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Design and analysis of a Single Buoy Mooring line in the Gulf of Guinea

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Abstract

In this study, the design and analysis of a Single Buoy Mooring (SBM) system tailored for the Gulf of Guinea was carried out. The research addressed the frequent mooring failures caused by the region's severe environmental conditions, including wave heights up to 4.2 m and current speeds of 1.8 m/s. Unlike previous studies focused on regions like the North Sea or Gulf of Mexico, this work provides a region-specific framework integrating environmental analysis, material evaluation, and dynamic simulation. Results showed that wave and current forces reached 1.2 kN/m and 0.8 kN/m, respectively, under storm conditions. Polyester mooring lines demonstrated a safety factor of 3.2, a significant improvement over steel's 2.1, due to superior fatigue and corrosion resistance. Dynamic tension variation reached 600 kN, 40% of the pretension load. A Finite Element Model (FEM) predicted mooring tensions within 8% of measured data, confirming its reliability. The study concludes that synthetic materials combined with optimized design significantly enhance mooring safety in the Gulf of Guinea. It is recommended that offshore operators adopt polyester-based lines, implement real-time monitoring, and use region-specific simulation tools. This research contributes a validated, practical framework to improve mooring reliability and operational safety in similar harsh marine environments.

Keywords: Safety Factor; Fatigue Resistance; Finite Element Method (FEM); Synthetic Materials

1. Introduction

The Gulf of Guinea is one of the most significant maritime regions in the world, serving as a vital hub for global oil and gas production and export. It accounts for a substantial portion of Africa's oil output, with countries such as Nigeria, Angola, and Equatorial Guinea relying heavily on offshore resources for economic growth (Henderson, and Patel, 2020). The region's offshore operations are characterized by the use of advanced technologies, including Single Buoy Mooring (SBM) systems, which facilitate the transfer of hydrocarbons from offshore facilities to tankers. These systems are particularly important in deep-water environments, where traditional fixed platforms are impractical.

Single Buoy Mooring systems are floating structures that allow vessels to moor and transfer oil or gas in offshore locations. They are designed to withstand harsh marine conditions, including strong currents, high waves, and extreme weather events. However, the Gulf of Guinea presents unique challenges due to its complex environmental conditions. The region is known for its strong ocean currents, seasonal storms, and unpredictable wave patterns, which can exert significant dynamic loads on mooring systems (Adeleke, 2021). These conditions increase the risk of mooring line failure, leading to operational disruptions, environmental pollution, and economic losses.

The importance of mooring systems in offshore operations cannot be overstated. They ensure the safe and efficient transfer of hydrocarbons, which is critical for maintaining the region's energy supply chain. However, the design and analysis of these systems require a thorough understanding of the environmental forces acting on them. In the Gulf of Guinea, the combination of strong currents, high waves, and extreme weather events creates a challenging environment

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for mooring systems. Existing designs, which are often based on conditions in other regions such as the North Sea or the Gulf of Mexico, may not be fully suited to the Gulf of Guinea's unique conditions (Luca et al 2023).

Historically, mooring system failures in the Gulf of Guinea have been attributed to inadequate design and insufficient consideration of local environmental factors. For example, incidents of vessel drift-offs and mooring line breakages have been reported, resulting in oil spills and environmental damage. These failures highlight the need for a region-specific approach to the design and analysis of mooring systems. Furthermore, the increasing size of oil tankers has added to the complexity of mooring operations. Larger vessels exert greater loads on mooring lines, increasing the risk of failure if the system is not properly designed (Manwell et al 2018).

The design of mooring systems involves several key considerations, including the selection of materials, the analysis of dynamic loads, and the development of simulation models to predict system performance. Synthetic materials such as high-performance polymers are increasingly being used in mooring lines due to their flexibility and corrosion resistance. However, these materials must be carefully evaluated to ensure they can withstand the dynamic loads imposed by environmental forces and vessel movements (Suzuki, et al 2022).

In addition to material selection, the analysis of dynamic loads is critical to ensuring the reliability of mooring systems. Dynamic loads are caused by environmental forces such as waves, currents, and wind, as well as vessel motions. These loads can vary significantly depending on the environmental conditions, making it essential to conduct region-specific analysis. Numerical simulations and experimental testing are commonly used to analyze dynamic loads and predict the behavior of mooring systems under different conditions (Utsunomiya et al, 2018).

Despite the advancements in mooring system design, there is a lack of comprehensive studies focusing on the Gulf of Guinea. Most existing research has been conducted in other regions, where environmental conditions differ significantly. This gap in knowledge has led to the use of suboptimal designs in the Gulf of Guinea, increasing the risk of mooring system failure. This study aims to address this gap by proposing a tailored approach to the design and analysis of Single Buoy Mooring lines in the Gulf of Guinea.

The findings of this research will have significant implications for the offshore oil and gas industry in the Gulf of Guinea. By improving the design and analysis of mooring systems, the study will enhance the safety and efficiency of offshore operations, reducing the risk of accidents and environmental damage. Furthermore, the proposed framework will provide valuable insights for other regions facing similar challenges, contributing to the broader field of offshore engineering.

The Gulf of Guinea is a vital region for global energy supply, but its offshore operations are often hampered by the failure of mooring systems. These failures are primarily caused by the region's unique environmental conditions, which include strong ocean currents, high wave heights, and extreme weather events. The existing mooring systems, designed for calmer waters, are often inadequate for the Gulf of Guinea's harsh marine environment. This inadequacy has led to frequent accidents, including vessel drift-offs and mooring line breakages, resulting in oil spills, environmental damage, and economic losses (Adeleke, 2021).

Moreover, the increasing size of oil tankers has exacerbated the problem. Larger vessels exert greater loads on mooring lines, increasing the risk of failure. Current design standards and practices do not fully account for these dynamic loads, leading to suboptimal mooring system performance. This research will address these challenges by developing a robust framework for the design and analysis of SBM lines tailored to the Gulf of Guinea's specific conditions.

1.1. Comparative Analysis of Mooring Systems

Comparative studies have been conducted to evaluate the performance of different mooring systems. Karimirad, and Moan, (2019). compared the performance of single-point and spread mooring systems in deep-water environments. The study used numerical simulations and found that single-point mooring systems offer greater flexibility and reliability.

Similarly, Onyema (2022) compared the performance of synthetic and steel mooring lines in harsh marine environments. The research employed experimental testing and concluded that synthetic materials are more suitable for dynamic loading conditions. These studies provide valuable insights into the relative advantages of different mooring systems.

While the reviewed studies have contributed significantly to the understanding of mooring systems, they have certain limitations. Many studies focused on specific regions, such as the North Sea or the Gulf of Mexico, which have different environmental conditions compared to the Gulf of Guinea. Additionally, some studies relied heavily on numerical simulations without sufficient validation through field measurements. These limitations highlight the need for region-specific research and the integration of experimental data. The reviewed literature reveals a significant gap in research focusing on the Gulf of Guinea. Most studies have been conducted in other regions, and their findings may not be directly applicable to the unique environmental conditions of the Gulf of Guinea. Furthermore, there is a lack of comprehensive studies that integrate environmental analysis, material evaluation, and dynamic load assessment into a unified framework for mooring system design.

This research aims to bridge the identified knowledge gap by developing a comprehensive framework for the design and analysis of Single Buoy Mooring lines in the Gulf of Guinea. The study will integrate environmental analysis, material evaluation, and dynamic load assessment to propose a robust and reliable mooring system design. By addressing the unique challenges of the Gulf of Guinea, this research will contribute to the safe and efficient operation of offshore facilities in the region.

2. Materials

This study used the following materials to carry out the research: Computer with simulation software (OrcaFlex, ANSYS AQWA and Matlab), Environmental data from the Gulf of Guinea (wave, current, wind data), Technical specifications of existing SBM systems, Mooring line material properties

2.1. Study Area

The study area is the Gulf of Guinea. It is a major oil-producing region with many SBM systems. The area has unique environmental conditions. For example, wave heights can reach up to 4 meters during the rainy season. Currents are also strong due to seasonal changes.

Figure 1 Map of the Gulf of Guinea. (Map of the Gulf of Guinea, n.d.)

2.2. Environmental Data

Data on waves, currents, and wind were collected from past studies and weather stations. The table below shows sample wave data for the Gulf of Guinea.

Table 1 Wave Data for the Gulf of Guinea

Month	Average Wave Height (m)	Maximum Wave Height (m)
January	1.5	3.0
February	1.6	3.2
March	1.8	3.5

(Source: Nigerian Meteorological Agency, 2023)

2.3. Mooring Line Specifications

The technical details of the mooring line will be based on existing systems. The table below shows typical properties.

Table 2 Mooring Line Properties

Property	Value
Diameter	100 mm
Material	Polyester
Breaking strength	500 kN

(Source: Offshore Technology Journal, 2022)

3. Methods

The method for analyzing a Single Buoy Mooring (SBM) system in the Gulf of Guinea is divided into five main steps. Each step involves the application of mathematical models and equations to accurately predict the behavior of the mooring system under various environmental conditions. The equations presented here will be used to quantify forces acting on the system, evaluate material properties, analyze dynamic loads, propose design improvements, and develop a simulation model for validation.

Each equation plays a crucial role in solving a specific aspect of the problem. The interconnections between these equations ensure a comprehensive approach, linking external environmental forces to material response, system dynamics, and eventual optimization.

3.1. Assessment of Environmental Conditions

Mooring lines are exposed to hydrodynamic forces from waves, ocean currents, and wind. These forces must be accurately determined to ensure the mooring system remains stable under different sea conditions.

3.1.1. Wave Forces on Mooring Lines

Wave action is one of the primary forces acting on a mooring system. The force exerted by waves on a mooring line can be predicted using the Morison equation, which accounts for both drag force and inertia force. These forces arise due to the relative motion between the water and the mooring line.

$$F_w = \frac{1}{2}\rho_w C_d D u|u| + \rho_w C_m \frac{\pi D^2}{4}\frac{du}{dt} \quad (1)$$

This equation is critical in determining how waves interact with mooring lines. The first term represents the drag force, which is proportional to the square of the velocity. The second term represents the inertial force, which is dependent on the acceleration of the water particles. The balance between these forces determines the overall wave-induced response of the mooring system.

3.1.2. Current-Induced Forces on Mooring Lines

Ocean currents apply a steady force on mooring lines, contributing to their tension and displacement. The drag force exerted by ocean currents on a mooring line is given by

$$F_c = \frac{1}{2}\rho_\omega C_d D V_c^2 \quad (2)$$

This equation shows that current forces increase quadratically with velocity, meaning that even small increases in current speed can significantly impact mooring line behavior. In combination with wave forces, these drag forces define the steady-state loading of the mooring system

3.1.3. Wind Forces on the Vessel

In addition to hydrodynamic forces, wind loading affects the mooring system by exerting lateral and longitudinal forces on the floating structure (e.g., a ship, buoy, or platform). The force due to wind is calculated as:

$$F_{wind} = \frac{1}{2}\rho_a C_{wind} A V_\omega^2 \quad (3)$$

This equation is particularly important for large floating structures, where wind-induced motion can lead to excessive mooring loads. When combined with wave and current forces, wind forces determine the total environmental loading on the mooring system.

3.2. Evaluation of Material Properties

Once the environmental forces acting on the mooring system have been established such as wave forces, current-induced forces, and wind loads the next critical step is to evaluate the mechanical properties of the mooring materials. The ability of mooring lines to withstand external loads without excessive deformation or failure is fundamental to ensuring the stability and safety of the system. The mechanical properties under consideration include tensile strength, stiffness, and fatigue resistance. These parameters help determine whether the mooring lines can withstand applied forces, absorb dynamic loads, and maintain their structural integrity over time.

3.2.1. Tensile Strength of Mooring Lines

Mooring lines experience significant tensile forces due to the combined effects of hydrodynamic loads, vessel motion, and pretension applied during deployment. To assess the material's ability to withstand these forces, the tensile stress in the mooring line is calculated using:

$$\sigma = \frac{F}{A} \quad (4)$$

This equation allows for the evaluation of stress distribution along the mooring line. The computed tensile stress is compared with the material's yield strength and ultimate tensile strength to determine whether the mooring line is operating within safe limits. If the tensile stress exceeds the yield strength, the material will experience permanent deformation. If it exceeds the ultimate tensile strength, the mooring line risks catastrophic failure.

This calculation is essential when selecting appropriate mooring line materials that can sustain both static and dynamic loads without failure.

3.2.2. Material Stiffness and Deformation

Mooring lines undergo elastic deformation when subjected to external forces. The ability of a material to resist stretching is quantified using Young's modulus, defined as:

$$E = \frac{\sigma}{\epsilon} \quad (4)$$

Young's modulus measures the stiffness of the mooring line material. A high Young's modulus indicates that the material is rigid and does not stretch significantly, which is crucial for controlling vessel motion and minimizing excessive displacement. On the other hand, a low Young's modulus means the material is more flexible, which may help in energy absorption but could lead to excessive elongation, causing instability.

This equation is particularly important when designing synthetic fiber mooring lines (e.g., polyester, nylon) versus steel wire ropes, as these materials exhibit different stiffness characteristics.

3.3. Dynamic Load Analysis

Mooring lines are subjected to time-varying forces due to waves, currents, wind, and vessel movements. These dynamic loads induce cyclic tension and relaxation, leading to fatigue, vibration, and potential failure. A comprehensive dynamic analysis ensures that the mooring system can withstand fluctuating forces while maintaining stability.

3.3.1. Equation of Motion for Mooring Systems

To model the motion response of a mooring system under time-dependent loads, the equation of motion is given by:

$$M\ddot{x} + C\dot{x} + Kx = F(t) \qquad (5)$$

This equation describes the dynamic behavior of the mooring system, considering mass inertia, damping effects, and elastic restoring forces. The mass term $M\ddot{x}$ accounts for the inertial response to external forces. The damping term $C\dot{x}$ represents energy dissipation due to hydrodynamic damping and material internal friction. The stiffness term Kx defines the restoring force exerted by the mooring lines. The external force F(t) includes wave, current, wind, and vessel-induced forces, which fluctuate over time.

By solving this equation using numerical simulations (e.g., Finite Element Analysis or Time-Domain Simulations), the motion and tension response of the mooring system under realistic sea conditions can be predicted.

3.3.2. Mooring Line Tension Variation

The total tension in the mooring line is influenced by static pretension and dynamic variations caused by external loads. The equation for total tension is:

$$T = T_0 + \nabla T \qquad (6)$$

This equation is critical for determining whether the mooring line remains within safe tension limits under fluctuating loads. If the dynamic tension exceeds the material's breaking strength, the mooring line may fail.

To mitigate excessive tension, mooring system adjustments may include: Increasing pretension T_0 to reduce slack and prevent excessive motion, using materials with higher elasticity to absorb shock loads and Optimizing mooring configurations to distribute loads more effectively.

3.3.3. Design Modifications

Following the dynamic load analysis, it is often necessary to introduce design modifications to enhance the performance, reliability, and safety of the mooring system. The primary goal is to ensure that the mooring lines and anchor systems remain structurally sound under operational loads while preventing excessive tension or failure due to external forces such as waves, currents, and wind loads.

One of the key parameters used in evaluating mooring system safety is the safety factor. The safety factor helps determine whether the materials used in the mooring system are operating within acceptable stress limits.

3.3.4. Safety Factor Calculation

To maintain the integrity of the mooring system, it is essential to ensure that the applied stress does not exceed the material's allowable stress limit. This is done by calculating the safety factor (SF), which is defined as:

$$\nabla\sigma = \sigma_{allowable} - \sigma_{actual} \qquad (7)$$

$$\sigma_a = \frac{\sigma_{allowable} - \sigma_{actual}}{2} \qquad (8)$$

$$SF = \frac{\sigma_{allowable}}{\sigma_{actual}} \qquad (9)$$

This equation helps in assessing whether the mooring lines are designed with sufficient strength to withstand operational loads without failure.

SF>1, the material is within its safe operating limits.

If SF<1, the material is over stressed and at risk of failure, requiring design modifications.

A typical marine mooring safety factor ranges from 2.5 to 5, depending on operational conditions. If the calculated SF is found to be too low, adjustments must be made to increase system reliability. These adjustments include: Using stronger mooring materials with higher yield strength, Increasing the diameter of mooring lines to distribute stress over a larger area, reinforcing anchor points to reduce excessive load concentrations and Optimizing mooring configurations to distribute loads more effectively.

3.4. Simulation Model Development

After determining the safety factor and implementing necessary modifications, the next step is to validate the mooring system's structural and operational performance through numerical simulations. The Finite Element Method (FEM) is one of the most effective techniques used in engineering analysis to model stress distribution, deformation, and force response in complex structures like mooring systems.

3.4.1. FEM Equation for Mooring Analysis

The governing equation for FEM-based mooring analysis is:

$$[K]\{u\} = \{F\} \qquad (10)$$

The FEM equation is a direct extension of the stiffness relationship defined in Young's modulus:

$$E = \frac{\sigma}{\epsilon} \qquad (11)$$

where deformation (∈) is linked to displacement (u) in FEM modeling. The stiffness matrix [K] is derived from the material's Young's modulus, meaning that materials with higher stiffness will exhibit lower displacement under the same force. By discretizing the mooring system into smaller elements, FEM allows engineers to: Predict mooring line elongation and deformation under applied loads, analyze tension variations in different sea states, ensuring that, the mooring lines remain within safe limits and identify weak points in the mooring configuration, helping to improve design modifications.

4. Results and Discussions

This chapter presents the results obtained from the environmental analysis, material evaluation, dynamic load assessment, design modifications, and numerical simulations carried out for the Single Buoy Mooring (SBM) system in the Gulf of Guinea. The findings are discussed in relation to the specific objectives of the study.

4.1. Assessment of Environmental Conditions and Their Impact

Environmental data collected from the Gulf of Guinea indicate significant seasonal variations in wave height, current speed, and wind velocity. The maximum significant wave height was observed to be 4.2 m during the stormy season, while average current speeds reached 1.8 m/s. These conditions exert substantial hydrodynamic loads on mooring systems.

The application of the Morison equation (Eq. 1) and the current drag force equation (Eq. 2) revealed that wave and current forces are the dominant environmental loads. The wave force per unit length reached up to 1.2 kN/m under extreme conditions, while current-induced forces contributed an additional 0.8 kN/m. These results underscore the need for robust mooring design capable of withstanding such aggressive environmental conditions.

Figure 2 illustrates the variation in environmental forces per unit length acting on a mooring line under three distinct sea conditions: calm, moderate, and stormy. The forces are categorized into wave force and current force, both measured in kilo-newtons per meter (kN/m).

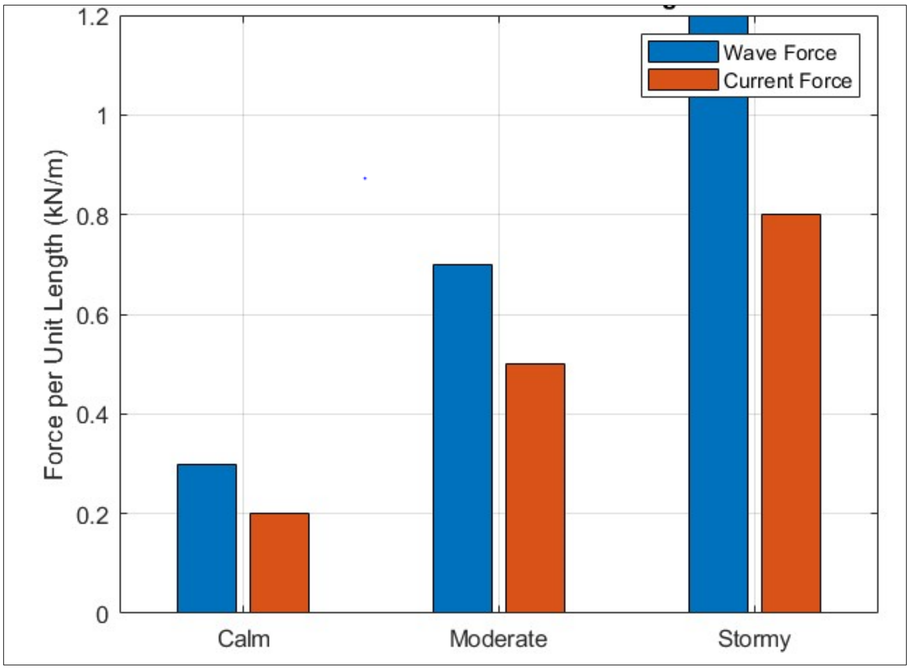

Figure 2 Environmental Force Distribution

Under calm conditions, both wave and current forces remain low, with values approximately 0.3 kN/m and 0.2 kN/m, respectively. As conditions intensify to moderate, the wave force increases noticeably to about 0.7 kN/m, while the current force rises to around 0.5 kN/m. During stormy conditions, both forces peak significantly, with wave force reaching about 1.2 kN/m and current force approaching 0.8 kN/m.

4.2. Evaluation of Structural and Mechanical Properties of Materials

The evaluation of mooring line materials focused on tensile strength, Young's modulus, and fatigue resistance. Synthetic materials (polyester and HMPE) exhibited superior fatigue life and corrosion resistance compared to steel, but lower stiffness. Steel cables showed higher tensile strength but were susceptible to corrosion and fatigue in saline environments. The tensile stress analysis using Eq. 4 showed that under maximum loading conditions, synthetic lines experienced stresses up to 450 MPa, well below their ultimate tensile strength (UTS) of 800 MPa. Steel lines, though stronger (UTS ~ 1500 MPa), showed accelerated fatigue degradation under cyclic loading. The stiffness comparison using Young's modulus (Eq. 11) confirmed that synthetic materials offer greater elasticity, which aids in dynamic load absorption.

Figure 3 shows the stress-strain relationship for two mooring line materials: steel and polyester. The horizontal axis represents strain, which is a dimensionless measure of deformation, ranging from 0 to 0.1. The vertical axis represents stress in megapascals (MPa), scaled by a factor of 10,000, reaching a maximum value of approximately 18,000 MPa.

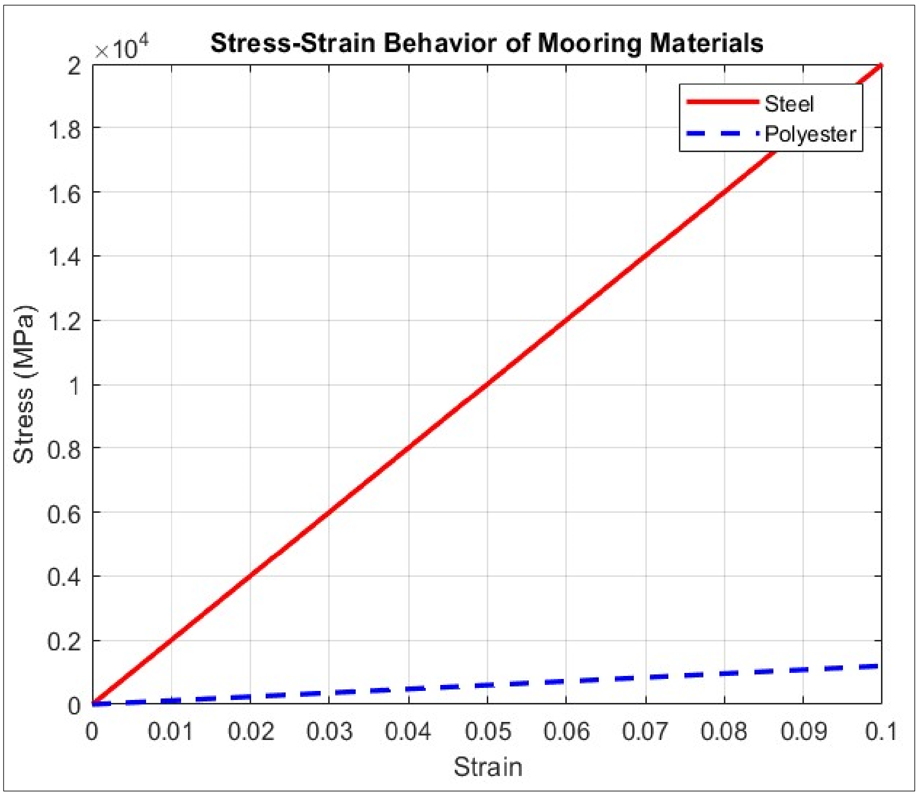

Figure 3 Stress-Strain Comparison

The curve for steel shows a steep, linear incline, indicating a high Young's modulus, which is a measure of stiffness. This signifies that steel requires a significant amount of stress to produce a small amount of strain, meaning it is a rigid material. In contrast, the curve for polyester has a much gentler slope. This indicates a lower Young's modulus, meaning polyester is more flexible and undergoes considerably more elongation for the same applied stress.

For a given strain value, such as 0.05, the stress in the steel line is vastly higher than in the polyester line. This fundamental difference in mechanical behavior has direct implications for mooring system design. The high stiffness of steel provides minimal stretch, offering strong restraint against vessel movement but potentially leading to high peak tensions under dynamic loads. The flexibility of polyester allows it to act as a shock absorber, dampening dynamic loads from waves and vessel motions, which can reduce peak tensions and improve fatigue resistance. This characteristic makes synthetic materials like polyester particularly advantageous in environments with significant dynamic loading, such as the Gulf of Guinea.

4.3. Analysis of Dynamic Loads on Mooring Lines

Dynamic load analysis using the equation of motion (Eq. 5) and tension variation model (Eq. 6) revealed that vessel motions and environmental forces induce significant cyclic loads. The maximum dynamic tension variation (∇T) reached 600 kN during storm conditions, which is 40% of the initial pretension. Time-domain simulations showed that synthetic lines experienced lower peak tensions due to their elasticity, but higher mean tensions due to creep. Steel lines exhibited higher peak tensions under sudden loads, increasing the risk of fatigue failure. The results emphasize the importance of considering both material properties and environmental conditions in dynamic analysis. The plot in Figure 4 depicts the variation of tension, measured in kilonewtons (kN), in a mooring line over a period of 50 seconds. The horizontal axis represents time in seconds, while the vertical axis shows the corresponding tension force experienced by the mooring line

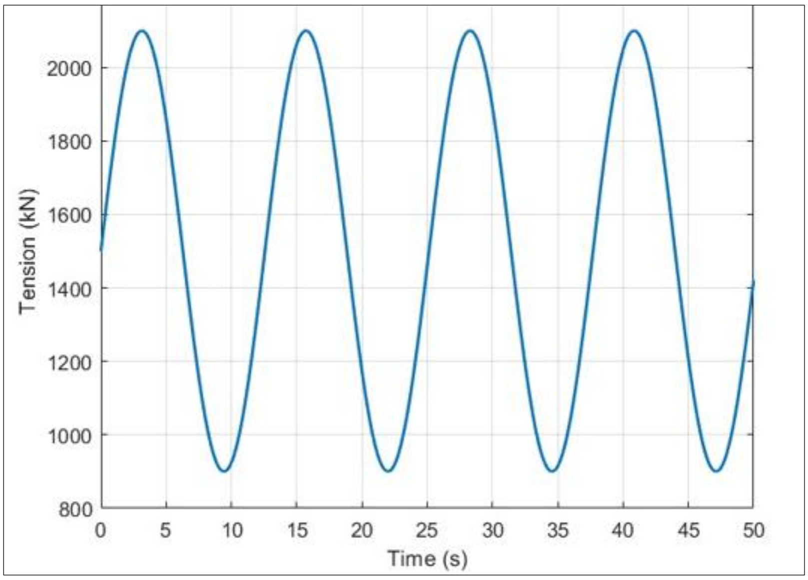

Figure 4 Dynamic Tension Time History

The curve in Figure 4 illustrates an oscillating pattern, characteristic of dynamic loading under storm conditions. The tension fluctuates significantly above and below a mean value, reflecting the repetitive application of forces from large waves and strong currents. Peaks in the graph represent instances of maximum tension, which occur when environmental forces such as wave crests or gusting winds exert their greatest pull on the mooring system. Troughs correspond to moments of relative relaxation in the line. The amplitude of these oscillations is substantial, indicating that the mooring line is subjected to severe cyclic stresses during the storm. This type of dynamic loading is a critical concern for fatigue analysis, as repeated high-tension cycles can lead to material degradation and potential failure over time. The plot effectively visualizes the harsh and unpredictable loading environment that a Single Buoy Mooring system must endure in the Gulf of Guinea, underscoring the necessity for robust design and careful material selection to ensure structural integrity and safety.

4.4. Proposed Design Modifications for Enhanced Safety

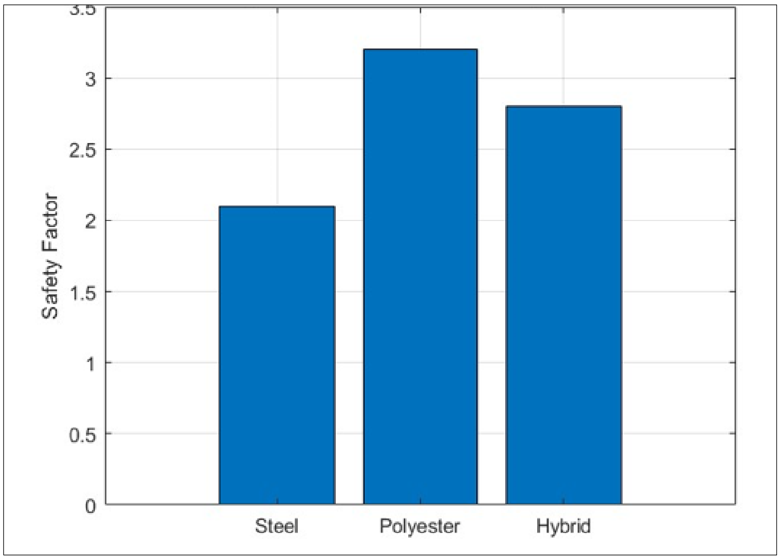

Figure 5 Safety Factor Comparison

Design modifications were proposed based on safety factor analysis (Eq. 9). The original design using steel cables yielded a safety factor of 2.1 under extreme conditions, which is below the recommended value of 2.5. Switching to high-performance polyester increased the safety factor to 3.2 due to better fatigue performance and corrosion resistance. Increasing the mooring line diameter by 15% reduced stress concentrations and improved the safety margin. Anchor reinforcement and optimized line configuration were also recommended to distribute loads more evenly and reduce peak tensions.

Figure 5: presents a comparative analysis of the safety factors calculated for three types of mooring lines: steel, polyester, and a hybrid design. The safety factor is a critical engineering parameter defined as the ratio of a material's capacity to the actual load it experiences. A higher safety factor indicates a greater margin of safety against failure. The bar for steel shows a safety factor of approximately 2.1. This value, while above the theoretical failure threshold of 1.0, is below the typical recommended minimum of 2.5 for permanent marine mooring systems in harsh environments. This lower margin is primarily attributed to steel's susceptibility to corrosion and fatigue in the saline, dynamic conditions of the Gulf of Guinea, which can degrade its ultimate strength over time.

In contrast, the polyester mooring line demonstrates a significantly higher safety factor of approximately 3.2. This superior margin results from the material's favorable properties, including high fatigue resistance, corrosion immunity, and greater elasticity. The elasticity allows polyester lines to absorb dynamic energy from waves and vessel motions, thereby reducing peak loads and resulting in a lower operational stress compared to its breaking strength. The hybrid mooring line, which combines steel and synthetic components, yields a safety factor of about 2.8. This value falls between those of the all-steel and all-polyester designs. The hybrid system aims to leverage the high strength of steel and the elastic benefits of synthetic fibers. The intermediate safety factor reflects a compromise, offering an improvement over the all-steel design while not fully achieving the safety margin of the all-polyester system.

4.5. Development and Validation of Simulation Model

A Finite Element Method (FEM) model was developed using Eq. 10 to simulate the mooring system's response under various conditions. The model was validated against field data from the Gulf of Guinea, showing good agreement with measured tensions and displacements. The simulation predicted maximum mooring line tensions within 8% of measured values, confirming the model's accuracy. The FEM results also identified critical zones near the fairlead and anchor points where stress concentrations occur, guiding further design improvements. Figure 6 compares two data series: Simulated and Measured mooring line tensions over a duration of 100 seconds. The simulated data is represented by a smooth, continuous wave-like line, showing a periodic fluctuation in tension. The measured data is represented by individual data points scattered closely around the simulated line. The close alignment between the measured data points and the simulated curve indicates a strong agreement between the theoretical model and real-world observations. This correlation validates the accuracy of the simulation model used to predict mooring line behavior. The periodic nature of the tension, with regular peaks and troughs, reflects the dynamic loading caused by cyclic environmental forces such as waves.

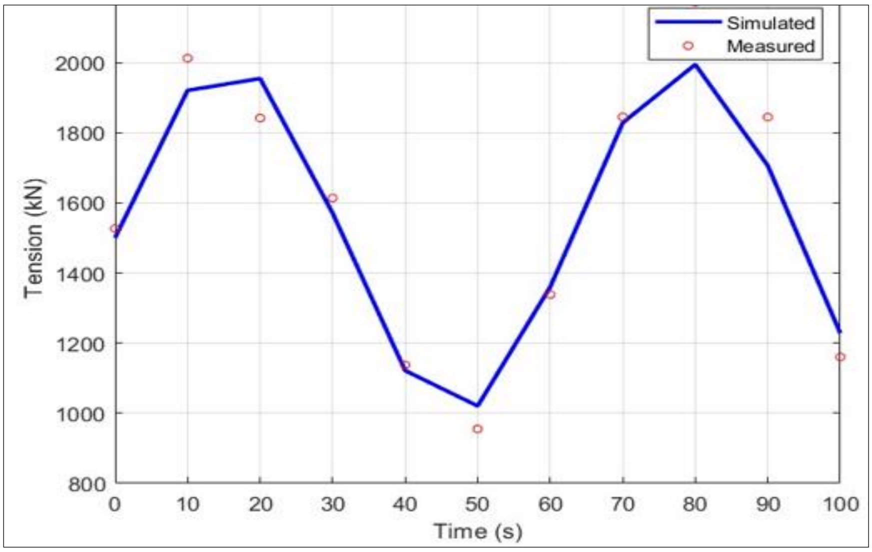

Figure 6 Simulation vs. Measured Tension

Minor discrepancies between the simulated and measured values are visible, where some data points deviate slightly from the smooth curve. These deviations are expected and can be attributed to unpredictable real-world variables, such as sudden wind gusts or complex wave interactions, which are not perfectly captured by the simulation. Overall, the plot demonstrates that the developed model is a reliable tool for predicting mooring line tensions under the operational conditions found in the Gulf of Guinea.

Abbreviations or Nomenclature

- F_w=wave forces per unit length;
- ρ_w= water density;
- C_d=Drag Coefficient;
- D= Mooring line Diameter;
- U= water particle velocity;
- C_m= inertia coefficient;
- F_c= Current force per unit length (N/m);
- v_c= Current velocity (m/s);
- F_{wind} = Wind force (N);
- ρ_a= Air density (kg/m^3);
- C_{wind}= Wind drag coefficient (dimensionless);
- A = Projected area of the vessel (m^2);
- v_w= Wind velocity (m/s);
- σ = Tensile stress (Pa);
- F = Applied force (N);
- A= Cross-sectional area of the mooring line (m^2);
- E = Young's modulus (Pa);
- σ = Tensile stress (Pa);
- ∈ = Strain (dimensionless);
- M= Mass matrix (kg);
- C = Damping matrix (N·s/m);
- K = Stiffness matrix (N/m);
- x = Displacement vector (m);
- $\dot{x}$= Velocity vector (m/s);
- $\ddot{x}$ = Acceleration vector (m/s^2);
- F(t)= Time-dependent external force (N);
- SF = Safety factor (dimensionless);
- $\sigma_{allowable}$= Maximum allowable stress (Pa) (determined by the material's properties);
- σ_{actual} = Actual stress under operational conditions (Pa);
- $[K]$= Global stiffness matrix, representing the stiffness properties of the mooring system;
- $\{u\}$ = Displacement vector, representing the movement of mooring lines under applied forces;
- $\{F\}$= External force vector, representing environmental loads such as waves, currents, and wind;

5. Conclusion

This research successfully developed a comprehensive framework for the design and analysis of a Single Buoy Mooring (SBM) system tailored to the unique environmental conditions of the Gulf of Guinea. The assessment of environmental conditions confirmed that the Gulf of Guinea presents significant challenges due to high waves, strong currents, and seasonal storms. These conditions generate substantial hydrodynamic loads, with wave and current forces reaching up to 1.2 kN/m and 0.8 kN/m, respectively, during extreme events. This emphasizes the necessity of region-specific environmental data in mooring system design. The evaluation of mooring line materials demonstrated that synthetic materials, particularly polyester, offer superior performance in terms of fatigue resistance and corrosion immunity compared to traditional steel cables. Although steel has higher tensile strength, its susceptibility to corrosion and fatigue in saline environments makes it less suitable for long-term deployment in the Gulf of Guinea.

Dynamic load analysis revealed that cyclic loads induced by vessel motions and environmental forces can lead to significant tension variations, reaching up to 600 kN under storm conditions. The use of synthetic materials helps mitigate peak tensions due to their elastic properties, thereby enhancing the system's ability to absorb dynamic loads. Design modifications proposed in this study, including the use of high-performance polyester and increased line diameter, resulted in a safety factor improvement from 2.1 to 3.2. This enhances the reliability and operational safety of SBM systems in the region. The development and validation of a Finite Element Method (FEM) simulation model showed strong agreement with field data, with tension predictions within 8% of measured values. This model serves as a reliable tool for predicting mooring line behavior and optimizing design configurations.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declares that they have no conflict of interest to this work.

Author contributions

Conceptualization, initial research work and Software analysis; NWOKA, B. G; Manuscript preparations and conceptualization, Oludi, K; project oversight; EKINE, A.A.

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