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System for Determining Dynamic Under Keel Clearance of Vessels Entering the Port of Swinoujscie (DRWPS)

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ABSTRACT: The article presents a system for determining dynamic under keel clearance. In order to build a DRWPS system, a mixed model was created based on the analysis of math models. The system includes advisory software for defining the conditions for the entering of large LNG vessels in the context of under keel clearance and software was built to support the decision-making of operators who are responsible for introducing these vessels to the Port of Swinoujscie.

1 INTRODUCTION

The navigation safety of ships that maneuver on inshore waters mostly depends on the size of available under keel clearance (UKC). The decision to allow a given vessel in or out of the port is influenced by many factors, among them, for example: wind waves, height of water surface, draft and heel of the vessel, ship squatting, taking into account possible errors in calculating these values at the same time.

In order for both the port and the ship operator to achieve optimum profit, a system was created with the main objective to determine and predict the dynamic under keel clearance (DRWPS) for ships such as Q-flex type LNG tankers that enter the Port of Swinoujscie.

The DRWPS system is a computer program that determines the under keel clearance based on the method of constant reserves using accurate models of squatting and change of the position of the lowest point of a ship's hull as a result of its movement of the wave. It is dynamically linked to with water gauges and the reading of the height and direction of the wave. It can work in the mode of planning the maximum speed or defining based on the speed given for the predicted UKC.

The system is based on the method of components where each component of the clearance is described as a model (squatting, ship's movement on the wave) or constant one that can be changed by an authorised user. The DRWPS takes into account both the analytical model of squatting that downloads data from a database in the program which can be calibrated with respect to the data from the echo sounder fitted on each ship, and the influence of wind waves which may be subject to calibration based on the current reading from the ships inclinometer. Online access to data on water level and wind waves increases the accuracy of the system. Maximum values of the following errors have been adopted as the system's constants:

- Error in determining the constant heel
- Error in determining the vessel's squatting
- Error in determining the water level
- Error in soundings
- Error in siltation taking into account the time passed between soundings

– Other errors and constants as agreed with the ordering party.

2 DESCRIPTION OF THE MATHS MODEL APPLIED IN THE DRWPS SYSTEM

In order to define safety with respect to dynamic under keel clearance, the following methods are applied:
1 Method of constant component reserves where reserves are defined as constant values;
2 Methods based on math models of reserves, including methods that apply probabilistic models;
3 Mixed methods.

Another division differentiates between:
1 Static methods;
2 Dynamic methods.

The model created for the DRWPS system should be deemed as a mixed (two reserves components – squatting and wave influence, are modelled using math models) and dynamic model, i.e. a model linked to external sensors and possible changes in a ship's speed and movement when it enters the port are taken into account.

2.1 *Method of constant component reserves*

The method of constant component reserves adopted assumes that in order to ensure a safe under keel clearance for actual vessels draft T under the most unfavorable conditions, it is necessary to:
1 Determine the influence of the most important factors on reserve for UKC (the so-called component reserves);
2 Determine the maximum or the most probable values of each reserve component Ri;
3 Add reserves individually and determine the so-called criterion reserve Rk=∑Ri;
4 Deepen the basin to the depth of H=T+ Rk;
5 Avoid introducing vessels when the sum of reserve components taking into account the change in squatting and water level is smaller than the value of the criterion reserve.

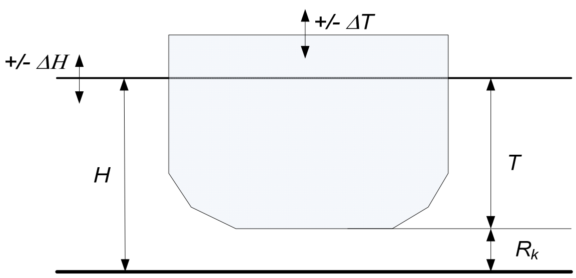


Figure 1. Diagram of the criterion reserve

2.2 *The model of dynamic under keel clearance adopted*

The model and some of its parameters have been based on the [6] document that was approved of by UMS in Szczecin titled "Projekt systemów zapewniających bezpieczną nawigacje i obsługę statków LNG na podejściu i w porcie zewnętrznym w Świnoujściu" [A project for systems that ensure safe navigation and handling of LNG ships when entering and staying in the external port in Swinoujscie] of 2012.

For calculations, the maximum Q-flex type LNG tanker of the following dimensions was adopted for the Port of Swinoujscie:

L=315m, B=50m, T_{LNG}=12.5m, H=14.5m

The values for each component reserves adopted are presented in Table 1

When forecasting safe exploitation of LNG vessels, the sum of component reserves (criterion reserve R_k) has to be larger or equal to:

$$R_k \geq H - T_{LNG} = 2m \quad (1)$$

The main dependence in the model is the dependence on the reserve difference (R_r), i.e. the value of the actual UKC reserve with respect to the assumed criterion reserve R_k=2m in the form of:

$$R_r = R_k - R_a(v) + \Delta H + \Delta T = 2m - R_a(v) + \Delta H + \Delta T \quad (2)$$

where:

R_k – criterion reserve value defined as 2m and 0.9m;

$R_a(v)$ – actual reserve comprised of component reserves where the reserve for squatting is calculated for various, changing speeds of the ship on the entrance;

ΔH – difference of the water surface level with respect to the zero level H=500cm;

ΔT – difference of a vessel's draught with respect to the maximum T_{LNG}=12.5m or T_{MAS}=13.6m.

As a result of the calculations according to the above dependence, two possibilities appeared:
1 $R_r \geq 0$ acceptable situation; a vessel can move along the waterway with the speed defined (Figure 2.1);
2 $R_r < 0$ unacceptable situation; the indispensable reserve is larger than the criterion one (Figure 2.2).

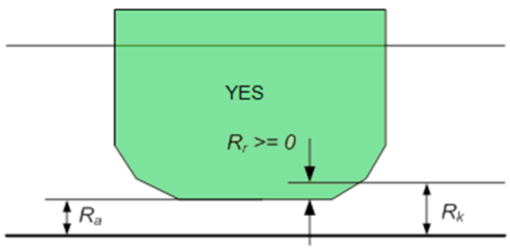


Figure 2.1. An acceptable situation – the actual reserve is smaller than the criterion one (the difference between reserves is larger than zero).

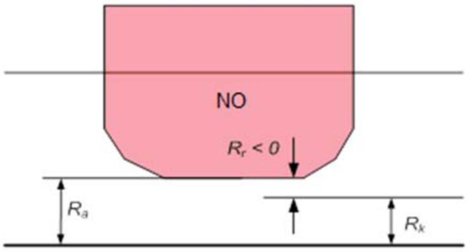
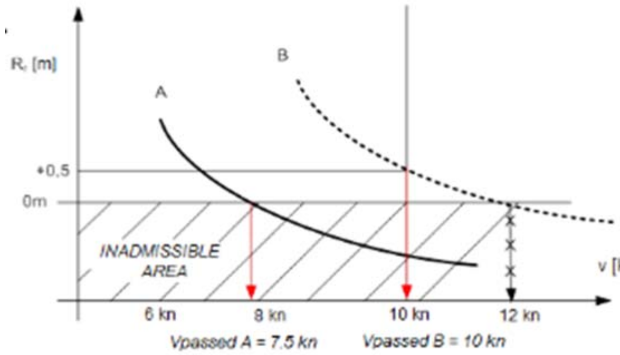


Figure 2.2. An unacceptable situation – the actual reserve is larger than the criterion one (the difference between reserves is smaller than zero).

In order to determine the criterion value of the speed of a vessel on the waterway, reserve differences R_r for various speeds were calculated which are presented in the diagram as a curve depending on the vessel's speed. The example in Figure 3 shows two situations:

1 Situation A where the speed needs to be reduced with respect to the maximum one;
2 Situation B where due to the positive value of the difference between reserves the speed can be equal to the maximum one on the stretch. In this case, there is a theoretical possibility of increasing the speed on the entrance (to be decided by the authorized parties).



A.(maximum speed is smaller than the maximum and equals Vpassed=7.5kn);
B (maximum speed equal the maximum, it is theoretically possible to achieve the speed of 12kn with the sum of reserves equal to the criterion reserve, in this situation for the speed of vmax=10kn the ship moves with the sum of reserves 0.5m larger than the criterion reserve, which means that the sum of all reserves is 2m+0.5m=2.5m for the speed of 10kn).
Figure 3. Sample possible situations for the reserve for LNG

Table 1. Component reserves adopted in the program based on [6] and [14]

Reserve symbol	Stretch	Stretch 2	unit	Name
Δ1	0.2	0.2	m	Reserve for an error in sounding
Δ2	0.2	0.2	m	Navigation reserve (value adopted as requested by UMS)
Δ3	0.0	0.1	m	Reserve for siltation
Δ4	0.0	0.0	m	Reserve for the height of tide
Δ5 LNG	0.3	0.5	m	Reserve for an error in determining the state of water for LNG
Δ6	0.1	0.1	m	Reserve for an error in the ship's draught
Δ7LNG	0.4	0.4	m	Reserve for the constant heel of the LNG ship (1 deg.)
Δ8	Variable depends on the speed		m	Reserve for squatting adopted as an average from the methods of Huuska, Barrasa3, Eryzulu, Icorels and Ankundinova
Δ9	Variable depends on the wave parameters		m	Reserve for heel and trim from the wave

As the calculations to find the criterion value for the UKC were conducted with the method of constant reserved, it was assumed that reserves from Δ1 to Δ7 will remain on the criterion level as constant values, whereas dynamic reserves Δ8 and Δ9 will be changed in the program.

2.3 *Stretches of waterways adopted*

The program allows to determine the squatting on three types of shallow-water basins:

– Shallow water (Restricted),
– Channel (Canal)
– Deepened waterway (Restricted Canal).

Two characteristic stretches for LNG tanker at the entrance to the Port of Swinoujscie were applied:

1 Stretch 1 – from buoys 1-2 (km 43) to buoys 9-10 (km 15);
2 Stretch 2 – from buoys 9-10 (km 15) to buoys 15-16 (km 0).

In each of these stretches, based on [6] the worst section was selected as far as the value of squatting is concerned (Stretch 1 – area of buoys 9-10; Stretch 2 – area of buoys 15-16) and its parameters were determined and introduced in the program. Both stretches represent the so-called deepened waterway.

2.4 *Models of squatting adopted*

The analysis and description of the models of squatting available were conducted based on the studies [PIANC 2014] and the precise model of Ankundinova. The following models of a moving ship's squatting were selected:

1 Huuska (applied by the authorities in Finland and Spain);
2 Barrasa 3;
3 Eryuzlu (applied by the Canadian Inshore Guard);
4 ICORELS (recommended by PIANC);

5 Ankundinova (new method that is well verified in reality and that allows to calculate the squatting at the bow and at the stern).

To calculate the final reserve for squatting Δ_8, average values for squatting were applied in the form of:

$$\Delta_8 = \sum_1^5 \Delta_{8i} / 5 \tag{3}$$

where: Δ_i – values calculated through each of the 5 models of squatting.

The Huuska method overstates the value of squatting as compared to other methods. According to Briggs [13], the Huuska/Guliev squat method can be used for all three channel types and it is defined as:

$$S_b = C_s \frac{D}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K \tag{4}$$

C_s – the squat constant, $C_s = 2.4$ is typically used as an average value, although Hooft (1974) had originally used $C_s = 1.96$ (values from 1.9 to 2.03 were used at times)

D – ship displacement

2.5 *Model of the influence of waves on the bow movement*

In analysing a ship's response (rolling) to waves, a linear model of dynamics in 6 stages of free movement is commonly applied, as well as the stochastic nature of the process of waves, described with the function of the so-called spectral density of the wave energy.

From the perspective of decreasing under keel clearance, only 3 elementary movements are crucial: one linear (vertical) movement and two angle movements. These are, respectively: heave, roll and pitch. Their amplitude characteristics, called response amplitude operators (RAOs), present a ship's response to the harmonic wave of a given amplitude and height, i.e. amplitude of a vessel's rolling and its shift with respect to the wave itself. Six functions have been given a scalar definition, i.e. the amplitude and phase characteristics for each of the three enumerated component movements.

In order to describe a ship's movement, a mobile (linked to the ship) clockwise system of coordinates (Figure 4) was applied and critical points responsible for UKC reduction were determined where movements (vertical displacements) are finally defined. They are the corners of a rectangle placed on the surface of the keel of the *L* (length between perpendicular) and *B* (length all over) dimensions, stretched between perpendicular and the ship's sides. Numbers and horizontal coordinates (x'_{UKC}, y'_{UKC}) of critical points are the following:

port side	starboard side
"-1" - bow $\left(+\frac{L}{2},\ -\frac{B}{2}\right)$	"+1" - bow $\left(+\frac{L}{2},\ +\frac{B}{2}\right)$
"-2" - stern $\left(-\frac{L}{2},\ -\frac{B}{2}\right)$	"+2" - stern $\left(-\frac{L}{2},\ +\frac{B}{2}\right)$

Amplitude characteristics of elementary rolling are usually determined directly in the system linked to the ship's centre of gravity – see the system $Gx_{SK}y_{SK}z_{SK}$ in Figure 4. For the needs of the UKC forecast system created, condensed functions of 4 arguments were used: wave amplitude, wave direction with respect to the ship (in the "where to" convention), ship's speed, depth of the basin determined based on the commercial SEAWAY software [Journee, 2001; Journee/Adegeest, 2003].

The vertical rolling of the critical point z_{UKC}, and to the same extent the decreasing UKC, for a regular wave is finally defined with the following equation:

$$z_{UKC}(t) = z_G(t) + \phi(t) \cdot y'_{UKC} + \theta(t) \cdot \left(x'_G - x'_{UKC}\right) \tag{5}$$

where all the values are expressed in the mobile *Oxyz* inertial system temporarily stopped on the level of calm water, whereas "primed" values as stiffly linked to *Oxyz* are constant:

z_{UKC} – vertical displacement (rolling) of the critical point in the *Oxyz* system [m];

z_G – vertical displacement (rolling) of the centre of gravity *G* [m];

φ – heeling angle (of rolling) [rad];

θ – trimming angle (of pitch) [rad];

t – time [s],

x'_G – longitudinal coordinate of the position of the ship's centre of gravity in the *Oxyz* system resulting from its weight layout [m];

x'_{UKC}, y'_{UKC} – longitudinal and crosswise coordinate of the position of a selected critical point in the *Oxyz* [m] system resulting from the definition as above.

The above calculations have to be carried out for each of the four critical points.

Determining the basic parameter for defining statistical parameters of rolling means determining the integral of the rolling spectre with respect to the wave amplitude as a variation of stochastic (random) process of rolling or the so-called zero moment of the spectre, marked as m_{0zUKC}. One of them based on the above-mentioned Rayleigh's layout is the amplitude of rolling $z_{UKC0\text{-}p\%}$, which can be overstated with the probability of $p_\%$ run by the operator/decision-maker (see [Dudziak, 1998], [Journee/Adegeest, 2003], [PIANC, 2014] among others):

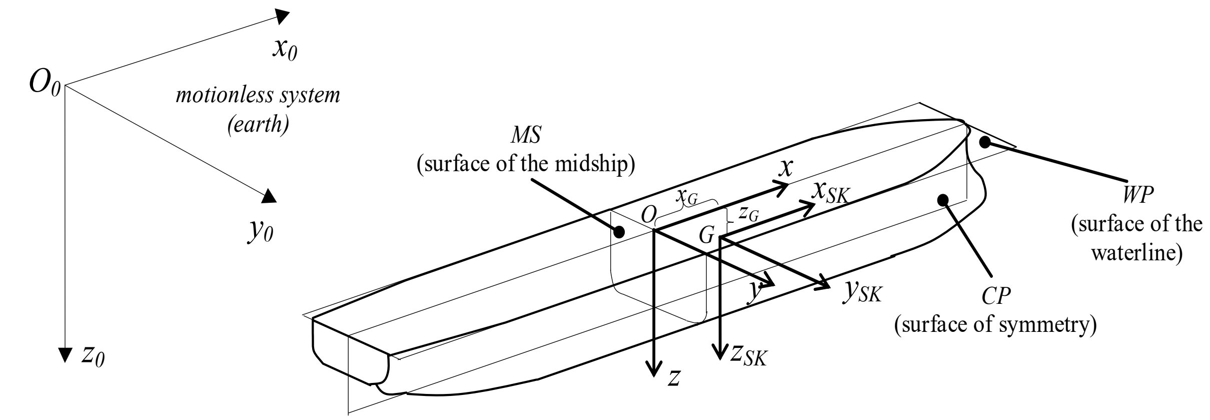


Figure 4. Systems of coordinates.

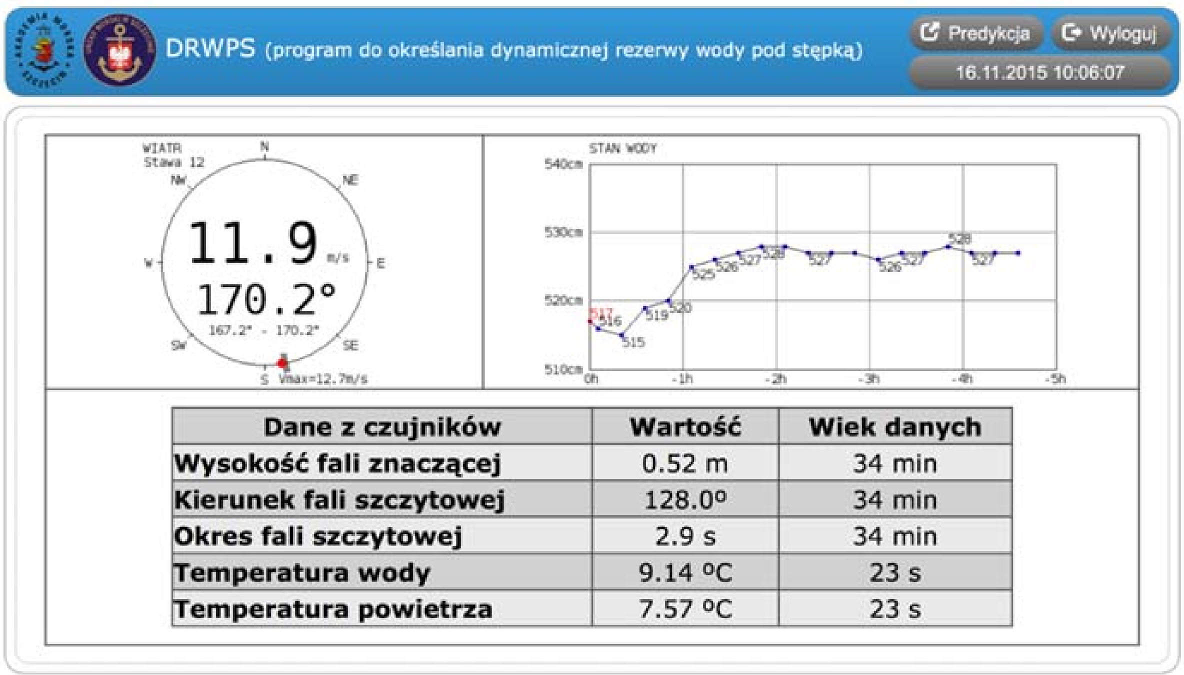


Figure 5. Weather parameters at buoy no 12.

$$z_{UKC0-p\%} = \sqrt{2\ln\frac{1}{p_{\%}}} \cdot \sqrt{m_{0zUKC}} \qquad (6)$$

The typical values of $p_{\%}$ is 0.05 or 0.01. The system of dynamic UKC designed selects the largest amplitude of all the critical points taken into consideration in line with (6).

In order to have a general overview as far as the size of rolling is concerned, the so-called significant amplitude of rolling $z_{UKC0\_1/3}$ is also used, which is the mean out of 1/3 (33%) of the highest amplitudes. It is close to the observed amplitude:

$$z_{UKC0\_1/3} = 2\sqrt{m_{0zUKC}} \qquad (7)$$

but smaller than the one given by the formula (6) with typical values of $p_{\%}$.

There is a possibility of introducing the actual full spectre of waves if it is known. In case of a lack of suitable statistical parameters of waves, e.g. period, they are estimated according to the implemented empirical and theoretical dependences.

3 THE DRWPS SYSTEM

The DRWPS system for dynamic under keel clearance created is a computer program divided into modules with the aim of a possible development. The main assumption of the system was to gather the following input data:

– Maximum speed allowed while maintaining the required clearance
– Under keel clearance for the speed selected
– Recording and painting the data in the form of a report on a vessel's entrance.

The input data required are:

1 Statistical data:
- Ship's data based on the data in the program database (for a precise model of squatting)
- Maximum speeds (port regulations)
- Dimensions of the model waterway.

2 Dynamic data (downloaded online):
- Water surface level
- Waves (height, direction, period)
- Wind (force, direction).

3 Data to be modified by an authorized user:
- Introducing constant component reserves
- Introducing ship data
- Other constant values.

4 Input data – determined by the user:
- Selection of the ship.

Selection of the work mode (determining maximum speeds for the maximum clearance selected / determining reserves for maximum speeds)

Parametr	Odcinek 1	Odcinek 2	Uwagi
Rezerwa na błąd sondaży (Δ1)	0.2 m	0.2 m	
Rezerwa nawigacyjna (Δ2)	0.2 m	0.2 m	
Rezerwa na zamulanie (Δ3)	0.0 m	0.1 m	
Rezerwa na wysokość pływu (Δ4)	0.0 m	0.0 m	
Rezerwa na błąd określania stanu wody (Δ5)	0.3 m	0.5 m	
Rezerwa na błąd zanurzenia statku (Δ6)	0.1 m		
Rezerwa na stały przechył statku (Δ7)	0.4 m		
Prędkość dozwolona (Vdoz)	10.0 w	8.0 w	
Rezerwa na osiadanie (Δ8)	0.67 m	0.51 m	dla Vdoz
Rezerwa na falowanie (Δ9)	0.10 m	0.06 m	dla Vdoz
Suma rezerw	1.97 m	2.07 m	dla Vdoz
Wartość referencyjna rezerwy	0.35 m	0.25 m	dla Vdoz

Dane z czujników	Wartość	Uwagi
Stan wody	527 cm	wiek danych = 13 s
Tendencja stanu wody dt = 1h	-0.3 cm/h	Stan wody sprzed 67 minut = 527 cm
Tendencja stanu wody dt = 2h	-0.2 cm/h	Stan wody sprzed 127 minut = 527 cm
Wysokość fali znaczącej	0.41 m	wiek danych = 6 min
Kierunek fali szczytowej	143.0º	wiek danych = 6 min
Okres fali szczytowej	2.6 s	wiek danych = 6 min
Kierunek wiatru	160.0º	wiek danych = 13 s
Siła wiatru	10.12 m/s	wiek danych = 13 s
Temperatura wody	9.17 ºC	wiek danych = 13 s
Temperatura powietrza	7.59 ºC	wiek danych = 13 s

Figure 6. Graphical user interface for dynamic UKC

4 CONCLUSIONS

The software created at the Maritime University in Szczecin can serve as an advisory program when taking decisions to introduce LNG tankers in the Port of Swinoujscie. The software was built by comparing the constant reserve for a given ship’s entrance to Swinoujscie while taking into account the squatting and wave reserve with respect to the criterion value. Above all, the program makes it possible to plan the maximum speed for the LNG vessel.

The further development of the DRWPS system shall rely on replacing the reserve for the change in the water level with a dynamic one and building a math model, and replacing the reserve for the heel by distributing this reserve to components such as: constant error in the list, heel caused by turning/circulation and heel caused by the wind, current and tug vessels.

To achieve more accurate final readings of DRWPS, the reserve for the fall in the water surface level should be replaced with a model of forecast that was already added to the program as an extension.

Instead of the referential reserve, the target DRWPS model should be based on (display on a chart) only the navigation reserve and determine other reserves through models (accepted by the Maritime Office). The navigation clearance should be of about 0.3m for vessels without hazardous cargo and 0.6m or more for vessels with hazardous cargo. The navigation reserve can be determined based on methods of risk estimation.

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