WHEN PRELOADING IS NOT SUFFICIENT: CYCLIC DEGRADATION RISKS IN LOOSE SILTY SOILS

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ABSTRACT

Preloading is a widely accepted method to establish the vertical bearing capacity for jack-up foundations. However, in loose silty soils, this approach may be insufficient due to significant cyclic degradation under storm loading conditions. While such soils may behave partially or fully drained during preloading, storm loads can trigger a rapid undrained response. This undrained behaviour can lead to substantial reductions in shear strength and vertical capacity, sometimes falling well below preload levels. Storm loads exceeding foundation capacity cause leg settlements that increase utilizations on the jack-up structure. This paper presents idealized examples illustrating the degradation process, its implications for foundation performance under storm loading, and the need to estimate reliable horizontal, vertical, and rotational fixities for the legs. Emphasis is placed on the role of drainage behaviour at different periods of operation (e.g., Preloading or survival condition) and their critical impact on the safety and performance of jack-up operations in loose silty sand seabed conditions.

KEYWORDS: skirted spudcans, foundation capacity, fixity, cyclic behaviour, loose silty soils, finite element analyses, soil structure interaction.

INTRODUCTION

Jack-up rigs remain important for offshore energy and construction activities, where operational safety hinges on the reliability of their spudcan foundations. Preloading is the established industry method for verifying jack-up foundation capacity as well as a key input for the jack-up site-specific assessment. Preloading is carried out by applying weight to the legs. In most sands, this practice is considered to provide a reliable foundation capacity since the drained shear strength is mobilized, settlements are observed, and bearing capacity is thought to be verified directly in situ [1]. In this case, a force-resultant spudcan model that depends on the achieved preload/penetration is utilized to define combined V–H–M capacity and stiffnesses (macro-element or equivalent) in sand as a function of preload and embedment for assessment of storm conditions.

However, in loose silty soils, the effectiveness of preload as a safety assurance is far less certain. Seabeds containing loose silty sands or sandy silts, which do not behave in a purely drained manner under all loading conditions may require further consideration for cyclic effects as highlighted by [2][3]. While drained or partially drained behaviour may prevail during the relatively slow preload process or under static still water conditions, storm loading introduces rapid cyclic forces, acting at much shorter time scales, may induce undrained soil response. This transition can cause significant cyclic degradation, which may lead to reductions in vertical bearing capacity well below preload levels. Such capacity losses have direct implications for design checks, potentially resulting in leg settlements, increased loads, and high utilizations that can threaten the strength or stability of the jack-up. This behaviour is not explicitly covered in current assessment procedures, as recognized in [1] and should be considered further.

Cyclic loading is a governing design condition for offshore foundations. The ISO 19901-4 [4] recognizes the need for site-specific assessment under cyclic and storm loading, though practical implementation often defaults to factored conservative drained parameters without explicit cyclic modelling. Loose silty sands are particularly susceptible to pore pressure build-up and cyclic strength loss. Failure to account for these mechanisms can result in underestimation of leg settlements and overestimation of jack-up stability. Such issue is also highlighted for carbonate sediments [5].

This paper demonstrates the consequence of cyclic degradation in silty sand in relation to preload practices. The idealized example cases illustrate how reliance on conservative static soil parameters does not necessarily ensure safety in loose silty sand. The discussion highlights the importance of considering drainage behaviour in design across different phases of operation, the structural implications of further penetration during storm events.

CASE ILLUSTRATION

To demonstrate the limitations of preload-based verification in silty soils, an idealized soil profile case, a loose sand–silt seabed layer overlying a stiff clay, was considered (see *Figure 1*). Still water load (SWL) is presented as a fraction of preload value. The soil profile comprises a surficial 10 m thick layer of loose silty sand (relative density, $D_r = 30\%, 50\%, and\ 70\%$, fines content $FC = 5\%, 10\%, and\ 15\%$), underlain by an overconsolidated stiff clay ($I_p = 27\%\ and\ OCR = 10$). For the jack-up foundation, a simplified cylindrical spudcan of diameter, D, and t_s thickness, is utilized in the analyses. For more details regarding the enhanced site-specific foundation assessments, readers are referred to [5],[7], and [8].

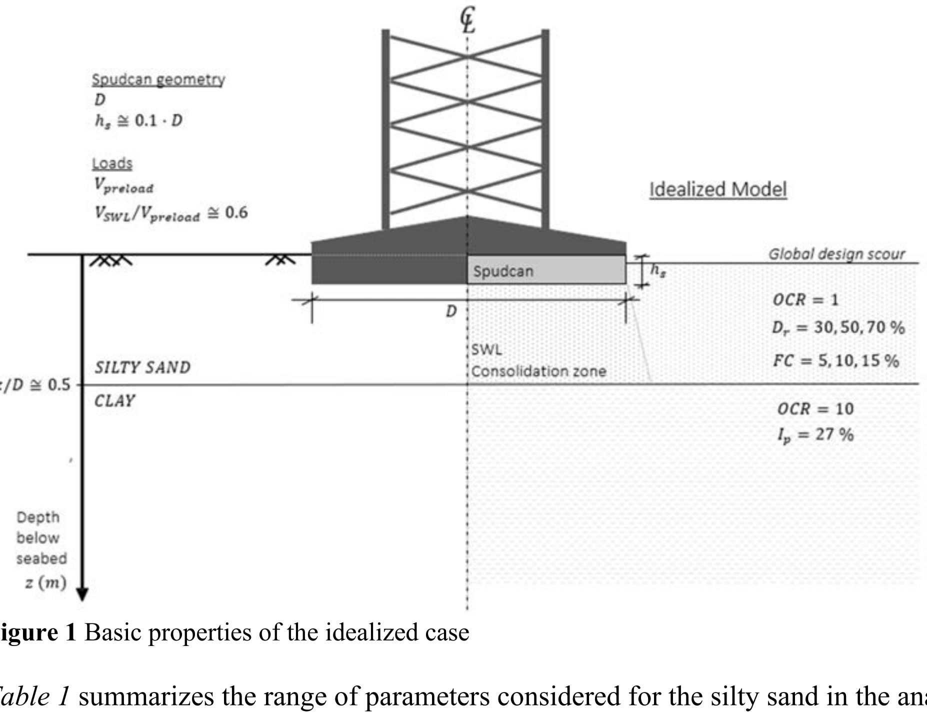

Figure 1 Basic properties of the idealized case

Table 1 summarizes the range of parameters considered for the silty sand in the analyses.

Table 1 Summary of range of parameters considered in the analyses.

D_r (%)	FC (%)	SWL Consolidation	Drainage under average loading, τ_a
30	5		
50	10	100%	Drained / Undrained
70	15		

Considering uncertainties in estimating the in situ drainage characteristics (e.g. permeability, compressibility, drainage length), as well as rate of change of average loading during storm loading, and to illustrate the significance of such characteristics, two cases are considered:

- Undrained soil behaviour under both static/average and cyclic loading.
- Drained soil behaviour under static/average loading.

Cyclic and static parameters are assessed utilizing [9], [10] and [9] (e.g. *Figure 2*), which are implemented in the *CPTU2SOIL* and *ACCUMUL* modules of *RedWin2* tool [12]. These are further merged into NGI's internal foundation capacity and stiffness assessment tool *SWIFT* developed for jack-up analyses. Cyclic contour diagrams together with reasonable anisotropy values are established based on the relative density and fines contents for the top normally consolidated silty sand, and plasticity index and OCR for the stiff clay beneath.

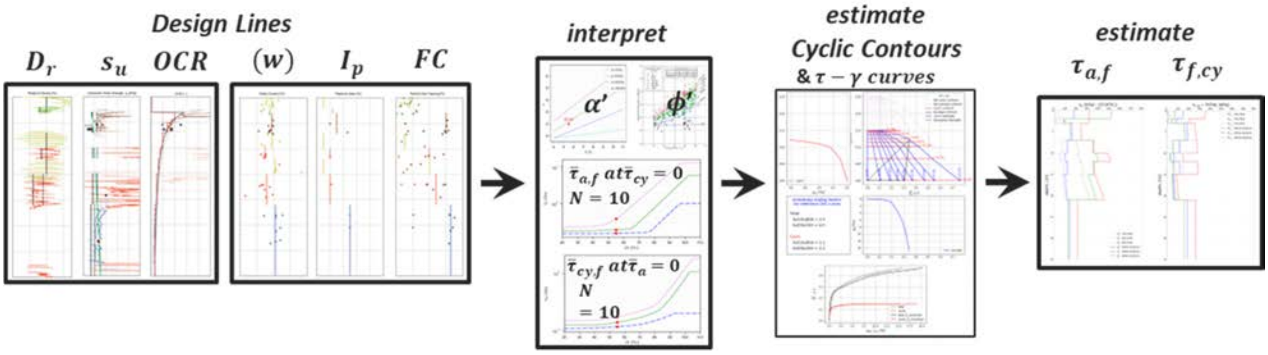

Figure 2 Design workflow for establishing static and cyclic shear strength based on Andersen (2015), Andersen et al. (2023)

Figure 3 presents representation of shear loads induced due to e.g. storm loading at an element level, which can be decomposed into an average and cyclic (amplitude) components.

Figure 4 presents a typical storm load compositions based on JONSWAP (Joint North Sea Wave Project) spectra, half cycle decomposition, uncertainty bands and *Figure 5* shows zoomed segments of the idealized (JONSWAP) storm load compositions, indicating possible average load component changes within 2-4 seconds. It is noted that loads are for illustrative purposes not representing actual loads on a jack-up spudcan.

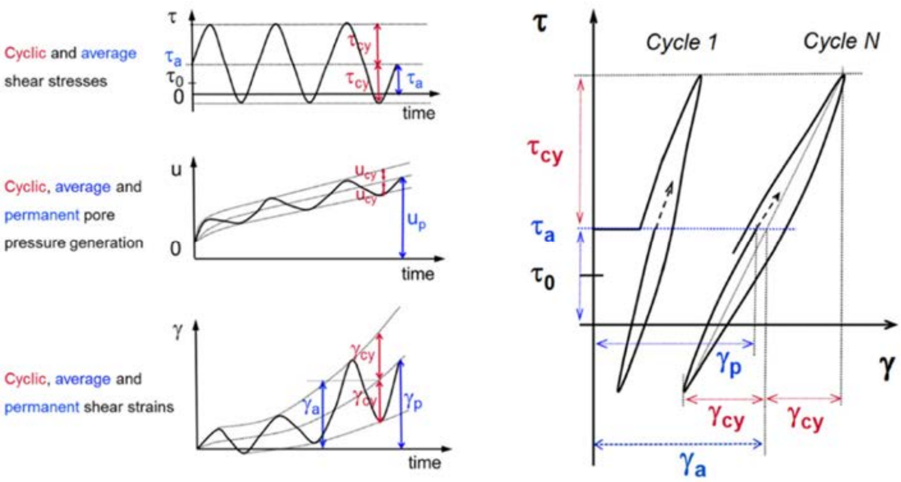

Figure 3 Schematic representation of the application of cyclic and average shear stresses and the development of corresponding cyclic, average, and permanent pore pressures and strains (after [10]).

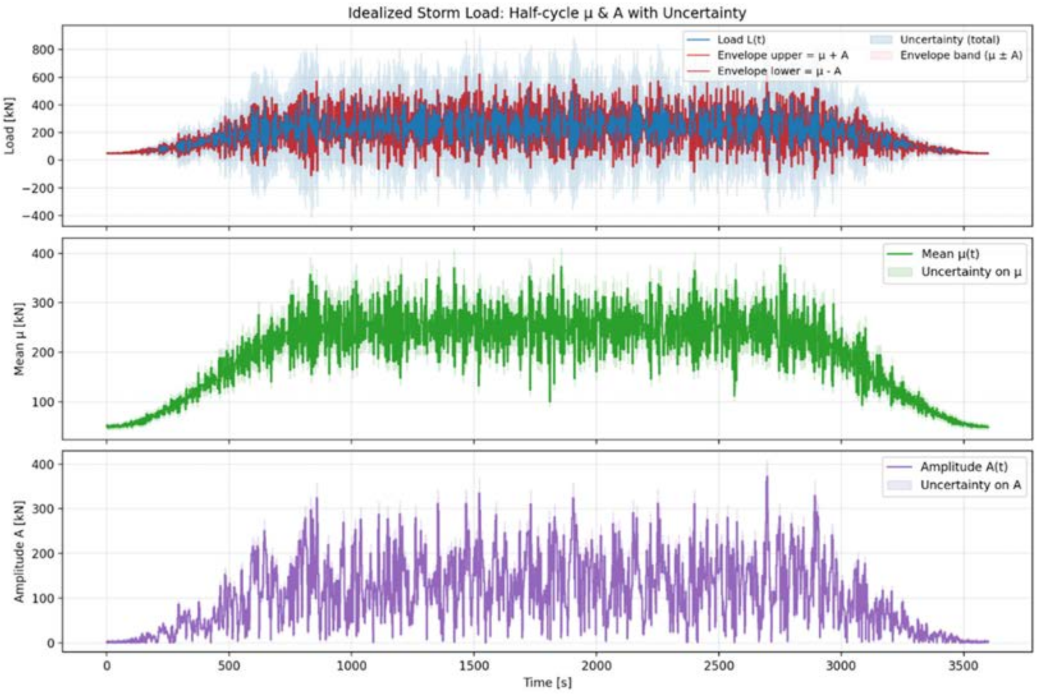

Figure 4 Idealized storm load compositions based on JONSWAP (Joint North Sea Wave Project) spectra, half cycle decomposition, uncertainty bands.

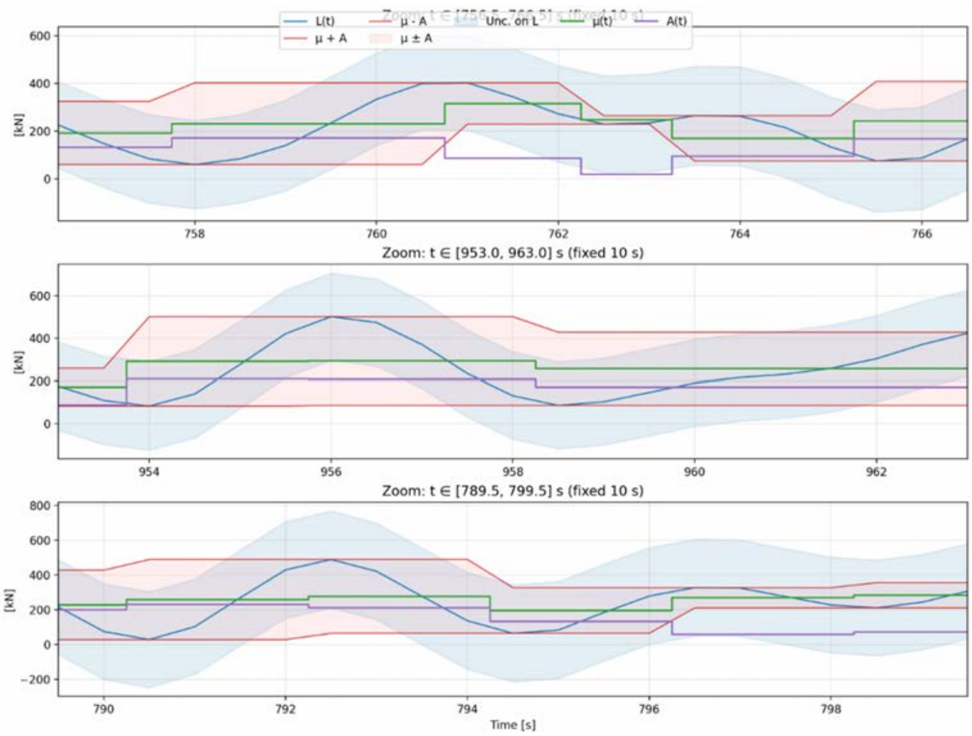

Figure 5 Zoomed segments of the idealized (JONSWAP) storm load compositions, indicating possible average load component changes within 2-4 seconds.

Figure 6 to *Figure* **8** show the estimated cyclic contour diagrams and utilized load paths to consider aforementioned drainage behaviour under average loading during different loading conditions (i.e. still water load conditions and storm loading), for the various relative density, D_r and fines content FC.

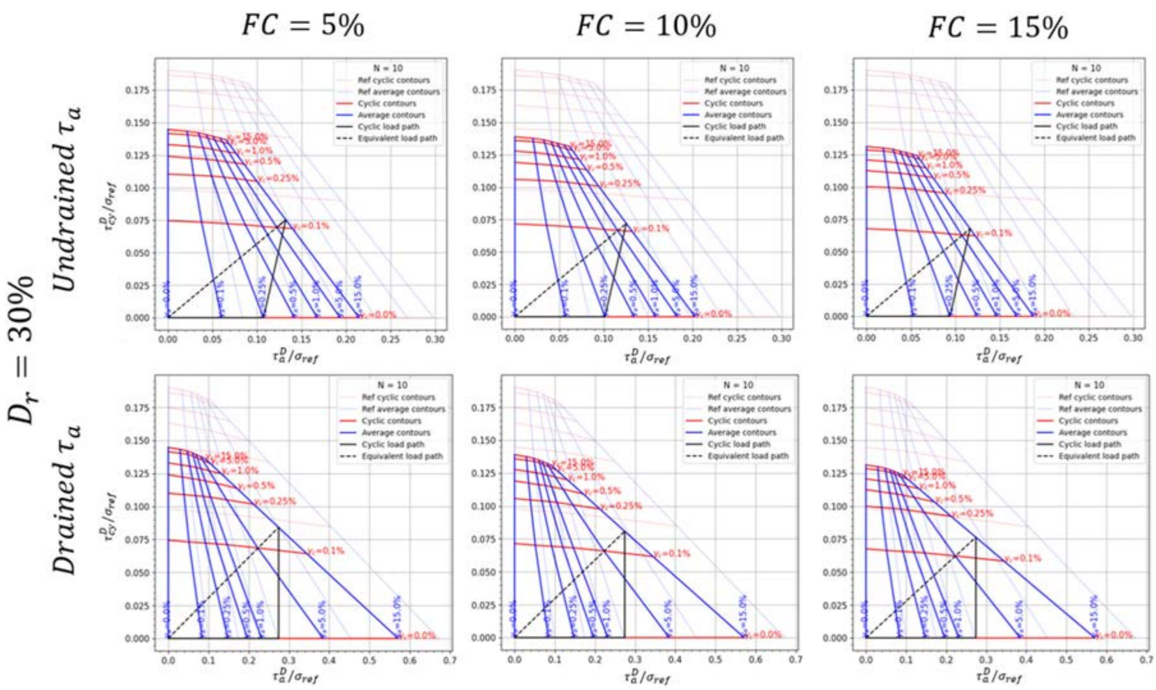

Figure 6 Considered load paths (cy/av) to account for different drainage behaviour utilizing undrained and drained contours for $FC = 5, 10, and\ 15\%$, $D_r = 30\%$.

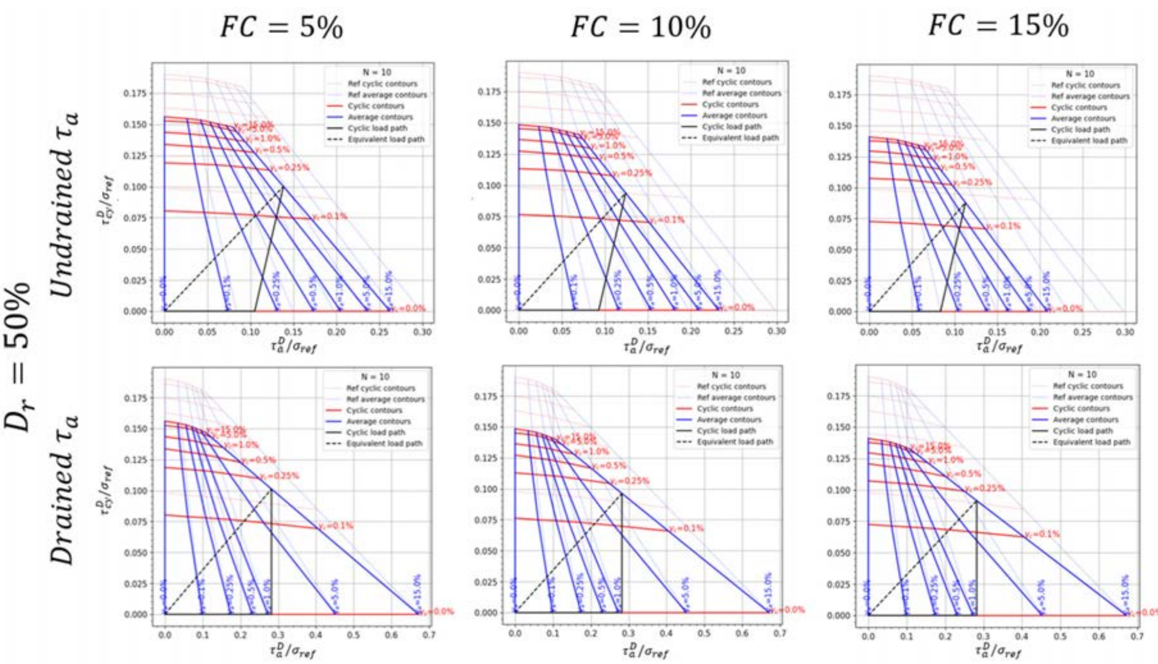

Figure 7 Considered load paths (cy/av) to account for undrained behaviour under varying average loading, utilizing undrained and drained contours for $FC = 5, 10, and\ 15\%$, $D_r = 50\%$.

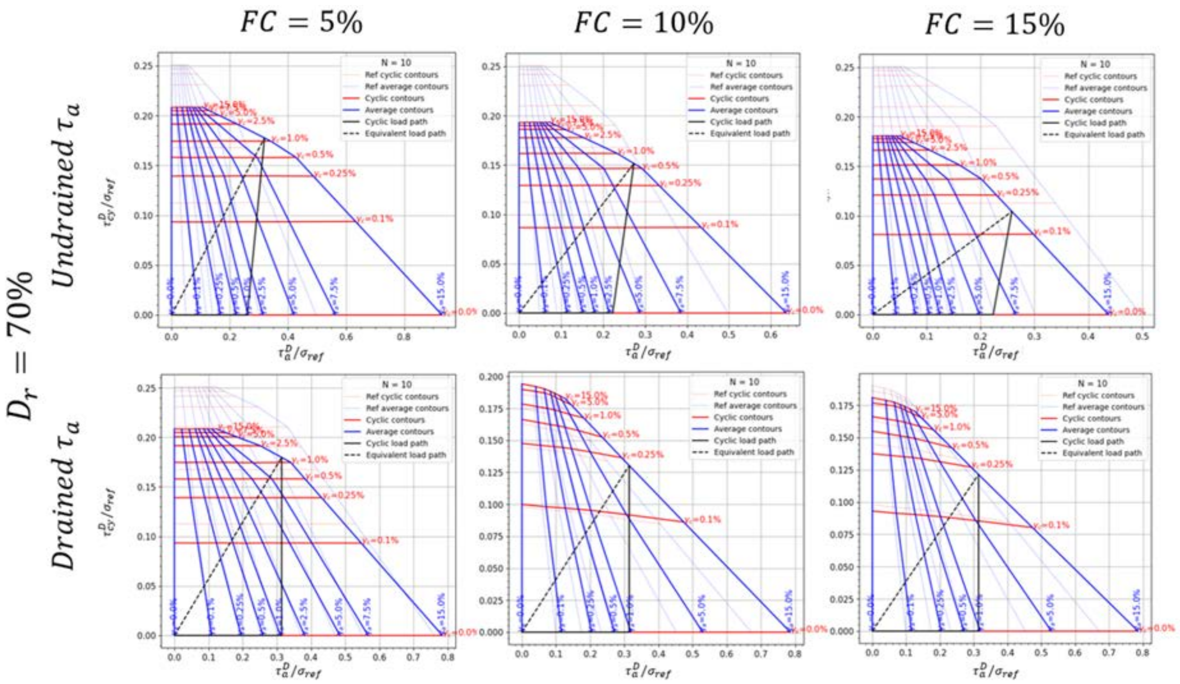

Figure 8 Considered load paths (cy/av) to account for undrained behaviour under varying average loading, utilizing undrained and drained contours for $FC = 5, 10, and\ 15\%$, $D_r = 70\%$.

Figure 9 presents the simplified axisymmetric finite element model utilizing *SWIFT* (in which a special version of *NGI-BIFURC* [11] is implemented) and example displacement contours at failure as an indication of mobilized depths and failure mechanisms.

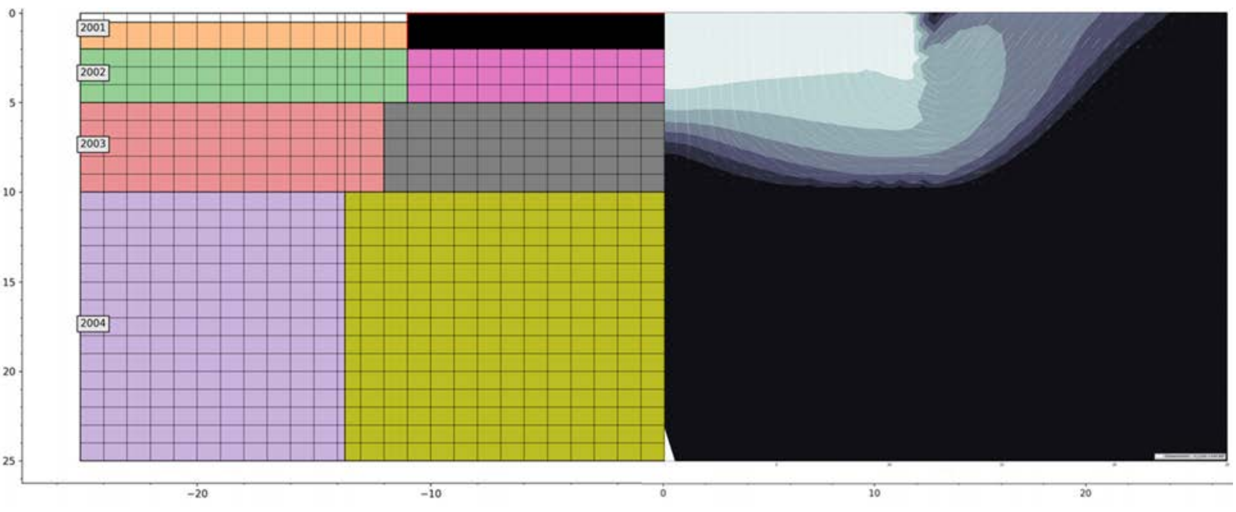

Figure 9 Example simplified axisymmetric finite element model and load displacement contours at failure

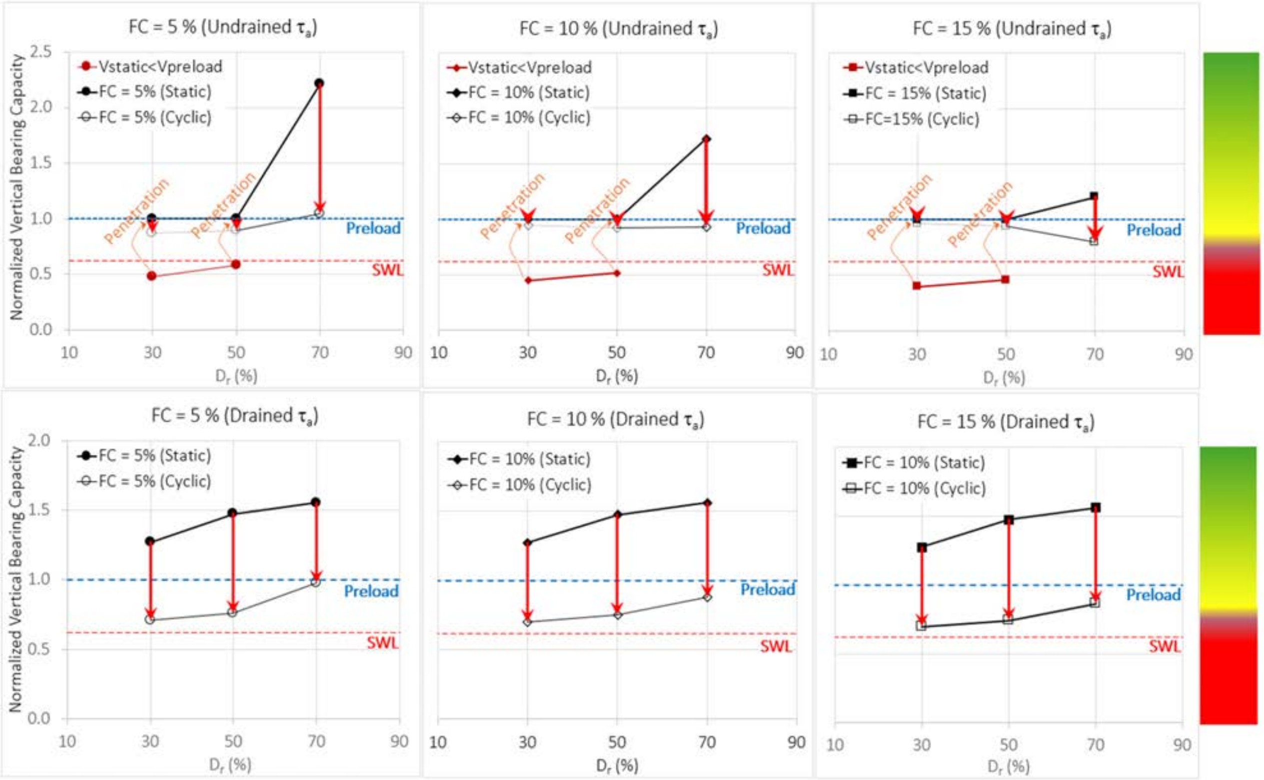

Figure 10 Reduction of vertical bearing capacities due to storm (cyclic) loading in comparison to preload (static) level considering undrained (first row) and drained (second row) behaviour for average load components and the effect of fines content (FC) and relative density (D_r). *Note: In some undrained cases, the calculated capacity falls below the preload level, indicating penetration. The depth of penetration and cyclic capacities at that depth are not computed. Instead, cyclic capacities are estimated from seabed-level calculations, adjusted by the difference between static and cyclic capacities.*

Figure 10 provides a concise comparison of all analyses. The static and cyclic capacities, together with the reference *still water load* (SWL), are normalized to the preload level.

The first row of plots shows the cases based on undrained contour diagrams. Even when accounting for the effective stress increase under SWL, the resulting static vertical capacities remained below preload. These are presented alongside adjusted values (scaled to preload level), which indicate the leg penetration required to satisfy preload. Cyclic loading led to a pronounced reduction in vertical capacity, particularly in the higher-density cases.

The second row summarizes the cases employing drained contours. Here, the reductions in vertical capacity under cyclic loading were even more severe, especially for low- and medium-density soils. This has direct implications for leeward legs, which typically experience increased vertical loading during storms. If cyclic degradation reduces the available capacity below these leg loads, additional penetration will occur, leading to higher utilizations. Importantly, operators and designers should not be misled if no significant penetration is observed during field preloading: vertical capacity may still decrease substantially during storm loading.

A key finding is that analyses using undrained contours (i.e., lower initial shear strength) do not predict as severe a reduction as the drained-contour cases. What may appear conservative — adopting lower undrained strengths that suggest penetration during preloading — may in fact prove less critical than relying on drained strengths. The latter yield higher apparent static capacities during preload yet undergo substantial shear strength degradation under cyclic storm loading, ultimately producing lower vertical capacities and more severe structural implications for the jack-up.

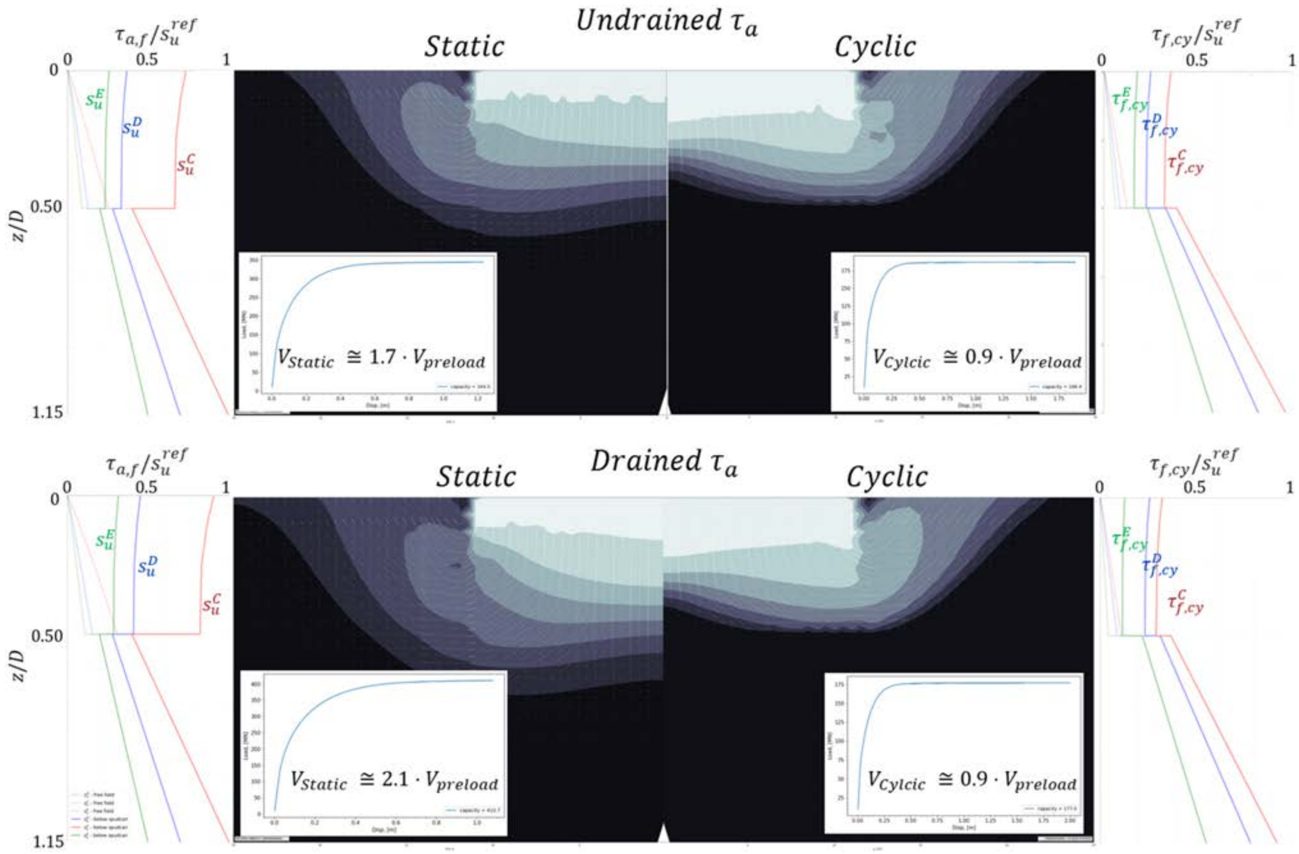

Figure 11 Shear strength profiles, displacement contours at failure and load displacement curves for the example case: $FC = 10$ %, $D_r = 70\%$ undrained and drained contours

Figure 11 presents a comparison of static versus cyclic shear strength, and vertical capacity for the representative case with fines content, $FC = 10$ %, and relative density, $D_r = 70\%$. This case exhibited the most pronounced reduction in cyclic capacity, illustrating how shear strength can deteriorate under storm-induced cyclic loading. The results emphasize the need for engineers to explicitly account for cyclic degradation in loose silty soil when assessing jack-up performance, as reliance on static capacities alone can significantly overestimate foundation reliability.

7. DISCUSSION AND CONCLUSIONS

Jack-up foundations are typically verified based on applied preload. This practice has proven reliable in many conditions and remains the basis of usual offshore wind and oil & gas site assessments. However, in silty or loose sand–silt soils, preload alone does not guarantee foundation safety under storm loading.

During severe storms, foundation loads may approach or exceed the preload capacity. Exceeding this threshold can cause additional settlements, which directly affect structural utilizations. Four-legged jack-ups have some redundancy, as load redistribution can occur when one leg settles. In contrast, three-legged units are more vulnerable, as settlement amplifies loads on the affected leg and may escalate into progressive failure.

The analyses presented demonstrate that in silty soils, cyclic degradation of shear strength and vertical capacity can be critical. While undrained analyses often yield lower initial static capacities (deemed conservative), they may not capture the more severe capacity loss that occurs when soils behave drained during preload but undrained under storm. In such cases, drained analyses may appear to support higher static loads, yet these can degrade sharply under cyclic loading, leaving the jack-up potentially not fit for purpose.

Several implications for site-specific assessment practice emerge:

- Preload verification alone can be insufficient. In silty and loose sandy soils, storm loading can reduce capacity significantly below preload levels.
- Drained conditions dominate during preload, operational conditions, however, storm loading can induce rapid undrained response and strength degradation.
- Differential settlements affect structural safety. Further penetration alters fixities, redistributes loads, and increases leg utilizations — particularly critical for three-legged units.
- Site-specific analyses should consider potential critical combinations of soil behaviour (e.g. drained behaviour during preload and undrained cyclic behaviour) during storms. For (loose) silty soils this should be considered explicitly.
- Foundation improvements such as dredging can be limited and costly. Early assessment, planning and optimisation of such measure can reduce the costs and increase reliability.

In summary, preload remains a useful verification step, but it cannot be the sole basis for jack-up foundation safety to be operating on (loose) silty sand. Routine inclusion of cyclic degradation in site-specific assessments, combined with careful treatment of drained and undrained conditions, is recommended to ensure robust and reliable design.

ACKNOWLEDGEMENTS

The support of the Norwegian Geotechnical Institute and GustoMSC are greatly acknowledged.

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