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Research Article

Structural performance analysis of steel piled offshore platforms under environmental loads

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ABSTRACT

Steel pile foundations used in offshore structures must be able to maintain their structural integrity and safety throughout the structure's service life under environmental effects such as waves, currents, and wind. In this context, this study conducts a detailed investigation of the structural performance of a steel-piled offshore platform under environmental wave loads with different return periods. Within the scope of the analysis, the behavior of a typical platform pile group was modeled and analyzed using the Sesam Genie software under wave loads with 1-year (operating), 100-year (extreme), and 10,000-year (abnormal) return periods, considering four different soil units (ZU1, ZU2, ZU3, and ZU4). The analysis determined the maximum internal forces acting on the piles (axial forces, lateral forces, and moments) as well as the maximum displacement values at the pile tips, which ranged between 0.012 m and 0.054 m depending on the load direction and return period. Furthermore, the maximum utilization factor (UF) for each pile was calculated, varying between 0.22 and 0.49, and compared against the minimum safety factors specified in the ISO 19902 standard. It was found that in all scenarios, the maximum utilization factors of the piles remained below the respective safety limits, and the horizontal displacements at the pile tips were within acceptable engineering levels. Unlike many previous studies focusing on single piles, this study systematically evaluates group pile behavior in layered soil conditions, providing more realistic insights into offshore foundation performance. In conclusion, this study highlights the importance of concurrently evaluating soil properties and environmental loads for the structural safety of steel pile foundations and contributes to the multifaceted engineering parameters that must be considered during the design phase.

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1. Introduction

The design and performance of pile foundations are of fundamental importance for the stability and integrity of offshore structures, especially under harsh environmental conditions. Such structures are subjected to dynamic forces resulting from waves, wind, and seismic activity, making it critical to accurately understand the interaction between pile foundations and the surrounding soil. Among the various factors influencing pile behavior, soil properties and composition play a decisive role. Soil types directly affect load transfer mechanisms, pile deformations, and the overall stability of the foundation under both vertical and lateral loading.

Pile foundations in offshore structures, as well as in many onshore civil engineering applications, are exposed to cyclic loading. These loads typically originate from sources such as waves, wind, traffic, and seismic effects. Under cyclic loading, the load-bearing capacity, stiffness, and soil–pile interaction may change over time.

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Andersen (2015) presented key parameters related to cyclic soil behavior, which are critical for the design of offshore foundations. Randolph and Gourvenec (2011) emphasized geotechnical engineering principles for offshore environments, forming a basis for the assessment of cyclic loading. LeBlanc et al. (2010) investigated the degradation tendencies in stiffness and capacity under long-term cyclic lateral loading of piles in sandy soils. Seidel and Coronel (2011) proposed a novel approach for evaluating axial cyclic loading on offshore piles, offering practical contributions to design methods. Basack and Banerjee (2014) experimentally studied lateral cyclic responses in layered soils, providing critical insights into pile–soil interaction. Similarly, Liu et al. (2019) numerically examined the dynamic responses of open-ended offshore piles under lateral cyclic loading and validated the findings with field data. Achmus et al. (2009) detailed the behavior of monopile foundations under cyclic lateral loading, highlighting the influence of soil properties and pile stiffness on performance. Buckley et al. (2023) contributed to offshore pile design principles through large-scale pile testing.

Although these studies provide valuable insights, most of them focus either on sandy soils or simplified single-layer soil conditions. Limited attention has been given to heterogeneous soil profiles that typically exist in offshore environments, and the combined influence of cyclic loading and layered soil properties is not fully captured.

Offshore structures are engineering systems that are continuously exposed to dynamic forces such as waves, wind, currents, and seismic loads (Yigit et al. 2018, Şermet et al. 2022). The long-term stability and durability of these structures depend on the accurate analysis of soil–structure interaction (Hacıefendioglu and Birinci 2015). Numerous studies have been conducted on this subject. Memarpour et al. (2012) investigated the cyclic lateral load response of pile foundations in offshore platforms using numerical methods. Cairo et al. (2005) examined interaction factors for pile groups in layered soils, providing insights into group effects. Sun et al. (2024) numerically analyzed stability under extreme environmental conditions and proposed design recommendations for wind energy applications. Chen et al. (2014) studied pile settlement in mixed soils and highlighted time-dependent variations in load-bearing capacity. Xu et al. (2021) analyzed dynamic stability under wave loading and offered practical design implications for offshore infrastructure. Ashour et al. (2004) explored the lateral behavior of pile groups in layered soils, emphasizing load sharing and group interactions. Basack et al. (2022) expanded the field by analyzing pile–soil interaction under cyclic loading in loose sands through both experimental and numerical approaches. Karalar et al. (2024) simulated the nonlinear behavior of soil type on structures. They stated that soil type significantly affects the behavior of the structure.

However, most of these studies emphasize lateral load behavior or settlement, while only a few explicitly incorporate both vertical and lateral responses under extreme cyclic loading. In addition, the consideration of return period–based wave loading (e.g., 1-year, 100-year, and 10,000-year scenarios) remains largely absent in existing research.

To provide a clear understanding of the research scope and methodology, this study systematically analyzes the vertical and lateral behavior of steel pile foundations under four different soil types (ZU1–ZU4) and three wave loading scenarios corresponding to return periods of 1, 100, and 10,000 years. Pile displacements were evaluated for each loading scenario, and the maximum safety factors of the piles were compared with the ISO 19902 standard. This approach allows a comprehensive assessment of soil–pile interaction under varying environmental conditions.

Piles, which form the foundation system of offshore platforms, are critically important for the stability and safety of the structure. The performance of these systems varies depending on soil conditions, loading scenarios, and environmental factors. In particular, the group pile effect refers to the condition in which multiple piles work together within the same structural system; this interaction can either enhance or reduce the overall load-bearing capacity by influencing the behavior of each individual pile in contact with the soil. This effect can be a determining factor in the platform's durability and long-term performance.

Al-Khazaali and Vanapalli (2019) conducted experimental studies on single piles and pile groups in saturated and unsaturated sandy soils, revealing variations in load-bearing capacity and load distribution. Basack (2014) developed comprehensive design methodologies by integrating field data with analytical approaches. Chandrasekaran et al. (2010) examined lateral cyclic loading in clay soils and proposed empirical correlations for design purposes. Horsnell et al. (1990) investigated the lateral behavior of pile groups in marine soils, producing findings that remain relevant today. Tedesco (2013) analyzed the numerical responses of single piles and pile groups in soft clay soils, exploring their interaction with lattice structures. Wang et al. (2024) studied the lateral performance of pile-supported wharves under cyclic loading using quasi-static model tests. It has been found that displacement accumulation is closely related to load amplitude and the number of loading cycles. Duan et al. (2024) conducted model tests to understand how cyclic lateral loads affect pile–soil interaction, identifying progressive failure modes and a reduction in stiffness. Qin et al. (2024) investigated the lateral resistance behavior of piles in sandy soils, demonstrating that stiffness initially increases but decreases with continued cycling due to soil loosening. Sallam et al. (2024) examined the response of piles subjected to simultaneous lateral and torsional loading, observing reductions in both capacity and stiffness, particularly in sandy soils. Thangavel and Rathod (2024) studied the behavior of rigid piles under unidirectional cyclic loading, showing an initial increase in stiffness followed by increased displacements with further cycles. Krishnanunni and Rathod (2024) tested the behavior of piles under lateral loads on sloped ground, reporting that the best performance was achieved when piles were placed at a distance of two diameters from the crest, though load eccentricity was found to reduce lateral resistance. Anastasopoulos and Theofilou (2016) compared hybrid foundations with monopile systems under environmental and seismic loading, showing that hybrid systems reduce rotational accumulation and offer improved overall performance. Chen et al. (2023) developed an analytical method to evaluate the behavior of offshore pipe piles under S-wave loading, revealing that hydrodynamic pressure has a significant influence on vibration and deformation responses. Hu et al. (2023) conducted full-scale tests on grouted large-diameter piles and demonstrated that grouting enhances load-bearing capacity, with greater effectiveness observed in coarse-grained soils. Xu et al. (2020) assessed the lateral performance of offshore piles through field tests using fiber optic sensors and proposed a modified p–y method that better fits the observed displacement and moment data. Dai et al. (2023) analyzed semi-rigid piles in cement-improved clay under both monotonic and cyclic loading, showing that soil improvement significantly reduces displacements and stiffness degradation, and that numerical models can effectively support design optimization.

Although these studies highlight group effects, soil improvement, and innovative design methods, there is still a lack of systematic comparison between different soil types and their influence on both vertical and lateral pile responses. In particular, the combined evaluation of soil heterogeneity and long-term wave loading scenarios is rarely explored.

In offshore engineering projects, a wide range of soil types- from soft clays to dense sands- are encountered, each presenting unique challenges. Soft soils are typically associated with excessive settlement and lateral displacement, whereas stiff soils, while offering higher load-bearing capacity, can lead to larger bending moments and increased structural stresses. However, hybrid soil profiles containing both soft and stiff layers have the potential to offer cost-effective solutions without compromising performance. Despite growing awareness of the significance of soil properties, there remains a need for detailed investigations into the performance of pile foundations under varying soil conditions and loading scenarios.

In summary, the literature demonstrates considerable progress in understanding cyclic loading, group effects, and soil–pile interaction. Nevertheless, four critical gaps remain: (i) limited integration of heterogeneous soil profiles in analyses, (ii) insufficient consideration of return period–based wave loading, (iii) almost no investigations into abnormal loading conditions associated with very rare events such as 10,000-year return periods, and (iv) lack of comparative evaluations aligned with international design standards such as ISO 19902.

Unlike earlier research that focused mainly on single piles, the novelty of this work lies in its integrated assessment of group piles, layered soil units (ZU1–ZU4), and wave loads with multiple return periods.

The primary objective of the study is to highlight the soil–pile interaction under various environmental loading conditions and provide valuable data to support the safe design of offshore pile foundations.

In this context, the main objectives of the study are as follows:

- To analyze the behavior of piles under different wave loading scenarios,
- To perform comparisons based on safety factor approaches in accordance with the ISO 19902 standard,
- To investigate the influence of soil types on pile–soil interaction.

A limitation of this study is that the numerical models have not been directly validated against field or experimental data; however, they are based on site-specific geotechnical parameters and measured environmental conditions (wave and wind data), ensuring a realistic representation of the Caspian Sea region.

2. Materials and Method

2.1. *Platform design and structural details*

The platform design is optimized for offshore conditions and consists of a lattice-type superstructure supported by a four-legged, slender jacket framework. The foundation system comprises a total of eight main steel piles arranged as 2×4, each having a diameter of 96 inches (2438 mm) and a wall thickness of 60 mm. The penetration depth of these piles is 117 meters. Fig. 1 illustrates the overall structure and design details of the platform.

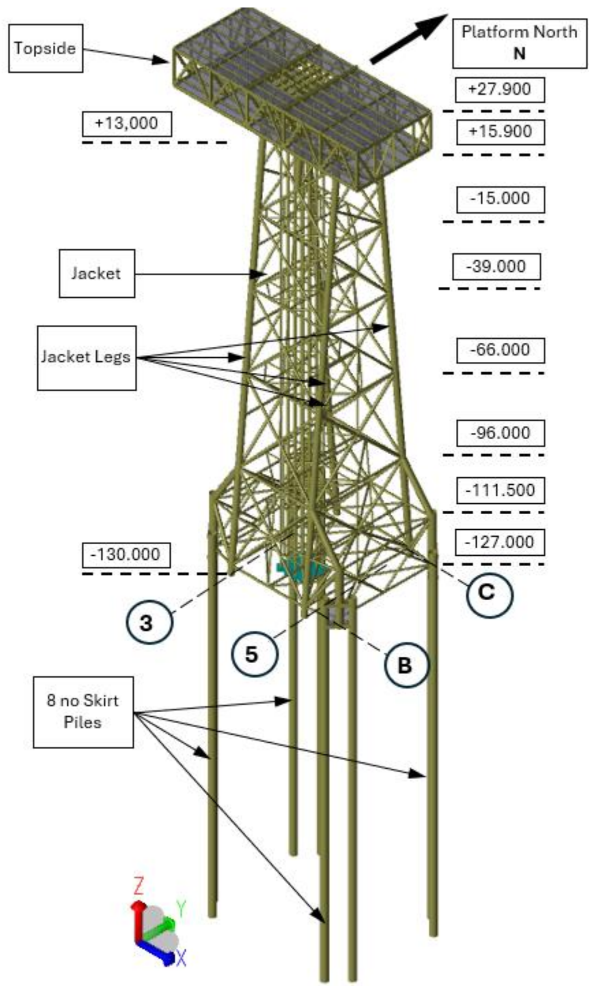


Fig. 1. The view of the modeled platform.

2.1.1. Superstructure geometry

The platform consists of a superstructure housing the Living Quarters (LQ), Modular Drilling Support Modules (MDSM), process area, utility services, wellhead area, and two cranes. Its dimensions are 12 m in height, 28 m in width, and 70 m in length. The 12 m deck height was determined considering structural stiffness and strength (Fig. 2).

The support legs measure 28 m by 15 m and are located at positions B5, C5, B4, C4, B3, and C3. The superstructure consists of two deck levels: the upper deck at elevation +15.9 m and the lower deck at elevation +27.9 m. Primary steel members were modeled with a yield strength of 460 N/mm^2, while secondary members were assigned 355 N/mm^2. Plates were modeled to carry shear forces only; axial stiffness was reduced so that the main lattice girders bear the global loads.

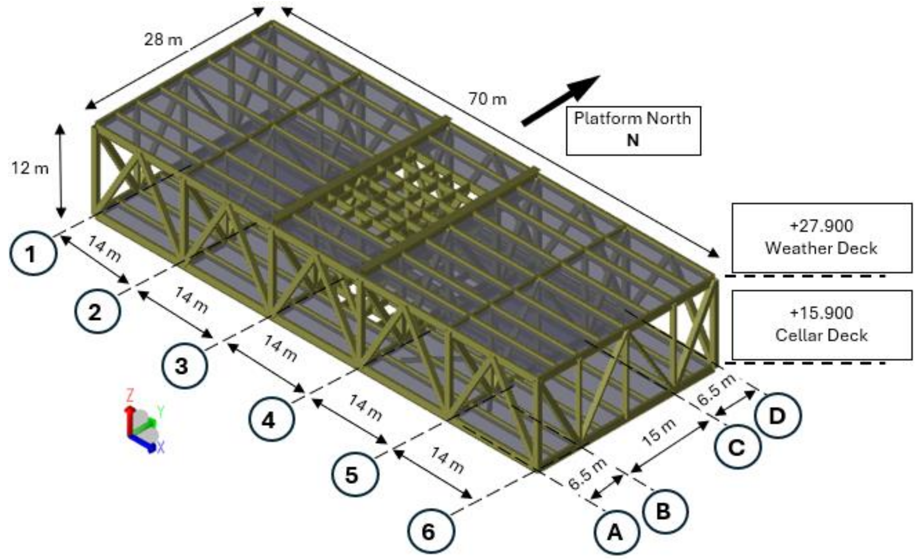


Fig. 2. Modeled superstructure dimensions.

2.1.2. Jacket geometry

The jacket structure is optimized for a water depth of 130 meters. Its top dimensions are 15 m × 28 m, while the base dimensions are 40 m × 48 m (Fig. 3). The superstructure rests on a total of six main legs; the two central legs are shorter than the others, terminating at elevation -1 m at the intersection of the jacket bracing. Inside the jacket, there are 16 conductor pipes, each with an outer diameter of 30 inches. These pipes are arranged at intervals of 2.8 m × 2.6 m and modeled to be self-supporting along the vertical axis. The conductor pipes are laterally stabilized by connections to the jacket members at elevations -15 m, -39 m, -66 m, and -96 m; however, they are not fixed vertically to the jacket structure.

2.1.3. Main skirt pile geometry

In this study, a total of eight steel piles with an outer diameter of 96 inches (2438 mm) and a wall thickness of 60 mm were used. The embedment depth of the piles into the soil is 117 m. The material selected is S460 grade steel; however, in accordance with applicable standards for wall thicknesses between 40 mm and 75 mm, the yield strength was reduced to 415 N/mm^2 (BS EN 10025-2:2019). The total length of each pile is 120 m, with a 3-meter section above the seabed reserved for connection to the jacket structure or the pile sleeve. This length also includes a shear allowance of 0.5 to 1.5 m to accommodate potential damage during pile driving operations (BS EN ISO 19902:2007). Furthermore, the pile length was determined considering field equipment limitations and dynamic effects during installation, ensuring adequate embedment for structural stability and load transfer. The modeled pile geometry is illustrated in Fig. 4.

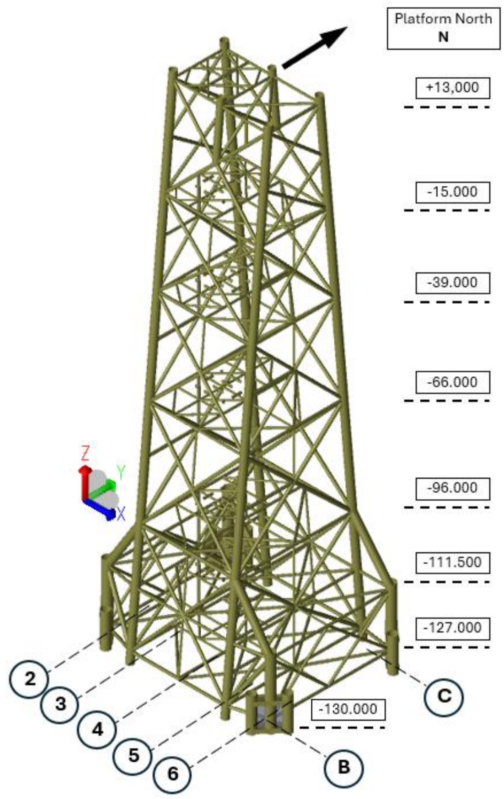


Fig. 3. Modeled jacket dimensions.

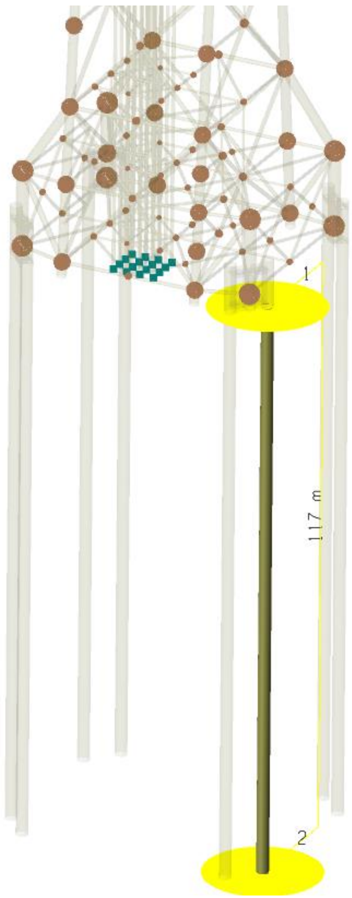


Fig. 4. Modeled pile geometry.

The piles will be driven to the target depth using an underwater hydraulic hammer and fixed to the jacket structure via a grouted pile–sleeve connection (BS EN ISO 19902:2007). Piles located beneath each jacket member are arranged in pairs with a center-to-center spacing of 7.2 m. This configuration aims to minimize soil–pile interaction effects.

The SESAM model also accounts for scour effects caused by marine currents on the seabed. A general scour depth of 2 meters and a local scour depth of 2 meters were defined in the upper soil layer. Temporary installation piles were excluded from this analysis.

2.2. Environmental loads and loading scenarios

This section summarizes the total weights acting on the platform structure. These data are critical for load analyses and structural stability assessments:

- Jacket Weight: The total weight of all components including legs, diagonals, and the base.
- Superstructure Weight: The weight of living quarters, process units, cranes, and other superstructure elements.
- Pile Weight: The total weight of eight steel piles with a diameter of 96 inches, wall thickness of 60 mm, and an embedment depth of 117 m.
- Guide Pipe Weight: The total weight of sixteen guide pipes with a diameter of 30 inches arranged at 2.8 m × 2.6 m spacing.
- Other Weights: Additional loads arising from various equipment and structural components not specified above.

Fig. 5 illustrates the main modules modeled in the system (MDR, DSM, LQ, Wellbay, Process) volumetrically, enabling accurate load distribution and structural interaction modeling.

The total weights of the superstructure, jacket, and piles are presented in Table 1.

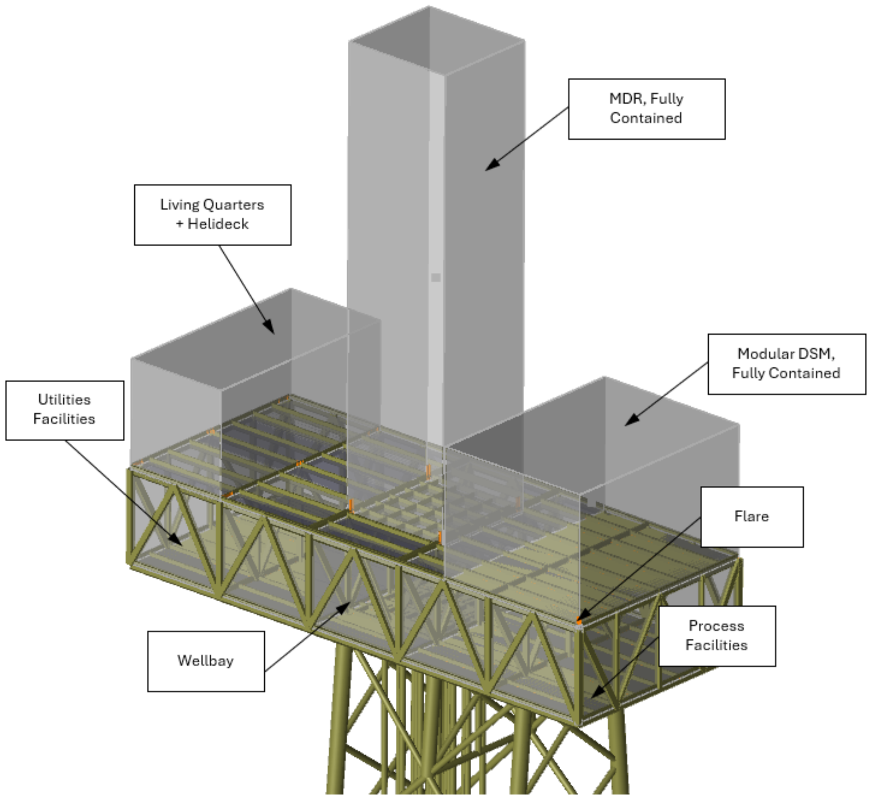


Fig. 5. Applied vertical loads.

Table 1. Total weight summary.

Structure	Self weight (t)	Content weight (t)	Total weight (t) (self weight+ content)
Topside	7638	3719	11357
Jacket	9666	–	9666
Pile	3294	–	3294

Wave and current loads acting on the platform were determined by considering wave height, wave period, current velocity, and flow direction. Using the "WAJAC" module of the SESAM-GeniE software, loads due to waves, wind, and currents were defined for operational (1-year), extreme (100-year), and abnormal (10,000-year) conditions.

A total of 18 different wave approach directions (Fig. 6) were considered, and these directions were transformed based on the positive X-axis reference defined within the "WAJAC" module of SESAM-GeniE.

As an example, wave and current loads for the 320° direction under 1-year, 100-year, and 10,000-year conditions, obtained from analyses performed with SESAM GeniE, are shown in Fig. 7.

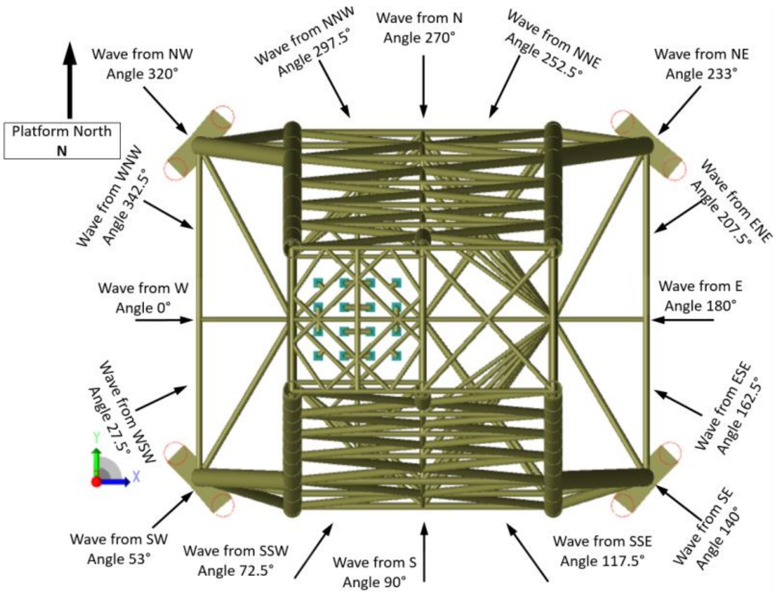


Fig. 6. Wave directions with respect to Sesam axes.

2.3. Analysis method

It should be noted that the 1-year, 100-year, and 10,000-year loading scenarios considered in this study pertain exclusively to the Inplace analysis and account only for dynamic environmental loads, specifically waves and wind, without including seismic effects. In this study, the structural behavior of a steel-piled offshore platform under environmental loading conditions was numerically modeled and analyzed using the Sesam Genie software developed by DNV GL. The analysis incorporated the interaction between the superstructure and pile foundation, soil properties, and various environmental loads.

The following modules were utilized throughout the modeling and analysis process:

- Splice: This module solves the interaction between a linear elastic superstructure and a nonlinear piled foundation. It calculates pile-head displacements and subsequently determines the distribution of internal forces, moments, and displacements along each pile. Advanced features such as pile-soil-pile interaction (group effects), multilayered soil profiles, second-order effects, and incremental loading are supported to enable comprehensive foundation analysis.
- Gensod: Generates nonlinear soil springs based on soil profiles defined within the Genie environment. It models the soil behavior realistically to represent pile-soil interaction accurately.
- Sestra: Performs linear static analysis of the jacket-type superstructure and evaluates global stability. The resulting global stiffness (K) and load (R) matrices are reduced and transferred to the Splice module for foundation analysis.
- Wajac: This module is used to apply wave and current loads. It employs Morison's equation with a nonlinear drag formulation to compute hydrodynamic forces in the time domain. In deterministic wave load analysis, the structure is subjected to unidirectional, periodic waves. At each step, the forces are computed up to the instantaneous water surface. Four wave theories are available for modeling: Airy, Stokes 5th-order, Dean's stream function, and Cnoidal wave theory.

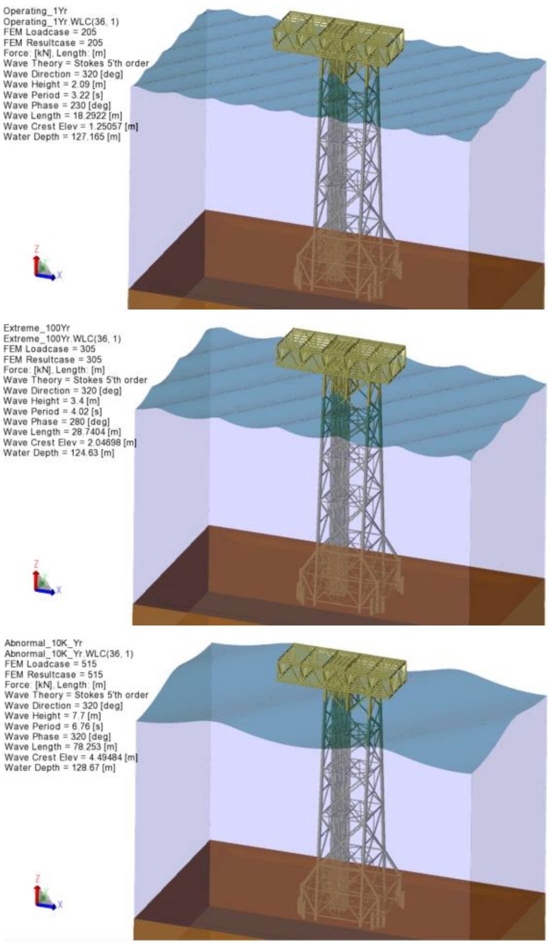


Fig. 7. Wave and current loads at 320° for 1, 100, and 10,000-year conditions.

In this study, Stokes 5th-order wave theory was applied to more accurately capture nonlinear wave effects. In addition, wind loads acting on the exposed jacket elements above the water surface were included using a stationary wind field assumption.

2.4. Soil models

A schematic illustration of the piled foundation system of a "Jacket Type" offshore platform and the soil structure surrounding this foundation is shown in Fig. 8.

The soil parameters (ZU1–ZU4) used in this study were derived from site-specific geotechnical investigations (Geotechnical Report, 2013). These soil units were used in various model combinations to evaluate the performance of pile foundations under coastal conditions. A summary of the soil models is presented in Table 2.

Each soil model includes variations in undrained shear strength, layer depth, and soil behavior under loading conditions (Table 3). The geotechnical parameters were obtained from detailed field investigations conducted in the Caspian Sea and were implemented into the structural models using the Sesam Genie software. These combinations were analyzed to evaluate pile capacity, deformation, and safety factors under operational, extreme, and exceptional loading scenarios.

Table 3 includes fundamental parameters such as depth intervals, unit weights (γ), shear strengths (Su), adhesion coefficients (α), shear stresses (τs), and layer thicknesses (ΔLi). These parameters are critical for understanding the geotechnical properties of each soil unit and for evaluating their effects on pile–soil interaction in the analysis.

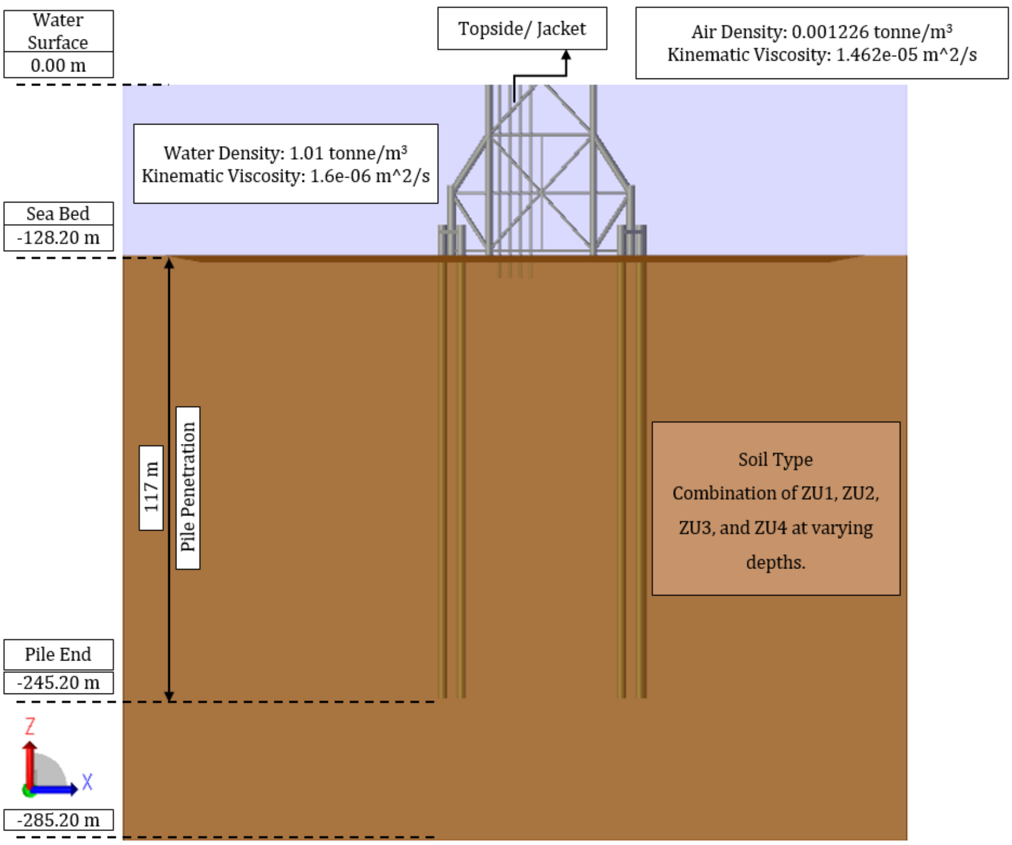


Fig. 8. Soil, water, and air geometry.

Table 2. Soil model units.

Soil unit	Soil type
ZU-1	Calcareous clay, yellowish gray, very soft to soft, with low plasticity, locally containing some shell fragments, organic matter inclusions, and layers of silt and fine sand. Representing soft clay with lower undrained shear strength values, commonly found in upper sedimentary layers.
ZU-2	Clay, greenish to bluish-gray, hard, high plasticity, with a plate and block structure and many slippery surface planes. A transitionary soil type, plastic and slightly stiffer than ZU1, used to simulate intermediate layers
ZU-3	Clay, hard, with a plate/block structure and many slippery surfaces. Medium stiff clay with higher resistance compared to ZU1 and ZU2. Represents more consolidated layers.
ZU-4	Clay, hard, with a plate/block structure and many slippery surfaces. Represents stiff clay with consistent strength and low plasticity index.

Table 3. Soil properties and geotechnical parameters.

Soil unit	Depth range (m)	Unit weight (γ) (kN/m^3)	Shear strength (Su) (kPa)	α	τs (kPa)	ΔLi (m)
ZU1	0 / 42	18.8	10 / 73	0.5/0.28	5.0 / 36.5	42
ZU2	−42 / −90	18.0	101 / 125	0.25	25.3 / 31.3	48
ZU3	−90 / −104	18.0	125 / 132	0.25	31.3 / 33.0	14
ZU4	−104 / −157	18.5	132 / 159	0.25	33.0 / 39.8	53

2.4.1. Soil model combination

In this study, a layered soil profile was created by combining four soil types: ZU1, ZU2, ZU3, and ZU4. Starting with a soft clay layer (ZU1) near the surface and transitioning to stiffer clay layers (ZU4) at greater depths, this configuration represents multi-layered soil conditions. Each layer is defined at different depths, and this approach was used to evaluate how pile–soil interaction varies under changing soil stiffness and strength. Fig. 9 visually presents the layered soil profile by displaying the ZU1–ZU4 soil units in different colors, illustrating their distribution with respect to depth. This visualization facilitates a clearer understanding of the pile–soil interaction.

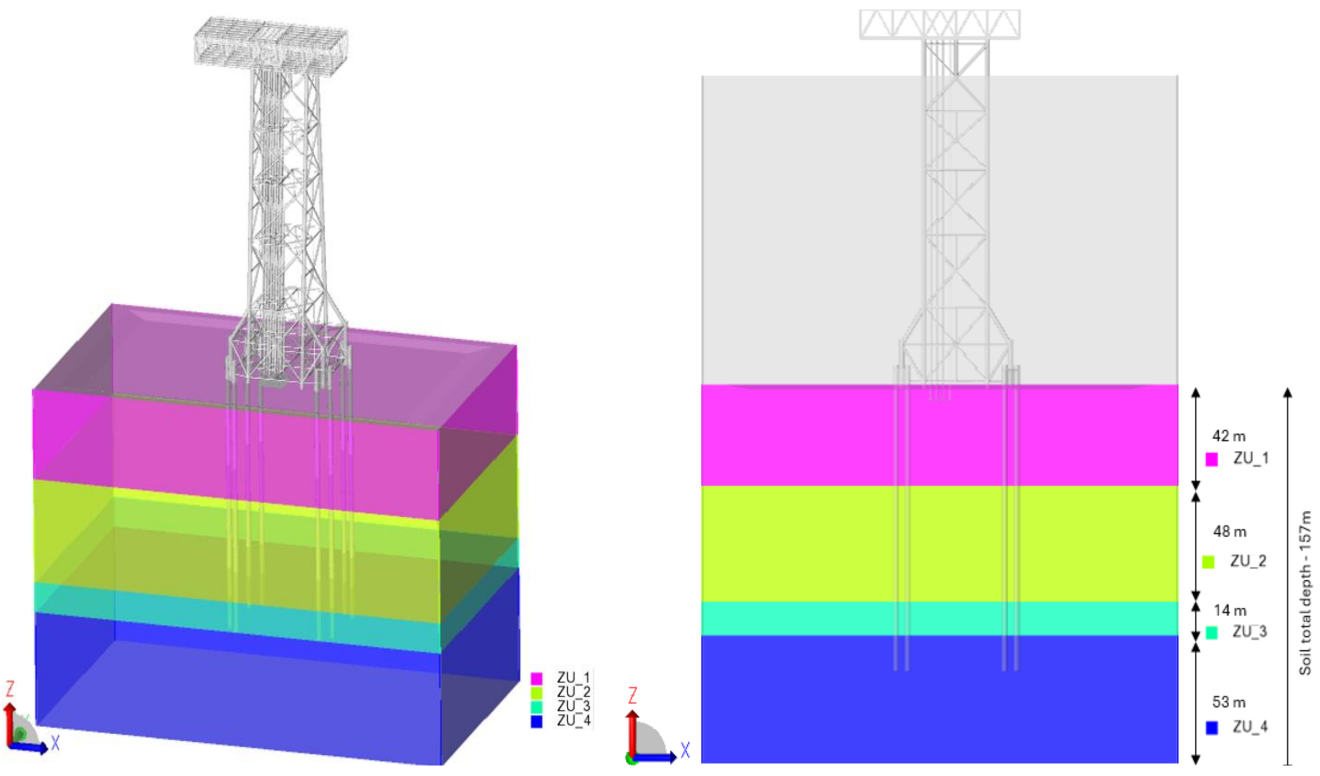
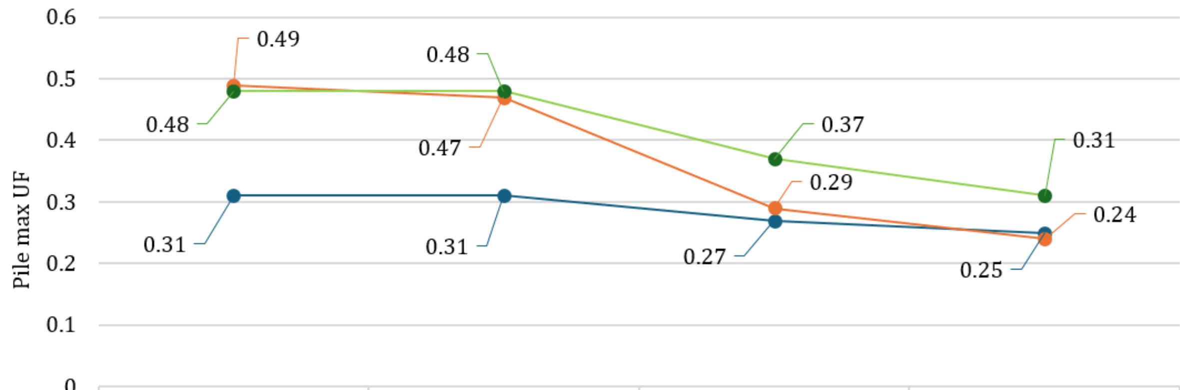


Fig. 9. Soil types and depths.

3. Results and Discussion

Fig. 10 presents the maximum utilization factors (UF) of the pile groups for each individual pile under 1-year, 100-year, and 10,000-year loading conditions. The utilization factor (UF) indicates the ratio of the applied load to the pile capacity; values approaching 1 signify that the capacity limit is nearly reached, while values exceeding UF>1 indicate that the capacity has been exceeded.

Below, code-check results for all pile groups are provided, considering operational (1-year), extreme (100-year), and abnormal (10,000-year) loading scenarios. Additionally, separate result tables are presented for each pile group. The evaluations are based on the most critical loading conditions and have been conducted in accordance with the ISO 19902 (2007).



	B2	B6	C2	C6
1yr Operating	0.31	0.31	0.27	0.25
100yr Extreme	0.49	0.47	0.29	0.24
10000yr Abnormal	0.48	0.48	0.37	0.31

Fig. 10. Maximum utilization factors (UF) of pile groups.

In the soil profile dominated by softer soils, pile utilization factors (UF) under lateral loading tend to exhibit relatively higher values. The highest utilization ratios occur under the combined effects of bending moments and lateral forces.

The UF values presented in Table 5 and illustrated in Fig. 11 reveal that pile groups B2 and B6 reach the highest utilization levels, particularly under the 100-year extreme and 10,000-year abnormal loading conditions. For example, Pile_B2_b attains a UF of 0.49 for the 100-year scenario and 0.48 for the 10,000-year scenario. Similarly, the B6 piles show high utilization values in the range of 0.47 to 0.48. These piles, located at the platform corners, are subjected to greater lateral moments and eccentric loads.

Conversely, the central piles in groups C2 and C6 demonstrate lower utilization ratios. For instance, Pile_C6_a exhibits a UF of 0.22 under the 1-year operational load, increasing to 0.30 under the 10,000-year abnormal condition. This indicates that central piles experience less impact from environmental loads and maintain a higher structural capacity reserve.

The most critical utilization factor (UF) values were observed under the 100-year extreme loading scenario rather than the 10,000-year abnormal loading scenario. This is primarily due to the fact that, in the 100-year wave scenario, the wave period and direction are more compatible with the natural frequencies of the structure, resulting in higher lateral responses in certain piles. In contrast, although the wave loads are generally higher in the 10,000-year scenario, the wave period and direction interact less with the structural stiffness, or the loads are more uniformly distributed, leading to lower local stresses in some piles.

This finding highlights that, in structural design, not only the magnitude of the loads but also the load direction, period, and the dynamic behavior of the structure have significant effects on the utilization factors.

3.1. Evaluation of maximum pile force and moment results

According to the results obtained by the SESAM Genie program, maximum tensile (positive) and compressive (negative) forces as well as moment values on the piles are reported for worst loading scenario (1-year operational, 100-year extreme, and 10,000-year abnormal). The force components acting on the piles are classified along the axial (NXX), transverse (NXY), and longitudinal (NXZ) directions; moment components represent rotations about the pile's X, Y, and Z axes (MXX, MXY, MXZ).

Focusing particularly on the NXX component, the highest tensile and compressive forces were observed in piles Pile_C6_b and Pile_B2_b. For example, under the 10,000-year loading scenario, Pile_C6_b experienced a tensile force of +38,397.6 kN and a compressive force of -58,092.8 kN. These values clearly demonstrate the effect of vertical loads (including dead loads and vertical environmental components) on the pile capacities.

Regarding the lateral forces NXY and NXZ, environmental effects such as waves and wind were dominant. Notably, Pile_C2_b carried a high lateral force of +4,839.7 kN in the NXZ direction under the 10,000-year condition. Similarly, Pile_B2_a was subjected to a lateral force of -3,007.4 kN in the transverse direction during the 100-year scenario. These forces vary depending on the orientation and magnitude of wave loads as well as the stiffness distribution of the structure.

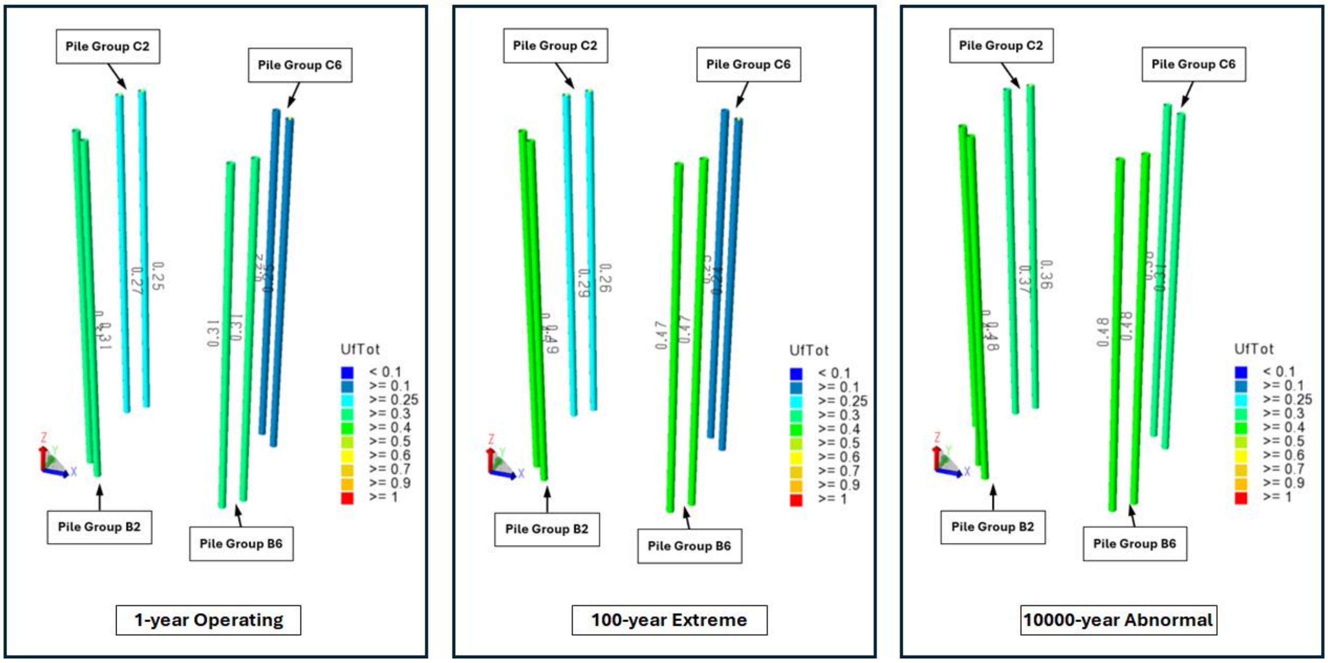


Fig. 11. Maximum utilization factors (UF) plot.

When examining moment components, the largest moments generally occurred at the pile toe and at piles located at corner positions. For instance, Pile_C6_a reached an MXZ moment value of -22,169.2 kN·m under the 10,000-year loading scenario, representing one of the highest moments. Additionally, Pile_C2_b exhibited an MXY moment of +19,862.1 kN·m. Such bending moments are critical parameters that directly influence the pile's stiffness under lateral loads and its anchorage behavior.

When the results are evaluated overall, it is observed that as the load magnitude increases, the forces and moments in the piles also increase. However, in some specific cases, the 100-year extreme loading scenario produces higher lateral forces or moments compared to the 10,000-year scenario. This difference arises from the wave direction and period resonating with the dynamic characteristics of the structure, thereby amplifying the response in certain piles. Particularly, corner piles (such as those in groups B2 and C6) carry greater loads in the rigid system and thus occupy the most critical positions, being subjected to maximum stress.

3.2. Evaluation of pile top displacement results

According to the pile head displacement analysis, limited horizontal and vertical displacements were observed for Pile_B2_a under the 1-year operational loading condition (Figs. 12 and 13). These displacements increased significantly under the 100-year extreme loading scenario, where a resonance-like behavior was observed. This resonance-like behavior is closely related to the interaction between the natural period of the structure and the excitation period of environmental loads. Although the natural period of the present jacket structure was not explicitly calculated in this study, its importance is acknowledged, and future research will aim to provide a detailed dynamic analysis to further clarify this effect. The highest displacement values were obtained under the 10,000-year loading condition. The horizontal and vertical displacements occurring at the pile head with increasing wave loads were evaluated in terms of structural stiffness and considered an important criterion for understanding the system's behavior.

Table 4. Maximum pile head displacements obtained from SESAM Genie program.

Pile name	Load case	DX [m]	DY [m]	DZ [m]
Pile_B2_a	1-Yr Operating	0.036	–	–
Pile_B2_a	1-Yr Operating	–	0.012	–
Pile_B2_a	1-Yr Operating	–	–	0.013
Pile_B2_a	100-Yr Extreme	0.051	–	–
Pile_B2_a	100-Yr Extreme	–	0.020	–
Pile_B2_a	100-Yr Extreme	–	–	0.020
Pile_B2_a	10000-Yr Abnormal	0.054	–	–
Pile_B2_a	10000-Yr Abnormal	–	0.025	–
Pile_B2_a	10000-Yr Abnormal	–	–	0.025

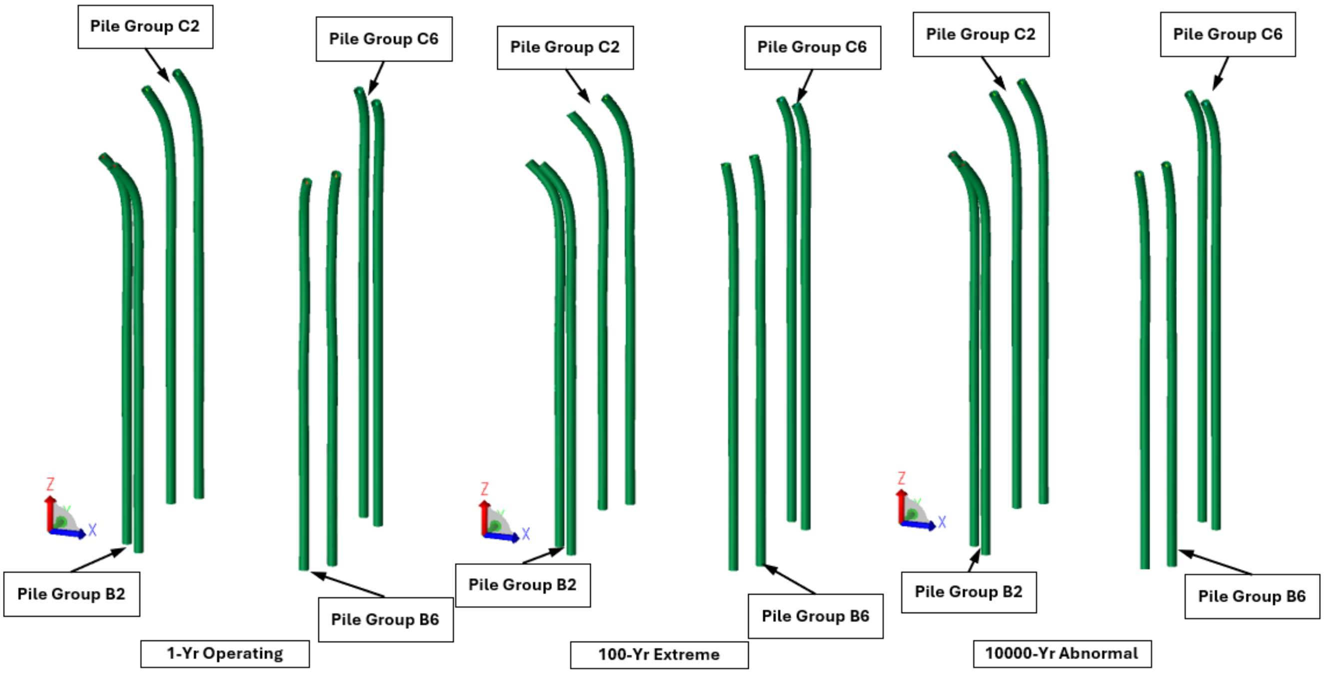


Fig. 12. Maximum displacement visualizations of piles.

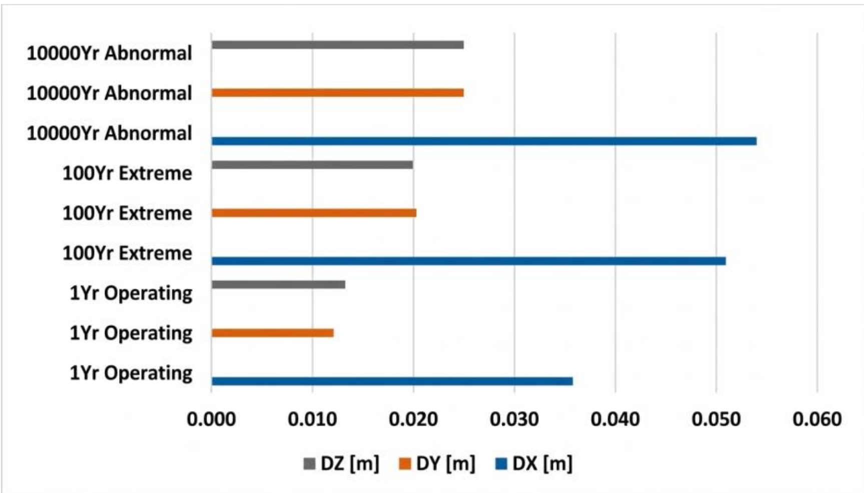


Fig. 13. Maximum displacements (DX, DY, DZ) at the top of Pile_B2_a.

3.3. Evaluation of maximum utilization factors of piles against ISO 19902 safety factors

In this section, the obtained maximum pile utilization factors (UF) are compared with the minimum safety factors specified in the ISO 19902 (2007) standard (Table 5). For each loading condition (1-year operational, 100-year extreme, and 10,000-year abnormal), the UF values were evaluated against the minimum allowable safety factors for the respective analysis cases to assess structural adequacy. This comparison reveals the extent to which the piles approach their design limits and whether the safety criteria for secure design are met.

The maximum pile utilization factors presented in Table 5 remain within safe limits when compared to the minimum safety factors specified in ISO 19902 (2007). Specifically, under the 1-year operational scenario (UF ≤ 0.67), 100-year extreme scenario (UF ≤ 0.80), and 10,000-year abnormal scenario (UF ≤ 1.00), none of the piles exceeded the allowable utilization limits. This indicates that the platform's load-carrying capacity is adequate (Fig. 14).

Figs. 15–17 show the program outputs for the maximum loads experienced by Pile_B2_a, which has the highest utilization factor (UF).

3.4. Evaluation of maximum pile head displacements against ISO 19902 allowable limits

The maximum pile head displacements (DX, DY, and DZ) observed under the 1-year, 100-year, and 10,000-year loading scenarios are summarized in Table 6. The allowable limits are based on ISO 19902 criteria.

All maximum displacements are well below the allowable limits, confirming that the pile foundation system maintains structural adequacy under the considered environmental loading conditions.

3.5. Comparison of utilization factors with literature

To provide context and highlight the novelty of the current study, Table 7 presents a comparison of maximum pile utilization factors (UF) reported in the literature for similar offshore platforms. It should be noted that the numerical results in the present study were obtained using the SESAM model with ZU1–ZU4 soil units, whereas the literature references used different modeling approaches, soil conditions, or experimental setups. Therefore, this comparison serves as a qualitative reference rather than a strict validation.

Table 5. Comparison of Utilization Factors (UF) and ISO minimum safety factors (FoS).

Pile group	Pile name	1 Yr Operating UF	ISO FoS (1/1.5 = 0.67)	1 Yr Extreme UF	ISO FoS (1/1.25 = 0.80)	10.000 Yr Anormal UF	ISO FoS (1/1.0 = 1.00)
B2	Pile_B2_a	0.31	✓ (0.67)	0.45	✓ (0.80)	0.43	✓ (1.00)
	Pile_B2_b	0.31	✓	0.49	✓	0.48	✓
B6	Pile_B6_a	0.31	✓	0.47	✓	0.48	✓
	Pile_B6_b	0.31	✓	0.47	✓	0.48	✓
C2	Pile_C2_a	0.25	✓	0.26	✓	0.36	✓
	Pile_C2_b	0.27	✓	0.29	✓	0.37	✓
C6	Pile_C6_a	0.22	✓	0.23	✓	0.30	✓
	Pile_C6_b	0.25	✓	0.24	✓	0.31	✓

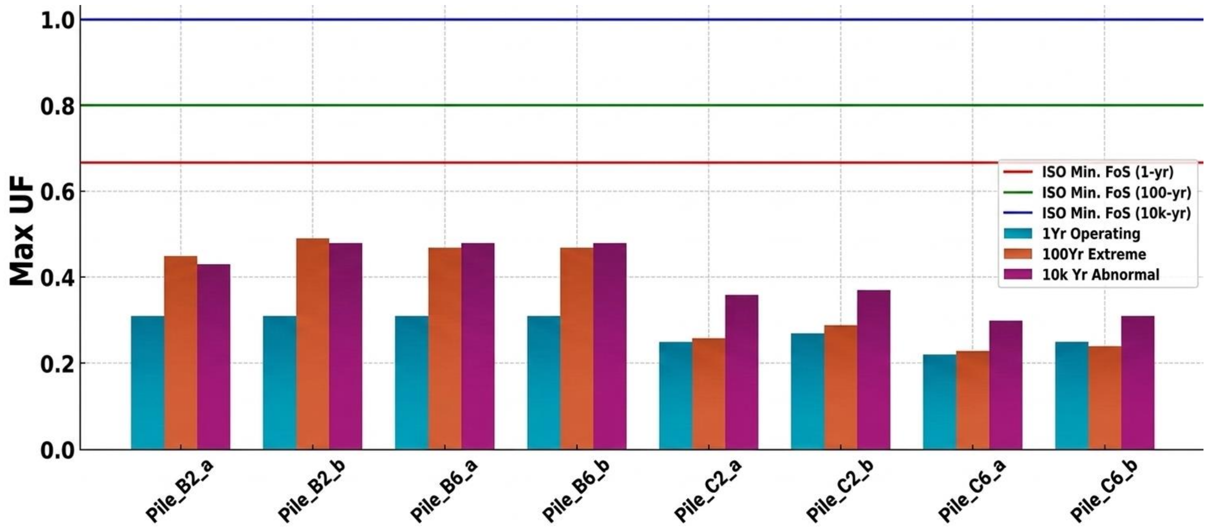


Fig. 14. Comparison of maximum utilization factors (UF) with ISO 19902 minimum FoS.

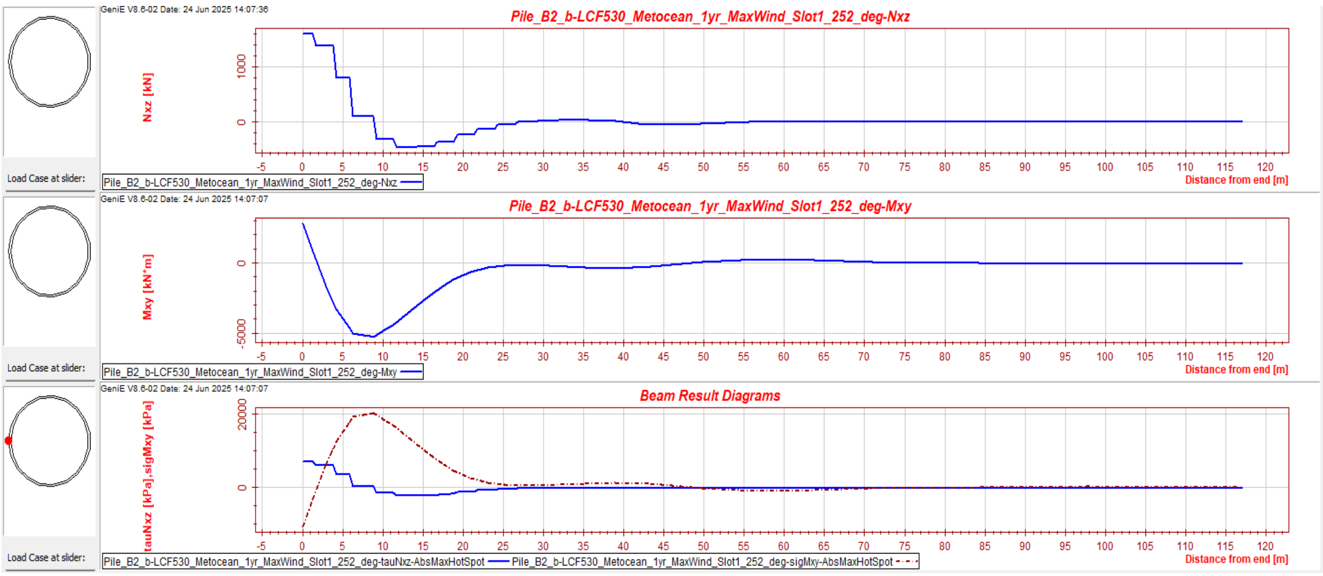


Fig. 15. Pile force outputs for Pile_B2_a under 1-year condition.

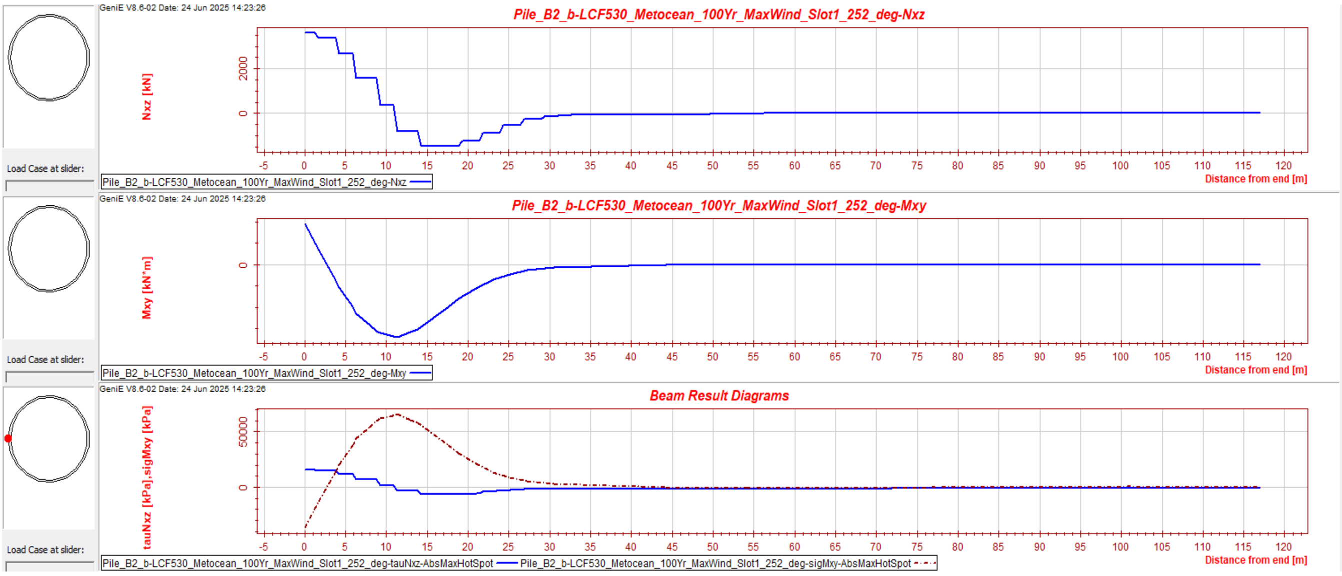


Fig. 16. Pile load outputs for Pile_B2_a under 100-year condition.

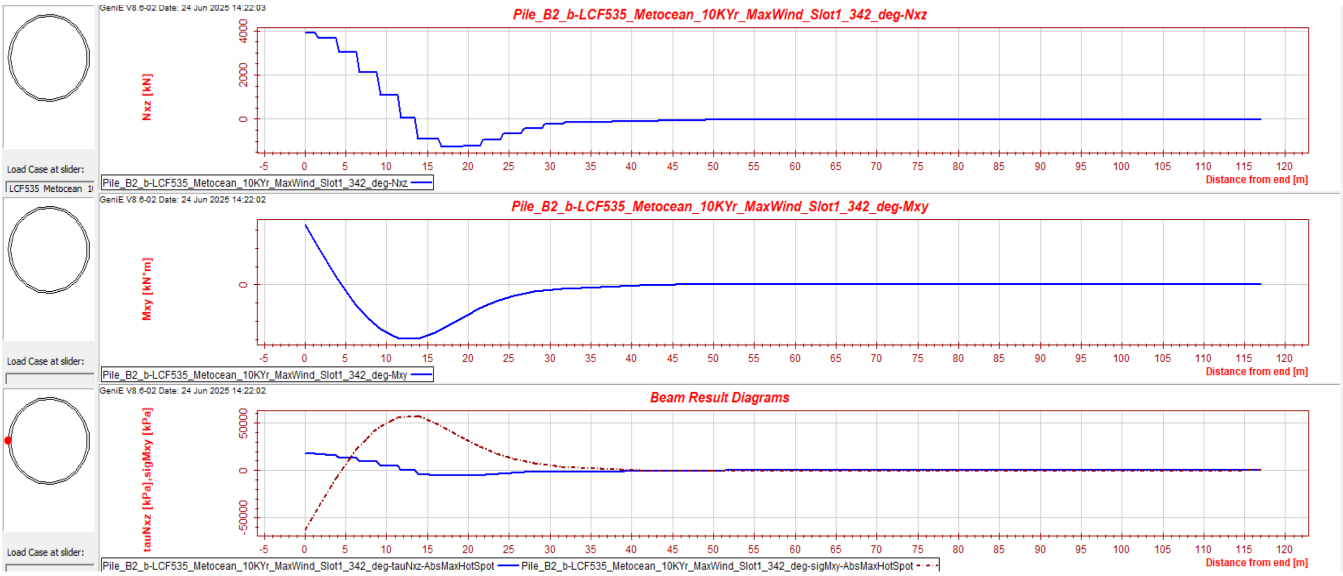


Fig. 17. Pile load outputs for Pile_B2_a under 10,000-year condition.

Table 6. Comparison of maximum pile head displacements against ISO 19902.

Worst pile	DX (m)	DY (m)	DZ (m)	Allowable DX/DY/DZ (m, ISO 19902) L/500	Compliance
Pile_B2_a	0.054	0.025	0.025	0.234 / 0.234 / 0.234	Acceptable

Table 7. Comparison of maximum utilization factors (UF) with literature.

Study / Source	Platform type	Soil type / Conditions	Maximum UF	Notes
Andersen (2015)	Jacket	Sand, layered	0.45	Laboratory and numerical data
LeBlanc et al. (2010)	Jacket	Stiff sand	0.40	Long-term cyclic lateral tests
Basack & Banerjee (2014)	Jacket	Layered soil	0.50	Numerical simulation
Liu et al. (2019)	Monopile	Sand	0.38	Lateral cyclic loadings
Xu et al. (2021)	Jacket	Clay / sand	0.55	Dynamic wave load analysis
This study	Jacket	Hybrid clay	0.49	SESAM model, 1-year / 100-year / 10,000-year loading

The comparison in Table 7 indicates that the maximum pile utilization factors obtained in this study are generally consistent with values reported in the literature for similar offshore platforms. While the literature results include different soil conditions and modeling approaches, the present work uniquely applies ZU1–ZU4 soil units in a detailed SESAM model under operational (1-year), extreme (100-year), and abnormal (10,000-year) wave and wind loading scenarios. Pile displacements are also in the expected range, reaching a maximum of 0.054 m in critical piles. This table therefore provides a qualitative benchmark rather than a direct validation.

3.6. Risk classification of piles based on UF

To provide an application-oriented interpretation of the utilization factor (UF) results, a simple risk classification framework was adopted (Table 8). In this scheme, piles with UF < 0.80 are categorized as Low Risk, UF between 0.80–0.90 as Moderate Risk, and UF > 0.90 as High Risk. This classification is consistent with practical engineering assessments of safety margins.

As shown in Table 8, all maximum UF values obtained in this study fall below 0.80, indicating that the analyzed pile foundations remain within the Low Risk category for all considered scenarios.

Table 8. Risk classification of piles based on utilization factors (UF).

Utilization Factor (UF)	Risk Level
UF < 0.80	Low Risk
0.80 ≤ UF < 0.90	Moderate Risk
UF ≥ 0.90	High Risk

4. Conclusions

This study provides a detailed evaluation of the structural performance of pile foundation systems installed in hybrid soil profiles (ZU1–ZU4) under different environmental loading scenarios. The analyses cover operational (1-year), extreme (100-year), and abnormal (10,000-year) conditions, considering axial and lateral force components (NXX, NXY, NXZ), moment components (MXX, MXY, MXZ), pile head displacements, and utilization factors (UF). The results were compared with the minimum safety factors specified in ISO 19902 (2007) to assess structural adequacy.

The maximum axial forces acting on the piles (NXX) reached approximately 58,100 kN under the 10,000-year scenario, testing the long-term strength reserves of the structure. Lateral force and moment components increased notably in scenarios dominated by wave and wind effects, highlighting the need to assess both axial capacity and lateral stability of pile foundations.

Pile head displacement analyses demonstrated reduced stiffness and increased horizontal displacements with higher loading intensities. For example, at Pile_B2_a, DX, DY, and DZ displacements increased from approximately 0.036 m, 0.012 m, and 0.013 m under the 1-year operational condition to about 0.054 m, 0.025 m, and 0.025 m under the 10,000-year loading condition. This indicates that pile–soil interaction evolves with loading and that structural stiffness control is critical for long-term performance.

Utilization factors remained well below critical limits across all scenarios, confirming that the current pile design maintains significant safety reserves. Corner piles (B2 and B6) experienced the highest UF values due to larger lateral moments, whereas central piles (C2 and C6) maintained lower utilization ratios, preserving structural capacity margins. Notably, some local UF maxima under the 100-year scenario exceeded those of the 10,000-year scenario due to resonance-like interactions between the wave period and the structure's natural frequencies. Although modal analysis was not included in this study, its potential influence is acknowledged and recommended for future investigations.

Overall, the pile geometry safely satisfies ISO 19902 requirements regarding load-carrying capacity and displacement criteria. However, displacement accumulation over long-term loading warrants careful monitoring. Critical areas of the structure should be instrumented to track performance and ensure durability under operational, extreme, and abnormal conditions.

From an engineering and practical standpoint, the significant safety margins identified in this study suggest opportunities for economic optimization. For instance, reducing pile diameter, wall thickness, or the total number of piles could result in cost savings without compromising safety, provided that ISO 19902 compliance is maintained.

For future research, additional aspects such as pile fatigue behavior, long-term soil degradation, scour evolution, and climate change–induced environmental loading should be incorporated. Furthermore, parametric studies involving different pile diameters, configurations, and soil types would enhance the generalizability of the findings and provide deeper insight for offshore foundation design.

5. Recommendations

- Analyze pile behavior under different wave loading scenarios to capture operational, extreme, and abnormal conditions.
- Perform seismic load case analyses to evaluate pile behavior under earthquake effects.
- Compare pile performance across different soil units, such as sandy, clayey, and other hybrid soil layers, to assess the influence of soil type on load-bearing capacity, displacement, and structural response.
- Extend analyses to include varying pile configurations and spacing within the different soil profiles to optimize foundation design.
- From an engineering and practical standpoint, the significant safety margins identified in this study suggest opportunities for design optimization and cost efficiency. For example, reducing pile diameter, thickness, or number of piles could provide economic benefits without compromising structural safety. Future research should further explore these optimization pathways, as well as incorporate aspects such as fatigue, long-term soil degradation, and climate change effects.

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Conflict of Interest

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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