Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-217

Material factors in cyclic soil analysis of offshore structures: a definable challenge?

Marco D'Ignazio
Terra Research Centre, Faculty of Built Environment, Tampere University & Ramboll Finland Oy, Tampere, Finland
marco.dignazio@tuni.fi

ABSTRACT: Accurately accounting for cyclic soil behavior is essential in offshore foundation design, yet detailed cyclic testing is often impractical in early project phases. While extensive databases exist for monotonic properties, equivalent resources for cyclic parameters remain scarce. As a result, cyclic shear strength is frequently estimated from limited data, scaled contour diagrams, and engineering judgement, with uncertainties rarely quantified. Current design codes apply material factors without distinguishing between monotonic and cyclic parameters, leaving open the question of whether these factors adequately capture cyclic degradation uncertainty. This paper reviews the main sources of uncertainty in defining cyclic shear strength and discusses how they influence material factor selection. It highlights the need to formalize degradation factor definition using measurable indicators—such as fit quality, level of site-specific testing, or alignment with independent datasets—and to reflect uncertainty explicitly in material or model factors. Looking ahead, probabilistic frameworks, supported by artificial intelligence, machine learning, and surrogate modelling, offer a means to integrate cyclic degradation effects into reliability-based design. These approaches could enable rapid, data-driven assessment, guide targeted cyclic testing and improve confidence in offshore foundation performance under dynamic loading.

KEYWORDS: offshore geotechnics, material factor, cyclic shear strength, uncertainty, probabilistic design, database

1 INTRODUCTION

Understanding the effect of cyclic loading on the performance of offshore foundation structures is crucial to ensuring safety under the stresses imposed by wind, waves, and ice. Cyclic loading is well known to alter soil properties (e.g., Andersen 2015), affecting both shear strength and moduli. These parameters may degrade due to the accumulation of shear strain or excess pore pressure during storm events. In some cases, however, cyclic loading can have a beneficial effect due to rate dependency—particularly in fine-grained soils—where the cyclic undrained shear strength and stiffness may exceed their monotonic counterparts, as observed for Drammen Clay (Andersen 2004).

Cyclic soil behavior is stress-path dependent and influences deformation mechanisms differently depending on the foundation type (Andersen 2015). Defining cyclic soil properties in design presents several challenges, as the number of cyclic laboratory tests is typically limited for a given soil unit—even in large offshore wind farms that may span several kilometers. These tests generally form the basis for selecting cyclic contour diagrams, which are widely accepted in the industry and serve as a key input to design.

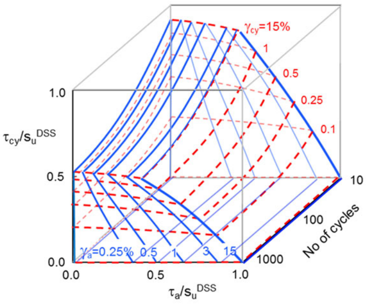


Figure 1. 3D representation of cyclic and average shear strains as functions of average and cyclic shear stresses and number of cycles. Normally consolidated Drammen Clay (Andersen 2015).

Cyclic contour diagrams (Figure 1) describe the relationship between average and cyclic shear stresses, strain accumulation, and the number of loading cycles. Deriving such diagrams from a small number of tests remains a significant challenge and can affect foundation design outcomes (Kanitz et al. 2025). In the absence of site-specific data—common in early project phases—databases may be used to estimate contour diagrams based on basic soil properties such as relative density, grain size, stress history, and index parameters (Andersen et al. 2023). Scaling factors are then applied to calibrate the diagrams to match trends observed in available test results.

These diagrams are typically used to define the cyclic shear strength of the soil for a representative number of load cycles and a design stress path, which includes both cyclic and average components, resulting in $\tau_{f,cy} = \tau_{cy} + \tau_a$. This cyclic strength is then applied in equivalent static analyses to evaluate the ultimate and serviceability limit state (ULS and SLS) performance of the foundation.

Shear stresses in cyclic contour diagrams are typically normalized by the monotonic undrained shear strength s_u for cohesive (C) soils or by the vertical effective stress at a reference pressure of 100 kPa (σ'_{ref}) for non-cohesive (NC) soils. The corresponding $\tau_{f,cy}/s_u$ or $\tau_{f,cy}/\sigma'_{ref}$ can be used to define correction or degradation factors (D'Ignazio et al. 2025) to the monotonic strength as follows:

$$d_{fC} = (\tau_{cy} + \tau_a)/s_u \quad (1)$$

$$d_{fNC} = \frac{(\tau_{cy} + \tau_a)/\sigma'_{ref}}{tan\varphi'_{mono}} \quad (2)$$

The factors are applied directly to the monotonic characteristic strength ($\tau_{mono,k} = s_u \ or \ tan\varphi'_{mono}$) of the soil to define a characteristic cyclic shear strength. A material factor γ_M = 1.0 – 1.4 is then applied to define the design cyclic shear strength as:

$$\tau_{f,cy,d} = \frac{\tau_{mono,k}}{\gamma_M} d_{f(C,NC)} \quad (3)$$

Current design codes (e.g., DNV 2019) do not differentiate between material factors for monotonic and cyclic strength properties. Instead, the characteristic strength shall include cyclic effects (DNV 2019), which effectively embeds the cyclic degradation within the characteristic value rather than addressing it separately.

In practice, the characteristic monotonic strength is typically derived using a rigorous statistical approach, whereas the corresponding cyclic degradation factor is often based on engineering judgement—through interpretation of limited laboratory test data, scaling of diagrams, and simplification of stress paths and cyclic histories. If material factors are intended to address uncertainty in the determination of a given property, is it appropriate to use the same factor for both monotonic and cyclic strength? Does this material factor sufficiently cover the uncertainty introduced when defining cyclic strength from just a few laboratory tests?

This paper addresses these questions by exploring the uncertainties associated with cyclic degradation factors and by proposing a strategy to improve material factors—or introduce model factors—to better reflect the uncertainty associated with cyclic strength estimation in offshore geotechnical design.

2 UNCERTAINTIES IN DETERMINING CYCLIC SHEAR STRENGTH OF SOILS

2.1 *Contour diagrams*

Planning a cyclic laboratory testing campaign presents numerous challenges, particularly due to the unknown a priori response of soil under different combinations of cyclic stress ratio (CSR) and average stress ratio (ASR). Initial CSR/ASR values are typically selected based on experience. However, it is common practice to refer to databases of similar soils or to derive preliminary diagrams from global databases using basic soil properties.

Andersen et al. (2023) describe a detailed methodology for selecting contour diagrams from the Andersen (2015) database, using parameters such as relative density, water content, fines content, plasticity index, friction angle, and overconsolidation ratio. The derived diagrams are intended for use: i) in the absence of site-specific data, ii) to select preliminary CSR/ASR values for cyclic laboratory test planning, and iii) to be scaled to reflect the actual cyclic test results.

Andersen et al. (2023) suggest applying linear scaling to the vertical and horizontal axes of the diagram (see Figure 2). However, the uncertainties associated with this empirically based method, which relies heavily on engineering judgement, are not explicitly addressed.

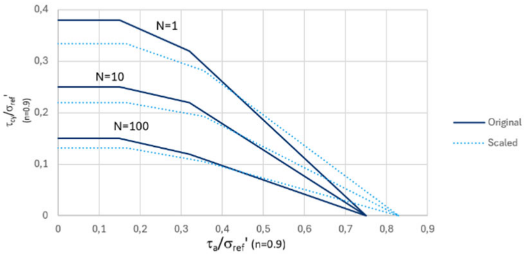


Figure 2. Type B cyclic shear stress contour diagram for sand or silt under drained average shear stress (Andersen, 2015) scaled for soil with Dr = 80 %, FC = 10 % and OCR = 1 (Isometsä 2025).

In the author's experience, the method provides reliable estimates of cyclic properties when compared to site-specific test results. For example, in a large offshore wind project off the US East Coast, the method resulted in an underestimation of the scaling factors by 3-6% on average, with an overall bias factor of ≈95% and a coefficient of variation (COV) of ≈12% (n=14). The testing campaign included cyclic DSS (cyDSS) tests on n. 6 cohesive units and n. 8 non-cohesive units (D'Ignazio 2024). However, this outcome cannot be generalized, and the methodology would benefit from further validation across a broader range of projects.

An alternative to using databases is the development of site-specific contour diagrams from laboratory test data. These may be: i) manually drawn based on expert judgement, or ii) generated by fitting a predefined τ_{cy} versus N decay law, with coefficients derived from regression analyses.

While both approaches involve uncertainty, the latter provides quantifiable metrics (e.g., R^2, MSE), offering insight into the quality of the fit.

Cyclic soil behavior is also stress-path dependent. Consequently, cyclic contour diagrams may be derived from both cyclic DSS and triaxial compression/extension tests. These test types generally capture the stress paths encountered beneath or around cyclically loaded foundations (Figure 3).

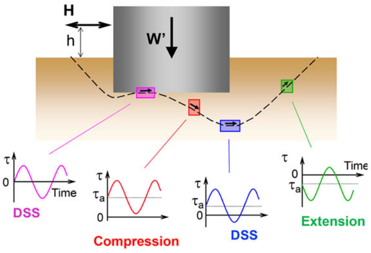
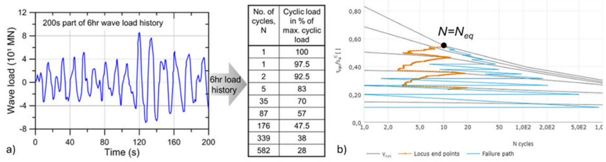


Figure 3. Simplified stress conditions for typical soil elements along a potential failure surface beneath a shallow foundation (Andersen 2015).

2.2 *Idealization of cyclic load history*

Another significant challenge in modelling cyclic soil behavior lies in translating the irregular storm load history—produced by waves and wind—into accumulated shear strain and pore pressure changes, which determine soil property degradation.

The accumulation procedure (Andersen 2015) involves decomposing the storm load history into segments defined by average load, cyclic amplitude, and number of cycles. Cyclic amplitudes are normalized with respect to the peak load. These load parcels are then applied in ascending order to the contour diagrams, resulting in an equivalent number of cycles, N_{eq} (see Figure 4). This value represents the number of cycles of peak load that would induce the same soil degradation as the full storm event, which may comprise thousands of cycles and last several hours (e.g., a 35-hour design storm).



No. of cycles, N	Cyclic load in % of max. cyclic load
1	100
1	97.5
2	92.5
5	83
35	70
87	57
176	47.5
339	38
582	28

Figure 4. a) Transformation of cyclic load history into parcels (Andersen 2015); b) determination of N_{eq} by strain accumulation (Isometsä 2025).

There are several limitations to this procedure. It assumes purely two-way cyclic loading, neglecting the effects of the average load component. While this may be acceptable for monopiles, it can significantly impact the performance of gravity-based foundations. Additionally, it is unverified whether applying load parcels in ascending order yields the most conservative estimate of accumulated strain or N_{eq}. The method also does not consider multidirectional cyclic loading, which is rarely accounted for in practice due to the scarcity of equipment capable of such testing. However, this limitation is especially relevant for floating offshore wind platforms with shared anchors (e.g., Abadie 2025).

2.3 *Shear strength definition from stress-path*

The process of determining cyclic shear strength and associated degradation factors (as outlined in Equations 1 and 2) involves several steps: i) selecting a representative contour diagram, often based on limited unidirectional cyclic laboratory data; ii) idealizing the storm load history and determining an equivalent number of cycles N_{eq}; and iii) selecting a representative cyclic-to-average shear stress ratio to define the cyclic τ_{cy} and average τ_{av} stress components at failure (Figure 5).

In practice, the cyclic-to-average stress ratio varies over time and across load segments. Typically, the ratio corresponding to the largest amplitudes (e.g., >90% of peak load) is selected. The resulting cyclic shear strength $\tau_{f,cy} = \tau_{cy} + \tau_a$ is used in equivalent static calculations, since time-domain cyclic analyses remain rare and computationally demanding, particularly for large wind farms. Such analyses also require advanced constitutive models, which are not widely adopted in industry practice.

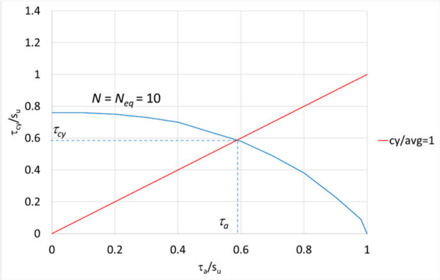


Figure 5. Determination of DSS τ_{cy} and τ_a for cyclic-to-average ratio of 1 (Drammen clay OCR=4, N=10).

3 ACCOUNTING FOR UNCERTAINTIES IN CYCLIC DESIGN OF OFFSHORE GEOSTRUCTURES

3.1 *General considerations*

As discussed in the previous section, the definition of cyclic shear strength for a given project and foundation type involves several sources of uncertainty. These are not fully addressed by the material factors recommended in current design codes, which are generally based on the typical variability encountered in the determination of monotonic shear strength from laboratory or in-situ testing.

When cyclic contour diagram methodologies are used, cyclic strength values are often selected through a subjective best-fit process to a small number of laboratory tests. In the Andersen et al. (2023) approach, the quality of the contour diagram fit depends on how well it captures the laboratory observations—i.e., stress, strain, and number of cycles to failure—based on typically 3–5 tests per unit. If the results from the Andersen database do not align well, contours may be redrawn manually or fitted using regression methods.

However, the number and representativeness of tests can significantly influence the final contour diagram. Adding more data—i.e., reducing epistemic uncertainty—may either increase or decrease the scaling factors depending on the natural variability of the soil. This is particularly relevant in offshore wind farms, where boreholes are often spaced kilometers apart, and laboratory samples for cyclic testing originate from different locations within a unit. As such, variability in basic soil properties—which strongly influence cyclic response—can lead to observable scatter in cyclic test results (Andersen 2015; Andersen et al. 2023).

3.2 *Use of databases in design*

Using soil behavior databases for preliminary cyclic assessments is a well-established industry practice and is typically accepted by certifying bodies, provided that the contour diagrams are adequately scaled to match site-specific test results. While increasing the number of cyclic tests may influence the selection of scaling factors, there is also the possibility that additional data would either confirm the original selection, with little or no adjustment required (Figure 6a-b—no influence on the initial scaling factor of 0.8), or result in a significantly higher or lower scaling factor (Figure 6c-d—initial scaling factor increased by 22%, from 0.9 to 1.1).

This raises the question: how should we compare cases where design is based on minimal testing with those supported by an extensive cyclic test campaign? Should material factors reflect the level of data confidence and effort expended on testing? In projects with limited data, should the chosen strength values reflect cautious (i.e., lower-bound) estimates, while more extensively tested cases adopt best-estimate values?

In essence, the notion of a "characteristic value" for cyclic shear strength becomes blurred. In practice, acceptance by the certifying authority often depends on consistency of interpretation and engineering judgement, rather than rigorous statistical treatment.

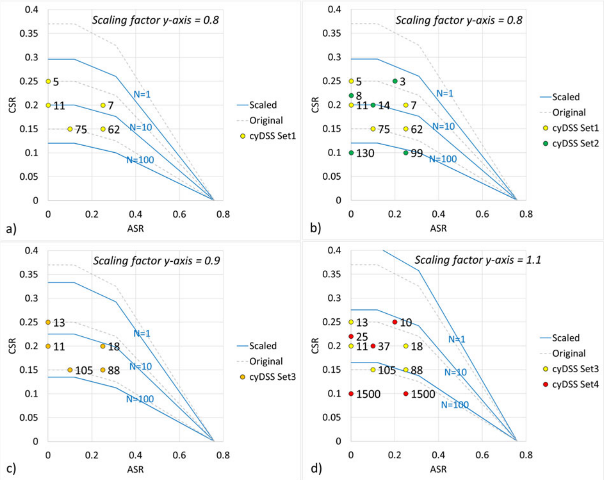


Figure 6. Cyclic contour scaling using different cyDSS sets indicating a)-b) low uncertainty (Sets 1 and 2) and c)-d) high uncertainty (Sets 3 and 4). Test labels indicating number of cycles at failure.

In the author's experience, this approach often leads to project-level discussions and even disagreements, as it relies heavily on engineering judgement and experience. Although the methodology is widely used in both offshore wind and Oil and Gas projects, a more quantitative treatment of uncertainty is warranted. A comprehensive study comparing database predictions with laboratory data across different soil types and regions would allow for the definition of model factors (or uncertainty bounds) associated with each method. While such broad studies are limited by data availability due to confidentiality, large offshore projects with ample data offer a promising testbed for site-specific uncertainty evaluations.

3.3 *Use of project-specific contours in design*

The drawing of project-specific cyclic contour diagrams is another industry-accepted approach. However, this method is inherently subjective and susceptible to user bias, whether the contours are manually drawn or generated through curve-fitting using assumed decay laws.

Compared to the database-based approach—which typically uses linear scaling—project-specific diagrams provide greater flexibility in capturing nuances in cyclic response. However, this flexibility can also introduce greater variability. For the same test data, different interpretation methods may result in noticeably different values of N_{eq}, thereby influencing cyclic degradation estimates (as discussed by Kanitz et al. 2025 and shown in Figure 7).

As with database approaches, the use of project-specific diagrams should be supported by uncertainty assessments—ideally involving comparisons across datasets and sites. While such evaluations are rarely undertaken due to cost and time constraints, they are essential for improving the robustness of cyclic design practices, particularly when engineering judgement plays such a dominant role in defining characteristic values.

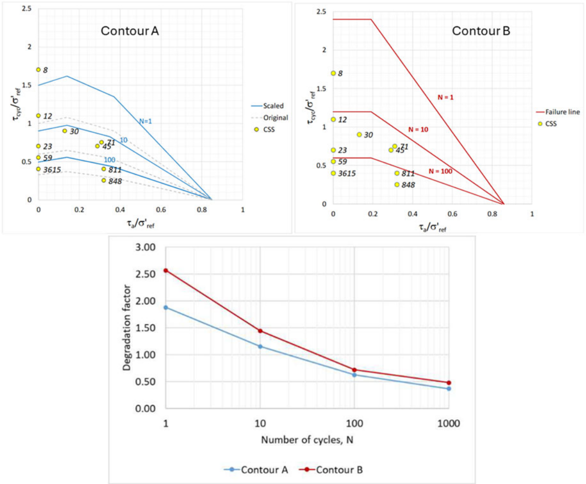


Figure 7. Impact of contour diagram selection on cyclic degradation factors (adapted from Kanitz et al. 2025; CSS = cyDSS).

4 DISCUSSION

This paper has explored the uncertainties involved in estimating cyclic shear strength and questioned whether the material factors currently applied in offshore geotechnical design adequately reflect these uncertainties. While the contour diagram methodology is widely accepted and applied in various forms, it remains rooted in empirical experience and engineering judgement. As cyclic degradation often governs offshore foundation design, reliance on a small number of laboratory tests or scaled database diagrams—without quantification of uncertainty—becomes a critical design concern.

In many projects, cyclic assessment is carried out in two components: the characteristic value is derived from monotonic strength data (which are generally more abundant), and a separate degradation factor is applied for cyclic effects, based on experience, contour fitting quality, or other metrics. While this framework is practical and widely recognized, the cyclic component often depends heavily on engineering judgement, and the associated uncertainty is rarely quantified. Future developments should aim to formalize this process by linking the degradation factor to measurable parameters—such as statistical fit quality, level of site-specific testing, or agreement with independent datasets—thereby reducing subjectivity and improving traceability.

The growing interest in probabilistic design frameworks for offshore geotechnics further highlights the need for a more transparent and quantifiable approach to cyclic strength definition. Offshore projects typically generate extensive datasets for monotonic parameters (e.g., CPT, laboratory strength tests), whereas cyclic test data remain sparse and costly to obtain. If uncertainties in cyclic strength cannot be statistically defined from the available data, they should be explicitly reflected in material or model factors that depend on the level of data confidence.

Emerging tools such as artificial intelligence, machine learning, and surrogate modelling offer promising opportunities to support cyclic design in a probabilistic context. Provided that access is granted to high-quality datasets from both published sources and industrial projects, these approaches could be used to construct predictive models that emulate advanced cyclic soil analyses. Surrogate models could be integrated into Monte Carlo simulations or reliability-based design workflows to efficiently quantify the influence of cyclic degradation uncertainty on foundation performance. Such capabilities would facilitate a shift from deterministic “characteristic value” approaches towards meeting explicit reliability targets, while also helping identify where additional cyclic testing would most effectively reduce uncertainty.

5 CONCLUSIONS

Cyclic shear strength of soil is a critical yet highly uncertain parameter in offshore geotechnical design. The reliance on limited cyclic test data, scaled diagrams, and engineering judgement means that current design practices may not fully capture the variability associated with cyclic degradation. While various approaches are in use, the cyclic component is rarely linked to quantifiable measures of confidence.

Improving this situation requires two parallel efforts: first, developing more transparent and measurable ways to define degradation factors, and second, adopting design frameworks that explicitly reflect the uncertainty in cyclic parameters. Progress will depend on broader access to high-quality datasets and closer integration of probabilistic methods into offshore geotechnics.

Advances in artificial intelligence, machine learning, and surrogate modelling present an opportunity to bridge current data gaps. By enabling rapid, probabilistic assessments of cyclic degradation, these tools could help focus testing resources where they most reduce uncertainty and support a shift towards explicit reliability targets in design. These developments would also support future updates to design codes, ensuring that cyclic effects are addressed with a level of rigor consistent with their role in offshore foundation performance.

6 REFERENCES

Abadie, C. N. 2025. Shared Anchor Pile Response to Multi-Directional Lateral Cyclic Loading. In *Bright Spark, 5th International Symposium on Frontiers in Offshore Geotechnics*, Nantes.

Andersen, K. H. 2004. Cyclic clay data for foundation design of structures subjected to wave loading. In Cyclic behaviour of soils and liquefaction phenomena, 371-387.

Andersen, K. H. 2015. Cyclic soil parameters for offshore foundation design. In *Frontiers in offshore geotechnics III*, 5, London, Taylor &Francis.

Andersen, K. H., Engin, H. K., D’Ignazio, M., and Yang, S. 2023. Determination of cyclic soil parameters for offshore foundation design from an existing data base. *Ocean Engineering*, 267, 113-180.

Det Norske Veritas, DNV, 2019. Recommended practice DNV-RP-C212: Offshore soil mechanics and geotechnical engineering. Edition September 2019. Norway: DNV AS. 185 p.

D’Ignazio, M. (2024) Cyclic loading of monopiles: engineering challenges and insights from Ramboll’s experience. Danish Geotechnical Society Seminar Weblink.

D’Ignazio M., Kanitz, M. and Dührkop, J. 2025. A simplified, novel approach for modelling cyclic degradation of soil properties around monopile foundations for offshore wind turbines. In *5th International Symposium on Frontiers in Offshore Geotechnics ISFOG*, Nantes, France.

Isometsä, V. 2025. Geotechnical performance of gravity-based foundations for offshore wind turbines in the Gulf of Bothnia’s soil conditions (M.Sc. Thesis, University of Oulu, Finland).

Isometsä, V., D’Ignazio, M., Haikola, M., Tuomela, A., and Batarlar, B. 2025. Geotechnical performance of gravity foundations for offshore wind in the Gulf of Bothnia’s soil conditions. In *5th International Symposium on Frontiers in Offshore Geotechnics ISFOG*, Nantes, France.

Kanitz, M., Dührkop, J., D’Ignazio, M., Bouteiller, A., Ghasemi, P., 2025. Impact of cyclic contour diagram definitions on monopile design for offshore wind turbines. In *5th International Symposium on Frontiers in Offshore Geotechnics ISFOG*, Nantes, France.