JACK-UP LEG EXTRACTION ANALYSES FOR DEEP SPUDCAN PENETRATIONS IN MULTILAYERED SOIL CONDITIONS

L. Kellezi* & F. Gobuzi
Geo, Copenhagen, Denmark

*corresponding author: Lindita Kellezi: LKE@geo.dk

ABSTRACT
After a jack-up rig in an Oil & Gas Field, or a jack-up vessel in an Offshore Wind Farm (OWF) have been installed and operated at a location, the spudcan footings have to be extracted from the seabed and manoeuvred to a new location. Difficulties are often encountered during this process, especially when the spudcans are deeply penetrated into the clays. The main issue is related to insufficient rig or vessel capacity to overcome the extraction resistance of the spudcans, which depends on the site soil conditions. This paper, except for the elaborations on the methods related to pull-out analyses, presents also the results of two case histories: one for an Oil & Gas project and one for an OWF project, where in both, as predicted, relatively deep spudcan penetrations were experienced during installation / preloading. Leg extraction analyses are carried out by means of conventional methods and FE analyses. The two different cases investigated correspond to different spudcan dimensions & loads and different soil conditions. As there is demand from different operators to carry out such analyses, conventional and numerical methods are combined by supplementing each other, and confirmed by installation / extraction feedback, resulting in proper tools, which make possible to deliver more and more accurate results.

KEY WORDS: Leg extraction, Conventional analyses, Spudcan penetration, Spudcan base suction, Soil bacfill, Jetting System, Pull-out force, Remoulded soil, Break out force, Finite Element (FE).

INTRODUCTION
Besides Oil & Gas, utilization of jack-up units has more and more an important role also in the Wind industry. Increased demand is mainly related to the effectiveness of these units, being both flexible and mobile, therefore having the possibility to be transported from one place to the other to carry out new operations. These mobile offshore jack-up units are all equipped with long legs attached to large diameter footings (i.e. spudcans) and depending on its purpose, the number of legs per unit also changes (jack-up rigs in Oil & Gas industry generally consist of three legs, while in the Wind industry jack-up vessels are normally made of (4-6) legs).
Installation of jack-up units depends greatly on the site / soil conditions and sometimes spudcan penetrations may reach large depths until sufficient bearing capacity is achieved (especially in soft clay). But in order to relocate the rig / vessel, each installation must be followed by a leg extraction and problematic installations will possibly be associated with problematic extractions. Jack-up leg penetration and extraction have been investigated by different researchers and using different methods [5]-[13]. Figure 1, illustrates a centrifuge test from University of Western Australia (UWA) and FE analyses from Geo / authors, are given.

This paper will focus mainly on the application of conventional methods and FE analysis for leg extraction and elaborating on the applied methodology and evaluating the results from two case histories in Oil & Gas and Wind industries. Both locations are part of the UK Sector of the North Sea. After installation, deep penetrations have been predicted / recorded for both cases, in site conditions where stiff Clay material is dominant to large depths. The aim is to provide some practical recommendations in assessing the pullout force required to extract the legs embedded deep under the seabed.

**CASE HISTORIES ON JACK-UP INSTALLATIONS AND EXTRACTIONS**

For the Oil & Gas jack-up rig (3 legs with equivalent diameter 18.2 m), based on the available borehole / cone penetration tests (BH/CPTs) carried out, the soil conditions at the legs are interpreted. They consist of a layer of firm clay with undrained shear strength (c_u) reducing with depth to about 15 m below seabed (bsb), overlying a 3 m thick layer of medium dense sand, further overlying stiff clay. Feedback from the jack-up rig installation showed (as predicted) spudcan tip penetrations of about 16.5 m, indicating that the required preload capacity was achieved when the footings reached the sand.

For the Wind Energy jack-up vessel (4 legs with equivalent diameter 8.4 m), based on the available BH/CPTs carried out, the soil conditions at the legs were interpreted. They consisted of multilayers of clay with strength increasing with depth from soft to firm to very stiff down to about 20 m bsb. Spudcan tip penetrations of about 9 m were measured and predicted from the leg penetration analyses, which indicated that the required preload capacity was achieved when the footings reached partial contact at the stiff clay layer.

Leg extraction resistance or the pullout force required, constitutes of the adhesion between the vertical sides of the spudcan and the soil, the effective weight of the backflow soil, the remoulded shear resistance of the soil on top of the spudcan and most importantly the suction at the base of the spudcan. High extraction resistance occurs in stiff clays, governed mainly by the suction at spudcan-clay interface. To overcome or reduce the suction, jetting system is generally applied. However, not all jack-ups are equipped with such system as further elaborated in the paper. Hence, accurate calculation of overall required pullout force to get the rig / vessel out of the site, is important before entering the location. On the other hand, for soil conditions where sand is present at the base of the spudcan, the effect of suction is greatly reduced, resulting in relatively low extraction resistance. The calculation of the cavity depth and / or its confirmation by seabed survey around the legs after installation, (having a clear knowledge on the amount of the soil back/in-flowed over the spudcans), are also important for predicting the extraction resistance and needed pullout force.

Conclusions and recommendations are drawn with regard to jack-up rig / vessel extraction capacity, especially in sites with experienced deep spudcan penetrations, possibly useful for engineers and practitioners working for Oil & Gas and Wind Industries in areas with ‘soft’ seabed.

**SPUDCAN DIMENSIONS & LOADS**

The spudcan geometries and loads from the two case histories also differ from one another. The dimensions for each spudcan are shown in Figure 2. For the Oil & Gas industry, where the rig is equipped with three legs, the dimensions of the spudcans are relatively large. The spudcans have an equivalent diameter of 18.2 m and full base area of 258 m². Distance from spudcan full base (largest contact area) to spudcan tip is about 1.8 m, Figure 1a. The jack-up rig has a maximum preload of around 13609 tons/leg, while the pullout capacity is unknown. Only
this jack-up unit is equipped with water jetting system. The jack-up vessel used in the Wind industry consists of four legs, each equipped with rectangular footings and a total bearing area of approximately 55 m², resulting in an equivalent diameter of 8.4 m and tip to full base contact height of 1.3 m, see Figure 1b. The maximum preload capacity is about 3360 tons/leg and the maximum uplift force is estimated at around 2640 tons/leg by considering the buoyant weight of the spudcan and the legs.

**SEABED SURVEY**
The water depth as measured from seabed surveys is around 96 m and 29 m LAT (Lowest Astronomical Tide) at the Oil & Gas Platform and OWF sites, respectively.
A seabed survey was also conducted at the Oil & Gas rig location after jack-up installation (i.e. during jack-up operation) in order to measure the depth of the depressions created from the spudcans. The investigation showed these depths to reach up to 7 m by considering the water depth at the site, see Figure 3a. Soil heave in the range of (1.0 - 2.0) m was also noted from the seabed survey caused mainly due to the squeezing of the clay layer during spudcan penetrations.

The seabed survey at the OWF location showed also different features in the seabed, including footprints from previous jack-up installations and extractions, which are useful for new jack-up vessel to be located / installed at the site, see Figure 3b.

**INTERPRETATION OF THE SOIL CONDITIONS**

Based on the available soil data, design soil profiles have been interpreted from the geotechnical data at each location, consisting of BH/CPTs. The lower bound (LB) and upper bound (UB) characteristic soil parameters are selected as a cautious estimate of the value affecting the occurrence of the relevant limit state [3]. The undrained shear strengths for the clay layers are derived based on the CPT data (q<sub>net</sub>) upon the correlation with the cone factor N<sub>kt</sub>. The peak friction angles, considered as UB values, are correlated from the CPT data using the methods proposed by [14], [15].

For the Oil & Gas project, the soil conditions consist of a firm layer of Clay to 15.0 m bsb with undrained shear strength decreasing with depth, followed by a 3.0 m thick layer of medium dense Sand, overlying stiff Clay to 24.0 m bsb, see Figure 4a. At the OWF location, the soil conditions are interpreted to consist of multiple Clay layers to large depths, with undrained strength increasing with depth and varying mainly from soft to very stiff, see Figure 4b. The interpreted soil profiles and the derived LB / UB soil parameters for both case histories are included in Table 1 & Table 2.
TABLE 1 INTERPRETED SOIL PARAMETERS AT OIL & GAS LOCATION

<table>
<thead>
<tr>
<th>Soil Description</th>
<th>Layer Depth [m]</th>
<th>Effective Unit Weight γ' [kN/m³]</th>
<th>Internal Friction Angle φ [°]</th>
<th>Undrained Shear Strength c_u [kN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Soil Type]</td>
<td>[from - to]</td>
<td>[BE]</td>
<td>LB (φ_{c,UB}) / UB (φ_{peak})</td>
<td>LB (N_{kt=20}/UB (N_{kt=15})</td>
</tr>
<tr>
<td>CLAY, firm</td>
<td>0.0 - 15.0</td>
<td>8.5</td>
<td>-</td>
<td>50 - 40 / 67 - 53</td>
</tr>
<tr>
<td>SAND, loose to dense</td>
<td>15.0 - 18.0</td>
<td>10.0</td>
<td>29 / 35</td>
<td>-</td>
</tr>
<tr>
<td>CLAY, firm to stiff</td>
<td>18.0 - 21.0</td>
<td>9.0</td>
<td>-</td>
<td>60 / 80</td>
</tr>
<tr>
<td>CLAY, stiff</td>
<td>21.0 - 24.0</td>
<td>9.0</td>
<td>-</td>
<td>110 / 147</td>
</tr>
<tr>
<td>SAND, dense to very dense</td>
<td>24.0 - 25.0</td>
<td>10.0</td>
<td>35 / 41</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 2 INTERPRETED SOIL PARAMETERS AT OWF LOCATION

<table>
<thead>
<tr>
<th>Soil Description</th>
<th>Layer Depth [m]</th>
<th>Effective Unit Weight γ' [kN/m³]</th>
<th>Internal Friction Angle φ [°]</th>
<th>Undrained Shear Strength c_u [kN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Soil Type]</td>
<td>[from - to]</td>
<td>[BE]</td>
<td>LB (φ_{c,UB}) / UB (φ_{peak})</td>
<td>LB (N_{kt=25}/UB (N_{kt=15})</td>
</tr>
<tr>
<td>CLAY, very soft to firm</td>
<td>0.0 - 0.5</td>
<td>8.0</td>
<td>-</td>
<td>10 - 40 / 17 - 67</td>
</tr>
<tr>
<td>CLAY, firm to stiff</td>
<td>0.5 - 1.7</td>
<td>8.0</td>
<td>-</td>
<td>40 - 50 / 67 - 83</td>
</tr>
<tr>
<td>CLAY, firm to very stiff</td>
<td>1.7 - 8.0</td>
<td>8.0</td>
<td>-</td>
<td>55 - 95 / 92 - 158</td>
</tr>
<tr>
<td>CLAY, stiff to very stiff</td>
<td>8.0 - 14.0</td>
<td>8.0</td>
<td>-</td>
<td>100 / 167</td>
</tr>
<tr>
<td>CLAY, stiff to very stiff</td>
<td>14.0 - 17.0</td>
<td>8.0</td>
<td>-</td>
<td>105 - 120 / 175 - 200</td>
</tr>
<tr>
<td>CLAY, stiff to very stiff</td>
<td>17.0 - 20.4</td>
<td>8.0</td>
<td>-</td>
<td>130 / 217</td>
</tr>
</tbody>
</table>

CONVENTIONAL SPUDCAN PENETRATION ANALYSES

Spudcan penetration analyses at both locations were carried out according to conventional methods for the spudcan geometries and the soil profiles described in the previous sections. The methodology for conventional penetration analyses follows the guidelines given in [1], [2], [5]-[8]. Spudcan static bearing capacity calculations for defining footing penetration over depth, are based on [4] and Geo in house methods and programs.

For calculation purposes the spudcan is simplified to a circular footing with a flat bottom. The effect of the actual spudcan shape is taken into account. The results of the conventional predictions representing all legs of the jack-up unit are presented in Figure 5a & 5b for Oil & Gas and Wind Industry cases, respectively.

Feedback from spudcan leg penetrations for the jack-up rig at the Oil & Gas location showed measured spudcan penetration depths of 16.5 m FWD (Forward) Leg, 15.2 m PS (Port) Leg and 15.5 m STB (Starboard) Leg which fall between the LB and UB back analyzed spudcan tip penetration curves, Figure 5a. The feedback received after jack-up rig installation indicates that the required capacity for maximum preload has been achieved when part of the footing reached the sand layer.

For the OWF location, the results from conventional penetration analyses show spudcan tip penetrations varying from (3.0 - 9.0) m for UB and LB soil parameters, respectively. In this case the footing has only penetrated in clay and the required capacity is reached when the spudcan partially interacts with the very stiff clay layer below 9 m. Equivalent measured penetrations from a different jack-up unit installed approximately 47 m away from the CPT location reached depths of maximum 10 m bsb for larger equivalent loads.
Both, conventional and FE analyses can be used for calculating the leg extraction at different locations. The conventional method are based on bearing capacity formulas, while the numerical modelling has the advantage of modelling more accurately the multilayered soil conditions etc.

**Conventional Approach:** The extraction analyses are performed for both locations considering the maximum / minimum footing penetrations for LB / UB soil profiles. For the Oil & Gas project, the maximum footing penetration as indicated from the installation feedback has been used.

The effective extraction force includes the adhesion between the spudcan (vertical side) and the soil, the effective weight of soil assumed to be back-flowed above the spudcan, the shear resistance of the back-flowed soil, and a breakout force due to suction.

The strength of the clay below, on the side and above the spudcans is reassessed to account for squeezing during installation, soil consolidation during operation, remoulded due to backflow and suction during extraction. The value of the clay sensitivity $S_t = 1.0$ is assumed and applied in the extraction analysis. However, no remoulded strength tests were performed to assess the clay sensitivity. Consolidation effects during operations can be applicable only for the jack-up rigs in the Oil & Gas industry due to generally long operation periods while in the Wind industry jack-up vessels operate for short terms, therefore it is unlikely for consolidation to occur.

Geo’s analyses consider the following extraction mechanism [10] – [13]:

- When there is mainly a single layer of clay with increasing strength with depth, the maximum resistance occur at the beginning of the extraction.
For cases with uniform strength with depth, the extraction process may be problematic due to similar resistance over the full extraction depth.

When stiff over soft clay, the maximum resistance it is mobilized in relation with the stiffer top layer.

Multilayer clays, will behave as a combination of the previous.

The presence of sand layer beneath the penetrated spudcan (or a soil plug) will significantly reduce the breakout force [11].

According to InSafeJIP Guideline [13] and Geo experience, the breakout force $Q_{\text{breakout}}$ may theoretically comprise the following components:

$$Q_{\text{breakout}} = Q_{\text{shear}} + Q_{\text{side}} + W_{\text{soil}} + Q_{\text{base}}$$

where

- $Q_{\text{shear}}$ is the shear resistance mobilized along vertical planes above the spudcan.
- $Q_{\text{side}}$ is the side friction mobilized along the spudcan’s side wall, for spudcans with a small side wall height, the $Q_{\text{side}}$ component can be omitted.
- $W_{\text{soil}}$ is the overburden effective soil weight.
- $Q_{\text{base}}$ is the base resistance due to suction effects developed at the spudcan-clay interface. The back-analysis results suggest that the breakout factor (suction factor) $N_{\text{breakout}}$ values fall between 3 and 5.

The results from leg extraction analysis for both cases, following the above methodology are shown in Figure 6.

For the Oil & Gas project, the spudcan is embedded partly on the sand and partly on clay since tip to base height is 1.83 m. This means that the effect of suction at the base of the footing is reduced due to less area being in contact with the clay layer. This is more effective for LB penetration curve, where the spudcan is embedded deeper in the clay layer (16.5 m bsb), instead of UB condition where spudcan tip penetrations of 15.2 m bsb were recorded resulting in larger footing contact area with clay.

Furthermore, the seabed survey carried out at the location after the rig installation, showed depressions i.e cavity at the legs reaching up to 7 m, indicating that soil has backflowed on top of the footing. These have been further used to estimate the backflow column for evaluating the weight of the soil above the spudcan. Due to the soil backflow, the soil on top will also be remoulded, therefore a lower strength is assigned for the clay when estimating the shear resistance mobilised along vertical planes on top of the spudcan. Detailed results of the components of the breakout force required for spudcan extraction are tabulated in Table 3.

Table 3 includes also the results of the pullout force components for the jack-up vessel in the OWF. Since no seabed survey was conducted after the vessel installation, the cavity depth and consequently the soil backflow column is estimated from [2] in accordance to the findings of [12]. No backflow is assumed for UB soil conditions.

In contrast to the previous case, the base of the spudcan is fully in contact with a stiff clay layer, meaning that suction is developed. Maximum breakout resistance will occur at the beginning of the extraction until the spudcan is freed from the suction effects, which as shown in Figure 6b and Table 2 represent the highest component of the breakout force. The uplift resistance will then start decreasing linearly and will consist mainly of the shear resistance, side friction and weight of the soil above the spudcan. If jetting is to be applied, suction effects will be overcome and the resulting extraction resistance with jetting application will reduce to 661 tons/leg.
a) Extraction resistance at the jack-up rig location  
b) Extraction resistance at the jack-up vessel location

**Figure 6. Spudcan Leg Extraction Analyses**

**TABLE 3 LEG EFFECTIVE EXTRACTION FORCE**

<table>
<thead>
<tr>
<th>Location</th>
<th>Components of Q\text{breakout}</th>
<th>Q_{\text{breakout}} = Q_{\text{total}}</th>
<th>Max. pullout capacity: F_{\text{pullout}}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q_{\text{shear}}</td>
<td>Q_{\text{side}}</td>
<td>W_{\text{soil}}</td>
</tr>
<tr>
<td>Oil &amp; Gas</td>
<td>659</td>
<td>132</td>
<td>1053</td>
</tr>
<tr>
<td></td>
<td>659</td>
<td>132</td>
<td>1053</td>
</tr>
<tr>
<td></td>
<td>721</td>
<td>102</td>
<td>1635</td>
</tr>
<tr>
<td>OWF</td>
<td>0</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>38</td>
<td>113</td>
</tr>
</tbody>
</table>

Even though the jack-up vessel in the OWF case has smaller spudcan dimensions and leg penetrations predicted to be much less than the penetrations recorded for the Oil & Gas project, the difference in the resulting extraction resistance between the two cases is relatively small.

This is highly attributed to the effect of suction in the interface between the spudcan base and the soil below being the main component of the breakout force while the presence of the sand under the footing in the Oil & Gas project will reduce suction effects and therefore the main component of the pull-out resistance will be the weight of the soil backflowed above spudcan due to the deep leg penetrations recorded at the site.
FE Analyses: FE modelling of the spudcan pullout capacity is carried out with Plaxis FE program [9], as an alternative to conventional analysis. Considering the program limitations, the following simplifications are made in building the FE model:

- The spudcan pullout is assumed to start with full base contact according to their respective measured penetrations during installation.
- An 2D axisymmetric FE model is constructed, simulating the 3D conditions considering that the pull out force is symmetrical / vertical.
- Mohr-Coulomb constitutive soil model is applied in drained conditions for the sand layers and undrained conditions for the clay layers.
- The initial geostatic conditions are calculated first with coefficient of lateral pressure $K_0 = 0.5$. Effective unit weight for the seabed soil layers are employed as in the conventional analyses.
- 15-noded and 6-noded finite elements are used for generating the mesh.
- The spudcan is modelled as a rigid weightless body.
- The deformation parameters, $(E$ moduli) are evaluated based on the CPT data for the sand layer, and as a function of undrained shear strength for the clay layers, where $E = 200 \times c_u$ is applied.
- Soil backflow during spudcan penetration is considered by assuming the spudcan to be completely buried.
- As an attempt to model large deformations, Updated Mesh (UM) analyses are carried out following [3].
- The calculations start with in-placing the spudcan at the respective penetration depth, applying the maximum preload and inserting the soil backflow and the soil uplift above the embedded spudcan and at the area around the spudcan.
- The calculations follow with unloading the spudcan to still water reaction (SWR) and after that to zero load.
- After that the pullout force is applied as point load or as a distributed force, or upward vertical displacement at the elevation of the spudcan maximum area.

Plaxis FE 2D Axisymmetric analyses, carried out for the two case histories are shown in the following figures. The embedded spudcans and the distributed loads applied upwards at the largest spudcan area, together with the corresponding deformed FE mesh are shown in Figure 7 & Figure 8 for the Oil & Gas and OWF location, respectively.
The results from the FE analyses for LB soil strengths for the two cases are presented in Figure 9 & Figure 10. They confirm the results of the conventional analyses given in Table 2. For the OWF location, the failure zone extends at the bottom of the spudcan, which is related to the effect of suction due to the footing being embedded fully on clay material.

The pullout force, which in the elasto-plastic calculations starts from zero increasing to the full plastic phase (the stage of the full capacity (breakout), when the spudcan and the soil mass above are heading up) is very much dependent on the assumption on the strength of the clay soil around the spudcan and the backflow soil over the spudcan.
RESULTS & CONCLUSIONS

In this paper, geotechnical engineering assessments were carried out for jack-up installation / leg penetration and pullout / extraction analyses for individual jack-up rig & jack-up vessel in the Oil & Gas and Wind Energy industries, respectively. Two different soil conditions were considered, consisting of multilayered Sand and Clay material for the Oil & Gas location, and multilayered Clay profile for the OWF location that showed increasing strength with depth.

For the Oil & Gas case, spudcan penetrations were recorded at approximately 16.5 m bsb when the footing was partly in contact with the Sand layer. This resulted in reduced extraction resistance (3630 tons/leg) due to the reduced suction effects from the Sand under the spudcan base.

The addition of the seabed survey after installation, to measure the depressions, allowed for the estimation of the cavity depth created above the spudcan and consequently the calculation of the weight of the backflowed soil, which comprised the main component of the breakout resistance for LB soil conditions. The maximum pullout resistance is approximately 27% of the applied preload during the installation phase in undisturbed soil, therefore no difficulties were expected during the leg extraction.

In the Wind Energy project, for the case with seabed Clay featuring strength increasing with depth, conventional leg penetration analysis predicted spudcan embedments of up to 9 m bsb for LB soil parameters. Having penetrated only in Clay, the spudcan is subjected to suction effects leading to an increase in the breakout resistance during leg extraction. The depth of cavity above the spudcan was estimated according to the findings from [12], however also due to the relatively shallow penetrations predicted, the effect of the weight of the backflow soil on the breakout force is relatively small.

Nevertheless, the results from the leg extraction analyses showed that the pullout force required, varies between (1440-3340) tons/leg for UB / LB soil parameters, respectively, which is higher than the available extraction capacity (2640 tons/leg). This means that the legs can either be extracted without any difficulties, or not be extracted due to large breakout / suction factor revealing at the location.
In this case, the large breakout force can be overcome by using a jetting system to reduce the effect of suction on the bottom of the spudcan and also shortening the shear plane and reducing the weight of the soil on top. Furthermore, if applicable, reduced preload during the installations leading to smaller spudcan penetrations as per analyses can be a way of minimizing the required extraction resistance.

During extraction, while the legs move up, the pullout force will be reduced as part of the soil above the spudcans will fall down due to stability issue, creating safe slopes and the resistance at the contact area of this soil mass and the spudcan, with the remaining soil, will be reduced.

For both locations, in addition to the conventional method, FE analysis were performed using Plaxis 2D. An upward distributed load is applied at the largest spudcan contact area to simulate the extraction force obtained from the conventional methods. In both cases, results from conventional extraction analyses were confirmed by Plaxis FE 2D Axisymmetric modellings.

To conclude, based on the observations made during these analyses, it is recommended that spudcans be equipped with water jetting system especially when installed in sites where Clay layers are dominant and when deep leg penetrations are predicted. If jetting system is fitted, [2] suggests to consider testing it prior to spudcan contact with the seabed. Other methods for jack-up removal include cyclic loading or excavation of the top soil to reduce the extraction resistance.

According to [2], the leg extraction force required to pullout the legs should be estimated prior to going on location if difficult operations are anticipated. However, performing leg extraction analyses after the jack-up is installed (i.e. knowing the final leg penetrations), accompanied with seabed surveys for identifying the cavity depth and carrying out remoulded laboratory test for the strength of the Clay backflowed above the spudcan, can facilitate the estimation of the required breakout resistance to extract the embedded legs.

REFERENCES


