The model of ship movement while touching the sea-bed

W. Galor
Maritime University of Szczecin, Poland

ABSTRACT: When a ship hits the sea-bed then it's hull pressing on ground. It caused the reversible passive ground reaction. The consequences of such event can result the ships hull damage. The paper presents of detailed model of ships movement while touching the ground. The pressure on ship hull and parameters of trajectory (ploughing and penetration) are determined.

1 INTRODUCTION

An analysis of navigational accidents shows that many of them take place in port waters area. There is an area surrounded by wharves and other marine buildings where ships moor and load or discharge cargo. This type of area intended for ship manoeuvres is particularly important for port operation. There has been a tendency in recent years to accommodate increasingly larger ship in ports, which with insufficient port infrastructure or its even minor changes may result in a navigational accident of serious economic consequences. Since 1970s was observed a rapid increase in seaborne cargo transport accompanied by fast growth of the global fleet. The growth mainly consisted in the increase of ship size (Fig.1). However, the increase of ship size stopped after it had reached a certain level. Among main factors behind that upper capacity limit was the fact that ports built decades ago couldn't the handling ships of the size larger than they were designed for. The building of new ports is restricted on the one hand by natural conditions of sea areas, and necessary large financial effort on the other hand. As economic and geopolitical conditions change, directions of cargo transport (bulk in particular) also change, sometimes in a cycle lasting a few years. This in turn, makes building new ports a risky enterprise for investors, as the invested capital return amounts to at least twenty years. Therefore, a need arises to use the existing ports for handling ships larger than those the ports are designed for. Safe manoeuvring of a ship within a given area requires that the manoeuvring area of a ship with a specific draft is comprised within available port water having a required depth.

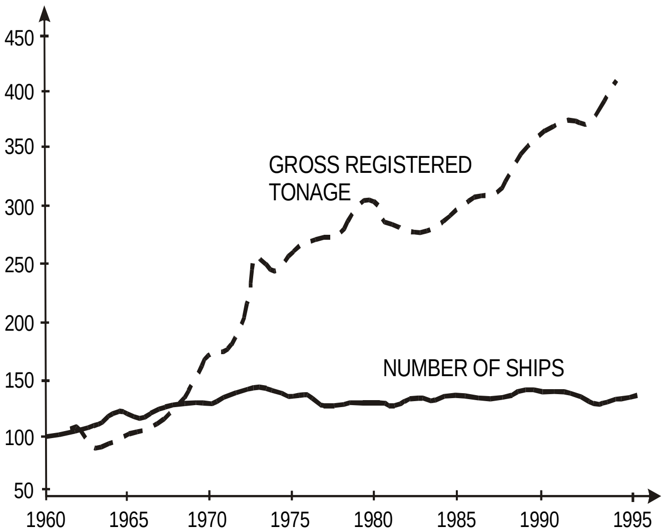


Fig. 1. Number of ships entering the Netherlands ports and their
total GRT

There are two undesired types of events that can lead to a navigational accident within a port area:

– impact on the shore (or another port structure),
– contact with the area bottom.

In the former case the area depth is sufficient, whereas the horizontal dimension is too small. In the latter case the ship's draft is too great in comparison with the port water area depth. This relation is defined by the distance of the lowest point of the ship keel to the sea-bottom, usually referred to as the under-keel clearance (UKC) or water depth under ship's keel. The under-keel clearance is used for the description of the criterion of safe manoeuvring in a port area. This criterion can be expressed in this way:

$$H - D_{max} \geq UKC_{min} \tag{1}$$

where H = water area depth; D_{max} = ship's maximal draft and UKC_{min} = safe under-keel clearance.

UKC_{min} is the value of minimum under-keel clearance of a ship manoeuvring within a given area that is to assure the ship safety that is no contact of ship's hull with the bottom should occur. The main limitation of handling the ships is the depth of port waters. The size of UKC in ports is defined by maritime administration, port authorities or ship masters.

The interests in this field are contradictory. Maritime administration responsible for the safety of navigation wants the UKC to be relatively high. This, in turn, reduces the possible use of ships' capacity to the full, which for both ship owners and charterers is far from advantageous. In extreme cases a ship's owner or charterer may give up using port's services. The determination of permanent value of UKC was connected with decade-long observations and restrictions in sufficiently accurate determination of its components. However, advances in the field, i.e. scientific methods enable the optimization of the UKC value. The objective function can be written as:

$$UKC = R_{min} \rightarrow min \tag{2}$$

with the restrictions

$$R \leq R_{ad} \tag{3}$$

where: R = risk of manoeuvring in an area and R_{ad} = admissible navigational risk defined at an acceptable loss level.

The risk concept used to be defined in different of way. Mainly the risk referred to as navigational risk may be expressed as:

$$R = P_A \cdot P_C \tag{4}$$

where R = navigational risk; P_A = probability of sea accident and P_C = probability of unacceptable losses,

and

$$R_{ad} = P_u \leq UKC_{min} \;\; for \;\; C \leq c_{ad} \tag{5}$$

where C = losses and c_{ad} = acceptable level of losses.

The losses arising from the fact that a ship hits the ground while moving, such as hull damage or, possibly, loss of cargo (particularly liquid cargo, which may pollute the marine environment) depend on a number of factors which can be expressed by a variety of measures. The one of these is maximum ship hull load less than admissible value caused damage of its. The maximum ship hull load when hitting the ground can be defined as dependent on the probability as:

$$P_c = f\,[P(Q_{sgr} > Z_G)] \tag{6}$$

where Q_{sgr} = admissible pressure on ship's hull and Z_G = passive ground pressure.

While determining the probability of ship hull damage during the impact one should take into account that not every such impact ends in a serious accident [Galor W., 2005, The managing…]. Therefore:

$$P_{uw} = P_u \cdot P_k \tag{7}$$

where: P_{uw} = probability of an accident during ship's manoeuvres, P_u = probability of a ship's touching the bottom and P_k = probability of hull damage.

The probability of ship's impact against the bottom may be assumed as a criterion for the evaluation of the safety of ship manoeuvres within port waters.

From statistical data displaying the number of damaged hulls against the number of impacts against the bottom (damage indicator), the probability of hull damage can be replaced by the hull damage indicator. Then the probability of an accident will be equal to:

$$P_{uw} = P_u \cdot w_w \tag{8}$$

where: w_w = hull damage indicator.

2 UKC METHODS DETERMINATION

The value of UKC in ports may be defined by:

- maritime administration (maritime offices, harbour master's offices),
- port authorities,
- ship masters.

Conclusions from analyses of selected methods are that UKC is mostly determined by the coefficient method of summed components.

The coefficient method consists in determining the value R_{min} as part of ship's draft:

$$UKC_{min} = \eta\, D_c \tag{9}$$

where: D_c = maximal draft of the hull and η = coefficient.

The values of coefficient η used in practice range from 0.03 do 0.4 [.Mazurkiewicz B., 2006, Morskie...].

The losses due to restriction of ships draft are as follows:

– limited quantities of cargo loaded and unloaded, which means lower earnings for the harbour and stevedoring companies;
– lower ship-owners' profits as the ship's capacity is not used to the full or longer turnaround time due to necessary lighter age at the roads, before the ship's entrance. It should be noted that the ship's operating costs are the same no matter whether the ship is fully laden or its capacity is unused,
– port charges are smaller as they depend on the ship's tonnage (berthing, towage etc.);
– in many cases large ships resign from using services of a port where they are not able to use their total cargo capacity.

In the other method the value R_{min} is determined as an algebraic sum of component reserves [Galor W., 2005, Analiza…] where in addition errors of the particular components are taken into account:

$$UKC_{min}=\sum_{i=1}^{n} R_i \tag{10}$$

where: R_i = component reserves of UKC.

3 STATIC AND DYNAMIC COMPONENTS OF THE UNDER KEEL CLEARANCE

The under keel clearance is divided into a static and dynamic component. This division reflects the dynamics of particular reserves. The static component includes corrections that change little in time. This refers to a ship lying on calm waters. The dynamic component consists of the reserve for the squatting of a moving ship and wave action. It should be noted that in this division the dynamic component should also include the reserve for listing caused when a ship turns. Therefore, the UKC can be defined as:

$$R_{min} = R_S + R_D + \delta_r \tag{11}$$

where: R_s = static component, R_d = dynamic component and δ_r = errors of component determination.

4 THE SHIP STRIKE ON THE SEA-BED

During a ship's striking the bottom of an area built of sandy or argillaceous ground, for a vessel in progressive movement, there occurs a gradual sinking of the hull into the ground (until the ship stops). The mechanism of the ship's striking the area's bottom depends on the ship's draft, namely whether the vessel is trimmed by the bows, the stern or if it is loaded on an even keel. During a ship's striking the bottom of an area of fragmented ground, for a vessel in progressive movement, there occurs gradual sinking of the hull into the ground (until the vessel's stoppage). During this process there can be distinguished the plough-in phase bound with longitudinal motion and the penetration (sinking) in a vertical direction. Fig. 2 presents this movement in the case of a vessel being trimmed by the bows. A similar phenomenon will occur in the case of being trimmed by the stern.

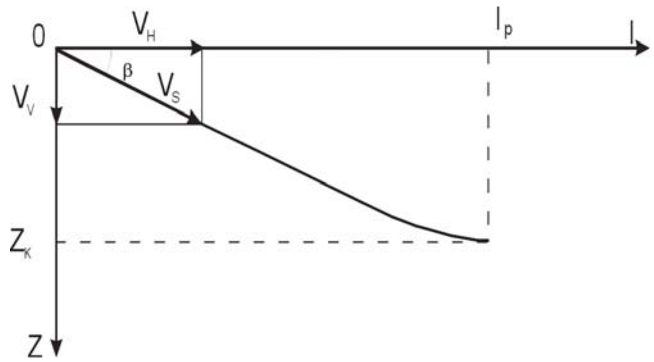


Fig. 2. Penetration of the ship's hull into the bottom

The penetration of the ship into the ground depends on the relation between the horizontal V_H and vertical V_v components of the ship's speed V_S. The ship will stop in a certain distance I_P from the point of the hull's first contact with the bottom and the penetration to a particular depth Z_K. In the initial stage of the ship's penetration into the ground, is mainly affected by horizontal forces. Stopping of the ship takes place on a horizontal plane until the ship stops, which is described as stopping distance I_P from the first contact point to the stopping of the vessel. During ploughing there are also vertical forces causing penetration of the ground with initial angle β. The exceeding the permissible value of hull strength may cause damage to the hull. These stages are affected by the kind of ground of the area bottom.

When a ship hits the bottom, its hull presses on the ground which results in the passive ground pressure. That pressure is the ground reaction to the hull pressure on the bottom. The passive ground pressure increases with the pressure of the hull. When the maximum admissible value is exceeded, the area of ground is formed and the blocks of ground begin to move aside from under the hull. An increase in the passive earth pressure (for non-cohesive grounds) along with the increase of hull pressure takes place due to structural changes in the ground [Galor W., 2003, The application] occur in both granular system and in particles of the ground. Initially, the elastic soil becomes elastic-plastic, then plastic. This is a state in which all the grains and particles are in the state of boundary equilibrium, which corresponds to the boundary value of passive pressure of the ground. The ship' pressure on the ground causes the hull to penetrate into the bottom ground. When the boundary passive pressure (reaction) is reached the expulsion of ground block and the ship's bottom penetrates the ground. That phenomenon takes place in both non-cohesive grounds, such as gravels and sands and their mixes, and in cohesive grounds, including clay gravels and sand-gravel mixes, clay sands, clay and silt. An analysis of the ship hull action on the ground when the bottom is hit shows that there are similarities to the action of fenders. This means that the ground is a medium absorbing the energy of the impact. The magnitude of energy absorption mainly depends on the ground properties. Ships penetrating a non-cohesive ground to a certain depth will not have their hull damaged.

In Polish ports there occur crumbled grounds, containing sandy particles produced by mechanical crumbling of primary rocks.

5 THE PARAMETERS OF SHIP MOVEMENT

On the basis of considerations presented there has been prepared an algorithm of calculating vessel movement parameters when striking the port water area ground and of forces impacting on the vessel's hull. It has been applied in a computer simulation model of the vessel's movement in the area. The model works in real time and serves the purpose of preparing navigational analyses. This permits risk determination of the vessel striking the area bottom and its results (likelihood of hull damage). The stopping of ship will be fulfill when the initial kinetic energy (in moment of first contact with sea-bed) became completely lost, i.e. will be change to following components:

$$mV^2_{Ho}/2 - \int P_{RT}dl - \int P_{B}dl - \int P_{RK}dl = 0 \qquad (12)$$

where: m = ships mass and water added mass, V_{Ho} = horizontal component of ships velocity in moment of contact with sea-bed, $\int P_{RT}dl$ = work performed for overcoming friction force of the hull's bottom part, $\int P_B dl$ = work performed for overcoming the resistance of friction of the lateral parts of the hull and $\int P_{RK}dl$ = work performed for overcoming soil wedge.

The ships velocity during contact with ground of sea-bed will be by and by decrease until stopping. The way of ship's stopping will be equal:

$$L_K = \int V_{Hi}\, dt \quad dla \;\; t \in (t_0 \div t_K)$$

where: L_K = way of ship's stopping, t_K = time to ship's stopping and V_{Hi} = horizontal component of ship's velocity during phase of ploughing.

$$V_{Hi} = (2 \cdot \Delta E_{Ki} / m)^{½} \qquad (13)$$

where: ΔE_{Ki} = decreasing of ship's kinetic energy due to alter on work performed for hull resistances during ploughing.

The friction force of the hull's bottom part is equal of hull friction force P_{RT} during penetration into the ground:

$$P_{RT} = \mu \cdot N \qquad (14)$$

where: μ = coefficient of ship's hull friction on ground and N = ground reaction force on ship's bottom during penetration.

The friction force of the latteral parts of the hull P_{KB}:

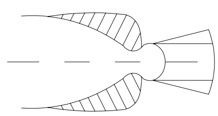
$$P_{KB} = 2 \cdot F_{odpb} (\cdot L_S / Z_{śr}) \cdot tgE \cdot \Delta L_i \qquad (15)$$

where: F_{odpb} = ground reaction force on lateral part of hull, L_S = line length of hull contact with ground, $Z_{śr}$ = average depth of ship's penetration into the ground, E = the friction angle on hull wall and ΔL_i = considered the ship's stopping ways segment.

The passive ground reaction connection with overcoming soil wedge E_{RK} (figure 3):

$$E_{RK} = f(Z, B_s, L_{pp}, \beta) \qquad (16)$$

where: Z = depth of ship's penetration into the ground, B_s = width of part of ship into the ground, L_{pp} = ship's length between perpendicular and β = angle of ship's trim.



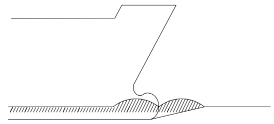


Fig. 3. The passive earth pressure wedge

The pressure of the ship on ground:

$$\sigma = \frac{N}{S} \tag{17}$$

where: N = the push force of ship's hull and s = area of hull contact with ground.

The ship's push on the ground is an effect of decreasing of ship's draft. The greater emergence bear witness about greater pushing. The magnitude of push force will be alter depending on ship's draft and trim. The pushing for even keel will be equal:

$$\sigma_i = \frac{\Delta T_i \cdot Lp_p \cdot B \cdot \delta}{S} \cdot \gamma \tag{18}$$

where: ΔT_i = currently draft decreasing, L_{pp} = length between perpendiculars, B = breadth of ship, δ = ship's block coefficient, γ = water weight specific gravity and S = surface area of hull contact with ground.

6 ALGORITHM OF DETERMINATION THE EFFECT OF SHIP STRIKE INTO SEA-BED

In successive steps ship movement parameters during contact with the ground are calculated, which permits the determination of its results. The following steps are accomplished:

- Calculating initial kinetic energy.
- Calculating pressure of the vessel on the area bottom, to decrease the water level or the vessel's draft.
- Checking whether passive earth pressure (the ground's reaction) does not exceed the permissible value.
- Calculating the friction force of the bottom part of the vessel's hull against the ground, taking into account the friction coefficient.
- Calculating the depth of the vessel's penetration into the ground.
- Calculating work performed for overcoming friction force of the hull's bottom part.
- Calculating work performed for overcoming the resistance of friction of the lateral parts of the hull for a specified depth of the vessel's penetration into the ground.
- Calculating work performed for overcoming soil wedge.
- Calculating the decrease of the vessel's kinetic energy caused by contact with the ground.
- Calculating the decrease of the vessel's speed components.

The example of calculation used algorithm is presented below. Basic dates:

- length between perpendiculars Lpp =250.0 m
- breadth of ship B = 40.0 m
- ship's draft T = 12.0 m
- ship's block coefficient δ = 0.8
- initial horizontal component of ship's speed V_H = 5.0 m/s
- initial vertical component of ship's speed V_V = 0.01 m/s

A.

The results of calculations are following:

- initial ship's kinetic energy E_K = 1553250 [kNm, kJ]

B.

In first step of calculation for period of time equal 10 sec:

- work performed for overcoming friction forces of the hull's P = 37000 [kNm, kJ]
- decreasing of ship's speed in first step of calculation up to V_H = 4.84 m/s

C.

In next steps of calculations the decreasing of ship's speed up to zero will be stayed:

- over 220 sec from first contact of ship with sea-bed
- the length of ship's stopping distance I_p = 261,0 m

D.

There wasn't overdoing the admissible pressure on ship's hull in this case.

7 CONCLUSIONS

The under keel clearance should ensure ship's safe manoeuvring in a port area on the one hand, and the maximum ship's draft on the other hand, particularly in port areas. This result can be achieved through the minimization of UKC value while risk is kept at an acceptable minimum. A ship can touch the bottom of a navigable area due to the reduction of its keel clearance. An algorithm permits to calculate the ship movement parameters when striking the port water area ground and of forces impacting on the ship's hull. It has been applied in a computer simulation model of the vessel's movement in the area. This permit enables to risk determination of the ship striking the area bottom and its results (likelihood of hull damage).

REFERENCES

Galor,W. (2003). *The application of navigational analysis to optimize port water areas modernization*. Proc. of Int. Conference "*Safety and Reliability*" KONBIN 2003, Gdynia.

Galor W.(2005): *Analiza określania zapasu wody pod stępką*. Materiały XI Międzynarodowej Konferencji Naukowo-Technicznej „Inżynieria Ruchu Morskiego". Szczecin 2005.

Galor,W. (2006). *The managing of the navigational safety of ships in port water areas*. Editors C.A. Brebbia a al. WIT PRESS. Southampton, Boston 2005.

Mazurkiewicz, B. (2006). *Morskie budowle hydrotechniczne*. Wyd. ARCELOR, Gdańsk 2006.