BalticMaster
maritime safety across borders

BALTIC MASTER REPORT
M II part 1/4

GENERAL ASSUMPTIONS FOR THE RISK ANALYSIS MODELS ON THE AREA OF THE BALTIC SEA

Theoretical models of marine risk waterway optimization and safety assessment

Maritime University of Szczecin

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BALTIC MASTER REPORT Milestone II part 1/4

This report is joint effort of Maritime University of Szczecin research team

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The researches presented in following sections are necessary for building general assumptions of risk models which will be necessary to build the common criterions and procedures in the integrated safety assessment model of costal safety assessment systems.

1. Model of vessel's maneuvering in limited sea areas in navigational risk aspect

Nowadays, one of the most essential problems concerning shipping safety in the world is navigational risk assessment in limited sea areas [Gucma S. 1998 (2)]. It characterises a degree of threat to the safety of the vessel manoeuvring in such areas.

The risk in question is defined as a combination of the probability of a collision occurrence and the effects it can cause during the manoeuvre being performed [Gucma S 1998 (1), Jazwinski 1993]. The manoeuvre is understood here as the process of vessel's movement on a waterway of specific type (e.g. vessel's turning in a turning basin, berthing in a port basin, sailing along a fairway etc.). Additionally, the risk definition presented has been completed with a relative frequency of performing a given manoeuvre in the sea area examined. Assuming that the collision and its effects are independent events, a navigational risk can be presented as the following product:

$$R = I_R \cdot P_A \cdot S \tag{1}$$

where:

I_R – mean annual intensity of performing a given manoeuvre (relative frequency),
P_A – probability of collision occurrence while performing a given manoeuvre,
S – effects resulting from a given collision.

This part of the study presents:

- model of probability of collision occurrence,
- model of collision effects in limited sea areas,
- simulation method of estimating a manoeuvring risk in limited sea areas using the models constructed.

The probability models of collision effects will be analysed separately, with the assumption that depths in limited sea areas decrease linearly, that there are only such forms as flat bottom and underwater slopes of various angles of inclination, and that the sea area is limited by hydrotechnical structures having the features of a vertical wall (quay, breakwater, platform etc.), which are supplied or are not supplied with fender facilities, or the features of bank protections of slope type of different angle of inclination.

While performing a specific manoeuvre by a vessel in limited sea areas, there may happen a collision resulting from the vessel's movement. The collisions are classified as follows:

1. A collision of the vessel with bank parts, next to which the area depth is bigger than the vessel's draught. These are usually such sea structures as quays, breakwaters, bank protections etc.
2. A collision of the vessel with the sea area bottom (grounding), where the depth is smaller than the vessel's draught. These are, as a rule, bank slopes or shallow water (underground slopes).
3. A collision of two vessels.

The discussion presented in this chapter concerns the first and second types of a collision. It does not include a collision by two vessels where, additionally, it is necessary to consider mutual relations between the vessels and the system of traffic control in use. The restriction considered refers to most manoeuvres in limited sea areas such as berthing, turning, port entering, sailing along one way fairway etc.

The probability of collision occurrence is determined by the following factors:

- navigational probability of performing a given manoeuvre in specified conditions,
- human factors in anthropotechnical aspect; vessel – navigator (navigator's reliability),
- technical reliability of a vessel.

The navigational reliability of performing a given manoeuvre in a specified sea area should be understood as probability of collision avoiding by a specified type of vessel with fixed objects (a vertical wall, sea area bottom) in specified hydrometeorological (external influence of wind and current) and operating conditions, as well as during reliable operation of all vessel's appliances. In the simulation method presented, the navigational reliability of the manoeuvre performed is combined with the reliability of a navigator. A human factor is here included through participation, in simulation tests, of the navigators who have qualifications appropriate to the reality.

Technical reliability should be understood as the probability of reliable operation of vessel's systems and appliances which affect a non-collision performance of a given manoeuvre.

The effects caused by a specific collision depend on a ratio between the energy of vessel's impact on a hydrotechnical structure and permissible energy of a safe impact which will not cause any damage to the hull or the structure.

1.1. MODEL OF PROBABILITY OF COLLISION OCCURRENCE WHILE MANOEUVRING A VESSEL IN LIMITED SEA AREAS

The probability of collision occurrence while performing a specified manoeuvre in limited sea area may by presented as the following dependence:

$$P_A = 1 - P_B \quad (2)$$

where:

P_B - probability of a safe performance of a given manoeuvre by a vessel of specified parameters, in specified navigational and hydrometeorological conditions (external influence of wind and current), steered by a navigator of specified qualifications.

Technical and navigational kinds of reliability including a human factor are practically independent, and, in connection with the above, probability of performing a given manoeuvre can be presented as follows:

$$P_B = P_n \cdot P_t \quad (3)$$

where:

P_n - probability that a vessel of specified parameters steered by a navigator of specified qualifications will not be involved in a collision in specified navigational and hydrometeorological conditions while performing a given manoeuvre,

P_t - probability of reliable operation of vessel's systems and appliances affecting a non-collision performance of a given manoeuvre.

The probability of performing a non-collision manoeuvre by a vessel of a given type, in specified navigational and hydrometeorological conditions, steered by a navigator of specified qualifications at a specified time and place is:

$$P_n = P\,(X_j \le d_j) \qquad (4)$$

and expressed by means of normal standardised distribution [1] is:

$$P_n = P\left(\frac{X_j - \overline{x_j}}{\delta_j} \le \frac{d_j - \overline{x_j}}{\delta_j}\right) = 1 - \alpha \qquad (5)$$

where:

X_j – maximum distance of an extreme point of the vessel to port or starboard of a fairway axis in j-section of the sea area (random variable),

$\overline{x_j}, \delta$ -mean value and standard deviation of maximum extreme distances of vessel's points to port or starboard of a fairway axis in j-section of the sea area,

d_j – least distance from danger in j- section of the sea area,

α - significance level.

The distribution parameters $\overline{x_j}, \delta_j$ are calculated on the basis of the simulation tests carried out for a given manoeuvre, which are used to specify the width of a movement lane (Fig.1.1).

The **technical reliability** has been reduced to a non-collision performance of a specified manoeuvre. It depends on reliable operation of the main engine, auxiliary engines with generators, steering gear, tugs and radar in case of bad visibility.

Each of the above-mentioned appliances is characterised by probability of reliable operation at time t, which is marked as follows:

$P_1(t)$ – probability of reliable operation of the main engine,
$P_2(t)$ – probability of reliable operation of the auxiliary engine with generator,
$P_3(t)$ – probability of reliable operation of the steering gear,
$P_4(t)$ – probability of reliable operation of a tug,
$P_5(t)$ – probability of reliable operation of a radar.

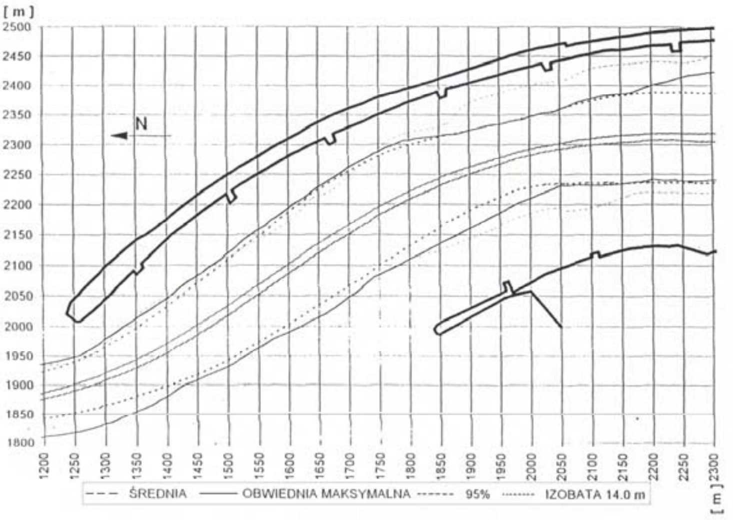

Fig. 1.1. Movement lane while entering the port of Świnoujście by a bulk-carrier of length of 260 m and draught of 12.8 m [Okreslanie 1995]

In order to calculate a reliable operation of the above appliances, there is used an intensity function of damage at time t, which is a density function of damage occurrence on the condition that no damage has taken place so far. The function can be presented as follows:

$$\lambda(t)=\lim_{\Delta t\to 0}\frac{n(t,\Delta t)}{N_s\cdot\Delta t}=\frac{N_o\left[P(t)-P(t+\Delta t)\right]}{N_s\cdot\Delta t} \tag{6}$$

where:

$\lambda\ (t)$ - intensity function of damage at time t,
n (t,Δt) - number of damage cases during statistical test at test time,
N_s - number of appliances working reliably at time $\varDelta\ t$,
N_o - number of items tested.

Accepting that $\frac{N_s}{N_o}=P(t)$, we receive

$$\lambda\left(t\right)=\lim_{\varDelta\ t\ \to 0}\frac{P(t)-P\left(t+\varDelta\ t\right)}{P(t)\cdot\varDelta\ t}=-\frac{P'(t)}{P(t)} \tag{7}$$

hence, after transforming:

$$P(t)=\exp\left(-\int_0^t\lambda\left(t\right)dt\right) \tag{8}$$

where the estimated value of a mean of non-collision service life for a given appliance is:

$$T=\int_0^\infty P(t)\ dt \tag{9}$$

A diagram of intensity function of damage while it is operated is presented in Fig. 1.2

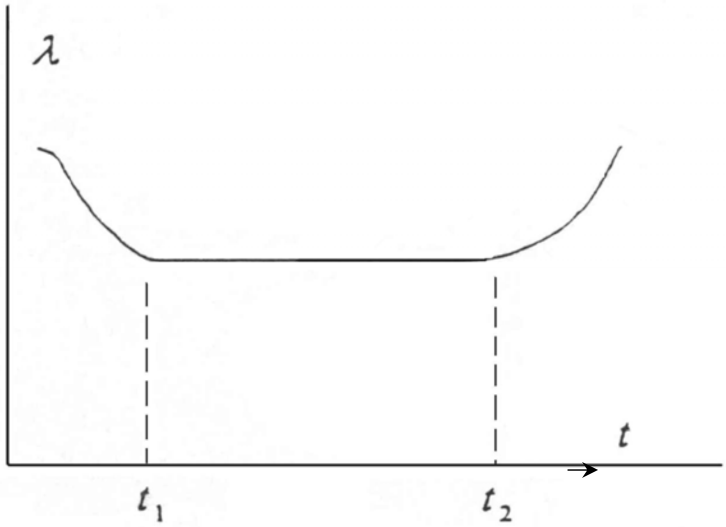

Fig. 1.2. A diagram of intensity function of damage at the time of its operation

The diagram shows three phases of appliance operation:

- phase of starting (from 0 t_0 t_2),

- fixed (stable)phase of operation (from t_1 t0 t_2),
- phase of aging (from t_2).

Considering only the stable phase of operation (which is of interest for classifying institutions), a risk function $\lambda\ (t)$ does not depend on time and is constant $\lambda = const$, and the probability of reliable operation is defined by the dependence:

$$P(t) = e^{-\lambda \cdot t} \tag{10}$$

Then the estimated value of a mean of non-collision service life is:

$$T = \frac{1}{\lambda} \tag{11}$$

and after substituting:

$$P(t) = e^{-\frac{t}{T}} \tag{12}$$

Factorising the expression $P\ (t)$ into power series:

$$P(t)=1-\frac{\lambda t}{1!}+\frac{\lambda^2 \cdot t^2}{2!}-\frac{\lambda^3 \cdot t^3}{3!}+...+\frac{(-\lambda t)^n}{n!}+... \tag{13}$$

and remembering about short durations of manoeuvres (Δt):

$$T \rangle\rangle \Delta t$$

we can accept, whit the accuracy proper for practice, that:

$$P(t)=1-\lambda\cdot \Delta t \tag{14}$$

In connection with the above, probability of reliable operation of particular appliances can be presented as follows:

$$\begin{aligned} P_1(t) &= 1 - \lambda_1\cdot\Delta t,\\ P_2(t) &= 1 - \lambda_2\cdot\Delta t,\\ P_3(t) &= 1 - \lambda_3\cdot\Delta t,\\ P_4(t) &= 1 - \lambda_4\cdot\Delta t,\\ P_5(t) &= 1 - \lambda_5\cdot\Delta t, \end{aligned} \tag{15}$$

Damage intensity for the tug can be calculated assuming that the reliability of its appliances is analogous with the vessel's appliances, that is:

$$\lambda_4=\lambda_1+\lambda_2+\lambda_3 \tag{16}$$

Assuming that damage to each of the above-mentioned appliances can, in specified circumstances, cause the vessel's collision, the probability of reliable operation of all the appliances is the product of probability of reliable operation of particular appliances:

$$P_t = P_1\cdot P_2\cdot P_3 \cdot P_4 \cdot P_5 \tag{17}$$

And it can be written with approximation to the second order of magnitude:

$$P_t = 1-(\lambda_1 \cdot \Delta t_1 + \lambda_2 \cdot \Delta t_2 + \lambda_3 \cdot \Delta t_3 + \lambda_4 \cdot \Delta t_4 + \lambda_5 \cdot \Delta t_5) \qquad (18)$$

where:

Δt_1 – time interval during manoeuvre performance at which failure of main engine causes a threat of collision,

Δt_2 - time interval during manoeuvre performance at which failure of auxiliary engine – generator causes a threat of collision,

Δt_3 - time interval during manoeuvre performance at which failure of rudder causes threat of collision,

Δt_4 - time interval during manoeuvre performance at which failure of a tug causes a threat of collision,

Δt_5 - time interval during manoeuvre performance at which failure of a radar causes a threat of collision.

Additionally, it is necessary to include double appliances working in the system of hot reserve.

During port manoeuvres, such appliances include:

- auxiliary engines,
- radars,
- tugs.

Using the dependence:

$$P = 1 - (1 - P_1)(1 - P_2) \ldots (1 - P_n) \qquad (19)$$

where:

n – time reserving,

it is possible to define the probability of reliable operation of double appliances:

a) auxiliary engines:

$$P_{2\times 2} = 1 - \lambda_2^2 \cdot \Delta t_2^2$$

b) tugs:

$$P_{2\times 4} = 1 - \lambda_4^2 \cdot \Delta t_4^2$$

c) radars:

$$P_{2\times 5} = 1 - \lambda_5^2 \cdot \Delta t_5^2$$

After substituting these values to the general formula of the probability of reliable operation of all the systems, we receive:

$$P_t = 1-(\lambda_1 \cdot \Delta t_1 + \lambda_2^2 \cdot \Delta t_2^2 + \lambda_3 \cdot \Delta t_3 + \lambda_4^2 \cdot \Delta t_4^2 + \lambda_5^2 \cdot \Delta t_5^2) \qquad (20)$$

Not every lack of reliability of the appliances examined while manoeuvring in the tested sea areas leads to vessel's collision. In depends, additionally, on the following factors:

- position of damage occurrence in the sea area tested,
- hydrometeorological conditions prevailing during the manoeuvre being performed,
- damage scope of a given appliance.

Considering particular factors, it can be stated that:

a) Only in some positions of the sea area tested, damage to a given appliance leads to vessel's collision. It is accepted by defining, individually for a given sea area, particular time intervals.

b) Only in some hydrometeorological conditions prevailing during the manoeuvre being performed, damage to a given appliance leads to vessel's collision.
c) Only at some damage scopes of some appliances, damage to a given appliance leads to vessel's collision (e.g. rudder stoppage in a given position).

Taking into consideration the above factors, the dependence is modified to its final form:

$$P_t = 1 - \left(\lambda_1 \cdot \Delta t_1 \cdot p_{h1} + \lambda_2^2 \cdot \Delta t_2^2 \cdot p_{h2} + \lambda_3 \cdot \Delta t_3 \cdot p_{h3} \cdot p_{z3} + \lambda_4^2 \cdot \Delta t_4^2 \cdot p_{h4} + \lambda_5^2 \cdot \Delta t_5^2 \cdot p_{h5}\right) \qquad (21)$$

where:

P_{hi} - probability of occurrence of the hydrometeorological conditions which result in vessel's collision during damage to i-appliance,

P_{z3} - probability of rudder stoppage in a given position which results in vessel's collision.

1.2. Model of Effects of Vessel's Collision with Bank Structures

Vessel's collision with bank parts takes place when the depth of a limited sea area is bigger than vessel's draught at the moment of the collision (t_1).

The limited sea area tested is presented as a set of depths **H**, whose elements, in Cartesian co-ordinates, can be presented as follows:

$$H(x, y) \in \mathbf{H} \qquad (22)$$

The vessel is presented as a set of her draughts **T**, whose elements, in Cartesian co-ordinates, at time (t_i) can be presented as follows (Fig. 3):

$$T(x, y, t_i) \in \mathbf{T}(t_i) \qquad (23)$$

The sets meet the following requirement:

$$\mathbf{T}(t_i) \subset \mathbf{H} \qquad (24)$$

and their elements remain in the dependence (Fig. 1.3);

$$\bigwedge_{T(x,y,t_i) \in \mathbf{T}} T(x,y,t_i) \geq H(x,y) \qquad (25)$$

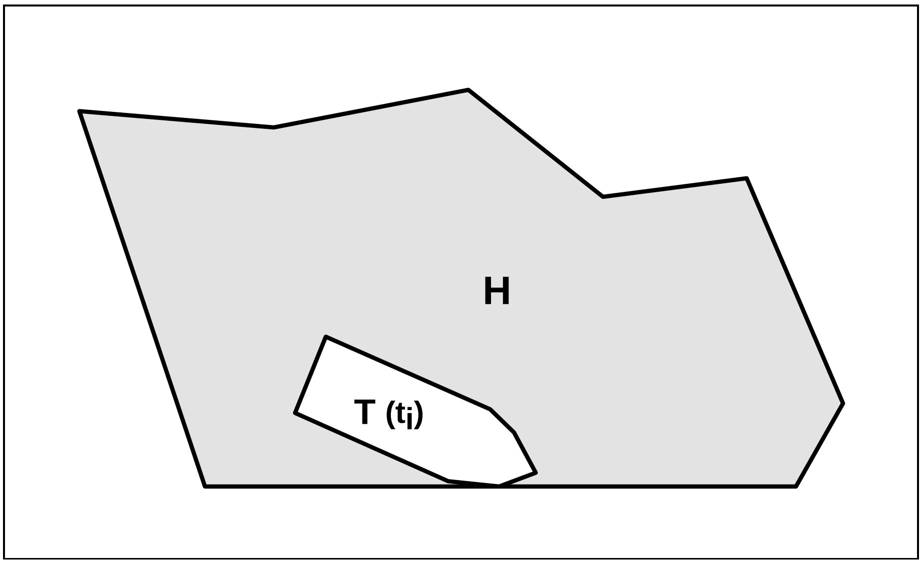

Fig. 1.3. Set of depths of limited sea area H and vessel's draught T_i at the moment of collision with bank parts

The effects caused by the discussed collision depend on such factors as maximum energy of vessel's impact on bank parts and permissible energy absorbed by a bank part (system of fender facility - hydrotechnical structure), and they can be presented as follows:

$$S = \frac{E(t_i)}{E_a} \tag{26}$$

where:

E (t_i) maximum energy of vessel's impact on bank parts,

E_a - permissible energy absorbed by a bank part (system of fender facility - hydrotechnical structure).

When the values S are within $0 < S \leq 1$, the collision which happens does not cause substantial losses. However, when $S>1$, the collisions are accompanied by major damage to vessel's hull, fender appliances or hydrotechnical structures.

Maximum energy of vessel's impact on bank parts is understood as kinetic energy which the vessel can have at the moment of impact (t_i) during the least favourable navigational conditions while performing the manoeuvre tested,. The energy is defined while using the simulation tests of the vessel's manoeuvre tested in a given sea area in specified hydrometeorological conditions

The permissible energy of the impact absorbed by the system of fender appliance - hydrotechnical structure is defined according to the following dependence:

$$E_a = \int_0^{y_{max}} Q(y) \cdot dy \tag{27}$$

where:

Q (y) - reaction force of the system of fender appliance - hydrotechnical structure in the function of its deformation,

y_{max} - border deformation of the system of fender appliance - hydrotechnical structure.

Border deformation y_{max} is defined by means of two methods:

1. When **the hydrotechnical structure is provided with a fender appliance**; y_{max} is a permissible working deformation of a fender appliance which the hydrotechnical structure has got.
2. When **the hydrotechnical structure is not provided with a fender appliance**; y_{max} is a structure deformation for permissible reaction force Q_{dop}. It is the force which, when exceeded, will cause damage to vessel's hull or hydrotechnical structure.

1.3.MODEL OF EFFECTS OF VESSEL' COLLISION WITH SEA AREA BOTTOM

The vessel's collision with the sea area bottom (grounding takes place when the depth of the limited sea area in which the collision happens is smaller than the vessel's draught at the moment of this collision (t_i).

In the case described, the set elements are in the following dependence (Fig. 1.4):

$$\bigvee_{T(x,y,t_i)\in \mathbf{T}} T(x,y,t_i) < H(x,y) \qquad (28)$$

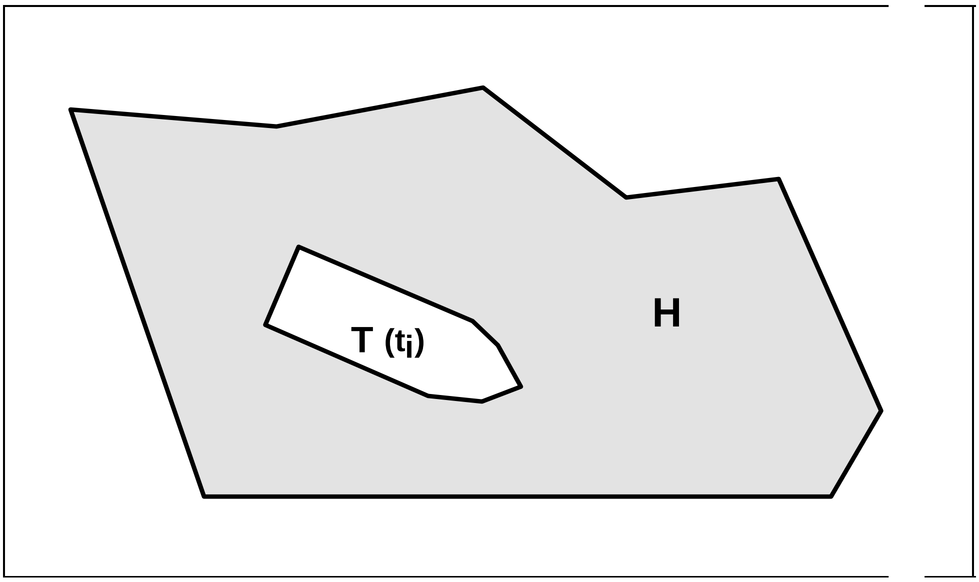

Fig. 1.4. Set of depths of limited sea area H and vessel's draught T_i at the moment of collision with a sea area bottom

The effects caused by the collision described depend on such factors as maximum energy of the vessel at the moment of her contact with bottom (t_i), and permissible energy of safe contact of the vessel with bottom. It can be presented in the following from:

$$S = \frac{E(t_i)}{E_p} \qquad (29)$$

where:

E (t_i) - maximum energy of the vessel at the moment of a contact between her hull and the bottom,
E_p - permissible energy of a safe contact between the vessel and the bottom.

Similarly to the model of a vessel's collision with bank parts, when the values is within $0 < S \leq 1$, the collision does not cause any substantial losses and the vessel can refloat by herself (or with assistance of the tugs manoeuvring with her) without any special salvage operation and damage to the hull. When, however, S>1 the collision is accompanied by damage to the hull, or, in order to help her refloat, it is necessary to undertake a special salvage operation involving financial consequences (stopping the traffic, equipment etc.). In most cases, damage to the hull results in arranging a salvage operation.

Maximum energy of the vessel, while the hull is in contact with the bottom, is understood as kinetic energy which the vessel can have at the moment of colliding with the bottom or grounding in the least favourable navigational conditions during a manoeuvre performance. The energy can be evaluated on the basis of simulation tests of a given manoeuvre of the vessel in a specified limited sea area in the hydrometeorological conditions tested.

Permissible energy of a safe contact of the vessel with the bottom should be interpreted as maximum energy of the contact with the bottom which will not cause any damage to the hull (rudder, propeller) and at which it will be possible for the vessel to refloat by herself, on condition that:

$$\left.\begin{array}{l} E_p \le E_{pm} \\ E_p \le E_{pu} \end{array}\right\} \tag{30}$$

where:

E_{pm} - permissible energy of refloating by herself,
E_{pu} - permissible energy of a contact with the bottom without any damage to the hull.

It is assumed that during the first contact of the hull with the bottom, vessel's main engine will be stopped (or adjustable blade propeller set to "0"). It is the rule during the manoeuvres in limited sea areas. With this assumption, permissible energy of refloating by herself at the moment of the first contact of the vessel with the bottom is calculated using the dependency:

$$E_{pm} = W_{in} = W_{out} \tag{31}$$

where:

P_{in} - work done by a friction force of the hull against the bottom (F_t) in the process of grounding,
P_{out} - work done by a towing power, (F_u) while refloating,

that is:

$$\int_0^{x_{\max}} F_t(x)\cdot dx = \int_0^{x_{\max}} F_u(x)\cdot dx \tag{32}$$

hence:

$$F_t\,(x) = F_u\,(x) \tag{33}$$

as well as:

$$F_t^{\max} = F_U^{\max}(x = x_{\max}) \tag{34}$$

where:

$F_{t\,(x)}$ - friction force of the hull against bottom,
$F_{u\,(x)}$ - towing power while refloating,
X_{max} - way of grounding (from the moment of the first contact with the bottom to the moment of stopping the vessel,
F_t^{max} - maximum value of friction force of the hull against the bottom while grounding ($x = x_{max}$),
F_u^{max} - maximum value of towing tower while refloating ($x = x_{max}$).

Starting with the rules of manoeuvring in limited sea areas and the definition of a limited sea area (see above), vessel's grounding is possible only with her bows or stern. The vessel can ground in shallow water of slope type of a certain inclination at any angle to a depth contour.

Maximum friction force of the hull against the bottom is calculated as follow:

$$F_t^{\max} = \mu \cdot N_{\max} \qquad (35)$$

where:

μ - a friction coefficient of the hull against the bottom (at zero speed),
$N_{\max}$ - maximum pressure by the vessel's hull on the bottom equal to the bottom reaction.

After substituting dependencies (35) in (34), maximum pressure of the hull against the bottom may be presented as follows:

$$N_{\max} = \frac{F_U^{\max}}{\mu} \qquad (36)$$

In the situation of less favourable grounding, i.e., vessel's point support, it is assumed that, while grounding, only one part of the vessel gets above the surface (bows or stern) while the other part increases its draught. Excluding the vessel's list, there has been calculated, for pressure $N_{\max}$, a draught change for the bows (or stern) according to the dependence :

$$\Delta T_d = \Delta T_{śr} + \Delta t \, \frac{L_{pp} - x_s}{L_{pp}} \qquad (37)$$

where:

ΔT_d - a draught change for the bows as a result of grounding,
$AT_{śr}$ - mean draught change as a result of grounding,
L_{pp} - length of vessel between perpendiculars,
x_s - tipping centre,
Δt - change of trim as a result of grounding.
and after transformations (2) the final definition is as follows:

$$E_{dm} = \frac{F_u^{\max 2}}{L_{pp} \cdot B \cdot \gamma \cdot \mu \cdot \mathrm{tg}\,\theta} \qquad (38)$$

where:

B - vessel's breadth,
Y - water weight density,
θ - angle of slope inclination.

Permissible energy of the contact with the bottom not resulting in damage to the hull [E_{pu}], can be calculated by means of two different methods depending on bottom type at which grounding takes place. There are distinguished two kinds of bottom [Simounsen 1997]:

1. Soft ground (clay, sand, gravel);
2. Hard ground (stones, stone plate, rock).

In the first case, grounding causes hull damage connected with exceeding its longitudinal strength (exceeding permissible shearing forces or bending moments).

In the second case, grounding causes hall damage in the point of its contact with the bottom connected with its local strength.

In the case of soft ground, the condition of safe grounding, from the point of view of hull longitudinal strength can be presented as follows:

$$\left.\begin{array}{l} Q \le Q_p \\ M \le M_p \end{array}\right\} \qquad (39)$$

where:

Q, M - shearing force and bending moment after grounding (maximum values),
Q_p , M_p - permissible shearing force and bending moment for a given vessel type.

In the case of hard ground, the local strength of the hull depends on the value of pressure force on the bottom, Exceeding a permissible force of pressure (N_p) causes a non- plastic strain of the construction or (as well as) its crack in the point of hull - bottom contact. The condition of a safe contact between the hull and the bottom is meeting the following dependences:

$$N_p \geq N_{max}$$

A permissible value of pressure force (N_p) depends mainly on the hull structure and is defined differently for vessel's single and double bottoms [Okreslanie 1995].

1.4. RISK NAVIGATIONAL ASSESSMENT DURING VESSEL'S MANOEUVRING IN LIMITED SEA AREAS BY USING THE MODEL CONSTRUCTED

The final a risk navigational assessment of the vessel manoeuvring in limited sea areas by using the model presented is carried out by means of the dependence (1).

Analysing the above dependence, it can be said that a threat to safety of the manoeuvring model depends on the size of the effects (S) and risk (R). When:

1. $S \leq 1$ - no threat to safety of the manoeuvring vessel independently of the size of the risk (R).
2. $S > 1$ - degree of a threat to safety of the manoeuvring vessel depends on the size of risk (R), and when
   - 2.1. $R > 0{,}07$ - it is unacceptable level of risk causing a threat to safety of the manoeuvring vessel,
   - 2.2. $R \leq 0{,}07$ - it is permissible level of risk causing a minor threat to safety of the manoeuvring vessel.

The border value of risk at $S>1$ has been calculated assuming that contemporary vessels are built maximum for 15 years of safe operation. The vessels to be built in 15 years will be far more modern structures of other (better) manoeuvring and technical characteristics of lower values P_A for the manoeuvres performed in identical conditions and, consequently, of smaller risks R. Taking it all into consideration, the estimated number of collisions in the year is $P_A \cdot I_R = 0.067 \approx 0.07$, assuming a 15-year operation of the vessel and a specified traffic intensity.

1.4. CONCLUSIONS

The model of risk of manoeuvring presented in this chapter is original particularly in reference to the energy method of evaluating collision effects, since, although there have been worked out a lot of methods of defining probability of collision occurrence, the methods of estimating collision results are very few [Gucma S. 1998].

A simulation method of evaluating a risk of manoeuvring in limited sea areas, using the model constructed can have practical application. It is based on simulation methods of vessel's movement in real time, worked out in a number of scientific organisations in the world [Gucma S. 1998].

In the writer's opinion, further developments of this model in the should mainly concentrate on: detailed working out of practical methods of risk evaluation such as the one which will be created within the ***BalticMaster*** project within the MUS scientific team. This will improve the models of evaluating vessel's collision effects in limited sea areas.

2. Mathematical Model of Effects of Ship Grounding

2.1. INTRODUCTION

The risk is defined in previous part as a probability combination of collision occurrence and the effects resulting from it. Assuming that the collision and its effects are independent events, a navigational risk can be presented as the following product:

$$R = P_A \cdot S \tag{1}$$

where:

P_A – probability of occurrence of a specific collision,
S – effects resulting from the collision.

While a number of methods defining the probability of collision occurrence has been worked out all over the world, the problem of methods estimating collision effects in limited sea areas has been neglected. The part of report presents a model of collision effects in limited sea areas. It is a physical model of effect estimation [Gucma S. 1998 (4)].

While performing a specified manoeuvre in limited sea areas, the vessels can cause a collision resulting from their movements. The collisions are classified as follows:

4. A collision of the vessel with bank parts, next to which the area depth is bigger than the vessel's draught. They usually include such sea structures as quays, breakwaters, bank protection etc.
5. A collision of the vessel with the sea area bottom (grounding), where the depth is smaller than the vessel's draught. These are, as a rule, bank slopes or shallow water (underground slopes).
6. A collision of two vessels.

This part discusses type 2 collisions. A model of collision effects is based on the assumption that the depths of limited sea areas decrease in a linear mode, that there are underwater slopes of varied angles of inclination there, and that the sea area is limited by sea (hydrotechnical) structures having the features of:

- a vertical wall (quay, breakwater, platform) which is supplied or not supplied with fender facilities,
- bank protections of slope type of different angle of inclination.

2.2. A MODEL OF EFFECTS OF VESSEL'S COLLISION WITH SEA AREA BOTTOM.

A vessel's collision with the sea area bottom or grounding occurs when a depth of the limited sea area in which the collision took place is smaller than the vessel's draught at the moment of the collision (t_i).

The effects resulting from the collision described depend on such factors as maximum energy of the vessel at the moment of her contact with the bottom (t_i) and acceptable energy of a safe contact of the vessel with the bottom. They may be presented as follows:

$$S = \frac{E(t_i)}{E_d} \tag{2}$$

where:

$E(t_i)$ – maximum energy of vessel at the moment of hull – bottom contact,

E_d – acceptable energy of safe contact between vessel and bottom.

Analogically to a model of vessel's collision with bank structures, when value S is between $0 < S \leq 1$, the collision does not cause substantial losses and the vessel is capable of refloating by herself (or with assistance of the tugs manoeuvring with her) without launching a special salvage operation and without damage to the hull.

When $S > 1$, the collision is accompanied by damage to the hull or, in order to help the vessel refloat, it is necessary to undertake a special salvage operation involving some financial consequences (stopping the traffic, use of equipment ect.). Damage to the hull is most frequently connected with a salvage operation being organised.

The notion of maximum energy of the vessel during a hull – bottom contact is understood as kinetic energy the vessel may have at the moment of striking against the bottom or grounding in the least favourable navigational conditions while performing the manoeuvre examined. The energy can be estimated on the basis of simulation tests of a specified manoeuvre of the vessel in a specified limited sea area in the hydrometeorological conditions examined.

Acceptable energy of safe contact of the vessel and the bottom should be understood as maximum energy of hull – bottom contact which does not cause damage to the hull (rudder, propeller), and at which it is possible to refloat without assistance, with the following condition to be met:

$$\left.\begin{aligned} E_d &\leq E_{dm} \\ E_d &\leq E_{du} \end{aligned}\right\} \tag{3}$$

where:

E_{dm} – acceptable energy of refloating by herself,

E_{du} – acceptable energy of hull – bottom contact, which does not cause damage to the hull.

It is assumed that at the moment of the first contact of the vessel and the bottom, the vessel's main engine is stopped (or adjustable blade propeller set for "0"), which is a rule during the manoeuvres in limited sea areas. If the above is assumed, acceptable energy of refloating by herself at the moment of the first contact between the vessel and the bottom is calculated using the following dependence:

$$E_{dm} = P_{wej} = P_{zej} \tag{4}$$

where:

P_{wej} – work done by the force of friction of the vessel against the bottom (R_t) in the process of grounding,

P_{zej} – work done by towing power (R_U) while refloating,

which means that:

$$\int_0^{x_{max}} R_t(x) \cdot dx = \int_0^{x_{max}} R_u(x) \cdot dx \tag{5}$$

hence

$$R_t(x) = R_u(x) \tag{6}$$

as well as

$$R_t^{max} = R_U^{max} \quad (x = x_{max}) \tag{7}$$

where:

$R_t(x)$ - force of friction of the hull against the ground,
$R_u(x)$ - towing power while refloating,
x_{max} - way of grounding (form the moment of the first contact with the bottom to the moment of vessel's stopping,
R_t^{max} - maximum value of force of friction of the hull while grounding ($x = x_{max}$),
R_U^{max} - maximum value of towing power while refloating ($x = x_{max}$).

Starting with the principles of manoeuvring in limited sea areas and the definition of a limited sea area (see above), vessel's grounding is possible only with her bow or stern. The vessel can go aground on shallow water of a slope type of the inclination of any angle to a fathom line.

The maximum force of friction of the hull against the bottom is calculated as follows [NMA 1994]:

$$R_t^{max} = \mu \cdot N_{max} \text{ [N]} \tag{8}$$

where:

μ - coefficient of friction of the hull against the bottom (at zero speed),
N_{max} – maximum pressure of the vessel's hull on the bottom equal to bottom reaction [N].

After substituting dependence (8) in (7), the maximum pressure of the hull on the bottom can be presented as follows:

$$N_{max} = \frac{R_U^{max}}{\mu} \qquad \text{[N]} \tag{9}$$

Assuming the least favourable case of grounding, i.e, point support, it is understood that on grounding only one part of the vessel (bow or stern) emerges while the other part increases its draught. Neglecting the vessel's list, a change of the draught of the bow or stern for pressure N_{max} was calculated according to the dependence [Dudziak 1998]:

$$\Delta T_d = \Delta T_{śr} + \Delta t \, \frac{L_{pp} - x_s}{L_{pp}} \qquad \text{[m]} \tag{10}$$

where:

ΔT_d – change of bow's draught as a result of grounding [m],
$\Delta T_{śr}$ – change of mean draught as a result of grounding [m],
L_{pp} – vessel's length between perpendiculars [m],
x_s- tipping centre [m],
Δt - change of trim as a result of grounding [m].

The change of mean draught is calculated according to the dependence:

$$\Delta T_{śr} = \frac{N_{max}}{F_w \cdot \gamma} \qquad \text{[m]} \tag{11}$$

with:

$$F_w = L_{pp} \cdot B \cdot \alpha \qquad \text{[m]} \tag{12}$$

after substituting:

$$\Delta T_{śr} = \frac{N_{max}}{L_{pp} \cdot B \cdot \alpha \cdot \gamma} \tag{13}$$

where:

F_w – area of waterline plane [m^2],
B – vessel's breadth [m],
α – coefficient of waterline plane,
γ – water weight density [N/m^3],

and the change of trim is:

$$\Delta t = \frac{N_{max}(x_d - x_s)}{M_j} \quad [\mathrm{m}] \tag{14}$$

where:

x_d – abscissa of support point of the vessel aground (bow or stern) [m],
M_j – inch trim moment [tm/m].

An inch trim moment can be calculated from the dependence:

$$M_j = \frac{D \cdot F_{ml}}{L_{pp}} \quad [\mathrm{Nm/m}] \tag{15}$$

where:

D – vessel's buoyancy [N],
F_{ml} – longitudinal metacentric radius,

where:

$$D = L_{pp} \cdot B \cdot T \cdot \delta \cdot \gamma \quad [\mathrm{N}] \tag{16}$$

and the longitudinal metacentric radius is, according to approximated dependence [Alferiew 1972] as follows:

$$F_{ml} = \frac{\alpha^2}{14\delta} \cdot \frac{L_{pp}^{\ 2}}{T} \quad [\mathrm{m}] \tag{17}$$

where:

δ -block coefficient of a vessel's hull.

After substituting dependencies (16) and (17) in (14), and then (15) in (14) as well as accepting the following assumptions:

- a support point is at either end of the vessel $x_d \approx L_{pp}$ (bow case),
- while grounding in limited sea areas, due to low speeds, the vessel causes small changes of trim $x_s \approx L_{pp}/2$

we get:

$$\Delta t = \frac{7 \cdot N_{max}}{L_{pp} \cdot B \cdot \alpha^2 \cdot \gamma} \quad [\mathrm{m}] \tag{18}$$

and substituting dependences (13) and (18) in (10) we get:

$$\Delta T_d = \frac{N_{max}}{L_{pp} \cdot B \cdot \alpha \cdot \gamma}\left(1 + \frac{7}{2\alpha}\right) \quad [\mathrm{m}] \tag{19}$$

Accepting for a contemporary loaded merchant vessel a mean coefficient of waterline plane a = 0.85 and taking into account dependencies (7), we get a permissible change of bow (or stern) draught:

$$\Delta T_d = \frac{6 \cdot R_U^{max}}{L_{pp} \cdot B \cdot \gamma \cdot \mu} \qquad [\mathrm{m}] \qquad (20)$$

A change of draught ΔT_d must be treated as a limiting (maximum) one, at which the vessel can still refloat by herself (Fig.2.1).

Knowing an angle of the slope inclination θ (Fig.1) entered by the vessel, it is possible to calculate the way of grounding:

$$x_{max} = \Delta T_d \cdot ctg\,\theta \qquad [\mathrm{m}] \qquad (21)$$

and on the basis of dependence (5), there was calculated a permissible energy for the vessel refloating by herself:

$$E_{dm} = \frac{R_U^{max} \cdot x_{max}}{2} \qquad [\mathrm{Nm}] \qquad (22)$$

where, after substituting (20) and (21) in (22) and simplifying the dependence, we finally get the following:

$$E_{dm} = \frac{{R_U^{max}}^2}{L_{pp} \cdot B \cdot \gamma \cdot \mu \cdot tg\,\theta} \qquad [\mathrm{Nm}] \qquad (23)$$

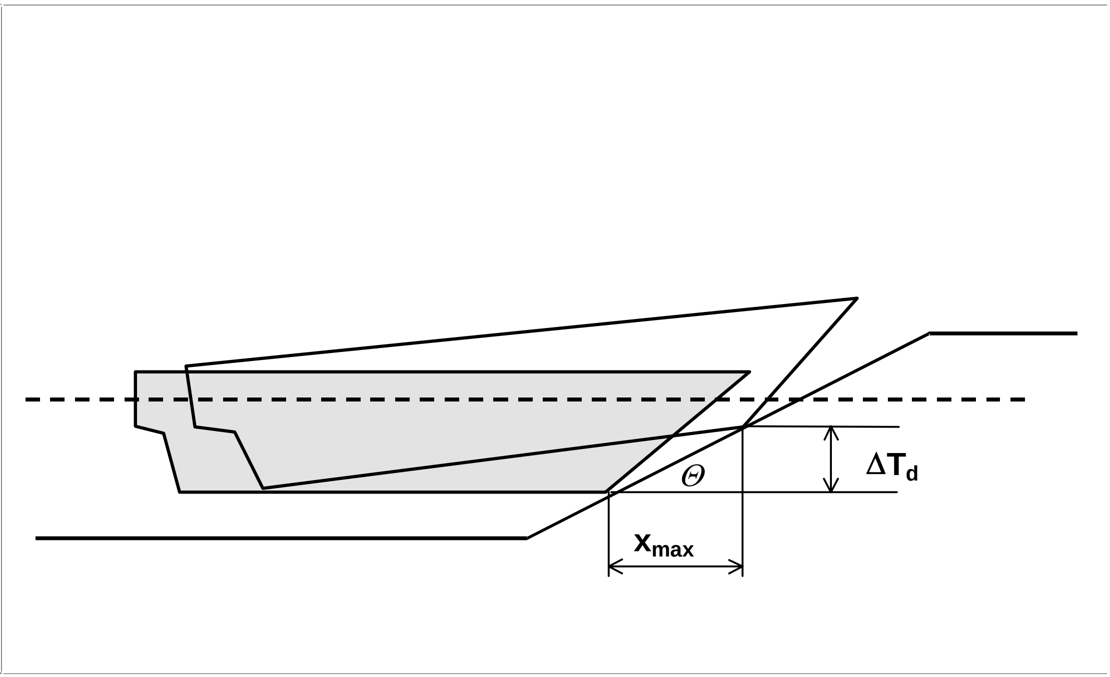

Fig.2.1. A diagram of vessel's grounding in a limited sea area.

A maximum towing power while refloating is equal to a towing power of the vessel on a pile as well as a towing power of the tugs on a pile which take part in vessel's manoeuvring in a specific area.

$$R_U^{max} = R_U^{pal} + \Sigma R_{Uhi}^{pal} \qquad [\mathrm{N}] \qquad (24)$$

where:

R_U^{pal} - towing power of the vessel on a pile at engine astern (a worse case),

R_{Uhi}^{pal} - towing power of i-tug.

Using the approximation methods of solution, a towing power of the vessel on a pile is determined by means of one of the following empirical dependencies [Kuzmienko 1982]:

$$R_U^{pal} = \frac{k \cdot N_n}{9 \cdot V_{CN}} \cdot 7220 \quad [\,\mathrm{N}\,] \tag{25}$$

or

$$R_U^{pal} = \mathrm{k} \cdot \mathrm{f} \cdot \mathrm{N_n} \cdot 7220 \quad [\,\mathrm{N}\,] \tag{26}$$

where:

N_n – total power of the main engines [kW],
k – coefficient of the use of towing depends on engine setting,
Full Ahed = 1
Full Astern = 0.3÷ 0.5 (mean – 0.4)
f – empirical calculating coefficient depends on type of vessel and propulsion:
- merchant and passenger vessel's 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 of the vessel at full ahead (knots)*

A coefficient of friction of the hull against the bottom depends on bottom type (Table 1).

Table 2.1. Coefficient of friction of the hull against bottom at zero speed [Kuzmienko 1982].

Type of ground	Friction coefficient μ
Loose clay (silt)	0.20 – 0.30
Clay	0.30 – 0.45
Clay and sand	0.30 – 0.40
Fine sand	0.40 – 0.45
Coarse sand	0.40 – 0.50
Gravel	0.45 – 0.50
Stone plate	0.35 – 0.60
Stones	0.45 – 0.60

A permissible energy of contact with bottom not resulting in damage to the hull (E_{du}) is calculated by means of two different methods depending on bottom type on which grounding took place. There are distinguished 2 kinds of bottom (Simounsen 1997).

1. Soft ground (clay, sand, gravel),
2. Hard ground (stones, stone plate, rock).

In the first case, the hull is damaged due to exceeding its longitudinal strength (exceeding permissible shearing forces or bending moments).

In the second case, the hull is damaged in the point of its contact with bottom due to exceeding the local strength of hull.

Ad. 1. **In the case of soft ground**, the condition of safe grounding from the point of view of hull longitudinal strength can be presented as follows:

$$\left.\begin{array}{l} Q \le Q_d \\ M \le M_d \end{array}\right\} \tag{27}$$

where:

Q [N], M [Nm] - shearing force and bending moment after grounding (maximum values),
Q_d [N], M_d [Nm] - permissible shearing force and bending moment for a given vessel type.

A maximum value of shearing forces after grounding is defined as equal to a maximum pressure of the hull on bottom:

$$Q = N_{max} \quad [N] \tag{28}$$

Accepting the former assumptions referring to grounding with a bow and a stern and, appropriately, that force of buoyancy and load (vessel, cargo) balance each other, a maximum bending moment is calculated according to the dependence:

$$M = N_{max} \cdot \frac{L_{pp}}{2} \quad [Nm] \tag{29}$$

for limiting conditions ($Q = Q_d$ and $M = M_d$) there were calculated maximum forces of pressure:

$$\begin{aligned} N^{q}_{max} &= Q_d \quad [N] \\ N^{m}_{max} &= \frac{2M_d}{L_{pp}} \quad [N] \end{aligned} \tag{30}$$

of which the smaller one is a permissible value (N_d).

On the basis of (26), it was possible to calculate a limiting change of bow draught:

$$\Delta T_d = \frac{6 \cdot N_d}{L_{pp} \cdot B \cdot \gamma} \quad [m] \tag{31}$$

and then, using dependences (28) and (29) , to calculate a permissible energy of the contact with bottom not resulting in damage to the hull while grounding (soft bottom):

$$E_{du} = \frac{{N_d}^2 \cdot \mu}{L_{pp} \cdot B \cdot \gamma \cdot tg\,\theta} \quad [Nm] \tag{32}$$

Permissible shearing forces and bending moments for large vessels according to JACS standards [Nita 1992] are respectively as follows:

$$\begin{aligned} Q_d &= 0.3 \cdot C \cdot L \cdot B\,(C_B + O.7) \quad [kN] \\ M_d &= 0.19 \cdot C \cdot L^2\,B \cdot C_B \quad [kNm] \end{aligned} \tag{33}$$

where:

$C_B = 0,6$

$$C = \begin{cases} 10.75 - \left(\dfrac{300 - L}{100}\right)^{1,5} & \text{for } 90\text{ m} \le L \le 300\text{m} \\ 10.75 & \text{for } 300\text{m} < L < 350\text{m} \\ 10.75 - \left(\dfrac{L - 350}{150}\right)^{1,5} & \text{for } 350\text{m} \le L \end{cases}$$

Permissible shearing forces and bending moments for fast vessels (V/ $\sqrt{L}$ >4,2, where V- a maximum speed in knots, L - vessel's length in metres are, according to Det Norske Veritas [NMA 1994], respectively as follows:

$$M_d = 0.3 \cdot L^2 \cdot C_w \cdot C_B$$

$$Q_d = \frac{4 \cdot M_d}{L} \tag{34}$$

where:

$$C_w = \begin{cases} 0.08\,L & \text{for } L < 100\text{m} \\ 6 + 0.02\,L & \text{for } L > 100\text{m} \end{cases}$$

Ad.2. **In the case of hard ground**, the local strength of hull depends on the value of pressure force on bottom. Exceeding a permissible force of pressure (N_d) causes a non-plastic strain of the structure or (as well as) its crack in the point of hull - bottom contact. The condition of a safe contact between the hull and hard bottom is meeting the following dependencies:

$$N_d \geq N_{max} \tag{35}$$

A permissible value of pressure force (N_d) depends mainly on the hull structure and is defined differently for vessel's single and double bottoms [10].

For limiting conditions $N_{max} = N_d$, there was calculated, on the basis of dependences (26), a limiting change of bow draught:

$$\Delta T_d = \frac{6N_d}{L_{pp} \cdot B \cdot \gamma} \ \text{[m]} \tag{36}$$

and, on the basis of dependences (21) and (22), permissible energy of the contact with bottom not resulting in damage to the hull during its contact with hard bottom:

$$E_{du} = \frac{N_d^{\,2} \cdot \mu}{L_{pp} \cdot B \cdot \gamma \cdot tg\,\theta} \ \text{[Nm]} \tag{37}$$

Meeting condition (3) means choosing the smaller of two energies E_{dm} and E_{du} and accepting it as E_d, i. e. permissible energy of a safe contact with bottom.

2.3. GENERAL CONCLUSIONS TO THE CHAPTER 2

The subchapter 2 presents a model of effects of vessel's collision with the following obstacles:

- a bank part at which the depth of a water area is bigger than vessel's draught,
- a water area bottom, where the depth is smaller than vessel's draught.

In both the cases, the models are based on a comparison of maximum energy of vessel's collision with an obstacle and the permissible energy, which does not cause major damage to the vessel or bank elements as well as expenses of a salvage operation.

A maximum energy of vessel's collision with an obstacle is the kinetic energy the vessel can have at the moment of collision in the least favourable navigational conditions, affected by probability of collision (P_A). The energy is defined on the basis of simulation tests of a given manoeuvre performed in specified navigational conditions.

The part of this report concentrates on the original problem of defining a permissible energy of vessel-bottom contact, which does not cause damage to the hull, and at which it is possible for the vessel to refloat by herself - without salvage operation which will be necessary for creation of integrated model of safety assessment.

3. Methods of navigational safety assessment on restricted water areas

Methods of navigational safety presented in the following section will be use for detailed decomposition of created integrated model of navigational safety and finding the most important elements of the model. The safety of navigation (according to Jurdziński and Urbański) is part of the shipping safety, which in turn contributes to the overall maritime safety. The state of danger in shipping is due to a marine accident understood as an undesired event causing substantial damage and losses, resulting from a collision or internally contradictory actions in the system: man-object-environment.

This notion is connected with:

1. Marine disaster: an accident causing very large losses with irreparable or hardly reparable tragic consequences (including human losses).
2. Accident: understood as an undesired event making it impossible or limiting to a large degree further operation of the object. It may be a circumstance for a serious accident, involving:
   - ship's fault,
   - port structure fault,
   - fault of hydrographic objects,
   - pollution of the marine environment.

Marine navigation can be divided according to the area of ship operation [Gucma S. 1997]:

- navigation in unrestricted open sea areas (ocean),
- navigation in offshore areas,
- navigation in restricted areas (pilotage navigation).

Navigation in restricted areas rarely results in marine disasters, simply because manoeuvring in restricted areas is executed with caution, with ships moving at slow speeds.

The safety of navigation is a state of the system related with handling a ship safely from point A to point B. In other words, it is the state of the system connected with accident-free performance of specific manoeuvres of a ship in a restricted area. The following navigational accidents can be distinguished:

- collision with another ship in a given area (ships are berthing, at anchor or proceeding).
- grounding (widely understood as unintended contact of the hull, rudder or propeller with the bottom),
- damage to the hull due to ship's contact with the shore (during the ship's impact on a shore element where the depth is larger than ship's draft),
- damage to port or offshore structures through ship's direct contact or as a consequence of propeller stream action,
- damage to a tug participating in manoeuvres of a ship,
- damage to a floating aid to navigation.

3.1. CRITERIA FOR THE ASSESSMENT OF NAVIGATION SAFETY

The indicator of navigation safety in restricted areas can be expressed in this form [Gucma S. 1997]:

$$B_i = f(A_i, S_i, N_i, H_i, M_i, I_i, R_i) \tag{1}$$

where:

B_i – indicator of navigation safety assessment,
A_i – area parameters,
S_i – ship parameters,
N_i – parameters of position determination systems,
H_i – hydro-meteorological parameters ,
M_i – parameters of the performed manoeuvre,
I_i – parameters of traffic intensity,
R_i – parameters of a VTS system.

The indicator of navigation safety (1) is a variable dependent on such independent variables as Ai, Si, Ni, Hi, Mi, Ii, Ri. These represent a number of factors describing the state of the system: ship – area – position determination system – prevailing hydro-meteorological conditions – traffic intensity – VTS system.

In order to define the effect of the variables Ai, Si, Ni, Hi, Mi, Ii, Ri on the navigation safety, numerical indicators have to be adopted. These indicators are different for various kinds of navigation areas (where a given manoeuvre is performed). The boundary values of these indicators constitute a basis for the assessment of navigation safety for specific elements of the waterway (type of manoeuvre performed).

Basic criteria for the assessment of navigation safety practically used are as follows:

- underkeel clearance allowing to define ship's safe draft;
- required dimensions of the manoeuvring area making it possible to establish minimum safe dimensions of a given area. This criterion is strictly related with the determination of manoeuvring scope (performance of a specific manoeuvre) in a preset area;
- admissible kinetic energy of ship's impact on the berth allowing to determine the safety of berthing manoeuvre;
- admissible speed of propeller stream at the bottom, for establishing safe engine manoeuvres in port areas;
- admissible accident rate, allowing to describe the quality of traffic processes for basically all kinds of waterways and types of manoeuvres;
- specific time of manoeuvre execution.

Required underkeel clearance is the basic criterion of navigation safety in all kinds of areas. A safely performed manoeuvre in restricted areas is connected with satisfying the basic condition of navigation safety. It can be written in the following form:

$$h(x, y, t) \geq T(x, y, t) + \Delta(x, y, t) \tag{2}$$

where:

$h(x, y, t)$ – area depth at the point with coordinates (x, y) at the moment t,
$T(x, y, t)$ – ship draft at the area point (x, y) at the moment t,
$\Delta(x, y, t)$ – underkeel clearance at the area point (x, y) at the moment t.

The underkeel clearance is critical for the safety of a ship's manoeuvre. The safe underkeel clearance depends on a variety of factors that can be written as this function:

$$\Delta(x, y, t) = f(A(x,y,t), S(x,y,t), H(x,y,t), M(x,y,t)) \tag{3}$$

where:

A(x, y, t) – area parameters at the point (x, y) at the moment t,
S(x, y, t) – ship's parameters at the point (x, y) at the moment t,
H(x, y, t) – parameters of hydro-meteorological conditions at the point (x, y) at the moment t,
M(x, y, t) - parameters of the manoeuvre performed at the point (x, y) at the moment t.

The underkeel clearance has a random character.

If we have the parameters of its distribution, we can define the probability of the hull contact with the bottom for various conditions, i.e. the accident probability (Fig. 3.1) as equal to:

$$P(T \geq h) = \int_h^\infty f(\Delta)d\Delta \tag{4}$$

where:

f(Δ) – function of density of underkeel clearance distribution.

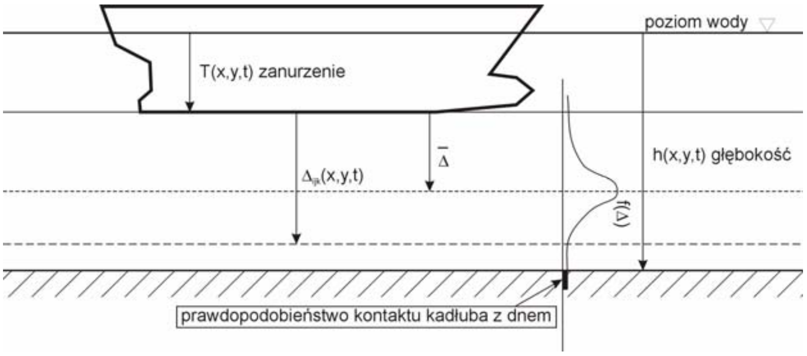

Fig. 3.1. The distribution of underkeel clearance (method of dynamic clearance)

There are two methods of the determination of underkeel clearance: static and dynamic.

In most ports of the world (including all Polish ports) the static method is used. In this method, where the safe underkeel clearance is assumed to be the maximum quantity of the clearance in a given area in all the period of port operation, that is:

$$\Delta(x, y, t) = \Delta = \text{const.} \tag{5}$$

The term underkeel clearance defined by the dynamic method consists in determining, for a specific level of clearance, the probability of accident-free manoeuvre execution. The clearance is determined for a specific area, manoeuvre, ship and hydro-meteorological conditions in a given moment of time.

The methods differ in the following:

- in the steady clearance method the level of navigation safety varies, and the navigational risk for a variety of conditions is much lower than the admissible value of the risk $(R(t) < R_{dop}; R_i << R_{dop})$,
- in the dynamic underkeel clearance method the level of navigation safety is steady, and the navigational risk does not exceed the admissible risk $(R = const.; R \leq R_{dop})$.

  where:

  R – navigational risk,
  R_{dop} – admissible navigational risk.

The determination of underkeel clearance by the ”steady clearance method” brings about the reduction of allowed ship draft in comparison with the ”dynamic clearance method”. As the ship has to adjust to limited draft requirement, its loading capacity is not fully utilized and the quantity of loaded and carried cargo has to be limited.

The safe manoeuvring area is a general criterion for the assessment of navigation safety. We define it having assumed that the ship can safely manoeuvre only in an area which at each point during the manoeuvre fulfils the condition of the required depth. This area is referred to as a **navigable area**. It can be presented as an area **D(t)**, that is a set of points $p(x, y)$ satisfying the condition of required depth at the moment t:

The examined area can be described if we assume as follows:

- a ship is manoeuvring in a restricted area, where its position is determined in the Cartesian coordinates (x, y) belonging to the sets, respectively, $x \in \mathbf{X}$, $y \in \mathbf{Y}$;
- the coordinates describing the set are a Cartesian product: $\mathbf{X} \times \mathbf{Y}$

A ship performing a given manoeuvre in a navigable area covers a specific area defined by the ship’s subsequent positions in that area. The parameters of the area are random in character and depend on a variety of factors. The area, calculated at a certain level of confidence is referred to as the **safe manoeuvering area** [Gucma S. 2001].

The examined manoeuvre can be formulated with these assumptions:

- ships that can manoeuvre in the examined area belong to the set of i-th parameters $i \in \mathbf{I}$. The parameters may refer to ship size (length, beam, draft) as well as ship types,
- a ship manoeuvring in the examined area can make one of the manoeuvres belonging to the set $j \in \mathbf{J}$. This is a set of types of maneuver performed in the examined area (maneuver type, number and power of tugs employed),
- examined ships can manoeuvre in navigational conditions contained in the set $k \in \mathbf{K}$. This refers to both hydro-meteorological conditions (wind and current speeds and directions, waves, visibility, icing, sea state etc.) and to aids to navigation, or other traffic in the area.

Both of the above mentioned criteria of safety assessment (horizontal and vertical) can be written as the **basic condition of navigation safety** [Gucma S. 2000]:

$$\left.\begin{array}{l} \mathbf{d}_{ijk}(1-\alpha) \subset \mathbf{D}(t) \\ \bigwedge\limits_{p(x,\,y)\in\mathbf{D}(t)} h(x, y, t) \geq T(x, y, t) + \Delta(x, y, t) \end{array}\right\} \qquad (6)$$

where:

$\mathbf{D}(t)$ – navigable area (set of points p(x, y) satisfying the condition of accessible depth at the moment t),

$\mathbf{d}_{ijk}(1-\alpha)$ – safe manoeuvring area of the i-th ship, performing the j-th manoeuvre in the k-th conditions, determined at the confidence level $1-\alpha$.

Kinetic energy of ship’s impact on the berth is analyzed for the berthing manoeuvre, where that energy is decisive for the safety of that manoeuvre. The kinetic energy is taken into consideration when the consequences of an unintended contact of a ship’s hull with a port structure (breakwater, berth etc.) occurs during manoeuvres in a restricted area.

The results of the analysis of manoeuvre types have shown that the first contact of a ship with the berth is critical. When a ship’s hull touches the berth, its kinetic energy changes into the impact work, which affects the hull and the berth with fenders. The fact that ship’s berthing does not result in any damage to the hull or berth depends on the quantity of the kinetic energy, as the subsequent contacts of the ship and the berth are much weaker in terms of the energy involved. Therefore, the berthing safety criterion is considered to be the value of kinetic energy $E(t)$ of the ship absorbed by the fender–berth system at the moment of the first ship-berth contact. That energy should be considered as the kinetic energy transferred to the berth [Gucma S. 1997].

The quantity of kinetic energy absorbed by the berth-fender-ship system affects the quantity of the system reaction forces that are needed for the manoeuvre to be performed safely. In this connection the quantity of energy for navigation safety can be written as follows:

$$\left.\begin{array}{l} E(t) \le E_d^{nab} \\ E(t) \le E_d^{stat} \end{array}\right\} \tag{7}$$

where:

$E(t)$ – maximum kinetic energy of ship's impact absorbed by the system berth-fender-ship [kNm],

E_d^{nab} – admissible kinetic energy absorbed by the system berth-fender [kNm],

E_d^{stat} – admissible kinetic energy, which creates the reaction forces of the berth-fender system that do not cause a permanent deformation of the ship's hull [kNm].

The admissible kinetic energy absorbed by the berth-fender system should be interpreted as follows:

$$E_d^{nab} = \int_0^{y_{\max}} Q(y) \cdot dy \tag{8}$$

where:

$Q(y)$ – reaction force of the berth-fender system as the function of its deformation,

y_{max} – maximum deformation of the system (admissible working deformation).

The distribution of points of the first ship-berth contact and the associated problem of the location of fenders are essential for the safety of berthing.

We assume that the quantity of kinetic energy of ship's impact on the berth for a specific ship in given navigational conditions has a random character. The random variable is the quantity of kinetic energy absorbed by the ship-fender-berth system in the *i*-th interval of berth length for the *j* –th manoeuvre, that is considered as the *j*-th simulated trial. This random variable is denoted as (x_{ij}).

The examined berthing manoeuvres have shown that these random variables can be well described by the gamma distribution [Guziewicz 1996], the density of which has this formula:

$$f(x) = \begin{cases} \dfrac{x^{p-1} \cdot e^{-\frac{x}{\lambda}}}{\lambda^p \cdot \Gamma(p)} & \text{dla } x>0 \\ 0 & \text{dla } x \le 0 \end{cases} \tag{9}$$

where:

p, λ - distribution parameters, $p > 0$, $\lambda > 0$;

$\Gamma(p)$ - Euler's gamma function defined by this formula:

$$\Gamma(p) = \int_0^{\infty} e^{-t} t^{p-1} dt \qquad (0 < p < \infty) \tag{10}$$

Admissible speed of propeller streams at the bottom is one of the basic criteria for the assessment of the safety of unassisted berthing of ro-ro ships and sea-going ferries. If the admissible water flow speeds area exceeded at the bottom, or near a port structure, it may cause the berth to be damaged, or the strengthened bottom or bank protections of the channel to be destroyed. These phenomena can be caused by:

- propeller streams generated by the action of the main propulsion or thrusters,
- backward currents caused by ship movement in a channel.

The navigation safety condition for manoeuvres in port areas (berthing or turning of a ship), taking into account the speeds of propeller streams, can be formulated as follows:

$$\vartheta_d\,(\Delta t) \le \vartheta_{dop}\,(\Delta t) \tag{12}$$

where:

$\vartheta_d\,(\Delta t)$ – speed of propeller streams of a ship at port structures (bottom, channel slope, berth etc.) in the time interval Δt,
$\vartheta_{dop}\,(\Delta t)$ – admissible water speed at the examined port structure in the time interval Δt.

Accidents of this type affect the safety of navigation of ships manoeuvring in restricted areas, especially while berthing or passing a channel. In these two cases the parameters of water streams are calculated in a different manner.

The distribution of accident numbers makes up a basis for navigation safety assessment in waterways running through restricted areas. The distributions of accident numbers are either area- or cause-based counted in various time intervals. This allows the determination of accident probability in specific sections of a waterway depending on the causes of accidents. Besides, it is possible to define the cause-effect relations of accidents that actually happen.

The consequences of navigational accidents can be classed as minor or major ones, as results of, respectively, incidents or serious accidents. Therefore, considerations concerning navigation safety in examined water areas refer to serious accidents or the total number of serious accidents and incidents. The conditions for safe navigation in examined waterways incorporating the number of serious accidents and incidents can be written as follows:

$$a_r \le A_r \tag{13}$$

or

$$a_r' \le A_r' \tag{14}$$

where:

a_r, a_r' – annual probable number of serious accidents and incidents of a specific type of ship in a given area (respectively, total and serious accidents),
A_r, A_r' – criterion of navigation safety (annual admissible number of accidents and serious accidents).

It should be noted that the criteria of navigation safety in restricted area depend on the area type:

- tidal areas with the maximum 0.004 of serious accidents a year or maximum 0.04 of total accidents,
- non-tidal areas with maximum 0.007 of serious accidents a year or maximum 0.07 of total accidents.

The duration of a manoeuvre performed affects the capacity of the given waterway. The condition of navigation safety of ships maneuvering within 24 hours in the examined waterway section, accounting for the duration of the executed manoeuvre can be formulated as follows:

$$\sum_{i\in I,\, j\in J,\, k\in K} t_{ijk} \le 24h \tag{15}$$

where:

t_{ijk} – time of the manoeuvre for the *i*-th ship type from the set ***I*** of ships manoeuvring within 24 hours, performing the *j*-th manoeuvre in the *k*-th navigational conditions.

3.2. NAVIGATIONAL RISK AS A MODERN MEASURE FOR THE ASSESSMENT OF NAVIGATION SAFETY IN RESTRICTED AREAS

Risk is understood as the anticipated consequences of a decision concerning the execution of a task in the conditions of uncertainty and hazards that one should be afraid of. Risk is defined as the probability of undesired events and the size of damage and losses resulting from these events The consequences are understood as the result of a specific undesired event**.**

Navigational risk is a complex indicator of navigation safety assessment. There exist two concepts of risk: technical and economic. They depend on the method of description of accident consequences. In the marine traffic engineering it is assumed that technical risk is equivalent to navigational risk. With this concept, the estimation of accident consequences consists in a mathematical description of ship's collision dynamics. This description provides a basis for physical indicators of the consequences. With economic risk, the estimation of the consequences comes down to the estimation of the costs to be incurred due to the accident consequences [Bobrowski 1984, Gucma S. 1997].

It should be noted that there are methods allowing the converting the physical effects into economic ones [Gucma S. 2000].

Navigational risk is defined as the product of the accident probability and the consequences caused by that accident. Additionally, a formal description of risk was supplemented with the relative frequency of the examined manoeuvre. The navigational risk indicator can be presented as the product:

$$R = I_R \cdot P_A \cdot S \tag{16}$$

where:

I_R – mean frequency of performing a given manoeuvre in a year,
P_A – probability of a specific accident ,
S – measure of the consequences due to the accident.

Estimation of navigational risk consists in:

- calculating the probability of an accident of a given type during the *j*-th type of manoeuvre in a preset area restricted by the *i*-th ship type in the *k*-th navigational conditions,
- estimation of the consequences of an accident of a given type occurring during the *j*-th type of maneuver in a preset area restricted by the *i*-th ship type in the *k*-th navigational conditions.

Using the definition of navigational risk, we can define the condition for safe navigation:

$$R_{\text{dop}} \geq R$$

after transformations:

$$R_{\text{dop}} \geq I_R \cdot P_A \cdot S \tag{17}$$

where:

R_{dop} – admissible risk of performing a specific manoeuvre.

In a simplified version, the admissible risk of performing a specific manoeuvre is the admissible number of accidents occurring during such a maneuver in one year. This assumption is acceptable when conventional mean consequences of an event are equal to one ($S_{\text{śr}} = 1$).

Navigational accidents can be classed, depending on their consequences, into two types:

- incidents – consequences $s \le 1$,
- serious accidents – consequences $s > 1$.

The consequences of incidents can often be removed without special rescue operations, and without maritime administrations or even the owner being notified of them. The elimination of the consequences of serious accidents requires a rescue operation. The research has shown that the ratio of serious accidents to the total number of accidents (including incidents) does not exceed 10% .

Dutch criteria of navigation safety in waterways (restricted areas) permit the maximum 0.004 of serious accidents (groundings) in a year. English criteria, on the other hand, permit the maximum 0.001 of serious accidents (groundings) in a year.

Waterways are usually designed for 50 years of operation, while ships are designed for 15-year operation. The following facts are to be borne in mind:

- within the 50 years of their operation, waterways are modernized a few times. Such modernization includes, among others, the introduction of better navigational systems, maneuvering methods and ships,
- each newer generation of ships (after 15 years) is more perfect in terms of manoeuvring abilities, navigational systems, technical reliability etc.

Considering these facts, we have concluded that the requirement of accident-free performance should not be flexibly defined. Therefore, the following admissible indicators of navigation safety are accepted for restricted areas (A_r):

- tidal areas - maximum 0.004 of serious accidents a year or maximum 0.04 of total accidents,
- non-tidal areas maximum 0.007 of serious accidents a year or maximum 0.07 of total accidents.

Probability of an accident depends on the following random variables:

- navigational accident-free performance of a manoeuvre in specific conditions,
- error-free performance of the navigator acting in the anthropo-technical system ship – navigator (navigator's reliability),
- technical reliability of the ship.

The indicator of navigational accident-free performance of a given manoeuvre in a specific area should be considered as the probability of avoiding a collision by a ship of a specific type with stationary objects (upright wall, bottom) in specific hydro-meteorological and operational conditions, provided that all shipboard machinery works reliably. In the methods presented, navigational reliability of a manoeuvre performed is connected with navigator's reliability. Human factor is taken into account by estimating the probability of a correct manoeuvre through real research with the participation of qualified navigators.

Technical reliability is to be regarded as the probability of reliable work of marine systems and machinery, i.e. those affecting the accident-free performance of a manoeuvre.

The probability of an accident occurring during a specific manoeuvre in a restricted area can be presented in this form:

$$P_A = 1 - P_B \tag{18}$$

where:

P_B – probability of a safely performed manoeuvre by a ship with specific parameters, in specific navigational and hydro-meteorological conditions, conned by a qualified navigator.

Technical reliability and navigational accident-free performance (comprising the human factor) can be considered as practically independent indicators. Therefore, the probability of accident-free (safe) manoeuvre execution can be written in this form:

$$P_B = P_n \cdot P_t \tag{19}$$

where:

P_n – probability that a ship with specific parameters conned by a navigator with specific qualifications will not have a collision in specific navigational and hydro-meteorological conditions during a particular manoeuvre,

P_t – probability of reliable operation of marine systems and machinery important for accident-free manoeuvre performance.

The probability of performing an accident-free manoeuvre by a ship of a given type in specific navigational and hydro-meteorological conditions, conned by a navigator with specific qualifications, in a given time interval and place has this formula:

$$P_n = P(X_j \leq d_j) \tag{20}$$

where:

X_j – maximum distance of the ship's extreme point to the port side or starboard side from the fairway centre line in the j-th section of the area (random variable),

d_j – shortest distance from the hazard in the j-th section of the area,

Technical reliability understood as correct and safe performance of a specific manoeuvre of a ship relies on the smooth work of the main engine, generating sets, steering gear, tugs and radars in the case of poor visibility. Each of these machines is characterized by a specific probability of reliable work in the time t; the notations below refer to the probability of reliable work of the:

- $P_1(t)$ – main engine,
- $P_2(t)$ – generating set,
- $P_3(t)$ – steering gear,
- $P_4(t)$ – tug,
- $P_5(t)$ – radar.

The failure rate function $\lambda(t)$ is used for the calculation of the probability of reliable work of the above mentioned machinery. If we consider only stationary conditions of the machinery operation (classification societies maintain this requirement) we assume that the risk function $\lambda(t)$ does not depend on time and thus it is constant $\lambda = \text{const.}$, so the probability of reliable work of particular machines can be approximately expressed in this form:

$$P_i(t) = 1 - \lambda_i \cdot \Delta t_i \tag{21}$$

Assuming that a failure of any of the above machines may in certain circumstances cause a ship accident, then the probability of reliable operation of all the machines is the product of particular probabilities of reliable work of individual machines:

$$P_t = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_5 \tag{22}$$

And with the second order approximation we obtain:

$$P_t = 1 - \left(\lambda_1 \cdot \Delta t_1 + \lambda_2 \cdot \Delta t_2 + \lambda_3 \cdot \Delta t_3 + \lambda_4 \cdot \Delta t_4 + \lambda_5 \cdot \Delta t_5\right) \tag{23}$$

where:

Δt_1 – time interval during manoeuvre execution in which a failure of the i-th machine or system causes hazards to the ship,

λ_i – failure rate of the i-th machine or system.

Each fault of a machine in question during manoeuvring in the examined area does not lead to an accident; this additionally depends on the following factors:

- ship’s position in the examined area at the moment of failure,
- hydro-meteorological conditions prevailing during manoeuvre execution,
- degree of failure of the particular machine.

Examining the particular factors we can conclude that:

1. A failure of a given machine will cause an accident of the ship, particularly in certain places of the area. This is accounted for by the determination of particular time intervals specific for each water area.
2. A ship’s accident may happen due to a failure of a given machine in specific hydro-meteorological conditions prevailing during the manoeuvre execution.
3. A ship’s accident may happen when a critical failure of a certain machine occurs (e.g. cogging of the rudder in a certain position).

Taking the above limitations into account, we can write:

$$P_t = 1 - \left(\lambda_1 \cdot \Delta t_1 \cdot p_{h1} + \lambda_2^2 \cdot \Delta t_2^2 \cdot p_{h2} + \lambda_3 \cdot \Delta t_3 \cdot p_{h3} \cdot p_{z3} + \lambda_4^2 \cdot \Delta t_4^2 \cdot p_{h4} + \lambda_5^2 \cdot \Delta t_5^2 \cdot p_{h5} \right) \tag{24}$$

where:

p_{hi} – probability of hydro-meteorological conditions, which results in ship’s accident during a failure of the i-th machine,

p_{z3} – probability of a critical failure when the ship is in a certain position, which will result in an accident.

Models of accident effects differ in relation to the kind of accident. To illustrate this, effects for two different kinds of accident will be discussed:

- ship’s impact on the shore,
- ship’s impact on the bottom.

A ship will hit the shore when the restricted area depth $h(x, y, t)$ is larger than the ship’s draft at the moment (t) of the event.

Effects that the accident will cause depend on such factors as the maximum energy of ship’s impact on the elements of the shore and the admissible energy absorbed by the shore element (fenders – port structure system), and these effects can be presented as follows :

$$S = \frac{E(t)}{E_d} \tag{25}$$

where:

$E(t)$ – maximum energy of ship’s impact on the shore elements,

E_d – admissible energy absorbed by the shore element (fenders – port structure system).

When the values S are contained in the interval $0 < S \leq 1$, the accident does not cause any essential damage or losses. If, however, $S > 1$ the accident will cause a serious hull damage or damage to fenders or port structure (quay).

The ship’s impact on the bottom (grounding) will take place when the restricted area depth on the scene is smaller than ship’s draft at the moment (t) of the event.

Effects that the accident will cause depend on such factors as the maximum energy of the ship at the moment of contact with the bottom and the admissible energy of safe contact with the bottom. These effects can be presented as follows:

$$S = \frac{E(t)}{E_d} \tag{26}$$

where:

$E(t)$ – maximum energy of the ship at the moment of hull contact with the bottom,
E_d – admissible energy of safe hull contact with the bottom.

Like in the model of ship's impact on the shore, when the value S is contained in this interval $0 < S \leq 1$, the accident will not cause any essential losses and the ship will be able to refloat by itself (or with the help of tugs assisting it in manoeuvres) so that no rescue operation is needed and the ship hull remains intact. On the other hand, when $S > 1$ the accident results in a damaged hull or ship's refloating requires rescue operation to be arranged at certain financial costs (traffic must be stopped, extra equipment is used etc.).

The maximum energy of the ship at the moment of hull contact with the bottom is understood as the kinetic energy that the ship may have at the impact on the bottom or grounding in the least favourable navigational conditions during the manoeuvre execution. This energy can be estimated through simulation research of the given manoeuvre in a specific restricted area in the examined hydro-meteorological conditions.

When a ship runs aground, its kinetic energy is converted into:

- force of friction of the hull against the bottom (which occurs from the moment *t* until the ship stops completely),
- increment of the potential energy of the ship connected with the elevation of its centre of gravity (SC) during grounding.

This relation can be written as follows:

$$E_d = E_d^{'} + \Delta E_p \tag{27}$$

where:

$E_d^{'}$ admissible kinetic energy converted into work of the friction force of the hull in contact with the ground,
ΔE_p ncrement of the potential energy of the ship due to the elevated centre of gravity during grounding.

The admissible energy of safe contact of the ship hull with the bottom should be interpreted as the maximum energy of the ship-bottom contact which does not cause hull damage (rudder or propeller) and which will be sufficient for the ship to refloat, provided that the following condition is satisfied [2, 7]:

$$\left.\begin{aligned} E_d^{'} &\leq E_{dm} \\ E_d^{'} &\leq E_{du} \end{aligned}\right\} \tag{28}$$

where:

E_{dm} – admissible energy in the case when a ship refloats by itself,
E_{du} – admissible energy of the ship's contact with the bottom that does not cause hull damage.

3.3. CONCLUSIONS TO THE CHAPTER 3

1. There are six basic criteria for the assessment of navigation safety in restricted areas. Three of them: underkeel clearance, safe manoeuvring area and the distribution of the numbers of accidents are applied for the assessment of safety of any manoeuvre in a restricted area, and the other three: kinetic energy of ship's impact, propeller stream speed at the bottom and the time of manoeuvre executed are used for the assessment of the safety of various types of manoeuvres.
2. Navigational risk is a universal measure of navigation safety in restricted areas and it takes into account such factors as:

- navigational accident-free performance of a specific manoeuvre in given conditions,
- error-free performance of the navigator acting in the anthropotechnical system ship – navigator,
- technical reliability of the ship,
- effects of a specific accident.

4. General models and methods for marine systems risk optimization

After defining acceptable risk level and reliable methods of its assessment it's we should concentrate on risk optimization methods that will be used in section stage of the researchers where results from integrated models should be carefully treated and optimized.

4.1. INTRODUCTION

The problems discussed in this part of the report are concern with the construction of a universal model of optimization of waterway parameters. An idea underlying such a model is the possibility of its application to testing waterways which consist of differently arranged elements. For this reason this part or report deals with a classical port model comprising all basic elements of waterways in limited areas. These are as follows: anchorage, outer approach channel, port entrance with entrance heads and breakwater protecting them, system of inner fairways, lock, turning basin, port basin with conventional quays and ferry terminals.

Shipping in the areas of such a port should be safe for:

1. Vessels lying in port and at anchor.
2. Vessels performing such port manoeuvres as:
   - anchoring,
   - port entering/ leaving,
   - going along outer and inner fairways,
   - lock entering/ leaving,
   - turning,
   - berthing and unberthing at port quays and ferry terminals.

The part of report presents and analyses two general (universal) models of optimization of waterway parameters which can be applied to solving optimization problems of different elements (and their arrangements) of a model port.

In the first model the manoeuvring safety has been determined by the following conditions: size of manoeuvring basin, amount of water under keel, kinetic energy of vessel's impact on the quay, speed of screw race at bottom.

In the second model the manoeuvring safety has been determined by risk of performing a given manoeuvre (a navigational risk) which must be understood as a product of occurrence probability of a collision and the effects it causes.

The report also discusses some methods of optimization of waterway parameters, and, which is worth mentioning, while there is a lack of universal methods, there are a lot of detailed simulation methods of optimization used to examine basic elements of waterways. A number of these detailed methods have been worked out in the Institute of Marine Traffic Engineering of Szczecin Maritime University and have been presented by the author [Gucma S. 2000, Gucma S. 1996, Gucma S. 1997, Gucma S. 1997, Gucma S. 1998, Praca 2000].

4.2. GENERAL MODELS OF WATERWAY PARAMETERS OPTIMIZATION

Defining an objective function in optimization models of waterway parameters as construction cost (reconstruction cost) of a given element (or elements) of a waterway, its marking and operation, the following initial assumptions have been accepted:

- a vessel tested manoeuvres in a limited area, where the position is defined in rectangular co-ordinates,
- an area tested is presented by means of a set $x \in \mathbf{X}$, $y \in \mathbf{Y}$, where the following subsets are distinguished :
  - of an area (water area) $\mathbf{X1} \subset \mathbf{X}$, $\mathbf{Y1} \subset \mathbf{Y}$
  - quay lines $\mathbf{X2} \subset \mathbf{X}$, $\mathbf{Y2} \subset \mathbf{Y}$
  - breakwater lines $\mathbf{X3} \subset \mathbf{X}$, $\mathbf{Y3} \subset \mathbf{Y}$,
- the co-ordinates describing the subsets are Cartesian products :
  - **X1** x **Y1**,
  - **X2** x **Y2**,
  - **X3** x **Y3**,
- an area tested is for the vessels comprised in the set $i \in \mathbf{I}$. It can refer to both vessel's size (length, breadth, draught) and vessel's type,
- a vessel manoeuvring in the area tested can perform one of the manoeuvres comprised in their set $j \in \mathbf{J}$. It is a set of manoeuvre types performed in the area tested (manoeuvre type, number and power of the tugs used),
- vessels tested can manoeuvre in the navigational conditions comprised in the set $k \in \mathbf{K}$ It concerns both hydrometeorological conditions (speed and direction of wind and current, waving, visibility, icing, state of water etc.) and navigational marking or state of other traffic in the area tested.

A general model of optimization of waterway with four limitations of manoeuvring safety. In this model the manoeuvring safety is determined by the following conditions:

- size of a manoeuvring basin,
- amount of water under keel,
- kinetic energy of vessel's impact on the quay or any other hydrotechnical structure (e.g. breakwater heads limiting the port entrance),
- speed of a screw race at bottom or quay walls, or slopes of fairways.

Berthing safety of a vessel at quay or at anchor is determined by a wave height in this position.

Accepting the above assumptions and conditions, the objective function of optimization of waterway parameters can be presented as follows:

$$Z = (a \cdot w + b \cdot t + c \cdot r + d \cdot l + e \cdot y + f \cdot s) \rightarrow \min \tag{1}$$

where:

a = $f_1(H_{xy})$, while (x,y) ∈ **X1** x **Y1**,
w = $f_2(D, H_{xy})$
b = $f_3(D, H_{xy})$
r = $f_4(D)$
d = $f_5(H_{xy}, E_{xy})$, while (x,y) ∈ **X2** x **Y2**,
l = $f_6(D)$
e = $f_7(H_{xy}, E_{xy})$, while (x,y) ∈ **X3** x **Y3**,

$y = f_8(D)$
$f = f_8(V_{xy})$, while (x,y) C **X1** x **Y1,**
$S = f_{10}(D)$

with the limitations:

$$D_{ijk} \subset D \tag{2}$$

where:
$i \in$ **I,** $j \in$ **J,** $k \in$ **K**

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \tag{3}$$

where:
$(x,y) \in$ **X1** x **Y1** – a subset of areas,

$$E_{ijkxy} \leq E_{xy} \tag{4}$$

where:
$(x,y) \in$ **X2** x **Y2** – a subset of quay lines,
$(x,y) \in$ **X3** x **Y3** – a subset of breakwater lines.

$$V_{ijkxy} \leq V_{xy} \tag{5}$$

where:
$(x,y) \in$ **X1** x **Y1** – a subset of areas.

$$F_{kxy} \leq F_{xy} \tag{6}$$

where:
$(x,y) \in$ **X2** x **Y2** – a subset of quay lines:

where:
Z - cost of constructing (reconstructing) the port entrance, its marking and operation,
a - cost per piece of extracting 1m^3 of spoil (it depends on bottom type),
w - amount of spoil in the process of dredging,
b - annual cost of dredging works and cost of maintaining hydrotechnical facilities and navigational marking,
t - expected duration of operating the waterway element,
c - cost per piece of constructing a navigational mark,
r - number of navigational marks in the system
d - cost per piece of a running metre of a given quay type together with fender facilities,
l - quay length,
e - cost per piece of a running metre of a given breakwater type or lock gates,
y - length of breakwater or lock gates,
f - cost per piece of protecting $1\ \text{m}^2$ of a given bottom type,
s - bottom area of a given protection type,
D_{ijk} - a set of points defining a manoeuvring basin of i type of vessel, j type of manoeuvre and k alternative of navigational conditions,
D - accessible manoeuvring basin for a vessel meeting the conditions of acceptable depth (3) for each point p(x,y) of set D,
I - a set of vessel types tested,
J - a set of manoeuvre types tested in a given area,

K - a set of characteristic navigational conditions,
Δ_{ijkxy} - safe amount of water under keel of i type of vessel in x, y point of the area for i type of manoeuvre and k alternative of navigational conditions,
H_{xy} - depth of area in x , y point,
T_j - draught of i vessel type,
E_{ijkxy} - kinetic energy of impact of i vessel type on quay (breakwater) in (x,y) point for j manoeuvre type and i k alternative of navigational conditions,
E_{xy} - Permissible kinetic energy of vessel's impact on (x,y) point of the quay (breakwater),
F_{kxy} - maximum wave height from k direction of wind in (x,y) point of the quay,
F_{xy} - Wave height safe for the vessel berthing in (x,y) point of the quay.

A general model of optimization of waterway with one limitation of manoeuvring safety. In this model the manoeuvring safety is determined by a navigational risk, and the berthing safety of a vessel at quay or at anchor is like in the above model, determined by a wave height in this position. Accepting the above assumptions and conditions, the objective function is presented analogically to that in the first model (1):

$$Z = (a \cdot w + b \cdot t + c \cdot r + d \cdot l + e \cdot y + f \cdot s) \to \min \tag{7}$$

with the limitations:

$$R_{ijkxy} \le R_{dop} \tag{8}$$

where:
$i \in \mathbf{I}, j \in \mathbf{J}, k \in \mathbf{K}, x \in \mathbf{X}, y \in \mathbf{Y}$

$$hF_{kxy} \le hF_{xy} \tag{9}$$

while:
$(x,y) \in \mathbf{X2} \times \mathbf{Y2}$ – is a subset of quay lines,

where:
R_{ijkxy} – a risk of performing j manoeuvre type by i vessel type in k alternative of navigational conditions in x, y point of the area,
R_{dop} – acceptable navigational risk.

A navigational risk is defined as a product of probability of collision accurrence and the effects it causes during a given manoeuvre [Gucma S. 2000], where a manoeuvre is to be understood as a movement process of a given vessel type an a specified waterway type in specified navigational conditions. The definition is additionally completed by relative frequency of performing a given manoeuvre and it can be presented in the following form:

$$R_{ijkxy} = I_{ijkxy} \cdot P_{ijkxy} \cdot S_{ijkxy} \tag{10}$$

where:
I_{ijkxy} – mean annual intensity of performing j type of a manoeuvre in a specified area defined by means of (x, y) co-ordinates by i vessel type in k navigational conditions,
P_{ijkxy} – probability of collision occurrence while performing j type of a manoeuvre by i vessel type in k navigational conditions in x, y point of the area.
S_{ijkxy} – the effects caused by the collision of i type of the vessel performing j type of a manoeuvre in k navigational conditions in x, y point of the area.

4.3. DETAILED METHODS OF OPTIMIZATION OF WATERWAY PARAMETERS

The existing detailed methods of optimization of waterway parameters are simulation methods. They refer to optimization of specific elements of waterways or their specified arrangement. The methods have been worked out on the basis of a model with four limitations of manoeuvring safety. At the moment there are also carried out some works on constructing methods based on a model with another limitation of manoeuvring safety and the research results are presented in this part of report as well.

4.4. DETAILED METHODS OF OPTIMIZATION CONSTRUCTED ON THE BASIS OF A MODEL WITH FOUR LIMITATIONS OF MANOEUVRING SAFETY.

Below there are presented some simulation methods of parameter optimization for the following sections (elements) of waterway:

1. Turning basins [Gucma S. 2000,1996].
2. Fairways [Gucma S. 2000,1996].
3. Ferry Terminals [Gucma S. 2000,1996].
4. Port basins [Gucma S. 2000,1996].
5. Port entrances [Gucma S. 1998].
6. Locks [Boogard et al 1998].

Methods 1÷ 5 have been worked out by a team of sea traffic engineering of Szczecin, Maritime University, method no. 6 by a team of scientists of Delft University.

A simulation method of optimization of turning basin parameters. The objective function is presented as follows:

$$Z = (a \cdot w + b \cdot t) \rightarrow \min \tag{11}$$

with the limitations

$$D_{ijk} \subset D \tag{12}$$

$$\bigwedge_{p(x,y) \in D} \qquad \Delta_{ijkxy} \geq H_{xy} - T_i \tag{13}$$

where:

$(x,y) \in \mathbf{X1} \times \mathbf{Y1}$ – a subset of areas.

In a practical method of optimization of turning basin parameters the limitations are presented in the following form [4,5]:

$$R^s_{\alpha ijk} \leq R^s_\alpha \tag{14}$$

$$R^h_{\alpha ijk} \leq R^h_\alpha \tag{15}$$

in bearing divisions $\alpha = 1^0,...,360^0$,

where:

R^{s}_{α} - a minimum leading radius of a turning basin for safe depth at bottom (h_s) for vessels,

R^{h}_{α} - a minimum leading radius of a turning basin for safe depth at bottom (h_s) for tugs,

$R^{s}_{\alpha ijk}$ - a leading radius of a safe manoeuvring area in the turning basin for i vessel type, j manoeuvre type and k alternative of navigational conditions at 95% of confidence level,

$R^{h}_{\alpha ijk}$ - a leading radius of a safe manoeuvring area in the turning basin for tugs for i vessel type, j manoeuvre type and k alternative of navigational conditions at 95% of confidence level.

The values $R^{s}_{\alpha ijk}$ and $R^{s}_{\alpha ijk}$ are defined on the basis of simulation research using real time models carried out for maximum operated vessel types at different existing speeds as well as current and wind directions. The research is carried out in sets of voyages (simulation manoeuvres) of a credible number for different navigational conditions.

A simulation method of optimization of fairway parameters. The objective function can be presented as follows:

$$Z = (a \cdot w + b \cdot t + c \cdot r) \rightarrow \min \tag{16}$$

with the limitations

$$D_{ijk} \subset D \tag{17}$$

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \tag{18}$$

where:

(x, y) ∈ **X1** x **Y1** – a subset of areas.

In practice the simulation method of optimization of fairway parameters takes advantage of models of real time and limits itself to defining widths of traffic lanes for subsequent points of a fairway axis (the distance between points is usually 10 m). The width of a traffic lane is specified to the right and left of a fairway axis, and the limitations are presented as follows:

$$B_{pijkn} \leq B_{pn} \tag{19}$$

$$B_{lijkn} \leq B_{ln} \tag{20}$$

where:

B_{prj}; B_{ln} – accessible width of n point of a fairway axis to the right (p) and to the left (l) from the fairway axis for its n point,

B_{pijkn}; B_{lijkn} – the width of right (p) and left (l) traffic lanes of i vessel and j vessel manoeuvre type for k navigational conditions in a point of fairway axis.

Width of traffic lanes are defined by means of simulation tests using the method of real time for maximum vessels to be operated in different navigational conditions. The tests are carried out in sets of voyages of credible number, for which there are specified (after statistical processing of results) values B_{pijkn} i B_{lijkn} calculated on the level of 95% of confidence. The method is a two-level one [ ] where, on the first level there are specified rail shapes, and then bank effect does not take place. After deciding about rail shape, on the second level. There are defined its detailed parameters and then bank effect forces start working again.

Simulation methods of optimization of ferry terminals and port basins.. The objective function can be written as follows:

$$Z = (aw + b \cdot t + c \cdot r + d \cdot l + f \cdot s) \rightarrow \min \tag{21}$$

with the limitations:

$$D_{ijk} \subset D \tag{22}$$

$$\bigwedge_{p(x,y) \in D} \quad \Delta_{ijkxy} \geq H_{xy} - T_i \tag{23}$$

$$V_{ijkxy} \leq V_{xy} \tag{24}$$

where, in both above cases :

$(x,y) \in$ **X1** x **Y1** – a subset of areas.

$$E_{ijkxy} \leq E_{xy} \tag{25}$$

where:

$(x,y) \in$ **X2** x **Y2** – a subset of quays.

In practical methods of parameter optimization of ferry terminals and port basins the limitations are presented as follows [4,5]:

$$B_{pijkn} \leq B_{pn} \tag{26}$$

$$B_{lijkn} \leq B_{ln} \tag{27}$$

$$E_{ijkqm} \leq E_{qm} \tag{28}$$

$$V_{ijkxy} \leq V_{xy} \qquad ((x,y) \in \mathbf{X1} \times \mathbf{Y1}) \tag{29}$$

where:

n – points of arbitrarily selected area axis(one or more),

q – quay number,

m – line point of q quay,

E_{ijkqm} – kinetic energy of impact of i vessel type for j manoeuvre type in k navigational conditions on m point of q quay calculated at 95% of confidence level using gamma distribution,

E_{qm} – permissible kinetic energy of vessel's impact on m point for q quay.

They are 2-level methods, where on the basis of research on level 1 it is possible to define terminal or area arrangement. On this level, quay reaction forces do not work at all or work partly. On level 2 the research is done for new arrangement of terminals or areas (defined on level 1) with quay reaction forces working. On this level, limitations (28) and (29) are examined. There is also defined kinetic energy of vessel's impact on the quay taking into consideration the vessels berthed and speed of screw race.

A simulation method of optimization of port entrance. The objective function can be written here as follows [Gucma S. 1998]:

$$Z = (aw + b \cdot t + c \cdot r + e \cdot y) \rightarrow \min \tag{30}$$

with the limitations

$$D_{ijk} \subset D \tag{31}$$

$$\bigwedge_{p(x,y) \in D} \quad \Delta_{ijkxy} \geq H_{xy} - T_i \tag{32}$$

where:
$(x,y) \in$ **X1** x **Y1** – a subset of areas,

$$E_{ijkxy} \leq E_{xy} \tag{31}$$

where:
$(x,y) \in$ **X3** x **Y3** – a subset of breakwaters,

$$F_{kxy} \leq F_{xy} \tag{32}$$

where:
$(x,y) \in$ **X2** x **Y2** – a subset of quays.

In a practical method of optimization of port entrance the limitations are presented as follows [6]:

$$B_{pijkn} \leq B_{pn} \tag{33}$$

$$B_{lijkn} \leq B_{ln} \tag{34}$$

$$E_{ijko} \leq E_o \tag{35}$$

$$F_{kq} \leq V_q \tag{36}$$

where:
o – line point of breakwater,
E_O – permissible kinetic energy of vessel's impact on o point of the breakwater,
F_q – wave height safe for a vessel berthing at q quay.

This is a 2-level method where, on level 1, there is initially defined an entrance shape meeting the safety criterion of the vessels lying in port (limitation (36)). Level 1 also comprises an expected movement of rubble in terms of siltation of port entrance. There are a few alternatives selected on this level. On level 2, there is selected the most profitable alternative of an entrance shape out of the alternatives defined on level I. It is followed by carrying out the modification of its shape. On this level, the limitations (33), (34), und (35) were used. Values B_{pijkn}, B_{lijkn} and E_{ijko} have been defined by means of simulation methods of real time.

A simulation method of optimization of lock parameters. The objective function can be written down as follows:

$$Z = \left(aw + b \cdot t + d \cdot l + e \cdot y + f \cdot s\right) \tag{37}$$

with the limitations

$$D_{ijk} \subset D \tag{38}$$

$$\bigwedge_{p(x,y) \in D} \quad \Delta_{ijkxy} \geq H_{xy} - T_i \tag{39}$$

$$V_{ijkxy} \leq V_{xy} \tag{40}$$

where:
$(x,y) \in$ **X1** x **Y1** – a subset of areas.

$$E_{ijkxy} \leq E_{xy} \tag{41}$$

where:

$(x,y) \in \mathbf{X2} \times \mathbf{Y2}$ – a subset of quay,
$(x,y) \in \mathbf{X3} \times \mathbf{Y3}$ – a subset of lock gates.

In practice the method used is a 2-level are [Boogard et al 1998], where, on level 1, there are defined lock dimensions (limitation (38) and (39)). The research on this level is carried out using simulation methods of non-real time. On level 2 the research is done for lock arrangement specified on level 1. On this level the limitations (40) and (41) are tested, and there is also defined kinetic energy of vessel's impact on the quay including the vessels berthed there and speed of screw race. The research on level 2 is carried out in real time. There is also a practical simulation method of optimization of lock parameters using only simulation models of real time [DeRouck et al 1998].

4.5. DETAILED METHODS OF OPTIMIZATION CONSTRUCTED ON THE BASIS OF A MODEL WITH ONE LIMITATION OF MANOEUVRING SAFETY

The attempts at working-out the method were undertaken by the team of sea traffic engineering of Maritime University of Szczecin during designing works connected with modernizing a part of the fairway of Szczecin – Świnoujście from entrance heads of the port of Świnoujście to Szczecin Transgression. There was worked out a 2-level simulation method of real time [Praca 2000].

On level 1, on the basis of the results of simulation tests, there is defined an initial shape of the area while using the following limitations;

$$B_{pijkn} \le B_{pn} \tag{42}$$

$$B_{lijkn} \le B_{ln} \tag{43}$$

The limitations are analogical to the ones in detailed methods of optimization constructed on the basis of model with four limitations of manoeuvring safety. On the basis of the results on this level, there are carried out hydrological tests (as required) and there is created an initial concept of the undertaking.

On level 2 there are carried out simulation tests in real time in the area specified during an initial designing project. On the basis of the test results and using are limitation of manoeuvring safety:

$$R_{ijkxy} \le R_{dop} \tag{44}$$

4. 6. CONCLUSIONS

1. Out of the two general models of optimization of waterway parameters presented in this part of the report the one with one limitation is a more modern model because it takes into account collision effects and traffic intensity. It seems that in near future it will be widely used.
2. Detailed simulation methods of optimization working in non-real time are far cheaper than the methods working in real time. The methods can be used directly by designers without forming special research teams and carrying out long-term research. At the moment there are intensive works carried out on constructing such simulation methods and apply them on the computer.

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