International Journal of
Materials
& Structural Reliability

International Journal of Materials & Structural Reliability Vol.4, No.1, March 2006, 89-97

An Assessment of Ship Impact on the Ground during Maneuvering in a Port Water Area

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Abstract

The building of new ports is restricted by natural conditions of sea water area and the required great financial effort. The existing ports are expected to handle ships bigger than those for which they were designed. The main restriction in serving these ships is the depth of port waters which directly affects the safety of a maneuvering ship. The under keel-clearance of a maneuvering ship in the port water area should be such that a ship moves safely. The 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. The article presents an assessment of navigational risk as a combination of the probability of ship impact against the ground and the result of hull damage.

Keywords: Navigational risk, Ship impact, Port water areas

1. Introduction

The rapid increase in seaborne transport observed since the 1970s has resulted in an intensive growth of the merchant fleet. Initially the tonnage was growing by building ships of larger and larger capacity, which, however, having reached a certain threshold of size, came to a halt. The predicted building of ships with the capacity up to one million tons has not been undertaken. The reason for that was that very few ports would be capable of handling such vessels. The construction of new ports is much restricted due to natural conditions of sea water areas (mainly their depths) on the one hand, and required huge financial investments on the other hand. The latter factor is particularly important if we bear in mind it refers to the carriage of bulk cargoes. As the economic and geopolitical conditions tend to change, the usual directions of bulk transport also change in cycles lasting a few years. Therefore, the building of a new port where the return on investment takes twenty years is a risky business. That is why there is a need to make the best of what there exists to handle larger ships than those for which the ports have been designed. Another significant factor is the standardization of newbuildings. In the case of bulk carriers this means that ship's parameters (size) have to be adjusted to restrictions existing throughout the world. One

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example is “Panamax” size ships, the breadth of which is adjusted to pass through the Panama Canal. Therefore, ships’ statistics in terms of size show that in certain size ranges there are far more vessels than in others.

Port areas are a particular type of navigable waters because maneuvering is limited by a number of factors. An analysis of marine accidents shows that a large number of such accidents occurs within port waters [3].

The minimum recommended keel clearance of a ship as required at present in Poland should not be less than 0.05 – 0.15 of the ship’s draft, depending on the type of area or fairway. However, the relevant figures required throughout the world are lower. For instance, in the approach channel leading to Rotterdam the keel clearance should not be less than 0.04 of the draft, even for ships drawing to about 22.5 meters [7]. At present, the minimum keel clearance in the port of Świnoujście has been set to be approximately 0.1 of the ship’s draft, which allows to accept ships drawing not more than 12.8 m. Comparing the two ports, it can be seen that in spite of larger size ships and worse hydrological conditions (tides) in the Rotterdam’s approach channel, the required keel clearance in that port is more than twice less than that in Polish ports. This, however, does not mean that the safety level is twice lower there. Those values of safe keel clearance result from scientifically proved method of predicting safe keel clearance. It is also possible to reduce the keel clearance in Polish ports, which will increase the allowed draft of ships with the safety level being maintained. Naturally, the appropriate method has to be used assuring the determination the safety level which can be defined by navigational risk [2]. The risk can be presented as a combination of the probability of ship’s impact against the bottom and the consequent hull damage.

Let us consider this example. About 60 ships calling yearly at Swinoujście have their actual capacity limited by the maximum permitted draft that cannot exceed 12.80 m (according to the Port Regulations in force), even if in many cases the draft could be deeper. The losses due to that restriction are as follows:

- limited quantities of cargo loaded and unloaded, which means lower earnings for the harbor and stevedoring companies;
- lower shipowners’ profits as the ship’s capacity is not used to the full or longer turnaround time due to necessary lighterage 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 by, say, 15%;
- 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.

Let us examine one case. If in the port of Świnoujście the maximum size ship is that with 260 m LOA and 40 metre beam, and its maximum draft will be increased by 10 cm in relation to the regulatory 12.80 m, the ship will be able to carry 800 tons more. This brings extra profit from freight and cargo handling operations and opens opportunities for attracting new ships carrying more cargo. This is important in the face of strong competition between Baltic ports in this region. In the year 2002, 60 ships entered or left Świnoujście with their cargo capacity partly unused. The total quantity of unused capacity was 312 657 tons [6]. The same problem applies to the ports of Gdynia and Gdańsk. Therefore, it seems necessary to do research aiming at the development of a method allowing to determine the minimum keel clearance with the safety level being maintained. Then decisions whether a ship can maneuver within port waters will be taken at the acceptable risk.

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:

$$R_B \geq \left(H_i - \delta_H\right) - \left(T - \delta_r\right) \tag{1}$$

where:

R_B – safe keel clearance,

H_i – depth of the area,

δ_H – errors in the determination of area depth,

T – ship's draft,

δ_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.

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. This is defined as the multi-year mean sea level (SW), which is referred to the NN_{55} system based on the so called Amsterdam datum. In Polish ports the water level gauge datum is located on the ordinate marking 500 cm of the NN_{55} system.

From ship's safety point of view, decreased water level is critical. Therefore, it is recommended that the allowance be made for low water level while determining the keel clearance. The allowance is found from:

The curve of the sum of duration periods of sea (water) levels for the given area, based on readouts of the water level gauge taken over years, where the water level lasting 98% or 99% of the considered period is taken for calculations. Research and theoretical consideration lead to a conclusion that in order to calculate the mean level (over many years) of a particular area it is recommended to take a continuous period of observations of the sea level, not shorter than 19 years. This results from the fact that all the sea level changes due to the sun and moon influences take place over that period of time. If the considered period is shorter than 19 years, then the mean sea level is referred to as the relative mean level (WSW). The mean low level is calculated as the arithmetic mean of the lowest observed levels.

The reserve for low water levels is determined from the difference between mean level (SW) and mean low level (SNW) and has the following values for the five largest Polish ports (1997):

- Gdansk - 0.60 m,
- Gdynia - 0.60 m,
- Kołobrzeg - 0.75 m,
- Szczecin - 0.50 m,
- Swinoujście- 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. Fig. 1 presents fluctuations in the measured water level in the port of Swinoujście in 2002.

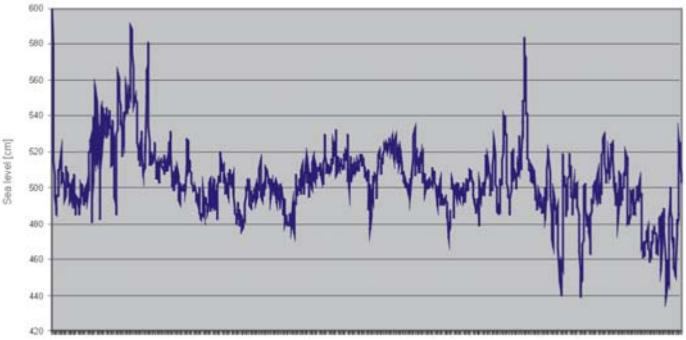

Fig. 1 Fluctuations of the sea water level in the port of Swinoujście in 2002

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 [7], 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 kind:

- 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:

$$P_u\left[z_c(t)_{\max} \le R_B / 0 \le t \le T_p\right] \quad dla \quad C \le c_{\min} \tag{2}$$

where:

P_u – probability of ship's impact against the bottom,
$z_c(t)_{\max}$ – closest distance of ship hull from the bottom during maneuvers,
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 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.

$$P_u = \lambda / I_R \cdot t \tag{3}$$

where:

P_u – probability of the impact,

λ – accident intensity,

I_R – annual traffic intensity,

t – considered period.

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 P_k for such a case can be defined as:

$$P_k(t) = 1 - \exp\left(-t(t_c)\right) \tag{4}$$

where:

t_c – period in which the pre-set hull load will be exceeded during the hull impact against the bottom.

$$t_c = \left[P/1 - P_k(P_u)\right]^{-1} \tag{5}$$

where:

$P_k(P_u)$ – probability of the hull load higher than admissible during its impact against the bottom.

$$P_k(P_u) = P\left[Q_{sgr} \geq Z_G\right] \tag{6}$$

where:
Q_{sgr} – admissible pressure on ship's hull,
Z_G – passive earth 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:

$$P_{uw} = P_u \cdot P_k \left(P_u\right) \tag{7}$$

where:
P_{uw} – probability of an accident during ship's maneuvers,
P_u – probability of a ship's touching 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 maneuvers 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.

The level of losses sustained by the ship hitting the bottom of the port water area depends on many factors, one of the 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 begins 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 1 illustrates the process.

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 or 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 [3]. 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 [4].

Ships penetrating a non-cohesive ground to a certain depth will not have their hull damaged..

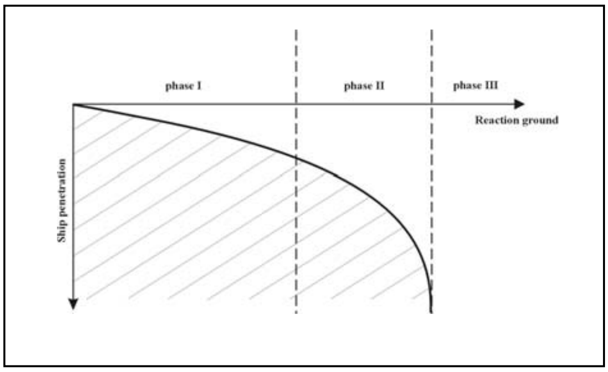

Fig. 2 Ship penetration in ground depends of ship pushing

6. Assessment of Ship's Hull Damage Degree

The kind and degree of hull damage depends mainly on the energy absorbed by the hull when hitting the bottom. The measure of hull damage used for the assessment of the impact is the volume of damaged hull material. The relationship combining the absorbed energy and the degree of damage has been empirically worked out by Minorsky [5]:

$$E = 47.2 \cdot R_T - 37.2 \tag{9}$$

where:
E – energy absorbed by the hull during impact [MNm],
R_T – degree of damage of hull material [m^3]

This empirical relation has been determined from the observations of the effects of numerous collisions and is used for the assessment of collision effects.

The relation shows that the degree of damage increases in direct proportion with the energy absorbed by the ship's hull during the impact against an obstruction.

This is, undoubtedly, a simplified approach as the quantity of absorbed energy depends on a lot of factors, but mainly on the structure of the ship's hull bottom, material properties and the type of damage. Therefore, further research is carried out to determine as accurately as possible the relation between the absorbed energy and the hull material damage which would account for the above conditions.

The energy absorbed by the ship's hull hitting the bottom is equal to the work done by the ship during the impact. The value of the energy can be determined from this relation:

The energy mainly depends on the force appearing between the hull and the bottom. It is difficult to define the force and its curve as the function of time by analytical methods. Therefore, simpler methods based on empirical research data are used. The empirical equation given below presents the energy of impact dependent on ship's mass and the velocity at the moment of impact [8]. The vertical component of ship's velocity should be taken into account in these calculations:

$$E_v = m_s V_v^2 / 2 \tag{10}$$

where:
E_v – energy absorbed during impact,
m_s – ship's mass,
V_v – vertical components of ships velocity

When a ship hits the bottom with part of its hull, the energy absorbed by the hull is reduced because some energy is converted into work connected with the trim and partial absorption of the energy by the ground when it is pressed by the hull.
The energy can be determined in this way:

$$E = E_H \cdot C_E \cdot C_G \tag{11}$$

where:
E – energy absorbed by ship's hull,
E_H – vertical component of ship's energy (for ship's virtual mass),
C_E – coefficient of eccentricy,
C_G – Coefficient of absorption of the impact energy by ground deformation

The coefficient of eccentricy can be determined by the method used in calculations of magnitudes connected with a ship berthing alongside. The coefficient C_G is expressed by work done by the ship's hull when pressing against the bottom. The above relations can be used for the description of a quasi-static situation, i.e. when the impact velocity is low (up to 1 m/s). When the velocity is higher (dynamic touch), the forces of reaction are substantial at the sea bottom – hull contact area. These forces and their time function can be hardly determined by analytical methods. That is why empirical methods are in use. These are based on the results of field research. Utilizing the studies if ship impact against port structures in horizontal movement [8], one can determine the force of ship's impact against the sea bottom using this relation:

$$F_s = 0.98\left(m_s\right)^{1/2} \cdot \left(V_v / 8.22\right) \tag{12}$$

where:
F_s – force of impact against the bottom [MN],
m_s – ship's mass [t],
V_v – vertical component of ship's velocity [m/s]

This will allow to determine the energy absorbed by ship's hull and to identify possible damage. Thus energy absorbed by ship's hull may be calculated as:

$$E_w = \int F_s dd \tag{13}$$

where:
d – depth of ship penetration in ground

The method of assessment of ship impact on ground presented above permits to the management of ship movement safety on port water area.

Conclusions

1. A ship can touch the bottom of a navigable area due to the reduction of its keel clearance.
2. One of the reasons of the decrease in keel clearance is a decrease in the water level.
3. The mechanism of ship's impact against the bottom basically differs from grounding or hitting a port structure (berth) and is not sufficiently described in the literature on the subject.
4. Phenomena such as ship's pressure on the bottom ground and its reaction (passive earth pressure) are essential in the assessment of the impact effects.

5. The kind and degree of hull damage mainly depend on the energy absorbed by the hull during its impact against the sea bottom.
6. The results of the research permits to assess of navigational risk and thus to improve the safety of ship maneuvering in port water areas.

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