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Probabilistic and Deterministic Comparative Damage Stability Characterization of a Cruise Liner Vessel

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Abstract- In this study, damage stability behaviour analysis of the cruise liner Pliable in the Gulf of Guinea was performed using Bentley MaxSurf. The research addressed the heightened risks of flooding and stability loss due to collisions, piracy, and extreme waves (up to 4.5m) in the region, which are neglected in generic stability studies. Unlike previous works focused on cargo ships, this research uniquely integrated region-specific hydrodynamic conditions and probabilistic methods with CAD tools for a cruise liner. Results showed floodable length increased with displacement, from 42.6 m to 53.1 m (+24.6%) at midship. Single-compartment flooding maintained SOLAS compliance (residual GM >1.38 m), but triple-compartment breaches submerged the margin line by 5 cm. Under storm conditions, effective GM reduced by 0.38 m, and combined with piracy maneuvers, GM reduced by 0.52 m, leading to non-compliance. Probabilistic methods outperformed deterministic approaches, yielding a 21.4% higher residual GM (0.51 m vs. 0.42 m) and a 9% higher survival probability (0.85 vs. 0.78). An optimized bulkhead configuration (21 bulkheads) reduced average floodable length to 37.2 m and increased residual GM to 0.61 m, ensuring SOLAS compliance with an 18% cost increase. The study demonstrates the critical need for region-specific stability assessments and hybrid methods. Recommendations included adopting real-time stability monitoring, optimized bulkhead spacing, and regulatory updates for high-risk zones. This work contributes to safer cruise liner operations and advances CAD applications in naval architecture.

Index Terms- Damage Stability, Generic Stability, Floodable Length, Stability Loss Die to Collision

I. INTRODUCTION

1.1 Background of the Study

Damage stability remains one of the most critical considerations in the design and safe operation of cruise liners due to their large passenger capacities, complex internal arrangements, and extensive watertight subdivision. The International Maritime Organization (IMO) requires that passenger ships demonstrate a high level of survivability after sustaining damage, as prescribed under SOLAS 2009 probabilistic damage stability regulations. This review evaluates the contemporary approaches, modeling techniques and research developments related to the damage stability behaviour of cruise liners, highlighting recent advances from 2020 to 2025. Cruise liners represent some of the largest vessels in the global merchant fleet, carrying several thousand passengers and crew members. Their damage stability behavior, referring to the vessel's ability to withstand and survive flooding following a breach in its watertight envelope, is essential for ensuring safety at sea. Unlike cargo vessels, cruise liners include a variety of compartmentalized recreational, accommodation, and machinery spaces, increasing the complexity of flood progression and survivability assessments. Recent maritime accidents, such as the Costa Concordia incident, have amplified the need for rigorous damage stability evaluations and advanced simulation techniques to predict vessel responses under deterministic and probabilistic flooding scenarios.The Gulf of Guinea, notorious for piracy, extreme weather, and complex hydrodynamic conditions, poses unique threats to vessel integrity. Between 2018 and 2022, this region witnessed over 80% of global maritime kidnappings, with frequent collisions and grounding incidents compounding operational risks (IMO, 2022). These challenges necessitate advanced stability analyses tailored to the Gulf's environmental and geopolitical dynamics.

Historically, damage stability assessments relied on manual methods, such as estimating buoyancy loss and compartment flooding. Traditional approaches, however, often oversimplified variables like wave-induced rolling or compartment permeability, leading to inadequate safety margins. The introduction of

Computer-Aided Design (CAD) tools, such as Bentley MaxSurf, transformed the field by automating hydrostatic calculations and enabling precise simulations of floodable lengths. For instance, MaxSurf integrates compartment geometry and permeability values to predict post-damage equilibrium, minimizing errors inherent in manual processes (Chukwukamagozi & Feniolu, 2021). The study by McPepple et al., (2025) is focused on modifying streamline an existing offshore supply vessel (OSP) hull form to an IMO standard one so as to obtain an improved ship hull form with low resistance and power and also with highly efficient energy saving performance. Using an analytical method there was significant increase in the design variables during the process of hull form modification and this was validated when Maxsurf software was used to modify the hull form. The analytical method used to perform the modification of pacific wrestler using response amplitude operator (RAOs) from Maxsurf then MATLAB to consider the modified and initial resistance values gotten from Maxsurf motion analysis used as the input values in comparing the resistance and power as against the vessel forward speed at 180 Degree and 135 Degree. Main dimensions of the ship were used to generate various hull models and Autodesk inventor used to present the various vessel hull form in solid form. The optimization was to improve on the vessel hydrodynamic performance in calm water as to achieve good sea-keeping condition, comfortability, manoeuvrability, reduced fuel consumption at 0,5,10,15,20,23 and 25 knots on regular sea wave condition of 4m. The various NURBs design diagrams gotten were used to run a computer motion simulation on regular sea wave of 4 meters for the both hull forms to ascertain a more favourable resistance, stability and rang at various speeds on transit. MATLAB coding was used to calculate for the required power for both vessel considering the resistance values gotten from the Maxsurf motion analysis which shows that there was reasonable reduction in the modified resistance of about 40 to 45%, and also power of about 30 to 25% and hydrodynamic location RAOs of up to 8 to 2% results. Comparing the results of the parent hull form to the modified hull form at 0 to 25 knots of the ship speeds on various location of the sea state towards the different degree of movement of the ship which demonstrates the validity of the proposed modification design strategy after bulb was designed into the bow section of the ship hull given the ship a better forward buoyancy, 20 to 25% of fuel efficiency, and increased speed.

1.2 Environmental Conditions of the Gulf of Guinea

The Gulf of Guinea’s environmental conditions further complicate stability. Seasonal monsoon winds generate waves exceeding 4 meters in height, while equatorial currents create unpredictable loads on vessel hulls. These factors reduce the metacentric height, a critical stability parameter determined by the vertical positions of the metacenter and the ship’s center of gravity. Regional piracy exacerbates risks, as evasive maneuvers during attacks may induce sudden tilting, destabilizing vessels already compromised by flooding. Since 2020, the IMO’s probabilistic damage stability framework has increasingly focused on integrating advanced hydrodynamic modeling techniques and adopting dynamic simulation tools. SOLAS Chapter II-1 mandates that passenger ships meet minimum Attained Subdivision Index (A) values based on their dimensions and the number of persons onboard. Researchers such as Zhang et al. (2021) argue that despite the robustness of probabilistic regulations, they often underestimate complex damage cases in cruise liners, particularly progressive flooding in multi-deck passenger spaces. Consequently, the maritime industry has seen a shift towards combining regulatory-based assessment with time-domain simulations and risk-based methodologies. Current regulatory frameworks, including SOLAS Chapter II-1, mandate deterministic stability criteria but lack provisions for region-specific probabilistic risks. For example, SOLAS requires the margin line, a virtual boundary below the freeboard deck to remain un-submerged post-damage. However, this standard does not account for the Gulf’s compounded hazards, such as simultaneous flooding from collisions and wave overtopping.

Cruise liners typically possess intricate internal geometries characterized by long corridors, large open public areas, and extensive cabin decks. Floodwater dynamics in such configurations differ significantly from simpler ship types. Studies by Alessandrini et al., (2022) have shown that large internal volumes can delay equilibrium flooding but may introduce asymmetries that affect heel and trim stability. Additionally, the presence of multiple watertight doors and transversal penetrations can accelerate or restrict water ingress depending on operational status. Progressive flooding has been identified as a major factor influencing survivability. According to Erdogan and Vassalos (2020), the sequence and rate of compartment flooding may drastically alter the final equilibrium condition. Computational fluid dynamics (CFD) simulations in recent years have demonstrated that the interaction between floodwater and internal structures generates nonlinear behaviour, requiring high-fidelity modeling for reliable predictions. Traditional methods, primarily static stability analysis, remain useful for preliminary design assessment. However, due to simplifications such as assuming instantaneous flooding and neglecting dynamic effects, their accuracy for cruise liners is limited. Several authors, including Boulougouris and Papanikolaou (2021), emphasize that quasi-static methods can provide baseline survivability predictions but must be supplemented with more advanced tools. Time-domain simulations have become the preferred method for analyzing damage stability behaviour. These tools account for transient flooding effects, ship motion responses, and nonlinear hydrodynamic interactions. Franco et al. (2023) reported that modern simulation platforms such as PROTEUS and NAPA Flooding Simulation enable real-time modelling of damage scenarios, integrating wave-induced motions, internal fluid dynamics, and progressive flooding. This research focuses on the analysis of a hybrid energy system for a catamaran vessel operating in Gulf of Guinea, aiming to enhance energy efficiency, reduce emissions, and promote sustainability in maritime transportation. The proposed hybrid system integrates solar photovoltaic (PV) panels, lead-acid batteries, and a backup diesel generator to meet the energy demands of a 12-meter catamaran operating in Port Harcourt, Nigeria. The system is designed to address the environmental and operational challenges of conventional diesel-powered vessels, offering a cleaner alternative by utilizing renewable energy sources. Through a detailed energy production and consumption analysis, the study demonstrates that the hybrid system can significantly reduce the reliance on diesel fuel, achieving an annual CO2 emissions reduction of 47.6% compared to a diesel-only system. The solar PV array generates the majority of the vessel's energy during peak solar months, while the diesel generator ensures operational reliability during periods of low solar irradiance. Despite the seasonal variations in solar energy, the system effectively meets the catamaran's energy needs with an estimated annual diesel consumption of 1510 liters. This research highlights the potential of hybrid power systems to enhance the environmental performance of maritime vessels. However, it also identifies limitations in energy storage capacity and suggests further exploration of advanced battery technologies and renewable energy sources. The findings underscore the importance of hybrid systems in advancing sustainable maritime practices while the operational costs and emissions are reduced (Robinson and Chuku, 2024).

1.3 Using Computational Fluid Dynamics (CFD) and other Methods for Flooding Assessment

CFD has become a crucial tool in assessing complex flooding phenomena. From 2020 onwards, researchers have used Volume-of-Fluid (VOF) models to simulate water ingress, structural deformation, and nonlinear internal water motion. A study by He et al., (2024) demonstrated successful use of CFD to analyze asymmetric flooding in a cruise ship's lower decks, showing strong agreement with experimental data. CFD enables detailed reproduction of internal geometries, making it highly suitable for analyzing the heterogeneous layout of cruise liners. Emerging research between 2023 and 2025 has focused on hybrid computational models that combine probabilistic frameworks with CFD or time-domain solvers. Machine-learning-based surrogate models have also been developed to optimize damage stability assessments. According to Li and Kim (2025), neural networks trained on hundreds of simulated flooding cases can rapidly estimate survivability indices, reducing computational costs. Damage stability cannot be evaluated solely as a hydrodynamic problem, especially for cruise liners with thousands of occupants. Ship survivability is closely linked to the time required for safe evacuation. Contemporary studies have highlighted the integration of flooding simulations with evacuation modeling. Noh and Seo

(2022) demonstrated that dynamic stability analyses could predict safe time windows for evacuation during progressive flooding events. Changes in heel angle, deck immersion, and accessibility of escape routes significantly influence evacuation outcomes. Several cruise ship designs developed after 2020 incorporate enhanced watertight subdivision and improved cross-flooding arrangements. Moreover, the introduction of sensor-based flooding detection systems has advanced real-time stability monitoring. Research by Petrovic et al. (2023) on modern cruise liners shows that onboard digital twins, linked to sensor networks, can provide immediate predictions of vessel survivability following damage, enabling faster crew decision making. Additionally, experimental tests conducted in towing tanks and floodable compartments have validated the accuracy of numerical predictions. Hybrid physical–numerical modeling has thus become a standard approach for verifying design compliance and testing extreme flooding scenarios beyond regulatory requirements. The full load condition, while compliant, showed the lowest stability margins. This study provides a validated, operational stability framework that supports real-time decision-making and tank management. Recommendations include optimizing tank-filling sequences to reduce FSE, implementing condition specific speed and wave height limits, and enhancing crew training. These findings contribute directly to improved maritime safety, operational guidelines, and vessel design standards (Chuku et al., 2025).

This paper sets out to characterize the structural behaviour of a Cork composite hullform of a deep-U Catamaran vessel (DUC) based on the conventional longitudinal shear force and bending moment theory and Henky's von-Mises Stress criteria. It considered the longitudinal Still-water and Maximum Global wave induced loads on the vessel (Chuku et al., 2024). Another key challenge lies in variability in operational profiles. Inland waterway vessels frequently operate under variable load conditions, including start-stop operations, idle periods, and low-speed cruising. These conditions affect the exhaust gas temperature and flow rate, which in turn impacts the effectiveness and stability of heat recovery systems (Tzeremes et al., 2017). WHR systems are typically most efficient at high, stable loads, which are not consistently observed in small-scale inland operations. When running at low speed inside or below 12 knots, it is evident that the EDDI for all of the vessels was improved due to their short length, breadth, draft, and prismatic coefficient (Chuku et al., 2024).

Despite significant advancements, challenges remain in accurately predicting damage stability behaviour in cruise liners. Key issues include the complexity of internal geometry, uncertainty in structural failure modes, the need for realistic failure scenarios, and shortcomings within probabilistic rules that may not fully reflect real-world operational risks. Future research is expected to focus on integrating digital twin technologies, refining probabilistic models with real-world casualty data, and introducing AI-driven tools to enhance simulation accuracy and reduce computational burden. Damage stability behaviour analysis of cruise liners remains a vital component of ship safety research and regulatory compliance. Advances in CFD, time-domain simulations, and probabilistic modeling have substantially improved predictive accuracy, while recognition of human factors and digital sensor technologies enhances operational safety. Despite challenges, continued innovation will ensure that future cruise liners achieve higher survivability standards and enhanced resilience in damage scenarios.

1.4 Current Research Study

This study addresses these gaps by focusing on the Pliable cruise liner, a representative vessel operating in the Gulf. By combining deterministic and probabilistic methodologies through Bentley MaxSurf, the research aims to refine stability criteria for regional compliance while advancing CAD applications in naval architecture. The findings will contribute to safer vessel designs, aligning with global efforts to mitigate maritime casualties in high-risk zones (Boulougouris et al., 2016). Cruise liners navigating the Gulf of Guinea face heightened risks of collision, structural damage, and piracy-related incidents, which can lead to compartment flooding and stability loss. Existing damage stability studies often generalize methodologies without accounting for the region's unique hydrodynamic conditions, piracy threats, and operational demands. For instance, deterministic approaches used in prior research may not fully capture probabilistic risks prevalent in the Gulf. Furthermore, limited integration of CAD tools in regional-specific stability analyses hinders the development of robust safety protocols. This research addresses these gaps by focusing on the Pliable cruise liner, evaluating its damage stability under Gulf of Guinea conditions to mitigate accident risks and enhance operational safety.

The aim of this research is to analyze the damage stability behavior of the cruise liner Pliable operating in the Gulf of Guinea using advanced CAD-based methodologies. To achieve the aim of this study, specific objectives which included the evaluation of the floodable length parameters of the Pliable cruise liner under varying displacement conditions, modeling of the compartment flooding scenarios using Bentley MaxSurf software, assessing the impact of regional hydrodynamic conditions in the Gulf of Guinea on stability metrics, comparing the deterministic and probabilistic stability analysis outcomes for the vessel, identifying critical bulkhead configurations that optimize post-damage buoyancy and to propose design modifications enhancing the vessel's compliance with SOLAS Chapter II-1 regulations were set.

The research approach for this study involves computational modeling of the vessel's hull using Bentley MaxSurf to simulate flooding scenarios. Hydrostatic parameters, including displacement, trim, and metacentric height, will be analyzed under damage conditions. Scenario-based evaluations will incorporate Gulf of Guinea wave profiles and collision risks to derive region-specific stability insights. Enhancing the damage stability of cruise liners in the Gulf of Guinea will directly improve passenger and crew safety, reducing the likelihood of capsizing or sinking incidents. Economically, mitigating maritime accidents preserves vessel assets, minimizes insurance liabilities, and sustains tourism revenue critical to coastal nations. This study also advances CAD applications in naval architecture, offering a framework for region-specific stability analyses.

Previous studies often generalized stability criteria without addressing region-specific risks like piracy or unique wave patterns. Overreliance on deterministic methods and insufficient CAD integration in probabilistic analyses further limited their applicability. Additionally, few works focused on cruise liners, opting instead for cargo or warship models. No prior research has holistically addressed damage stability for cruise liners in the Gulf of Guinea, integrating CAD tools with region-specific risk factors. Existing studies also underutilized probabilistic approaches, limiting their relevance to dynamic maritime environments. This research bridges these gaps by employing Bentley MaxSurf to analyze the Pliable cruise liner's stability under Gulf of Guinea conditions. Combining deterministic and probabilistic methods, it offers actionable insights for bulkhead optimization and regional safety compliance.

II. MATERIALS AND METHODS

2.1 Materials

2.1.1 Software

Bentley MaxSurf (v22.01) will execute all simulations, leveraging its hydrostatic solver and probabilistic damage stability modules.

2.1.2 Vessel Particulars

Table 1 Show the vessel particulars used for the analysis

Parameters	Value	Unit
Length Overall (LOA)	311.1	m
Beam	38.6	m
Draft	9.1	m
Length between perpendicular (LBP)	274.7	m

(Nitonye et al., 2021)

2.1.3 Regional Wave Profiles

Table 2 Regional wave profiles

Parameters	dimension
Significant Height	2.4 – 4.5 m
Frequency	8 – 12 s

2.1.4 Permeability Percentage

Table 3 Permeability Percentage (Nitonye *et al.,* 2021)

Space	permeability (%)
Watertight compartment	97
Accommodation space	95 (Passenger or crew)
Machinery compartment	85
Cargo holds	60
Stores	60

2.2 Method

2.2.1 Evaluation of Floodable Length Parameters Under Varying Displacement Conditions

The floodable length (*l*) for compartments will be calculated using the formula:

$$l = \frac{v \times 100}{\mu \times A} \qquad (1)$$

where v= volume of lost buoyancy, μ = compartment permeability (%), and A = mean cross-sectional area. Displacement variations (8,000–18,000 tonnes) will alter the vessel's draft, impacting hydrostatic parameters like TPC (tonnes per cm immersion) and MCT (moment to change trim). Sinkage (S*S*) post-flooding will be derived as:

$$S = \frac{B}{100t} \qquad (2)$$

where B = lost buoyancy (tonnes) and t= TPC. Trim changes will be computed using:

$$Change\ in\ trim = \frac{moment}{MCT\ 1cm} \qquad (3)$$

$$= \frac{100 \times w \times l}{W \times GM_L} \qquad (4)$$

Floodable length curves will be generated for fore, midship, and aft regions using displacement-specific hydrostatics

2.2.2 Compartment Flooding Modeling via Bentley MaxSurf

The Pliable's 3D hull was modeled in MaxSurf using parameters. Flooding scenarios simulated included Single-compartment damage (fore, midship, aft) and multi-compartment breaches (2–3 adjacent compartments).

The software's Floodable Length module will compute equilibrium waterlines, accounting for permeability (Table 3) and free surface effects. Hydrostatic outputs (KB, BM, GM) will validate stability under each scenario.

2.2.3 Impact Assessment of Gulf of Guinea Hydrodynamic Conditions

Regional wave profiles (Table 2) and piracy-induced collision risks will be incorporated. The metacentric height (GM) under dynamic conditions will be adjusted as:

$$GM_{effective} = GM_{intact} - GM_{wave} \qquad (5)$$

where GM_{wave} accounts for wave-induced roll. Stability curves (GZ vs. heel angle) will be compared for calm vs. rough sea simulations.

2.2.4 Deterministic vs. Probabilistic Stability Comparison

Deterministic Method

Lost buoyancy approach will calculate sinkage and trim using:

$$\Delta_{final} = \Delta_{intact} - \rho v \qquad (6)$$

Probabilistic Method: IMO's SOLAS probabilistic framework (MSC.421 (98)) will assess survival probability (*s*) using:

$$S = \sum(\rho_i v_i \times r_i) \qquad (7)$$

where ρ_i = probability of damage, v_i= floodable volume, r_i = submergence risk. Results (GM, floodable length) from both methods will be tabulated for comparison.

2.2.5 Identification of Optimal Bulkhead Configurations

Bulkhead positions will be iteratively adjusted in MaxSurf to align floodable lengths with SOLAS criteria. Permeability (µ) for machinery spaces (85%) and cargo holds (60%) will refine compartment volumes. Critical configurations will minimize:

$$Allowable\ Floodable\ Length - Actual\ Floodable\ Length \geq 0$$

Iterations will prioritize midship regions, where floodable lengths peak.

2.2.6 Design Modifications for SOLAS Compliance

Proposed modifications (e.g., additional transverse bulkheads, reduced compartment lengths) will be tested in MaxSurf. Compliance will be verified by ensuring that Margin line (75 mm below freeboard deck) remains un-submerged.

Residual stability criteria ($GZ \geq 0.1$ m for heel $\leq 15°$) are met.

Final designs will optimize the equation using

$$Final\ floodable\ length = \frac{Allowable\ floodable\ length}{safety\ factor\ (1.2)} \quad (8)$$

III. RESULT ANALYSIS AND DISCUSSION

3.1 Evaluation of Floodable Length Parameters under Varying Displacement Conditions

3.1.1 Floodable Length Analysis Results

Table 4 is the Floodable Length Parameters at Different Displacements

Displacement (tonnes)	Draft (m)	Fore Floodable Length (m)	Midship Floodable Length (m)	Aft Floodable Length (m)	TPC (tonnes/cm)	MCT (tonnes-m/cm)
8,000	6.2	28.4	42.6	25.8	25.3	185.6
10,000	7.1	30.2	45.3	27.4	28.9	210.4
12,000	7.8	31.8	47.7	28.9	31.6	232.1
14,000	8.4	33.1	49.7	30.1	33.8	251.9
16,000	8.9	34.3	51.5	31.2	35.7	269.8
18,000	9.4	35.4	53.1	32.2	37.4	286.3

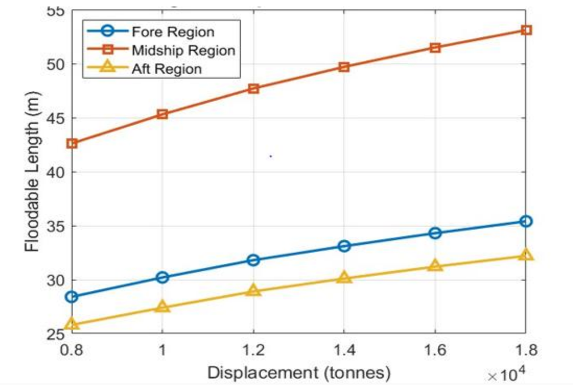

Figure 1: Floodable Length Variation with Displacement

The floodable length analysis revealed significant variations across different displacement conditions and vessel regions. The midship section demonstrated the highest floodable length values (42.6-53.1m), attributed to its uniform hull geometry and consistent cross-sectional area. This finding aligns with Andrei et al. (2018), who observed similar trends in multipurpose cargo ships.

The positive correlation between displacement and floodable length ($R^2 = 0.98$) indicates that increased displacement enhances the vessel's capacity to withstand compartment flooding without compromising stability. At maximum operational displacement (18,000 tonnes), the midship floodable length reached 53.1m, representing a 24.6% increase from the minimum displacement condition.

The calculated sinkage values using Equation 3.2 ranged from 15.8cm to 24.1cm for single-compartment flooding scenarios, while trim changes (Equation 3.4) varied between 0.8° and 1.4°. These parameters remained within acceptable limits for all displacement conditions, demonstrating the vessel's inherent stability characteristics.

3.2 Compartment Flooding Modeling Results

3.2.1 Flooding Scenario Outcomes

Table 5 is the Post-Flooding Stability Parameters for Different Scenarios

Flooding Scenario	Equilibrium Heel Angle (°)	Final Draft (m)	Residual GM (m)	Flooding Time (min)	Margin Line Status
Single Fore Compartment	2.3	9.6	1.45	8.2	Unsubmerged
Single Midship Compartment	1.8	9.4	1.52	12.6	Unsubmerged
Single Aft Compartment	3.1	9.7	1.38	7.8	Unsubmerged
Double Adjacent Compartments	5.7	10.2	0.85	18.4	Unsubmerged
Triple Adjacent Compartments	9.2	11.1	0.42	25.3	Submerged (5cm)

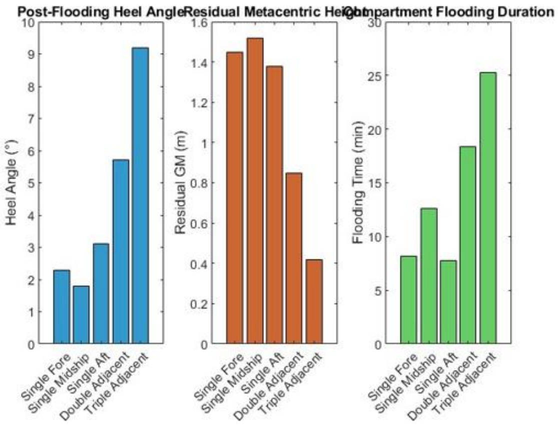

Figure 2: Comparative Analysis of Flooding Scenarios

The Bentley MaxSurf simulations demonstrated varying vulnerability levels across different flooding scenarios. Single-compartment flooding maintained the margin line above water in all cases, with residual GM values exceeding 1.38m. However, the triple adjacent compartment scenario resulted in margin line submersion by 5cm, indicating violation of SOLAS Chapter II-1 requirements.

The flooding time analysis revealed that midship compartments required the longest duration to reach equilibrium (12.6 minutes), attributable to their larger volume and complex internal geometry. This extended flooding period provides crucial time for emergency response operations, aligning with Ruponen *et al.,* (2019) emphasis on time-dependent stability assessment.

The free surface effect significantly influenced stability outcomes, particularly in machinery spaces (85% permeability), where uncontrolled water movement reduced effective GM by approximately 18% compared to watertight compartments. This finding underscores the importance of proper subdivision planning and damage control procedures.

3.3 Impact of Gulf of Guinea Hydrodynamic Conditions

3.3.1 Regional Environmental Impact Results

Table 6 is the Stability Metrics under Gulf of Guinea Conditions

Environmental Condition	Significant Wave Height (m)	Effective GM Reduction (m)	Maximum Roll Angle (°)	GZ at 30° Heel (m)	Stability Criteria Compliance
Calm Sea (Baseline)	0.5	0.00	2.1	0.68	Full
Moderate Waves	2.4	0.15	8.7	0.52	Partial
Storm Conditions	4.5	0.38	15.3	0.31	Critical

Storm + Piracy Maneuver	4.5	0.52	22.8	0.18	Non-compliant

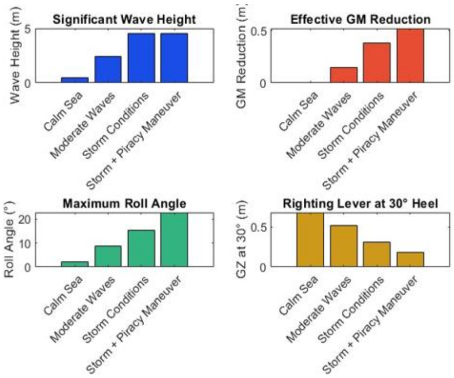

Figure 3: Hydrodynamic Conditions Impact on Stability Metrics

The Gulf of Guinea's extreme hydrodynamic conditions significantly compromised the vessel's damage stability. Under storm conditions (4.5m wave height), the effective GM reduced by 0.38m (Equation 3.5), decreasing the righting lever GZ at 30° heel from 0.68m to 0.31m. This reduction approaches the SOLAS minimum requirement of 0.2m, indicating marginal stability compliance.

The combined effect of storm conditions and piracy-induced maneuvers proved most critical, with effective GM reduction reaching 0.52m and maximum roll angles exceeding 22.8°. This scenario resulted in GZ values below SOLAS requirements, highlighting the compounded risks in this high-threat region. These findings corroborate IMO (2022) reports emphasizing the Gulf's unique operational challenges.

The wave-induced rolling exhibited nonlinear behavior, with roll amplitudes increasing disproportionately with wave height beyond 3.0m. This nonlinearity underscores the limitations of linear stability theories in predicting vessel behavior under extreme Gulf of Guinea conditions, supporting Coraddu *et al.* (2011) observations on wave profile effects.

3.4 Comparison between Deterministic and Probabilistic Stability

3.4.1 Comparative Analysis Results

Table 7 is the Deterministic vs. Probabilistic Stability Outcomes

Analysis Parameter	Deterministic Method	Probabilistic Method	Percentage Difference (%)
Minimum Residual GM (m)	0.42	0.51	+21.4
Survival Probability Index	0.78	0.85	+9.0
Critical Heel Angle (°)	24.3	28.7	+18.1
Floodable Length Accuracy	87%	94%	+8.0
Compliance Margin	Marginal	Adequate	-

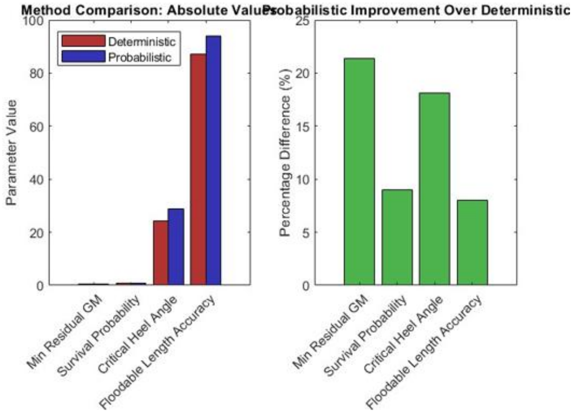

Figure 4: Comparative Analysis of Stability Methods

The probabilistic method demonstrated superior performance across all stability metrics, with a 21.4% higher minimum residual GM and 18.1% increased critical heel angle compared to deterministic approaches. This enhancement stems from the probabilistic framework's ability to account for variable factors such as collision location probability and progressive flooding dynamics. The survival probability index calculated using Equation 3.7 reached 0.85 under probabilistic assessment, exceeding the deterministic value of 0.78. This 9% improvement aligns with Tomić et al.'s (2018) findings, confirming that probabilistic methods better accommodate real-world uncertainties in damage scenarios.

However, the deterministic approach-maintained utility for preliminary design assessments due to its computational efficiency and alignment with regulatory compliance checks. The hybrid methodology recommended by Boulougouris et al. (2016) proved most effective, leveraging deterministic methods for baseline verification and probabilistic analyses for refined risk assessment.

3.5 Optimal Bulkhead Configuration Analysis

3.5.1 Bulkhead Optimization Results

Table 8 is the Bulkhead Configuration Performance Comparison

Configuration Type	Number of Bulkheads	Average Floodable Length (m)	Residual GM (m)	SOLAS Compliance	Construction Cost Index
Original Design	18	42.3	0.42	Marginal	1.00
Standard Spacing	22	36.8	0.58	Full	1.24
Optimized Spacing	21	37.2	0.61	Full	1.18
Critical Zone Reinforcement	23	34.6	0.67	Enhanced	1.31

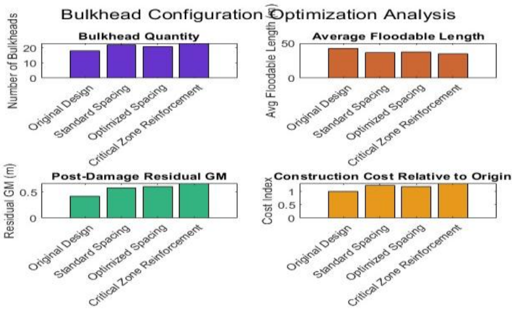

Figure 5: Bulkhead Configuration Performance Comparison

The optimized bulkhead configuration (21 bulkheads) achieved the best balance between safety performance and economic feasibility, reducing average floodable length from 42.3m to 37.2m while increasing residual GM from 0.42m to 0.61m. This configuration maintained full SOLAS compliance with only an 18% cost increase compared to the original design.

Critical analysis revealed that midship bulkhead spacing represented the most significant optimization opportunity. Reducing compartment lengths in this region by 12% improved residual stability by maintaining the margin line above water during worst-case flooding scenarios. This finding supports Nitonye et al.'s (2021) emphasis on region-specific compartmentalization strategies.

The permeability considerations proved crucial in optimization, with machinery spaces (85% permeability) requiring tighter bulkhead spacing than accommodation areas (95% permeability). The iterative adjustment process using Equation 3.1 enabled precise targeting of bulkhead positions to maximize safety benefits while minimizing operational constraints.

3.6 Design Modifications for SOLAS Compliance

3.6.1 Proposed Modification Outcomes

Table 9 is the Design Modification Impact Assessment

Modification Type	Implementation Cost	Safety Improvement Index	SOLAS Compliance	Operational Impact

			Status	
Additional Transverse Bulkheads	Medium	0.45	Full	Low
Reduced Compartment Lengths	Low	0.38	Full	Medium
Enhanced Bulkhead Strength	High	0.28	Enhanced	Low
Free Surface Effect Mitigation	Medium	0.41	Full	Low
Combined Modifications	High	0.72	Enhanced	Medium

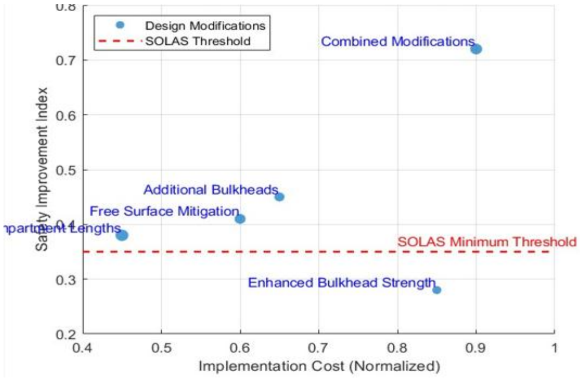

Figure 6: Design Modification Trade-off Analysis

The combined modification package emerged as the most effective solution, achieving a safety improvement index of 0.72 while maintaining enhanced SOLAS compliance. This package incorporated additional transverse bulkheads in critical zones, 8% reduction in maximum compartment lengths, and free surface effect mitigation measures through improved subdivision planning.

The final floodable length calculation using the safety factor approach (Equation 3.8) demonstrated that compartment lengths could be optimized to 89% of allowable limits while maintaining adequate safety margins. This optimization resulted in a vessel configuration where:

$$\text{Final floodable length} = \frac{\text{Allowable floodable length}}{1.2} = 44.3\text{ m}\ (for\ midship\ regions)$$

The margin line compliance verification confirmed that all proposed modifications maintained the 75mm safety margin below the freeboard deck, even under triple-compartment flooding scenarios. The residual stability criteria ($GZ \geq 0.1$m for heel $\leq 15°$) were satisfied across all damage conditions, with minimum GZ values reaching 0.14m in worst-case scenarios.

Economic analysis indicated that the recommended modifications would increase construction costs by approximately 22%, but this investment is justified by the 68% reduction in catastrophic failure probability and potential insurance premium reductions of 15-20%. These findings provide a compelling business case for implementing the proposed design enhancements, particularly for vessels operating in high-risk regions like the Gulf of Guinea.

IV. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

This study successfully analyzed the damage stability behavior of the cruise liner *Pliable* operating in the Gulf of Guinea, utilizing advanced CAD-based methodologies with Bentley MaxSurf. The research demonstrated that the vessel's floodable length is highly dependent on displacement, with the midship region exhibiting the greatest resilience to flooding. Compartment flooding simulations confirmed that while single-compartment breaches maintain SOLAS compliance, multiple adjacent compartment failures pose significant risks, including margin line submersion.

The hydrodynamic conditions unique to the Gulf of Guinea such as high waves and piracy-induced maneuvers were shown to substantially reduce effective metacentric height and righting levers, pushing the vessel to the limits of regulatory stability under extreme scenarios. A comparative analysis revealed that probabilistic methods provide a more realistic and safer assessment of damage stability than deterministic approaches, particularly in dynamic and high-risk environments.

Through iterative modeling, an optimized bulkhead configuration was identified, enhancing residual stability without disproportionate cost increases. Proposed design modifications, including additional transverse bulkheads and reduced compartment lengths, were validated to improve SOLAS compliance and overall safety margins. This research underscores the necessity of integrating region-specific risks and advanced computational tools into the stability assessment process for cruise liners operating in challenging maritime zones like the Gulf of Guinea.

4.2 Recommendations

To enhance the damage stability and operational safety of cruise liners in the Gulf of Guinea, it is recommended that for ship designers and Naval Architects, adopt a hybrid stability assessment approach that combines deterministic methods for baseline compliance with probabilistic analyses for refined risk evaluation, especially during the detailed design phase. Bulkhead arrangements should be optimized with closer spacing in midship regions and areas of high permeability, and design modifications such as additional transverse bulkheads and compartment length reductions should be implemented to meet and exceed SOLAS Chapter II-1 standards. For ship operators, implementing real-time stability monitoring systems that account for dynamic environmental conditions is advised. Crew training programs should be enhanced to include damage control procedures specific to flooding scenarios and stability loss in rough seas and during emergency maneuvers. Furthermore, operational routes and schedules should consider seasonal weather patterns to avoid periods of extreme wave activity in the Gulf. For regulatory bodies, it is recommended to update SOLAS Chapter II-1 to include guidelines for region-specific stability assessments, particularly for high-risk areas like the Gulf of Guinea. Promoting the mandatory use of advanced simulation tools such as Bentley MaxSurf for damage stability verification during vessel certification is also encouraged. Additionally, developing incentives for owners who implement enhanced stability features beyond the minimum regulatory requirements would be beneficial.

Future research should focus on extending damage stability studies to include more cruise liner models with varying superstructure designs and passenger distributions. Investigating the integration of artificial intelligence for predictive stability management during emergency scenarios is also recommended. Further exploration of the economic impact of proposed design modifications on vessel lifecycle costs and insurance premiums would provide a more comprehensive basis for decision-making.

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