# QUALITATIVE ASSESSMENT OF UNCERTAINTIES IN ESTIMATION AND MODELLING OF CYCLIC DESIGN PARAMETERS, AND THE CONSEQUENCES ON CALCULATED SPUDCAN FOUNDATION CAPACITY AND STIFFNESSES OF JACK-UP PLATFORMS

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ABSTRACT
Site-specific assessment of jack-up platforms with skirted spudcans may require advanced geotechnical foundation analyses, especially at large water depths, where foundation stiffnesses (fixities/soil springs) dictate dynamic behaviour and structural utilization of jack-up platforms. For these analyses, it is essential to consider the non-linear behaviour of the soil layers under combined average and cyclic loading. The effective stress change during different operational stages of the jack-up is essential for the foundation behaviour, and the drainage characteristics of the soil is an essential part of the assessment. NGI have compiled a database of different soil parameters based on laboratory tests and experience from research and offshore design projects, and developed methodologies to estimate the cyclic behaviour of sandy and clayey soils based on this database when site-specific data is limited or lacking. The methods employ index characteristics such as relative density ($D_r$), plasticity index ($I_P$), water content ($w$), fines content ($FC$) as well as undrained shear strength and overconsolidation ratio (OCR) as a basis. When selecting design profiles and parameters to be employed in the assessments, different levels of uncertainties are inevitably introduced. The idealization of the established soil properties by a constitutive model introduces another level of uncertainty. The finite element analyses employed for the calculation of foundation stiffness and capacities also have uncertainties due to discretization errors. This paper discusses, qualitatively, the uncertainties in the soil parameter estimation and modelling and the consequences this can have on calculated foundation capacity and stiffnesses.

KEYWORDS: site-specific assessment, skirted spudcans, jack-up, foundation capacity, fixity, cyclic behaviour, finite element analyses.

## INTRODUCTION

Jack-up rigs with skirted spudcans are widely used as mobile drilling, installation, or accommodation units. Utilization of foundation loads that are larger than preload is mostly inevitable at large water depths. Hence, taking into account the cyclic capacity and the moment fixity of the footings to reduce the critical moment in the lower leg guides, reducing the inertia forces (i.e. increasing the natural frequency of the platform) and reducing the second-order moment in the leg ($p - \Delta$ effect) is essential. [1] compared industry practice [2] with a procedure that accounts for the complex behaviour of soil subjected to combined average and cyclic loading for undrained behaviour. [3] also compared the existing recommended practice for jack-up platforms [2] with a similar procedure that accounts for the complex behaviour of soil subjected to combined average and cyclic loading considering partial drainage. They verified their procedure by back calculating the behaviour of a gravity-based structure (GBS) model test on soft clay subjected to cyclic loading and demonstrated that the procedure is also suited for cases where the cyclic degradation varies within the soil mass (as for instance monopile foundations). [4] demonstrated the benefit of employing non-linear foundation response in the dynamic amplification calculation of jack-up structures. Their method utilizes hysteretic soil damping and cyclic stiffnesses that are calculated by the finite element method. As a result of having a significant increase in foundation damping, a lower inertial response (i.e. dynamic amplification) is obtained compared to [2].

[5] summarized the method for estimating soil parameters (Figure 1) and numerical analyses for estimating foundation capacity and fixities. Establishing non-linear stress-strain relationships from cyclic shear strain contour diagrams [6] and foundation analyses contains different levels of uncertainties and corresponding effects on the estimated capacity and fixity of the footings. In order to increase the awareness of the jack-up and offshore geotechnical community, in this paper, we have focused on the assessment of both aleatoric and epistemic

uncertainties [7] and their impact on the calculated foundation capacity and fixities in a qualitative manner. One should note that the level of uncertainties discussed and summarized herein <u>do not</u> necessarily cover different engineering approaches, and the quality and amount of site-specific data may give different levels of conservatism.

One needs to establish design profiles for obtaining the input parameters for the foundation analyses following the workflow presented in Figure 1. Each parameter and correlation contain different levels of uncertainties, which should be considered when establishing the design profiles.

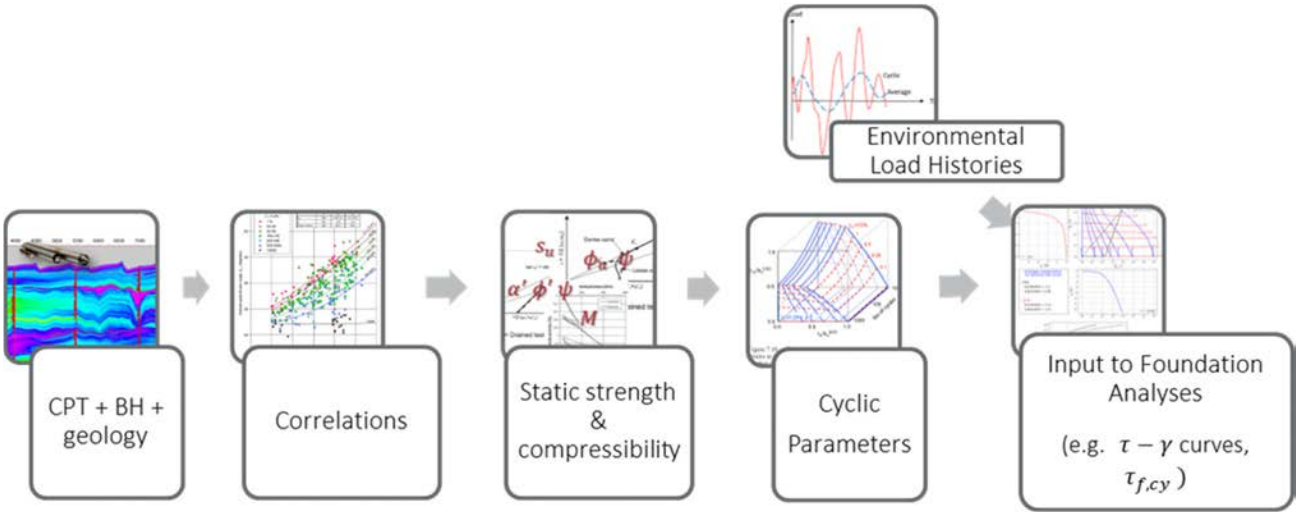


Figure 1: Workflow for the assessment of cyclic soil parameters as input to capacity and fixity calculations

The cyclic parameters should be based on cautiously estimated design profiles of static undrained shear strength ($s_u^C$) or relative density ($D_r$), overconsolidation ratio ($OCR$) and drainage properties assuming that this covers all uncertainties related to the profile. As these design profiles are used as reference and normalization values for the cyclic parameters, a reasonable approach is thus to select best estimate cyclic parameters to avoid duplication of caution. The uncertainty related to best estimate values is discussed in the following sections, which are organized following the advanced geotechnical analyses and design steps, i.e. establishing static and cyclic soil parameters, foundation penetration, capacity and stiffness analyses. At the end of each section, a summary table is presented to indicate the uncertainty levels of each parameter discussed, which engineering parameter they affect, the conservatism levels commonly used when establishing design profiles and their significance level considering their influence on the calculated foundation capacity and fixities. Table 1 provides the list of icons and their definitions.

Table 1: List of icons

| **Uncertainty Level** | | **Design (Conservatism level)** | | **Significance level** | |
|---|---|---|---|---|---|
| Icon | Indicates | Icon | Indicates | Icon | Indicates |
| | *High* | | *Optimistic* | | *High* |
| | *Moderate* | | *Best estimate* | | *Moderate* |
| | *Low* | | *Conservative* | | *Low* |

UNCERTAINTIES IN THE ASSESSMENT OF SOIL PARAMETERS

Site-specific assessments are required for the jack-up structures [8] to reduce uncertainties in both foundation and structural analyses. From a geotechnical perspective, location-specific soil investigations are essential. Generally, 1 borehole (containing sufficient sampling and CPT measurements) per leg is considered sufficient. However, it is quite common to have a variation even within the footprint of the spudcan, if not among different legs depending on the (site-specific) spatial variability. The geotechnical engineer may try to address these uncertainties by selecting conservative design profiles (i.e. $D_r, I_P, w, FC, s_u^C, OCR, \dots etc.$), which are the basis for estimating cyclic parameters. This section summarizes the uncertainties in different aspects of soil parameter assessment from monotonic to cyclic behaviour [6].

*Layering*

Soil investigations with high quality and relevant field and laboratory measurements should have sufficient coverage of the soil volume that is expected to be mobilized under structural loads and influence the foundation response. This is essential, especially for advanced foundation analyses. For sites with significant spatial variations in layering and soil properties, the uncertainty levels may become significant and need to be carefully considered in the assessment. Laboratory tests on good quality samples should be used to establish a reliable CPT interpretation framework, especially for low permeable dilative soils, e.g. overconsolidated clays and (dense) silts. Table 2 summarizes the uncertainties regarding layering, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

Table 2: Summary of the uncertainties, design aspects and significance levels of layering

| **Category** | **Parameter** | **Uncertainty Level** | **Affects** | **Design (Conservatism level)** | **Significance level** |
|---|---|---|---|---|---|
| Layering | Design layering | ? | Mobilization/failure surfaces for stiffness and capacity calculations | Can be accounted by:<br>✓ lumping weak layers<br>✓ Selecting conservative design layering among different boreholes (focusing on the operational position of the jack-up) | ! |

*Index parameters*

Index parameters such as water content ($w$), plasticity index ($I_P$), fines content ($FC$), clay content, overconsolidation ratio ($OCR$) and relative density ($D_r$) have in general significant influence on the engineering properties and dictate the static and cyclic behaviour. Figure 2 – Figure 4 highlights the effect of these parameters on static and cyclic shear strength together with the background data as an indication for the uncertainty levels.

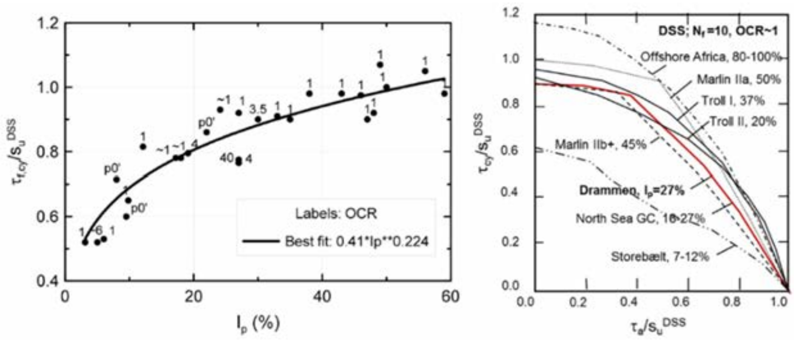



Figure 2: a. Normalized cyclic shear strength after 10 cycles with symmetrical loading in DSS tests on normally consolidated clay as a function of plasticity index ($I_p$), b. Combinations of average and cyclic shear stresses that cause failure in 10 cycles in DSS tests on different normally consolidated clays [6].

Similarly, Figure 5 shows the effect of OCR on the extracted total and cyclic tau-gamma curves, which are input to capacity and stiffness calculations for clay type materials. The response becomes softer with increasing OCR for the same static undrained shear strength.

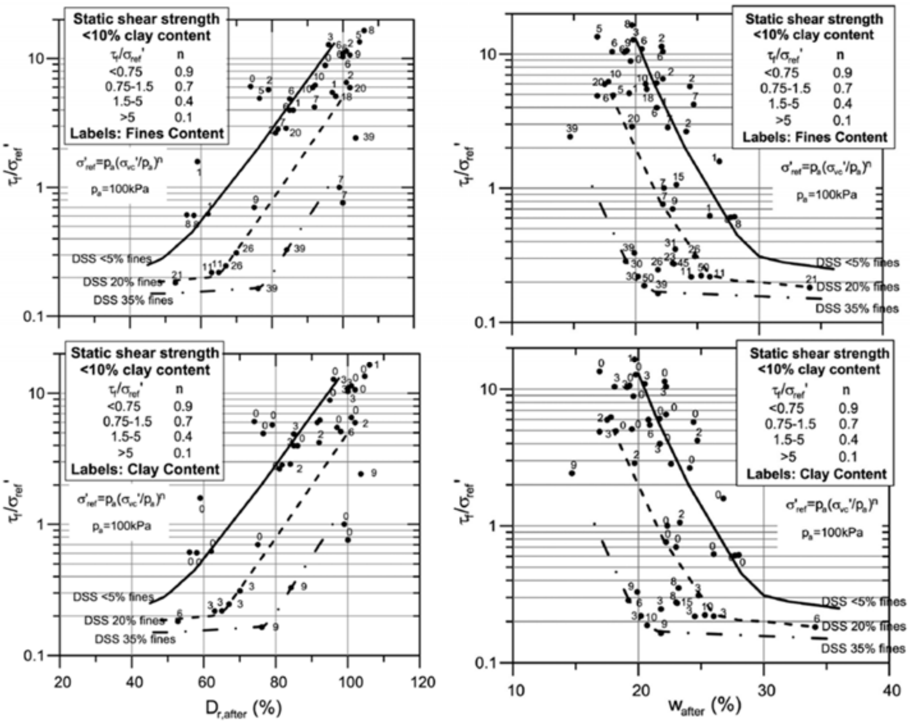



Figure 3: Static undrained shear strength in DSS on NC sand and silt (<10% clay content) as a function of a. relative density after consolidation, b. water content [6].

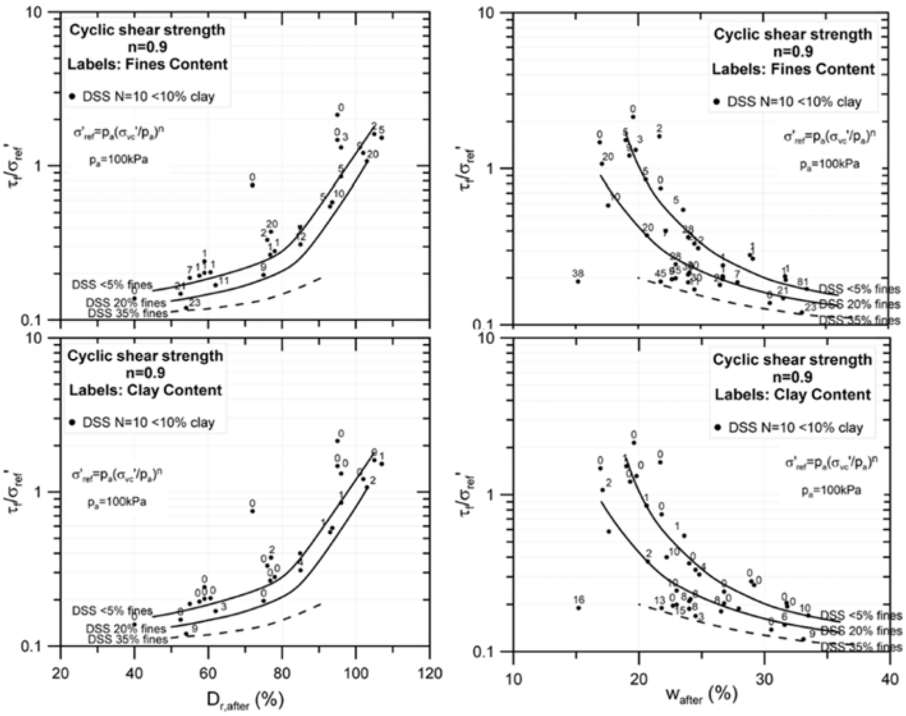



Figure 4: Cyclic undrained shear strength for 10 cycles with symmetrical loading in DSS on NC sand and silt as a function of a. relative density after consolidation, b. water content [6].

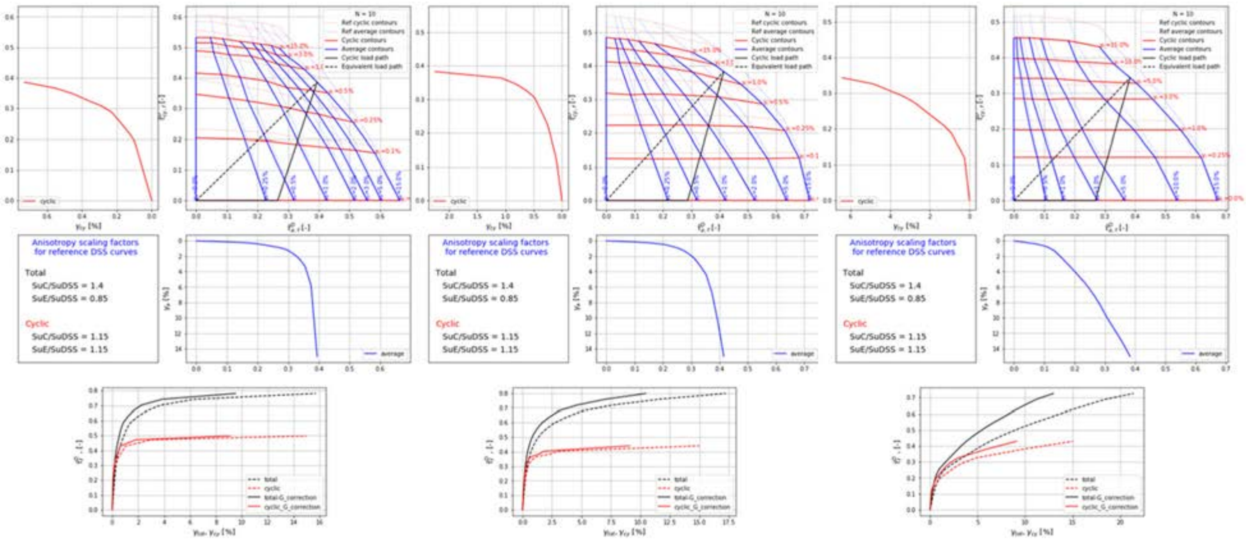


Figure 5: Scaled contours and extracted tau-gamma curves for OCR =1, 4 and 40 (left to right) based on Drammen clay contours.

The uncertainty levels for $w$, $D_r$ and $OCR$ of sand/silty sand is quite high, while other index parameters, in general, have a moderate level of uncertainty. Relative density contains all types of uncertainty, which increase with increasing fines and overconsolidation effects. Unfortunately, it is still difficult to reduce the uncertainty in estimating $D_r$ with the present state-of-the-art techniques. Hence, the geotechnical engineer should be careful when utilizing $D_r$ for estimating static and cyclic shear strength. Table 3 summarizes the uncertainties regarding index parameters, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

Table 3: Summary of uncertainties, design aspects and significance levels of index parameters

| Category | Parameter | Uncerta-inty Level | Affects | Design (Conservatism level) | Significance level |
|---|---|---|---|---|---|
| Index para-meters | Water content (for sand/silty sand) | | -static NC strength $\tau_a^{f,NC}/\sigma'_{ref}$<br>-cyclic NC strength $\tau_{cy}^{f,NC}/\sigma'_{ref}$<br>-contour diagrams | | |
| | Plasticity Index ($I_P$) | | | | |
| | Fines Content ($FC$) | | | | |
| | Clay content (for sand) | | | | |
| | Relative density ($D_r$) | | | | |

*Stiffness, permeability and consolidation characteristics*

Soil stiffness and hydraulic conductivity (permeability) are essential for the assessment of the drainage behaviour of silt and sand. Depending on load conditions (e.g. load period, single cycle, several cycles, storm history and duration), drained, partially drained or undrained response could be expected. The foundation behaviour can be quite sensitive to the estimated permeability values. The most challenging condition in terms of analysis point of view is in general partially drained behaviour.

The shear modulus at small strain ($G_{max}$) is generally estimated based on empirical correlations (e.g. [9]) as a function of $OCR, w, K_0, I_p$ and effective stress. Lab tests (e.g. resonant column (RC)) can help reduce the uncertainty levels, acknowledging the uncertainty in in-situ $OCR$, stress history, sampling disturbance.

Permeability has a large uncertainty due to sampling challenges and not the least representativeness of larger volume due to spatial and directional variability. Site-specific permeability measurements are essential and can be used in combination with databases [6], as illustrated in Figure 6. However, the uncertainty in site-specific measurements in soil with significant layering if there are only limited spot values from site-specific measurements. Figure 6 also shows the influence of uncertainty in index parameters when the database is utilized.

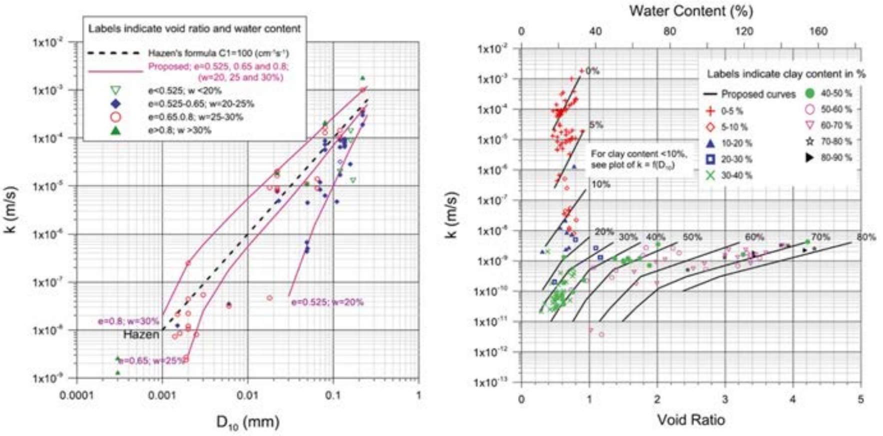



Figure 6: Estimation of permeability as function of a. grain size $D_{10}$, and b. Void ratio [6]

Similarly, stiffness parameters (i.e., constrained modulus that is non-linear and significantly different during loading, unloading and reloading), which can be estimated from oedometer tests as well as empirical correlations [10], are important for the assessment of drainage conditions together with permeability.

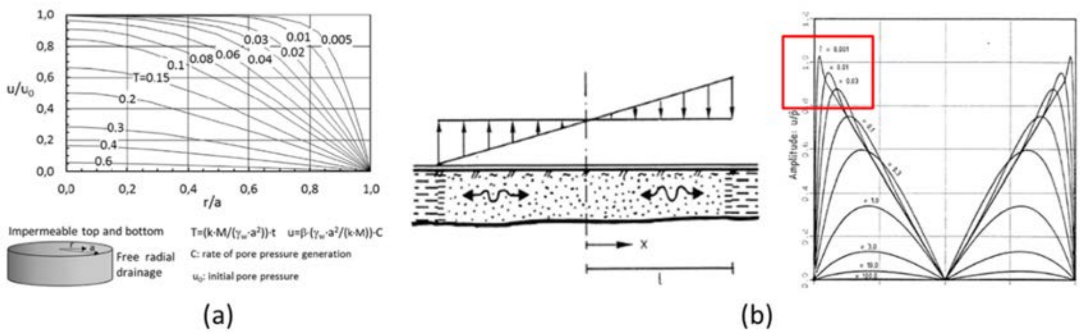



Figure 7: Dissipation of pore pressure in circular disk with radial drainage a) with initial pore pressure $u = u_0$ in entire volume at $t = 0$ [10], b) under cyclic rocking motion [11].

Assessing the drainage conditions dictates the calculated capacity and stiffnesses, hence is a key design stage. The drainage under different operational conditions (and corresponding durations) can be estimated by using relevant compressibility and permeability characteristics (e.g. Figure 7). Figure 8 shows an example of estimated drainage conditions for different operational loads based on best and low estimates of drainage conditions, which may give large ranges from drained to undrained conditions. Table 4 summarizes the uncertainties regarding index parameters, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

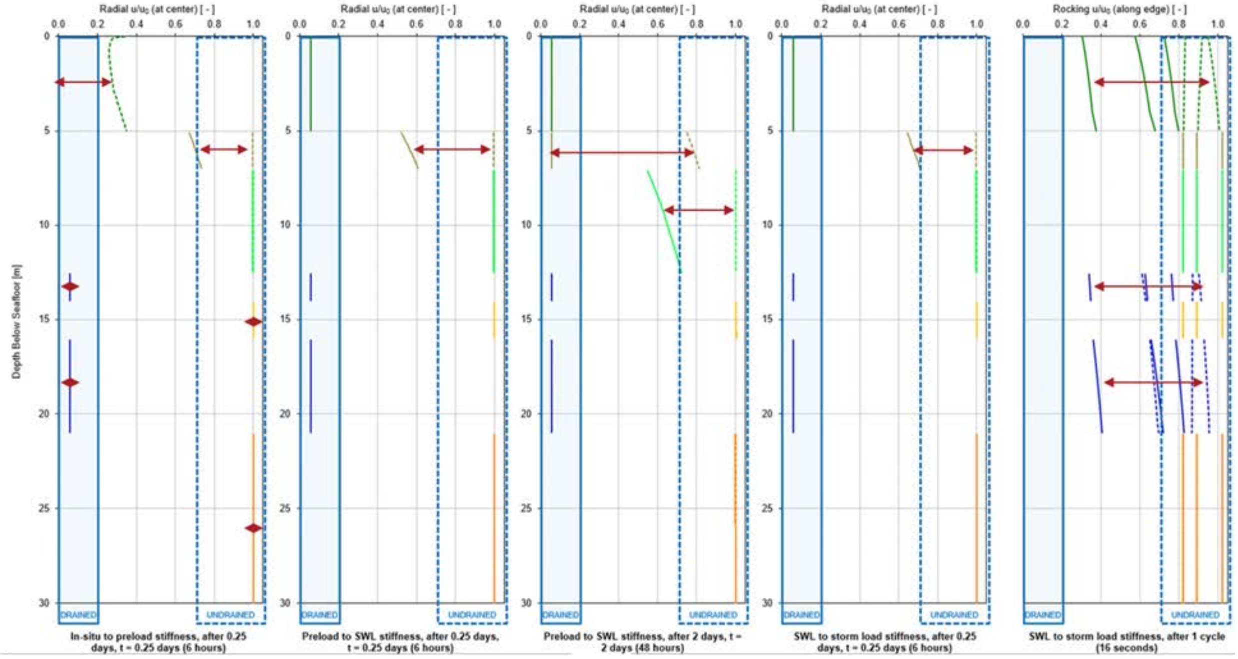



Figure 8: Example of estimated drainage conditions $u/u_o$ for each layer for different operational loads.

Table 4: Summary of uncertainties, design aspects and significance levels of stiffness, permeability and consolidation characteristics

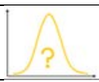
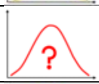
| **Category** | **Parameter** | **Uncerta-inty Level** | **Affects** | **Design (Conservatism level)** | **Significance level** |
|---|---|---|---|---|---|
| Stiffness, permea-bility and consoli-dation characte-ristics | $G_{max}$ |  | Initial stiffness of τ–γ curves |  |  |
| | Permeabi-lity, k |  | - Consolidation during Preloading, under SWL → static NC strength $\tau_a^{f,NC}/\sigma'_{ref}$<br>- $N_{eq}$ |  |  |
| | Constrained modulus, M |  | |  |  |
| | OCR |  | - static NC strength $\tau_a^{f,NC}/\sigma'_{ref}$<br>- cyclic NC strength $\tau_{cy}^{f,NC}/\sigma'_{ref}$<br>- constrained modulus<br>- contour diagram | <br>OCR correction to be utilized<br><br>considering stiffness correction |  |

Figure 9 indicates the uncertainty of the OCR effect on the undrained cyclic shear strength with an example case of the effect on an undrained cyclic contour diagram of a clean sand.

Figure 10 demonstrates the effect of selecting drained and undrained contour diagrams for sand and silty/sand on the extracted total and cyclic tau-gamma curves, which are input to capacity and stiffness calculations. For this example, the undrained response is stiffer and stronger than the drained changes in average stresses.

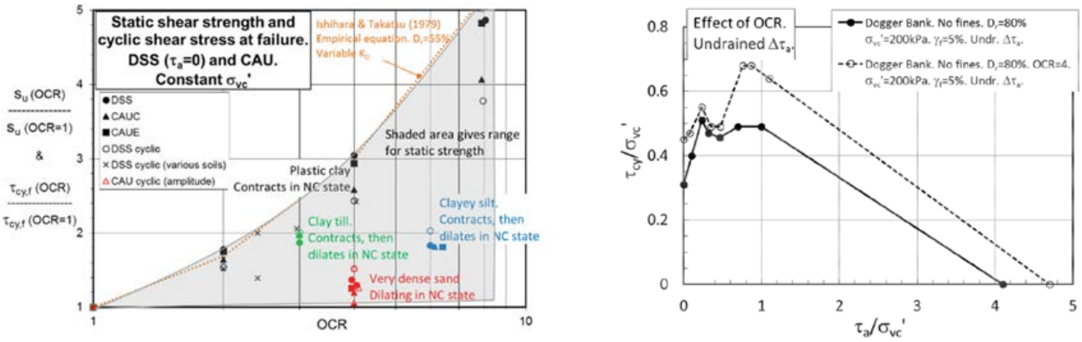



Figure 9: a. Undrained cyclic shear strength as a function of OCR, b. Effect of OCR on cyclic shear strength in DSS tests on clean sand for undrained $\Delta\tau_a$ [6].

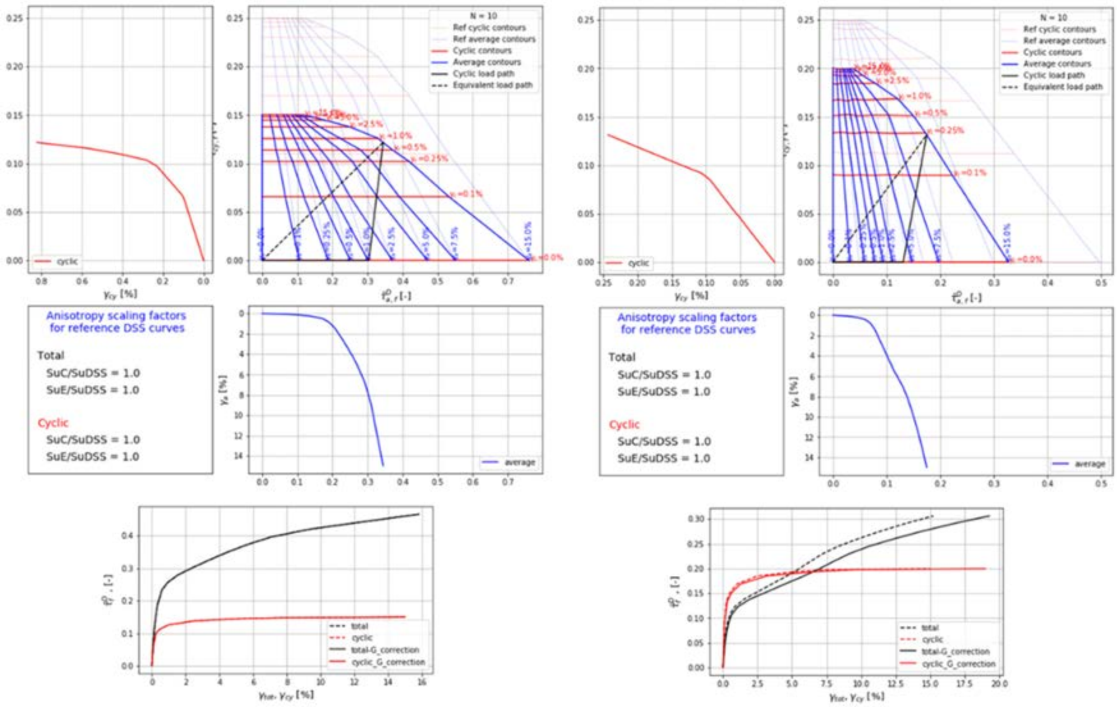



Figure 10: Scaled contours and extracted tau-gamma curves of Dr=100% sand considering a. Drained $\Delta\tau_a$and b. undrained $\Delta\tau_a$ based on database of sand contours [6].

*Static shear strength*

Static shear strength of sands and silts is a function of water content/relative density (Figure 3), over-consolidation ratio (Figure 9), permeability and compressibility (Figure 10). An important aspect of the soil behaviour is the so-called strength anisotropy, i.e. stress path dependent shear strength.

The uncertainty of estimated static shear strength for silts and sands stems from the difficulties in sample recovery and reconstitution in the laboratory. Furthermore, if the databases are employed, relative density and water content estimation increase the level of uncertainties.

Static shear strength of clayey soils is mainly governed by plasticity index and overconsolidation ratio. The uncertainty arises mostly from the interpretation of CPT, which can be reduced by laboratory tests carried out on good quality (less disturbed) samples.

Table 5 summarizes the uncertainties regarding the estimated static shear strength, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

Table 5: Summary of uncertainties, design aspects and significance levels of static shear strength

| **Category** | **Parameter** | **Uncerta-inty Level** | **Affects** | **Design (Conservatism level)** | **Significance level** |
|---|---|---|---|---|---|
| Static shear strength | Undrained static shear strength, $s_u$ | | - static vertical capacity<br>- mobilization under SWL<br>- cyclic shear strength | | |
| | Drained friction angle | | | | |
| | Static anisotropy | | | | |
| | Drainage at different operational periods | | | can be accounted by considering most conservative $\tau_a^{f,NC}/\sigma'_{ref}$ | |

*Loads and cyclic accumulation*

The significant levels of uncertainty in environmental loads have an impact on the foundation assessment. A deterministic design approach requires load and material factors to be incorporated in structural utilization and integrity checks. Several dynamic and quasi-static structural analyses with the input of foundation stiffnesses (initial estimate) need to be carried out to assess critical load conditions to be checked against structural reliability and robustness. Due to the nonlinear behaviour of soil and the corresponding foundation response, foundation fixities are determined iteratively.

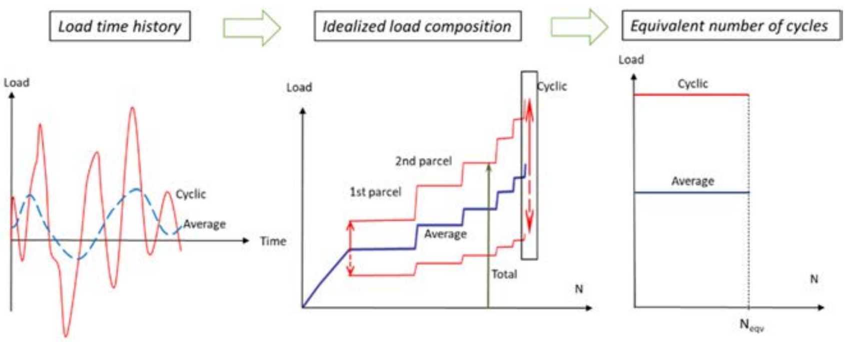



Figure 11: Total foundation load history decomposed into average and cyclic components, idealization of the load history and calculated equivalent load cycles.

Uncertainties in the cyclic strain or pore-pressure accumulation procedures for the calculation of the equivalent number of constant load cycles ($N_{eq}$) of the peak load can have a significant impact on the estimated cyclic foundation capacity and fixity. The simplification of the load histories [12] with increasing cyclic load amplitudes as shown in Figure 11 does not always give the largest cyclic degradation of the stiffness and accumulated strains (especially for low permeable sols). While for partially drained conditions it may be too conservative to use this type of idealized load history. Table 6 summarizes the uncertainties regarding the cyclic accumulation, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

Table 6: Summary of the uncertainties, design aspects and significance levels of cyclic accumulation

| Category | Parameter | Uncerta-inty Level | Affects | Design (Conservatism level) | Significance level |
|---|---|---|---|---|---|
| Cyclic accumulation | Load discretization | | - $N_{eq}$<br>- contour diagram | | |
| | Pore pressure accum. | | | | |
| | Strain accum. | | | | |

*Cyclic soil behaviour*
The cyclic response of soil under different average and cyclic load components can be estimated by the cyclic contour diagram concept [6]. The construction of these contour diagrams involves uncertainties. In addition, the uncertainties in index properties will also influence the uncertainty level of estimated contour diagrams and calculated foundation response employing these diagrams. These uncertainties due to index properties and the use of databases could be reduced by site-specific cyclic laboratory tests.

The cyclic/average load ratio employed for the assessment of cyclic stress-strain curves (e.g. [1]) is not constant for a given storm load history. Uncertainties can be addressed by selecting a representative ratio (within the actual range) yielding low shear strength and softer response. Table 7 summarizes the uncertainties regarding the cyclic shear strength, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

Table 7: Summary of the uncertainties, design aspects and significance levels of cyclic shear strength

| Category | Parameter | Uncerta-inty Level | Affects | Design (Conservatism level) | Significance level |
|---|---|---|---|---|---|
| Cyclic shear strength | Static shear strength (for clay) | | - $\tau$–$\gamma$ curves<br>- Cyclic and total foundation stiffnesses<br>- Total foundation capacity | | |
| | Cyclic contours | | | | |
| | Anisotropy ratios | | | | |
| | Load paths (cy/av) | | | | |
| | Drainage during individual cycles | | | | |

UNCERTAINTIES IN PENETRATION ANALYSES
The penetration analyses can cover a range from installation checks of skirt penetration, leg penetration based on simplified progressive bearing capacity checks, which may also account for the interaction of layers e.g. SPLAT to advanced large deformation finite element analyses. Both simplification (e.g. selection of representative friction angle/shear strength) and adding complexity brings in additional uncertainties (e.g. large strain and anisotropic behaviour).

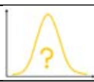
*Simplified bearing capacity*
Industry practice generally employs simplified bearing capacity methods for the estimation of possible spudcan leg penetration assessments. The methods become as advanced as accounting for different layer interactions, backflow,… etc. [13]. However, these methods have quite many limitations due to their empirical nature and contain significant level of uncertainties.

*Lagrangian (small deformation) geometry updates FEAs*
Considering the effect of geometrical changes, by employing simplified FEAs, e.g. [14], [15] contain significant levels of uncertainties due to their limitations (i.e. not very well suited for deep penetrations, e.g. capturing complex mechanisms such as backflow).

*Large deformation FEAs*
Spudcan penetration in weak soil conditions often involves large deformation in surrounding soil as well as the possible backflow soil. Techniques like Coupled Eulerian-Lagrangian (CEL) has been proven as a suitable and efficient modelling approach for capturing complex mechanisms and geometric nonlinearity effect during spudcan penetrating through layered soils (e.g. [13],[16],[17]). Uncertainties arise due to generally being quite sensitive to shear strength profile just below the skirt tip level. In this case, the calculated capacity is found to be significantly lower than obtained from classical bearing capacity equations using an average strength over a depth equal to the diameter of the footing. Extrapolation of stress-strain curves to large strain to model softening behaviour introduces additional uncertainty, which affects the penetration mechanism significantly.

Table 8 summarizes the uncertainties regarding the penetration analyses, corresponding effects and the significance level considering their influence on the calculated foundation capacity and fixities as well as the suggested design profile.

Table 8: Summary of the uncertainties, design aspects and significance levels of penetration calculations

| **Category** | **Scope** | **Uncerta-inty Level** | **Affects** | **Design (Conservatism level)** | **Significance level** |
|---|---|---|---|---|---|
| Penetration analyses | Installation check |  | - Penetration, wished-in-place modelling depth,<br>- Foundation capacity and stiffnesess |  |  |
| | Leg penetration |  | |  |  |
| | Large deformation Analyses |  | |  |  |

UNCERTAINTIES IN THE ASSESSMENT OF FOUNDATION CAPACITY
*Static and cyclic capacity of the foundation*
It is important to assess the static vertical bearing capacity of the skirted spudcans, especially when utilizing capacities exceeding preload level. In addition, estimating the initial mobilization level under still water load is an important input for assessing cyclic parameters as it affects the cyclic to average load ratio during storm loading.

As mentioned earlier, another key aspect in the foundation analyses is the effect of stress-path dependency (strength anisotropy). In general, soil investigations generally lack sufficient test data at representative locations and depths. Performing different tests (e.g. DSS, CAUC and CAUE) on samples from different boreholes and depths for a given soil unit increase the level of uncertainties regarding strength anisotropies.

Cyclic foundation capacities (i.e. VHM envelopes) are an essential part of the site-specific assessment. Calculation of these envelopes requires extensive finite element calculations, which contain uncertainties due to simplifications of finite element models (e.g. using 2D plane strain models with side-shear), mesh dependency (e.g. discretization errors, squeezing out or other complex mechanisms depending on the layering), errors in iterative calculation schemes. These uncertainties can be reduced by rigorous sensitivity checks. Table 9 summarizes the uncertainties regarding the capacity analyses and the significance level.

Table 9: Summary of the uncertainties, design aspects and significance levels of penetration calculations

| Category | Scope/Method | Uncerta-inty Level | Affects | Design (Conservatism level) | Significance level |
|---|---|---|---|---|---|
| Capacity Analyses | Static vertical capacity | | - Foundation capacity | Can be accounted for by considering<br>✓ Global scour<br>✓ Low interface friction<br>✓ Correction factor for discretization errors<br>✓ Narrow consolidation zone (1h:3v load spread) | |
| | Cyclic vertical capacity | | | | |
| | VHM envelopes | | | | |

UNCERTAINTIES IN THE ASSESSMENT OF FIXITYAND FOUNDATION DAMPING

Foundation stiffnesses (fixity) or global soil spring stiffnesses play an important role in dynamic behaviour and structural utilization of jack-up platforms, especially at large water depths [1]. In order to establish reliable values for this fixity, the complex non-linear behaviour of the different soil layers involved under combined average and cyclic loading should be accounted for. The procedure for establishing non-linear and stress path dependent stress-strain relationships to be used as input to finite element analyses of jack-up footings has uncertainties stemming from the construction of contour diagrams, anisotropy ratios, uncertainties in loads, interpolations.

Calculation of foundation capacity and fixities using finite element analyses contain lower uncertainties compared to those related to establishing soil parameters, which are discussed in the previous section. Estimating constitutive model parameters (e.g. curve fitting to extracted cyclic stress-strain curves) increase the level of uncertainties especially due to limitations in the fitting process for capturing small and large strain behaviour. One should check the fitted curves with the level of mobilizations for different (total and cyclic) foundation loads. Uncertainties related to discretization, element formulation and geometrical simplification should be studied and can be reduced with sensitivity analyses. Table 10 summarizes the uncertainties regarding the stiffness analyses, corresponding effects and the significance level.

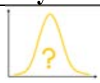
Table 10: Summary of the uncertainties, design aspects and significance levels of foundation capacity and stiffness calculations

| Category | Method | Uncerta-inty Level | Affects | Design (Conservatism level) | Signifi-cance level |
|---|---|---|---|---|---|
| Stiffness analyses | ISO | | - Dynamic amplifications<br>- Jack-up leg utilizations<br>- $p-\Delta$ effects | Difficult to account for complex layering | |
| | Finite element m. | | | Can be accounted for by considering:<br>✓ Global scour<br>✓ Low interface friction<br>✓ High V for WW<br>✓ Fine discretization and employing correction factor for discretization errors.<br>✓ Nonlinear elastic constitutive model (softer compared to plastic hardening models) | |
| | Geometric effects | | | Considering softening | |

## UNCERTAINTIES IN SOIL AND FOUNDATION DAMPING

Soil material damping has an important contribution to the resonant response of jack-up platforms and the corresponding demands in the leg's truss members and the foundation loads. The soil damping and thus also foundation damping is dependent on the soil type and strain and will vary with the loads acting on the foundation. Site-specific strain-dependent soil damping can be evaluated based on laboratory tests. There are a large amount of laboratory-based soil damping curves in the literature see e.g. [18],[19],[20],[21]. The soil damping is affected by the plasticity index, the effective confining pressure, and the over consolidation ratio. The laboratory testing and employment of empirical correlations bring in additional uncertainties, which are challenging to reduce. In addition, a special program that integrates the damping in the soil domain is necessary to calculate foundation damping. Table 11 summarizes the uncertainties regarding the foundation damping estimations, corresponding effects and the significance level.

Table 11: Summary of the uncertainties, design aspects and significance levels of foundation capacity and stiffness calculations

| **Category** | **Method** | **Uncerta-inty Level** | **Affects** | **Design (Conservatism level)** | **Significance level** |
|---|---|---|---|---|---|
| Foundation damping | Finite element m. |  | - dynamic amplifications |  Can be accounted for by considering soil damping:<br>- Based on Darendeli (2001)<br>- Cut-off at a low strain level |  |

## CONCLUSIONS

Advanced foundation analyses of jack-ups provide valuable information in reducing the uncertainties of the foundation response considering stress history, cyclic behaviour, large deformation effects and complex soil layering. However, the methodology contains uncertainties at each level of the assessment, the details of which are discussed in this paper. The design engineer should be aware of these uncertainties and consider the suggestions for reducing those for a more reliable geotechnical assessment of jack-ups with skirted spudcans.

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