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Time scaling of cyclic loading and consolidation between centrifuge and field conditions for prediction of life-time seabed-structure interaction

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ABSTRACT: In offshore environments, short-term undrained cyclic loading events, such as storms, can cause reductions in seabed strength due to excess pore pressure generation. However, recent studies have shown that periods of consolidation during the operational life of offshore structures can lead to strength recovery, potentially exceeding the original intact strength. Accurately capturing this interplay between degradation and recovery is essential for reliable and resilient foundation design. Centrifuge modelling offers an effective means to investigate these processes by accelerating pore pressure dissipation and enabling simulation of millions of load cycles within short timescales. A key challenge, however, lies in the mismatch between centrifuge and field conditions: the relative rates of cyclic loading and consolidation differ significantly. Due to apparatus limitations, cyclic motions cannot be applied at frequencies that match the rate of pore pressure dissipation, which is scaled by N^2, where N is the centrifuge acceleration. This discrepancy leads to an unrealistically high degree of consolidation relative to the number of cycles. This study investigates the impact of this time scaling mismatch on the evolution of seabed strength under combined cyclic loading and consolidation. The findings aim to enhance the interpretation of centrifuge test results and provide insight for modelling of the long-term soil–structure interaction behaviour of offshore foundation systems.

1 INTRODUCTION

The global expansion of offshore energy has diversified the range of subsea infrastructure, moving beyond traditional oil and gas platforms to include renewable energy assets such as offshore floating wind turbines, wave energy converters, and their associated dynamic power cables. These facilities are increasingly reliant on station-keeping systems, such as plate or suction anchors, and subsea pipelines or cables that interact directly with the seabed. Throughout a typical design life of 25 to 30 years, these foundations are subjected to complex environmental and operational loading, often involving millions of cycles of cyclic motion (Rui et al. 2025; Foglia et al. 2025).

A primary challenge in anchoring design is accurately predicting the long-term geotechnical resistance of the seabed. Traditional design methodologies, such as those prescribed by DNV standards (e.g. DNV-RP-C212; Andersen et al. 2015), typically adopt a conservative "total stress" approach. These methods generally focus on ensuring that the soil's cyclic softened resistance, accounting for degradation during a peak storm event, remains greater than the maximum design load. While this ensures short-term stability, it fails to account for the realistic, time-dependent evolution of soil strength (Zhou et al. 2019; Zhou et al. 2020a, Zhou et al. 2020b; Wang et al. 2023).

As illustrated in Figure 1, the geotechnical response of the seabed is a highly dynamic process governed by complex soil-structure interaction. Short-term undrained cyclic loading generates excess pore water pressure, leading to soil remoulding and subsequent strength degradation. Conversely, offshore foundations undergo prolonged periods of maintained loading or low-amplitude operation where pore pressure dissipation outpaces its generation. This consolidation-dominated process reduces the specific volume of the soil, resulting in a substantial regain in both strength and stiffness throughout the asset's operational life. Current design standards tend to be overly conservative, often overlooking the cumulative benefits of reconsolidation-induced resistance (Gourvenec 2022; Zhou et al. 2019; Wang et al. 2023). Understanding this evolving interaction is essential for optimizing safety margins, supporting infrastructure life extension, and managing the decommissioning of modern offshore foundations.

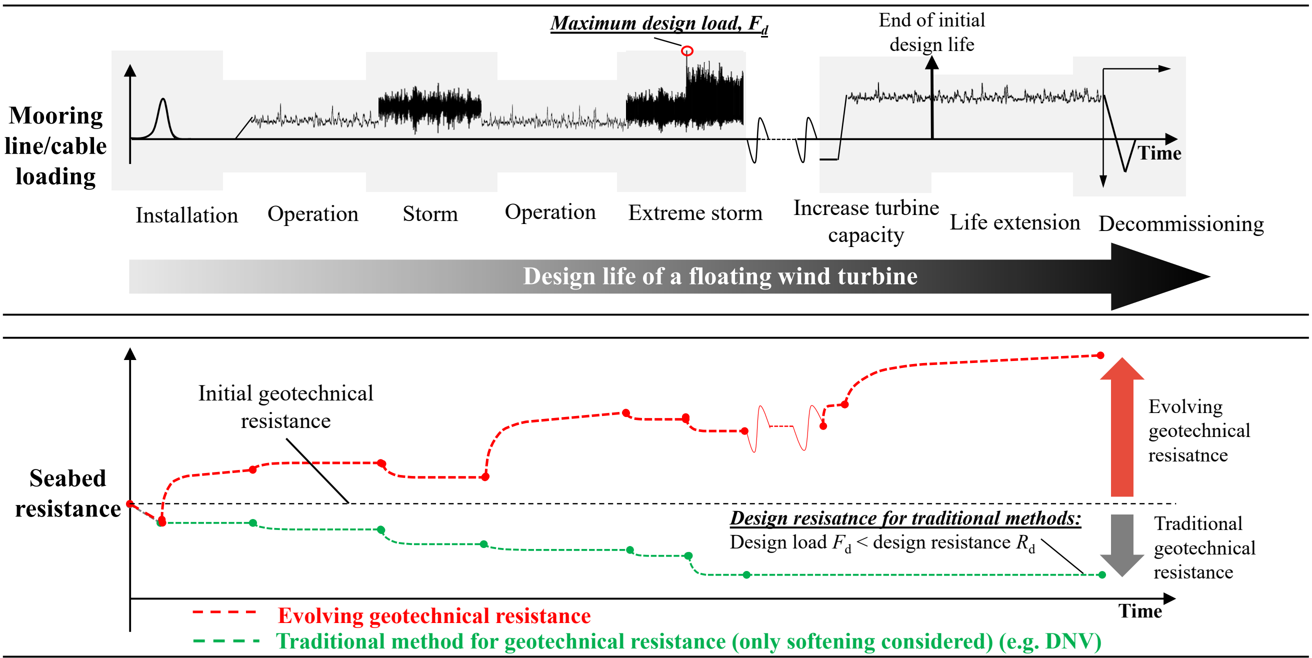

Figure 1. Illustration of mooring line/cable loading throughout design life of a floating wind (upper) and corresponding evolving seabed response (lower).

2 CENTRIFUGE MODELLING OF LIFETIME PERFORMANCE

2.1 he principle and benefits of centrifuge modelling: the 'time machine'

Centrifuge modelling has long been recognized as a cornerstone of offshore geotechnical research, acting as a powerful "time machine" that allows for the simulation of long-term soil-structure interaction within practical laboratory timescales (Zhou et al. 2020a; Wang et al. 2023; Wang et al. 2025). The fundamental principle of the geotechnical centrifuge is the creation of an inertial acceleration field N times that of Earth's gravity (g). By rotating a model at high speeds, the physical dimensions are reduced by a factor of $1/N$, while the self-weight induced stresses and strains remain identical to those found in the prototype. This preservation of stress levels is critical because the mechanical behavior of soil, including its strength, stiffness, and compressibility, is highly non-linear and dependent on the effective stress state (Muir Wood 2004).

For offshore foundations, the centrifuge provides a unique environment to study the transition from short-term undrained behavior to long-term consolidated states. By recreating the geostatic stress profile of the deep-water seabed, researchers can observe how foundations for renewable energy assets or traditional oil and gas platforms interact with seabed over their entire service life. This capability is essential for validating the "whole-life" reliability of systems like plate anchors, cable & pipeline touchdown zones, where the soil state is continuously altered by mooring line or structural loads.

Beyond replicating stress conditions and soil–structure interaction, centrifuge modelling offers another critical advantage: the ability to compress time. This acceleration of time-dependent processes, particularly consolidation, is governed by well-established scaling laws, as discussed in the following section.

2.2 Time scaling laws and consolidation acceleration

The primary advantage of centrifuge modelling in the context of lifetime performance lies in its ability to accelerate time-dependent consolidation processes. Consolidation is governed by the dissipation of excess pore water pressure, a process where the time required for a specific degree of dissipation is proportional to the square of the drainage path. In the centrifuge, where length scales are reduced by $1/N$, the drainage paths are similarly shortened. Consequently, the time scale for consolidation is accelerated by a factor of N^2. For a typical offshore study conducted at 100g (N = 100), the consolidation process occurs 10000 times faster than in the field. At higher accelerations, such as the 150g used in plate anchor testing, this acceleration factor reaches 22,500. This scaling law (Muir Wood 2004) enables researchers to model decades of seabed evolution—including the cumulative effects of maintained loading and periodic storm cycles—within a few hours of laboratory testing. This acceleration is vital for observing combined effects of cyclic loading and reconsolidation, and strength regain that would otherwise take years to manifest in field-scale pilot projects.

2.3 The scaling limitation: actuator frequency limits and drainage mismatch

Despite the N^2 benefit for consolidation, a significant technical limitation arises from the restricted loading frequency of centrifuge actuators. To maintain the same degree of drainage as the prototype (i.e., the same ratio of loading period to consolidation time), the cyclic loading frequency in the centrifuge would technically need to be increased by a factor of N^2. For an environmental wave frequency of 0.1 Hz in the field, a 50g centrifuge test would require a loading frequency of 250 Hz to achieve prototype-equivalent drainage conditions. In practice, achieving such high frequencies is mechanically unfeasible for standard centrifuge actuators, which are generally limited to a few Hertz due to power, control, and data acquisition constraints. Consequently, while the "consolidation clock" runs at a speedup of N^2, the structural "loading clock" is often restricted to a speedup of only N or even less. This creates a fundamental scaling mismatch: because the actuator cannot cycle fast enough to keep up with the N^2 acceleration of water dissipation, the soil in the centrifuge model drains much faster relative to the load cycles than it would in the field. The physical consequence of this mismatch is that the centrifuge model fails to replicate the predominantly undrained conditions typically associated with storm events in the field. Instead of the rapid accumulation of pore pressure and subsequent softening that characterizes early-life field performance, the centrifuge model allows for excessive inter-cycle consolidation and hardening. This means that raw experimental data can provide an overly optimistic view of seabed stability, potentially masking critical phases where cyclic degradation might dominate before consolidation can effectively harden the soil. Understanding this limitation is essential for developing a numerical "bridge" to translate these accelerated observations into reliable field-scale designs.

3 MODELLING EXAMPLE

3.1 Centrifuge modelling

This section describes a long-term cyclic pipe penetration test used to investigate and understand the changing response of seabed soil at centrifuge and field conditions. The experimental data was originally reported by Yuan et al. (2017). These tests were conducted using a centrifuge at 50g at the University of Western Australia to simulate stress conditions in deep-water soft soil environments.

The experiment was performed in a normally consolidated kaolin clay. During the test, the model pipe was moved cyclically between two points: a starting position at z/D = -1 (one pipe diameter, D = 20mm at model scale, above the mudline) and a maximum depth where the applied soil pressure reached q = 8 kPa. The specific properties of the kaolin clay are listed in Table 1, and the full-time history of the loading cycles is shown in Figure 2. During the test, the penetration rate of the pipe was set at 2.5 mm/s (which is 0.125D/s) at the model scale. For a single stroke moving between -1D and +1D, the time required for one cycle is approximately 32 seconds in the centrifuge. To calculate the equivalent time at the full prototype scale, we apply the standard centrifuge scaling law (N^2 for consolidation time):

$$t_{\text{prototype}} = t_{\text{model}} * N^2 \quad (2)$$

Given N = 50, the $t_{\text{prototype}}$ is about 80000s. Note that the cyclic penetration was a load-control mode, so the time for each cycle was changed as the penetration depth.

Table 1. Geotechnical properties of the Kaolin clay from Yuan et al. (2017).

Property	Value
Specific gravity, G_s	2.6
Soil sensitivity, S_t	2.5 (4*)
Gradient of normal compression line, λ	0.205
Gradient of unload-reload line, κ	0.044
Effective unit weight, ϒ' (kN/m^3)	6
Coefficient of consolidation at about 1D depth, c_v (m^2/year)	2.6

**Value in brackets consider water entrainment*

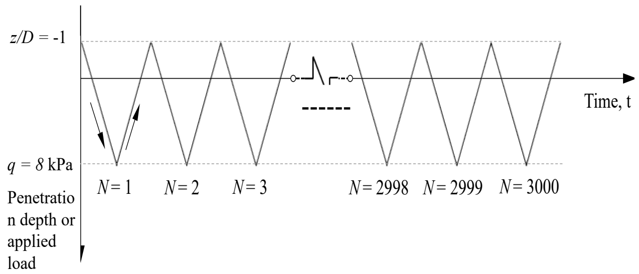

Figure 2. Time history of long-term pipe test (from Yuan et al. 2017)

For offshore structures such as subsea risers or power cables, the penetration stiffness, k_{soil}, is a fundamental parameter required for engineering design. This value defines the relationship between the load applied and the resulting displacement, and is calculated as follows

$$k_{soil} = q_{max}/z \quad (1)$$

In this equation, q_{max} represents the maximum pipe penetration resistance measured during each individual loading cycle. This resistance value is not constant; rather, it changes throughout the long-term cycles as the underlying soil strength evolves. The variation in q_{max} is driven by two competing physical mechanisms:

- Cyclic softening: the repeated movement of the pipe causes a reduction in soil strength due to the generation of excess pore pressure and the corresponding reduction in effective stress.
- Consolidation hardening: during the process of long-term cyclic loading, the rate at which excess pore water pressure dissipates is greater than the rate at which it is generated. This net reduction in pore pressure leads to a steady increase in the effective stress within the soil. As the effective stress rises, the soil becomes denser, causing the material to become more compact and gain shear strength.

By calculating k_{soil} using the maximum resistance from each cycle, designers can better account for how the seabed support fluctuates under long-term environmental loading.

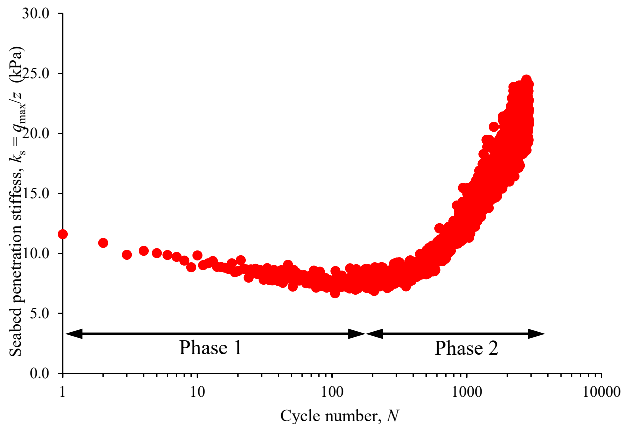

Figure 3. Measured seabed penetration stiffness during long-term cyclic penetration (from Yuan et al. 2017)

Figure 3 illustrates the measured evolution of penetration stiffness as a function of the number of cycles. The experimental result includes some scatter as the limiting pressure achieved in the experiments varied slightly between cycles, in the range from q=8 to 10 kPa. The initial reduction in stiffness over the first ~100 cycles reflect the lower soil strength due to remoulding (Phase 1). This stiffness is regained as the soil strength increases through consolidation, with final values of ks that are approximately 1·8 times the initial value (Phase 2).

To simply quantify the progress of consolidation throughout the testing process, the degree of consolidation, U, can be estimated using a hyperbolic model proposed by Chatterjee et al. (2013)

$$U = 1- 1/(1+T/T_{50})^{m} \quad (3)$$

where T_{50} is the dimensional time factor for 50% dissipation of the excess pore pressure, m is a constant. For a penetration pipe in soft clay, the T_{50} = 0.09 and m = 1.4 (Zhou et al. 2020c). Based on these values, a single loading cycle of 32 s results in a consolidation degree of only U = 9% (almost undrained condition). However, over the course of 3,000 cycles, the cumulative consolidation exceeds U > 95%. At the prototype scale, a typical storm period lasting approximately 3 hours would result in U < 15%, suggesting that significant pore pressure remains during such events (i.e. undrained condition).

3.2 Numerical modelling

To further investigate the relationship between centrifuge observations and field conditions, a series of numerical simulations were performed. The primary objective of these simulations is to understand the scaling factors governing consolidation and how the differences between model and prototype scales influence variations in soil strength and penetration stiffness. Specifically, the numerical study aims to bridge the gap between high-gravity laboratory testing and the actual temporal progression of drainage in the field, ensuring that the laboratory results can be reliably extrapolated to realistic design scenarios.

The numerical framework used in this study is based on critical-state soil mechanics, following the conceptual approach illustrated in Figure 4 and previously established by Zhou et al. (2019, 2020c). In this methodology, the seabed is represented by a series of one-dimensional soil elements, each assigned specific constitutive properties to simulate local soil behaviour under vertical loading. By discretizing the soil column in this way, the model can account for vertical gradients in effective stress and pore pressure that are difficult to measure directly in a physical test. A key feature of this model is that the analysis is conducted entirely within the effective stress domain. This allows the simulation to explicitly capture the two competing processes of excess pore pressure generation (caused by cyclic loading) and pore pressure dissipation (which leads to consolidation hardening). By tracking these changes at the individual element level, the model can accurately predict how the soil strengthens or softens over thousands of cycles. This approach provides a robust platform for evaluating the long-term soil-structure interaction. Comprehensive technical details and the governing equations for this numerical framework are provided in Zhou et al. (2020c).

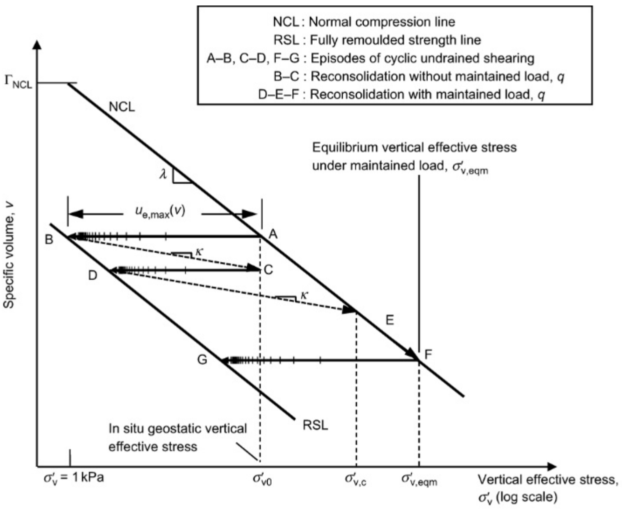

Figure 4. Framework concept to capture changes in vertical effective stress and specific volume during undrained cyclic loading, reconsolidation and maintained load

The numerical framework is first employed to replicate the centrifuge test results, providing a deeper insight into how soil behaviour evolves under long-term cyclic loading within a high-gravity environment. By validating the model against the experimental data, the reliability of the numerical approach is established. Following this validation, three additional simulations are conducted to investigate the influence of drainage time on soil response. In these cases, the duration allowed for consolidation during each loading cycle is varied, while the cyclic penetration sequence remains identical to the original test. This parametric study allows for a clear comparison of how the time available for pore pressure dissipation affects the final soil strength and stiffness. The specific details for each simulation case are summarized below:

- Simulation 1 (benchmark case – centrifuge condition): this simulation directly replicates the centrifuge test conditions, using an average consolidation time of 80000s per cycle.
- Simulation 2 (extended drainage): using the same penetration sequence, the consolidation period is doubled to average 160000s per cycle to observe the effects of increased drainage and potential hardening.
- Simulation 3 (reduced drainage): the consolidation period is reduced to 40000s per cycle, simulating a faster loading frequency where pore pressure has less time to dissipate.
- Simulation 4 (field condition): in this case, the consolidation time is restricted to only 10 s per cycle. This duration is chosen to represent a typical wave period, which generally ranges between 10 and 15 s in offshore environments. This case effectively represents a near-undrained state, where cyclic softening is expected to dominate due to the minimal dissipation of excess pore pressure.

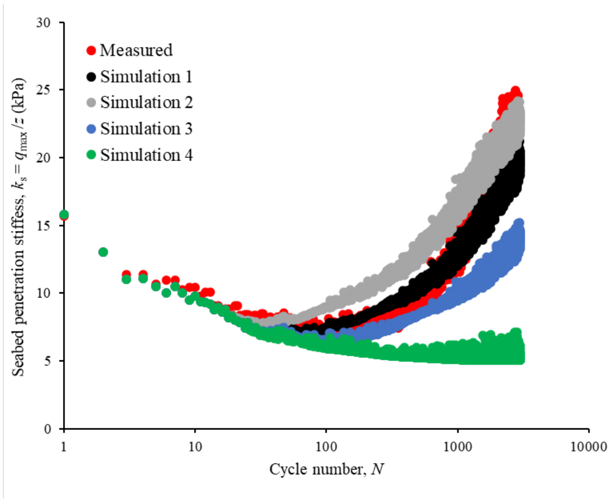

Figure 5. Comparison of experimental and predicted seabed penetration stiffness with different consolidation period for each cycle

The results of the numerical simulations are presented in Figure 5. The model successfully captures the complex evolution of seabed stiffness, accurately reflecting the initial cyclic softening followed by the long-term consolidation-induced hardening. This dual-phase behaviour matches the trends observed in the physical centrifuge tests. A detailed comparison of the four simulation cases reveals the following:

- Simulation 2 (increased cycle duration): in this case, the time allowed for consolidation was doubled to 160000s. Because the pipe moves more slowly, there is a significantly higher dissipation of excess pore pressure. Consequently, the soil experiences a more rapid gain in effective stress, leading to a higher stiffness (after 100 cycle) compared to the benchmark case.
- Simulation 3 (reduced cycle duration): conversely, when the cycle duration was reduced to 40000s (effectively doubling the loading rate), the gain in soil stiffness was lower than in Simulation 1. The faster movement limits the time available for excess pore pressure to dissipate, which restricts the soil hardening process.
- The "centrifuge gap": it is important to note that Simulations 1, 2, and 3 all utilise relatively slow penetration rates due to the mechanical limitations of centrifuge actuators. While these tests are valuable for understanding consolidation, they do not fully replicate the high-frequency loading caused by offshore environmental loading.
- Simulation 4 (field conditions): when a realistic wave period of 10 s is applied, the soil remains almost entirely in an undrained condition throughout the 3000 cycles. Under these high-frequency field conditions, the dissipation of pore pressure is negligible. As a result, cyclic softening dominates the soil response, causing the penetration depth to gradually increase as the soil loses its bearing capacity.

This comparison highlights that while laboratory tests often show an eventual increase in stiffness due to consolidation, real-world offshore structures subjected to rapid wave loading may experience continuous softening and result in a lower seabed stiffness.

4 A PROPOSED STRATEGY FOR PREDICTION OF LIFETIME OFFSHORE SSI

To address the inherent time-scaling mismatch between laboratory centrifuge models and field conditions, a systematic procedure is proposed to bridge the gap between experimental observations and design applications. This strategy utilises the "time machine" benefits of the centrifuge while correcting for the over-optimistic hardening often seen in accelerated tests. Procedure for integrated lifetime assessment is:

1. Benchmarking via centrifuge modelling: conduct high-gravity centrifuge tests to capture the fundamental soil-structure interaction over a high number of load cycles. These tests provide the necessary data to observe the interplay between cyclic remoulding and pore pressure dissipation under controlled stress conditions.
2. Numerical replication and calibration: utilise an effective-stress-based numerical framework, such as the one described by Zhou et al. (2020c) and extension model (Wang et al. 2024a and 2024b; Wang et al. 2026), to replicate the specific conditions of the centrifuge test. The model must be calibrated to match the measured evolution of soil strength and stiffness by accounting for the specific inter-cycle drainage times allowed in the centrifuge environment.
3. Correction for the "loading clock": once the numerical model is validated against experimental results, adjust the "loading clock" within the simulation to reflect field-scale temporal conditions. This involves replacing the slower model-scale penetration rates with realistic wave- or wind- induced loading periods, typically ranging between 10s and 30s.
4. Long-term performance prediction: perform full-scale simulations over the target design life of 25 to 30 years. This step allows for the prediction of the true seabed response, identifying periods where undrained cyclic softening may dominate (such as during peak storm events) and quantifying the long-term benefit of consolidation-induced strength regain during operational periods.
5. Reliability and optimization: use the predicted evolution of soil stiffness and strength to refine foundation safety margins. This procedure enables designers to move beyond

conservative total-stress snapshots and adopt a more resilient "whole-life" design approach.

5 CONCLUSION

This study underscores the critical need to accurately scale the temporal interaction between cyclic loading and consolidation when predicting the lifetime performance of offshore foundations. While centrifuge modelling accelerates consolidation by a factor of N^2, actuator frequency limits constrain cyclic loading, resulting in unrealistically high consolidation compared to field conditions during storms or operation.

Seabed response is governed by the interplay between cyclic softening, which reduces strength and stiffness through remoulding, and consolidation hardening, which restores and even enhances these properties as pore pressure dissipates. Numerical frameworks in the effective stress domain are essential for capturing this competition, enabling prediction of transitions from softened to hardened states over cycles.

Relying solely on raw centrifuge data risks overly optimistic or unreliable assessments, while traditional standards focusing only on storm-induced degradation remain overly conservative. The proposed approach—using centrifuge data to calibrate numerical models—provides a robust basis for extrapolating laboratory observations to field conditions, supporting accurate evaluation of long-term integrity and life extension of modern offshore energy assets.

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REFERENCES

Andersen, K.H. (2015). Cyclic soil Parameters for offshore foundation design. In *Frontiers in Offshore Geotechnics–ISFOG III*. 3-82, Oslo, Norway, Taylor & Francis Group, London.

DNV (Det Norske Veritas) (2021). *DNVGL-RP-C212. Offshore soil mechanics and geotechnical engineering*.

Muir Wood, David. *Geotechnical Modelling*. London: Spon Press, 2004.

Yuan, F., White, D. J., and O'Loughlin, C. D. (2017). The evolution of seabed stiffness during cyclic movement in a riser touchdown zone on soft clay. *Géotechnique*, 67(2), 127–137.

Chatterjee, S., Randolph, M. F., and White, D. J. (2013). The effects of penetration rate and strain softening on the vertial penetration resistance of seabed pipelines. *Géotechnique*, 62(7), 573–582.

Foglia, A., Zhou, Z., Wang, Y., Polania, O., Olsen, C., Berg, D. V., Cerfontaine, B., White, J. D., Gourvenec, S., Cabrera, M. A., Gavin, K., Kolios, A. and Laham, N. (2025). First Steps towards Sustainable-by-Design Anchors for Floating Offshore Wind, *Proc. 5th International Symposium on Frontiers in Offshore Geotechnics*, ISFOG2025-239, France, Nantes.

Rui, S., Zhou, Z., Gao, Z., Jostad, H. P., Wang, L., Xu, H. and Guo, Z. (2024). A review on mooring lines and anchors of floating marine structures. *Renewable and Sustainable Energy Reviews*, volume 199, 114547.

Gourvenec, S. (2022). Whole life design: Theory and applications of this new approach to offshore geotechnics. *Indian Geotechnical Journal*, 52(4), 711–736.

Wang, C., O'Loughlin, C. D., Bransby, M. F., Watson, P., & Zhou, Z. (2023). Consolidation-induced improvements in plate anchor capacity. *Canadian Geotechnical Journal*, https://doi.org/10.1139/cgj-2022-0382.

Wang, C., O'Loughlin, C. D., Bransby, F., Watson, P., & Zhou, Z. (2025). Time-dependent processes influencing offshore foundations in clay: An experimental study on plate anchors. *Géotechnique*, 75(1), 68–80. https://doi.org/10.1680/jgeot.22.00389

Wang, Y., O'Loughlin, C. D., Zhou, Z., & Gaudin, C. (2024a). A two-dimensional effective stress framework for modelling whole-life soil strength changes due to pore pressure generation and dissipation, Part 1: Formulation. *Canadian Geotechnical Journal*, 61(9), 1801–1818. https://doi.org/10.1139/cgj-2022-0331

Wang, Y., O'Loughlin, C. D., Zhou, Z., & Gaudin, C. (2024b). A two-dimensional effective stress framework for modelling whole-life soil strength changes due to pore pressure generation and dissipation, Part 2: Applications. *Canadian Geotechnical Journal*, *61*(9), 1819–1836. https://doi.org/10.1139/cgj-2022-0332

Wang, Y., O'Loughlin, C. D., Zhou, Z., & Gaudin, C. (2026). The response of a plate anchor and embedded mooring in clay to environmental loading: experimental observations and numerical simulations. *Géotechnique*, ahead of print. https://doi.org/10.1680/jgeot.25.00083

Zhou, Z., White, D. J., & O'Loughlin, C. D. (2019). An effective stress framework for estimating penetration resistance accounting for changes in soil strength from maintained load, remoulding and reconsolidation. *Géotechnique*, 69(1), 57-71.

Zhou, Z., White, D.J. and O'Loughlin, C.D. (2020a). The changing strength of carbonate silt: parallel penetrometer and foundation tests with cyclic loading and reconsolidation periods. *Canadian Geotechnical Journal*, Volume 57, Issue 11.

Zhou, Z., O'Loughlin, C.D., White, D.J. and Stanier, S.A. (2020b). Improvements in plate anchor capacity due to cyclic and maintained loads combined with consolidation. *Géotechnique*, 70(8), 732–749.

Zhou, Z., O'Loughlin, C. D., & White, D. J. (2020c). An effective stress analysis for predicting the evolution of SCR–seabed stiffness accounting for consolidation. *Géotechnique*, 70(5), 448–467. https://doi.org/10.1680/jgeot.18.P.313