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Navigational risk management with under-keel clearance consideration

Keywords

risk management, under-keel clearance, decisionmaking, Monte Carlo model

Abstract

The paper presents idea of the safety management system established for safety UKC (under-keel clearance) for ships entering to ports. System consists of three components which can be used for navigational risk management during decision making in port. Application of newly system was presented for example research which carried out by Marine Traffic Engineering team for Ystad port.

1. Introduction

The minimal depth on approach to sea ports is very important factor which influence safety of navigation in respect to under keel clearance which is along horizontal area the most important factor of navigational safety.
Some ports have special VTS procedures for entering and leaving, and Marine Authorities have problem with decision according to entrance big-draught vessels. The maximum draught is limited by the available water depth minus under-keel clearance [2].
Marine staff at the ports needs an adequate decision support system to allow them to take ship allowance decisions based on proper and reliable data [7]. Existing systems for dynamic UKC are mostly dedicated towards dynamic UKC evaluations for ships [1], [3], [6], [7], [8], [9]. Presented system is more complex. It consist of two independent systems and probabilistic model for under-keel clearance evaluation. This solution could be helpful at working port with restrictions concerning ship's draught.

2. UKC safety management system in ports

The UKC safety management consists of two subsystems connected by probabilistic model of UKC evaluation (Fig 1.):

1. Long time UKC risk management system;
2. Dynamic UKC decision support system;
3. Monte Carlo based probabilistic model of UKC assessment.

Long time UKC management system should be applied continuously in given time periods (from one year to few years). The main output from this system is depth or draught of maximal ships or changes in port regulations.
Dynamic UKC decision system is used as decision support system which delivers necessary information for port captains for single ship admittance possibility. System output is risk based decision for ship entrance.
Probabilistic model of UKC determination is used in both systems for finding distributing of UKC for given ships in given conditions. With use this information probability of touching the bottom could be estimated.

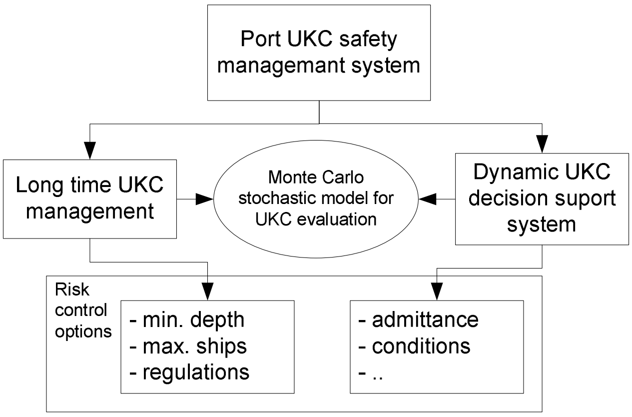

Figure 1. UKC safety management system in ports

3. Long time UKC risk management

The risk of collision with the bottom can be defined as probability of certain losses during expected period of time (one year/ lifetime of ships or waterway):

$$R = P_A C \qquad (1)$$

where:
P_A – probability of serious grounding accident
C – consequences of accident

With assumption that accidents consequences are similar we can expressed risk as probability of accident only.
Probabilistic acceptance criterion is proposed in this study. Such criteria are widely used in Marine Traffic Engineering (Dutch, England, Denmark, Poland).
Monte Carlo model enable to find probability of accident in single passage assumed when *UKC*<0 is expressed as $P_{UKC<0}$.
Probability of serious accident can be calculated with assumption that serious accidents are 10% of all of total number of accidents: P_{SA} =0.1 (so called Heinrich factor usual assumption in restricted water areas, validated by real accidents statistics). Under above assumptions probability of serious accident P_{SA} can be calculated as:

$$P_A = P_{SA} P_{UKC<0} \qquad (2)$$

Intensity of all accidents in given time (ex. one year) can be calculated as:

$$\lambda = N P_A \qquad (3)$$

where:
N – ship movement intensity per one year.

Standard probabilistic criterion for risk of collision with the bottom is based on Poisson process the collisions with the bottom are random with intensity λ [collision/time] and expected number *n* during given time [5,10]:

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \qquad (4)$$

where:
n – expected number of collision with bottom per time,
λ – intensity in given time.

No accident probability in given time *t* can be calculated with assumption that *n*=0 as $P(n=0) = e^{-\lambda t}$. The opposite to above most important safety factor can be expressed as occurrence at least of one accident in given time *t* and expressed as:

$$P(n \geq 1) = 1 - e^{-\lambda t} \qquad (5)$$

Typical probabilistic safety criterion is probability of no accident in given time. For example Dutch criterion on approach to Rotterdam (with tides consideration) is 10% probability of any accident in 25 years of waterway operation which is expressed as $P(n \geq 1) = 1 - e^{-\lambda t} = 0.1$ (where *t*=25 years) which gives $\lambda t = 0.105$. Assuming that *t*=25 years of operation we obtain $\lambda = 0.0042$ of all accidents per year which lead to following criterion: one accident in 238 years period (=1/λ). The criterion comprise all accidents so with assumption that serious accidents are 10% of all accidents we can calculate yearly intensity of serious accident as $\lambda_S = 0.1\lambda = 0.00042$.
Polish criterion that is being used in Marine Traffic Engineering works for risk assessment is slightly less restrictive due to less traffic intensity, and nature of the bottom in Polish ports. We assume limit accident rate per year at the level $\lambda = 0.007$ of all accidents or $\lambda = 0.0007$ for serious accidents where special action should be undertaken as criterion value (the criterion is based on acceptance of one serious accident per ships lifetime which equals 15 years, because ships during this time are not likely to be rebuild in opposite to waterway which during 50 years of operation will be rebuild few times most likely).
In further step taking into consideration the passages of ships (*N*) it is possible to calculate limited

probability of collision with the bottom (accident) in single passage as $P_{A-accept} = \lambda / N$

4. Monte Carlo model of under keel clearance determination

The main assumption of probabilistic method for UKC determination is that the model takes into account depth measurement uncertainty, uncertainty of draught determination in port, error of squat determination, bottom irregularity, tides and waves influence. On the basis of this method Monte Carlo model of under-keel clearance determination was built. Model consists of five main modules.

Random draught module

User-entered draught is corrected for draught determination error value ship's heel error and wave clearance. Additionally iterated draught (T_i) is calculated as follows:

$$T_i = T + r_{T_i} + r_{p_i} + r_{f_i} + S_i \tag{6}$$

where:

- T – ships draught [m]
- r_{T_i} – draught determination error
- r_{p_i} – ships heel error
- r_{f_i} – wave clearance
- S_i – ships squat

Water level module

Water level PW_i can be automatically load from online automatic gauges if such exists (Polish solution). In some researches the level can be modelled as normal cut distribution with parameters (0, +/-0.1m).

Depth module

Depth h_i was assumed as constant in given sections.

$$h_i = h_{s_i} + r_{s_i} + r_{m_i} + \Delta pw_i + r_n \tag{7}$$

where:

- h_{s_i} – depth of water area determined on the basis of cumulative distribution function
- r_{s_i} – sounding error,
- r_{m_i} – mudding component clearance,
- Δpw_i – change of water level,
- r_n – navigational clearance.

Squat module

Squat (ship sinkage due to decrease of water pressure during movement) is calculated in three stages. First module calculates squat with analytical methods used to obtain moving vessel squat (Huuska, Millward 2, Turner, Hooft, Barrass 1, Barrass 2). Next standard errors of each method are applied. Squat model selection and their standard errors were verified by GPS-RTK experimental research. As a result of the experiment uncertainty of each model was assessed and each squat method assigned weight factor. Method's weights and statistical resampling bootstrap method are used later on to calculate final ship's squat.

Under-keel clearance module

Under-keel clearance UKC_i is determined by using draught, depth, water level and squat results which were calculated before. Under-keel clearance is defined as:

$$UKC_i = \left(h_{s_i} + r_{s_i} + r_{m_i} + \Delta pw_i + r_n\right) - (T + r_{T_i} + r_{p_i} + r_{f_i} + S_i) \tag{8}$$

where:

- h_{s_i} – up-to-date depth,
- r_{m_i} – mudding component clearance (normal cut distribution with 0 and +/-0.1m),
- r_{s_i} – sounding error (normal cut distribution with 0 and +/- 0.1m),
- T – ships draught,
- r_{T_i} – uncertainty for draught determination (0,+/-0.10m),
- S_i – iterated squat (bootstrap model),
- r_n – navigational clearance (constant = 0,3m),
- Δpw_i – change of water level,
- r_{f_i} – wave clearance (wave height for particular weather conditions).

Program is capable to consider above mentioned uncertainties using distributions and their parameters. Where uncertainty is greater for certain factor components due to less available data or data accuracy, it is possible to make grater allowances in that factor. The remaining necessary data are taken from XML file located from the server and this file could be modify.

Decision model results was added to making application user friendly. Simplified decision model is based on mean expected value. Decision-maker receives suggestion which concerns to level of acceptable risk for given situation. The main algorithm of model is presented in *Figure 2*.

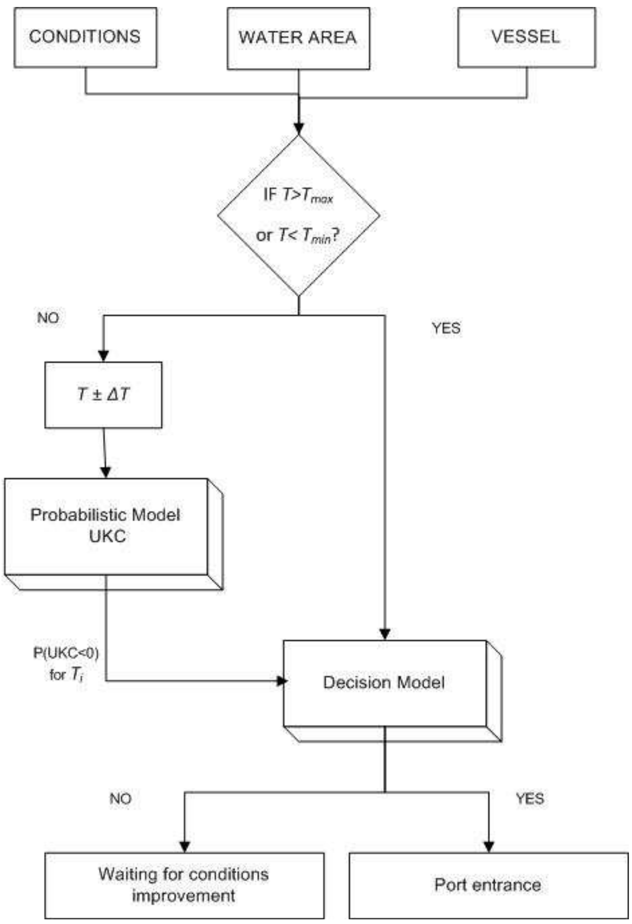

Figure 2. Algorithm of making decision during ship's entrance to the port

5. Dynamic under keel clearance decision support system

Decision maker importance is to choose option with the best consequences. In case the maximal vessel entrance, decision maker have to take into consideration costs connected with unjustified ship's delay and costs of possible accident of touching the bottom (as a consequence insufficient under-keel clearance)

Decision support system was built on the basis of decision tree which is presented in *Figure 3* [11]. The actions are denoted as *A*, possible state of nature as *P* and outcomes as *U*. The *P* can be understood as state of nature (multidimensional random variable) that could lead in result to ship accident. The main objective of decision can be considered as minimization of accident costs and ship delays for entrance to the harbour due to unfavorable conditions. The limitation of this function can be minimal acceptable (tolerable) risk level. The expected costs of certain actions (or more accurate distribution of costs) can be calculated with knowledge of possible consequences of accident and costs of ship delays. The consequences of given decision actions expressed in monetary value can be considered as highly non-deterministic variables which complicates the decision model. For example the cost of single ship accident consists of:

- salvage action,
- ship's repair,
- ship's cargo damages,
- ship's delay,
- closing port due to accident (lose the potential gains),etc.

The decision tree can be used also for determination of acceptable level of accident probability if there are no regulations or recommendations relating to it. If we assume that accident cost is deterministic and simplified decision model is applied (*Figure 3*) then with assumption that the maximum expected value criterion is used in decision process, the probability p_a^* can be set as a limit value of probability where there is no difference for the decision maker between given action a_1 and a_2. This value can be expressed as follows:

$$p_a^* = \frac{1}{\frac{u_1 - u_3}{u_4 - u_2} + 1} \qquad (9)$$

where: u_1, u_2, u_3, u_4-consequences of different decisions expressed in monetary values.

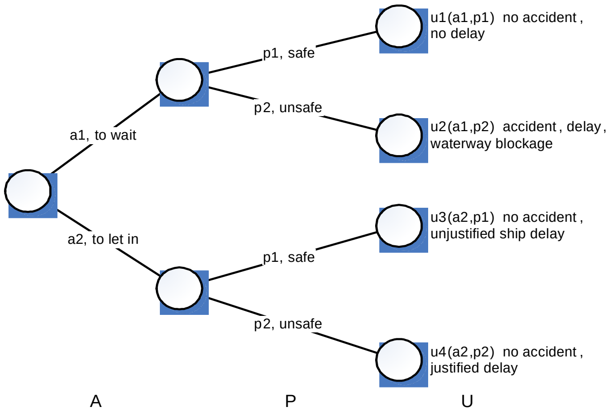

Figure 3. Simplified decision tree of ship entrance to the port

Costs of ships accident and delay

Usually during the investigation of ship grounding accident are restricted waters it is not necessary to take into consideration the possibility of human fatalities nor injures. The cost of accident *Ca* could be divided into following costs:

$$Ca = Cr + Cra + Cos + Cpc \quad (10)$$

where:

Cr – cost of ships repair,
Cra – cost of rescue action,
Cos – cost of potential oil spill,
Cpc – cost of port closure.

The mean cost of grounding accident in these researches was calculated for typical ship (bulk carrier of 260m). The mean estimated cost of serious ship accident is assumed as C_1=2500000 zl (around 700000 Euro) [4]. The oil spill cost is not considered. Following assumption has been taken in calculations:

- number of tugs taking part in rescue action: 3 tugs,
- mean time of rescue action.: 1 day,
- trip to nearest shipyard: 0.5 day,
- discharging of ship: 4 days,
- repair on the dry dock: 2 days,
- total of oil spilled: 0 tons.

Mean cost of loses due to unjustified ships delay according to standard charter rate can be estimated as 90000 zl/day. It is assumed that after one day the conditions will change scientifically and the decision process will start from the beginning.

The decision making process

The maximization of mean expected value criterion is used to support the decision of port captain. Decision tree leads to only 4 solutions. Each decision could be described in monetary values. The expected results (losses) of given decisions are as follows:

- *u1*= 0 zl;
- *u2*= - 2500000 zl;
- *u3*= - 90000 zl;
- *u4*= 0 zl.

Taking into consideration the results of grounding probability calculations of example ship entering to Świnoujscie Port the probability of ship under keel clearance is less then zero equals *p2*=0 which is assumed as accident probability. No accident probability in this case is estimated as *p1*=1-*p2*=1. We can evaluate the mean expected values of given decisions *a1* and *a2* as:

- *a1*=0zl+(-0,0×2500000zl)= 0zl;
- *a2*=-(-1×90000zl)+0zl= - 90000zl;

With use of mean expected value it is obvious to prefer action *a1* (to let the ship to enter the port) because total mean expected loses are smaller in compare to unjustified delay due to decision *a2*.

6. System application for large ferries entering to Ystad port

As the result of combined method Monte Carlo with simulations results in sections of waterway (breakwater=0m) we obtain parameters of distributions of *UKC* in distance from breakwater for real mean depth existing in Ystad port (*Figure 4*).

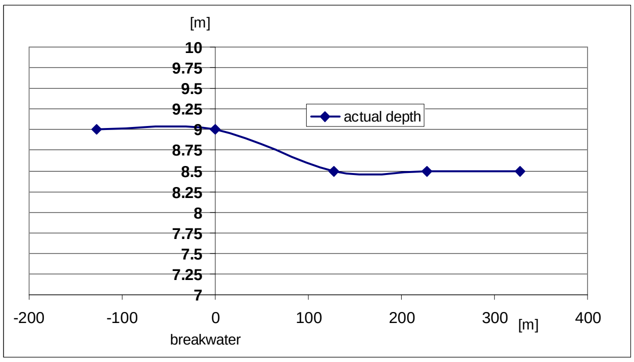

Figure 4. Mean actual depth in given sections (sounding from fall 2007)

Speed of approaching ships was determined from simulations (extreme conditions E20 m/s wind) was applied. Speed applied in Monte Carlo model was calculated with 95% probability level [5].

In next step Monte Carlo model described in section 4 was applied to determine histograms and parameters of distributions of UKC (*Figure 5*). Wave influence was taken into account.

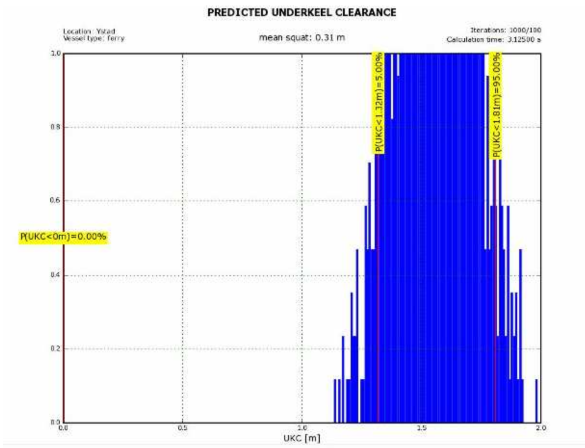

Figure 5. Histogram UKC of Piast ferry and squat value 230m behind heads /sea wave =0m/

In the further step on the basis of Monte Carlo results the UKC on 95% and squat was calculated (*Figure 6*). Important for the probability calculations is mean UKC and standard deviation of UKC.

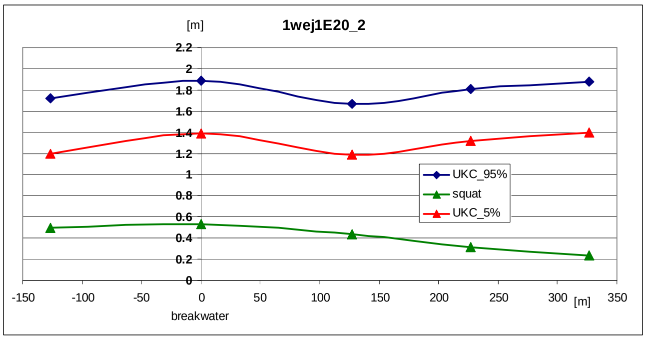

Figure 6. UKC on 95% and 5% level of confidence and squat in meters of m/f *Piast* approaching with E20m/s wind (x=0 outer breakwater)

Due to lack of distribution or probabilities of given water levels the water level assumed in this study is equal to Mean Low Water.
With taking into consideration the entrances of ships to Ystad Port of 10 par day (N=10*365=3650 passages/year) it is possible to calculate limited probability of collision with the bottom (accident) in single passage as:

$$P_{A-accept} = \lambda / N = 0.0042 / 3650 = 1.15 * 10^{-6}$$

Final calculation of required depth (*H*) for distribution with parameters *m* and σ to fulfill Dutch criterion is based on following formula:

$$P_A = 1 - \int_H^{-\infty} f_{(m,\sigma)}(x)dx \le P_{A-accept} = 1.15 * 10^{-6} \quad (11)$$

The results as required depth on approach to Ystad Port are presented in *Figure 7.*

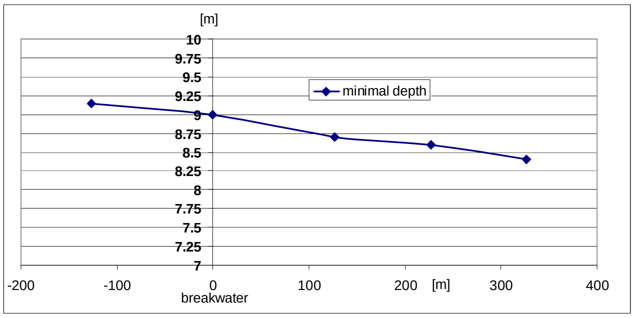

Figure 7. Minimal depth in Ystad port with acceptance criterion $P_A \le P_{A-accppt} = 1.15 * 10^{-6}$

7. Conclusion

The novel method of safety management was presented in the paper. The method consists of two subsystems connected by probabilistic model of UKC evaluation.

Application of one subsystem (long time UKC risk management) is presented as case study in the paper for determination of safety of maximal ferries entering to Ystad port.
Presented safety management system could be applied in any port where necessary information's about ship safety are available.

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