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Suction Installation Envelopes for Caissons in Loose Stratified Offshore Seabeds

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ABSTRACT

The rapid global expansion of offshore renewable energy infrastructure has driven the need for reliable, cost-effective, and efficient foundation solutions. Suction caissons have emerged as a highly viable alternative to traditional driven piles due to their rapid installation, minimal noise emissions, and reversibility for decommissioning. However, their installation in loose stratified offshore seabeds presents complex geotechnical challenges, including the risk of premature refusal, excessive soil plug heave, and piping. This paper presents a comprehensive investigation into the development of suction installation envelopes for caissons penetrating through loose stratified soil profiles, specifically alternating layers of loose sand and soft clay. Through a rigorous combination of physical centrifuge modeling and advanced large-deformation finite element analysis, the research delineates the critical boundaries that define safe and successful installation trajectories. The study identifies the complex hydro-mechanical interactions that occur at the interface of distinct soil strata, highlighting how seepage forces and localized shear failure mechanisms interact to govern penetration resistance. The findings indicate that stratification significantly alters the required suction pressure and the allowable suction limits compared to homogeneous soil profiles. By synthesizing the experimental and numerical data, the paper proposes robust installation envelopes that provide critical predictive guidelines for offshore geotechnical engineers. These envelopes serve as a practical tool for optimizing installation procedures, ensuring structural integrity, and mitigating the risks associated with complex seabed conditions.

KEYWORDS

Suction Caisson, Stratified Seabed, Installation Envelope, Geotechnical Engineering, Offshore Foundations

1. Introduction

1.1 Global Context of Offshore Foundations

The transition toward sustainable and renewable energy sources has catalyzed an unprecedented expansion in offshore wind energy development across the globe. As near-shore locations with favorable shallow water conditions become increasingly saturated, the offshore wind industry is inexorably

moving toward deeper waters and more challenging geological environments. This migration necessitates the development and implementation of innovative foundation technologies capable of withstanding severe hydrodynamic loads while remaining economically viable. Among the various foundation concepts, the suction caisson, also known as a suction bucket or suction pile, has gained substantial traction. Originally developed for the offshore oil and gas industry to secure floating platforms, suction caissons have been successfully adapted for both monopile and jacket structures in the offshore wind sector. The installation process of a suction caisson is conceptually straightforward yet physically complex. It involves an initial penetration phase driven by the self-weight of the foundation structure, followed by an active suction phase where water is pumped out from the sealed internal cavity of the caisson. This pumping creates a differential pressure across the caisson lid, generating a net downward driving force that pushes the cylindrical skirt into the seabed. This method eliminates the need for heavy hydraulic hammers, thereby significantly reducing underwater noise emissions, which is a critical environmental consideration for marine life preservation. Furthermore, the installation process can be reversed by injecting pressurized water into the caisson cavity, facilitating complete decommissioning and structural retrieval at the end of the design life. Related work has addressed installation and uplift resistance of suction caisson foundation based on CPTU and DMT methods [1].

1.2 Challenges in Loose Stratified Seabeds

Despite the numerous advantages associated with suction caisson foundations, their installation is highly sensitive to the site-specific geotechnical and hydrological characteristics of the seabed. While extensive research has been conducted on the installation behavior of caissons in homogeneous deposits of either pure sand or pure clay, natural offshore seabeds are rarely perfectly uniform. Geological depositional processes, oceanic currents, and historical sea-level fluctuations frequently result in complex, stratified soil profiles characterized by alternating layers of varying composition, density, and permeability. One particularly challenging scenario involves loose stratified seabeds, where layers of unconsolidated, highly permeable loose sand are interspersed with layers of low-permeability soft clay. The installation of a suction caisson through such a sequence introduces intricate hydro-mechanical phenomena that are not observed in homogeneous soils. In loose sand layers, the application of suction induces an upward seepage flow within the internal soil plug, which effectively reduces the effective stress and the corresponding internal shaft friction, thereby facilitating penetration. However, if the suction pressure is applied too aggressively, the upward seepage gradient can exceed the critical hydraulic gradient, leading to localized fluidization, piping, or massive soil plug heave. Conversely, in clay layers, penetration occurs under undrained conditions, and the required driving force is governed primarily by the undrained shear strength of the soil. When a caisson transitions from a loose sand layer into an underlying clay layer, or vice versa, the abrupt change in permeability and shear strength profoundly disrupts the established seepage regime and resistance mechanisms. For instance, penetrating a low-permeability clay layer underlying a loose sand layer can trap excess pore water pressures, increasing the risk of structural refusal before the target penetration depth is achieved. Given these complexities, the development of comprehensive suction installation envelopes, which graphically define the safe operational window of applied suction against penetration depth, is of paramount importance for ensuring the structural and operational success of offshore wind projects in complex geological environments.

2. Theoretical Background and Literature Review

2.1 Mechanics of Suction Penetration in Uniform Soils

The mechanics governing the installation of suction caissons have been systematically investigated over the past three decades, primarily focusing on uniform soil deposits. The total resistance encountered by the caisson during penetration is conventionally conceptualized as the sum of three distinct components: the external shaft friction, the internal shaft friction, and the tip resistance at the skirt edge. In homogeneous clay deposits, the installation process is generally assumed to be fully undrained due to the low permeability of the material and the relatively rapid rate of penetration. The resistance is thus a

function of the undrained shear strength, modified by an adhesion factor that accounts for soil remolding and strain-softening effects along the caisson-soil interface. The required suction is calculated by equating the net driving force to the total penetration resistance minus the submerged weight of the foundation. The primary risk in clay is structural refusal if the required suction exceeds the maximum allowable suction, which is typically limited by the structural buckling capacity of the caisson skirt or the cavitation limit of the pore fluid. In homogeneous sand deposits, the mechanics are fundamentally different and significantly more complex. The high permeability of sand allows for a fully drained or partially drained response during installation. The application of internal suction creates a complex hydrodynamic seepage field, drawing water from the surrounding external seabed, under the skirt tip, and up through the internal soil plug. This seepage flow exerts upward body forces on the internal soil plug, which drastically reduces the internal effective stresses and, consequently, the internal shaft friction and tip resistance. This phenomenon is the primary reason why suction caissons can be successfully installed in dense sand deposits where self-weight penetration alone would be negligible. However, as numerous researchers have demonstrated, this seepage-induced effective stress reduction must be carefully controlled. If the upward hydraulic gradient inside the caisson approaches unity, the effective stress becomes zero, resulting in a quicksand condition. Under these circumstances, further application of suction does not contribute to penetration but instead causes massive internal soil heave, effectively reducing the internal volume available for the foundation structure and potentially leading to premature refusal. Shi and colleagues examine installation effects on the performance of hybrid suction caissons in sand [2].

2.2 Installation Complexities in Stratified Profiles

While the mechanisms in uniform soils provide a foundational understanding, the literature addressing stratified profiles remains comparatively sparse, despite its critical relevance to actual offshore conditions. Early attempts to model stratified seabeds often relied on simple averaging techniques, where the soil properties of the distinct layers were homogenized into a single equivalent layer. However, empirical evidence from field installations and preliminary physical modeling has shown that this approach can yield highly inaccurate and potentially dangerous predictions regarding required suction pressures. When a caisson penetrates a layered system, the interaction between layers dictates the failure mechanisms. A critical scenario identified in recent literature is the penetration from a loose sand layer into an underlying stiff or soft clay layer. As the caisson skirt approaches the clay interface, the clay acts as an impermeable barrier. The seepage flow that previously circulated freely under the skirt tip and into the internal cavity is abruptly truncated. This restriction causes a rapid dissipation of the favorable seepage gradients that reduced internal friction in the overlying sand, leading to a sudden and severe spike in penetration resistance. Researchers have noted that this interface transition zone is where a substantial number of offshore installation failures occur. Conversely, when penetrating from a clay layer into an underlying loose sand layer, the sudden release of confinement and the sudden exposure to high-permeability material can cause an uncontrolled loss of suction pressure and rapid downward acceleration, which can damage the foundation structure or the attached monitoring equipment. The concept of an installation envelope, which plots the boundaries of feasible suction pressures at varying depths, has been proposed as a methodological tool to manage these risks. However, the existing installation envelopes are predominantly empirical and derived from specific site data, lacking a generalized theoretical framework that can be systematically applied to diverse combinations of loose stratified soils. This significant gap in the literature underscores the necessity for comprehensive experimental and numerical investigations that can capture the intricate hydro-mechanical coupling and large deformation kinematics inherent in layered soil penetration. For a broader comparison, related research addresses benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: A case study of the guadalupian (middle permian) in eastern Sichuan basin [3].

3. Conceptual Framework of Suction Installation Envelopes

3.1 Definition and Boundaries of the Envelope

The suction installation envelope is an analytical and graphical construct that defines the permissible range of differential pressure that can be safely applied to a suction caisson at any given stage of its penetration into the seabed. The operational state of the caisson must continuously remain within this multidimensional boundary to ensure successful installation to the target design depth. The envelope is mathematically bounded by several distinct criteria that represent different physical failure mechanisms. The lower boundary of the envelope is defined by the minimum required suction pressure. This represents the absolute minimum driving force necessary to overcome the sum of the external friction, internal friction, and tip bearing capacity, minus the effective self-weight of the caisson assembly. If the applied pressure falls below this lower boundary, the downward velocity of the caisson will decelerate to zero, resulting in premature structural refusal. This boundary is highly dynamic and non-linear, particularly in stratified soils, as the resistance parameters change instantaneously as the skirt tip crosses the geological interfaces. The upper boundary of the envelope is governed by two distinct constraints: the structural capacity of the caisson and the geotechnical stability of the soil plug. From a structural perspective, the differential pressure across the caisson lid and walls exerts massive compressive forces that can induce elastic or plastic buckling of the cylindrical skirt. This structural limit is a function of the caisson diameter, wall thickness, material yield strength, and the extent of lateral support provided by the surrounding soil. From a geotechnical perspective, the maximum allowable suction is constrained by the critical hydraulic gradient that induces soil plug heave or piping, particularly in loose sand layers, or by the reverse bearing capacity failure of the internal soil plug in clay layers. Operating above this geotechnical upper bound leads to excessive soil ingestion, which can fill the caisson cavity before the target depth is reached, rendering the foundation useless.

3.2 Geotechnical Parameters and Seepage Considerations

The geometry and topology of the installation envelope are highly sensitive to the constitutive properties of the stratified soil profile and the complex seepage regimes generated during the active suction phase. In loose sand layers, the internal friction angle, initial void ratio, and hydraulic conductivity are the paramount parameters dictating both the lower and upper boundaries of the envelope. The hydraulic conductivity governs the rate at which pore pressures can dissipate and the magnitude of the steady-state seepage forces. In loose stratified conditions, the presence of distinct permeability boundaries significantly complicates the prediction of these seepage forces. When the skirt tip is located within a loose sand layer, the seepage flow is predominantly radial and upward. However, the proximity of adjacent clay layers forces the streamlines to deviate, concentrating the flow gradients in localized zones. This concentration can trigger localized piping channels that propagate along the inner wall of the caisson, drastically reducing the efficiency of the applied suction and invalidating the assumptions of uniform porous media flow. In the clay strata, the undrained shear strength profile, the overconsolidation ratio, and the sensitivity of the clay define the resistance. Because the installation process causes massive shearing and remolding of the soil adjacent to the caisson walls, understanding the strain-softening behavior of the clay is critical for accurately predicting the reduction in shaft friction over time. Furthermore, the interaction between the sand and clay layers at their interface plays a crucial role. For example, sand particles can be dragged down into the underlying clay layer by the penetrating skirt, creating an artificial smear zone with altered drainage and friction characteristics. The conceptual framework developed in this research systematically integrates these diverse geotechnical parameters and complex seepage phenomena to mathematically formulate the dynamic boundaries of the installation envelope, ensuring that all potential modes of geotechnical and structural failure are comprehensively accounted for across the entire penetration depth.

4. Physical Modeling and Experimental Methodology

4.1 Centrifuge Setup and Instrument Calibration

To accurately replicate the complex stress states and hydro-mechanical behavior of full-scale suction

caisson installations in loose stratified seabeds, a comprehensive physical modeling program was executed utilizing a state-of-the-art geotechnical centrifuge facility. Small-scale physical models tested under earth gravity fail to reproduce the correct stress-dependent soil behavior, particularly in loose sands where the friction angle, dilatancy, and stiffness are heavily influenced by the confining effective stress. By accelerating the model to a predetermined gravitational acceleration level, the macroscopic stress distribution in the scaled model is made identical to that of the full-scale prototype. The experimental program utilized a highly instrumented, half-symmetry cylindrical aluminum caisson model, designed to represent a typical offshore wind foundation with a prototype diameter of eight meters and a skirt length of eight meters. The model was equipped with a network of miniature total earth pressure cells and high-capacity pore water pressure transducers embedded flush with the internal and external surfaces of the skirt. These sensors were critical for continuously monitoring the evolution of contact stresses and transient pore pressure regimes during the dynamic penetration process. The caisson lid was fitted with a high-precision differential pressure transducer to record the applied suction, and a linear variable differential transformer was mounted on the central loading actuator to track the precise vertical displacement of the caisson. Prior to the commencement of the testing program, all instrumentation underwent rigorous calibration procedures in a pressurized environmental chamber to ensure linearity, minimize hysteresis, and correct for any temperature-induced signal drift. Another relevant line of investigation concerns experimental investigation of suction installation behavior of caissons in loose saturated sands [4].

Table 1:Geotechnical parameters of the materials used in the physical and numerical modeling.

Soil Stratum	Saturated Unit Weight	Permeability Coefficient	Undrained Shear Strength
Loose Sand Layer	18.5 kN/m3	1.2 x 10-4 m/s	Not Applicable
Soft Marine Clay	16.2 kN/m3	3.5 x 10-9 m/s	15.0 kPa
Medium Dense Sand	19.8 kN/m3	8.5 x 10-5 m/s	Not Applicable
Stiff Basal Clay	17.5 kN/m3	1.0 x 10-9 m/s	65.0 kPa

4.2 Preparation of Loose Stratified Seabeds

The validity of the physical modeling outcomes is entirely dependent on the accurate and repeatable preparation of the stratified soil profile within the rigid centrifuge strongbox. The target soil profile consisted of alternating horizontal layers of fine loose silica sand and soft, normally consolidated kaolin clay. To simulate the loose sand strata, an automated air pluviation system was employed. The sand was deposited through a calibrated diffuser plate at a strictly controlled drop height and mass flow rate, ensuring a uniform and highly repeatable relative density corresponding to a loose state. To maintain the loose structure, the sand was deposited directly into the water-filled strongbox, effectively utilizing a water pluviation technique to prevent entrapment of air bubbles and ensure complete saturation. The soft clay layers were prepared using a vacuum consolidation process. Kaolin clay powder was initially mixed with deionized water under a high vacuum to create a homogeneous slurry with a water content significantly above its liquid limit. This slurry was carefully pumped into the strongbox overlying the prepared sand layer. A rigid loading platen was then placed over the clay, and a sequential mechanical loading scheme was applied to consolidate the clay to the desired uniform undrained shear strength profile. To prevent the migration of fine clay particles into the underlying loose sand pores during the consolidation phase, a highly permeable but ultra-fine synthetic filter mesh was placed at the geological

interface. The entire strongbox assembly was then transferred to the centrifuge basket and spun up to the target acceleration level. A period of in-flight reconsolidation was allowed to ensure that the pore pressure distribution reached hydrostatic equilibrium and the effective stress profile matched the theoretical prototype conditions before the automated installation sequence was initiated. The literature also considers integrating automated machine learning and interpretability analysis of shear wave velocity [5].

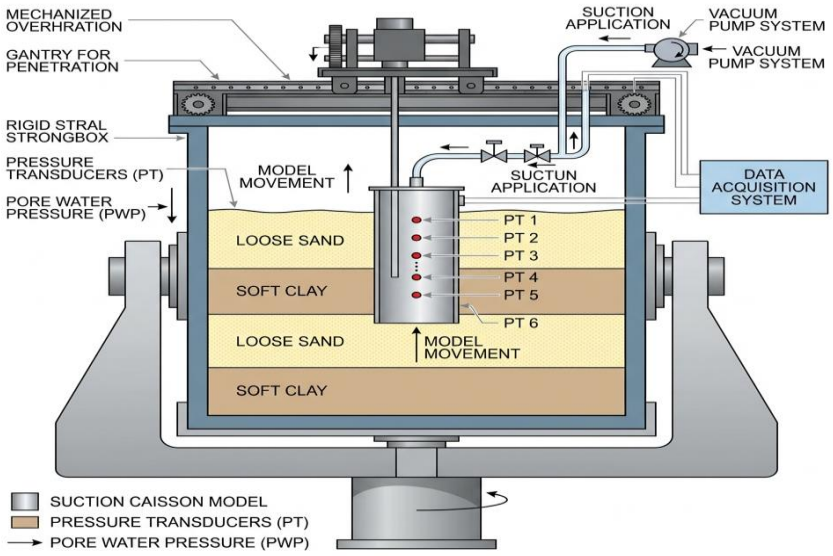


Figure 1: Comprehensive Schematic of the Geotechnical Centrifuge Experimental Setup

5. Numerical Modeling Methodology

5.1 Finite Element Framework and Mesh Discretization

To complement the physical modeling and to permit a broader parametric investigation of variables not easily modified in the centrifuge, an advanced three-dimensional finite element model was developed. The numerical simulations were conducted using a commercial geotechnical finite element software package equipped with capabilities for modeling extreme geometric non-linearity and complex coupled hydro-mechanical processes. Simulating the complete installation of a suction caisson from the seabed surface to its final design depth involves massive localized soil displacements, particularly around the cutting edge of the skirt, which inevitably leads to severe mesh distortion and numerical non-convergence in standard Lagrangian frameworks. To overcome this fundamental limitation, the numerical model employed an Arbitrary Lagrangian-Eulerian formulation. This advanced mathematical technique allows the finite element mesh to continuously and automatically adapt and smooth itself independently of the underlying material deformation, thereby preserving element quality and ensuring continuous calculation accuracy throughout the deep penetration process. The computational domain was discretized using high-order coupled pore-pressure and displacement elements, allowing for the simultaneous resolution of the solid skeletal deformation and the transient fluid flow through the porous media. The mesh density was highly optimized, featuring an extremely fine resolution immediately adjacent to the caisson walls and skirt tip to capture the steep stress gradients and localized shear banding, while gradually coarsening toward the far-field boundaries to optimize computational efficiency without sacrificing accuracy.

Table 2: Constitutive model parameters for the finite element numerical analysis.

Parameter Description	Loose Sand (Mohr-Coulomb)	Soft Clay (Modified Cam Clay)	Interface Elements

Friction Angle	28 Degrees	Not Applicable	18 Degrees
Cohesion / Intercept	0.1 kPa	Not Applicable	0.0 kPa
Poisson Ratio	0.30	0.35	Not Applicable
Interface Friction Factor	Not Applicable	Not Applicable	0.65

5.2 Boundary Conditions, Constitutive Models, and Seepage Coupling

The rigorous definition of initial and boundary conditions is essential for the reliability of the numerical predictions. The bottom boundary of the cylindrical computational domain was fixed against displacements in all translational directions and was defined as an impermeable boundary. The lateral far-field boundaries were fixed in the radial direction but permitted to move vertically, with a hydrostatic pore pressure distribution continuously enforced to simulate the infinite expanse of the surrounding offshore seabed. The top surface of the soil domain was left completely free to deform, allowing for the accurate simulation of seabed heave, and was subjected to a constant hydraulic head representing the overlying ocean water depth. The interaction between the steel caisson and the stratified soil was modeled using surface-to-surface contact mechanics governed by a Coulomb friction law, incorporating a penalty formulation to prevent unphysical interpenetration of the foundation elements into the soil mesh. The loose sand layers were modeled using an advanced elastoplastic constitutive model incorporating isotropic hardening and a non-associated flow rule to accurately capture the dilative and contractive volumetric responses characteristic of granular materials under varying effective confinement. The soft clay layers were represented by a critical state constitutive framework, specifically calibrated to capture the logarithmic compression behavior, the stress-history dependence, and the generation of excess pore water pressures during undrained shearing. The active suction installation was simulated dynamically by applying a time-varying negative pressure boundary condition strictly to the internal surface of the soil plug and the underside of the caisson lid. This internal pressure boundary was dynamically coupled with the fluid continuity equations, generating the necessary hydraulic gradients that drive the seepage flow, alter the effective stress state, and ultimately govern the massive large-deformation penetration mechanics through the stratified profile.

6. Results and Comparative Analysis

6.1 Evolution of Penetration Resistance

The integration of data derived from both the centrifuge physical models and the sophisticated numerical simulations provided profound insights into the mechanics of suction caisson installation in loose stratified seabeds. The primary output analyzed was the evolution of penetration resistance as a function of normalized installation depth. During the initial self-weight penetration phase in the uppermost loose sand layer, the resistance accumulated linearly, governed primarily by the drained frictional resistance along the external and internal skirt surfaces. However, upon the initiation of the active suction phase, a dramatic and instantaneous divergence in the resistance profile was observed. The application of suction induced the anticipated upward seepage gradient within the internal soil plug, which systematically reduced the internal effective stress. Consequently, the measured required driving force plummeted to a fraction of the value that would have been required for continuous drained mechanical pushing. The numerical model excellently captured this phenomenon, showing an exact correlation with the centrifuge data regarding the magnitude of effective stress degradation. The complexity emerged as the caisson skirt approached the first geological interface, transitioning from the loose sand into the underlying soft clay layer. At a distance approximately equivalent to one-quarter of the caisson diameter above the interface, the required suction pressure began to escalate exponentially. The physical sensors indicated that the underlying clay acted as a highly effective hydraulic barrier, forcing the downward propagating seepage streamlines to rapidly compress and deviate horizontally. This sudden restriction in fluid flow dissipated the favorable upward seepage gradients inside the sand plug, leading to an immediate

recovery of internal effective stresses and a corresponding massive spike in penetration resistance.

Table 3:Summary of critical experimental results at key penetration depths.

Normalized Depth (z/D)	Stratum Location	Average Required Suction	Soil Plug Heave Ratio
0.25	Upper Loose Sand	12.5 kPa	2.5 Percent
0.50	Sand-Clay Interface	45.0 kPa	6.8 Percent
0.75	Middle Soft Clay	38.5 kPa	8.2 Percent
1.00	Clay-Sand Interface	22.0 kPa	11.5 Percent

6.2 Plug Heave Dynamics and Critical Suction Limits

Beyond penetration resistance, the absolute limit states of the installation envelope are dictated by the stability of the internal soil plug. The physical models provided continuous visual and sensory data regarding the vertical displacement of the soil surface within the caisson cavity. In the upper loose sand layers, when the applied suction was deliberately escalated towards the theoretical critical hydraulic gradient, an immediate and aggressive volumetric expansion of the soil plug was recorded. This expansion was not uniform; rather, the numerical vectors demonstrated that localized piping channels initiated at the skirt tip and propagated upwards along the smooth internal aluminum wall, leading to asymmetric plug heave. This localized failure severely compromised the efficiency of the suction process, as the differential pressure short-circuited through the highly permeable piping channels, providing negligible additional driving force. When the caisson successfully penetrated the clay layer, the mechanism of plug heave altered fundamentally. The clay deformed as a coherent undrained mass. As the required suction increased to overcome the bearing capacity of the deeper strata, the internal clay plug was subjected to massive reverse bearing stresses. The experimental results clearly demonstrated that the maximum allowable suction in the clay layers was not governed by seepage or piping, but strictly by the undrained bearing capacity of the plug acting upwards. If the suction exceeded this threshold, the entire clay plug moved bodily upwards into the caisson cavity. The numerical simulations successfully replicated both the localized piping in the loose sand and the global undrained failure in the soft clay, confirming that the upper boundaries of the installation envelope must dynamically shift between seepage-governed criteria and strength-governed criteria depending on the instantaneous location of the skirt tip within the stratified profile.

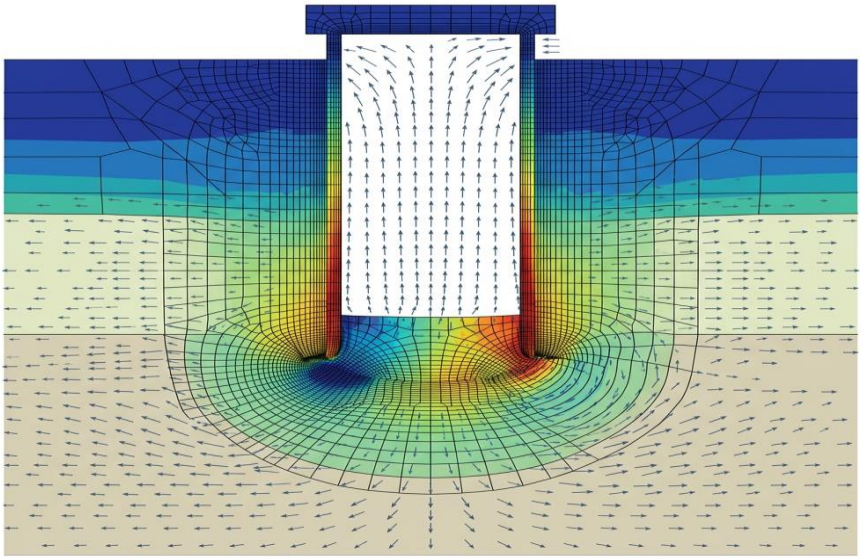


Figure 2:Large

7. Development of Installation Envelopes and Design Guidelines

7.1 Formulating the Operational Boundaries

Synthesizing the wealth of data acquired from the physical and numerical investigations enables the construction of robust, predictive suction installation envelopes tailored specifically for loose stratified offshore environments. The envelope is mathematically constructed on a Cartesian coordinate system, where the vertical axis represents the applied suction pressure and the horizontal axis denotes the penetration depth normalized by the caisson diameter. The lower boundary, representing the minimum required suction to ensure continuous downward movement, is constructed by integrating the depth-dependent frictional and bearing resistance profiles, modified continuously by the instantaneous seepage state determined from the coupled numerical analysis. A critical feature identified in this research is the pronounced necessity for an operational margin directly above this lower boundary. The natural heterogeneity of marine deposits dictates that localized zones of slightly denser sand or stiffer clay can cause transient spikes in required resistance. Operating exactly on the theoretical lower boundary leaves zero margin for these anomalies, increasing the probability of premature structural refusal. The upper boundary is a composite limit. In the loose sand strata, the upper boundary is defined by calculating the critical applied pressure that induces an upward hydraulic gradient of 0.85, incorporating a necessary safety factor against localized piping along the caisson wall. As the foundation transitions into the soft clay layers, the algorithm governing the upper boundary switches seamlessly to evaluate the reverse end bearing capacity of the internal plug based on the continuous undrained shear strength profile, while simultaneously running continuous checks against the structural buckling capacity limits of the specified steel geometry. For a broader comparison, related research addresses benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan basin, china [6].

Table 4:Proposed safety margins for defining the boundaries of the installation envelope.

Boundary Condition	Controlling Failure Mechanism	Recommended Safety Factor	Application Rationale
Lower Bound Limit	Premature Refusal / Hanging	1.15 to 1.25	Accounts for localized dense inclusions.
Upper Bound	Piping and Quicksand Failure	1.50	Mitigates wall-channeling effects.

(Sand)			
Upper Bound (Clay)	Reverse Undrained Bearing	1.35	Prevents massive bodily plug heave.
Structural Limit	Hydrostatic Buckling	2.00	Ensures absolute structural integrity.

7.2 Practical Implementation in Offshore Engineering

The practical utility of the formulated installation envelopes lies in their deployment as real-time predictive and diagnostic tools during actual offshore construction operations. Geotechnical engineers can utilize these envelopes during the pre-construction design phase to optimize the dimensions of the caisson. If the required lower boundary intersects or exceeds the safe upper boundary at any point in the stratified profile, it indicates that the specific geometry is unfeasible for that seabed location. The engineer must then iteratively adjust the caisson diameter, skirt length, or wall thickness until a continuous, viable operational window opens from the mudline to the target depth. During the actual installation process on an offshore vessel, the theoretical envelope is programmed into the central control systems governing the hydraulic pump stations. As depth and pressure sensors continuously feed live data back to the control cabin, the operator can visualize the exact operational state of the caisson relative to the safe boundaries of the envelope. If the required suction unexpectedly surges toward the upper limit while penetrating a complex interface between loose sand and clay, the operator has immediate visual warning to halt the pumping process, allow pore pressures to dissipate, or initiate mitigating procedures such as cyclical pressure application. This real-time integration significantly mitigates the financial and structural risks associated with offshore foundation installation, ensuring that the transition to complex deep-water renewable energy sites can proceed with confidence and high reliability. The literature also considers development of an ABAQUS-Python simulation model of offshore caisson [7].

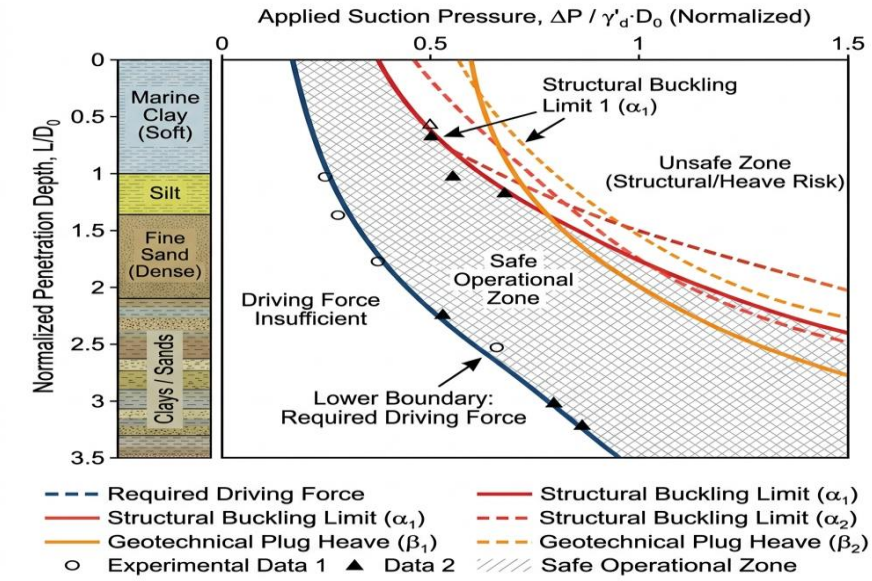


Figure 3:Predictive Suction Installation Envelope Chart

8. Conclusion

The installation of suction caisson foundations in loose stratified offshore seabeds represents a highly complex geotechnical challenge governed by intricate interactions between structural mechanics, large-deformation soil kinematics, and transient hydrodynamics. This comprehensive research program has successfully elucidated the fundamental mechanisms dictating penetration resistance and soil plug stability when crossing critical geological interfaces between highly permeable loose sands and low-

permeability soft clays. Through the synergistic application of advanced physical centrifuge modeling and highly refined arbitrary Lagrangian-Eulerian finite element simulations, this study has definitively shown that traditional homogenization techniques are dangerously inadequate for stratified profiles. The sudden restriction of seepage flows at the sand-clay interface leads to rapid and severe increases in required suction pressures, creating critical pinch points where the risk of premature refusal is highest. Conversely, operating too aggressively in the loose sand strata invariably triggers localized piping and massive soil plug heave, compromising the internal capacity of the foundation. By systematically defining the mathematical and physical limits of these failure mechanisms, this research has established a robust theoretical framework for generating dynamic suction installation envelopes. These envelopes provide a continuous, depth-dependent operational window bounded by minimum required driving forces and maximum allowable structural and geotechnical limits. The implementation of these meticulously derived envelopes offers offshore geotechnical engineers a powerful, reliable tool for optimizing foundation design, formulating safe installation protocols, and ensuring the successful deployment of critical renewable energy infrastructure in increasingly complex global marine environments.

References

Liang, Z., Malik, B. A., Jie, S., Duan, M., & Ouyang, Z. (2025, June). Investigation of Installation and Uplift Resistance of Suction Caisson Foundation Based on CPTU and DMT Methods. In ISOPE International Ocean and Polar Engineering Conference (pp. ISOPE-I). ISOPE.

Shi, J., Malik, B. A., Liang, Z., Jing, L., Lu, Y., Gao, F., & Ouyang, Z. (2026). Installation effects on the performance of hybrid suction caissons in sand. Ocean Engineering, 359, 126025.

Peng, Y., Li, H., BouDagher-Fadel, M., Wang, L., Zhang, D., Zheng, T., & Yang, K. (2022). Benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: A case study of the Guadalupian (middle Permian) in eastern Sichuan Basin. Marine Micropaleontology, 170, 102079.

Malik, B. A., Jie, S., Zeyu, L., Ouyang, Z., & Wang, D. (2025). Experimental investigation of suction installation behavior of caissons in loose saturated sands. Canadian Geotechnical Journal, 62, 1-21.

Sun, M., Liang, D., Wang, J., Bate, B., & Xue, F. (2026). Clarity in DEM cementation predictions: Integrating automated machine learning and interpretability analysis of shear wave velocity. Advanced Engineering Informatics, 69, 104060.

Peng, Y., & Li, H. (2023). Benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan Basin, China. Palaeogeography, Palaeoclimatology, Palaeoecology, 618, 111522.

Malik, B. A., Soni, A. K., Mandhnaiya, P., & Ouyang, Z. (2024, December). Development of an ABAQUS-Python simulation model of offshore caisson. In Vietnam Symposium on Advances in Offshore Engineering (pp. 123-133). Singapore: Springer Nature Singapore.