

## Comprehensive method of formal safety assessment of ship manoeuvring in waterways

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### Abstract

The following paper presents an original, universal method of formal safety assessment of ship manoeuvring in sea waterways. The method allows evaluation of a ship's formal safety assessment on various types of waterways. It may be a basis for standardizing the methods of performing the 'navigational analyses' which are required in Poland.

### Introduction

Formal Safety Assessment (FSA) is a methodology increasingly used at different stages of port and waterway design. Ship operation safety assessment, an essential component of FSA, is employed in most design or optimization tasks. Designers and research teams worldwide (acting similarly to the team of Marine Traffic Engineering, Maritime University of Szczecin) simply recommend incorporating safety assessments, even the entire FSA procedure, as a method for risk assessment of operations in existing or planned infrastructure of waterways and ports.

Global institutions engaged in the standardization of design work in the maritime sector include the FSA procedure in their design recommendations, indicating important elements that affect the optimal selection of technical parameters of the waterway in relation to the operational capability of a watercraft (IMO, 2002; IMO, 2006).

In marine traffic engineering, as in most engineering applications, risk  $R$ , defined as the possibility of loss occurrence within a specified time interval, is expressed as a product of accident probability and consequential losses.

In addition, the definition of risk has been supplemented with the concept of relative frequency of the examined manoeuvre (manoeuvre where risk of a specific accident exists). Assuming that an accident and its consequences are independent events, navigational risk can be represented as a product (Gućma, 2001):

$$R = P_A I_R S \quad (1)$$

where:

- $P_A$  – likelihood of a specific accident during the performance of a given manoeuvre;
- $I_R$  – annual average intensity (frequency) of a manoeuvre performance;
- $S$  – consequences that this accident will cause (determinant of consequences).

Consequences of an accident are characterized by the determinant of consequences  $S$ , commonly called 'consequences'. It should be noted that the product  $I_R P_A$  is the likely number of occurrences of a specific accident in a year, i.e.:

$$a_r = P_A I_R \quad (2)$$

In the case of many hazards occurring in a specific waterway section, risks of individual types of accident are added:

$$R_i = \sum_{q=1}^p P_{Aiq} I_{Ri} S_{iq} \quad (3)$$

where:

$P_{Aiq}$  – likelihood of  $q$ -th type of navigational accident in  $i$ -th section of the waterway;

$I_{Ri}$  – annual frequency of performing a given manoeuvre in  $i$ -th section of the waterway;

$S_{iq}$  – consequences of  $q$ -th type of accident in  $i$ -th section of the waterway (determinant of consequences).

There are a number of methods of detailed estimation of navigational risk (Kite-Powell & Patrikalakis, 1996; D'Angremond, 1998; Kristiansen, 2005; Dhillon, 2011; Rausand, 2011; Vinnem, 2014), including the method of dimensioning the safe manoeuvring area width in waterways using navigational risk models, developed at the Maritime University of Szczecin, Poland (Gucma, Ślącza & Zalewski, 2013; Gucoma, 2015). These methods, however, require specific statistical or simulation studies, which are not always used in designing waterways or determining conditions for their safe operation. For this reason, a universal, practical safety assessment method was developed, applicable in the design of waterways, based on deterministic and probabilistic methodology, involving statistical calculations and simulations. The universal method for the assessment of ship manoeuvring safety in sea waterways meets the requirements of the Formal Safety Assessment (Gucma, Ślącza & Zalewski, 2013; Analiza, 2015) and hereinafter is called the formal safety assessment method.

### Likelihood of accidents in sea waterways

Analysing risks and the types of accidents that may occur during ship manoeuvres in waterways, we can distinguish two general causes of their occurrence, the likelihood of each being determined by different methods (Table 1). These are:

- crossing the available navigable area due to deterioration in navigational conditions;
- technical failures of shipboard machinery: the rudder, main engine, generating sets, or tugs.

**The likelihood of crossing the available navigable area due to deterioration of navigational conditions** is estimated by the following procedure.

Calculated by marine traffic engineers, sea waterway parameters critical for the safety of navigation on waterways are as follows:

- vertical dimensions of the area – safe (allowable) depth of the waterway ( $h$ ) for specified vessels in conditions of safe operation in the examined waterway;
- horizontal dimensions of the area – available width of the waterway ( $D$ ) and its shape, fulfilling criteria for navigational safety of specified vessels in conditions of their safe operation in the examined waterway.

Conditions for the safe operation of ships in the designed, built or modernized, waterway for one-way and two-way traffic are determined at the system design stage, following this algorithm:

1. Identify ports and terminals to which the examined waterway leads.
2. Specify 'maximum ship' characteristic for each port and terminal.
3. Group 'maximum ship' characteristic for each port and terminal by type ( $k$ ).
4. Specify 'maximum ship' for each type. The term 'maximum ship' is used in marine traffic engineering when one of its basic parameters ( $L_c$ ,  $B$ ,  $T$ ,  $H_{st}$ ) attains the maximum value in a considered set of ships.
5. Marine traffic engineering methods are used for determining:
  - characteristic sections of the waterway ( $i$ );
  - allowable speeds of 'maximum ships' of examined types in specific sections of the waterway ( $V_{ik}$ );
  - allowable hydrometeorological conditions in each waterway section for examined types of vessel ( $H_{ik}$ ).
6. A set (matrix) that we build represents expected conditions of safe ship operation in  $i$ -th section of the examined waterway. The rows in the matrix represent conditions for safe operation of 'maximum ships' of  $k$  types expected to be operated:

$$M^p = \begin{bmatrix} t_{yp1}, L_{c1}, B_1, T_1, H_{st1}, V_{i1}, C_{i1}, H_{i1} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ t_{ypk}, L_{ck}, B_k, T_k, H_{stk}, V_{ik}, C_{ik}, H_{ik} \end{bmatrix} = \begin{bmatrix} W_{i1}^w \\ \dots \\ W_{ik}^w \end{bmatrix} \quad (4)$$

The conditions for safe operation of ships in a maritime waterway are described by a set of safe operating conditions for a 'maximum ship' in  $i$ -th section of the examined waterway, written in this form (Gucma, 2015):

**Table 1. The matrix of formal risk assessment in marine waterways and in ports (Risk Assessment Matrix – RAM)**

Consequences of an accident				Likelihood of an accident				
Scale	Risk to people	Risk to the environment	Economic risk	Close to zero	Very low	Low	Elevated	High
				1/10 000 years	1/1000 years	1/100 years	1/10 years	1/year
1 serious	Fatalities – passengers, bystanders	Serious environmental pollution, persistent highly exceeded environmental standards, intervention of independent or governmental organisations.	Losses: Value of two ships with cargo	YELLOW SPACE		RED SPACE		
2 significant	Fatalities – crew members	Significant environmental pollution, covering an area above 1 km <sup>2</sup> , greatly exceeding environmental standards, raising an alert by independent or governmental organisations.	Losses: The value of one ship with cargo	GREEN SPACE	YELLOW SPACE		RED SPACE Risk must be reduced	
3 moderate	Seriously injured – permanent disability	Moderate environmental pollution, covering an area above 10 000m <sup>2</sup> , multiple exceedance of ALARP* level, public concerns expressed by independent or governmental organisations.	Losses: 10–100 million PLN or one-month shipyard repairs	GREEN SPACE		YELLOW SPACE Reduce risk to ALARP level		RED SPACE
4 slight	Slightly injured – medical care required	Slight environmental pollution, limited to the area of operation, numerous cases of standard exceedance assessed to be at ALARP level, lack of attention of independent and governmental organisations.	Losses: 1–10 million PLN or shipyard repairs 3–10 days	GREEN SPACE Acceptable risk		YELLOW SPACE		
5 insignificant	No fatalities or injured persons	Trace environmental pollution locally, acceptable standards slightly exceeded, but assessed to be at ALARP level, lack of involvement of independent and governmental organisations.	Losses: to 1 million PLN or shipyard repairs – 3 days	WHITE SPACE No actions required		GREEN SPACE		YELLOW SPACE

$$W_i = [t_{yp}, L_c, B, T, H_{st}, V_i, C_i, H_i] \quad (5)$$

where:

- $t_{yp}$  – type of ‘maximum ship’;
- $L_c$  – length overall of ‘maximum ship’;
- $B$  – breadth of ‘maximum ship’;
- $T$  – draft of ‘maximum ship’;
- $H_{st}$  – air draft of ‘maximum ship’;
- $V_i$  – allowable speed of ‘maximum ship’ in  $i$ -th section of the waterway;
- $C_i$  – tug assistance in  $i$ -th section of the waterway (required number and bollard pull of tugs);
- $H_i$  – the set of hydrometeorological conditions acceptable for a ‘maximum ship’ in  $i$ -th waterway section.

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

where:

- $d/n$  – allowable time of day (day or no restrictions);
- $s$  – allowable visibility;
- $\Delta h_i$  – allowable drop of water level
- $V_{wi}$  – allowable wind speed in  $i$ -th section;

$KR_{wi}$  – wind direction restrictions (if any exist in  $i$ -th section);

$V_{pi}$  – allowable current speed in  $i$ -th section;

$h_{fi}$  – allowable wave height in  $i$ -th section;

$KR_{fi}$  – wave direction restrictions (if any).

7. Traffic density in vessel size groups for each type is planned for each waterway section. Generally, three size groups are determined by length overall of the ‘maximum ship’ for a given waterway ( $L_c = \max$ ):

1. Large ships, 80–100% of max  $L_c$ ;
2. Medium size ships, 50–79% of max  $L_c$ ;
3. Small ships, < 50% of max  $L_c$ .

First, a matrix of vessel traffic intensity in  $i$ -th waterway section is built. The matrix rows are traffic intensities of three size groups of  $k$ -th type of vessels:

$$I = \begin{bmatrix} t_{yp1}, I_{d1}, I_{s1}, I_{m1} \\ \dots & \dots & \dots & \dots \\ t_{ypk}, I_{dk}, I_{sk}, I_{mk} \end{bmatrix} \quad (7)$$

Calculations of safe manoeuvring area widths carried out by simulation or METC

deterministic-probabilistic method are made at the following confidence levels:

- $(1 - \alpha) = 0.997$  for vessels carrying dangerous goods (gas/product/oil/ chemical tankers);
- $(1 - \alpha) = 0.95$  for other vessels.

In the process of waterway design, we determine the safe manoeuvring area of a ‘maximum ship’, i.e. its breadth or a distance to dangers on one side, while widths of the available navigable area are determined using the relationship:

$$D_i \geq d_{i(1-\alpha)} \quad (8)$$

where:

$d_{i(1-\alpha)}$  – width of the safe manoeuvring area of a ‘maximum ship’ established at the confidence level of  $(1-\alpha)$ ;

$D_i$  – width of the available navigable area limited by safe depth contours of  $i$ -th section of the waterway.

The above considerations apply to the width of the waterway bounded by a safe depth contour on both sides and to a one-side distance to a safe depth contour. The safe width of manoeuvring area of a ‘maximum ship’ is defined for maximum allowable wind and current speeds and their least favourable directions, determined by a set of safe operating conditions for a maximum ship (vector of hydrometeorological conditions acceptable for a maximum ship). Given the above, it is assumed that, when the width of the safe manoeuvring area is equal to the width of the available navigable area:

$$d_{i(1-\alpha)} = D_i \quad (9)$$

the probability of a vessel going beyond the width of the navigable area is, accordingly (Gucma, Ślącza & Zalewski, 2013):

$P_{ai} = 3 \cdot 10^{-3}$  – ships with dangerous goods,

$P_{ai} = 5 \cdot 10^{-2}$  – other ships.

The safe width of manoeuvring area of a ‘maximum ship’ depends on the speed and direction of wind and current. For the least favourable wind and current directions programmed in the simulation tests, it was found that:

$$d_{(1-\alpha)} = f(V_w; V_p) \quad (10)$$

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

- The ‘maximum ship’ is not permitted to navigate in the fairway when the wind speed exceeds the allowable value  $V_w > V_w^{\text{dop}}$ ;
- During fairway passage, wind speed may increase by not more than 2.5 m/s.

Simulation tests showed that statistically significant reduction of safe manoeuvring area width occurs when the wind speed drops by about 2.5 m/s (Gucma, 2015).

The allowable wind speed for commercial vessels in Polish ports, not applicable to sea ferries, is around 10 m/s (5–6°B) and winds ranging 7.5–12.5 m/s occur approximately 30–40 days per year, i.e., the approximate frequency of wind speeds in the above range is approximately 10% in a year. The annual frequency of maximum wind speed occurrence for a specific manoeuvre is, respectively:

$$P_h = 0.1 \quad (11)$$

Given the frequency of wind speeds in the maximum range for a given manoeuvre, the likelihood of accident (grounding of a ‘maximum ship’ proceeding along the fairway) is defined by the following relationship:

$$P_a = P_{ai} \cdot P_h \cdot I_r \quad (12)$$

The likelihood of a ‘maximum ship’ grounding calculated at specified (design) confidence levels for allowable wind speed of 10 m/s is:

$P_a = 3 \cdot 10^{-4}$  – ships carrying dangerous goods, design confidence level of  $(1-\alpha) = 0.997$ ;

$P_a = 5 \cdot 10^{-3}$  – other ships – design confidence level of  $(1-\alpha) = 0.95$ .

The likelihood of grounding for another allowable wind speed will depend on the annual frequency of wind occurrence ( $P_h$ ) on  $(V_w^{\text{dop}} - 2.5 \text{ m/s}) \div (V_w^{\text{dop}} + 2.5 \text{ m/s})$  interval.

**The likelihood of an accident caused by technical failure of the rudder, engine or tugs** is determined according to the procedures below.

The technical reliability is understood as smooth, failure-free performance of a specific manoeuvre. It depends on the reliable operation of the main engine, generating sets, steering gear and tugs. Each of the above listed machines has at instant  $t$  a specific probability of reliable working of:

$P_1(t)$  – main engine;

$P_2(t)$  – generating sets;

$P_3(t)$  – steering gear;

$P_4(t)$  – tug.

To calculate the probability of reliable working of the above machinery, we use the failure rate function  $\lambda(t)$  at instant  $t$ , which is the failure density function, provided a failure has not occurred till that instant.

Considering only the phase of stable working of the marine machinery considered here (as observed by classification societies), we established that the

risk function  $\lambda(t)$  does not depend on time and is constant. The probability of reliable working of individual machines can be written as (Gućma & Łusznikow, 1995; Gućma, 2001):

$$\begin{aligned} P_1(t) &= 1 - \lambda_1 \cdot \Delta t \\ P_2(t) &= 1 - \lambda_2 \cdot \Delta t \\ P_3(t) &= 1 - \lambda_3 \cdot \Delta t \\ P_4(t) &= 1 - \lambda_4 \cdot \Delta t \end{aligned} \quad (13)$$

With the assumption that a failure of any of these machines can cause an accident in certain circumstances, the probability of reliable working of all the machines is a product of the probability of reliable working of individual machines:

$$P_t = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \quad (14)$$

which, approximated to the second order of magnitude, can be written in the form:

$$P_t = 1 - (\lambda_1 \cdot \Delta t_1 + \lambda_2 \cdot \Delta t_2 + \lambda_3 \cdot \Delta t_3 + \lambda_4 \cdot \Delta t_4) \quad (15)$$

where:

$\Delta t_1$  – time interval during the performance of a manoeuvre, in which the failure of the main engine creates a risk of an accident;

$\Delta t_2$  – time interval during the performance of a manoeuvre, in which the failure of generating sets creates a risk of an accident;

$\Delta t_3$  – time interval during the performance of a manoeuvre, in which the failure of the rudder/steering gear creates a risk of an accident;

$\Delta t_4$  – time interval during the performance of a manoeuvre, in which the failure of a tug creates a risk of an accident;

$\lambda_1$ – $\lambda_5$  – failure rate of individual machines and systems.

Some of the failures of the machines under consideration during manoeuvring in the examined area will not result in an accident. This depends on additional factors:

- ship's position in the examined area when a failure occurs;
- hydrometeorological conditions prevailing during the performed manoeuvre;
- the scope of the failure of a specific machine.

Considering the individual factors, we can conclude that:

- 1) Only in certain ship positions in the examined area a failure of a given machine leads to an accident. This is taken into account by determining specific time intervals for a given area;
- 2) Only in some hydrometeorological conditions, prevailing during the performance of a manoeuvre,

an accident may occur due to a failure of a given machine;

- 3) Only a certain extent of a failure of some machines may cause an accident (e.g., jamming of the rudder at some of its angles).

Given the above factors, the technical reliability of a ship can be written in this final form (Gućma & Łusznikow, 1995; Gućma & Ślącza, 2012):

$$P_t = 1 - \left( \lambda_1 \cdot \Delta t_1 \cdot p_{h1} + \lambda_2^2 \cdot \Delta t_2^2 \cdot p_{h2} + \lambda_3 \cdot \Delta t_3 \cdot p_{h3} \cdot p_{z3} + \lambda_4^2 \cdot \Delta t_4^2 \cdot p_{h4} \right) \quad (16)$$

where

$p_{hi}$  – probability of the occurrence of hydrometeorological conditions that may lead to an accident during a failure of  $i$ -th machine;

$p_{z3}$  – probability of rudder jamming in a specific position, which leads to a ship's accident.

The probability of an accident during the performance of a specific manoeuvre caused by a failure of one of the ship's machines under consideration can be written as follows:

$$\left( \lambda_1 \cdot \Delta t_1 \cdot p_{h1} + \lambda_2^2 \cdot \Delta t_2^2 \cdot p_{h2} + \lambda_3 \cdot \Delta t_3 \cdot p_{h3} \cdot p_{z3} + \lambda_4^2 \cdot \Delta t_4^2 \cdot p_{h4} \right) \quad (17)$$

The failure rate of a tug is calculated on the assumption that its machinery reliability is similar to that of ship's machines, i.e.:

$$\lambda_4 = \lambda_1 + \lambda_2 + \lambda_3 \quad (18)$$

The failure rate of machines affecting the safety of manoeuvring is shown in Table 2.

**Table 2. The failure rate and estimated value of mean failure-free working time (Gućma & Łusznikow, 1995)**

Type of machine	Estimated mean failure-free working time $T$ [h]	Failure rate $\lambda$ [1/h]
main engine	3000	0.00033
generating set	1000	0.001
steering gear	6500	0.00015
radar	300	0.0033
tug	650	0.0015

### Consequences of accidents in sea waterways

Accidents that may occur during ship manoeuvring in sea waterways and their consequences can be divided into three general types, with consequences determined using different methods. These are:

- grounding;

- collision with another vessel;
- ship's unintended impact against the shore or exceeded allowable kinetic energy during berthing.

**Consequences of grounding** are determined taking into account the following assumptions. Ship's grounding consists of two stages. In the first stage, the force with which the underwater part of the hull strikes the bottom acts on the ship. It is assumed that both the hull and the bottom at the point of impact are elastic bodies, so during impact of the hull against the bottom, the hull will not get permanently deformed, but the longitudinal initial speed  $V$  abruptly decreases. As a result, the ship is subjected to surging motion; the hull rises and then falls rapidly, which generates speed components  $v_x$ ,  $v_z$  and angular acceleration around the  $Y$  axis. If the ship structure was not damaged in the first stage due to impact of the hull against the bottom, it maintains a sliding motion, while the remaining energy will be turned into potential energy of the emerging part of the hull, overcoming friction forces.

The consequences of the described accident depend on such factors as the maximum kinetic energy of the ship at the instant of hull-seabed contact and allowable energy of safe contact with the bottom, at which the ship will, on its own, remain afloat. The determinant of the consequences can be represented in this form:

$$S_m = \frac{E(t)}{E_{\text{dop}}^m} \quad (19)$$

where

$E(t)$  – kinetic energy of the ship at the instant of the hull-seabed contact;

$E_{\text{dop}}^m$  – allowable energy of safe ship-bottom contact at which the ship will manage to refloat.

If the value of  $S_m$  is contained within the interval  $0 < S_m < 1$  the accident will not cause significant losses and the ship will be able to refloat on its own (or using tug assistance) without commencing a special salvage operation and without damage to the hull. However, when  $S_m > 1$ , the accident involves damage to the hull or a special salvage operation is required to pull the vessel off the ground, which is costly (vessel traffic stopped, equipment used, etc.). Damage to the hull often calls for arranging a salvage operation.

Kinetic energy of the ship at the instant it contacts the bottom accounting for added mass is determined from the following relationship (Ślącza, 1999):

$$E(t) = \frac{1}{2} M \left( 1 + \frac{2T}{B} \right) V^2 \quad [\text{kNm}] \quad (20)$$

When using simplified relationships (Gucma, 2001), the allowable kinetic energy at which a ship will refloat on its own, can be defined as follows:

$$E_{\text{dop}}^m = \frac{3 \cdot U^2}{L_{pp} \cdot B \cdot \gamma \cdot \mu \cdot \tan \theta'} \quad (21)$$

The maximum pulling force required for ship refloating is a sum of the bollard pull of the ship and that of the tugs assisting the ship in manoeuvring in a given area.

$$U = U_s^{pal} + U_h^{pal} \quad [\text{N}] \quad (22)$$

where:

$M$  – ship's mass [t];

$U$  – pulling force required for refloating [N];

$U_s^{pal}$  – ship's bollard pull with engine running astern [N];

$U_h^{pal}$  – bollard pull of the assisting tugs [N];

$\gamma$  – specific gravity of water [ $\text{N}/\text{m}^3$ ];

$\mu$  – coefficient of hull friction on the ground (depends on type of bottom);

$\theta'$  – angle of the slope in relation to grounding ship's centre line.

Using approximate methods, we can calculate the ship's bollard pull using one of the following empirical relationships (Gucma, 2001):

$$U_s^{pal} = \frac{k \cdot N_n}{9 \cdot V_{CN}} \cdot 7220 \quad [\text{kN}] \quad (23)$$

or

$$U_s^{pal} = k \cdot f \cdot N_n \cdot 7220 \quad [\text{kN}] \quad (24)$$

where:

$N_n$  – total power of main engines [kW];

$k$  – coefficient of pulling force used depends on the engine setting,

CN K = 1,

CW K = 0.3–0.5 (mean 0.4);

$f$  – empirical conversion factor depending on type of ship and propulsion:

- merchant and passenger vessels

$f = 0.005–0.011$  (mean 0.008),

- tugs (conventional propeller)

$f = 0.010–0.016$  (mean 0.013),

- tugs (Kort nozzle)

$f = 0.017–0.025$  (mean 0.021);

$V_{CN}$  – speed at full ahead [knots].

**Consequences of a collision with another vessel** are determined using the following procedure.

The main factor affecting the magnitude of the consequences of a collision involving two ships is the kinetic energy induced at the point of first contact. The kinetic energy induced at the point of first

contact of two ships in the open sea or fairway is calculated as follows:

1. Determination of the impact angle  $\beta$  of the striking ship ( $sr$ ) in relation to the course made good of the ship being struck ( $su$ ) or calculation of the angle of impact of two vessels going in opposite directions, head-on or nearly head-on.
2. Calculation of the impact energy from the relationship (Pedersen & Zhang, 1998):

$$E_K = 0.5M_{sr}(V_{sr} \sin \beta)^2 + 0.5 \frac{M_{sr}^2 (V_{sr} \sin \beta)^2}{M_{sr} + M_{su}(1 + C_{sr})} \text{ [kJNm]} \quad (25)$$

where:

$E_K$  – kinetic energy induced in the place of both hulls contact during a collision in a two-way fairway [Nm];

$M_{sr}, M_{su}$  – mass of the ships involved in a collision [kNs<sup>2</sup>/m];

$C_{sr}$  – added mass coefficient of the striking ship;

$\beta$  – impact angle of the striking ship in relation to the course made good of the struck ship [deg];

$V_{sr}$  – striking ship speed [m/s].

Consequences of a collision of vessels manoeuvring in the fairway are calculated following this procedure:

1. Determination of the impact angle  $\beta$  of the ship approaching the fairway in relation to the course made good ship of the ship on the two-way fairway or the calculation of the impact angle of ships approaching each other head-on or nearly head-on.
2. Calculation of the impact energy.
3. Calculation of the depth of hull penetration in a ship struck by another ship's bow (Zhang, 1999; Kristiansen, 2005):

$$L_p = 2.67 \ln E_k - 1.97 \ln \frac{M_{sr}}{1000} + 1.66 \quad (26)$$

where:

$L_p$  – depth of the hull penetration by the striking ship's bow [m].

The above formula is the result of an analysis of numerical function models of the absorbed energy and penetration depth. The formula, based on regression analysis, was proposed by Zhang (1999).

4. Calculation of the consequences of a collision of ships proceeding in a two-way fairway:

$$S_k = \frac{L_p}{L_{dop}} \quad (27)$$

where:

$S_k$  – consequences of a collision of vessels in the two-way fairway;

$L_{dop}$  – distance between the ship's hull-plates, regulated by separate classification society regulations.

The Polish Register of Shipping regulations for passenger and cargo vessels (except for tankers) concerning the spacing between plating of double skin hull stipulate that the adopted  $L_{dop}$  value cannot be less than 760 mm and need not be greater than 2000 mm.

**Consequences of an impact against a shore structure** are considered depending on the type of accident (accident scenarios). The following types of accidents and their consequences are distinguished:

- consequences of an unintended impact against an offshore structure, shore, or moored vessel;
- consequences of an impact against a mooring structure during berthing, which causes damage to the ship or berth (fender).

**The consequences of an unintended impact against an offshore-port structure or moored ship** depend on such factors as maximum impact energy and allowable impact energy that will not damage the hull plating. The determinant of the consequences can be represented in this form:

$$S_u = \frac{E(t)}{E_{dop}^u} \quad (28)$$

where:

$S_u$  – determinant of the consequences of an impact against an offshore/port structure, shore, or moored vessel;

$E(t)$  – maximum kinetic energy of the ship at impact against an offshore/port structure or moored ship [kJNm];

$E_{dop}^u$  – allowable energy of an impact against an offshore/port structure that will not damage the hull plating [kJNm].

When the value of  $S_u$  is contained within the interval  $0 < S_u \leq 1$ , the accident does not cause significant losses or jeopardise the environment, and a ship is able to continue a certain manoeuvre. However, when  $S_u > 1$ , damage to the hull will require specific efforts to repair it.

The maximum kinetic energy of the ship at an unintended impact against an offshore/port structure or moored vessel is determined using the approximate relationship (Gućma, 2001):

$$E(t) = \frac{M \cdot u^2}{4} \text{ [kJNm]} \quad (29)$$

where

$M$  – ship's mass and added mass [ $\text{kN} \cdot \text{s}^2/\text{m}$ ];  
 $u$  – ship's speed at impact (normal to the structure line or to moored ship side) [ $\text{m/s}$ ].

The allowable kinetic energy of an impact against a structure or moored vessel can be estimated using the fender factor. The fender factor is the ratio of maximum reaction force to kinetic energy of the impact against berth or fender. If a berth is not protected by fenders, the equivalent factor can be adopted as equal to  $k = 150 \text{ kN/kNm}$  (PIANC, 2002).

Knowing the allowable load of the hull ( $q$ ) (PIANC, 2002) and approximate surface area of the ship-berth contact ( $f$ ), we can determine the allowable impact energy.

$$E_{\text{dop}}^u = q \cdot f / k \quad [\text{kNm}] \quad (30)$$

where:

$q$  – allowable load on the hull, depending on the size and type of vessel [ $\text{kN/m}^2$ ];

$f$  – approximate surface area of ship-berth contact [ $\text{m}^2$ ];

$k$  – fender factor [ $\text{kN/kNm}$ ].

Allowable hull loads for different types of vessel are summarised in Table 3 (PIANC, 2002).

**Table 3. Allowable loads of different types of vessel hulls (PIANC, 2002)**

Type of vessel	Allowable hull load $\text{kN/m}^2$
<b>Container ship, 1<sup>st</sup> or 2<sup>nd</sup> generation</b>	< 400
3 <sup>rd</sup> generation (Panamax)	< 300
4 <sup>th</sup> generation	< 250
5 <sup>th</sup> and 6 <sup>th</sup> generations (Superpost Panamax)	< 200
<b>General cargo ship</b>	
=/ < 20,000 DWT	400–700
> 20,000 DWT 40	< 400
<b>Tanker</b>	
=/ < 60,000 DWT	< 300
> 60,000 DWT	< 350
<b>VLCC</b>	150–200
LNG/LPG tanker	< 200
Bulk carrier	< 200

**Consequences of exceeded allowable berthing energy** are determined with an assumption that, during berthing manoeuvres, the first ship-fender contact has the largest kinetic energy (Gucma, 2001; Ślaczka, Galor & Galor, 2001). The kinetic energy absorbed by the berth-fender-ship system affects the

magnitude of the reaction forces, which are critical for accident-free manoeuvre. In this connection, the berthing ship safety condition can be written as follows:

$$\begin{aligned} E(t) &\leq E_{\text{dop}}^{\text{nab}} \\ E(t) &\leq E_{\text{dop}}^{\text{stat}} \end{aligned} \quad (31)$$

where:

$E(t)$  – maximum kinetic energy of berthing (first contact with fender) absorbed by the berth-fender-ship system [ $\text{kNm}$ ];

$E_{\text{dop}}^{\text{nab}}$  – allowable kinetic energy absorbed by the berth-fender-ship system [ $\text{kNm}$ ];

$E_{\text{dop}}^{\text{stat}}$  – allowable kinetic energy at which the created reaction forces of the berth-fender-ship system do not cause permanent deformation of the hull (belting) [ $\text{kNm}$ ].

Exceeded allowable kinetic energy of the ship's first impact against the berth may result in damage to the hull and/or fender and hence, in this type of emergency scenario, the consequences of hull and fender damage are calculated separately:

- determinant of fender (berth) damage consequences:

$$S_o = \frac{E(t)}{E_{\text{dop}}^{\text{nab}}} \quad (32)$$

- determinant of hull damage consequences:

$$S_s = \frac{E(t)}{E_{\text{dop}}^{\text{stat}}} \quad (33)$$

If  $S_o > 1$ , the fender sustains damage, while  $S_s > 1$  leads to permanent deformation of the hull.

The maximum kinetic energy of berthing can be determined by simulation or empirical methods. When a port basin, i.e., its waterway and shore equipment, is designed by simulation methods, the maximum kinetic berthing energy is chosen as the largest of those obtained in all series of simulated trials. Using empirical methods, we can determine the maximum kinetic energy of berthing using the following approximate relationship:

$$E(t) = \frac{M \cdot u_a^2}{4} \quad [\text{kNm}] \quad (34)$$

where:

$u_a$  – speed normal to the berthing line at the time of emergency approach to berth [ $\text{m/s}$ ].

Normal speed of emergency berthing is determined empirically as 1.5 times greater than design speed for fenders and piers:

$$u_a = 1.5u_o \quad (35)$$



where:

$u_o$  – ship speed normal to the berthing line at the instant of contact is adopted as the design speed for fenders and berthing structures [m/s].

Design berthing speed normal to the berth is determined using a chart of the function of a five-degree scale of navigational conditions and ship's deadweight capacity (DWT) (Figure 1).

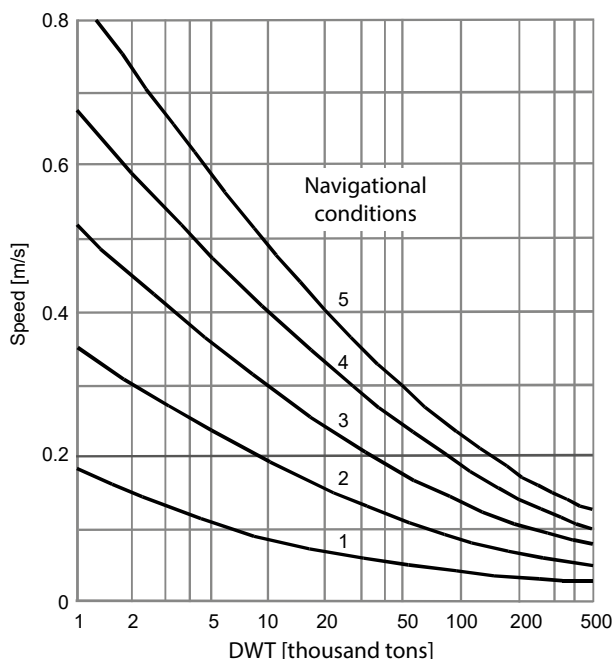


Figure 1. The design berthing speed as a function of ship's capacity (PIANC, 2002): 1 – easy berthing, sheltered, 2 – difficult berthing, sheltered, 3 – easy berthing, unsheltered, 4 – moderate berthing, unsheltered, 5 – difficult berthing, unsheltered

The allowable kinetic energy absorbed by the ship-berth-fender system  $E_{dop}^{nab}$  should be adopted as equal to the allowable kinetic energy of the fender protecting the berth.

The allowable kinetic energy at which the created reaction forces of the ship-berth-fender system do not cause permanent deformation of the hull  $E_{dop}^{stat}$  is determined using the energy performance characteristic of the fenders installed on the berths. The allowable reaction force of the hull is an input parameter for this characteristic:

$$Q_{dop}^{stat} = f_o \cdot q \quad (36)$$

where:

$Q_{dop}^{stat}$  – allowable reaction force of the hull during contact with the fender [kN];

$f_o$  – surface area of a fender shield installed on the berth [m<sup>2</sup>];

$q$  – allowable load of the hull [kN/m<sup>2</sup>].

## Conclusions

1. The universal method of formal safety assessment of ship manoeuvring in sea waterways allows us to assess the safety of ship operation on various types of waterway and in ports.
2. The method can be employed in designing waterways and ports using different methodologies: deterministic (empirical methods of marine traffic engineering) and probabilistic (statistical and simulation methods of marine traffic engineering).
3. The developed universal method of formal safety assessment of ship manoeuvring may be a basis for standardizing in Poland the methods of performing 'navigational analyses'. This is important because, unlike the developed countries of Western Europe, the Polish legal system has a gap in the consistent approach to risk management addressing newly built and existing elements of sea waterways and ports. The only mandatory document in this field is the so called 'navigational analysis', carried out in accordance with a regulation of the minister responsible for the maritime economy. This analysis should include a safety assessment performed in an objective and measurable manner, which is consistent with IMO recommendations (IMO, 2002; IMO, 2006).

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