Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 14 (2016) 123 – 132

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

# Ship and quay wall mooring system capability evaluation

Vytautas Paulauskas [a,]*

[a]*Klaipeda university. Manto 84, Klaipeda, LT92224, Lithuania*

## Abstract

Ship mooring in adverse conditions is very important for ports and terminals, which work with big ships and ships with big wind surface areas what as a result create high hydrodynamic and aerodynamic forces on a ship and quay wall mooring systems. Traditional ship mooring systems are safe, but quay wall mooring systems sometimes are not capable enough depending on inertia and other acting forces, therefore, new solutions for increasing quay wall mooring system capability should be found.

The article presents the analysis of complicated ship mooring situations and methods, which can assist to calculate loads, acting on quay wall mooring systems in complicated conditions; the mathematical basis of calculations of ship mooring in complicated conditions and practical recommendations. The suggested methods can be used in many ports and terminals for practical application.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

*Keywords:* Ships mooring; complicated mooring conditions; aerodynamic forces; mooring system capability; rope tension

## 1. Introduction

Ship and quay wall mooring systems must guarantee safe ship mooring to a quay wall in any practical situation. The capability of ship mooring systems is defined by the regulations of the Classification Associates and this insures keeping ships near quay walls in most practical cases.

---

* Corresponding author. Tel.: +370-685-60884.
*E-mail address:* donatasp@takas.lt

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.048

Quay wall mooring systems are designed and constructed according to particular national or international standards and regulations, such as BS (2003), EAU (2012), etc. but sometimes quay wall mooring equipment is not strong enough in adverse hydro meteorological and other internal and external factors affecting ship conditions. Limitations of the quay wall mooring equipment should be known in advance to avoid incidents and accidents on ships and quay walls, therefore, adequate ship mooring schemes have to be prepared or other relevant precaution measures taken.

Standards and regulations in many countries do not take into account all possible forces, created by hydro meteorological conditions, especially the periodical inertial forces (PIANC 1984; 2002), (BS 2003), (EAU 2012), hydrodynamic interaction between moored and passing ships in cases when the quay wall location is close to the navigational channels (PIANC 1995), (Paulauskas et al. 2014), as well in the case of wave penetration from the open sea to the port quay wall area (Wijffels et al. 2009).

In this paper the capability of the ship and quay wall mooring equipment and their evaluation methods; practical testing in real ship mooring conditions and testing results by calibration on the basis of real data and simulators are presented and discussed; practical recommendations on internal and external factors, such as wind, current, ships passing close to moored ships are presented and could be used for the ship and quay wall mooring equipment planning and design, the evaluation of the existing quay wall mooring equipment; evaluation of ship mooring schemes and readiness to guarantee safe ship mooring to quay walls in particular hydro meteorological and other adverse conditions to avoid incidents and accidents with the ships moored to quay walls and the quay walls themselves.

Ship mooring to relatively open quay walls in open port areas (Zalewski et al. 2007), especially for the ships with big wind surface areas, and possible ship movement as the result of periodical acting forces must be taken into account (Wijffels et al. 2002). A high board of the ships, such as Ro-Ro, container, bulk in ballast and some other types of ships, have big vertical mooring rope angles and not all mooring ropes can be used effectively, which decreases the mooring system capability (Paulauskas et al. 2008).

Theoretical basis for ship mooring in complicated conditions is necessary for preparation of correct practical solutions and recommendations to insure safety of ship mooring and minimize any risks.

## 2. Analysis of ship mooring systems

Ships usually are moored along quay walls (container, bulk, etc.), or along quay walls and ramps (Ro-Ro ships), when mooring ropes are fastened on quay walls and ramps at big angles (Wijffels et al. 2009), (Paulauskas 2013) (Fig. 1, Fig. 2). Fig. 1 shows a typical ship mooring scheme. The mooring line numbers are clarified in Table 1.

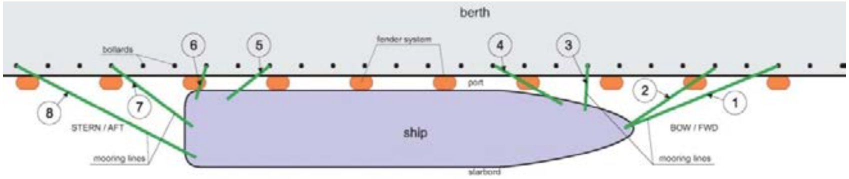

Fig. 1. Typical mooring scheme.

The mooring capacity is defined by:

- Allowable mooring line load
- Capacity of the mooring line winch
- Allowable bollard load.
- Configuration of the mooring line winches and hawseholes (fairleads) on the ship
- Variation of the mooring lines’ lengths

As a consequence of external influences: wind gusts, angled wind impact, inertia, current, wave loads, the ship will surge, sway, heave, pitch, roll and yaw (Wijffels et al. 2002). The restrictions of the mooring lines, bollards and fender system will create the addition to the constant loads: the periodical aerodynamic, hydrodynamic and inertia loads (Catmac et al. 2007; Paulauskas 2004; Wijffels et al. 2009).

Table 1. Mooring ropes number, names and purposes.

| Mooring line (hawse) number: | Mooring line name: | Purpose: |
|---|---|---|
| 1 | Bow (FWD) long line | Prevent backward movement |
| 2 | Bow (FWD) line | Prevent backward movement |
| 3 | Forward Breast line | Keep close to berth |
| 4 | After Bow Spring line | Prevent from advancing |
| 5 | Forward Quarter Spring line | Prevent from moving back |
| 6 | Quarter Breast line | Keep close to berth |
| 7 | Stern (AFT) line | Prevent forward movement |
| 8 | Stern (AFT) long line | Prevent forward movement |

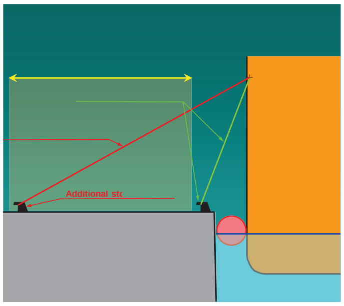

Fig. 2. Big mooring rope angles and possible additional storm bollards on quay wall for increasing quay wall mooring capability.

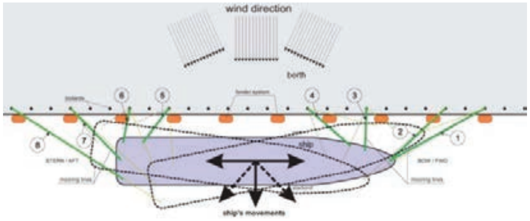

Fig. 3. External loads creating moored ship’s movements (for example aerodynamic loads).

In ports, which have navigational channels close to the quay walls with moored ships, passing ships make big impact on the moored ships and the moored ships make impact on quay walls structures, bollards and fenders. Dynamic forces, created by passing ships, depend on the mass of a passing ship, distances between the moored and passing ships (horizontal clearance) and the speed of passing ships (Paulauskas et al. 2014) make big impact on the quay wall mooring system. In many ports and other similar places where moored ships are close to a navigational channel there are speed limitations for the passing ships, but sometimes the speed of passing should be enough for good ship steering (Paulauskas 1998).

The above mentioned conditions are very important for the port quay walls and safety of ships, moored to the quay walls, and should be studied on the basis of theoretical and experimental methods as well by calibrated simulators (SimFlex, 2012) and included in quay wall design and preparation of ship mooring schemes for taking precaution measures for the safety of the ships passing near quay walls or moored to quay walls.

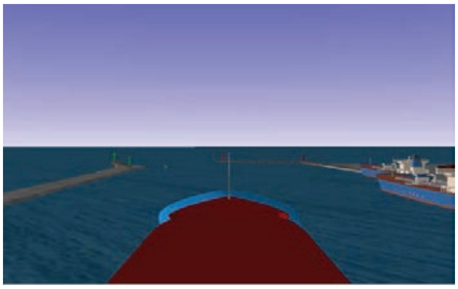

Fig. 4. Ship passing near quay walls with moored ships (visual picture).

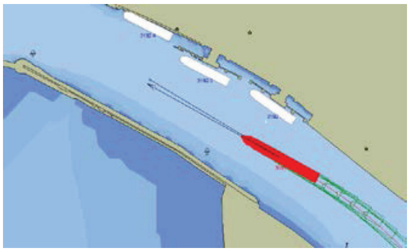

Fig. 5. A passing ship and ships moored to a quay wall on a digital map.

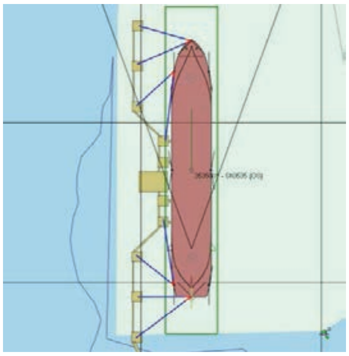

Fig. 6. Forces created by a moored ship affecting quay wall mooring lines and quay wall bollards.

## 3. Theoretical basis of forces created on the moored ships and spreading on the mooring ropes and the quay wall mooring system

In places, which are protected from sea wave penetration and where there are strong currents or wind acting on ships passing close to the moored ships, it is necessary to take the mentioned interaction into account. Wind impact can be divided into two components: constant, which is equal to average wind velocity, e.g. 10 min average wind velocity and periodical (harmonic), which depends on wind gusts, e.g. 3 s or 10 s average wind velocity, which is in average higher up to 30 – 40 % in comparison to the average 10 minute wind velocity.

The constant wind component creates forces, which can be calculated as follows (Wijffels et al. 2009):

$$F_C = C_a \frac{\rho_1}{2}(S_x \cdot \cos q_a + S_y \cdot \sin q_a) v_{aC}^2 \;, \qquad (1)$$

where: $C_a$ - aerodynamic coefficient, for such type of calculations it can be taken equal to 1 or can be taken for a concrete data for a ship, which model was tested in an aerodynamic tube; $\rho_1$ - wind density, for the calculations it can be taken as 1,25 kg/m³; $S_x$ - wind surface area on diametrical plane ; $S_y$ - wind surface area on middle frame plane; $q_a$ - wind course angle; $v_{aC}$ - average wind velocity.

Periodical forces can be calculated via acceleration as follows (Paulauskas 1998):

$$F_P^{''} = \frac{4\pi^2 t}{\tau^2} a \cdot \sin\frac{2\pi t}{\tau} \quad , \tag{2}$$

Finally periodical force can be expressed as follows:

$$F_P = F_P^{''} \cdot m, \tag{3}$$

Where: m – ship mass; $\tau$ - period of wind gusts; *a* – integration constant, which can be calculated as follows:

$$a = C_a \frac{\rho_1}{4} \Delta v_a^2 (S_x \cdot \cos q_a + S_y \cdot \sin q_a) \tag{4}$$

Maximum forces, which can create periodical component of the wind, will be:

$$\sin\frac{2\pi t}{\tau} = 1, \tag{5}$$

and maximum periodical forces will be:

$$F_{P\max} = \frac{4\pi^2 t}{\tau^2} a \cdot m \ . \tag{6}$$

Ships passing near quay walls create hydrodynamic forces, which influence ships moored to quay walls due to the pressures and big quantities of the circumfluent water (water added mass), which affect the moored ships similar to a current. The forces created on ships moored to the quay wall depend on the mass of passing ships (*V)*, speed (v), and the distance between ships (*S*) (Paulauskas et al. 2014):

$$F = f(V, v, S) \tag{7}$$

The study of the above mentioned dependences by theoretical and experimental methods in the real conditions in few ports, using RTK (real time kinematic) navigational and laser systems, which have accuracy of the moored ship's position up to +/- 3 – 5 mm (Dockmaster – 3 system), confirms the dependences, received by theoretical methods (Paulauskas 2013).

The main dependency created by passing or moored to a quay wall ships, received in a theoretical way, could be expressed as follows Paulauskas et al. (2014):

$$F = \left(A \cdot exp\left(-\frac{S}{S'}\right) + F'\right) \cdot k(V) \cdot k(v) \tag{8}$$

Where: *A* – a coefficient; *S* – actual distance between ships (horizontal clearance); *S'* – distance at which there is no real influence between passing and moored ships; *F'* – force on distance *S'*; *k(V)* – passing ship mass dependence; *k(v)* – passing ship speed dependence.

Coefficient *A* could be received on the basis of experimental investigations for a concrete type of ships. *S'* distance in many cases could be taken about 3*B* (*B* – width of the ship) of the passing ship, because as received by theoretical studies and experimental results in Klaipeda and other ports for the different type of the ships, at distances more than 3*B*, no real influence is observed. *F'* – force at distance *S'* should be close to 0, but in reality there could be some additional constant influence by current, wind, waves, which should be detected and included in calculations.

The dependence of the mass of a passing ship (*k(V)*) received for a big ship shows that it could be calculated as follows:

$$k(V) = D\left(\frac{V}{V_1}\right)^2 \tag{9}$$

Where: *D* – coefficient, could be calculated on the basis of the experimental data; *V* – displacement of a passing ship; $V_1$ - displacement of a moored ship.

The influence of the speed of a passing ship on a ship moored to a quay wall $k(v)$ could be calculated as follows:

$$k(v) = Cv^2 \tag{10}$$

*C* – coefficient, could be calculated on the basis of the experimental data; *v* – the speed of a passing ship.

Finally, the force, which is created by a passing ship on a ship moored to a quay wall, could be calculated as follows:

$$F = (C \cdot v^2 + A\left(\frac{S}{3B}\right)) \cdot D\left(\frac{V}{V_1}\right)^2 \tag{11}$$

Force *F* created by a passing ship spreads on a moored ship, fenders and ship mooring ropes. In many cases force and energy distribution could be about 50 % on fenders and about 50 % on ship mooring ropes. Ship mooring ropes can extend in length $\Delta l$ from 3 % (steel ropes) up to 30 % (synthetic ropes).

The force, created by a passing ship, starts moving a moored ship along a quay wall. The research carried out at several terminals shows that inertia loads are distributed in about 50 % to mooring lines and 50 % to the fender system.

The inertia force, creating the moored ship movement, could be calculated as follows:

$$F_1 = m \cdot a \tag{12}$$

Where: *m* - mass of the ship, together with water added mass; *a* - acceleration.

Acceleration of the moored ship can be expressed as follows:

$$a = \frac{dv}{dt} = \frac{2\Delta l}{T \cdot \Delta t} \tag{13}$$

Where: $\Delta l$ - the shortest long line or spring mooring line; *T* – ship movement period, which was investigated by theoretical and experimental methods and could be calculated as follows:

$$T \approx L/3 \tag{14}$$

In relation to the mass inertia of vessels, it is not the short-term peak of gusts (order of magnitude = second) relevant for determining mooring rope loads but rather the average wind over a period of time (T). The value of T should be taken as 30 sec. for vessels up to 50,000 dwt and 60 sec for larger vessels (Wijffels et al. 2002). The wind intensity of the maximum wind averaged over one minute is generally 75 % of that of the value over one second. A 50-year return wind is recommended for design purposes (PIANC 1984; EAU 2012).

Horizontal tension forces of a mooring rope oriented to quay wall direction *A* and along quay wall direction *D* can be expressed as in fig. 7 (Paulauskas et al. 2008):

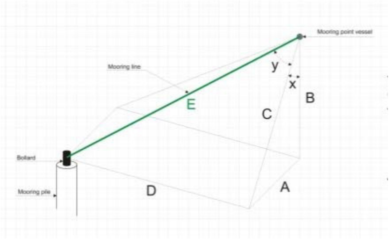

Fig. 7. Mooring rope tensions: A – total payloads perpendicular to quay wall direction, created by moored vessel; D – total payloads along to quay wall direction, created by moored vessel; E – total loads on a mooring line; B – vertical distance between a quay wall bollard and a mooring point on a vessel.

External forces comprised on mooring ropes and acting on the quay wall mooring system (bollards and fenders) could be calculated as follows (Paulauskas et al. 2008):

$$A = E \cdot \cos y \cdot \sin x \tag{15}$$

$$D = E \cdot \cos y \cdot tgy \tag{16}$$

Total horizontal tensions, acting on bollards and fenders can be calculated as follows:

$$\sum F = \sqrt{(E \cdot \cos y \cdot \sin x)^2 + (E \cdot \cos y \cdot tgy)^2} \tag{17}$$

Thus, the forces shown on Fig.7, keep a ship to a quay wall and alongside the quay wall, which prevents ship movement close alongside to the quay wall. The vertical forces do not act as forces, which keep a ship to or alongside a quay wall.

Mooring ropes must withstand the total forces, which are created by wind and other external forces and in case of constant tension in mooring ropes, which can be regulated by mooring winches (for big ships 500 kN or 600 kN, for smaller ships 100 kN, 200 kN or 300 kN, depending on ship size), and it means that forces *E* could be less or equal to maximum possible tension of the mooring ropes for a particular ship (Tomczak, 2008).

Sometime use on ship moored to quay wall ship's thrusters or port tugs push moored ship to quay wall and decrease ship's movement along the quay wall. This method looks very simple but in same time very much increase loads on quay wall fenders and as result very often damage fenders and quay wall. Ship's pushing to quay wall by thrusters and tugs should be use very carefully.

The presented methods can be implemented into the planning and design of the quay wall mooring system capability as well as for the preparation of ship mooring schemes.

## 4. Practical implementations and results

For the case study and calculation of the evaluation of the mooring and passing ship influence on a ship moored to a quay wall and the quay wall, where taken large passing ships of 290 m length, 48 m width and 12,5 m draft at 100% laden capacity, which have displacement of 120000 t, and 8,5 m draft in ballast (displacement of 88000 t); the space of the projection onto a diametrical plane (DP) of the wind surface area of the vessel is 6000 m² at 100% laden capacity and 7,200 m² in ballast; the space of the projection onto a diametrical plane (DP) of the underwater area of the vessel is 3750 m² at 100% laden capacity and 2260 m² in ballast. The moored ship was taken a loaded PANAMAX type tanker: length 220 m, width 32,4 m, draft 12,5 m, displacement 85000 t.

The evaluation of the passing ship influence on a ship moored to a quay wall was investigated by a visual simulator SIMFLEX Navagator (Denmark) (SimFlex, 2012) after calibration on the basis of testing results on real ships of similar dimensions. For the calibration the E-Sea Fix RTK system and the laser mooring system (DOCKMASTER 3) were used. The visual view of a passing ship close to a moored ship is presented on Fig. 9 and mooring lines tensions, received by the simulator are presented on Fig. 10.

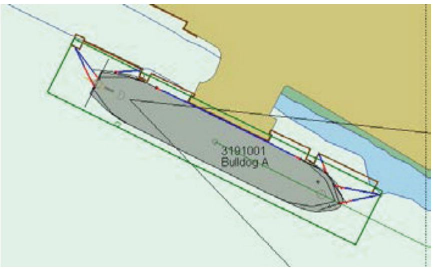

Fig. 8. Mooring arrangements for a PANAMAX type tanker. The centres of the ship are set approximately align to the manifold ashore.

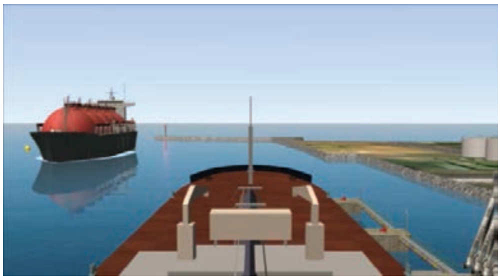

Fig. 9. A big passing ship sails at 90 m distance from a ship moored to a quay wall (a visual view).

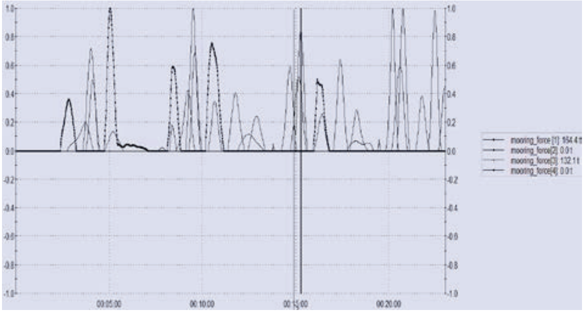

Fig. 10. The morred ship forces on the mooring lines in case of the big ship passing at 90 m distance from a ship moored to a quay wall (Fig. 9).

Testing of passing and moored ships were made by a calibrated simulator at the speed of a passing ship from 6 to 9 knots and distances between a moored ship and a passing ship from 20 m up to 160 m by increasing the given distance every 20 meters. During the testing an average wind from South West 14 m/s and the current, according to a current map in the mentioned wind conditions were used. The evaluation results (testing and calculations) are presented on Fig. 11 – 14.

The received results were used for design of mooring schemes for Klaipeda and other East Baltic ports. The above mentioned mooring schemes were tested for some years and showed good substantial results.

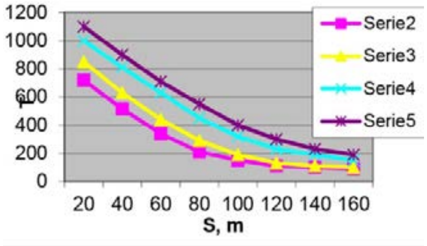

Fig. 11. Fore long lines and aft springs forces on moored PANAMAX tanker in tones (T) depend on the distance between the passing and moored ship (S) and the speed of a passing ship: Series (*Seka*) 2 – speed of the passing ship - 6 knots; Series 3 – speed of the passing ship -7 knots; Series 4 – speed of the passing ship – 8 knots; Series 5 – speed of the passing ship -9 knots.

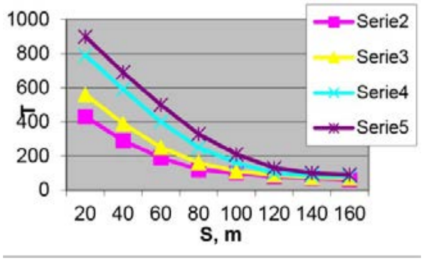

Fig. 12. Aft long lines and fore springs forces on a moored PANAMAX tanker in tones (T) depend on the distance between the passing and moored ships (S) and the speed of the passing ship: Series (*Seka*) 2 – speed of the passing ship - 6 knots; Series 3 – speed of the passing ship - 7 knots; Series 4 – speed of the passing ship – 8 knots; Series 5 – speed of the passing ship - 9 knots.

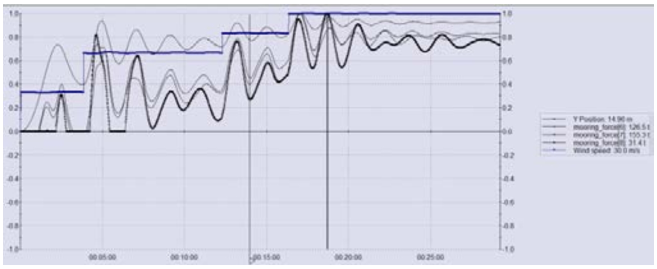

Fig. 13. Aft long line and fore spring forces on a moored PANAMAX tanker depend of wind velocity and a ship passing at 7 knot speed in case of W wind velocity: 10 m/s, 20 m/s, 25 m/s, 30 m/s (10 min) and constant current NNE 0,5 knots, received by simulator (SimFlex, 2012).

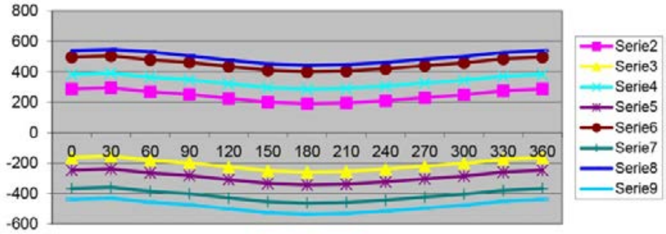

Fig. 14. Total loads on mooring ropes of the PANAMAX tanker, moored to a quay wall in case of different wind direction (from 0 ° up to 360 °) 20 m/s and a ship passing (length 290 m) at 66 m distance from a moored ship at 6 knots (Series (*Seka*) 2, 3), at 7 knots (Series 4, 5), at 8 knots (Series 6, 7) and at 9 knots (Series 8, 9).

## 4. Conclusions and discussions

Ship mooring and safe stay near a quay wall is very important in all ports and in all conditions. Under storm conditions, inertia loads are an important factor. The mooring and fender systems of ships and berths should be designed to accept inertia loads.

Forces produced by ships passing near ships moored to a quay wall, as well as wind, current and waves and energy of ship mooring significantly affect quay walls, and can have an impact on the safety and stability of the quay wall.

The wind acting on the ship has two components: constant and periodical, which must be properly calculated and evaluated to ensure safety of ship mooring. The constant force component of the wind can be calculated on the basis of typical aerodynamic methods, just real wind surface areas of a ship must be considered. The periodical force component of the wind can be calculated on the basis of harmonics created by accelerations and forces, which try to move a ship along a quay wall and can create much bigger forces than the constant component. The presented calculation and evaluation methods were tested in a number of ports and can be implemented in port areas, particularly in those open to passing ships, waves, current and wind actions.

## References

BS 6349: 2000 – British Standard Maritime Structures – Part 1: Code of Practice for General Criteria (British Standard Institution, July 2003) (BS 2003).

Cakmak T., Ersoz F., 2007. Methodology recommendation for one-criterion transportation problems: Cakmak method. Transport, Vilnius:Technika. Vol. XXII, No. 3, p. 221 – 224.

Criteria for Movements of Moored Vessels in Harbours (PIANC 1995).

EAU 2012: Recommendations of the Committee for Waterfront Structures – Harbours and Waterways (Ernst & Sohn, 2012) (EAU 2012).

Gucma, L.; Montewka, J., 2005. Land borne laser rangefinder measurements for navigation safety assessment. European Journal of navigation,3(4), pp.1 – 6.

Guidelines for the Design of Fender Systems: 2002 (PIANC, 2002).

Paulauskas V., 1998. Ship’s steering in complicate conditions. Klaipeda University publish house, Klaipeda, 164 p.

Paulauskas V., 2004. Ports terminal planning. Klaipeda University publish house, Klaipeda, 382 p.

Paulauskas V., 2006. Navigational risk assessment of ships. Transport, 2006, Vol. XXI, No. 1, p. 12 – 18.

Paulauskas V., 2013. Ships entering the ports. N.I.M.S publish house, Riga, 240 p. ISBN: 9984-679-71-3.

Paulauskas V., Paulauskas D., Maksimavicius R., Jonkus. (2014). Hydrodynamic interactions between ships in narrow channels /Transport/ Vilniaus Gedimino Technikos Universitetas. Vilnius: Technika. ISSN: 1648 – 4142, 29(2). p. 212 - 216.

Paulauskas V., Paulauskas D., Wijffels J., 2008. Ships mooring in Complicated Conditions and possible solutions. Transport Means – 2008, Kaunas, Technologija, p. 67 – 70.

Report of the international commission for improving the design of fender systems (PIANC 1984).

SimFlex Navigator – Ship simulator system, 2012 version (SimFlex 2012).

Tomczak, A., 2008. Safety evaluation of ship’s maneuvers carried out on the basis of integrated navigational system (INS) indications. Journal KONBIN, 1(4), pp. 247 – 266.

Wijffels J., Paulauskas V., 2010. Safety of high freeboard ships in ports. //PIANC-AIPCN, Liverpool, UK, 2010. ISSN: 1878 – 2057; P55. p. 459–475.

Wijffels J., Paulauskas V., Dubruel J., 2002. Fender design for complex nautical situation.//PIANC-AIPCN, Sydney Australia, 2002. ISSN: 1878–2057; S4B P55. p. 679 – 691.

Wijffels J., Paulauskas V., Paulauskas D. 2009. Ship’s safety in open ports. Transport 24(2), Vilnius, p. 313 – 320.

Zalewski, P; Montewka, J., 2007. Navigation safety assessment in an entrance channel, based on real experiments. Guedes-Soares & Kolev Maritime Industry, Ocean Engineering and Coastal Resources, pp. 1113 – 1117.