Indian Journal of Geo Marine Sciences
Vol. 53 (12), December 2024, pp. 747-763
DOI: 10.56042/ijms.v53i12.13700

Research Article

Nonlinear structural assessment of self-installing platforms in the Indian Ocean for offshore wind turbines using push-over analysis

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Received 12 September 2024; revised 30 November 2024

The Indian offshore wind energy industry is gaining momentum, driven by strong coastal wind resources and national efforts toward clean energy, economic development, and climate change mitigation. However, the installation of wind turbines in deep-water regions poses significant technical and economic challenges. This study explores the development and assessment of a novel Self-Installing Platform (SIP) tailored for a 10 MW offshore wind turbine at a depth of 75 meters. The SIP aims to overcome current installation limitations by eliminating the need for heavy-lift vessels, thereby reducing cost, increasing efficiency, and enhancing deployment flexibility. A coupled numerical modelling approach is employed, integrating structural analysis using SACS software and geotechnical evaluation through PLAXIS 3D, including the modelling of a suction bucket foundation. The platform's performance is analysed under a range of environmental conditions, including extreme wave and wind loads, over a design life of 100 years. Nonlinear static pushover analysis is conducted to determine the maximum load capacity and assess system resilience. Results demonstrate that the SIP meets structural safety requirements, with Reserve Strength Ratios (RSRs) exceeding 2.5 in all directions, and maintains acceptable displacement levels under critical load cases. Additionally, the study identifies the most vulnerable structural sections under extreme E180° loading, enabling targeted design improvements. Overall, the SIP exhibits robust structural and geotechnical performance, proving to be a viable, cost-effective solution for deep-water offshore wind turbine installations. This research contributes valuable insights into the behaviour of self-installing platforms in harsh marine environments and supports the advancement of sustainable offshore wind energy infrastructure installation, especially in challenging deep-water environments.

[**Keywords**: Offshore renewable energy, Pushover analysis, Reserve strength ratio, SACS, Self-Installing Platform (SIP)]

Introduction

Offshore wind power, generated by wind farms at sea, benefits from higher and steadier wind speeds compared to land-based farms. In India, initial assessments indicate vast potential, with Gujarat and Tamil Nadu alone possessing around 70 GW capacities, enough to power over 50 million homes. However, slow progress in offshore wind power plant development is attributed to high initial costs relative to solar and onshore wind projects. Nevertheless, the country has set a target of installing 30 GW of offshore wind projects by 2030, leveraging its extensive 11,098.81 kilometre coastline[1]. The global wind energy capacity has surpassed 700 GW onshore and 35 GW offshore by 2024. India, the third-largest electricity producer, targets 60 GW of wind power as part of its 175 GW renewable energy goal by 2022(ref. 2). With its vast coastline, India has significant offshore wind potential, particularly in Tamil Nadu and Gujarat, despite challenges in infrastructure and regulation. Wind energy also plays a vital role in sustaining rural jobs and promoting energy self-sufficiency. Coastal areas globally, including the United States, with high energy demands, could benefit from offshore wind farms as a nearby and reliable energy source[3]. The offshore structures for wind turbine development are designed to accommodate a range of water depths and environmental conditions[4].

Fixed platforms include steel template structures and concrete gravity structures, suitable for depths up to 50 m. Compliant towers, guyed towers, and tension leg platforms are utilised in deeper waters, with tension leg platforms capable of operating in depths up to 1200 m(ref. 5). Floating structures such as floating production systems and floating production, storage, and offloading systems are adaptable to varying depths, from 600 m to 2500 m(ref. 3). The self-installing platform concept offers advantages like rapid installation, cost reduction, and engineering simplicity.

In place analysis has been conducted to verify that the structural components of the platform, with all updated parameters applied, possess sufficient robustness and capacity to withstand the imposed load under operational or storm condition[6]. The pushover analysis is commonly employed for assessing the structural integrity of the jacket platform. Additionally, it aids in estimating the seismic structural deformation and evaluating the reliability through a safety ratio. This analysis method is crucial for identifying failure modes, determining the maximum load-bearing capacity, and evaluating seismic resilience in offshore structure[7]. The initial geometric deformation and self-weight minimally impact the pushover results. Moreover, the probability of the damage is greatly influenced by the environmental conditions and the model for wave height utilised[8]. Reserve Strength Ratio (RSR) obtained, which indicates the structures capacity post-yielding under lateral loads[9,10]. The RSR ratio and base shear were affected by some contributing factors from the waves in deck[11].

The jacket substructure for offshore wind turbines was optimised using a fast parametric FEM approach, considering realistic loading conditions. Parametric and Genetic Algorithm (GA) optimisations achieved significant mass reductions, with GA offering more substantial savings but requiring more computational resources. Both methods provide efficient solutions for improving structural performance and cost-efficiency in Offshore Wind Turbine (OWT) designs[12]. The research focuses on improving pressure control in self-elevating mats for offshore wind power platforms. It compares conventional PID and fuzzy PID controllers, finding the fuzzy PID superior in adjustment time and overshoot but less resistant to interference. An optimised fuzzy neural network PID controller achieves significant improvements, reducing overshoot by 9.71 % and stability time by 68.9 %. The paper addresses the challenges in designing substructures for floating offshore wind turbines, particularly for a 10 MW turbine. It highlights the lack of established design methods and proposes a design procedure based on dominant load parameters such as acceleration and turbine thrust[13]. The study includes frequency response analysis and load case generation to simulate real-world conditions. Key findings show that the maximum equivalent stress in the substructure exceeds allowable limits, suggesting the need for further refined analysis to meet safety standard[14]. The research highlights floating offshore wind turbines as a promising yet costly technology, emphasising the need for cost reduction to match fixed offshore and onshore projects[15]. A comprehensive optimisation framework, using the RAFT frequency-domain dynamic model and a genetic algorithm, aims to minimise structural mass while maintaining performance. The detailed methodology and preliminary results show significant potential for cost savings and improved efficiency. Additional research could further refine these designs and explore added optimisation parameters for enhanced effectiveness. The design parameters for the Self-Installing Platform (SIP) includes the selection of material properties such as steel yield strength and hydraulic lift capacity. The design follows established offshore foundation codes, including API RP 2A and ISO 19902, ensuring compliance with industry standards for structural safety. The load cases considered include extreme wave loading, wind forces, and seismic activity.

The objective is to develop a self-installing platform for a 10 MW wind turbine, ensuring structural robustness and safety through comprehensive analysis using SACS software at a depth of 75 m. The topside is where the wind turbine is mounted, the substructure consists of the legs and support frame, and the foundation anchors the platform securely to the seabed. This division is illustrated in Figure 1. Pushover analysis to be conducted to ascertain the ultimate load capacity of the structure, as well as to examine its behavioural characteristics. This analysis aims to provide insights into the platform's ability to withstand extreme loads and its overall structural performance under different conditions. Furthermore, the Reserve Strength Ratio of the platform will be calculated to estimate its ultimate strength, offering a quantitative measure of its structural robustness. These comprehensive assessments will contribute to ensuring the reliability and safety of the wind turbine platform throughout its operational lifespan. Tamil Nadu pre-feasibility study highlighted high risks due to uncertain site data for offshore wind resources, climate, and geotechnical conditions. In response, the FOWIND consortium conducted a detailed desk-based site investigation, refining the conceptual design and cost modelling[1].

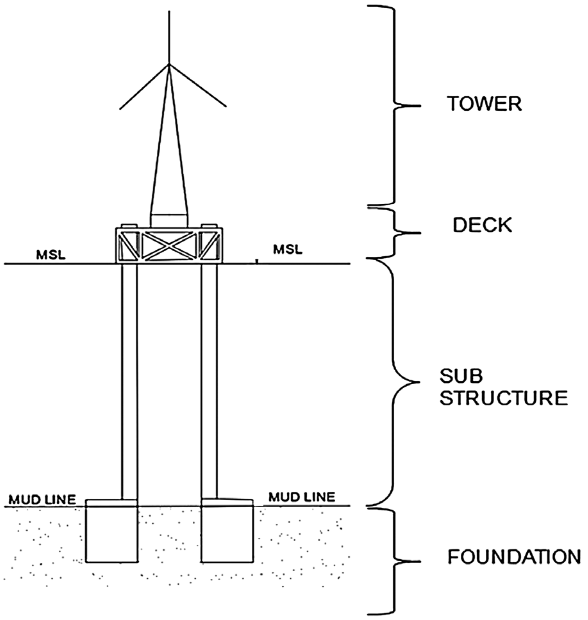


Fig. 1 — Schematic representation of offshore SIP

Based on the FOWIND study, environmental data for eight different locations in the Gulf of Mannar region, including Dhanushkodi and Rameshwaram in Tamil Nadu, India shown in Figure 2 were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF)[6]. The datasets utilised in the analysis included wave height, wave period, current speed, and wind speed for both 100-year and 1-year return periods. ECMWF provides reliable and comprehensive datasets that are widely used in research and engineering applications. Previous studies on offshore wind turbine foundations have mainly focused on fixed and floating platforms, particularly for shallow water environments. This study presents a new approach by evaluating a self-installing platform for deep-water applications, where traditional methods are challenging. Unlike previous work, this study combines both structural analysis and soil-structure interaction using a coupled modelling approach with SACS and PLAXIS 3D, which ensures a more holistic understanding of the platform's performance. The inclusion of economic efficiency in terms of installation time and cost is another novelty, marking this work as a significant contribution to offshore wind energy.

Material and Methods

Structural Analysis Computer Software (SACS)

SACS software is a comprehensive engineering tool designed specifically for the analysis and design of offshore structures. It integrates a range of advanced functionalities, including static and dynamic structural analysis, offshore transportation, and installation capabilities. SACS incorporates multiple modular structural analysis programs interconnected to maintain efficiency, with algorithm functions serving as the core node checking program. In SACS, the collapse module accurately analyse and simulate ship impact, effectively identify critical nodes and reduce inspection dive time by 75 percent. Specialised in analysing offshore structures, the SACS software accurately confirms compliance and predicts performance, providing crucial information to understand post-impact behaviour and identify potential threats to platform integrity[16]. The SACS was widely employed across various industries, as the efficiency of the software played a crucial role in adopting 3D construction modelling, particularly for anti-ice cones, resulting in significant time and cost

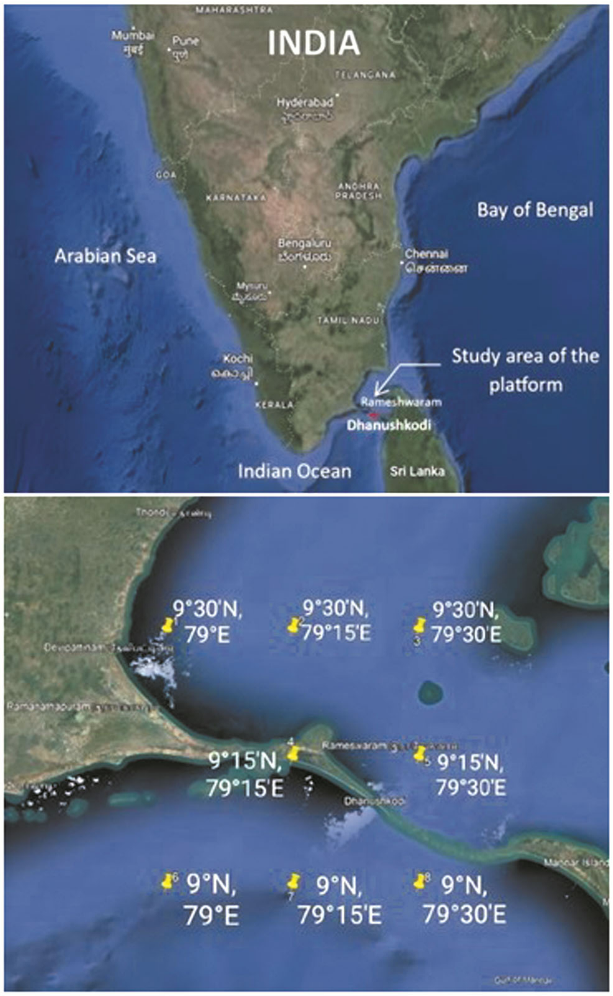


Fig. 2 — Proposed study area of SIP

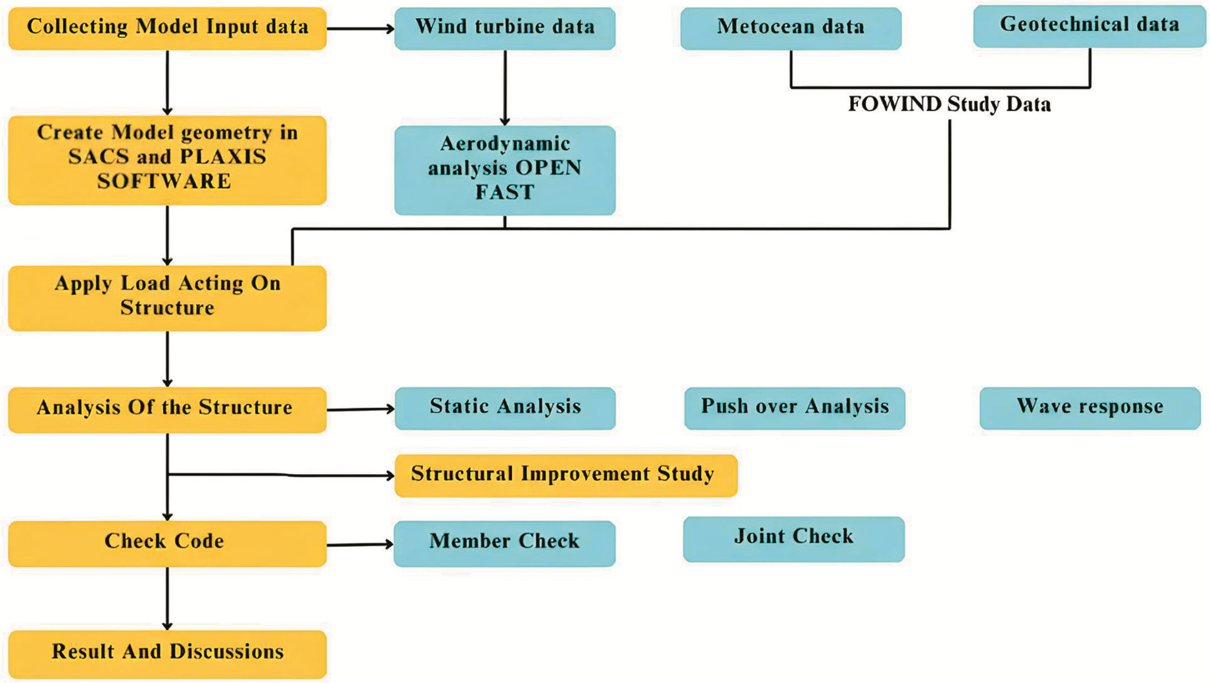


Fig. 3 — Design methodology of SIP

savings. It played a key role in assessing loads from ice, wind, and waves in various project phases, including construction, transportation, installation, and operation. Design considerations encompassed treatment facilities, equipment, and piping layouts. Support units, designed through 3D modelling, were implemented to ensure durability against the platform's weight, preventing damage from ice loads. The jacket weight was optimised for an overall reduction in structural weight by Shanghai Investigation, Design, & Research Institute Co., Ltd., 2022. SACS is a reliable and user-friendly software, allowing design engineers to employ numerical analyses, reducing the need for physical prototypes resulting in significant time and cost cutting[17].

PLAXIS 3D

PLAXIS 3D is a robust software tool widely employed in geotechnical engineering for conducting three-dimensional finite element analysis. It offers advanced capabilities for simulating complex soil-structure interaction phenomena, allowing engineers to accurately model and analyse various geotechnical problems. PLAXIS 3D, with its intuitive interface and powerful modelling features, aids in the design and assessment of geotechnical structures. Its comprehensive analysis capabilities enable engineers to gain valuable insights into soil behaviour and performance under different loading conditions, aiding in the development of safe and cost-effective engineering solutions. Both SACS and PLAXIS 3D are advanced software tools commonly utilised in engineering applications, especially in the analysis and design of structures, providing capabilities for conducting complex structural analyses with their specific focus and features. Figure 3 represents the design flow of the offshore wind turbine SIP for various environmental scenarios in the Indian Ocean.

Geometric modelling

The study examines the design and implementation of a jacket with a self-installing platform for a 10 MW wind turbine located in Dhanushkodi, in the Gulf of Mannar. This platform is engineered to support the turbine in a challenging offshore environment, with a robust structure composed of four tubular steel legs, each 90 meters high, arranged in a square plan view. Figure 4 provide plan and elevation views of the deck. The deck, measuring 20 m × 20 m and standing 8 m high, is supported by these legs. Tubular steel is used for the legs, horizontal bracing, and suction bucket transition frame, ensuring stability and durability. A box section is used for the main deck topside connection, enhancing structural integrity. Table 1 shows the geometrical properties of the section. A detailed description of the platform's layout, with a

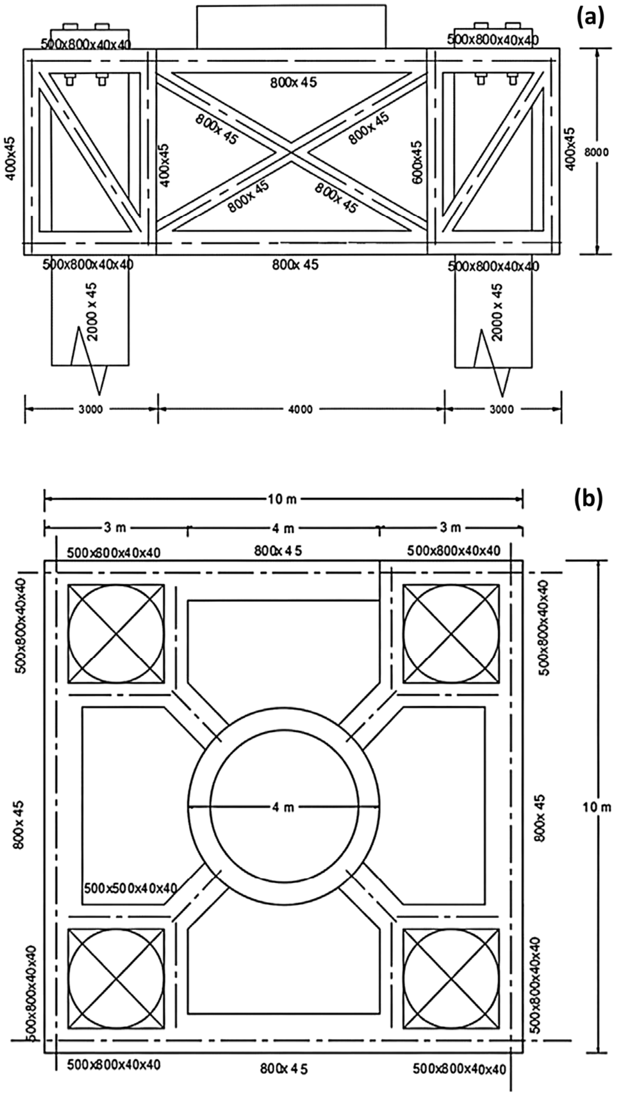


Fig. 4 — Geometrical properties of the platform: a) Elevation view; and b) Plan view

Table 1 — Geometrical properties of SIP

Name	Section (mm)
Main deck (Topside, connection box)	2000 × 2000 × 80 × 80
Support column for topside	1000 × 45
Turbine tower	5000 × 55
Horizontal bracing	1000 × 45
Leg	2500 × 80
Transition frame	1200 × 20
Suction bucket	1200 × 20

3D finite element model is mentioned in Figure 5. The location for this platform, Zone A in the Gulf of Mannar, was carefully chosen based on an assessment of offshore wind potential in Tamil Nadu, conducted by the FOWIND consortium in collaboration with the National Institute of Wind Energy (NIWE). The study identified eight zones in Tamil Nadu with favourable wind and wave conditions for offshore wind energy development, selecting Zone A for its optimal conditions. In designing the platform, the study also considers wave effects on non-structural elements such as grating and handrails. These elements, although not part of the main structural framework, can attract significant wave forces. To accurately model these effects, the study employs hydrodynamic coefficient overrides. Additionally, dummy members like boat landings and risers, which do not influence the platform's overall structural stiffness but attract wave forces, are considered in the design process to ensure platform's stability under various environmental conditions. The material properties of the steel used in constructing the platform are outlined in Table 2, ensuring that the chosen materials are suitable for the harsh offshore environment. A critical feature of the platform's design is the transition frame, which plays a vital role in reducing the unbraced

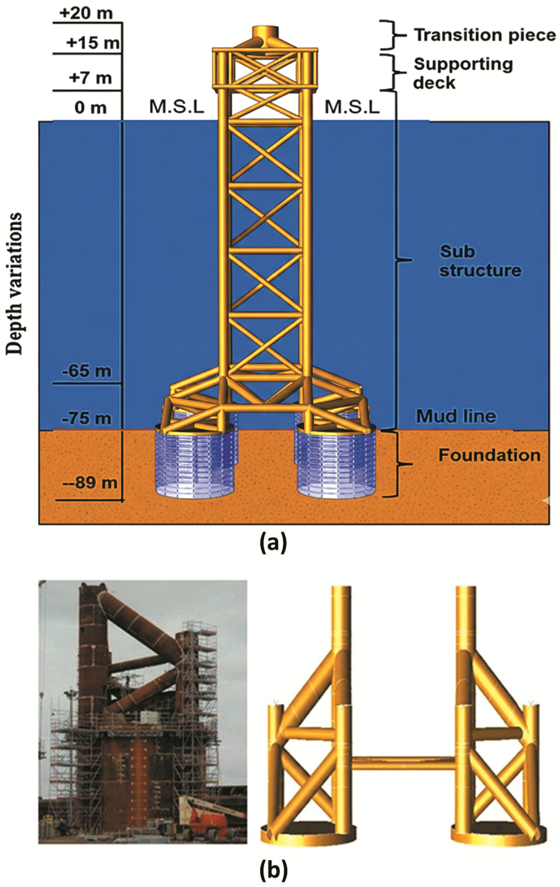


Fig. 5 — 3D finite element model of proposed SIP: a) FE model; and b) Model of suction bucket node

Table 2 — Material property of SIP

Parameter	**Values**
Young modulus	2×10^8 kN/m^2
Poisson ratio	0.3
Steel density	78.5 kN/m^3
Yield stress	3.2×10^5 kN/m^2
Ultimate stress	4×10^5 kN/m^2
Mass of the deck	1000 tonnes

Table 3 — Specifications of 10 MW OWT

Properties	**Values**
Rating	10 MW
Rotor orientation, configuration	Upwind, 3 blades
Rotor, hub diameter	126 m, 4 m
Hub height	53 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rated tip speed	80 m/s
Overhang	5 m
Rotor mass	1079 KN
Nacelle mass	2534 KN
Tower mass	3410 KN

length of the legs[18]. The specifications for the 10 MW wind turbine that the platform supports are provided in Table 3. This frame supports the legs from the perimeter of the suction bucket, effectively transferring the loads from the platform to the sea floor. This study provides a comprehensive analysis of the design and construction of a self-installing jacket platform for a 10 MW wind turbine in the Gulf of Mannar. Through careful selection of materials, detailed structural design, and consideration of environmental factors, the platform is engineered to withstand the challenging offshore conditions while efficiently harnessing wind energy in Tamil Nadu. The design and implementation of this platform contribute significantly to the advancement of offshore wind energy in the region, supporting sustainable energy development and the broader goals of renewable energy expansion.

Suction bucket foundation

The suction bucket, which resembles an inverted bucket, is a modern and innovative foundation type used in offshore engineering. Characterised by a skirt length-to-diameter ratio of less than one ($L/D < 1$), suction buckets are generally larger than traditional pile foundations[19]. This design offers several advantages, particularly in terms of installation efficiency and ease of recovery during platform decommissioning. Compared to conventional methods, suction buckets can be installed more quickly and recovered more simply, potentially eliminating the need for expensive heavy-lift vessels during both operations. The Self-Installing Platform (SIP) works by utilising hydraulic jacks to elevate itself above the water, allowing for self-installation without the need for external heavy-lift vessels. The design requirements include structural strength to withstand extreme wind and wave loads, geotechnical stability to ensure safe foundation interaction with the seabed, and the ability to self-elevate during installation. These requirements ensure that the SIP is both cost-effective and operationally feasible in deep-water environments. The working principle of the suction bucket is detailed in Figure 6.

The installation process of the suction bucket involves a series of steps designed to ensure the bucket's secure placement in the seabed:

- The process begins with the bucket being lowered into the water. Gravity assists the bucket in sinking into the seabed.
- As the bucket's walls make contact with the seabed, a valve located on top of the bucket is opened. This allows for the controlled pumping out of air and water from within the bucket.
- The removal of air and water reduces the pressure inside the caisson, creating a strong downward suction force. This force is crucial for the bucket’s penetration into the seabed.
- The suction force drives the bucket deeper into the seabed, mobilising skin friction along the bucket's wall surface and soil tip resistance at the wall sleeves' toe. When the bucket is under tension, its resistance is governed by the combination of skin friction along its wall surface and the bucket's self-weight.

The American Petroleum Institute (API) has established guidelines for evaluating pile capacity under lateral and axial bearing loads in various soil conditions, such as clay and sandy soils[20]. For the purpose of this study, the feasibility of using a suction bucket foundation was assessed with specific reference to soil data from Tamil Nadu[21]. This data was instrumental in creating a detailed soil profile using PLAXIS 3D. The PLAXIS 3D analysis provided critical insights, including lateral load deflection (P-Y curves), axial load displacement (T-Z curves), and the characterisation of the suction bucket as a non-linear spring element at specific offshore

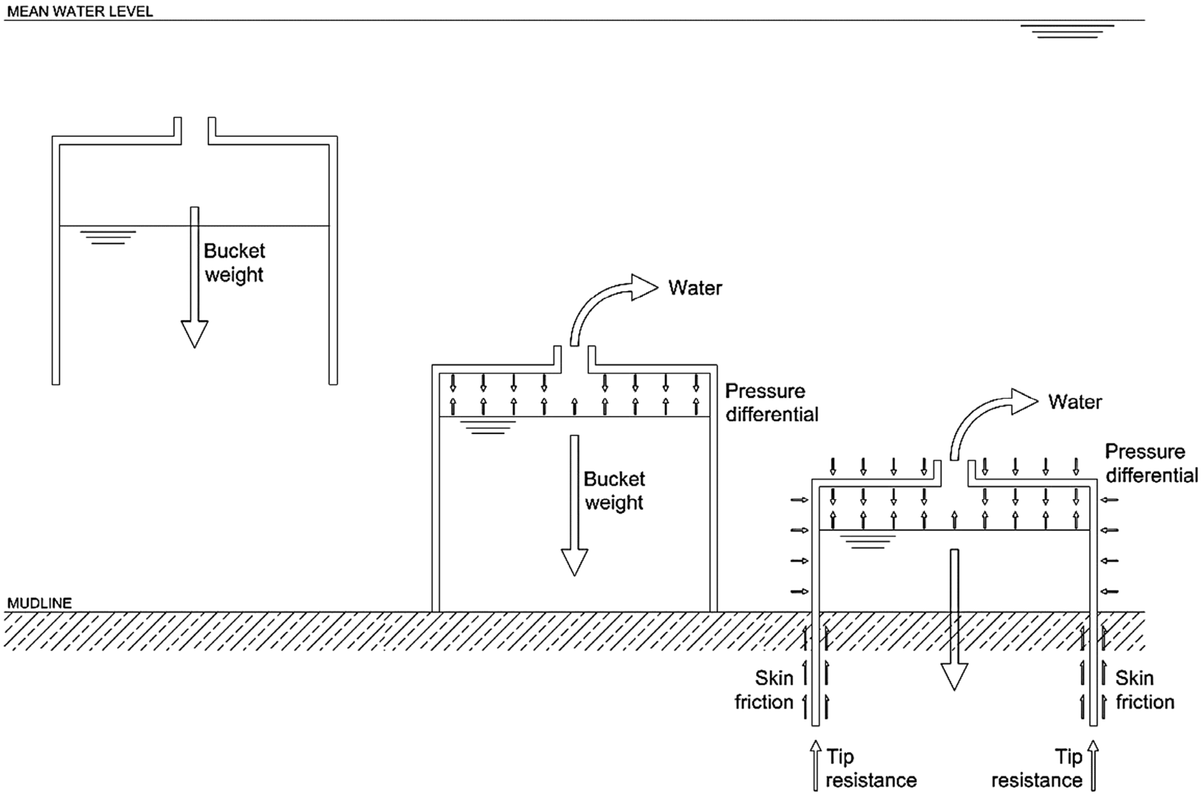


Fig. 6 — Working principle of suction bucket

sites[21]. The P-Y data, in particular, describes the non-linear relationship between lateral soil resistance and pile depth, a key factor in understanding the suction bucket's performance under lateral loading conditions.

The overall process begins with the creation of a comprehensive superstructure model that includes all relevant member information, stiffness properties, and loading conditions, with the exception of the suction buckets themselves. This model is then transferred to the SACS suction bucket program, which generates a suction bucket database file suitable for input into PLAXIS 3D. Within PLAXIS 3D, the shell plates of the bucket are meticulously meshed, and the necessary loads, soil parameters, and soil layer depths are assigned for detailed analysis. This two-way interaction ensures accurate representation of soil-structure behaviour. PLAXIS 3D conducts advanced plastic calculations based on the input soil data, producing results that detail stress distribution, displacement patterns, and skin friction values. These results are critical for understanding the interaction between the soil and the suction bucket. Once this interaction is fully modelled, PLAXIS 3D exports the result file back to the SACS program. This file serves as the foundation for creating the non-linear spring element, which is essential for accurately representing the suction bucket's behaviour within the overall structural model. This methodical and comprehensive approach to designing and modelling suction bucket foundations ensures offshore platforms are securely anchored to the seabed, providing the necessary stability for supporting large structures such as offshore wind turbines. This is particularly important in regions with challenging environmental conditions, where reliable foundation solutions are crucial for the long-term success and safety of offshore projects. The various stages involved in the creation and analysis of the suction bucket using SACS software are illustrated in Figure 7.

Structural loading on the self-installing platform

The dead load of an offshore wind turbine platform encompasses the weight of the fixed facilities on the deck and jacket, along with the self-weight of the structural members. This represents the permanent load the structure must support, covering both the platform and its attached equipment. Figure 8 shows the application of load. The total turbine weight is applied as a vertical load, with the resulting horizontal forces and moments also determined and applied to

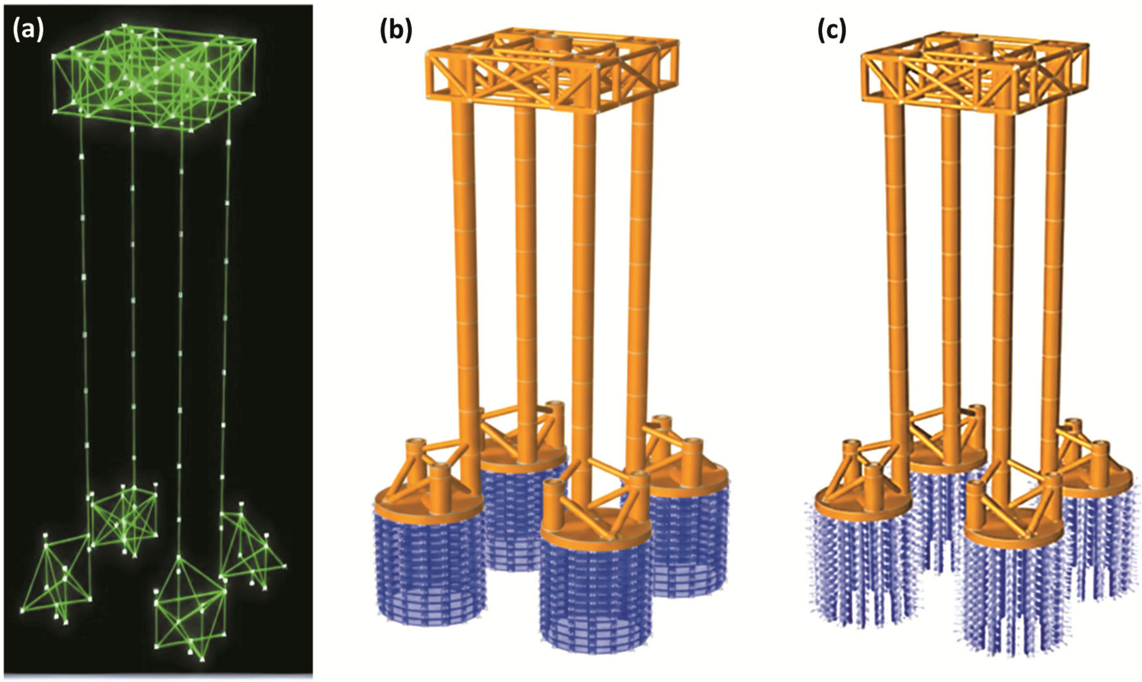
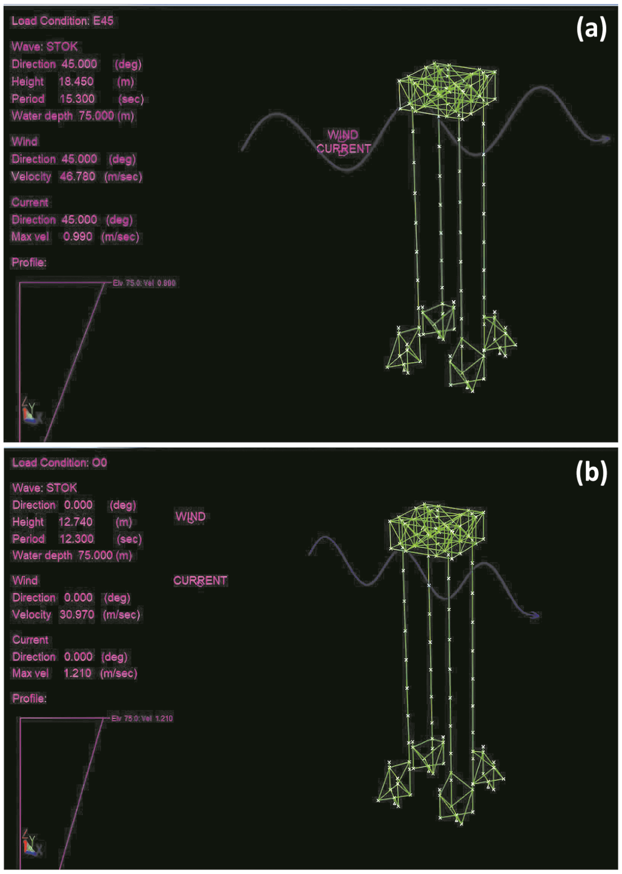


Fig. 7 — Creation of suction bucket foundation: a) SIP model withou suction bucket; b) Suction bucket with mesh; and c) Suction bucket with mesh soil characteristics



Load Condition: E45
Wave: STOK
Direction 45.000 (deg)
Height 18.450 (m)
Period 15.300 (sec)
Water depth 75.000 (m)
Wind
Direction 45.000 (deg)
Velocity 46.780 (m/sec)
Current
Direction 45.000 (deg)
Max vel 0.990 (m/sec)
Profile:
Elv 75.0: Vel 0.990

Load Condition: O0
Wave: STOK
Direction 0.000 (deg)
Height 12.740 (m)
Period 12.300 (sec)
Water depth 75.000 (m)
Wind
Direction 0.000 (deg)
Velocity 30.970 (m/sec)
Current
Direction 0.000 (deg)
Max vel 1.210 (m/sec)
Profile:
Elv 75.0: Vel 1.210

Fig. 8 — Environmental loading on SIP: a) Operational load case; and b) Extreme load case

the structure. The dead load parameters are as follows: The cell weight is 112.5 kN, while the main weight is 225 kN. The self-weight of the structure is 34,025.54 kN. Additionally, the turbine weight is 7,027 kN. Live loads are defined as temporary, movable loads that are not part of the permanent structure. These include variable factors such as equipment, personnel, or materials that may change over time, especially during maintenance, construction, or operation. In this case, the cell weight and main weight are reported as 562.5 kN and 1500 kN, respectively. Anodes installed on the steel structural members of offshore structures, such as jacket platforms, act as projections on the surface of tubular members. These anodes increase the hydrodynamic forces and alter the hydrodynamic coefficients of the tubular members. The anode load is recorded as 460 kN. The extent of this impact depends on various factors. In practice, the industry often accounts for this by applying a global multiplier to the total hydrodynamic force, which can be conservative and may result in inefficiencies.

Environmental loading

Wind load is a vital factor in offshore wind turbine design, directly affecting the platform's stability and structural integrity. This load is influenced by wind speed, direction, turbulence, and the platform's shape

Table 4 — Oceanographic data

Direction	**Wave height (m)**	**Wave period (sec)**	**Current speed (m/s) Elevation from mudline (m)**					**Wind speed (m/s)**
			0 m	**25 m**	**50 m**	**75 m**	**100 m**	
Load case: Operating (1-year return period)								
All eight directions	12.74	12.3	0.5	0.85	1.01	1.21	1.38	30.97
Load case: Extreme (100-year return period)								
N – 0	16.6	14.6	0.561	1.067	1.309	1.54	1.804	46.78
N 45 W – 45	18.45	15.3	0.341	0.759	0.946	1.122	1.353	45.02
W – 90	18.78	15.6	0.231	0.671	0.825	0.99	1.199	44.36
S 45 W – 135	19.45	15.9	0.297	0.726	0.902	1.089	1.298	45.69
S – 180	14.59	13.2	0.407	0.891	1.122	1.331	1.595	47.89
S 45 E – 225	19.8	16.1	0.341	0.792	1.188	1.32	1.397	47.89
E – 270	17.6	15.5	0.275	0.715	0.913	1.045	1.276	47.89
N 45 E – 315	15.93	14	0.275	0.715	0.902	1.078	1.342	47.89

and orientation. A thorough assessment of wind load ensures that offshore wind platforms can harness wind energy efficiently while maintaining structural stability and reliability. Hydrodynamic loading refers to the forces exerted on offshore structures by water motion, including waves, currents, and tides. These forces depend on factors such as wave height, wave period, current velocity, water depth, and the structure's design. Hydrodynamic loading has a significant impact on the platform's structural performance and stability, making it crucial to address these forces during design and analysis[22]. In older structures, reliability may decrease when wave crests hit the deck. The American Petroleum Institute (API) provides guidelines for calculating wave and current loads in its recommended practice for planning, designing, and constructing fixed offshore platforms[20]. This standard outlines procedures for static analysis, considering the combined effects of waves and currents. Wind, wave, and current load data, as shown in Table 4, are sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF). Both wind and hydrodynamic loads are applied in eight different directions, evaluated under normal operating conditions. The load cases depicted in Figure 8 shows the environmental loading for operating load and extreme load case.

Selection of wave theory

A representative calculation for selecting an appropriate wave theory in the north direction (N–0°) is presented below, considering key oceanic parameters such as wave height (H), wave period (T), and mean water depth (d).

$H / gT^2 = 16.6 / (10 \times 14.6\ 2) = 0.0077$; and $d / gT^2 = 75 / (10 \times 14.6\ 2) = 0.035$

For the value of $H / gT^2 = 0.0077$, and $d / gT^2 = 0.035$ from the API chart for the N–0° direction, Stokes 5th order wave theory is selected as the most suitable, as illustrated in Figure 9.

Marine growth on offshore wind turbine platforms presents a significant challenge for maintenance and operational efficiency. Over time, marine organisms such as algae, barnacles, and mussels can accumulate on the platform's structure, leading to increased drag and reduced performance of the turbines. To mitigate this issue, regular maintenance and cleaning operations are necessary to remove the marine growth and ensure optimal functioning of the turbines. Additionally, innovative solutions such as anti-fouling coatings and underwater cleaning technologies are being developed to minimise the impact of marine growth on offshore wind energy infrastructure. These efforts are crucial for maximising the lifespan and productivity of offshore wind farms while minimising environmental impacts. In offshore structures, drag force is the resistance experienced as the structure moves through water, caused by friction between water and the structure's surface. Inertia force arises from the structure's acceleration or deceleration due to wave and current action. Both forces are crucial in structural analysis and design to ensure stability and safety[23].

Results and Discussion

Static analysis

The in-place analysis involves the stability and strength determination of the structure when subjected

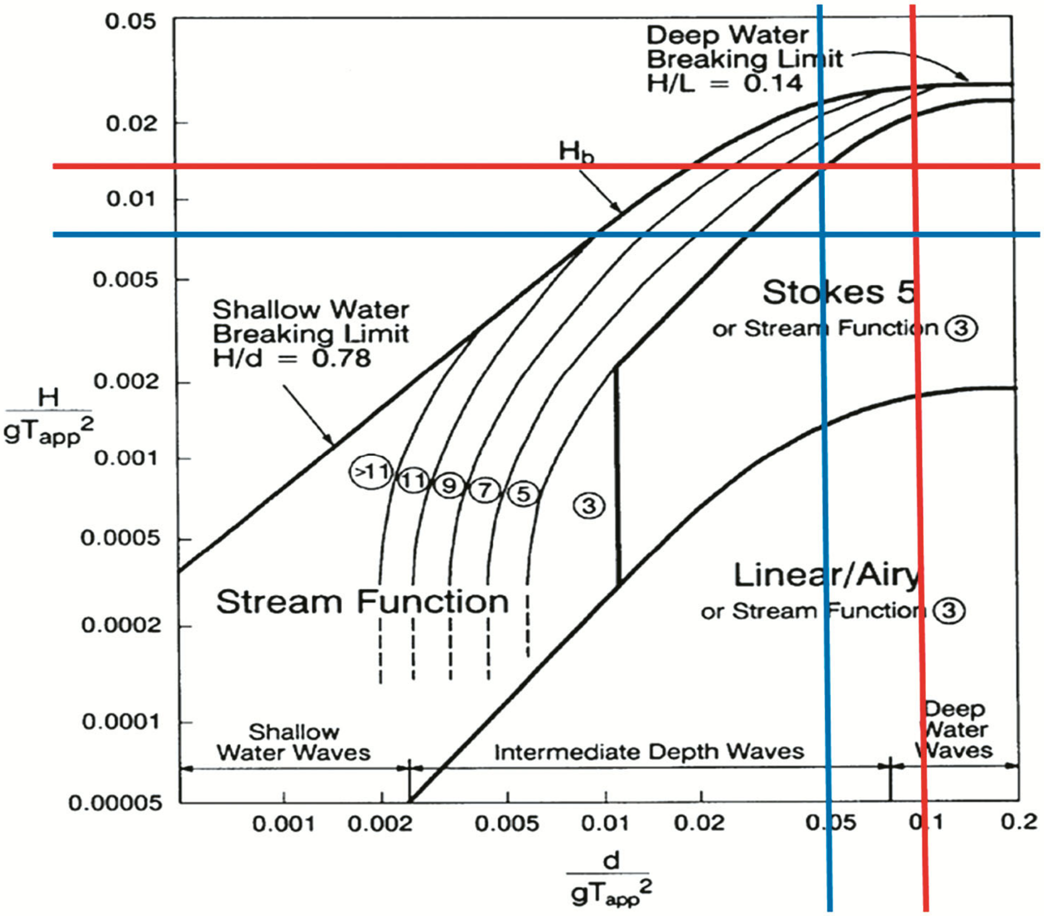


Fig. 9 — Selection of appropriate wave theory

to the normal operational condition and the extreme (or survival) condition[28]. For this platform, the normal operating condition covers the 10-year return period, and the survival condition covers the 100-years return period for wind, current and wave actions. In-place analysis is done to check the global integrity of the structure against premature failure. Static analysis of the structure was performed for wave loads acting in eight directions, as per API guidelines.

Static analysis is conducted according to API and local guidelines, assessing various components of the platforms under both operational and extreme storm conditions. The load combinations applied in the simulations include dead load (weight of the SIP), live load, wave loading, and wind loading. The loading conditions are applied at specific points on the platform, including the centre of mass and peripheral locations that experience higher stresses. Table 5 presents load combinations (OLC1 to OLC8 and ELC1 to ELC8) under various loading conditions, including dead load, wave and current loads, and wind loads, each applied from eight different directions (ranging from 0° to 315°, at 45° intervals). The primary distinction between these conditions lies in factors such as wave height, current velocity, wind speed, and wave period. The operational case represents sea conditions likely to occur at least once a month, while the storm/survival case presents an extreme sea state condition with a 10^{-2} probability of occurrence in one year. Both operating and extreme sea state conditions must adhere to standard requirements for the design and reassessment of offshore self-installing platform structures. Soil and foundation data are obtained from the suction bucket result file in PLAXIS 3D software. Subsequently, a joint can file is generated for analysing critical joints within the section. A sea state file is then incorporated to analyse environmental loading conditions.

The displacement results have been analysed according to the API-RP2A code, and the allowable displacement for the structure is calculated as (D/T) 2500/70 = 36.25 mm. Where, D is diameter and T

Table 5 — Load combinations for the analysis

Load combination	**Dead load**	**Wave & current load in 8 attack directions**								**Wind load in 8 attack directions**							
		0°	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**
OLC1	1	1								0.5							
OLC2	1		1								0.5						
OLC3	1			1								0.5					
OLC4	1				1								0.5				
OLC5	1					1								0.5			
OLC6	1						1								0.5		
OLC7	1							1								0.5	
OLC8	1								1								0.5
ELC1	1	1								1							
ELC2	1		1								1						
ELC3	1			1								1					
ELC4	1				1								1				
ELC5	1					1								1			
ELC6	1						1								1		
ELC7	1							1								1	
ELC8	1								1								1

OLC1 – 8: Operating case load combination; ELC1 – 8: Extreme case load combination; Dead load: Structure self-weight + deck load + anode load + marine growth

represents the thickness of a leg member. The structure's actual maximum displacement of 35 mm, which is obtained in SACS remains within this limit, ensuring compliance with serviceability criteria. This calculation was added to the displacement verification section. The maximum horizontal deflection is constrained to 0.3 % of height as prescribed by the API-RP2A code. The maximum displacement is obtained in E225°.

Base shear and overturning moment

In the analysis of base shear and overturning moment relative to the mudline differential wave positions, the position labelled as 0° is identified as the most critical. This specific position refers to the scenario where the wind turbine's rotor faces directly into the prevailing wind direction, aligning with the platform's orientation. At a mudline elevation of 75 m, when the platform is subjected to wave forces at the 0° phase angle, the structure experiences the maximum moment and shear. These values highlight the significant forces acting on the structure under this particular wave loading condition. Further examination of the load cases shows that the maximum forces occur during both operational and extreme load scenarios, affect the structure in both X and Y directions. Figure 10 shows the base shear at mud level for the Operational Load Case (OLC) and Extreme Load Case (ELC). These findings underscore the critical nature of the 0° and 90° phase angles in influencing the structural response of the wind turbine platform. The results provide essential insights into the design and safety considerations necessary to ensure the platform's stability under extreme environmental conditions[24].

Pile joint reaction

The load cases labelled OLC1 to OLC8 and ELC1 to ELC8 involve vertical loads combined with emergency factors and are applied during the placement analysis of the structure. These load combinations play a crucial role in assessing the behaviour of the self-installing wind turbine model under various conditions[22]. The structural system illustrated in Figure 11 comprises a tower supported by four foundation legs, labelled PL1, PL2, PL3, and PL4. The resulting moments generated by these load combinations at OLC1, OLC1-X, and ELC3-X for extreme and operational load case results demonstrate that the highest reaction moment occurs under the load combination ELC3-X. The peak value of 7018 kNm is particularly concentrated on PL4. The other load combinations show significantly lower moments, distributed across all four legs, with notable increase in moments for combinations like ELC1-X and ELC1-Y. The analysis of joint moments for load cases OLC1, OLC3, ELC1, and ELC4 reveals that the structure is engineered to effectively withstand significant forces in these scenarios, ensuring its structural integrity.

Combined unity check with knuckle joint

In the structural engineering process, the ratio between the actual stress that affects the structural

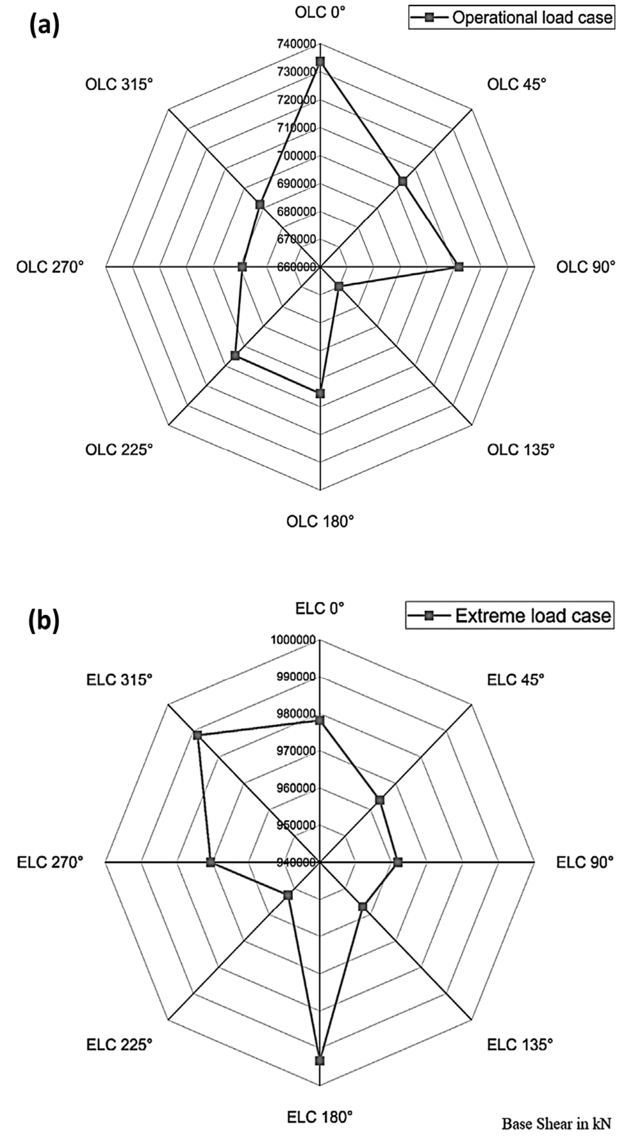


Fig. 10 — Base shear at mud level: a) Operational load case; and b) Extreme load case

member and the allowable stress is termed Unity Checks (UC), is an essential evaluation metric used to determine whether a structural member has adequate strength to support the applied loads[25]. The unity check compares the actual load effects on a member to its capacity, providing a ratio that indicates the safety and adequacy of the member under given conditions. When the unity check value is less than 1, it indicates that the member's capacity exceeds the applied load. In this case, the member is sufficiently strong to handle the load, and no redesign is required. This condition ensures that the member operates within safe limits. Whereas, when the unity check value exceeds 1, it signifies that the applied load surpasses the member's capacity, meaning the member is overstressed. This condition necessitates a redesign of the member to ensure safety and compliance with structural design standards.

The unity check is typically applied to all critical members of a structure during the design and analysis phase. Figure 12 presents the unity check values for various structural members under different load combinations, specifically OLC1, OLC3, ELC1, and ELC3. Unity check values represent the ratio of demand (applied load) to capacity (design strength), with values approaching or exceeding 0.8 indicating that certain members, such as the Box section (BOX), Legs (LEG), and Connections (CON), are subject to higher stress relative to their design limits under specific load scenarios. These elevated UC values suggest that these components are approaching critical thresholds of their structural capacity.

Maximum horizontal and vertical displacement

The analysis of displacements for the structure under operational and extreme load cases indicates satisfactory performance within safety limits. Figure 13 shows the maximum displacements in the X and Y directions for operational and extreme load cases at the top level of substructure. For the operational load case (OLC3), the vertical displacement is limited to 3.023 cm, and for the extreme load case (ELC1), the maximum horizontal displacement is 6.756 cm. These displacements are well within the limits, with column movements restricted to 0.3 % of the column height and beam deflections capped at L/200. The foundation joint reactions for various load combinations confirms that the structure can adequately support the applied loads. Overall, the design demonstrates resilience and compliance with safety standards, ensuring the structure's stability and reliability under different loading conditions.

Pushover analysis

Pushover analysis is a method used in structural engineering to evaluate how a structure will respond to increasing loads until it reaches failure. This technique is especially important for offshore platforms, such as self-installing platforms, which are subject to harsh environmental conditions and significant loading from various sources[26]. In pushover analysis, lateral loads are applied to the structure incrementally. The lateral load pattern simulates the effects of seismic forces and wind loads

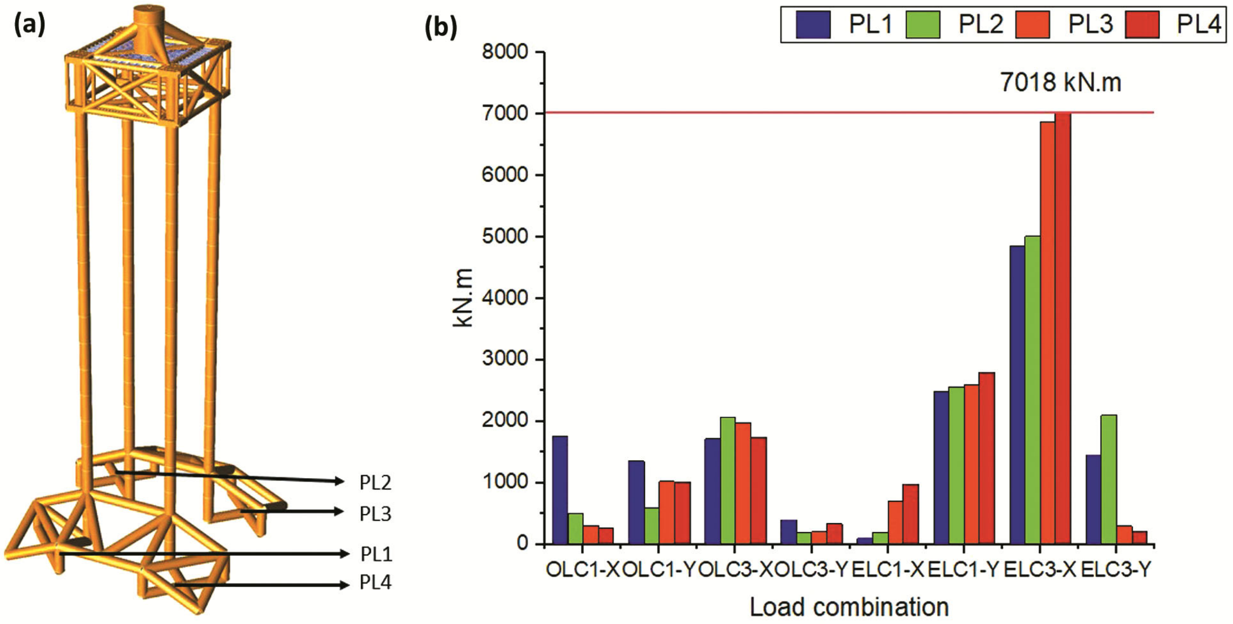


Fig. 11 — Resulting moment at foundation joints: a) Pile joint at suction bucket level; and b) Moment for critical load cases

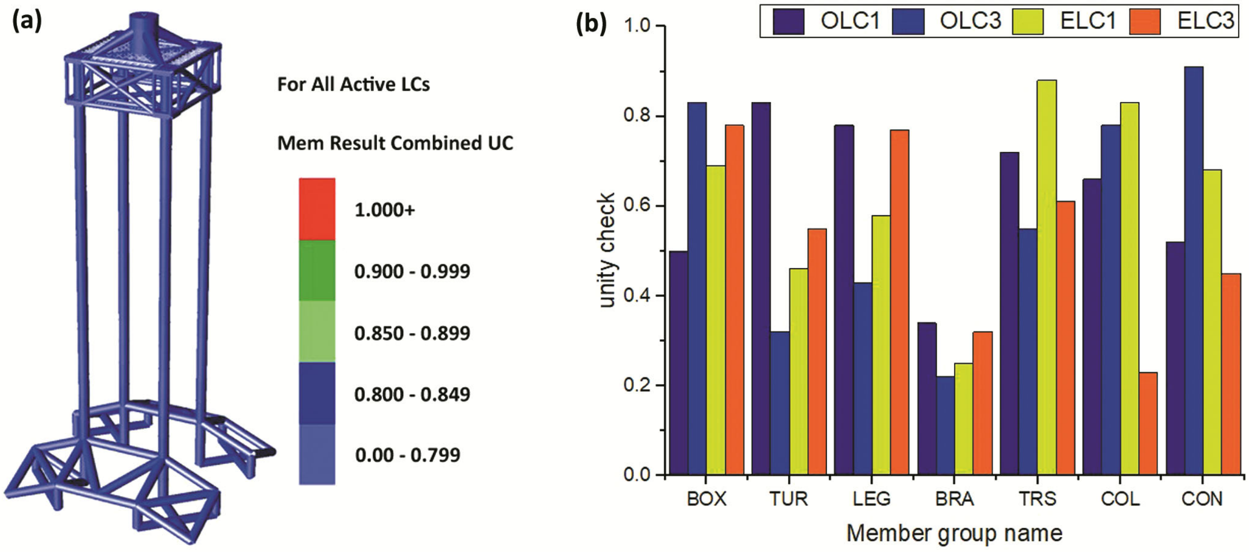


Fig. 12 — Member combined unity check value: a) Level of UC range; and b) Members UC value for critical load cases

on the platform. The load is applied in incremental steps to determine how the structure responds to progressive lateral displacements. The results help assess the platform's stability and structural integrity under extreme lateral loading conditions, ensuring that the Self-Installing Platform (SIP) remains within acceptable safety margins. By simulating these conditions, engineers can understand how the structure behaves under stress, identify potential weaknesses, and determine the points where failure might occur. This analysis is critical for ensuring the safety, reliability, and stability of offshore platforms. Weather conditions that the platform might encounter lead to Environmental loads. Basic loads include dead loads, live loads and anode loads.

The pushover analysis involved applying these loads incrementally to the platform to simulate real-world conditions. The structure was tested through 16 load cases, starting with basic loads and progressing to extreme scenarios. The platform began to experience severe stressing during the 8th load case, which included a combination of dead, anode, live, and extreme

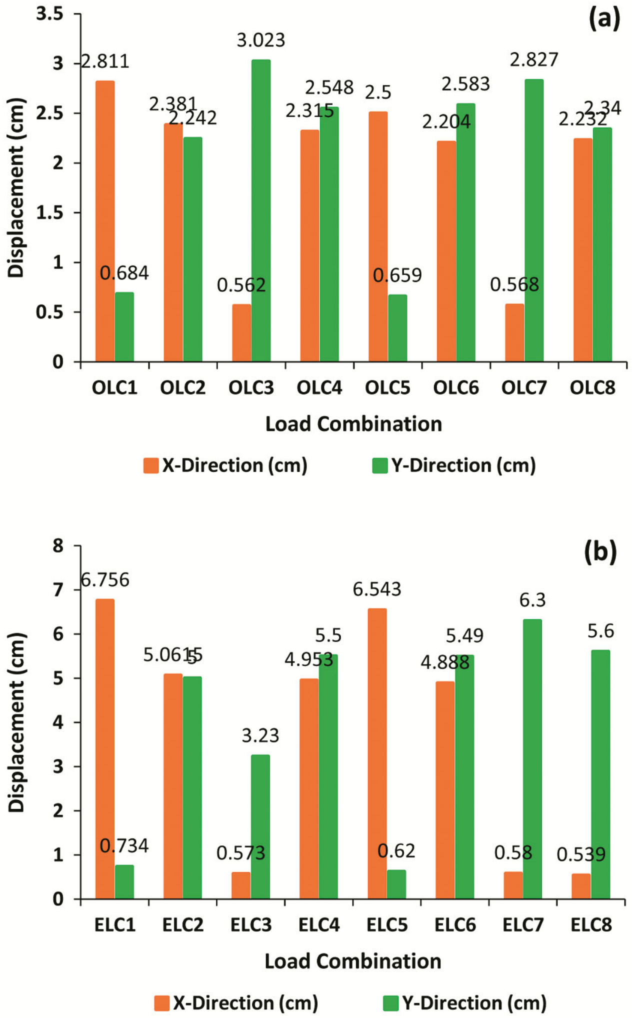


Fig. 13 — Maximum horizontal and vertical displacement: a) Operational load case; and b) Extreme load case

environmental loads at the knuckle joint. The structure fully collapsed during the 9th load case, specifically under the E225° load condition at the knuckle joint. The base shear value at collapse was 2,556.60 MN. Figure 14 shows the stress conditions at the knuckle joint and the collapse under the E225° load condition.

The RSR (Reserve Strength Ratio) is a crucial parameter in pushover analysis for offshore platforms. It represents the ratio of the available structural strength to the applied demand at a specific performance level. In simpler terms, it indicates how much reserve strength the structure has before reaching a predefined performance limit, often associated with collapse or failure. A higher RSR indicates a more robust structure with greater capacity to withstand loading conditions. Conversely, a lower RSR suggests that the structure is closer to its limit and may be vulnerable to failure[27]. Therefore, monitoring and analysing the RSR throughout the pushover analysis helps engineers assess the structural safety and performance of offshore platforms under various loading scenarios.

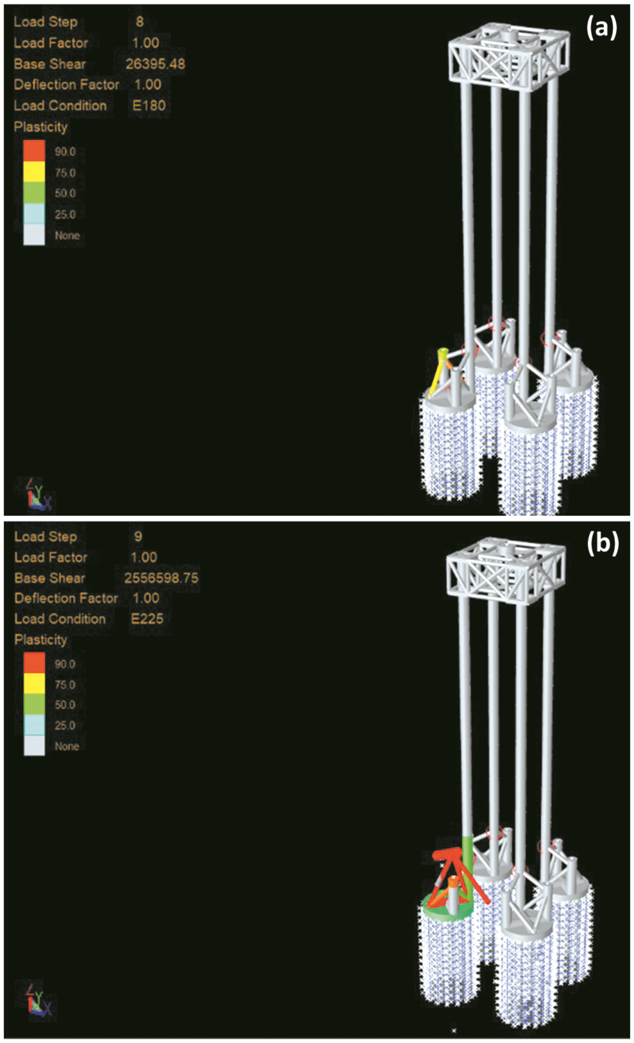


Fig. 14 — Stress conditions at knuckle joint: a) Stress at yielding stage; and b) Stress at collapse stage

$$RSR = BS_{\text{collapse}} / BS_{\text{extreme environmental load}}$$

The performance levels of the SIP are defined in terms of displacement limits, structural strength. RSR (Reserve Strength Ratio) is used to evaluate the safety margin of the platform, with an RSR value greater than 2.5 indicating acceptable performance under extreme loads. These performance criteria ensure that the SIP can safely install offshore wind turbines in deep-water conditions while maintaining structural integrity and stability. In all analysed directions, the

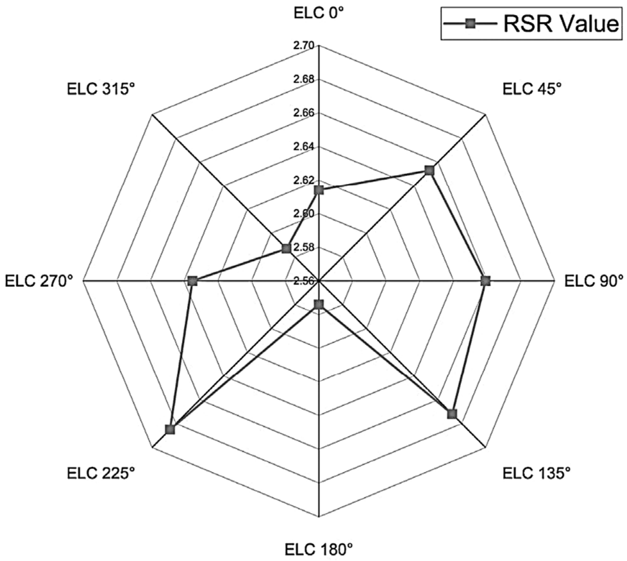


Fig. 15 — RSR value of the platform along different direction

RSR values were above 2.5. According to research by Wan Mahmood bin Wan Abdul Majid *et al*.[28], the minimum RSR value for a self-installing platform is two. As the analysis in the current study shows RSR values above this threshold, the structure is deemed safe under all examined load cases. Figure 15 displays RSR values for different directions and reveals that the lowest RSR value occurs in the E180° direction, indicating that this direction is the weakest point of the offshore platform. The pushover analysis confirms that the self-installing offshore platform generally meets safety and performance standards. The platform can withstand significant loads and stresses, with all RSR values exceeding the minimum required level. The critical direction identified (E180°) provides insight into where improvements might be necessary to enhance the platform's overall robustness. By understanding these results, engineers can ensure the structural integrity and reliability of offshore platforms in challenging environments.

Conclusion

The study of the Self-Installing Platform (SIP) for offshore wind turbine installations, under extreme environmental conditions, presents valuable findings for both structural integrity and cost-efficiency. By using SACS and PLAXIS 3D software for static and non-linear analysis, the research provides essential insights into the platform's strength, displacement, and Reserve Strength Ratio (RSR), ensuring that the SIP meets safety and reliability standards.

The key findings include:

- The combined Unity Check (UC) for all member groups was found to be less than 1.0, confirming that the structural sections are not overstressed and are therefore economically designed without compromising safety.
- The allowable displacement for the structure is calculated as 2500/70 = 36.25 mm. The obtained total displacement in the structure is 35 mm, which is less than the allowable displacement, confirming compliance with the standards.
- Reserve Strength Ratio (RSR) values were greater than 2.5 in all eight directions, well above the minimum requirement of 2.0 for self-installing platforms. This indicates a high margin of structural redundancy, ensuring the platform's robustness even under extreme load conditions.
- The identification of E180° as the critical direction for combined environmental loading helps in targeting reinforcement or design optimisation in the most vulnerable zone of the structure.

This study is particularly relevant and useful for recent developments in offshore wind energy. The SIP's ability to self-install without reliance on heavy-lift vessels offers a cost-effective solution to the major challenge of high installation costs, making it highly applicable to current offshore wind energy projects. Moreover, the coupled structural-geotechnical model provides a comprehensive understanding of soil-structure interaction and dynamic wave forces, which are critical for evaluating offshore structures in real-world conditions.

In light of the growing demand for sustainable offshore wind energy solutions, the Self-Installing Platform (SIP) presents a timely advancement in reducing installation costs and enhancing installation efficiency, making it a valuable contribution to the future of offshore wind energy. The insights from this study are not only relevant to ongoing research but also offer a practical approach to improving offshore wind turbine installation, supporting the global transition to renewable energy.

Acknowledgements

We express our sincere thanks to The National Institute of Ocean Technology (NIOT), Chennai, for their help towards the collection of all meteorological data.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper**.**

Author Contributions

PA: Conceptualization, methodology, investigation, and writing - original draft; and CM & JP: Review and editing.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Some data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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