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## A Non-Dimensional Approach Safety Index for Jetty Berthing under Wind, Current, and Tug Assistance

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### ABSTRACT

This paper develops and validates a simple, nondimensional decision metric for jetty berthing that compares the combined environmental disturbance loads from wind and current against the effective corrective capability provided by assisting tugs. The approach formulates wind-induced lateral force using a drag-based expression on the vessel's exposed lateral area and current-induced force using a hydrodynamic drag formulation on the projected underwater area, while tug control is represented through the sum of available bollard pull adjusted by an efficiency factor. These components are combined into the Approach Safety Index (ASI), defined as the ratio of total environmental forcing to effective tug-assisted control, where lower values indicate greater controllability and values approaching unity indicate insufficient control margin. Model performance is evaluated through a full mission Wärtsilä simulator exercise using a Handysize bulk carrier in ballast, supported by two ASD tugs rated at 36 t bollard pull each, with wind and current progressively increased across scenarios. The computed ASI values align closely with the harbour pilot's qualitative controllability assessments, distinguishing clearly between manageable, marginal, and unsafe operating states. Based on the simulation outcomes, provisional empirical screening bands were identified to support first-pass pilotage judgement under simplified live berthing conditions. The findings

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suggest that ASI can serve as a practical decision support and screening tool for pilots and port operators using limited readily available inputs.

**Keywords:** Jetty Approach Safety; Mathematical Model; Approach Safety Index (ASI); Meteorology-Based Pilotage Decision; Maritime Risk Assessment

## 1. Introduction

Berthing a vessel at a jetty is a complex manoeuvre that requires the careful balancing of environmental disturbances against the control forces available to the vessel. These disturbances, specifically wind and current, vary markedly between ports and can change rapidly in real time<sup>[1,2]</sup>. Notwithstanding advances in simulation, automation, and situational monitoring technologies, berthing safety assessment in most ports remains predominantly experience-based. Pilots often depend on intuition and local knowledge rather than a consistent quantitative standard for determining whether environmental loads can be safely counteracted during the approach<sup>[3,4]</sup>.

Early research on berthing mechanics proposed force-based and energy-based frameworks to describe ship-to-quay interactions<sup>[5,6]</sup>, while classical tug and manoeuvring studies established the operational importance of wind disturbance, tug power, and low-speed control limitations during berthing<sup>[7,8]</sup>. These studies remain important because they established the physical basis for force balance during approach and contact. However, contemporary berthing research has moved beyond these early formulations toward more structured low-speed manoeuvring models, Computational Fluid Dynamics (CFD)-assisted hydrodynamic estimation, sensor based berthing perception, and intelligent decision support systems.

Recent reviews show that modern berthing models commonly decompose manoeuvring forces into hull hydrodynamic loads, propulsion and steering forces, environmental disturbances, and auxiliary device inputs, often within related modular frameworks adapted for low speed, high drift, and high yaw rate operation<sup>[9]</sup>. In these models, force distributions are no longer treated only in aggregate form. Instead, they are estimated through data-based, system-based, and CFD-

based methods, with explicit treatment of wind, current, shallow water effects, and tug assistance as part of the overall manoeuvring response. Parallel to this, recent autonomous berthing studies have expanded the field through sensing technology, control logic, and evaluation methods that combine mathematical models with real-time operational data<sup>[10]</sup>.

In addition, recent smart port and berthing aid studies have introduced real-time LiDAR tracking, multi-sensor fusion, and spatial state monitoring to improve relative position awareness and support safer berth approach decisions<sup>[11-13]</sup>. Tug research has also advanced toward intelligent escort control and sea trial validated autonomous assistance functions<sup>[14]</sup>. Against this background, the contribution of the present study is not to compete with high-fidelity Mathematical Modelling Group (MMG), CFD, or sensor fusion-based berthing systems, but to provide a simpler operational index that compresses the most decision-critical relationship, namely, environmental disturbance versus effective tug-assisted control, into a transparent and quickly interpretable threshold metric for live pilotage.

The literature therefore shows strong development in berthing mechanics and control support, but a weaker contribution in relation to a compact, non-dimensional indicator that integrates the two dominant transverse disturbances, namely wind and current, with effective tug-assisted control in a form usable for rapid go or no-go assessment. In particular, a gap remains in translating complex environmental loading into a pilot usable index that can support pre-arrival planning, tug sufficiency checks, and transparent operational justification across ports. This study addresses that gap by developing the Approach Safety Index (ASI) as a simplified load-to-control ratio and examining whether its values correspond with observed controllability in both simulator-based and field-referenced conditions.

## Research Objective, Research Question, and Novelty

The primary objective of this study is to develop and validate a mathematical model for evaluating the safety of a vessel's approach to a jetty by accounting for the combined effects of wind, current, and tug assistance. More specifically, the study seeks to convert these interacting factors into a simple operational index that can be interpreted quickly by harbour pilots and port operators during approach planning and execution.

The study is guided by the following research question: Can a simple non-dimensional ratio between combined environmental disturbance loads and effective tug assisted control provide an operationally meaningful measure of jetty approach safety and produce usable threshold bands consistent with pilot controllability assessments?

The novelty of this study lies in translating these interacting forces into a compact decision metric for operational use during live pilotage, rather than examining them only through detailed manoeuvring analysis, automated control design, or tug allocation optimisation.

The proposed ASI is intended as a simplified first-level pilotage support tool for live berthing situations in which full manoeuvring information is not immediately available to the pilot. It is therefore designed to support rapid preliminary judgement based on the most observable operational inputs, rather than to replace full dynamic assessment of ship response.

## 2. Literature Review

### 2.1. Wind Force as a Dominant Berthing Parameter

Wind force consistently appears as one of the most influential external forces affecting berthing safety across the reviewed literature. Research on cooperative manoeuvring<sup>[15]</sup>, tugboat handling elements<sup>[16]</sup>, and tug operation optimisation<sup>[17]</sup> emphasises that wind acting on a vessel's exposed superstructure can generate substantial lateral drift, particularly during low-speed approaches. This effect is further underscored in early studies by Takashina<sup>[7]</sup> and Honda<sup>[8]</sup>, which show that even moderate winds can markedly degrade steering response. Similarly, CFD-based investigations of un-

manned ship berthing<sup>[18]</sup> and autonomous tug operations<sup>[19]</sup> identify wind as a primary destabilising factor that increases control complexity and challenges the robustness of automatic control algorithms. More recent reviews on ship particular design<sup>[20]</sup> and emerging berthing simulation technologies<sup>[9]</sup> reaffirm that wind loads may exceed a vessel's available manoeuvring capability, reinforcing wind induced drift as a persistent and critical theme in berthing research.

### 2.2. Current-Induced Hydrodynamic Force

Current forces acting on the underwater hull constitute the second major variable identified in the literature, with many studies emphasising their effects on approach stability and positional accuracy. Hydrodynamic resistance modelling and CFD-based simulations<sup>[9, 18]</sup> indicate that currents can induce substantial surge, sway, and yaw responses, particularly in confined port environments characterised by complex flow fields. Research on emergency unberthing scenarios<sup>[21]</sup> and integrated port operation assessments<sup>[22]</sup> further demonstrates that current induced drift can reduce rudder effectiveness at low speeds, thereby increasing the likelihood of unintended lateral displacement. Studies on autonomous berthing support systems<sup>[23-25]</sup> similarly show that current estimation and prediction must be embedded within control algorithms to minimise track deviation and improve trajectory adherence. Overall, the literature recognises current as a dominant hydrodynamic parameter that introduces nonlinear behaviour, often complicating both manual and automated approach strategies. From a modelling perspective, recent berthing studies increasingly treat environmental and manoeuvring forces within modular low speed ship motion frameworks rather than as isolated empirical terms. Contemporary automatic berthing models commonly separate hull forces, propulsion and steering forces, external disturbances, and auxiliary device actions so that the resulting sway, surge, and yaw responses can be resolved more explicitly under berthing conditions<sup>[9, 18]</sup>. This is particularly important because low speed operation, large drift angles, and high yaw sensitivity cause force distributions during berthing to differ materially from those assumed in conventional mod-

erate speed manoeuvring models. The present study draws on this modern understanding, but simplifies the problem deliberately by retaining only the force components most directly relevant to rapid pilotage interpretation, namely wind, current, and tug-assisted control.

### 2.3. Tug-Assisted Control as the Corrective Mechanism

The third recurrent parameter concerns the corrective role of tugboats, which most studies identify as the primary counterforce to environmental disturbances during berthing. Foundational research on tug power requirements<sup>[8, 26]</sup> and tug handling procedures<sup>[16]</sup> indicates that tug-generated forces largely determine a vessel's ability to maintain its intended trajectory under the influence of wind and current. Optimisation studies<sup>[17, 27, 28]</sup> further show that appropriate tug allocation, effective bollard pull distribution, and coordinated pushing or pulling strategies can materially reduce berthing risk. Recent work has extended the tug allocation literature beyond berth-level assistance to broader waterway-level deployment and risk management. A recent study proposed a systematic framework for optimal tugboat placement in the Dardanelles using Fuzzy Delphi, P-Median, and Linear Programming, showing that improved tug positioning can reduce accident frequency and severity while improving emergency response<sup>[29]</sup>. Another study developed a risk-based ship-tug allocation approach for the Istanbul Strait and demonstrated how vessel classification and structured allocation logic can support safer tug assignment in complex waterways<sup>[30]</sup>. Although these studies focus on strategic straits rather than jetty berthing, they reinforce the broader importance of structured tug allocation and support the present study's emphasis on quantifying whether available tug assisted control is sufficient under prevailing environmental conditions.

Research addressing shuttle tankers, container terminals, and dual carbon operational contexts<sup>[31, 32]</sup> similarly reinforces the reliance on tug assistance for safe manoeuvre execution, particularly for large vessels with limited inherent manoeuvrability. In addition, mathematical models of cooperative ship tug manoeuvring<sup>[15, 33]</sup> emphasise that tug-assisted control is cru-

cial for maintaining heading, managing speed reduction, and achieving accurate lateral positioning during the final metres of approach. Overall, the literature indicates that tugboats function as the essential corrective mechanism through which ships counteract wind and current loads during berthing.

Taken together, the reviewed studies consistently identify wind, current, and tug assistance as principal variables shaping berthing controllability, but recent literature also shows that these variables are increasingly embedded within broader MMG-based manoeuvring models, CFD-informed hydrodynamic estimation, sensor fusion perception systems, and intelligent control frameworks. Accordingly, the present study adopts a simplified force-based methodology not because these higher fidelity approaches are unimportant, but because pilotage operations often still require an interpretable threshold tool that can be applied quickly with a limited set of observable inputs. The contribution of the present study is therefore to complement, rather than replace, modern berthing support technologies by expressing the balance between disturbance and control as the ASI, a non-dimensional load-to-control ratio intended to support transparent go-or-no-go judgments during jetty approaches.

## 3. Mathematical Model

In practical pilotage, full information on yaw moment balance, pivot point migration, tug lever arm geometry, and time-varying hydrodynamic interaction is not always available in a form that can be quantified quickly during a live approach. For this reason, the present model is intentionally simplified to use a limited number of inputs that are more readily observable or operationally estimable by pilots and port operators during berth approach. The resulting ASI is therefore intended as a preliminary screening aid for live judgement, rather than as a complete mathematical representation of all manoeuvring dynamics.

This study adopts a simplified analytical modelling approach because its purpose is not to reproduce the full dynamics of berthing with high fidelity, but to develop a practical decision metric that can be interpreted

quickly during live pilotage. In line with the literature reviewed above, the method focuses on the three variables that recur most consistently in shaping controllability, namely wind, current, and tug assistance. Because these forces are directional in practice, their effective contribution to berth approach control depends on the angle at which they act relative to the ship's longitudinal axis. In the most general case, only the transverse component of each force contributes directly to lateral drift or corrective control. However, for the present study, the ASI is formulated as a conservative worst-case screening index by adopting the maximum transverse loading condition, namely when wind and current act approximately at right angles to the ship and tug corrective action is also taken in its maximum effective transverse direction. This choice preserves interpretability, transparency, and operational usability while retaining a clear grounding in force-based berthing research and tug assisted manoeuvring studies.

### 3.1. Wind-Induced Force

Consistent with the literature review, the model formulation represents wind and current as the dominant disturbance forces and tug assistance as the principal corrective mechanism during berthing. Building on the drag formulation presented by Fuss<sup>[34]</sup>, the lateral wind force can be approximated as follows:

$$F_w = 0.5\rho_{air}C_{dwind}A_{wind}W^2 \quad (1)$$

Where:

$$\rho_{air} = 1.225 \text{ kg/m}^3;$$

$C_{dwind}$  = Empirical drag coefficient for ship superstructure;

$$A_{wind} = \text{Exposed lateral area above waterline (m}^2\text{);}$$

$$W = \text{Mean wind speed (m/s)}.$$

### 3.2. Current-Induced Force

The current induced force is represented using a drag-based hydrodynamic formulation applied to the projected underwater area, adapted from standard force expressions used in hydrodynamic and manoeuvring studies<sup>[18, 22]</sup>.

$$F_c = 0.5\rho_{water}C_{dcurrent}A_{current}C^2 \quad (2)$$

Where:

$$\rho_{water} = 1,025 \text{ kg/m}^3;$$

$C_{dcurrent}$  = Hydrodynamic drag coefficient for underwater hull;

$A_{current}$  = Projected underwater area normal to current;

$$A_{current} = \text{Block Coefficient} \times B \text{ (beam)} \times T \text{ (draft);}$$

$$C = \text{Current Velocity (m/s);}$$

### 3.3. Tug Assisted Control

Available tug-assisted control is represented operationally as the sum of available bollard pull reduced by an effective efficiency factor that depends on tug operating condition. Rather than being treated as universally constant, tug efficiency is better understood as a dynamic variable influenced by speed through water, current, tow or push geometry, and operational mode. This is consistent with recent tug performance literature showing that bollard pull alone may be insufficient as a stand-alone capability measure, and with escort trial practice in which tug performance is evaluated across multiple speeds and towing angles rather than by a single fixed value<sup>[8, 16, 26]</sup>. Accordingly, the available corrective force is written as:

$$F_T = \eta(U_{rel}) \sum_{i=1}^n BP_i \quad (3)$$

Where:

$\eta(U_{rel})$  = effective tug efficiency factor as a function of relative speed through water;

$U_{rel}$  = tug speed through water or equivalent relative flow condition during assistance;

$$BP_i = \text{bollard pull of assisting tug } i.$$

In the present study,  $\eta = 0.7$  is retained only as a nominal reference value for simplified harbour assistance screening under controlled low-speed conditions. It should not be interpreted as a universally valid ASD tug efficiency. As the relative water flow acting on the tug increases, the effective corrective force available for push or pull assistance may be reduced by hydrodynamic resistance, thrust deduction, and operational geometry effects. The simplified ASI therefore uses  $\eta = 0.7$  as a practical first-pass assumption, while recognising that the true corrective capability may be lower in de-

manding current conditions.

### 3.4. Approach Safety Index (ASI)

To assess operational safety, this study proposes the ASI as a nondimensional ratio between transverse disturbing force and available transverse corrective force. In the general case, if the wind and current act at angles  $\theta_w$  and  $\theta_c$  relative to the ship's longitudinal axis, their effective transverse components may be written as:

$$F_{w,\perp} = F_w \sin \theta_w \quad (4)$$

$$F_{c,\perp} = F_c \sin \theta_c \quad (5)$$

and if the assisting tug or tugs act at an effective angle  $\beta_i$  relative to the ship's longitudinal axis, the transverse corrective component may be written as:

$$F_{T,\perp} = \eta \sum_{i=1}^n BP_i \sin \beta_i \quad (6)$$

Accordingly, a more general directional form of the index can be expressed as:

$$ASI = \frac{F_w \sin \theta_w + F_c \sin \theta_c}{\eta \sum_{i=1}^n BP_i \sin \beta_i} \quad (7)$$

Where:

$\theta_w$  = wind angle relative to the ship's longitudinal axis;

$\theta_c$  = current angle relative to the ship's longitudinal axis;

$\beta_i$  = effective angle of tug  $i$  force relative to the ship's longitudinal axis;

$F_{w,\perp}$  = transverse component of wind force;

$F_{c,\perp}$  = transverse component of current force;

$F_{T,\perp}$  = total effective transverse corrective force from assisting tugs.

For the purpose of the present study, a conservative worst-case transverse loading assumption is adopted. Under this condition, wind and current are taken to act approximately at right angles to the ship, and tug corrective action is taken in its maximum effective transverse direction, so that:

$$\theta_w \approx 90^\circ, \theta_c \approx 90^\circ, \beta_i \approx 90^\circ$$

Since  $\sin 90^\circ = 1$ , Equation (7) reduces to the simplified operational form used in this study:

$$ASI = \frac{F_w + F_c}{\eta \sum_{i=1}^n BP_i} \quad (8)$$

This simplified form should therefore be interpreted as a conservative upper-bound screening metric for transverse environmental loading rather than as a full vector-resolved manoeuvring model. Lower ASI values indicate greater controllability, whereas values approaching or exceeding unity indicate an inadequate corrective margin.

Accordingly, the ASI should not be interpreted as a full substitute for detailed manoeuvring analysis that explicitly resolves rotational moments, pivot point behaviour, and tug leverage effects. Its intended purpose is to provide a simplified and conservative first pass indication of whether the observed environmental loading is likely to challenge the available corrective capability during live berthing.

## 4. Simulation-Based Validation

### 4.1. Experimental Setup

Model validation was designed in two stages. First, a Wärtsilä full mission ship simulator was used to test whether the proposed ASI varies in a manner consistent with pilot perceived controllability under controlled and progressively more demanding environmental conditions. The simulator was selected because it allows wind and current to be varied systematically while vessel type, tug configuration, and operational context remain controlled, thereby making it suitable for initial validation of a simplified decision metric. Second, a field-based application using an actual jetty approach by an LPG tanker at Johor Port was included to examine whether the index also retains operational meaning outside the simulator environment. This combined validation design was chosen because the study seeks to demonstrate practical usefulness and interpretability, rather than only mathematical consistency.

For the purpose of ASI calculation, the environmental and corrective forces were interpreted conservatively using the maximum transverse effect assumption, so that the index represents an upper-bound screening condition for lateral drift risk during approach. Likewise, tug efficiency was treated in the simulations using a nominal  $\eta$  reference value for simplified comparison

across cases, rather than as a fully speed-dependent performance function.

All trials employed a Handysize bulk carrier in ballast condition, supported by two ASD tugs with a rated bollard pull of 36 t each, thereby providing a consistent level of available control authority. Seven simulation scenarios were executed, with wind and current speeds increased progressively between runs. The scenarios were

conducted under the command of a newly licensed harbour pilot to represent a conservative, worst-case experience level<sup>[35]</sup>.

### 4.2. Vessel Particulars

The particulars of the selected vessel for the study are summarised in **Table 1**.

**Table 1.** Vessel particulars.

Ship's Particular	Details
Vessel Category	Bulk carrier
$\Delta$	23,565.0 t
Approach Speed	1.0 knots
Engine Category	Slow speed diesel (1 × 8,827 kW)
Propeller Category	Fixed Pitch Propeller
Length	183 m
Breadth	23 m
Draft	7.6 m
Freeboard	9.0 m

### 4.3. Results

Across the seven trials, the ASI values showed a clear correspondence with the pilot's qualitative assessment of vessel controllability. When the calculated ASI was below 0.40, the vessel remained consistently manageable, with predictable drift behaviour and only simple corrective actions required. As wind and current effects increased and the ASI fell within the range

of 0.40 to 0.70, the available control margin was noticeably reduced. Under these conditions, continuous corrective inputs, greater rudder utilisation, and closer operational monitoring were necessary. When the ASI reached or exceeded 0.70, the environmental loads exceeded the available tug-assisted control capability, resulting in unsafe drift behaviour and an operational decision to abort the approach. These observations are summarised in **Table 2**.

**Table 2.** Simulation results.

Case	Wind (kn)	Current (kn)	$F_{wind}$ (kN)	$F_{current}$ (kN)	ASI	Simulation Result
1	6	1	9.61	23.71	0.07	Safely alongside
2	9	1	21.63	23.71	0.09	Safely alongside
3	12	2	38.44	94.84	0.27	Safely alongside
4	15	2.5	60.07	148.18	0.42	Significant corrections needed. Delayed berthing
5	18	3	86.50	213.38	0.61	Continuous corrections needed. Difficult to control. Delayed berthing
6	21	3	117.74	213.38	0.67	Continuous corrections needed. Difficult to control. Delayed berthing
7	25	3	166.86	213.38	0.77	Highly difficult to control. Abort berthing

### 4.4. Operational Thresholds

Based on the seven simulator runs, provisional empirical screening bands were derived by comparing calculated ASI values with the pilot's qualitative controllability assessment in each case. In the present dataset, all cases completed safely without notable difficulty fell below ASI 0.30, the first case requiring sig-

nificant correction and delayed berthing occurred at ASI 0.42, the next two difficult but still completed cases occurred at ASI 0.61 and 0.67, and the first aborted case occurred at ASI 0.77, as shown in **Table 3**. On that basis, the lower transition boundary was conservatively rounded to 0.40 to separate clearly manageable cases from those requiring materially increased

corrective effort, while the upper transition boundary was conservatively rounded to 0.70 to provide an early warning band below the first observed abort case. The

resulting values are therefore not presented as universal safety limits, but as provisional screening thresholds calibrated to the present simulation dataset.

**Table 3.** Provisional empirical screening bands derived from the present simulation dataset.

No.	ASI	Proposed Operational Status	Description
1	<0.40	Manageable	Vessel remains controllable with standard pilotage effort.
2	0.40–0.70	Conditional/Increased control demand	Marginal conditions; operation possible with reduced control margin.
3	>0.7	Critical/High abort likelihood	High risk of uncontrolled drift; approach should be suspended.

Although these provisional screening bands are not intended to function as universal operational limits, they remain useful as a structured interpretive aid for pilotage planning. In practical terms, the bands help distinguish between conditions that are broadly manageable under normal corrective effort and those that require greater caution, additional monitoring, or stronger tug support. This is particularly valuable in live pilotage, where decisions often must be made rapidly and under incomplete dynamic information. By converting the simulator-observed transition from manageable to difficult to abort-prone conditions into a simple numerical screening framework, the ASI bands provide an initial reference point that can support more transparent pre-berthing discussion between pilots, tug masters, port control, and terminal operators.

These bands should be interpreted as provisional empirical screening thresholds rather than fixed operational limits. They were derived from a limited dataset comprising seven simulation cases assessed by a single pilot and are intended to support first-pass interpretation of increasing disturbance severity relative to available corrective force. They are not intended to replace full pilotage assessment, and their practical meaning remains dependent on ship type, loading condition, tug configuration, environmental directionality, and effective tug performance. A reduction in effective tug performance at higher relative water speeds would increase ASI and reduce the available safety margin.

The ASI captures key elements of approach safety by representing controllability as a simple load-to-control ratio. Importantly, the index can be used not only to interpret present conditions, but also to test operational alternatives such as increasing tug allocation, selecting higher bollard pull support, or delaying the ma-

noeuve until environmental loading decreases. This gives pilots and port operators a structured basis for documenting berthing decisions and for aligning tug deployment with measurable environmental demand.

## 5. Field Validation Using an LPG Tanker at Johor Port

To further examine the operational realism of the proposed ASI, the framework was applied to an actual jetty approach conducted at Pengerang Jetty 6212, Johor Port Berhad. The manoeuvre was executed by a senior pilot with 14 years of licensed experience, under close monitoring by port control, which provides a credible professional benchmark for evaluating controllability under challenging conditions. The vessel particulars and manoeuvring parameters are presented in **Table 4**.

Using the ASI formulation, the wind and current disturbances were interpreted under the conservative worst-case transverse loading assumption and compared against the effective transverse corrective capability of the assisting tugs, using  $\eta = 0.7$  as a nominal reference value. Because the field case involved a transverse current of 4.5 knots, this ASI should be interpreted as a simplified screening estimate rather than an exact representation of actual tug effectiveness, since the true effective corrective force may have been lower under the prevailing relative flow condition. This means that the reported ASI of 0.630 may be viewed as a nominal baseline rather than an upper certainty value. If the effective tug efficiency in the field case were lower than 0.7, the corresponding ASI would increase and the operation would move closer to, or further into, the high-risk range. For example, at  $\eta = 0.6$ , ASI becomes 0.735, and at  $\eta = 0.5$ , ASI becomes 0.882.

In the pilot’s assessment, the operation was categorised as Hard, primarily because the vessel was exposed to a strong transverse current within a restricted manoeuvring area. The current created a persistent lateral set that reduced the available margin for positional correction and increased the difficulty of maintaining the intended approach line. Unlike a more open water

manoeuvre, the limited sea room around the jetty meant that even a small delay in corrective action could result in rapid drift toward an unsafe position. For this reason, the pilot had to maintain a high level of situational awareness and continuously balance the vessel’s heading, speed, drift, and tug response throughout the approach.

**Table 4.** Maneuvering parameters.

Parameter	Value
Vessel Type	LPG Tanker
Length Overall (LOA)	119 m
Beam (B)	17 m
Draft (T)	8.0 m
Freeboard	3.0 m
Current Speed	4.5 knots
Wind Speed	15 knots
Number of Tugs	2
Tug Type	ASD (Azimuth Stern Drive)
Bollard Pull per Tug	45 t
Total Bollard Pull	90 t
Tug Efficiency	0.7 (pushing/backing mode)

The pilot’s narrative assessment indicated that safe completion of the manoeuvre depended heavily on keeping the vessel’s heading as close as practicable into the current. This was necessary to reduce the transverse component of the current acting on the hull and to prevent excessive sideways movement during the final approach. At the same time, the assisting tugs were required to provide almost continuous corrective force, especially at the bow, where drift control was critical. The need for sustained tug input showed that the vessel was not operating with a large reserve of control capability, but rather within a reduced safety margin where rapid communication and immediate tug response were essential.

This operational description is consistent with the computed ASI value of 0.630, which falls within the conditional operating band identified in the simulation results. The value indicates that the environmental disturbance forces were significant in relation to the available tug-assisted control capability. Although the manoeuvre remained possible, it required continuous correction, close monitoring, and limited tolerance for deviation. Therefore, the ASI did not merely produce an abstract numerical result, but reflected the practical difficulty experienced by the pilot during the actual ap-

proach.

The close agreement between the computed ASI and the pilot’s professional judgement supports the usefulness of the index as a practical decision support measure. It demonstrates that ASI can translate operational experience into a repeatable quantitative indicator that may assist pilots, tug masters, port control, and terminal operators in discussing berthing risk more transparently. While the index does not replace pilot expertise, it provides a simple and structured way to express whether the prevailing wind and current conditions are approaching the available tug control limit. This makes ASI useful as a preliminary screening tool for operational planning, tug adequacy assessment, and post-operation review using inputs that are readily observable during live pilotage.

## 6. Conclusion

This study developed a streamlined mathematical framework for assessing the safety of a vessel’s approach to a jetty by integrating wind disturbance, current disturbance, and tug-assisted corrective capability into a single non-dimensional ratio, namely the Approach Safety Index, or ASI. Unlike earlier work that primarily em-

phasizes detailed manoeuvring mechanics, automatic berthing control architectures, or tug optimisation at a more complex modelling level, the present study contributes a simpler operational index intended for direct pilotage interpretation. This distinction is important because much recent berthing research has increasingly relied on Modular Mathematical Group type modelling, Computational Fluid Dynamics assisted force estimation, real-time LiDAR based perception, and multi-sensor fusion systems. While such approaches offer high analytical value and can represent ship response with much greater fidelity, they also demand levels of data, modelling detail, and system integration that are not always available in a live pilotage setting. In this respect, the ASI should be understood as a conservative transverse screening index based on a maximum adverse loading assumption, rather than as a full vector resolved manoeuvring model.

The simulator-based validation demonstrated that the proposed index is capable of distinguishing broad levels of controllability in a manner that corresponded well with the pilot's practical assessment of the approach. Across the seven full mission simulator trials, lower ASI values were associated with manageable conditions in which the vessel remained controllable with relatively standard pilotage effort, predictable drift behaviour, and limited corrective demand. As the ASI increased, the available control margin visibly reduced, and the scenarios moved into a condition requiring continuous correction, closer monitoring, and greater operational caution. At the highest values observed in the study, the index aligned with a critical condition in which the vessel was no longer considered safely controllable and the manoeuvre was aborted. Although these results do not establish universal safety limits, they demonstrate that the ASI captures a meaningful relationship between environmental loading and available corrective capability and can therefore contribute to practical berthing judgement in a structured way.

An important contribution of the present study lies in its operational interpretability. The ASI does not attempt to replace detailed hydrodynamic models, surge sway yaw equations, or pilot expertise. Instead, it translates a complex decision environment into a sim-

pler form that can support rapid preliminary assessment. In practice, pilots and port operators often need to make timely decisions under conditions where only a limited set of immediately observable or operationally estimable parameters is available. Wind speed, current speed, tug bollard pull, and general awareness of ship condition are more readily usable in live situations than complete dynamic information on turning moments, pivot point behaviour, or time varying force redistribution. By focusing on this limited but operationally relevant input set, the ASI offers a pragmatic method for screening whether the prevailing environmental forces are likely to challenge the available tug-assisted control margin.

From a practical and policy perspective, the ASI offers several potential applications. At the operational level, it can support more structured pre-arrival and pre-berthing assessments by helping pilots and port operators translate prevailing environmental conditions into a quantified indication of controllability. At the organisational level, it may assist pilotage service providers and terminal operators in defining preliminary operating windows, identifying cases in which additional tug support may be prudent, and documenting the basis on which a manoeuvre was permitted, delayed, or discontinued. At the governance level, the ASI may also support post-operation review, incident analysis, simulator based training, and the development of more transparent local berthing guidance. In that sense, the proposed metric has value not only as a manoeuvring aid, but also as a governance support tool that may improve consistency, accountability, and communication in tug assisted berthing operations.

The field based application further strengthened the practical relevance of the study. The case involving an LPG tanker approach at Pengerang showed that the computed ASI of 0.630 corresponded closely with the senior pilot's narrative assessment of the manoeuvre as hard, particularly under the influence of strong transverse current and the need for persistent corrective tug action. This agreement is significant because it suggests that, even when applied in a simplified form, the ASI can provide a quantitative frame for understanding pilot judgment rather than merely reproducing an abstract

mathematical ratio. The value of the index in such a case is not that it eliminates the need for pilot expertise, but that it offers a transparent numeric reference that can support discussion, decision making, and retrospective evaluation under demanding environmental conditions.

At the same time, the present formulation remains intentionally simplified. It does not explicitly resolve yaw moment balance, rate of turn effects, wave-induced forces, bank effect, shallow water interaction, or time-varying hydrodynamic control dynamics. It also does not fully represent the geometry-dependent effectiveness of tug forces under every operating condition. These omissions were not accidental. They reflect a deliberate design choice to preserve usability, transparency, and speed of interpretation for operational decision support. Nevertheless, these simplifications also define the clear boundary of the present contribution. The ASI is best understood as a conservative first-level screening tool that helps interpret whether a manoeuvre is moving from manageable toward critical conditions, rather than as a complete substitute for full ship handling analysis.

Future work should therefore move in two related directions. First, additional validation should be conducted across a wider range of vessel types, loading conditions, tug configurations, and port geometries so that the empirical interpretation of the index can be strengthened and refined. Second, the model itself may be extended to incorporate more realistic treatment of directional effects, tug performance reduction, and coupled force and moment considerations while preserving the core simplicity that makes the index operationally attractive. In this way, the present study should be seen as an initial but meaningful step toward a more structured and transparent method for supporting live berthing judgment under environmental uncertainty.

### Limitations of the Study

The present ASI formulation is intentionally simplified and should be understood as a live pilotage screening tool rather than a full manoeuvring model. In practical berthing, pilots do not always have access to complete real-time information on yaw moment balance, pivot point migration, tug leverage arm, or time-varying hydrodynamic interaction in a form that can be quantified immediately. The ASI therefore focuses on

the most readily usable operational inputs to support rapid preliminary judgement, while recognising that final berthing decisions must still incorporate pilot expertise and broader ship handling considerations.

A further limitation of the present study is that the simulator validation was conducted using only one vessel type, namely a Handysize bulk carrier in ballast condition. The resulting ASI interpretation may therefore reflect the response characteristics of this vessel class and loading condition more strongly than those of other ship types, sizes, propulsion arrangements, or loading states. Although the provisional screening bands are explained in Section 4.4, their broader applicability remains limited because the validation dataset is small and tied to one pilot's qualitative assessment.

The present formulation uses a nominal tug efficiency assumption for screening purposes, whereas actual ASD tug effectiveness varies with speed through water, current, and operating geometry. Future development should therefore replace the fixed efficiency factor with tug-specific performance curves or speed-dependent correction functions.

In addition, the threshold bands proposed in this study are based on a limited simulation dataset and one pilot's qualitative assessment, and should therefore be interpreted as provisional calibration values rather than universal safety thresholds.

## Author Contributions

Conceptualization, A.S.K.; methodology, N.M.A.H.J. and A.S.K.; software, A.S.K.; validation, N.M.A.H.J., A.S.K. and A.F.A.F.; formal analysis, N.Y. and A.A.; investigation, A.A.; resources, J.L.; data curation, N.M.A.H.J. and A.S.K.; writing—original draft preparation, A.S.K.; writing—review and editing, A.S.K. and M.N.R.; visualization, A.S.K. and M.N.R.; supervision, A.F.A.F.; project administration, J.L.; funding acquisition, A.S.K. All authors have read and agreed to the published version of the manuscript.

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## Institutional Review Board Statement

Not applicable.

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## Data Availability Statement

Data are unavailable due to privacy restrictions.

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## Conflicts of Interest

The authors declare no conflict of interest.

## AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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