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SHIPS SPEED LIMITATIONS FOR RELIABLE MAINTENANCE OF THE QUAY WALLS OF NAVIGATION CHANNELS IN PORTS

OGRANICZENIA PRĘDKOŚCI STATKÓW DO NIEZAWODNEGO UTRZYMANIA ŚCIAN NABRZEŻY ZLOKALIZOWANYCH PRZY KANAŁACH NAWIGACYJNYCH W PORTACH

There is a number of ports where approach or inside navigation channels are located close to the quay walls. In difficult hydrometeorological conditions appropriate speed of ship is needed to keep proper ship's steering while passing through channel. The ships that pass near the quay walls with high speed create high interaction forces on moored ships and negatively interact on their mooring equipment and quay walls. Ports should ensure relevant maintenance and reliability of quay walls and ships' mooring equipment. That is why investigation of the ships interaction forces during ship passing near the ships moored to quay walls is very important to find limitations of the passing ship speed depending on passing ship's parameters, distances and environmental conditions to provide reliable maintenance of navigation channel. In the article the conditions of dynamic forces caused by passing ships are investigated, including possible external forces influencing on moored ships, mooring equipment and quay walls. The methodology to assess the forces exerted on ship moored to quay wall by ship passing close to them is created. On the basis of the case study analysis results, the recommendations for the limitations to ships passing near the ships moored to quay walls were proposed that will allow providing relevant maintenance and reliability of navigation channel and its infrastructure.

Keywords: *dynamic forces, navigation safety in ports, quay walls maintenance and reliability, port infrastructure, ship mooring, quay walls mooring equipment.*

Istnieje wiele portów, w których tory podejściowe lub wewnętrzne kanały nawigacyjne znajdują się obok ścian nabrzeży. W trudnych warunkach hydrometeorologicznych należy utrzymywać odpowiednią prędkość statku, aby zapewnić jego prawidłowe sterowanie podczas przemieszczania się przez kanał. Statki, które przepływają z dużą prędkością w pobliżu ścian nabrzeży, wywierają duże siły na zacumowane jednostki i negatywnie oddziałują na urządzenia cumownicze statków i ściany nabrzeży. Porty powinny zapewniać należyte utrzymanie oraz niezawodność ścian nabrzeży i urządzeń cumowniczych statków cumowanych przy nabrzeżach. W związku z tym ważne jest zbadanie sił interakcji podczas przemieszczania się statku w pobliżu jednostek przycumowanych przy nabrzeżu, aby znaleźć ograniczenia prędkości przepływającego statku w zależności od jego parametrów, odległości i warunków środowiskowych, co pozwoli zapewnić niezawodną eksploatację kanału nawigacyjnego. W artykule zbadane są uwarunkowania sił dynamicznych wywieranych przez przepływające statki, w tym możliwe siły zewnętrzne, które wpływają na zacumowane jednostki, urządzenia cumownicze i ściany nabrzeży. Opracowano metodologię oszacowania sił wywieranych na statek przycumowany przy nabrzeżu przez przepływającą obok jednostkę. Na podstawie wyników analizy studium przypadku zaproponowano zalecenia dotyczące ograniczeń w odniesieniu do statków przepływających w pobliżu statków przycumowanych przy nabrzeżu, które pozwolą zapewnić należytą eksploatację i niezawodność kanału nawigacyjnego i jego infrastruktury.

Słowa kluczowe: *siły dynamiczne, bezpieczeństwo żeglugi w portach, eksploatacja i niezawodność ścian nabrzeży, infrastruktura portowa, cumowanie statku, urządzenia cumownicze ścian nabrzeży.*

1. Introduction

There are many ports in the world where approach and inside navigation channels (fairways) are located very close to quay walls where small and large ships may be moored [1]. Hydrodynamic interaction between the passing ships and ships moored to quay wall influence the moored ships, together with additional external forces that are caused by wind, waves, shallow water effect, inertia forces, created by movements of the moored ship and currents [2, 3, 5, 18, 39]. That is why it is important to provide relevant maintenance and reliability of the quay walls of navigation channel and to conduct calculations of generated external forces influence on quay wall and its equipment (quay wall bollards and fenders), as well as on moored ships mooring equipment (winches, bollards, mooring ropes, etc.) [4, 16].

Ships passing with high speed near the vessels moored to quay walls create high hydrodynamic interaction forces between ships and have negative influence on moored ships mooring equipment and quay walls [26, 41, 43]. Examination of the ship's interaction forces during ship passing near moored vessels is necessary in order to find limitation of the passing ship's speed that may depend on the passing ship's parameters, distances, hydro-meteorological and hydrological conditions [30, 36, 43]. In ports located at the mouth of the rivers or close to the seashore (Fig. 1), such as Southampton (UK), Livorno (Italy), Klaipeda (Lithuania) and others, the precaution measures must be taken to minimize the possible negative influence of the passing ships on moored ships and quay walls to avoid their damages [1, 28, 37, 40, 42].

In some ports passing ships speed limitations are introduced. Such restrictions depend mainly on ships size. It should be mentioned that this limitation approach is rather risky, because ships with different size create different hydrodynamic interaction forces on moored ships and do not always provide relevant maintenance of navigation channel infrastructure. The main solution used in ports to decrease the risk of the moored vessels and quay walls damages - is to reduce the passing ships speed. However, at the same time very low speed of these ships decreases their manoeuvrability, reliability of vessels and quay walls and finally increases the risk of the passing ships navigation and probability of collision with moored vessels or quay wall [3, 4, 8, 11].

a)
b)
c)

Fig. 1. The examples of ports' where ships are mooring very close to navigation channel, where special attention should be given to relevant maintenance and reliability of the ships and quay walls [1]: a) Southampton port (UK), b) Livorno port (Italy), c) Klaipeda port (Lithuania)

For example, in Klaipeda port the regulations were set for Ro-Ro vessels, and other ships, stating that during passing near the ships that are moored to quay wall they had to decrease the speed up to 6 knots. Such low speed in worse weather conditions (strong wind, current and high waves) was not enough to steer the ship safely. Moreover, there were incidents when Ro-Ro vessels rubbed against tankers moored to the oil terminal jetties. After the occurrence of a few accidents the decision was taken to increase permitted speed of passing ships in port up to 8 knots. The implementation of decision created new problems, because this speed did not take into account moored and passing ships parameters, as well as environmental conditions, such as wind velocity and its direction, currents speed, wave's parameters, shallow water influence etc. [3, 17, 26, 41, 42].

The conducted analysis of available literature sources revealed that there are a lot of studies and research articles describing ships interaction in open and restricted waters. There is a number of research works and articles showing the ways to assess the critical areas for a ship facing collision encounter, risk assessment approaches based on ships safety patterns, especially during LNG and other terminals studies and design. However, most of those sources are concentrated mainly on anti-collision tasks and do not take into account ship to ship complex influences occurring, for example, in narrow and shallow channels and acting on moored ships hydro-meteorological and hydrological conditions. Moreover, available calculation and evaluation methods is usually hard to apply for solving practical tasks, such as evaluation of influences of passing ships on the vessels moored to quay walls close to navigation channels and guaranty reliability of the moored ships and quay walls. The main findings of available literature analysis can be formulated as follows:

- there is a lack of complexity in available approaches used to analyse interaction between passing ships on vessels moored to quay walls close to narrow channels, because inertia forces created by moored ship movement alongside quay wall are not taken into account,
- there is a lack of clear and complex methods allowing to calculate the forces or energies distribution between fenders and mooring ropes of the moored ship and quay wall, as well as mooring ropes pretension forces.

The identified gap motivated the authors to undertake the research on moored ships and quay wall safety and reliability in situation when the forces created by ships passing very close to moored ones occur together with other external forces like wind, waves, current, shallow water effect. It also justifies the need to develop the complex calculation method that could be used in practice to assess the influence of passing ships on moored ones and quay walls.

The article aims to investigate the ship to ship interaction in mentioned conditions, develop methodology to assess the forces exerted on ship moored to quay wall by ship passing close to them and find the solution to minimize the risk of damage to ships moored to quay walls when other ships are passing close to them. Moreover, it aims to find optimal passing ship speed considering different environmental conditions (e.g. hydro-meteorological and hydrological) that will allow increasing the reliability of navigation channel operation.

2. State of the art analysis

The situation when ships are moored to the quay wall very close to the narrow navigation channel is observed in different ports [1, 2, 3, 42, 43]. Such situations may take place when port is located at the mouth of the river and has narrow fairway, as well as when it is situated near the seashore, but has limited infrastructure. Port location and layout may influence the volume of investments needed to widen channels. Such investments could be very expensive, time consuming or even not feasible due to the ground and other conditions [12]. In such cases the ships movement should be planned and organized in a safe and efficient way using existing infrastructure.

Based on observations made it could be stated that ships may be moored to one or both sides of the navigation channel. For example, in Livorno port in Italy (Fig. 2) ships are moored to both sides of the channel and large vessels are passing very close to the moored ones, sometimes even on the distance less than width of the passing ship [1].

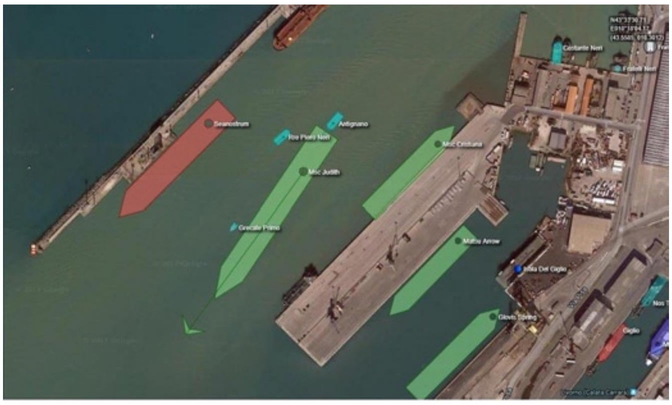

Fig. 2. *Livorno port with ships moored to both sides of navigation channel [1]*

In some ports the passing ship should make manoeuvres, e.g. turn to large angle (Fig. 3), due to infrastructure limitations, and pass very close to the moored ships. It is possible to perform such operation just with tugs assistance. At the same time, it happens that passing ships cannot decrease speed, because external forces caused by wind, current and waves, as well additional shallow water influence the decrease of the passing ship manoeuvrability [3, 18, 22, 29, 36, 42]. In these cases the probability that passing ship will move out of navigation channel increases and internal possibilities, like thrusters, or external assistance, like tugs, sometime are not able to keep passing large ships in channels and provide relevant reliability level.

In some ports the specific terminals, like container terminal in Bremerhaven port, are located very close to the navigation channel through which MEGA container vessels (with length about 400 m) pass very close to the other moored ships during their mooring and unmooring operations (Fig. 4). Very high hydrodynamic interaction forces created by passing MEGA container vessels have negative influence on moored ships and quay walls mooring equipment [1, 2, 5, 28]. Sometimes large passing ships create very high propeller screw flow that has negative impact on moored ships as well [7, 38, 42].

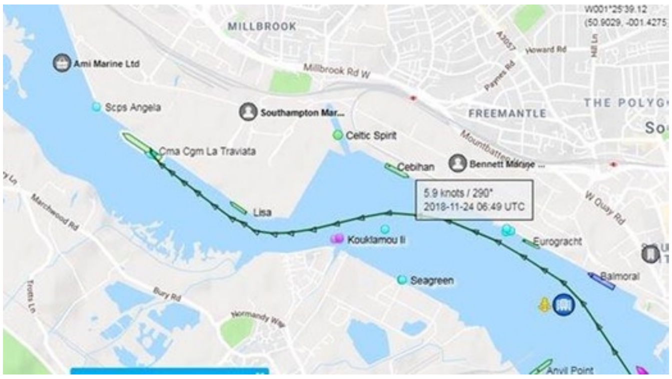

Fig. 3. *Container vessel "CMA CGM La Traviata" (L= 334 m, B = 43 m, T = 13 m) passing through narrow channel close to the moored ships in Southampton port (UK) [1]*

The analysis of the available literature revealed that currently a lot of attention is paid to the aspects of traffic and navigation safety. Researches investigate i.a. interaction between the elements of transport systems [29], the impact of traffic conditions on transport safety [23], ship manoeuvring [33], navigation safety [9, 24, 42], as well as interactions between ships [34, 36] in navigation channels etc. Ships accidents are analysed in order to find the ways to prevent their occurrence [8, 13, 15, 21, 22]. These accidents are generally collision situations that may take place in different sailing areas. However, mentioned research works do not take into account ships mooring to

Fig. 4. *Container vessel "Maribo Maersk" (L = 399,2 m, B = 59 m, T = 13,8 m) in Bremerhaven port (Germany) [1]*

quay walls and quay walls reliability in case of different forces are acting simultaneously.

In order to prevent extraordinary situations appearance risk assessment methods are proposed [10, 11, 30, 32, 37, 38]. These methods aim to use mathematical models to evaluate risk level and possible losses of its influence. Separate literature positions analyse the risk-based target reliability indices for quay walls [19, 20, 31] that deals with their maintenance in ports and influence the quays design models [12, 16]. It should be mentioned that risk of quay walls damage influenced by different forces on quay walls and moored ships was not presented sufficiently.

Moreover, ship to ship interaction problems are considered in the literature. The available positions describe the selected aspects of ships interaction in selected conditions. Kadri and Weihs [14] modelled hydrodynamic interactions between two slender bodies of revolution moving in close proximity, in an unbounded, inviscid, and incompressible fluid. Von Graefe et al. [35] introduced the nonlinear steady flow method that accounts for the nonlinear free-surface conditions, ship wave, and dynamic trim and sinkage. Hydrodynamic interactions between two ships advancing in waves were also considered by Chen and Fang [5].

Yuan et al. [41] analysed interaction between two ships with side-by-side arrangement by using 3-D Rankine source panel code, investigating the influence of the distance between the vessels. Yuan et al. [39, 40] also investigated hydrodynamic interaction between two ships travelling or being stationary in shallow water. Bhautoo et al. [3] considered Port of Brisbane conditions to assess moored vessel interaction induced by passing ships. The developed model included a 2D numerical hydrodynamic and wave model, validated against recorded tidal elevations and wave conditions. Weiss et al. [36] validated the criteria for dimensioning pretension suitable for mooring lines of Post-Panamax class ships docked at a port channel. Hydrodynamic interaction phenomena investigations during the ship overtaking manoeuvre for marine related simulators with the use of CFD methods was analysed by Nikushchenko and Zubova [27], as well as Wnęk et al. [37].

There are several positions that consider ship and bank interaction [6, 26]. Time-domain numerical method based on a three-dimensional potential flow solver was developed by Nam and Park [25] to investigate the passing ship problem with a moored barge alongside quay. Potential flows around the passing ship and the moored barge alongside a quay was solved by using a classical finite element method. Lataire and Vantorre [17] described hydrodynamic interaction between ships in restricted Waterways. In turn, Lee et al. [18] investigated hydrodynamic interaction forces between two large vessels, moving each other in curved narrow channel, this topic was also analyzed by Zalewski and Montewka [42].

Comparing the research undertaken in the presented article to similar research works it should be highlighted that reviewed research articles and other available sources do not contain the complex view on interactions between ships sailing through the navigation channels and moored ships. These positions also do not take into account created movement of moored ships and insufficient pretension of the mooring ropes result in inertia forces of the moored ship. These forces influence is analysed separately. Moreover, forces or energies distribution between fenders of the quay wall and mooring ropes of the moored ship, mooring ropes pretension forces evaluation to avoid or minimize moored ship movement near the quay wall were not explained sufficiently.

The examples presented above, as well as results of conducted literature analysis, confirm the need to develop heuristic methodology that will allow analysing and calculating hydrodynamic interaction of the passing ships influence on ships moored to the quay walls and determine the speed limitations of ships moving along the navigation channel.

3. Hydrodynamic interaction between passing and moored ships together with theoretical basis of possible external forces

3.1. Research methodology

In order to develop methodology, first of all, the available literature analysis was conducted that allowed to review the state of the art in the area of ships maintenance, reliability, hydrodynamics and models used to assess the interactions between the ships etc. Necessary data was collected based on literature sources and observations of ships movement in port area and experimental data received from ports (Fig. 5).

It was stated that methodology used in the research should take into account ships particular geometrical and sailing parameters, hydro-meteorological and hydrological conditions in a certain place. Main ships parameters have to be considered, such as: passing ship's displacement, displacement of ship moored to quay wall, width of a passing ship, draft of passing ship, moored ship air projection on diametric square, moored ship air projection on middle square, area of the moored ship's hull in water, moored ship length between perpendiculars, moored ship average draft, moored ship block coefficient, moored ship width, moored ship's speed near the quay wall (in case if ship moves near the quay wall), mass of the ship moored to quay wall, mooring scheme of the moored ship.

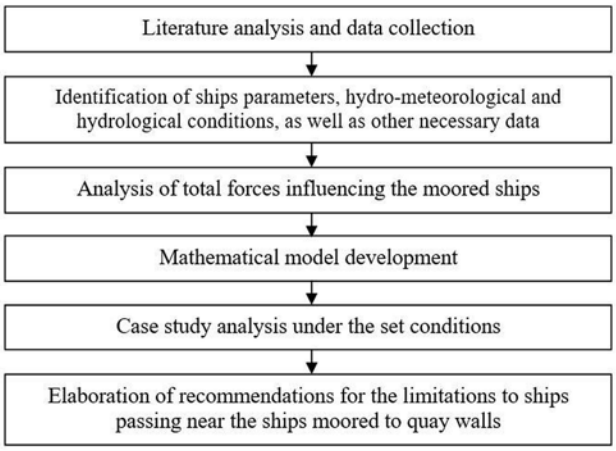

Fig. 5. The algorithm of the research methodology

Hydro-meteorological and hydrological conditions that have to be taken into account in the proposed method are: wind velocity, wind course angle (the angle to a quay wall), current velocity, current course angle to moored ship, waves course angle on moored ship, waves high, speed of movement of water particles in the waves.

Moreover, additional data, such as: navigation channel width (evaluated distance between passing and moored ships), channel depth and depth near the quay wall, necessary for conducting the research should be collected and analysed. Furthermore, the relevant coefficients, received by theoretical and experimental investigations, should be considered.

In order to assess the total forces exerted on ship moored to quay wall by vessels passing close to them and additional external forces acting on moored ship the appropriate separate forces were identified and analysed. Those forces include: dynamic interaction force between passing and moored ships, current created force on moored ship, aerodynamic forces created on moored ship, forces on moored ship created by waves, shallow water influence on moored ship.

Then, the mathematical model was developed to calculate the forces acting on moored ship in case other ship passing near this vessel, as well as wind, current, waves, shallow water and additional inertia forces. This model takes into consideration implementation of following steps:

- collection and analysis of data mentioned above,
- planning possible distances between passing and moored ship,
- calculation of hydrodynamic interaction between ships based on collected needed data, distances between passing and moored ships and passing ship's speed,
- calculation of particular external forces acting on moored ship,
- calculation and analysis of total forces acting on moored ship,
- evaluation of forces or energies distribution between fenders and mooring ropes based on ship's mooring scheme,
- calculations of mooring ropes pretension of the moored ship,
- drawing the conclusions and recommendations for the specific conditions.

Boundary conditions of methodology and model are as follows: minimum distance between moored and passing ships should be not less than 0,25 B_1 in case passing ship's speed is more than 4 knots; maximum distance between passing and moored ships should be less than 3 B_1, current speed - not more than 4 knots from any direction, wind velocity cannot be more than 18 m/s, waves high cannot be more than 1,5 m. In case of distance between moored and passing ships is more than 3 B_1, boundary conditions based on possible real conditions in port areas or interaction influence on moored ship do not have to be taken into account because, for example, the hydrodynamic interaction on the moored ship is very low.

The proposed methodology was verified on the basis of case study analysis. The ship movement in Klaipeda port was analysed in detail and calculations based on real data were carried out. On the basis of the archived results recommendations for limitations to ships passing near the vessels moored to quay walls were proposed.

3.2. Mathematical model

The limitations of ships passing near the quay walls should be based on the balance between hydrodynamic interaction between ships and their manoeuvrability in case of external forces occurrence, like wind, currents, waves and shallow water effect. Very often in narrow navigation channels the quay walls influence the possible ships speed, because hydrodynamic interaction take place [17, 23, 31]. In case when current, wind, waves and hydrodynamic interaction forces are acting in one direction, it is very difficult to compensate all this external forces by ship's and quay wall mooring facilities. In general, moored ship mooring lines (ropes) pretension must be equal or bigger then the created external forces on longitudinal and transverse forces.

Total forces that can act on ships and quay wall mooring equipment (bollards and fenders) in the longitudinal direction by passing ship together with other external forces could be calculated as follows:

$$F = F_{inter} + F_c \cdot \cos q_c + F_a \cdot \cos q_a + F_w \cos q_w + F_s \, , \qquad (1)$$

where: F - total forces that can act on ships and quay wall mooring equipment; F_i – particular forces: F_{inter} - dynamic interaction force between passing and moored ships; F_c - current created force on moored ship; q_c - current course angle to moored ship; F_a - aerodynamic forces created on moored ship; q_a - wind course angle on moored ship; F_w - forces on moored ship created by waves; q_w - waves course angle on moored ship; F_s - shallow water influence on moored ship.

Hydrodynamic interactions between ships are based on pressure distribution around the sailing ship [16]. Revising the case of impact of ship passing near a vessel moored to a quay wall reveals that the passing ship moves and turns the moored ship (Fig. 6) [11, 16].

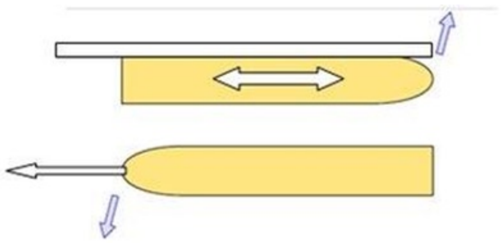

Fig. 6. The influence of passing ship on a moored vessel, where: purple arrow – forces that turn the ship, white arrow – ship's moving direction

The hydrodynamic interaction force (F_{inter}) that acts on moored ship depends on ship's dimensions and speed, distance between the ships and the depths of the channel. Basing on theoretical and experimental investigations, it could be estimated as follows:

$$F_{inter} = k_1 \cdot D_1 (1 + \frac{D_1}{D_2}) \cdot v_1^2 \cdot \frac{k_2 B_1}{S^2} (1 - \frac{H - T_1}{H}) \, , \qquad (2)$$

where: k_1 - coefficient, for calculations could be taken from 0,10 up to 0.20 depending on the ship's block coefficient, expressed in Fig. 7, based on theoretical and experimental studies [2]; D_1 - passing ship's displacement; D_2 - displacement of ship moored to quay wall; v_1 - passing ship's speed; k_2 - coefficient depending on passing ship's speed, based on theoretical and experimental investigations [2] expressed in Fig. 8; B_1 - width of a passing ship; T_1 - draft of passing ship; S - distance between the ship moored to a quay wall and the passing ship; H - channel depth.

Wind and current acting on a ship moored to a quay wall can be calculated using the established ship theory methods [7, 16, 17]. Aerodynamic (wind) force (F_a) could be calculated as follows:

$$F_a = C_a \cdot \frac{\rho_1}{2} \cdot (S_{2x} \cdot \sin q_a + S_{2y} \cdot \cos q_a) \cdot v_a^2 \, , \qquad (3)$$

where: C_a - aerodynamic coefficient, which in average is about 1,07 (specific data could be taken from aerodynamic tube testing); ρ_1 - air density, for the calculations could be taken as 1,25 kg/m³; S_{2x} - moored ship air projection on diametric square; S_{2y} - moored ship air projection on middle square; v_a - wind velocity; q_a - wind course angle (the angle to a quay wall).

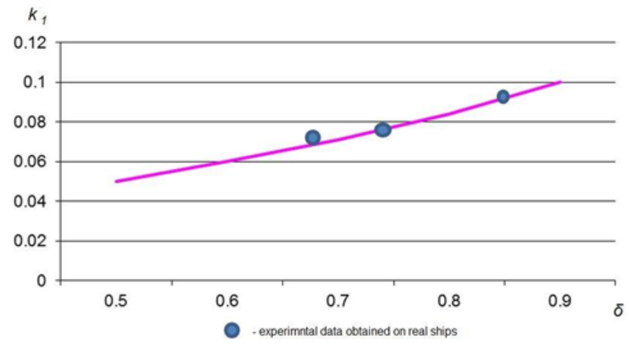

Fig. 7. Dependence of coefficient k_1 on the ship's block coefficient

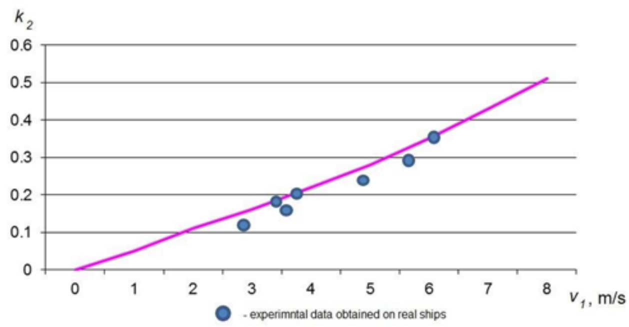

Fig. 8. Dependence of coefficient k_2 on the passing ship's speed

In turn, force caused by current (F_c) could be calculated as follows [2]:

$$F_c = C_y^{'} \cdot \frac{\rho}{2} \cdot \Omega \cdot v_c^2 \, , \qquad (4)$$

where: $C_y^{'}$ - hydrodynamic coefficient of the ship and in case low current velocity it could be taken in average as 0,15; ρ - water density; v_c - current velocity; Ω - area of the ship's hull in water, can be calculate as follows [22]:

$$\Omega = 1{,}05 L_2 (1{,}7 T_2 + \delta_2 B_2) \, , \qquad (5)$$

where: L_2 - moored ship length between perpendiculars; T_2 - moored ship average draft; δ_2 - moored ship block coefficient; B_2 - moored ship width.

Forces on moored ship created by waves (F_w) could be calculated as it is presented below:

$$F_w = C_w \frac{\rho}{2} L_2 \cdot h_w \cdot v_w^2 \, , \qquad (6)$$

where: C_w - wave acting on ship's hull coefficient, could be taken as hydrodynamic coefficient of the ship and in case of low current (water) velocity it could be taken in average as 0,15; h_w - waves high; v_w - speed of movement of water particles in the waves, could be taken as 0,6 v_a .

Shallow water effect on moored ship (F_s) could be calculated as follows:

$$F_s = k'_{R11} \cdot L_2 \cdot B_2 \cdot \frac{T_2}{H_2} \cdot v_2^2 , \tag{7}$$

where: k'_{R11} - shallow water resistance coefficient, depending on the ratio T/H, based on theoretical and experimental studies [2], expressed in Fig. 9; B_2 - moored ship width; T_2 - moored ship average draft; H_2 - depth near the quay wall; v_2 - moored ship's speed near the quay wall (in case if ship moves near the quay wall).

Finally, total forces acting on a ship moored to a quay wall could be calculated as follows:

$$\vec{F} = \vec{F}_{inter} + \vec{F}_a + \vec{F}_c + \vec{F}_w + \vec{F}_s . \tag{8}$$

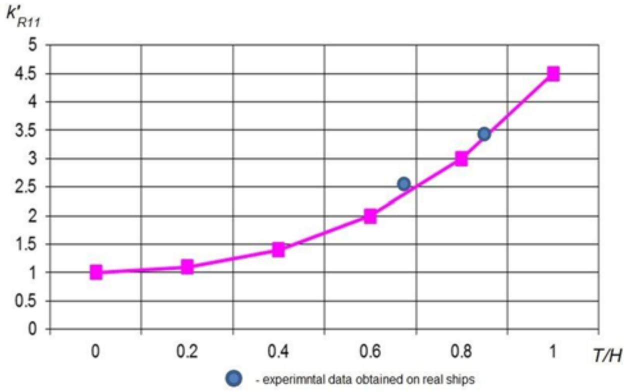

Fig. 9. Dependence of ship's resistence coefficient k'_{R11} on ship's draft and depth T/H

The total force $\vec{F}$ must be absorbed by quay wall fenders and bollards. This force will influence the reliability of the quay walls and moored ships. In case of correct mooring scheme, about 50 % of the total force is absorbed by quay wall fenders and about 50 % should be absorbed by ship's mooring ropes and quay wall bollards [2]. Moored ship will be stable near quay wall just in case if ships mooring ropes pretension will be not less than external forces acting on mooring ropes and quay wall mooring bollards: longitudinal and transverse forces. In case if there is not enough ship mooring rope pretension, the moored ship starts move along the quay wall and creates inertia forces (F_{in}), that sometimes could be higher as any other forces. The inertia forces could be calculated as it is shown below [2]:

$$F_{in} = m'_2 \cdot a , \tag{9}$$

where: m'_2 - the mass of the ship moored to quay wall; a - acceleration that could be calculated as follows:

$$a = \frac{v'_2}{2 \cdot T_P} , \tag{10}$$

where: v'_2 - maximum possible ship movement speed near the quay wall that could be calculated on the basis of ship movement distance near the quay wall and the movement period. The movement distance near the quay wall for the moored to quay wall ship could be taken up to 25 – 30 % of the shortest mooring rope depending on pretension. Ship movement period (T_P) near a quay wall could be equal to $L_1/2 - L_1/3$.

Finally, inertia forces (F_{in}) could be calculated as it is presented below:

$$F_{in} = k_P \cdot l_r \cdot \frac{m'_2}{2 \cdot T_P^2} , \tag{11}$$

where: k_P - mooring rope pretension coefficient, based on theoretical and experimental studies [2] (Fig. 10), its values could change between 0,0001 and 0,25 (0,25 assumes that there is no mooring rope pretension at all).

Mooring ropes pretension in one direction could be calculated as bow direction that is compensated by astern long mooring ropes and bow springs, as astern direction, that is compensated by bow long mooring ropes and astern springs, and could be calculate as follows:

$$T_{pretb} = \sum_{i=1}^{n_{amr}} T_{amr} \cos\frac{\sum_{i=1}^{n_{amr}} \alpha_{amr}}{n_{amr}} \cdot \sin\frac{\sum_{i=1}^{n_{amr}} \beta_{amr}}{n_{amr}} + \sum_{j=1}^{n_{bsr}} T_{bsr} \cos\frac{\sum_{j=1}^{n_{bsr}} \alpha_{bsr}}{n_{bsr}} \cdot \sin\frac{\sum_{j=1}^{n_{bsr}} \beta_{bsr}}{n_{bsr}}, \tag{12}$$

$$T_{preta} = \sum_{y=1}^{n_{bmr}} T_{bmr} \cos\frac{\sum_{y=1}^{n_{bmr}} \alpha_{bmr}}{n_{bmr}} \cdot \sin\frac{\sum_{y=1}^{n_{bmr}} \beta_{bmr}}{n_{bmr}} + \sum_{z=1}^{n_{asr}} T_{asr} \cos\frac{\sum_{z=1}^{n_{asr}} \alpha_{asr}}{n_{asr}} \cdot \sin\frac{\sum_{z=1}^{n_{asr}} \beta_{asr}}{n_{asr}}, \tag{13}$$

where: T_{pretb} - sum of the pretension forces on ship's bow direction; $\sum_{i=1}^{n_{amr}} T_{amr}$ - total pretension astern long mooring ropes force, $i = 1,...,n_{amr}$; $\sum_{i=1}^{n_{amr}} \alpha_{amr}$ - sum of the horizontal aster long mooring ropes angles, n_{amr} - number of astern long mooring ropes; $\sum_{i=1}^{n_{amr}} \beta_{amr}$ - sum of the vertical astern long mooring ropes angles, $j = 1,...n_{bsr}$; $\sum_{j=1}^{n_{bsr}} T_{bsr}$ - sum of the pretension forces of the bow springs; $\sum_{j=1}^{n_{bsr}} \alpha_{bsr}$ - sum of the horizontal bow springs angles, *j=1, …,* n_{bsr} ; $\sum_{j=1}^{n_{bsr}} \beta_{bsr}$ - sum of the vertical bow springs angles, *j=1, …,* n_{bsr} ; n_{bsr} - number of bow springs; T_{preta} - sum of the pretension forces on ship's astern direction; $\sum_{y=1}^{n_{bmr}} T_{bmr}$ - total pretension bow long mooring ropes force, y=1, …, n_{bmr} ; $\sum_{y=1}^{n_{bmr}} \alpha_{bmr}$ - sum of the horizontal bow long mooring ropes angles, y=1, …, n_{bmr} ; $\sum_{y=1}^{n_{bmr}} \beta_{bmr}$ - sum of the vertical bow long mooring ropes angles, y=1, …, n_{bmr} ; n_{bmr} - number of bow long mooring ropes; $\sum_{z=1}^{n_{asr}} T_{asr}$ - sum of the pretension forces of the astern springs, z=1, …, n_{asr} ; $\sum_{z=1}^{n_{asr}} \alpha_{asr}$ - sum of the horizontal astern springs angles, z=1, …, n_{asr} ; $\sum_{z=1}^{n_{asr}} \beta_{asr}$ - sum of the vertical astern springs angles, z=1, …, n_{asr} ; n_{asr} - number of astern springs.

The theoretical basis presented above could be used for the calculation of the real forces, acting on ship moored to a quay wall close to the navigation channel crossed by other vessels, as well as for design

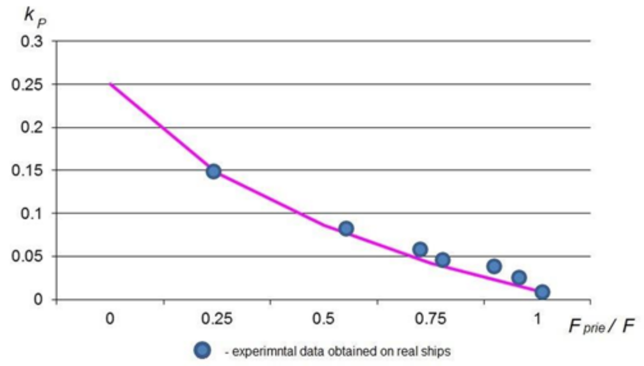

Fig. 10. Dependence of mooring rope pretension coefficient k_P on the mooring rope pretension and total external forces acting on moored ship F_{prie}/F

of the quay walls and its elements, such as fenders, mooring bollards and others [9, 30].

While conducting calculations it is important to take into consideration the fact that ship mooring ropes pretension depends on the ship parameters and they should be equal to periodical forces, which are created by periodical influence, such as wind, waves, or hydrodynamic interaction of passing ships. In case pretension forces of the mooring ropes are equal to the periodic forces, the increase of the length of mooring ropes could be minimized and inertia forces will decrease or even could be close to 0.

4. Case study of limitations for the passing ship's speed and distance to vessel moored to the quay wall to ensure quay walls maintenance and reliability

In order to investigate the limitations for passing ship's speed and distance between a passing ship and a vessel moored to a quay wall, taking into account external forces caused by wind, current, waves and shallow water effect, a case study of Klaipeda port was considered. Such conditions are typical for the ships moored to quay wall in oil terminal of this port.

Experimental studies were carried out in Klaipeda port during different types of ships (Handy size, PANAMAX, POST PANAMAX tankers and bulk vessels) sailing close to moored vessels. The laser measurement system "Dockmaster 3" was implemented on oil terminal quay walls No.1 and No. 2 (Fig. 11) to measure mooring ropes tension and ships movement. Accuracy of "Dockmaster 3" system while measuring ship's position was about +/- 2-3 mm, ships movement speed was measured with accuracy +/- 0,1 knot (0,05 m/s), ropes tension was assessed with accuracy +/- 0,2 kN. Additionally, during the experiments video cameras were implemented on a quay wall close to a moored ship, which recorded moored ship movement while other vessels passed through navigation channel (Fig. 12). Passing ships movement parameters and distances between the ship moored to the quay wall and passing vessels were measured by Differential GPS and additionally checked by AIS.

Figure 13 presents the situation when Standard LNG tanker (with the capacity of 150000 m³) is passing near the Klaipeda port oil terminal, where Handysize tanker (with the capacity about 30000 t) is moored to the quay wall. The distance between passing and moored to quay wall vessels is usually about 100 m up to 80 m. In turn, POST PANAMAX (DWT 110000) tanker passing near the Klaipeda port oil terminal, where Handysize tanker is moored to the quay wall, is shown in Fig. 14.

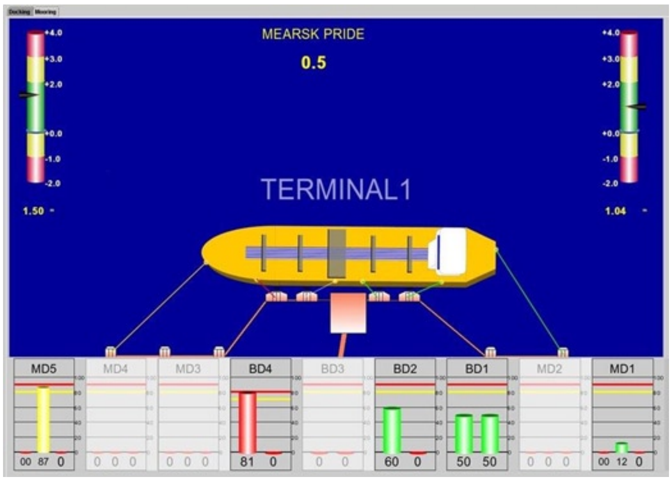

Fig. 11. Laser "Dockmaster 3" measuring system, implemented on quay walls No. 1 and No. 2 in Klaipeda port ring rope pretension and total external forces acting on moored ship F_{prie}/F

Fig. 12. Moored ship movement fixed by video cameras (example)

Fig. 13. Standard LNG tanker passing near the Klaipeda port oil terminal where Handysize tanker is moored to the quay wall

The calculations for the specific case study were conducted under the set assumptions. Moored ship's parameters (Handysize tanker in ballast) are as follows: length (L_2) - 170 m; width (B_2) - 27 m; draft

Fig. 14. POST PANAMAX (DWT 110000) tanker passing near the Klaipeda port oil terminal where Handysize tanker is moored to the quay wall

Fig. 15. Dependance of total forces (F) acting on moored vessel and forces acting on mooring ropes on speed (v_1) under the set conditions

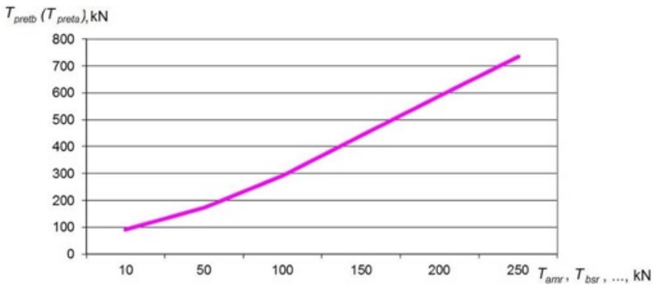

Fig. 16. Dependance of total mooring rope pretension forces in one direction (bow or astern) on each mooring rope pretention

(T_2) - 7,0 m; water displacement of the moored vessel (D_2) - 20800 t, moored ship air projection on diametric square (S_{2x}) - 2600 m²; moored ship air projection on middle square (S_{2y}) - 400 m². For ship's mooring the ropes scheme 3 + 2 + 2 is used, that means there are 3 long mooring ropes on bow and astern, 2 breast mooring ropes and 2 springs. Total bow and astern long mooring ropes horizontal angle ($\sum_{i=1}^{n_{amr}} \alpha_{amr}; \sum_{j=1}^{n_{bsr}} \alpha_{bsr}$) is 15° each, total vertical angle or the bow and astern long mooring ropes angle ($\sum_{i=1}^{n_{amr}} \beta_{amr}; \sum_{y=1}^{n_{bmr}} \beta_{bmr}$) - 80° each, bow and astern springs horizontal angle ($\sum_{j=1}^{n_{bsr}} \alpha_{bsr}; \sum_{z=1}^{n_{asr}} \alpha_{asr}$) - 20° each, vertical angle ($\sum_{j=1}^{n_{bsr}} \beta_{bsr}; \sum_{z=1}^{n_{asr}} \beta_{asr}$) - 70° each. The depths near the quay wall (H_2) is 14 m. Moreover, the external factors influence was also assumed: wind blows 30° to quay wall; wind velocity is 12 m/s; current along quay wall is 0,5 m/s; waves influence - 30° to quay wall, waves height is 1 m.

Passing through the navigation channel Standard LNG tanker has the distance (S) 100 m to moored Handysize tanker. LNG tanker length is 290 m, width (B_1) - 49 m, draft (T_1) – 12 m; displacement (D_1) - 125000 t, block coefficient (δ) - 0,75, ship's speed (v_1) is from 6 up to 8 knots (from 3,1 up to 4,1 m/s), depth in area (H) - 14,5 m.

Total forces acting on moored ship should be divided into forces, that are taken by mooring ropes and resistance forces created between moored ship's hull and fenders. In case of goods pretension mooring ropes, about 50 % of forces are taken by mooring ropes and about 50 % of forces belong to resistance between ship hull and fenders. Considering the mentioned conditions, the total forces (F) that have arisen by influence of wind, waves, current, passing LNG Standard tanker on the distance of 100 m to a moored ship depending on its speed are presented in Fig. 15. Total mooring ropes pretension forces in one direction, depending on pretension of every mooring rope, is presented in Fig. 16.

On the basis of the conducted calculations it was possible to compare and analyse the achieved results. In case LNG Standard tanker is passing with the speed range from 6 knots up to 8 knots (from 3,1 m/s up to 4,1 m/s) on the distance of 100 m from Handysize tanker moored to quay wall, as it was explained in the case study, LNG tanker interaction forces together with external ones (wind, waves, current and shallow water effect) that act on moored tanker mooring ropes, are in the range of 430 kN up to 720 kN. In order to prevent the movement of moored Handysize tanker along the quay wall, moored tanker mooring ropes should be pretensioned from 150 up to 250 kN each to provide relevant maintenence and reliability of the moored ships and quay walls.

5. Conclusion

The organization of safe navigation in the port area should be one of the port's priority tasks. Therefore, complex methods should be applied to assess totality of forces affecting the ships moored to the quay walls of navigation channels while other ships are passing near these vessels. Mooring ropes pretension of the ships moored to quay wall close to navigation channels have to be considered and calculated in order to assure safe maintenance of quay walls and ships. Limitations for ships passing near the quay walls should be established for the particular conditions that may occur in port. Considering these aspects, the relevant methodology and mathematical model were elaborated and the case study was analysed.

It should be highlighted that implementation of methodology presented in this article allows to ensure relevant maintenance of quay walls and ships moored to quay walls in navigation channels in ports. Proposed methodology could be applied to different ports, where wind, current, waves and shallow water effects may take place. The received findings may be interesting and useful for seaports with navigation channels and may allow them to calculate i.a. passing ships speed depending on the distance between ships, conduct moored ships mooring ropes pretension evaluations and other calculations. The research bridges the gap in the area of reliability of the navigation channels operation in ports where ships are moored close to quay walls.

Preliminary calculations carried out using the developed methodology may form the basis for the decision-making about the speed of ships movement in navigation channels where the vessels are moored near the quay walls. Proper preparation of ships mooring to quay walls and ships passing near moored ships can ensure moored vessels and quay walls safety and reliability. Comparing the calculations results under certain conditions with real forces acting on moored ship, good correlation of achieved values may be noted. That shows the possibility to use presented methodology for solving the practical tasks.

Presented methodology has also its drawbacks; it does not take into consideration the wide range of the coefficients used to calculate the forces acting on moored ships. This problem, as well as problem of measuring the individual component forces will be considered in our further research.

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References

1. AIS. Ships automatic identification system, 2019, www.marinetraffic/ais.
2. Barzdziukas R. el at. Shipping engineering (in Lithuanian). Klaipeda University publish house, 2019: 544 p.
3. Bhautoo P, Mortensen S, Hibberd W, Harkin A, Kirkegaard J, Morley B. Moored vessel interaction induced by passing ships at the Port of Brisbane. Australasian Coasts & Ports Conference 2015, 15-18 September 2015, Auckland, New Zealand, pp. 1-9.
4. Biehl F, Lehmann E. Collisions of ships with offshore wind turbines: Calculation and risk evaluation. In: Köller J., Köppel J., Peters W. (eds.) Offshore Wind Energy. Berlin: Springer, 2006: 281-304, https://doi.org/10.1007/978-3-540-34677-7_17.
5. Chen G-R, Fang M-C. Hydrodynamic interactions between two ships advancing in waves. Ocean Engineering 2001; 28(8): 1053-1078, https://doi.org/10.1016/S0029-8018(00)00042-1.
6. Chun-Ki L, Sam-Goo L. Investigation of ship manoeuvring with hydrodynamic effects between ship and bank. Journal of Mechanical Science and Technology 2008; 22(6): 1230-1236, https://doi.org/10.1007/s12206-008-0309-9.
7. EAU 2012. Recommendations of the Committee for Waterfront Structures - Harbours and Waterways. Ernst & Sohn 2012; 620 p.
8. Erol S, Başar E. The analysis of ship accident occurred in Turkish search and rescue area by using decision tree. Maritime policy and management 2015; 42(4): 377-388, https://doi.org/10.1080/03088839.2013.870357.
9. E-Sea Fix navigation system. Denmark: Marimatech, 2012; 120 p.
10. Gill A. Optimization of the technical object maintenance system taking account of risk analysis results. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2017; 19 (3): 420-431, https://doi.org/10.17531/ein.2017.3.13.
11. Gucma L, Gucma M, Perkovic M, Vidmar P. Simulation methods for risk assessment in LNG terminal design. In: Rizzuto, Soares, Guedes (eds.). Sustainable Maritime Transportation and Exploitation of Sea Resources. London: Taylor & Francis Group, 2012; 755-761, https://doi.org/10.1201/b11810-113.
12. Gucma S, Gucma M: Optimization of LNG terminal parameters for a wide range of gas tanker sizes: the case of the port of Świnoujście. Archives of Transport 2019; 50(2): 91-100, https://doi.org/10.5604/01.3001.0013.5696.
13. Huang, Y., Chen, L., Chen, P., Negenborn, R.R., van Gelder, P.H.A.J.M. Ship collision avoidance methods: State-of-the-art. Safety Science 2020; 121: 451-473, https://doi.org/10.1016/j.ssci.2019.09.018.
14. Kadri U, Weihs D. Higher order hydrodynamic interaction between two slender bodies in potential flow. Journal of Marine Science and Technology 2015; 20: 249-256, https://doi.org/10.1007/s00773-014-0275-0.
15. Krata P, Montewka J. Assessment of a critical area for a give-way ship in a collision encounter. Archives of Transport 2015; 34(2): 51-60, https://doi.org/10.5604/08669546.1169212.
16. Kuancheng H, Suprayogi, Ariantini. A continuous berth template design model with multiple wharfs. Maritime policy and management 2016; 43(6): 763-775, https://doi.org/10.1080/03088839.2016.1169449.
17. Lataire E, Vantorre M. Hydrodynamic interaction between ships and restricted Waterways. International journal of maritime engineering 2017; 151, https://doi.org/10.3940/rina.ijme.2017.a1.391.
18. Lee C.-K., Moon S.-B., Jeong T.-G. The investigation of ship manoeuvring with hydrodynamic effects between ships in curved narrow channel. International Journal of Naval Architecture and Ocean Engineering 2016; 8: 102-109, https://doi.org/10.1016/j.ijnaoe.2016.01.002.
19. Lendering KT, Jonkman SN, Peters DJ. Risk approach to land reclamation: Feasibility of a polder terminal. Safety, Reliability and Risk Analysis: Beyond the Horizon - Proceedings of the European Safety and Reliability Conference, Amsterdam, The Netherlands, ESREL 2013; 2507-2514, https://doi.org/10.1201/b15938-376.
20. Lendering KT, Jonkman SN, Van Gelder PHAJM, Peters DJ. Risk-based optimization of land reclamation. Reliability Engineering and System Safety 2015; 144, 5380: 193-203, https://doi.org/10.1016/j.ress.2015.07.025.
21. Leveson N. A new accident model for engineering safer systems. Safety Science 2004; 42(4): 237-270, https://doi.org/10.1016/S0925-7535(03)00047-X.
22. Lisowski J. Sensitivity of the game control of ship in collision situations. Polish Maritime Research 2015; 22 No. 4(88): 27-34, https://doi.org/10.1515/pomr-2015-0067.
23. Luty W. Simulation-based analysis of the impact of vehicle mass on stopping distance. Eksploatacja i Niezawodność - Maintenance and Reliability 2018; 20 (2): 182-189, https://doi.org/10.17531/ein.2018.2.03.
24. Mironiuk W. Model-based investigations on dynamic ship heels in relation to maritime transport safety, Archives of Transport 2015; 33(1): 69-80, https://doi.org/10.5604/08669546.1160928.
25. Nam B., Park J. Numerical simulation for a passing ship and a moored barge alongside quay. International Journal of Naval Architecture and Ocean Engineering 2018; 10: 566 - 582, https://doi.org/10.1016/j.ijnaoe.2017.10.008.
26. Nazrul Islam Md, Rafiqul Islam M, Sadiqul Baree Md. Passing ship effects on a moored ship: a numerical study. Proceedings of MARTEC The International Conference on Marine Technology, BUET, Dhaka, Bangladesh, 11-12 December 2010: 201-207.
27. Nikushchenko D V, Zubova A A. Hydrodynamic interaction phenomena investigations during the ship overtaking maneuver for marine related simulators with the use of CFD methods. International Conference on Ship Maneuverability and Maritime Simulation (MARSIM 2015), Newcastle University, United Kingdom, 8-11 September 2015, paper 3-4-3: 13.
28. Pallotta G, Vespe M, Bryan K. Vessel pattern knowledge discovery from AIS data: A framework for anomaly detection and route prediction. Entropy 2013; 15(6): 2218-2245, https://doi.org/10.3390/e15062218.

29. Podvezko V, Sivilevičius H. The use of AHP and rank correlation methods for determining the significance of the interaction between the elements of a transport system having a strong influence on traffic safety. Transport 2013; 28(4): 389-403, https://doi.org/10.3846/16484142.2013.866980.
30. Quy N M, Vrijling J K, Gelder P, Groenveld R. Modeling risk and simulation-based optimization of channel depths at Campha coal port. IASTED Asian conference, Beijing, 8-10 October 2007: 192-198.
31. Roubos A A, Steenbergen R D J M, Schweckendiek T, Jonkman S N. Risk-based target reliability indices for quay walls. Structural Safety 2018, 75: 89-109, https://doi.org/10.1016/j.strusafe.2018.06.005.
32. Semenov JN. Risk management in maritime economy. Volume I. Safety management of transport vessels and oceanotechnical facilities (in Polish). Technical University of Szczecin publishing house, Szczecin, 2003.
33. Skjetne R. Ship maneuvering: The past, the present and the future. Sea Technology 2003; 44(3): 33-37, https://doi.org/10.1177/003932070303300104.
34. Tuck E, Newman J. Hydrodynamic interactions between ships. Symposium on Naval Hydrodynamics, 10th, Proceeding, Pap and Discuss, Cambridge, Mass, June 24-28, 1974, 47 p.
35. Von Graefe A, Shigunov V, el Moctar O. Rankine source method for ship-ship interaction problems. Journal of Offshore Mechanics and Arctic Engineering 2015; 137, https://doi.org/10.1115/1.4029316.
36. Weiss J, de Araujo M, Pereira A, Carmignotto M, Candara M. Hydrodynamic interactions between ships in navigation channels. 11th International Marine Design Conference 2012, At University of Strathclyde, Glasgow, 2012: Proceedings 3: 56-74.
37. Wnęk AD, Sutulo S, Guedes Soares C. CFD analysis of ship-to-ship hydrodynamic interaction. Journal of Marine Science and Application 2018; 17(1): 21-37, https://doi.org/10.1007/s11804-018-0010-z.
38. Yang Z, Adolf KY, Wang NJ. A new risk quantification approach in port facility security assessment. Transportation Research. Part A 2014; 59: 72-90, https://doi.org/10.1016/j.tra.2013.10.025.
39. Yuan Z-M, Incecik A, Dai S, Alexander D, Ji C-Y, Zhang X. Hydrodynamic interaction between two ships travelling or stationary in shallow waters. Ocean Engineering 2015; 108: 620-635, https://doi.org/10.1016/j.oceaneng.2015.08.058.
40. Yuan Z-M, Incecik A, He S. Hydrodynamic interaction between two ships arranged side by side in shallow water. Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2014, At San Francisco, California, USA, 2014; 8A:1-9, https://doi.org/10.1115/OMAE2014-23325.
41. Yuan Z-M, Ji C-Y, Incecik A, Zhao W, Day A. Theoretical and numerical estimation of ship-to-ship hydrodynamic interaction effects. Ocean Engineering 2016; 121: 239-253, https://doi.org/10.1016/j.oceaneng.2016.05.032.
42. Zalewski P, Montewka J. Navigation safety assessment in an entrance channel, based on real experiments. Proceedings of the 12th International Congress of the International Maritime Association of the Mediterranean (IMAM 2007), Varna, Bulgaria, 2007: 1113-1120.
43. Zwijnsvoorde T, Vantorre M, Ides S. Container ships moored at the port of Antwerp: modelling response to passing vessels. 34th PIANC World Congress, Panama, 2018: 476-493.

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