A STRAIGHTFORWARD METHOD FOR CALCULATION OF ICE RESISTANCE OF SHIPS

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ABSTRACT

This paper presents an engineering tool for the evaluation of ice resistance. The main parameters that influence ice resistance are already known. This paper is an attempt to transform this knowledge into a useful calculation formula.

The parameters included in the method are; main dimensions, hull form, ice thickness, friction and ice strength.

First, the paper presents the parameters and their importance. Then straightforward formulas are developed, in which the influence of each factor is generated using dependences that approximate the physical processes of icebreaking. Finally, the results are evaluated against full scale tests with different ships.

1. INTRODUCTION

Ice resistance can be estimated using experience from ships in service, model-scale testing or analytic formulas. Each method has its strong and weak points. The use of experience is reliable if the new design is close to some tested designs. This is not always the case today when new innovative solutions are being sought.

Model-scale testing has become reasonably reliable with the improvement of the model ice and testing techniques. The main drawbacks are the relatively high costs, and the slowness of the testing process.

Analytical methods are so far inexpensive, but are not reliable. Greater reliability will be achieved as the knowledge of the physics of icebreaking advances.

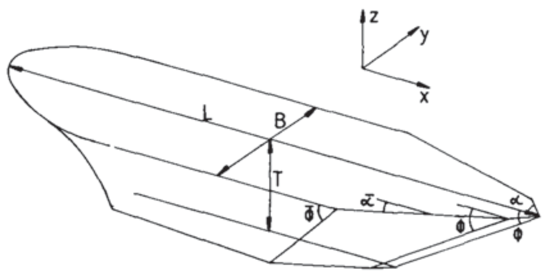

Figure 1. Approximation of hull form.

2. METHOD

The approach used in this paper is to identify the main components of the ice resistance and approximate their contribution with simple but physically sound formulas. In this method the whole icebreaking process is simplified, the goal being not to describe icebreaking with scientific exactitude but to create a tool for evaluation of ice resistance.

The aim is thus to achieve an uncomplicated method of estimating the resistance level and also of showing how resistance is affected by the main dimensions, the hull form and the friction. This method can never be a substitute for model testing; it is rather a tool for deciding what hull forms should be tested.

The main resistance components used are breaking. submersionand speed dependence. These are generally accepted as the main components of resistance / 1 / and thus acceptable, although the truth can be more complicated. The underwater form of the icebreaker is approximated with flat surfaces, to make the calculations shorter.

3. BREAKING

The earliest attempts to calculate the ice resistance ignored the submersion component. When this component was found, it was overestimated and the breaking component underestimated / 2 /.

One reason for the underestimation of the breaking process was that only the energy dispersed in bending the ice was considered. This part of the breaking resistance is small, as natural ice is quite rigid and is not greatly deflected prior to breaking.

A probable explanation of the high breaking resistance is that much energy is absorbed by the crushing of the ice prior to the final failure by bending.

In the present method the breaking process is simplified, all forces in the breaking process are genereted by crushing the edges of the floes. In order to keep the calculations short, both deflection of the ice and trimming of the vessel are ignored. This simplification can cause underestimation of the breaking resistance in very thick ice, in which the vessel trims considerably.

3.1 CRUSHING AT THE STEM

Crushing at the stem in a wedge-shaped icebreaker is almost continuous. It seems that the force never grows great enough to break the ice in the bending mode. This is probably due to two reasons. One is that the bending failure force is greater at the stem than further aft, due to the different geometry. The other reason is that the ice is undamaged at the stem, whereas further aft there are clearly many microcracks due to the interaction at the stem.

The exact magnitude of the force is not known. It can be measured by instrumentating the stem, or perhaps by simultaneous recording of the breaking pattern and the trim of the vessel. As this has not yet been done. we have to estimate this force by making an intelligent guess. The average vertical force acting on the ice is estimated as:

$$F_v = 0.5 * \sigma_b * H_{ice}^{\ 2} \qquad (1)$$

In this formula, sigma is the bending strength of the ice, and Hice is the ice thickness. Analysis of the force components using cumulative friction and assuming that the friction force acts along the verticals shows that the resistance force is:

$$R_c = F_v * (\tan\phi + \mu * \cos\phi / \cos\psi)/(1 - \mu * \sin\phi / \cos\psi) \qquad (2)$$

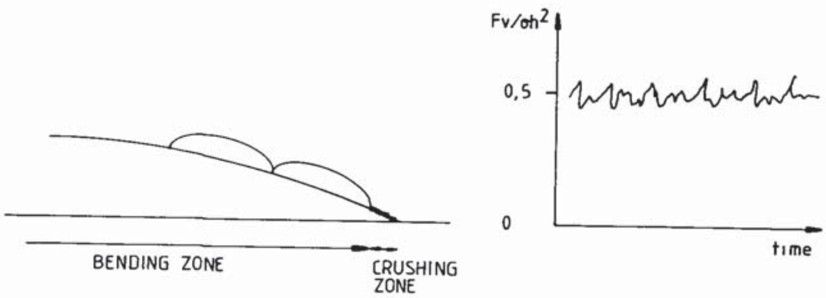

Figure 2. Stem crushing and vertical force.

μ is the friction coefficient, phi (ϕ) is the stem angle, alfa (α) is the waterline entrance angle and psi is the angle between the normal of the surface and a vertical vector ($\psi = atn(\tan\phi / \sin\alpha)$).

This resistance term explains the great resistance experienced by small icebreakers. The ice resistance of an extremely narrow icebreaker is thus not zero.

The spoon-shaped or cylindrical bow is intended to eliminate this resistance term by changing the geometry at the stem. With a square bow a crushing zone can be seen at the edges and this resistance term is thus not eliminated /4/.

3.2 BREAKING BY BENDING

Ice is clearly broken in the bending mode some distance aft of the stem. Although the final failure is in the bending mode, this is preceeded by crushing and shearing /7/. As the ship comes into contact with the a sharp edge of the ice, the edge is crushed until the force is big enough to shear away a small piece of ice. The plane of failure is close to the contact area and the crushing continues in a similar way; the only change is that the breadth of the contact area increases. This process continues until the force transmitted through the contact area is big enough to cause a bending failure.

Figure 3 shows the geometry and force. The mathematical calculation of this process is shown in appendix 1. The result of the calculation is:

$$R_b = k * b * (H_{ice}^3 / l_c^2) * (\tan\psi + \sin\phi / (\sin\alpha * \cos\psi)) * (1 + 1/\cos\psi) \qquad (3)$$

where the angles are defined in figure 1,k is a constant, H_{ice} is the ice thickness, l_c is the characteristic length of the ice and B is the breadth of the vessel. The characteristic length, which determines the size of the floes, is proportional to the thickness to the power of 0.75. Using the constants shown in appendix 1, the formula can thus be rewritten:

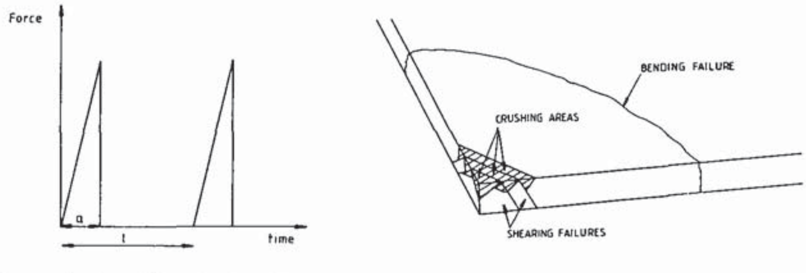

Figure 3. Breaking by bending.

$$R_b = 0.003 * \sigma_b * B * (H_{ice}^{1.5} / \sqrt{m}) * (\tan\psi + \mu * \cos\phi / (\sin\alpha * \cos\psi)) * (1 + 1/\cos\psi) \qquad (4)$$

This is an interesting approximation, for two reasons. One is that the resistance is proportional to the ice thickness to the power of 1.5. This is a very realistic value. The other point of interest is that the resistance is highly dependent on the breaking angle psi. This dependence has been observed earlier in full-scale tests / 3 /. These two points explain why conventional wedge-shaped bows are relatively inefficient in very thick ice.

4. SUBMERSION

Model tests and underwater observations from full-scale tests have shown that when the ship is running in level ice the hull is almost completely covered by ice. In view of this observation, the calculation of the submersion component is uncomplicated. As ice is lighter than water, it is lifted against the hull and the resistance comes directly through the normal force and indirectly through the friction.

In calculating the friction component the bow is assumed to be completely covered by ice and the bottom to be covered for 70 % of the length of the ship. This is because the stern region is not completely covered by ice. The ice is assumed to move along the verticals. The influence of ploughs is not taken into account. On the one hand, the plough reduces the area covered by ice, but on the other hand some energy is used to transfer the ice to the sides.

The resistance coming from the normal force is not calculated separately for all surfaces. Instead, this component is calculated through the potential energy. In this approach, it is only necessary to know the distribution of ice at the deepest section to calculate this term. The mathematical calculations are in appendix 2 and the result is:

$$R_s = \delta\rho * g * H_{ice} * (T * (B + T) / (B + 2 * T) + \mu * (A_u + \cos\phi * \cos\psi * A_f)) \qquad (5)$$

where $\delta\rho$ is the density difference between the water and the ice, g is the gravitational constant, H_{ice} is the ice thickness, L, B and T are the length, breadth and draft of the ship, μ is the friction coefficient, A_u is the area of the flat bottom and A_f is the area of the bow. According to the formula the resistance is the loss of potential energy plus frictional forces. Using approximations for the area of the surfaces, we obtain the formula:

$$R_s = \delta\rho * g * H_{ice} * B * (T * (B + T) / (B + 2 * T)$$
$$+ \mu * (0.7 * L - T / \tan\phi - B / (4 * \tan\alpha) + T * \cos\phi * \cos\psi * \sqrt{(1/\sin\phi^2 + 1/\tan\alpha^2)})) \qquad (6)$$

For a frictionless hull, this resistance term is proportional to ice thickness times breadth times draft. For normal friction values, the importance of the draft is reduced and the length of the ship influences the result.

It is difficult to determine the true friction between the ship and the ice. Recent research has shown that it depends upon pressure and temperature. A reasonable approximation is 0.1 for a ship with low friction paint and close to 0.16 for a ship with normal antifouling paint / 5 /

Another unresolved question is what allowance should be made for the snow thickness in the calculations. In the present method the pure ice thickness is used in the breaking calculations and ice plus snow thickness in the submersion calculations.

5. SPEED

Both the breaking and the submersion component are fairly well known. Their relative importance can be discussed and the accuracy of the formulas can still be improved, but these are minor questions.

The speed dependent component is more uncertain. It is important, as at normal operating speeds it accounts for about half of the total resistance. The exact reasons for this component are unknown, though many factors can be suggested. Such factors are: increase of breaking resistance, increase of submersion resistance, acceleration of ice floes, ventilation of ice floes and viscous drag.

The breaking resistance can increase if floe size decreased with increasing speed. The water pressure at the bow area is increased and can affect the forces needed to break the ice.

The speed will clearly influence the flow lines of the broken ice and the submersion component will therefore change with the speed. The friction component can also increase when the dynamic water pressure outside the ice increases or because the friction coefficient changes.

Acceleration of ice floes and the water close to the floes contribute to the resistance, but how much?

Full ventilation of the ice floes means that only air exists between the floes and the hull. The water pressure then creates a great normal force on the ice floes and thereby increases resistance due to the friction. This is obvious, but calculation of the ventilated areas is difficult and requires more research.

A viscous drag is created if there is only a very thin water film between the ice and the hull. The thickness of the water film is so far unknown, so it is hard to calculate this component.

At present we do not know how much each factor influences the resistance.

More research is clearly needed in this area before progress is possible. As the factors are not well known, it is futile to calculate this term at this stage. It seems possible that both the submersion and the breaking component are increased, and this assumption is used. Instead of calculating the increase of this term, the static components are used and the increase is approximated using empirical constants.

The resistance seems to increase fairly linearly with the speed. To obtain a dimensionless term, the increase in the breaking resistance can be assumed to be proportional to speed divided by the square root of ice thickness times the gravitational constant. In the same way the increase in the submersion term is proportional to speed divided by the square root of the length of the ship times g. Using two empirical constants we obtain the total ice resistance:

$$R_{ice} = (R_c + R_b)*(1 + 1.4*v/\sqrt{(g*H_{ice})}) + R_s*(1 + 9.4*v/\sqrt{(g*L)}) \quad (7)$$

6. EXAMPLES

To test the formula it has been run against the results obtained with seven different ice going ships in Baltic conditions. The Baltic was chosen to eliminate large differences in ice conditions and because a relatively large number of tests have been made in these conditions.

To check whether the formula accounts adequately for the size of the ship, it has been tested against three icebreakers with different displacements. The smallest is the harbour tug Jelppari, with a displacement of about 70 tons. The medium-size icebreaker is the relatively new Baltic icebreaker Otso, with a displacement of 8,000 tons. The largest icebreaker is the Arctic icebreaker Vladivostok, with a displacement of about 13,000 tons. The main dimensions and shapes of the ships are given in table 1 and the resistance in figure 4.

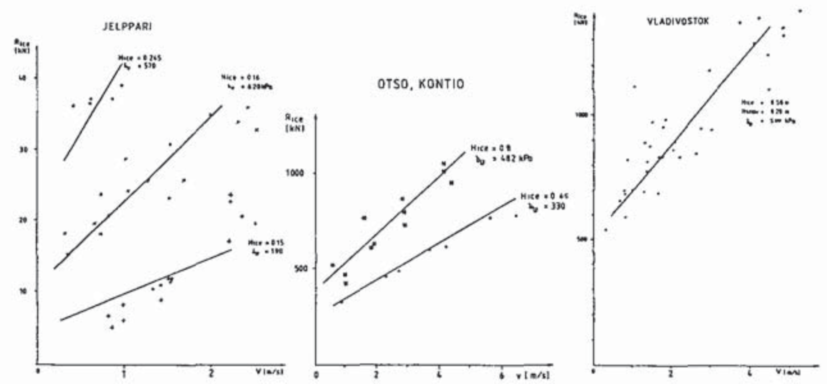

Figure 4. Calculated resistance (line) and measured (dots).

The formula seems to be fairly reliable for larger ships; for smaller ships, the speed dependent part is unreliable, although the calculated resistance is of the right order of magnitude.

To check how the formula can predict ice resistance for different hull shapes, it has been run against four rather small ships tested in about 0.5 metre ice. Two have rather poor icebreaking lines, as the bows are very sharp, their average breaking angle psi being 65 degrees. These are the 600 ton displacement Coast Guard cutters Valpas and Silmä. At the time of testing, Valpas was four years old and had a coating of normal paint, Silmä was eleven years old, but had low friction paint. The friction coefficient was not measured, but it should be between 0.1 and 0.16.

The ships with good breaking angles are Mergus (average psi = 22 degrees) and the Warc testing bow (average psi = 20 degrees). Mergus is of the same size as Valpas and is a small ferry operating in the sheltered waters of the archipelago outside Turku. Low resistance lines were easily achieved, as the ferry needed a large deck area, but not a large displacement.

The Warc bow is a 300 ton icebreaking bow, which was connected to a tug and was tested extensively in 1985. It is cylindrical and has a very small stem angle. The bow and test results are presented in more detail in ref /3/.

The formula predicts the ice resistance for some known ships with fairly good accuracy. This does not of course prove that the formula is "right" in all cases. The formula is rather a tool that can be used or abused. The greatest uncertainty attaches to its ability to predict how changes in the mechanical properties of the ice affect the resistance, as all the tests presented here have been made in almost identical ice conditions. Its reliability is better when the main dimensions of the ship change or if the shape of the ship changes.

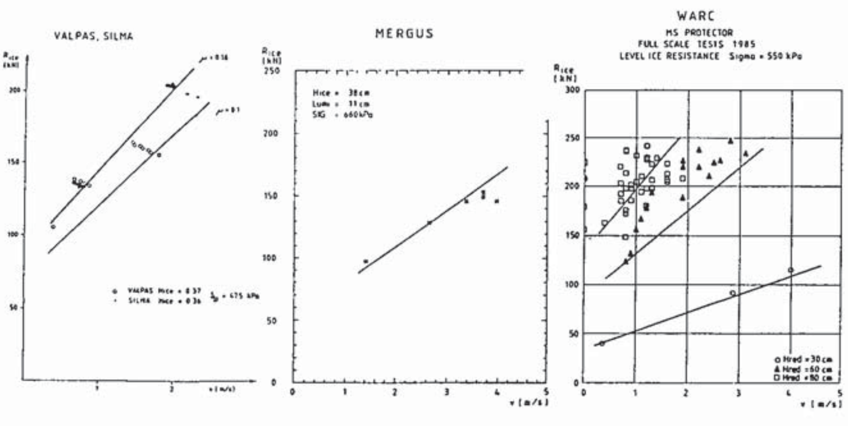

Figure 5. Results with different bows (calculated = line, measured = dots).

An interesting question for both designers and ship owners is how much the ice resistance can be reduced by optimizing the lines. To evaluate this point the ice resistance was calculated for a medium-size icebreaker with two different bow forms. One was a conventional wedge-shaped bow, similar to that of Vladivostok, and the other a development of the cylindrical bow, called the conical bow. In the conical bow, the breaking angles are minimized at the shoulders as well to achieve minimal breaking resistance and good manoeuvrability.

According to the calculations, the resistance of the conical bow is about 40 % less than that of the conventional bow. This means that the same ice can be broken with less than half the power, a significant improvement.

This improvement is of the same order as that reported with the Waas bow. The resistance of the Waas bow cannot however, be calculated with the present formula, as the breaking mechanism is different, at least at the sharp shoulders.

7. CONCLUSIONS

This paper has presented an easy method of calculating the ice resistance encountered by ice-going ships. The static resistance components are approximations of physical phenomena. The formulas have deliberately been kept short, as they are intended to be a tool in the design process and not a scientific explanation of the icebreaking process.

The speed dependency of this formula is too simple and requires refinement. This part of the formula should therefore be used with caution.

The formula shows that a significant improvement in icebreaking capability is possible with new hull shapes. This has been known earlier, but a relatively reliable method of estimating the resistance makes optimization for a certain operational profile much easier.

This method differs from earlier attempts to estimate the resistance with short formulas, as it takes account of both the friction and the shape of the ship. As space is restricted, it has not been possible in this paper to make any comparison with earlier methods.

Figure 6. Cusp geometry and cross-section.

APPENDIX 1. CALCULATION OF THE BENDING RESISTANCE

The edge of the cusp shown in figure 6 is crushed and sheared until the vertical force is great enough to break the ice in the bending mode.

The required vertical force is assumed to be:

$$F_v = 0.5 * \sigma_b * H_{ice}^2 \qquad (8)$$

If the force is increases linearly as shown in figure 3, the average vertical force $F_v ave.$ is:

$$F_v ave. = 0.5 * F_v * a / l \qquad (9)$$

where a is the vertical distance crushed and sheared and l is the length of the cusp. To determine a, we have to look closer at the crushing area and shearing forces. Using the two dimensional approach shown in figure 6 and classical stress analysis, we can calculate that the height of the crushing zone h_c is limited in the following way :

$$h_c * \sigma_c \leq 4 * H_{ice} * \tau / (3 * (1 + \cos\psi)) \qquad (10)$$

where σ_c is the effective crushing strength and τ is the shearing strength. The width of the crushing zone b is twice the penetration distance a in the described geometry. Using this, we obtain a new expression for the vertical force:

$$F_v = 2 * \sigma_c * h_c * a * \cos\psi \qquad (11)$$

Using equations 8,10 and 11, we can rewrite equation 9 to obtain a final expression for the average vertical force associated with the breaking of one cusp:

$$F_v ave. = (3/64) * \sigma_b * (\sigma_b / \tau) * (H_{ice}^3 / l) * (1 + 1/\cos\psi) \qquad (12)$$

The total average vertical breaking force for the whole breadth (B) of the ship is the average vertical force for one cusp times the average number of cusps n, which according to a geometrical analysis is:

$$n = B/(l^{*}\sin\alpha) \qquad (13)$$

where alpha is the angle between the water-line and the direction of the ships motion.

Assuming that the ice is moving along the buttock lines, we obtain the resistance force (R_b) from the vertical force with the following formula:

$$R_b = F_v ave^{*} n^{*}(\tan\psi^{*}\sin\alpha + \mu^{*}\cos\phi/\cos\psi) \qquad (14)$$

Using equation 12, we finally obtain the bending resistance :

$$R_b = (3/64)^{*}\sigma_b^{*}(\sigma_b/\tau)^{*}B^{*}(H_{ice}^{3}/l^{2})^{*}(\tan\psi + \mu^{*}\cos\phi/(\cos\psi^{*}\sin\alpha))^{*}(1 + 1/\cos\psi) \qquad (15)$$

The length of the cusps l is proportional to the characteristic length of the ice l_c , which is:

$$l_c = (E^{*}H_{ice}^{3}/(12^{*}(1-\upsilon^{2})^{*}\rho_w{}^{*}g))^{0.25} \qquad (16)$$

where E is Youngs modulus, υ is the poisson coefficient, ρ_w is the density of the water and g is the gravitational constant.

Assuming that the length of the cusps is one third of this characteristic length and the shearing strength is equal to the bending strength, we obtain the following breaking resistance:

$$R_b = (27/64)^{*}\sigma_b{}^{*}B^{*}\frac{H_{ice}^{1.5}}{\left(\sqrt{\left(E/\left(12^{*}(1-\upsilon^{2})^{*}g^{*}\rho_{(w)}\right)\right)}\right)}$$

$$^{*}(\tan\psi + \mu^{*}\cos\phi/(\cos\psi^{*}\sin\alpha))^{*}(1 + 1/\cos\psi) \qquad (17)$$

Using an elastic modulus of 2*10^9 N/m^2 and a poisson coefficient of 0.3, we obtain formula 4.

To make the calculations faster, average angles are used in the resistance computations. The average psi angle is, for example:

$$\psi_{(ave)} = (2/B)^{*}\int_{(0)}^{(B/2)}\psi(y)\partial y \qquad (18)$$

APPENDIX 2. CALCULATION OF THE SUBMERSION RESISTANCE

The submersion resistance is calculated separately for the loss of potentional energy and the frictional resistance.

To calculate the loss of potentional energy, we only have to look at the ice distribution at the deepest point of the ship which is generally the midship section. If the ice is assumed to be evenly distributed along the section, the ice cover has an effective thickness H_e , which is:

$$H_e = H_{ice}*B/(B+2*T) \qquad (19)$$

where B is the breadth of the ship and T is the draft. The potentional energy lost is the lifting force times submersion draft. The submersion draft for the floes under the ship bottom is equal to the ship draft, and the average submersion draft for the side pieces is half the ship draft. The potentional energy lost is therefore:

$$E_p = \delta\rho*g*H_e*(B*T+T*T)*\partial x \qquad (20)$$

where $\delta\rho$ is the density difference between the water and the ice, g is the gravitational constant and ∂x is a small distance in the length direction. As force times distance is energy, we can conclude that the resistance due to the loss of potentional energy is:

$$R_p = \delta\rho*g*h_{ice}*B*T*(B+T)/(B+2*T) \qquad (21)$$

The frictional resistance caused by the floes under the bottom is the lifting force times the frictional coefficient:

$$R_u = \mu*\delta\rho*g*H_{ice}*A_u \qquad (22)$$

where A_u is the area of the flat bottom covered with ice. If the bottom is assumed to be completely covered with ice up to 70% of the length, the area in the simplified hull geometry is:

$$A_u = B*(0.7*L-T/\tan\phi-0.25*B/\tan\alpha) \qquad (23)$$

For the bow region with ice moving along the verticals, the resistance due to frictional forces is:

$$R_f = \mu*\delta\rho*H_{ice}*A_f*\cos\psi*\cos\phi \qquad (24)$$

In this case the resistance force is reduced as the frictional force is directed slightly downwards and as the bow plane is inclined and the normal force therefore reduced. The total area of the bow planes is:

$$A_f = B*T*\sqrt{(1/\sin\phi^2 + 1/\tan\alpha^2)} \qquad (25)$$

The total submersion resistance is the resistance due to the loss of potentional energy plus the resistance due to the friction. This total submersion resistance is:

$$R_s = \delta\rho*g*H_{ice}*B*(T*(B+T)/(B+2*T) + \mu*(0.7*L - T/\tan\phi - 0.25*B/\tan\alpha + T*\cos\psi*\cos\phi*\sqrt{(1/\sin\phi^2 + 1/\tan\alpha^2)})) \qquad (26)$$

TABLE 1. MAIN PARAMETERS AND CALCULATED RESISTANCE AT 0 AND 2 m/s.

SHIP	Jelppari	Otso	Vladiv.	Silmä	Valpas	Mergus	Warc
L(wl)/m	15.0	90	112	45	44	44	48
B(wl)/m	5.1	23.4	23.5	8.0	8.2	8.3	11.1
T/m	2.9	7.4	9.5	3.8	3.7	3.3	3.3
ϕ_{stem}	26	22	26	32	32	19	15
α_{stem}	31	30	24	15	16	77	90
$\phi_{av.}$	28	22	24	28	28	15	15
$\alpha_{av.}$	25	25	18	13	14	50	59
$\psi_{av.}$	52	48	56	67	65	22	20
μ	0.16	0.1	0.16	0.1	0.16	0.1	0.1
Hice/m	0.15	0.65	0.58	0.35	0.36	0.38	0.3
Hsnow/m	0	0	0.28	0.02	0.02	0.11	0
σ_b/kPa	190	330	500	475	475	660	550
R(0)/kN	4.9	242	499	72	87	48	31
R(2)/kN	14.3	435	884	171	204	105	68
Hice/m	0.15	0.73					0.6
Hsnow/m	0.02	0.14					0
σ_b/kPa	620	480					550
R(0)/kN	10.7	360					84
R(2)/kN	33.3	648					170
Hice/m	0.24						0.8
Hsnow/m	0.02						0
σ_b/kPa	570						550
R(0)/kN	21.6						130
R(2)/kN	59.8						254

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