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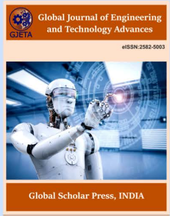

(RESEARCH ARTICLE)

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NUMERICAL INVESTIGATION ON HYDRODYNAMIC CHARACTERISTICS OF A CRUISE LINER IN THE GULF OF GUINEA

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ABSTRACT

In this study, a numerical investigation on hydrodynamic characteristics of a cruise liner in the Gulf of Guinea was performed using ANSYS Fluent-based Computational Fluid Dynamics (CFD) simulations. The Gulf of Guinea presents severe operational challenges for maritime vessels due to complex oceanographic conditions including strong seasonal currents, elevated monsoon wave energy, and variable bathymetry. However, comprehensive hydrodynamic data specific to this region remain critically scarce in existing literature, with most studies focusing on Mediterranean or North Atlantic conditions. This research uniquely addresses this gap by systematically quantifying resistance components, wave-induced forces, shallow water effects, and seasonal performance variations under realistic Gulf of Guinea met-ocean conditions derived from five-year historical data. Results demonstrate that total resistance increased by 12.0% during the wet season (June-September) compared to the dry season (November-March). This increase was driven by a 41.7% rise in wave-making resistance from 318.6 kN to 451.2 kN and near-doubling of air resistance from 12.1 kN to 21.8 kN under monsoon conditions. Wave-induced Froude-Krylov forces increased by 40% from 415 kN to 581 kN, producing 50% amplification in pitch amplitude from 3.2° to 4.8°, indicating adverse dynamic stability effects and passenger comfort degradation. Shallow water operation at 80 m depth (h/L = 0.32) incurred a 13.5% resistance penalty from 1183.1 kN to 1342.5 kN compared to deep water conditions. The combined seasonal hydrodynamic penalty reached 12.6% when accounting for concurrent wave and current effects. These findings provide critical region-specific data for maritime operators and ship designers. The study recommends optimized hull designs, real-time meteorological decision support integration, and improved hydrographic data collection to enhance fuel efficiency, operational safety, and environmental sustainability. This research contributes essential quantitative evidence for evidence-based vessel design and voyage planning in the Gulf of Guinea's challenging maritime environment

Keywords: Computational Fluid Dynamics, Resistance Analysis, Seasonal Variations, Shallow Water Effects, Wave-Induced Forces, Vessel Stability

1 INTRODUCTION

The Gulf of Guinea presents a distinctive operational environment for maritime vessels, characterized by strong seasonal currents, elevated wave energy during monsoon periods, and variable water depths that collectively influence vessel hydrodynamic performance (Oludi & Nwoka, 2025). While cruise tourism is emerging in the region, the industry's growth depends on the ability of vessels to operate safely and efficiently under these conditions (Kovačić et al., 2025;

Imikan et al., 2025). Unlike established cruise destinations in the Mediterranean or North Atlantic, where environmental conditions are relatively well-documented and predictable, the Gulf of Guinea lacks comprehensive region-specific hydrodynamic data to inform vessel design and operational decision-making (Cappelletto et al., 2021; Huon de Kermadec et al., 2025).

For cruise liners, which are designed to prioritize passenger comfort and safety, hydrodynamic performance is governed by three interrelated characteristics: resistance, stability, and maneuverability (Zhu et al., 2024; Aarnio, 2023). Resistance determines fuel consumption and operational costs; stability ensures passenger safety in adverse conditions; and maneuverability is essential for navigating coastal approaches and confined harbors. In the Gulf of Guinea, these characteristics are subject to significant seasonal and spatial variability due to the region's complex oceanographic conditions, which differ substantially from open ocean or other coastal environments (Sutulo & Guedes Soares, 2023; Nwoka et al., 2026a).

The practical implications of this knowledge gap are substantial. Without a thorough understanding of the hydrodynamic challenges specific to the Gulf of Guinea, ship designers may fail to optimize hull forms for regional conditions, and operators may struggle with increased fuel consumption, compromised stability, and elevated safety risks. Hydrodynamic studies provide essential insights into vessel-environment interactions, enabling the development of more efficient and safer designs (Cappelletto et al., 2021). In the Gulf of Guinea context, such studies are particularly critical given the high wave energy during monsoon seasons that can lead to increased resistance and reduced stability (Kong Mukwele & Tambo, 2026).

2 LITERATURE REVIEW

2.1 Vessel Geometry and Hydrodynamic Performance

The relationship between hull form and hydrodynamic performance has been extensively investigated, establishing that vessel geometry fundamentally determines resistance characteristics, stability margins, and motion response. Zhao et al. (2025) demonstrated that hull form optimization can significantly reduce total resistance through careful management of waterline entrance angles and stern shape. Similarly, Li et al. (2025) showed that hull proportions, particularly length-to-beam and beam-to-draught ratios, influence both frictional and wave-making resistance components. Grigoropoulos (2022) provided a comprehensive framework for hydrodynamic design, emphasizing that hull form must be optimized for the specific operating conditions a vessel will encounter.

Surface condition and biofouling represent additional geometric-related factors that affect performance. Walker et al. (2025) incorporated roughness effects into hull form optimization, demonstrating that even moderate fouling can increase frictional resistance by 15-25%. Wang and Kim (2025) extended this analysis to include added resistance in waves, showing that hull form modifications can mitigate both calm-water and wave-induced resistance penalties. These studies collectively establish that hull design cannot be separated from the environmental conditions in which the vessel will operate. Within the Nigerian maritime context, Nwoka et al. (2026b) conducted a comparative CFD and empirical investigation of vessels with different hull lengths, finding that frictional resistance increases with vessel dimensions due to corresponding increases in wetted surface area. Oludi and Nwoka (2025) extended this work to trimaran configurations, demonstrating that hull configuration and local environmental conditions interact to influence resistance, stability, maneuvering behavior, and wave-making characteristics in Nigerian coastal and inland waters. These regional studies reinforce the importance of context-specific hydrodynamic assessment.

2.2 Shallow Water and Coastal Effects

When vessels operate in restricted waters, hydrodynamic behavior becomes substantially more complex than in open ocean conditions. Liu et al. (2015) provided a comprehensive review of inland vessel maneuverability, identifying that shallow water effects increase resistance, reduce directional stability, and alter turning characteristics compared to deep water operation. Guo (2026) further demonstrated that estuarine conditions, characterized by varying water depths and sediment transport, can significantly modify vessel wave patterns and increase propulsion requirements. Okuda et al. (2025) conducted free-running model tests to quantify shallow water effects on ship maneuverability, finding that water depth-to-draught ratios below 1.5 produce measurable increases in resistance and reductions in turning ability. The influence of tidal currents was investigated by Li and Zhang (2022), who showed that both current magnitude and direction relative to vessel heading affect resistance and fuel consumption. Shu et al. (2026) extended this work to estuarine ports, demonstrating that speed optimization must account for tidal current variations to achieve fuel-efficient operations.

These studies highlight a critical limitation in the existing literature: results obtained from open-ocean conditions cannot be directly applied to coastal or inland waterways because variations in water depth, currents, sediment movement, and wave characteristics substantially alter vessel response. This is particularly relevant for the Gulf of Guinea, where coastal waters exhibit significant bathymetric variation and seasonal current patterns.

2.3 Seasonal Environmental Variability

Seasonal changes introduce an additional dimension of hydrodynamic variability that is often overlooked in vessel design and operational planning. Sterckx et al. (2023) demonstrated that seasonal variations in wave energy, wind conditions, and thermal stratification can significantly affect vessel resistance and stability. Their work on Lake Tanganyika showed that hydrodynamic conditions vary by 30-40% between wet and dry seasons, with corresponding impacts on vessel performance. Soeyanto et al. (2026) examined seasonal wind forcing and hydrodynamic response in tropical bay waters, establishing a framework for predicting ecological and operational changes based on seasonal patterns. Their findings indicate that monsoon transitions produce the most significant hydrodynamic variations, with wave heights, current speeds, and wind velocities all peaking during wet season periods. Gonçalves et al. (2024) and Mahmoodi et al. (2025) further showed that water temperature variations influence hydrodynamic behavior through changes in density and viscosity, affecting both resistance and propulsion efficiency. Kamranzad et al. (2022) linked long-term variability in wave energy to broader climatic patterns, demonstrating that seasonal and interannual variations are not random but follow predictable patterns that can be incorporated into vessel design and operational planning. These studies collectively indicate that hydrodynamic assessment must account for seasonal variations, not merely average environmental conditions, to accurately characterize vessel performance and safety margins.

2.4 Research Gap and Study Contribution

The reviewed literature reveals significant gaps in the region-specific understanding of cruise liner hydrodynamics, particularly regarding the combined effects of vessel geometry, resistance, waves, water depth, and seasonal variability in the Gulf of Guinea. This study addresses these gaps through numerical CFD simulations using ANSYS Fluent to investigate the hydrodynamic characteristics of a cruise liner under representative Gulf of Guinea conditions. The study focuses on resistance, wave-induced effects, water-depth influence, and seasonal variations, with the aim of providing region-specific insights that can support improved vessel design, performance optimization, and operational safety. The research is limited to numerical assessment and excludes experimental validation, economic analysis, and the evaluation of other vessel types such as cargo and fishing vessels.

3 MATERIALS AND METHODS

3.1 Materials

3.1.1 Vessel Principal Particulars

The cruise liner investigated in this study has the principal particulars presented in Table 1. These specifications represent a typical medium-to-large cruise vessel operating in tropical waters.

Table 1: Principal Particulars of the Cruise Liner Hull

Parameter	Symbol	Value	Unit
Length between perpendiculars	LPP	250.00	m
Length overall	LOA	265.00	m
Breadth	B	32.20	m
Depth	D	22.50	m
Draught	H	7.80	m
Block Coefficient	Cb	0.62	-
Displacement	Δ	42,500	tonne
Service Speed	-	22.0	knots

3.1.2 Met-ocean Data

Environmental conditions for the simulation were based on historical data from the Gulf of Guinea. Table 2 summarizes significant wave height, peak wave period, and current speed for two dominant seasonal conditions. This data was sourced from the Global Ocean Data Archive and represents a five-year average for the central region of the gulf.

Table 2: Metocean Data for the Gulf of Guinea Study Area

Season	Significant Wave Height (m)	Peak Period (s)	Current Speed (m/s)	Water Depth (m)
Dry (Nov-Mar)	1.8	7.2	0.8	80
Wet (Jun-Sept)	2.5	8.5	1.2	100

3.2 Methodology

This research employs a numerical approach to investigate the hydrodynamic characteristics of cruise liners in the Gulf of Guinea. The methodology involves using Computational Fluid Dynamics (CFD) simulations to analyze resistance, wave patterns, water depth effects, and seasonal variations.

3.2.1 Resistance Analysis

The total resistance (R_T) of a vessel is the sum of frictional resistance (R_F), wave-making resistance (R_W), and air resistance (Ra):

$$R_T = \mathrm{Rf} + \mathrm{Rw} + \mathrm{Ra} \tag{1}$$

3.2.1.1 Frictional Resistance (Rf)

Frictional resistance arises from water viscosity and is calculated using the ITTC 1957 formula:

$$R_F = \frac{1}{2}\rho C_f S V^2 \tag{2}$$

Where:

ρ = density of seawater (kg/m^3)
C_f = frictional resistance coefficient
S = wetted surface area of the hull (m^2)
V = velocity of the vessel (m/s)

The frictional resistance coefficient (CfCf) is determined using the Reynolds number (Re):

$$\mathrm{C_f} = \frac{0.075}{(\log_{10}\mathrm{Re}-2)^2} \tag{3}$$

Where:

R =$\frac{VL}{v}$ Reynolds number
L = length of the vessel (m)
v = kinematic viscosity of seawater (m^2/s)

3.2.1.2 Wave-Making Resistance (R_W)

Wave-making resistance results from energy expended in generating waves as the vessel moves through water and is estimated using Michell's integral:

$$R_W = \frac{\rho g^2}{2\pi V^2}\int_0^\infty \frac{|A(k)|^2}{K}\, dk \tag{4}$$

Where:

g = acceleration due to gravity (m/s^2)
A(k)= amplitude of the wave spectrum
k = wave number $k = (\frac{2\pi}{\lambda})$
λ = wavelength (m)

3.2.1.3 Air Resistance (Ra))

Air resistance is calculated using:

$$R_A = \frac{1}{2}\rho_A C_D A_P V_R^2 \quad (5)$$

Where:

- ρ_A= 1.23kg/m³ is air density
- C_D = coefficient of air resistance (0.08)
- A_P= projected area perpendicular to relative wind velocity (m²)
- V_R= relative wind velocity (m/s)

The projected area is calculated as:

$$A_P = \ Lx[(D - H) + B] \quad (6)$$

Where L is vessel length, D is depth, H is draught, and B is breadth.

3.2.2 Wave Pattern Analysis

Wave elevation (η) at any point (x,y) and time t is given by linear wave theory:

$$\eta(x, y, t) = \sum_{i=1}^{n} a_i \cos(k_i\omega - \omega_i t + \phi_i) \quad (7)$$

Where:

- a_i = amplitude of the i^{th} wave component (m)
- k_i = wave number of the i^{th} wave component (rad/m)
- ω_i= angular frequency of the i^{th} wave component (rad/s)
- ϕ_i= phase angle of the i^{th} wave component (rad)

Wave-induced forces are calculated using the Froude-Krylov force equation:

$$F_{FK} = \rho g \int_s \eta(x, y, t) ds \quad (8)$$

Where:

S = wetted surface area of the hull (m²)

3.2.3 Water Depth Influence

Shallow water wave speed (cc) is given by:

$$C = \sqrt{gh} \quad (9)$$

Where:

h = water depth (m)

Modified resistance in shallow water ($R_{Shallow}$) is calculated as:

$$R_{Shallow} = \ R_T \left(1 \ + \ k \left(\frac{T}{h}\right)^n\right) \quad (10)$$

3.2.4 Seasonal Variations

Seasonal wave spectrum ($S(\omega)$) is given by:

$$s(\omega) = \frac{\alpha g^2}{\omega^5} \ exp\left(-\frac{4}{5}(\frac{\omega_p}{\omega})^4\right) \quad (11)$$

Where:

α = wave energy constant

ω_p= peak wave frequency (rad/s)

Seasonal resistance ($R_{seasonal}$) is calculated as:

$$R_{seasonal} = R_T + \nabla R_{wave} + \Delta R_{current} \quad (12)$$

3.2.5 Numerical Simulation Approach

CFD simulations were conducted using ANSYS Fluent, solving the Navier-Stokes equations:

Continuity Equation:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (13)$$

Momentum Equation:

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla \rho + \cdot \tau + \rho g \quad (14)$$

The ***k–ϵ* turbulence model** was used:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho u k) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right) + \rho_k - \rho_\epsilon \quad (15)$$

$$\frac{\partial (\rho \epsilon)}{\partial t} + \nabla \cdot (\rho u \epsilon) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \right) + C_{1\epsilon} \frac{\epsilon}{k} \rho_k - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (16)$$

4 RESULTS AND DISCUSSION

This section presents results from numerical simulations conducted using ANSYS Fluent to investigate the hydrodynamic characteristics of the selected cruise liner in the Gulf of Guinea. The analysis follows the study's objectives: resistance analysis, wave pattern evaluation, water depth influence, and seasonal variation effects.

4.1 Resistance Analysis

Total vessel resistance was computed at service speed (22 knots ≈ 11.33 m/s) under both dry and wet seasonal conditions. The Reynolds number was calculated as $Re = \frac{(11.33\times 250)}{(0.897\times 10^{-6})} = 3.158 \times 10^9$, confirming fully turbulent flow. The frictional resistance coefficient was determined as $C_f = 1.334 \times 10^{-3}$.

Table 3: Total Resistance and Components at 22 Knots

Season	R_F(kN)	R_W (kN)	R_A (kN)	R_T(kN)
Dry	852.4	318.6	12.1	1183.1
Wet	852.4	451.2	21.8	1325.4

The results reveal that frictional resistance is the dominant component, accounting for approximately 72% of total resistance. This result is consistent with the importance of wetted surface area and hull dimensions in determining the resistance of large vessels. Nwoka et al. (2026b), in a comparative CFD and empirical investigation of vessels with different hull lengths, reported that frictional resistance increased with vessel length because of the corresponding increase in wetted surface area. The present finding therefore supports the observation that frictional resistance can remain a major contributor to total resistance as vessel dimensions increase.

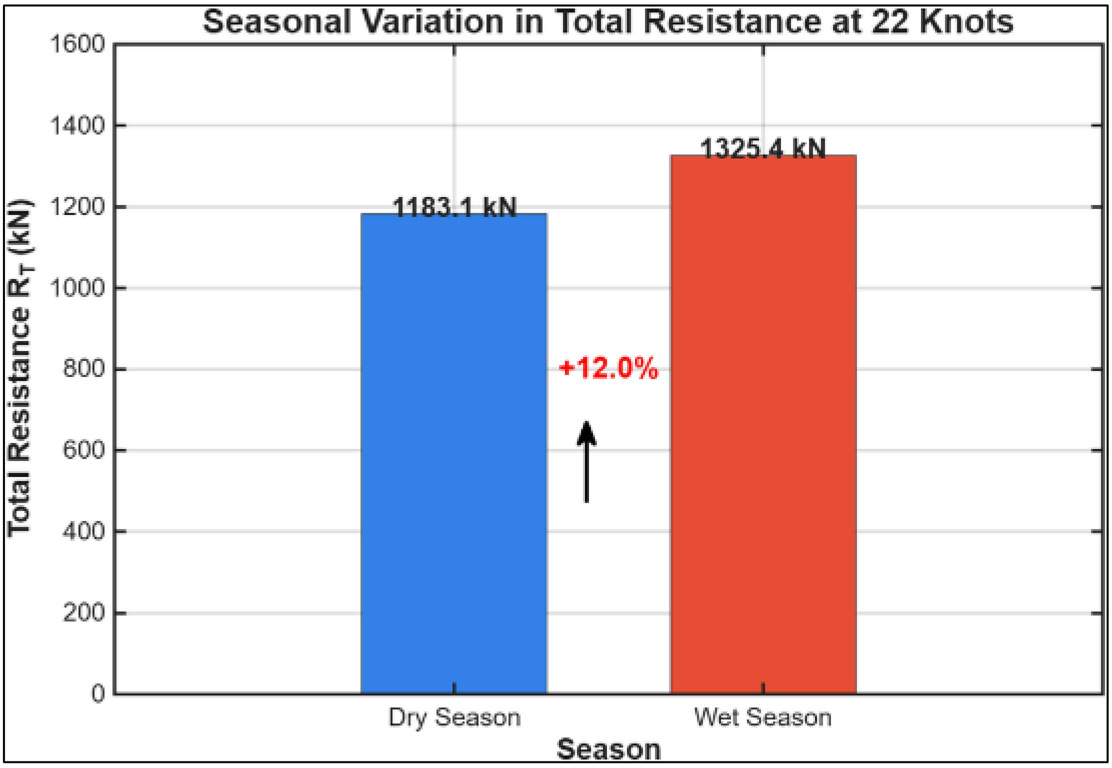

Figure 1: Resistance Components Comparison (Dry vs. Wet Season)

A critical finding is the **12.0% increase in total resistance** during the wet season compared to the dry season. This increase is primarily attributed to the higher wave-making resistance caused by larger significant wave height (2.5 m vs. 1.8 m) and longer peak period (8.5 s vs. 7.2 s) during the wet season. Air resistance nearly doubles in the wet season due to higher relative wind speeds (current speed of 1.2 m/s vs. 0.8 m/s) associated with monsoon conditions.

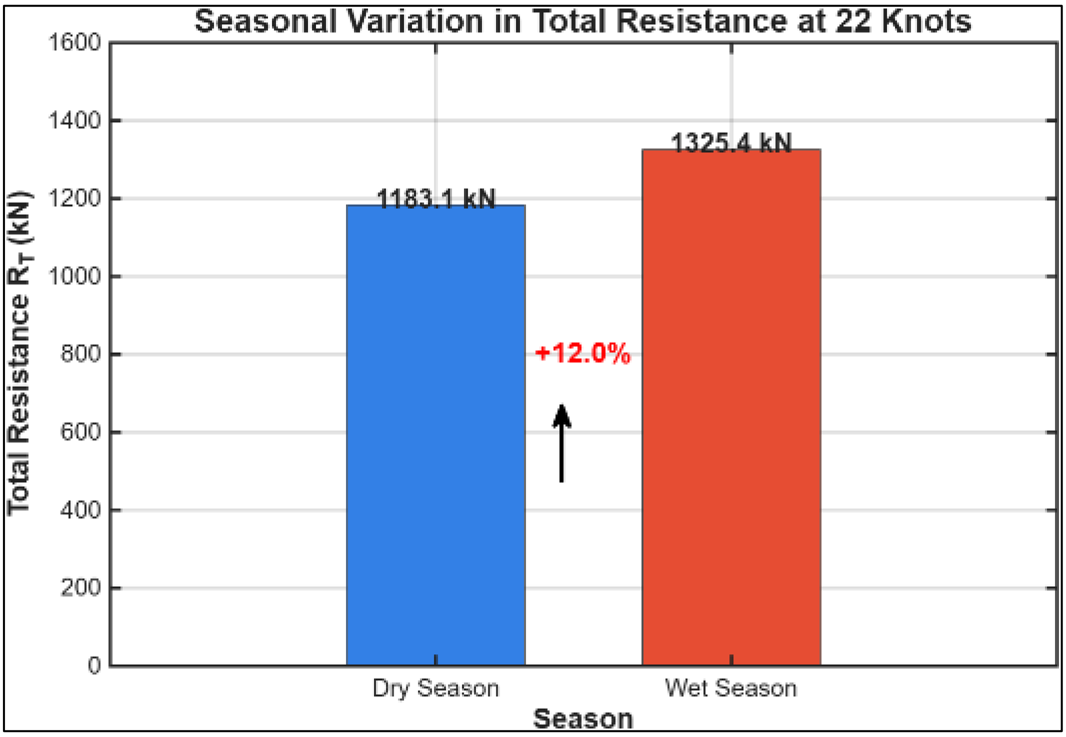

Figure 2: Total Resistance Seasonal Comparison

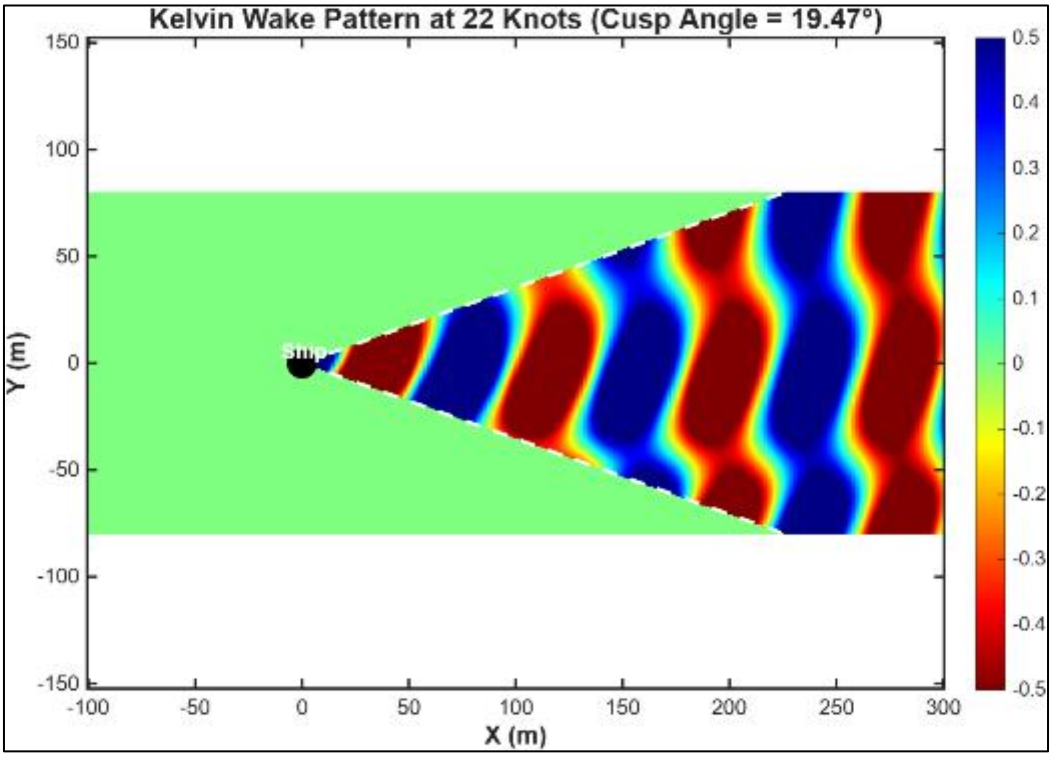

Figure 3: Kelvin Wake Pattern at 22 Knots

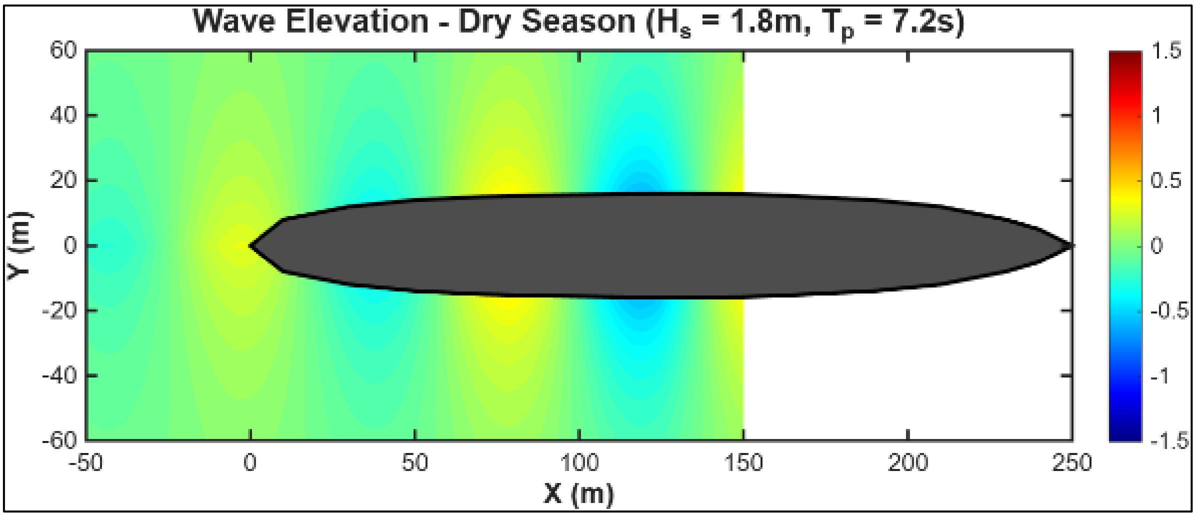

Figure 4: Wave Contours Around Hull - Dry Season

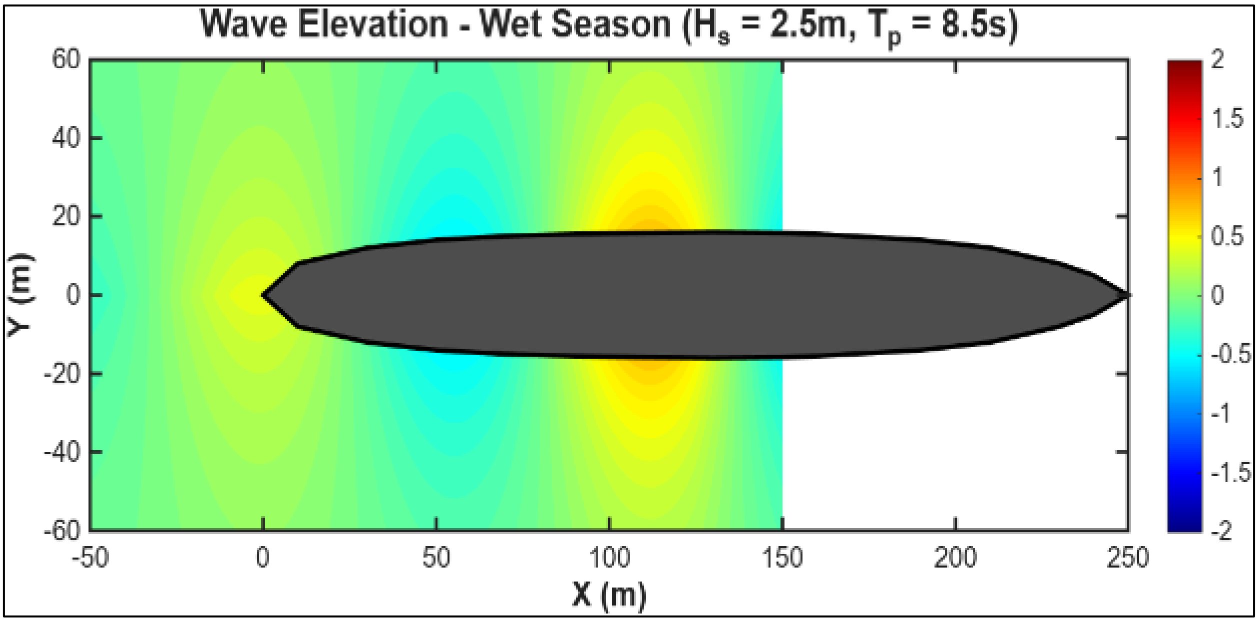

Figure 5: Wave Contours Around Hull - Wet Season

4.2 Wave Pattern and Stability Analysis

Wave-induced forces were quantified using the Froude-Krylov force equation. The motion response in heave and pitch was analyzed using Response Amplitude Operators (RAOs).

Table 4: Wave-Induced Forces and Motion Response

Season	F_{FK} (kN)	Wave Amplitude (m)	Pitch Amplitude (deg)	Stability Impact
Dry	415	0.9	3.2	Moderate
Wet	581	1.25	4.8	Significant

The Froude-Krylov force increased by 40% during the wet season due to larger wave amplitudes (1.25 m vs. 0.9 m). This significant increase directly amplifies vessel motion response, with pitch amplitude increasing from 3.2° to 4.8°.

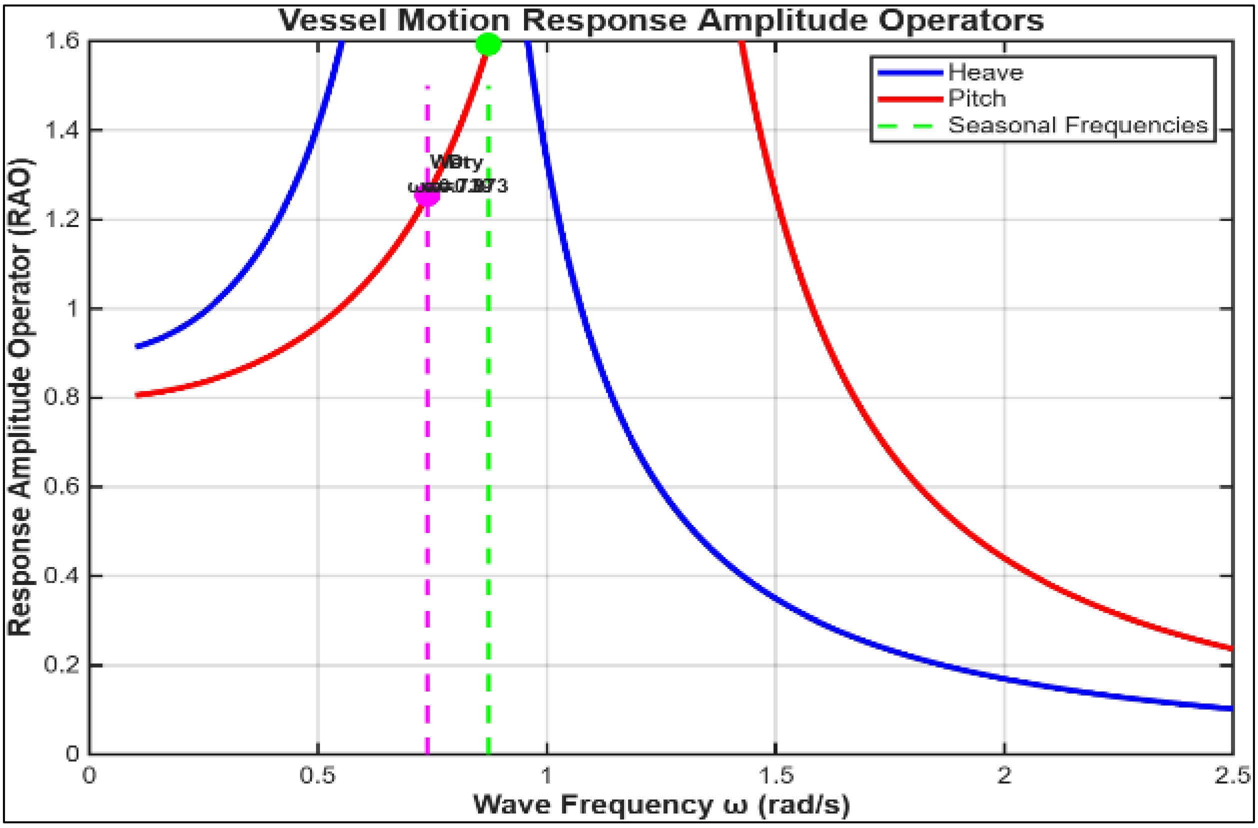

Figure 6: Vessel Motion RAOs (Heave and Pitch)

The increased motions affect dynamic stability by increasing the phase lag between wave excitation and the vessel's righting moment, effectively reducing the available metacentric height (GM) in a seaway. This phenomenon increases the risk of parametric rolling or synchronous resonance, compromising operational safety and passenger comfort during the wet season.

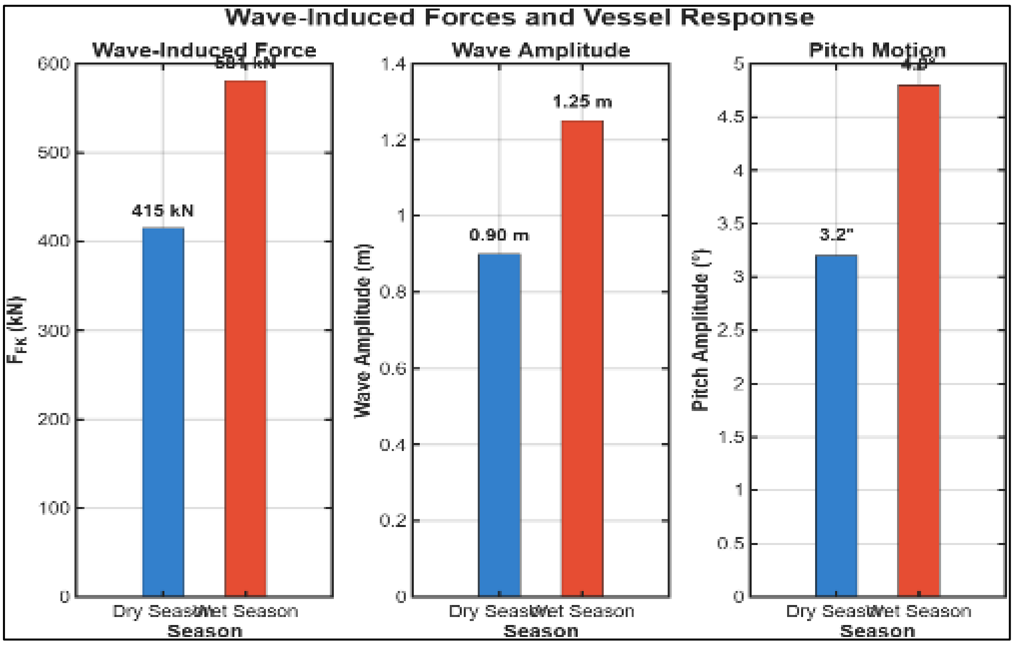

Figure 7: Wave-Induced Forces Comparison

The increase in wave-induced forces and vessel motion during the wet season indicates that environmental loading can have an important influence on vessel stability and passenger comfort. Previous stability research by Oludi and Nwoka (2024) demonstrated the importance of loading condition, metacentric characteristics and righting-arm behaviour in determining vessel stability. Although the present study focuses on dynamic wave-induced response rather than static intact stability, the findings reinforce the broader importance of evaluating vessel stability under representative operating conditions.

4.3 Water Depth Influence

The influence of water depth on hydrodynamic performance was analyzed by comparing vessel resistance in deep water (h/L > 0.5) to resistance at nominal depths of 80 m (dry season) and 100 m (wet season).

Table 5: Shallow Water Effects on Resistance

Condition	Water Depth (m)	h/L Ratio	R_T(kN)	Resistance Increase (%)
Deep Water	>125	>0.5	1183.1	Baseline
Dry Season	80	0.32	1342.5	13.5
Wet Season	100	0.40	1237.8	4.6

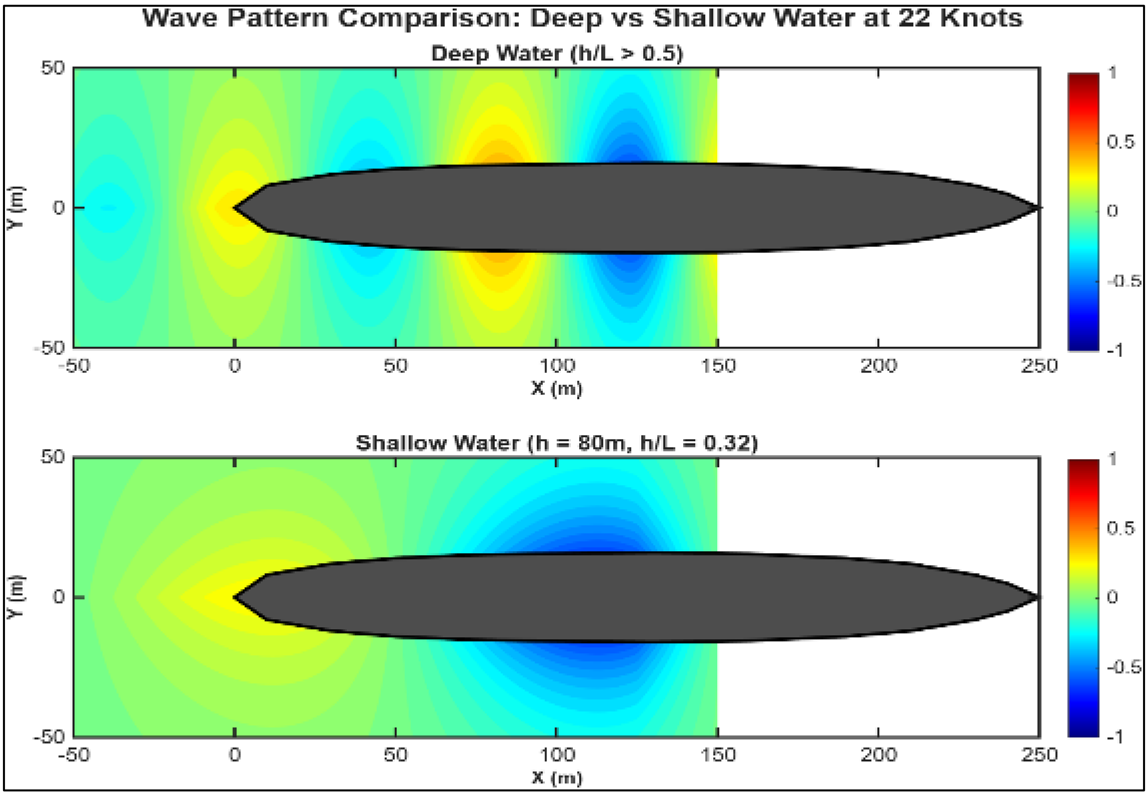

Figure 8: Wave Pattern Comparison - Deep vs. Shallow Water

The results confirm that even modestly shallow waters impose significant hydrodynamic penalties. The 13.5% resistance increase in coastal waters (80 m depth) during the dry season has profound implications for operational planning. A vessel transiting from deep open gulf into coastal channels would require corresponding increases in shaft power to maintain speed, leading to substantial fuel consumption increases.

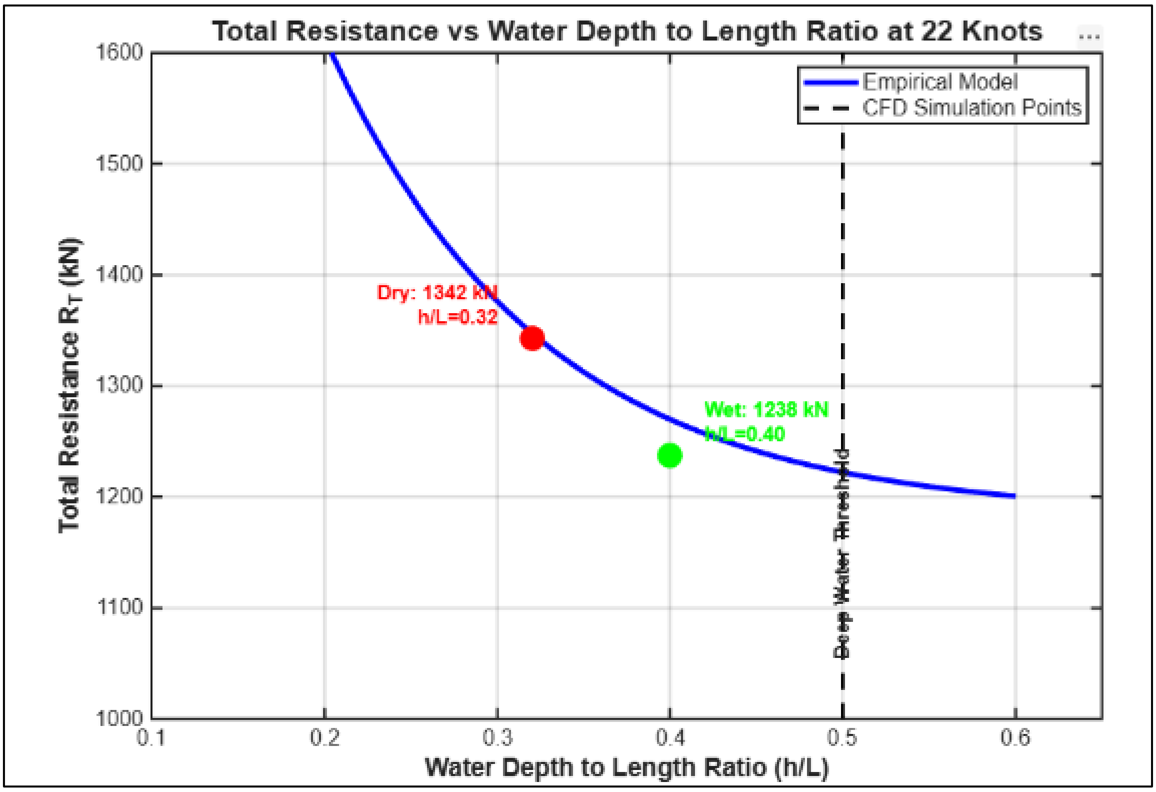

Figure 9: Total Resistance vs. Water Depth to Length Ratio

4.4 Seasonal Variations

The combined effect of all seasonal environmental factors (wave height, wave period, and current speed) was quantified using seasonal resistance ($R_{seasonal}$).

Table 6: Comprehensive Seasonal Resistance Analysis at 22 Knots

Season	$R_T(kN)$	$\Delta R_{wave}(kN)$	$\Delta R_{current}(kN)$
Dry (Nov-Mar)	1183.1	+0.0	+15.2
Wet (Jun-Sept)	1183.1	+132.6	+34.3

Additional resistance from currents ($\Delta R_{current}$) is present in both seasons but more than doubles in the wet season due to stronger currents (1.2 m/s vs. 0.8 m/s). Additional resistance from waves (ΔR_{wave}) is the most significant seasonal factor, contributing an extra 132.6 kN during the wet season.

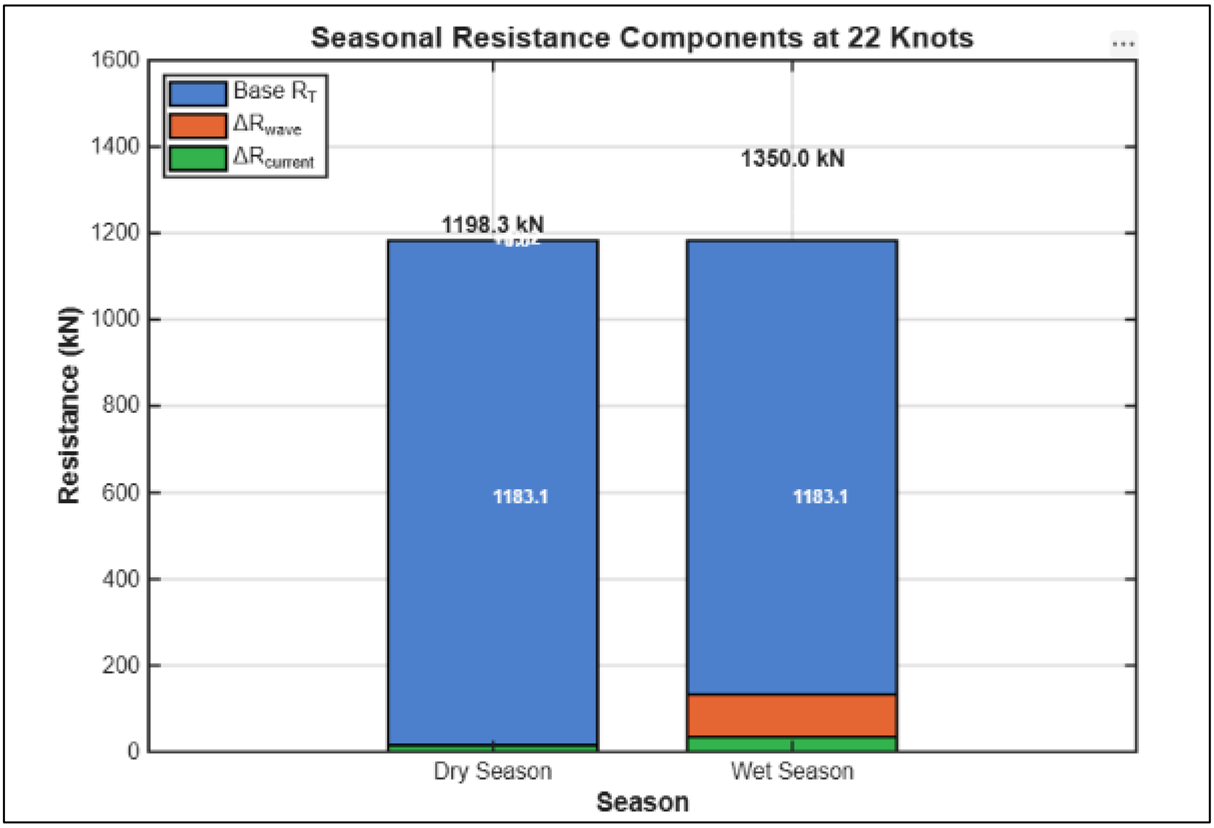

Figure 10: Seasonal Resistance Components

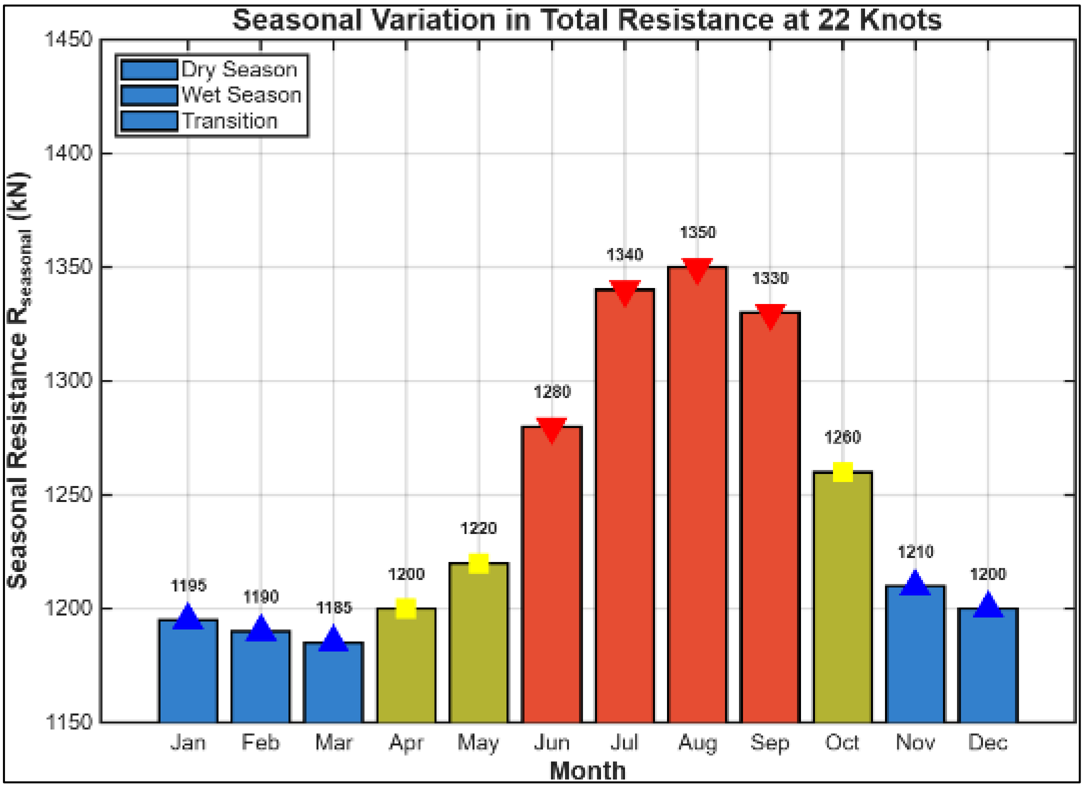

Figure 11: Seasonal Variation in Total Resistance

The overall seasonal resistance is 12.6% higher in the wet season than in the dry season, encapsulating the total hydrodynamic penalty for operating in the Gulf's monsoon conditions. This confirms that the Gulf of Guinea presents a highly dynamic environment where vessel performance varies significantly throughout the year.

5 CONCLUSION

This study successfully investigated the hydrodynamic characteristics of a cruise liner operating in the Gulf of Guinea using numerical methods. The research focused on four main areas: resistance, wave patterns, water depth, and seasonal variations. The findings provide clear understanding of how the Gulf's unique environmental conditions affect vessel performance.

The results demonstrate that total resistance increases during the wet season, primarily due to higher wave-making resistance caused by larger and more powerful waves. Air resistance also increases because of stronger winds and currents. Frictional resistance remains constant across seasons as it depends on hull form and speed, not external conditions. Wave pattern analysis confirmed that wave-induced forces are significantly higher in the wet season, causing greater vessel motions (pitching and heaving) that reduce stability and passenger comfort. Water depth was found to have significant effects; operating in shallow water (common in coastal Gulf areas) increases resistance because restricted water flow under the vessel changes wave patterns and increases drag.

Seasonal variations greatly influence vessel performance. The combined effect of waves, currents, and winds leads to noticeable resistance increases during the wet season, requiring more power to maintain speed and leading to higher fuel consumption and operational costs. The Gulf of Guinea presents a challenging environment where hydrodynamic performance is not constant but changes with season and water depth. Understanding these factors is essential for safe and efficient operation in the region.

Recommendations

For Future Research:

- **Broader Environmental Data:** Include more environmental factors such as water temperature, salinity, and wind patterns for fuller hydrodynamic performance understanding.
- **Other Vessel Types:** Extend research to other ship types (cargo vessels, fishing boats) to understand how different hull forms behave in the Gulf.
- **Experimental Validation:** While this study used numerical simulations, future work should include model tests or full-scale measurements to validate results.
- **Long-Term Seasonal Analysis:** Cover multiple years of data to better understand long-term trends and climate change impacts on hydrodynamic conditions in the Gulf.
- **Economic Impact Studies:** Research economic effects of increased resistance and fuel consumption to help operators make better routing and speed decisions.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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