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Simplified methods for the assessment of consequences of navigational accidents as a tool for development of port regulations: Liquefied Petroleum Gas ships in Świnoujście–Szczecin waterway taken as example

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Abstract

The paper presents research performed in order to indicate the threats posed to liquid petroleum gas (LPG) carriers maneuvering in the ports and fairway of Szczecin–Świnoujście. The effects of collision with another vessel, going aground, or striking a stationary object are taken into account. As a safety criterion, the possibility of damage to the cargo tanks is taken. As a result of the research, recommendations for ship movement in the ports and fairway were issued. The research method applied in this study consisted of several stages. In the first stage, experts determined possible scenarios of collision and grounding, taking into consideration local and navigational conditions. In the following steps, the external energy was calculated and an empirical model was used to determine the damage to the LPG carrier. In the last step, the necessary measures to be introduced port regulations are presented as conclusions of the research.

Introduction

The entrance of vessels carrying dangerous goods in a particular area should be preceded by risk analysis. The aim of this assessment is to determine whether the risk is acceptable or not and what actions should be taken in order to minimize it to acceptable level.

The article describes an analysis of navigational risks based on the following accidents:

1. Collision of an LPG carrier with another ship on crossing courses, aimed at gathering the substantive information required to regulate the traffic of LPG and other vessels;
2. Collision of an LPG carrier with another ship on parallel courses, aimed at developing regulations on overtaking and passage;
3. Grounding of an LPG carrier;
4. LPG carrier striking infrastructure.

Other accidents, such as fire on an LPG carrier during passage, pollution as an effect of an operation error during passage, pollution during discharge operation, and accidents during mooring operations, are not taken into consideration because the navigational analysis concerns terminal building permissions, whereas the above-mentioned accidents are the result of operational.

In this analysis, risk reduction methods are taken into account as follows:

1. Suspension of traffic of LPG carriers or other vessels during passage;
2. Additional tug assistance during passage;
3. LPG carrier speed reduction;
4. Restrictions concerning LPG carrier movement in times of limited visibility;
5. Establishment of safety zones around the LPG Carrier;

6. Active use of VTS beyond the normal responsibilities for planning and monitoring the passage of LPG carriers;
7. Ensuring tow services during mooring and unmooring.

Acceptable risk determination

The concept of acceptable risk is not specified in Polish legislation regarding maritime structures; in addition, operations involving vessels of such large size are too limited in number, in the researched area, to be able to create acceptable risk standards (Gucma, 2005; 2009).

To date, no damage to LPG carriers as a result of navigational accidents have been reported. This should be considered as a very rare event, for which a statistical analysis of recorded data cannot be used.

It was decided to carry out a risk analysis by analyzing accident scenarios and determining only the effects of accidents. In this approach, the risk is reduced to an analysis of the potential consequences of an accident, without analyzing its frequency.

As a consequence of this choice, it is assumed that the risk may only belong to two categories:

R = {damage to the cargo tanks;
no damage to the cargo tanks}

An acceptable risk, *Ra,* is on in which there is no possibility of damage to the LPG cargo tanks:

Ra = {no damage to the cargo tanks
due to accident}

An unacceptable risk is one in which there is a possibility of damage to the LPG cargo tank as a result of a navigational accident.

Determination of accident scenarios

The potential accident scenarios are endless, in the present study they have been narrowed them to the worst ones (i.e. WCS – Worst Case Scenarios), a practice often used when enough information is known to allow a classification of the effects of accidents. The analysis focused on the area of the port of Świnoujście, chosen because of the high presence of tourists. The four types of accidents with the greatest consequences were selected. All of them were analyzed:

1. LPG tanker collision with another ship on crossing courses;
2. LPG tanker collision with another ship on parallel courses;
3. Grounding of LPG tanker;
4. LPG tanker striking infrastructure.

From here on, accidents will be indicated as "Ad.".

Ad. 1. It was assumed that the vessel does not move (worst-case scenario because of the collision energy) and is hit by the bow perpendicularly, which can cause the most severe effects. The goal is to determine the speed and size of vessel that can move with opposing courses in the area where the LPG tanker maneuvers.

Ad. 2. It was assumed that a bow to bow collision occurs as both vessels are moving. This is an unlikely scenario because of the construction of vessels. Vessels usually slip along each other's sides and the effects are not significant.

Ad. 3. It was assumed that, as a result of loss of control, the LPG tanker hits the elements of the breakwater in Świnoujście with its bow, at the speed which it had during the passage.

Ad. 4. It was assumed that LPG tanker engine fails, the vessel drifts toward the breakwater in Świnoujście and collides with the elements of its strengthening (e.g. tetrapod block) or there is a rudder fail and the LPG tanker is subject circulation crashing into the side of the breakwater.

In all cases, the LPG tanker and colliding vessel speed were varied (case 1 and 2) to determine the critical values of energy.

Determining the effects of accidents

Detailed information on methods for determining the consequences of sea accidents can be found in the publication (Gucma, 2012).

In the presented study the procedure adopted was as follows:

1. determination of the energy released during the collision;
2. identification of the material damaged in the collision;
3. determination of the volume of the element colliding with tanker;
4. determination of the expected maximum distance of penetration of the hull;
5. determination of whether the risk is exceeded, i.e. cargo is damages.

The energy was determined separately for each method, considering the movement of each vessel before and after the crash. To determine what material was destroyed following each collision, two methods were used complementarily.

For high-energy (> 50 MJ) collisions, a modified Minorski method was used, which was presented by Reardon and Sprung (Reardon & Sprung, 1996) as the correlation shown in Figure 1 in the form of:

$$E = 47.087R_T + 28.4 \qquad (1)$$

where: E is the energy absorbed in the collision [MJ]; R_T is the damaged hull material [m^3].

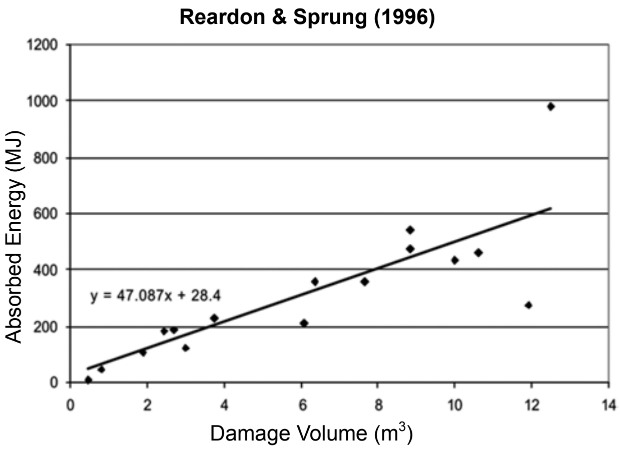

Figure 1. Reardon–Sprung method for determining the material damaged in a collision

In the case of low energy (E < 50 MJ) collisions, the general method of Zhang was used (Zhang, 1999) in the form of:

$$E = 3.5\left(\frac{t}{d}\right)^{0.67} \sigma\, R_T \qquad (2)$$

where: t is the plating thickness in the area of collision, d is the average size of plates and stiffeners, σ is the steel ductility limit [N/mm^2].

Assumptions for testing LPG tanker damage

Several typical LPG tankers of similar size were used to calculate the average values of their parameters in relation to the analyzed LPG tanker, as shown in Table 1.

Table 1. Parameters of researched tanker in terms of collision analysis

Parameter	LPG	Units	Name, description
$L =$	220	m	length
$B =$	32	m	breadth
$T =$	11	m	draft
$\delta =$	0.75	[–]	block coefficient
$V = L \cdot B \cdot T \cdot \delta =$	58 080	m^3	volume of displacement
$m = V \cdot 1000 =$	58 080 000	kg	vessel mass
$C_{my} = 1+2T/B =$	1.69	[–]	mass ratio of accompanying water in y direction (lateral movement)
$m_{vy} = m \cdot C_{my}$	98 010 000	kg	virtual mass
$C_{mv} =$	1.05	[–]	mass ratio of accompanying water in x direction
$m_{vx} =$	60 984 000	[kg]	mass with accompanying water mass in x direction (longitudinal movement)
$H/T =$	0.55	[–]	typical ratio of H/T
$H =$	20.00	[m]	freeboard
$d_b/B =$	0.0496	[–]	typical ratio of d_b/B
$d_d/H =$	0.124	[–]	typical ratio of d_d/H
$d_{dz}/L =$	0.125	[–]	typical ratio of d_{dz}/L
$d_b =$	1.60[1]	[m]	distance between tank and hull
$d_d =$	2.50[1]	[m]	distance between tank and bottom
$d_{dz} =$	27.50[1]	[m]	distance between tank and bow
$t =$	35	[mm]	Plating thickness
$d =$	2	[m]	the average size of plates (stiffeners)
$t/d =$	0.018	[–]	ratio of t/d
$\sigma =$	270	[N/mm^2]	steel ductility limit

[1] The key parameters for risk analysis

The key parameters for risk analysis are highlighted in red and include the distance of tanks from the sides, bottom and bow, as shown schematically in Figure 2. Exceeding any of these parameters, causing the insurgence of risk in particular scenario, is not acceptable.

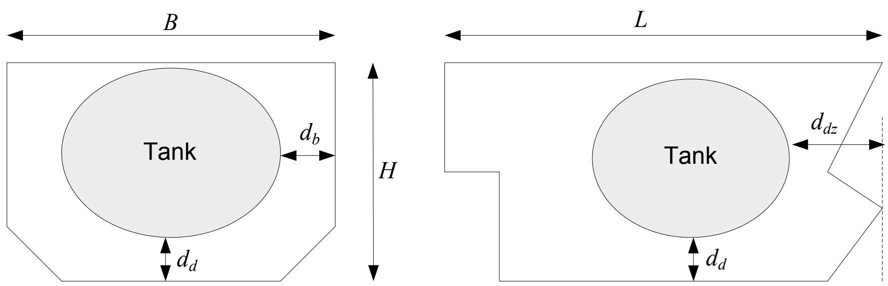

Figure 2. The critical distances for the tanks

Effects of a collision with another ship on crossing courses

In this situation, it is assumed that the vessel is not in movement, representing the worst-case scenario because of the collision energy, and is hit perpendicularly by the other vessel's bow, which can cause the most severe effects (Figure 3). In case the LPG tanker were moving, the absorbed energy would be lower because of the losses due to the change in speed and slipping of the vessels along each other's side after the accident.

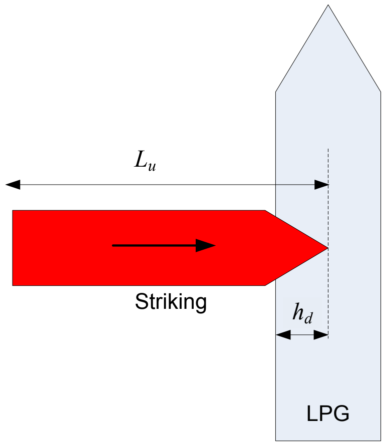

Figure 3. Collision scenario No. 1

Energy was estimated based on the coefficient of the accompanying water mass, equal to 0.66 even for stationary tankers (Zhang, 1999):

$$E = \frac{m_{LPG}}{m_{LPG} + 0.6 m_u} E_0 \quad (3)$$

where: E_0 is the energy of striking vessel ($E_0 = 0.5 m_{ux} v^2$).

The striking vessel is assumed as a general cargo carrier, with variable length and speed. Expected parameters of striking vessels are presented in Table 2.

Table 2. Parameters of striking vessels

L_u [m]	m [t]	B [m]	H [m]	R_l [m]	R_v [m]
50	1100	10	7	2.10	0.88
80	4000	13	9.1	2.73	1.14
100	7500	16	11.2	3.36	1.40
120	13000	17	11.9	3.57	1.49
150	20000	22	15.4	4.62	1.93
170	32000	24	16.8	5.04	2.10
190	40000	28	19.6	5.88	2.45

where: R_l and R_v are parameters for calculation the size of bulbous bow.

The shape of the bow was modeled in the simplified form presented in Figure 4. The angle $\phi = 20^o$, taken for calculation, is adequate for a slim vessel. In these conditions, the safety factor will be greater than for vessels with bigger ϕ angle, such as bulk carriers.

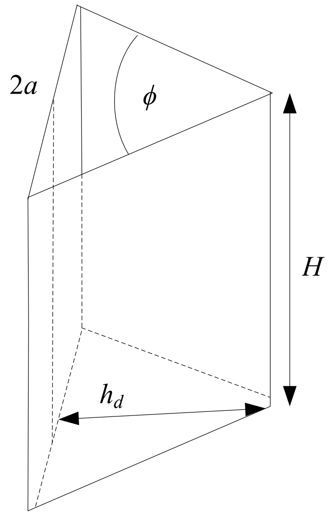

Figure 4. The simplified form of colliding bow section

The volume of the penetrating part was calculated according to a simple trigonometric formula (Figure 4) as follows:

$$h_d = \sqrt{\frac{3R_t}{2H \tan(\phi/2)}} \quad (4)$$

where: R_t is the volume of damaged material, H is the freeboard length, ϕ is the bow angle.

In literature, it is possible to find information (Zhang, 1999) regarding the amount energy absorbed by the bow of the colliding ship. The values range from 0 to 20% depending on the stiffness and construction characteristics of the bow. In the presented calculations, 0% absorption was assumed, meaning that the bow of striking vessel is not damaged and thus increasing the safety margin.

The results of the calculations are presented in Table 3. The energy, amount of damaged material, and depth of penetration, $h_{d,}$ are reported. The colors indicate that a critical limit has been exceeded there is a possibility of damage to the tank.

The ranges of h_d have been marked as follows:

1. red color – exceeded the critical value of h_d, certain damage to the tank i.e. $h_d >= 1.5$ m;
2. orange color – very likely damage to the tank, dangerous values, i.e. 1 m $< h_d <$ 1.5 m;
3. yellow color – possible damage to the tank, values close to dangerous ones i.e. 0.5 m $< h_d <$ 1.0 m.

Table 3. Energy, damaged material and the depth of penetration, h_d, for LPG struck in the side by a cargo ship with different parameters and speed

Energy [MJ]

L_u [m]	Speed [m/s]				
	1	2	3	4	5
50	1	2	5	9	14
80	2	8	18	33	51
100	4	15	34	60	94
120	6	25	56	100	157
150	9	37	83	148	231
170	14	55	124	221	346
190	17	66	149	265	414

Damaged material [m^3]

L_u [m]	Speed [m/s]				
	1	2	3	4	5
50	0.009	0.009	0.009	0.009	0.009
80	0.033	0.033	0.033	0.1	0.5
100	0.060	0.060	0.1	0.7	1.4
120	0.100	0.100	0.6	1.5	2.7
150	0.147	0.2	1.2	2.5	4.3
170	0.220	0.6	2.0	4.1	6.7
190	0.263	0.8	2.6	5.0	8.2

Depth of hull penetration h_d [m]

L_u [m]	Speed [m/s]				
	1	2	3	4	5
50	0.1	0.1	0.1	0.1	0.1
80	0.2	0.2	0.2	0.3	0.7
100	0.2	0.2	0.3	0.7	1.0
120	0.3	0.3	0.7	1.0	1.4
150	0.3	0.3	0.8	1.2	1.5
170	0.3	0.5	1.0	1.4	1.8
190	0.3	0.6	1.1	1.5	1.9

Effects of a collision with another passing ship

The possible consequences of an accident during passage including an LPG carrier were calculated. Such collisions are rare, and their effects, due to the geometry of the bow, are usually not significant. Besides, energy dissipation due to friction usually occurs and the ships continue their movement. For the purpose of the present research, it was assumed that the collision occurs bow to bow and the all energy absorbed causes damage to the ships' material. The geometry of the collision is shown in Figure 5. As a simplified model, the wedge-shaped bow was used (Figure 4). It was assumed that half of the energy is absorbed by LPG carrier and half by striking ship. The energy is calculated as:

$$E = E_{\text{LPG}} + E_U \tag{5}$$

where: E_{LGP} is the energy of LPG carrier, E_U is the energy of a striking vessel.

For simplicity, it is assumed that the LPG carrier is moving at a speed of 4 m/s (approx. 8 kn). However the size and speed of the striking vessel were changed in each trial. The results are presented in Table 4.

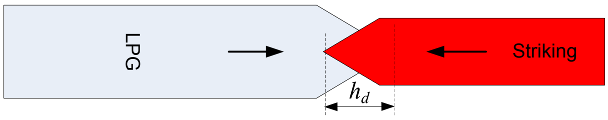

Figure 5. Collision scenario No. 2

Table 4. Energy, damaged material and the depth of penetration, hd, for LPG struck in the bow part by a cargo ship with different parameters and speed

Energy [MJ]

L_u [m]	Speed [m/s]				
	1	2	3	4	5
50	244	245	247	249	251
80	245	248	253	261	270
100	246	252	262	275	293
120	247	258	275	299	329
150	249	265	291	328	375
170	252	278	320	378	454
190	254	286	338	412	506

Damaged material of the bow part [m^3]

L_u [m]	Speed [m/s]				
	1	2	3	4	5
50	4.6	4.6	4.6	4.7	4.7
80	4.6	4.7	4.8	4.9	5.1
100	4.6	4.7	5.0	5.2	5.6
120	4.6	4.9	5.2	5.7	6.4
150	4.7	5.0	5.6	6.4	7.4
170	4.8	5.3	6.2	7.4	9.0
190	4.8	5.5	6.6	8.1	10.1

Depth of penetration of the bow part h_d [m]

L_u [m]	Speed [m/s]				
	1	2	3	4	5
50	2.4	2.4	2.4	2.4	2.4
80	2.1	2.1	2.1	2.1	2.2
100	1.9	1.9	1.9	2.0	2.1
120	1.8	1.9	1.9	2.0	2.1
150	1.6	1.7	1.8	1.9	2.0
170	1.6	1.6	1.8	1.9	2.1
190	1.4	1.5	1.7	1.9	2.1

In any of the scenarios studied, there were no significant damages as the distance between the bow and the tank, d_{dz}, typically over 20 m, was not exceeded (Table 1).

Effects of a side impact with a stationary object

In the event of a loss of power or uncontrolled turn as an effect of malfunctioning, such as the jam of a rudder, the vessel can hit a stationary object, for example the breakwater in Świnoujście. It was assumed that such a collision occurs amidships (the largest energy for absorption) and that the LPG carrier is moving only in the direction of the colliding side. The geometry of the collision is shown in the Figure 6.

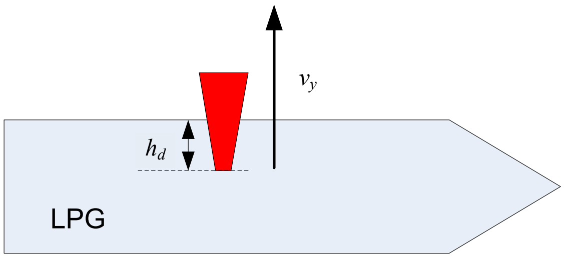

Figure 6. Collision scenario No. 3

It was assumed that the LPG carrier strikes a tetrapod block having the size presented in Figure 7. These dimensions were used to model the hull penetration depth, h_d, assuming that its volume is that of a truncated cone:

$$V = \frac{\pi}{3}(R^2 + r^2 + Rr) \qquad (6)$$

where: R and r are the diameters of the upper and lower parts, respectively.

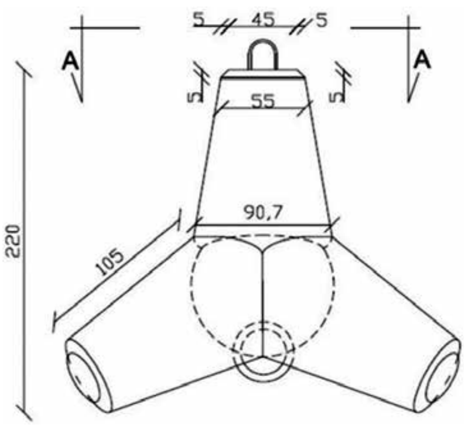

Figure 7. Tetrapod block used for protection the breakwater in Świnoujście

The energy, damaged material, and depth of penetration, h_d, are presented in Table 5.

Table 5. Energy and damages of LPG carrier colliding with stationary object (tetrapod block)

Lateral speed v_y [m/s]	0.25	0.5	0.75	1
Energy [MJ]	3	12	28	49
Damaged material [m^3]	0.05	0.19	0.44	0.78
Hull penetration h_d [m]	0.03	0.12	0.28	0.49

The possible lateral speeds were estimated by using a model of the ship's motion when it is drifting with wind having speeds of 10 and 20 m/s, as well as during the uncontrolled turn resulting from the jam of the rudder in position of 20° and 35° (Tables 6 and 7).

Table 6. Lateral speed of LPG carrier caused by side wind (model)

Wind [m/s]	Drift lateral speed v_y [m/s]
10	0.32
15	0.46
20	0.71

Table 7. Lateral speed of LPG carrier during uncontrolled turn at a speed of v = 4 m/s

Rudder [°]	Drift lateral speed v_y [m/s]
20	0.52
35	0.68

Comparing the results obtained in the different conditions, it can be concluded that, besides intentional turning and mooring, there is no situation in which an LPG carrier has a lateral speed greater than 1 m/s, and thus the possibility of damage to the hull of the ship is never present in the area of the port Świnoujście.

Effects of going aground

The possibility of LPG carrier grounding as a result of a loss of control (rudder jam) was examined. In most part of the fairway, the bottom is soft and the effects of grounding will not be significant; however, in case of grounding on the Świnoujście breakwater, serious damage to the carries is expected. Such a situation will be examined in this section. Results of a crash have been calculated under the assumption that the tanker enters aground where the bottom is inclined at an angle of α = 45°. The angle of the bow was assumed to be ϕ = 30°. The simplified form of damage to the hull in the form of a pyramid was assumed (Figure 8), which resulted in a dependence on the depth of penetration, h_x, calculated from the bow:

$$h_x = \sqrt[3]{\frac{3Rt}{\tan(\phi/2)\tan\alpha\sqrt{1+\tan(\phi/2)}}} \qquad (7)$$

The calculated energy values, deformation, and depth of penetration of the bow, h_x, are shown in Table 8.

It is worth mentioning that in any case there is no damage (h_x value) that represents an actual threat to the LPG tanks, which are situated at a distance of more than 20 m from the bow.

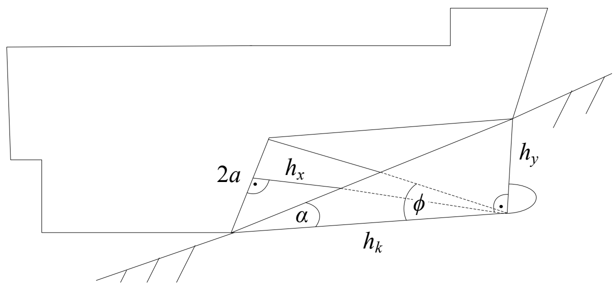

Figure 8. Simplified form of the bow of an LPG carrier after grounding

Table 8. Energy and damage the LPG tanker ran aground

Speed [m/s]	1	2	3	4	5	6
Energy [MJ]	30	122	274	488	762	1098
Material [m^3]	0.00	1.99	5.22	9.76	15.58	22.70
Depth of penetration form the bow h_x [m]	0.0	2.8	3.9	4.8	5.7	6.4
Height of the pyramid penetration h_y [m]	0.0	1.6	2.3	2.8	3.3	3.7

Conclusions

The acceptable risk limit is exceeded only in the case of collision with a large vessel with the following parameters:

- length of striking ship: $L > 100$ m;
- speed of striking ship: greater than 6 kn;
- angle of impact: 90°;
- place of impact: close to amidships of LPG carrier.

In other cases, there is no risk of damage to the cargo tanks. Based on the analyzed data regarding the possibility of damage to the LPG tanks as a result of accidents, a few recommendations could be given regarding the movement of LPG carriers in the ports and the fairway of Szczecin–Świnoujście:

1. LPG carriers cannot cross courses with the underway vessels having a length $L > 100$ m if its speed exceeds $v > 4$ kn;
2. LPG carriers can cross courses with the underway vessels with a length $L < 50$ m moving with any speed;
3. LPG carriers can pass any vessel on the fairway;
4. Going aground or side impact with a stationary object (e.g. elements of a Świnoujście breakwater) as a result of technical failure does not cause damage to cargo tanks;
5. In the vicinity of moored LPG carriers, a vessel with length $L < 150$ m can pass with a reduced speed of $v < 4$ kn.

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