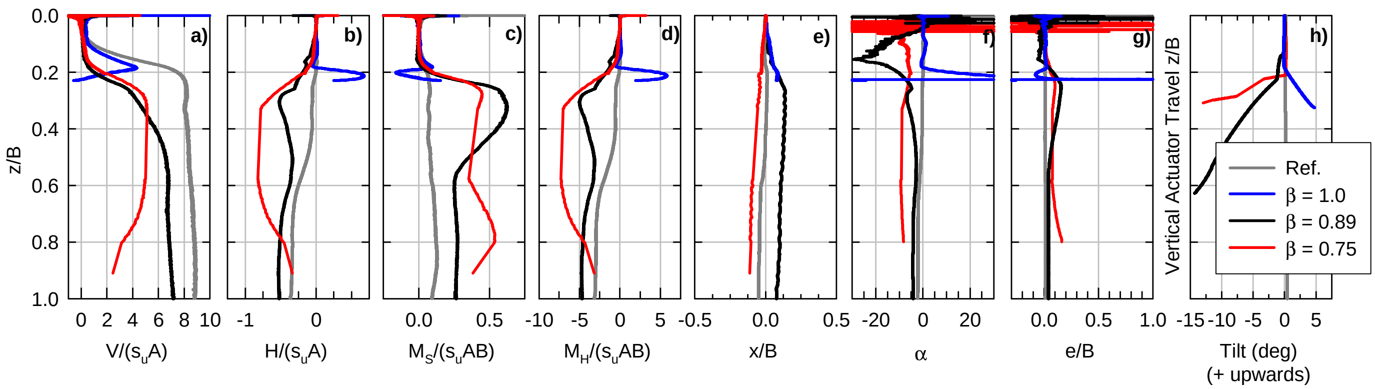

Figure 8. Comparison of measured and derived data obtained from the forward leg during penetration at three offset ratios from the center of a vertical walled footprint in undisturbed soil during full jack-up installation.

and hull rotation cause rear legs to bend towards the front of the jack-up.

For the β = 1.0 test, the jack-up behavior differs. For this case, the forward leg rotates upwards and away from the existing footprint during penetration, much like in the reference test. This causes a dramatic failure of the soil under the forward spudcan (Figure 9d) and near instant changes in M_S and M_H (Figure 8). Concurrently, M_S in the rear legs approaches zero and changes in M_H and H occur in response to failure of the footprint wall. While jack-up rotation is similar to the reference case, all jack-up legs experience greater M_H at lower z/B, x/B displacement, and rotation (< 4°). The difference is likely because jack-up motion is laterally restrained during reference installation. Provided greater bending moments can be sustained, an offset of β = 1.0 (and likely greater) from a surface discontinuity that is not accompanied by a reduction in s_u may be sufficient to ensure jack-up installation is no more critical than if the jack-up was installed on a level surface.

Comparison of results for vertical walled footprint offsets (Figure 8) shows that H and M_H are more critical and hull rotation occurs more rapidly over a shallower depth of jack-up penetration for β= 0.75. M_S and x/B are, however, greater when β = 0.89. While lower β tests show large hull rotations and measured forces and moments, the β = 1.0 test shows rapid failure of the footprint soil at shallow penetration depths, which will likely cause a more catastrophic failure of the jack-up in real field conditions. Analysis of e/B and α for the vertical footprints shows they are greatest at soil failure for the β = 0.75 test, although α is also nearly 30° for the β = 0.89 test at shallow z/B. These values are nearly 6 times greater than for installation in undisturbed soil, clearly indicating the influence of the surface discontinuity.

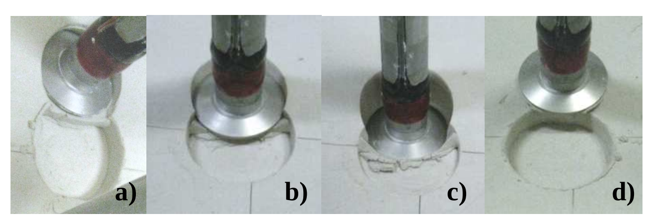

Figure 9. Vertical-walled footprint penetration – jack-up forward leg at maximum penetration: a) β = 0.75; b) β = 0.89 (start of penetration); c) β = 0.89; and d) β = 1.0.

Comparison of these results with offset tests from spudcan footprints shows that for a specific offset, $\boldsymbol{H}$ and $\boldsymbol{M_H}$ may be higher (β = 0.75) or lower (β = 0.89) for the spudcan footprint offset tests than for installation in similarly shaped footprints in undisturbed soil. Results show distinct differences in forward leg behavior occur in the presence of lower, non-uniform strengths (e.g. Figure 5). Installation adjacent to spudcan generated footprints results in lower $\boldsymbol{V}$, as well as lower overall $\boldsymbol{M_S}$, x/B, α, and e/B for similar offset ratios for installations adjacent to spudcan footprints when compared to installations adjacent to the vertical walled augered footprints.

6.4 SLOPE IN INTACT SOIL

These tests were performed to analyze the effect of penetration of the single leg on a slope similarly shaped to the footprints generated during spudcan installation in situ and in centrifuge tests in normally consolidated soils during full jack-up installation. This information is useful in bridging the gap between previous work performed using a single leg in overconsolidated soils (Teh et al. 2006), as well as analyze the effect of footprint shape on jack-up behavior. For these tests, the initial position of the spudcan center is at the intersection of the slope and horizontal soil when β = 1.0 and is on the slope for the lower β tests (Figure 6). As noted, the β = 0.89 and 1.0 tests were performed with the footprint behind the forward leg, while the β = 0.75 footprint was in front of the forward leg. While the latter test may not provide exact correlation with other results due to differences in full jack-up on leg behavior, it is believed to be adequate in assessing the magnitude of the leg forces and moments at the β = 0.75 offset.

Results are presented in Figure 10. For all offset ratios, installation resulted in downward rotation of the forward leg into the footprint much like for the installations adjacent to spudcan footprints. Additionally, installation near the sloped footprints did not result in the bearing capacity failures that occurred for the vertical walled augered footprints. Similarly with forward leg penetration near the augered vertical walled footprints, the β = 0.89 and 0.75 tests developed similar leg bending and loading conditions. For example, $\boldsymbol{M_H}$ indicated leg bending occurred away from the footprint at the hull level. Among slope footprint tests, maximum α, e/B, $\boldsymbol{M_H}$, $\boldsymbol{M_S}$, and $\boldsymbol{H}$ are similar at lower β, however, slightly greater horizontal motion (x/B) towards the footprint occurred for β = 0.89.

Analysis of β = 1.0 results shows that $\boldsymbol{V}$ is similar to that measured for installation in undisturbed soil (reference), however the forward leg experienced significantly greater $\boldsymbol{M_S}$ with a peak at full engagement of the spudcan diameter (z/B ~ 0.2). For this test, all legs experienced bending towards the front of the jack-up, where the forward spudcan experienced bending away from the footprint because of spudcan embedment before initiation of rotation. Additionally, $\boldsymbol{M_H}$ indicates bending towards the rear of the jack-up due to forward rotation and horizontal displacement for the β = 0.75 and 1.0 tests, while forward rotation and rear horizontal displacement results in bending towards the front of the jack-up for the β = 0.89 test.

Overall, these tests exhibit significantly lower hull rotations than both auger and spudcan generated vertical walled footprint tests. Additionally, β = 0.89 and 1.0 offsets from sloped footprints have similar maximum $\boldsymbol{M_S}$, while the β = 1.0 offset test has the greatest overall $\boldsymbol{M_H}$, $\boldsymbol{H}$, $\boldsymbol{V}$, and x/B. Leg moments and displacements also increase with increasing β for this series. Comparison of results presented in Figure 10 shows that the forward leg experiences similarly large $\boldsymbol{M_S}$, $\boldsymbol{M_H}$, **H**, etc. between the β = 0.89 and β = 1.0 offset tests for the sloped footprint, though not at the elevations. For β = 1.0, $\boldsymbol{M_S}$ and e/B are more critical at shallow depths (z/B < 0.2), while $\boldsymbol{M_H}$ and x/B are more critical for deeper (z/B > 0.5) penetrations. Peak values of $\boldsymbol{M_S}$, $\boldsymbol{M_H}$, e/B, and x/B occur at z/B ~ 0.25 or just before engagement of the full spudcan diameter. It appears the β = 1.0 offset is the most critical scenario due to the location of the center of the spudcan at the peak of the slope, but this is not known for certain as greater offset distances were not investigated. Additionally, these tests confirm that the greatest eccentricity and α occurs at z/B values nearest to full engagement of the spudcan diameter, indicating this scenario may also be critical.

7 INFLUENCE OF FULL JACK-UP ON TESTING

These experimental results provide valuable information regarding model scale testing of spudcan penetration into seabed irregularities, some having non-uniform strengths. They highlight the advantage of modeling behavior of a single leg adjacent to an irregularity through coupling of the full jack-up structure having free rotation and horizontal motion.

This is evident when comparing results from this study and those reported by Teh et al. (2006) for laboratory installation of a single leg and similarly shaped spudcan adjacent to a 30° sloped footprint in overconsolidated clay having near constant s_u = 11.3 kPa with depth at an offset of β = 1.0 (Figure 11). The spudcan used by Teh et al. (2006) was 125 mm in diameter and full engagement of the spudcan diameter was expected to occur at z/B = 0.35. Their installation, however, did not allow for rotation or lateral translation. Figure 11 shows that maximum $\boldsymbol{M}$, $\boldsymbol{H}$, e/B and α occur for the horizontally constrained spudcan at full spudcan engagement. For full jack-up installation at β = 1.0, Figure 10 shows maximum $\boldsymbol{M_S}$ occurs upon engagement of the full spudcan diameter (at z/B ~ 0.2 for the smaller diameter spudcan). However, maximum $\boldsymbol{H}$ occurs at a greater depth and maximum α and e/B occur well before full spudcan engagement. Additionally moments and forces measured during full jack-up installation are noticeably greater than for the single leg installation, by two to five times. This indicates a coupled interaction of the spudcan-leg system with the full structure and the use of more degrees of freedom when modeling spudcan interaction with an uneven seabed may be necessary.

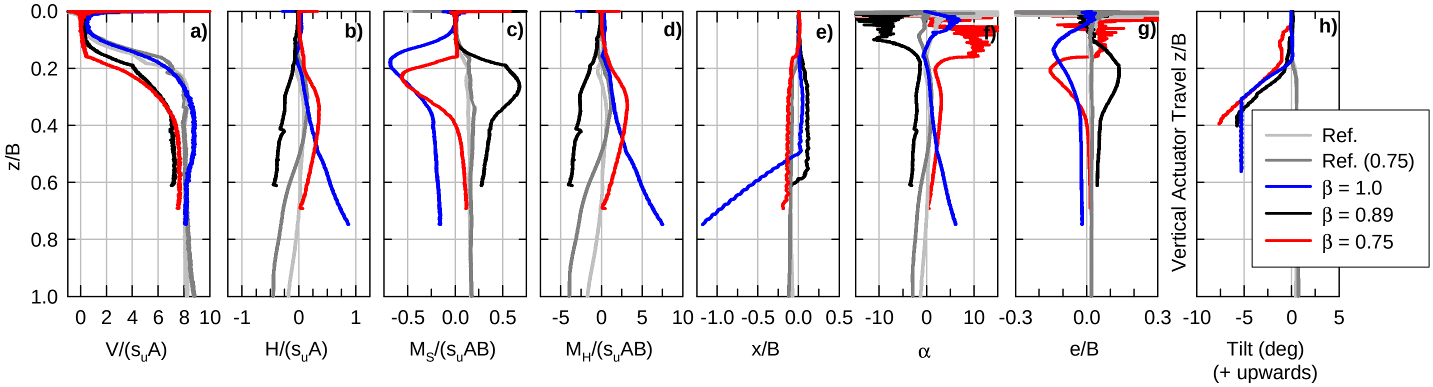

Figure 10. Comparison of measured and derived data obtained from the forward leg during penetration at three offset ratios from the center of a 14° slope footprint in undisturbed soil during full jack-up installation.

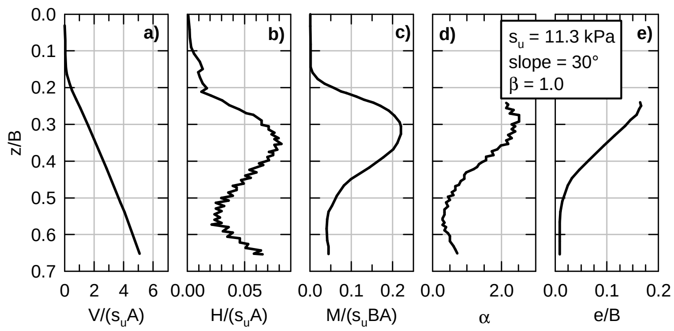

Figure 11. Results from installation of a single jack-up leg-spudcan system on a 30° slope in undisturbed overconsolidated kaolin clay (after Teh et al. 2006).

Results from this study are compared with results from installation of a single leg and spudcan in normally consolidated clay within a drum centrifuge performed by Gaudin et al. (2007) in Figure 12 and Figure 13. Gaudin et al. (2007) employed a single spudcan-leg system having dimensional and structural properties similar to this study, and allowed free horizontal motion during spudcan installation. Offset footprints were spudcan generated resulting in a disturbed s_u profile, and were shallowly sloped due to testing at higher stresses in the centrifuge.

Figure 12 shows that α and e/B are far more unstable at lower z/B values for footprints that are surface discontinuities alone than for footprints having disturbed s_u profiles when $\beta = 0.75$. This is not the case for $\beta = 1.0$ (Figure 13), where the vertical walled footprints from this study have α and e/B values that are greater and more variable than the shallow sloped footprints.

Comparison of sloping footprints for $\beta = 0.75$ shows that $\boldsymbol{V}$, $\boldsymbol{H}$, and α profiles are similar in magnitude and behavior when $z/B > 0.2$ to 0.4, with the spudcan tending towards the existing footprint for both test types. While the shape of the $\boldsymbol{M_S}$, α and e/B profiles are similar between these tests, peak values are greater, occur at greater z/B and persist for greater depths for the full jack-up test. Similarity in profile shape is likely directly related to similarity in footprint shape, although differences in magnitude with depth are due likely to single leg tests having a disturbed s_u profile. Depth profiles of x/B differ between these tests, as the influence of the full jack-up results in overall displacement away from the footprint.

Comparison of full jack-up installations adjacent to vertical walled auger and spudcan footprint for $\beta = 0.75$ shows similarly shaped $\boldsymbol{M_S}$, α and e/B profiles, although peak $\boldsymbol{M_S}$ values are greater, occur at greater z/B, and persist for greater penetration depths for the footprint in intact soil. Similarity in the shape of the data with depth is likely directly related to similarity in footprint shape. Differences in force and moment magnitudes are likely the result of the disturbed s_u profile for the spudcan footprint. For example, e/B for the spudcan generated footprint at $\beta = 0.75$ is greater than for the shaped footprint alone. When $\beta = 1.0$, behavior between the shaped and spudcan generated footprints is noticeably opposite, due to the overwhelming effect of the disturbed s_u profile for installation near the spudcan-generated footprint.

Generally, measured and derived forces and moments are greater when a single leg of a fully coupled model jack-up is installed adjacent to a surface discontinuity or spudcan footprint than for a single leg alone as shown by comparison with the Teh et al. (2006) and Gaudin et al. (2007) findings. This is not the case for $\boldsymbol{V}$ measured for the centrifuge testing of a single leg, as the centrifuge provides more realistic soil stresses and a better assessment of soil-structure interaction. Gaudin et al. (2007) concluded that incorporation of free horizontal motion into models of spudcan-soil interaction adjacent to existing footprints provides a better measure of expected behavior. When compared with the findings of Gaudin et al. (2007) and

Teh et al. (2006), this study confirms the benefit of analyzing jack-up soil-structure interaction when the structure is allowed lateral and rotational motion.

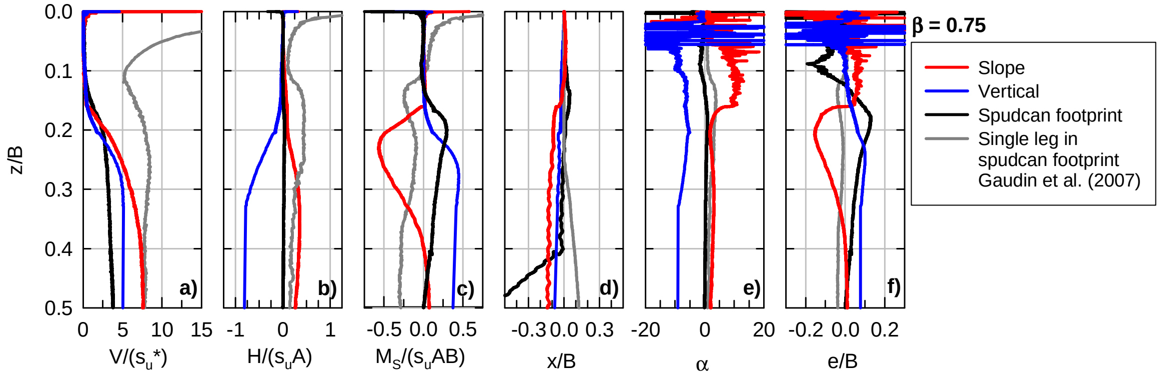

Figure 12. Comparison of jack-up forward leg behavior during penetration in augered footprints in intact soil with results from jack-up forward leg penetration in a spudcan generated footprint and a single leg installed in a spudcan generated footprint during centrifuge testing in normally consolidated kaolin for β = 0.75 (after Gaudin et al. 2007).

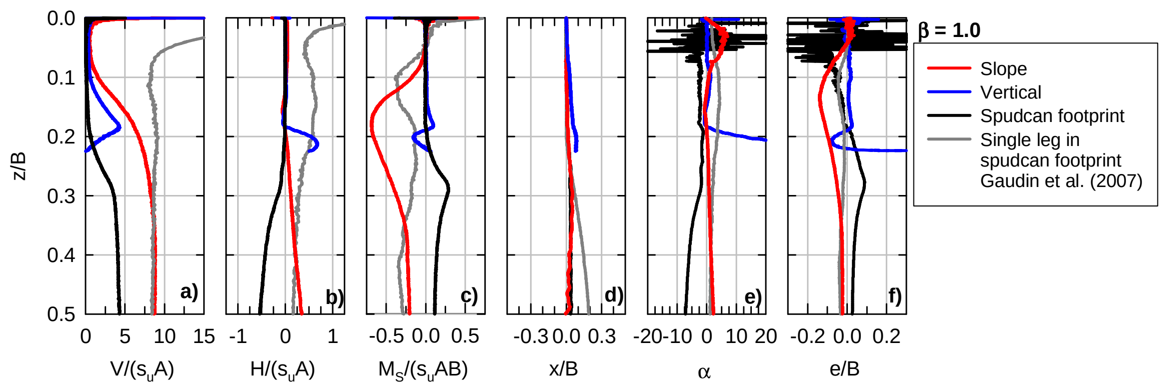

Figure 13. Comparison of jack-up forward leg behavior during penetration in augered footprints in intact soil with results from jack-up forward leg penetration in a spudcan generated footprint and a single leg installed in a spudcan generated footprint during centrifuge testing in normally consolidated kaolin for β = 1.0 (after Gaudin et al. 2007).

However, the rigid fixity between the jack-up legs, hull, and spudcan used is an upper bound analysis for expected loading during installation adjacent to surface discontinuities in intact and disturbed soils, as full scale jack-ups do not have rigidly fixed leg connections.

8 CONCLUSIONS

This study describes an experimental testing program using a reduced-scaled model of a three-legged jack-up performed to investigate the fully coupled structural interaction when a single leg is installation adjacent to an existing footprint. The study focused on the effect of shape and non-uniform strength on the behavior of a single leg of the jack-up offset from three different footprint types (spudcan, vertical wall, 14 slope) at three different offset distances (0.75, 0.89, and 1.0 times spudcan diameter). The study builds on previous studies involving installations of single leg systems employing restrained or unrestrained horizontal motion by integrating both the fully coupled behavior of the full jack-up structure and free lateral and rotational motion during installation. Footprint offset distanced were chosen to bracket critical displacement, force, and bending criteria based on literature reported single leg studies. Results confirm these critical offsets for the leg influenced by the existing footprints during installation.

Installation adjacent to spudcan generated footprints having non-uniform and reduced soil strengths resulted in jack-up behavior dominated by shear strength, not footprint shape. Regardless of offset, penetration of the footprint influenced leg resulted in rotation of the jack-up into the footprint direction due to the discontinuity in s_u. An offset of β = 0.89 resulted in the highest horizontal force and moments at the hull and spudcan ($\boldsymbol{H}$, $\boldsymbol{M_H}$, $\boldsymbol{M_S}$). With increased offset distance, it appears that the risk of leg failure decreases.

For spudcan installation adjacent to vertical walled footprints in uniform strength soil, jack-up behavior varied with offset distance based on the relative bearing surface of the spudcan. An offset of β = 0.75 results in critical horizontal forces and bending of the leg at the hull ($\boldsymbol{H}$ and $\boldsymbol{M_H}$), an offset of β = 0.89 results in the greatest leg bending at the spudcan and normalized horizontal motion ($\boldsymbol{M_S}$ and x/B), and an offset of β = 1.0 results in the most rapid failure of the footprint soil during penetration. It can be concluded that installation in similar situations should likely occur at β > 1.0 to prevent failure of the deformity wall.

For spudcan installation adjacent to a shallow slope in uniform soil results in jack-up rotation (i.e., overturning) in the direction of the slope. For this scenario, the greatest bending moment at the hull ($\boldsymbol{M_H}$), leg forces, and normalized horizontal displacement were measured for β = 1.0, when the center of the spudcan is located at the interface between the sloped and horizontal soil surfaces. Greater offset distances were not tested, and it is therefore inconclusive if β = 1.0 represents the most critical case.

This study provides important development for the future modeling of jack-up damage and failure. The use of reduced scale models of full jack-up structures is likely to better predict soil-structure interaction and critical force, bending, displacement, and overturning scenarios when the structure is installed adjacent to existing surface discontinuities. Single leg tests likely underestimate development of the bending moments in the leg influenced by the discontinuity. This is partially confirmed when comparing results from this study and single leg studies that appear to underestimate leg bending (it is noted the latter were conducted under different soil and footprint conditions). While this study is limited, it confirms that further study using a model of a full jack-up in a multitude of soil type and stress conditions at a greater range of footprint offsets would increase our understanding of overall jack-up behavior in complicated in situ environments.

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