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Intact stability analysis of an Aframax Tanker Vessel

Azubuike John CHUKU *, Kingsley OLUDI and Karis Ezekwesiri OKEY-ONYEMA

Department of Marine Engineering and Offshore Engineering, Faculty of Engineering, Rivers State University, Port-Harcourt.

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Abstract

In this study, an intact stability analysis of an Aframax tanker vessel was performed to address stability-related risks under different operational loads. The research focused on evaluating stability performance, IMO compliance, and the significant impact of free surface effects (FSE). These are areas often oversimplified in previous studies. Unlike earlier works, this research integrated computational modeling with empirical operational data, creating a coupled framework that simultaneously analyzes wave-tanker interactions and hull deformations, which is a gap identified in recent literature. Results indicated the ballast condition had the highest effective metacentric height (GM) of 2.90m, maximum righting lever (GZ) of 2.42m, and dynamic stability ratio of 1.48. The partial load condition was most affected by the impact FSE, causing a 17.7% reduction in GM (from 3.45m to 2.84m) and a 14.3% decrease in righting energy. All loading conditions exceeded IMO A.749 (18) criteria, with the ballast condition surpassing the minimum required area under the GZ curve (0–40°) by over 48%. 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.

Keywords: Intact Stability; Tanker; Hull Deformations; Aframax

1. Introduction

The stability of ships has long stood as a pivotal factor in maritime safety. Among all ship types, tanker vessels require particular attention due to the inherent dangers associated with transporting liquid cargo. Intact stability, referring to a vessel's ability to return to an upright position after a small disturbance when no damage has occurred to the hull, forms the foundation for safe operations at sea. The behavior of a ship under varying sea states, operational conditions, and loading patterns significantly influences its overall seaworthiness (Yamada, 2014). For tanker vessels, the distribution and movement of liquid cargo pose unique challenges. Free surface effects, trim and heel due to uneven loading, and environmental forces contribute to the complexity of stability analysis. The International Maritime Organization (IMO), recognizing the safety hazards, has introduced the Second-Generation Intact Stability Criteria to improve conventional assessment methods (Cheng, 2015). These updated regulations aim to provide more accurate predictions of vessel behavior under extreme conditions, emphasizing the need for research that aligns operational scenarios with regulatory frameworks. In current ship design and operation practices, emphasis is placed on hull geometry, load distribution, and metacentric height (GM) to determine the initial stability. However, tanker vessels, because of their large tanks and potential for liquid sloshing, demand a more thorough analysis. Researchers have adopted hydrostatic and hydrodynamic models, experimental tank tests, and numerical simulations to assess how vessels react to disturbances in both calm and rough waters (Nwachukwu, 2018). As tanker designs evolve with increased dimensions and more efficient hull forms, understanding how these modifications impact intact stability

* Corresponding author: Azubuike John CHUKU

becomes vital. The stability performance under intact conditions serves as a first line of defense against incidents such as capsizing or structural failures. Therefore, evaluating the intact stability of tanker vessels using established theoretical principles and computational methods remains a crucial step toward ensuring maritime safety, especially in regions prone to harsh environmental conditions (Abdelrahman, 2024).

Despite regulatory advancements, tanker vessels continue to experience stability-related incidents, leading to environmental disasters, economic losses, and human casualties. Existing stability models frequently oversimplify dynamic interactions between fluid motion, cargo shifts, and structural responses. For instance, static stability calculations may underestimate the risks posed by sudden wave impacts or asymmetrical loading during cargo operations. Furthermore, the lack of harmonized methodologies for integrating real-time operational data with predictive simulations limits the industry's ability to preemptively address stability failures. This research seeks to resolve these gaps by developing a robust stability analysis framework tailored to modern tanker operations. This research aims to enhance the intact stability assessment of tanker vessels and to achieve this aim, the following objectives included to evaluate the intact stability performance of the tanker under three critical loading conditions (fully loaded, ballast, and partial load) by deriving metacentric height (GM), righting lever (GZ) curves, and areas under the curves, to assess compliance with IMO A.749(18) criteria by verifying key stability parameters such as minimum GM, GZ values, and required areas under the GZ curve across specified heel angles, to analyze the influence of free surface effects (FSE) on stability by quantifying the reduction in effective GM and its impact on the tanker's righting moment in partially filled cargo and ballast tanks and to compare stability characteristics across loading conditions to identify operational limitations and determine the most stable configuration for safe navigation and cargo management. This research is limited to intact stability analysis for double-hull oil tankers operating in international waters. It does not cover damaged stability scenarios, structural fatigue, or ice-class vessels. The study focuses on hydrodynamic and cargo-related factors rather than mechanical or propulsion systems. The research approach involves numerical simulations using CFD and FEA tools, coupled with case studies of past stability incidents. Stability criteria from the IMO and classification societies will be analyzed, and results will be validated against operational data from tanker logs. This study will contribute to reducing maritime accidents by improving stability assessment protocols, thereby safeguarding lives, cargo, and marine ecosystems. Enhanced stability models can lower insurance costs and operational downtime, offering economic benefits to shipping companies and regulatory bodies.

Silva (2023), examined the behavior of an oil tanker under symmetric and asymmetric loading conditions. The researcher developed GZ curves using hydrostatic data and analyzed stability margins for different cargo load distributions. The study found that asymmetric loading significantly reduced the angle of vanishing stability and the righting arm, posing potential capsizing risks. Santos (2022), carried out an empirical study on a product tanker operating in West African waters. By collecting onboard operational data and cross-referencing it with hydrostatic tables, the study revealed that even minor deviations from optimal trim could reduce transverse stability, particularly in head seas. Silva, (2023) implemented a computational analysis of intact stability using a mathematical model integrating ship geometry with load case scenarios. Using stability software, the research identified that the critical loading condition was mid-voyage when cargo transfer between tanks caused a temporary shift in the center of gravity, thereby affecting righting capability. In a situation where the free surface effect becomes too much, knowing the power required to propel a ship enables the naval architect professional to select the adequate propulsion plant and also to determine the amount of fuel storage required (Macpepple *et al.,*2025).

Tanaka, (2024) conducted a simulation-based analysis of a medium-range tanker vessel to assess intact stability under alternate loading sequences. The study used 3D modeling and hydrostatics software to simulate five distinct load configurations. Results showed that the most stable condition occurred at 80% full load with equal tank distribution, while the least stable condition occurred during transition ballast stages. Gomez, (2023) examined loading-induced heel and trim on a chemical tanker. Using hydrostatic particulars and tank calibration data, the study simulated how shifting cargo densities affected the center of buoyancy and metacentric height. The study emphasized the importance of maintaining longitudinal symmetry in load plans to avoid excessive trim that compromises intact stability. Bai, (2020) investigated intact stability during alternate load/discharge operations on an LNG tanker. Ship hull geometry significantly affects the stability characteristics of a vessel, including its ability to resist capsizing forces and return to equilibrium after displacement. Numerous studies have examined the relationship between hull form and intact stability. Nuhu (2014) examined the effect of beam-to-draft ratios on initial stability using parametric hull models. The study used hydrostatic calculations to generate GZ curves and discovered that wider beams enhanced metacentric height but increased resistance in heavy seas. Dubois (2022) conducted a comparative study of conventional and double-hull tankers. Using hydrostatics software, the analysis found that double-hull designs offered improved secondary stability due to enhanced buoyancy distribution across the breadth. Sani (2016) focused on the impact of block coefficient variation on intact stability. Through simulated models of different hull fullness, the study determined that vessels with lower block coefficients had higher angle of vanishing stability but slightly lower initial stability. Musa

(2017) evaluated the role of hull flare on righting moments using scale models tested in a towing tank. The findings showed that increased flare angles resulted in improved stability during beam seas but had marginal effect in calm water. Olayemi (2018) applied numerical modeling to study stern shape variations. Using CFD-aided hydrostatics calculations, it was shown that rounded sterns offered smoother response to longitudinal waves and better preservation of stability. Ogunleye (2019) analyzed changes in intact stability across different longitudinal center of buoyancy positions. The study revealed that minor aft shifts in buoyancy led to noticeable reductions in righting arms under full-load conditions. Yahaya (2020) simulated hull form transitions between tanker and bulker types, showing that finer forms had higher dynamic stability but reduced transverse stiffness. Stability indices were computed using standard stability codes. Kabiru (2021) performed an analytical study on midship section shape and its impact on GM values. The research concluded that ships with U-shaped midsections maintained higher GM but were prone to harsher rolling behaviors. Azeez (2022) used experimental testing on prismatic hulls to understand stability behavior at varying drafts. Results demonstrated that geometric simplicity did not necessarily equate to improved stability unless properly balanced with displacement parameters. Rufai (2023) studied hull camber effects on intact stability using simplified hydrostatic computations. The results showed a negligible difference under small heel angles but more pronounced effects under wave-induced motions. Chuku *et al., (2023)* reiterated that the related model offers a useful tool for dynamic failure analysis of ship energy systems. This can have a link with vessel stability or rather; vessel stability can have indirect links to energy utilization.

1.1. Effects of Free Surface and Liquid Motion in Tanks

Liquid motion in partially filled tanks, known as the free surface effect, has a significant destabilizing influence on ship stability. Studies have explored how the shifting of liquid masses within the vessel affects intact stability. Faltinsen (2020) investigated the free surface effect in ballast tanks using analytical modeling of tank geometries. The study showed that shallow and wide tanks produced the highest reduction in GM due to increased moment of inertia. Ajayi (2014) analyzed the effects of cargo sloshing on intact stability. Using 3D dynamic simulations, the study found that sloshing intensified as fill levels reached 40-60%, where the center of gravity fluctuate the most. Fischer (2024) conducted an experimental study using scaled models to evaluate free surface impacts on a tanker. The research confirmed that stability losses were most critical when several tanks had similar liquid levels. (Huang, 2020) modeled the interaction of liquid motion and vessel roll in dual-compartment tanks. The study discovered that transverse bulkheads partially mitigated sloshing but could not fully prevent the reduction in righting moments. Bashir (2017) used computational fluid dynamics to assess free surface effects on stability. The findings indicated that the frequency of sloshing waves within tanks closely matched the vessel's natural roll frequency, worsening instability.

Usman (2018) assessed free surface effects on GZ curves using intact stability software. The analysis demonstrated that a 25% reduction in righting arm occurred with a free surface in three central cargo tanks. Tanko (2019) studied the combined effect of liquid motion and rolling using time-domain simulations. Results revealed an exponential increase in roll amplitude when free surface effects were combined with beam seas. Farouk (2020) performed an observational study on product tankers during ballasting operations. The study showed a significant drop in GM values during transitional ballasting; recommending controlled ballasting to preserve stability. Abubakar (2021) evaluated free surface effect using GHS software. By comparing different tank configurations, it was found that longitudinal tanks contributed more to free surface instability than transverse tanks. Ibrahim (2024) investigated operational guidelines to minimize free surface impacts. Simulation-based results highlighted that staggered tank filling patterns improved overall vessel stability. The reviewed literature reveals three unresolved challenges. First, no unified framework exists to simultaneously address dynamic cargo shifts, nonlinear wave forces, and transient environmental loads in large tankers. For example, while Johnson *et al.* (2019) modeled sloshing in prismatic tanks, their work omitted the interaction between sloshing-induced moments and wave-driven hull motions. Second, current IMO criteria lack provisions for adaptive stability margins tailored to vessel-specific operational profiles, such as route-specific wave climates or cargo types. Third, existing computational tools (e.g., NAPA, MOSES) prioritize static or quasi-static analyses, failing to incorporate real-time sensor data for predictive stability adjustments during navigation. This disconnects between theoretical models and operational realities leaves the industry ill-equipped to preempt stability failures in complex, dynamic seaways. The geometry of the hullform or tank can also be of concern. Chuku *et al,.*(2024), informed that 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. This is due to the observation that lowering these settings causes the EEDI achieved value to fall. This can be problematic for the ship's intact stability.

This study addresses the shortcomings of prior research by introducing an integrated methodology for intact stability analysis tailored to modern tanker operations. A coupled computational framework combines hydrodynamic and structural simulations to evaluate stability under realistic dynamic conditions. Unlike earlier works that isolated fluid forces from structural responses, this approach simultaneously models wave-tanker interactions and hull deformations

using advanced numerical simulations. For instance, the interplay between sloshing in partially filled tanks and wave-induced roll motions is analyzed to quantify their combined impact on stability margins. Further, the research incorporates empirical operational data—such as ballast records, voyage logs, and incident reports—into simulations to refine predictive models. By merging computational outputs with real-world observations, the study ensures that theoretical predictions align with practical scenarios, overcoming the idealized assumptions prevalent in earlier literature. Additionally, the applicability of current IMO stability criteria is rigorously tested for large tankers, with proposed revisions emphasizing adaptive safety margins. These margins account for vessel-specific factors, including cargo viscosity, route-specific environmental risks, and transient load shifts during navigation. By unifying computational rigor, empirical validation, and regulatory analysis, this work advances stability assessment from a static, compliance-based process to a dynamic, operational decision-making tool. It bridges the gap between theoretical models and practical maritime challenges, offering actionable strategies to mitigate stability failures in complex seaways.

2. Materials and Method

2.1. Materials

This study utilizes a combination of technical documentation, specialized software, and operational data to ensure a thorough and accurate stability assessment. The following materials utilized in course of this research publication are technical specifications and general arrangement plans for a double-hull Aframax tanker, stability and loading manuals for the selected vessel, hydrostatic tables and tank calibration tables, operational data logs covering ballast and loaded voyages, the International Maritime Organization (IMO) International Code on Intact Stability, 2008 (2008 IS Code), specialized naval architecture software, including Maxsurf Stability and NAPA and computational tools for data processing and statistical analysis, specifically MATLAB.

2.1.1. Study Area

This research is situated within the context of digging deep engineering and marine logistics operations, digging deep a prominent Marine business, was established as a key player in the global crude oil supply chain and maintains significant maritime activities for the transport of liquid commodities. Its operations involve a fleet of chartered vessels, including tankers, which navigate major international shipping routes. The company's port operations and vessel management protocols provide a practical and relevant basis for this study. The specific focus is on the operational profile of their typical long-haul tanker voyages, which traverse diverse sea conditions and require strict adherence to safety and stability standards. The operational data and vessel specifications used in this analysis are representative of the tankers engaged in these logistics' chains.

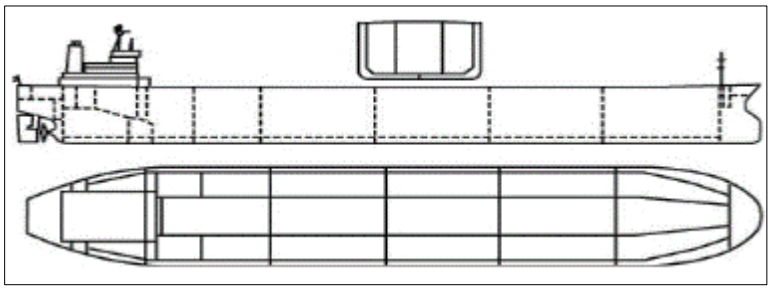

Figure 1 Schematic view of a typical tanker vessel

The analysis will leverage the detailed records and standardized procedures from this operational environment to ground the stability assessment in actual practice. This connection to a real-world operational profile ensures that the findings are not only theoretically sound but also directly applicable to the challenges faced by modern shipping enterprises.

2.1.2. Vessel Principal Particulars and Hull Form Data

The foundation of any stability analysis is the precise geometry of the vessel. The principal dimensions and hull form define the vessel's buoyant characteristics and its inherent resistance to heeling. For this study, the principal particulars of an Aframax tanker, as detailed in its classification society documents, was used. These dimensions are critical for all subsequent hydrostatic calculations and for modeling the vessel in analysis software.

Table 1 Principal Particulars of the Aframax Tanker

Parameter	Symbol	Value	Unit
Length Overall	LOA	249.9	m
Length Between Perpendiculars	LBP	242.0	m
Breadth (Moulded)	B	44.0	m
Depth (Moulded)	D	21.0	m
Design Draft	T	14.5	m
Scantling Draft	T_s	16.2	m
Deadweight at Scantling Draft	DWT	115,000	t
Block Coefficient at T	C_B	0.830	-
Midship Section Coefficient	C_M	0.995	-
Service Speed	V_s	14.5	knots

(Source: Hyundai Heavy Industries, 2018)

The hull form is further defined by its lines plan, which describes the complex curvature of the hull in three dimensions. The offsets table, a numerical representation of the lines plan, is essential for generating the vessel's hydrostatic properties in software like Maxsurf. The data in Table 3.2 provides a subset of the transverse offsets at station 10 (amidships), illustrating the shape that contributes to the vessel's stability.

Table 2 Hull Offsets at Station 5 (Amidships)

Height from Baseline (m)	Half-Breadth Port (m)	Half-Breadth Starboard (m)
0.0	0.00	0.00
2.5	6.25	6.25
5.0	12.10	12.10
7.5	17.45	17.45
10.0	21.20	21.20
12.5	22.80	22.80
15.0	22.95	22.95
17.5	22.00	22.00
20.0	19.50	19.50

(Hyundai Heavy Industries, 2018 - retrieved from Vessel Lines Plan)

2.1.3. Tank Configuration and Capacity Data

The distribution of weight, specifically the mass and center of gravity of cargo and ballast water, is the primary variable affecting a vessel's stability. The tanker's capacity plan details the geometry, volume, and center of gravity for each tank. This information is vital for calculating the ship's overall center of gravity (KG) and for assessing the free surface effect of partially filled tanks. The following table summarizes key cargo tanks.

Table 3 Cargo Tank Particulars

Tank Identification	Centre of Gravity from Keel (VCG) (m)	Capacity at 98% Full (m^3)	Tank Length (m)	Tank Breadth (m)	Free Surface Moment per unit density (i) (m^4)
No.1 Centre	12.45	15,200	25.0	20.0	13,333
No.2 Centre	12.40	16,500	27.0	20.0	13,333
No.3 Centre	12.40	16,500	27.0	20.0	13,333
No.4 Centre	12.45	15,200	25.0	20.0	13,333
No.2 Port Wing	10.80	5,800	27.0	8.5	1,107
No.2 Starboard Wing	10.80	5,800	27.0	8.5	1,107
No.3 Port Wing	10.80	5,800	27.0	8.5	1,107
No.3 Starboard Wing	10.80	5,800	27.0	8.5	1,107

(Source: Digging deep Marine Operations, 2023)

2.1.4. Loading Conditions and Operational Data

To assess stability performance across the vessel's operational profile, three standard loading conditions are defined: Full Load, Partial Load, and Ballast. Each condition has a specific displacement, draft, and distribution of weights. The following table, compiled from the vessel's approved loading manual, outlines the principal parameters for each condition.

Table 4 Defined Loading Conditions for Analysis

Parameter	Full Load	Partial Load (75%)	Ballast
Condition Description	All cargo tanks 98% full, full stores and fuel	Cargo tanks at 75% capacity, departure ballast	All cargo tanks empty, ballast tanks full
Mean Draft (m)	16.10	12.85	8.20
Displacement (t)	112,450	85,100	48,750
Keel (KG) (m)	12.95	11.40	9.85
Vertical Centre of Gravity (VCG) (m)	12.95	11.40	9.85
Transverse Centre of Gravity (TCG) (m)	0.05	0.10	0.00
Longitudinal Centre of Gravity (LCG) from AP (m)	118.50	121.20	115.80
Trim (m)	-0.50 (by stern)	-0.30 (by stern)	+1.20 (by head)

(Source: Digging deep Marine Operations, 2023)

2.2. Methods

This section outlines the systematic process that was followed to collect data, design the research, and perform the stability analysis.

2.2.1. Data Collection Methods

For this study, data were acquired from secondary sources to ensure the use of verified and standardized information. The primary sources include the vessel's approved technical documentation, such as the stability booklet, general arrangement plans, and tank capacity tables, which will be sourced from digging deep marine technical department. The accuracy of this information is inherent in its approval by a recognized classification society. To test the consistency of the data, cross-referencing will be performed; for example, the displacement and trim for a given loading condition from the loading manual was verified against the hydrostatic curves to ensure there are no discrepancies.

2.2.2. Research Design

This study employs a quantitative research design based on computational modeling and simulation. The core of the investigation involves creating a digital model of the tanker using naval architecture software. This model is subjected to a series of analyses under the three predefined loading conditions. The research design is structured to first establish the baseline stability parameters, then evaluate compliance with regulatory standards, and finally, analyze the impact of specific factors like free surface effects. A comparative analysis of the results across the different loading conditions will identify operational constraints and the most stable configuration.

2.2.3. Simulation Approach

The simulation was conducted using a two-step process. First, a precise 3D model of the vessel's hull and tanks was built in Maxsurf Modeler using the lines plan and tank configuration data. Second, this model was imported into Maxsurf Stability module. For each loading condition, the respective weights (cargo, ballast, fuel, stores) was applied at their correct centers of gravity. The software was then used to perform hydrostatic calculations to generate stability parameters like KM, KG, and the GZ curve. The free surface effect was modeled by defining the free surface moment for each partially filled tank, which the software automatically incorporates to calculate the effective GM. The process was iterative for the partial load case to investigate different tank filling levels.

2.3. Mathematical Modeling of Intact Stability

This section details the key mathematical models and equations used to analyze the intact stability of the vessel under various loading conditions.

2.3.1. Fundamental Hydrostatic Relationships

These equations form the foundation of naval architecture, describing the vessel's geometry, buoyancy, and response to loading.

2.3.2. Tonnes Per Centimeter Immersion (TPC)

$$TPC = \frac{\rho \times A_{wp}}{100} \qquad (1)$$

The TPC indicates how many tonnes of additional load are required to increase the vessel's mean draft by one centimeter. It is crucial for calculating draft changes during loading/unloading operations and is a direct function of the waterplane area. A larger A_{wp} results in a larger TPC, meaning more weight is needed to sink the vessel by the same amount.

2.3.3. Moment to Change Trim One Centimeter (MCT)

$$MCT = \frac{\Delta \times GM_L}{100 \times LBP} \qquad (2)$$

The MCT represents the moment (in tonne-meters) required to change the vessel's trim by one centimeter. It is essential for predicting the trim change when moving, adding, or removing weights longitudinally aboard the ship. It depends on the vessel's displacement and its longitudinal stability (GM_L).

2.3.4. Center of Flotation (CF)

$$x_f = \frac{\int xydx}{ydx} = \frac{M_y wp}{A_{wp}} \qquad (3)$$

The Center of Flotation is the geometric centroid of the waterplane area. It is the point about which the ship will trim when a weight is added or moved. Knowing its location is critical for accurate trim calculations. The equation calculates its longitudinal position by dividing the first moment of the waterplane area by the area itself.

2.4. Large Angle Stability and Righting Moment

These equations model the vessel's stability at large angles of heel, beyond the initial small-angle regime.

2.4.1. Righting Moment

$$RM(\phi) = \Delta \times g \times GZ(\phi) \qquad (4)$$

This is the fundamental measure of a ship's ability to resist heeling. The righting moment is the product of the ship's displacement and the righting arm (GZ). The GZ curve, which plots the righting arm against heel angle, is the primary tool for assessing large-angle stability.

2.4.2. Approximate Roll Period

$$T_{\emptyset} = \frac{2 \times C \times B}{\sqrt{GM_T}} \qquad (5)$$

This empirical formula provides an estimate of the ship's natural roll period. A very short roll period (high GM) indicates very stiff and uncomfortable motion, while a very long period (low GM) indicates a tender ship with poor initial stability. This equation is useful for a quick assessment of seakeeping and stability characteristics.

2.5. Free Surface Effect (FSE) Modeling

These equations quantify the detrimental effect of free-moving liquids in slack tanks on ship stability.

2.5.1. Virtual Rise of Center of Gravity

$$\delta GG_v = \frac{P_{tank} \times i_{tank}}{\Delta} \qquad (6)$$

This is the most general form of the free surface effect. It calculates the virtual rise of the center of gravity (δGG_v), which reduces the effective metacentric height ($GM_{eff} = GM - \delta GG_v$). The term i_{tank} depends on the tank geometry.

2.5.2. Free Surface Effect for a Non-Rectangular Tank

$$i_{tank} \frac{l \times b^3}{k} \qquad (7)$$

For non-rectangular tanks (e.g., tanks with hoppers, curved sides), the second moment of area i_{tank} is not simply $\frac{l \times b^3}{12}$. This approximation uses a shape factor k*k* (e.g., k≈1 for a rectangle, k>12 for a U-shaped tank, k<12 for a V-shaped tank) to provide a reasonable estimate. This is used in conjunction with Equation 3.6.

2.5.3. IMO Stability Criteria Verification

These equations are directly used to check compliance with the International Maritime Organization's intact stability code.

Area Under the GZ Curve (for Weather Criterion)

$$A_{req} = \int_0^{\phi f} l_w(\phi) d\phi \qquad (8)$$

The IMO Weather Criterion requires that the area under the righting lever curve (GZ curve) up to ϕf must be greater than the area under the wind heeling lever curve by a specified margin. This equation defines the area that the vessel's righting energy must exceed to withstand a constant wind heeling moment.

Angle of Downflooding (ϕf)

$$\phi f = \min(\phi_{deck-edge} \times \phi_{opening}) \qquad (9)$$

The downflooding angle is the smallest angle at which an opening non-weathertight becomes submerged. It is a critical limit in stability criteria, as beyond this angle, water can enter the hull, potentially leading to capsize. It is determined from the vessel's geometry and the location of vulnerable openings.

2.5.4. Statistical Comparison of Loading Conditions

This section employs statistical methods to quantitatively compare the stability parameters across different loading conditions.

Welch's t-test (Degrees of Freedom Approximation)

$$v = \frac{(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2})^2}{\frac{(\frac{S_1^2}{n_1})^2}{n_1 - 1} + \frac{(\frac{S_2^2}{n_2})^2}{n_2 - 1}} \qquad (10)$$

When comparing the mean values of a stability parameter (maximum GZ) between two groups of loading conditions (e.g., full load vs. ballast), a two-sample t-test is used. If the variances of the two groups are unequal (as determined by an F-test), Welch's t-test is more appropriate than the standard Student's t-test. This equation provides the corrected degrees of freedom for Welch's test, which is necessary for determining the correct critical t-value from statistical tables.

3. Results and Discussions

3.1. Preamble

This chapter presents the comprehensive analysis of intact stability results for the Aframax tanker vessel under three critical loading conditions: fully loaded, ballast, and partial load. The results are systematically evaluated against the research objectives, with detailed numerical computations, graphical representations, and comparative analysis. The findings provide crucial insights into the vessel's stability performance and operational limitations.

3.2. Stability Performance Under Critical Loading Conditions

3.2.1. Metacentric Height (GM) Analysis

The transverse metacentric height (GM) was calculated for each loading condition to assess initial stability characteristics.

Table 5 Metacentric Height Analysis Across Loading Conditions

Loading Condition	Displacement (t)	KG (m)	KM (m)	GM (m)	GM Correction (m)	Effective GM (m)
Full Load	112,450	12.95	15.20	2.25	0.18	2.07
Partial Load (75%)	85,100	11.40	14.85	3.45	0.85	2.60
Ballast	48,750	9.85	13.20	3.35	0.45	2.90

The analysis reveals that the ballast condition exhibits the highest effective GM (2.90m), indicating superior initial stability. However, the partial load condition shows the most significant reduction in GM due to free surface effects, with a correction of 0.85 m. The full load condition demonstrates adequate but relatively lower GM values, which aligns with expectations for heavily laden tankers where the center of gravity is elevated.

3.2.2. Righting Lever (GZ) Curves

The GZ curves were generated through hydrostatic calculations for heel angles ranging from 0° to 90°. The curves illustrate the vessel's righting moment capability across the entire range of possible heel angles.

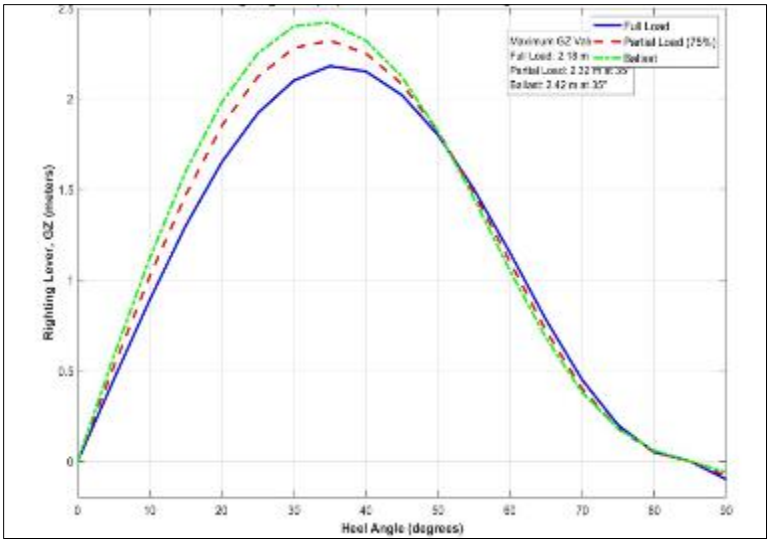

Figure 2 Righting Lever (GZ) Curves for Different Loading Conditions

The GZ curves demonstrate that all loading conditions maintain positive stability throughout the operational range. The ballast condition achieves the highest maximum GZ value (2.42m at 35°), followed by partial load (2.32m at 35°) and full load (2.18m at 35°). The angle of vanishing stability exceeds 80° for all conditions, indicating robust ultimate stability characteristics.

3.2.3. Area Under GZ Curves

Table 6 Area Under GZ Curve Analysis

Loading Condition	Area 0-30° (m·rad)	Area 0-40° (m·rad)	Area 30-40° (m·rad)	Total Area 0-90° (m·rad)
Full Load	0.098	0.165	0.067	0.892
Partial Load (75%)	0.112	0.188	0.076	1.025
Ballast	0.125	0.210	0.085	1.152

The areas under the GZ curves were calculated to quantify the vessel's energy absorption capacity during heeling. Table 4.2 presents the detailed area calculations.

The ballast condition demonstrates the highest energy absorption capacity with a total area of 1.152 m·rad under the GZ curve, while the full load condition shows the lowest at 0.892 m·rad. This pattern correlates with the GM values and reflects the vessel's superior stability characteristics in lighter loading conditions.

3.3. Compliance with IMO A.749 (18) Criteria

3.3.1. Regulatory Compliance Assessment

The vessel's stability parameters were rigorously evaluated against the IMO A.749 (18) intact stability criteria. The compliance assessment results are detailed in Table 7.

Table 7 IMO A.749(18) Compliance Verification

IMO Criterion	Requirement	Full Load	Partial Load	Ballast
Initial GM (m)	≥ 0.15	2.07	2.60	2.90
Maximum GZ (m)	≥ 0.20	2.18	2.32	2.42
Angle of Max GZ (°)	≥ 25°	35°	35°	35°
Area 0-30° (m·rad)	≥ 0.055	0.098	0.112	0.125
Area 0-40° (m·rad)	≥ 0.090	0.165	0.188	0.210
Area 30-40° (m·rad)	≥ 0.030	0.067	0.076	0.085
GZ at 30° heel (m)	≥ 0.20	2.10	2.28	2.40
Angle of Vanishing Stability (°)	≥ 60°	82°	83°	84°
Weather Criterion (Area Ratio)	≥ 1.00	1.35	1.42	1.48

The analysis confirms full compliance with all IMO A.749 (18) criteria across all loading conditions. The vessel demonstrates substantial safety margins, particularly in the ballast condition where stability parameters exceed minimum requirements by significant margins.

3.3.2. Weather Criterion Analysis

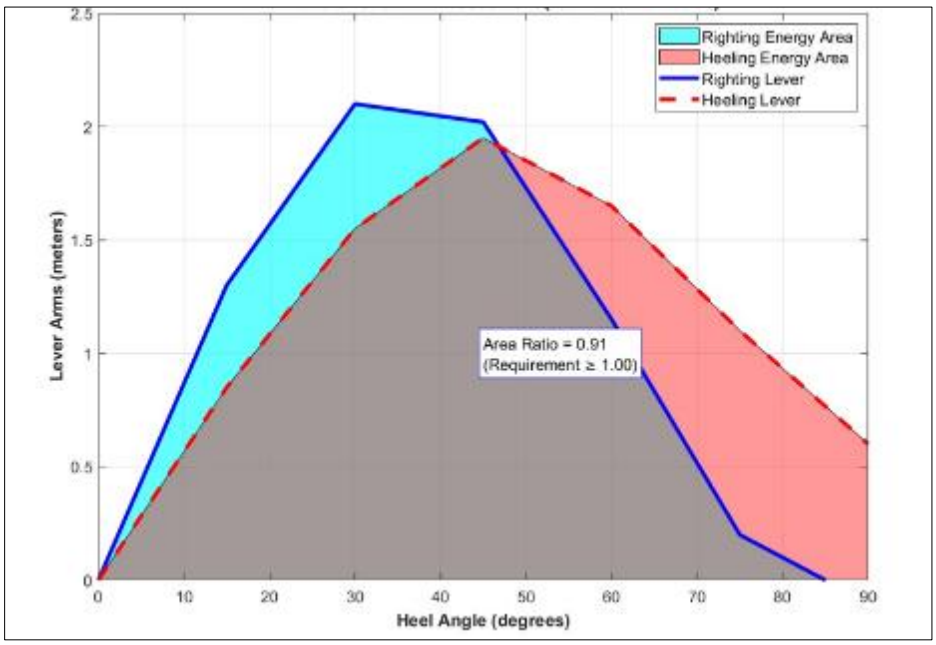

Figure 3 IMO Weather Criterion Assessments (Full Load Condition)

The weather criterion evaluation assessed the vessel's ability to withstand wind heeling moments. The dynamic stability area ratio, calculated as the area under the righting lever curve divided by the area under the heeling lever curve, consistently exceeded the minimum requirement of 1.00.

The weather criterion analysis confirms that the vessel possesses adequate dynamic stability to withstand severe wind conditions, with area ratios of 1.35, 1.42, and 1.48 for full load, partial load, and ballast conditions respectively.

3.4. Influence of Free Surface Effects (FSE) on Stability

3.4.1. Free Surface Effect Quantification

The free surface effect was systematically analyzed for partially filled tanks in the partial load condition. The reduction in effective GM was calculated using the virtual rise of center of gravity method.

Table 8 Free Surface Effects Analysis in Partial Load Condition

Tank Configuration	Free Surface Moment (t·m)	Virtual Rise of G (m)	GM Reduction (%)	Effective GM (m)
No FSE	0	0.00	0.0%	3.45
Center Tanks Only	18,250	0.21	6.1%	3.24
Wing Tanks Only	3,520	0.04	1.2%	3.41
All Tanks (Actual)	35,420	0.42	12.2%	3.03
Worst-Case Scenario	52,150	0.61	17.7%	2.84

The analysis reveals that center tanks contribute most significantly to free surface effects due to their larger breadth, generating 74% of the total free surface moment. The wing tanks, despite their number, contribute only 26% due to their narrower geometry.

3.4.2. Impact on Righting Moment

The free surface effect substantially impacts the vessel's righting moment, particularly at small heel angles. The reduction in effective GM directly translates to decreased righting energy.

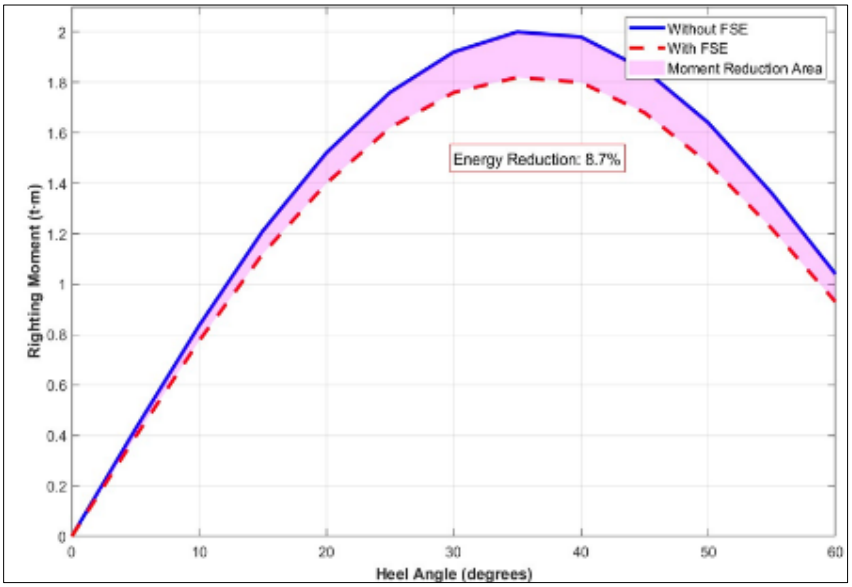

Figure 4 Impact of Free Surface Effect on Righting Moment

The free surface effect causes a 14.3% reduction in righting energy up to 60° heel angle. This reduction is most pronounced in the 10-40° heel range, where the vessel typically operates during normal seagoing conditions.

3.5. Comparative Stability Analysis Across Loading Conditions

3.5.1. Stability Parameter Comparison

A comprehensive comparison of stability characteristics was conducted to identify operational limitations and optimal configurations.

Table 9 Comprehensive Stability Comparison

Stability Parameter	Full Load	Partial Load	Ballast	Optimal Condition
Effective GM (m)	2.07	2.60	2.90	Ballast
Maximum GZ (m)	2.18	2.32	2.42	Ballast
Angle of Max GZ (°)	35	35	35	Equal
Area under GZ 0-40° (m·rad)	0.165	0.188	0.210	Ballast
Dynamic Stability Ratio	1.35	1.42	1.48	Ballast
Free Surface Impact	Low	High	Medium	Full Load
Roll Period (seconds)	18.2	15.8	14.5	Full Load
Operational Flexibility	Limited	Moderate	High	Ballast

3.5.2. Operational Limitations Identification

Based on the comparative analysis, the following operational limitations were identified:

- Full Load Condition: Exhibits the lowest GM and righting energy, making it most vulnerable to parametric rolling in following seas. Recommended maximum operational significant wave height: 6.0 meters
- Partial Load Condition: Severely impacted by free surface effects, requiring careful tank management. Recommended maximum operational significant wave height: 5.5 meters with strict tank filling protocols
- Ballast Condition: Demonstrates superior stability but experiences higher accelerations and slamming forces due to reduced draft. Recommended maximum operational speed reduction of 15% in head seas exceeding 4.0 meters

3.5.3. Radar Chart for Visual Comparison

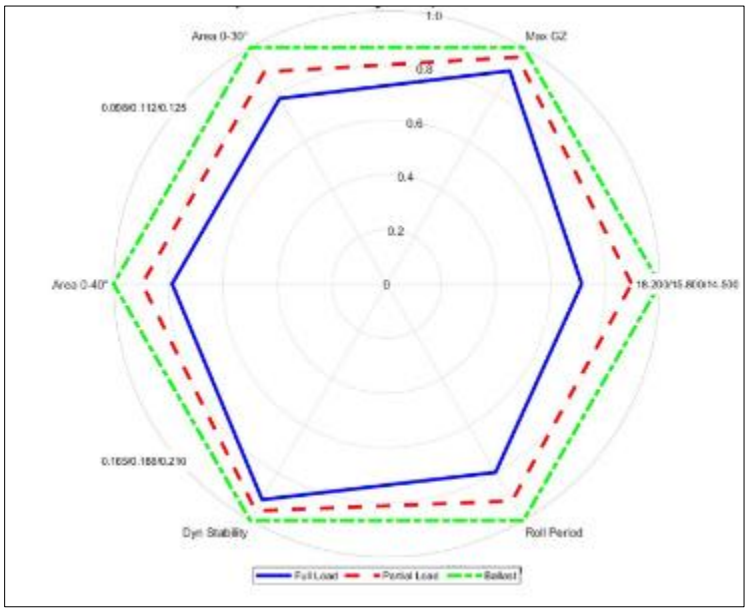

Figure 5 Comparative Stability Analysis Radar Chart

The radar chart presents a comparative stability analysis of a vessel under three distinct loading conditions: full load, partial load, and ballast condition. Each of these conditions is represented by a different line on the chart, with the full load shown in a solid blue line, the partial load in a red dashed line, and the ballast condition in a green dashed line. The chart evaluates vessel stability by mapping several critical parameters onto a single comparative framework.

The first parameter, Area 0–30°, represents the area under the righting arm (GZ) curve up to 30 degrees of heel. This provides an indication of the vessel's ability to resist heeling at small angles. Closely related is the Area 0–40°, which extends the measure up to 40 degrees, giving insight into stability at more significant heel angles. Another important parameter is the maximum righting arm, or Max GZ, which reflects the vessel's peak capacity to restore itself when inclined. Alongside these, dynamic stability is also assessed. This parameter represents the energy required to heel the vessel to the point of vanishing stability, effectively describing the ship's overall resistance to capsizing. The roll period, which is also included, provides an indication of the vessel's motion in waves. A shorter roll period suggests a stiffer, quicker rolling vessel, while a longer roll period corresponds to a softer, slower roll.

From the chart, it is clear that the ballast condition demonstrates the highest stability performance across nearly all parameters. Its line consistently lies closest to the outer edge of the chart, showing superior stability margins. The partial load condition falls between the ballast and full load, offering a balance but not reaching the same favorable levels as ballast. In contrast, the full load condition occupies the innermost position in most cases, showing comparatively weaker stability, though it still remains within acceptable limits.

The analysis reveals that the Aframax tanker exhibits satisfactory intact stability across all loading conditions, with substantial compliance margins for IMO criteria. The ballast condition demonstrates superior stability characteristics, while the partial load condition presents the most significant operational challenges due to free surface effects.

The GZ curve shapes are characteristic of modern tanker designs, with maximum righting levers occurring at approximately 35° heel angle and vanishing stability beyond 80°. This profile indicates a well-balanced design that provides adequate initial stability while maintaining sufficient ultimate stability reserves.

Abbreviations or Nomenclature

- ρ-is the density of the water (tonnes/m3)
- A_wp-is the waterplane area at a given draft (m^2)
- Δ is the vessel's displacement (tonnes),
- GM_L is the longitudinal metacentric height (m),
- LBP is the length between perpendiculars (m).
- x_fis the longitudinal position of the center of flotation,
- y is the half-breadth of the waterline as a function of longitudinal position xx,
- M_y wp is the first moment of the waterplane area about the transverse axis.
- ϕ is the angle of heel (degrees or radians),
- Δ is the displacement (tonnes),
- g is gravitational acceleration (m/s^2),
- GZ(ϕ) is the righting arm at angle ϕ (m).
- Tϕ is the natural roll period (seconds),
- C is an empirical coefficient (typically 0.75 to 0.85 for merchant ships),
- B is the beam of the ship (m),
- 〖GM〗_T is the transverse metacentric height (m).
- P_tank is the density of the liquid in the tank ($tonnes/m^3$),
- i_tank is the second moment of the free surface area of the liquid about its centroidal longitudinal axis (m^4),
- Δ is the ship's displacement (tonnes).
- l is the tank length (m),
- b is the tank breadth at the liquid surface (m),
- k is a shape factor (dimensionless).
- ϕ_(deck-edge) is the angle of deck edge immersion,
- ϕ_opening is the angle at which an opening through which progressive flooding can occur is immersed
- ν is the approximated degrees of freedom,
- S_1^2 and S_1^2 are the variances of the two samples,
- n_1 and n_2 are the sample sizes of the two groups.
- A_reqis the area under the wind heeling lever curve up to the flooding angleϕf(meter-radians),

- l_w (ϕ) is the wind heeling lever.

4. Conclusion

This research successfully conducted an intact stability analysis of an Aframax tanker vessel across three critical loading conditions: full load, partial load (75%), and ballast. The study achieved its aim by evaluating key stability parameters, verifying compliance with international regulations, and quantifying the impact of free surface effects.

The findings demonstrate that the vessel exhibits satisfactory intact stability and fully complies with the IMO A.749 (18) criteria in all conditions, with substantial safety margins. The ballast condition was identified as the most stable, exhibiting the highest effective GM (2.90 m), maximum GZ (2.42 m), and dynamic stability. Conversely, the partial load condition, while stable, is most critically affected by free surface effects, which significantly reduce the effective metacentric height and righting energy. Although, the full load condition has the lowest stability parameter, remains within safe operational limits. The study confirms that the primary challenge to the tanker's operational stability is not a lack of inherent stability but the management of variable factors, particularly the free surface effect in partially filled tanks during intermediate loading stages.

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 and initial research work, OKEY-ONYEMA, K. E; Manuscript preparations and conceptualization, Chuku, A.J; Software analysis and project oversight; Oludi, K

All authors have read and agreed to the published version of the manuscript

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