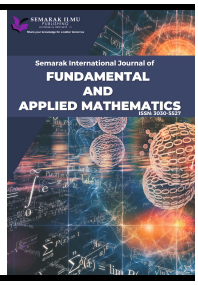
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Development of a Mathematical Model and Difficulty Index for Bulk Carrier Jetty Approach under Adverse Meteorological Conditions

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ABSTRACT

Adverse meteorological and oceanographic conditions can significantly increase the difficulty of low-speed jetty approaches. However, wind, current, tug assistance, vessel response, and under-keel clearance are often assessed separately. This study develops a non-dimensional Jetty-Approach Difficulty Index (J) that integrates these factors into a single quantitative measure. The model was applied to a loaded bulk carrier approaching Kapar Power Station during strong winds, currents, a spring tide, and a squall. Time-resolved operational and environmental data were analysed and compared with an independent marine pilot assessment. The calculated index was J = 4.481, representing Difficulty Level 4, classified as Challenging, and was consistent with the pilot's rating of 4/5. Environmental sway and yaw loading contributed approximately 84.5% of the total index. The proposed framework provides a practical basis for quantifying approach difficulty, although further cases are required for calibration and validation.

1. Introduction

Safe and efficient ship berthing is strongly influenced by meteorological and oceanographic conditions, particularly at terminals where water depth, approach-channel geometry, and tug availability impose operational constraints. During low-speed jetty approaches, wind, current, and shallow-water effects can significantly alter vessel surge, sway, and yaw responses, thereby reducing manoeuvring margins and increasing the difficulty of maintaining the intended approach trajectory [1,2]. Large bulk carriers are particularly sensitive to cross-wind and cross-current forces because of their large exposed areas and reduced hydrodynamic control at low speed, making quantitative assessment of these combined effects important for evaluating approach difficulty and operational safety [3,4].

At the coal and oil unloading jetty of Kapar Power Station, Selangor, Malaysia, the combination of a narrow approach channel, sloping seabed, and limited under-keel clearance (UKC) further

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increases the complexity of bulk carrier manoeuvring. These constraints amplify the influence of wind and current forces while reducing the vessel's available manoeuvring margin and tolerance to deviation during the final approach [5,6]. Consequently, an assessment of approach difficulty requires not only consideration of environmental loading but also the interaction between vessel motion, tug assistance, and bathymetry-related UKC. Integrating these parameters within a common mathematical framework provides a more systematic basis for quantifying the operational difficulty of the jetty-approach process.

Although maritime safety research frequently attributes a large proportion of accidents to human error, commonly reported at approximately 80–84%, such statistics provide limited information on the actual level of environmental and operational difficulty experienced by ship operators during demanding manoeuvres [7-9]. In practice, pilots must continuously respond to variations in wind, current, tide, vessel motion, and tug availability using local knowledge, professional judgement, and real-time coordination with tug masters and bridge teams. Quantifying the physical and operational difficulty within which these decisions are made can therefore provide a more objective basis for evaluating pilotage operations. A mathematical measure of approach difficulty may complement conventional accident-based analyses by distinguishing the severity of the operating environment from the effectiveness of the human response to that environment.

This study therefore develops an integrated mathematical framework for quantifying the difficulty of bulk carrier jetty-approach operations under adverse meteorological and oceanographic conditions. The framework combines low-speed surge, sway, and yaw dynamics with wind and current loading, tug-force capacity, manoeuvring response, and bathymetry-based UKC to formulate a non-dimensional Jetty-Approach Difficulty Index. The proposed model is applied to a documented bulk carrier approach at Kapar Power Station during a squall coinciding with a spring-tide event. By integrating time-resolved environmental and operational variables within a single quantitative formulation, the study aims to provide an objective measure of approach difficulty while also examining how successful pilot and bridge–tug coordination contributed to maintaining safe control of the vessel under challenging conditions.

1.1 Research Motivation

Existing studies have examined the influence of wind, current, shallow-water effects, and other environmental factors on ship manoeuvring and berthing safety. However, these factors are often assessed separately, and there remains a need for an integrated mathematical framework capable of representing their combined influence on jetty-approach difficulty. In particular, the interaction between environmental loading, tug-force capacity, UKC, vessel manoeuvring response, and approach duration is not commonly expressed within a single quantitative measure that can be directly interpreted in operational terms.

This study addresses this gap by developing a mathematical model and a non-dimensional Jetty-Approach Difficulty Index that combine multiple time-varying environmental and operational parameters. The proposed formulation is intended to quantify the level of difficulty encountered during a real bulk carrier approach while providing a basis for comparing future operations under different environmental conditions. The model also enables the physical difficulty of the operating environment to be distinguished from the effectiveness of human response, allowing successful pilotage and bridge–tug coordination to be interpreted within a measurable operational context.

1.2 Research Objectives

This study aims to develop and apply an integrated mathematical framework for quantifying the difficulty of bulk carrier jetty-approach operations under adverse environmental conditions. Specifically, the study seeks to:

a) Establish a low-speed surge, sway, and yaw mathematical framework incorporating wind and current loads, tug-force capacity, and bathymetry-related UKC;
b) Formulate a non-dimensional jetty-approach difficulty index that integrates environmental loading, manoeuvring response, effective tug-control capacity, and UKC into a single quantitative measure;
c) Numerically evaluate the proposed model using time-resolved operational data from a real bulk carrier approach at Kapar Power Station; and
d) Perform a preliminary evaluation of the computed difficulty level by comparing it with the pilot's subjective operational assessment.

The study also examines how the quantified operational difficulty provides a measurable context for interpreting successful pilotage and bridge–tug coordination under challenging conditions.

2. Methodology: Development of Jetty-Approach Mathematical Model

The methodology begins with the development of a mathematical model describing the main factors affecting low-speed jetty approach, including wind and current loads, tug-control capacity, UKC, and vessel manoeuvring response. These parameters are then integrated to formulate and justify the Jetty-Approach Difficulty Index, as a quantitative measure of operational difficulty.

The Kapar Power Station coal and oil unloading jetty, Selangor, Malaysia, is selected as the case-study location. A real bulk-carrier berthing approach is conducted and time-resolved operational and environmental data are collected throughout the manoeuvre. After the operation, the marine pilot provides an independent subjective assessment of the approach difficulty. Finally, the pilot's assessment is compared with the calculated Jetty-Approach Difficulty Index to evaluate whether the proposed index reflects the actual level of difficulty experienced during the operation

2.1 Coordinate System and State Variables

The jetty approach is represented in a horizontal earth fixed coordinate system system (x, y), where the x -axis is aligned approximately along the jetty axis in the approach direction and the y--axis is normal to the jetty face to represent lateral motion toward or away from the wharf. In this frame, the vessel heading ψ is measured relative to the x -axis

Low-speed motion is described using body-fixed velocities: surge u (along ship axis), sway v (lateral), and yaw rate r (heading change rate) [10,11].

Eq. 1, $\mathbf{z}$ is the state vector that collects all main motion variables of the ship during the jetty approach,

$$\mathbf{z} = [x, y, \psi, u, v, r]^T \tag{1}$$

Where:

x: longitudinal position along the jetty in the earth-fixed (x)-direction;
y: lateral position normal to the jetty, representing the distance from the berth;
ψ: vessel heading or yaw angle;
u: surge velocity along the vessel longitudinal axis;
v: sway velocity along the vessel transverse axis; and
r: yaw rate, representing the rate of change of vessel heading.

2.2 Kinematics

The kinematic equations describe the relationship between the vessel's body-fixed velocities and its motion in the earth-fixed coordinate system. These equations determine the rate of change of longitudinal position, lateral position, and heading without directly considering the forces and moments acting on the vessel [10,11].

For the jetty-approach model, the kinematic relationships are expressed as follows:

$$\dot{x} = u\cos\ \psi - v\sin\ \psi \tag{2}$$

$$\dot{y} = u\sin\ \psi + v\cos\ \psi \tag{3}$$

$$\dot{\psi} = r \tag{4}$$

Where $\dot{x}$ and $\dot{y}$ represent the rates of change of the vessel position in the earth-fixed coordinate system, while $\dot{\psi}$ represents the rate of change of vessel heading.

Eqs. (2) and (3) transform the body-fixed surge velocity (u) and sway velocity (v) into earth-fixed longitudinal and lateral motion according to the instantaneous vessel heading ψ. Eq. (4) relates the vessel heading directly to the aw rate r. Together, these equations provide the kinematic relationship required to reconstruct the vessel trajectory during the jetty approach.

2.3 Low-Speed Surge–Sway–Yaw Dynamics

At the low vessel speeds associated with the final jetty-approach phase, the horizontal-plane vessel motion is represented within a surge–sway–yaw dynamic framework incorporating rigid-body inertia, added mass, and the principal external forces and moments [11]. In the present study, this formulation provides the physical basis for identifying and decomposing the environmental and control-related loads used in the Jetty-Approach Difficulty Index. The full dynamic equations are not forward-integrated as a predictive manoeuvring simulation; instead, the index is evaluated using the recorded time-resolved vessel-motion and environmental data as shown in Eq. (5),

$$\boldsymbol{M}\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}\boldsymbol{X}\\ \boldsymbol{Y}\\ \boldsymbol{N}\end{bmatrix} \tag{5}$$

where $\mathbf{M}$ is the combined rigid-body and added-mass matrix, and , X, Y, N are the total surge force, sway force and yaw moment respectively.

The total forces and moments are decomposed according to their principal physical and operational contributions [10,12]:

$$X = X_H + X_C + X_W + X_T + X_P \tag{5a}$$

$$Y = Y_H + Y_C + Y_W + Y_T + Y_P \tag{5b}$$

$$N = N_H + N_C + N_W + N_T + N_P \tag{5c}$$

where the subscripts H, C, W, T, and P denote contributions from hull hydrodynamics, current, wind, tug assistance, and propulsion/rudder action, respectively.

This decomposition allows the individual force and moment components X, Y, N, to be represented separately before being combined to determine the overall vessel response. In the present study, particular attention is given to the environmental sway force Y_E and environmental yaw moment N_E generated primarily by wind and current, because these quantities directly contribute to the formulation of the Jetty-Approach Difficulty Index. Tug forces $Y_T$and moments $N_T$represent the available external control capacity, while propulsion and rudder actions contribute to maintaining the required vessel trajectory.

2.4 Environmental Force Models
2.4.1 Wind-induced loads

The wind-induced sway force, Eq. (6), Y_W and yaw moment Eq. (7), N_W are modelled using quadratic expressions proportional to the square of the relative wind speed [13,14]:

$$Y_W = \frac{1}{2}\rho_a C_{YW} A_L V_w^2 \sin\,\gamma_w \tag{6}$$

$$N_W = \frac{1}{2}\rho_a C_{NW} A_L L V_w^2 \sin\,\gamma_w \tag{7}$$

where $\rho_a = 1.225$ kg/m (air density), $C_{YW} = 0.4$ is the wind-induced sway-force coefficient and $C_{NW} = 0.2$ is the wind-induced yaw-moment coefficient, $A_L = 3500m^2$, is the lateral projected area of the vessel, L = 229m is the vessel length, V_w is relative wind speed, and γ_w is the relative wind angle.

The relative wind angle is defined as:

$$\gamma_w = \theta_w - \psi \tag{7a}$$

Where θ_w represents the wind direction in the earth-fixed reference frame and ψ is the instantaneous vessel heading. The term $\sin\,\gamma_w$therefore accounts for the lateral component of the wind acting on the vessel.

Because the wind-induced force and moment proportional toV_w^2, increases in wind speed, particularly during squall conditions, produce a nonlinear increase in the environmental loading imposed on the vessel. The resulting values of γ_w and N_w are subsequently combined with the

corresponding current-induced components to determine the total environmental sway force and yaw moment used in the Jetty-Approach Difficulty Index.

2.4.2 Current-induced loads

The current-induced lateral force and yaw moment acting on the vessel are represented using quadratic expressions based on the relative transverse velocity between the vessel and the surrounding water [15,16]. The current-induced sway force is expressed as per Eq. (8),

$$Y_C = \frac{1}{2}\rho_w C_{YC} A_C |v_{\text{rel}}| v_{\text{rel}} \tag{8}$$

while the corresponding current-induced yaw moment, Eq. (9), is expressed as,

$$N_C = \frac{1}{2}\rho_w C_{NC} A_C L |v_{\text{rel}}| v_{\text{rel}} \tag{9}$$

where $\rho_w = 1025$ kg/m³ (water density), C_{YC}= 1.2 and C_{NC} = 0.3 were adopted for the current-induced sway force and yaw moment, respectively, A_C is the underwater lateral projected area of the vessel, L=229 m is the vessel length, and v_{rel} is the relative transverse velocity between the vessel and the surrounding water.

The total environmental sway force, Eq.(10), Y_E and yaw moment, Eq. (11), N_E are then obtained as:

$$Y_E = Y_W + Y_c \tag{10}$$

$$N_E = N_W + N_C \tag{11}$$

The resulting Y_E and N_E are subsequently used in the formulation of the Jetty-Approach Difficulty Index.

2.4.3 Tug force representation

Each tug is characterised by its bollard-pull capacity, position along the vessel, and direction of applied force [17,18]. For the Kapar case, two ASD harbour tugs were employed, each with a nominal bollard pull of 50 t, giving a combined nominal bollard-pull capacity of; BP_total=50+50=100 t

For the mathematical model, an effective tug-force factor of $\eta_{\text{eff}} = 0.90$ was adopted as a modelling assumption to account for the fact that the full nominal bollard pull is not continuously available as pure lateral force because of tug position, force direction, and operational efficiency. The effective maximum combined sway-force capacity is therefore; $Y_{T,\max} = \eta_{\text{eff}} BP_{\text{total}} = 0.90(100) = 90$ t

Thus, $Y_{T,\max} = 90$ t represents the effective combined lateral tug capacity used for normalisation in the proposed mathematical model, rather than the nominal combined bollard pull of 100 t. The

maximum effective tug yaw-moment capacity was calculated using the effective tug force and an adopted effective yaw lever arm of 20.4 m per tug, giving $N_{T,\max} = 18{,}000$.

During the approach, the actual tug force varies according to the recorded tug-utilisation factor $\eta_T(t)$, where $0 \leq \eta_T(t) \leq 1$

Here, $\eta_T(t) = 0$ represents no utilisation, while $\eta_T(t) = 1$ represents full utilisation of the effective available tug capacity. The instantaneous tug force is therefore expressed as per Eq. (12),

$$T(t) = \eta_T(t) Y_{T,\max} \tag{12}$$

where $T(t)$is the instantaneous effective tug force, $\eta_T(t)$is the time-dependent tug-utilisation factor, and $Y_{T,\max}$is the maximum effective combined lateral tug capacity. The quantities $Y_{T,\max}$and $N_{T,\max}$ are subsequently used as reference control capacities against which the environmental sway force Y_E and environmental yaw moment $N_E$are normalised in the Jetty-Approach Difficulty Index.

2.5 Jetty-Approach Difficulty Index
2.5.1 Definition and formulation

The Jetty-Approach Difficulty Index, J, is formulated as a non-dimensional, time-averaged measure of the combined environmental and operational demands acting on the vessel throughout the approach interval $[0, t_b]$. The index integrates environmental sway loading, environmental yaw loading, UKC risk, and manoeuvring effort into a single quantitative measure as per Eq. (13),

$$J = \frac{1}{t_b} \int_0^{t_b} \left[w_1 \frac{|Y_E(t)|}{Y_{T,\max}} + w_2 \frac{|N_E(t)|}{N_{T,\max}} + w_3 \frac{\mathrm{UKC_{ref}}}{\mathrm{UKC}(t)} + w_4 \frac{|r(t)|}{r_{\mathrm{ref}}} \right] dt \tag{13}$$

where t_b is the total jetty-approach duration, $Y_E(t)$ is the time-dependent environmental sway force, $N_E(t)$ is the corresponding environmental yaw moment, Y_(T,max) is the effective maximum combined lateral tug capacity, and $N_{T,\max}$ =18,000 kNm is the maximum effective combined tug yaw-moment capacity derived in Section 2.4.3.

The environmental loading terms;

$$\frac{|Y_E(t)|}{Y_{T,\max}} \tag{13a}$$

and

$$\frac{|N_E(t)|}{N_{T,\max}} \tag{13b}$$

represent the fractions of the available tug sway-force and yaw-moment capacities required to counteract the environmental loading. Higher values therefore indicate greater environmental demand relative to the available tug-control capacity.

The UKC contribution is represented by:

$$\frac{\mathrm{UKC_{ref}}}{\mathrm{UKC}(t)} \tag{13c}$$

where UKC(t) is the instantaneous $\mathrm{UKC_{ref}}$ = 1.0m is a reference clearance introduced solely for non-dimensionalisation of the UKC contribution. The parameter $\mathrm{UKC_{ref}}$should therefore be distinguished from the critical-clearance threshold UKC_{min} = 0.30m

As UKC(t) decreases, the value of the clearance term increases, representing increasing sensitivity to grounding risk.

The manoeuvring-effort term is defined as:

$$\frac{|r(t)|}{r_{\mathrm{ref}}} \tag{13d}$$

where r(t) is the instantaneous yaw rate and r_ref=4^∘/min is the reference yaw rate used for normalisation. Larger values indicate greater heading-control effort during the approach.

The weighting coefficients are selected such that; $w_1 + w_2 + w_3 + w_4 = 1$, with; $w_1 = 0.30$, $w_2 = 0.25$, $w_3 = 0.25, w_4 = 0.20$

representing environmental sway loading, environmental yaw loading, UKC risk, and manoeuvring effort, respectively. These weights are retained as preliminary model parameters and should be subjected to sensitivity analysis and further calibration using additional approach cases.

The factor 1/t_b normalises the integral by the total approach duration, ensuring that J remains non-dimensional and represents the average difficulty over the complete jetty-approach period, rather than increasing solely because of a longer manoeuvring duration.

2.6 Difficulty Rating Scale

For this preliminary study, the computed Jetty-Approach Difficulty Index, J, is interpreted using a five-level operational difficulty scale. The use of numerical screening bands follows the approach adopted in previous jetty-berthing index research, where non-dimensional index values were grouped into operational categories by comparing computed values with pilot assessments of controllability. Previous work demonstrated that such threshold bands can provide a practical interpretation of a continuous mathematical index, while emphasising that the numerical boundaries should initially be regarded as provisional and subject to further calibration using additional operational cases [19].

The general interpretation of the five difficulty levels is defined as shown in Table 1.

Table 1
Difficulty level category

Rating	Category	Range of (J)	Operational Characteristics
1	Routine	$0 < J < 1.0$	Low environmental and operational demand; standard manoeuvring effort
2	Normal	$1.0 \leq J < 2.0$	Minor environmental influence with routine tug and heading corrections
3	Moderate	$2.0 \leq J < 3.5$	Noticeable environmental loading and increased corrective effort
4	Challenging	$3.5 \leq J \leq 5.0$	Strong environmental loading, reduced operational margin, and high tug utilisation
5	Extreme	$J > 5.0$	Environmental and operational demand approaching or exceeding available control margins

The proposed ranges are intended as an initial interpretive framework rather than universally validated operational limits. Similar to previous non-dimensional berthing-index research, the numerical boundaries require further calibration using a larger dataset involving different vessels, environmental conditions, tug configurations, terminals, and pilot assessments.

3. Kapar Power Station Bulk Carrier Approach

3.1 Vessel, Tugs and Berth Configuration

The information presented in this study is limited to that consented to by the marine pilot. Certain information has been omitted to protect confidentiality and vessel security; however, the omitted information is not required for the calculations performed in this study.

The case vessel was a fully loaded bulk carrier approaching the coal and oil unloading jetty at Kapar Power Station Terminal, Selangor, Malaysia, at approximately 14:00 local time (UTC+8). The principal vessel particulars used in the mathematical model are presented in Table 2.

Table 2
Principal particulars of the case vessel

Vessel particular	Details
Gross Registered Tonnage (GRT)	41,900
Displacement	80,000 tonnes
Length Overall (LOA)	229 m
Breadth	32 m
Mean Draft	13.8 m (13.7 m forward, 13.9 m aft)
Propulsion	Fixed-pitch propeller
Rudder	Conventional

The berth is located at the coal and oil unloading jetty of Kapar Power Station Terminal. The approach area has a charted depth of approximately 14–15 m and a turning-basin radius of approximately 500 m. The vessel's approach geometry relative to the jetty is illustrated in Figure 1.

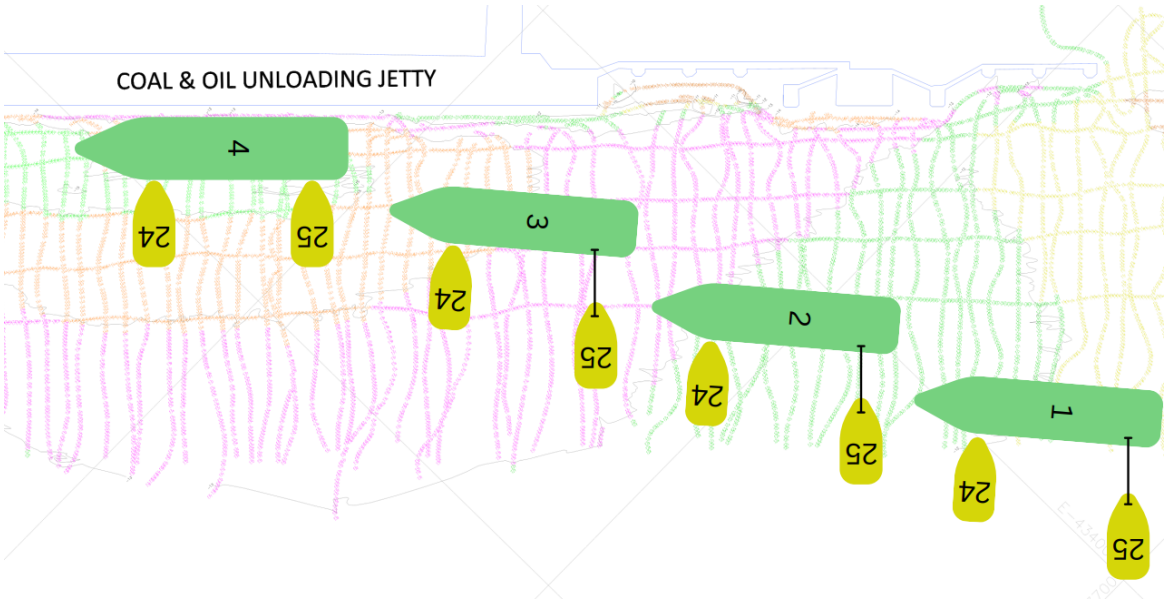


Fig. 1. Re-illustration of the bulk carrier's approach to jetty by author

Two azimuth stern drive harbour tugs were assigned to assist the manoeuvre. Their configuration and nominal bollard-pull capacities are presented in Table 3.

Table 3
Tug allocation and operational configuration

Tug	Bollard Pull	Position and Operational Role
Tug 24 (Forward)	50 t	Positioned at the forward starboard shoulder, approximately 30 m from the vessel reference position, primarily in push mode
Tug 25 (Aft)	50 t	Positioned at the aft starboard shoulder, approximately 35 m from the vessel reference position, operating in standby and pull-off mode

The approximate 30 m and 35 m values describe the operational positioning of the forward and aft tugs. For yaw-moment normalisation in the mathematical model, an effective perpendicular lever arm of 20.4 m per tug was adopted to account for the effective direction of the applied tug force relative to the vessel reference point. The tug arrangement provided lateral control during the approach while maintaining the capability to generate a pull-off force if the vessel needed to be moved away from the jetty. The tug positions, bollard-pull capacities, and operational utilisation levels were subsequently incorporated into the mathematical representation of the available tug force and yaw-control capacity.

3.2 Environmental Conditions

The jetty approach was conducted between 14:00 and 14:55 local time. During this period, the vessel was exposed to adverse meteorological and oceanographic conditions that varied throughout the manoeuvre. The principal environmental conditions recorded during the approach are summarised in Table 4.

Table 4
Summary of environmental conditions during the jetty approach

Parameter	Recorded Condition
Wind	Westerly, 28–36 knots, with gusts reaching 42.6 knots during the squall at approximately 14:30
Current	Southerly flooding current increasing from 2.6 to 3.7 knots
Tide	Spring tide, with water level approximately 3.00–3.43 m above chart datum
Sea/Swell	Significant wave height approximately 0.60–1.13 m
Notable Event	Squall onset at approximately 14:20, with peak wind and rain conditions around 14:30

The coincidence of the squall with the spring-tide flooding phase produced a particularly demanding environmental condition during the approach. Strong cross-wind and cross-current effects acted simultaneously on the vessel, while the available UKC remained limited because of the local bathymetry. These time-varying environmental parameters were subsequently used as inputs to the mathematical model to estimate wind- and current-induced forces and moments throughout the approach.

3.3 Bathymetry and Under-Keel Clearance (UKC)

Hydrographic survey data for the Kapar Power Station approach area were used to represent the local bathymetry along the approach channel, turning basin, and jetty frontage. The survey data provide water depths referenced to chart datum at approximately 1 m contour intervals. The seabed becomes progressively shallower toward the wharf, resulting in reduced UKC for the case vessel, which had a mean draft of 13.8 m.

For the present preliminary case study, a minimum UKC threshold of; UKC_{min} = 0.30m was adopted as a modelling criterion for identifying critically restricted clearance conditions. This value is used only to identify critical stages of the approach and is not intended to represent a universally applicable minimum UKC requirement. During the approach, the minimum calculated UKC was approximately 0.31 m at 14:20 h, coinciding with the onset of the squall. This condition therefore represented one of the most critical stages of the manoeuvre from a grounding-risk perspective.

Throughout the approach, the vessel remained above the adopted minimum UKC threshold, although the available clearance margin remained small. The time-varying UKC values derived from vessel draft, tidal level, and hydrographic depth data were incorporated into the Jetty-Approach Difficulty Index as a bathymetry-related constraint, allowing reduced clearance to contribute quantitatively to the calculated operational difficulty.

The UKC values used in the present analysis represent geometric clearance derived from vessel draft, tidal level, and hydrographic depth data. Dynamic effects such as squat, heel, wave-induced vertical motion, and hydrographic uncertainty are not explicitly incorporated in the present preliminary model.

3.4 Pilot Assessment

The jetty approach was independently assessed by the licensed marine pilot who conducted the manoeuvre. The pilot had 13 years of operational experience and rated the overall difficulty of the approach as 4 on a 1-to-5 scale, corresponding to a Medium to Hard operation.

The total approach duration was approximately 55 minutes, compared with a typical duration of about 40 minutes under normal operating conditions, representing an increase of approximately 38%. The pilot identified strong current, prevailing wind, and the onset of the squall as the main factors contributing to the increased operational difficulty. Tug assistance was reported to have reached near-maximum utilisation during the most demanding stage of the approach, while continuous communication between the pilot, bridge team, and tug masters was required to maintain coordinated vessel control.

The pilot's subjective difficulty rating was not used to formulate the mathematical index or determine its weighting coefficients. Instead, it was retained as an independent operational reference for preliminary comparison with the difficulty level subsequently calculated using the proposed Jetty-Approach Difficulty Index.

4. Results: Jetty-Approach Difficulty for the Kapar Case

4.1 Computed Difficulty Index

The Jetty-Approach Difficulty Index was evaluated over the complete 55-minute approach using the time-resolved environmental, vessel-motion, effective tug-control capacity, and UKC data. Let the instantaneous weighted difficulty function be defined as; $D(t) = w_1 \frac{|Y_E(t)|}{Y_{T,\max}} + w_2 \frac{|N_E(t)|}{N_{T,\max}} + w_3 \frac{UKC_{\text{ref}}}{UKC(t)} + w_4 \frac{|r(t)|}{r_{\text{ref}}}$. The time-averaged difficulty index is therefore; $J = \frac{1}{t_b} \int_0^{t_b} D\,(t)\, dt$

For the discrete time-series data, the integral was evaluated numerically using the trapezoidal rule; $J \approx \frac{1}{t_b} \sum_{i=0}^{n-1} \frac{D(t_i)+D(t_{i+1})}{2} (t_{i+1} - t_i)$ where n is the number of time intervals and t_b is the total approach duration.

Therefore, for the Kapar Power Station bulk carrier approach, the numerical evaluation produced:

$$\boxed{J = 4.481}$$

According to the proposed difficulty classification,

$$3.5 \leq J \leq 5.0$$

corresponds to Difficulty Level 4: Challenging.

The computed classification is consistent with the pilot's independent subjective assessment of 4/5, or Medium to Hard, providing preliminary operational support for the interpretation of the calculated index. The agreement should be regarded as an initial comparison rather than full validation because the present analysis is based on a single operational case.

4.2 Component Contribution Analysis

To examine the relative influence of each component on the overall Jetty-Approach Difficulty Index, J was decomposed into four weighted contributions as per Eq. (14),

$$J = J_Y + J_N + J_{\text{UKC}} + J_r \tag{14}$$

where J_Y, J_N, J_"UKC" , and J_r represent the contributions from environmental sway loading, environmental yaw loading, UKC, and manoeuvring effort, respectively. The individual contributions are defined as:

$$J_Y = \frac{1}{t_b}\int_0^{t_b} w_1 \frac{|Y_E(t)|}{Y_{T,\max}}\, dt \tag{14a}$$

$$J_N = \frac{1}{t_b}\int_0^{t_b} w_2 \frac{|N_E(t)|}{N_{T,\max}}\, dt \tag{14b}$$

$$J_{\mathrm{UKC}} = \frac{1}{t_b}\int_0^{t_b} w_3 \frac{\mathrm{UKC}_{\mathrm{ref}}}{\mathrm{UKC}(t)}\, dt \tag{14c}$$

$$J_r = \frac{1}{t_b}\int_0^{t_b} w_4 \frac{|r(t)|}{r_{\mathrm{ref}}}\, dt \tag{14d}$$

The percentage contribution of each component is calculated as per Eq. (15):

$$P_k = \frac{J_k}{J} \times 100\% \tag{15}$$

where J_k represents the contribution of an individual component to the total index.

Based on the present calculation, the environmental sway and yaw components dominate the overall difficulty, as shown in Table 5.

Table 5
Component contributions to the Jetty-Approach Difficulty Index

Component		Contribution
Environmental sway load term	(w_1)	1.939 (43.27% of J)
Environmental yaw load term	(w_2)	1.849 (41.26% of J)
Under-keel clearance (UKC) term	(w_3)	0.565 (12.61% of J)
Manoeuvring effort term	(w_4)	0.128 (2.86% of J)

The combined environmental sway and yaw contributions account for approximately; 43.27%+41.26%=84.53%

of the total calculated difficulty. This indicates that environmental loading was the dominant factor affecting the Kapar jetty approach. The UKC component contributed approximately 12.6%, while manoeuvring effort contributed 2.9%.

The relatively low value of J_r suggests that the vessel was controlled without excessively large or continuous yaw corrections despite the high environmental loading. In contrast, the large combined values of J_Y and J_N demonstrate that the principal contribution to the calculated difficulty arose from the wind- and current-induced forces and moments.

4.3 Critical Moments during Approach

To identify the most demanding stages of the manoeuvre, the time-resolved operational data were examined for simultaneous changes in UKC, wind and current conditions, tug utilisation, and vessel yaw response. Three critical moments were identified during the 55-minute approach as shown in Table 6.

At 14:20 h, the first critical moment occurred when UKC reached its minimum value of 0.31 m. At the same time, wind speed reached 32.5 knots with gusts up to 38.5 knots, the current was approximately 3.0 knots, and tug utilisation was about 60%. This stage coincided with the onset of the squall and represented the point of greatest bathymetric constraint during the approach.

At 14:30 h, the second and most demanding critical moment coincided with the peak squall and maximum tug utilisation. Wind speed reached 34.6 knots with gusts up to 42.6 knots, while the current increased to 3.5 knots. Both tugs reached 100% utilisation. The UKC had increased to 0.43 m, while the yaw rate reached r = 3.7°/min. The calculated environmental sway force reached approximately Y_E ≈ 803 tf, compared with the effective combined lateral tug capacity of 90 tf. This time point therefore represented the largest environmental loading and the highest corrective demand observed during the manoeuvre.

At 14:50 h, the third critical moment occurred when the first mooring line was ashore. The UKC had increased to 0.55 m and tug utilisation had reduced to approximately 50%. At this stage, the tugs were used primarily to provide holding and positional control while the vessel completed the transition from manoeuvring to the alongside condition.

The progression of these three moments illustrates that operational difficulty was not governed by a single variable. The minimum UKC occurred at 14:20 h, whereas the maximum environmental loading and tug demand occurred approximately 10 minutes later at 14:30 h. This temporal separation supports the use of a time-resolved mathematical index that integrates multiple environmental and operational components rather than relying on a single limiting parameter.

Table 6
Critical moments identified during the Kapar jetty approach

Time	Wind / Gust	Current	UKC	Tug Utilisation	Operational Significance
14:20 h	32.5 / 38.5 kn	3.0 kn	0.31 m	60%	Minimum UKC; squall onset
14:30 h	34.6 / 42.6 kn	3.5 kn	0.43 m	100%	Peak environmental loading and corrective demand
14:50 h	33.2 / 40.1 kn	3.5 kn	0.55 m	50%	First line ashore; holding and positional control

4.4 Environmental Force Magnitudes

To quantify the environmental demand relative to the available tug-control capacity, the instantaneous environmental-to-tug sway-force ratio is defined as per Eq. (16),

$$R_Y(t) = \frac{|Y_E(t)|}{Y_{T,\max}} \tag{16}$$

where Y_E (t) is the total environmental sway force and Y_(T,max)=90 "tf" is the effective combined lateral tug capacity used in the mathematical model.

Throughout the approach, the calculated magnitude of the environmental sway force ranged from approximately 403 "tf" to 803 "tf" . The corresponding environmental-to-tug demand ratio therefore varied from; $R_{(Y,min)}=403/90\approx4.48$ and $R_{(Y,max)}=803/90\approx8.92$ hence, $4.48\leq R_Y(t)\leq8.92$.

The maximum environmental sway demand occurred around 14:30 h during the peak squall, when $|Y_E|\approx803$ "tf" and both tugs were recorded at 100% utilisation. This represents the period of greatest lateral environmental demand relative to the effective tug-control capacity.

The large value of $R_Y(t)$ should not be interpreted as a direct measure of total vessel-control deficiency, because the vessel response also depends on hull hydrodynamics, propulsion, rudder action, heading control, and speed management. Rather, the ratio quantifies the magnitude of the environmental sway demand relative specifically to the available tug lateral capacity. The high values of $R_Y(t)$ are consistent with the component analysis in Section 5.2, where the environmental sway and yaw terms together contributed approximately 84.5% of the overall Jetty-Approach Difficulty Index.

Despite the high environmental loading, the vessel was safely brought alongside as shown in Figure 2. The result demonstrates that the proposed index captures the increasing environmental demand imposed on the manoeuvring system while allowing the overall operational outcome to be interpreted together with the vessel-control actions applied during the approach.



Fig. 2. Ship safely berthed at the jetty

5. Discussion

5.1 Objective Difficulty vs. Subjective Rating

The computed Jetty-Approach Difficulty Index provides a quantitative representation of the operational demand experienced during the Kapar Power Station approach. The calculated value was $J = 4.481$. According to the proposed classification scale, $3.5 \leq J \leq 5.0$ corresponds to Difficulty Level 4, classified as Challenging. The numerical result therefore indicates that the vessel was operating

under a high level of combined environmental and operational demand during the final jetty approach.

The calculated classification is consistent with the marine pilot's independent subjective assessment of 4/5, described as Medium to Hard. This agreement provides preliminary operational support for the interpretability of the proposed index. However, the correspondence between the calculated and subjective ratings should not be interpreted as full validation, because the present analysis is based on a single operational case and one pilot assessment.

The time-resolved analysis also shows that the calculated difficulty was primarily associated with the combined effects of strong cross-wind and cross-current, the onset and peak of the squall between 14:20 h and 14:30 h, high tug utilisation, and limited UKC over the sloping seabed. The minimum UKC reached 0.31 m, while the environmental sway and yaw components together accounted for approximately 84.5% of the total index.

The close correspondence between the computed index and the pilot's operational perception suggests that the mathematical formulation is capable of representing the relative severity of the approach conditions in a manner that is meaningful to professional pilotage. Nevertheless, additional cases involving different vessels, environmental conditions, tug configurations, terminals, and pilots are required before the numerical classification bands can be regarded as calibrated operational thresholds.

5.2 Human Performance under Quantified Operational Difficulty

The Kapar approach was completed without contact with the jetty, grounding, or reported loss of vessel control, despite the high operational demand represented by J = 4.481. The quantified difficulty therefore provides a measurable context within which the pilot's actions and bridge-tug coordination can be interpreted. Rather than treating the safe outcome as evidence of low-risk conditions, the model indicates that the vessel was successfully managed within a challenging environmental and operational envelope.

During the onset and peak of the squall, the pilot reduced the approach speed, increased tug assistance, and adjusted the vessel heading to control lateral drift. At approximately 14:30 h, both tugs reached full recorded utilisation, corresponding to $\eta_t = 1.0$, while the vessel yaw rate reached r = 3.7°/min. This remained close to, but below, the reference value $r_(ref)$ = 4°/min used in the manoeuvring-effort component of the Jetty-Approach Difficulty Index. The response therefore indicates a high but controlled level of heading correction during the most demanding stage of the manoeuvre.

The aft tug was maintained in a position that allowed pull-off assistance if required, while continuous communication between the pilot, bridge team, and tug masters supported coordinated corrective action. These operational responses were especially important because the environmental sway and yaw components contributed approximately 84.5% of the total calculated difficulty, indicating that the dominant challenge arose from external environmental loading rather than excessive manoeuvring activity.

The present case should therefore be interpreted as an example of successful human adaptation under quantified operational difficulty. The analysis does not demonstrate that an accident would necessarily have occurred in the absence of the observed actions; such a counterfactual conclusion cannot be established from a single case. However, it does show that professional judgement, timely tug utilisation, and coordinated bridge-tug interaction were associated with the safe completion of an approach that the mathematical model classified as Challenging.

This distinction is important for the interpretation of the proposed index. The Jetty-Approach Difficulty Index quantifies the severity of the operating conditions, whereas the operational outcome reflects how effectively the vessel was managed within those conditions. Separating these two concepts allows future studies to examine whether similar values of J are associated with different outcomes under varying levels of pilot experience, tug availability, bridge-team coordination, and terminal constraints.

5.3 Interpretation Relative to Human-Error Statistics

Maritime accident literature frequently reports that approximately 80–84% of accidents are associated with human error. Such statistics are useful for identifying the importance of human performance in maritime safety, but they do not directly quantify the level of environmental and operational difficulty within which decisions are made.

The present case provides a complementary perspective. The Kapar approach was classified by the proposed mathematical model as Difficulty Level 4, with J = 4.481, indicating a challenging combination of environmental loading, limited UKC, and high corrective demand. Despite these conditions, the manoeuvre was completed safely through coordinated pilot, bridge-team, and tug actions.

This result does not contradict accident statistics or imply that human error is unimportant. Rather, it demonstrates that a quantitative measure of operational difficulty can help distinguish between the severity of the operating environment and the effectiveness of the human response. In this case, a high value of J was associated with a successful outcome, showing that challenging conditions do not necessarily lead to an adverse event when the operation is managed effectively.

Accordingly, the Jetty-Approach Difficulty Index may provide a useful basis for future studies that compare quantified operational difficulty with different outcomes, pilot assessments, and levels of corrective intervention. Such comparisons could contribute to a more balanced interpretation of maritime safety by considering both the magnitude of external operational demands and the human capacity to manage them.

5.4 Implications for Ports and Pilotage

The proposed Jetty-Approach Difficulty Index provides a quantitative framework for translating time-varying environmental and operational conditions into a single interpretable measure of approach difficulty. In the present Kapar case, the value J = 4.481 was associated with a prolonged approach duration, high tug utilisation, and reduced operational margins. This relationship illustrates the potential value of the index as a structured support tool for port and pilotage decision-making.

For operational planning, repeated application of the model to a larger dataset could allow port-specific relationships to be established between J, environmental conditions, tug requirements, and manoeuvring outcomes. Once sufficiently calibrated, such relationships could support the development of dynamic operating guidance in which increasing values of J indicate progressively greater environmental and corrective demand. The index could therefore complement existing pilot judgement when considering whether additional tug support, a delayed approach, or more favourable weather and tidal window may be appropriate.

The mathematical structure of the index also allows individual contributions to be examined separately. For example, the high value of the environmental sway component JY would indicate that lateral environmental loading is the dominant source of difficulty, whereas an elevated JUKC would indicate that bathymetric constraint and reduced UKC are contributing more strongly to the overall

condition. This decomposition can provide more useful operational information than a single overall rating because it identifies which factors are driving the calculated difficulty.

For tug allocation, the normalised environmental terms compare the external sway force and yaw moment against the available effective tug-control capacities. This provides a mathematical basis for examining whether the assigned tug configuration offers sufficient control margin under the forecast or observed conditions. The present model should not yet be used to prescribe fixed tug requirements, because the weighting coefficients and classification ranges remain preliminary and require broader calibration.

From a pilotage and training perspective, the index can also provide a common numerical reference for post-operation review and simulator exercise evaluation. By comparing calculated difficulty with pilot assessments, tug utilisation, and manoeuvring outcomes across multiple cases, future studies could establish more robust operational bands and identify how professional intervention changes as J increases. In this role, the model is intended to complement, rather than replace, pilot expertise by providing a transparent mathematical representation of the environmental and operational demands surrounding the manoeuvre.

6. Conclusions and Future Work

6.1 Key Findings

This study developed and applied an integrated mathematical framework for quantifying the difficulty of a bulk carrier jetty approach under adverse meteorological and oceanographic conditions. The framework combines low-speed surge, sway, and yaw dynamics with wind and current loading, effective tug-control capacity, bathymetry-based UKC, and vessel manoeuvring response within a single Jetty-Approach Difficulty Index.

Application of the model to the Kapar Power Station case produced a time-averaged difficulty index of J = 4.481, corresponding to Difficulty Level 4, classified as Challenging. This classification was consistent with the marine pilot's independent subjective assessment of 4/5, or Medium to Hard, providing preliminary operational support for the interpretability of the proposed index.

Component decomposition showed that the environmental sway and yaw terms contributed approximately 84.5% of the total calculated difficulty, while the UKC component contributed 12.6% and the manoeuvring-effort component contributed 2.9%. The results therefore indicate that the principal source of difficulty in the Kapar case was the combined environmental loading generated by wind and current.

$$J = J_y + J_n + J_{uk\subset} + J_r$$

The time-resolved analysis identified distinct critical stages during the 55-minute approach. The minimum UKC of 0.31 m occurred at approximately 14:20 h during the onset of the squall, whereas the highest environmental loading and full tug utilisation occurred at approximately 14:30 h. This temporal separation demonstrates that operational difficulty cannot be represented adequately by a single limiting variable and supports the use of a multi-component, time-resolved mathematical index.

Despite the challenging operating condition quantified by the model, the manoeuvre was completed without contact with the jetty, grounding, or reported loss of control. The result illustrates that the Jetty-Approach Difficulty Index measures the severity of the operating environment, while the operational outcome reflects how effectively the vessel is managed within that environment. In

the present case, professional pilot judgement, coordinated bridge-tug interaction, and timely tug utilisation were associated with the safe completion of the approach.

Overall, the findings demonstrate the potential of the proposed mathematical framework to convert multiple time-varying environmental and operational variables into a single quantitative measure of jetty-approach difficulty. The present results should be interpreted as a preliminary application rather than full validation, and broader calibration using multiple vessels, terminals, environmental conditions, tug configurations, and pilot assessments is required before the classification bands can be adopted as general operational thresholds.

6.2 Preliminary Model Evaluation

The proposed Jetty-Approach Difficulty Index was preliminarily evaluated by comparing the computed difficulty classification with the independent assessment provided by the marine pilot who conducted the manoeuvre. The mathematical model produced J = 4.481. According to the proposed classification scale, $3.5 \leq J \leq 5.0$ corresponds to Difficulty Level 4, classified as Challenging. The pilot independently rated the same operation as 4/5, or Medium to Hard. The correspondence between these two assessments indicates that the proposed index produced an operational interpretation consistent with the pilot's perception of the approach difficulty.

This agreement should be interpreted as preliminary support for the model rather than full validation. The present evaluation is based on a single bulk-carrier approach, one terminal configuration, and one pilot assessment. Consequently, the current result demonstrates consistency between the computed and perceived difficulty for this case, but it does not establish the general validity of the numerical classification bands.

Further model calibration should therefore involve repeated applications of the same formulation across multiple approaches with different vessel types, loading conditions, environmental states, tug configurations, terminal geometries, and pilot assessments. Such a dataset would allow the relationship between the continuous index J and the proposed operational difficulty levels to be examined statistically and would provide a stronger basis for refining the classification thresholds.

In addition, sensitivity analysis should be conducted to determine how variations in the weighting coefficients, reference parameters, and effective tug-control assumptions influence the calculated value of J. Demonstrating that the resulting difficulty classification remains stable under reasonable parameter variation would strengthen the robustness of the mathematical formulation and support its wider application.

6.3 Future Work

Future work should extend the present single-case application by collecting time-resolved jetty-approach data from a larger number of manoeuvres at Kapar Power Station and other terminals. The expanded dataset should include different vessel types, loading conditions, environmental states, tug configurations, berth geometries, and pilot assessments. This will allow the relationship between the continuous Jetty-Approach Difficulty Index J and the proposed five-level operational classification to be calibrated statistically rather than interpreted from a single case.

A second priority is sensitivity analysis of the model parameters. The weighting coefficients w_1, w_2, w_3, and w_4, together with the reference parameters used for UKC, yaw rate, and effective tug capacity, should be varied systematically to determine their influence on the calculated value of J.

The robustness of the proposed classification should then be examined by determining whether reasonable parameter variations change the resulting difficulty level.

The treatment of tug capability should also be refined. The present model uses an effective combined lateral tug capacity of $Y_{t,max}$ = 90 tf as a simplified operational representation. Future development should incorporate tug-specific performance curves, force direction, lever-arm effects, speed through water, and time-varying tug efficiency so that both the effective sway-force capacity $Y_{t,max}$ and yaw-moment capacity $N_{t,max}$ can be represented more realistically under different operating conditions.

Further mathematical development should also examine additional physical effects that may become important during constrained approaches, including dynamic UKC, squat, shallow-water interaction, bank effects, wave-induced motion, and more detailed coupling between sway and yaw. These extensions should be introduced progressively so that the model retains its principal advantage: a transparent and interpretable quantitative measure of operational difficulty.

With a sufficiently large calibration dataset, future studies may evaluate whether port-specific threshold values of J can support dynamic operating guidance, tug-allocation assessment, simulator training, and pilotage decision support. Until such calibration is completed, the present classification bands should remain preliminary interpretive ranges rather than fixed operational limits.

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