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THE MOVEMENT OF SHIP IN WATER AREAS LIMITED BY PORT STRUCTURES

ABSTRACT The marine environmental is one of human activity areas where risk is greater then average. Among water areas there are those where ship maneuvering is limited more then other sea areas. There are waters limited by port structures. The article presents methods of assessment of navigational risk as a combination of probability of ship collision to port structures and its consequences. The models of describing of accident probability are presented. Besides the result of ship port structure collision is determined by probability of structure collapse.

INTRODUCTION

It should be evident acknowledged that almost all human activities involve risk. Accepting the thesis of "zero risk" into consideration is a mistakenly. Many branches of human activity can bring about different kinds of risk. The marine environment is one where risk is greater than the average. It refers chiefly to shipping activities which main purpose is to provide services by merchant ship involved in trading. It is fulfilled by handling the ship to port of destination in safely manner. The main purpose of navigation is a safe and efficient leading of the ship between various positions. This purpose is put into practice by steering the ship movement on a planned trajectory. The ship, however, may be affected by various factors during that process, which sometimes make it difficult. These factors result from the ship's functioning in a determined system of man – technology – environment (M–T–E). This means that in certain conditions just any trajectory cannot be planned for the ship, and on the other hand, steering the traffic on a properly planned trajectory is not always possible. An important element of the M–T–E system is the environment, understood as a water area where the ship moves. The occurrence of factors affecting the ship's movement causes its free way limitation. As the ship's leading should be safe first of all, which means it should not cause any navigational accident. A navigational accident is an undesirable occurrence which can cause different loss. Mainly there are life or health, loss or damage to ship or cargo, the pollution of natural environment, damage to the port structure, economical loss due to blocking of the port or its part, cost of salvage operation and other.

The process of safe maneuvering of the ship in the area is called safe navigation. Its estimation is measured by the safety of navigation. It may be defined as a set of states and technical, organizational, operational and working conditions and also as a set of orders, regulations and procedures the applications of which and complying with brings down to minimum the probability of undesirable events that can cause losses [Urbański, 1994].

Among water areas there are those where ship manoeuvring is limited more then in other sea areas. These areas are called as limited waters. They are mainly characterized a relatively high number of navigation accidents. There are many definition and names of such type of waters. The universal definition of limited waters may be that it is area, where the ship can not choose the free way. This limitation is caused by factors that affect the ship manoeuvring.

They are caused by factors that affect the ship manoeuvring. These factors may be present in group as follows:

– water area dimensions, shape and connected phenomena as the shallow water, suction effect etc.;
– hydrometeorological conditions such as unfavourable direction of wind, currents, tides, icing;
– port structures such a breakwaters, dredged channels, berths, locks, bridges;
– great density of sea-going ships traffic;
– a large number of sailing crafts such as barges, fishing boats, inland ferries, tows, recreation navigation, which although in general is subject to marine traffic regulation, sometimes may hinder manoeuvring of seagoing ships;
– operation connected with renovation, modernization, rebilling or building of port element structures;
– international or national legislation affecting the trajectory of a ship in motion.

As a rule, a limited waters feature a great number of these factors being present at the some time. It caused the possibility of navigational accident in these areas is more many times then in other ones. It means the navigation safety is lower in limited waters.

THE ASSESSING OF NAVIGATIONAL SAFETY

Criteria serve for base of estimation, while measures make its performance possible by means of rates. These criteria permit the qualification of accident with damage, raising its possibility over limited values. Next, it permits to make a control of safety level. There is applied to designing and modernizing waterways and defining the conditions of these exploitation and navigation marking. It makes it possible in an optimal way up to the economical point of view to build and modernize waterways elements (fairway, entrance to port and port basin, anchorage area, turning area etc.) keeping a proper level of ship safety. Apart from it is used to design ships parameters optional in the operation in limited water area. To solution of these problems is used the branch called marine traffic engineering.

The assessment of navigational safety (state) requires that appropriate criteria, measures and indicators be used. The criteria make up a basis for assessment, while measures enable assessment presentation by means of indicators. On the whole, one may say that the state of safety is connected with a possibility of loss, or risk. The notions of loss and risk are used interchangeably in the literature on the subject. Last time the risk is defined as combination of probability of navigational accident and its consequences.

The 1970s witnessed a rapid increase in seaborne cargo transport accompanied by fast growth of the global fleet. The growth mainly consisted in the increase of ship size. However, the increase of ship size stopped after it had reached a certain level. The anticipated construction of ships up to one million tonnes capacity did not come true. Among main factors behind that upper capacity limit was an enhanced threat to the environment in the event of a marine accident. Besides, there were few ports capable of handling such huge ships. The latter reason, in particular, was critical for the continued record breaking in the size of new buildings. Nevertheless, the fact is that harbours built decades ago today are facing the necessity of handling ships of the size larger than they were designed for. The construction of new harbours is costly and for certain reasons impossible. That is why the existing ports have to be adjusted to be able to handle ships larger than they were intended for. This goal can be achieved through the modernization of port basins, equipping harbours with appliances for ship traffic management, appropriate towage and pilotage services.

The process of safe ship movement in an area can be considered as a system. The navigation safety system can belong to a set of various states. A basic set of such states includes the states of safety, hazard and danger [Galor, 2003].

The safety state can be described by the probability of an accident (P_A):

$$P_A = P(x > X) \tag{1}$$

where, x is a system state;
X – restrict;
P_A – probability of an accident.

The safety state P_B is associated with a navigational accident probability and makes up its complement:

$$P_B = 1 - P_A = P(x < X) \tag{2}$$

Some considerations lead to a conclusion that "complete" safety state $P_B=1$ is connected with a situation when the probability of an accident will be $P_A=0$. In practice such a situation is nearly impossible. If we take into consideration the whole ship route (from port to port, movement along a fairway), there will always occur a situation where the accident probability will grater than zero $(P_A>0)$. Figure 1 shows the probability of an accident happening to a ship travelling from port ***A*** to port ***B***. Considering the fact that even in the high seas with good hydrological and meteorological conditions some undesired phenomena can take place resulting in an accident (e.g. fire on board), the ship will never be in the state of "complete" safety.

That is why measures and indicators determining the safety level in quantitative terms are taken for the assessment of safety. These are mainly expressed as the probability of an accident. In this approach, the safety level equals:

$$P_{BKR} = 1 - P_{AKR} = 1 - P(x < Y) \tag{3}$$

where: P_{BKR} *is acceptable level of safety;*
P_{AKR} *– assumed probability of an accident;*
X – system state;
Y – restricts corresponding to the assumed acceptable level of the safety state

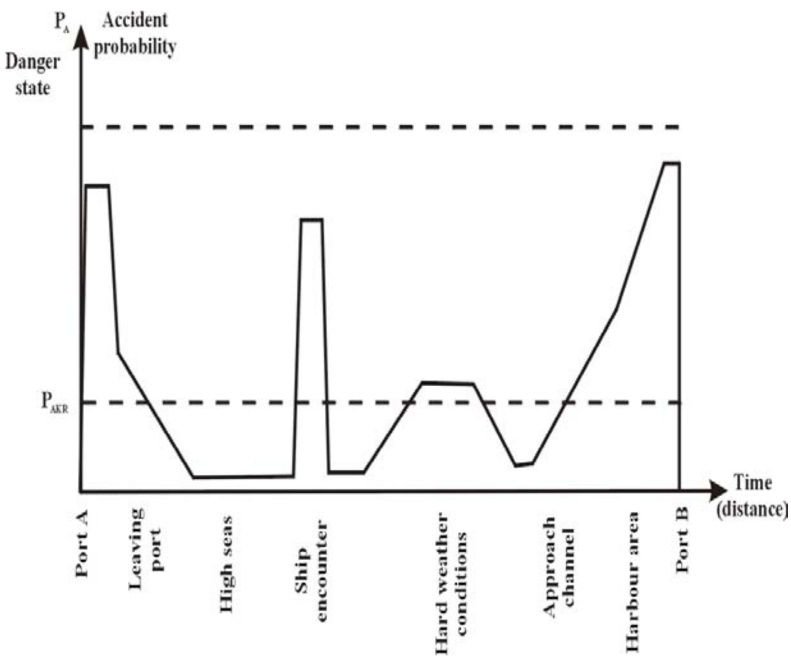

Fig. 1. The probability of a navigational accident of a ship moving from port ***A*** to ***B***

Therefore, the hazard state P_H can be expressed as:

$$P_{AKR} \leq P_H < 1 \tag{4}$$

$$P_H = 1 - P_{BKR} = P(X > x > Y) \tag{5}$$

Taking into account the fact that for the state losses do not have to happen or their level is acceptable, we can write that the hazard state comprises undesired events:

$$P_H = P(X > x > Y) \quad \text{for } C<c \tag{6}$$

where: c is limit of minimum losses;
C – loss caused by an undesired event, e.g. consequence of accident expressed in relevant units

If losses are above the minimum limit $C>c$ the system goes into the danger state (accident probability occurs).

Based on above consideration it may be ascertained that measure of safety navigation should be include probability of accident and its consequences (losses). It is realized by risk defined as:

$$R_N = P_A \cdot C \tag{7}$$

where: R_N is navigational risk;

Consequences of every accident can be of different dimension. The converging all the results to one dimension is very difficult. It requires suitable transformation. Being able to step out simultaneously damage of ship, load, port structures, loss of life and health, pollution of the environment and loss of potential profit, and in consequence the limitations of the port's work or ships is difficult to be estimated. An effort of universal estimations of results is an economic method. Independently from kind of losses, all of them can have a fixed price by means of proper sums of money. However, it has in some cases large defects. Loss of life can fix the price by means of sums of insurance in case of death. However, on the one hand this sum depends on quantities of paid collections, companionships insurance company, etc., while on the other hand it does not make up for psychological losses of the closest relatives, or sociological ones pertaining to a group of society. Similarly, an accident whose result is pollution of the environment is difficult to estimate by economic values. Overflow of oils from a damaged ship produces such various consequences for the environment, that its estimation by means of one criterion is very difficult. Thus, generally the results of a navigational accident can be examined in the aspect of the event – catastrophe. The catastrophe produces results difficult to be described. Because of the wide variety of effects, attempts to provide a universal description of effects are made. The following methods of ship estimation can be distinguished:

- the economical method based on a financial estimation of particular kinds of ships, which can be expressed in sums of money or other units;
- the physical method based on description of effects expressed in physical value, e.g. the energy of the ship's strike against an element of the coast;
- the method of relative estimation, based on an assumed pattern of accident effects, e.g. comparing an accident of a ship with dangerous cargo with that of a one with cargo of a lesser danger.

Intensive research is made and works are carried out on models of effects. It is significant both for the present state of navigation safety and for making decisions in a variety of planning situations.

This is a very important method of risk estimation by means of physical estimations of an accident outcome. However, this method of risk estimation does not take into account the additional results of accidents, connected with transported cargo. These results can be various depending on the type of transported cargo (toxic, explosive, polluting, combustible, corrosive and others). The same ship participating in an accident in the same conditions in water area, once for example with mass – cargo (coal), next with liquid (crude oil), in cases of hull damages can cause considerably worse consequences in the second case. Hence, the necessity of taking into account the kind of transported cargo regarding accident consequences with risk estimation will be made.

PORT STRUCTURES

An analysis of navigational accidents shows that their percentage in limited areas ranges up to 65%. Most of them take place in port waters area. There is an area surrounded by wharves and other marine buildings where ships moor and load or discharge cargo. This type of area intended for ship manoeuvres is particularly important for port operation. There has been a tendency in recent years to accommodate increasingly larger ship in ports, which with insufficient port infrastructure or its even minor changes may result in a navigational accident of serious economic consequences.

The port approach and port areas are characterised by various port structures. These man-made structures comprise surface or submerged structures which together with installations, construction arrangements associated with these structures, technical equipment and other equipment relevant for the function a given structure make up one technical-functional object. From the point of view of limitations of traffic in an area, hydrotechnical structures include:

- objects formed due to dredging and silting work, particularly harbour and shipyard water areas, such as outer harbours, basins, sea and inland fairways, approach channels, passing and turning areas;
- channels;
- wharves making up enclosures of the shore and generally allowing ships to berth and lie alongside;
- shore protecting structures, mainly breakwaters, bottom strengthening, dredged fairway slope strengthening structures;
- structures of fixed aids to navigation, especially lighthouses situated in a sea area, land- and water-based beacons, leading marks and navigational lights, dolphins;
- sea locks;
- structures situated within sea harbours, particularly mooring cargo handling islets, landing stages;
- port buildings situated in sea ports, particularly breakwaters, wave breakers, cargo-handling, lying alongside and others;
- buildings connected with transport, such as road and rail bridges, submerged tunnels;
- structures connected with the seabed exploitation (oil rigs, platforms and pipelines).

Besides, they comprise structures of floating navigational marks, particularly moored navigational buoys. Fig. 2 presents an example of water area restricted by port structures.

SHIP MANOEUVRING SAFETY ASSESSMENT

The assessment of navigational safety is changing as there are new methods being developed. Qualitative assessment of the "right/wrong type" is being replaced by quantitative methods of safety assessment based on navigational risk. Knowing the probability of the accident, its effects can be taken into account in the calculations. When applying the risk, three methods can be distinguished [Galor, 2002]:

- the value of absolute risk;
- risk constant;
- relative increase of risk.

In the first method the determined risk value refers to the assumed value limit. Sometimes this value is specified in regulations.

$$R_N \leq R_p \tag{8}$$

where: R_p *is* assumed risk value limit

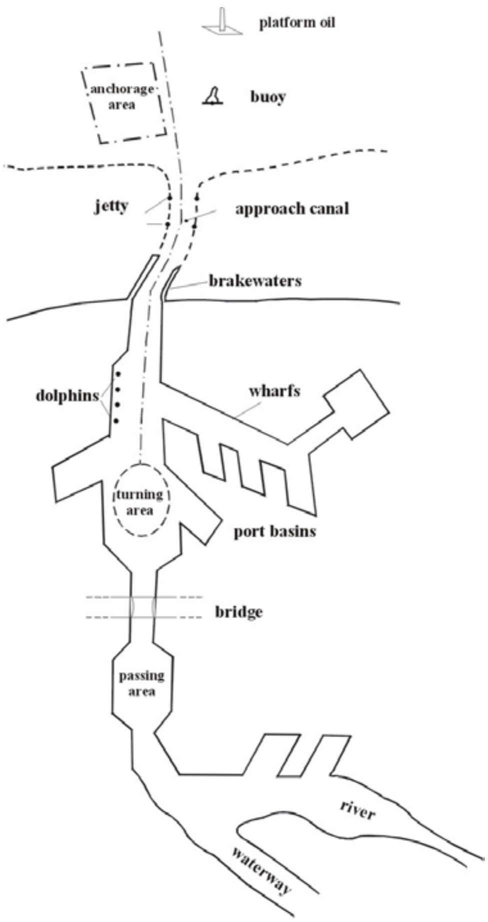

Fig. 2. An example of port water area limited by hydrotechnical port structures.

The next method of constant risk is a development of the first. It is applied in situations where the consequences of the accident are likely to change. This can take place when a ship of a specified size manoeuvring in a certain water area is carrying in turn cargoes of various hazard degrees (various consequences in case of accident, e.g. coal, and the other time crude oil products). Then, to maintain a steady level of safety, the risks must be equal to each other.

$$R_{N1} = R_{N2} = P_{A1} \cdot C_1 = P_{A2} \cdot C_2 \tag{9}$$

where: R_{N1} ,R_{N2} are navigational risk in different situations;
P_{A1}, C_1 – probability of an accident and consequences of the accident with cargo of low hazard degree;
P_{A2}, C_2 - probability of an accident and consequences of the accident with cargo of higher hazard degree;

If the consequences of an accident change, then, in order to maintain the assumed risk level the value of accident probability is changed too.

$$P_{A2} = P_{A1}\left(C_1 / C_2\right) \tag{10}$$

If the effects of an accident increase, the probability of an accident has to diminish. In the case of the criterion of required manoeuvring area size, its size should be increased. If it is impossible of local conditions, other measures must be undertaken, lowering the permissible boundary of hydrometeorological conditions speed and direction of wind and current or increasing the tug service. In special cases, when the accident effects can be so enormous, extraordinary measures are undertaken. Let me mention an example of the transport of explosives brought out in the port water area and taking them to maritime firing areas. Manifold measures are undertaken then, i.e. certain units are prohibited to move, people from the coastal area are evacuated etc.

In certain cases there may appear plans of increasing the size of operated ships. Then, the experience of many years' observations concerning the operation of ships on a given area will not permit to directly support a decision to allow the traffic of larger units. Simulation research which could solve the problem is not always possible to be carried out at a particular time. And yet, the maritime administration should make a decision based on justified consideration, as it happens in many cases, that the decision is made intuitively and the one who makes it is led by irrational factors, as for instance pressure on the part of the port authorities. Therefore, in such cases a method is suggested to determine the relative risk increase.

$$\rho_R = \Delta R / R_p = \left(R_U - R_p\right) / R_p \tag{11}$$

where: ρ_R is relative risk increase;
ΔR – unconditional risk increase;
R_p – navigational risk before the introduction of changes;
R_U - navigational risk after the introduction of changes;

Taking into consideration that the risk is a combination of accident probability and its consequences, the following can be written:

$$\rho_R = \rho P_A + \rho S \qquad (12)$$

where: ρP_A is relative increase of accident probability;
ρS - relative increase of accident consequences.

MODELLING OF SHIP PORT SRTUCTURE COLLISION EVENT

Accidents in limited waters and especially ship port structure collision are very rare events which happen at random and under influence of various conditions. Accidents may caused by human errors, mechanical failures and hydrometeorological conditions. If a failure happens on board of ship will move an accident course which may lead to a harmless path such a passing a navigation obstacle like a port structure. The accidental track which will follow is resulted of type of failure, the reaction of navigators, the ship maneuvering characteristics, deviation from the planned course and hydrometeorological conditions. As random variables describing the accidental course of the ship a deviation on the maneuvering path with angle φ and the stopping distance D_H are chosen (fig.3).

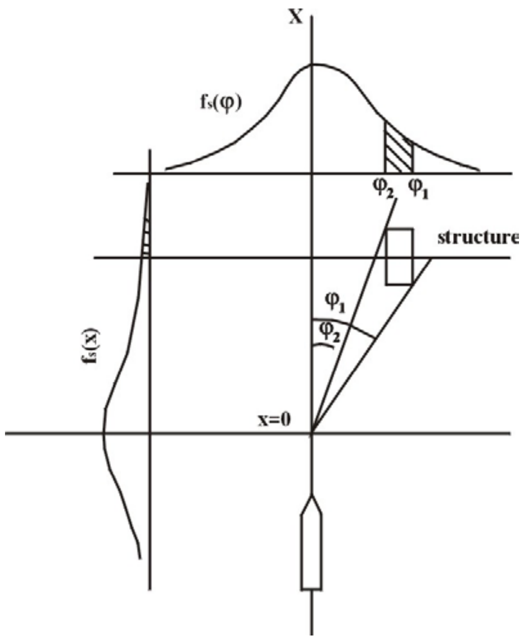

Fig.3. Probability of ship collision with port structure while steering devices are damaged.

The collision model may be written as [Kunz, 1998]:

$$P_A = N \cdot \int (d\lambda / ds) \cdot P_\varphi(s) \cdot P_D(s) \cdot ds \tag{13}$$

where: N is the number of ships passing the structure;
$d\lambda/ds$ – the failure rate per travel unit;
$P_\varphi(s)$ – probability of collision course.

Where $$P_\varphi(s) = F_\varphi(\varphi_1) - F_\varphi(\varphi_2) \tag{14}$$

$$F_\varphi(\varphi) = \frac{1}{\sqrt{2\pi\sigma_\varphi}} - \int_{-\infty}^{\kappa} \exp\left(\frac{(\varphi - \overline{\varphi})}{2\sigma_\varphi^2}\right) \cdot d\varphi \tag{15}$$

where: $\overline{\varphi}$, σ_φ are mean value and standard deviation of course;
$P_D(s)$ - the probability not to come to a stop before collision to structure;

$$P_D(s) = 1 - F_D(s) \tag{16}$$

$$F_D(s) = \frac{1}{\sqrt{2\pi\sigma_D}} \int_{-\infty}^{x} \exp\left(\frac{(D - \overline{D})^2}{2\sigma_D}\right) \cdot d_D \tag{17}$$

where: $\overline{D}$, σ_D are mean value and standard deviation of stopping distance.

By calculation of probability P_φ and P_D for each position along the approaching course of the ship any probability of collision can be determined. The failure rate may be determined by accidents analysis, simulation, or by transferring such value from other technical systems. Mainly this one is determined by statistical accident analysis. Very often the usable measure of ship movement in waterway is width of swepth path. The moving ship along of planned course (axis of canal) changes his course due to influence of affecting of outer conditions. It requires its corrections (return to previous course). In result of such maneuvers the ship occupies even water area describing by perpendicular distance to canal axis. Deviations of ship position from this axis can be defined by standard distribution (fig. 4).

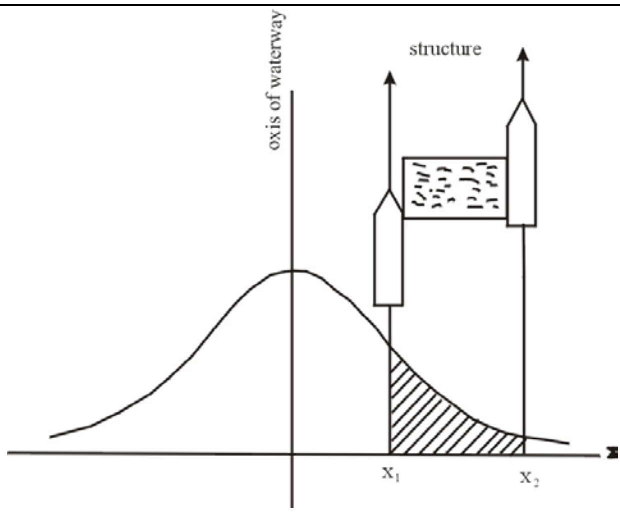

Fig.4. Probability of collision to structure based on maneuvering line.

Then collision probability can be described as:

$$P_A = N \cdot P_Z \int_{x_1 - B/2}^{x_2 + B/2} f(x)dx \tag{18}$$

where: P_Z is probability of events causality;
B – beam of ship;
x_1, x_2 – distance of edges structure to waterway axis;
f(x) – function of maneuvering line distribution.

The function of maneuvering line (mean value and standard deviation) can be determined exactly based on of simulation study supported by computer model of ship movement in water area.

THE RESULTS OT SHIP COLLISION TO PORT STRUCTURE

The results of ship collision to port structure can be damage of ship bulk and port structure. Most unwanted situation is catastrophically state when ship hits in structure caused its collapse (bridge pier, platform). In instant of ship hitting with much velocity in structure appears great impact force in short time. The ships impact force may be computed by empirical formula [Knott, 1998]:

$$Ps = 0.98(DWT)^{1/2} \cdot (V/16) \tag{19}$$

where: *Ps* is an impact force [MN];
DWT – deadweight tonnage of ship (t);
V – ship's impact speed (knots).

The ship impact force of different dimensions of ships for given speeds is presented on Fig. 3.

As ship collisions to port structure are often rare it may be therefore described by Poisson counting process. The probability of an impact load during a time interval can be modeled from the distribution function of time between related events:

$$F_T(t) = 1 - \exp(-P_A \cdot t) \tag{20}$$

where: $F_T(t)$ is probability of event in time t;
P_A – collision rate determined by proper model.

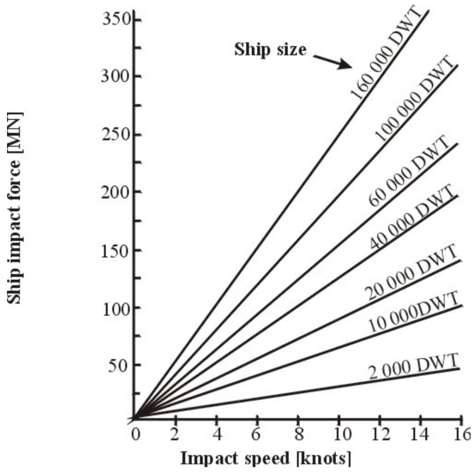

Fig.3. The force of ships load in structure [Knott, 1998]

For the estimation of extreme impact loads a connection with the distribution function of possible loads is required. They can base on deformation energy as a result of ship impact force. This energy is calculated by classifying ship type, ship mass, the impact speed, wind and current conditions, the impact angle and other.

The probability of on impact load during a time interval can be modeled by:

$$F_T(t) = 1 - \exp(-t / t_R) \tag{21}$$

where: t_R is return period of particular impact load exceeding acceptable value.

$$t_R = \{P_A \cdot [1 - F_P(p)]\}^{-1} \tag{22}$$

where: $F_P(p)$ – probability of exceeding of acceptable impact load leads to structure collapse.

Analyzing ship port structure accidents leads to certain conclusion that probability of structure collapse is very low. For example the German accident statistics show that in less than 1% of all impacts the ship is heavily damaged.

The measure of safety navigation in water limited by port structures can be expressed by level of risk of port structure collapse. Within this conception a total probability F_L can be estimated:

$$F_L = 1 - \exp(-T_N / t_r) \tag{23}$$

where: T_N is service lifetime of the structure;
t_R – return period of a particular impact leads to structure collapse.

CONCLUSION

Analysing problems connected with ship movement in water area limited by port structures it can be concluded:

1. From one side the port structures permit to safety manoeuvring of ship in port water area but from the other side limit the movement of ship.
2. Despite of small number of ship collision to port structure its results can achieve catastrophically states (collapse of structure).
3. The ship collision to port structure can be estimated by collision risk based on probability of impact for major damage.
4. Probability of collision depends on many conditions that there are used many models to its assessment. Mainly they are based on statistical date of collision accident.
5. The simulation methods based on computer ship movement in water are a proper way to determine of collision risk.
6. The quantitive determination of collision risk of ship to port structure is recommended to assessment of safety navigation and designing of structures.

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