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Review Paper

A critical review on deep-water oil and gas development equipment research and application: Floating platform, mooring cable and pile foundation

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A B S T R A C T

As a crucial component of the global energy supply, deep-sea oil and gas resources exist in highly complex environments and pose significant technical challenges, necessitating reliance on floating platforms, mooring systems, pile foundations, and risers. Reviewing and analyzing recent advancements in these systems can promote technological innovation and ensure safer, more efficient, and sustainable resource development. This paper reviews the research and engineering applications of floating platform, mooring system, and pile foundation in deep-sea oil and gas development. It also examines their technical characteristics, recent research progress, and future development directions. The review covers various floating platform type, including the tension leg platform, SPAR platform, semi-submersible platform as well as floating production storage and offloading. It also reviews mooring pile foundations such as suction piles, slender anchor piles, torpedo anchors, and claw anchors. Additionally, this paper summarizes the connection mechanisms of mooring systems linking floating platforms and anchoring foundations, and introduces the classification and mechanical behavior of risers. Together, these components contribute to structural stability and reliable performance in complex marine environments. Recent advances in artificial intelligence also offer new opportunities for enhancing fatigue assessment and operational monitoring in deep-water systems. Based on the above summary, this paper presents insights and future directions for the integrated equipment system comprising the floating platform, mooring system, and pile foundation in deep-sea oil and gas development. It also serves as an important reference for promoting technological innovation and contributing to global energy sustainability.

1. Introduction

Offshore oil and gas resources constitute a crucial component of the global energy supply. As land and shallow-sea resources have been gradually depleted, the ocean emerges as a vital alternative for future energy exploration. Oceans cover approximately 70% of the Earth's surface, with waters up to 500 m deep containing more than 80% of the total proven seabed reserves (Bernardino et al., 2020). While this offers vast opportunities for deep-sea oil and gas development, it also presents significant technical challenges.

In offshore oil and gas engineering, water depth is a primary criterion for classifying development regions and selecting suitable production systems. Depths less than 300 m are generally defined as shallow water, where development has traditionally relied on fixed platforms. Depths between 300 and 500 m are categorized as sub-deep water, typically developed using Compliant Tower platforms or floating production systems. While floating platforms are predominantly deployed in deep and ultra-deep waters, they are also employed in shallow and sub-deep water fields when dictated by environmental constraints,

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reservoir conditions, or economic considerations. As illustrated in Fig. 1, water depths exceeding 500 m are classified as deep water, and those greater than 1500 m as ultra-deep water. At such depths, fixed platforms are impractical, and only floating production systems—such as tension leg platforms (abbreviated as TLP), deep draft spar platforms (function include: sparing, production, and reservoir, abbreviated as SPAR), semi-submersible platforms (abbreviated as SEMI), and floating production storage and offloading units (abbreviated as FPSO)—are technically and economically feasible (Uspenskaya, 1967; Speight, 2014; Xu and Guo, 2018; Caralb, 2023). Operating in these environments imposes stringent demands on station-keeping capability, as platforms are subjected to complex environmental loads from waves, currents, and winds, often with significant directional variability. To ensure operational stability, floating platforms rely on advanced mooring systems that integrate high-strength mooring lines—comprising steel chains, synthetic fiber ropes, or hybrid segments—with robust subsea foundations such as suction anchors, slender pile anchors, torpedo anchors, or claw anchors. The design of these systems must account for coupled dynamic responses between the platform, mooring lines, and seabed foundation, incorporating nonlinear hydrodynamic effects, soil–structure interaction, and long-term cyclic degradation of holding capacity. Consequently, the stability and efficiency of the mooring–foundation system are not merely structural considerations but decisive factors governing the safety, operability, and economic viability of deep-water oil and gas projects.

Recognizing the progressive coupling relationship among the floating platform (carrier), mooring system (constraint), pile foundation (support), and riser (response), this paper aims to provide a comprehensive review of their structural types, design principles, and engineering applications in deep-sea oil and gas development. In Fig. 1, floating platforms are broadly categorized into four types—TLP, SPAR, SEMI, and FPSO—each serving as a primary carrier that accommodates production facilities and responds to environmental loads (Caralb, 2023). The mooring system functions as a dynamic constraint, transmitting loads from the platform to the seabed while maintaining positional stability under extreme ocean conditions. Beneath the mooring lines, pile foundations provide the ultimate geotechnical support, ensuring anchoring integrity through suction, friction, or penetration mechanisms. The riser, as the final responsive component in this structural chain, exhibits complex dynamic behavior that is highly sensitive to platform motion, mooring stiffness, and seabed boundary conditions. Its fatigue performance directly reflects the degree of the overall coordination and resilience of the entire floating–mooring–foundation system. By systematically analyzing the interaction mechanisms and performance dependencies among these four subsystems, this review identifies critical research advances and associated coupling challenges. Furthermore, artificial intelligence and data-driven frameworks are highlighted as promising approaches for capturing system-level behavior—integrating platform motion prediction, mooring tension monitoring, pile degradation assessment, and riser fatigue evaluation—to achieve intelligent monitoring and optimization of deep-water offshore systems. These developments collectively contribute to safer, more efficient, and sustainable deep-sea energy exploitation.

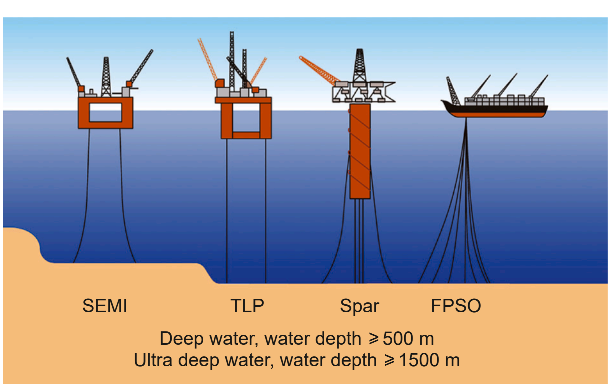


Fig. 1. Classification of floating platform.

2. Research progress of deep-sea floating platform

As key facilities in deep-sea oil and gas development, TLP, SPAR, SEMI, and FPSO shown in Fig. 1, demonstrate exceptional adaptability and functionality in complex marine environments owing to their distinct design concepts and technical characteristics (Caralb, 2023). Together, these four major facilities serve as the technological pillars of deep-sea oil and gas development, playing a crucial role in ensuring global energy security.

2.1. Tension leg platform

Since its initial development by ConocoPhillips in the North Sea during the 1980s, the TLP has become a critical facility in deepwater oil and gas development. Its design concept ensures a stable working environment for oil and gas production by generating buoyancy forces significantly greater than its self-weight. This is achieved through a semi-compliant and semi-rigid structure that utilizes pre-tensioning to maintain equilibrium. The TLP's unique upright pontoon structure effectively mitigates the sagging issues encountered by other floating platforms and significantly boosts kinematic performance (Ye et al., 2022). Over nearly five decades of development, the TLP's design has evolved from a simple to a more complex structure, continuously optimizing platform performance, stability, and motion response. This evolution has solidified its role as an indispensable tool in deep-water oil and gas development.

Research on TLP platforms has advanced progressively across four interrelated themes: structural design evolution, hydrodynamic motion response, adaptability in harsh environments, and structural health monitoring. Significant progress has been made in hull design, tendon connectors, and modular concepts, improving restoring capacity and extending use in deep water and marginal fields. For instance, Leverette and Hodges (2020) reviewed the historical development of TLPs, noting that innovations in hull geometry and riser systems substantially advanced adaptability while reducing costs. Further design innovations such as the multi-column TLP (Tahar et al., 2016) and modular floating body systems with hinged connectors (Li et al., 2024) highlight efforts to refine stability, collision resistance, and applicability in shallow-water or marginal fields. Beyond design aspects, hydrodynamic motion response has emerged as a key research focus, with studies emphasizing wave–current interactions and second-order nonlinear effects that dominate surge, heave, and pitch responses, thereby directly influencing tendon tension. Zhang et al. (2018) demonstrated that extreme heave and oscillatory motions occur under specific wave headings, while increased draft and column spacing are effective strategies for motion mitigation. Building on this, Wang et al. (2022) developed a coupled time-domain piston–cylinder model in Fig. 2, showing that second-order combined-frequency forces strongly affect displacement and tension spectra, whereas rogue waves induce disproportionately large platform responses. Similarly, Huang et al. (2023) extended this framework by decomposing horizontal and vertical hull responses under multiple excitation frequencies, and also proposed a quasi-dynamic method for efficient prediction of tendon tension and platform motions. Taken together, these studies provide robust theoretical guidance for motion response control in severe sea states. In parallel, structural health monitoring and fatigue reliability assessment have advanced as crucial elements in ensuring lifecycle performance. Early efforts included piezoelectric-based fault diagnosis and fuzzy classification methods for tendon integrity evaluation (Jahangiri et al., 2016). More recent approaches, such as the quasi-dynamic time-domain fatigue method proposed by Li et al. (2025), reconstruct stress time histories from decomposed wave loads with strong agreement to experimental and coupled simulations, thereby enabling efficient fatigue assessment under realistic ocean conditions.

Recent studies have considerably advanced TLP research in design optimization, hydrodynamic behavior, kinematic response, and fatigue analysis. Despite these contributions, several gaps persist. Comprehensive field data on long-term fatigue performance are still lacking, limiting the validation of numerical predictions. The effects of coupled environmental loads (e.g., waves, currents, and earthquakes) remain insufficiently understood, especially under extreme nonlinear conditions. In addition, although modular and multi-column concepts show potential, their scalability and cost-effectiveness in ultra-deep waters require further demonstration (Li et al., 2024a, 2024b). Intelligent monitoring strategies, including digital twin-enabled systems, remain in the early stages, with limited application in real-time prognosis and decision-making (Jahangiri et al., 2016; Li et al., 2025a, 2025b). Research on advanced materials and adaptive designs remains limited but has the potential to advance resilience and sustainability. Future research should emphasize empirical validation and integrated analyses that couple environment, structure, and materials to foster safety and adaptability in next-generation ultra-deep water developments.

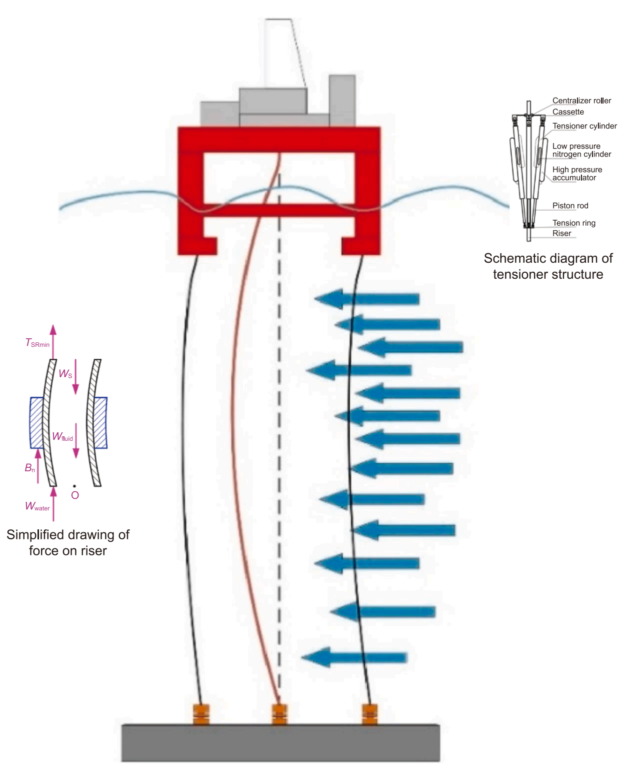


Fig. 2. Diagram of forced vibration in flow direction (adopted from Wang et al. (2022)).

2.2. SPAR platform

SPAR platform is a floating structure designed for deep-water drilling and oil extraction, comprising a superstructure, a vertical cylindrical hull, mooring lines, and risers. The floats provide buoyancy to support the superstructure while the ballasted bottom ensures that the center of buoyancy remains above the center of gravity, enhancing stability similar to that of a neutrally buoyant vessel. In 1987, Edward E. Horton proposed the SPAR concept, which is regarded as the precursor to modern SPAR production platforms because of its structural suitability for deep-water environments. In 1996, Kerr-McGee successfully installed the first SPAR production platform in the Gulf of Mexico. Kerr-McGee's successful installation of the NEPTUNE SPAR in 1996 in the Gulf of Mexico demonstrated its reliability in supporting risers, process facilities, and drilling systems. Over the past two decades, SPAR platforms have evolved into three distinct types—classic, truss, and cell-SPAR—improving both economic efficiency and hydrodynamic stability, solidifying their role as critical facilities for deep-water oil and gas development (Carpenter, 2020b).

Research on SPAR platform fundamentals has gradually evolved from motion response studies to hydrodynamic mechanisms and structural safety evaluations, forming a systematic framework that bridges theory and application. It can be seen from Fig. 3 that Zhu and Yoo (2015) identified wave loading as the primary driver of longitudinal and vertical oscillatory motions. They further clarified the effects of dynamic equilibrium and complete submergence on transverse oscillations, thereby laying the foundation for subsequent motion response research. Building on this, Soeb et al. (2017) revealed that increasing water depth augments mooring line damping and suppresses platform oscillations, while static current forces induce horizontal displacement and reduce pendulum and rocking motions, underscoring SPAR stability in ultra-deep water conditions. Wang and Zhou (2020) and Qin et al. (2025) expanded the understanding of internal and surface wave interactions, emphasizing the need for refined hydrodynamic models for deep-water conditions.

In parallel, significant efforts have been devoted to nonlinear wave interactions and resonance phenomena. Yang and Xu (2015) introduced moving weights and damping plates to mitigate instability under complex waves, providing theoretical guidance for stability design. Complementing this, Junianto et al. (2020) compared different hull configurations and confirmed the superior kinematic performance of four-column platforms compared with catamaran structures, offering a pathway for structural optimization. Internal wave influences were also emphasized by Kurup et al. (2015), who showed their strong effects on platform deflection and pitching motions, while Ruzzo and Arena (2019) developed a deterministic approach to characterize extreme wave groups, reducing computational complexity and enabling more efficient safety assessment. These studies refined SPAR response prediction under nonlinear and extreme conditions.

A further research stream centers on damage detection. O'Donnell et al. (2020) found that the free decay test was ineffective in differentiating the degree of damage when simulating various damage scenarios. However, the distribution characteristics of platform motion responses—such as surge, heave, and pitch—could be leveraged to identify structural changes. Zhu et al. (2021) revealed asymmetric tension distributions between onshore and offshore tendons and further quantified the dynamic impact of line failures. Together, these studies underscore that monitoring integrity is integral to maintaining SPAR safety, and

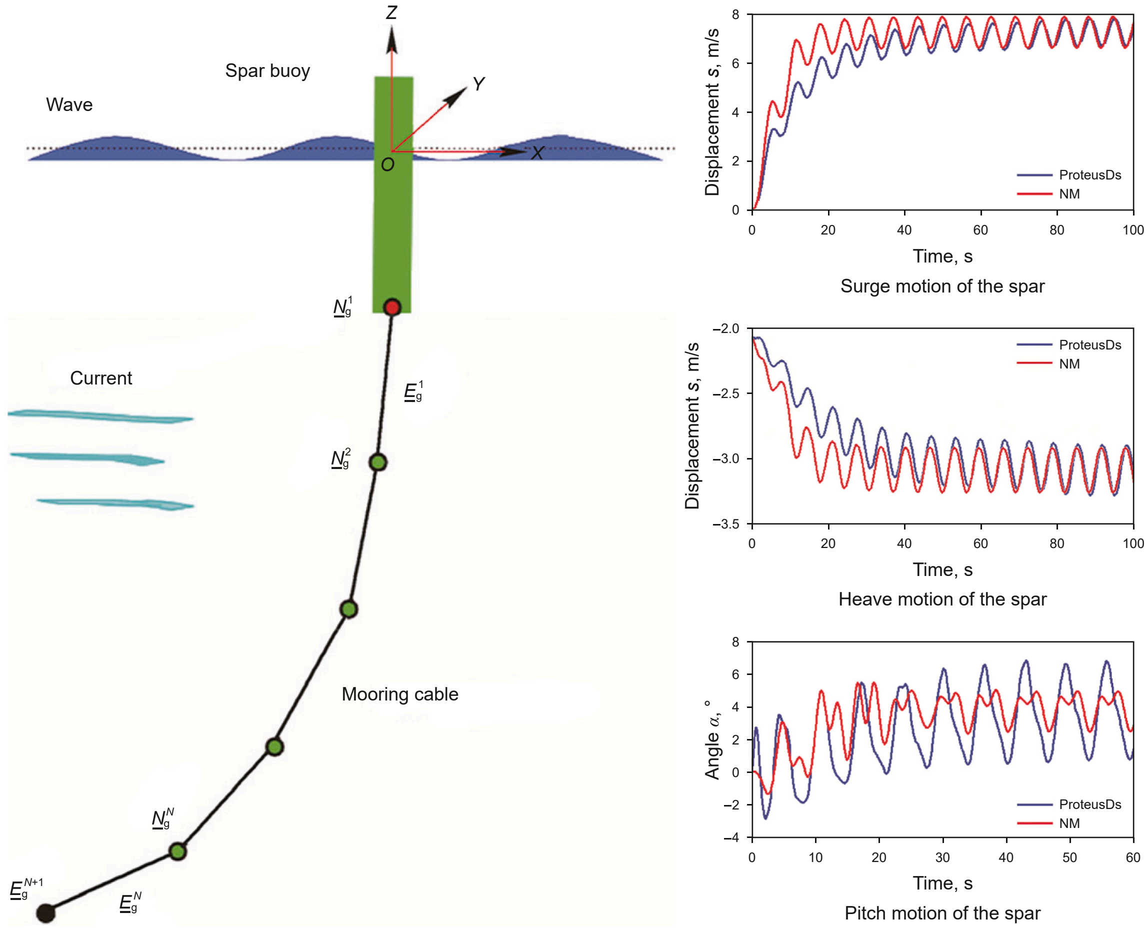


Fig. 3. Floating spar platform fastened by a cable (adopted from Zhu and Yoo, 2015).

that future work should strengthen links between hydrodynamic loading, nonlinear response, and damage progression.

SPAR research has evolved from motion response analysis to hydrodynamics, structural optimization, and integrity monitoring, linking theory with engineering practice. The foundational studies by Soeb et al. (2017) provided critical theoretical support for the practical engineering applications later conducted by Wang and Zhou (2020) and Yang et al. (2024). Conversely, the works of Ruzzo and Arena (2019) and Junianto et al. (2020) offered complementary perspectives for design optimization of SPAR platforms, particularly regarding extreme wave conditions and multi-platform comparisons. Despite these advances, key challenges remain unresolved. Long-term field data on SPAR behavior across diverse environments are still scarce, limiting the reliability of fatigue life assessments and hindering validation of theoretical models. Most studies consider single environmental factors; however, research on combined wave–current–wind effects remain limited. These efforts will enhance the adaptability, safety, and longevity of SPAR platforms in harsh deep-water environments.

2.3. Semi-submersible platform

SEMI platforms are a type of mobile offshore facility and consist of floats, decks, and columns. Their buoyancy is controlled by adjusting the ballast water, making them suitable for operating at water depths ranging from tens to thousands of meters. As shown in Fig. 4, the development of SEMI platforms began in the 1960s, when Shell, aiming to adapt to complex marine environments, converted a fixed platform into the first SEMI platform, Blue Water I. This was followed by the construction of the world's first semi-submersible drilling platform, Ocean Driller, in 1963. Since then, SEMI platforms have undergone significant advancements. Notably, the Troll B platform represents a milestone in concrete structure production platforms, and the design has gradually evolved into the modern configuration featuring an annular pontoon and four columns (Zhao, 2022). With their stability, adaptability, and cost-effectiveness, SEMI platforms offer substantial advantages in complex marine environments, making them a key option for deep-sea oil and gas exploration. To further augment their stability, economic efficiency, and safety, researchers have conducted extensive studies on structural design, motion control, and multifunctional applications.

Research on SEMI platforms has evolved from fundamental design considerations to advanced optimization strategies, with particular focus on structural stability, hydrodynamic response, and motion control. Early studies highlighted the coupling between pendulum-transverse and longitudinal rocking (Wang et al., 2015) and explored how hull weight, platform dimensions, and droop affected dynamic behavior (Tian et al., 2021), laying the theoretical basis for design optimization. Innovative approaches such as neural network-based design methods (Qiu et al., 2019), rotary inertia dampers outperforming fixed droop plates in suppressing pendulum motions (Ma et al., 2019), and integrated dynamic positioning systems for cost reduction (Yuan et al., 2023) illustrate the progression toward intelligent and efficient platform

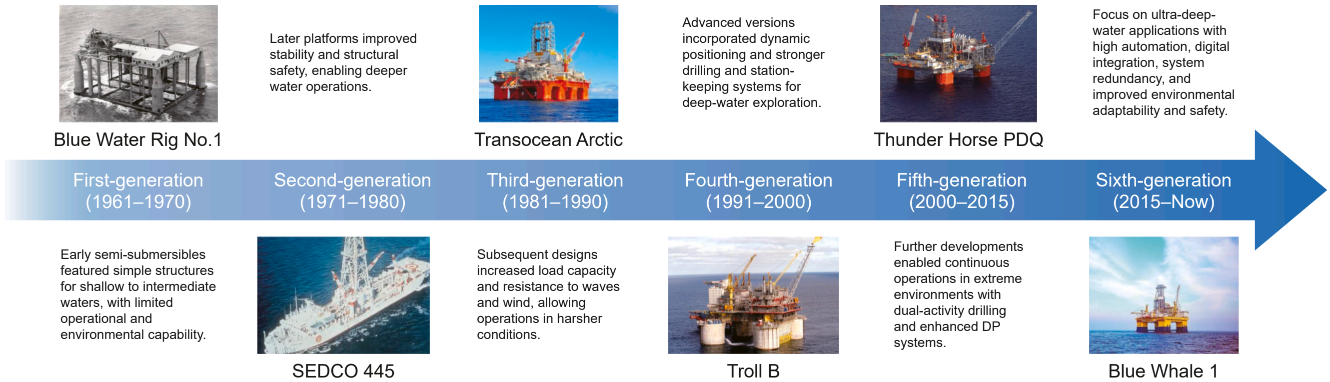


Fig. 4. Evolution of semi-submersible platforms (adopted from Amaechi et al. (2022a, 2022b); Collier and Hammett (1974); Fernandez and Pardo (2013); Dymarski and Dymarski (2016); Wu et al. (2024)).

design. In parallel, energy utilization concepts have been integrated into SEMI platforms, including point absorber arrays that enhance wave energy conversion despite increased motion (Sun et al., 2021) and tuned lifting plate systems that simultaneously suppress motion and harvest power (Liu et al., 2016c). Research has also extended to multi-module designs, with findings that connector configurations significantly influence rotational motions but not translational motions (Miao et al., 2022), as well as innovative production platforms with storage and shuttle tanker offloading capability (Jia et al., 2018), reflecting the application-driven development of SEMI platforms for deep-water gas fields.

From the perspective of hydrodynamic analysis and intelligent prediction, researchers have advanced methods to evaluate SEMI platforms under complex marine environments. Spectral analyses have shown that SEMI platforms exhibit relatively small longitudinal, transverse, and rocking oscillations, while significantly reducing heave responses, thereby improving stability (Chen et al., 2017). Further, numerical simulations revealed that wave effects dominate over wind effects in determining structural stress and deformation, especially in extreme sea states (Ma et al., 2019), offering crucial insights for structural optimization. Recently, attention has shifted toward real-time monitoring and prediction of platform motion responses. These responses are critical for ensuring stability and safety. Chen et al. (2024c) introduced a base-mixed model capable of accurately predicting platform dynamic responses in real time. As illustrated in Fig. 5, their model outperforms other mainstream approaches in prediction accuracy and robustness, demonstrating strong generalization capability. This development not only boosts the stability and operational reliability of SEMI platforms but also provides a methodological reference for other nonlinear time-series monitoring tasks in ship and ocean engineering. In addition, recent studies have introduced digital-twin frameworks for SEMI platforms, enabling real-time fatigue damage assessment (Wu et al., 2024) and long-term

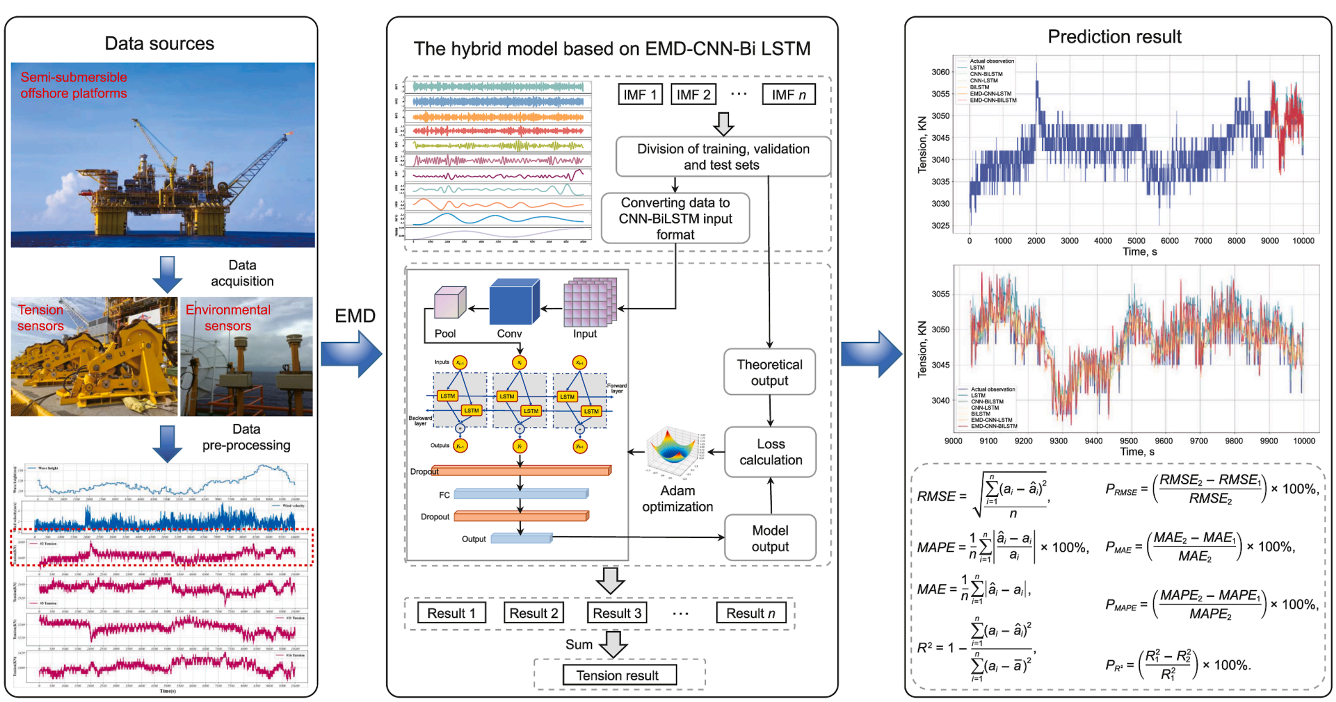


Fig. 5. The framework of the proposed method (adopted from Chen et al. (2024c)).

prediction under varying sea conditions (Ge et al., 2024). These digital twins combine physics-based modeling and data assimilation to continuously update damage estimates and improve decision-support for maintenance and safe operation.

Research on SEMI platforms has progressed from fundamental hydrodynamic analyses to advanced optimization strategies, revealing both opportunities for performance enhancement and persistent challenges in complex marine environments. The rotary inertia damper proposed by Ma et al. (2019) and the tuned lift plate energy harvesting system introduced by Liu et al. (2016c) offer innovative solutions for motion control and energy utilization by integrating conventional designs with emerging technologies. Nevertheless, key challenges remain. Long-term field data on fatigue performance are still scarce, limiting the reliability of current predictions. Most studies focus on single environmental factors, whereas research on combined effects under extreme conditions remains limited. Future work should emphasize long-term validation and multifunctional optimization of SEMI platforms. These developments will further enhance the reliability of deep-sea oil and gas operations.

2.4. Floating production storage and offloading

FPSOs play a pivotal role in global deep-sea oil and gas development due to their flexibility, cost-effectiveness, and multifunctionality. However, FPSOs operate in complex marine environments where they are exposed to various environmental loads, including wind, waves, and currents. The reliability of their structural integrity and motion response is crucial, as it directly impacts both operational efficiency and safety (Chakarapani, 2015).

Research on the structural safety and stability of FPSO platforms has evolved along several interconnected themes, primarily focusing on base structure design, environmental load effects, and motion response mechanisms. For structural design, according to Fig. 6, Kim et al. (2017) employed a Hadoop-based approach to estimate superstructure weight, improving efficiency in big data-driven engineering design. Wen et al. (2024) demonstrated that underdeck reinforcement more effectively reduces structural stresses compared with deck plate thickening, offering both safety and economic benefits. Similarly, Jensen (2019) highlighted that side compartments can increase damping coefficients by up to 400%, emphasizing the critical role of nonlinear damping effects in stability design. These studies collectively establish a foundation for understanding the structural performance of FPSOs under complex loading conditions. Environmental load analysis has also been central to FPSO research, with attention directed toward hydrodynamic, wind, and fire–explosion effects. Ibinabo and Tamunodukobipi (2019) found that transverse rocking motion, represented by the RAO response, exerts the most significant influence on overall platform stability. Complementing this, Miao et al. (2022) showed that CFD-based wind load simulations not only improve prediction accuracy but also capture shading effects, providing more reliable input for stability design. Xie et al. (2022) extended this perspective by simulating fire and explosion risks, finding that westerly winds increase topside ventilation but leave the hull region vulnerable. At the conceptual level, Zou (2020) proposed the eco-FPSO design with a specialized external wall layout, improving global stability. More recently, Zhang et al. (2025a) introduced a fluid momentum wheel system to actively mitigate rolling motions, verifying its effectiveness in improving both roll stability and operational safety. Taken together, these studies demonstrate how FPSO platform stability has gradually shifted from static structural reinforcement toward dynamic load-resilient and safety-oriented design solutions.

Beyond structural and environmental considerations, optimization of FPSO construction and operations has become a distinct research frontier. Chen et al. (2024b) reported on the South China Sea 80,000-ton cylindrical FPSO project, showing that system integration and functional optimization markedly improve

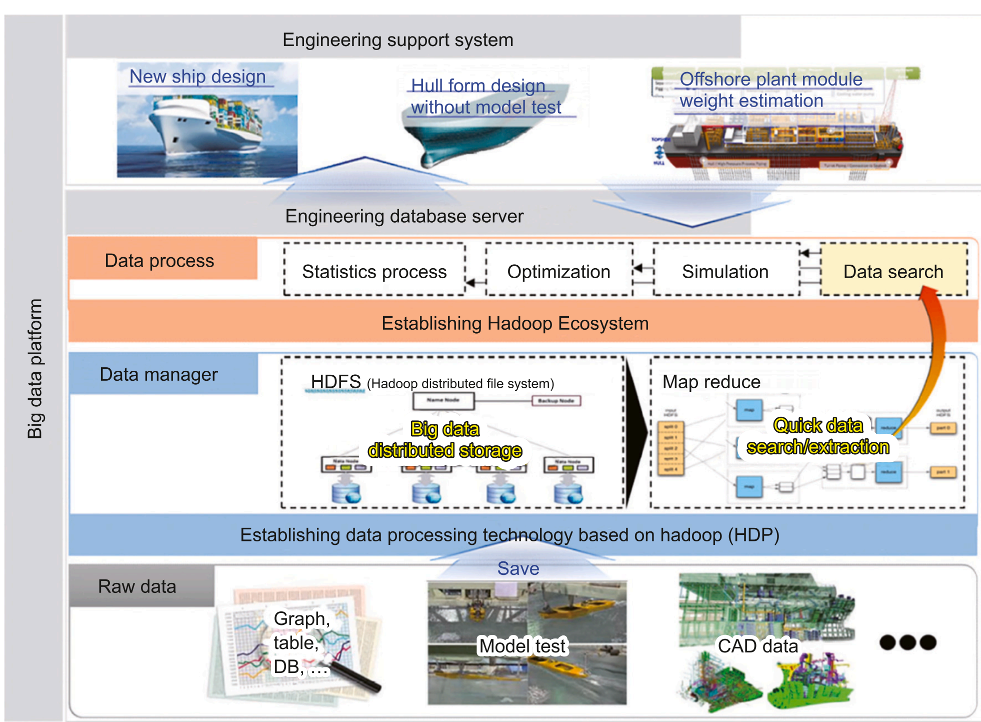


Fig. 6. Big data platform for application in the shipbuilding and offshore industry (adopted from Kim et al. (2017)).

construction efficiency. At the operational level, Affonso et al. (2024) introduced the concept of a “digital body” to support digital asset management, thereby reducing costs and enhancing design quality. In addition, Bhat et al. (2021) developed a structural digital twin of an FPSO hull and topsides based on inspection data and load measurements for monitor and predict structural health. Neves et al. (2023) proposed a digital twin framework to predict hull failure probability of an FPSO using corrosion-based models and data assimilation. Bailey et al. (2022) generated a digital twin for the Glen Lyon FPSO to integrate structural monitoring and operational response prediction. These studies demonstrate how digital twins enable continuous structural monitoring, real-time condition assessment, and improved decision support for FPSO lifecycle management. Risk management in offloading operations has also attracted sustained attention. For example, Gaidai et al. (2024) developed a bivariate statistical method to predict extreme unloading responses, while Chakarapani (2015) optimized Arctic FPSO storage capacity. Earlier, Chen and Moan (2004) quantified the collision probability between shuttle tankers and FPSOs, recommending operational strategies to extend the time window and reduce operator workload. These studies show a shift from construction-focused approaches to digitalized and risk-aware operational strategies, enhancing FPSO safety.

FPSO research now centers on structure, environment, and operation. Miao et al. (2022) and Xie et al. (2022) examined the effects of wind loads and explosion-induced fires on FPSOs, highlighting the necessity of studying superimposed effects in safety design. Ibinabo and Tamunodukobipi (2019) and Zou (2020) investigated the impacts of wave loads and external wall design on FPSO stability, respectively, while Gaidai et al. (2024) analyzed mooring cable tension during unloading operations through numerical simulations, offering multi-dimensional theoretical insights for optimizing FPSOs design under various environmental conditions. Together, these studies provide a multidimensional framework that links structural configuration, environmental interactions, and operational practices. Despite such advances, several challenges persist. Long-term fatigue data of FPSO hulls and topsides remain scarce, limiting reliability-based design over extended service lives. Digitalized operation and adaptive management remain underdeveloped, creating gaps in intelligent monitoring. Future research should focus on long-term validation and intelligent operation strategies for extreme conditions. The adoption of high-performance, low-carbon designs will further enhance economic and environmental performance.

2.5. Engineering applications of floating platform

In deep-sea oil and gas development, the selection of floating platforms varies significantly by region, influenced by sea conditions, water depth, and the distribution of oil and gas resources. Fig. 7 presents the global distribution of floating platforms and their key characteristics across different sea areas. Brazil has the highest number of floating platforms. Its offshore environments are predominantly deep water and ultra-deep water. In this region, FPSOs are widely utilized due to their versatility and flexibility, enabling efficient large-scale oil and gas production. As a result, 39 FPSOs are currently in operation (BNamericas, 2024). Additionally, SEMI platforms are extensively deployed in Brazilian waters, with 16 units in operation, owing to their stability and adaptability in deep-water environments. Similarly, West Africa, Southeast Asia, China, and Australia have also adopted FPSOs as the mainstream floating platform choice, particularly in moderate water depths and relatively mild environmental conditions, where their cost-effectiveness and operational flexibility provide significant advantages. However, in challenging sea-state regions, platform selection is more tailored to specific environmental or production requirements, ensuring optimal performance under unique conditions (Modec, 2023; Nes Fircroft, 2024; VesselFinder, 2024; Tass, 2024; Woodside Energy, 2023).

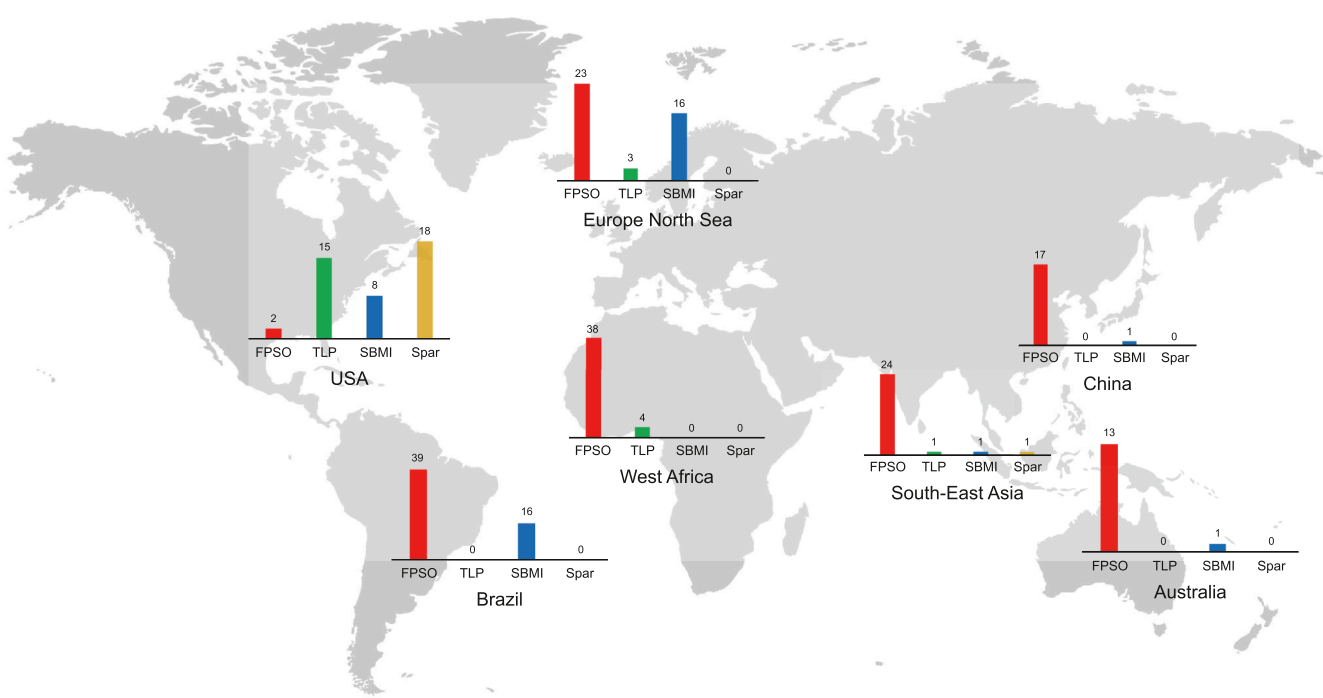


Fig. 7. Distribution of different types of floating platforms in the world (redraw from BNamericas (2024); MODEC (2023); NES Fircroft (2024); VesselFinder (2024); TASS (2024); Woodside Energy (2023); U.S. Energy Information Administration (2023); Harbour Energy (2023)).

In contrast, platform selection in the U.S. Gulf of Mexico and the European North Sea exhibits distinct characteristics. The U.S. Gulf of Mexico is predominantly deep and ultra-deep water, characterized by harsh sea conditions and occasional hurricanes. As a result, SPAR and TLP platforms are the primary choices. SPAR platforms offer high stability in deep water through their deep-draft columnar buoyant structure and bottom ballast design, making them particularly suited for the Gulf of Mexico's complex environment. On the other hand, TLPs achieve a balance between buoyancy and gravity through a pre-tensioning system, effectively mitigating the platform's oscillatory motion and making them ideal for deep water and high-precision operational requirements (U.S. Energy Information Administration, 2023). Although the water depth in the European North Sea is relatively shallow, the environment is harsh, with high winds, waves, and frequent winter storms, complicating the metocean conditions (Harbour Energy, 2023). Consequently, SEMI platforms have become a popular choice in this region. Their combined float and column design enables them to effectively withstand high wind and wave environments.

In summary, the selection of platforms for deep-water oil and gas development is strongly influenced by the environmental characteristics and water depth conditions of the specific sea area. FPSOs dominate in deep water and moderate sea conditions because of their versatility and flexibility, while SPAR, TLP, and SEMI platforms offer distinct technological advantages for complex sea conditions and deep-water areas. This region-based selection strategy shows the diversity of ocean engineering technologies. It also supports the efficient development of global deep-water oil and gas resources.

3. Classification of mooring system and research progress

The performance of floating platforms is critically governed by the configuration and efficiency of mooring systems, which must be optimized with respect to water depth, environmental conditions, and platform type. To ensure station-keeping and operational safety in deep-sea environments, various mooring technologies have been developed and refined (Rui et al., 2024a,b,c,d). The mooring system serves as a dynamic constraint between the platform and the seabed, transmitting environmental forces to the foundations and influencing both platform motion and anchor bearing behavior through its configuration and stiffness. Although risers are not structural components of the mooring system, they function as essential connecting equipment between the floating platform and subsea production facilities. From a mechanical perspective, risers and mooring lines exhibit notable similarities: both act as tension-bearing, flexible members subjected to hydrodynamic and structural coupling effects, jointly influencing platform motions and system fatigue performance.

Accordingly, this section reviews the classification of mooring systems, mechanical behavior of mooring chains, chain–soil interaction, and advances in the mechanics of polyester mooring cables. The classification and mechanical characteristics of risers are also included to provide an integrated understanding of line-based dynamic systems that collectively govern the stability and reliability of deep-water offshore platforms.

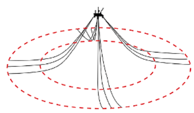
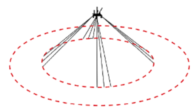
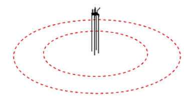
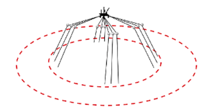
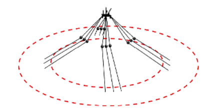
3.1. Classification of mooring type and research progress

To accommodate varying water depths, sea conditions, and platform types, a diverse range of mooring technologies has been developed in ocean engineering. Based on their structure and working principles, mooring systems are divided into two main types: catenary mooring and taut mooring. The latter is further classified into taut mooring, TLP mooring, taut-line with buoys, and taut-line with clump weight. This paper summarizes the characteristics, advantages, and disadvantages of these 5 mooring types, as presented in Table 1 (Xu et al., 2024b; Kang et al., 2019; Neisi et al., 2023; Yuan et al., 2014). Among them, catenary, taut, and TLP mooring systems have been widely implemented in engineering practice, while taut-line configurations with buoys or clump weights are mainly at the conceptual or research stage, showing great potential for future deep-water applications. Therefore, Table 1 also includes representative engineering examples to highlight the distinction between established and emerging mooring technologies, providing a clearer understanding of their applicability and development trends. It also reviews research on suspension chain mooring and tension mooring, each type has distinct features. Finally, through a discussion of future research directions for floating platform mooring, this study aims to support the safe operation of floating platforms and promote the efficient development of deep-sea resources.

Designers and researchers have progressively refined the theoretical framework of suspended chain mooring systems through parametric studies, optimization algorithms, and advanced computational methods. Figueiredo and Brójo (2017) used the Glen Lyon FPSO in the Schiehallion field as a case study, demonstrated that optimizing the mooring system reduced costs and mitigated deflections. By modeling a multi-segmented mooring line and conducting quasi-static and dynamic analyses with ORCAFLEX software, they found that structural optimization of mooring lines can effectively lower costs and minimize platform offset while ensuring operational safety. Molins et al. (2015) developed an optimization algorithm to match the horizontal restoring force, vertical restoring force, and tension of a truncated system to those of a prototype system within the expected displacement range, it provided a valuable tool for laboratory simulations and prototyping. Xu et al. (2024b) proposed a non-Lagrangian exact solution for elastic suspension lines and solved the transcendental equations associated with suspension line moorings. Their case study verified the feasibility of this approach and offered strong support for conceptual design and front-end engineering applications. Research on catenary mooring dynamics in harsh seas have also progressed. Zhang et al. (2025b) conducted large-scale wave basin experiments to investigate the spatio-temporal distribution of wave impact loads on semi-submersibles. Their work provided insights into load transmission mechanisms and their influence on mooring line response. Dyson et al. (2025) introduced a novel Coupled Eulerian-Lagrangian framework. It simulated the hydro-geomechanical interactions within moored systems and enabled high-fidelity prediction of seabed-moored line behavior under combined environmental and geotechnical conditions. He et al. (2025) advanced this field by developing an extreme value prediction method. This method incorporated potential mooring line failures and offered a robust tool to evaluate platform response reliability under extreme sea states. These studies have jointly refined the accuracy of mooring tension prediction and failure risk assessment for catenary systems. They support the development of more resilient and efficient offshore structures.

In the design and optimization of tensioned moorings, researchers have significantly improved system performance and reduced costs through optimization algorithms, parameter sensitivity analyses, and innovative design concepts. West et al. (2021) developed an optimization tool based on multi-objective genetic algorithms. This tool minimized both mooring component costs and spatial occupation, it balanced these factors and introduced a novel approach to mooring system design. Kang et al. (2019) identified the mooring line's top angle as the most influential

Table 1
Classification and characteristics of mooring type.

	Catenary mooring	Taut mooring	TLP mooring	Taut-line with buoys	Taut-line with clump weight
Diagram					
Type of mooring cable	Anchor chain	Anchor chain + Polyester line	Special steel pipe/Steel cable	Anchor chain + Polyester line + Buoys	Anchor chain + Polyester line + Clump weight
Sources of restoring force	Changes in the overhanging section of the anchor chain	Tensile deformation of polyester line	Steel tension	The buoyancy of buoys	The gravity of clump weight
Anchor loadable capacity	Horizontal tension	Horizontal tension + Vertical tension	Vertical tension	Horizontal tension + Vertical tension + Buoyancy of buoys	Horizontal tension + Vertical tension + Gravity of clump weight
Advantage	• Simple structure, low cost, easy to install and maintain. • The restoring force is provided by a naturally overhanging anchor chain. It cushions the movement of the platform.	• The system achieves high positioning accuracy through pre-tensioning. It is suitable for deep-water projects in water depths greater than 1000 m. • The system has a lighter weight. This feature allows greater control and stability of the platform.	• It effectively suppresses the vertical movement of the platform. This provides very high stability and makes it suitable for TLP platforms.	• The buoys provide additional buoyancy. They optimize the force distribution along the mooring line and reduce mooring tension. • It has good motion control of the platform and is suitable for complex sea conditions.	• The clump weight increase the stability of the mooring system. • It is suitable for deep water and ultra-deep water projects and effectively reduces the movement of the platform.
Disadvantage	• Suitable for medium water depths of less than 1000 m. Deeper water depths will increase the weight of the anchor chain and reduce the efficiency of the system. • Limited ability to control the horizontal movement of the platform. In extreme sea states, the anchor chain may generate large dynamic loads.	• Higher installation and maintenance costs. And mooring materials need to be durable. • There is a risk of mooring cable breakage in extreme sea states.	• It requires high subsea geological conditions and is difficult to install. • In extreme sea states, steel cables can be subjected to significant dynamic loads and risk of failure.	• The addition of buoys increases system complexity and cost and makes maintenance difficult. • In extreme sea states, the buoys may generate additional dynamic loads. These loads can affect the stability of the system.	• The increase in heaviness leads to higher weight and cost of the mooring system. • Installation and maintenance are difficult, and in extreme sea states, clump weight may generate large inertial loads, increasing system risk.

factor affecting mooring line tension and platform motion. They modified design parameters such as the mooring line's top angle, mooring hole positions, and mooring arrangement methods, they demonstrated that segment length also had a measurable impact on tension. Neisi et al. (2023) introduced a new mooring concept that used both buoys and clump weights. This system showed better performance in both intact and failure modes. It significantly reduced platform deflection compared with conventional systems. Yuan et al. (2014) proposed a hybrid mooring system. They attached a heavy block to the lower end and a float to the upper end of the mooring line. This configuration reduced mooring line tension and platform displacement, lowered the anchor's pull-out force, and enabled analysis of the float's volume and position effects on mooring line tension. This design expanded the system's applicability to various water depths. In the modeling and prediction of mooring line behavior, Kwon et al. (2025) developed an optimized artificial neural network model. This model estimated directional wave spectra from FPSO motion data. It offered an effective method to infer environmental conditions and assess mooring line loads under operational scenarios. Jebari et al. (2025) proposed a two-step ANN-based method for mooring failure detection. This method improved real-time reliability assessment of tensioned mooring systems. Zhang et al. (2025c) examined mooring performance under iceberg collisions. They highlighted the structural vulnerability and dynamic load features of tension-leg platforms in ice-prone regions. Chen et al. (2025) introduced a deep learning model that combined CEEMDAN and neural networks to forecast mooring line tension. This model showed better accuracy in capturing nonlinear and non-stationary load variations. From Fig. 8, Dermatis et al. (2025) developed a prediction method based on design waves. This method addresses slow-drift responses caused by wave excitation and improves long-term fatigue assessments under extreme sea states. Yin et al. (2025) proposed a deep learning-based optimization strategy for semi-submersible platform mooring. Their strategy improved load distribution and dynamic response control. Overall, these studies have advanced intelligent modeling and robust prediction for tensioned mooring systems, supporting safer and more resilient offshore operations.

Recent studies have increasingly incorporated artificial intelligence and data-driven methods into the fatigue assessment and integrity management of mooring systems. In the area of fatigue life prediction, traditional numerical and probabilistic approaches (Xue et al., 2018; He et al., 2022; Aursand et al., 2023) are now being complemented by machine-learning-assisted frameworks that improve the accuracy and efficiency of life-time estimation under complex dynamic loading conditions. Regarding real-time monitoring, researchers have developed advanced sensing and

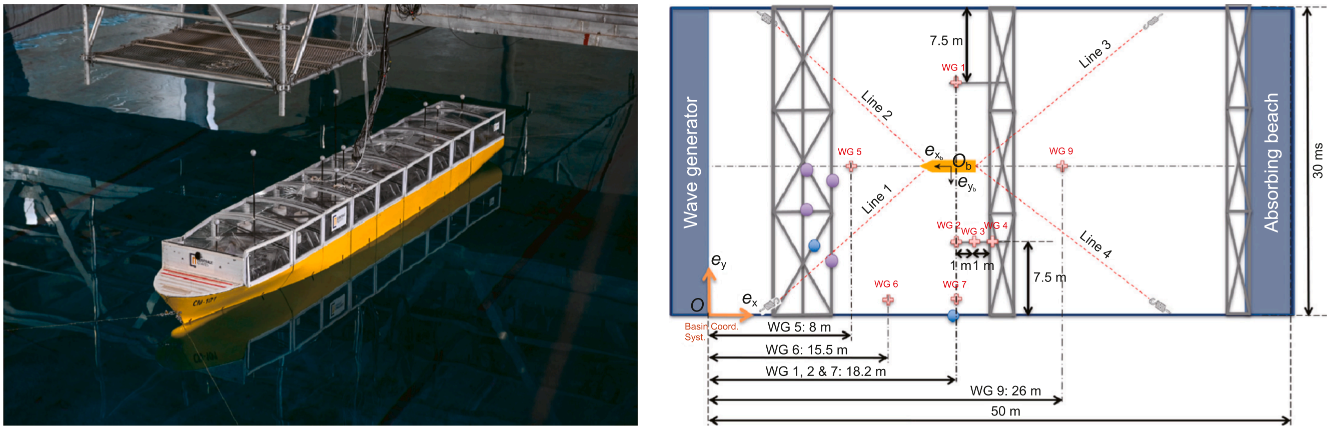


Fig. 8. Ship model and experimental setup (adopted from Dermatis et al. (2025)).

simulation techniques capable of continuously tracking mooring-line responses (Qiao et al., 2021; Chen et al., 2023). These systems enable rapid detection of abnormal tension variations and enhance situational awareness during offshore operations. For fault detection, AI-based diagnostic models and hypothesis testing methods have demonstrated strong potential in identifying mooring line failures and anomalies from motion or vibration-data (Fang et al., 2015; Hassani et al., 2018; Park et al., 2025). Collectively, these developments highlight AI's growing role in enabling predictive maintenance, real-time integrity monitoring, and autonomous fault diagnosis, thereby improving the safety and resilience of deep-water mooring systems.

Scholars have progressively refined the design theory of mooring systems through parametric studies, optimization algorithms, and advanced computational methods, facilitating their wider application in deep-sea environments. As marine resource development extends into deeper and more complex waters, mooring systems must satisfy increasingly stringent technical requirements and address more complex challenges. Consequently, existing mooring designs and parameters will continue to be optimized, and more robust mooring solutions may be developed to further enhance system reliability and adaptability.

3.2. Mooring chain mechanics and chain-soil interaction

The interaction mechanism between the anchor chain and seabed soil is a critical factor that influences the safety and stability of floating platform mooring systems. As marine resource exploitation has progressed into deeper and more complex waters, understanding the motion behavior of anchor chains within seafloor environments and their effects on mooring system performance has become increasingly important.

Regarding the interaction mechanism between mooring chains and submarine soil, recent studies have progressively clarified the physical processes governing seabed groove development and their implications for mooring stability. Gao et al. (2022) demonstrated that current velocity and motion period significantly influence trench evolution in sandy seabed environments. They further proposed empirical relationships for the nondimensional trench length, width and depth under sway and heave motions Eqs. (1)–(4), where the fitted parameters a_1–a_8 and exponents b, c describe the power-law dependence of maximum trench depth and displacement amplitude. Rui et al. (2024a) further highlighted that groove formation is closely related to soil engineering properties, and as illustrated in Fig. 9, they identified soil erosion caused by chain movement as the dominant mechanism. In addition, Xiong et al. (2016) analyzed variations in mooring line tension considering soil resistance and chain elongation, proposing a dynamic analysis method based on a concentrated mass model. Somoano et al. (2024) observed that larger seabed slopes significantly reduce peak mooring line tension, while Low et al. (2018) proposed strategies to mitigate tension fluctuations caused by node grounding. Moreover, Lu et al. (2022b) identified a ratcheting effect in the mooring line induced by chain—soil interaction, where cyclic excitation led to irreversible movement and a gradual reduction in mooring tension. When considered together, these studies not only elucidate the fundamental mechanisms of chain—soil interaction but also provide essential insights into mooring system performance under complex seabed conditions.

$$\alpha = a_1 \ln^2 N + a_2 \ln N + a_3 \tag{1}$$

$$\beta = a_4 \ln N + a_5 \tag{2}$$

$$S_{max} \big/ D = a_6 N^b \tag{3}$$

$$\gamma = a_7 N^c + a_8 \tag{4}$$

where, α is dimensionless length of the trench, β is dimensionless width expansion of the trench, N is porosity, S_{max}/D is dimensionless maximum trench depth, γ is distance between the front end of the trench and anchor point, the parameters a_1–a_7 represent the fitted parameters calculated from the experimental data, the parameters b and c represent the power exponents for the maximum trench depth and γ.

$$r_0(T, C_i, V) = 0.056 \exp(0.065T) \frac{C_i}{C_B} (1 + 4.6V) \tag{5}$$

where, r_0 is the expression for corrosion rate, T is temperature, C_i is dissolved oxygen concentration, V is average water velocity, C_B is the dissolved oxygen concentration.

Beyond the interaction mechanism, corrosion and wear have been widely recognized as persistent challenges affecting mooring chain integrity. Molnár et al. (2017) experimentally revealed that the fracture, flexural, and torsional strengths of steel ropes decrease exponentially with increasing corrosion. Fontaine et al. (2012) identified microbial-influenced corrosion as a major factor in the degradation of FSO mooring chains in West Africa.

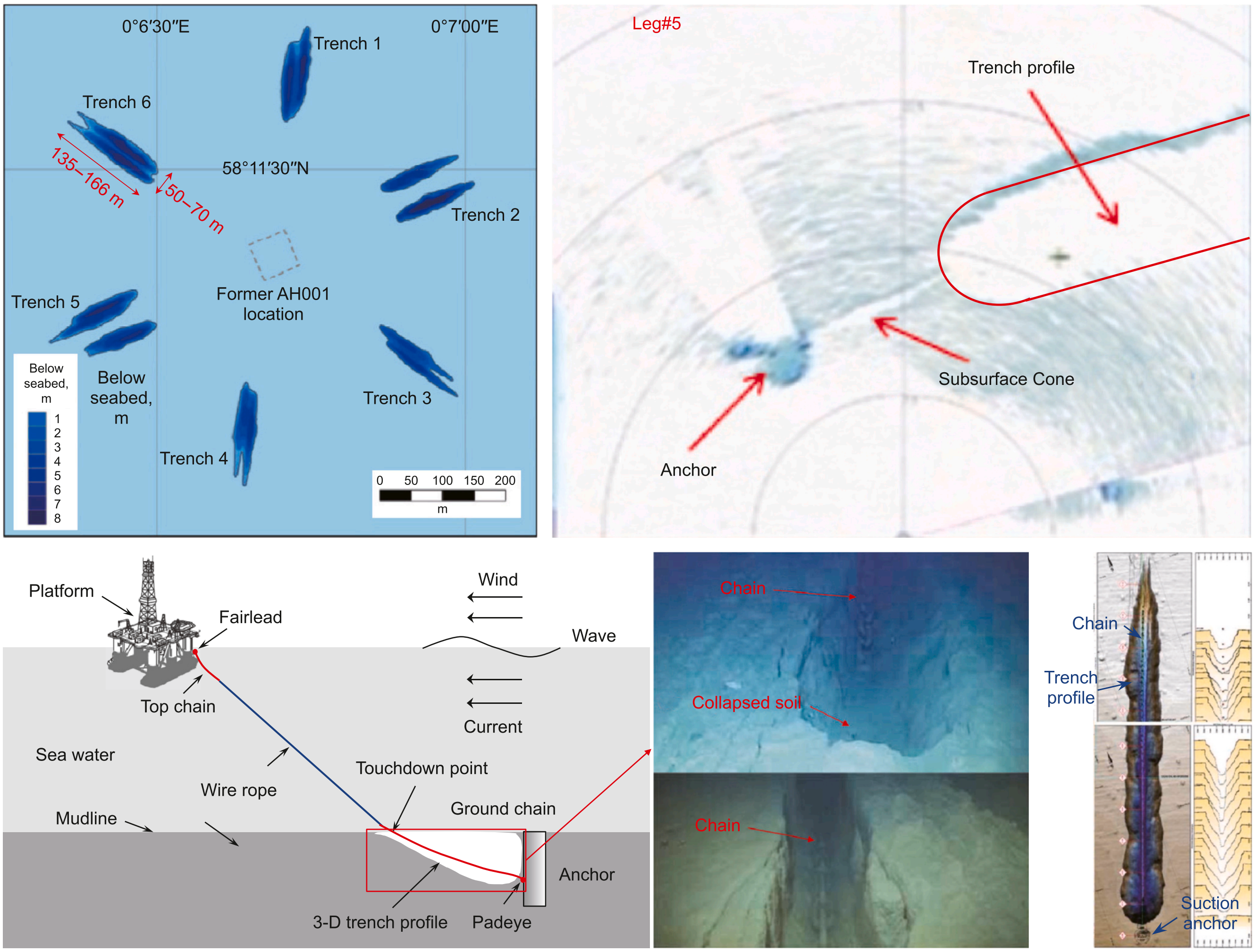


Fig. 9. Seabed trenches during chain-soil interaction (adopted from Rui et al. (2024a)).

Building on this, Melchers et al. (2007) developed a corrosion loss estimation model based on seawater environmental parameters, as expressed in Eq. (5), while Wang et al. (2024) emphasized the importance of reducing surface roughness to enhance resistance. Protective measures have also been proposed: Divi and Janoff (2020) verified the effectiveness of barrier agents at low temperatures, Shahzad et al. (2022) suggested clamped anodes for cathodic protection, and Angulo et al. (2017) introduced ultrasonic guided waves and acoustic emission for defect detection and crack monitoring. Together, these studies not only elucidate corrosion mechanisms but also advance monitoring and protection strategies for long-term service safety.

In terms of operational safety design, the focus has shifted toward capturing the cyclic and dynamic behavior of mooring systems under realistic seabed conditions. Sun et al. (2020a) simulated cyclic loading on anchor chains using a coupled Euler–Lagrange finite element approach, demonstrating the complex soil–chain interactions under repeated excitation. Rui et al. (2020, 2024b, 2024d) extended this work by developing a design framework that integrates floating-body hydrodynamics with sandy soil response, allowing prediction of groove evolution and enabling optimization strategies, such as extending mooring line length or redistributing components, to mitigate seabed degradation. These advances provide both theoretical support and practical pathways for improving design methodologies and enhancing the reliability of mooring systems in ocean engineering.

Research on anchor chain–seabed soil interactions has primarily focused on trench formation mechanisms, soil resistance effects, and design optimization strategies. Xiong et al. (2016) and Low et al. (2018) examined the influence of soil resistance and nodal grounding on mooring line tension. Somoano et al. (2024) further examined how seabed topography affects mooring lines. Their findings provided multidimensional theoretical support for optimizing mooring system design in complex environments. Lu et al. (2022b) identified the ratchet effect caused by anchor chain–soil interaction. Rui et al. (2020, 2024b, 2024d) created a numerical method to predict scour groove evolution. Taken together, these studies established a solid foundation for analyzing anchor chain behavior under various seabed conditions. Looking ahead, long-term research should focus on enhancing the durability and resilience of mooring systems through integrated design strategies, where corrosion protection, fatigue resistance, and seabed–chain interaction are jointly considered. Meanwhile, future research should move toward broader environmental and geological scenarios, especially non-homogeneous seabeds such as sand–clay mixtures and rock–soil interfaces, where localized stress concentration and irregular chain motion may occur. Real-time monitoring combined with advanced numerical modeling could also be employed to investigate coupled effects of extreme environmental loads (e.g., typhoons, internal waves) and seabed dynamics. Such efforts will provide a comprehensive understanding of chain–soil interactions and guide more reliable mooring system design.

3.3. Progress in mechanics and materials of mooring polyester cable

In deep-sea oil and gas development, the mooring system is a critical component of floating platforms. Polyester cable is an important synthetic material that has recently received increased attention due to its unique mechanical and material properties. It is flexible, lightweight, and strong. These features can improve platform motion and mooring performance.

In the study of mooring cable mechanics, researchers have emphasized that mooring configuration, preload, water depth, and chain length are key factors determining fatigue life and critical damage locations (Wu et al., 2015; Du et al., 2019; Barros et al., 2023). A common conclusion is that inaccuracies in line properties, such as reference length, and additional dynamic effects like out-of-plane bending, can sharply increase mooring tension and accelerate fatigue damage, highlighting the risk of cascading failure when one line breaks (Barrera et al., 2019, 2020; Xu et al., 2023).

Another major research focus is the selection and optimization of mooring materials as material stiffness directly controls platform motion, restoring force, and long-term fatigue performance. Studies show that nylon ropes, while highly flexible and capable of dissipating energy, are more prone to fatigue damage, whereas polyester multi-stranded fibers reduce the mean and amplitude of mooring forces (Xu et al., 2021; Liu and Soares, 2024). Chains and wire ropes with higher stiffness increase mooring tension, but also boost stability, while low-stiffness fibers reduce tension at the expense of greater motion responses (Saparuddin and Assidiq, 2024; Ja'e et al., 2022). These results consistently demonstrate that balancing stiffness and flexibility is essential for safe and reliable operations (Li et al., 2024).

Recently, high-modulus polyethylene (abbreviated as HMPE) fiber ropes have gained increasing attention as next-generation alternatives to conventional polyester mooring lines, owing to their high strength-to-weight ratio, low elongation, and superior fatigue and creep resistance. Early experimental work (Lian et al., 2017; Humeau et al., 2018) established baseline mechanical and fatigue characteristics of HMPE ropes, clarifying the relationships between cyclic load amplitude, stiffness evolution, and operation life. Subsequent full-scale investigations (Bain et al., 2020; Li et al., 2021) confirmed that dynamic stiffness tends to increase gradually with cyclic loading, while bedding-in behavior strongly affects initial performance. To capture long-term behavior, Da Cruz et al. (2023) and Hai et al. (2024) explored creep mechanisms in low-creep HMPE fibers using high-temperature testing and viscoelastic damage modeling, revealing nonlinear time-dependent deformation characteristics. Furthermore, Lin et al. (2022) and Xie et al. (2025) quantified quasi-static and dynamic stiffness variations under multi-level tension cycles, providing essential input for fatigue simulation and mooring system optimization. When considered together, these studies establish HMPE as a promising mooring material for deep-water applications, combining high performance with improved durability and reduced maintenance requirements.

In terms of novel mooring materials and monitoring strategies, synthetic fiber designs have shown superior fatigue resistance compared with conventional alloys (Miller and Albertani, 2015), and innovative hybrid ropes that combine the strength of steel with the lightweight characteristics of polyester have been proposed for deep-water and harsh environments (Mohanraj et al., 2011; Fletcher et al., 2010). To further foster resilience, elastic materials have been introduced to reduce transient tension peaks, particularly in chain-nylon hybrid systems (Somoano et al., 2022). In addition, advanced monitoring techniques have been developed. One example is the acoustic emission method. It identifies high-amplitude signals as precursors of rope failure. Another example is the sensor—fusion approach. It estimates mooring tension from displacement and dynamic data (Bashir et al., 2017; Sauder et al., 2022). Fig. 10 illustrates the acoustic emission characteristics of synthetic mooring ropes under tensile loading, demonstrating the potential of such methods for early warning of damage.

Research on mooring cables primarily focuses on fatigue damage, mechanical properties, and material optimization. Wu et al. (2015) and Xu et al. (2021) examined the fatigue damage and dynamic response of mooring cables using numerical simulations and model tests, respectively. They established validation from theoretical analysis to experimental results. Miller and Albertani (2015) and Fletcher et al. (2010) explored performance optimization from the perspectives of both traditional and novel materials. They demonstrated that synthetic fibers and high-strength steel ropes exhibit superior mechanical and fatigue properties compared to conventional materials. Bashir et al. (2017) and Sauder et al. (2022) further investigated performance optimization using acoustic emission characterization and sensor fusion techniques, respectively. Their findings highlight that multi-source fusion approaches enhance the operational safety of mooring cables. Most existing studies examine the effects of individual physical fields on cable performance. However, limited research addresses the influence of multi-physical field coupling

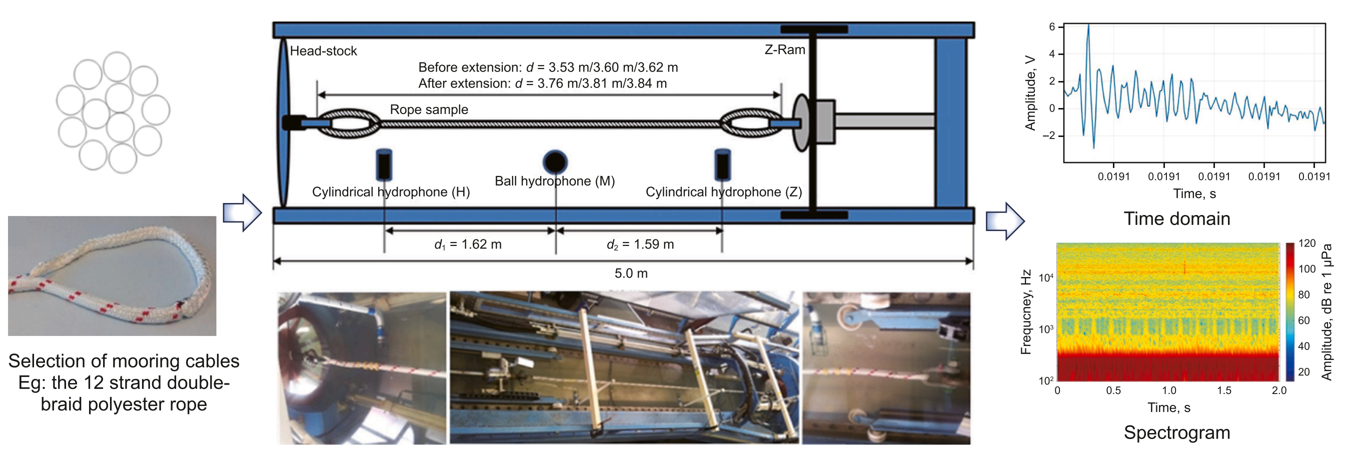


Fig. 10. Underwater acoustic rope testing inside the DMaC test rig and measurement process (adopted from Bashir et al. (2017)).

(e.g., mechanics–corrosion–biofouling). This gap is particularly critical under long-term service conditions, as coupled degradation mechanisms may significantly accelerate cable deterioration. Future efforts should therefore prioritize experimental and numerical studies on multi-field coupling effects, complemented by long-term monitoring strategies, to ensure reliable mooring system performance in deep-sea environments.

3.4. Classification and mechanical properties of riser

The floating platform, mooring system, and pile foundation must jointly maintain structural integrity to ensure safe and efficient deep-water production. Among them, the production riser plays a unique and indispensable role as the conduit for hydrocarbon transport between subsea wells and surface facilities. Unlike mooring lines that primarily provide horizontal station-keeping, risers act as vertical constraints that transfer dynamic loads and accommodate platform motion while maintaining continuous fluid transport. The mechanical behavior of risers is strongly coupled with the global motions of the platform-mooring-foundation system. Variations in mooring stiffness, platform motion characteristics, and seabed boundary conditions influence riser configuration, tension distribution, and fatigue response. The risers bridge global hydrodynamic loads and localized structural stresses, making their design central to the reliability and longevity of deep-water production systems. This section reviews the classification and mechanical properties of different riser types. In addition, recent advances in riser mechanics—covering bending stiffness modeling, clump weight optimization, vortex-induced vibration suppression, and artificial intelligence—based fatigue prediction—are summarized to highlight emerging trends and challenges in achieving resilient and intelligent riser systems for deep water and ultra-deep water environments.

From Table 2, the six major riser types—SCR, TTR, DR, UFR, BFR, and FSHR—represent distinct technical solutions for offshore oil and gas field development, each with specific structural features and functional advantages. SCR has a simple suspended catenary configuration and offers cost-effective deployment, though its fatigue resistance is limited under significant dynamic platform motion (Yu et al., 2023). In contrast, TTR remains vertically aligned through active top-tensioning systems. This allows precise production and intervention operations but requires greater platform stability and tensioning infrastructure (Sivaprasad et al., 2023). DR is used for temporary drilling and prioritizes strength and buoyancy over fatigue performance (Abimbola et al., 2021). UFR features a multilayer composite structure and is widely used in dynamic floating production systems due to its flexibility and ability to handle motion-induced stress (Dai et al., 2024). BFR is stiffer than UFR and provides enhanced pressure integrity and structural bonding, making it suitable for moderate-depth or high-pressure environments (Ragheb and Sobey, 2021). Lastly, FSHR combines vertical steel risers with buoyancy cans and flexible jumpers, effectively isolating platform motion and offer high fatigue resistance and design flexibility in deep water and ultra-deep water fields (Bomfimsilva and Netto, 2024).

Bending stiffness plays a key role in maintaining the structural integrity and fatigue life of flexible production risers, especially under complex dynamic loads in deep-water environments. Instead of addressing individual studies separately, recent research can be broadly grouped into two themes: advanced stiffness modeling and local stress analysis at critical interfaces. Ragheb and Sobey (2021) investigate the effects of axial extensibility and composite lay-up and reveal that ignoring these features leads to large errors in deformation and stress predictions. As depicted in Fig. 11, Du Kim et al. (2020) propose a hysteretic bending stiffness model as described in Eqs. (6) and (7), which captures the nonlinear moment–curvature behavior and energy loss during cyclic loading, thereby improving global dynamic analysis accuracy. Lu et al. (2022a) use finite element analysis on the tensile armour layer near bend stiffeners and identify stress concentrations that reduce fatigue life. He et al. (2020) build an analytical model for the riser–bend stiffener–I-tube interface which includes geometric nonlinearity and boundary conditions to explain load transfer. Tang et al. (2015) apply nonlinear modeling and multi-objective optimization to improve bend stiffener design. Their goal is to balance flexibility, fatigue resistance, and material use. These studies show that nonlinear mechanics and interface modeling are essential for improving riser durability and performance.

$$\sigma_{\mathrm{lb2}} = EH_3\left(1+\sin^2\alpha\right)\cos\alpha\,\sin\theta\psi \tag{6}$$

$$\sigma_{\mathrm{lb3}} = EH_2\cos^4\alpha\,\cos\alpha\,\cos\theta\psi \tag{7}$$

where, σ_{lb2} and σ_{lb3} are the local bending stress terms, H_2 is horizontal distance from cross-section center of wire, H_3 is vertical

Table 2
Classification of risers.

Category	Riser type	Structural features	Applicable platforms	Advantages	Disadvantages
Rigid riser	Steel catenary riser (abbreviated as SCR) (Yu et al., 2023)	Steel structure, self-weight forms a catenary shape suspended in water	SEMI, SPAR	Simple structure, relatively low installation cost, suitable for deep water	Sensitive to platform motion, fatigue-prone
	Top tensioned riser (abbreviated as TTR) (Sivaprasad et al., 2023)	Vertically aligned with tension applied at the top via tensioning system	TLP	Excellent verticality, suitable for well control and intervention	Complex tensioning system required, high platform stability needed
	Drilling riser (abbreviated as DR) (Abimbola et al., 2021)	Used in drilling, connects platform and wellhead	Drilling platform	Supports well control equipment and drilling tools, high strength	Not suitable for long-term production, poor fatigue resistance
Flexible Riser	Unbonded flexible riser (abbreviated as UFR) (Dai et al., 2024)	Multi-layer structure (steel + composite), layers can slide relative to each other	FPSO, barge-type floating unit	Highly flexible, adapts well to platform motions	Expensive, frequent maintenance, limited lifespan
	Bonded flexible riser (abbreviated as BFR) (Ragheb and Sobey, 2021)	Multi-layer bonded structure, relatively higher stiffness	Dynamic platform	Good structural integrity, high internal pressure resistance	Lower fatigue resistance, less flexible than unbonded types
Hybrid riser	Free standing hybrid riser (abbreviated as FSHR) (Bomfimsilva and Netto, 2024)	Vertical rigid riser supported by buoyancy can, connected to host via flexible jumper	FPSO, SEMI	Decouples platform motion, excellent fatigue resistance, good for ultra-deep water	Complex installation, buoyancy system required

distance from cross-section center of wire, E is modulus of elasticity, α is laying angle θ is angular coordinate of tensile wire.

Clump weights are another essential design measure for managing axial tension and improving the dynamic stability of production risers, particularly in ultra-deep water environments. The research emphasis here lies in both strategic deployment and functional performance. Carpenter (2020a) highlighted their role in hybrid riser systems as a cost-effective means to enhance operability under harsh conditions, while Saglar et al. (2015) stressed the need for accurate placement beyond 3000 m water depth to maintain tension control. Ruan et al. (2018) further demonstrated that clump weights contribute to riser stability during pipelaying operations. Synthesizing these results, the findings confirm that optimal clump weight configuration enhances riser design robustness and reduces operational risk.

Vortex-induced vibration (abbreviated as VIV) remains one of the most significant fatigue challenges for production risers in offshore environments. To mitigate its effects, researchers develop a wide range of passive and active suppression technologies. Liu et al. (2019) propose an optimization method for suppression device layout to improve vibration control while maintaining hydrodynamic performance. Passive methods, especially helical strakes, are still widely used. Jiang et al. (2021) and Barroso et al. (2024) evaluate their effectiveness on multi-riser and rigid-riser systems, respectively, and demonstrates that optimized strake configurations reduce coupled interference and vibration amplitudes. Li et al. (2025) and Zou et al. (2024) conduct experimental and numerical studies to explore suppression mechanisms, and emphasize that wake stabilization and energy dissipation are key factors. Han et al. (2020) use a bidirectional fluid–structure interaction model to simulate VIV in long flexible risers, and capture nonlinear behaviors often missed by simplified models. Beyond passive methods, active control strategies are also gaining attention. For example, Liu et al. (2020) develop a water jetting system for real-time suppression that adapts to changing flow conditions. These findings show that combining structural and flow-control methods is essential for improving riser reliability and extending operation life in harsh marine environments.

Artificial intelligence is increasingly applied to refine fatigue assessment and life prediction of risers, offering data-driven solutions that complement traditional analytical and numerical methods. Hejazi et al. (2021) develop a Bayesian machine learning framework to rapidly quantify the fatigue probability of failure for steel catenary risers, significantly reducing computational demand while improving reliability in probabilistic design. Bhowmik (2020) employs a hybrid machine learning model to analyze fatigue in flexible risers, demonstrating improved accuracy compared with conventional approaches. Viana et al. (2020) further combine machine learning with innovative monitoring techniques to extend the operational life of flexible risers,

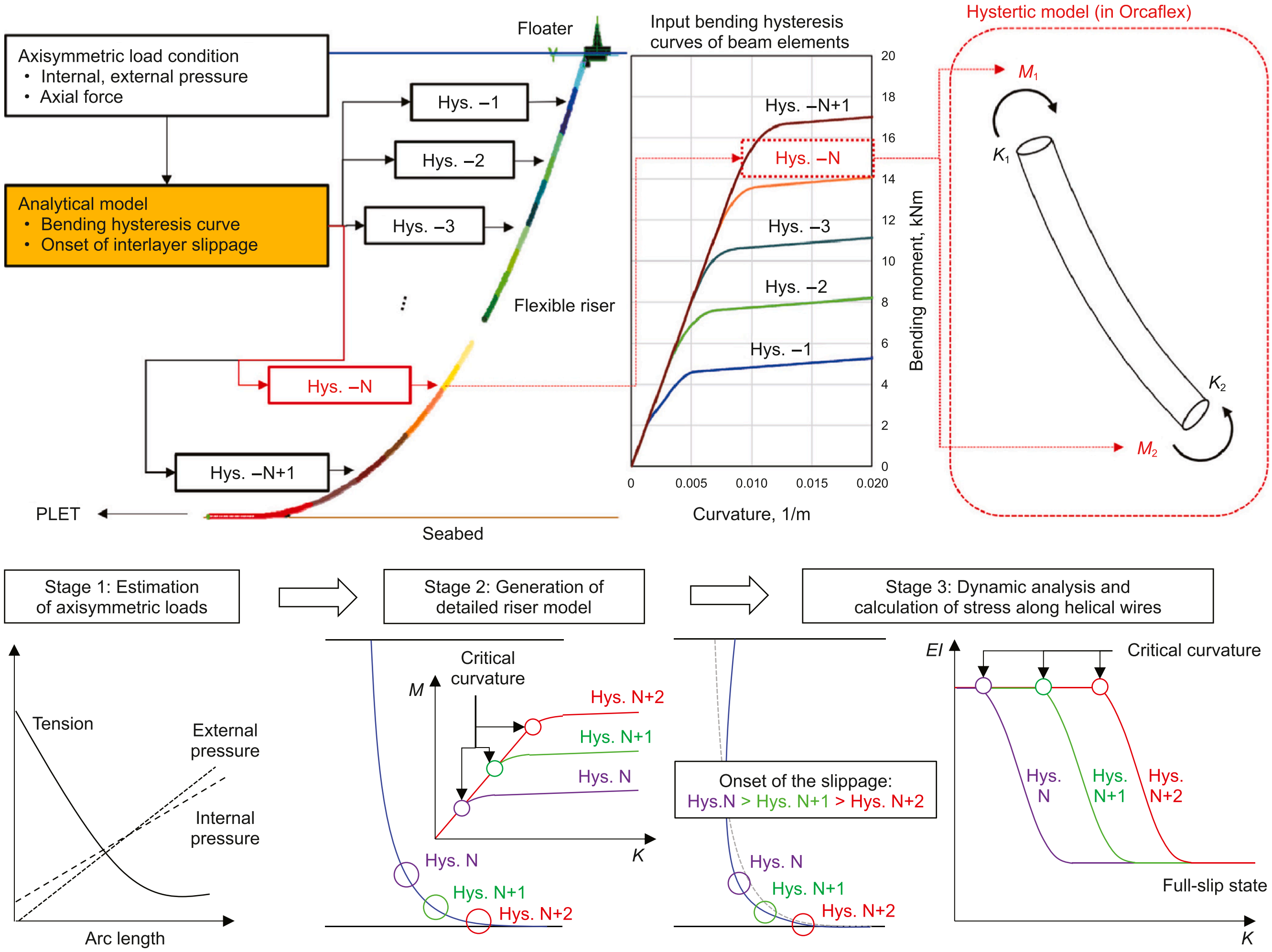


Fig. 11. Concept of multi-hysteresis modeling and bending stiffness of detailed riser model generated by MHM method (adopted from Du Kim et al. (2020)).

highlighting its potential for real-time applications. More recently, Dai et al. (2024) apply a data-driven approach to predict maximum fatigue damage in unbonded flexible risers, confirming the capability of AI to capture complex nonlinear behaviors. Together, these studies demonstrate that AI provides powerful tools for fatigue prediction, life extension, and risk management of risers under diverse operating conditions.

Current studies on production risers highlight a shared focus on fatigue resistance and dynamic stability, but they differ in research emphasis and technical approach. Some studies focus on global configurations such as SCR, TTR, and FSHR. Others examine local mechanical behavior, such as bending stiffness (Du Kim et al., 2020) and clump weights (Carpenter, 2020a). However, few studies link global and local scales. This reveals a gap between system-level design and localized stress control. VIV suppression research is well developed for passive methods, such as strakes (Jiang et al., 2021). In contrast, active suppression techniques (Liu et al., 2020) are still under developing. The absence of hybrid strategies and limited real-time adaptability suggest future research opportunities. Many existing models simplify riser–platform–seabed interactions. Only a few studies (Han et al., 2020) consider full fluid–structure coupling. This limitation reduces the simulation accuracy under real offshore conditions. Looking forward, future research should aim to bridge the gap between global and local analyses. Risers should be treated as a coupled mechanical system. In these systems, configuration, clump weight distribution, and bending stiffness interact dynamically. Developing adaptive hybrid suppression strategies that integrate passive devices with active control is another promising direction for addressing VIV under variable conditions. High-fidelity, fully coupled simulations that account for riser–platform–seabed interactions, supported by long-term monitoring data, are essential to refine prediction accuracy. Finally, artificial intelligence and digital twin frameworks (Hejazi et al., 2021; Dai et al., 2024) can be leveraged not only for fatigue life prediction but also for real-time decision support, paving the way for resilient and intelligent riser systems in deep water operations.

4. Installation and stability of mooring pile foundation

The stability and safety of deep-sea oil and gas floating platforms depend heavily on the performance of the mooring system. As a core component, the design and optimization of mooring piles are critical to overall platform performance. Fig. 12 shows several types of mooring piles, including suction piles, slender anchor piles, torpedo anchors, and sheet anchors. Each type exhibits distinct mechanical characteristics suited for specific applications. From a system-level perspective, pile foundations serve as the ultimate geotechnical support of the floating–mooring–foundation chain. The loads transmitted from mooring lines are directly resisted by the pile through bearing and friction mechanisms, whereas the seabed properties and installation conditions, in turn, influence mooring tension and platform stability. Hence, understanding pile behavior under coupled hydrodynamic and cyclic loads is essential for ensuring the integrated stability of the entire offshore system.

With continued advances in deep-water exploration, the innovation and optimization of mooring pile technology remain key research focuses in ocean engineering (Rui et al., 2024c). This section reviews theoretical studies and recent technological developments in mooring pile foundations. It aims to provide insights for improving design and anchorage performance in future research.

4.1. Suction pile

As an efficient and economical marine foundation structure, suction piles involve key technical issues in ocean engineering, such as installation and penetration depth prediction, bearing capacity analysis, and performance changes during operation. These issues directly affect the safety and stability of offshore platforms. Through experimental research, numerical simulations, and theoretical analysis, scholars have gradually revealed the installation behavior of suction piles and identified the factors affecting their bearing capacity and performance variations during operation.

In research on installation and penetration depth prediction, studies have mainly focused on establishing analytical models, investigating installation parameters, and improving predictive capability. Bang et al. (2000) established the relationship between the penetration depth of suction piles and the applied suction pressure. They proposed an analytical method that integrates the effects of suction pressure, soil properties, pile weight, and pile size, verifying its reliability through field tests. Zhang et al. (2013) investigated the influence of tilt angle on suction penetration

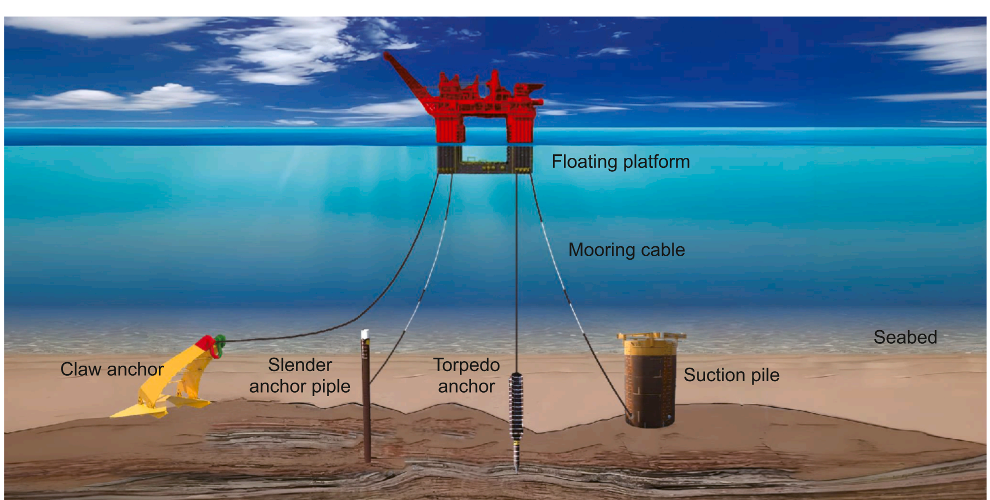


Fig. 12. Classification of pile foundation.

behavior during pile installation, and they explored the feasibility of adjusting the tilt angle by applying suction/positive pressure and intermittent pumping. As illustrated in Fig. 13, Xu et al. (2024a) proposed a nonlinear spring model incorporating a mass module to account for foundation inertia effects. They also developed a reverse end-bearing spring and an earth-plug slider assembly to predict the dynamic response of suction piles under impact loading, this model enables decoupling of the overall vertical stiffness of the suction piles. Their findings indicated that an increase in impact load amplitude significantly enhanced the cumulative differential pressure and inertia force of the suction pile, while the soil-structure interface frictional resistance reaches its peak earlier and then decays rapidly. To further quantify this process, the authors established expressions for the critical differential pressure (Eq. (8)), and the corresponding threshold condition (Eq. (9)). Taken together, these works provide a framework for understanding suction pile installation mechanisms and improving depth prediction.

The critical differential pressure:

$$S_{\mathrm{N,cr}} = \varpi \times \frac{\gamma_w}{\gamma'} \times \frac{\frac{\pi}{4}\frac{k_i}{k_0} + \beta + \frac{11}{4}\frac{z_h}{D} \times \chi}{\frac{11}{4}\frac{z_h}{D} + \varepsilon} \tag{8}$$

$$p_{\mathrm{crit}} = S_{\mathrm{N,cr}} \times \gamma' z_h \tag{9}$$

where, $S_{\mathrm{N,cr}}$ represents the critical differential pressure that triggers the onset of the critical hydraulic gradient, p_{crit} denotes the critical hydraulic gradient–inducing pressure defined by the model, k_0 and k_i are the soil permeability outside and inside the caisson, respectively. Parameters ϖ, β, χ, ε are related to the distance (z_h) from skirt tip to the deeper impermeable layer; $\frac{\gamma_w}{\gamma'}$ represents ratio of unit weight of water and effective unit weight of soil in the flow layer; $\frac{z_h}{D}$ represents normalized skirt penetration into the flow layer.

$$\left(\frac{H}{H_{0,\mathrm{opt}}}\right)^i + \left(\frac{V}{V_{0,\mathrm{opt}}}\right)^j - k\left(\frac{H}{H_{0,\mathrm{opt}}}\right)\left(\frac{V}{V_{0,\mathrm{opt}}}\right) = 1 \tag{10}$$

where, V and H represent the vertical and horizontal load components acting on the suction anchor, and their combinations form the V–H failure envelope that defines the limit state under combined loading. The loading direction is described by the inclination angle θ. The ratios $V/V_{0,\ \mathrm{opt}}$ and $H/H_{0,\ \mathrm{opt}}$ denote the normalized vertical and horizontal loads relative to the optimal pull-out capacities.

The bearing capacity of suction piles is influenced by soil properties, loading conditions, and pile parameters, and recent research can be grouped into numerical modeling, analytical corrections, and data-driven prediction. Peng and Yin (2023) employed a DEM–FEM coupled model to investigate pile–soil interaction under different horizontal pulling angles, showing that peak pulling force decreases as the angle increases, but rises with higher interface friction. A summary of the studied suction pile dimensions, soil properties, and load conditions is provided in Table 3. Bang et al. (2011) found that load-carrying capacity increases with downward movement of the mooring position, and proposed a correction method for vertical pullout capacity. Gao et al. (2013) emphasized the role of load tilt angle and pile slenderness, showing that optimal load location varies with tilt. To elevate predictive accuracy, Luan et al. (2024) developed ISM- and DNN-based models to estimate vertical pullout capacity, identifying soil properties, pile geometry, and load conditions as dominant factors, with the DNN model achieving higher reliability. Zhang et al. (2023) numerically showed that torsion markedly reduces suction-anchor pull-out capacity in sand and identified 0.7 L as the optimal padeye depth. They further established the V–H failure envelope using Eq. (10), providing a practical framework for torsional-condition design.

The bearing capacity of suction piles also varies significantly during operation due to environmental effects such as scour and cyclic loading. Research in this area has emphasized both degradation mechanisms and mitigation strategies. Feng et al. (2019) showed that increasing scour width reduces both vertical and horizontal capacity, and proposed mitigation by adjusting initial padeye positions. Wang et al. (2025) demonstrated the both amplitude and mean value of cyclic loading induce nonlinear responses in pile behavior, and that trench size strongly affects pile movement patterns. These findings highlight the importance of accounting for environmental degradation in design and point toward adaptive strategies for maintaining long-term pile stability.

Research on suction piles primarily focuses on installation and penetration depth prediction, analysis of factors influencing bearing capacity, and the long-term changes in bearing capacity during operation. Scholars have promoted technological progress through experimental studies, numerical simulations, and theoretical analyses. Bang et al. (2000) and Zhang et al. (2013) experimentally investigated the installation behavior of suction piles, while Peng and Yin (2023) and Luan et al. (2024) used numerical simulations and machine learning models to predict suction pile bearing capacity and failure mechanisms. Despite these advances, several challenges remain. Current research has mainly addressed short-term installation and load-

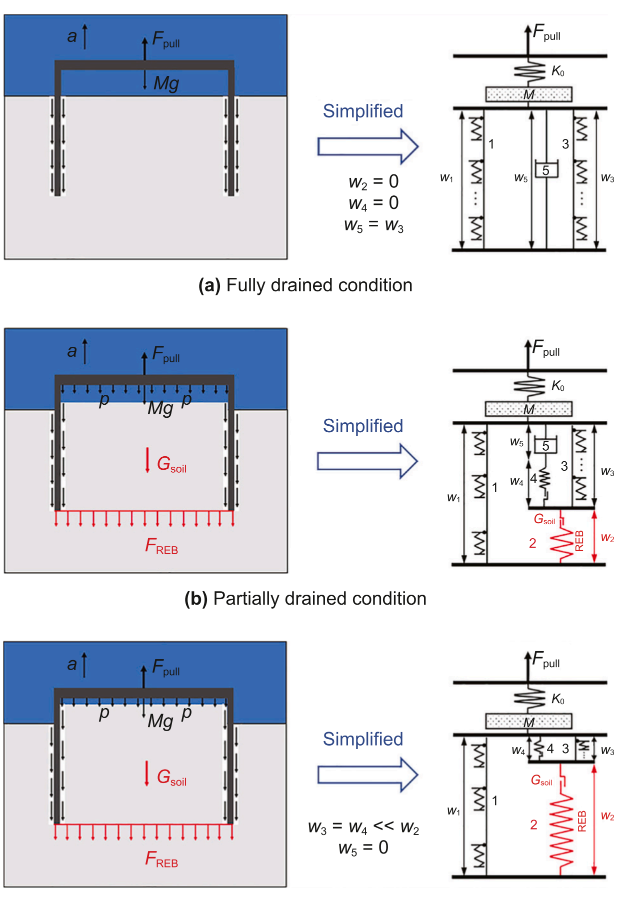


Fig. 13. Suction pile nonlinear spring method (adopted from Xu et al. (2024a)).

Table 3
Mooring pile foundation dimensions, soil properties and applied load values.

	References	Soil type	Soil properties	Load type	Load properties	Research method	Pile foundation size
Suction pile	Zhang et al. (2023b)	Sand	Angle of internal friction: 30°; Effective unit weight: 8 kN/m^3.	Inclined load and torsional effect	Pull-up $v = 0.005$ m/s.	Numerical simulation	$D = 2.5–6$ m; $L = 4–12$ m; $L/D = 1, 2, 3$.
	Peng and Yin (2023)	Sand	Angle of internal friction: 39°; Porosity: 0.37; Density: 1650 kg/m^3; Friction coefficient: 0.45.	Inclined load	Pull-up $v = 2$ mm/s.	Numerical simulation	$D = 30$ mm; $L = 60$ mm; Wall thickness = 1.0 mm.
	Gao et al. (2013)	Sand	Density: 1.44 g/cm^3; Angle of internal friction: 36.8°.	Inclined load	Loads are applied in increments. Each load stage is 1/10th of the predicted load capacity.	Experimental research	$D = 101$ mm; Wall thickness = 2.0 mm; $L = 202, 404, 606$ mm; $L/D = 2, 4, 6$.
Slender anchor pile	Sun et al. (2020b)	Sand	Density: 20.31, 19.76,19.10 kN/m^3; Angle of internal friction: 40°, 35°, 30°; Poisson's ratio: 0.200, 0.250, 0.300.	Lateral load	Small load: the horizontal displacement of the pile is small; Medium load: yielding of the soil above the point of rotation; Large load: yielding of soil over the entire pile body.	Numerical simulation	$D = 0.61, 0.91$ m; $L = 5.2$ m.
	Zhou et al. (2019)	Sand	Angle of internal friction: 33°.	Vertical load	Cyclic load = 0.2 Q_u, 0.3 Q_u, 0.4 Q_u); $T = 10$ s.	Numerical simulation	$D = 2.2$ m; $L = 55$ m.
	Zou et al. (2021)	Layered soil	Sand: Density: 1750 kg/m^3; Porosity: 0.86; Angle of internal friction: 34.6°. Clay: Density: 1690 kg/m^3; Porosity: 1.35; Undrained shear strength: 4.6 kPa.	Vertical load + torsional load	Vertical load: progressive loading, maximum displacement 0.05D. Torque: progressive loading, max 0.05° turn.	Experimental research	$D = 0.036$ m; $L = 0.6$ m; Wall thickness = 0.001 m.
Torpedo anchor	Sabetamal et al. (2016)	Clay	Angle of internal friction: 23°–25°; Porosity ratio: 1.8–2.14; Poisson's ratio: 0.3; Effective unit weight:17–20 kN/m^3.	Dynamic shock load	free-fall $v = 4.7–22$ m/s.	Numerical simulation	$D = 0.6–1$ m; $L = 6.8–12$ m $L/D = 6–12$.
	Kim et al. (2015)	Clay	Undrained shear strength: 2–10 kPa; Effective unit weight: 5–8 kN/m^3.	Dynamic shock load	Anchor dry weight: 23–115 t.	Numerical simulation	$D = 0.75–1.2$ m; $L = 4–11$ m; Width = 0.45–0.9 m; Anchor tip angle: 30°–60°.
	Wang et al. (2016)	Clay	Undrained shear strength: 611–6035 Pa; Porosity ratio: 25.6%–68.7%.	Dynamic shock load	Experiment: free-fall $v = 3.13–7.0$ m/s Engineering: free-fall $v = 30$ m/s	Experimental research + engineering	Experiment: $D = 1.9–3.2$ cm; $L = 9.5–35.2$ cm. Engineering: $D = 1.07$ m; $L = 17$ m.

(*continued on next page*)

Table 3 (*continued*)

	References	Soil type	Soil properties	Load type	Load properties	Research method	Pile foundation size
Plate anchor and claw anchor	O'Loughlin et al. (2014)	Kaolin soil	Liquid limit: 61%; Plastic limit = 27%; Compression index: 0.205; Rebound index: 0.044.	vertical load	free-fall $v = 30$ m/s.	Experimental research	$L = 51.5, 76.0, 101.5$ mm; $D = 16$–37.6 mm; Width = 26.73 mm
	Zhao et al. (2019)	Clay	Undrained shear strength increases linearly with depth.	vertical load + cyclic load	free-fall $v = 20$–30 m/s.	Numerical simulation	Square or round plate, area = 1–5 m^2
	Charlton et al. (2016)	Clay	Undrained shear strength increases linearly with depth; Effective unit weight = 10 kN/m^3; Poisson's ratio:0.22.	vertical load + inclined load	Evaluated by a dimensionless coefficient of pullout resistance.	Numerical simulation	Width = 2 m; burial depth ratio = 1–10; tilt = 0°–90°.

bearing behavior, while systematic investigations of long-term performance, particularly under combined multi-hazard marine conditions, are still lacking. In addition, most existing studies concentrate on conventional steel suction piles, whereas the potential of novel materials and hybrid structural forms for improving fatigue resistance and durability has not been fully explored. Looking forward, future research should place greater emphasis on long-term monitoring of suction pile behavior in situ, the development of predictive frameworks that integrate cyclic degradation and scour evolution, and the design of more resilient suction piles capable of maintaining stability under extreme events. These directions will be essential to support the safe and reliable deployment of deep-water mooring systems in increasingly harsh ocean environments.

4.2. Slender anchor pile

As a widely used mooring pile foundation in ocean engineering, the investigation of the bearing capacity, structural response, and failure mechanisms of slender anchor pile is essential for ensuring the safety and stability of floating platforms. In recent years, researchers have conducted comprehensive studies on slender anchor piles from multiple perspectives, including theoretical modeling, engineering applications, and emerging technologies. Various analytical methods and optimization strategies have been proposed to enhance their performance and reliability. These efforts have expanded the understanding and practical application of slender anchor piles.

In the theoretical study of slender anchor piles, recent research has gradually evolved from isolated case analyses to more systematic frameworks that integrate soil–pile interaction mechanisms, load transfer models and design methodologies. Yu et al. (2015b) proposed a novel theoretical prediction model and found that while the strength gradient has a minimal effect on bearing capacity, it significantly influences the failure mechanism. Building on this, the bearing-capacity formulations for rough anchors and smooth anchors are expressed in Eqs. (11) and (12), respectively, capturing the distinct interface behaviors that govern their load-transfer mechanisms. Zhou et al. (2019) introduced a new *t-z* model suitable for evaluating the cumulative displacement evolution of submarine interbedded foundations and determined that factors such as cyclic loading pattern and cyclic load amplitude have a substantial impact on the axial response of piles. Li et al. (2020) developed a framework that incorporates 3D effects, including the ultimate bearing capacity of the pile, the pile compatibility coefficient, and the initial modulus of the subgrade. They applied this framework to theoretical *p-y* curves derived from the full displacement loading extended movable strength design method. Wang et al. (2020b) referenced three models proposed by Byrne et al. (2020), Zhang and Andersen (2019), as illustrated in Fig. 14(a)–(c), and introduced a two-spring method, shown in Fig. 14(d), to predict the lateral behavior of soft-clay monopiles with varying length-to-diameter (L/D) ratios. This model accounts for soil resistance in terms of base shear and base moment and successfully replicates numerous field and centrifuge test results for laterally loaded monopiles across a wide range of L/D ratios using uniform parameters.

Rough anchor:

$$N_c = N_{c0}\left[1-\left(\frac{\rho B}{c_{u0}}\sin\alpha\right)^2\right]-\frac{\pi}{4}\left(\frac{\rho B}{c_{u0}}\right)^2 \tag{11}$$

Smooth anchor:

$$N_c = N_{c0}\left[1-\frac{\rho B}{2c_{u0}}\sin\alpha-\frac{1}{4\pi}\left(\frac{\rho B}{c_{u0}}\right)^2\right] \tag{12}$$

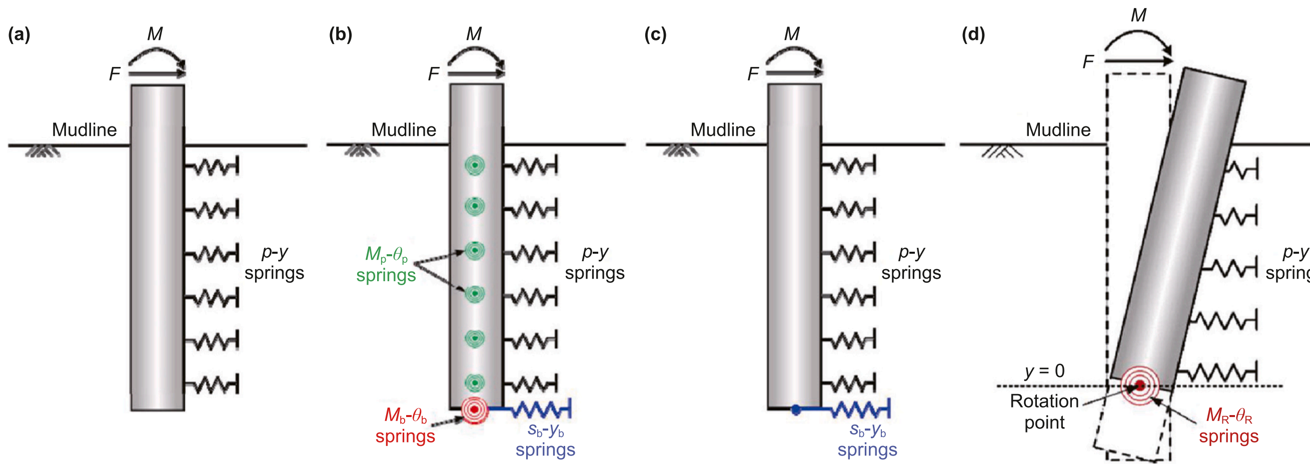


Fig. 14. Existing models for predicting lateral response of monopiles: **(a)** one-spring *p-y* model; **(b)** four-spring model (adopted from Byrne et al., (2020)); **(c)** two-spring model (adopted from Zhang and Andersen (2019)); **(d)** monopiles with varied *L/D* model (adopted from Wang et al. (2020b)).

where, N_c denotes the dimensionless bearing capacity factor of the suction anchor, N_{c0} denotes the capacity factor for uniform soil, while α represents the loading inclination angle that governs whether the response is uplift- or bearing-dominated. $\rho B/c_{u0}$ defines a normalized gradient ratio, where ρB is the strength gradient at the base and c_{u0} is the undrained shear strength at the mudline; this ratio controls how soil strength increases with depth and strongly influences the optimal mechanism angles, particularly for rough anchors. The formulation applies over a full loading cycle ($0^\circ \leq \alpha \leq 360^\circ$), with 90°–270°corresponding to bearing conditions, and the symmetry of N_c about $\alpha = 0^\circ$ and 90° highlights the inherent symmetry of the failure mechanism under opposite loading directions.

The uplift capacity factor of the fully rough piles:

$$N_0 = a_1\left(\frac{L}{D}\right) + a_2\left(\frac{L}{D}\right)^{0.5} + \left[a_3\left(\frac{L}{D}\right) + a_4\left(\frac{L}{D}\right)^{0.5}\right]\tan\phi + \left[a_5\left(\frac{L}{D}\right) + a_6\left(\frac{L}{D}\right)^{0.5}\right]\tan^2\phi \tag{13}$$

where, N_0 is the dimensionless reference capacity factor that characterizes the baseline uplift or bearing resistance of the anchor. The term *L/D* is the embedded length ratio. ϕ is the soil internal friction angle, a_1–a_6 is individual contribution coefficients.

In terms of lateral pile behavior, simplified yet robust models have been proposed to strengthen the reliability of prediction accuracy across different soil conditions. Sun et al. (2020b) introduced a nonlinear analysis method for large-diameter monopiles subjected to lateral loading and found that the depth of the rigid rotation point at the pile head depends on pile diameter and load eccentricity. Table 3 summarizes the investigated pile sizes, soil properties, and loading scenarios. Parallel efforts have focused on practical design optimization and reliability-based approaches. Ukritchon and Keawsawasvong (2019) formulated an approximate statistical design equation to predict the pullout capacity of circular piles in sandy soils, as shown in Eq. (13). Their equation produced more accurate predictions than existing models. Wang et al. (2020a) examined how pile diameter and bending stiffness affect the *p-y* curve in sandy soils. They found that the API code overestimates initial stiffness and underestimates soil resistance for large-diameter piles. They attributed the variation in *p-y* curves mainly to changes in soil deformation mechanisms. Zou et al. (2021) determined that soil profile and loading sequence significantly influence pile bearing performance. They observed that the ultimate torsional and vertical bearing capacities differed under combined loading compared with pure torsional loading. Overall, these studies demonstrate a progression from purely theoretical approaches to more comprehensive, design-focused frameworks.

The study of slender anchor piles has advanced through investigations under different loading conditions. These conditions include axial, lateral, and torsional loading. Together, these loading conditions provide a more comprehensive evaluation of pile–soil interaction. Zhou et al. (2019) highlighted the importance of cyclic axial loading on cumulative displacement, while Zou et al. (2021) demonstrated that combined vertical-torsional loading induces distinct variations in ultimate bearing capacity compared with single-mode loading. These findings indicate that soil response is highly dependent on the loading sequence and type, making it essential to consider complex coupled loads in design. Furthermore, studies in sandy soils (Wang et al., 2020a; Ukritchon and Keawsawasvong, 2019) and soft clays (Wang et al., 2020b; Zhou et al., 2019) show that conventional *p-y* curve formulations, such as those in the API code, may either overestimate initial stiffness or underestimate soil resistance, particularly for large-diameter piles. This reveals a critical challenge: existing design frameworks often fail to capture the nonlinear, soil-dependent behavior of slender piles under realistic offshore loading scenarios. Looking ahead, long-term progress will depend on the integration of coupled loading mechanisms, soil heterogeneity, and scale effects into predictive models. Experimental and numerical studies need to evolve toward unified frameworks capable of simultaneously capturing axial, lateral, and torsional performance. In parallel, design methods must account for installation efficiency and long-term cyclic degradation to ensure long-term operational safety. These developments will gradually transition pile design from simplified formulations toward robust, performance-based approaches, thereby enhancing the reliability of slender anchor piles in deep-water applications.

4.3. *Torpedo anchor*

As an efficient and economical deep-sea mooring solution, the torpedo anchor presents key technical challenges in ocean engineering. These include its dynamic installation process, anchoring capacity, and design optimization strategies. Each factor directly affects platform safety and stability.

The dynamic installation process of torpedo anchors plays a decisive role in determining their final embedment depth and subsequent anchoring performance, and recent studies have progressively deepened the understanding of this process. Early investigations primarily focused on penetration mechanisms. Sabetamal et al. (2016) analyzed the dynamic penetration process of torpedo anchors in saturated soil and revealed that strain rate exerts significant effects on pore water pressure, bearing capacity, and interface friction. Building on this, Zhang and Evans (2019) demonstrated that penetration depth increases linearly with impact velocity and anchor weight but decreases with greater inter-particle friction, while microscopic observations clarified the system response mechanism. Complementarily, Kim et al. (2015) distinguished two installation phases—acceleration and deceleration—and uncovered the associated soil damage pattern and chamber formation mechanism. Further experimental work expanded these insights, such as Wang et al. (2016), who examined penetration depth in cohesive soft soils and derived an energy-based calculation formula, and Raaj et al. (2022), who highlighted the role of anchor-nose shape on hydrodynamic efficiency, showing superior performance of shaped-nose configurations compared to tapered ones. More recently, innovative approaches have been proposed, Dong (2022) investigated penetration under combined water jetting and mechanical vibration, proposing a new penetration mechanism and a predictive method for determining the critical depth. The key dimensions of these studied anchors, together with soil properties and loading conditions, are summarized in Table 3.

Once installed, the anchorage capacity of torpedo anchors emerges as a central performance criterion influenced by multiple interacting factors. Wang et al. (2018) derived an equation for undrained monotonic anchorage capacity and clarified its dependence on embedment depth, net weight, geometry, and soil properties. Yang et al. (2021) further extended this understanding by showing that embedment depth, soil strength gradient, anchor orientation, and loading angle significantly influence the end bearing coefficient, and proposed a corresponding expression. At the group level, Santiago et al. (2020) demonstrated that pile spacing and loading direction affect efficiency, with vertical loading producing the greatest capacity enhancement. Numerical modeling has also provided predictive tools, Liu et al. (2016a), as illustrated in Fig. 15, developed an Euler–Lagrange coupling model to predict embedment depth, identifying undrained shear strength and impact velocity as dominant factors. In parallel, Raie and Tassoulas (2016) simulated soil reconsolidation after installation and analyzed pore pressure dissipation and strength recovery, offering critical insights for estimating time-dependent pullout capacity. As a whole, these works establish a more comprehensive framework linking installation dynamics with anchorage performance.

To further improve torpedo anchor performance, several design optimizations have been developed. Sun and Liu (2022) introduced a gravity-mounted anchor with an annular tail wing. This design enhanced directional stability and improved flow separation. CFD analysis confirmed higher terminal velocity and better stability. Similarly, Liu et al. (2018) proposed a booster concept that substantially increased impact velocity, while Chen et al. (2021) designed a self-penetrating torpedo anchor employing vibratory shear to reduce soil resistance and optimize penetration efficiency. Liu et al. (2021) advanced lightweight flat-plate gravity anchors combined with retrievable boosters, validating penetration depth through model tests and theoretical analysis. Zhan et al. (2017) optimized hollow gravity anchors to minimize rotation angle and drift distance, thereby improving both practicality and economic feasibility. Most recently, Huang et al. (2025) conducted numerical investigations on a novel gravity-installed plate anchor, demonstrating that refined geometric design is crucial for hydrodynamic behavior and installation success in deep-water applications. These progressive design innovations, together with the mechanistic and performance-oriented studies discussed above, form an

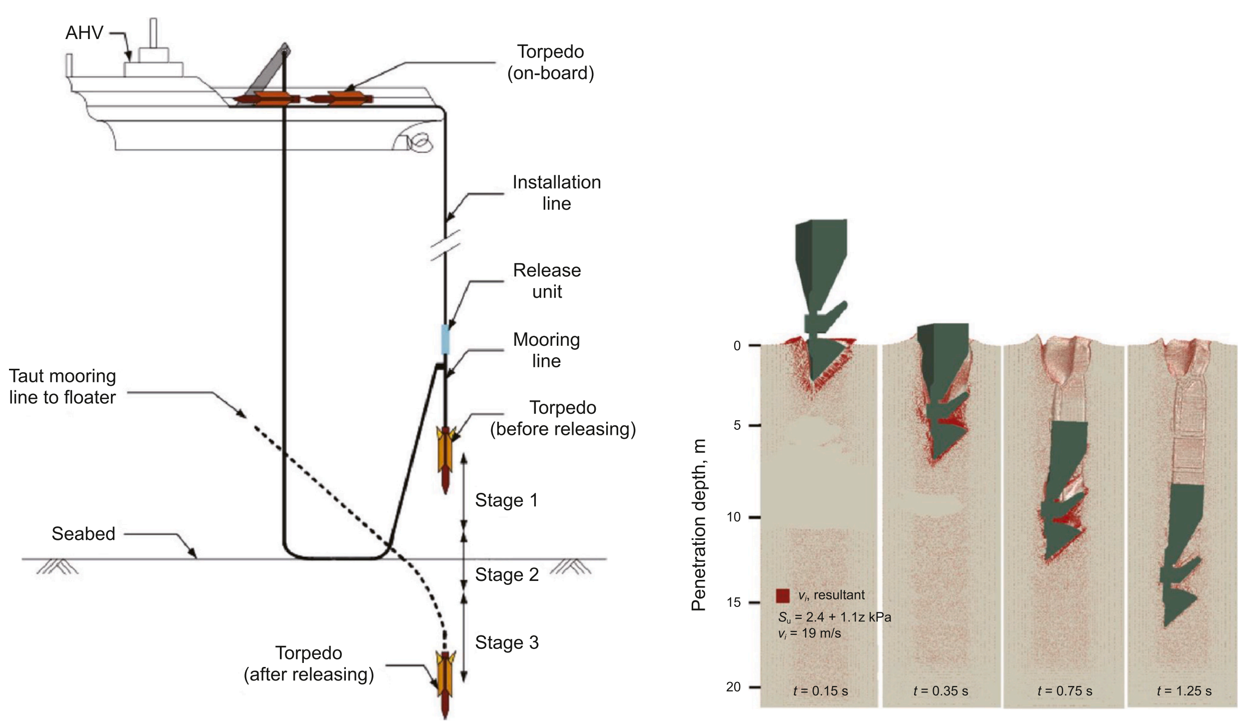


Fig. 15. Torpedo anchor installation procedure and deformation of the soil (adopted from Liu et al. (2016a)).

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integrated body of knowledge that underpins the continued advancement of torpedo anchor technology.

Research on torpedo anchors has centered on understanding the dynamic installation process, anchorage capacity, and structural optimization. Sabetamal et al. (2016) and Kim et al. (2015) studied strain rates, soil damage patterns, and chamber formation during installation, while Wang et al. (2016, 2018) and Raaj et al. (2022) examined how impact velocity, anchor weight, and geometry affected installation performance. Furthermore, Yang et al. (2021) and Santiago et al. (2020) investigated how soil strength gradient, pile spacing, and load direction influenced anchoring capacity. Their findings contributed to improved installation performance and anchoring stability. Despite these advancements, two key challenges persist. First, most studies remain confined to controlled soil types or simplified conditions, with limited investigation of complex seabed heterogeneity, cyclic loading, and multi-directional forces that dominate real deep-sea environments. This gap hinders the ability to establish robust predictive models for long-term anchor stability. Second, the reusability, retrieval mechanisms, and environmental compatibility of torpedo anchors remain underexplored. This limitation constrains their sustainable application in large-scale offshore developments. Looking ahead, future research should progress along two parallel directions. From a long-term development perspective, efforts are required to establish unified theoretical frameworks that integrate installation dynamics, soil–structure interaction, and post-installation consolidation under deep-water conditions, which should be supported by high-fidelity physical modeling and large-scale experiments. From a future advancement perspective, emphasis should be placed on developing sustainable and recyclable anchor systems, optimizing hydrodynamic and geotechnical adaptability across diverse seabeds, and enhancing predictive models of cyclic degradation and time-dependent bearing capacity. Such integrated approaches will not only improve installation efficiency and service reliability but also align with the broader objectives of sustainable ocean engineering.

4.4. Plate anchor and claw anchor

Plate anchors and claw anchors function as key anchoring structures. Both are embedded in submarine soil to provide pullout resistance. Their performance is directly linked to the stability and safety of marine facilities. With the increasing development and utilization of marine resources, research on the embedding behavior, bearing capacity, and pullout mechanisms of plate anchors has attracted increasing attention.

The embedding behavior and bearing capacity of plate anchors and claw anchors are essential in ocean engineering because they directly determine anchoring performance and overall system stability. Research in this field has gradually advanced from the fundamental evaluation of embedment depth and soil–anchor interaction to performance optimization and, ultimately, to detailed analyses of pullout mechanisms under complex conditions. O'Loughlin et al. (2014) experimentally evaluated the penetration depth and bearing capacity of dynamically embedded plate anchors in normally consolidated clays, they found that the tip embedment depth ranged from 1.6 to 2.8 times the anchor length, and a cross-shaped wing arrangement significantly increased the bearing capacity. Table 3 summarizes the dimensions, soil properties, and loads of the studied plate and claw anchors. Zhao et al. (2019) analyzed the dynamic installation of sheet anchors in water and examined their penetration behavior in soil, they highlighted both the advantages and limitations of numerical modeling. Chen et al. (2022) investigated the pullout bearing capacity and failure mechanisms of square sheet anchors in spatially variable clay soils. As depicted in Fig. 16, their results indicate that soil strength variability and burial depth significantly influenced the failure pattern. They proposed a method to predict the failure probability.

To enhance the performance of plate and claw anchors, researchers have proposed various novel design and optimization strategies. Zhang and Fu (2023) analyzed the influence of anchor geometry on installation efficiency and positioning accuracy. They recommended geometric optimization to improve both efficiency and performance. Cheng et al. (2024) found that the presence of a clay layer significantly reduced the pullout bearing capacity of plate anchors. They developed a calculation framework to account for the effect of clay layer thickness. Charlton et al. (2016) determined that degradation of the clay structure led to a reduction in the pullout bearing capacity coefficient, and they recommended considering the softening characteristics of subsea soils in plate anchor design. Liu et al. (2016b) investigated the effects of anchor loading angle, anchor lug eccentricity, and soil strength profile on the embedment behavior of gravity-installed plate anchors. They suggested keeping the anchor loading angle below 30° and the lug eccentricity angle between 15° and 25°.

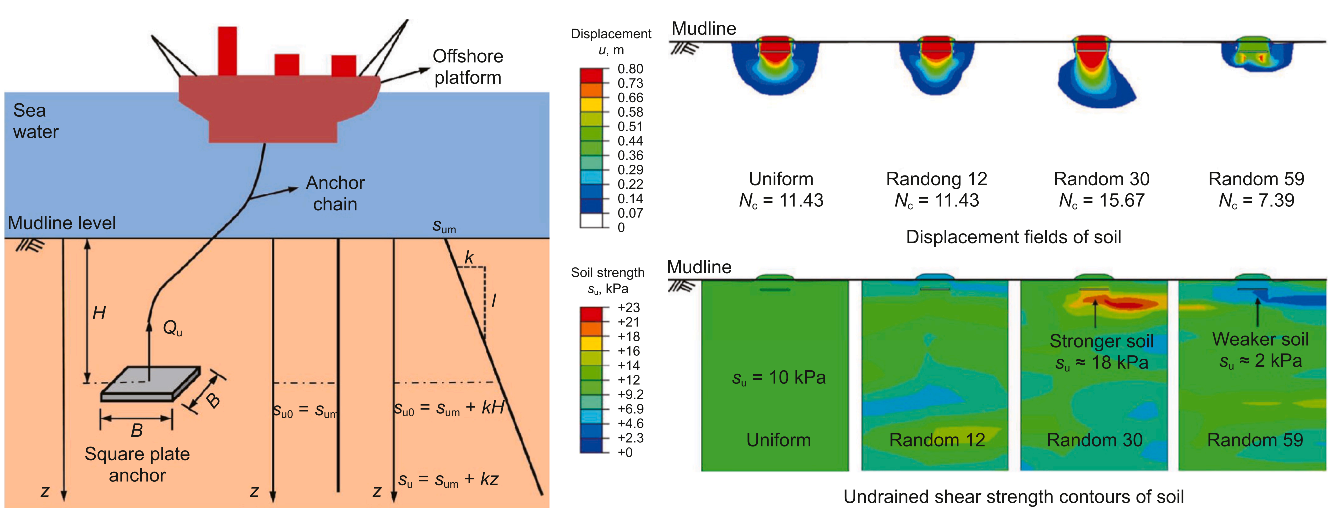

Fig. 16. Displacement fields and undrained shear strength contours of soil surrounding a square plate anchor (adopted from Chen et al. (2022)).

Table 4
Classic floating platform mooring Pile Foundation.

Platform name	Sea area	Pile type	Number of pile foundation	water depth, m	Platform type
Nansen (Offshore Technology, 2021)	Gulf of Mexico	Slender anchor pile	9	1120	Spar
Hoover (Offshore Technology, 2021)	Gulf of Mexico	Slender anchor pile	12	1463	Spar
Shenhai-1 (Jia et al., 2018)	South China Sea	Slender anchor pile	16	1450	SEMI
Ursa (Offshore Technology, 2021)	Gulf of Mexico	Suction pile	16	1158	TLP
Mad Dog (Offshore Technology, 2021)	Gulf of Mexico	Suction pile	11	1347	Spar
Poly saga (Ryggvik, 2015)	North Sea, Norway	Suction pile	8	95	FPSO
Shenlantansuo (Chen and Ou, 2024)	South China Sea	Claw anchor	8	<1000	SEMI
InterMoor (Acteon, 2024)	West African Sea	SEPLA-plate anchor	12	26	FPSO
Enauta's Atlanta II (Enauta, 2025)	Brazilian Sea	Torpedo anchor	20	1500	FPSO
Mero 1 (Offshore Technology, 2022)	Brazilian Sea	Torpedo anchor	24	2100	FPSO

Recent studies have shifted attention to detailed mechanisms of pullout behavior, a critical factor throughout the operation life. Kanitz et al. (2019) examined soil displacement and pore water pressure changes during the pullout process using Particle Image Velocimetry and CFD-DEM simulations. They found that inclined shear zones formed during pullout. They also observed that pore pressure evolved in three distinct stages. Liu et al. (2022) analyzed the anchor-soil-water interactions of gravity anchors during dynamic installation and developed a theoretical model to predict the final penetration depth. Wu et al. (2020) studied the effect of shallow embedment behavior in horizontal anchor jaws on drag anchor trajectories. They found that this behavior was critical in the presence of rough interfaces and soil non-homogeneity. Yu et al. (2015a) demonstrated that cumulative plastic shear strain reduced the ultimate pullout capacity of plate anchors.

Research on plate and claw anchors has primarily concentrated on embedment behavior, bearing capacity, and pullout mechanisms. Experimental and numerical studies have revealed that penetration depth, soil properties, and anchor geometry are the dominant factors controlling anchor performance (O'Loughlin et al., 2014; Zhao et al., 2019; Yu et al., 2015a). Recent advances in design optimization, such as incorporating clay-layer effects (Cheng et al., 2024) and accounting for soil softening behavior (Charlton et al., 2016), have further improved reliability. In addition, geometric refinement has been shown to enhance installation efficiency and positional accuracy (Zhang and Fu, 2023). Despite these efforts, existing research remains fragmented, often isolating single variables or specific failure modes while overlooking the coupled effects of soil heterogeneity, cyclic loading, and multi-directional forces. Looking forward, long-term development should emphasize the integration of multiple influencing factors into unified design frameworks, bridging the gap between laboratory-scale insights and field-scale performance. Future progress is also expected in the application of novel materials, improved constitutive soil models, and performance-based design approaches, thereby enabling anchors to maintain stability and serviceability under increasingly complex deep-sea conditions.

4.5. Engineering applications of pile foundation

As illustrated in Fig. 12, suction piles, slender anchor piles, torpedo anchors, and plate anchors each offer distinct advantages depending on water depth and soil conditions. The selection of an appropriate anchoring system primarily depends on factors such as platform type, marine environment, water depth, and the number of pile foundations. Suction piles and torpedo anchors are particularly effective in deep and ultra-deep waters. They perform well in soft clay and sandy clay, where they provide high bearing capacity and stability. Slender anchors are suited for medium to deep waters in soft clay and medium-strength soils. They offer design flexibility to accommodate complex geological conditions. Plate and claw anchors are mainly used in shallow to moderately deep waters with sandy soils and moderately strong clays. Their ease of installation and retrieval makes them suitable for mobile rigs that require frequent relocation.

In practical engineering applications, the selection of a mooring method depends on factors such as water depth, soil conditions, platform type, and specific project requirements. As shown in Table 4, suction piles and torpedo anchors are preferred in deepwater oil and gas development because they performed well in extreme depths. In contrast, plate anchors are chosen in shallow waters or for mobile drilling platforms. They are easy to install and retrieve. With continuous advances in ocean engineering, new materials and intelligent monitoring systems offer new possibilities for mooring system optimization. In the future, more efficient and environmentally friendly mooring solutions will be developed by leveraging big data and artificial intelligence. These systems will promote the safety and stability of marine structures and provide strong support for deep-sea resource development.

5. Summary

Deep-water floating platforms, mooring systems, and mooring pile foundations are crucial for ensuring the safety and efficiency of deep-water oil and gas operations. This paper provides a comprehensive review of significant scientific advancements in these three areas. Additionally, it summarizes relevant engineering practices and presents emerging trends, outlining future research directions and technological developments in this field.

(1) Research on deep-water floating platforms has advanced in hydrodynamics, fatigue assessment, and structural optimization. Nevertheless, gaps remain in long-term fatigue validation, multi-hazard coupling effects, and mooring–foundation degradation under cyclic loads. Future work should strengthen the integration of experiments, numerical simulations, and monitoring, while improving design methods, structural resilience, and life-cycle safety strategies. These efforts are vital for enhancing the safety, sustainability, and cost-effectiveness of ultra-deep water developments. Globally, FPSOs dominate Brazil and West Africa, SPARs and TLPs are prominent in the Gulf of Mexico, and SEMIs are crucial in harsh regions like the North Sea. The practical implication of these advances is that they provide engineers with more reliable tools for platform design, stability evaluation, and operational planning under extreme offshore conditions.

(2) Anchor chain–seabed interactions are better understood in terms of trench formation, resistance, and ratcheting effects, but heterogeneous seabeds and long-term degradation

under extreme environmental loads require further study. Synthetic and high-strength cables improve fatigue performance, though multi-physical field coupling, including mechanical, corrosion, and biofouling effects, is still underexplored. Riser research highlights fatigue resistance and vibration suppression, yet gaps persist between global system design and local stress control, and fully coupled riser–platform–seabed dynamics are rarely considered. Future efforts should focus on integrated design strategies, long-term monitoring, coupled environmental and mechanical effects, and high-fidelity simulations to enhance resilience, safety, and performance of deep-water mooring and riser systems. These developments provide practical guidance for predicting system behavior, optimizing mooring layouts, and mitigating operational risks in complex offshore environments.

(3) Research on suction piles, slender piles, torpedo anchors, and plate/claw anchors has advanced in installation mechanics, bearing capacity, and structural optimization. Key gaps remain in long-term cyclic performance, seabed heterogeneity, and multi-hazard effects. Existing design frameworks often simplify soil–structure interactions, limiting predictive accuracy and operational reliability. Future research should focus on integrating installation dynamics, soil-structure interaction, and cyclic degradation into unified predictive models, improving material and geometric designs, and enhancing anchor durability and resilience. Such efforts will strengthen the reliability, operation life, and adaptability of mooring foundations, supporting safe and sustainable deep-water offshore operations under increasingly complex environmental conditions. These efforts will strengthen the reliability, operation life, and adaptability of mooring foundations, providing engineers with robust solutions for safe, efficient, and sustainable deep-water operations under increasingly complex environmental conditions.

(4) Artificial intelligence is increasingly applied in deep-water offshore systems for fatigue assessment, life prediction, and operational monitoring. For risers and floating platforms, AI effectively captures nonlinear behaviors, supports real-time decision-making, improves fatigue life estimation, and enhances system stability and reliability. However, its wider integration in structural design, hydrodynamics, and pile foundations remains limited due to extreme conditions and scarce long-term data. Future research should combine scaled experiments in real marine environments with theoretical analysis and AI to develop robust predictive methods, integrate AI with classical numerical and analytical models, capture multi-factor and multi-scale interactions, and ensure interpretability and reliability for safe and efficient deep-water operations.

In a word, despite significant advancements in deep-water floating platforms, mooring systems, and mooring foundations, considerable challenges persist. Addressing these challenges is essential to ensure the safe, efficient, and sustainable development of ultra-deep water oil and gas resources in increasingly complex and harsh offshore environments.

CRediT authorship contribution statement

Dong-Sheng Xu: Writing – original draft, Methodology, Investigation, Data curation. **Jin Yang:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jian-Chun Fan:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Ying-Fang Zhou:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

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.

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