A model of ship impact against the ground in the port water area

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Abstract
The existing ports are expected to handle ships larger than those for which they were designed. The main restriction in serving these ships is the depth of the port waters which directly affects the safety of a manoeuvring ship. The under keel-clearance of a manoeuvring ship in the port water area should be such that a ship moves safely. An undesired impact against the ground can damage the ship hull and block the port. Therefore, there is a need to develop a scientific method of specifying the safe under-keel clearance such that the safety of a ship will be maintained for different conditions. This article presents an assessment of navigational risk as a combination of the probability of ship impact against the ground and the resultant hull damage.

Keywords: port water area, ship impact, navigational risk.

1 Introduction
Criteria serve for the basis of estimation, while measures make its performance possible by means of rates. These criteria permit the qualification of accidents with damage, raising its possibility over limited values, and of the making of the control of safety levels. These are applied to designing and modernizing waterways, and defining and exploiting these conditions, and of navigation marking [2]. It makes it possible in an optimal and economical way to build and modernize waterways elements (fairway, approach channel, entrance to port and port basin, quay, anchorage area, turning area) keeping a proper level of ship safety. Also, it is used to design ships parameters optional in the operation in limited water areas. To solution to these problems is used in the branch called marine traffic engineering.

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

The process of safe ship movement in an area can be considered as a system. The navigation safety system can belong to a set of various states. A basic set of such states includes the states of safety, hazard and danger [2].

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

$$ P_A = P(x > X) $$

where:

- $x$ – system state,
- $X$ – restrict.

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

$$ P_B = 1 - P_A = P(x < X) $$

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

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

$$ P_{BKR} = 1 - P_{AKR} = 1 - P(X < Y) $$
where:

- $P_{BKRP}$ – acceptable level of safety,
- $P_{AKR}$ – assumed probability of an accident,
- $x$ – system state,
- $Y$ – restricts corresponding to the assumed acceptable level of the safety state.

Figure 1: The probability of a navigational accident of a ship moving from port A to port B.

Therefore, the hazard state $P_H$ can be expressed as:

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

(4)

$$P_H = 1 - P_{BKRP} = P(X > x > Y)$$

(5)

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

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

(6)

where:

- $x$ – system state,
- $X$ – restricts,
\( Y \) – assumed level of restricts,
\( C \) – loss caused by an undesired event,
\( c \) – limit of minimum losses.

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

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

\[
R_N = P_A \cdot C
\]

where:
\( R_N \) – navigational risk,
\( P_A \) – probability of accident,
\( C \) – consequence of accident expressed in relevant units.

Consequences of every accident can be of a different dimension. Converging all the results to one dimension is very difficult; it requires suitable transformation. Being able to step out simultaneously the damage of a ship, load, port structures, loss of life and health, pollution of the environment and loss of potential profit, and in consequence the limitations of the port’s work or ships is difficult to be estimated. An effort of universal estimations of results is an economic method. Independently from these kind of losses, all of them can have a fixed price by means of proper sums of money. However, on the one hand this sum depends on quantities of paid collections, companionships insurance company, etc., while on the other hand it does not make up for psychological losses of the closest relatives, or sociological ones pertaining to a group of society.

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

2 Ship’s keel clearance

Safe movement of a ship in a certain area can be described as a state in which its hull will not touch the sea bottom. The condition that has to be met is as follows:
\[ R_B \geq (H_i - \delta_H) - (T - \delta_T) \]  

(8)

where:
- \( R_B \) – safe keel clearance,
- \( H_i \) – depth of the area,
- \( \delta_H \) – errors in the determination of area depth,
- \( T \) – ship’s draft,
- \( \delta_T \) – error in the determination of ship’s draft.

The overall error in depth determination is connected with errors done in:
- inaccurate soundings,
- determining the navigational reserve,
- determining water level; and
- an error due to muddy bottom.

The error of ship draft determination is affected by errors done in:
- determining the change of draft in fresh water,
- estimated ship’s list,
- draft determination due to waves,
- assessment of proceeding ship’s squatting.

Figure 2: Fluctuations of the sea water level in the port of Świnoujście in 2002.

One of the most important factors affecting the keel clearance is the water level and associated error. The water level changes due to a variety of factors. In non-tidal waters, such as Polish ports, the chart datum refers to the mean sea level.

The reserve for low water levels has the following values for the five largest Polish ports (1997):
Gdańsk - 0.60 m,
Gdynia - 0.60 m,
Kołobrzeg - 0.75 m,
Szczecin - 0.50 m,
Świnoujście - 0.80 m.

However, the recent detailed studies of water level in Polish ports indicate that the adoption of such values in many cases excludes a possibility of increasing the admissible ship’s draft. Figure 2 presents fluctuations in the measured water level in the port of Świnoujście in 2002.

The chart shows clearly that the maximum drop of water level equals 60 cm and lasts over a relatively short period of time. Thus we can state that the water level reserve for low states assumed so far can be reduced. This will enable the port to accept ships of deeper draft, enhancing its effectiveness and competitiveness.

3 Safety of a ship moving in port waters

As research shows [4], situations when a ship’s hull touches the sea bottom do not often result in serious damage. Only incidents in which the ship’s hull is damaged are regarded as accidents. The damage may be of various kinds:

- tearing of bottom plating,
- crushing of deck,
- folding of web frames,
- stretching of shell plating.

That is why the evaluation of ship’s movement safety should allow for its impact against the bottom, on condition that the effects of the impact (losses) do not exceed the accepted level (hull damage). That incident can be described as follows:

\[ P_u \int_{z_c(t)_{max} \leq R_B / 0 \leq T_p} d\alpha \ C \leq c_{min} \]  

where:

- \( P_u \) – probability of ship’s impact against the bottom,
- \( z_c(t)_{max} \) – closest distance of ship hull from the bottom during manoeuvres,
- \( R_B \) – safe keel clearance,
- \( C \) – losses due to the impact against the ground,
- \( c_{min} \) – acceptable level of losses.

The level of losses sustained from the impact against the ground depends on many factors, the most important of which is the type of bottom (ground). If the bottom is soft, penetration to a certain depth does not cause any hull damage. In
the Rotterdam approach channel penetrations were observed to be as deep as 40 cm where no serious damage to the ship hull occurred.

Impacts against the ground are obviously caused by wrong determination of the keel clearance, i.e. its assumed value has been too small. On the other hand, if too large keel clearance value is assumed, the probability of impact will be decreased, but the admissible ship’s draft will also be smaller.

Therefore, there is a need to develop a scientific method of forecasting the proper keel clearance for the acceptable safety level. The example of Rotterdam shows that a dynamic system of determining and forecasting the keel clearance can be successfully implemented [5]. A similar method can be developed for Polish ports where the average keel clearance is 0.1 of the draft. The method should be based on the evaluation of the ship movement safety using the proper criteria. The risk of ship’s hull impact against the ground resulting in hull damage may be used for the purpose.

The level of damage caused by hull impact against the bottom depends on a number of factors, the most important of which is the type of bottom (ground). Situations when a ship hits the ground obviously are due to erroneous determination of keel clearance when its assumed value is too low. However, the excessive value of keel clearance leads to lower probability of ship’s impact against the bottom on the one hand and decreased admissible ship’s draft on the other hand.

Knowing the number of entries of ships in a year (annual intensity of traffic), one can determine the probability of ship’s impact against the bottom for one ship passage.

\[ P_u = \frac{\lambda}{I_R} \cdot t \]  

where:
- \( P_u \) – probability of the impact,
- \( \lambda \) – accident intensity,
- \( I_R \) – annual traffic intensity,

While determining the probability of ship’s hull damage on impact against the bottom, we should take into account the fact that not every hull-bottom contact results in an accident.

4 Consequences of ship impact on the bottom

The consequences 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 [3].

The maximum ship hull load \( F_k \) for such a case can be defined as:

\[ F_k(t) = 1 - \exp(-t(t_c)) \]
where:
\[ t_c \quad \text{period in which the pre-set hull load will be exceeded during the hull impact against the bottom.} \]

\[ t_c = \left[ \frac{P}{1 - F_k(P_u)} \right]^i \]  \hspace{1cm} (12)

where:
\[ F_k(P_u) \quad \text{probability of the hull load higher than admissible during its impact against the bottom.} \]

\[ F_k(P_u) = P\left[ Q_{sgr} \geq Z_G \right] \]  \hspace{1cm} (13)

where:
\[ Q_{sgr} \quad \text{admissible pressure on ship’s hull,} \]
\[ Z_G \quad \text{passive ground pressure} \]

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. Therefore:

\[ P_{uw} = P_u \cdot F_k(P_u) \]  \hspace{1cm} (14)

where:
\[ P_{uw} \quad \text{probability of an accident during ship’s manoeuvres,} \]
\[ P_u \quad \text{probability of a ship’s touching the bottom,} \]
\[ F_k(P_u) \quad \text{probability of the hull load higher than admissible during its impact against the bottom.} \]

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:

\[ P_{uw} = P_u \cdot w_w \]  \hspace{1cm} (15)

where:
\[ w_w \quad \text{hull damage indicator.} \]

The level of losses sustained by the ship hitting the bottom of the port water area depends on many factors, most important being the type of the bottom ground.
5 Ground reaction pressure during hull impact against the 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 [1]. The changes 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. Figure 3 illustrates the process.

The ship’s 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 or their mixes, and in cohesive grounds, including clay gravels and sand-gravel mixes, clay sands, clay and silt.

Figure 3: Ship penetration in ground depends of ship pushing.

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.

Additionally, when there is ship’s hull impact against the ground there may also occur shearing forces and bending moments; if these are exceeded, the hull can be damaged. These factors will occur if the hull is supported on an
underwater obstacle of small size. The ship proceeding within the dredged port waters should not encounter such obstacles. Nevertheless, one may expect the following situations to happen:
- part of ship’s hull hits the ground (particularly when the ship is trimmed),
- the hull hits brought in earth (a bump) caused by a natural water current or propeller streams.

6 Summary

1. The main restriction in safely serving of bigger ships in the ports is the depth of waters.
2. A ship can touch the bottom of port water areas due to reduction of its keel clearance.
3. The main component of under keel clearance in polish port is alternation of water keel. The reduction of error in determination of this one permits to enhance of ship maximal draught.
4. An assessment of these facts may be based on navigational risk as a combination of the probability of ship impact in the ground and the results of hull damage.
5. Phenomena such as ship’s pressure on the sea bottom and its reaction (passive soil reaction) are essential in the assessment of the impact effects as possibility of ships hull damage.

References