**Scientific Journals**
**of the Maritime University of Szczecin**

**Zeszyty Naukowe**
**Akademii Morskiej w Szczecinie**

**2018, 53 (125), 114–122**
**ISSN 1733-8670 (Printed)**
**ISSN 2392-0378 (Online)**
**DOI: 10.17402/273**

*Received: 24.10.2017*
*Accepted: 21.02.2018*
*Published: 16.03.2018*

# A simulation method to determine the safe operating conditions for designed sea-going ferries

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**Key words:** conditions of safe operation of ferries, simulation of ferry manoeuvring, design of marine ferries, safety of navigation, marine simulation

### Abstract

The presented method for defining the conditions of safe operation of marine ferries in ferry terminals allows verification of shipowner ferry designs. In the first stage of this method, simulations are used to determine the allowable wind speed. The second stage comprises simulations of ferry berthing aimed at defining safe manoeuvring areas, the energy of berthing impact and propeller stream speeds at allowable wind speeds. The method was used in the design of a 228 m long hybrid ferry.

## Introduction

Sea-going ferries are often designed to be the 'maximum' allowable for a specific ferry terminal, i.e. having the maximum length and breadth allowing it to safely moor at a specific berth. This is done to maximise ferry cargo and passenger capacity. Maximised ferry capacity is often associated with minimised operating costs, including fuel consumption on a given shipping line. This approach involves reducing the main propulsion power, which, in turn, leads to limited manoeuvrability, i.e. limitations to the ferry's safe operation during arrival and departure (Gucma et al., 2012; Gucma & Artyszuk, 2015).

One of the fundamental problems of sea ferry operation in ferry terminals is the determination of acceptable hydrometeorological conditions in which the ferry can safely berth or unberth. This problem is usually solved at the re/construction stage and consists of defining the conditions of safe operation of the ferry during terminal entry/departure manoeuvres.

## Conditions for the safe operation of sea ferries

A ferry terminal is a system composed of various marine waterways, such as entrance to the terminal, turning basin and berth approach basin. Conditions for the safe operation of a ferry at a terminal are a function of the waterway system parameters.

$$\mathbf{W}_i^t = \begin{bmatrix} \boldsymbol{A}_i^t \\ \boldsymbol{K}_i^t \\ \boldsymbol{N}_i^t \end{bmatrix} \tag{1}$$

where:
$\boldsymbol{W}_i^t$ – a set of conditions for the safe operation of a ferry approaching the *i*-th berth of the ferry terminal;
$\boldsymbol{A}_i^t$ – the area subsystem of the ferry terminal (*i*-th berth);
$\boldsymbol{K}_i^t$ – subsystem of the *i*-th berth and its equipment;
$\boldsymbol{N}_i^t$ – navigational subsystem of the ferry terminal (subsystem for determining the position and speed of a ferry approaching the *i*-th berth).

Conditions for the safe operation of a ferry approaching the *i*-th berth are defined by a vector written in the form of a set of parameters (Gucma et al., 2015):

$$\mathbf{W}_{\boldsymbol{i}}^{\boldsymbol{t}} = \left[L_c, B, T, H_p, F, n, M, M_{sd}, M_{sr}, \boldsymbol{H}_{\boldsymbol{i}}^{\boldsymbol{t}}\right] \quad (2)$$

where:

$L_c$ – ferry's overall length;
$B$ – ferry's breadth;
$T$ – ferry's draft;
$H_p$ – airdraft;
$F$ – lateral windage area;
$n$ – number of main propulsion propellers;
$M$ – power supplied to the propeller;
$M_{sd}$ – power of bow thrusters;
$M_{sr}$ – power of stern thrusters;
$\boldsymbol{H}_{\boldsymbol{i}}^{\boldsymbol{t}}$ – hydrometeorological conditions permitted for un/berthing manoeuvres to/from the terminal's *i*-th berth.

Hydrometeorological conditions acceptable for manoeuvres to/from the ferry terminal to the *i*-th position are defined in the form of a set:

$$\boldsymbol{H}_{\boldsymbol{i}}^{\boldsymbol{t}} = \left[\Delta h_i, V_{wi}, KR_{wi}, V_{pi}, KR_{pi}, h_{fi}, KR_{fi}\right] \quad (3)$$

where:

$\Delta h_i$ – allowable drop of water level
$V_{wi}$ – allowable wind speed at *i*-th berth;
$KR_{wi}$ – wind direction restrictions (if any) at *i*-th berth
$V_{pi}$ – allowable current speed at *i*-th berth;
$KR_{pi}$ – current direction restrictions (if any) at *i*-th berth
$h_{fi}$ – allowable wave height at *i*-th berth;
$KR_{fi}$ – wave direction restrictions (if any) at *i*-th berth.

The area subsystem of the ferry terminal (approach to *i*-th berth) is described by a set of parameters:

$$\boldsymbol{A}_{\boldsymbol{i}}^{\boldsymbol{t}} = \begin{bmatrix} r_i \\ l_i \\ D_i \\ h_i \end{bmatrix} \quad (4)$$

where:

$r_i$ – type of approach area to *i*-th berth;
$l_i$ – length of approach area to *i*-th berth [m];
$D_i$ – width of available navigable area within the approach to *i*-th berth [m];
$h_i$ – minimum depth of approach to *i*-th berth [m].

The following types of berthing are distinguished:

- berthing alongside:
  - ferry approach parallel to the berth;
  - ferry approach at an angle ($\beta > 30°$);
  - berthing with turning of the ferry.
- berthing bow or stern first to a ramp:
  - approach parallel to the berth (perpendicular to the ramp);
  - ferry approach at an angle ($\beta > 30°$);
  - berthing with turning of the ferry.

The subsystem of a ferry berth and its equipment is described by a set of these parameters:

$$\boldsymbol{K}_{i}^{\boldsymbol{p}} = \begin{bmatrix} T_i \\ k_i \\ b_i \\ E_i \\ q_i \\ v_i \end{bmatrix} \quad (5)$$

where:

$T_i$ – type of structure of *i*-th berth;
$k_i$ – length of the berthing line of *i*-th berth [m];
$b_i$ – spacing of fenders at *i*-th berth [m];
$E_i$ – allowable kinetic energy absorbed by a fender at *i*-th berth [kNm];
$q_i$ – allowable reaction force on 1 m$^2$ of the front fender of *i*-th berth (allowable unit pressure on the hull) [kN/m$^2$].
$v_i$ – allowable speed of propeller streams at the bottom of the approach area [m/s].

There are different types of mooring structures:

- quay (solid structure) – mooring alongside;
- wharf (piled structure) – mooring alongside;
- ramp – mooring stern-to or bow-to.

The navigational subsystem for position and speed determination is described by a set of parameters:

$$\boldsymbol{N}_{in}^{\boldsymbol{p}} = \begin{bmatrix} p_{in} \\ m_{in} \\ n_{in} \\ w_{in} \end{bmatrix} \quad (6)$$

where:

$p_{in}$ – accuracy of *n*-th navigational system during approach to *i*-th ferry berth (directional error of ship position and speed perpendicular to the quay and assessment error of ship speed normal to the berth);
$m_{in}$ – availability of *n*-th navigational system during approach to *i*-th ferry berth (dependent on type of navigational system or on day/night visibility for optical systems);
$n_{in}$ – reliability of *n*-th navigational system during approach to *i*-th ferry berth;
$w_{in}$ – dependability of *n*-th navigational system.

For the determination of conditions of safe ferry operation at the existing ferry terminal, terrestrial methods are usually used, which is justified by the reliability of Pilot Navigation and Pilot Navigation and Docking Systems.

The regularity of ferry shipping throughout the whole period of terminal operation is provided by adopting the following assumptions:

- allowable drop of water level ($\Delta h_i$) is determined by adopting the lowest water level in port in a period of 10 years;
- allowable current speed ($V_{pi}$) is taken as the average maximum speed of the current in a given area;
- allowable wave height ($h_f$) is taken as the maximum wave height occurring in a given area.

Given the above restrictions, detailed hydrometeorological conditions acceptable during manoeuvres of un/berthing to/from the *i*-th berth position can be described as follows:

$$\boldsymbol{H}_{\boldsymbol{i}}^{\boldsymbol{t}} = \left[V_{wi}, KR_{wi}, V_{pi}^{\max}, KR_{pi}^{\max}\right] \qquad (7)$$

where:

$V_{pi}^{\max}$ – maximum current speed at a ferry terminal (maximum average);

$KR_{pi}^{\max}$ – directions of maximum speed current.

This means that the conditions for the safe operation of a ferry berthing at the *i*-th berth of the terminal are only determined by wind speed and direction at a maximum average current.

Conditions for the safe operation of ferries at a terminal are defined by two methods: empirical and simulation. The empirical (experimental) method is based on the results of expert tests performed by a group of captains manoeuvring different ferries at a ferry terminal (Gucma & Kowalski, 2006). This method is rather inaccurate and allows the determination of approximate conditions for safe ferry operation at a specific terminal. The simulation method herein presented is accurate, assuring precise determination of safe operating conditions for a designed ferry at a specific ferry terminal berth.

## Simulation method for defining conditions for the safe operation of designed sea ferries

The simulation method for the determination of safe ferry operating conditions aims to verify shipowners' designs. The method aims to determine the safe conditions for ferry operation at terminals which are expected to handle the designed ferry. The method can also be used to modify ferry parameters that will result in achieving the planned-for conditions of safe operation (Gucma L. et al., 2017).

The method makes use of standard simulation test (experiment) procedures (Gucma, 2001; PIANC, 2014):

- specification of the test goal, simulation methods and types of simulators;
- construction of ferry movement model on a selected simulator, its verification and calibration;
- design of the simulated system and performing the experiment;
- processing and statistical analysis of test results.

The safe operating conditions for a designed ferry in a specific terminal to be determined include the allowable speeds/directions of the wind and current in which the ferry can safely manoeuvre on its own. The criteria for ferry un/berthing safety used when establishing allowable wind and current speeds are:

1) mean time of ferry berthing;
2) maximum settings of propellers during ferry berthing;
3) duration of maximum propeller and thruster settings in relation to average periods of the whole berthing manoeuvre;
4) safe areas of approach/berthing, and unberthing/departure manoeuvres performed at allowable speeds of wind and current;
5) maximum kinetic energy of first ferry-fender contact during berthing;
6) maximum speeds of propeller streams at the bottom during un/berthing.

The simulation method for determining the safe ferry operating conditions makes use of simulators with a 3D projection and 2D visualization superimposed on an electronic chart. The simulator-based experiments can be characterised as follows:

- 3D simulators offer greater accuracy, but are more time-consuming and more expensive;
- experiments on 2D simulators are slightly less accurate, but cheaper and less time-consuming.

The mathematical model of ship motion, also known as a dynamic model, usually assumes three degrees of freedom for motion in the horizontal plane. These are the longitudinal, transverse and rotary motion of the ship's waterplane (surging, swaying and yawing), called manoeuvring motions. Sometimes, three other motions, rolling, pitching and heaving, are added, which are related to draft changes. The basic mathematical model (three manoeuvring motions) is represented by equations of rigid body dynamics written in a moving ship reference system, *Mxy*, where the *M* pole is placed at the intersection of the symmetry plane and the midship section plane. The equations describe linear and angular velocity changes in time. Based on these velocities, the position of pole $M$ and the orientation of the ship's axis, $x$, in the Earth reference system, $Ox_oy_o$, are determined, i.e. ship position and course.

The primary problem in constructing a ship movement model for a designed ferry is model verification and calibration (Artyszuk, 2013). The verification of ship movement models requires a comprehensive comparison and conformity assessment of actual ship manoeuvres with the forecast (modelled) ones. Characteristic manoeuvres that are most universal in terms of quality and quantity of conveyed information should be chosen for this purpose. It is also important for the manoeuvres (controls) to be similar to those performed in ultimate simulation tests and to involve similar navigational conditions (e.g. shallow water) or hydrometeorological conditions.

Such requirements are not always possible. For many reasons, available results for ship manoeuvring tests comprise relatively simple manoeuvres, usually with simultaneously maximum values of the initial advance speed, propeller settings (rpm or pitch) and rudder angle. Other manoeuvres include free stopping, active stopping, turning, zigzag test and the Williamson loop. These manoeuvres form the main portion of shipbuilding trials preceding ship delivery are usually performed for a ship under ballast. Sea trials are not always carried out in good weather conditions and sea current parameters are often unknown. In addition, not all movement parameters important for model movement assessment are registered and/or published in sea trial reports. Sea trial results are also given in a ship's manoeuvring documentation for the navigator, introduced under International Maritime Organization (IMO) Resolutions (booklet and wheelhouse poster) developed for simple navigational and collision avoidance tasks in the open sea. Although IMO-required documentation also contains many simulation results based on mathematical models of ship movement used by shipyards, these data should be taken with caution.

Significant importance shall be applied to the zigzag test, particularly its 10°/10° variant. This test reveals fundamental manoeuvring qualities of a ship by starting and stopping turns at slight rudder angles – qualities essential in pilotage. Common parameters of the zigzag test chart include: track travelled till course alteration by 10° (in 10°/10° test) known as the initial turning ability, overshoot and full period of yawing.

To verify a model, data from vessels of a similar type or loading condition are used, even if the vessel size expressed by its main dimensions and block coefficients differs from the ship to be modelled. It is necessary to properly calculate (re-scale) the test results according to the laws of hydro mechanical similarity, which is possible to a large extent even with differences in initial manoeuvring speed between the model and reference ships.

The model verification is usually also combined with calibration (adjustment) of the model in cases where large discrepancies are found between the ship and model behaviour. This can also be called model identification according to kinematic manoeuvring data. The identification consists of establishing the values of the dynamic parameters of the model, i.e. the parameters of relevant physical relationships describing the forces acting on the ship. These parameters may be permanent or function-dependent. Due to the stiffness of the movement model structure and limitations of the identification techniques, a full similarity of the real ship and model behaviour is rarely achieved. Kinematic data may come not only from the actual, full-scale ship, but also from a free-running scale model.

A simulation experiment for determining the safe operating conditions for a designed ferry in an examined terminal is carried out in two stages:

Stage 1 – determination of allowable wind speed that is safe for berthing/mooring and unberthing/departure from the terminal (expert tests);

Stage 2 – simulated ferry manoeuvres of berthing/mooring and unberthing/departure from the terminal at allowable speeds of wind blowing from the least favourable directions.

Allowable wind speeds at average maximum current speeds are defined separately for berthing/mooring manoeuvres ($V_w^{cum}$) and for unberthing and departure ($V_w^{odc}$). The least favourable wind directions are assumed; that is, pushing away from the berth during berthing and pushing towards the berth during unberthing manoeuvres. The allowable wind speed at the terminal ($V_w$) is adopted as the lower of the two speeds, i.e.:

$$V_w = \min\left[V_w^{cum}, V_w^{odc}\right] \tag{8}$$

**Stage 1**. In order to determine the maximum allowable wind speeds for the examined ferry in a given terminal, the following simulation experiment should be performed (expert tests involving ferry captains):

- mean maximum wind (not gusting) is determined for the ferry berth ($V_w^{\max}$) allowing for

occurrences from directions perpendicular to the berth line;
- simulation experiment of ferry berthing is carried out for winds pushing the ferry away from the berth. The manoeuvre of the ferry begins when the stern is 50 m from the berth ramp and 50 m from the berth line. The manoeuvre ends when the ferry is parallel to the berth line, its hull contacts the fenders and the ship is kept at berth using only its own propulsion and steering mechanisms;
- the initial speed and course are established as instructed by the captain performing the manoeuvre;
- pushing-away wind speed is taken as equal to the maximum wind speed for the ferry berth. In the case of negative safety criteria, the maximum wind speed is reduced by 2 m/s, i.e. to -2 m/s, and the berthing manoeuvre is repeated. Maximum wind speeds are repeatedly lowered until positive safety criteria are obtained. The current speed takes the mean maximum value, and its direction should be the least favourable for a given manoeuvre;
- manoeuvres are performed by sea ferry captains;
- five berthing manoeuvres are carried out for each wind speed tested;
- the allowable wind speed is determined using the safety criteria of berthing manoeuvres and the opinions of the captains performing the manoeuvres.

Based on the authors' research involving a questionnaire completed by expert navigators, ferry captains and sea pilots, the determined safety criteria for berthing wind speeds are as follows:

1. The mean duration of ferry berthing from the beginning (at a distance of 50 m from the berth line) to the end of the manoeuvre with a stern position 10 m from the ramp and contact with berth fenders made using only the ship's own propulsion and steering mechanisms. This duration may not exceed ten minutes:

$$t_{cum} \leq 10 \text{ min} \tag{9}$$

2. Maximum settings of the propellers should not exceed 80% of the nominal load. The duration of maximum propeller and thruster settings cannot exceed 80% of mean berthing duration.

**Stage 2**. Simulation tests are usually carried out in the following two series:
- entry and berthing manoeuvres made at allowable wind speed pushing the ferry away from the berth;
- unberthing/departure manoeuvres at allowable wind speed pushing the ferry toward the berth.

The conditions of simulation experiment are as follows:
- 10–15 manoeuvres are carried out in one series;
- current speed is taken as the average maximum at any area, and its direction as the least favourable for a given manoeuvre;
- random changes are made in the ship's initial position, speed and course, within the limits acceptable by good sea practices;
- simulated manoeuvres are performed by different ferry captains (each captain performs one or two manoeuvres from one series).

The safety criteria for entry/berthing and unberthing/departure manoeuvres at allowable wind speeds are as follows (Gucma, Gucma & Zalewski, 2008):

1. The safe area of approach/berthing manoeuvres and unberthing/departure manoeuvres made at allowable wind speeds and current speeds, which must fit within navigable waters of the terminal:

$$d_{(1-\alpha)} \subset D \tag{10}$$

Calculations are made at the confidence level $(1 - \alpha) = 0.95$.

2. The maximum kinetic energy of first contact of the ferry during berthing shall not exceed the allowable energy absorbed by the fenders:

$$E_{(1-\alpha)} \subset E_{\text{dop}} \tag{11}$$

3. The maximum speed of propeller streams at the bottom for propeller settings used during un/berthing cannot exceed the acceptable speeds of propeller streams at the bottom of a given water area:

$$v \leq v_{\text{dop}} \tag{12}$$

## Determination of the conditions for safe operation of a designed 228 m ferry at the Ferry Terminal in Świnoujście

The simulation method for defining conditions for the safe operation was used in designing a ferry with $L_c$ = 228 m. The ferry is intended for Świnoujście–Ystad line service and is to be handled at berth No. 1 of the Świnoujście Ferry Terminal. The Polska Żegluga Bałtycka shipowner's design was developed by a specialized design office. The ferry's main particulars are as follows:
- overall length $L_c$ = 228.0 m;
- length between perpendiculars $L_{pp}$ = 210.0 m;
- breadth $B$ = 31.8 m;
- draft $T$ = 6.3 m;
- deadweight = 11,000 tonnes;

- displacement = 29,000 tonnes;
- lateral windage area $F_L$= 6486 m$^2$;
- front windage area $F_T$ = 1000 m$^2$;
- main propulsion power 2 × 9000 kW;
- 2 Becker rudders, surface area of 19 m$^2$;
- bow thrusters 2 × 2300 kW;
- stern thruster 1 × 1500 kW.

Simulation tests were carried out on the FMBS Polaris simulator from Konsberg, installed at the Marine Traffic Engineering Centre, Maritime University of Szczecin. The model of the 228 m ferry's motions was developed using Hydrodynamic Modelling Tool (HDMT) software (Gucma S. et al., 2017). Verification and calibration of the model was based on its manoeuvring characteristics compared to those of existing ferries with similar parameters.

The simulation experiment was divided into two stages:

1. Determination of the maximum wind speed pushing the ferry away from the berth for safe berthing manoeuvres (expert tests);
2. Conduct of simulated manoeuvre tests:
   - ferry berthing at the maximum safe wind speed, with wind pushing away from the berth;
   - unberthing at the maximum safe wind speed pushing the ferry toward the berth and turning in the Obrotnica Mielińska basin.

The maximum wind speed pushing away from the berth, safe for a berthing ferry 228 m long, was established by performing the following simulation experiment (expert tests).

- the berthing manoeuvre begins when the ferry's stern is 50 m from berth No. 1's ramp and 50 m from the berth line; the manoeuvre was completed when the ferry was positioned parallel to the berth with the stern 5–10 m from the ramp and hull in contact with the fenders with the ship kept at the berth using only its own propulsion and steering mechanisms;
- the speed and course were altered as instructed by a ferry captain performing the manoeuvres;
- E winds were tested at berth No. 1 at selected wind speeds of $V_w$ = 12.0 m/s, 15.0 m/s and 17.0 m/s (equivalent to wind speeds at sea of 17 m/s, 20 m/s and 22 m/s respectively); these are mean maximum speeds;
- simulated manoeuvres were performed by sea ferry captains;
- the criteria for assessing the simulated manoeuvres were:
  - – duration of each manoeuvre (trial in a series);
  - – loads of main propulsion engines and bow/stern thrusters.

Five berthing manoeuvres were carried out for each wind speed in the tests.

The expert tests were carried out by captains performing berthing manoeuvres of a ship 228 m in length to berth No. 1 at the Ferry Terminal in Świnoujście. A safe manoeuvre is one that, in an expert navigator's opinion, could be performed in given hydrometeorological conditions, while the propeller and steering settings during the manoeuvre remain within their operational ranges (up to 70% of maximum setting) used in real conditions by this type of ship. A safe manoeuvre allows the ferry to berth and stay at berth using only its own propulsion and steering mechanisms.

The results of expert tests of the ferry model on an FMBS Polaris simulator clearly showed that the maximum safe wind speed for berthing manoeuvres is 15 m/s E (pushing away from berth).

Given the above results, the simulation experiment was arranged as follows:

Series 1. Ferry berthing:

- wind: E 15 m/s;
- incoming current: 1.5 knots;
- position of commencement of manoeuvre: abeam berth No. 4, Świnoujście Ferry Terminal; ferry speed 6 knots;
- position of manoeuvre completion: ferry parallel to the berth, stern 5–10 m from the ramp, the ferry kept at the berth using only its own propulsion and steering mechanisms.

Series 2. Ferry unberthing and turning in the Obrotnica Mielińska basin:

- wind: W 15 m/s;
- outgoing current: 1.5 knots;
- position of manoeuvre completion: abeam berth No. 2, Świnoujście Ferry Terminal (fairway Świnoujście–Szczecin); ferry speed 6 knots.

Each series consisted of 10 manoeuvres. The manoeuvres were performed by currently serving ferry captains or captains experienced in manoeuvring ferries. Each of the captains handling the ferry could execute a maximum of two manoeuvres (trials) in one series.

The statistically processed simulation results, in the form of the identified safe manoeuvring areas and the following specific values are shown for each series in Figures 1 and 2:

- mean from the series,
- maximum from the series,
- 0.95 confidence level

An analysis of the results of the simulation experiment leads to the following conclusions for both manoeuvres:

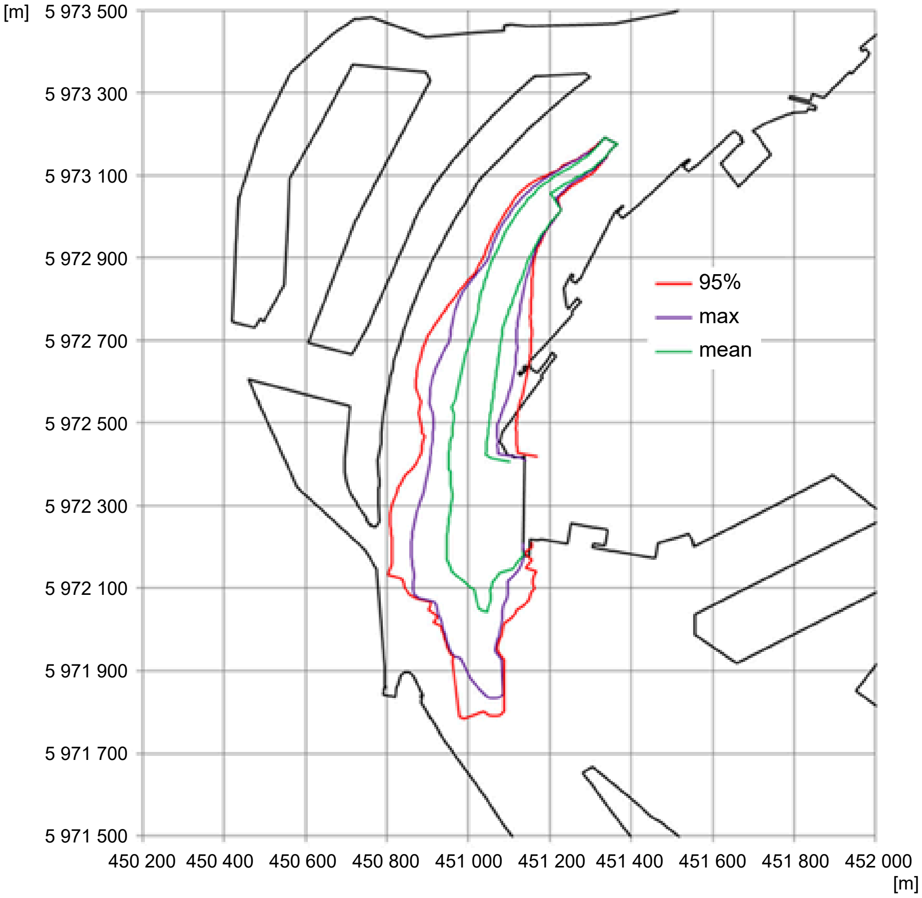

**Figure 1. Berthing of a ferry, $L_c$ = 228 m, at berth No. 1, Ferry Terminal Świnoujście. Wind E 15 m/s. Incoming current 1.5 knots (Series 1)**

1. The ferry berthing in 15 m/s E wind, incoming current 1.5 knots:
   - the maximum safe manoeuvring area is contained within the navigable area, meeting the basic conditions of navigational safety;
   - the safe manoeuvring area at the confidence level of 0.95 at berth No. 1 of Świnoujście's terminal exceeds the navigable area and is also significantly larger than the maximum safe manoeuvring area. This is because the available navigable area in that region is redundant, therefore shiphandling is not so restricted;
   - the maximum kinetic energy of the first impact against the berth in simulated berthing manoeuvres is $E(t) \approx 350$ kNm. The relatively low magnitude of this energy results from the conditions during berthing – wind pushing from the berth. The allowable kinetic energy absorbed by the fenders on the berth $E_d$ = 1000 kNm ensures that the energy criterion of manoeuvring safety is satisfied.

$$E(t) \leq E_d \tag{13}$$

2. The ferry unberthing at 15 m/s W wind, outgoing current 1.5 knots:
   - safe manoeuvring areas – at maximum and 0.95 confidence levels – are contained within the navigable area, that is they satisfy the basic conditions for navigation safety;
   - in southern and western parts of Obrotnica Mielińska (turning basin) the safe manoeuvring area at a 0.95 confidence level exceeds significantly the maximum area, which means that shiphandlers have some freedom during manoeuvring due to the redundant navigable area.

Summing up the results of the expert tests and simulation experiment, we can state that berthing and unberthing manoeuvres of a 228 m long ferry to/from berth No. 1 of Świnoujście's Ferry Terminal and turning in the Obrotnica Mielińska basin are safe for winds up to 15 m/s and current speeds up to 1.5 knots. A wind speed of 15 m/s at berth No. 1 corresponds to a 20 m/s wind blowing in the open sea.

If the ferry is to perform safe un/berthing manoeuvres in winds up to 17 m/s, one of the following solutions should be implemented:

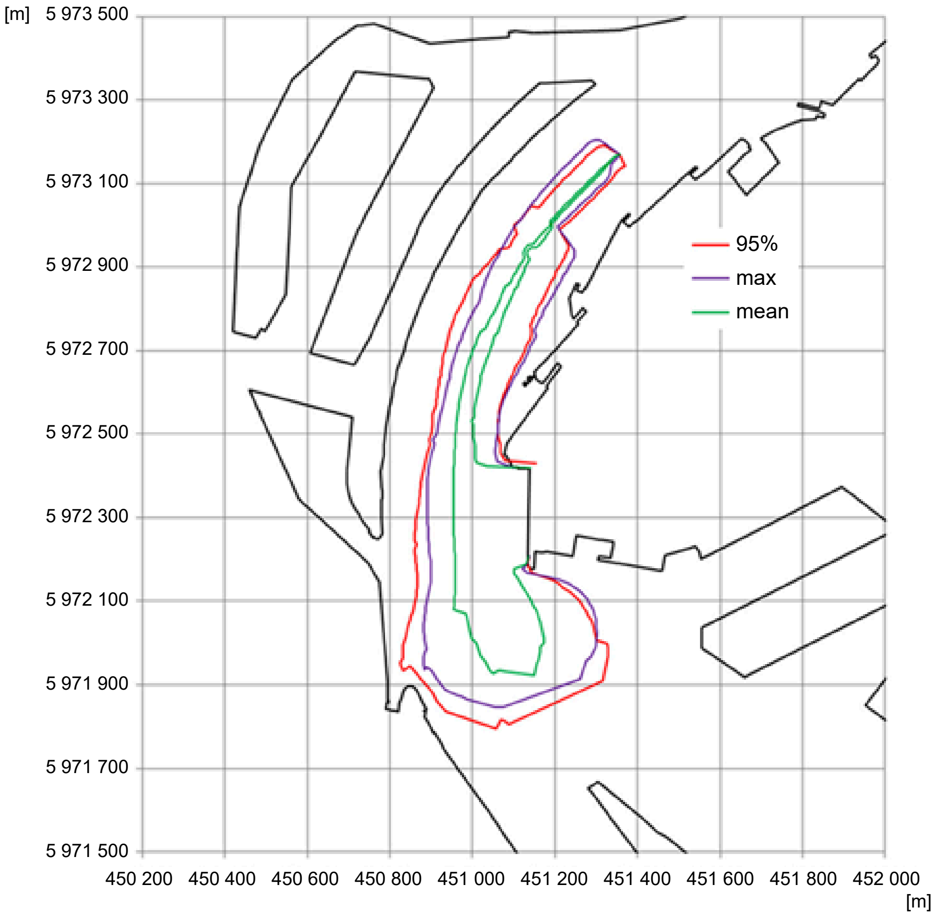

**Figure 2. Unberthing of a ferry, $L_c$ = 228 m, from berth No. 1, Ferry Terminal Świnoujście, turning in the Obrotnica Mielińska basin; wind W 15 m/s; outgoing current 1.5 knots (series 2)**

- increase the power of the stern thruster from 1500 kW to 2500 kW;
- ensure greater efficiency of the propeller-Becker rudder units while the propellers rotate in opposite directions by building a central skeg.

Increasing the maximum safe wind speed during berthing manoeuvres in port is of particular importance in Ystad, where prevailing wind speeds are greater than in Świnoujście (Gucma, 2008).

## Conclusions

The simulation method for determining conditions of safe operation of ferries was developed to verify shipowners' designs. At a shipowner's design stage, the method allows one to calculate the allowable safe operating conditions for the ferry in a specific ferry terminal. It also enables the modification of ferry parameters aimed at assuring the safety of operation in conditions expected by the shipowner.

Simulation experiments in this method are performed on full mission bridge simulators in two stages:

1. Determination of maximum wind speeds – expert tests carried out on a shiphandling simulator following a specific procedure of experiment planning and analysis of the results.
2. Simulation tests of entry/berthing and unberthing/departure manoeuvres to/from the terminal at allowable wind speeds, established at stage one. The tests are aimed at determining the safe manoeuvring areas, maximum energy of hull impact against the berth and acceptable propeller stream speeds at the bottom.

The simulation method for determining the safe operating conditions of sea ferries was used in designing a hybrid ferry (diesel/LNG fuel), with a length of 228 m, intended to operate between Świnoujście (berth No. 1) and the port of Ystad. The shipowner's design was prepared for the Polish Baltic Shipping Company (Gucma S. et al., 2017).

## Acknowledgments

This research outcome has been achieved under the grant No. 1/S/CIRM/2016 financed from a subsidy of the Ministry of Science and Higher Education for statutory activities.

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