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Simplified Method for Estimating Maximum Ship's Draught when Navigating in Shallow Water on the South of Stolpe Bank in the Aspect of the Vessels with Maximum Dimensions and Draught

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ABSTRACT: This paper considers analysis of maximum draught of a merchant vessel, which can maintain safety of navigation in different exterior condition (average and extreme) on shallow water in Stolpe gutter and keep required under keel clearance, i.e. navigational reserve of depth. To depict maximum draught of a vessel we use practical method which incorporates risk of navigational and model of ship's domain. Results are compared with guidelines published by Decree of Minister of Transport and Maritime Economy from 01.06.1998 about technical conditions, which should be met by hydro mechanical sea structure, which operate vessels with the given particulars.

1 SAFETY OF NAVIGATION IN STOLPE GUTTER

1.1 *Introduction*

This paper considers analysis of maximum draught of a merchant vessel, which can maintain safety of navigation in average and extreme exterior (weather) conditions in Stolpe gutter and keep required under keel clearance, i.e. navigational reserve of depth.

Analysis of navigational reserve of depth (under keel clearance) is made in different exterior condition (average and extreme) for merchant vessels such as:

– VLCC vessel or bulk carrier whose particulars are: LOA (length over all) L=350,0 m, beam B=60,0m, draught in the Baltic Sea[1] $T_D=T_R$=15,00 m, block coefficient C_B=0,85.
– Container ship whose particulars are: LOA (length over all) L=250,0 m, beam B=32,0m, draught $T_D=T_R$=12,00 m, block coefficient C_B=0,70.
– Passenger ferry whose particulars are: LOA (length over all) L=140,0 m, beam B=16,0m, draught $T_D=T_R$=7,50 m, block coefficient C_B=0,65.
– Fishing boat whose particulars are: LOA (length over all) LOA= 40,0 m, beam B=8,5m, draught $T_D=T_R$=4,00 m, block coefficient C_B=0,63.

Results are compared with guidelines published by Decree of Minister of Transport and Maritime Economy from 01.06.1998 about technical conditions, which should be met by hydro mechanical sea structure, which operate vessels with the given particulars.

2 GUIDELINES OF POLISH MINISTER OF TRANSPORT AND MARITIME ECONOMY CONCERNING UNDER KEEL CLEARANCE

Let us consider the theoretical establishing of Separation Zone in the area of Stolpe gutter in accordance with guidelines published in the Decree of Polish Minister of Transport and Maritime Economy from 01.06.1998 (Dz.U.98.101.645) about technical conditions, which should be met by hydro mechanical sea structure and the location – Section II, Chapter 3, § 25 to § 35.

[1] Limitation of draught T=15,0 m was accepted in Baltic Sea such as maximum for the vessel wanted to sail safe across Danish straits (Great Belt with Hn=17,0m). Since November 2007 according to the Notice to Marines limitation of ship's draught has been reduced to 14,50m due to shallow water in Great Belt with depth Hn=16,50m.

Every sea structure situated within Polish area description three depths of water:

- Designed depth H_p,
- Acceptable depth $H_{dop.}$
- Technical depth H_t,

Designed depth H_p is specified by formula:

$$H_p = H_t + t_b \quad (1)$$

where: H_p - designed depth, [m]; H_t – technical depth, [m]; t_b - dredge reserve tolerance, [m].

A value of tolerance for dredge reserve, accepted to estimate sea structures and design drawing works, with respect to the location of drawing works, is:

- t_b = 0,25 m – for drawing works made in port and harbours,
- t_b = 0,35 m – for drawing works carried out outside limits of harbours, especially on the roads, in the approaching channels, for placing cables and pipelines in territorial sea and interior sea waters as well as profiling sea bed for sea's structures.

Every designed project includes specific width of sea bed lane along sea structure, in which one should keep acceptable depth ($H_{dop.}$). If the technical documentation, such as navigational chart, describes only one depth of the area, we assume that this depth constitutes acceptable depth ($H_{dop.}$). In this way technical depth (H_t) can be presented in meters on the basis of the following formula:

$$H_t = H_{dop.} - t_b \quad (2)$$

where: H_t- technical depth, [m]; H_{dop}- acceptable depth, [m]; t_b- full tolerance for dredge reserve, [m].

When we use navigational depth (H_n) we think about difference between horizontal planes, measured from average sea level SW to horizontal plane, which is adjoined with the highest bed situated in the given area, which is designed for vessel traffic.

Actual navigational depth (H_{na}) is navigational depth (H_n), which refers to actual water level.

Acceptable depth (draught) of the ship (T_a) in traffic areas describes difference between actual navigational depth ($H_{na\ a}$) and total under keel clearance (R_t) required in sailing condition:

$$T_a = H_{na} – R_t \quad (3)$$

where: T_a- acceptable ship's depth (draught), [m]; H_{na} - actual navigational depth, [m]; R_t - total under keel clearance depth, which enables the vessel to float in the place where sea structure is located, even for the unfavourable hydro meteorological conditions, [m].

The next link (4) shows relationship between the highest acceptable ship's depth (draught) (T_c) and technical depth (H_t):

$$H_t = T_c + R_t \quad (4)$$

where: T_C - is the highest ship's depth (draught) on even keel, [m]; R_t - total under keel clearance depth, which enables the vessel to float in the place where sea structure is located, even for the unfavourable hydro meteorological conditions [m].

Total under keel clearance, which is included in formulae (3) and (4), cannot be smaller than minimum of total reserve of water depth (R_t^{min}), described in meters by the following formula:

$$R_t^{min} \geq \eta \odot T_c \quad (5)$$

where: T_C - is maximum acceptable ship's depth (draught) on even keel, [m]; η - not dimensional coefficient, dependent on the type of area or fairway, described in Table 1.

Table 1. Values of not dimensional coefficient, with respect to type of area or fairway. Dz.U.98.101.645.

No	Type of area or fairway	η
1	Harbour areas covered from waves	0,05
2	Interior fairways, ship's rotary area, basin and port channel in which floating units use tugs	0,05
3	Exterior approaching lane from sea to port and marina	0,10
4	Open sea areas	0,15

In this case the minimum value of total reserve of water depth R_t^{min} established for different type of ships (unit) is described in Table 2.

Table 2. Minimum value of total reserve of water depth R_t^{min} established for different type of ships (units) in shallow water in Stolpe gutter.

No	Type of units (L,B,T, CB)	Tc [m]	R_t^{min} [m]
1.	VLCC (350m; 60m; 15m; 0,85)	15,0	2,25
2.	Container ship (250m; 32m; 12m; 0,70)	12,0	1,80
3.	Passenger's ferry (140m; 16m; 7,5m; 0,65)	7,50	1,13
4.	Fishing boat (40m; 8,5m; 4m; 0,63)	4,00	0,60

Assuming actual navigational depth area in average navigational conditions H_{na} =17,00m and ship's particulars of the biggest units which could enter to the Baltic Sea through the Danish Strait (Great Belt, H_{na} =17,00m, T=15,0m) minimum of under keel clearance should be not less than 2,25 m. In this case criterion of safety navigational depth cannot be used, because: H_t= 17,0m-2,25m= 14,75m and is smaller than maximum unit's draught T_a=15,0m.

In extreme conditions, such as huge wave, situation can be worse, as one should reduce navigational depth of the area to H_{n1}=16,50m and increase the maximum of ship's draught T_a due to wave effect: yawing, pitching, rolling etc. For example mere list of about ±5° of the rolling vessel whose beam

B=60m and departure draught T_{a0}=15,0 m, can increase maximum of ship's draught for 2,56m to T_{a1}=17,56m.

The increase of the ship's draught, which is caused by the list, can be depicted by means of the following formula:

$$\Delta T_7^{II} = T_M[\cos(\theta) - 1] + \frac{1}{2} \cdot B \cdot \sin(\theta) \qquad (6)$$

where: ΔT^{II}_7 - change of draught in case of ship's list [m]; T_M - average ship's draught [m]; θ - angle of ship's list [°]; B - ship's beam [m].

The increase in the ship's draught, which is caused by yawing, can be calculated by means of the formula:

$$\Delta T_7^I = \frac{1}{2} \cdot L_w \cdot tg(\Psi) \approx \frac{1}{2} \cdot L_{pp} \cdot tg(\Psi) \qquad (7)$$

where: ΔT^I_7 - change of draught in case of yawing [m]; L_W - ship's length on sea surface [m]; L_{pp} - ship's length between perpendiculars [m]; Ψ - angle of trim due to yawing [°].

In bad weather conditions one can observe heaving, yawing, pitching, rolling, swaying and surging due to huge influence of sea wave to ship's hull. In practice in order to define maximum ship's draught one uses only bigger value of corrections ΔT^I_7 or ΔT^{II}_7 defined by the formulas (6) and (7).

For this reason, on the basis of formulas (4) and (5) one can define simplified formula for maximum acceptable ship's draught Tc, which could indicate safe navigation in area with technical depth H_t:

$$T_c \le \frac{H_t}{1+\eta} \qquad (8)$$

where: T_C - is maximum acceptable ship's draught, on the even keel, [m]; η - not dimensional coefficient, dependent on type of area or fairway, described in table 1; $H_{t.}$ - technical depth, [m].

According to formula (8) in order to navigate safely near the Stolpe gutter (open area) the highest acceptable ship's draught T_c, should not be higher than T_{c1}=14,78m for H_t=17,0m (average conditions) and T_{c1}=14,35m for H_t=16,5m (rough sea).

When planning separation zone area on the south of the Stolpe Bank, minimum of water depth read from navigational chart (chart 252, INT1219) is 18 m estimated with reference to chart datum with respect to MSL (Mean Sea Level). According to the formula (2) this depth should be treated as acceptable depth of area (H_{dop}) with error for so-called acceptable unevenness of sea bottom. For open sea areas, such as Stolpe gutter, in which sea bed isn't durably strengthened, acceptable sea depth H_{dop} could be described by formula:

$$H_{dop.} = H_t + R_p \qquad (9)$$

where: H_{dop} - acceptable draught of sea structures, [m]; H_t - technical depth of sea structures, described with accordance to the rules mentioned above; R_p - reserve for acceptable unevenness of sea bottom in the area, where sea bed isn't durably strengthen, during the whole period when the sea structure is used.

According to the Decree of Minister of Transport and Maritime Economy value of reserve for acceptable unevenness of sea bottom shouldn't be less than R_p=1,0 m. For the sea structures without durable strengthening and for sea structures located in the following areas:

- on bend and outlet of river and strait to the sea,
- on narrowing river bed,
- with huge wave or significant stream of water near the sea bed, the value of reserve R_p cannot be less than 1,5 m.

Hence, with respect to the formulae (3), (4) and (6) we assume the value of navigational depth of area as H_{n1}=17,0m in normal navigational conditions (18,0m–1,0m=17,0m), and H_{n2}=16,5m (18,0m–1,5m=17,0m) for extreme conditions, i.e. huge wave or strong stream of water near sea bottom.

The research about the real value of navigational depth of the given area is confirmed by the opinion from employers of Maritime Office in Gdynia. The depth of the discussed area depth was controlled by employers of Maritime Office in Gdynia in 2007. They confirmed the localization of the navigational dangers such as rock, sand, wrecks within shallow water on the depth from 17,00 m with respect to actual sea level, the possible inaccuracy being ±0,50m.

Polish sea areas are treated as sea without tides. Water depth is measured on these areas from chart datum, which is defined from average sea level SW (±0,50m). According to long term observation made by Institute of Meteorology and Water Management in Gdynia in the area which we discuss one can expect significant changes of sea level in the aspect of mean sea level (MSL=500). Those changes cross the value ΔHn=Rp=±1m. They are especially visible in autumn–winter term. For example in 2001 difference between extreme values of high sea water level (HHW) and low water (LLW) on the Polish coast varied from 146 cm in Ustka, 150cm in Łeba to 206 cm in Świnoujście (Institute of Meteorology and Water Management, 2004).

In long-term scale (between 1971-2000) one can observe high water (HW) 130 higher than mean sea level (MSL) in Ustka and 140cm in Łeba and low water (LW) about 54 cm lower than mean sea level (MSL) in Łeba and 60 cm in Ustka.

Total reserve of ship's draught R_t should be analyzed for every vessel navigating in this area. In every case total reserve of ship's draught R_t should not be less than minimum of total reserve of sea depth R_t^{min} defined earlier. Additionally, the reserve of ship's draught R_t should enable navigation and manoeuvring of a ship in the worst hydro-meteorological conditions, possible in this area.

According to the Decree of Minister of Transport and Maritime Economy from 1998 in order to establish the total reserve draught R_t one must consider the total of following components:

Reserve R_1 for inaccurate hydrographical measurement of water depth.

The value of reserve R_1 depends on the area's depth. Depth in navigational charts is presented with accordance to the defined standard of accuracy. International Hydrographic Organization IHO (Joseph, 1991) accepted the following standard (P= 95,4 %) in 1987:

0,52 m for H= (0 ÷30)m;

1,72 % h for H> 30m.

Since January 1991 in the British Admiralty charts (BA) the accuracy of data has been defined with measurement depth error (P= 95,4%) and has the value:

$$2 \cdot \delta_H = \sqrt{0{,}5^2 + (0{,}009 \cdot H)^2} \quad [\text{m}] \tag{10}$$

Hence, the error equals about 0,53m for the area of Stolpe gutter whose average depth is about 20m.

Charts published by local maritime administration (other than British) may have different standard accuracy due to local legal regulations. According to S.Gucma and I.Jagniszczak (1997) navigational reserve R_1 for area whose depth is 20m should be about 0,20m in practice.

Table 3. Reserve R_1 for hydrographical measurement error of water depth (sound error). Gucma, Jagniszczak, 1997.

	Area's Depth H [m]	Water Reserve R1 [m]
1.	do 4	0.10
2.	4-10	1015
3.	10-20	0.20
4.	20-100	0.01H

We do not make mistake if we accept for further research 0.35m as average value of reserve R_1 for hydrographical error of measurement of water depth.

Navigational reserve R_2, is minimum of under keel clearance units, which is sufficient to floating, and depends on type of sea bed or method of sea bed fortification near sea structure

Navigation reserve R_2 results from the fact that we do not know the exact sea depth, sea bed clearance, interpolation error between sounding or result of the hull contact with sea bed. In practice, the value of reserve R_2 ranges from 1,00m to 1,50m for not coastal areas, which are exposed to huge wave and currents near the sandy and rocky sea bed with low density of sounding. In the area of Stolpe gutter sea bed is tough and sandy with many rocks and stones.

Reserve R_3 for low level of sea waters, defined on the basis of: a) curve of total time of stay water level, with respect to the measurements on sea water level patch, which are based on long term research, when the water level remained on the higher level during about 99% of time during research period or

b) differences between sea level SW and sea level SNW,

Navigational reserve R_3 is the result of observation of difference of sea level with reference to chart datum which is caused by specific hydro-meteorological conditions. Long lasting and strong wind which blows in land direction as well as flooding on the river increase the water level. Strong winds blowing from the land and low water state on the river decrease this level.

In practice, navigational reserve R_3 in such areas as in the Stolpe gutter without tides on South Baltic Sea, navigational reserve R_3 can reach 0,30m. Anyway, we must remember that long term observations of water state in this area carried out by measurement stations in Ustka and Łeba confirm higher, that is about 0,60m reduction of water state from mean sea level (MSL). Those observations are also kept the whole year (Institute of Meteorology and Water Management, 2004). In extreme weather (hydro-meteorological) conditions value of navigational reserve R_3 should be increased to 0,60m.

Reserve R_4 for shallow water in the area, which enables full exploitation of area in period between dredging and bottom cleaning operation

In the area which we discuss there is no dredging or bottom cleaning operation. Sea Bed is formed naturally, so we can omit the value of navigational reserve R_4 for future considerations.

Reserve R_5 for wave and swell,

In order to estimate value of parameter R_5 concerning sea wave we use the methods which are approximated, and show us only outline of the real situation.

In order to describe difference of draught ΔT_5 for sluggish vessel on wave we often use empirical formula prepared by Dand and Ferguson (1973) and recommended by Nowicki (1999) - Method 1:

$$\Delta T_5 = k \cdot h_f \ [m] \tag{11}$$

where: k - coefficient depending on the relation between beam and length of ship with respect to length and course angle of the wave, the coefficient ranges from 0,33 to 0,66; h_f - height of wave [m].

Coefficient k depends on relation between beam and length of ship with respect to length and course angle of wave. In case of the ship, which is situated board to wave and whose beam constitutes less than half length of wave, the coefficient is the biggest one. For huge vessels in relation to size of wave this coefficient has minimum value. The following rules apply to the huge vessels:

- Sea wave direction is equal to the ship's heading line (q ≈ 000° or 180°) and length of the vessel is bigger than length of the wave ($L \geq \lambda$);
- Sea wave direction is perpendicular to ship's heading line (q ≈ 090°) and ship's width is bigger than half length of sea wave ($B \geq 0,5\lambda$);

where: λ - wave length [m]; B - ship's beam [m]; L - ship's length [m].

When the vessel is on the way the value of reserve must be increased (Jurdzinski, 1998) with respect to the vessel speed:

- 12,5 % when speed $v \leq 10$ knots;
- 25,0% when speed $v > 10$ knots.

The next method which enables us to count vertical parameter of navigational reserve for the vessel on the wave is the method of L.E. van Houten (Nowicki, 1999) - Method 2. However, this method is limited to the vessels whose size ranges from 15000DWT to 65000 DWT. In case of vessels smaller than 15 000 DWT this method can be misleading and inaccurate due to mistakes concerning amplitude of waves for vessels on the way.

From the point of view of safety of navigation we could consider the additional element with respect to formula (11). The case of navigating obliquely to wave direction is presented in table as the value of total difference under keel clearance on the bow and aft, amidships and height of bow and aft part of the vessel. Parameter R_5 is: either $\delta_p(\Delta Z)_5$, that is the error which results from defining the change, or change in draught $\Delta Z_5 = \Delta T_5$ increased by error

$$\delta_p(\Delta Z)_5 : R_5 = \Delta T_5 + \delta_p(\Delta Z)_5 \ [m] \tag{12}$$

In real conditions vessel on the wave makes very complicated movement, which is combination of simple movement in one direction. Usually one type of movement results in another. These two types mutually interact, as it is in the case of scenting which is in fact combination of heaving and rolling. In case of ship's movement on the wave the prognosis of changes in complex movement is based on usual accumulation of results. On the other side, additional increase of safety contour, especially in very bad weather condition, has positive influence on reducing risk of navigation, and increasing safety of navigation. For example, according to "Report of Working Group IV of the Pianc International Commission for The Reception of Large Ships", for traffic lane exposed to huge swelling minimum of the under keel clearance must constitute 15% of maximum ship's draught (Method 3).

Similar solution is described by Gucma and Jagniszczak, (1997), in which minimum reserve for wave in the open sea area on the straightforward traffic lane without dredgering, with sea wave height up to 3,0m is assumed as 40% of maximum ship's draught (Method 4).

Table 4. Numerical value of coefficient m dependent on the ship's particulars (v, B, L, C_B) and wave parameters (λ, h_f , q).

m	For the wave from bow or aft (q ≈ 000° or 180°)	For the wave from board (q ≈ 090°)
0,500	When: $v = 0$, and $L > \lambda$	When: $v = 0$, and $B > \lambda$
1,000	When: $v \geq 10$w, and $L \geq \lambda$	When: $v \geq 10$w, and $B \geq 0,5 \cdot \lambda$
1,125	When: $v < 10$w, and $L < 0,5 \cdot \lambda$	When: $v < 10$w, and $B < 0,5 \cdot \lambda$
≥1,250	When: $v \geq 10$w, and $L < 0,5 \cdot \lambda$	When: $v \geq 10$w, and $B < 0,5 \cdot \lambda$

Rutkowski (2000) gives us another solution for reserve R_5 (Method 5):

$$R_5 = 0,66 \cdot m \cdot h_f \tag{13}$$

where: R_5 - reserve for wave [m]; h_f - height wave [m]; m - numeral coefficient (factor), dependent on ship's particulars (v, B, L, C_B) and parameters of wave (λ, h_f, q).

Exemplary values of navigational depth reserve R_5 for wave estimated by means of the above methods for different type of ships on shallow water in Stolpe gutter are presented in Table 5. The calculation considers various methods for the vehicles proceeding with 10 knots speed along traffic lane straight to wave with height 3,0m and length 150m in the open sea area, exposed to sea waves and current, with no dredging requirement.

Table 5. Hypothetical value of navigation depth reserve R_5 for wave calculated with the above described methods for different type of ships for shallow water in Stolpe gutter. In calculation we assume that every unit sails along traffic lane with 10 knots speed straight to wave whose height is 3,0m and length 150m.

Type of Vessel (L; B; T; C_B)	Value of reserve R_5 [m] for wave calculated with different methods 1	2	3	4	5
VLCC (350m; 60m; 15m; 0,85)	1,00	3,15	2,25	6,00	1,98
Container ship (250m; 32m; 12m; 0,70)	1,50	2,52	1,80	4,80	1,98
Passenger ferry (140m; 16m; 7,5m; 0,65)	2,00	1,58	1,13	3,00	2,23
Fishing boat (40m; 8,5m; 4m; 0,63)	2,00	0,84	0,60	1,60	2,48

Due to big discrepancy of results we use the data from method 5 for further research. This method assumes that the reserve R_5 depends on the wave parameters and gives us result similar to methods 1,3 and 4. Methods 2 and 4 are very general and do not include interaction between ship's particulars and wave's parameters.

Long term observation of waves near Polish coast in area of Stolpe gutter in south part of Baltic Sea confirms that period with high frequency of storm and gale appears in winter time between November and February. In this period one can observe sea waves with height of about 3m. Sea appears to be calm in summer time from May to September. Maximum of wind speed in the given area is up to 32m/s. The maximum values of wave height are observed in winter time and they are up to 7m in western part of Polish coast and up to 8m in eastern part of Polish coast. Maximum waves are observed during the strong and long-lasting winds from W, N and NE. The maximum waves amount to 160m of length in eastern coast and about 120m length in western coast. Predominantly the frequent waves are up to 3,0m high and 40m long. More than 90,85% of all waves in the area near the eastern coast and about 96,53% of all waves in area near the western coast are the waves whose height $H_{5\%}$ equals or is less than 1,5 m. Maximum sea waves whose heights $H_{5\%}$ reach more than 3,00m are hardly ever observed. The probability that we can expect extreme weather condition ($H_{5\%}$ >3,00m) in researched area is less than 0,3% in eastern coast and less than 0,01% in western coast.

Table 6. The frequency of wave height in % on the South Baltic Sea. Paszkiewicz, 1989.

Wave's height $H_{5\%}$ [m]	Eastern part of coast	Western part of coast
$H_{5\%}$ < 1,0 m	75,26	88,64
1,0m – 1,5m	15,59	7,89
1,5m – 3,0m	8,85	3,46
$H_{5\%}$ > 3,0 m	0,30	0,01

Reserve R_6 for the increasing ship draught when manoeuvring in breaking waters near the Polish coast on Baltic Sea established by means of the formula:

$$R_6 = 0{,}025 \times T_c \tag{14}$$

where: T_C - the maximum draught of the vessel loaded on even keen, [m].

The reserve R_6 applies to all vessels proceeding to the Baltic Sea from the North Sea. This reserve concerns the increase off the ship's draught when manoeuvring in water near Polish coast. The density of sea water in Baltic sea equals from γ_1= 1,00525 g/cm^3 to γ_2= 1,00250 g/cm^3 what with relation to density of sea water in the North Sea (γ_3= 1,025 g/cm^3) can increase the draught of each vessel which enters the Baltic Sea from the North Sea.

For the example the value of reserve R_6 estimated by means of the formula (14) for different type of the vessel are presented in Table 7.

Table 7. The value of reserve R_6 for increasing ship's draught in breaking sea water near Polish coast on the Baltic Sea established by means of the formula 14 for different types of vessel.

No.	Type of ship (L; B; T; C_B)	R_6 [m]
1.	VLCC (350m; 60m; 15m; 0,85)	0,38
2.	Container Ship (250m;32m;12m;0,70)	0,30
3.	Passenger Ferry (140m;16m;7,5m;0,65)	0,19
4.	Fishing Boat (40m;B=8,5m;4m; 0,63)	0,10

Reserve R_7 , depicted in meters, for trim (pitch) up to 2° and list (roll) up to 5° established for all floating units by means of the following formulas:

1 reserve for trim due to pitch up to 2°:

$$R^{I}_{7} = 0{,}0016 \odot L_c \tag{15}$$

where: L_c– ship's overall length, [m].

2 reserve for list (roll) up to 5°:

$$R^{II}_{7} = 0{,}008 \odot B_c \tag{16}$$

where: B_c – maximum ship's beam, [m].

In order to examine the depth of water we assume that the biggest value of reserve R_7 is bigger than two values a) and b) but not smaller than R_7=0,15 m.

The value of reserve R_7 can be estimated also by means of the formulas (6) and (7).

Reserve R_8 for trim to aft for all vessels proceeding with speed over ground when dredging channels, approaching fairways, proceeding in interior fairways and channels, basin and port waters

In this case as the area which we are discussing is the open sea with natural sea bottom the value of reserve R_8 can be ignored.

Reserve R_9 for ship's squat when proceeding in restricted sea area across the shallow water

When studying professional publications there are many methods for estimating reserve R_9 for ship's squat when proceeding in restricted sea area across the shallow water. In practice we can use only one of the following methods:

1 C.B.Barrass precise method for estimating ship's squat in sea area (Method 1) (with limitation: $0{,}5 \le C_B \le 0{,}9$; $0 \le t/L \le 0{,}005$; $1{,}1 \le h/T \le 1{,}4$):

$$R_9 = \frac{1}{30} \cdot C_B \cdot \left(\frac{BT}{bH - BT} \right)^{\frac{2}{3}} \cdot v^{2,08} \text{ [m]} \qquad (17)$$

2 C.B.Barrass simplified method (Method 2) for estimating ship's squat in:

– shallow water (with limitation: $1{,}1 \le h/T \le 1{,}2$):

$$R_9 = 0{,}01 \cdot C_B \cdot v^2 \text{ [m]} \qquad (18)$$

– narrow channel (with limitation: $0{,}06 \le \frac{B \cdot T}{b \cdot h} \le 0{,}3$):

$$R_9 = 0{,}02 \cdot C_B \cdot v^2 \text{ [m]} \qquad (19)$$

3 N.E.Eryuzlu and R.Hausser method for estimating ship's squat in sea area (Method 3)

$$R_9 = 0{,}113 \cdot B \cdot \left(\frac{h}{T} \right)^{-0,27} \cdot \left(\frac{0{,}514 \cdot v}{\sqrt{g \cdot H}} \right)^{1,8} \text{ [m]} \qquad (20)$$

(with limitation: $C_B \ge 0{,}7$; $1{,}08 \le \frac{h}{T} \le 2{,}78$)

4 G.I.Soukhomela and V.M.Zass method for estimating ship's squat in shallow unrestricted water (Method 4):

$$R_9 = l \cdot \left[0{,}049047542 \cdot v^2 \cdot \sqrt{\frac{T}{H}} \cdot \left(\frac{L}{B} \right)^{-1,11} \right] \text{ [m]} \qquad (21)$$

(with limitation: $3{,}5 \le \frac{L}{B} \le 9$)

where: B, L, T_{max}, C_B - ship's particulars: beam B[m], length L[m], maximum draught T[m], block coefficient C_B [-]; v- speed over ground in knots, [kn]; b,H,h_f- area characteristics: depth H[m], wide b [m], wave's height (swell) [m]; l- numeral coefficient (factor) ($1{,}1 \le l \le 1{,}5$) dependent on ship's length L and ship's beam B, [-].

Ship's squat (reserve R_9), estimated for vessel proceeding with 5knots speed and 10 knots speed in shallow water whose depth Hn=17,0m and minimum width b=1000m is presented in Table 9.

Table 8. Relation between numeral coefficient (factor) l from formula (21), ship's length L and ship's beam B.

Value of numeral coefficient (factor) l dependent on ship's length L and ship's beam B		
$7 \le \frac{L}{B} \le 9$	$5 \le \frac{L}{B} < 7$	$3{,}5 \le \frac{L}{B} < 5$
1,10	*1,25*	*1,50*

Table 9. The value of ship's squat (reserve R_9) estimated by means of formula 17 to 21 (Method 1,2,3 and 4) for different types of vessel proceeding with 5kn and 10 kn speed in shallow water with depth Hn=17,0m and wide b=1000m.

Method	Method 1		Method 2		Method 2		Method 4	
Speed [kn]	5	10	5	10	5	10	5	10
Ship's type	The value of ship's squat (reserve R_9) [m]							
VLCC	0,12	0,50	0,21	0,85	0,36	1,25	0,20	0,81
Container	0,05	0,23			0,18	0,63	0,12	0,46
Passenger							0,08	0,32
Fishing Boat							0,16	0,64

To sum up, navigational reserve of depth R_t described as a sum off all parts from R_1 to R_9 estimated for shallow water in Stolpe gutter should be dependent on size and type of a ship and actual weather condition; in Stolpe area the value should range from 4,61m to 5,57m.

Table 10. Maximum ship's draught Tc in shallow water estimated by means of formula (4) and navigational reserve of depth Rt as a sum of all parts from R_1 to R_9 in normal and bad weather condition (h_f=3m, λ=150m, H_N=18,00m) estimated for different type of vessel proceeding with speed 10 kn and 5 kn.

Good weather condition, Ship's speed 10 knots							
Ship's type	$R_{1\div4}$ [m]	R_5 [m]	R_6 [m]	R_7 [m]	$R_{8\div9}$ [m]	R_t [m]	Tc [m]
VLCC	1,75	1,98	0,38	0,56	0,81	5,38	12,62
Container vessel	1,75	1,98	0,30	0,40	0,46	4,79	13,21
Passenger Ferry	1,75	2,23	0,19	0,22	0,32	4,61	13,39
Fishing Boat	1,75	2,48	0,10	0,15	0,64	5,02	12,98
Bad weather condition, Ship's speed 5 knots							
Ship's type	$R_{1\div4}$ [m]	R_5 [m]	R_6 [m]	R_7 [m]	$R_{8\div9}$ [m]	R_t [m]	Tc [m]
VLCC	2,45	1,98	0,38	0,56	0,20	5,57	12,43
Container vessel	2,45	1,98	0,30	0,40	0,12	5,25	12,75
Passenger Ferry	2,45	2,23	0,19	0,22	0,08	5,17	12,83
Fishing Boat	2,45	2,48	0,10	0,15	0,16	5,34	12,66

In this case the highest acceptable ship's draught T_c (see Table 10), which could guarantee safe navigation near the Stolpe gutter with maximum swell and wave's height about h_f=3m and length about λ=150m, should not exceed the value T_{c1}=12,43m in bad weather condition for VLCC when proceeding with 5 knots speed and T_{c2}=13,39m in normal weather condition for Passenger Ferry when proceeding with 10 knots speed. Otherwise, the Decree of Minister of Transport and Maritime Economy will be not accepted.

What is more, in extreme weather conditions, such as winter time, wave (swell) which equals about h_f=5m and whose length is about λ=160m) one can expect higher value of navigational reserve of depth Rt, that is to say about 1,32m.

Probability that we can expect extreme weather condition ($H_{5\%}$ >3,00m) in this area, i.e. S of Stolpe Bank is less than 0,3% (See Tables 6 and 11). Extreme weather conditions can be expected only during winter from November to February with strong and long-lasting winds from W and NE.

Table 11. Maximum ship's draught Tc in shallow water estimated by means of a sum of all parts of the navigational reserve of depth Rt from R_1 to R_9 in extreme weather conditions (h_f=5m, λ=160m, H_N=18,00m.

Extreme weather conditions. Ship's speed 5 knots							
Ship's type	$R_{1\div4}$ [m]	R_5 [m]	R_6 [m]	R_7 [m]	$R_{8\div9}$ [m]	R_t [m]	Tc [m]
VLCC	2,45	3,30	0,38	0,56	0,20	6,89	11,11
Container vessel	2,45	3,30	0,30	0,40	0,12	6,57	11,43
Passenger Ferry	2,45	3,71	0,19	0,22	0,08	6,65	11,35
Fishing Boat	2,45	4,13	0,10	0,15	0,16	6,99	11,01

3 SIMPLIFIED METHOD FOR ESTIMATING MAXIMUM SHIP'S DRAUGHT WHEN NAVIGATING IN SHALLOW WATER BY MEANS OF THE MODEL OF THE SHIP'S DOMAIN.

In this chapter we present methods that can be used for estimating maximum ship draught of a vessel. One must take into consideration safety of navigation, i.e. navigational risk in the restricted sea areas by means of the model of the ship's domain.

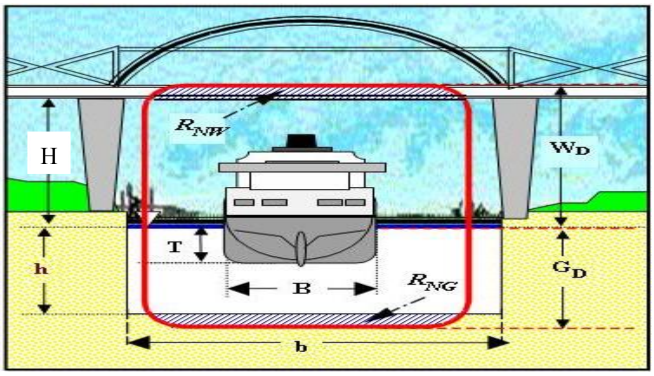

Figure 1. Presentation of navigational risk for ship passing shallow water and bridge.

According to the ship's domain (Rutkowski, 2002) definition, every ship will be safe (in navigational meaning) as long as she is the exclusive object which can generate danger within her domain.

With reference to vertical plane of the three dimensional co-ordinates established down from the central point of the local ship's reference system we can affirm unambiguously, that every ship will remain safe as long the value of G_D is smaller than the real value of the sea depth *H*. Therefore, component R_{NG} of R_N can be referred to as vertical component of navigational risk that concerns keeping under keel clearance, or risk concerning under keel clearance. The component mentioned above can be depicted by means of the following formulas:

$$R_{NG} = \begin{cases} 0 & \text{when} \quad H \geq G_D \\ 0 \div 1 & \text{when} \quad T_{\max} < H \leq G_D \\ 1 & \text{when} \quad H \leq T_{\max} \end{cases} \quad [-] \qquad (22)$$

According to the formula (22), assumption $H \geq G_D$ can be defined as the guarantee of the safe shipping (navigation) with reference to all underwater objects or obstructions immersed on the depth smaller than *H*. If sea depth *H* is smaller or equal to the ship's draught *T,* that is $H \leq T_{\max}$, according to the formula (22) sea passage can be unfeasible[2] or highly risky. In that situation the value of navigational risk R_{NG} will equal one, and in all probability it will signify unquestionable (100%) risk of collision with some underwater objects immersed on the depth less than *H*. Furthermore, we can also say that the value of navigational risk R_{NG} for the sea depth *h* limited between T_{max} and G_D ($T_{max}<H\leq G_D$) will be limited between zero and one ($R_{NG} \in[0,1]$) (see formula (22) middle line). General formula, which can be used to estimate navigational risk R_{NG} , depending on *H* factor from the range ($T_{\max} < H \leq G_D$), is presented below:

$$R_{NG} = \frac{G_D - H}{G_D - T_{\max}} \quad [-] \qquad (23)$$

Additionally when we not only accept Barrass method, recommended by shipyards and ship's owners for estimating ship's squat, but also take into consideration ship's particulars, Pilot Cards (manoeuvre characteristic) and other information (meteorological, navigational warnings and etc.) freely available during normal sea passage, simple formula for depth of the ship's domain according to Rutkowski (2002) can be presented as follows:

– Using precisely Barrass method for estimating ship's squat: (with limitation: 0,5≤ C_B ≤ 0,9; 0 ≤ t/L ≤ 0,005; 1,1 ≤ h/T ≤ 1,4):

$$G_D = n \cdot T_{\max} + 0{,}66 \cdot m \cdot h_f + k \cdot \left(\frac{1}{30} \cdot C_B \cdot \left(\frac{BT}{bh - BT} \right)^{\frac{2}{3}} \cdot v_d^{2,08} \right) \ [\text{m}] \qquad (24)$$

[2] In our analyses we exclude the situation, when the ship can change her draught due to for example deballasting operation.

– Using simplified Barrass method for estimating ship's squat in shallow water (with limitation: $1{,}1 \le h/T \le 1{,}2$):

$$G_D = n \cdot T_{\max} + 0{,}66 \cdot m \cdot h_f + k \cdot \left(0{,}01 \cdot C_B . v^2\right) \text{ [m]} \quad (25)$$

where: G_D - depth of ship's domain calculated vertically down from water line (line showing actual ship's draft) [m]; B,L,T_{max}, C_B - ship's particulars: beam B[m], length L[m], maximum draught T[m], block coefficient C_B [-]; v - speed over ground, [kn]; b, H, h_f - area characteristics: depth H[m], wide b [m], wave's height (swell) [m]; n - numeral coefficient (factor) ($1{,}1 \le n \le 1{,}3$) dependent on type of sea areas and sea bottoms, which determines ship's static vertical navigational reserve. In this paper n = 1,2 (see table 17); m - numeral coefficient (factor) ($0{,}5 \le m \le 1{,}5$) dependent on ship's particulars: v, B, L, C_B and waves characteristics: λ, h_f and q. See table 13; k- numeral coefficient (factor) ($1{,}0 \le k \le 2{,}0$) dependent on ship's particulars, type of sea areas and navigational situation (overtaking, crossing, sailing in ice, navigating in restricted sea areas or shallow waters and etc.). The fact that in normal sea passage we cannot exactly estimate all ship's or area's parameters, such as for example ship's squat, depth etc. results in this factor. In this paper k = 1,0.

Table 12. Numeral coefficient (factor) dependent on type of sea areas and sea bottoms, which determines ship's static vertical navigational reserve.

n	Type of the sea area	Type of the sea bottom
1,1	Port area, internal and inshore channels	Mud
1,15	Road, Approaching channels to the port, inshore area	Sand
>1,2	Open sea	Rock, Stone

Additionally when we accept that navigational risk R_{NG} will equal zero when G_D=H_N then after transformation of the formula (24) or (25) comparatively to unknown T, we can estimate maximum ship's draught in restricted sea area. As an example using simplified formula (25) with limitation: $1{,}1 \le h/T \le 1{,}2$, the maximum ship's draught in shallow water can be presented as below:

$$T_{\max} = \frac{H_N - 0{,}66 \cdot m \cdot h_f - k \cdot \left(0{,}01 \cdot C_B . v^2\right)}{n} \text{ [m]} \quad (26)$$

where: T_{max} - maximum draught of the vessel T [m]; H_N -navigational depth of the sea H [m]; C_B - block coefficient C_B [-]; v - speed over ground, [kn]; h_f - wave's height (swell) [m]; n - numeral coefficient (factor) ($1{,}1 \le n \le 1{,}3$) dependent on type of sea areas and sea bottoms, which determines ship's static vertical navigational reserve. In this paper n = 1,2 (see table 12); m - numeral coefficient (factor) ($0{,}5 \le m \le 1{,}5$) dependent on ship's particulars: v, B, L, C_B and waves characteristics: λ, h_f and q. See table 13; k - numeral coefficient (factor) ($1{,}0 \le k \le 2{,}0$) dependent on ship's particulars, type of sea areas and navigational situation (overtaking, crossing, sailing in ice, navigating in restricted sea areas or shallow waters and etc.). The fact that in normal sea passage we cannot exactly estimate all ship's or area's parameters, such as for example ship's squat, depth etc. results in this factor. In this paper k = 1,0.

Table 13. Numeral coefficient (factor) dependent on ship's particulars: v,B,L,C_B and waves characteristics: λ,h_f and q.

m	Sea wave direction equal with ship's heading line (waves from ahead or astern of the vessel q ≈ 000° or 180°)	Sea wave direction perpendicular to ship's heading (waves from the port or starboard beam of the vessel, q ≈ 090°)
0,500	When: $v = 0$ and $L > \lambda$	When: $v = 0$ and $B > 0{,}5 \cdot \lambda$
1,000	When: $v \ge 10$ kn and $L > \lambda$	When: $v \ge 10$ w and $B > 0{,}5 \cdot \lambda$
1,125	When: $v < 10$ kn and $L < 0{,}5 \cdot \lambda$	When: $v < 10$w and $B < 0{,}5 \cdot \lambda$
≥1,25 0	When: $v \ge 10$ kn and $L < 0{,}5 \cdot \lambda$	When: $v \ge 10$w and $B < 0{,}5 \cdot \lambda$

Table 14. Maximum ship's draught in shallow water estimated by means of formulae (26) for average (h_f=3m, λ=150m, Δh= ±0,30 m, H_{N1}=17,70m) and extreme (h_f=5m, λ=160m, Δh= ±0,60 m, H_{N2}=17,40m) weather condition, with limitation: $1{,}1 \le h/T \le 1{,}2$, for different ship's type (her block coefficient C_B) and different ship's speed v. (n=1,20; m=1 and k=1,0).

Speed	4 kn		6 kn		8 kn	
C_B	*Average*	*Extreme*	*Average*	*Extreme*	*Average*	*Extreme*
0,5	13,03	11,68	12,95	11,60	12,83	11,48
0,6	13,02	11,67	12,92	11,57	12,78	11,43
0,7	13,01	11,66	12,89	11,54	12,73	11,38
0,8	12,99	11,64	12,86	11,51	12,67	11,32
0,9	12,98	11,63	12,83	11,48	12,62	11,27
1,0	12,97	11,62	12,80	11,45	12,57	11,22
Speed	10 kn		12 kn		14 kn	
C_B	*Average*	*Extreme*	*Average*	*Extreme*	*Average*	*Extreme*
0,5	12,68	11,33	12,50	11,15	12,28	10,93
0,6	12,60	11,25	12,38	11,03	12,12	10,77
0,7	12,52	11,17	12,26	10,91	11,96	10,61
0,8	12,43	11,08	12,14	10,79	11,79	10,44
0,9	12,35	11,00	12,02	10,67	11,63	10,28
1,0	12,27	10,92	11,90	10,55	11,47	10,12

4 CONCLUSIONS

To depict maximum draught of a vessel we can use practical method which incorporates risk of navigational and three-dimensional model of ship's domain.

Maximum ship's draught in shallow water estimated by means of formulae (26), with limitation: $1{,}1 \le h/T \le 1{,}2$, are presented in table 14. Maximum ship's draught is estimated in shallow water (S of Stolpe Bank) with navigational depth no less than H_N=G_D=18,0m estimated with reference to chart datum related to MSL (Mean Sea Level).

Additionally, maximum ship's draught is estimated for average (wave's height (swell) no more than h_f=3m and length no more than λ=150m, maximum fluctuation of the sea water level observed in the area Δh= ±0,30 m, H_{N1}=17,70m) and extreme weather condition (winter time, maximum wave's height (swell) about h_f=5m and length about λ=160m, maximum fluctuation of the sea water level observed in the area Δh= ±0,60 m, H_{N2}=17,40m) for different ship's type (her block coefficient C_B) and different ship's speed. Numeral coefficients (factors): n=1,20 (see table 12), m=1 (see table 13) and k=1,0.

The probability that we can expect extreme weather condition ($H_{5\%}$ >3,00m) in the researched area (S of Stolpe Bank) is less than 0,3% (See table 6). Extreme weather condition can be expected only during the winter from November to February with strong and long-lasting winds from W and NE.

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