POAC'15
Trondheim, Norway

Proceedings of the 23rd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2015
Trondheim, Norway

THREE YEARS OF MEASUREMENTS OF FIRST YEAR RIDGES IN THE BARENTS SEA AND FRAM STRAIT

Bjørnar Sand[1], Victoria Bonath[2], Denise Sudom[3], Chris Petrich[1]
[1]Northern Research Institute (Norut), Narvik, NORWAY
[2]Luleå University of Technology, Luleå, SWEDEN
[3]National Research Council, Ottawa, CANADA

ABSTRACT
During three expeditions in March 2011, March 2012 and April/May 2013 with the Norwegian coastguard vessel "KV Svalbard", two pressure ridges around Svalbard, one ridge in Fram Strait and three ridges in Olga strait have been studied with respect to ridge geometry and physical and mechanical properties. With a discrete measurement, which is of most interest here, information can be obtained on the overall size and shape of an individual ridge at one particular location, both above and below the waterline. This approach provides detailed quantitative information on both the sail and keel size and shape, of a specific ridge, as well as its porosity. It does not supply any information on ridge spacing. The results of individual profile measurements are discussed. Measurements of vertical profiles along the spine and transects perpendicular to the spine are presented for these ridges. The sail height, sail width, keel depth and keel width, consolidated layer thickness, rubble block sizes and porosities are examined for each ridge. The results presented in this paper contribute to more data in terms of geometry and morphology of the first-year ridge off Svalbard, in Fram Strait and Barents Sea. Compression and tensile strength properties are important input data for constitutive modelling. Still strength properties of ridged ice are not yet sufficiently investigated. Uniaxial compressive tests were performed with horizontal and vertical loading directions and the results from the testing of level ice and consolidated layer are summarized with consideration of total porosity.

INTRODUCTION
Ridges are important in geophysical as well as in engineering contexts. Ice ridges may determine the design load for marine and coastal structures such as platforms, ships, pipelines and bridges, and geophysically they are important for both ice volume estimations and for the strength of pack ice. However, the current knowledge about ice ridges and forces from ridges is not exhaustive, and both ridge characteristics and physical and mechanical properties, are so far, insufficiently investigated. Field studies are vital to increase the background information for physical ice load models, to compare level ice strength and level ice loads to those of a ridge. First-year ridges play an important role in many ice-related processes, and are often a key consideration from an engineering perspective. In many cases first-year ridges control the design of offshore structures. Ridges also impede significantly the navigation in ice-infested regions and can scour the sea floor in shallow waters, which has significant consequences for the design of pipelines and other sub-sea installations. The Barents Sea is becoming an important area for Norwegian and Russian and international petroleum activity, but published research on first-year ice ridges in this area is scarce. Recently, work has been done in the Eastern and the South-Eastern parts of the Barents Sea, but few results are published so far. The same applies to the North-Western region of Barents Sea, and only the

results from the work carried out on first year ridges by Høyland and Løset (1999a,b), Høyland et al. (2000), Høyland (2002,2005,2007), Bonnemaire et al.(2003), Shafrova and Høyland (2008), Strub-Klein et al. (2009) are so far published for this region. These ridge data are included in the comprehensive analysis of the morphology of first-year ice ridges carried out by Strub-Klein and Sudom (2012). Knowledge gaps in sea ice ridge properties have been identified by Strub-Klein and Sudom (2012) and Sudom and Timco (2013). In the present paper, an attempt is made to address some of these knowledge gaps with respect to performing better mapping of the keels through longitudinal and cross sectional profiles of the each ridge. During three expeditions in March 2011, March 2012 and April/May 2013 with the Norwegian coastguard vessel "KV Svalbard", two pressure ridges around Svalbard, one ridge in Fram Strait and three ridges in Olga strait have been studied with respect to ridge geometry and physical and mechanical properties. In this study, holes are drilled through the sail and keel, and the thickness is measured using a tape measure into the drill holes. A levelling telescope was used to measure the surface elevation and the thickness of the ice blocks in the sail was also measured using a measuring tape. This approach provides detailed quantitative information on both the sail and keel size and shape, as well as the ice block size and the consolidation of first-year ridges with some considerations on the porosity and the variation of the consolidated layer thickness. This paper only contains a summary of the compressive strength of these ridges, but Bonath et al. (2013) presented some other preliminary results. It does not supply any information on ridge spacing. The results presented in this paper contribute to more data in terms of geometry and morphology of the first-year ridge off Svalbard, in Fram Strait and Barents Sea

SITE AND EXPERIMENTAL METHOD

The first ridge (R1-2011) was located in Woodfjorden, while the second one (R2-2011), was located in the Barents Sea between Svalbard and Hopen Island, see Figure 1. The surveys were conducted in the period from 20–30 March 2011. The third ridge (R2-2012) was located in the Fram Strait and was surveyed on 14 March 2012. The locations for the three ridges (R1-2013, R2-2013 and R3-2013) surveyed in the Olga strait outside Edge island between 27 and 30 May 2013 are also plotted in Figure 1.

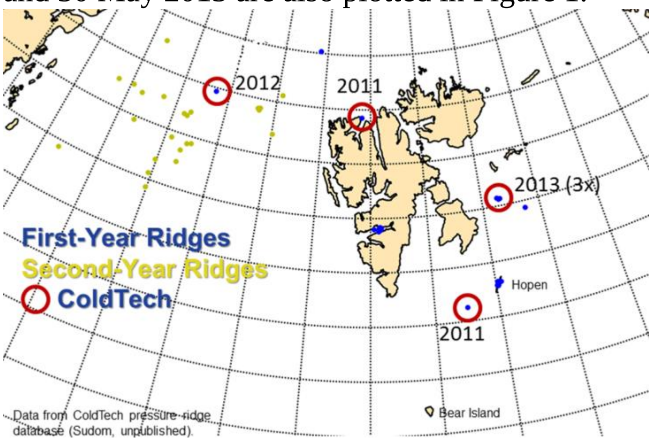


Table 1. Locations and dates for ridges.

Ridge:	Date:	Coordinates:
R1-2011	19 Mar 2011	14.237 E, 79.847 N
R2-2011	29 Mar 2011	22.521 E, 76.249 N
R2-2012	14 Mar 2012	1.48 W, 79.93 N
R1-2013	27 Apr 2013	26.645 E, 78.124 N
R2-2013	28 Apr 2013	26.523 E, 78.116 N
R3-2013	29 Apr 2013	26.381 E, 78.142 N

Figure 1. Map showing the locations for the investigated ridges.

RIDGE GEOMETRY AND MORPHOLOGY

The ridges investigated in 2011 and 2012 are not described in detail here, as the results and drilled cross sections are published elsewhere (Sand et al. 2013). A summary of geometric properties of the surveyed ridges are given in Table 2 and may be compared with properties of typical or average ridges in Svalbard waters and Barents Sea as reported by Strub-Klein and Sudom (2012) as shown in Figure 2a. The values for sail height, keel depth, sail width and keel width summarized in Table 2 are maximum values, while average values are reported for the thickness of blocks and surrounding level ice.

Table 2 Summary of geometric properties of the investigated ridges, compared with averages reported by Strub-Klein and Sudom(2012).

Ridge	$H_{s,max}$ [m]	$H_{k,max}$ [m]	$W_{s,max}$ [m]	$W_{k,max}$ [m]	α_s [deg.]	α_k [deg.]	$h_{i,avg}$ [m]	$h_{b,avg}$ [m]	h_{cl} avg. [m]	h_{cl} max. [m]
R1-2011	2.3	5.1	18.0	37.4	15	15	0.37	0.26	-	-
R2-2011	2.4	6.8	5.0	37.1	41	20	0.80	0.78	1.48	6.06
R2-2012	2.0	6.7	6.8	23.8	23	24	0.94	0.87	1.80	3.65
R1-2013	2.3	3.4	8.0	26.0	21/22	8/15	0.64	0.45	1.19	3.02
R2-2013	2.6	6.8	16.0	30.0	24	29	0.62	0.36	1.48	3.48
R3-2013	3.4	7.6	8.0	58.0	32	16	0.61	0.25	1.54	3.93
Avg. for above ridges	2.5	6.1	10.3	35.4	27	21	0.66	0.50	1.50	4.03
Avg. for Svalbard[1)]	1.3	4.8	12.7	13.8				0.31	1.37	
Avg. for for Barents Sea[1)]	2.1	8.5	10.2	37.0				0.67	1.55	

Remarks: [1)] From Strub-Klein and Sudom (2012).

Ridge R1-2013 surveyed in Olga Strait

Figure 2b shows a photo of the first year ridge R1-2013 surveyed in Olga Strait on 27 April 2013 and illustrates the drilled cross sections marked as line A along the spine (19 holes with 5 m spacing, see Figure 2c) and line B across the spine (20 holes at 2 m spacing, see Figure 2d). This means that A8/B11 is the hole where transect B crosses the spine. The sail height along the spine varies between 0.21 m to 2.28 m, with an average of 0.91 m.

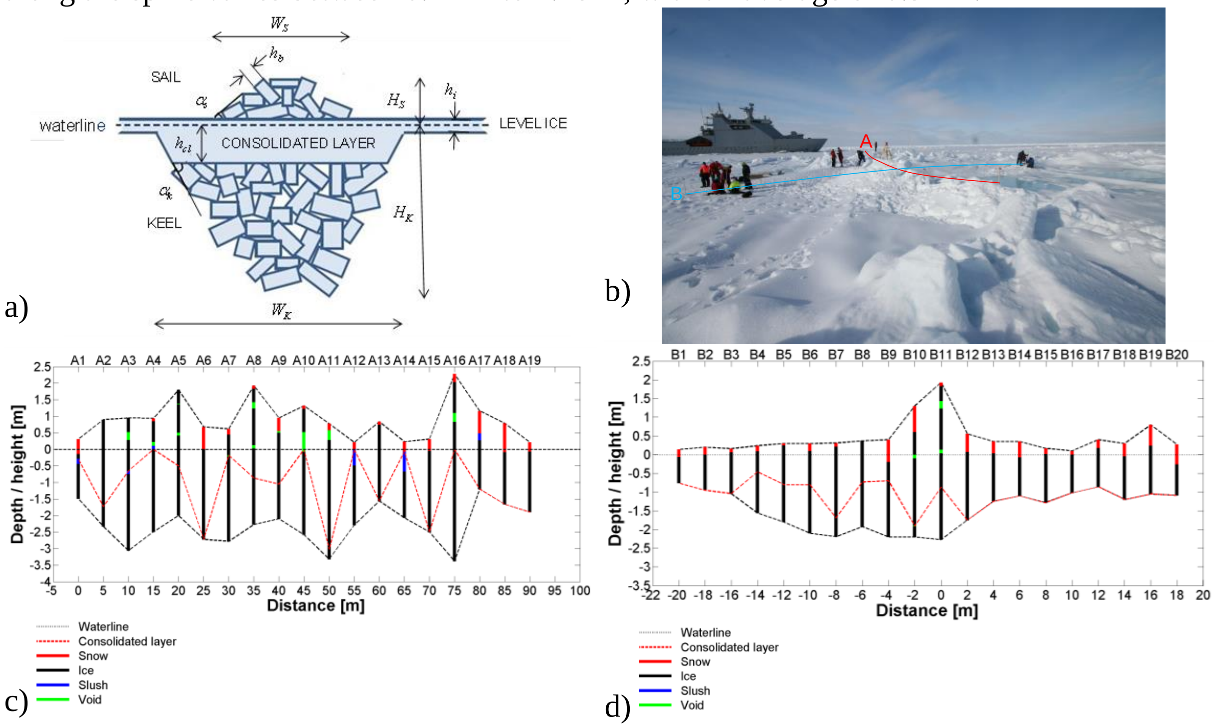


Figure 2. a) Typical model of a first-year ice ridge, after Strub-Klein and Sudom (2012). b) Photo of the ridge R1-2013. c) Cross section along the spine. d) Cross section along transect B.

The keel width is 26 m and keel angles of 8° and 15° are somewhat lower compared to what has been discovered by Strub-Klein and Sudom (2012) while the sail width is more narrow (8m) and the sail angle is about 22°. The average thickness of the surrounding ice sheet is 0.64 m and the average thickness of the ice blocks in the sail is 0.45 m. The consolidated layer is estimated based on drilling and is plotted in Figure 2c-d. The top of the consolidated layer is defined at the water level, i.e. in the same manner as done by Strub-Klein and Sudom (2012) see Figure 2a. The water level is set to zero depth for all plots of cross sections in this paper. Maximum thickness of consolidated layer is 3.0 m with an average of 1.32 m along the spine. As seen in Figure 2c, the consolidated layer at the holes A6, A11 and A15 are quite thick and it is possible that it is overestimated since these holes may follow the long axes of stacked ice blocks. The variation of thickness of the consolidated layer along transect B is not as large compared to along the spine. Maximum consolidated layer thickness is 1.9 m, with an average of 1.1 m. The average consolidated layer thickness for the entire ridge is 1.2 m

Ridge R2-2013 surveyed in Olga Strait

Figure 3a shows a photo of the ridge 21-2013 surveyed 28 April 2013 and illustrates the drilled cross sections marked as line A along the spine (13 holes drilled at 5 m spacing, see Figure 3a) and two lines B and C across the spine, (17 holes drilled at 2 m spacing for each section). Transects B and C crosses the spine at holes A6/B9, and A10/C9, respectively, see Figure 3b-d.

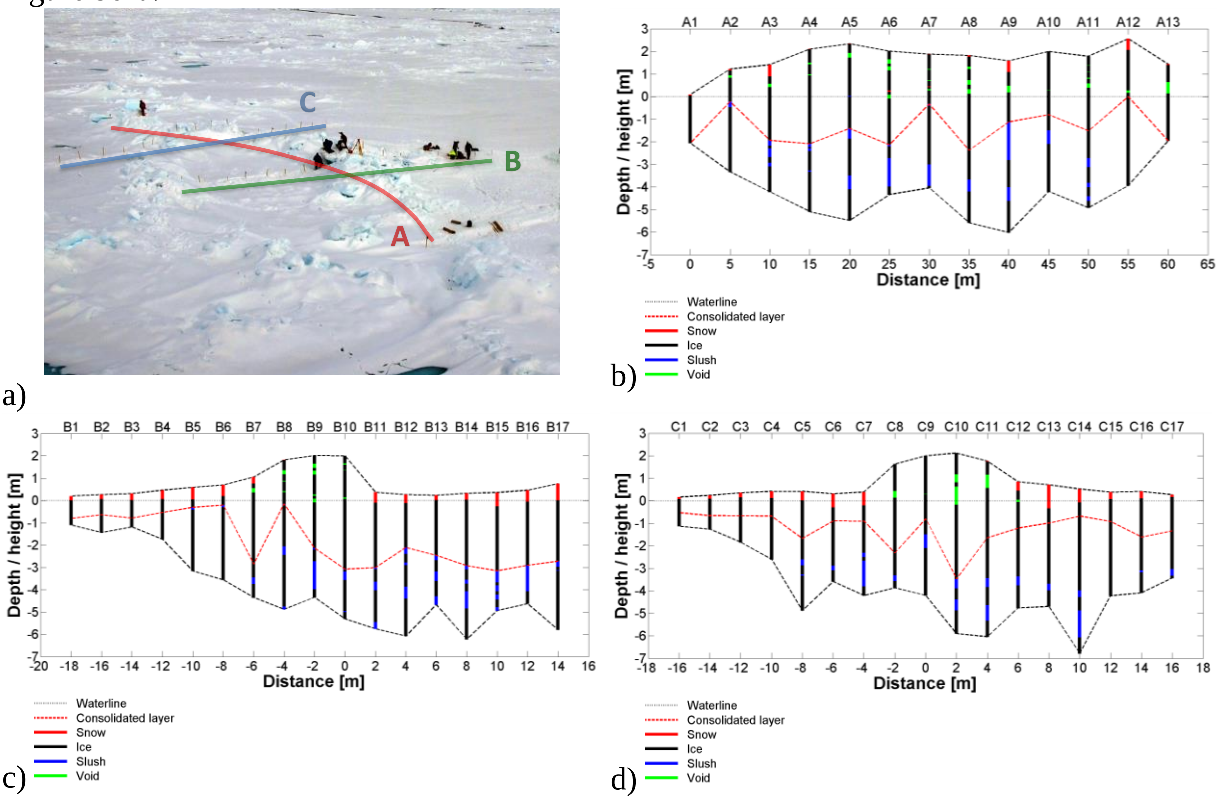


Figure 3. ridge R2-2013 a)Photo of the ridge and illustrates the lines established for drilling of holes along the spine A and cross sections B and C. b) Cross section along the spine c) Cross section along transect B. d) Cross section along transect C

It can be observed from the photo in Figure 3a, that transect B ends where the sail of the next ridge starts, i.e. approximately at hole B17. The shape of the sail in cross section B and C are somewhat rounded at the top. Maximum sail height is 2.6 m, with an average of 1.7 m, and maximum keel depth is 6.0 m with an average of 4.2m. For transect B, the sail and keel width are 12.0 m and 26 m, respectively. For transect C, the sail and keel width are 24.0m and 39 m.

The sail and keel angles vary along the ridge; the sail angle is between 9° and 39°, while the keel angle is between 6° and 20°. The average thickness of the surrounding ice sheet is 0.62 m and the average ice block thickness in the sail was measured to be 0.4 m. The consolidated layer thickness varies between 2.8m and 0.9m, with an average of 1.38 m. The average consolidated thickness is 1.8m and 1.2m for transect B and C, respectively. The average consolidated thickness is 1.5 m for the entire ridge.

Ridge R3-2013 surveyed in Olga Strait

The survey of the ridge R3-2013 took place in Olga Strait 29 April 2013 at air temperature -1°C. The geometry of this ridge was investigated by drilling a profile along the sinuous shaped spine and only one transect, perpendicular to the spine. The drilled sections are marked as line A along the spine and line B crosses the spine as illustrated in the aerial photo shown in Figure 4a.

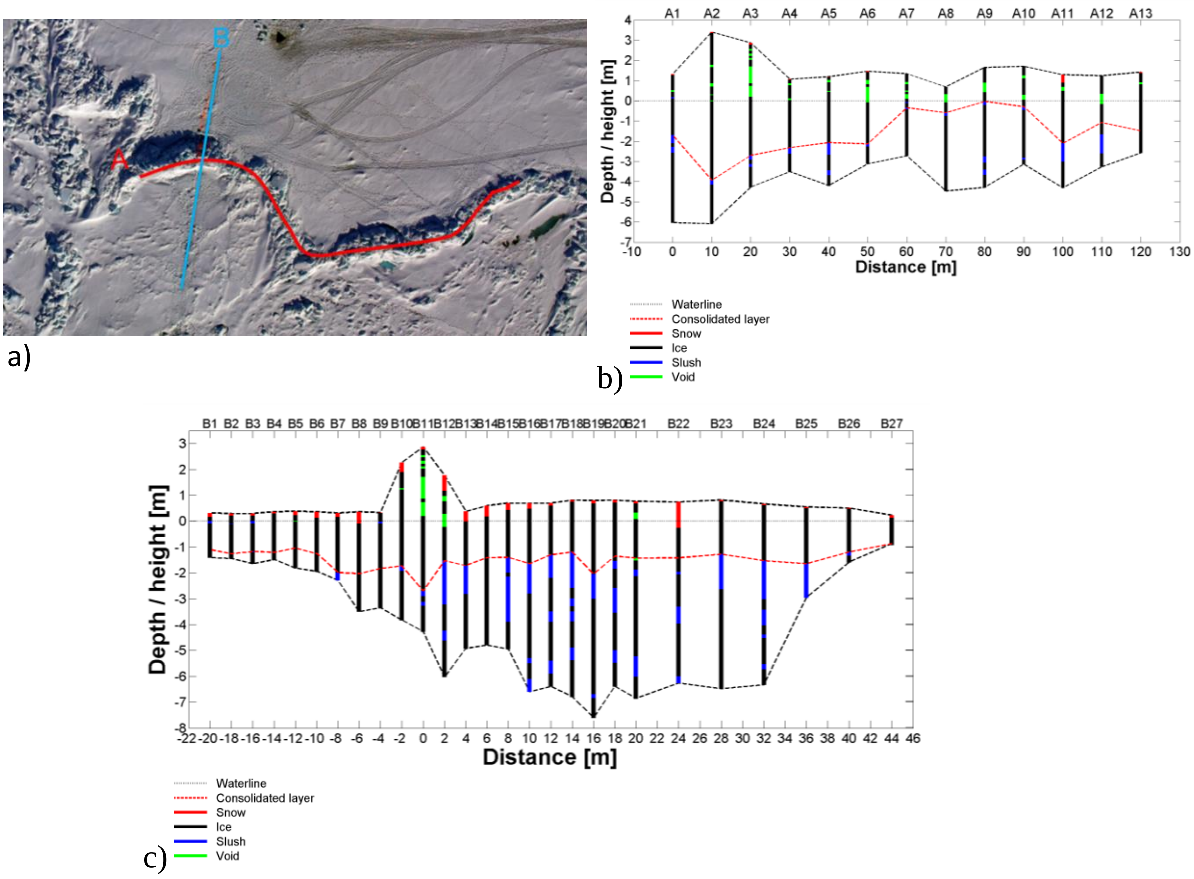


Figure 4. Photo from UAV camera of the ridge R3-2013 and illustrates the lines established for drilling of holes along the spine A and cross section B. b) cross section along the spine. c) Cross section along transect B

The drilled profile along the spine (13 holes drilled at 10 m spacing) of the ridge is shown in Figure 4b, and the profile along transect B (27 holes, 2 m spacing between B1 and B21 and 4m spacing between holes B21 and B27) is shown in Figure 4b. Transect B crosses the spine at hole A3/B11. The sail height along the spine varies between 3.4 m and 0.7 m with an average height of 1.6 m and the keel depth varies between 2.6 m and 6.1m, with an average depth of 4.0 m. The cross section along transect B shows a classic shape with a triangular sail and keel, but the cross section is not symmetric as the top of the sail and bottom of the keel are skewed relative to each other. The sail height and width is 2.9 m and 8m, respectively, with a sail angle of 32°. The keel depth and width is 7.8 and 58 m, respectively, and the keel angles are 11° and 22°. The consolidated layer is very thick, i.e. 3.9 m at hole A2, where the sail is highest. The consolidated layer thickness along transect B is smoother compared to the spine. The average consolidated thickness is 1.6 m along the spine, and 1.5 m for transect B. The average consolidated thickness is 1.5 m for the entire ridge. The average thickness of the surrounding ice sheet is 0.61 m and the average ice block thickness in the sail was measured to be 0.26 m.

ANALYSIS AND DISCUSSION

Ridge geometry

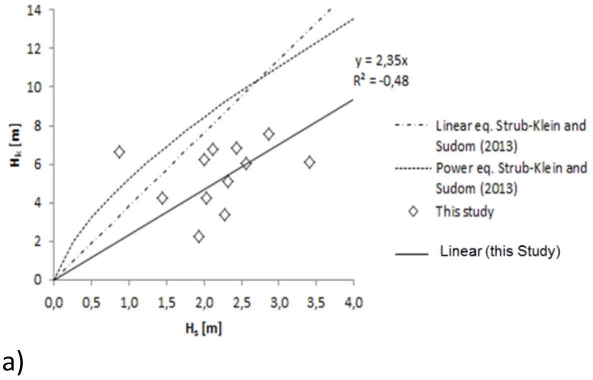
Parametric relationships for the investigated ridges are given in Table 3 and compared with similar data reported by Strub-Klein and Sudom (2012) for large samples of first-year ridges. Figure 5a shows the maximum sail plotted against maximum keel depth for all ridge cross sections, i.e. along all spines and transects. The best linear fit curve is given by H_k=2.35 H_k (n=12). As seen in Table 3, the average H_k/H_s ratio is 2.4 with standard deviation of 0.6. This relationship is considerably lower compared to previous studies on first-year ridges:

- H_k=4.5H_s typical value given by ISO, 19906, (2010)
- H_k =3.95H_s or H_k =4.60 $H_s^{0.88}$ Timco and Burden, (1997); n=97
- H_k =3.54H_s or H_k =4.43 $H_s^{0.82}$ Sudom et al., (2011); n=126
- H_k =3.82 H_s or H_k=5.11$H_s^{0.69}$ Strub-Klein and Sudom, (2012)

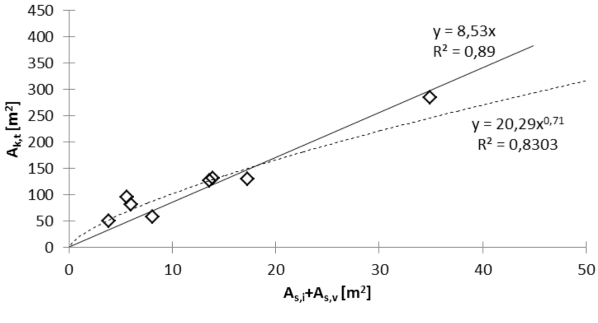
Table 3. Parametric relationships for the investigated ridges compared with relationships values reported by Strub-Klein and Sudom (2012).

Ridge	H_k/H_s [-]	W_k/H_k [-]	W_k/H_s [-]	W_s/H_s [-]	W_k/W_s [-]	h_{cl}/h_i [m]
R1-2011	2.21	7.29	16.11	7.76	2.08	-
R2-2011	2.80	5.45	15.26	2.06	7.42	1.85
R2-2012	3.28	3.58	11.72	3.33	3.52	1.92
R1-2013	1.48	7.69	11.40	3.51	3.25	1.86
R2-2013	2.65	4.42	11.72	6.25	1.88	2.38
R3-2013	2.23	7.63	17.01	2.35	7.25	2.53
Avg.	2.44	6.01	13.87	4.21	4.23	2.11
Strub-Klein and Sudom (2012)	5.17	4.85	20.91	3.75	6.75	1.33-1.83

The comprehensive study by Strub-Klein and Sudom (2012) includes all relevant data from Timco and Burden (1997), Sudom et al. (2011) and Strub-Klein (2011). The best fit curves obtained by Strub-Klein and Sudom (2012) are also shown in Figure 5. As seen in the figure, the data have quite a bit of scatter. Strub-Klein and Sudom (2012) also reported a substantial spread when analyzing their data.



a)



b)

Figure 5. a) Keel depth versus sail height for all drilled profiles along transects and along spines. b) Keel area versus sail area.

The total area of the sail $A_{s,t}$ is the sum of the area of snow, $A_{s,t}$, voids $A_{s,v}$, area of ice $A_{s,i}$, and slush $A_{s,sl}$ (due to warm spell or rain), while the total area of the keel $A_{k,t}$ is the sum of the area of ice $A_{k,i}$ and water filled voids $A_{k,v}$. Figure 5b shows a plot of the total keel area $A_{k,t}$ versus the ice and void area of the sail $A_{s,i}+A_{s,v}$, i.e. total sail area exclusive the area of snow. The best linear relationship is $A_{k,t}=8.53(A_{s,i}+A_{s,v})$ ($R^2=0.89$) or a power relationship $A_{k,t}=20.29(A_{s,i}+A_{s,v})^{0.71}$ ($R^2=0.83$). This is close to the relationships found by Timco and Burden (1997): $A_{k,t}=7.96(A_{s,i}+A_{s,v})$ or a power relationship $A_{k,t}=17.46(A_{s,i}+A_{s,v})^{0.82}$.

Ridge morphology and porosity

Ice blocks dimensions in sail

Although block thicknesses in a ridge sail can decrease as the season progresses, the blocks are considered to be a better representation of the original level ice thickness at the time of ridge formation than the level ice surrounding the ridge at the time measurements are made.

There was a great variety of ice block shapes. Principally the block shape can be classified as square, rectangular or triangular. The size and shape of the blocks is given by the thickness h_b, width W_b and length L_b, and the longest aspect of the block is defined as block length and the shortest is defined as thickness. The inclination angle α_b, measured from the horizontal plane defines the block orientation. Average values of measured ice block dimensions in sails are summarized in Table 4. The ice block length to block thickness ratio L_b/W_b defines shapes of the ice blocks. The aspect ratio L_b/W_b increases from 1.0 for quadratic (or triangular shape), to more rectangular or elongated triangular shape for higher aspect ratios. The sail of R2-2012 is made of the thickest ice blocks with an average block thickness of 0.87 m. The average block width block and length are 1.6 m and 1.7 m, respectively. For the two ridges with thinner ice blocks, maximum values of L_b/W_b are between 3.3 and 3.6. Most of the thickest ice blocks in ridge R2-2012 were lying in a flat or near flat position, i.e. the inclination angle α_b is less than 20^o for more than 80% of the blocks. For ridges R2-2013 and R3-2013, with intermediate and thinnest blocks, the block orientation seems random as the inclination angle α_b is, more or less, evenly distributed in the range of 0^o to 90^o.

Table 4. Average values of measured ice block dimensions.

Ridge	h_b [m]	W_b [m]	L_b [m]	α_b [deg.]
R2-2012	0.87	1.6	1.7	14
R1-2013	0.45	-	-	-
R2-2013	0.36	1.0	1.4	48
R3-2013	0.25	1.0	1.3	48

In this study the average block thickness h_b=0.48 m, block width W_b=1.2m and L_b=1.5m. The average block thickness and block width are in the same range as average values reported by Strub-Klein and Sudom (2012) (h_b=0.67m, W_b=0.88m and L_b=9.47m), but the average block length in this study is considerable shorter. Strub-Klein and Sudom (2012) pointed out that the high value for ice block length may be due to some large block thicknesses up to 1.9 m in Barents Sea. The best fit line is given by $h_b=0.79h_i$ with coefficient of determination $R^2=0.69$. The slope of this line is considerable steeper than the best-fit line obtained by Strub-Klein and Sudom (2012), i.e. $h_b=0.43h_i$.

The block thicknesses were considered more relevant than the surrounding level ice thickness to relate to the sail height. It is common to relate the maximum sail height to the square root of block thickness as given by Eq. (1):

$$H_s = a\sqrt{h_b} \qquad (1)$$

The best fit curve for this study is a=3.36. The fitting parameter a is found to be between 3.69 and 3.71, (Tucker and Govoni, 1981, Tucker et al. 1984, Strub-Klein and Sudom, 2012). There is a considerable scatter in the data, and as pointed out by Tucker and Govoni (1981), this model does not indicate whether the ridges have reached their maximum sail height or not.

Porosity of surveyed ridges

The porosity is an important property of a ridge as it indicates its degree of consolidation and therefore factors into a better estimation of the force a ridge can exert against a structure. Porosity of ice rubble η_m is defined as $\eta_m = V_c/V = 1 - V_i/V$, where V_c is the volume of voids between the solid ice blocks (water, slush, snow and air) and V_i is the volume of solid ice blocks. The porosity can be estimated for every part of the ridge and can vary as a function of depth and/or ice temperature. It is often estimated from one cross section, and these results might not be representative of the whole ridge porosity, since a single (or several) big void(s) could have been detected or missed when drilling. Table 5 summarizes the porosities of the surveyed ridges.

Table 5. Porosity of surveyed ridges.

Ridge	sail $\eta_{m.,s}$ [%]	keel $\eta_{m.,k}$ [%]	ridge $\eta_{m.}$ [%]	$R_{snow} = A_{s,sn}/A_{s,t}$ [%]
R1-2011	73	11	21	72
R2-2011	0	13	12	0
R2-2012	54	6	12	40
R1-2013	43	4	15	40
R2-2013	48	14	19	27
R3-2013	33	16	20	15
Avg. along spines	26	10	15	13
Avg. along transects	50	10	17	44
Avg. all ridges	40	11	16	32

The average sail porosity along the spines is lower than the sail porosity along transects. The reason for this effect is the higher snow contents along transects compared to the spines, as snow tends to be blown off the top of the sail at windy conditions. Porosity of sail $\eta_{m,s}$ is plotted vs. porosity of keel $\eta_{m,k}$ for all drilled sections in Figure 6.

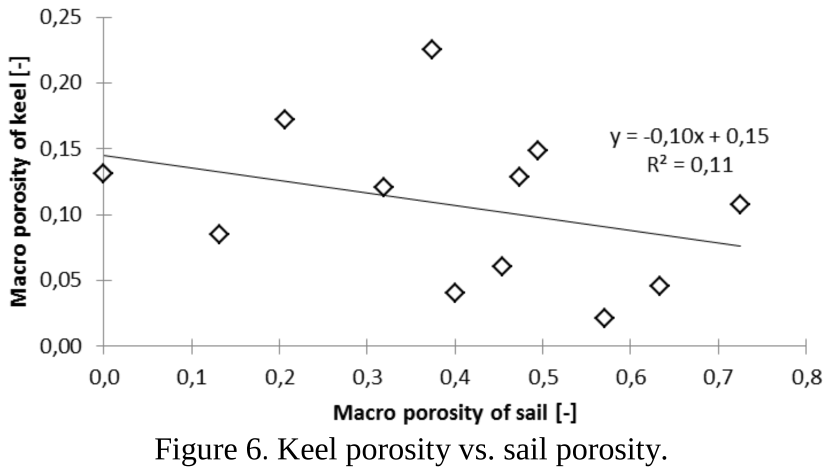


Figure 6. Keel porosity vs. sail porosity.

Due to the small number of data points, no clear relationship can be seen. The best-fit line is given by Eq. (2):

$$\eta_{m,k} = -0.10\eta_{m,s} + 0.15 \quad (2)$$

That is, for this data set, the keel porosity appears to decrease as the sail porosity increases. Timco and Burden (1997) performed an analysis to determine the porosity of the sail and keel regions, based on an assumption of iso-static equilibrium for the ridge. Using this approach, the best-fit equation obtained by Timco and Burden (1997) is given by Eq.(3):

$$P_k = 0.73P_s + 0.14 \quad (3)$$

i.e, the keel porosity increases as the sail porosity increases. Timco et al. (2000) suggested that a ridge is in iso-static equilibrium if keel porosity increases as the sail porosity increases, while ridges showing the opposite trend are not in iso-static equilibrium. This has to be investigated further.

Consolidated layer

The spatial variation of the consolidated layer thickness is an important input in the improvement of ridge loads predictions. The dynamics around ridges can be such that the surrounding ice thickness changes with time; more rafting events can occur, or the existing surrounding ice can grow, melt or even disappear. As shown in Table 3, the average consolidated thickness for all ridges is 1.50 m and is in good agreement with the value of 1.47 m reported by Strub-Klein and Sudom (2012) for Barents Sea. Bonnemaire et al. (2003) assumed a consolidated layer to level ice ratio between 1.3 and 1.6 in the ridge they investigated in the Barents Sea. Høyland (2007) reported a ratio of 2.0 for three ridges in the Barents Sea, but also identified the difficulty of measuring an undisturbed level ice close the ridges. Strub-Klein and Sudom (2012) reported a ratio 1.83. This is only slightly lower than the average ratio of 2.11 (median is 1.92) found for the investigated ridges presented herein. The Arctic structures standard (ISO 19906, 2010) recommend that in the absence of field data, to assume the consolidated layer is twice as thick as the surrounding level ice which has grown under the same conditions as the ridge.

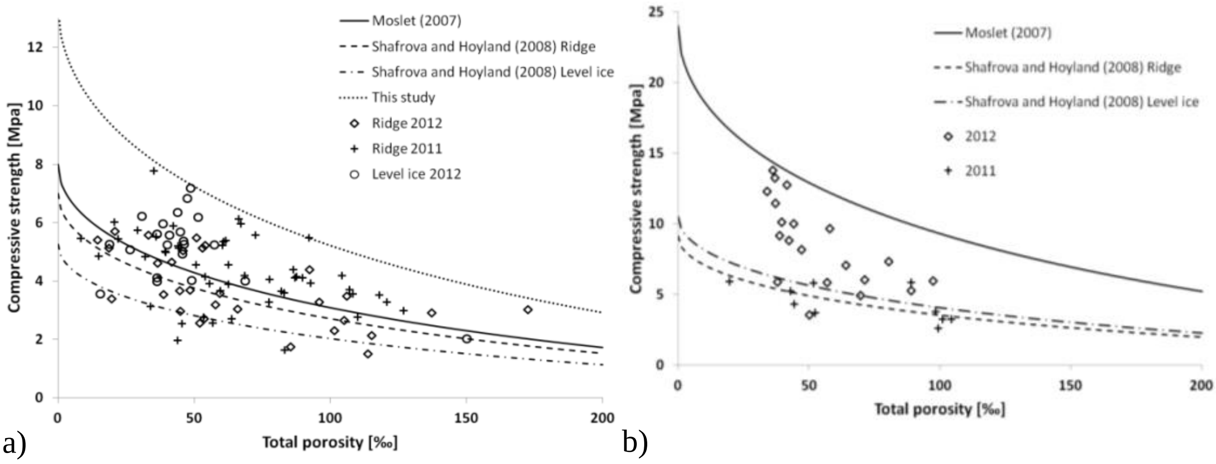
Uniaxial compressive strength

Expressing ice strength as a function of strain rate and total porosity was suggested by Timco and Frederking (1990). They presented this relationship for different crystal types, loading directions and strain rates between 10^{-7} and 10^{-4} s^{-1} at which ductile failure of ice is expected. Since most of our samples showed ductile material behaviour, this approach might be applicable even at a strain rate of 10^{-3} s^{-1}. Anyhow a fit of the data was not successful. Moslet (2007) proposed that the maximum compressive strength of ice can be estimated by the total porosity ν_t as given by Eq. (4):

$$C_i = A_i(1 - \sqrt{\frac{\nu_t}{B}})^2 \quad (4)$$

Where $i=h$ for compressive strength in horizontal direction and $i=v$ for vertical strength. A_i is a fitting parameter and B is the limiting porosity at which sea ice loses its strength, B=0.7 is chosen by Moslet (2007) and empirical values for parameter A_h =8 MPa for horizontal and A_v=24 MPa for vertical loading. Moslet (2007) assumed, independent of the total porosity, a constant proportionality C_v/C_h of 3 between vertical and horizontal strength. Shafrova and Hoyland (2008) used the same function after testing 376 specimen from both level ice, consolidated layer and ice rubble, yet when fitting to their maximum values A_v=10.5MPa and

A_h=5.25 MPa for vertical and horizontal strength in level ice and A_v=9.1 MPa and A_h=7 MPa respectively for ice samples taken from the consolidated layer. Regarding horizontal strength, Figure 7a shows that our data are clearly higher and a new parameter A_h=10.3 MPa is representative for both level ice and consolidated layer. Even though only a small number of vertical tests were performed in this study, Moslet's (2007) approach is valid for our data, as can be seen in Figure 7b. Unlike Shafrova and Hoyland (2008) the maximum strength for level ice was higher than for ice in the consolidated layer in 2012. By analysing the crystal structure profiles from each borehole from ridge R2-2012, it was found that the closer the samples were located to the centre of the keel, the more ice with a mix of columnar and granular grains can be expected. In 2012 61% of the samples from a ridge were classified as mixed ice, and in 2011, 90% of the specimen were of mixed type.



a) b)

Figure 7. a) Horizontal and b) vertical compressive strength for all tested specimen at strain rate 10^{-3} s^{-1} and temperature -10° C. The level ice samples are marked with a circle; all other samples are from consolidated layer. Trend lines expressing maximum compressive strength are added from earlier studies.

SUMMARY

During three expeditions in March 2011, March 2012 and April/May 2013 with the Norwegian coastguard vessel "KV Svalbard", two pressure ridges around Svalbard, one ridge in Fram Strait and three ridges in Olga strait were studied with respect to ridge geometry and physical and mechanical properties. The key results from this investigation are summarized below:

- In this study, the following maximum values were obtained: sail height H_s=3.4m, keel depth H_k=7.6m, sail width W_s=18.0m and keel width W_k=58.0 m.
- The level ice thickness was between 0.37 m and 0.94 m, with an average of 0.66 m.
- Ice block thickness versus average level ice thickness is given by the best fit line h_b=0.79h_i. The slope of this line is steeper than the best-fit line obtained by Strub-Klein and Sudom (2012).
- Keels were relatively shallow in the field studies reported in this paper. The best fit correlation for keel depth and sail height is given by the best fit line H_k=2.35H_k. This relationship is considerable lower compared to previous studies on first-year ridges:
- The keel width to keel depth ratio of 6.0 is higher than reported by Strub-Klein and Sudom (2012) and Timco and Burden (1997).
- The keel width to sail height ratio of 13.9 is lower than reported by Strub-Klein and Sudom (2012), but is comparable to the ratio found by Timco and Burden (1997).

- The average keel width to sail width ratio of 4.23 is lower than the average ratio found by Strub-Klein and Sudom (2012).
- In average the sail width to sail height ratio is 4.21 and is higher than reported by Strub-Klein and Sudom (2012)$_s$.
- The best linear relationship for total keel area $A_{k,t}$ versus total sail area exclusive the area of snow is $A_{k,t}$ =8.53($A_{s,i}$+$A_{s,v}$) This is close to the relationships found by Timco and Burden (1997).
- Maximum sail height is related to the square root of block thickness given by $H_s = 3.36\sqrt{h_b}$, which is lower than reported by Strub-Klein and Sudom (2012).
- The best fit line between keel- and sail porosity is given by $\eta_{m,k} = -0.10\eta_{m,s} + 0.15$. In comparison Timco and Burden (1997) found the relationship $P_k = 0.73P_s + 0.14$.
- The consolidated layer thickness to level ice thickness ratio of 2.1 (median of 1.92) is slightly higher than reported by Høyland (2007) and Strub-Klein and Sudom (2012).
- The uniaxial compressive strength is given as $C_i = A_i(1-\sqrt{\nu_t / 0.7})^2$, where i=h for loading in horizontal direction and i=v for vertical strength. For the consolidated layer, A_h=10.3 MPa and A_v=10.5MPa. For level ice with columnar crystal structure, A_h=10.3 MPa and A_v=24 MPa when loaded in horizontal and vertical direction, respectively.

Fieldwork in ice infested waters is difficult and requires time, manpower and sufficient economic resources, which are often not available for complete investigations of ridges. Knowledge gaps in sea ice ridge properties have been identified by Strub-Klein and Sudom (2012) and Sudom and Timco (2013). In this work, an attempt is made to address some of these knowledge gaps carrying out better mapping of the keels including both longitudinal and cross sectional profiles of each ridge. Ridge widths are also seldom mentioned in the literature, which is important to note since keel widths can be crucial in the prediction of ice loads on structures. Another important dimension too seldom reported is the keel area, which would also give an indication of the shape of the keel. Very few data are available on ridge widths and angles. All these properties were also analyzed as part of the field work presented herein. The consolidated layer thickness is a crucial element in terms of ridge actions against Arctic offshore structures, yet it is not always reported. We examined the variation of the consolidated layer thickness and made comparisons of uniaxial compressive strength of the consolidated layer of ridges and the surrounding level ice.

ACKNOWLEDGEMENTS

The work reported in this report was funded by the Research Council of Norway, project no. 195153 (ColdTech) and consortium partners.

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