Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2019, 57 (129), 49–55
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/325

Received: *16.01.2019*
Accepted: *20.03.2019*
Published: *22.03.2019*

A simulation method for the determining the minimum pull of tugs assisting in port manoeuvres

Stanisław Gucma, Maciej Gucma✉, Rafał Gralak, Mateusz Bilewski
Bartosz Muczyński

Maritime University of Szczecin
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: {s.gucma; m.gucma; r.gralak; m.bilewski; b.muczynski}@am.szczecin.pl
✉ corresponding author

Key words: port manoeuvring, simulation of ship movement, manoeuvring safety, tug assistance, determination, minimum safe pull

Abstract

The article presents a simulation method for determining the minimum safe pull of tugs assisting in port manoeuvres. The method can be used to determine the relationship between the minimum safe pull, understood as the tension on the line, of the assisting tugs and the overall length, cargo capacity or net capacity of ships manoeuvring in a given port under allowable hydrometeorological conditions. The method was verified through simulated tests of gas tankers' entry, turning and berthing at the LNG terminal of Świnoujście.

Introduction

The proper choice of tugs to handle large ships in seaports is determined by the following factors:
- the safety of the ship to be towed;
- time required for the performed port manoeuvres;
- cost of both the construction and operation of the tugs.

This particularly applies to terminals that serve large ships that carry dangerous cargo (e.g. LNG terminals) in which towage represents a large part of the port charges.

Modern tugs usually have an azimuth stern drive (ASD), although some have cycloidal Voith-Schneider propellers (VSP), which makes them extremely manoeuvrable, a necessary capability for port operations, so further considerations will solely refer to these types of tugs (Artyszuk, 2013).

Tug assistance in the port manoeuvres of a ship of a specific size is characterised by the following parameters (Determination, 2018):
- the minimum number of assisting tugs;
- the minimum safe total pull of the assisting tugs;
- the minimum safe pull of each tug assisting in the port manoeuvres, where *pull* should be considered as the tension on the lines, not the bollard pull of the tug.

The parameters of tug assistance in port manoeuvres depend on:
- the available navigable area of a given port;
- the type of manoeuvre (waterway passage, entry, turning, berthing);
- the maximum allowable hydrometeorological conditions (wind, current, waves);
- the parameters of the ship being handled (length, draft, windage surface area, main propulsion power and propellers, thruster type and power).

At present, the parameters of tug assistance in the port concerned are usually determined on the basis of the force of the allowable lateral wind pressure force acting on a ship of a given size and established port practice (PIANC, 2014; Thoresen, 2014). Such an approach usually results in a redundant minimum tug pull, which translates into higher costs of the ship's port operations. This can be seen especially during the construction of terminals for ships handling dangerous goods, which is justified by a certain safety margin on the side of the maritime administration (Port Regulations, 2017).

The simulation method that has been presented in this paper for determining the minimum safe pull of tugs assisting in port manoeuvring has taken into account the specific features of manoeuvring on the waterways of the port (terminal) and it has made it possible to accurately determine the parameters of the tug assistance for ships with different parameters. The application of this method has enabled the optimal selection of the tugs assisting in port manoeuvres and the associated minimisation of towage costs.

The method was used to determine the minimum safe pull of tugboats assisting different size gas tankers entering the LNG terminal in Świnoujście (Determination, 2018). The existing and planned conditions for the operation of gas tankers in the LNG terminal in Świnoujście can be characterised by:

- the increased size of the LNG tankers being handled (from a cargo capacity of 120,000 m^3 to 220,000 m^3);
- the transshipment berth being designed for LNG tankers and feeders with a cargo capacity of 75,000 m^3 to 220,000 m^3;
- the current port regulations that impose an excessive minimum bollard pull of tugs (80 tons) as they do not take into account the size of the LNG tankers being handled.

The purpose of this study was to determine the functional relationships between the minimum pull of tugs assisting during entry manoeuvres at the Świnoujście LNG terminal and the tanker cargo capacity and overall length in the examined range of 120,000 m^3 to 220,000 m^3.

Conditions for the safe operation of tug-assisted ships manoeuvring in port

Port waterways in which tugs assist large manoeuvring vessels usually include:

- port entrance – entry manoeuvre,
- turning basin – turning the ship,
- port basin – berthing.

The port entrance, the basin, with a designated turning area, and the berths make up a waterway system composed of area, navigation and berth subsystems that are a function of the safe operating conditions of manoeuvring ships (Gucma et al., 2017):

$$\mathbf{W} = f\begin{bmatrix}\mathbf{A}\\ \mathbf{N}\\ \mathbf{K}\end{bmatrix} \tag{1}$$

The port basin area subsystem, that may consist of several berths, is defined by a set of parameters:

$$\mathbf{A} = \begin{bmatrix}\mathbf{D_i}\\ h_i\end{bmatrix} \tag{2}$$

where:

$\mathbf{D_i}$ – available navigable area for the i-th waterway (meeting the condition of minimum depth);

h_i – minimum depth of the i-th waterway.

The navigation subsystem of the i-th waterway is described by the set of parameters:

$$\mathbf{N} = \begin{bmatrix}M_{ij}\\ m_{ij}\\ n_{ij}\\ w_{ij}\end{bmatrix} \tag{3}$$

where:

M_{ij} – accuracy of the j-th navigation system – distance root mean square error in the i-th waterway;

m_{ij} – availability (percentage of time where the system can be used) of the j-th navigation system in the i-th waterway;

n_{ij} – reliability (defined as the ability to perform safe navigation) of the j-th navigation system of the i-th waterway;

w_{ij} – dependability (factor related to the maintainability of the waterway) of the j-th navigation system of the i-th waterway;

The berth subsystem is described by the set of parameters:

$$\mathbf{K} = \begin{bmatrix}T_i\\ k_i\\ a_i\\ E_i\end{bmatrix} \tag{4}$$

where:

T_i – type of the i-th berth's construction (dolphins or solid);

k_i – length of the line of the mooring of the i-th berth;

a_i – spacing of the i-th berth's fenders;

E_i – allowable kinetic energy that can be absorbed by the fenders at the i-th berth.

The conditions required for the safe operation of ships performing tug-assisted manoeuvres in port waterways of this kind can be written in the form of the set (Gucma, 2015):

$$\mathbf{W} = \left[t_{yp}, L_c, B, T, F, M, M_{st}, V_i, n_h, U_h, \mathbf{H_i}\right] \quad (5)$$

where:
t_{yp} – type of ship;
L_c – overall length of the ship;
B – breadth of the ship;
T – draft of the ship;
F – lateral windage;
M – power of the ship's main propulsion;
M_{st} – power of the bow thrusters;
V_i – allowable speed of the ship on the *i*-th waterway;
n_h – number of tugs assisting in the manoeuvres;
U_h – total pull of tugs assisting in the manoeuvres;
$\mathbf{H_i}$ – the set of allowable hydrometeorological conditions for the berthing manoeuvre of a 'maximum ship' arriving at a given berth.

$$\mathbf{H_i} = \left[d/n, \Delta h_i, V_{wi}, V_{pi}, h_{fi}\right] \quad (6)$$

where:
d/n – allowable time of day (daylight or no restrictions);
Δh_i – allowable drop in water level;
V_{wi} – allowable wind speed in the *i*-th section;
V_{pi} – allowable current speed in the *i*-th section;
h_{fi} – allowable wave height in the *i*-th section;

Conditions for safe operation can be grouped as:
- the conditions associated with the ship and its movement, defined by the set:

$$\mathbf{S} = \left[L_c, B, T, F, M, M_{st}, V\right] \quad (7)$$

- the conditions associated with tug assistance, defined by the set:

$$\mathbf{h} = \left[n_h, U_h\right] \quad (8)$$

Given the above, the following can be written:

$$\mathbf{W} = \left[\mathbf{S}, \mathbf{h}, \mathbf{H}\right] \quad (9)$$

As the vector of the safe operating conditions in the given area clearly determines the safe manoeuvring area of a ship (Gucma et al., 2015) then:

$$\mathbf{d}_{(1-\alpha)} = f(\mathbf{W}) \quad (10)$$

thus:

$$\mathbf{d}_{(1-\alpha)} = f(\mathbf{S}, \mathbf{h}, \mathbf{H}) \quad (11)$$

On the assumption that a tug-assisted manoeuvre in a given waterway, characterised by the available navigable area (**D** = const), is performed under certain hydrometeorological conditions (**H** = const), then the safe manoeuvring area of the ship concerned depends on the operating conditions of the ship and the assisting tug:

$$\mathbf{d}_{(1-\alpha)} = f(\mathbf{S}, \mathbf{h}) \quad (12)$$

For manoeuvres where the wind speed is dominant (waters partly sheltered from waves, with a sea current speed of up to one knot) it can be assumed that the lateral wind pressure acting on the ship is the main parameter that affects the size of the safe manoeuvring area. This results from the relationship between the safe manoeuvring area, the force of the lateral wind pressure and the tug assistance. Therefore:

$$\mathbf{d}_{(1-\alpha)} = f(Q, \mathbf{h}) \quad (13)$$

while the force of the lateral wind pressure on the ships is:

$$Q = \frac{1}{2}\rho_p C V_w^2 F \quad (14)$$

where:
Q – the pressure of the lateral wind with a maximum speed V_w;
ρ_p – density of the air;
C – air resistance coefficient for the LNG tankers (Report, 2007).

As a result, it can be assumed that the safe manoeuvring area of the ship in a given area under specific hydrometeorological conditions depends on the lateral windage (area) and the tug assistance:

$$\mathbf{d}_{(1-\alpha)} = f(F, \mathbf{h}) \quad (15)$$

The safety of manoeuvring in port waterways will be assured if the following condition of navigational safety can be satisfied (Gucma et al., 2015):

$$\left.\begin{array}{r} \mathbf{d}_{\mathbf{i}(1-\alpha)} \subset \mathbf{D_i} \\ \bigwedge_{p(x,y)\in \mathbf{D}} h_{xy} \geq T_{xy} + \Delta_{xy(1-\alpha)} \end{array}\right\} \quad (16)$$

where:
$\mathbf{D_i}$ – the available navigable area in the *i*-th section of the waterway (where the safe depth condition is satisfied);
$\mathbf{d}_{\mathbf{i}(1-\alpha)}$ – the safe manoeuvring area of the examined ship carrying out a manoeuvre in the *i*-th section of the waterway under allowable navigation conditions determined with the confidence level 1–α;
h_{xy} – the area's depth at the point (x, y);
T_{xy} – the ship's draft at the point (x, y);
$\Delta_{xy(1-\alpha)}$ – the underkeel clearance at the point (x, y) determined with the confidence level (1–α).

Based on the relationship defining the safe manoeuvring area of ships ($\mathbf{d}_{(1-\alpha)}$) manoeuvring in the available navigable area (**D**) under allowable hydrometeorological conditions (**H** = const) and with the condition of navigational safety having been satisfied, the following can be written:

$$\mathbf{D} = f(Q, \mathbf{h}) \quad (17)$$

therefore:

$$\mathbf{h} = F(Q, \mathbf{D}) \quad (18)$$

Simulation method for the determination of the minimum pull of tugs assisting in port manoeuvres

Assuming that four tugs are always engaged in port manoeuvres for large ships where $L_c > 200$ m, the tug assistance could be reduced to a minimum total pull of the engaged tugs, referred to here as the minimum safe pull. This applies to ships without thrusters or with a relatively weak bow thruster. Adopting these simplifications, the minimum safe pull of the tugs can be determined using this function:

$$U_h = F(Q, \mathbf{D}) \quad (19)$$

where:

U_h − minimum safe pull of four tugs assisting in port manoeuvres;

Q_j − lateral pressure of the maximum wind speed acting on the ship;

This relationship means that, by adopting a pre-defined available navigable area (**D** = const) and under allowable hydrometeorological conditions (**H** = const), the minimum safe pull of the tugs assisting in port manoeuvres is solely the function of the lateral wind pressure:

$$U_h = F(Q) \quad (20)$$

The dependence of the minimum safe pull of tugs assisting in port manoeuvres on the parameters of the ships being handled (length, cargo capacity, net capacity) was determined based on the following assumptions:

- the manoeuvre for port entry, turning and berthing is more difficult than the manoeuvre for unberthing and departure, regardless of the ship's loading condition;
- the dependence of the minimum safe pull of the tugs on the overall length and cargo capacity of the manoeuvring ships of a specific type is linear;
- the equations of these relationships only differ in constant coefficients from the equations of lateral wind pressure force on a gas tanker.

The method is designed to determine the relationship between the size of the 'characteristic' manoeuvring ships represented by parameters such as the overall length, cargo capacity or net capacity and the minimum safe pull of the assisting tugs (total pull). The achievement of this objective requires the following tasks to be carried out:

1. The determination by the statistical method of the relationship between the force of the lateral pressure of the maximum wind speed and the overall length or/and cargo capacity of the set of existing ships being handled, or expected to be handled, in a given terminal (port).
2. The determination by the simulation method of the minimum safe pull of the tugs assisting a ship that belongs to the examined set.
3. Based on the results of the statistical method (point 1) and the simulation method (point 2), the determination of the relationship between the minimum safe pull of the tugs and the overall length, cargo capacity or net capacity in the examined range of ship sizes for the maximum allowable hydrometeorological conditions.

Ad. 1. The linear relationship between the force of the lateral wind pressure acting on a specific type of ship being operated in the port (terminal) and their overall length or/and cargo capacity is determined by the linear regression method for the following assumptions:

- the size range is established for the examined ships of a specific type being handled or intended for operation in a given port (terminal);
- the lateral wind pressure acting on ships is determined for the maximum wind speed;
- the lateral wind pressure is determined for a ship entering the port (loaded or under ballast);
- the lateral wind pressure is determined for the set of 'characteristic' ships of a specific type entering the examined port; the following principles should be applied during the construction of the set of 'characteristic' ships:
  - minimum number $n = 10$,
  - only one sister ship is included,
  - 'characteristic' ships should evenly cover the entire range of the examined sizes.

Ad. 2. The simulation experiment was intended to determine the minimum safe pull of the tugs for one of the ships selected from the examined size range. Tests were carried out on the full mission bridge simulator with 3D visualization and a capability to control two tugs from separate stations (Gucma, Gucma & Zalewski, 2008).

The simulation test procedure consisted of:

- The construction of the simulated model of the test area (port entrance, basin with a turning area and berths).

- The construction and verification of the simulated model of the selected ship's movement.
- The construction and verification of three ASD tugs with pulls of:
  $U_{h1} = 2Q/4$,
  $U_{h2} = 2.5Q/4$,
  $U_{h3} = 3Q/.4$
- The design of the experimental system came down to the determination of a series of simulated manoeuvres that consisted of 10 passages each, which started from the port entry and finished once the ship was berthed. The hydrometeorological conditions during the tests included the allowable wind speed, which was perpendicular to the berth, either pushing away or diagonal (45° from the ship's stern) and a prevailing mean current in the area. The specific series were run with the following combinations of the assisting pull of the tugs:
  series 1 – 4 × U_{h1};
  series 2 – 2 × U_{h2} + 2 × U_{h1};
  series 3 – 4 × U_{h2} or 2 × U_{h3} + 2 × U_{h2}, depending on the results of series 1 and 2.

  The simulated manoeuvres were carried out by pilots from the examined port.
- The analysis of the test results of the simulation came down to the determination and comparison of:
  – the safe manoeuvring areas in each series at the confidence level (1–α) = 0.95 and the comparison of their shape and surface area;
  – the time taken for manoeuvring at each stage (entry, turning, berthing);
  – the kinetic energy of berthing (first contact with the berth).

The above data and the expert tests results from the simulated manoeuvres performed by pilots made up the basis for the determination of the minimum safe pull of the tugs required for the examined ship.

Ad. 3. The equation of the relationship between the minimum safe pull of the assisting tugs and the overall length, cargo capacity or net capacity of a ship from the examined size range for the maximum hydrometeorological conditions of the examined port only differed in the constant coefficient from the equation of the lateral wind pressure force acting on the ship. The constant coefficients of the linear equations of the minimum safe pull were greater than the coefficients of the linear equations of the lateral wind pressure force acting on the ships and the difference between the minimum safe pull required by the examined ship that was determined by the simulation and the lateral wind pressure force acting on that ship.

The determination of the safe assistance of the tugs during the entry of gas tankers into the LNG terminal in Świnoujście – verification of the method

The dependence of the lateral wind pressure forces on the cargo capacity and overall length of the gas tankers with a cargo capacity range of 120,000 m^3 to 220,000 m^3 entering the LNG terminal in Świnoujście was defined with the assumptions that:

- the lateral wind pressure acting on the gas tankers was determined for a wind speed V_w = 12.5 m/s, which was used in the simulation tests;
- the lateral wind pressure was determined for loaded LNG tankers entering the LNG terminal and tankers leaving the terminal under ballast;
- the lateral wind pressure was determined for a set of 14 existing 'characteristic' LNG tankers with a cargo capacity from 123,857 m^3 to 211,899 m^3, with prismatic and spherical cargo tanks.

The linear relationships between the lateral wind pressure and the parameters of the ship were determined by statistical linear regression methods. The linear equations coefficients have been set out in Table 1 that, for each equation, also contains:

- the standard deviation of the remainders – S_e,
- the coefficient of multiple determination – R^2.

Table 1. The coefficients of the equations of lateral wind pressure as a function of the length and cargo capacity of a tanker, and the standard deviation of the remainders and coefficients of multiple determination of these relations

$y = ax + b$	Parameter	Total		Prismatic	
		under ballast	loaded	under ballast	loaded
length	a	0.564	0.559	0.448	0.471
	b	–91.664	–98.076	–56.106	–70.854
	S_e	5.952	5.747	5.791	6.014
	R^2	0.629	0.641	0.561	0.567
capacity	a	0.000271	0.000267	0.000215	0.000226
	b	29.466	22.279	39.636	29.515
	S_e	5.497	5.382	5.976	6.183
	R^2	0.684	0.685	0.533	0.542

The coefficients of multiple determination in all the equations were contained in the interval R^2 = 0.533–0.685. Taking this into consideration, it could be concluded that the developed equations satisfied the requirements of accuracy and reliability.

Figure 1 has presented a linear relation between the lateral wind pressure acting on the gas tanker and the overall length of LNG tankers with prismatic tanks and combined, prismatic and spherical tanks.

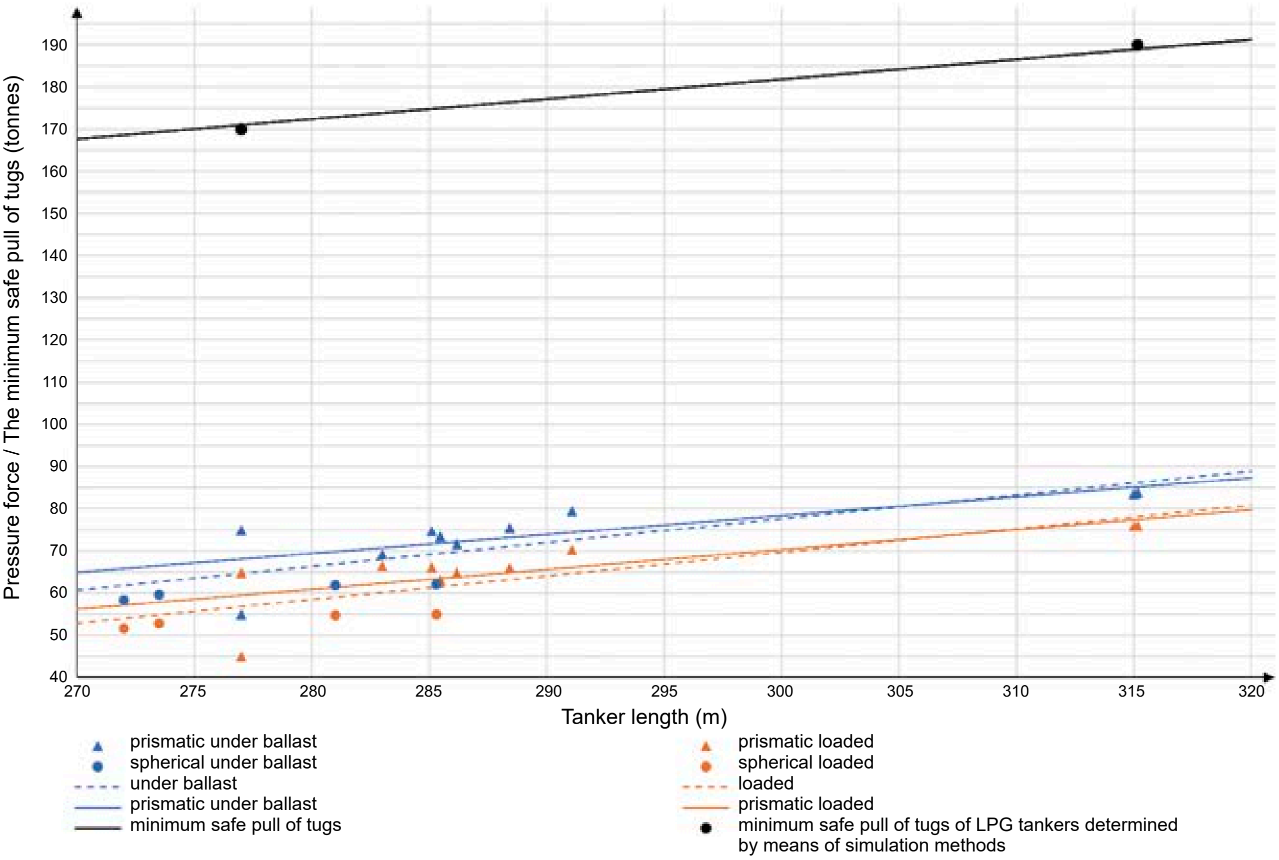

Figure 1. The relationship between the lateral wind pressure force and the minimum safe pull of the tugs (total pull) and the overall length of an LNG tanker entering the port

In order to verify the method, a simulation experiment was performed for two LNG tankers, rather than just one, for the examined range of ship sizes, each having an extremely different cargo capacity (Figure 1). These were:

1. A Q-Flex type LNG tanker, cargo capacity $P = 211{,}000\ m^3$, $L_c = 315$ m; $B = 50$ m; $T = 12.5$ m.
2. An LNG gas tanker, cargo capacity $P = 138{,}000\ m^3$, $L_c = 277$ m; $B = 43.4$ m; $T = 11.5$ m.

The simulated experiment was performed in a series featuring various pulls of the assisting tugs in the manoeuvres of loaded tankers entering the LNG terminal in Świnoujście. An example of the safe manoeuvring areas of a Q-Flex tanker entering the outer port of Świnoujście with the assistance of tugs with different pull capabilities have been shown in Figure 2 (Badania, 2014; Determination, 2018).

The following factors were taken into account while analysing the results of the simulated tests:

- safe manoeuvring areas for the different pull of the assisting tugs,
- time taken for the manoeuvres,
- the kinetic energies of the first contact with the berth (fender-fitted dolphin),
- the opinions of experts (pilots performing the simulated manoeuvres).

The analysis resulted in the determination of the minimum safe pulls of the tugs assisting gas tankers entering the port of Świnoujście under the maximum allowable hydrometeorological conditions:

- a Q-Flex LNG tanker with a cargo capacity of $211{,}000\ m^3$ – $U_h = 190$ tons,
- an LNG tanker with a cargo capacity of $138{,}000\ m^3$ – $U_h = 170$ tons.

The relationship between the minimum safe pull of the tugs assisting in the entry manoeuvres at a wind speed of $V_w = 12.5$ m/s for a tanker range of cargo capacity of $120{,}000\ m^3$ to $220{,}000\ m^3$ as a function of the overall length has been presented in Figure 1.

The equations of these relationships as functions of cargo capacity and overall length can be written, respectively, as follows:

$$U_h = 0.000226 \cdot P + 140.8 \text{ [tons]} \tag{21}$$

$$U_h = 0.471 \cdot L_c + 40.55 \text{ [tons]} \tag{22}$$

where:

U_h − the minimum total pull of the tugs [tons],

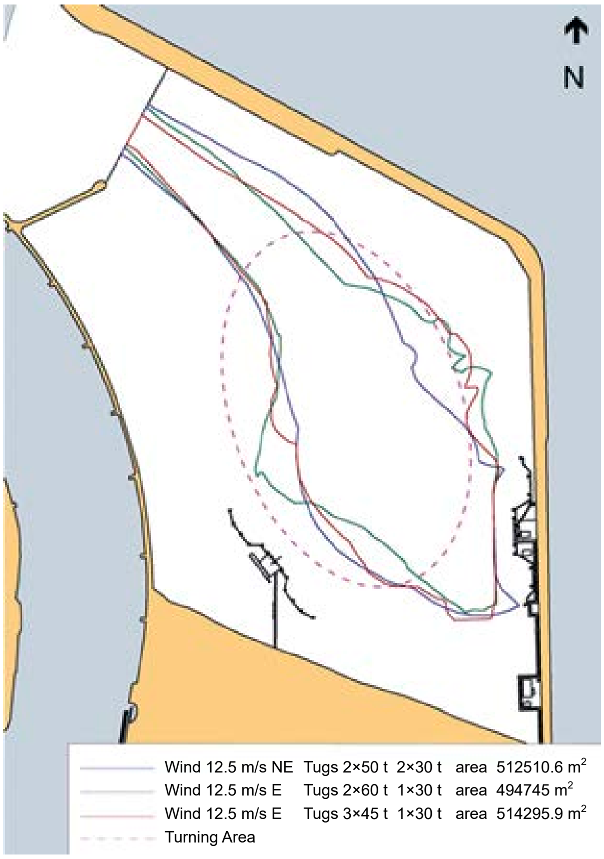

Figure 2. Safe manoeuvring areas for Q-Flex LNG tankers in the outer port of Świnoujście specified at the level of confidence (1–α) = 0.95 – entry manoeuvre

P – the cargo capacity of an LNG tanker [m^3],
L_c – the overall length of an LNG tanker [m].

The differences between the minimum safe pull of the tugs assisting the two simulation-tested ships and the corresponding lateral pressure of the wind, determined statistically, differed by approximately 2.5 tons. This meant that the error of the method can be accepted within the limits of up to 1.5% of the safe minimum pull of the tugs. Both equations for the U_h calculation require the same time frame for calculation with different factors (and units of measurement).

Therefore, for the presented scope of simulation tests, the simulation method of determining the safe pull of tugs assisting entry manoeuvres should be considered as verified and accurate (the error ~ 1.5% of the tugs' pull).

Conclusions

The article has presented a newly developed method of determining the minimum safe pull of tugs assisting in port manoeuvres.

The method allows for the determination of the linear relationships between the minimum safe pull of the assisting tugs and the overall length, cargo capacity or net capacity of specific types of ships manoeuvring in the examined port under the maximum hydrometeorological conditions. This method can be used for large ships with an overall length of L_c > 200 m, where, in the manoeuvres of entering, turning and berthing, a ship is assisted by four tugs.

The method has been verified on the basis of simulation tests of gas tankers in the size range of 120,000 m^3 to 220,000 m^3, entering the LNG terminal in Świnoujście. The errors of the method were estimated to be approximately 1.5% of the safe minimum pull of the tugs.

References

1. Artyszuk, J. (2013) *Types and power of harbor tugs – the latest trends*. Prace naukowe Politechniki Warszawskiej, Transport workbook No. 98. Oficyna Wydawnicza Politechniki Warszawskiej.
2. Badania (2014) *Badania symulacyjne wejścia i wyjścia gazowca Q-Flex do/z Terminalu LNG w Świnoujściu z asystą czterech holowników o uciągach na palu 55 t oraz 65 t*. Praca naukowo-badawcza zlecona przez PGNiG S.A. Akademia Morska w Szczecinie.
3. Determination (2018) *Determination of the conditions for safe operation of gas tankers of 120,000 to 220,000 m^3 capacity entering the LNG terminal in* Świnoujście. Praca naukowo-badawcza zlecona przez PGNiG S.A. Akademia Morska w Szczecinie.
4. Gucma, S. (2015) Studying sea waterway system with the AID of computer simulation methods. *Polish Maritime Research* 1 (85), 22, pp. 10–15.
5. Gucma, S. et al. (2015) *Morskie drogi wodne – projektowanie i eksploatacja w ujęciu inżynierii ruchu*. Gdańsk: Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej.
6. Gucma, S. et al. (2017) *Inżynieria ruchu morskiego. Wytyczne do projektowania morskich dróg wodnych i portów oraz warunków ich bezpiecznej eksploatacji*. Gdańsk: Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej.
7. Gucma, S., Gucma, L. & Zalewski, P. (2008) *Symulacyjne metody badań w inżynierii ruchu morskiego*. Szczecin: Wydawnictwo Naukowe Akademii Morskiej w Szczecinie.
8. PIANC (2014) Harbour Approach Channels Design Guidelines. PIANC Report, PIANC Secretariat General, Bruksela.
9. Port Regulations (2017) Zarządzenie nr 3 Dyrektora Urzędu Morskiego w Szczecinie z dnia 26 lipca 2013 r. tekst ujednolicony wg stanu prawnego na dzień 24.05.2017.
10. Report (2007) *Prediction of wind loads on large liquefied gas carriers*. Society of International Gas Tanker & Terminal Operators Ltd.
11. Thoresen, C.A. (2014) *Port Designer's Handbook*. London: ICE Publishing.