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DEVELOPMENT OF BRASH ICE IN CHANNELS NAVIGATED BY SHIP

Anita Nortala-Hoikkanen
Kvaerner Masa-Yards Technology, Helsinki, Finland

ABSTRACT

The ice navigation channels were intensively studied during winters 1996-1998 by Kvaerner Masa-Yards Arctic Research Centre (MARC). The objective of the study was to get reliable data on the brash ice formation through the whole ice navigation period in different types of channels. The gathered data were intended to use both in developing further the modelling technique of brash ice channels and in adjusting the calculation methods of the brash ice resistance.

Concurrently with the full-scale measurements the theories and experiments of the brash ice formation and the calculation methods for the brash ice resistance of the ships were examined. Also some model tests with a tanker model were carried out to verify the found brash ice formation phenomena and definitions used in the resistance calculation methods.

In this paper, results of the conducted full-scale measurements of the ice navigation channels will be presented and compared with the earlier studies. In addition, the theories on the brash ice formation have been compared and evaluated.

1. STUDIED CHANNELS AND CONDUCTED MEASUREMENTS

1.1 Choice of the channels

The target was to observe two types of channels: a southern channel with a modest number of frost degree days and a northern channel with a relatively high number of frost degree days - both relatively frequently operated. The southern channel was represented by the Sköldvik channel in the eastern part of the Gulf of Finland. The ferry channel from Oulunsalo to Hailuoto in the northern part of the Gulf of Bothnia, operated scheduled numbers of times a day by the same vessel, was chosen as the northern channel. The water depths at the observation sites were 30 m and 9 m respectively.

In addition to the proper test channels, the Pirttisaari channel in the eastern part of the Gulf of Finland, the Oulu deep-water channel and new, only a few times operated channels in the lake Saimaa in eastern Finland were studied. In Pirttisaari, the water depth was 14 m while in the deep-water channel of Oulu it was 10 m. At the studied parts of the lake Saimaa, the depth varied from 15 to 40 m.

The location of the channels has been outlined in the map, in Figure 1.

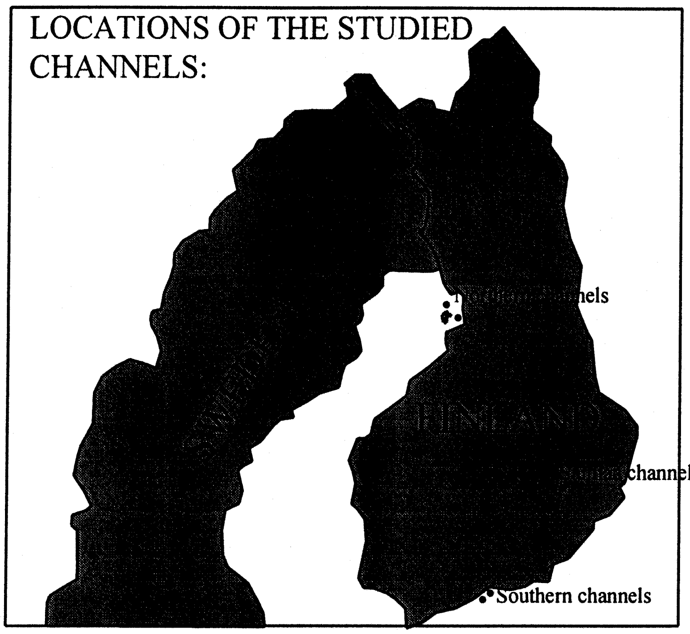

Figure 1. Location of the studied channels.

1.2 Conducted measurements

Every time when making measurements. the transversal thickness profile of the ice across the channel was determined by drilling through the ice either with a motor drill or a thermal drill. Usually the level ice portion, the edge ridges of the channel and the brash ice could be distinguished in the measured profiles. During some of the measurements, also the longitudinal profiles along the channel itself or along the channel edge (edge ridge) were determined. Concurrently with the measurements, the ice thickness, the porosity of the ice was determined. Every time the brash ice was also photographed to find out the piece size distribution.

The measurements were mainly conducted by MARC. In Hailuoto, the students of the Oulu University, who were specially trained for the measurements, were also used in conducting the measurements.

2 OBSERVATIONS AND RESULTS

2.1 Level ice thickness during the observation period

The development of the southern channels - the Sköldvik channel and the Pirttisaari channel - was observed during the winter 1996. The level ice grew from 0.4 m to 0.55 m during the observation period February-April. Near the Hailuoto channel in the North the level ice thickness varied from 0.6 m to 0.9 m during the observation period January-April in 1996 and from 0.55 m to 0.7 m in the corresponding time in 1997.

Level ice thickness close to the Oulu deep-water channel was 0.7 m at the beginning of April. The ice thickness in the lake Saimaa varied from 0.5 m to 0.85 m in March-April.

The winter 1995/1996 was classified as an average winter and the winters 1996/1997 and 1997/1998 as mild winters, [1]. The degree days of frost index were in maximum in the order of -1000...-1200°C days at all the studied sites. An example of the weather data is presented in Figure 2, [2].

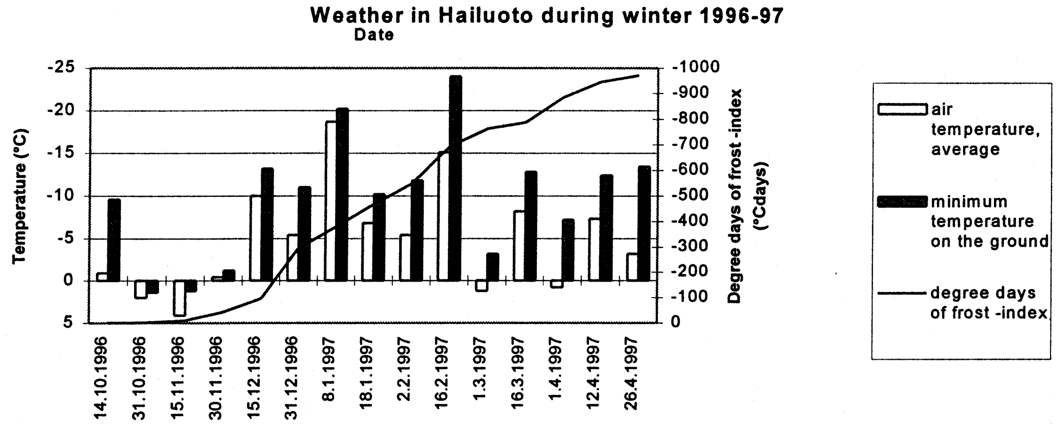

Figure 2. Air temperature and the degree days of frost -index in Hailuoto.

2.2 Results of the conducted measurements of the channels

Typical cross-sections of the measured channels can be seen in Figures 3-5.

The width of the channel - over 200 m – was typical for the Sköldvik channel. The width is due to the wide channel area where the ships can choose their track relatively freely. It was detected that the profiles measured in Sköldvik had often several edge ridges in the same cross-section of the channel, which means that the edge ridges can also be formed in wide brash ice. The brash ice thickness in the central channel area varied typically from 0.1 m to 1.5 m while the edge ridge thickness varied between 1.5 m to 2.2 m.

The width of the Hailuoto channel was in the order of 30 - 40 m and it could also change its location to some extent but definitely less than the Sköldvik channel. The brash ice thickness in the central channel varied from 0.2 m to 1.5 m and the edge ridge thickness between 0.9 m to 3 m.

The thickest edge ridges – the under-water thickness over 5 m and the above-water thickness over 1 m - were met in the Oulu deep-water channel, the width of which was only about 20 m. The brash ice thickness varied there from 0.1 m even up to 2.5 m. It is typical for the Oulu deep-water channel that in practice it does not change its location during winter at all. The same is true with the location of the Pirttisaari channel in the South. The brash ice thickness in Pirttisaari varied from 0.3 m to 1.4 m, the edge ridge thickness being in the order of 2.4 m. The width of the Pirttisaari channel is in the order of 70 m.

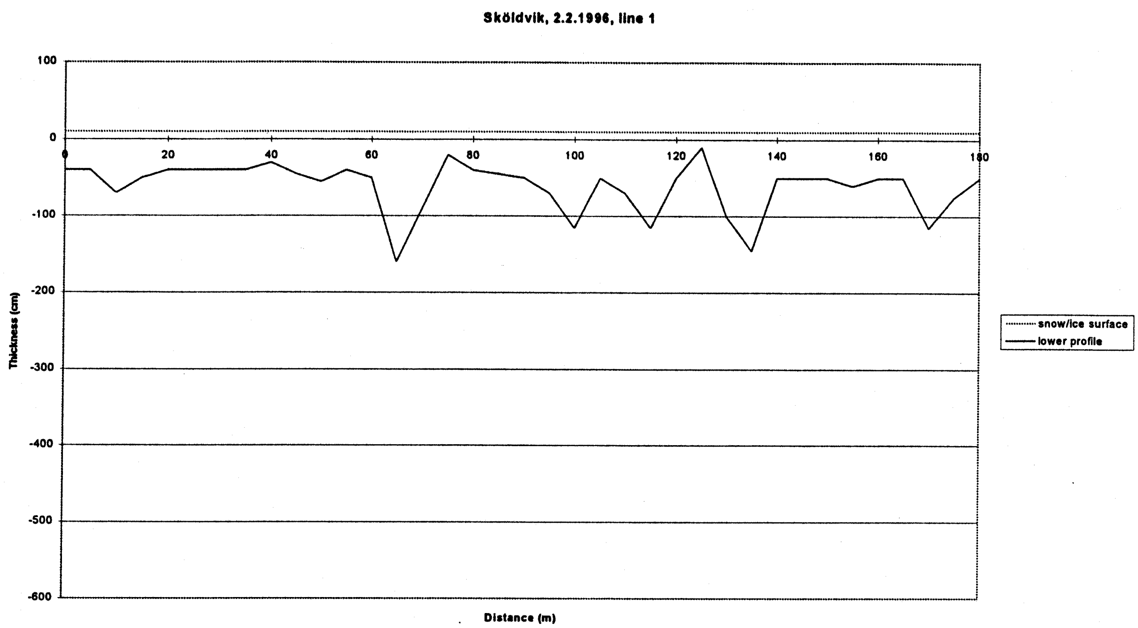

Figure 3. Transversal profile measured in Sköldvik.

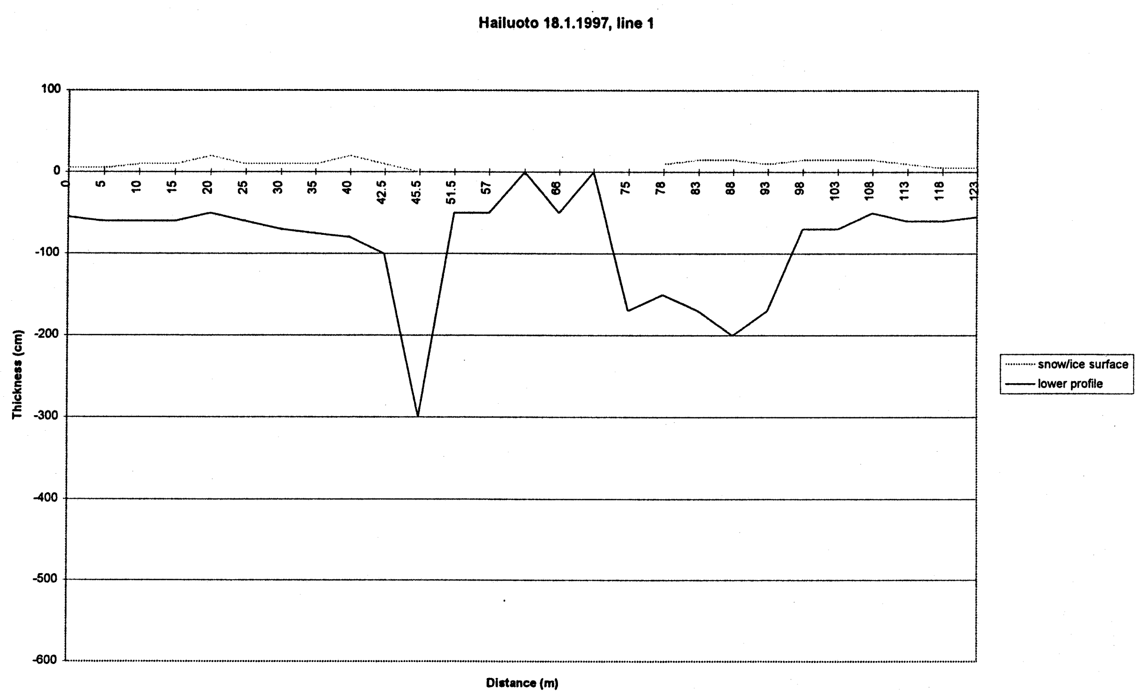

Figure 4. Transversal profile measured in Hailuoto.

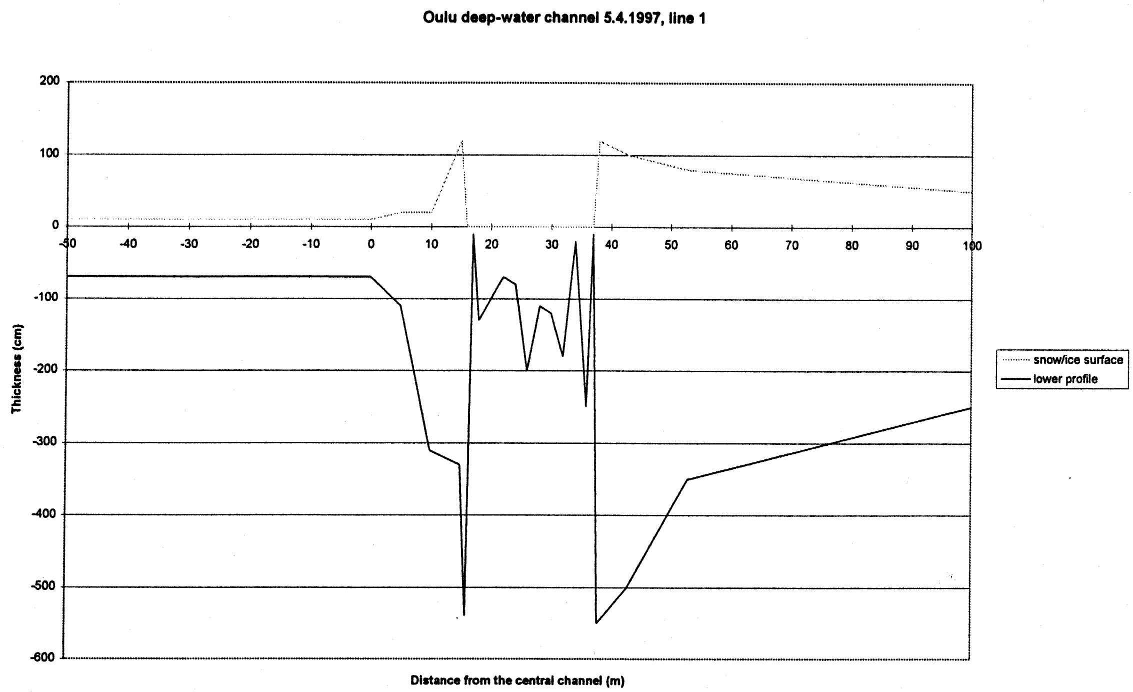

Figure 5. Transversal profile measured in the Oulu deep-water channel.

The prevailing diameter of ice blocks in the central channel was 0.2 m or less in all the measured channels. The portion of the smallest ice blocks in the central channel was also increasing towards the end of the ice navigation period in all the studied channels, Figure 6.

When considering the size of the biggest ice blocks in the central channel, the variation between different channels is obvious: in the Oulu deep-water channel and in the Pirttisaari channel the biggest ice blocks had nearly the same size than the prevailing ice blocks, in the Hailuoto channel the diameter of the biggest ice blocks varied from 0.6 m to 1.1 m and in the Sköldvik channel from 0.8 m to 1.5 m, respectively. The size of the biggest ice blocks decreased during the ice navigation period only in channels that either kept their location or changed it only slightly.

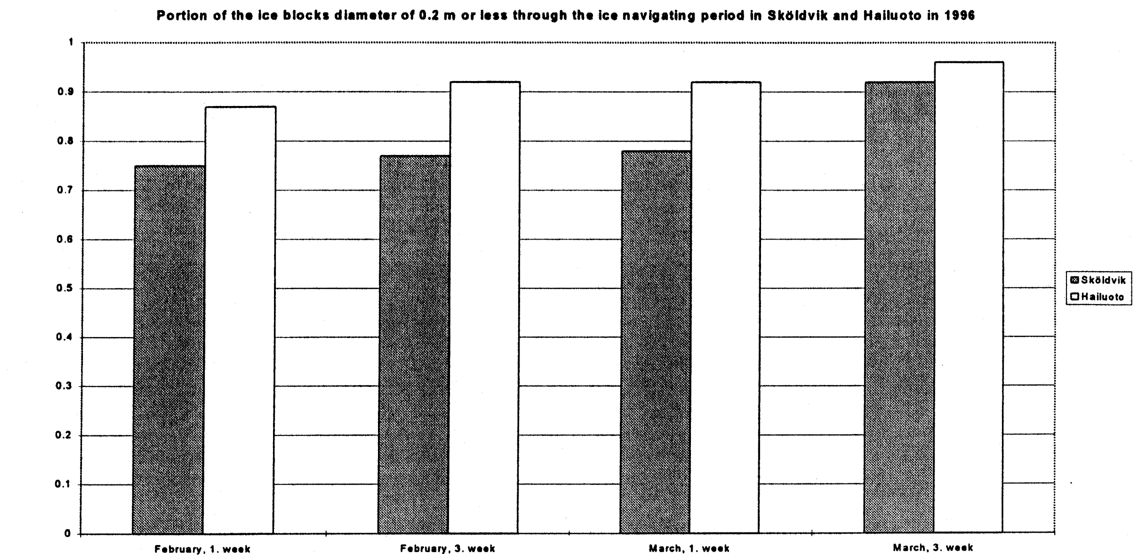

Figure 6. Portion of the smallest ice blocks through the ice navigation period.

Based on the drilling results, the structure of the brash ice in the channel and the ice in the edge ridges were outlined and the porosity calculated, Figure 7. The porosity in the edge ridges varied from 0 even up to 0.49, being typically 0.1-0.3. In brash ice in the channel the porosity varied typically from 0 to 0.36. According to these measurements, the progress of the winter seemed not to have any effect on the porosity.

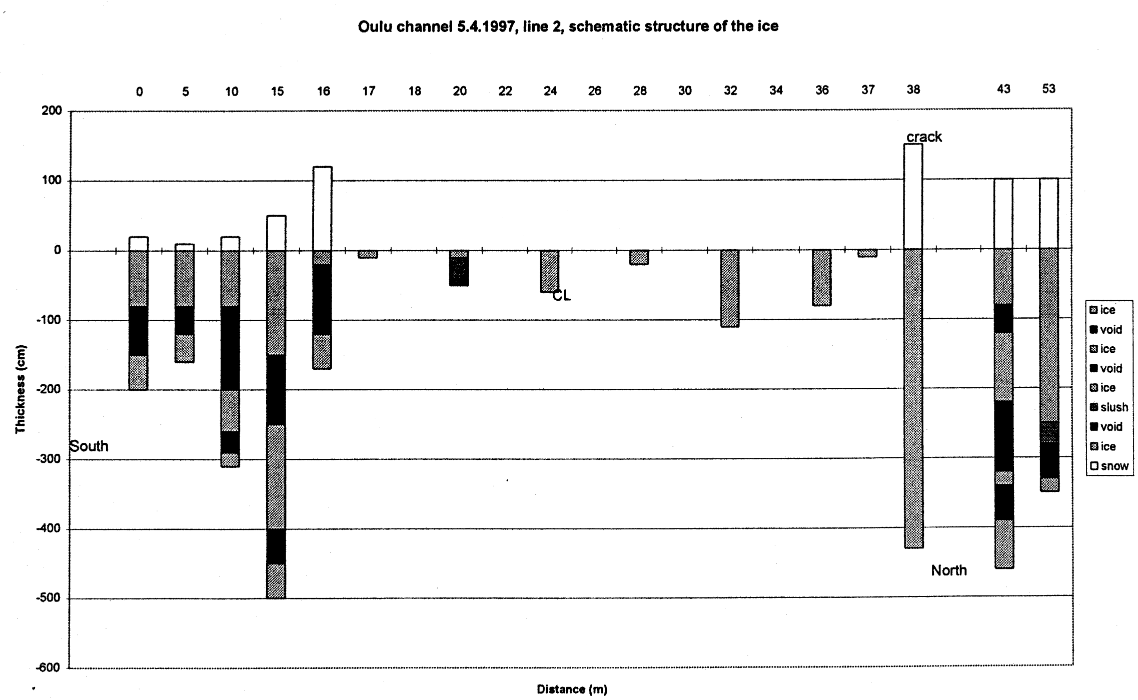

Figure 7. An example of the structure of the ice in the drilled transversal profile.

3. EARLIER STUDIES AND COMPARISONS

3.1 Theories on the brash ice formation

Nearly all the attempts that have been made to explain the brash ice formation η computationally or semi-empirically are based on the well-known Stefan's equation, [3]

$$\eta = \alpha \left(\sum_{j=1}^{N_i} S_d \right)^{0.5} \qquad (1)$$

where $\sum S_d$ is the degree days of frost-index and α Stefan's coefficient.

For coefficient α in Stefan's equation, several values have been proposed: in 1971 Michel recommended to use an α value of 28 mm/(°C-days)$^{0.5}$ for windy lakes without a snow cover, 17-13 mm/(°C-days)$^{0.5}$ for average rivers with snow and 14-7 mm/(°C-days)$^{0.5}$ for sheltered rivers, [3].

Ashton takes into account the ice grown on open water between the transits in his semi-empirical equation presented in 1974 for the average thickness of the brash ice. Berenger and Michel take into account the ice grown on open water, the ice growth within the pores of layers of brash ice and also the ice grown under the brash ice layer in their equation presented in 1975. Vance's equation presented in 1980 takes into account the continuous thickening of the brash ice pieces as well as the ice growth on open water, [3].

Sandkvist's, [3], also a Stefan's equation based equation, takes into account the initial ice cover thickness before the first transit as well as the ice formation due to the next transits. In addition, Sandkvist introduces a term, the "equivalent thickness", in which the formed brash ice is thought to be accumulated in a vessel's track of a width equal to the vessel's beam. For the α coefficient Sandkvist suggests a value of 12 mm/(°C-days)$^{0.5}$ which is based on field observations. Eranti reported in 1983, using the Sandkvist's equation with an α value of 6.5 mm/(°C-days)$^{0.5}$ based on the ice formation observations in the Saimaa canal.

Kannari [5] used expression the "accumulated mass thickness" to describe the growth of the brash ice mass in a channel. When using the accumulated mass thickness, the total cross-sectional area of the brash ice is divided by the beam of the widest ship that uses the channel regularly.

Here, the values for the accumulated mass thickness presented by Kannari were calculated from the measured profiles and compared both with Sandkvist's theory and its Eranti modification. According to the Sandkvist's theory, the equivalent brash ice thickness is pronounced increasing in accordance with transit times. The Eranti modification of the theory seems to work in channels the location of which is stable, Figure 8. The measurements, however, indicate that the brash ice thickness is constant and even decreasing during the ice navigation period in the Hailuoto type of channels, location of which can be changed, Figure 9.

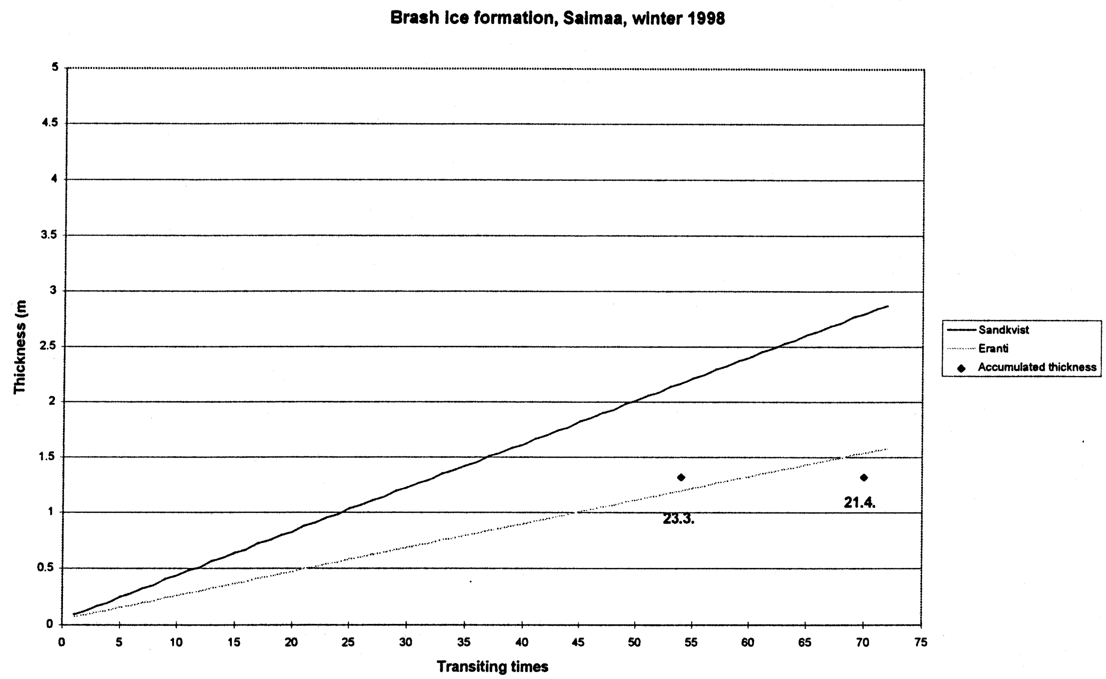

Figure 8. Brash ice formation in Saimaa in 1998

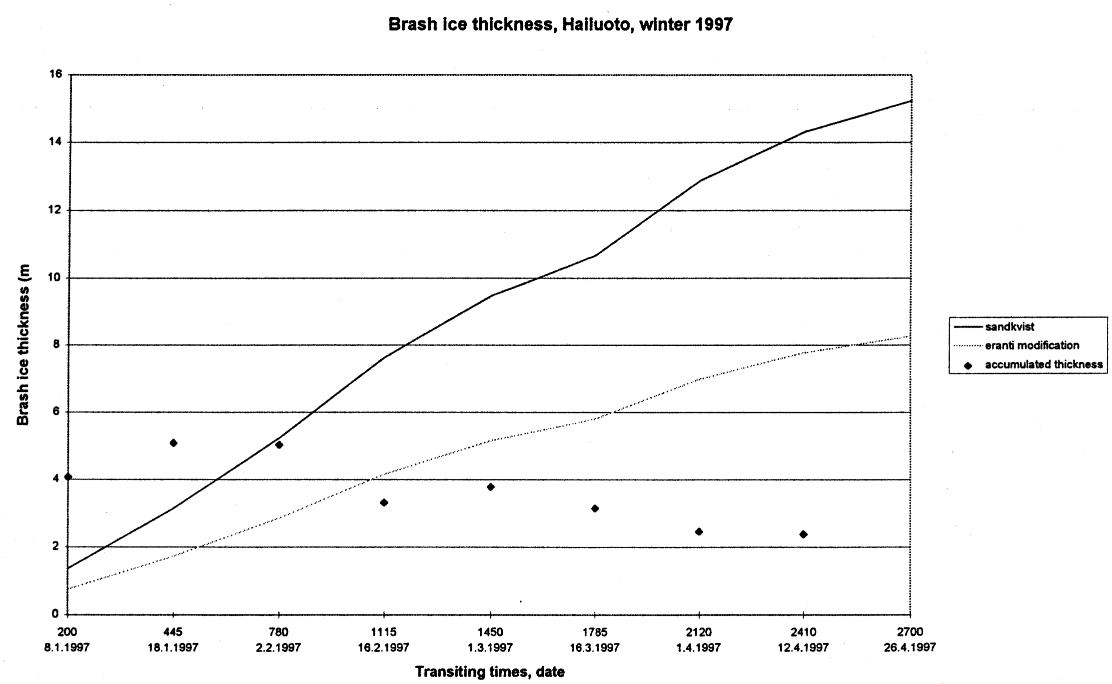

Figure 8. Brash ice formation in Hailuoto in 1997.

3.2 Earlier full-scale studies and observations on the brash ice formation

Sandkvist [4] made field experiments in order to investigate the growth and distribution of brash ice in the Luleå harbour with the harbour icebreaker Valkyria during the winter 1978-1979. He reported 2.5 m for the equivalent thickness of brash ice at the end of March.

Kannari [5] studied characteristics of channels in the Gulf of Bothnia in 1982. Kannari reported accumulative mass thicknesses as follows: 3.06 m in Kemi, 2.66 m in Oulu and 1.76 m in Vaasa.

The accumulated thicknesses of the brash ice formation calculated from the profiles measured here are in the order of: 2.5 - 5 m in Hailuoto, 6 m in Oulu, 3 m in Sköldvik and 6 m in Pirttisaari. It should be noted that the channels which had a particularly high value - 6 m - for the accumulated thickness are very narrow compared with the others examined here and they were studied only once at the worst time of the navigation period.

Helsinki University of Technology (HUT) has also studied the brash ice properties in connection with a long-term project of the efficiency of winter navigation [6], [7], [8], [9], [10]. The brash ice thickness/level ice thickness and the edge ridge thickness/level ice thickness ratios were calculated from the observations made in the northern part of the Gulf of Bothnia by HUT (1991, 1992, 1993, 1996) and MARC (1996, 1997), Table 1. The observations have been collected from different locations during different years, but still, an obvious similarity can be found in the results.

Table 1. Comparison of the results of the channel characteristics of MARC and HUT.

Month	Brash ice thickness/ Level ice thickness (HUT)	Brash ice thickness/ Level ice thickness (MARC)	Maximum edge ridge thickness/ Level ice thickness (HUT)	Maximum edge ridge thickness/ Level ice thickness (MARC)
1	0.75...1.9	0.9...2.5	4.5	1.3...5.5
2	1...2.6	0.7...2.1	3.7	1.3...2.6
3	0.5...2	0.25...2.1	3...5.3	1...3.8

3.3 Model tests on the brash ice formation and its nature

Ettema and Hung-Ping-Huang [3] presented a numerical model to simulate the brash ice formation and the development of the transversal shape of the brash ice channel. The model tests showed, for example, the increased volume of the ice growth not to be as dramatical as expected: they reported that the intense transiting leads to thickening of the brash ice with a thickness of 2-3 times the surrounding level ice thickness, the edge ridge thickness being 3-4 times the surrounding level ice thickness.

The average brash ice thickness/level ice thickness ratio and the maximum edge ridge thickness/level ice thickness ratio calculated from the measured full-scale profiles are presented in Table 2. It can be seen that the upper values for the brash ice thickness/level ice thickness ratio as well as the edge ridge thickness/level ice thickness ratios, except the values received in the Oulu deep-water channel, are concordant with model test results presented above.

The measurements conducted here showed the same as the model tests above: the ice growth was somewhat less than expected.

Table 2. Average brash ice thickness/level ice thickness ratio and the maximum edge ridge thickness/level ice thickness ratio

Site	Average brash ice thickness/ Level ice thickness	Maximum edge ridge thickness/ Level ice thickness
Sköldvik	1.3...3	3...4
Hailuoto	0.5...1.3	1...3.8
Pirttisaari	2	4.8
Oulu	0.7...1.85	7.1...7.9
Saimaa	0.6...1.6	1.1...3.3

4. CONCLUSIONS

On the basis of the measurements and observations, the ice navigation channels can be divided into three classes when examining the brash ice formation: firstly, the channels whose location does not or cannot be changed during the winter – e.g. the Oulu deep-water channel and the Pirttisaari channel; secondly, the channels whose location will remain within some ten metres – e.g. the Hailuoto ferry channel; thirdly, the channels whose location can be widely changed – e.g. the Sköldvik channel.

In the first type of channels, both Sandkvist's model and Sandkvist's Eranti modification give reasonable estimates at least at the end of the navigation period. In the second type of channels the examined computational models seem to predict the brash ice formation reasonably at the beginning of the ice navigation period, but after that it seems that the models are overestimating the brash ice formation. In the third type of channels, the amount of the brash ice seems to be rather constant through the ice navigation period and thus, does not behave according to the theory.

When determining the pure brash ice resistance, the computational models presented here should not be used as the basis of the calculations, because they give the maximum brash ice volume, only a part of which participates in forming the ice resistance.

5. FUTURE WORK

All the three winters during which the observations were made were classified as mild winters. Thus, it would be both necessary and interesting to make the corresponding measurements also in a severe winter. In addition, the work could also be connected with the measurements of the ship brash ice resistance. Then also some extra measurements to clarify the inner properties of the brash ice mass would be needed.

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