EXPERIENCE FROM FULL-SCALE SUCTION CAISSON TRIAL INSTALLATIONS AT THE SEAGREEN OFFSHORE WIND FARM

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ABSTRACT

This paper details experience gained from full-scale suction caisson trial installations at the planned Seagreen offshore wind farm, which is located in the Firth of Forth, offshore Scotland. Issues encountered during the trial campaign are discussed and key conclusions provided.

A total of 30 trial installations were undertaken across 20 locations; these comprised 25 monotonic tests, 3 cyclic tests and 2 set down tests. Trial installations were conducted in very dense sands, overconsolidated clays and complex layered soils representative of the wide range of ground conditions present at the site. The main objectives were to prove the feasibility of suction caisson installation across the site and calibrate future predictions of installation resistance.

Successful trial installations were conducted at 19 of the 20 locations. Observations confirmed installation feasibility in various strata, including high strength clays and layered profiles, without indication of piping or plug failure. The single installation refusal highlighted that the presence of high resistance and high permeability surficial layers was a critical consideration for suction caisson installation. With this experience, isolated areas of the site were deemed unsuitable for suction caissons and mitigations planned accordingly, thereby reducing foundation installation risk.

Quantitative back-analysis of the trial installation results enabled improved site-specific predictions of foundation installation resistance, thereby further de-risking suction caisson foundation design and identifying areas for potential design optimisation. The results of the back-analysis also meant more areas of the site were considered feasible for suction caisson installation. Performance of the trial installation campaign therefore provided notable benefits to de-risking the project and to lowering overall foundation cost.

Keywords: Suction caisson, foundation installation, offshore wind

INTRODUCTION

Suction caisson foundations are an appealing foundation option for offshore wind applications given their potential economic benefits, speed of installation/decommissioning, and environmental benefits (e.g. reduced installation noise) relative to other foundation options. Furthermore, as offshore wind farms are expected to be developed in deeper water in future, the use of suction caisson foundations for offshore wind applications is expected to increase.

One of the key risks for suction caisson foundations is ensuring that they can be installed to the required penetration depth to ensure adequate in-place performance. Inability to achieve the required depth could lead to instability or geotechnical failure, so mitigation measures would need to be considered. Mitigation measures may include pressure cycling to reduce installation resistance, micrositing the structure to a new position at the current wind turbine generator (WTG) location, or relocating the structure to a spare WTG location. These mitigation measures would necessitate additional cost and time, so it is important to understand installation risk at a given site.

The Seagreen Phase 1 offshore wind farm (OWF) is planned to comprise WTGs supported by 3-legged jacket structures founded on suction caissons. To prove the feasibility of suction caisson installation at the Seagreen Phase 1 OWF site, a full-scale trial installation campaign was conducted. This campaign also aimed to improve understanding of potential installation risks at the site and calibrate future predictions of installation resistance to increase design reliability.

SITE DETAILS

The Seagreen Phase 1 OWF is located in the Firth of Forth, offshore Scotland, approximately 48 km east of Montrose. Water depths at the site range from approximately 40 m to 60 m relative to Lowest Astronomical Tide (LAT). Table 1 summarises the soil units relevant for suction caisson installation which have been identified at the site.

Table 1. Summary of inferred soil units

Soil Unit	Unit ID	General Description
Undifferentiated Holocene	A	Loose to medium dense, yellow and greyish brown, silty, fine to coarse SAND with shell fragments. Subordinate low to very high strength slightly silty CLAY layers also present.
Forth Formation	B/C	Interbedded lightly overconsolidated CLAY and SAND.
Marr Bank (undisturbed)	D_1A	Dense to very dense, dark grey, silty, fine SAND with occasional layers of clay, organic material and occasional silt.
Marr Bank (glaciotectonised)	D_1B	Similar to Unit D_1A but with more common layers of SILT and CLAY.
Wee Bankie Formation	D_2	Greyish brown and reddish brown, silty, sandy, high to extremely high strength CLAY with occasional gravel. Subordinate layers of reddish brown medium dense to very dense sand.

OVERVIEW OF TRIAL INSTALLATION CAMPAIGN

General

SPT Offshore were contracted by Seagreen Wind Energy (a wholly-owned subsidiary of SSE Renewables and the developer of the Seagreen OWF) to undertake the trial installation campaign. The primary objectives of the trial installation campaign were to prove the feasibility of suction caisson installation across the site, increase understanding of the installation-related risks, and calibrate installation resistance factors which could be used to improve design predictions of suction caisson installability. The campaign was performed between 21 March and 12 April 2019.

A total of 30 trial installations were undertaken across 20 locations; these comprised 25 monotonic tests, 3 cyclic tests and 2 set down tests. Locations were selected to obtain data in a range of different soil units and ground conditions.

Equipment

To ensure results from the trial installation campaign were directly applicable to the WTG foundations, a full-size suction caisson of comparable dimensions to the WTG suction caissons was selected. Table 2 summarises the test suction caisson properties.

Table 2. Summary of test suction caisson properties

Suction Caisson Property	Specification
Outer diameter	9.45 m
Length below top plate	7.80 m
Total height	9.44 m
Wall thickness	40 mm
Dry weight (including ballast)	305 t
Submerged weight (including ballast)	220 t
Suction inlet internal diameter	470 mm
Padeye safe working load for lifting (4x)	300 t each
Compatible pump system	SAPS-007

The uppermost part of the test suction caisson contained approximately 70 m^3 of concrete ballast to represent the additional ballast of a jacket structure. Penetration markings every 0.25 m were painted on the suction caisson every 120° circumferentially to enable Remotely Operated Vehicle (ROV) visual survey during penetration.

The vessel mobilised to conduct offshore operations was the MV Connector. This is a multi-purpose subsea construction vessel with Level III dynamic positioning, two rapidly deployable ‘Shilling HD’ underwater ROVs, a 400 t main crane for suction caisson deployment and recovery, and a secondary 50 t crane.

The main elements of the suction pump and measurement system are the 440 V, 60 Hz pump unit (SAPS-007), umbilical for pump power and communication, certified control container, open top storage container and power sheaves for controlled umbilical handling. The electric powered centrifugal pumps can produce a flow rate up to approximately 300 m^3/hour and a maximum differential pressure of 500 kPa. The pump skid was mounted and secured on the test suction caisson and interfaces via a standard SPT Offshore 20″ (0.508 m) suction inlet. Sensors mounted around the pump skid included two pressure sensors for interior and exterior water pressure, a flow meter to measure pump discharge, an inclinometer to measure the caisson pitch and roll, and an echo sounder to measure the water column inside the caisson (i.e. inferred penetration depth). There was also a reference sensor to measure water pressure at seafloor elevation.

Figure 1 presents schematics of the suction caisson and sensor equipment used in the trial campaign along with an image of its deployment from the MV Connector.

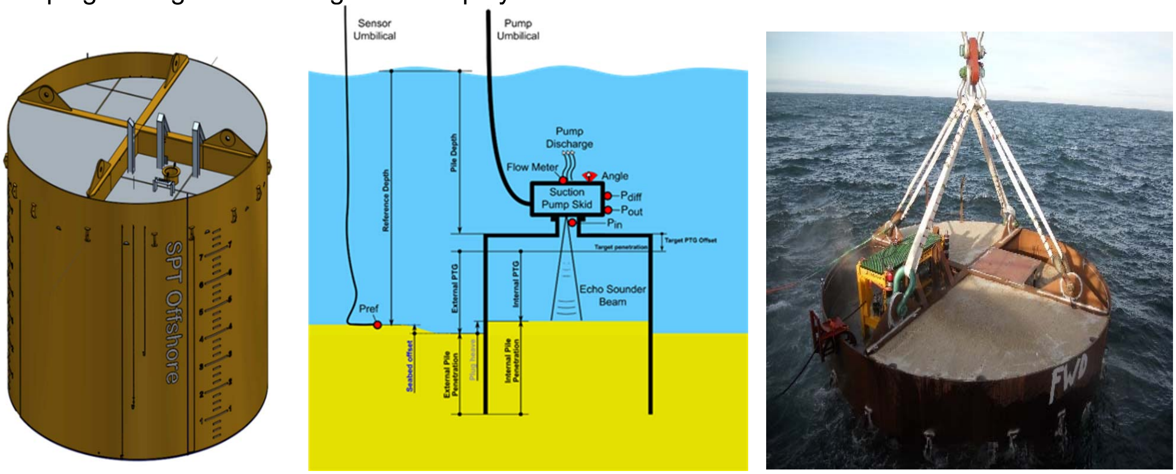

Figure 1. Equipment used during trial installation campaign and its deployment offshore

Installation Procedure

Three types of tests were performed during the trial installation campaign:

- Set down tests: these involved suction caisson set down and measurement of self-weight penetration, initiation of suction pressure to verify a good seal between suction caisson and soil, followed by retrieval;
- Monotonic tests: these involved suction caisson set down followed by continuous suction-driven penetration to target depth followed by retrieval using overpressure;
- Cyclic tests: these involved introducing several one-way or two-way pressure reversal cycles during penetration to target depth, followed by retrieval using overpressure.

Prior to undertaking each trial installation, a pre-installation ‘as found’ seabed survey was conducted using an ROV. The purpose of this pre-installation survey was to visually examine the seabed conditions and identify potential obstructions to suction caisson installation.

After confirming the seabed was free from obstructions and deciding to undertake a test, the suction caisson was lowered to 5 m above seafloor (ASF) before further lowering to the seafloor at a controlled rate. For monotonic and cyclic tests, lowering from 5 m ASF to seafloor was conducted at a rate of 1 m per minute to minimise potential installation-induced scour. The set down tests were specifically conducted to assess the potential for installation-induced scour, so the final 5 m of lowering was conducted with the 20″ vent valve closed (leaving only the 6″ discharge valve open) at the fastest rate the crane would allow. Due to crane capabilities, lowering speeds from 5 m ASF for both set down tests were 0.05 m/s; this is greater than the (theoretical) maximum safe lowering speed ($v_{lowering}$), calculated according to DNVGL (2017), of 0.004 m/s for flat seabed without pressure relief gap conditions, but less than the $v_{lowering}$ of 0.26 m/s for a 0.5° seabed slope with pressure relief at the base.

Following set down on the seafloor, the crane tension was gradually reduced to encourage self-weight penetration and the formation of a seal between the suction caisson and soil. Set down tests were terminated after establishing a seal – which was confirmed after successfully applying suction – whereas suction pressure was gradually increased in monotonic and cyclic tests to progress installation at a steady rate of penetration. To maintain control and limit tilt of the test suction caisson, a small crane tension load (minimum value of 30 t) was applied throughout suction penetration; the self-weight penetration therefore never involved the full self-weight of the test suction caisson.

Monotonic tests involved applying suction pressure until the target penetration was achieved. Once the target penetration was reached, the test suction caisson was removed by application of overpressure and increasing the crane tension. Target penetrations varied for each location as tests were specified to target specific geotechnical risks or obtain data in specific soil conditions.

Cyclic tests were performed following the performance of a monotonic test on a nearby position. The test procedure for the cyclic tests is similar to the monotonic tests except that pressure cycling was performed prior to reaching target penetration. One-way pressure cycles involved opening the valve to dissipate all suction pressure before resuming suction penetration. Two-way pressure cycles involved applying overpressure until the suction caisson was pressed out by 0.5 m, then resuming suction penetration to drive the suction caisson deeper. The depths to undertake pressure cycling were specified with consideration of the local stratigraphy and monotonic test results.

Geotechnical refusal criteria for monotonic and cyclic tests were defined as follows:

- Less than 0.05 m of penetration is achieved whilst applying the maximum allowable suction pressure for at least 5 minutes;
- Soil heave inside the suction caisson exceeds 0.5 m over 5 minutes, suggesting rapid plug uplift/plug tear.

The maximum allowable suction pressure depends on the the test suction caisson wall and top plate buckling pressures. For all soil conditions analysed, the buckling pressure of the suction caisson wall generally increased with depth until the top plate buckling pressure of 550 kPa governed.

For a suction caisson-supported jacket structure, levelling is achieved by simultaneously adjusting the pressure applied at each suction caisson: some suction caissons may be subject to overpressure while others are subject to underpressure (suction) until the structure is within its required out-of-verticality tolerance, after which suction will resume on all caissons to drive them to their target penetrations. Typically this procedure provides excellent control and allows suction caisson-supported structures to be installed to within 0.25° of vertical. For a monobucket structure, such as the test suction caisson, there are no adjacent suction caissons to assist with levelling, so a further refusal criterion of tilt exceeding 5° was applied to ensure the test results were meaningful. This tilt refusal criterion was considered a technical refusal criterion for the purposes of the trial installation campaign only, since levelling of the planned WTG jackets would be possible. Therefore, where a technical refusal due to tilt occurred, repeat tests at adjacent positions were performed.

Post-Installation In Situ Testing

To assess the effect of suction caisson installation and retrieval on the in situ soil properties, post-installation CPTs were performed within the footprint of several trial installation locations. The locations targeted were OSP1 (predominantly sand), OSP2 (predominantly sand) and T169 (predominantly clay). The time from suction caisson retrieval to undertaking the post-installation CPT was 90 days for OSP1, 82 days for OSP2, and 102 days for T169. The distance between the original and post-installation CPTs was 14.4 m for OSP1, 17.3 m for OSP2 and 7.9 m for T169.

Summary of Trial Installation Tests

Table 3 summarises the trial installation tests performed during the trial installation campaign.

Table 3. Summary of trial installation tests performed

Test No.	Location	Test Type	Water Depth (m LAT)	Final Penetration (m BSF)	Suction Time (hh:mm)	Reason for Termination
1	T166	Monotonic	57.2	6.6	02:08	Maximum pressure
2	T167	Monotonic	57.4	4.5	02:01	Target reached
3	T168	Monotonic	56.8	6.5	02:00	Target reached
4	T169	Monotonic	48.8	6.8	01:42	Target reached
5	T174	Monotonic*	53.0	5.0	04:20	Target reached
6	T175	Monotonic	53.5	4.2	01:36	Target reached
7	CPT-67	Monotonic	56.0	1.8	01:04	Tilt
8	CPT-67	Monotonic	56.0	1.2	00:34	Tilt
9	CPT-67	Monotonic	56.0	5.3	01:26	Target reached
10	CPT-24	Monotonic	57.0	4.5	01:01	Target reached
11	SCPT-37B	Monotonic	48.2	4.3	01:28	Target reached
12	OSP2	Monotonic	51.2	7.4	01:53	Target reached
13	OSP1	Monotonic	50.6	7.0	02:14	Target reached
14	CPT-22A	Monotonic	53.2	1.8	01:03	Tilt
15	CPT-22A	Monotonic*	53.2	4.2	03:12	Target reached
16	CPT-11	Monotonic	49.1	1.2	01:27	Tilt
17	CPT-11	Monotonic	49.1	4.1	02:34	Target reached
18	CPT-14B	Monotonic	51.1	3.9	01:27	Target reached
19	CPT-05	Monotonic	47.1	1.1	02:45	Tilt
20	CPT-05	Monotonic	47.1	7.2	02:41	Target reached
21	CPT-05	Cyclic	47.1	5.0	05:59	Target reached
22	CPT-08A	Monotonic	47.3	5.2	01:53	Target reached
23	CPT-32C	Monotonic	47.7	0.5	02:16	Refusal
24	SCPT-49A	Monotonic	54.2	4.2	00:57	Target reached
25	CPT-23	Monotonic	57.6	4.0	01:40	Target reached
26	CPT-23	Cyclic	57.6	5.0	02:19	Target reached
27	CPT-66	Monotonic	56.9	5.4	01:00	Target reached
28	CPT-66	Cyclic	56.9	5.0	02:30	Target reached
29	CPT-66	Set down	56.9	1.8	N/A	Target reached
30	CPT-66	Set down	56.9	2.5	N/A	Target reached

Notes:
LAT = Lowest astronomical tide
BSF = Below seafloor
* = Pressure cycling undertaken to prevent excessive monobucket tilt

BACK-ANALYSIS

One of the key aims of the trial installation campaign was to improve design predictions of suction caisson installation resistance so that installation risk could be mitigated more reliably at the design stage. DNVGL (2019) outlines a method using a direct correlation with CPT cone tip resistance (q_c) and is suitable for dense sands and overconsolidated clays, which are prevalent at the Seagreen Phase 1 site. Furthermore, as CPT data was acquired at each planned WTG jacket leg, this CPT-based approach was considered suitable for predicting suction caisson installation resistance.

The DNVGL (2019) method is based on a dataset from gravity base platforms with shallow foundation skirts (e.g. mudmat skirts) installed under their own self-weight. Due to the different nature of suction-assisted penetration, it was necessary to calibrate the DNVGL (2019) method for suction caisson installation.

In the DNVGL (2019) method, the penetration resistance (R) is calculated using Equation 1:

$$R = A_p k_p(d) q_{c,av}(d) + A_s \int_0^d k_f(z) q_{c,av}(z)\ dz \qquad [1]$$

Where A_p is the tip area of the penetrating member, d is the depth of the penetrating member, k_p is the end bearing installation resistance factor, $q_{c,av}$ is the average CPT cone tip resistance (averaged at even intervals; in this study, 0.1 m intervals were used with averaging over ±0.1 m), A_s is the side area of the penetrating member, z is depth, and k_f is the shaft friction installation resistance factor.

To calculate the required suction pressure (s), R is input to Equation 2:

$$s = \frac{4(R - W')}{\pi {D_i}^2} \qquad [2]$$

Where W' is the net submerged weight of the suction caisson (i.e. after accounting for crane tension) and D_i is the internal diameter of the suction caisson.

The installation resistance factors, k_p and k_f, are empirical coefficients. To calibrate the DNVGL (2019) method for suction caisson installation, installation resistance factors for each soil type within each soil unit were back-calculated from the measured suction pressures at each location. This back-calculation involved selecting the optimal combination of k_p and k_f factors to best match the suction pressure profiles within each soil layer at each trial installation location.

After determining the optimal k_p and k_f factors for each test location, these data were compiled into plots of k_p versus k_f for each soil type and soil unit to determine bounding values for use in future predictions of installation resistance. These bounding values would then be used in lieu of the DNVGL (2019) 'highest expected' k_p and k_f factors.

RESULTS

Set Down Tests

Figure 2 presents the measured pressure versus time for the two set down tests.

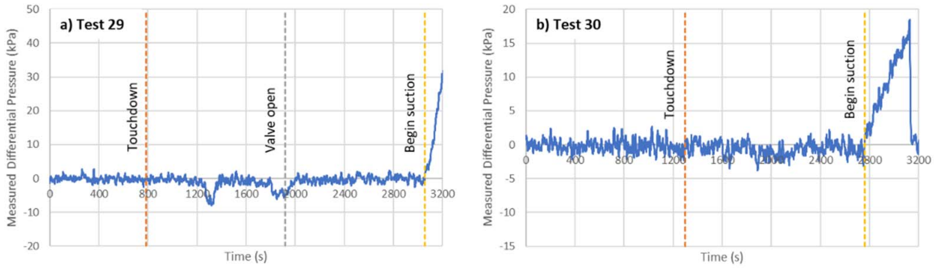

Figure 2. Evaluation of pressure build-up: (a) Test 29 and (b) Test 30

Monotonic Tests

It was hoped that flow measurements from monotonic tests could provide full-scale, in situ vertical hydraulic conductivity (k_v) data for use in design. However, given the volume measurement error of ±0.5% and echosounder measurement error of ±0.1 m, inferring k_v with these data could lead to seepage volumes being incorrect by up to 20 m^3. For some tests, inferred k_v was negative due to this inaccuracy. Back-calculating k_v from installation records is therefore considered unreliable.

Figure 3 presents the measured suction pressure versus depth for each successful (i.e. no excessive tilt or refusal) monotonic test along with the predicted suction pressure using the installation resistance factors inferred for each location. Also presented in Figure 3 is the prediction of required suction pressure using the site-wide 'highest expected' installation resistance factors.

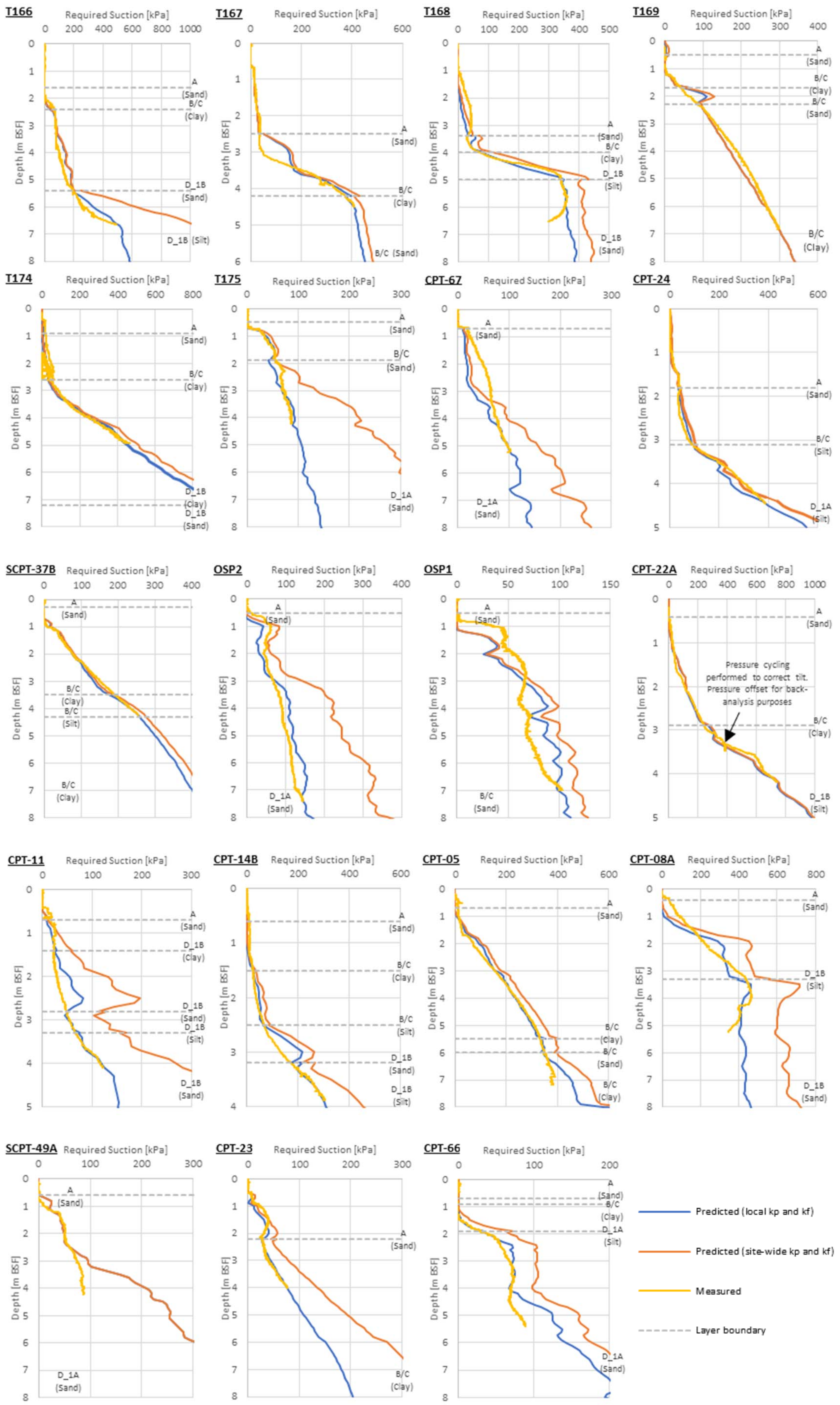

Figure 3. Comparison of measured and predicted suction pressures

Figure 4 shows the derivation of site-wide ‘highest expected’ k_p and k_f factors for each soil unit; the selected ‘highest expected’ factors are represented by black lines which bound the site-wide data. Contrary to the DNVGL (2019) method, no additional reduction was applied to k_p and k_f factors in the shallowest 1.5 m of soil; the back-calculated values implicitly account for any near-surface effects. Silt layers can be difficult to classify using CPT data and some of the data may in fact be overconsolidated, dilatant clays.

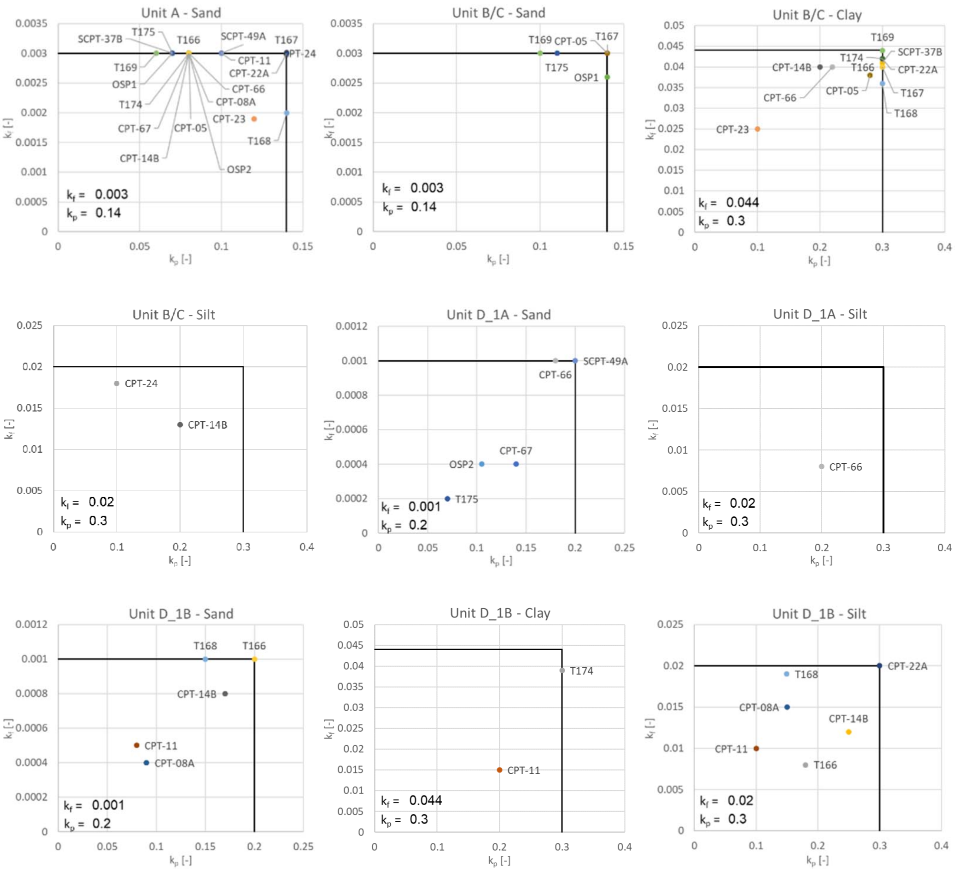

Figure 4. k_p-k_f scatter graphs for each soil unit with selected highest expected values

Plug heave was calculated as the difference between the penetration measured with the echosounder inside the suction caisson minus the penetration measured with the pressure sensors outside the suction caisson at the end of monotonic penetration; negative values therefore indicate the soil level inside the caisson is higher than outside. For some tests, the results were affected by unstable variations of the reference sensor signal. This was caused by the reference sensor lifting from the seabed due to current drag (‘flying’). Table 4 summarises the valid plug heave results.

Table 4. Plug heave results at the end of monotonic penetration

Test Number	Location	Plug Heave (m)
2	T167	0.0
6	T175	-0.3
11	SCPT-37B	-0.6
12	OSP2	-0.1
13	OSP1	0.0
15	CPT-22A	+0.5
17	CPT-11	+0.6
20	CPT-05	+0.4
24	SCPT-49A	-0.1
25	CPT-23	-0.1
27	CPT-66	+0.1

Cyclic Tests

The effect of pressure cycling was considered in two ways:

- The change in required suction when returning to the same depth after each cycle;
- The additional depth required to achieve the same suction pressure as before cycling.

Due to complications during the monotonic test at location T174 (Test 5), it was necessary to apply pressure cycling, so these results were also considered to assess pressure cycling effects. Table 5 summarises pressure cycling results. Inferred plug heave data at full penetration are also provided for comparison to monotonic results; plug heave data for T174 was unreliable.

Table 5. Summary of cyclic test results

Location	Cycle No.	Cycling Type	Predominant Soil Type	Change in Required Suction (%)	Additional Depth Achieved (m)	Plug Heave (m)
T174	1	One-way	Clay	-9	0.2	–
	2	Two-way		-57	0.8	
CPT-05	1	Two-way	Clay	-46	0.8	+0.1
	2	Two-way		-17	0.2	
	3	Two-way		-15	0.2	
CPT-23	1	Two-way	Clay	-57	0.3	-0.5
	2	Two-way		-35	0.2	
	3	Two-way		-20	0.2	
CPT-66	1	Two-way	Sand	0	0.0	+0.9
	2	Two-way		-29	0.1	
	3	Two-way		-9	0.0	

CPT Data Before and After Trial Installations

Figure 5 compares CPT data obtained before and after several trial installations.

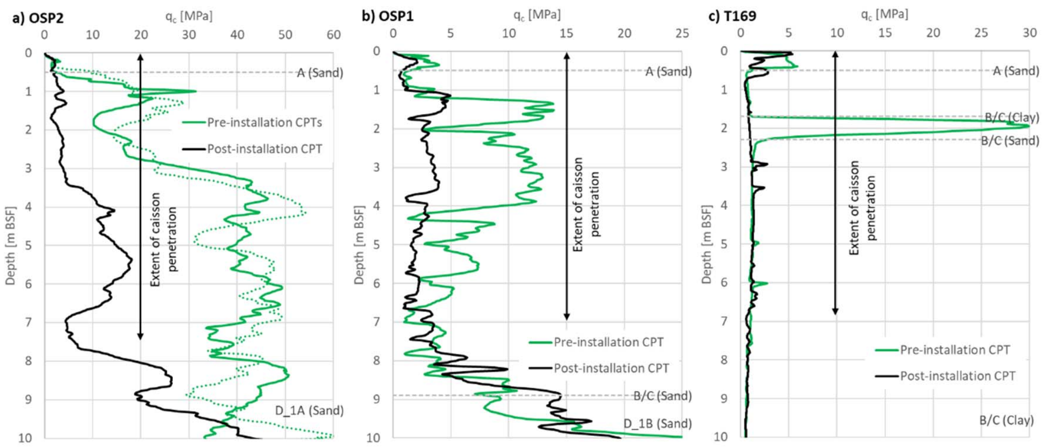

Figure 5. Comparison of pre-installation and post-installation CPTs: (a) OSP2; (b) OSP1; (c) T169

DISCUSSION

Set Down Tests

Set down tests were only performed at location CPT-66 since this location had loose surficial sand which would be most susceptible to installation-induced scour. Lowering stages of other tests can also be used to assess installation-induced scour, but CPT-66 was planned as a worst-case.

The ROV footage indicated no significant soil disturbance during the set down tests. The measured pressure data in Figure 2 also indicate negligible pressure change before and immediately after touchdown. In tests with significant tilt, ROV footage and sonar imaging indicated that soil gapping occurred. Excessive tilt should therefore be avoided to minimise gapping.

Back-analysis
The back-analysis results presented in Figure 3 show a generally good match to the measured data. Discrepancies may be due to local soil variation or shortcomings of the relatively simplistic DNVGL (2019) method. The derived 'highest expected' k_p and k_f factors from Figure 4 are lower than recommended for the DNVGL (2019) method though still lead to conservative results – particularly for predominantly sand locations, where some significant overpredictions are observed. Overpredictions in predominantly sand locations are likely the result of the DNVGL (2019) method not explicitly accounting for potentially beneficial flow effects. Reductions to the installation resistance factors are understandable given the nature of suction-assisted installation, which involves weakening the soil adjacent to the suction caisson wall by inflow of water.

After several tests were performed, the test suction caisson was observed to have become smoother due to soil abrasion. However, no clear trend was found between installation sequence and k_f.

Plug Heave
There was no clear relationship between soil type and amount of plug heave. Four trial installations appeared to indicate plug sinkage occurred. However, instances of apparent plug sinkage occurred at locations where tilt at the final penetration was relatively large. The relatively large tilt coupled with undulating seafloor may explain this apparent plug sinkage.

Tilt
Several tests were terminated early due to excessive tilt of the suction caisson and were subsequently repeated. The excessive tilt was believed to have been caused by laterally variable soil layering across the suction caisson plan area. Such lateral variability results in the installation resistance profile varying laterally across the suction caisson plan area, with tilt occurring as the suction caisson penetrates relatively more through the weaker soils.

It should be noted that tilting of a monobucket foundation, such as used during the trial installation campaign, is not comparable to tilting of a multi-legged suction caisson-supported jacket structure due to the rigid connection to the jacket structure and adjacent suction caissons. Furthermore, any tilting during jacket installation can be corrected by varying the suction pressure between adjacent suction caissons.

Refusal at Location CPT-32C (Test 23)
The only test to experience a geotechnical refusal was location CPT-32C (Test 23). At this location it was not possible to form a seal and drive the suction caisson to depth with suction pressure. A seal could not be formed because of the presence of surficial cobbles and gravel, which were clearly observed from ROV footage. It was therefore not possible to test in the Wee Bankie formation.

The presence of high strength, high permeability surficial layers is considered critical to the feasibility of suction caisson installations. CPT data alone could not be used to reliably determine the presence of surficial cobbles and gravel. Additional characterisation effort is therefore recommended to identify such ground conditions. This may involve sampling the surficial soils or integrating in situ test data with geophysical data to improve surficial soil characterisation.

Evaluation of Results from Cyclic Testing
The following observations are made regarding suction caisson pressure cycling:

- In clayey soils, pressure cycling leads to a significant reduction in differential pressure after cycling – particularly for the first cycle where the change in differential pressure before and after cycling was approximately 50 %. Subsequent cycles proved less effective;
- In clayey soils, two-way pressure cycling was significantly more effective than one-way pressure cycling at reducing penetration resistance. This is explained by the lack of overpressure, which means that there is no upwards vertical displacement and therefore less remoulding of the soil at the suction caisson-soil interface;
- In sandy soils, pressure cycling was less effective in terms of reducing penetration resistance. This is explained by the relatively lower frictional resistance in sandy soils.

Effect of Suction Caisson Installation and Retrieval on Soil Properties

For sandy soils, CPT data suggest substantial soil plug loosening following suction caisson retrieval. These effects are observed even after 3 months. This soil plug loosening is likely caused by the upwards flow that occurs during suction installation. However, it should be noted that these effects were observed on a soil plug after suction caisson retrieval, so the plug was no longer confined. Moreover, the results presented in Figure 5 are not directly applicable for a suction caisson which remains in-place.

For clayey soils, no significant changes to soil plug properties were observed following retrieval of the suction caisson. This can be explained by the relatively lower permeability and localised failure at the suction caisson-soil interface.

The above observations suggest suction caisson retrieval from sandy soil profiles can leave a locally weaker soil zone (i.e. a 'footprint'), which may subsequently interact with other foundations. Potential interaction with a suction caisson footprint should therefore be considered in design, particularly if local micrositing is considered as a mitigation for suction caisson installation refusal.

CONCLUSIONS

The trial installation campaign demonstrated that suction caissons could be installed in a range of different ground conditions at the Seagreen Phase 1 OWF. Understanding of different installation risks was also improved by conducting the trial installation campaign.

The following high-level conclusions are made:

- No significant soil disturbance was observed during set down of suction caissons. However, soil gapping was observed where excessive suction caisson tilt occurred;
- Site-specific 'highest expected' k_p and k_f installation resistance factors were derived to improve predictions of suction caisson installation resistance using the DNVGL (2019) method (see Figure 4). The alternative installation resistance factors are lower than recommended by DNVGL (2019), though still lead to reasonable predictions of required suction pressure. Overpredictions of installation resistance for sandy soil profiles may be the result of the DNVGL (2019) method not explicitly accounting for potentially beneficial flow effects;
- There was no clear relationship between soil type and amount of plug heave;
- Monobucket foundations are susceptible to excessive tilting, which is believed to be caused by laterally variable soil layering across the monobucket plan area. Tilting of a monobucket is not comparable to tilting of a multi-legged suction caisson-supported jacket structure;
- The presence of high strength, high permeability surficial layers (e.g. cobbles and gravels) is critical to the feasibility of suction caisson installation. Additional characterisation effort is therefore recommended to identify such ground conditions;
- Two-way pressure cycling is shown to be an effective mitigation measure to overcome high soil resistance, particularly in clayey soils. One-way pressure cycling is less effective;
- Significant soil plug loosening can occur in sandy soils following caisson installation and retrieval. No significant effect was observed in clayey soils. Potential suction caisson footprint interaction is considered possible following retrieval of a suction caisson foundation from sandy soils.

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