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Damage probability of offshore pipelines due to anchoring ships

SUMMARY

The paper presents a simulation method for evaluation of underwater pipeline safety in the aspect of anchoring vessels in emergency. The simulation model is probabilistic, based on Monte Carlo simulation principle including a simplified algorithm of human decision making and a simulation module of mechanics of anchoring ships. Results achieved with the presented model can be applied to determine safety of underwater pipelines and as guidelines for pipeline protection. The paper presents also an example case study of safety determination of a planned underwater gas pipeline to be located on the Baltic Sea bed.

INTRODUCTION

The evaluation of safety of complex marine systems demands creation of various models which include such factors as : ship's traffic, meteorological conditions, human reliability and other relevant navigational features. Most of the parameters has a random nature and analytical models are not fully suitable to describe it. Safety evaluation of such systems can be performed by means of simulation methods, particularly those using Monte Carlo simulation approach. The paper presents a method of creating simulation models for determination of offshore pipeline safety regarding possible damage caused by anchoring ships. The basic advantage of the applied models is that a large amount of simulated data from a wide span of time can be obtained faster, and changing the input parameters is very simple. It should be also noticed that the presented model takes into account the human factor associateded with any errors and decisions to be made (e.g. decision to drop the anchor). The presented method takes also into account physical and hydrodynamical aspects of ship's behaviour in different conditions including lying at anchor.

ESTIMATION OF PROBABILITY OF ANCHORING - INDUCED DAMAGE BY MEANS OF TRAFFIC SIMULATION MODEL

There are several important parameters which affect the model input parameters. The most significant are : modelling the ships' traffic, meteorological conditions, technical failures and human reliability.

Ships' traffic

The traffic of ships along a definite route is considered as a process affected by many factors changing with time, as well as by the route length. The factors make the process random, hence probabilistic methods are used for its description. The stream of ships in the water area can be represented on a time axis where the instants of passing ships through a given point are random. The random stream of ships can be analyzed by examining the distributions of :

- the number of ships passing through a given point within the time interval Δt
- the time intervals between events of successive ship's passing
- ship's speed in a given area
- the scatter of ship positions against the assumed (mean) trajectory.

The number of ships passing through a given route point in the case of free movement, i.e. that when the ships are free to choose the speed and manoeuvres, can be considered as a random process described by the Poisson distribution (Fig.1), where the probability of the appearance of the number of ships X = n within the time interval Δt, is equal to :

$$P(X = n) = \frac{(\lambda \Delta t)^n}{n!} e^{-(\lambda \Delta t)} \quad (1)$$

$$\Delta t \geq 0$$

where : λ - traffic intensity [ships/h].

The distances between vessels thus comply with the exponential distribution. In the considered case when a minimum safe distance between successive ships is assumed, a two-parameter shifted exponential distribution is selected for this research.

The ship's speed in free traffic is described by the normal distribution [3] of the following density function :

$$f(V_s, \delta_V) = \frac{1}{\delta_V \sqrt{2\pi}} e^{-\frac{(V-V_s)^2}{2\delta_v^2}} \tag{2}$$

where :

V_s – mean speed of ships of a given class

δ_v – standard deviation of ship speed.

It is assumed that the speed this way determined is limited by the speed possible to be obtained with the propulsion machinery installed on the ship, as the upper bound.

Statistical data on ship's parameters such as length, breadth, draught, and type can be easily calculated with the use of an appropriate distribution function.

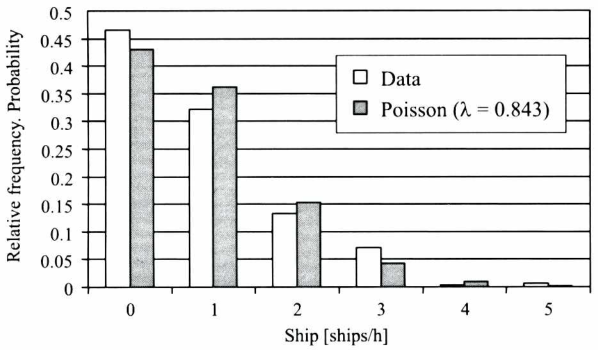

Fig. 1. Statistical sample of ships entering and leaving Świnoujście Port, fitted to the Poisson distribution

Course and position of ships

The scatter (offset) of ship positions against the chosen trajectory (route course) can be described by normal distribution, and in the case of a navigational obstruction - by an asymmetric distribution (e.g. Rayleigh's distribution). For modelling the ship traffic in open waters a combination of normal and uniform distributions is usually applied. It is assumed that only 1% of the traffic is distributed uniformly and the normal distribution is hence modified accordingly [1 , 5].

Weather conditions modelling

For the presented models the effects of wind and current are crucial. Knowledge of winds and currents affecting behaviour of disabled ships (drift speed and direction) can be very useful for modelling consequences of an accident. The wind vector is usually modelled with the use of available long-term statistical data. It should be noted however that the wind speed is correlated with its direction, hence a conditional probability distribution of wind from a given direction, should be applied. Statistical data bases are usually prepared for meteorological stations located on land, therefore special correction factors for wind speed at open sea should be applied.

Technical failures

Technical reliability (i.e. influence of possible failures of some ship equipment elements) can be taken into account for such devices as main engines, steering gears, auxiliary engines, generators, radars etc. It can be estimated by using the technical reliability functions. In order to calculate the reliable operation probability of the above mentioned appliances, an intensity function of damage with time, i.e. a density function of damage occurrence on the condition that no damage has taken place so far, is used. After multiplication of the probabilities under assumption of its independence the overall technical failure probability can be estimated. For commercial vessels it is estimated to be about 10^{-4} failure per hour of operation. The technical reliability calculation can be performed under the assumption that an examined device has been operating failure-free for some time. Then it is possible to consider the device reliability in its stable stage of operation. During the stable stage of operation the risk function $\lambda_e B(t)$ does not depend on time and it can be considered constant. On this basis the probability of reliable operation can be expressed by the below given equation under the assumption that the times between successive technical failures of ship can be represented by the exponential distribution with the failure intensity λ_e :

$$P(t) = e^{-\lambda_e t} \tag{3}$$

In the presented models the technical failure probabilities are calculated with the use of the exponential distribution taking into account the time of sailing in an investigated area.

EFFECT OF EXTERNAL CONDITIONS ON MOVEMENT OF DISABLED AND ANCHORED SHIPS

Any technical failure of the main engine, leading to lack of propulsion, can be dangerous for ships especially during unfavourable external conditions (waves, wind). The extensive rolling could result in cargo shifting and loss of stability. In bad weather conditions, in the case of main engine's damage, the navigator usually tries to drop anchor and thus to stop ship's drifting. The anchor drop should be performed at a speed as low as possible, as the greater ship's speed and the greater ship's size the greater the chance of breaking the anchor chain. The anchor, after dropping, can be dragged due to its insufficient holding force. In this case the ship at anchor moves with a determined speed.

To determine the way (distance) and time of free (inertial) braking from full ship's speed up to full stop, with no wind, the real average parameters of free stopping of ships were assumed for the model on the basis of the analysis of the ship manoeuvrability trial results [8]. The analysis enclosed real ways and times necessary for the free stopping of the ship as a result of the FULL AHEAD-STOP manoeuvre, and it concerned ships of the size from 3,000 dwt up to 25,000 dwt, the block coefficient ranging from 0.7 to 0.87, and the initial speed of 14 knots. The analysis might also be applied to smaller initial speeds and final speeds greater than zero when assuming 10 % accuracy and knowing the percentage of the relative drop of ship's speed and free stopping way in function of time (Tab.1) [8].

Tab. 1. The relative drop of ship's speed, free stopping way and duration time resulting from FULL AHEAD-STOP manoeuvre [%]

Time [%]	**Speed** [%]	**Way** [%]
10	78	28
20	59	45
30	45	59
40	34	70
50	25	78
60	18	85
70	12	90
80	8	94
90	4	98
100	0	100

Tab.2. The average covered way (distance) and free stopping time resulting from FULL AHEAD-STOP manoeuvre, in function of ship's deadweight, calculated on the basis of Tab.1 and publ. [8]

Ship's deadweight	Covered way (distance) of free braking		Time of free braking	
[thou t]	under ballast [m]	loaded [m]	under ballast [min]	loaded [min]
1	740	1030	5.6	12
2	1480	2075	8	16
5	2070	2960	12.8	24
20	3700	5180	23.2	36
40	5180	6660	30.4	44
60	6220	8000	35.2	48.8

In order to determine the ship's movement parameters in conditions of wind and wave effects, some analytical-experimental formulae were used [7, 8, 9]. Namely :

1. To assess the wind drift velocity of the stopped ship the following was determined [8] :

the wind pressure force causing ship's drift, R_w :

$$R_w = 0.674 S_{wr}^2 F_n \sin\alpha_w \ \ [N] \tag{4}$$

where :

S_{wr} – relative wind speed [m/s] (for a stopped ship - equal to the real wind speed)
F_n – windage area [m^2] (at the most - the longitudinal cross section area of the above-water part of the drifting ship)
α_w – wind course angle [°],

the resistance of the underwater body of the drifting ship, R_{dr} :

$$R_{dr} = 0.5\psi_{dr}\gamma V_{dr}^2 F_P \ \ [N] \tag{5}$$

where :

ψ_{dr} – resistance coefficient :
0.10 – for the drift speed close to zero
1.15 – for common drift speeds (usually in practice $V_{dr} > 0.5$ m/s)
γ – specific water gravity (of 10150 N/m^3 on average, for the South Baltic)
V_{dr} – drift speed [m/s]
$F_P \approx L\cdot d$ – the longitudinal cross section area of the underwater part of the drifting ship

finally, by comparing the expressions (4) and (5), the maximum wind drift speed V_{dr} was determined :

$$V_{dr} = \sqrt{\frac{0.674 S_{wr}^2 F_n}{0.5\psi_{dr}\gamma F_P}} \ \ [m/s] \tag{6}$$

while the drift direction corresponds to that of the wind.

2. To determine the movement parameters of the drifting ship affected by the wind, the following was established [7, 9] :

the speed loss due to the drift :

$$V = 0.514 V_n + -\left(0.745 H - 0.275\frac{\pi}{180}\alpha H\right)\left(1 - 0.6939 D V_n 10^{-6}\right) \tag{7}$$

where :

V – ship's speed under wind and waves [m/s]
V_n – ship's speed in calm water [m/s]
H – mean wave height [m]
α – course angle of either wind or waves [°]
D – ship's displacement [t]

the drift angle β :

for ship's speed greater than wind speed :

$$\sin\beta = k\left(\frac{S_w}{V}\right)^2 \sin\alpha \tag{8}$$

where :

β – wind drift angle
k – drift coefficient, determined experimentally for a given ship : 1.3 - for ships of the displacement from 2,000 to 20,000 t
S_w – wind speed [m/s]

for ship's speed smaller than wind speed :

the drift direction was assumed the same as the resultant vector of ship speed and wind speed

the drift current speed V_{dc} :

$$V_{dc} = \frac{0.000508 t_w S_w}{\sqrt{\sin\phi}} \ \ [m/s] \tag{9}$$

where :

V_{dc} – drift current speed [m/s]
t_w – wind duration time [h]
ϕ – geographic latitude [°]

to determine the direction of the wind current on the open sea surface it was assumed that the wind current is deviated from the wind direction by about 40° to the right due to the effect of Coriolis force in the Northern hemisphere.

3. The holding force of the anchor was determined by estimating the holding force coefficient related to the anchor weight, W_a, dependent of a kind of anchor and sea bottom [8] :

Tab.3. Relative anchor holding force coefficient k_a

Type of anchor	Kind of sea bottom						
	Flat rock covered with layer of silt	Very soft silt	Silt	Clay	Sand	Sand and gravel	Sand, gravel and clay
Hall	1.3	1.6	2.2	2.6	3.2	3.4	4.8
A.C.14	2.8	6.1	8.0	12.5	7.0	7.6	12.0

For the investigated sea bed area the value of the Hall's anchor force coefficient k_a amounts to 3.3. The anchor holding force R_a for particular ship size groups was determined on the basis of the graph (Fig.2) showing average changes in the anchor weight in function of the ship's deadweight, described by the following expression :

$$R_a = k_a P_a \ [N] \tag{10}$$

where : P_a - anchor weight.

4. The ship speed at which the anchor chain will be broken, V_b, was determined with the use of the formula [8] :

$$V_b = \sqrt{\frac{2M}{\rho L d(\delta B + 0.785\ d)}}\ [m/s] \tag{11}$$

where :

V_b – speed breaking the anchor chain
M – moment to break anchor chain according to the test certificate, [Nm]
ρ – water density (1028 kg/m^3 for salt water)
L – ship's length between perpendiculars
d – average ship's draft
δ – hull block coefficient
B – ship's breadth [m].

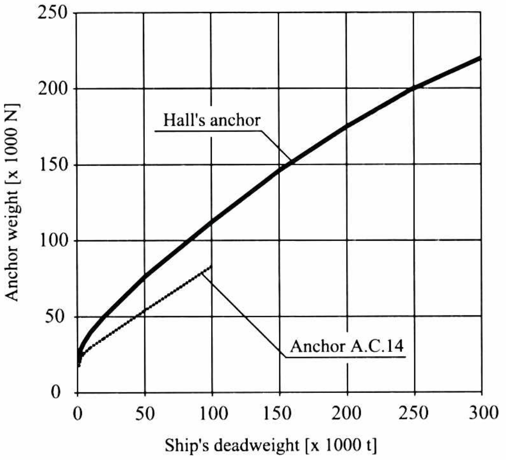

Fig.2. Average anchor weight versus ship's deadweight [8].

It is generally assumed that for ships of over 3000 dwt having a new chain the chain breaking speed V_b is contained in the range of 1 to 2 knots [8]. Hence in the presented model it was assumed that :

★ for the ship's speed relative to the bottom, of 2 knots : the chain will be broken

★ for the speed in the range of 1-2 knots : in 50 % of cases the anchor will be broken or dragged, and the anchor holding force will fall to 30 % of its maximum value (for a corresponding chain length) [8].

The variables appearing in the above given formulae dependent on the size and type of ship were averaged for particular ship groups sailing over the investigated sea area, in order to obtain appropriate coefficients for calculation of ship deadweight, draft, anchor weight, windage area, breadth, wetted surface and inertial braking parameters, expressed in function of ship's length. The so estimated data are given in Tab.4 and Fig.3. The assumed hull block coefficient was equal to 0.8.

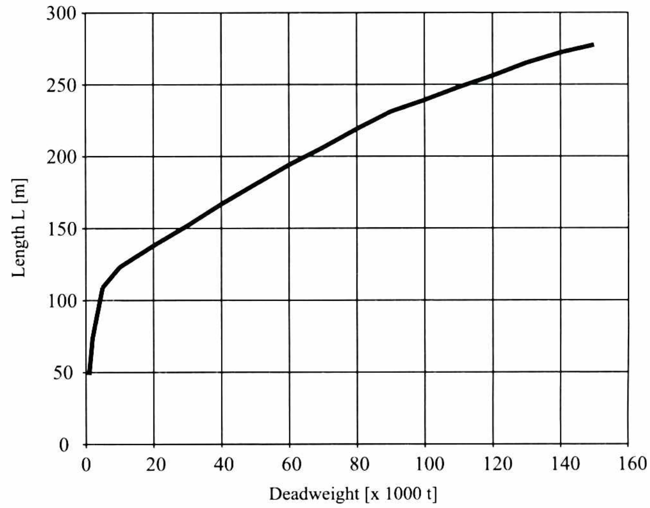

Fig.3. Statistical relationship between deadweight and length of ships

EXAMPLE CASE STUDY RESULTS

The example application of the above described modelling method is prepared for one class of models, i.e that designed to estimate the occurence probability of accidents of an offshore gas pipeline, due to anchoring ships in emergency. In the model possible modes of pipeline damages were divided into three groups depending on their consequences. It was assumed that the damages can occur due to :

1. anchor dragging during emergency anchoring
2. dropping an anchor in close vicinity of the pipeline
3. the ship's running aground in the pipeline location area.

Tab.4. The estimated coefficients of variables appearing in the model versus ship's length

Ship's length	Anchor weight coefficient	Free braking way coefficient – ship under ballast	Free braking way coefficient – loaded ship	Free braking time coefficient – ship under ballast	Free braking time coefficient – loaded ship	Coefficient of ship longitudinal windage area (ship under ballast)	Coefficient of ship longitudinal windage and wetted area (loaded ship)	Coefficient of ship longitudinal wetted area (ship under ballast)
[m]	[kN/m]	[-]	[-]	[-]	[-]	[m]	[m]	[m]
45	0.40	16.44	22.89	0.12	0.27	4.44	3.11	2.12
75	0.37	19.73	27.67	0.11	0.21	4.13	2.96	1.97
105	0.31	19.71	28.19	0.12	0.23	5.05	3.62	2.40
135	0.37	27.41	38.37	0.17	0.27	12.64	9.04	6.02
165	0.39	31.39	40.36	0.18	0.27	16.36	9.70	7.79
195	0.42	31.90	41.03	0.18	0.25	17.95	12.82	8.55

The first type is most common. In such circumstances the ship, due to extremely unfavourable conditions, is not able to be held by the anchor and it moves towards the gas pipeline while dragging the anchor. A schematic diagram of the model of such event is presented in Fig.4.

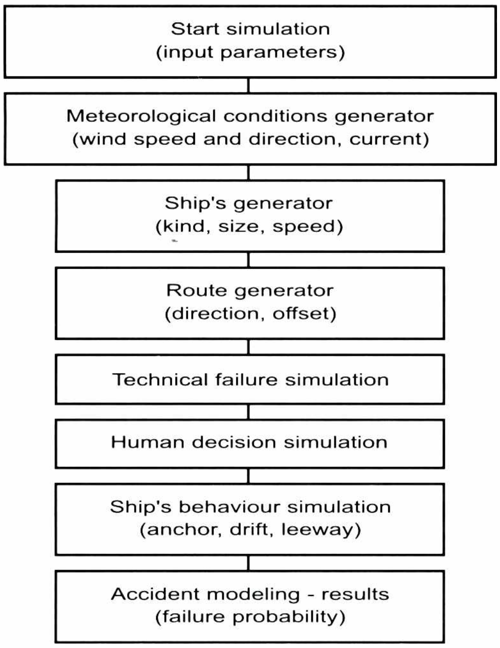

Fig.4. *Overall schematic diagram of the presented models.*

The model was implemented by means of the Delphi complier in the Pascal Object computer language. The applied model interface makes it possible to follow the simulation outcome, to control simulation time step and to introduce some basic initial parameters necessary for analyzing the sensitivity of the obtained results.

The method of constant time step was used in simulation. The input variables was prepared as a separate data file and loaded by the main program. Most important variables for simulation (traffic intensities on given routes, technical failure intensities, simulation time step etc.) were controlled by means of a simplified user's interface. Output variables like time and place of a given accident, kind of accident, environmental conditions during accident were stored into disk file for further analyses. Simulation was stopped automatically after a desired time.

Fig.5 presents examples of simulated locations where technical failures would occur (e.g. main engine's breakdown) during 100 years of the investigated system operation. The presented results confirm the self-evident thesis that technical failures occur mostly in locations of the highest traffic intensity.

In Fig.6 presented are simulated several chosen gas pipeline accidents and the dropping anchor events preceding them just before. Most frequent accidents are caused by dragging anchor in bad meteorological conditions. The distance of anchor dragging is different for various accidents, but it exceeds 10 km as a rule, and its direction complies with that of wind. In Fig.7 simulated pipeline accidents possible to happen during 30000 years of the simulated procces, are presented.

The most important results obtained with the use of the presented model are those concerned with the investigated accident probability. In the case when the time between accidents is relatively long the time of the simulation sufficient to get stable results would amount to 30000 years. After the main simulation is completed the sensitivity analysis may by performed with consequent changes in the main input model parameters to find their influence on simulation results.

Another important safety factor is the distribution of time between successive simulated pipeline accidents. The obtained times between pipeline accidents were fitted to some known random variable distributions. It was found out - in accordance with the previous supposition - that the best fit was provided by the exponential distribution. The estimated mean time between failures λ = 391 years (Fig.8). By means of this distribution it can be estimated that an accident would occur in a shorter time than the expected lifetime

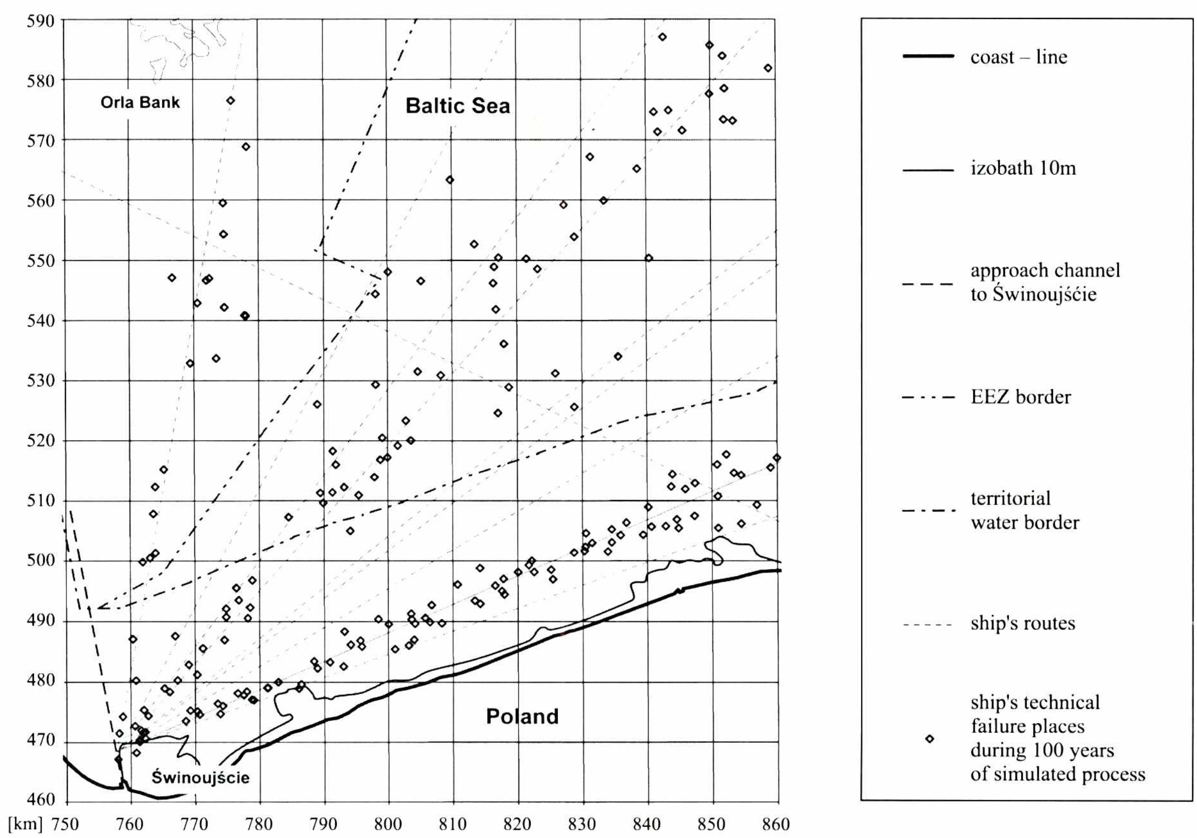

Fig.5. *Locations of simulated ship main engine technical failures*

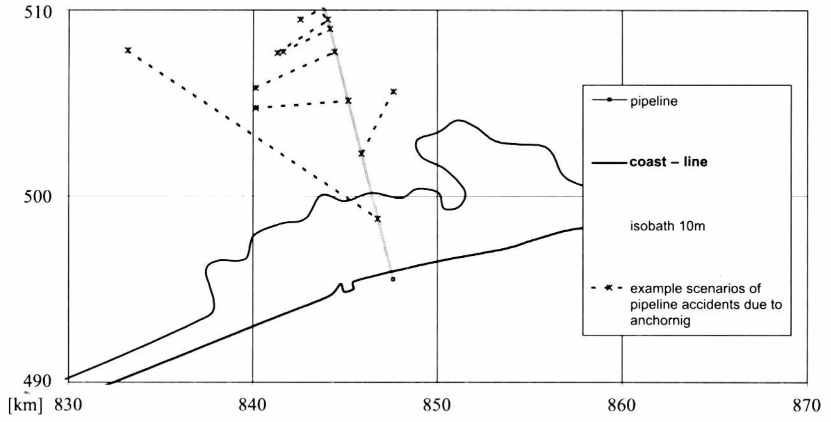

Fig.6. Examples of simulated directions of anchor dragging preceding gas pipeline accidents.

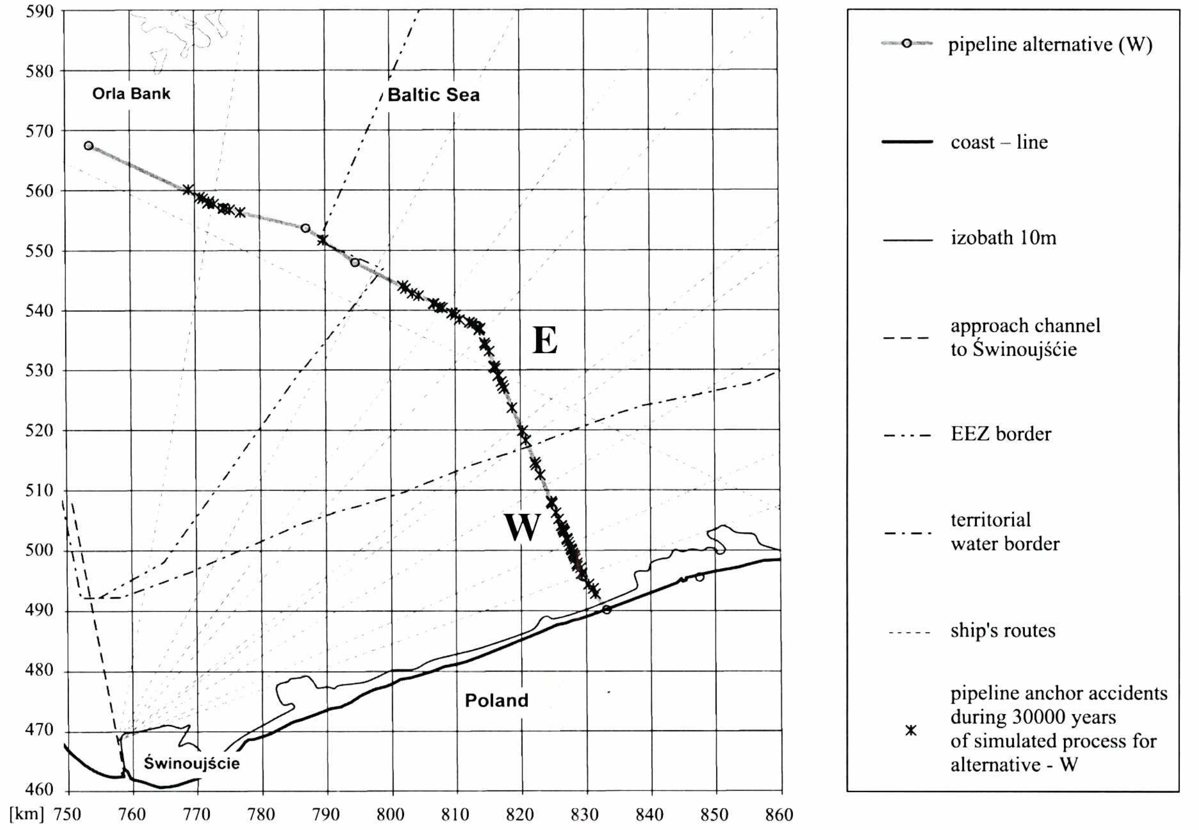

Fig.7. Locations of simulated gas pipeline accidents throughout the simulation time

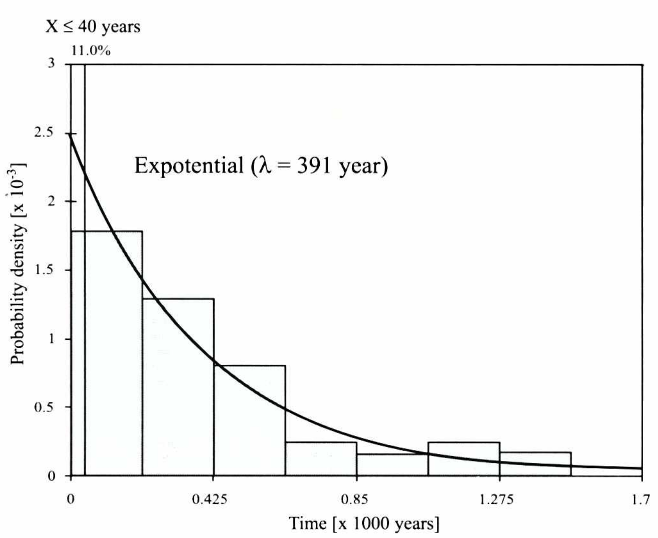

Fig.8. Distribution of time between successive simulated gas pipeline accidents

of the gas pipeline (40 years). The probability of such event amounts to 11.0 % for the whole segment of the examined pipeline (alternative E).

CONCLUSIONS

- The presented modelling method can be also applied for determination of occurence probability of ship collision with offshore structures.
- The presented methodology is very useful for estimating the probability of anchor accident of ship and pipeline, as well as most exposed places of such accidents and expected time periods between such accidents.
- Further research steps in this field should be focussed on verification of the basic model parameters and creating more sophisticated models of human decision making in different conditions and those of ship's behaviour before and after accident.

Appraised by Wiesław Galor, Assoc.Prof.,D.Sc.

NOMENCLATURE

- d – average draft of the ship [m]
- F_n – windage area [m^2], for a drifting ship - at most the area of the longitudinal cross section of the above-water part of the ship
- F_p – area of the longitudinal cross section of the underwater part of the ship
- k_a – coefficient of the anchor holding force
- L – ship's length between perpendiculars [m]
- R_a – anchor holding force
- S_w – wind speed [m/s]
- S_{wr} – relative speed of the wind [m/s], for a stopped ship equal to the real speed of the wind
- t – time value
- Δt – time internal value
- V – speed of ship on wind wave [m/s]
- V_b – ship's speed to break the anchor chain
- V_{dc} – speed of the drift current [m/s]
- V_{dr} – drift speed [m/s]
- V_n – ship's speed in calm waters [m/s]
- V_s – mean speed of ship of a given class
- X – number of ships
- α – course angle of the wind or waves [°]
- γ – specific gravity of the water [N/m^3]
- λ_e – failure intensity
- ψ_{dr} – resistance coefficient

BIBLIOGRAPHY

1. Fancourt, R. : *Fixed and Floating Structures – Maritime Risk Assessment and Desiderata for Safe Navigation*. The Journal of Navigation Vol. 44, 1991
2. Gucma, L. , Materac M.: *Risk of collision of ships with maritime offshore wind farms in aspect of its localization* (in Polish). Influence of Offshore Wind Power Plants Location on Navigation Safety, Wind Power - Planning and Realization. Proc. Intern. Conf. Sopot, 2002
3. Gucma, L. : *Distributions of ship's on Szczecin-Świnoujście waterway.* The Role of Navigation in Support of Human Activity on the Sea. Proc. Intern. Conf. Gdynia, 2002
4. Hansen, P.F. & Simonsen, B.C.: *GRACAT: Software for Grounding and Collision Risk Analysis.* Collision and Grounding of Ships. Proc. Intern. Conf. Copenhagen, 2000
5. Karlsson, M. & Rasmussen, F. & Frisk, L. : *Verification of Ship Collision Frequency Model.* H. Gluver & D.Olsen (eds). *Ship Collision Analysis*. Balkema, Rotterdam, 1998
6. Merrick, J.R.W. et al. : *Modelling Risk in Dynamic Environment of Maritime Transportation.* Winter Simulation Conference. Proc. Intern. Conf. Washington, 2001
7. Nogid L. M.: *Theory of Ship Designing* (in Polish). Wydawnictwo Morskie. Gdynia, 1962
8. Nowicki A.:*Science of manuouvring seagoing ships – Fundamentals of theory and practice* (in Polish). Ed. Trademar. Gdynia, 1999
9. Walczak A., at al.: *Effect of hydrometeorological conditions on ship's drift value and ship's speed changes* (in Polish). Zeszyty Naukowe nr 3. Maritime University of Szczecin, Szczecin, 1973
10. Wennink, J.: *Offshore Platform Collision Exposure to Passing Ships*. The Journal of Navigation, Vol. 41, 1988

Conference

DIAG' 2003

On 13÷17 October 2003 at Ustroń, a health resort in southern Poland, held was 5th National Conference on :

Technical diagnostics of devices and systems

It was organized by Faculty of Electronics of Military Engineering Academy, Warsaw, in cooperation of Polish Society of Technical Diagnostics and Diagnostic Unit, Utility Foundations Section, Mechanical Engineering Committee, Polish Academy of Sciences.

107 persons participated in the Conference, majority of which was scientific and education workers from 30 Polish universities and institutes, whereas the rest represented servicing and production enterprises.

Within the frame of 8 plenary and 6 poster sessions 87 papers were presented, including 29 invited and 58 free-submitted posters. They dealt with the following topical areas :

- Principles and methods of diagnostics (21 papers)
- Diagnostics of mechanical devices (21 papers)
- Physical phenomena applied in diagnostics (14 papers)
- Diagnostics of electric and electronic devices (14 papers)
- Diagnostic devices and systems (11 papers)

and with those of a minor interest :

- Diagnostic procedures and algorithms
- Computer models of failure and diagnostic processes
- Diagnostics of antropotechnical systems
- Diagnostics of safety
- Environmental diagnostics.

The following papers were submitted by the seaside scientific circles :

Maritime University of Szczecin

- *Achievements and research trends in the field of diagnostic theory and practice* – by P. Bielawski
- *Possible utilization of acoustic emission signals in diagnosing selected ship power plant devices* – by A. Bejger
- *Diagnosing with the use of friction power* – by P. Bielawski
- *Wear diagnostics by means of ENPAC system* by P. Bielawski and T. Burnos
- *Assessment of diagnostics of operation of ship main diesel engines* – by J. Monieta

Polish Naval University, Gdynia

- *Some problems of diagnostics based on Bayesian methods* by J. Jaźwiński (Airforce Technical Institute, Warsaw) and F. Grabski (Polish Naval University, Gdynia)
- *Investigations of torsional vibrations of ship propulsion system shafting* – by S. Bruski and Z. Korczewski

Institute of Fluid Flow Machinery, Polish Academy of Sciences, Gdańsk

- *New state indices in diagnosing fractures of shafting* by J. Kiciński
- *Some diagnostic problems of large power plants* by A. Prońska and J. Kiciński

Gdynia Maritime University

- *Symptoms contained in torsional vibrations of ship propulsion shafting* – by J. Rosłanowski

Gdańsk University of Technology

- *Application of diagnosis credibility to decision-making during process of operation of devices* – by J. Girtler

Technical University of Szczecin

- *Threshold analysis in fire safety systems of technical objects* by Z. Sychta.