OPTIMIZATION OF SOIL INVESTIGATION FOR ENHANCED SITE-SPECIFIC ASSESSMENT OF JACK-UP PLATFORMS USING AN EXISTING DATABASE

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ABSTRACT
For the site-specific assessment of jack-up platforms with skirted spudcans, it is recommended to carry out site-investigation campaigns to acquire information about the sub-soil beneath each spudcan footprint with a cone penetration testing (CPT) complemented by a sampling borehole. The recommended depth of CPTs and boreholes are independent of the layering and soil properties. However, the depth of influence on the capacity and stiffness (fixity) of a spudcan heavily depends on the shear strength and stiffness changes/contrast of the soil layers. This paper illustrates possible optimization of an ongoing soil investigation campaign and planning of laboratory testing programs using static and cyclic soil parameter estimates based on published databases and utilizing finite element capacity and stiffness calculations. As a result, uncertainties, excessive utilization of resources, time and cost (i.e. uncertainties of soil parameters, length of boreholes/amount of samples collected and tested) can be reduced.

KEYWORDS: soil investigation, optimization, site-specific assessment, skirted spudcans, foundation capacity, fixity, cyclic behaviour, finite element analyses.

INTRODUCTION

Jack-up rigs are widely utilized as mobile offshore units for the exploration and production of hydrocarbons to installation of wind turbines. *Site-specific assessment* (SSA) of the jack-ups is required as recommended in [1] and [2].

For detailed information regarding finite element-based skirted spudcan analyses, the readers are referred to the following references:
 - [3] to understand the finite element (FE) procedure utilizing cyclic contour diagrams to calculate foundation fixity in comparison to the ISO approach [1],
 - [4] to study the important aspects of the site-specific analyses from a geotechnical point of view, and
 - [5] to consider the uncertainties of input parameters and their significance on the estimated foundation capacity, fixity, and damping.

Such assessment requires site-specific ground investigations. As summarized in [6], SSA generally comprises:

- Acquisition of geological and geotechnical data
- Geological desk study to develop the ground model
- Geophysical site survey for the refinement of the ground model
- Geotechnical site investigation (SI) for further refinement of the ground model
- Generation of geotechnical design profiles and engineering parameters
- Jack-up foundation analyses based on the established engineering parameters.

In addition, the latest seabed bathymetry information is essential to evaluate unevenness, seabed-spudcan interaction or potential slope instabilities.

For the geotechnical site investigation (SI) planning and execution, the industry generally adopts the recommendation regarding the selection of the number, location and depth of field tests and sampling boreholes

[6] (Figure 1) and [1]. At larger water depths (e.g. >100m in the North Sea where most of the drilling jack-ups are operating), jack-up legs can be utilized significantly, and moment fixities need to be considered. For that purpose, piezocone tests (CPTu) at each leg location with a minimum depth of the largest of 1.5 times the spudcan diameter + anticipated spudcan penetration or 30m. To characterize the soil properties (both static and cyclic), a sampling borehole is selected generally near the most critical leg in terms of leg utilization or the most concerning soil profile in terms of static and cyclic properties.

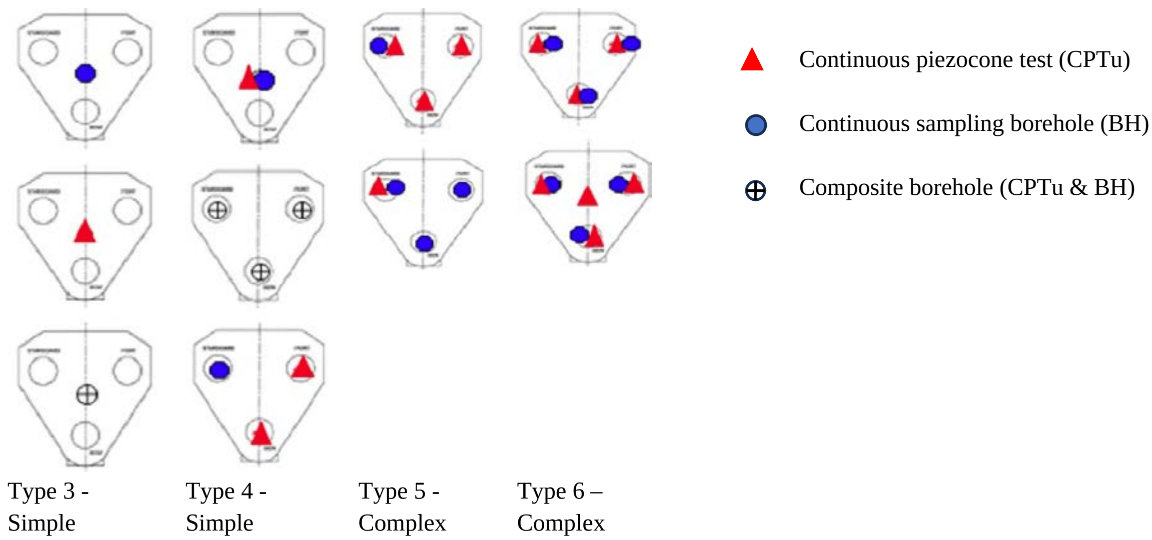


Figure 1 Example industry adopted guidelines for the geotechnical work scope for open locations for simple to complex geological settings after [3]

CPTu provides a good basis for identifying possible problematic layers (e.g. soft clays, loose to medium-dense silty sands) and should be performed prior to the sampling. Therefore, live (on-site) engineering is important to verify and if necessary, change the location of the sampling borehole if the CPTu data obtained during the SI campaign indicate more critical layers in a particular leg location. The shallow soil layers beneath the spudcans will have the largest influence on the foundation response. Hence enough soil samples should be collected for lab testing. Furthermore, the engineer can utilize databases for conservatively estimating static and cyclic soil parameters necessary for the calculation of foundation capacity and fixity using finite element analyses (FEA), which can provide valuable information regarding the most critical soil layers based on mobilizations. As a result, the SI campaign can be optimized by focusing on those layers, especially during sampling.

This paper illustrates possible optimization of an ongoing soil investigation campaign and planning of laboratory testing programs using static and cyclic soil parameter estimates based on published databases and utilizing finite element capacity and stiffness calculations. As a result, uncertainties, excessive utilization of resources, time and cost (i.e. uncertainties of soil parameters, length of boreholes/amount of samples collected and tested) can be reduced.

METHODOLOGY

This section summarizes the simplified workflow for the assessment of critical layers utilizing the procedure exemplified in [7], using an existing database [8], [9] and [10] to estimate static and cyclic soil parameters and finite element analyses.

The methodology proposed herein consists of the following stages, which are outlined in Figure 2:

1) Estimation of design profiles
2) Estimation of static and cyclic parameters using an existing database
3) Finite element analysis (FEA) of static and cyclic vertical capacity
4) Finite element analysis (FEA) of foundation stiffness (where fixity and/or damping is of significance)

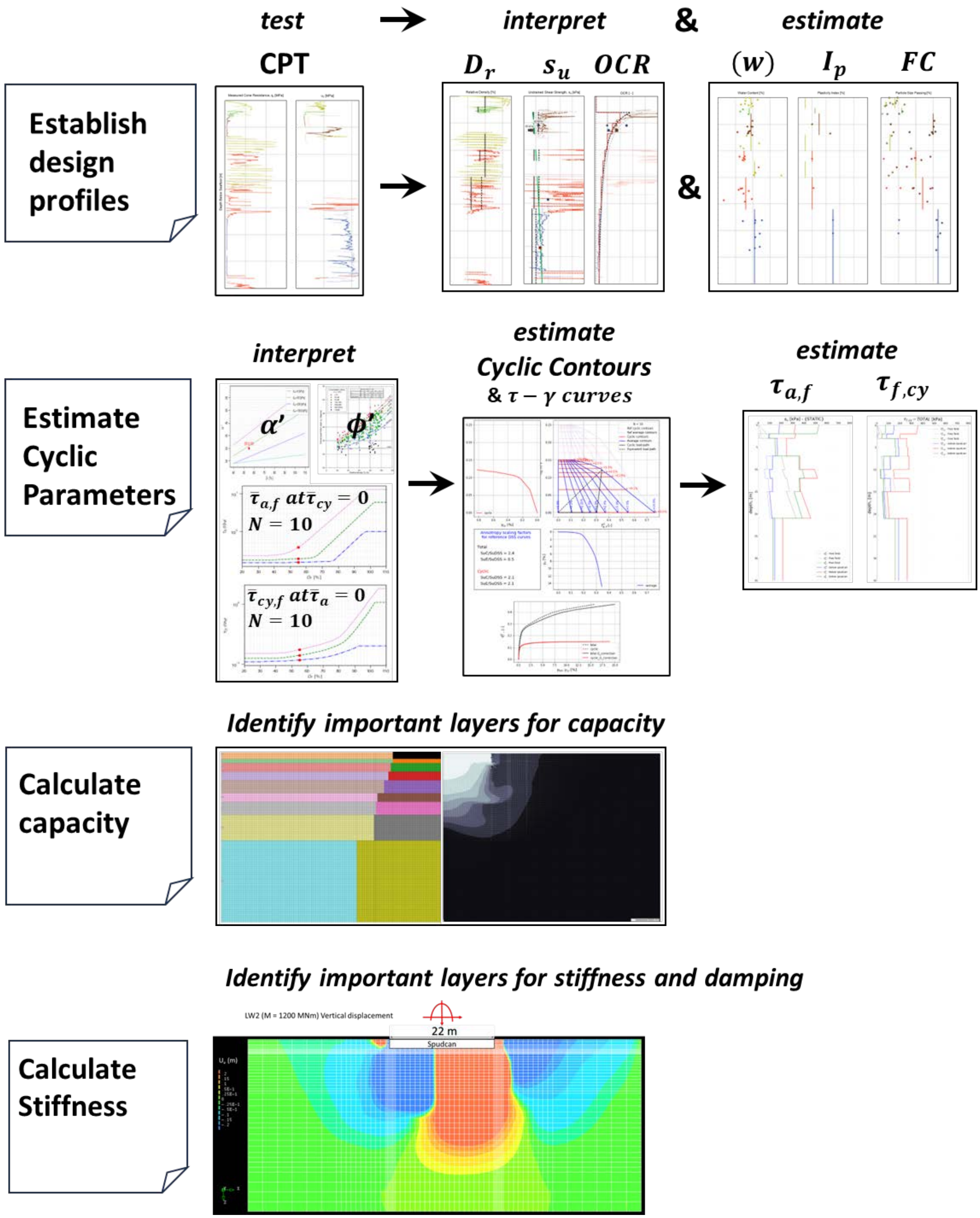


Figure 2 Workflow for the assessment of critical layers based on the design profiles estimated from on-site CPTu data using an existing database presented in [8], [9] and [10].

Estimation of design profiles

Empirical correlations (e.g. evaluation of relative density, D_r, in sands [11] including fines correction proposed by [12] and [13]) can be employed to estimate necessary relative density and shear strength profiles. In addition, based on the engineering interpretation index properties such as fines content (FC) and plasticity index (Ip) can be conservatively estimated (e.g. [9] presented that FC=35% results in the lowest shear strength, and stiffness).

Estimation of static and cyclic parameters using an existing database

[7] provides detailed examples for estimating static and cyclic parameters for sand and clay soils. The necessary input parameters for the database are listed in Table 1.

Table 1 Input parameters necessary for utilizing [8], [9] and [10] databases.

Clays	Sands (and silts)
vertical effective stress (σ'_{vc})	vertical effective stress (σ'_{vc})
undrained shear strength (s_u)	relative density (D_r) and/or water content (w)
plasticity index (I_p)	fines content (FC)
overconsolidation ratio (OCR)	overconsolidation ratio (OCR)

Understanding the drainage (permeability and compressibility) is also important to estimate consolidation levels beneath the spudcan.

Finite element analysis (FEA) of static and cyclic vertical capacity

An axisymmetric FE analysis using the estimated static and cyclic properties can be employed to check vertical capacities and more importantly, critical layers that would affect the capacity and fixity of the spudcan. In this paper, we have utilized the SWIFT tool (python scripts) for running the internal FE software BIFURC [14], which accounts for the different consolidation stresses beneath the spudcan (simplified with 1:3 (horizontal:vertical) load spread).

Finite element analysis (FEA) of foundation stiffness (if possible)

A more elaborate approach for analysing the layers that might affect the fixity is running stiffness calculations for possible critical load cases (e.g. leeward leg loads). The SWIFT tool (python scripts) can be also used for running the internal FE software INFIDEP [15]. The input requires the initial shear stiffness, G_{max} and the stress-strain ($\tau - \gamma$) curves estimation for the zones beneath the foundation and free field. Mobilisation plots as well as $\tau - \gamma$ can provide good insight into the depth of influence, which can aid decision-making on sampling depths and amounts.

The following section provides an example case of how the proposed methodology has been utilized in an actual SI campaign.

EXAMPLE CASE

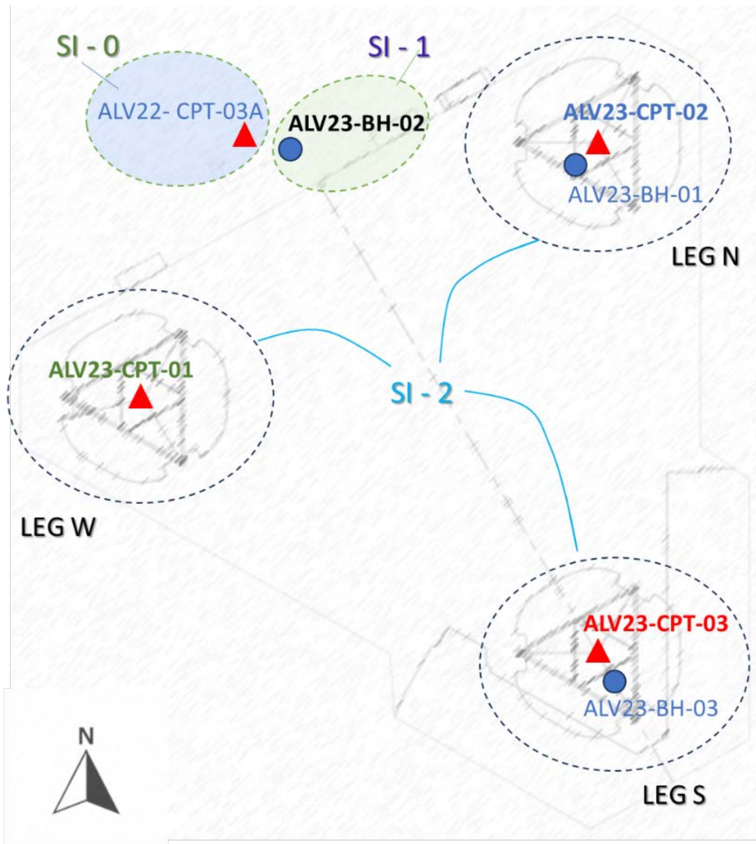
Jack-up and site information

The example case is from a recent site investigation campaign at the Alvheim-Deep in the Alvheim area in the Norwegian sector of the North Sea regarding Aker BP's planning for drilling activities a jack-up rig. The water depth in the investigated area is around 120 m relative to Mean Sea Level. Alvheim is a subsea field tied back to Alvheim floating production storage and offloading (FPSO).

A geotechnical site investigation for jack-up placement was planned in March 2023, with the following objectives:

- Characterising the ground conditions at the proposed locations,
- Determine the thickness/extents/variability of geotechnical layers; and
- Obtain the necessary data and seabed samples so that geotechnical properties required for the design/assessment of proposed infrastructure can be derived.

Figure 3 presents the CPTu and BH locations as well as the jack-up spudcan information. Leg N as anticipated leeward (LW) leg (with the largest vertical load, Westerly storm directions), was the focus of the SI for collecting site-specific data to reduce the uncertainty.



	Value	unit
Spudcan diameter	~22	m
Spudcan area	~380	m^2
Skirt length	2	m
Inner skirt length	1	m
SWL	14000	$tons$
Preload	21000	$tons$
Ave. water depth	~120	m

Figure 3 a. Location of CPTs and sampling boreholes for jack-up orientation from different SI campaigns.
b. Approximate jack-up geometry info and foundation loads.

Prior to the SI campaign, a reference CPT at the production well was available, which indicated medium to dense sandy soils thickly laminated with silt and clay. A de-risk CPT campaign was carried out (ALV23-BH-02) based on prior but limited knowledge of the area (i.e. ALV22-CPT-03A). The sampling (ALV23-BH-02) had to be terminated at 7.8 m and the actual SI scope had to be postponed due to weather and equipment limitations.

During the 2nd offshore campaign, operational conditions were much more favourable. On the other hand, the CPTu indicated weaker soil layering down to 16m at the south leg. Hence, the SI was revised to have an additional sampling borehole at Leg S, where the SI optimization was reducing uncertainty instead of reducing sampling volume.

The summary of the CPT and BH work scope and realizations are given in Table 2 in execution order.

Table 2 CPT and BH work scope summary from two complementary SI campaigns in execution order

SI campaign	Location ID	Piezocone Test/ Sampling	Penetration (m) Target	Penetration (m) Actual	Sample Recovery (m)
0*	ALV22-CPT-03A*	Continuous CPTu	25	25.2	-
1	ALV23-BH-02	Continuous sampling	35	7.8	3.7
	ALV23-CPT-03	Continuous CPTu	35	33.9	33.1
	ALV23-CPT-02	Continuous CPTu	35	35	33.2
2	ALV23-CPT-01	Continuous CPTu	35	35.4	34.4
	ALV23-BH-01	Continuous sampling	35	32.8	17.6
	ALV23-BH-03	Continuous sampling	16	15.5	4.1

** CPTu from a different scope*

Estimation of static and cyclic parameters using an existing database

Figure 4 presents the CPTu and relative density (D_r) profiles established at the beginning of the first SI campaign to study the relative importance of different layers. Similarly, Figure 5 presents the CPTu and D_r profiles during the second SI campaign. Weaker spots were identified at Leg S, from ALV23-CPT-03. A D_r profile accounting for the weakest zones, with conservative estimates of FC based on available index data and pore pressure responses were used to estimate static and cyclic shear strength using RedWin2 [16] – CPTU2Soil tool in which [8], [9] and [10] databases are implemented. Details of such procedure are exemplified in [7]. For the sake of conciseness, the plots of intermediate steps of the procedure are not presented in this paper. The procedure can account for a higher OCR by a correction factor, which can increase the cyclic and static shear strengths significantly when the soil behaves undrained. On the other hand, the stiffness needs to be reduced for $OCR > 1$. In the example case, an $OCR = 1$ is assumed for the sake of conservatism (i.e. in the capacity calculations). Hence no OCR correction is applied on the estimated shear strengths.

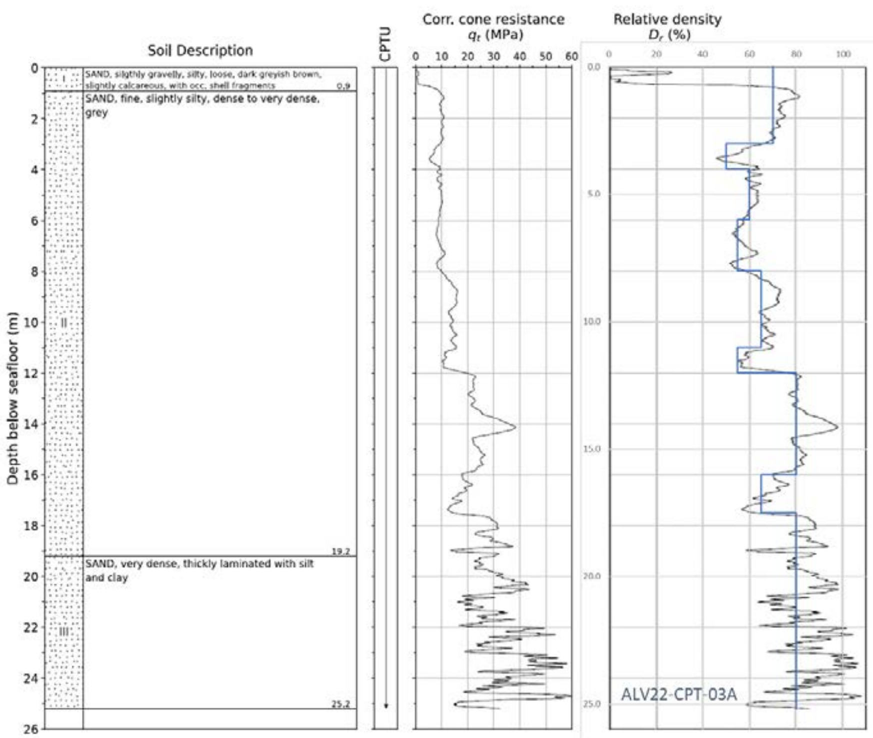


Figure 4 CPTu, simplified and more refined relative density profiles based on ALV22-CPT-03A (PWL location) prior to the SI campaign

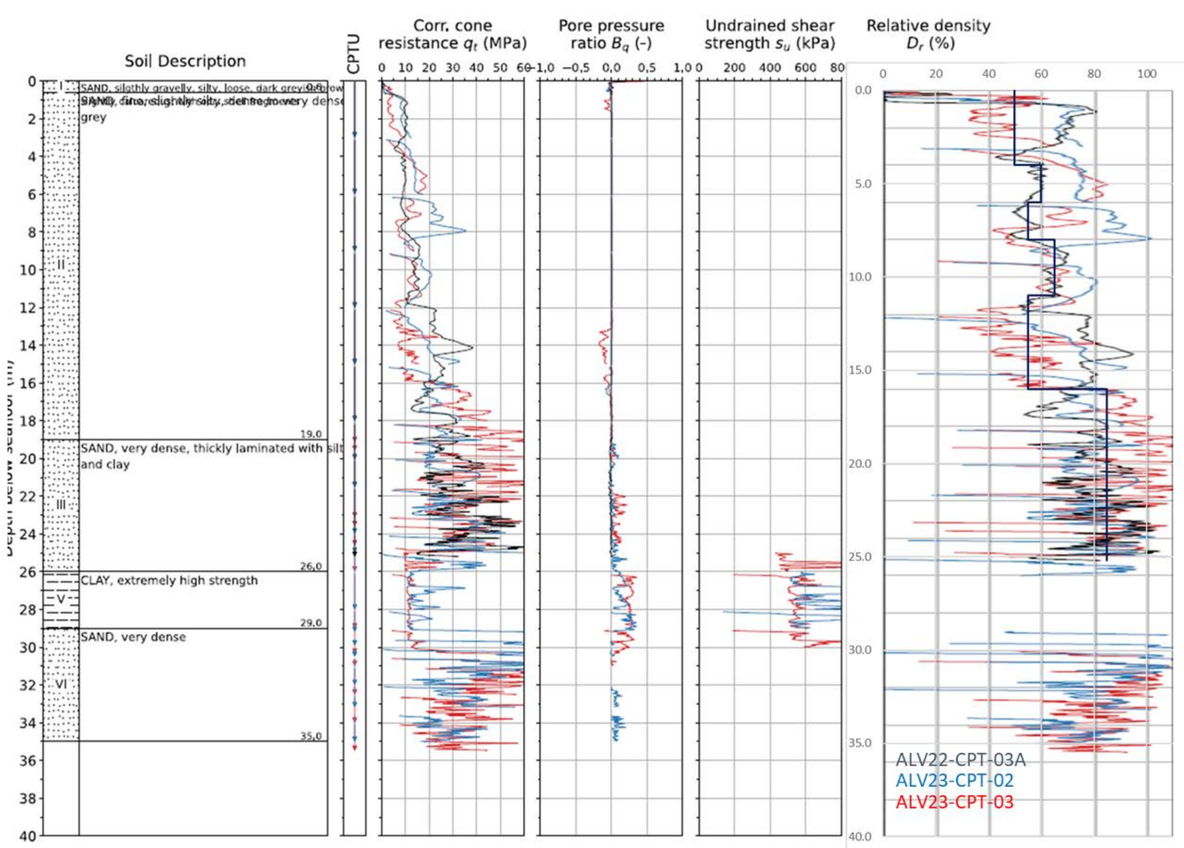


Figure 5 CPTu and refined relative density profiles based on CPTu data at all leg locations

Table 3 Summary of soil units and index parameters based on the interpretation report

Soil unit	Depth range below the seafloor (m)	General soil description	w %	I_p %	Clay content %	FC %
I	0.0 – 2.5	SAND, silty, clayey, loose to medium dense, with occasional presence of thin to thick laminae of clay	27.0	-	6	20.0
II	0.6 – 19.0	SAND, medium dense to very dense	24.0	-	-	3.0
IIIa	11.5 – 15.9	SAND/SILT, very clayey. Some sub-samples are at the borderline of clay and silt.	22.0	non-plastic[3)]	11.0	38.0
IIIb	15.9 – 20.0	SAND, very dense	23.0[2)]	-	-	3.0[2)]
IIIc	18.7 – 26.0	CLAY, silty, sandy, extremely high strength, with extremely closely spaced thin to thick laminae of silt or sand, q_t > 20 MPa	18.0	13.5	24.9	67.9
IV	24.0 – 33.0	CLAY, silty, sandy, extremely high strength, with extremely closely spaced thin to thick laminae of silt or sand, q_t > 10 MPa	15.0	18.0	30.0	83.2
V	29.0 – 35.5	CLAY, extremely high strength	20.0	17.0	17.5	66.2

1) Representative value.
2) Estimated value based on engineering judgement.
3) Not measurable in the lab due to high silt and sand content.

Table 4 Summary of depths below the seafloor for each of the soil units at the different boreholes

		Location groups							
		Leg-W		Leg-N		Leg-S		PWL	
Soil unit	Main soil type	Top (m)	Bot (m)	Top (m)	Bot (m)	Top (m)	Bot (m)	Top (m)	Bot (m)
I	SAND	0.0	0.7	0.0	0.6	0.0	2.5	0.0	0.7
II	SAND	0.7	18.7	0.6	19.0	2.5	11.5	0.7	19.0
IIIa	SAND/SILT					11.5	15.9		
IIIb	SAND					15.9	20.0		
IIIc	CLAY	18.7	24.0	19.0	26.0	20.0	25.0	19.0	25.2[1)]
IV	CLAY	24.0	33.0	26.0	29.0	25.0	30.1		
V	CLAY	33.0	33.9[1)]	29.0	35.0[1)]	30.1	35.5[1)]		

1) End of borehole, not necessarily end of unit

At an early stage of an SSA, i.e. SI stage, in general, there is limited or no load storm history, as well as drainage and compressibility info. The level of cyclic degradation was considered using an equivalent number of cycles, $N_{eq} = 10$ since in many cases the number from a cyclic accumulation calculation ends up around such value.

Finite element analysis (FEA) of static and cyclic vertical capacity

FEA of vertical capacity calculations considering isotropic static and cyclic soil parameters indicate an influence depth down to about 15 m (~0.7D) depth, in Figures 6 and 7, respectively. Furthermore, the silty layer (at Leg S) ~11-15m could be quite weak if there would not be any consolidation under the still water load (SWL). Figure 8 shows the benefits of considering anisotropic shear strength, yet highlights potential weak layers between 11-15m. Hence, during the SI campaign, we decided to add another sampling borehole (ALV23-BH-03) at Leg S to collect the necessary amounts of samples from this unit.

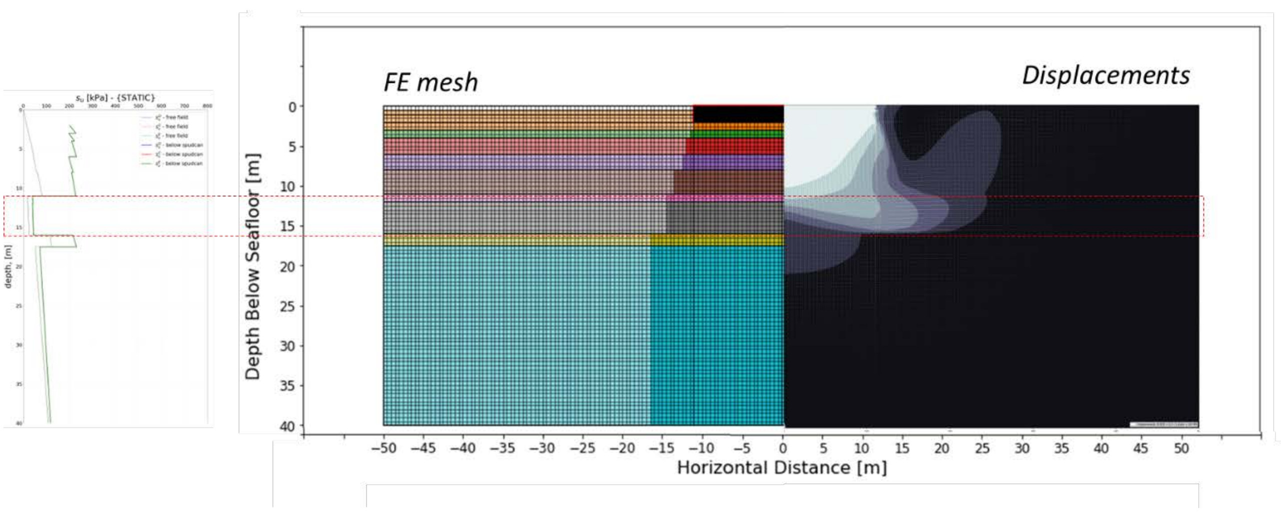


Figure 6 Isotropic static shear strength profiles beneath the spudcan and free field, FE model and displacement contours at capacity

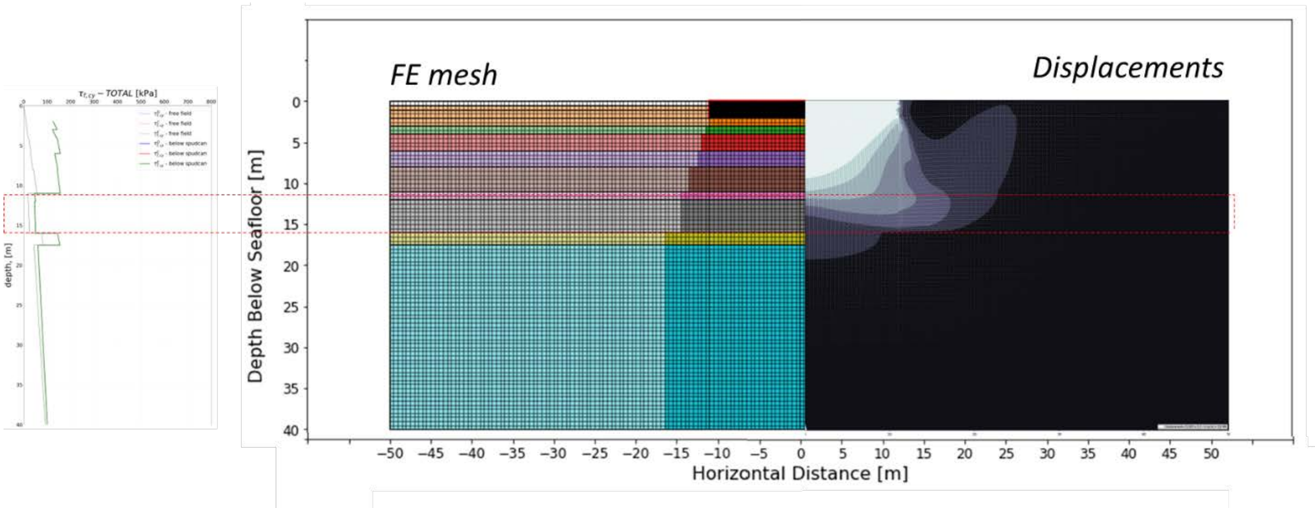


Figure 7 Isotropic (total) cyclic shear strength profiles beneath the spudcan and free field, FE model and displacement contours at capacity

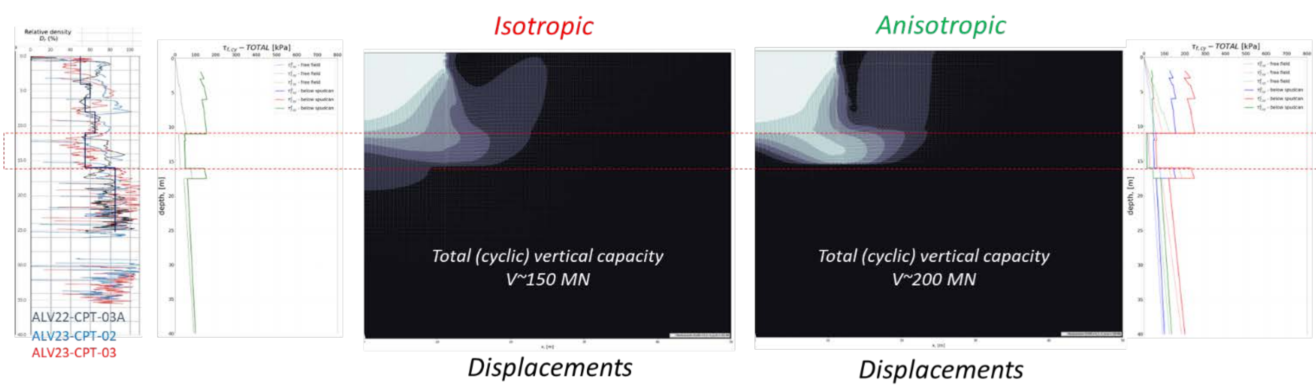


Figure 8 Comparison of displacement contours at capacity from isotropic and anisotropic (total) cyclic shear strength profiles beneath the spudcan and free field.

Finite element analysis (FEA) of foundation stiffness

Stiffness may require info to greater depth than capacity, and it can be non-conservative to base the sampling depth on capacity. We ensured sampling down to 35m following the scope of work. We couldn't study the effects of different layers in terms of their significance to the foundation stiffness due to limited time.

The cyclic parameters established based on the samples from the site confirmed the benefit of the additional borehole (ALV23-BH-03), which was important to sample, and that might have been left out if there had not been geotechnicians onboard. The corresponding cyclic lab testing (on intact samples), indicated better shear strength and stiffness compared to conservatively estimated cyclic parameters employing the database (using RedWin2) due to differences in the D_r, OCR, σ'_{vc}, structure, mineralogy and particle size distribution of site-specific and database sands.

CONCLUSIONS

Soil investigations are essential for geotechnical assessments of jack-up foundations. A successful SI should provide a good resolution of the mechanical behaviour of the soil layers affecting the foundation response, for capacity, stiffness, and damping, e.g., utilizing high-quality and relevant field and laboratory measurements. The process is bound by operational (weather, vessel, personnel, time, budget, etc.) constraints and should account for various levels of uncertainty. Previous and/or neighbouring site data/experience can provide valuable data for planning the SI campaign. In addition, on-site engineering will help with better execution of the field testing and sampling by reviewing and revising the plan based on the most recent/live data.

With this paper, we have presented a finite element and (cyclic) database utilized procedure to aid optimal selection of the location, depth, and number of samples during a site investigation campaign with an example case from the North Sea. In the example case, the SI was revised to collect more samples to study a silty and weaker soil unit that potentially affects the foundation capacity and fixity, which was important to sample, and that might have been left out if there had not been geotechnicians onboard. The lab results showed higher cyclic shear strength than that of conservatively estimated values during the SI campaign.

To summarise, SI campaigns for SSA of jack-up foundations can be optimized by on-site engineering utilizing a cyclic database with FE, which can help identify important layers, ensuring sufficient CPTu, collection of samples and avoiding re-visiting the site for further collection of samples due to lately identified foundation capacity or stiffness issues. Furthermore, the methodology presented here can be utilized for optimizing lab testing considering critical and anticipated geotechnical conditions, i.e. drained/undrained, consolidation stress levels, stress paths, etc.

ACKNOWLEDGEMENTS

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