EXPERIENCES WITH LEG PENETRATION AND EXTRACTION OF OFFSHORE WIND JACK-UP VESSELS ON SITES WITH LONDON CLAY

S. Raymackers*, C. Morris, K.Vannieuwenhuyse and D. Rabaut
Design and Engineering Department GeoSea
DEME GROUP

*corresponding author: Raymackers.sylvie@deme-group.com

ABSTRACT

GeoSea is DEME's specialist in offshore & marine engineering projects, it has amongst its fleet the offshore wind jack-ups INNOVATION and NEPTUNE. In recent years GeoSea has been active in multiple offshore renewables design and construction projects in the Thames Estuary. The soil conditions at these projects were dominated by London Clay, which is a stiff overconsolidated fissured clay of high plasticity.

This type of clay has provided some interesting insights on the geotechnical aspects of jack-up deployment. The article takes the reader through the different steps of the jack-up installation process. The influence of aspects such as the broad range of N_{kt} values, the variability between CPTs and the strain rate effect is discussed from a practical perspective. Furthermore, the observed relation between soil heave and leg penetrations and the experiences with leg extraction will be detailed.

KEY WORDS: London Clay, Offshore wind, Jack-ups, Soil heave, Jetting, Experience

INTRODUCTION

GeoSea is DEME's specialist in offshore & marine engineering projects, it has a fleet of offshore wind jack-up vessels which have been working across Europe and beyond in versatile soil conditions with penetrations ranging from rock at seabed to silts and weak clays.

The London Clay encountered in the Thames estuary is rather homogeneous and well described, but challenging for jacking with offshore wind vessels due to the deep leg penetrations which have been experienced by various jack-ups. Therefore it was chosen as the subject for this article on jacking experiences.

GeoSea's vessels NEPTUNE (fig. 2) and INNOVATION (fig. 3) have recently operated on sites where the London Clay is found from seabed until great depth. NEPTUNE is a 4 legged jack-up with tubular legs which can be fitted with spudcans but can also operate without. INNOVATION is a 4-legged lattice leg jack-up with spudcans, it can be fitted with spudcan extensions which reduce the bearing pressure.

In project preparation phase one can base itself solely on own past experiences or from others, the available soil data and literature. Often this does not lead to a conclusive answer on the operability of a jack-up on a site, some uncertainty always remains. During the project and afterwards the experiences are followed up until the predictions can be confirmed.

The paper discusses firstly the parameters of the London Clay of influence for jacking, some details of the preloading process with the 4-legged offshore wind vessels and the calculation methods applied. After this theoretical part, two cases are presented, site 1 where NEPTUNE operated and site 2 where INNOVATION operated.

LONDON CLAY

The London Clay formation is a heavily fissured clay, which extends from seafloor to large depth in the Thames Estuary. The clay is overconsolidated (OCR~2-4 on site 1, average OCR=7 on site 2) and the plasticity is very high (site 1: LL~75%, PI~45%, site 2: LL~85%, PI~55%).

The fissured nature of the clay has large influence on the undrained shear strength of the London Clay. On both projects $S_t<1$ was measured on multiple samples. By reworking the clay, the fissures are destroyed and the clay becomes stronger but more ductile.

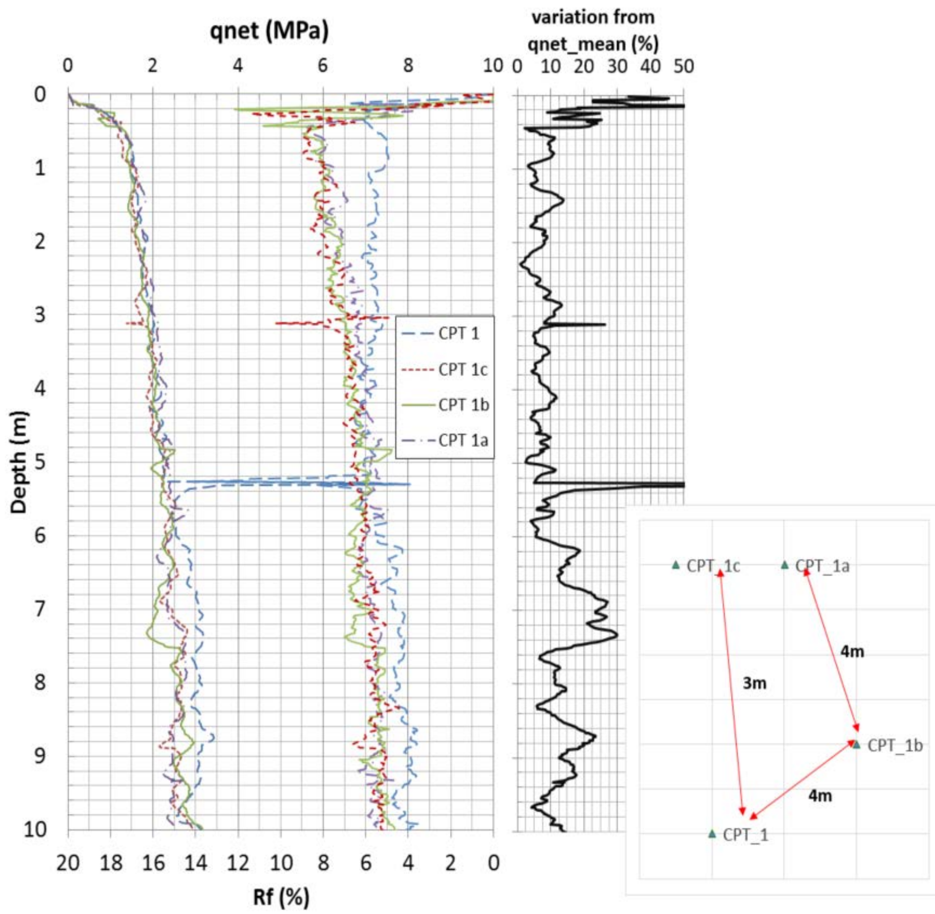

Figure 1: net cone resistance of 4 CPTs in close proximity, from site 2. The variation from the mean CPT, shown in the middle graph, is between 5 to 10% in the upper 6m and larger for greater depths.

The cone resistance varies typically from 1 MPa at seabed to about 4MPa at 20m depth. Figure 1 shows the first 10m of 4 CPT graphs in close proximity on site 2. It can be noted that the cone resistance varies by 5 to 10% in the upper 6m, below 6m the variability is even larger. The N_{kt} value ranges between 20 and 45 on site 1, the best estimate is defined at 32.5. On site 2 the N_{kt} values from the lab tests (UU and CAU) ranged between 10 and 36, with a mean of 22. These values lie outside the range of values quoted in InSafe JIP [1] as common values.

Due to this variability in both cone resistance and N_{kt} values, predictions will inevitably show a large range.

OFFSHORE WIND JACK-UPS

Offshore wind jack-ups have typically 4 to 6 legs, which provides them with the capability to predrive or preload the legs 2-by-2 on a diagonal and reduces or eliminates the need to ballast for preloading purposes. Having 4 legs means it is possible to increase (and decrease) the load gradually on the legs while the other legs never loose contact with the seabed. This leads to fast deployment (within few hours) and provides additional safety when for example faced with rapid penetrations due to the fact that loads are redistributed to the ‘unloaded legs’ when penetration occurs.

Figure 2: NEPTUNE ©DEME Group

Offshore wind jack-ups can have either truss legs fitted with a spudcan or tubular legs, not necessarily fitted with spudcans. Bearing pressures under the spudcans during preloading are generally higher for offshore wind jack-ups (~1000 to 800kPa when operating with spudcans) than what is common in oil and gas (~400kPa). Bearing pressures for tubular jack-ups without spudcans are typically ~3000kPa but the skin friction on the legs also contributes to the foundation resistance.

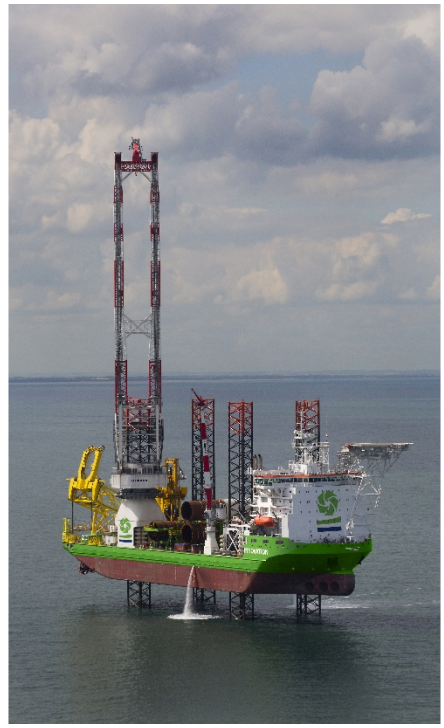

Figure 3: INNOVATION ©DEME Group

An offshore wind jack-up operating in good weather conditions, installs several foundations or turbines per week, therefore the residence on site is often limited to a couple of hours or days. This means that site preparation to overcome adverse soil conditions, such as gravel beds, is seldom an economical solution in offshore wind. It also means that any time lost during jacking or leg extraction has a large impact on the project.

LEG PENETRATION, HEAVE AND EXTRACTION

For leg penetration calculation, the methods of SNAME [2] or ISO19905-1 [3] are used for jack-ups with spudcans. For jack-ups without spudcans shaft friction is added to the calculation based on for example API [4], [5] and [6].

At the start of the leg penetration process a shallow bearing failure will occur, the soil will be pushed sideways and upwards resulting in soil heave around the spudcan. At a certain depth the failure mechanism will not reach the seabed anymore, but it will be localized. This is the depth where backflow starts. From this depth the cavity above the spudcan will remain constant [3].

The zone around the spudcan influenced by remoulding during penetration and extraction of the spudcan is described to be in the order of 2 times the diameter of the spudcan (or one spudcan radius from the spudcan edge) [7] [8]. Le Tirant [9] states that the depressions left by a jack-up in soft normally consolidated clays are described to be equivalent to twice the spudcan diameter.

The extent of the footprints is important as the jack-ups will be deployed nearby the foundations, which could lead to interaction with cable routes, scour protection or the foundation itself.

For a jack-up without spudcans the force needed to pull the legs is dependent of the base suction and the shaft friction. In a soil with S_t=1, the shaft friction during extraction after short residence on site is equal than during penetration. The reversed end bearing is typically reduced by either prolonged pulling or by jetting. A jetting system functions by removing reversed end bearing resistance and is more efficient than prolonged pulling because it allows immediate breakout.

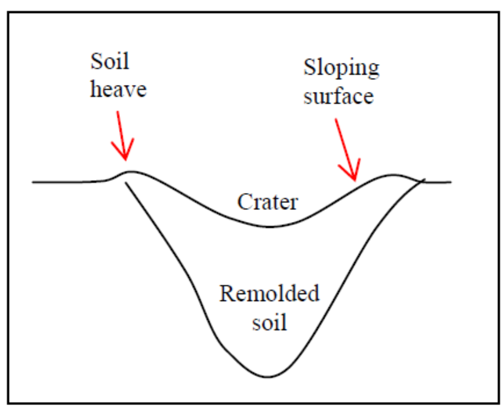

Figure 4: Schematic cross-sectional view of a footprint, from [9]

For a jack-up operating with spudcans the leg retraction resistance is solely dependent of the base suction in case of shallow embedment. In case of intermediate embedment (H_{cav}<D<H_{deep}), the shear resistance mobilized along vertical planes above the spudcan, the side friction mobilized along the spudcan side wall and the weight of the backflow on top of the spudcan should also be accounted for. [10]

SITE 1: NEPTUNE

NEPTUNE has 3.5m diameter tubular pile legs. The legs have a flat bottom plate with 6 spokes welded on forming a conical tip. The tubular legged jack-ups like NEPTUNE can preload rapidly, therefore the site specific assessment is often performed for the maximum preload of the vessel.

The site where NEPTUNE worked was an extension of an existing windfarm. Previously 2 jack-ups, a tubular legged jack-up and a jack-up with spudcans had experienced issues on the site with deep penetration and consequential leg extraction difficulties.

Based on in-house experience it was considered safer for smooth operations to operate without spudcans on this site. The extraction resistance due to reversed end bearing and skin friction was expected to be high due to large leg penetrations.

NEPTUNE was equipped with a tailor made jetting system during project mobilization. The piping and nozzles are designed for sufficient pressure to allow the nozzles to open in strong soils. Once the nozzles are open the pressure is reduced and the flow rate increased for fast extraction. The maximum jetting pressure to avoid hydraulic fracturing of the clay was evaluated based on formulas for calculating maximum mud pressure in directional drilling [11], a constant low pressure during pulling was deemed feasible at 25m embedment of the leg. The flow rate was determined based on the anticipated extraction speed as suggested in Gaudin et al. [12].

The remaining resistance due to skin friction was reduced by optimizing the preload. Since the NEPTUNE had some reserve on the crane capacity for operations and the environmental conditions were not governing the site specific assessment, the preload could be lower than the maximum preload of the vessel. By reducing the preload by about 10%, the leg penetrations remained shallower (26m in lower bound instead of 29.5m) and the ratio pulling/preload capacity was larger. As illustrated in figure 5, this created some reserve capacity in overcoming the shaft friction on the leg.

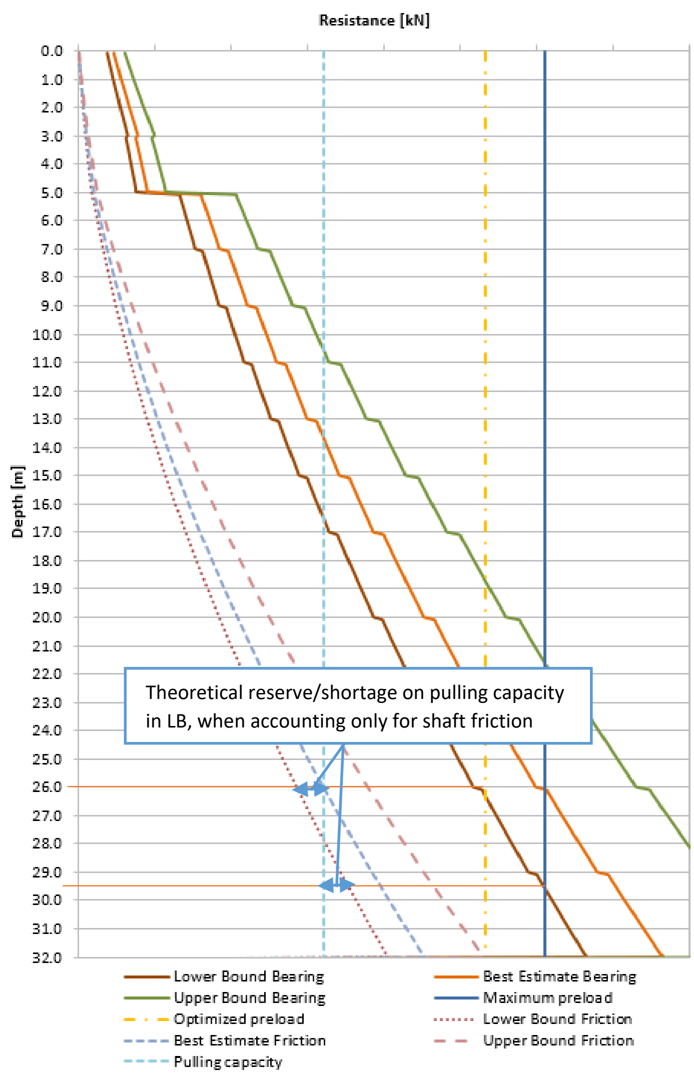

Figure 5: a leg penetration prediction for location A of Site 1 for NEPTUNE. On this location the lower bound expected penetration is 29.5m for the maximum preload and 26m for the optimized preload. The related shaft friction equals the pulling capacity at 28m depth.

In line with the predictions, leg penetrations up to 25m were measured on locations with only London Clay (CPT A, B and D, fig 6) and up to 30m on locations where the London clay was overlain with weaker sediments (CPT C, fig 6). Table 1 shows significant variations in penetration between the legs of the jack-up at the same location. This is surprising since the preload was equal on all 4 legs and the soil was expected to be homogeneous.

Immediate breakout was possible with the assistance of the jetting system at all locations. Prolonged or cyclic pulling of the legs was not required. A positive pressure was developed in the cavity below the leg, which suggests that the jetting system could create upward force on the leg tip. The jetting system was operated until approximately 16m embedment after which the spudlegs displayed very limited extraction resistance other than self-weight.

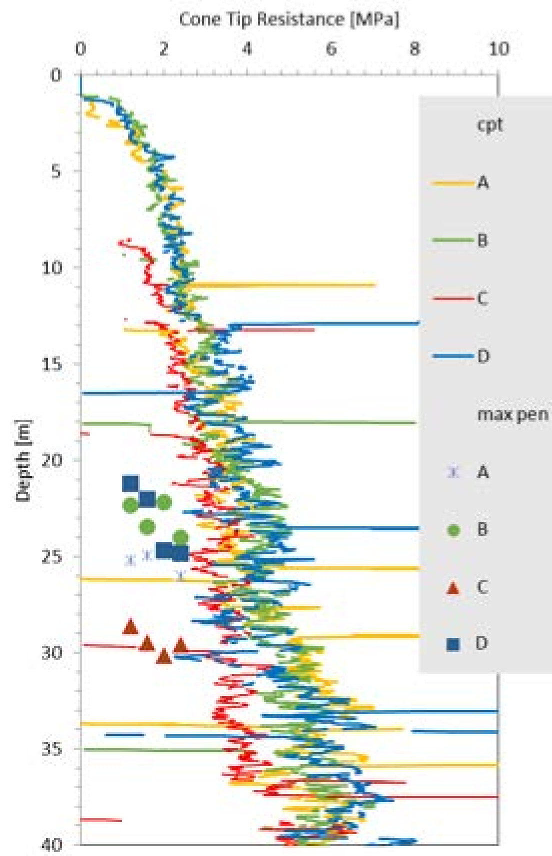

Figure 6: 4 CPTs from site 1 – with measured leg penetrations

Table 1: measured leg penetrations, per leg at 4 locations on site 1

Location	leg penetration (m) - per leg			
A	24.9	26	25	25.2
B	22.2	24	23.4	22.3
C	30.1	29.6	29.5	28.6
D	24.7	24.8	22.1	21.2

SITE 2: INNOVATION

INNOVATION is a heavy lift jack-up with 4 truss legs. It is equipped with spudcans without a spigot.

For the site where it had to work no other jacking logs for similar vessels were available. A large range of N_{kt} values were noted from triaxial tests, with an average of 22 but with variations between 10 and 36. Therefore a large range of potential penetrations was predicted. In upper bound soil conditions the penetrations would be limited to 4m, in lower bound 16m could be expected. In the latter case jack-up deployment would be time consuming.

To reduce the uncertainty in predictions and allow for optimisations, offshore jacking trials were undertaken at several locations on the site. During trials all penetration curves were below best estimate and some even below lower bound. Two examples of predicted curves and measured penetrations are presented in figure 7, the predictions are based on SNAME formulas with N_{kt} 15 (UB), 22 (BE) and 29 (LB).

Penetrations of 9m and more were attained during the trials, without reaching the target preload. After the trials the top of the spudcans appeared to be covered with remoulded London Clay, probably deposited during backflow.

The trials led to the decision to increase the spudcan bearing area. The increased area would reduce the pressure from 800-1000kPa to 450-550kPa below the footing. In the year between the trials and the actual project add-on spudcan shoes were designed, fabricated and installed.

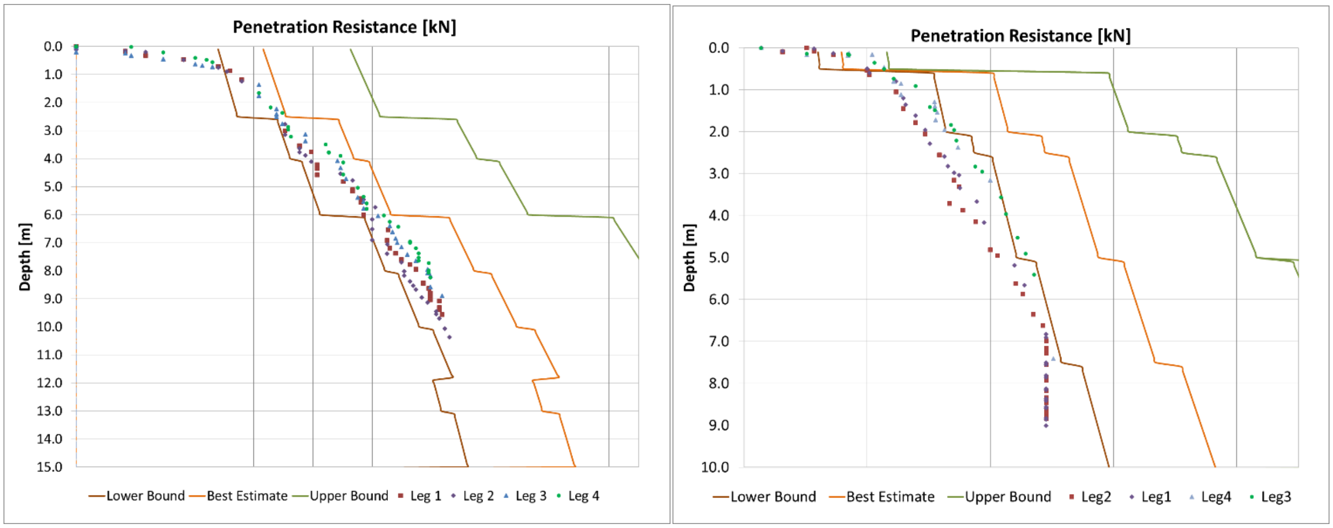

Figure 7: leg penetration prediction and measured penetrations for 2 trial locations with INNOVATION (penetrations were stopped before final preload).

The increased bearing surface reduced the penetrations during works on the site to less than 5.5m on all locations.

Extraction was feasible during the trials with the assistance of the jetting system. Measurements indicated that positive uplift pressure could be generated below the spudcan. The breakout occurred generally at about 3m below seafloor, after which jetting was not required.

At that time INNOVATION had the typical jetting system with half pipe outlet guards. The outlet guards are susceptible to clogging. This was seen as a risk because the trials had proven how crucial the jetting system was to achieve immediate breakout and avoid long extraction operations. Therefore it was decided to equip INNOVATION with a tailor made jetting system like the one which was already fitted on NEPTUNE. The system on NEPTUNE had proven to be very robust against clogging. The flow rate of the jetting system was also increased to improve extraction rate.

During trials and later on the project it was noted that once the target load was reached, the penetrations kept on increasing at the same load level. Typically 1 to 2m additional penetration occurred before the load could be held without further penetration as shown in the right on figure 7. This is attributed to the strain rate effect of the clay; the clay will react stiffer under rapid loading than under prolonged loading. This effect is further described in Versteele et al. [13].

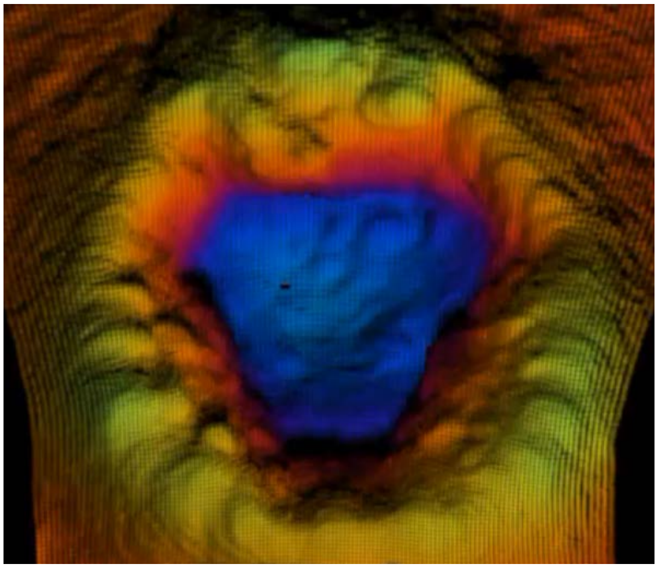

Figure 8: footprint of INNOVATION with spudcans

A back-analysis was performed on the achieved load penetration graphs on all locations based on ISO formulae for bearing capacity. A narrow fit between CPT and penetration record could not be obtained on all locations, potentially due to the relatively shallow penetrations and the significant variation in cone resistance at close proximity (fig. 1). The fitted N_{kt} values varied between 22 and 31. This is at the higher end of the range of N_{kt} values derived from lab tests.

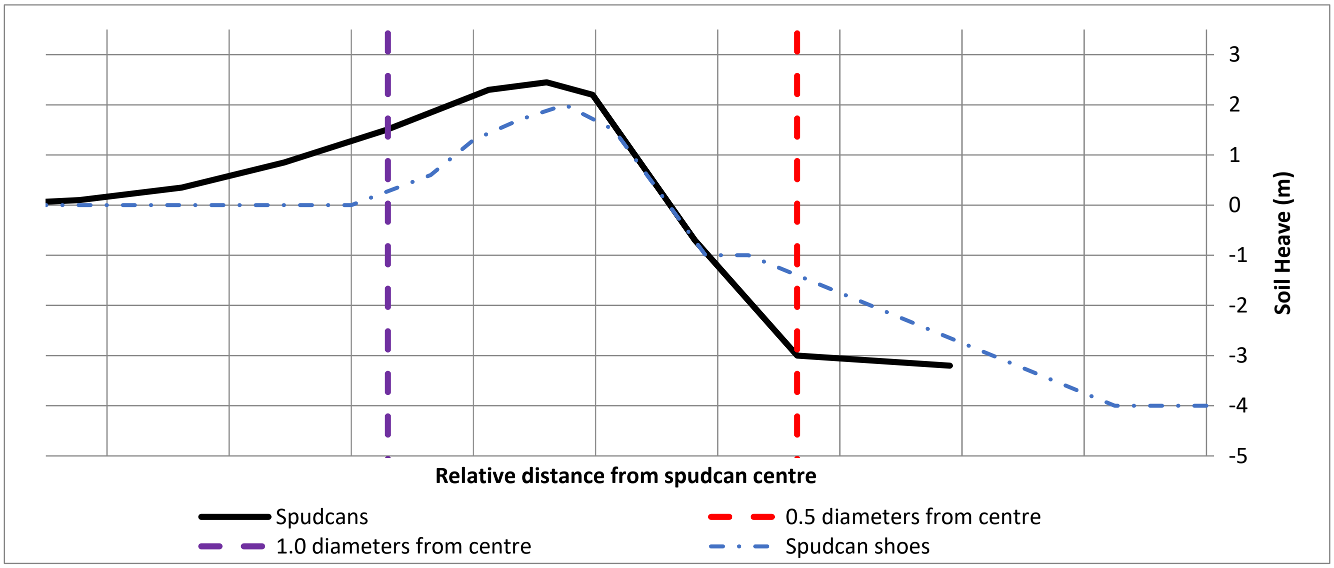

Figure 9: example of measured heave berm from multibeam survey, for 2 cases; one with spudcans and one with spudcanshoes

As discussed the soil heave around the spudcan was monitored during jacking trials in real-time as penetration increased using a multibeam echoscope mounted on the jack-up leg. The footprints left after spudcan extraction were also surveyed with the echoscope (fig. 8). Surveys were also made of footprints when the INNOVATION returned to the site fitted with spudcan shoes. For the locations on the trials the zone affected by the footprint was in total about 3 spudcan diameters, at 2.5 spudcan diameters the heave was less than 0.5m. When operating with the spudcanshoes, penetrations were more limited and the disturbed zone was only 2 spudcan diameters. An example of a heave berm for both spudcans and spudcan shoes are compared in figure 9. It is noted however that the zone influenced by the footprints can thus exceed experience mentioned in literature, more research would be welcomed on this topic.

APPEARANCE OF LONDON CLAY

During the trials an ROV made video footage of the cavity above the spudcans. In figure 11 images at different locations in the cavity and on the heave berm are shown. The images show how the fissured clay is broken up in blocks and gravel pieces, it does not show signs of remoulding. This substantiates the hypotheses that the fissured nature of the clay is causing the very high Nkt values [14].

This appearance of the clay is in contrast with the appearance of the clay which was removed from the spudcans (no images) and found in the spudlegs of NEPTUNE (fig. 10), which was completely remoulded. This is probably related to the different failure mechanisms (shallow versus deep).

Figure 10: remoulded London Clay at the interior of the legs of NEPTUNE

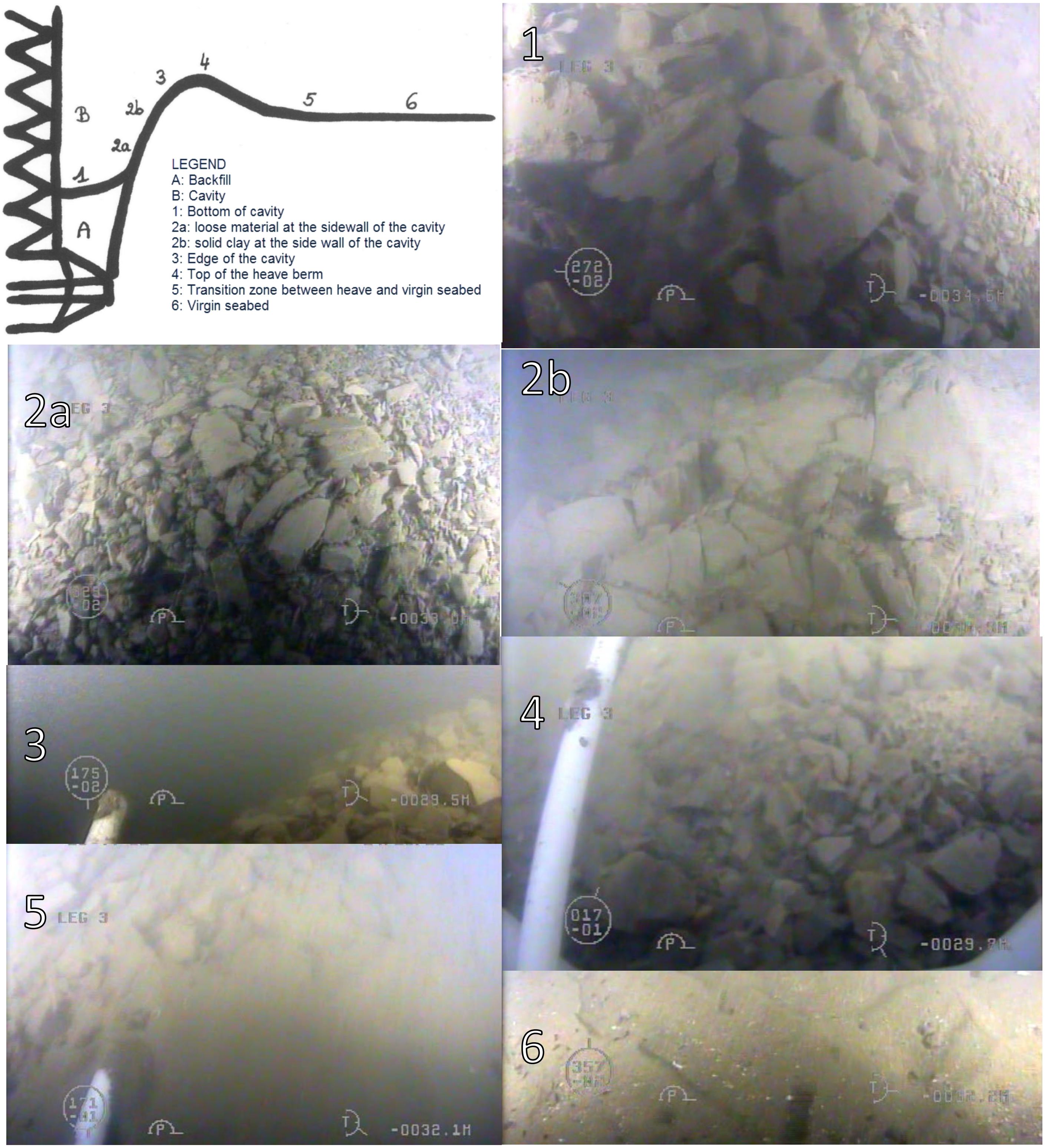

Figure 11: ROV images of the footprint and seabed at 9m leg penetration. The images show how the clay is broken up in pieces of gravel and block size. In 2b the intact London Clay is seen.

CONCLUSION

The paper describes experiences gained on 2 projects with London Clay, with a reflection on the theoretical background on which it is based. It has shown how uncertainties regarding soil conditions challenge us in daily practice, even in a homogeneous soil like London Clay. Experiences show that a narrow fit in predictions is utopic when accounting for the variation in the soil properties (q_{net} and N_{kt}) at short distance in a homogeneous clay.

The derived N_{kt} values from the laboratory tests are higher than the common range found in literature, however they are confirmed by the experiences with leg penetrations. The fissured nature of the clay is believed to be the main cause of this. The presented ROV images show how the clay is broken up into pieces along the fissure surfaces.

The tailor made jetting system allowed immediate breakout on both sites, making leg extraction fairly easy. The experiences with positive uplift pressure and extraction rate were in agreement with literature.

The influence zone of the footprints was not in line with the limited available literature. Further research on the subject would be interesting.

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LIST OF SYMBOLS

CAU	consolidated anisotropic undrained triaxial test
CPT	cone penetration test
H_{cav}	maximum cavity height
H_{deep}	penetration depth from which extraction failure pattern becomes localised
LL	liquid limit
N_{kt}	cone factor $N_{kt}=q_{net}/S_u$
OCR	over consolidation ratio
PI	plasticity index
q_c	cone resistance
q_{net}	net cone resistance
S_t	sensitivity $S_t=S_u/S_{u\_remoulded}$
S_u	undrained shear strength
$S_{u\_remoulded}$	remoulded undrained shear strength
UU	unconsolidated undrained triaxal test