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Navigational Risk of Ships Proceeding Through a Fairway

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Abstract:

Purpose: *Navigational risk is a criterion for navigational safety assessment on fairways. To estimate navigational risk, we must determine the probability of an accident and its consequences.*
Design/Methodology/Approach: *The authors have developed methods of determining navigational risks caused by deterioration in navigational conditions during the passage of ships through the waterway system and for the estimation of risk caused by shipboard equipment failures. In a simulation experiment, full ships with 5.000 DWT to 100.000 DWT capacity performed emergency stopping after rudder jamming.*
Findings: *The results of simulation tests developed in the form of mathematical models constitute data for the determination of ship's navigational risk due to rudder failure.*
Practical implications: *The models can be used for defining simplified relationships allowing authors to determine the width of safe emergency manoeuvring areas.*
Originality value: *The procedure has been developed and navigation algorithms for determining the risk associated with the failure of the steering of the vessel passing through the different types of the fairway.*

Keywords: *Navigational safety, navigational risks in fairways, ship emergency manoeuvres, ship simulation, maritime traffic engineering.*

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1. Introduction

In restricted areas such as sea fairways, similarly to most engineering applications, where human life is not threatened, risk R is defined as a possibility of loss occurrence within a specific time interval (Chen *et al.*, 2019), and is expressed as the product of accident probability and losses resulting from the accident (Goerlandt and Montewka, 2015). Emergency scenarios of various accidents, which incidentally are commonly used to define ship domains (Szłapczyński and Szłapczyńska, 2017), are precisely defined for manoeuvres performed by ships of a given type and size based on risk analysis and statistics of accidents in restricted areas *(Khan et al.*, 2020; Ozturk and Cicek, 2019; Zhang *et al.*, 2019). These scenarios are defined for ship-to-ship and ship-to-shore accidents (Zhang *et al.*, 2019) during fairway passing and harbour mooring manoeuvres (Vidmar *et al.*, 2020) as well as quey damages due to ship-to-ship interactions (Paulauskas *et al.*, 2020).

If sea fairways include dredged approach channels, port entrances and inner harbour fairways, where ships proceed without tug assistance, two basic emergency scenarios are distinguished:

- moving out of the available navigable area due to deteriorated navigational conditions,
- moving out of the available navigable area due to technical failures of shipboard equipment, such as rudder, main engine, generator sets.

In case a number of risks arise in a specific waterway section, the risks of individual accident types add up (Dhillon, 2016):

$$R_i = \sum_{q=1}^{p} P_{Aiq} I_{Ri} S_{iq}, \tag{1}$$

where:

- P_{Aiq} – probability of q-th type of navigational accident in i-th section of the waterway,
- I_{Ri} – annual frequency of performing a given manoeuvre in i-th section of the waterway,
- S_{iq} – consequences of q-th type of accident in i-th section of the waterway - determinant of consequences, based on (S. Gucma et al., 2019).

Analysing accidents that may occur during manoeuvring in fairways and their consequences, we can distinguish general types of accidents, for which consequences (indicator of consequences) are determined differently:

- ➢ blocking of the fairway by a ship anchored in an emergency condition,

- grounding in shallow water or on a fairway slope,
- ship colliding a port structure (breakwater, mooring facility, etc.),
- ship colliding a moored vessel,
- collision with another vessel underway.

In the former case failure consequences boil down to the costs of tug assistance and commercial shipping losses due to traffic reduction on the fairway, depending on where the failure took place. The consequences of grounding, impact on a port structure or moored ship should be increased by salvage operation costs and ship and port infrastructure repair costs. These are a function of consequences determinant S (Liu and Frangopol, 2018).

The probability of an accident for specific emergency scenarios is determined as a function of human factors (Akhtar and Utne, 2014; Fan *et al.,* 2020; Hu *et al.,* 2020), vessel parameters, type and its motion (Aalberg *et al.,* 2016; Zhang *et al.,* 2019), hydrometeorological conditions (Adland *et al.,* 2021; Fang *et al.,* 2019) and parameters of the available navigable area, such as the width of available navigable area, or minimum distance from the fairway centre line to a danger (Gucma, 2019).

The survey of methods for the analysis of structural damage in ship collisions and grounding in terms of empirical, numerical, experimental and analytical methods points out that, in basic approach, the consequences of accidents of a specific type are estimated as a function of kinetic energy of the ship which depends on ship size and speed. These consequences are defined as costs of:

- salvage operation of vessels after an accident,
- shipping losses related to the restriction of traffic on the waterway (Gao and Lu, 2019),
- repairs of ships involved,
- repairs of port infrastructure.

There are many methods of formal safety assessment of a ship's collision (Liu and Shi, 2020) and grounding (Zhang *et al.,* 2019) in restricted areas. As the analysis conducted by Mazaheri (A Framework for Evidence-Based Risk Modeling of Ship Grounding, 2017) shows, most of the models used in practice implement one or a maximum of two methods simultaneously, i.e., Geometrical scenarios, Fault Tree Analysis, Bayesian Networks or Simulation.

The authors, making a detailed analysis of the models' framework in the area of the subject in presented publication, stated that only the models of Uluscu *et al.* (2009) and van Dorp and Merrick (2011) at the same time use the geometrical scenarios and simulation methods, and include in the probabilistic risk assessment the technical failures of the ship, as possible causes of accidents, without treating the probability of accidents as the basic input variable (in most models a collision or grounding is implemented from databases (Mujeeb-Ahmed *et al.*, 2018) and treated as an event without giving a technical reason (Youssef and Paik, 2018)).

In the above-mentioned models, the risk analysis is performed by incorporating a probabilistic accident risk model into the simulation model, where the simulation model is understood as a fast-time autonomous model. A mathematical model is developed based on probabilistic arguments and historical data and subject matter expert opinions, including technical failures of the ship.

The main objective of this paper is to present the navigation accident risk assessment model using the Geometrical scenarios and Simulation methods, while the implemented simulation model, unlike the two mentioned above, is defined as non-autonomous real-time. This solution allows to treat the failures in a complex way, which allows for their parameterization, e.g., a different value of the deflection of the rudder at the time of jamming. The model, by applying the method of non-autonomous simulation in real time, also takes into account the human factor in the emergency operation.

Basically, to estimate navigational risk of accidents in fairways due to technical failures of shipboard equipment we should know:

1. The safe area of emergency anchoring, i.e., the distance between the fairway centre line and the point where a ship will anchor after a specific machine failure.
2. The ship speed before emergency anchoring at the moment of possible grounding or impact against a port/sea structure or a moored ship.

The model uses the following methods:

- probabilistic - deterministic MTEC method (Gucma and Zalewski, 2020),
- non-autonomous, real-time computer simulation of 6 DOF ship movement - to determine the ship's speed and position at the moment of an accident.

This paper aims at the development of a model of determining navigational risk of ship passage through various types of fairways, including:

- determination of the risk of navigational accidents caused by the deterioration of navigational conditions during the passage of the ship through the restricted waterway system,
- determination of the risk of navigational accidents caused by technical failures of ship's equipment (machines, power generators and rudders, determination of ship speed and position at the moment of an accident.

The results allow us to accurately determine the probability and consequences of accidents on sea fairways.

2. Risk of Accidents in Fairways Due to Deterioration of Navigational Conditions

Moving outside the available navigable area by a ship as a result of a deteriorated navigational conditions creates accident risk that depends on area restrictions. An accident may involve grounding (on a channel slope), hitting a marine structure or moored ship. The accident probability can be determined if we know the safe manoeuvring area of the ship concerned in fairways in deteriorated navigational conditions.

The probability of performing a collision-free manoeuvre by a ship of given type and size, in specific navigational and hydrometeorological conditions, conducted by a navigator with specific qualifications, in some period of time and place, is:

$$P_{nj} = P(X_j \leq d_{nj}), \tag{2}$$

and expressed by the normal standardized distribution:

$$P_{nj} = P\left(\frac{X_j - \overline{x_j}}{\delta_j} \leq \frac{d_{nj} - \overline{x_j}}{\delta_j}\right) = 1 - \alpha, \tag{3}$$

where:

- X_j – maximum distance of the ship's extreme point in *j*-th direction perpendicular to the fairway centre line or from the waterway centre line (random variable),
- $\overline{x_j}, \delta_j$ – mean value and standard deviation of maximum distances of ship's extreme points in *j*-th direction perpendicular to the fairway centre line,
- d_{nj} – minimum distance from danger in *j*-th direction perpendicular to the fairway centre line,
- $1-\alpha$ – confidence level.

The distribution parameters $\overline{x_j}, \delta_j$ are calculated from real, simulation or empirical tests of a given manoeuvre that are intended for the determination of safe manoeuvring area parameters, based on (McBride *et al.*, 2014). Calculations of safe manoeuvring area widths performed by simulation or MTEC deterministic-probabilistic methods are made at the specific confidence level.

The probability of an accident during a year due to ship's moving out of the width of available navigable area by a 'maximum ship' in *i*-th section of the fairway due to deteriorated navigational conditions is calculated by the following relationship (S. Gucma *et al.*, 2019):

$$P_{wi} = P_{ai} * P_h * I_r * \Delta t_i / G_r \; [year^{-1}], \tag{4}$$

For calculating accident probability, the maximum probability of passing the available navigable area is chosen from a set of two directions perpendicular to the fairway centre line:

$$P_{ai} = \max_j P_{aj}, \tag{5}$$

where:

- P_{wi} – probability of an accident during a year caused by moving outside of the available navigable area by the examined ship on *i*-th waterway due to the deterioration of navigational conditions [year^{-1}],
- P_{ai} – maximum probability that the safe manoeuvring area of the examined ship shifts beyond the available navigable area,
- P_h – annual occurrence of wind in the maximum range,
- I_r – mean annual intensity of ship's passage through *i*-th section of the fairway [year^{-1}],
- Δt_i – mean time of ship passage through *i*-th fairway section by the examined ship [h],
- G_r – hours per year (8760 h),
- P_{aij} – probability that the examined ship's safe manoeuvring area will go beyond the available navigable area on *i*-th waterway in *j*-th direction perpendicular to the fairway centre line.

The particular components of this expression are determined by the following algorithm:

1. The determination, by simulation or MTEC method, of widths of safe manoeuvring areas of 'maximum ship' manoeuvring in deteriorated navigational conditions in *i*-th section of the fairway: $d_i\ (1-\alpha)$.
2. The determination of the probability that the maximum ship's safe manoeuvring area will move outside the safe depth contour in deteriorated navigational conditions. The standardization of the normal distribution of the random variable X_{ij} is used.

The width of safe manoeuvring areas in fairways depends on:

- wind direction and speed,
- current direction and speed,
- visibility related with the use of the system for ship position determination in a fairway.

For least favourable wind and current directions assumed in the tests it was found that the width of the safe manoeuvring area of the ship depends on wind and current speeds:

$$d_{i(1-\alpha)} = f(V_w; V_P), \tag{6}$$

For operating conditions of commercial vessels, the following was adopted:

- the ship is not permitted to enter the fairway, when wind speed exceeds the allowable value $V_w > V_w^{dop}$, although during a fairway passage the wind speed may increase,
- as indicated by simulation tests, statistically significant reduction of the width of the safe manoeuvring area occurs when wind speed increases by approximately 2.5 m/s.

Therefore, for the determination of safe manoeuvring areas of a ship passing through a fairway in deteriorated navigational conditions, we assume:

- wind: perpendicular to the fairway centre line + 2.5 m/s,
- current: longitudinal, from the stern or perpendicular to the fairway centre line (if present) with mean speed equal to the maximum for the area,
- poor visibility z < 1 Nm.

The probability of an accident in the examined section of the fairway caused by moving outside the navigable area due to deteriorated navigational conditions is defined as the probability of moving out of the available width of *i*-th section of the fairway (D_i) by the width of the safe manoeuvring area of *k*-th 'maximum ship', determined for deteriorated navigational conditions in *i*-th section of the fairway ($d_{ik(1-\alpha)}$).

The width of the safe manoeuvring area of a 'maximum ship' for deteriorated navigational conditions is determined by two parameters: mean value (d_{ik}) and standard deviation (δ_{ik}). Parameters of the safe manoeuvring area width of the 'maximum ship' for deteriorated navigational conditions are determined using two methods:

- methods of computer simulation of ship movement,
- probabilistic - deterministic MTEC method (empirical method).

The computer simulation of ship movement is generally used in the design of sea waterways and their safe operation conditions. Using this method, we can conduct a simulation experiment for deteriorated navigational conditions. Based on a performed experiment, the width of the safe manoeuvring area of the 'maximum ship' is determined for deteriorated navigational conditions in *i*-th section of the fairway at the specific confidence level $d_{ik(1-\alpha)}$.

The probabilistic-deterministic MTEC method is an empirical method developed at the Maritime University of Szczecin. The width of the safe manoeuvring area determined by this method (Gucma and Zalewski, 2020) equals:

$$d_{ik(1-\alpha)} = d_{mik} + \Delta d_{ik} + 2p_{iD(1-\alpha)}, \tag{7}$$

where:

- $d_{ik(1-\alpha)}$ – width of the safe manoeuvring area of *i*-th section of the fairway for *k*-th ship at the confidence level (*1-α*),
- d_{mik} – manoeuvring component of the safe manoeuvring area of *i*-th fairway section for *k*-th ship,
- Δd_{ik} – widening of the manoeuvring component for a fairway bend,
- $p_{iD(1-\alpha)}$ – navigational component, i.e., direction error of ship's bow position perpendicular to the centre line of *i*-th fairway section at the confidence level (*1-α*).

Widths of safe manoeuvring areas for deteriorated navigational conditions are determined by the probabilistic-deterministic MTEC method, with the following assumptions:

- basic manoeuvring width is accepted for a low manoeuvrability ship, where $d_{mp} = 1.8B$,
- additional corrections of the manoeuvring component width are accepted for overestimated wind and current speeds (corresponding to deteriorated navigational conditions),
- the ship's manoeuvrability coefficient for a bend is assumed for a low manoeuvrability ship, where $k = 1$,
- direction error of ship's position determination is accepted for less accurate navigational systems (of the systems used on a specific ship and in the examined section of the fairway (S. Gucma & Zalewski, 2020).

3. Accident Risk in Fairways Due to Shipboard Equipment Technical Failure

A failure of the rudder, main engine or generator sets may result in a ship moving outside the available navigable area and an accident resulting in specific consequences, or anchoring that also creates specific consequences (emergency tug assistance, reduced vessel traffic on the waterway etc.).

Moving outside the available navigable area by a ship due to a technical failure of ship’s machines depends on machine reliability. Technical reliability is understood as smooth, failure free performance of a specific manoeuvre. It depends on the reliable operation of the main engine, auxiliary engines and generators, or steering gear. Each of the above listed machines has a specific probability of reliable work during manoeuvre performance.

To calculate the probability of these machines' reliable operation, the failure intensity $\lambda(t)$ in time t is used, which is the function of the density of failure occurrence, provided that until that instant no damage was present. By looking only at the stable phase of operation of machines under consideration (as observed by classification societies), it was established that the risk function $\lambda(t)$ is time-independent and constant λ.

The failure rate of machines affecting manoeuvring safety is shown in Table 1. This data is based on studies conducted by the authors (Gucma and Gralak, 2008), and revised using data from research done by Ulusçu *et al.* (2009), van Dorp *et al.* (2011), and Rasmussen *et al.* (2012).

Table 1. *The failure rate and estimated value of mean failure-free working time of marine machinery and tugs*

Type of machine	**Estimated mean failure-free working time T [h]**	**Failure rate λ [1/h]**
Main engine	6000	$1.7 * 10^{-4}$
Generating set	2000	$5.0 * 10^{-4}$
Steering gear	13000	$7.7 * 10^{-5}$

Source: *Own study.*

Only some of the examined machine failures during manoeuvring in the examined area will lead to an accident. This depends on additional factors:

- location of the failure in the tested area (fairway),
- hydrometeorological conditions prevailing during the performed manoeuvre,
- the scope of the failure of a specific machine.

Considering the individual factors, we can state that:

1. Only in some points of the tested fairway the failure of a given machine leads to an accident.
2. Only in some hydrometeorological conditions, prevailing during the performance of a manoeuvre, an accident may occur due to a failure of a given machine.
3. Only a certain extent of a failure of some machines may cause an accident (e.g., jamming of the rudder at some of its angles).

The probability of an accident caused by ship moving outside the available navigable area due to technical failures of ship equipment is determined, depending on the type of waterway and the manoeuvres performed and prevailing hydrometeorological conditions in the area (wind direction and speed).

The probability of an accident involving a non-assisted ship manoeuvring on the fairway or in the port entrance is determined for three types of failures, which differ for straight sections of fairway and bends.

1. Straight fairway or port entrance:
   - jamming of the rudder at 5° angle to ship's side (this reflects the manoeuvring in fairways where larger rudder angles are rarely used),
   - engine failure,
   - blackout, i.e. failure of generator sets.
2. Fairway bend or port entrance bend:
   - jamming of the rudder deflected to the turning side (depending on the bend turn angle)
   - jamming of the rudder put up to 5° to the side opposite to turning (reducing the ship's rate of turn),
   - engine failure,
   - blackout, i.e. failure of generator sets.

The least favourable hydrometeorological conditions occurring in emergency manoeuvres induce the largest emergency safe widths of the manoeuvring area ($d_{a(1-\alpha)}$). These are the least favourable scenarios of accidents, the probability of which is determined by the computer simulation or MTEC methods.

Probabilities of accidents in one year involving a ship passing without tug assistance due to machine failure (rudder, engine or generator set) can be written as follows:

- rudder jamming

$$P_{ws} = P_{is} * \lambda_s * \Delta t * I_r * p_z * p_{ws} \ [year^{-1}], \tag{8}$$

- engine failure

$$P_{wm} = P_{im} * \lambda_m * \Delta t * I_r * p_{wm} \ [year^{-1}], \tag{9}$$

- blackout (generator set failure)

$$P_{wa} = P_{ia} * \lambda_{ap}^2 * \Delta t * I_r * p_{ws} \ [year^{-1}], \tag{10}$$

where:

- P_{ws} – annual probability of ship's accident due to rudder jamming at 5° (straight fairway section),
- P_{ws} – annual probability of ship's accident due to engine failure,
- P_{ws} – annual probability of ship's accident due to failure of generator sets (blackout),
- P_{is} – maximum probability that the available navigable area will be exceeded due to rudder jamming at 5° deflection,

- P_{im} – maximum probability that the available navigable area will be exceeded due to engine failure,
- P_{ia} – maximum probability that the available navigable area will be exceeded due to failure of generator sets (blackout),
- λ_s – steering gear failure rate [h^{-1}],
- λ_m – generator sets failure rate [h^{-1}],
- λ_{ap} – failure rate of the main engine [h^{-1}],
- Δt – mean time of passing the examined fairway section or manoeuvre performed [h],
- p_z – probability of rudder jamming on one side (p_z = 0.67 - fairway limited on both sides),
- p_{ws} – probability of the occurrence of maximum allowable speed of cross wind (range 90°),
- p_{wm} – probability of the occurrence of maximum allowable speed of wind from the stern (range 90°).

Moving out of the available navigable area by a ship due to a technical failure of ship's machinery (steering gear/rudder, main engine or generator sets) may result in an accident: grounding, or hitting a stationary object (breakwater, quay, or a moored ship). The determination of the probability of moving out of the available navigable area requires the identification of emergency manoeuvring areas and after-failure speed distributions.

In each of three cases of examined shipboard machinery failure different manoeuvres are performed; the resulting emergency manoeuvring areas as well as ship's speed after failure are different. From an analysis of various emergency manoeuvres the following conclusions can be drawn:

- failure of generator sets leading to a blackout usually creates the most serious consequences due to impossibility of steering the ship until the anchors are dropped;
- main engine failure creates relatively lowest consequences, because the ship can be controlled till it reaches steerageway and the anchors are dropped within an available navigable area of the fairway;
- rudder failure can generate relatively large consequences; the area of emergency manoeuvres after rudder jamming has been poorly recognized so far, so the paper addresses this issue in particular.

The generator set failure leads to blackout and engine stoppage, and the rudder gets blocked at its current angle. The ship then moves along its free stoppage trajectory till it slows down to about three knots, a speed when anchors can be dropped (ships of 30,000 DWT or above). When anchors are dropped at a higher speed and dredged, the chains may break. The track and speed during free stoppage depends on ship type and size, its loading condition and fairway speed. These parameters can be read out from the track curve and the speed recorded during stopping manoeuvre performed in sea trials of every ship. Having these data, we can determine the speed of a moving ship at any moment after blackout. In restricted areas the blackout probability is very low, because two generator sets are running then, and their failure rate is $\lambda^2 \approx 2.5\ 10^{-7}$ [1/h].

The engine failure enables manoeuvring of the ship to steerageway, a minimum speed at which the ship can be controlled. Steerageway depends on the type of a ship, its loading condition and hydrometeorological conditions. It is usually a speed within 3 to 5 knots. At 3 knots, the anchors can be let go in an available navigable area of the fairway, without the risk to break the anchors' chain, regardless of ship size. For small ships (DWT < 10,000), the safe anchoring speed is approximately 5 knots.

A rudder failure generates relatively serious consequences, as the rudder blocked at a specific angle often leads to a situation where the ship's emergency manoeuvring area goes outside the available navigable area. The emergency manoeuvre consists of changing the engine setting to 'full astern' continued till the ship slows down to about three knots and lets go anchor(s). The anchoring speed of 3 knots was adopted for full-form ships with a capacity of over 30,000 DWT. The consequences of such accidents can be determined when we know speed distribution as a function of distance of ship's bow to the fairway centre line during emergency manoeuvres.

4. Methods for the Determination of Navigational Risk of Accident in a Fairway Due to Rudder Failure

The navigational risk of a ship's accident on fairways due to rudder jamming at deflected position can be determined when these data are known:

1. The distance from the ship's bow to the fairway centre line at an emergency anchoring after rudder jamming on *j*-th side of fairway (d_{akj}). This anchoring should be understood as stopping the ship after 'full astern' manoeuvre and letting go anchor at a speed appropriate for the ship size (V_{akj}).
2. The ship speed during emergency manoeuvre, from reversing the engine to full astern (after rudder jamming on *j*-th side of the fairway) to letting go anchor (V_{ekj}).

To determine the speed distribution as the function of the bow-fairway centre line distance during jammed rudder emergency manoeuvre we used the method of computer simulation of ship movement in real time. The simulation experiment was conducted for three loaded full-form ships (tankers) with the following parameters:

1. L_C = 103.6 m; B = 16.6 m; T = 7.1 m; capacity ~ 5,000 DWT,
2. L_C = 176.8 m; B = 31.3 m; T = 11.88 m; capacity ~ 30,000 DWT,
3. L_C = 249.9 m; B = 43.8 m; T = 13.46 m; capacity ~ 100,000 DWT.

The simulation experiment was conducted on a Kongsberg Polaris full mission bridge simulator at the Maritime University of Szczecin. The conditions of simulation experiment were as follows:

- ship's speed at the instant of rudder jamming $V = 8$ knots,
- jammed rudder angle 5° and 10°,
- wind speed $V_w = 0$ and $V_w = 10$ m/s, direction: perpendicular to the fairway centre line, pushing towards the turning side (increasing bow-fairway centre line distance),
- emergency manoeuvre consisted of a few engine actions:
- stop - after 5 seconds from rudder jamming,
- emergency full astern - after 10 seconds from rudder jamming.

An emergency manoeuvre after 5° rudder jamming may be performed in a straight section or a bend (turn) while the ship's rate of turn is being controlled (rudder deflected to opposite side). The rudder jamming at 10° to one side may occur in the fairway bend, when the rudder is put to the side of the turn. The jammed rudder angles, least favourable wind directions and emergency manoeuvres were established based on expert tests carried out by sea pilots and captains with considerable piloting experience.

A statistical analysis was brought down to the calculation of the arithmetic mean and standard deviation of the ship's bow - fairway centre line distance for each speed and the arithmetic mean and standard deviation of the ship's heading angle relative to the fairway centre line for each speed. As a result of simulation experiment, the following were determined (Figure 1):

1. The ship linear speed during the emergency manoeuvre of rudder jamming as a function of ship's bow to the fairway centre line distance:
2.

$$V_{ek} = f_1(d_{ek}), \tag{11}$$

where:

- V_{ek} – ship's linear speed from reduced fairway speed of k-th ship (about 6 knots) to 3 knots, which is the speed at which a ship with capacity of 100,000 DWT can drop anchor,
- d_{ek} – distance from the fairway centre line of k-th ship's bow during an emergency manoeuvre.

3. The distance from the fairway centre line to the ship's bow at the instant of stopping at anchor, assuming that the ship stops after passing/travelling 0.5 of length overall after letting go anchor:
4.

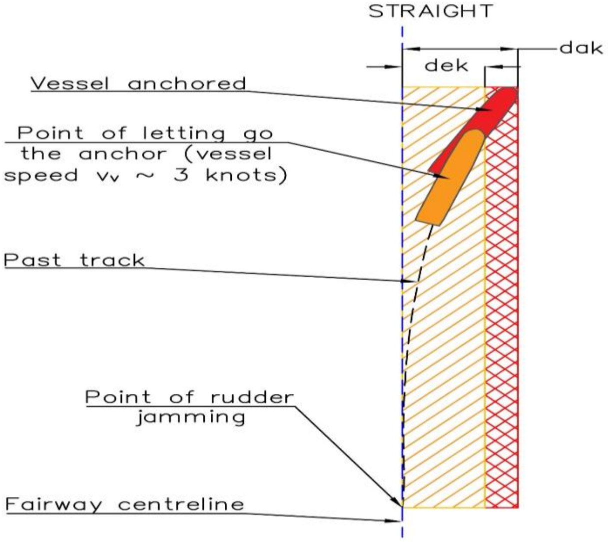
$$d_{ak} = f_2(V_{ak}), \tag{12}$$

where:

- V_{ak} – the linear speed of *k*-th ship at instant of letting go the anchor,
- d_{ak} – distance of *k*-th ship's bow from the fairway centre line at the instant of stopping at the anchor.

It was assumed that the ship stopped after passing half of the own length ($0.5L_C$) from the instant of dropping the anchors, at 3 knots for large vessels (DWT > 30,000) and at 5 knots in the case of small vessels (DWT < 10,000).

Figure 1. *Areas of emergency manoeuvres at rudder jamming, straight section of the fairway*



Source: *Own study.*

The speed of three tested vessels (V_e) as the function of bow-fairway centre line distance (d_e) during an emergency stopping manoeuvre at the rudder deflected 5° to starboard is shown in Figure 2. The emergency manoeuvres are plotted for wind speeds variants: V = 0 and V = 10 m/s. Mathematical models of these distances as a function of the ship's length and the bow distance from the fairway centre line after rudder jammed at 5° angle can be written as follows:

- rudder angle 5° $V_w = 0$:

$$V_e = 0.00895L_C - 0.0410d_e + 6.23$$
$$\delta = 3.88\,m \tag{13}$$
$$R^2 = 0.943$$

- rudder angle 5° $V_w = 10$ m/s:

$$V_e = 0.00663L_C - 0.0488d_e + 6.73$$
$$\delta = 2.27\,m \tag{14}$$
$$R^2 = 0.964$$

where:

- V_e – ship's speed at the bow to the fairway centre line distance equal to d_e,
- d_e – distance of *k*-th ship's bow from the fairway centre line,
- L_C – maximum length of the ship,
- d – standard deviation,
- R^2 – coefficient of determination.

For rudder jamming 10° to the side the ship's speed and length relationship (in the examined scope) is practically irrelevant, and mathematical models of the ship's speed as a function of the bow-fairway centre line distance after rudder jamming at 10° angle may be written as follows (Figure 3):

- rudder angle 10° $V_w = 0$ m/s:

$$V_e = 0.0287 d_e + 8.16$$
$$\delta = 4.0\ m \quad (15)$$
$$R^2 = 0.945$$

- rudder angle 5° $V_w = 10$ m/s:

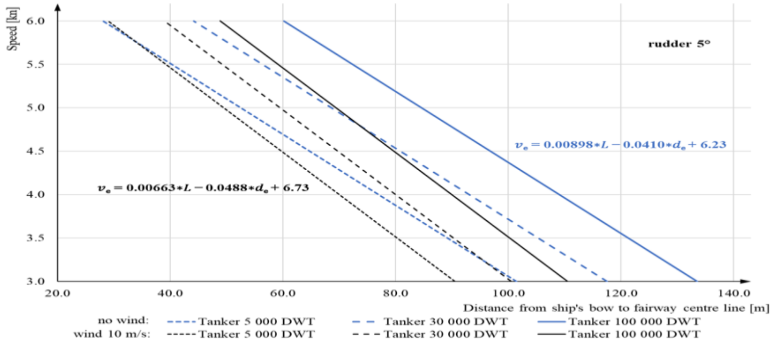
$$V_e = 0.0282 d_e + 8.31$$
$$\delta = 5.25\ m \quad (16)$$
$$R^2 = 0.923$$

The determination coefficients indicate that all models are well matched ($0.9 < R < 1.0$). The ship speed at the instant of accident (after moving out of the available navigable area) allows us to determine its consequences that depend on the type of accident (grounding, hitting a port structure or moored ship) and are calculated as a function of that speed.

Using the graphs in Figures 2 and 3, while assessing navigational risk due to rudder jamming, we can determine the ship's speed at the moment of the accident, i.e. when the ship moves outside the available navigable area. It is speed V_e at $d_e = d_n$ (d_n is a distance to the danger). For ship capacities other than those indicated in the graphs, the speed can be estimated through interpolation of the ship capacity concerned (tanker or bulker) with block coefficient $C_B = 0.72 \div 0.82$ and capacity ranging from 5,000 DWT to 100,000 DWT.

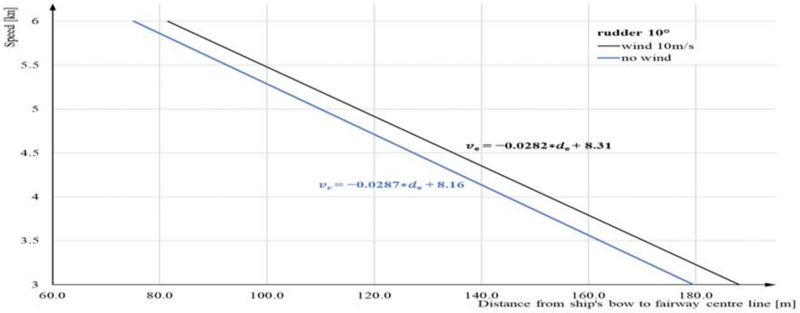
A separate problem is to determine the minimum width of the available navigable area, where the accident will not occur as the anchoring ship will remain within its limits. Minimum distances of the ship's bow to the fairway centre line at the instant of emergency anchoring are determined using graphs in Figure 4. The graphs show the ship's bow to fairway centre line distance at the moment of anchoring (stopping) corresponding to safe speed for anchor dropping: 3 knots for large, 100,000 DWT ships and 5 knots for 5,000 DWT ships.

Figure 2. *The ship speed as a function of the ship's bow distance to the fairway centre line during an emergency manoeuvre after rudder jamming at 5° angle (wind 0, speed Vw = 0 m/s and Vw = 10 m/s)*



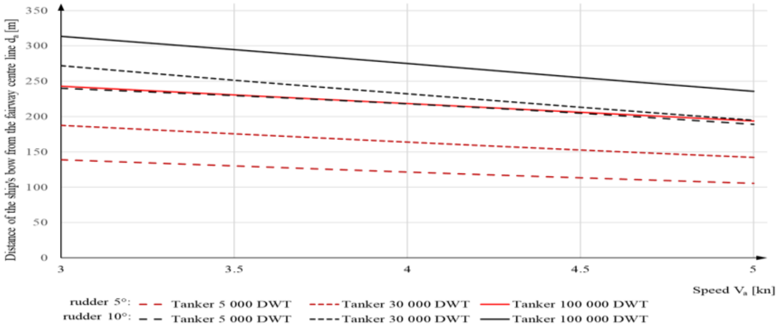
Source: *Own study.*

Figure 3. *The ship speed as a function of the ship's bow distance to the fairway centre line during an emergency manoeuvre after rudder jamming at 10° angle. Tankers with 5,000 DWT ÷ 100,000 DWT (wind 0, speed Vw = 0 m/s and Vw = 10 m/s)*



Source: *Own study.*

Figure 4. *The distance from the ship's bow to the fairway centre line at the instant of stopping at anchor as a function of speed at the instant of letting go anchor V_a (lateral wind 10 m/s)*



Source: *Own study.*

Analysing minimum distances of the ship's bow to the fairway centre line when stopping at anchor at these speeds:

- V_a = 3 knots – ship 100,000 DWT; L_C = 103.6 m,
- V_a = 3.5 knots – ship 30,000 DWT; L_C = 176.8 m,
- V_a = 5 knots – ship 5,000 DWT; L_C = 249.9 m.

We determined approximate relationships of practical use. The distance from the ship's bow to the fairway centre line at the instant of emergency anchoring with lateral wind 10 m/s is:

- rudder jamming 5°: $d_a = L_C$,
- rudder jamming 10°: $d_a = L_C + 70$ m,

These relationships refer to straight sections of the fairway; in fairway bends the curvature of the turn has to be taken into consideration. When the rudder jamming at 10° angle occurs in a bend, the curvature of the bend is subtracted from the ship's bow distance to the centre line of straight fairway section for 10° angle of jamming (Figure 5).

$$d_{za10} = d_{a10} - l * tg\left(\frac{l}{r} 57.3°\right) [m], \tag{17}$$

where:

- d_{za10} – distance of the ship's bow from the fairway centre line at the instant of stopping at anchor at rudder jamming 10° to the side of the turn [m],
- l – length of an arc along the fairway centre line from the rudder jamming position to stopping at anchor [m],
- r – radius of bed arc [m].

When the rudder gets jammed to the side opposite to the direction of turn the bend curvature is added to the ship's bow to straight centre line distance for 5° rudder jamming.

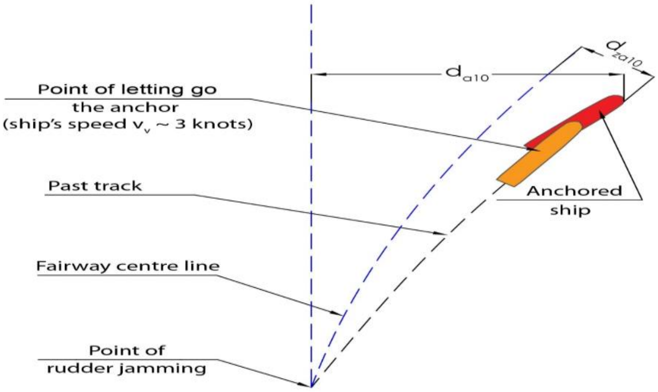
$$d_{za5} = d_{a5} + l * tg\left(\frac{l}{r} 57.3°\right) [m], \tag{18}$$

where:

- d_{za5} – distance of the ship's bow from the fairway centre line at the instant of stopping at anchor at rudder jamming 5° to the side of the turn [m],

Length of the bend arc along the fairway centre line from the rudder jamming position to the stopping at anchor based on manoeuvring characteristics of a full-form ship and results of simulation tests can be assumed as equal to $l = 2.5L_C$.

Figure 5. *The area of emergency manoeuvre in the fairway bend for rudder jammed to the turning side*



Source: *Own study.*

The navigational risk of an accident caused by rudder jamming of the 'maximum ship' at the examined section of the fairway is determined according to the algorithm shown in Figure 6. The algorithm input data include:

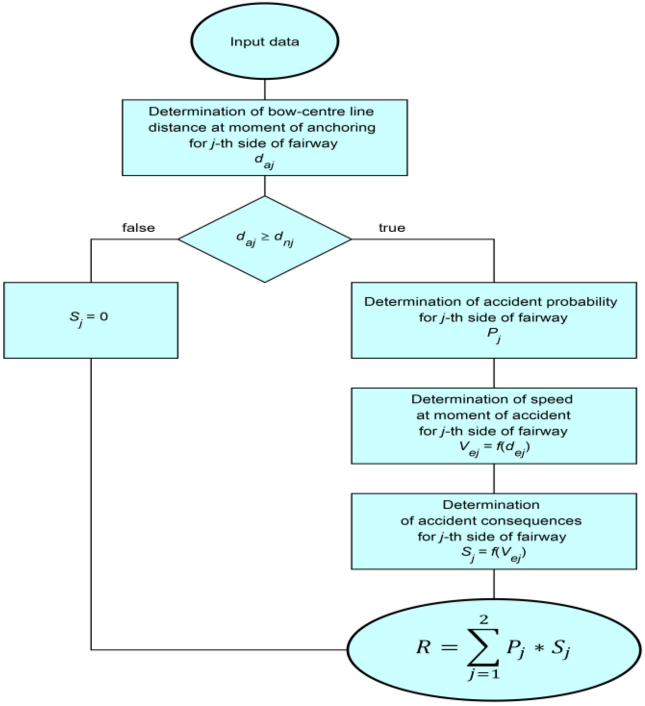
- ship parameters:
  - type of a ship,
  - DWT – capacity
  - L_C – length overall,
  - C_B – block coefficient,
  - I_r – mean annual traffic intensity of the examined ships,
- parameters of the straight fairway section:
  - d_{np}, d_{nl} – minimum distance from the fairway centre line to the danger, right and left side of the fairway, respectively,
- parameters of fairway bend:
  - r – radius,
  - d_{nz}, d_{nw} – minimum distances from the fairway centre line to the danger on the external and internal side of the bend.

5. Conclusions

The paper presents navigational risk assessment methods for ship passage through specific sea fairways. The developed methods relate to:

- determination of navigational risk of accidents due to deteriorated navigational conditions during ship passage through a waterway system,
- determination of navigational risk of accidents caused by technical failures of shipboard equipment (main engine, generator sets and rudder).

Figure 6. *Methods for the determination of navigational risk of accident on fairways due to rudder failure. Note: distances from the bow to the fairway centre line in straight sections and bends are determined in a different way*



Source: *Own study.*

The probability of an accident due to deteriorated navigational conditions during ship passage along a fairway is determined by two methods:

- methods of computer simulation of ship movement,
- probabilistic – deterministic MTEC method.

Analysing accidents caused by technical failure of shipboard equipment we can draw the following conclusions:

- failure of generator sets causing blackout on board usually creates the most serious consequences due to the lack of ship manoeuvring ability till the anchors are dropped (such failure is unlikely as two generator sets work in parallel),
- main engine failure creates relatively lowest consequences, because the ship can be controlled till it reaches steerageway and the anchors are dropped within an available navigable area of the fairway,
- rudder failure can generate relatively large consequences; the area of emergency manoeuvres after rudder jamming has been poorly recognized so far, so the article addresses this issue in particular.

The described simulation experiment involves full ships with 5,000 DWT to 100,000 DWT capacity which performed emergency stopping after rudder jamming. The experiment results allowed to determine:

- ship speed as a function of the ship's bow distance from the fairway centre line during an emergency manoeuvre after rudder jamming,
- distance of the ship's bow from the fairway centre line at the moment of its emergency anchoring (stopping).

The results of simulation tests developed in the form of mathematical models constitute data for the determination of ship's navigational risk due to rudder failure. The models were also used for defining simplified relationships allowing us to determine the width of safe emergency manoeuvring areas (by doubling the distance of ship's bow to the fairway centre line at the moment of emergency anchoring).

Finally, a procedure and algorithms were developed for the determination of navigational risk due to rudder failure of a ship passing through various types of fairways.

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