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A METHOD FOR BOTTOM SCANTLINGS CALCULATIONS FOR SHIPS PERFORMING ICEBREAKING IN SHALLOW WATERS

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Abstract

In IACS UR I "Polar Class Requirements", which has been introduced in the Rules of all Classification Societies participating in IACS, there is no special consideration for the icebreaking in shallow waters where grounding on the ice can occur.

Areas where we can have this problem are rivers or the Caspian Sea, where the mean depth is about 5 meters. The Caspian Sea is an area rich in oil and in recent years several Offshore Service Vessels have been built for operation in this area, under the supervision of Bureau Veritas.

In this paper we investigate the influence of shallow waters on the bottom scantlings of icebreaking ships. While these ships are performing icebreaking operations in shallow waters, which are defined as less than 2 meters keel clearance, we can have grounding on pieces of ice which are trapped below the ship. Due to this, additional forces are applied to the bottom structure from the ice trapped below.

During normal icebreaking (not aggressive operation) we can assume that the angle of the longitudinal inclination of the ship is not greater than 5 degrees. Taking into account the kinetic energy of the ship at the vertical direction due to grounding on the ice and applying energy and force balance on this direction, we can come to a formula which gives us the force applied to the bottom. In the energy and force balance we take into consideration the variations of the kinetic and dynamic energy of the ship, the work of buoyancy and the work due to vertical ice crushing. We can come to the same formula by applying Lagrange formulation on the vertical movement of the ship.

The above formula has been introduced in Bureau Veritas Rules and can be used for the bottom scantlings calculations of ships performing icebreaking in shallow waters.

1. Introduction

In recent years, at least 7 offshore service vessels for use in the Caspian Sea have been built under the supervision of Bureau Veritas. The Caspian Sea is an area rich in hydrocarbons representing reserves estimated at 3.5% of world oil reserves and 5% of world gas reserves. One example is the Kashagan field operated by Total. Bureau Veritas is also involved in the certification of fixed platforms and drilling platform projects in the Caspian Sea. Exploration and production in this area are steadily increasing, especially in the north of the Sea. Figure 1 shows a map of the Caspian Sea with the main areas of hydrocarbon fields.

Figure 1. Hydrocarbons in the Caspian Sea

Figure 2. Vessel operating in the Caspian Sea

The main features of the Caspian Sea are as follows [1]:

• Average depth: 5.0 m
• Swell: 3.0 m (5% probability)
• Salinity: 10 ‰
• Air temperature: - 30 ° C / - 10 ° C
• Seawater temperature: 0 °C / 0.5 °C
• Typical wind speed: 12 knots
• Strong wind speed > 30 knots
• Annual Ice thickness < 1.0 m

The Caspian Sea is characterized by its shallow depth which causes an increased risk of ice pressure on the ship's bottom.

In this paper, we will initially examine the influence of the shallow water on the ice loads applied on the bottom of a ship while performing icebreaking operation, before seeing how to change the Bureau Veritas Rules formulae in order to calculate the bottom scantlings in this case. We will explain the changes made in the Rules for Bureau Veritas for classification of ice reinforced ships to meet the fact that regulations for ice strengthening do not take into account the special conditions in areas with shallow water like the Caspian Sea.

2. Ship types

Figure 2 shows one of the vessels operating in ice in the Caspian Sea. This type of vessels, specially designed for use in the Caspian Sea, have the following features:

• Independent operations throughout the year in the Northern Caspian
• Icebreaking capability: 0.6 m
• Length: 66.0 m
• Width: 16.4 m
• Depth: 4.4 m
• Draft: 2.5 - 3.0 m
• Engine: 3 azimuth thrusters
• Total power 4.8 MW

It is interesting to note the low draft of these vessels. Ships of this type are in service in the Caspian Sea for 4 to 5 years to the satisfaction of their operators.

3. Rules "Polar Class"

In 2007, IACS has published the UR (Unified Requirements) I1, I2 and I3 [2] defining Polar Classes of ice reinforced ships. These requirements have been taken by Bureau Veritas and introduced in a regulatory note, the NR527 [3] published in 2007. The ice classes are 7 and range from PC7 (lowest, for annual ice) to PC1 (highest, for multi-year ice)

Table 1 provides an overall view of the Polar Classes, providing for each one the ice type suitable for operation. In the Caspian Sea, Polar Classes PC6 or PC7, are largely sufficient.

Polar Class	Ice Description (based on WMO Sea Ice Nomenclature)
PC 1	Year-round operation in all Polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice which may include multi-year ice inclusions.
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

Table 1. Definition of ice Classes

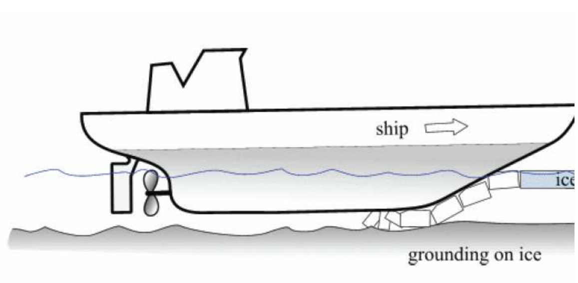

Figure 3. Grounding on trapped ice

4. Definition of the problem

The problem we are going to deal with in this paper, is the operation of ships in areas, where due to shallow water, broken pieces of ice can be trapped below the ship during the ice breaking operation as we can see in Figure 3. In this case we have grounding of the ship on the trapped, below the bottom, piece of ice. The ship during the ice breaking operation may:

1) Slip/climb on the trapped below the ship ice.
   In this case the ship will equilibrate on the ice, above its floating position, where part or all of its kinetic energy will be transformed to potential energy and crushing energy of the ice. The work of buoyancy has also to be considered.

2) Fall on the trapped below the ship ice, as it breaks the ice by climbing on it.

The ice trapped below the ship can has any geometry, or placed in any position or angle.

In this paper we are going to examine case (1). In the case when the ship breaks the ice a big part of its kinetic energy is used for the ice breaking operation.

The kinetic energy of the ship available for breaking the ice below the bottom will be: $E_{KIN} = \frac{1}{2} \cdot M \cdot V_V^2$ where V_V is the vertical component of ship's speed V_{ship}.

For V_{ship} we use the ramming speed according to [3] without taking into account any speed reduction due to the ice breaking. We also assume that there is no reduction in the velocity of the ship due to friction on the ice.

The vertical velocity of the ship is $V_V = V_{ship} \cdot \sin(\varphi)$, where φ is the angle of the longitudinal inclination of the ship due to the grounding (See Figure 4). If φ' is the transverse inclination of the bottom. (See Figure 5) then the velocity normal to ship's bottom will be: $V'_V = V_{ship} \cdot \sin(\varphi) \cdot \cos(\varphi) \cdot \cos(\varphi')$

We assume that the ship as it sails hits the ice in a smooth way. So angle φ takes values up to 10^o. Also we assume that the transverse inclination of the bottom φ' (deadrise angle) is small ($\varphi' < 10^o$) and the ship does not roll. So we can assume that the ship will perform a vertical movement having no trim as we can see in Figure 6. (i.e. it will move vertical to the level of the sea) with speed $V_V = V_{ship} \cdot \sin(\varphi)$.
We do not take into account the consequences of the rotation of the ship. (e.g. kinetic energy due to rotation $E = \frac{1}{2} \cdot I \cdot \omega^2$)

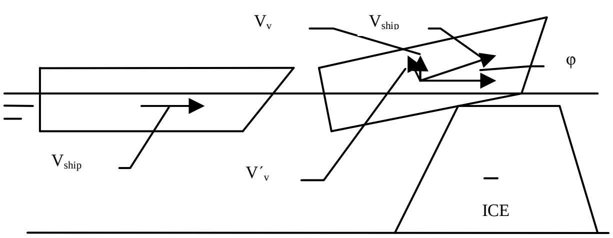

Figure 4. Longitudinal inclination due to grounding

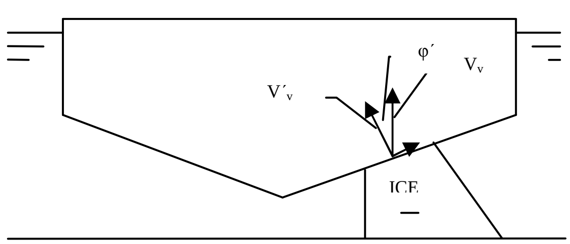

Figure 5. Bottom Transverse inclination

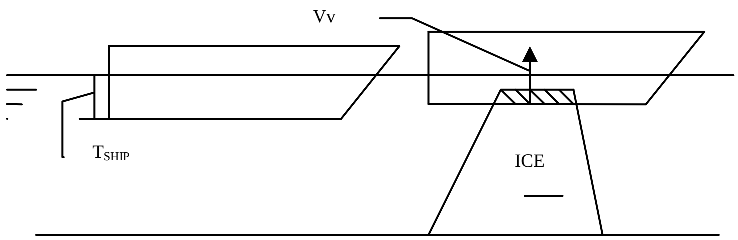

Figure 6. Vertical movement of the ship without longitudinal inclination (trim)

5. Definition of shallow water

We adopt the following definition of shallow water, as given in [6].

Quote

For all ships operating frequently in shallow water the bottom area should be the entire flat of bottom all fore and aft. Operating frequently could be defined as "Navigating in and out of rivers and in shallow waters service or scheduled voyages". Shallow water could be defined as less than 2 meters keel clearance.

Unquote

6. Buoyancy calculation

We consider a cube floating on the water as per Figure 7.

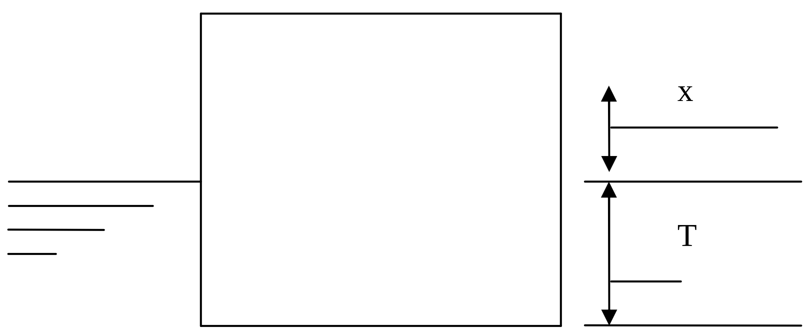

Figure 7. Cube floating on water

T = Draft, L = Length, B = Breadth, F = normal force, x = vertical movement
p = Density of the liquid, C_{WL} = Waterline coefficient at draft T

We consider that the cube moves vertically for a distance (x). (x is positive upwards) The force of buoyancy (FB) and its work (W) for a cube with dimensions L, B, D, draft T, which is moving vertically in a liquid with density ρ for a distance (x), are calculated as follows:

Buoyancy (B)

$FB\,(0) = B_T, \qquad FB\,(x) = B$

$$dFB = -\rho \cdot L \cdot B \cdot dx \Rightarrow \int_{B_T}^{B} dFB = -\int_{0}^{x} \rho \cdot L \cdot B \cdot dx \Rightarrow B = \rho \cdot L \cdot B \cdot (T - x) \qquad (1)$$

Work of Buoyancy (W_B)

$W_B\,(0) = 0, \qquad W_B\,(x) = W_B$

$$dW_B = B \cdot g \cdot d(x/2) \Rightarrow \int_{0}^{W} dW_B = \int_{0}^{x} \rho \cdot L \cdot B \cdot g \cdot (T - x) \cdot d(x/2) = \frac{1}{2} \cdot \rho \cdot L \cdot B \cdot g \cdot x \cdot \left(T - \frac{x}{2}\right) \qquad (2)$$

For a ship we have to use the prismatic coefficient C_B of the volume submerged or immersed. But since this is very difficult to calculate and as we assume that we will have normal ship operation, which means only small variations of draft due to ice grounding, we can instead use the waterline coefficient $C_{W.}$

So we have from Eq.2:

$$W_B = \frac{1}{2} \cdot C_W \cdot \rho \cdot L \cdot B \cdot g \cdot x \cdot \left(T - \frac{x}{2}\right) \Rightarrow W_B = \frac{1}{2} \cdot k \cdot x \cdot \left(T - \frac{x}{2}\right) \qquad (3)$$

Where: $k = C_W \cdot \rho \cdot L \cdot B \cdot g$

7. Ice crushing force

We also assume that there is only crushing failure of the ice. Then the force F_n acting on the ship in relation with the ice and ship's bottom geometry (see Figure 8) is given in [4] by the formulae below:

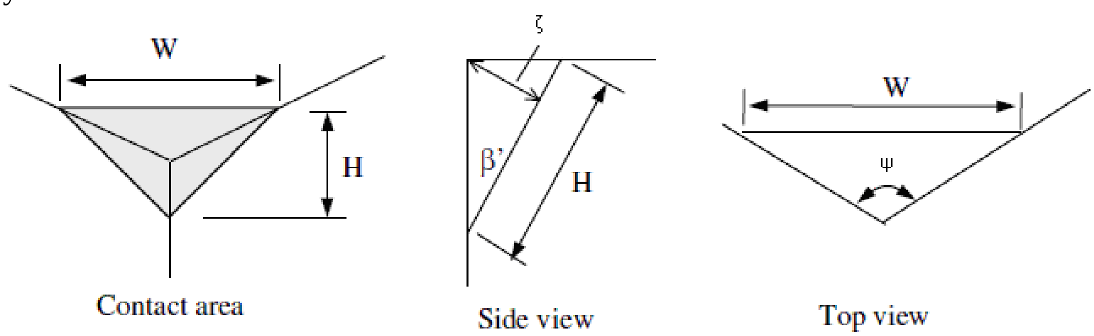

Figure 8. Ship / Ice geometry

$$F_n(\zeta) = Po \cdot ka^{1+ex} \cdot \zeta^{2+2ex} \qquad ka = \frac{\tan(\psi/2)}{\cos^2(\beta') \cdot \sin(\beta')} \qquad ex = -0.1 \qquad (4)$$

8. Mathematical formulation (energy equilibrium)

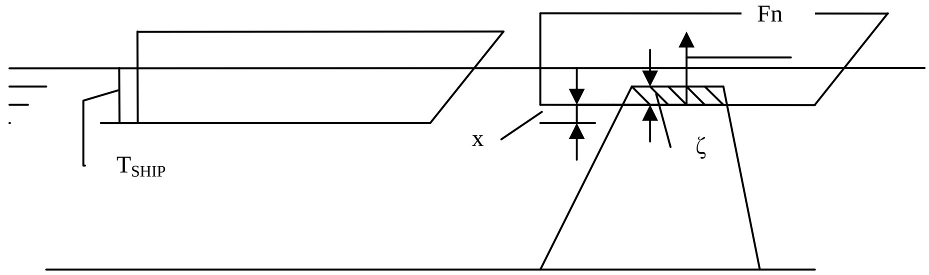

Figure 9. Ship equilibration on the ice

In the case of ship grounding on the ice, we consider as position of zero potential energy the position of equilibrium of the ship on the water before the grounding. As the ship hits the ice with the bottom, it will move vertically for a distance x and it will crush at the same time ice of thickness ζ. (See Figure 9)

The kinetic energy which corresponds to the vertical component V_V of the horizontal ship's speed V_{ship}, is transformed to potential energy (vertical movement of the ship: x) and crushing energy (ice crushing depth: ζ) at the final equilibrium position. Since the ship does not return to its initial floating position, where it was before the grounding, the work of buoyancy should also be considered, as calculated in §6. As the buoyancy helps the vertical movement of the ship the work of buoyancy should be added to the kinetic energy. The crushing energy is calculated by integrating the normal force F_n, as given in Eq. 4, over the penetration depth (ζ)

P_0 = Ice pressure (Mpa)
ζ = normal ice penetration (m)
F_n = normal ice force (MN)
g = 9.81 (m / sec^2)
ρ = density of the sea water (ktn/m^3)
M = mass of the ship (ktn)
$V_V = V_{ship} \cdot \sin(\varphi)$ (vertical component of ship's speed in m/sec)
The angle φ is defined in §4

The V_{ship} will be the ramming speed according to [3].

$$E_{KINETIC} = \frac{1}{2} \cdot M \cdot V_V^2, \quad E_{POTENTIAL} = M \cdot g \cdot x, \quad E_{CRUSH} = \int_0^{\zeta} F_n(\zeta) \cdot d\zeta \overset{(4)}{=} P_0 \cdot ka^{0.9} \cdot \frac{\zeta^{2.8}}{2.8}$$

So we can write:

$$E_{KINETIC} + W_{BUOYANCY} = E_{POTENTIAL} + E_{CRUSHING} \Rightarrow E_{KINETIC} = E_{POTENTIAL} - W_{BUOYANCY} + E_{CRUSHING} \Rightarrow$$

$$\frac{1}{2}\cdot M\cdot V_V^2 = M\cdot g\cdot x-\frac{1}{2}\cdot k\cdot x\cdot\left(T-\frac{x}{2}\right)+P_0\cdot ka^{0.9}\cdot\frac{\zeta^{2.8}}{2.8} \qquad (5)$$

At the equilibrium position the crushing force equals with the loss of buoyancy. So we have:

$$F_n(x)\overset{(4)}{=} Po\cdot ka^{0.9}\cdot\zeta^{1.8} = C_W\cdot\rho\cdot L\cdot B\cdot x\cdot g \Rightarrow x=\frac{Po\cdot ka^{0.9}\cdot\zeta^{1.8}}{C_W\cdot\rho\cdot L\cdot B\cdot g}\Rightarrow x=a\cdot\zeta^{1.8} \qquad (6)$$

where $a=\dfrac{Po\cdot ka^{0.9}}{C_W\cdot\rho\cdot L\cdot B\cdot g}$

So from Eq. 5, 6 we have:

$$\frac{1}{4}\cdot k\cdot a^2\cdot\zeta^{3.6}+P_0\cdot ka^{0.9}\cdot\frac{\zeta^{2.8}}{2.8}+\left(M\cdot g-\frac{1}{2}\cdot k\cdot T\right)\cdot a\cdot\zeta^{1.8}-\frac{1}{2}\cdot M\cdot V_V^2=0 \qquad (7)$$

9. Mathematical formulation (Langragian equation)

We can also use the Lagrangian equation in order to model the vertical movement of the ship. The vertical kinetic energy $\frac{1}{2}\cdot M\cdot V_V^2$ is transformed in vertical movement $\frac{1}{2}\cdot M\cdot\dot{x}^2$ and crushing energy $\frac{1}{2}\cdot M\cdot\dot{\zeta}^2$.

For every system the Lagrangian equation gives:

$$L=E_{KIN}-E_{POT}\Rightarrow L=\frac{1}{2}\cdot M\cdot V_V^2-M\cdot g\cdot x\Rightarrow L=\frac{1}{2}\cdot M\cdot\dot{x}^2+\frac{1}{2}\cdot M\cdot\dot{\zeta}^2-M\cdot g\cdot x \qquad (8)$$

Also the work of buoyancy W_B works always against *Weight*. The crushing energy $E_{CRUSHING}$ is the energy given by our system. So we can write:

$$L=\frac{1}{2}\cdot M\cdot\dot{x}^2+\frac{1}{2}\cdot M\cdot\dot{\zeta}^2-M\cdot g\cdot x+W_B-E_{CRUSHING}\Rightarrow$$

$$L=\frac{1}{2}\cdot M\cdot\dot{x}^2+\frac{1}{2}\cdot M\cdot\dot{\zeta}^2-M\cdot g\cdot x+\frac{1}{2}\cdot k\cdot x\cdot\left(T-\frac{x}{2}\right)-P_0\cdot ka^{0.9}\cdot\frac{\zeta^{2.8}}{2.8} \qquad (9)$$

The integral *I(x)* of the Langragian must be minimized. (Principle of least action)

$$I(x)=\int_0^t\left[\frac{1}{2}\cdot M\cdot\dot{x}^2+\frac{1}{2}\cdot M\cdot\dot{\zeta}^2-M\cdot g\cdot x+\frac{1}{2}\cdot k\cdot T\cdot x-\frac{1}{4}\cdot k\cdot x^2-P_0\cdot ka^{0.9}\cdot\frac{\zeta^{2.8}}{2.8}\right]\cdot dt \qquad (10)$$

I(x) is minimum when Euler equation is satisfied:

$$\frac{\partial L}{\partial x} - \frac{d}{dt}\frac{\partial L}{\partial \dot{x}} = 0 \quad (11) \qquad \text{and} \qquad \frac{\partial L}{\partial \zeta} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\zeta}} = 0 \quad (12)$$

This system of differential equations describes the movement of the ship.

So we have from Eq. 11 for $z = \dot{x}$:

$$\frac{\partial L}{\partial x} - \frac{d}{dt}\frac{\partial L}{\partial \dot{x}} = 0 \Rightarrow M \cdot g \cdot x - \frac{1}{2} \cdot k \cdot T \cdot x + \frac{1}{4} \cdot k \cdot x^2 = \frac{M \cdot V_{Vx}^2}{2} \qquad (13)$$

From Eq.12 we have for $z = \dot{\zeta}$

$$\frac{\partial L}{\partial \zeta} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\zeta}} = 0 \Rightarrow \frac{P_0 \cdot ka^{0.9} \cdot \zeta^{2.8}}{2.8} = \frac{M \cdot V_{V\zeta}^2}{2} \qquad (14)$$

The vertical kinetic energy of the ship will be the sum of the kinetic energy which is transformed to vertical movement and the kinetic energy which is transformed to crushing energy. So from Eq. 13, 14 we can write.

$$\frac{1}{2} \cdot M \cdot V_V^2 = \frac{M \cdot V_{Vx}^2}{2} + \frac{M \cdot V_{V\zeta}^2}{2} = M \cdot g \cdot x - \frac{1}{2} \cdot k \cdot T \cdot x + \frac{1}{4} \cdot k \cdot x^2 + P_0 \cdot ka^{0.9} \cdot \frac{\zeta^{2.8}}{2.8} \qquad (15)$$

The Eq. 15 is the same as the Eq. 5 in §8. So following the same procedure as in §8, we can come to Eq.7 for the calculation of the ice crushing ζ.

10. Solving the equation of ice crushing

The roots (values of *ζ*) of the Eq.7 calculated with "Mathematica" are given in Figure 10 in relation with the angle *β'*.

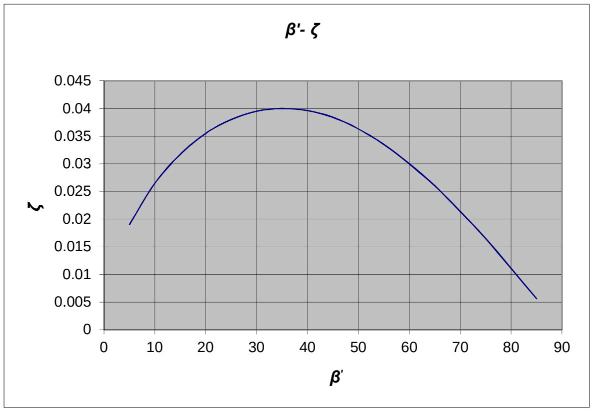

Figure 10. Ice crushing *ζ* versus angle *β'*

We can see that we obtain the maximum value of ζ for β' = 35°. So for β' = 35° we have:

$$ka = \frac{\tan(\psi/2)}{\left(\cos^2(\beta')\cdot\sin(\beta')\right)} = 9.7 \quad \text{as} \quad \psi = 150^{\circ} \quad (\text{See § 7})$$

For the above value of $k\alpha$ the Eq. 7 becomes:

$$\frac{1}{4}\cdot k\cdot a^2\cdot\zeta^{3.6} + 7.73\cdot P_0\cdot\frac{\zeta^{2.8}}{2.8} + \left(M\cdot g - \frac{1}{2}\cdot k\cdot T\right)\cdot a\cdot\zeta^{1.8} - \frac{1}{2}\cdot M\cdot V_V^2 = 0 \quad (16)$$

$$\text{where}: a = \frac{7.73\cdot Po}{C_W\cdot\rho\cdot L\cdot B\cdot g} \qquad k = C_W\cdot\rho\cdot L\cdot B\cdot g$$

Since we are interested for normal ship operation, which means very small values of ζ, we can eliminate the first two terms of Eq. 16, as they are very small (they are of order 3.6 and 2.8) compared with the third term (order of 1.8). So the Eq. 6 becomes:

$$\left(M\cdot g - \frac{1}{2}\cdot k\cdot T\right)\cdot a\cdot\zeta^{1.8} - \frac{1}{2}\cdot M\cdot V_V^2 = 0 \quad \Rightarrow \zeta = \sqrt[1.8]{\frac{\frac{1}{2}\cdot M\cdot V_V^2}{\left(M\cdot g - \frac{1}{2}\cdot k\cdot T\right)\cdot a}} \quad (17)$$

$$F_n(\zeta) = P_0\cdot ka^{1+ex}\cdot\zeta^{2+2ex}\cdot 10^3 \qquad (18) \qquad \text{with ex} = \text{-0.1} \quad (\text{see §7})$$

From Eq. 17, 18 for β' = 35° and angle φ=5°, we take the Eq. 19 below, which gives in kN, the force on the bottom, due to ice grounding:

$$F_n = \frac{\Delta\cdot V^2}{(C_B/C_W - 0.5)\cdot T}\cdot 10^{-3} \qquad (19)$$

Δ : Displacement in tn. C_W : Waterline coefficient at draft T.
C_B : Block coefficient at draft T. V : Ship speed, in knots

With the force given in Eq. 19 we can calculate the bottom scantlings through the IACS URI [2] or BUREAU VERITAS Rules [3]. without using any reduced values for the hull area factor C_{AF}. We always use C_{AF} = 1. The force on bottom structure due to ice grounding can be also calculated for bigger angles φ (see figure 4), as long as we can stay in line with the assumptions made in §4.

In Figures 11, 12 we can see plots of the original Eq. 16 and the approximation Eq. 17 for β' = 35° and angle φ=5°

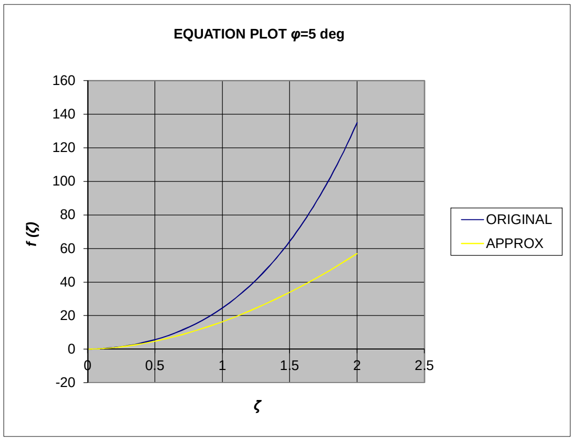

Figure 11. Solution of Eq. 16, 17

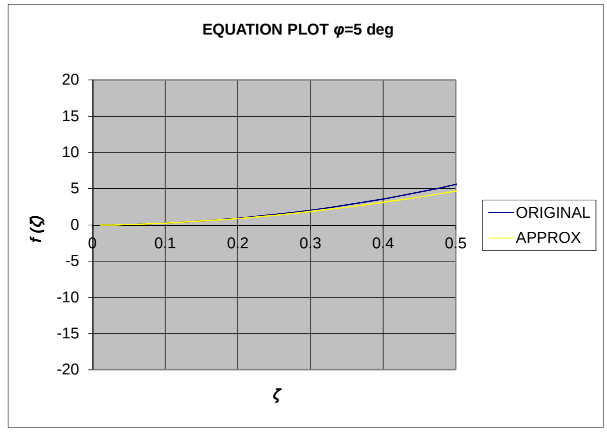

Figure 12. Zoom of Figure 11

From Figures 11, 12 we can see that Eq. 17 is a good approximation of Eq. 16 for small values of ζ ($\zeta < 0.3$ m).

11. Comparison between existing rules (IACS URI [2]) and new formula

In order to investigate the influence of shallow water on bow scantling requirements, we will apply this approach on a test ship (Polar class 6) with the characteristics shown in Table 2. This ship is constructed with longitudinal construction system. In order to check the influence of shallow water also on the transverse construction system we are going to apply the same calculation on a hypothetical transverse construction system with scantlings (*s* and *l*) as defined in Table 4.

D	2450	tn
s (T)	0.3	m
l (T)	1.8	m
s (L)	0.3	m
l (L)	1.8	m
L	63	m
B	16.4	m
T	3.0	m
V_{ship}	4.5	knots
Cw	0.795	
Cb	0.771	

Table 2. Characteristics of a test ship

s (L): spacing of longitudinal ordinary stiffeners at bottom.
l (L): span of longitudinal ordinary stiffeners at bottom.
s (T): spacing of transverse ordinary stiffeners at bottom. (hypothetical)
l (T): span of transverse ordinary stiffeners at bottom. (hypothetical)

In Tables 3, 4 below we can see for $\varphi = 10^o, 5^o, 2^o$ (See Figure. 4) a comparison concerning the scantling requirements (**net**) for stiffeners and plating between this paper and IACS URI [2] or BUREAU VERITAS Rules [3]. The coefficients we see in the Tables 3,4 express the increase/decrease of the IACS URI [2] bottom scantling requirements due to the application of the shallow water requirements as these are expressed in this paper .

In the Tables 3 and 4 below we see the influence, according to this paper, of shallow draft on bottom plate thickness, shear area and stiffener section modulus requirement, (**net**) for the ship mentioned in Table 2.

POLAR CLASS or ICEBREAKER	Plate (mm)			Shear area (cm^2)			SM (cm^3)		
	$\varphi = 10^o$	$\varphi = 5^o$	$\varphi = 2^o$	$\varphi = 10^o$	$\varphi = 5^o$	$\varphi = 2^o$	$\varphi = 10^o$	$\varphi = 5^o$	$\varphi = 2^o$
PC 1	1.49	1.08	0.66	0.93	0.21		0.88	0.17	
PC 2	1.46	1.05	0.64	0.82	0.16		0.80	0.15	
PC 3	1.43	1.02	0.62	0.75	0.11		0.74	0.11	
PC 4	1.36	0.96	0.58	0.58	0.04		0.57	0.04	
PC 5	1.45	1.03	0.62	0.75	0.10		0.74	0.10	
PC 6	1.41	1.00	0.60	0.66	0.07		0.66	0.07	
PC 7	1.47	1.05	0.63	0.79	0.11		0.79	0.11	

Table 3. Increase/decrease of IACS URI [2] bottom scantling requirements, due to application of the shallow water requirements for all Polar classes. (Longitudinal system)

POLAR CLASS or ICEBREAKER	Plate (mm)			Shear area (cm^2)			SM (cm^3)		
	$\varphi = 10^o$	$\varphi = 5^o$	$\varphi = 2^o$	$\varphi = 10^o$	$\varphi = 5^o$	$\varphi = 2^o$	$\varphi = 10^o$	$\varphi = 5^o$	$\varphi = 2^o$
PC 1	1.09	0.72	0.38	0.65	0.28	0.09	0.76	0.33	0.11
PC 2	1.06	0.70	0.36	0.66	0.28	0.09	0.77	0.34	0.11
PC 3	1.04	0.68	0.35	0.65	0.28	0.09	0.76	0.33	0.11
PC 4	0.98	0.63	0.31	0.58	0.25	0.08	0.68	0.30	0.10
PC 5	1.07	0.70	0.35	0.73	0.31	0.10	0.84	0.37	0.12
PC 6	1.03	0.67	0.34	0.67	0.29	0.09	0.77	0.34	0.11
PC 7	1.10	0.72	0.36	0.80	0.34	0.11	0.90	0.40	0.13

Table 4. Increase/decrease of IACS URI [2] bottom scantling requirements, due to application of the shallow water requirements for all Polar Classes. (Hypothetical transverse system)

12. Longitudinal strength

In the case where we will have grounding on the ice, the ice loads need only to be combined with still water loads. We can give the following formulae for the global Bending Moment and Shear force due to grounding on ice (at the middle of the L_{WL} of the ship):

$$M_{ICEGROUDING} = \frac{F_n \cdot L_{WL}}{4} \qquad Q_{ICEGROUDING} = \frac{F_n}{2}$$

L_{WL} = Length of waterline $\quad$ F_n = Vertical grounding force

As we can see in Table 5 below, the above calculation of longitudinal strength in the case of grounding and for angle $\varphi < 5^o$ give us very small values for shear force Q and Bending Moment M compared with the maximum values taken from IACS URI [2] in the case of ramming. In Table 5 we can see the values for $\varphi = 2^o$, 5^o and 10^o

	$\varphi = 2^o$	$\varphi = 5^o$	$\varphi = 10^o$	RULES (max)
Q (MN)	0.003	0.018	0.070	8.29
M (MNm)	0.089	0.556	2.207	59.92

Table 5.

13. Conclusion

In this investigation we have checked the influence of ice grounding, due to shallow water, on bottom construction of Polar Class ships and Icebreakers.

We have modeled the vertical movement of the ship as it climbs on the ice below the ship, assuming that this happens due to a vertical component of the ship's horizontal velocity. This vertical component V_V is created due to the longitudinal inclination of the ship as it climbs on the ice and is connected to the velocity of the ship V_{ship} with the formula $V_V = V_{ship}\ sin(\varphi)$ where φ is the angle of the longitudinal inclination of the ship as it hits the ice. Since we are modeling normal operation in ice, angle φ will be small. We have used $\varphi = 5^o$ in our calculations. This angle can be greater, in order to modelize more aggressive operation in ice, as long as we can stay in line with the assumptions we made in §4.

Also we have to mention that we use for ship's speed the ramming speed from BUREAU VERITAS Rules. [3] We have also to mention that during ramming as the ship brakes the ice, pieces of ice go below the bottom of the ship (see Figure 3) and we have the grounding on the ice. At that moment ship's speed will be lower than the ramming speed used in our calculations since part of the kinetic energy of the ship has been spent for ice breaking. Also no reduction of ship's speed due to friction with the ice is considered.

We have considered that the contact point with the ice is in line with the centre of gravity of the ship which is the case that gives us the most conservative results. In general this will not be the case and we will have a transverse or longitudinal inclination of the ship, which will result to smaller bottom loading.

With the value of the force applied to the bottom due to ice grounding as calculated in this paper we can calculate the bottom scantlings through the IACS URI [2] or BUREAU VERITAS Rules [3] using hull area factor $C_{AF} = 1$.

The method described in this paper can be applied to sea areas where the keel clearance is less than 2 meters, which can be the case for the Caspian Sea.

14. References

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