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A REVIEW OF THE MORPHOLOGICAL AND MECHANICAL PROPERTIES OF FIRST-YEAR SEA ICE RIDGES

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ABSTRACT

A review of full-scale first-year sea ice ridges is presented with a special focus on the morphological and mechanical properties. Ridges from 1971 to present are described. The study area covers the Arctic Ocean, the Canadian and Russian Seas, the Barents Sea, the Baltic Sea and the fjords of Svalbard. The morphological properties (e.g. the sail height and the keel depth) of 204 ridges are listed. The morphology of a ridge is commonly specified by the keel-to-sail ratio, which is influenced by the shape of the ridge itself and the calculation method. Each of these calculation methods leads to much different results and interpretations. The correlation between the sail height and the keel depth was best characterized by a logarithmic relationship. A short statistical analysis revealed that the keel-to-sail ratios had a lognormal distribution. Finally, determining the strength of a first-year ice ridge is more difficult than level ice. It can be described by “localized” tests (confined and unconfined compressive tests, drop ball tests), where separate samples from the ridge are tested, or by “globalized” tests (direct shear tests, punch shear tests), where the resistance of the whole structure is tested. Very little data exist and are available, but a list of authors reporting such tests is given as well.

INTRODUCTION

Sea ice ridges are a special feature of the ice cover, created by shear or compression. They are an accumulation of ice blocks partly refrozen together and therefore consist of sea ice (pure ice and brine), air and water. Ridges are classified by their age. This paper will focus on full-scale first-year ridges.

Ridges are complex structures with a high variability of shape and size, but are usually composed of three distinguishable parts: the sail (above the waterline) and the keel (below the waterline). The keel itself is divided into a consolidated layer, where the broken pieces of ice have refrozen together, creating a layer of consistent ice, and the rubble, where all the blocks pushed down are partially refrozen together. Water is trapped in between the ice pieces.

First-year ridges are usually sketched as isoscele triangles and characterized by their widths, thicknesses and angles (Figure 1).

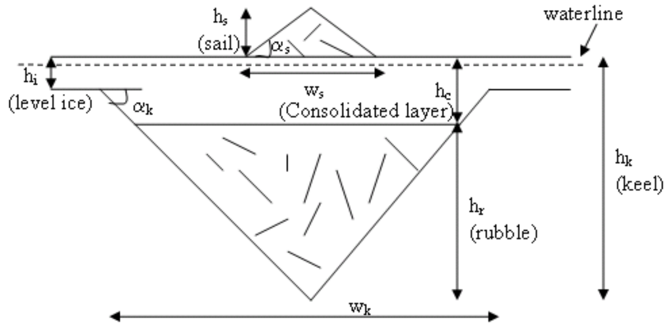

Figure 1. Common morphological model for ice ridges

Some of these dimensions are used to establish functional relationships such as the keel-to-sail ratios, essential when it comes to shipping or designing arctic offshore structures. In fact, ice ridges can generate high loads against offshore structures such as platforms or pipelines and are, in the absence of icebergs, the design load in many arctic marine areas (Blanchet, 1998). The macroporosity of the rubble and the physical and mechanical properties of a ridge are important inputs for the calculation of these loads. However, models and codes describing the load that ridges exert on structures are still incomplete because very little is known about their properties and internal composition. Therefore, one needs to know better the strength of a ridge. Different methods can be used to determine it and they will be explained in a further section of this paper.

Descriptions of ridges have been published over the last 20 years, focusing on different aspects. Burden and Timco (1995) and Timco and Burden (1997) collected data from 1971 until 1995 and presented a detailed analysis of the shape of ridges. The aim of this paper is somewhat similar, but updates their work with 13 more years of data by summarizing most of the available information collected on first-year ridges morphology and strength since 1971. Information about first-year sea ice ridges characteristics were obtained from 38 different sources, covering a large area in the Arctic region: the Barents Sea, the Arctic Ocean, the Canadian and Russian Arctic areas, the Svalbard archipelago and the Baltic Sea. In total, the morphology of 204 ridges has been summarized. In addition, a list of the authors presenting mechanical tests performed in field in first-year ice ridges is given. The present study is not complete, but gives a first good overview of first-year ice ridges studied over the world.

METHODOLOGY

Definitions

The sail height (h_s) is the distance between the waterline and the top of the ridge. The keel depth (h_k) is the distance between the waterline and the bottom of the ridge (see figure 1). The keel-to-sail ratios are defined as h_k/h_s.

These ratios can be calculated by three different ways which also lead to three different values of the same fraction. Method 1 consists in only considering the maximum sail measured and the maximum keel measured amongst all the boreholes. 92% of the keel-to-sail ratios presented in this study have been calculated that way. Method 2 consists in dividing the average keel depth by the average sail height (Williams and Kirby (1994), Beketsky et al (1996), Kharitonov (2007), Strub-Klein et al (2009)). Method 3 consists in determining the keel-to-sail ratio for each borehole and calculating the average. None of the presented authors have used it. Kankaanpää (1997) also proposed a calculation based on Archimedes's law, and compared the keel/sail ice

volume instead. She showed a significant difference in the results. In addition, it should not be forgotten that a ridge can present a multitude of shapes. Determining their corresponding ratio is done by using Newton's 3rd law, when the buoyancy force and the gravity force are in equilibrium. However, these calculations require knowledge on the macroporosities, the widths, the angles and the heights of both the keel and sail, which are seldom.
A point of interest developed in a further section was to know which statistical distribution the keel-to-sail ratios followed best. The best match was found using the Quantile-to-Quantile plots (QQ-plots) method. A QQ-plot is a graphical technique for determining if two data sets come from populations with a common distribution. It represents the quantiles of two distributions against each other. It is common to add a line y=x on a QQ-plot. If the two distributions that are compared are identical, the plots should follow that line.

Geometry

Several procedures exist to measure the sail height and the keel depth. A theodolite was most often used to survey the surface elevation, as described by Voelker et al (1981a,b), Kankaanpäa (1997), Leppäranta and Hakala (1992), Løset et al (1998), Høyland and Løset (1999a), Bonnemaire et al (2003), Høyland (2005), Høyland (2007), and Shafrova and Høyland (2008).
The thickness of the consolidated layer can be determined by:
- using a power auger (generally 2''diameter). The consolidated layer ends when the ice becomes softer or when some water/slush is brought up by the drill (Evers (1986), Kankaanpää (1997), Johnston and Barker (2000), Høyland (2002a), Strub-Klein et al (2009)).
- deploying some thermistor strings and recording the ice temperature. If $T<T_f$ (where T_f is the freezing point of sea ice), the sensor is still in the consolidated layer. If $T=T_f$, the sensor is in the rubble (Løset et al (1998), Liferov and Høyland (2004), Høyland et Liferov (2005)). Høyland (2002a) actually compared both temperature measurements and drilling results. More details are given in Høyland (2002b).
- thermal drilling. This method is well described by Surkov and Truskov (1995), Mironov et al (1998), and Kharitonov (2007). The thermal drill consists of a warm drill being progressively inserted in the ice. The ice consistency and the ridge macroporosity are estimated with the penetration rate recordings.
Hniatuk (1978), Voelker et al (1981a,b) and Leppäranta and Hakala (1992) also reported observations from divers that checked the profile drillings and measured the dimensions of the submerged blocks.

Mechanical properties

Many mechanical tests exist to characterize the resistance of a ridge. Timco et al (2000) list and give a detailed description of the different techniques.
-**Compressive tests**: Samples for the ridge are tested in a compression rig (Veitch et al (1991), Høyland et al (2000), Høyland (2002a), Bonnemaire et al (2003), Høyland (2005) and Shafrova and Høyland (2008)). The ice is placed between two platens and the applied load as well as the displacement of one platen is monitored while the other platen is fixed.
- **Confined compressive (in-situ) tests**: Evers (1986) investigated the confined in-situ strength of first-year ridges with a borehole jack. This device is composed of a hydraulic cylinder equipped with an indentation plate coming out from one side of the piston housing. Both displacement and pressure are recorded.

- **Drop ball tests**: they determine the hardness of the ice (Bonnemaire et al (2003) and Høyland and Liferov (2005)). The procedure of the test is described by Khrapaty and Wessels (1984). A steel ball of a given diameter is being dropped from a certain height. The hardness of ice is obtained by studying the impact of the ball onto the ice.
- **Shear tests**: Direct shear tests, punch shear tests and pull up tests usually determine the shear strength in the rubble. The direct shear test is described by Leppäranta and Hakala (1992) and Croasdale et al (2001). A trench is dug through the consolidated layer of the ridge and a rectangular slab is isolated. The load required to displace the slab horizontally is measured and its corresponding displacement is recorded. As the failure plane occurs at the bottom of the consolidated layer, the shear strength of the top of the rubble will be obtained. The punch shear test is described by Croasdale et al (2001) and Heinonen (2004). A plug of the consolidated layer is cut through the underlying rubble. A load is then applied to determine the failure of a plug of the keel downwards. It is then possible to get the in situ shear strength of the ridge. Pull up tests are also described by Croasdale et al (2001). This helps to verify the existence and the nature of the bonds existing between the consolidated layer and the rubble. It consists in cutting a rectangular slab in the consolidated layer and inserting a toggle through a hole near the centre of the slab. The ice block will fail any bond between the slab and the rubble.

Some other tests like the ice scouring test and the shear off test have been performed by Liferov and Høyland (2004). The first experiment aimed at getting more information about the scouring of rubbles, such as the penetration depth and the load generated by the ridge on the seabed while towing the artificial ridge, whereas the second experiment provided some information about the shear strength of the keel.

RESULTS

First-year ice ridges morphology

Figure 2 shows all keel depths and sail heights reported in different articles and the frequency histogram of the keel-to-sail ratios. The left graph shows the correlation between the sail height and the keel depth for 204 ridges.

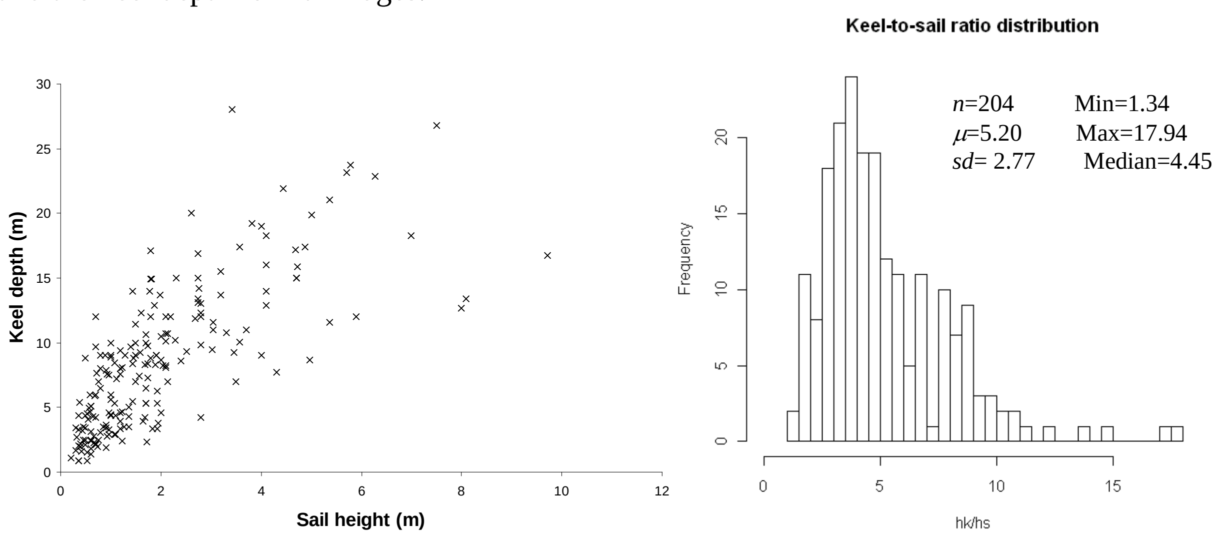

Figure 2. Keel-to-sail ratios for first-year sea ice ridges

n is the number of samples, *μ* is the average ratio and *sd* is the standard deviation. The scale of the histogram is such that one bar corresponds to a step of 0.5 in the value of the ratios. The right

tail on the histograms reflects very high h_k/h_s ratios. They result from ridges presenting high keels and very low sails. A possible explanation would be some misinterpretation of the measurement technique as the lower boundary of the rubble is often difficult to determine. Slush could be “felt” (when drilling for example) as a part of the rubble when it is usually considered as part of the macroporosity of the ridge (Strub-Klein et al, 2009).
The ratios were also separated according to the area and the method of investigation (see Table 1). The total number n_{ratios} of ratios (which is also the number of cross-sections) is different from the number of ridges (n_{ridges}) investigated because several cross-sections had been made on some of them (see further) or because only mechanical tests were performed (Croasdale et al (2001), Heinonen (2004)). In most of the papers summarized in that review, only the maximum sail and the maximum keel depth were given so that the number of measurements made on the ridge is unknown. Therefore the minimum number of cross-sections made on a ridge could actually just reflect the fact that the authors only gave the maximum sail height and the minimum keel depth from all the measurements they made.

Table 1. Ratios per area and per technique

Area						**Method**		
	hk/hs	n_{ratios}	n_{ridges}	*min CS/ridge*	*max CS/ridge*		*hk/hs*	n_{ratios}
Baltic Sea	6.64	56	43	1	8	Drilling	5.83	101
Barents Sea	4.27	12	7	1	4	Diving	6.68	15
Arctic Ocean	5.21	7	4	1	2	Thermal drilling	5.25	31
Russia	5.18	25	22	1	2	Survey+Sonar	5.43	8
Svalbard	4.73	8	8	1	1	Drilling+Sonar	3.11	9
Canada	4.53	96	88	1	4	Drilling+Survey+Sonar	3.42	40

CS: cross-section

The highest average ratio obtained when differentiating by areas was in the Baltic Sea. It is very close to the average ratio proposed by Kankaanpää (1997). The Arctic Ocean and the Russian areas present similar ratios around 5.2, whereas the ratios for Svalbardian and Canadian Sea ridges are close to 4.6.

First-year ice ridges mechanical properties

Scarce but various mechanical tests have been performed on first-year sea ice ridges. It is due to this large variety of tests that comparing the strengths with only a few details on the set-up and the measurements would lead to important inaccuracies and maybe misunderstandings. Therefore it was chosen in this paper to present the authors who report mechanical tests performed on first-year sea ice ridges. They were classified by the area of investigation.

- **Canada:**

Croasdale et al (2001) proceeded to 11 direct shear tests, 9 punch shear tests and 8 pull-up tests in field from February to March 1997.
Evers (1986) used the borehole jack on 2 ridges as an indicator of the confined compressive strength of the ice in the sail. The ice was tested along a cross section (8 holes) in the sail of the ridge and at 3 different depths per hole. In total, 48 borehole jack tests were reported.
McGonigal (1978) also perfomed 13 borehole jack tests on 13 ridges in April-May 1978.

- **Baltic Sea:**

Heinonen (2004) carried out 12 full-scale punch shear tests from 1998 to 2001 (in February-March) whereas Leppärantä and Hakala (1992) proceeded to 5 direct shear tests. Høyland et al.(2000) and Veitch et al (1991) performed uniaxial compressive tests. Høyland et al. (2000) tested 46 samples from different depths of one ridge at a loading rate of $\dot{\varepsilon} = 10^{-3}s^{-1}$. The tests were carried out in a cold laboratory and the temperature of the ice was -10ºC. The sampling had taken place between February and March 1999. Veitch et al (1991) proceeded to 56 unaxial compressive tests on ice samples taken in the sail and the consolidated layer of two ridges. The ice was brought back and tested in the cold laboratory of the research vessel they were using.

- **Barents Sea:**

Bonnemaire et al (2003) tried the drop ball testing technique on every part (sail, CL and rubble) of the ridge in May 2002 while Høyland et al (2003) report 144 uniaxial compressive tests performed on samples from the same ridge brought back in a cold laboratory and tested 5 months later at two loading rates: $\dot{\varepsilon} = 10^{-3}s^{-1}$ and $\dot{\varepsilon} = 10^{-4}s^{-1}$. Høyland (2007) reports uniaxial compressive tests for the ice taken in the sail and the keel and in the surrounding level ice. He differentiated vertical and horizontal samples. In total, 387 samples were compressed both in lab and in field. The samples were collected in May 2004 and 2005.

- **Arctic Ocean:**

Shafrova and Høyland (2008) also tested the ice constituting the keel of a ridge and the level ice. In total, 180 tests were carried out. The samples were both horizontally and vertically orientated and compressed in field in May 2006.

- **Svalbard:**

Høyland and Liferov (2005) built 2 mini-ridges in a fjord on Svalbard and performed some drop ball tests in the rubble and the level ice in April 2003.

Not all mechanical tests reflect the same property. Some, like the punch shear tests, give an indication of the resistance of the keel as a whole whereas the compressive tests for example give a more localized indication of the strength of the ice constituting the ridge.

The punch shear test results as reported by Heinonen (2004) indicate a wide variability. The shear strength depends on the ridge morphology. Although it was not obvious, Heinonen (2004) reported that the higher the thickness of the keel, the higher the load capacity.

It seemed that uniaxial compressive tests are the most employed to determine strength in ice ridges. Level ice and sail strengths are most often estimated, because the ice is easier and faster to sample. When the strengths of the sail, the consolidated layer and the rubble were all assessed, it appeared that the ice of the sail was the strongest and the ice from the rubble was the weakest. It is believed that at the time the tests were performed, the cold air temperature was having a stronger influence on the ice of the blocks permanently exposed in the air, contrary to the level ice which endures warm heat fluxes from the water below. However, the temperature is not the only factor that governs the ice strength. Amongst them one can quote the salinity, the grain size and orientation, the testing conditions, the testing speed and the degree of consolidation of the ice (eg the porosity).

DISCUSSION

Morphology

The keel-to sail ratios may vary from one region to another mostly because the same method was used in the same area. For example, the thermal drilling has been almost exclusively utilized in the Russian Seas and the Arctic Ocean (except for Shafrova and Høyland (2008) who drilled through the ridge). Therefore the ratios from Russia and thermal drilling are closely related. In addition, it was observed that the techniques including a sonar resulted in a lower ratio. This measurement technique could indicate lower keel depths, because of possible misinterpretations of the observations. Each technique has its pros and cons. The mechanical drilling has for big advantage to be rapid and easy. On the other hand, one loses quite some accuracy in the measurements and the estimation of the boundary between the consolidated layer and the rubble strongly depends on the operator since he/she has to feel the ice consistency. The sonar is also easy to deploy but could not reflect the whole thickness on the ice if some blocks are loose or if there is a lot of slush. Diving requires more manpower and qualified people. It is a more risky and expensive method which would give a good indication of the ice consistency but not necessarily accurate measurements of the ice thickness. The thermal drilling is longer to deploy because electrical power is needed, but the results are more reliable. Also, the acquisition of such equipment can be costly. Nevertheless, this method is accurate and one evaluates not only the ice thickness but also the ice consistency (and therefore the different parts of the ridge) with great precision.

Usually, only a part of the ridge is examined due to lack of time, relevant material, or quickly changing weather conditions, and the surveying area is generally chosen to be easy to drill. Therefore, the complete shape of the ridge is almost never surveyed. Even so, very few studies took place during several days and presented a more complete description of the shape of the ridge (Leppäranta et al, 1995 - 3 visits of a ridge - 1 cross-section per visit; Veitch et al, 1991 - 2 ridges - 8 and 6 cross-sections; Strub-Klein et al, 2009 - 1 ridge - 4 cross-sections in five days; Evers, 1986 – 4 ridges - 3 cross-sections per ridge; Johnston, 2000 – 2 ridges – 4 cross-sections per ridge).

The keel-to-sail ratios are strongly influenced by the method used to estimate them. Strub-Klein et al (2010) calculated the keel-to-sail ratios of second-year sea ice ridges using the first and the second method described earlier: method 1 gives ratios that are in average 60% higher than the ones resulting from method 2. No details on the cross sections were given in the other papers. This shows that it is important to state how the keel and the sail are measured and specify the data that are reported so to know which computation method was used. But first, it is essential to try to survey the ridge as much as possible to obtain a better overview of the ice feature.

Timco and Burden (1997) tried to establish some relationships between different characteristics of first-year sea ice ridges. In particular, they looked for a correlation between the sail height and the keel depth. They chose to characterize it by a simple linear relationship ($h_k=3.95h_s$ with a coefficient of determination $R^2=0.783$) and by a power relationship ($h_k=4.60h_s^{0.88}$ with a coefficient of determination $R^2=0.793$). These relationships were based on 97 measurements. Kankaanpää (1997) also analyzed the shape of first-year sea ice ridges in the Baltic Sea exclusively. She based her study on 36 ridges and found $h_k=6.355h_s-0.02$ with a coefficient of determination $R^2=0.719$ or $h_k=6.28h_s^{1.015}$ with a coefficient of determination $R^2=0.719$. The amount of data is considerably larger. In the present analysis, a similar work has been performed in order to check the consistency of these ratios. In addition to the linear and power relationships, a quadratic and a logarithmic correlation were examined.

The linear and power fits were very poor and therefore figure 3 only shows the plots for the quadratic and logarithmic fits of the sail heights versus keel depths. The coefficient of determination is strong enough for both models, given the variety of ridges and methods of investigation that have been grouped in this study. In addition, the significance of the two relationships was assessed by calculating the p-value. Both p-values were extremely low, which means that both relationships were significant, or in other words, that the null hypothesis (null hypothesis= there is no relationship between the data and the proposed model) is rejected.

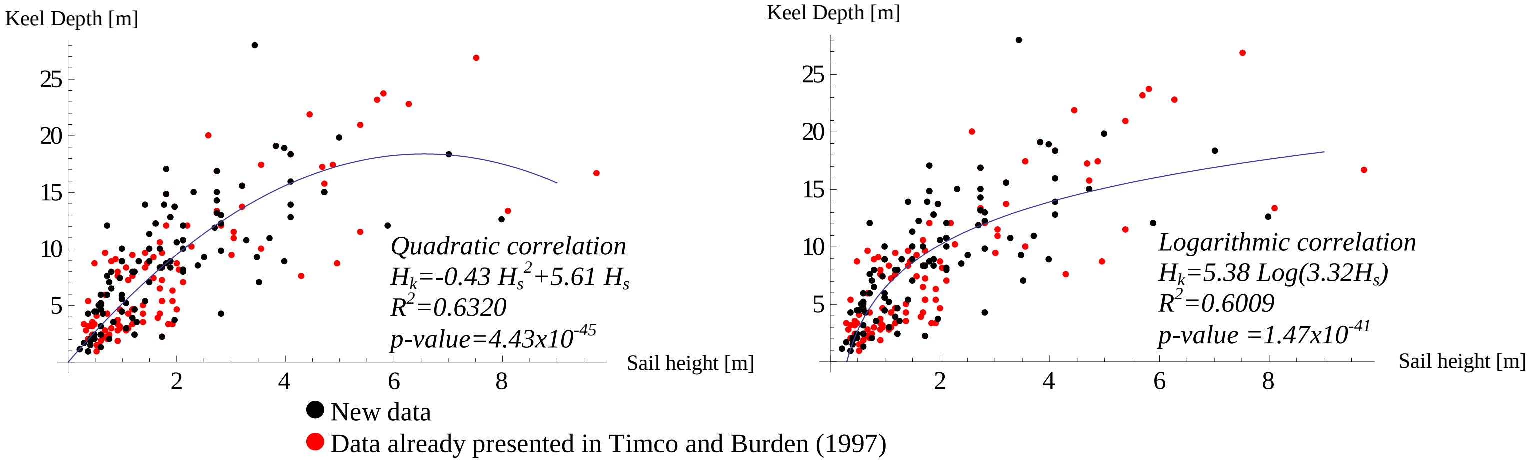

Figure 3. Relationships between the h_k and h_s of 204 first-year ice ridges.

A parabolic relationship reflects a diminution of the keel depth when the sail has reached a certain height. This could seem logical if we think in terms of cohesion: if too many ice blocks accumulate, the keel could collapse and grow in width instead. However, it is very unlikely that for a sail of 13m, the keel would be almost inexistent and that the sail would not collapse too. The logarithmic relationship shows that the keel depth is increasing fast for sails up to 2m high, and that it will reach an asymptotical value, which could also suggest a partial collapse of the ice blocks in the rubble. In that respect, this relationship seems more appropriate to model the correlation between the sail height and the keel depth in first-year sea ice ridges.

As the number of data is not large enough to proceed to a proper statistical analysis, it was decided that the distribution of the keel-to-sail ratio would be determined by comparing QQ-plots for a normal, a gamma, a t-Student and a lognormal distribution (see figure 4).

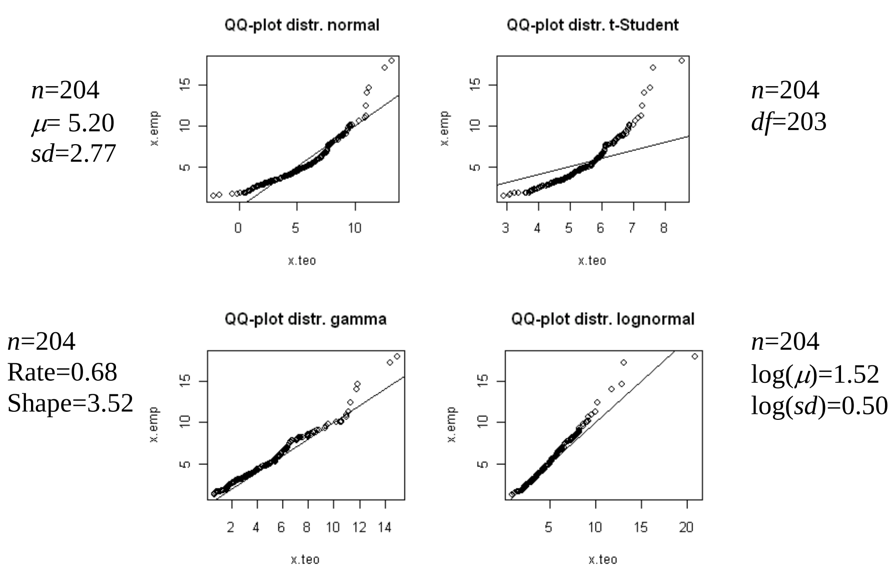

Figure 4. QQ plots for normal, t-Student, gamma and lognormal distribution

Each plot is accompanied by the corresponding parameters used in the computation: *n* is the number of samples, μ the average ratio, *sd* the standard deviation, *df* the degrees of freedom. The shape and the rate are function of the average and the standard deviation.
It appears that the gamma and the lognormal distribution fit best. The lognormal distribution is actually the best match amongst the four proposed models. As a lognormal distribution is commonly used to model statistical processes that tend to create random variables, it seems very suitable to represent the keel-to-sail ratios. Timco and Burden (1997) proceeded to chi-squared tests and goodness-of-fits tests and also found the lognormal distribution as the best match.

Mechanical properties

Loads generated by ice ridges are usually divided into a contribution of the sail, the consolidated layer and the rubble, although the sail contribution is often neglected and that that of the consolidated layer is thought to be the most important. Due to the different failure mechanisms by which the consolidated layer can break, the flexural and crushing strengths should be considered. The strength of the rubble is treated with soil mechanics concepts (Mohr-Coulomb model). The punch tests seem then suitable for this model, since they enable the calculation of the cohesion and the angle of internal friction.
The internal structure of the ridges is not always very well known, which makes the comparison of different tests a bit more inaccurate. In his thesis, Heinonen (2004) used experimental data obtained by several series of punch tests. He performed numerical simulations describing the deformation and the failure modes measured in full scale. The results were quite satisfactory, but for a better model, he recommends to analyze more the spatial dependency of the material parameters, and in particular the evolution of the cohesion through the ridge. In addition, more bending tests should be performed to understand the failure mechanisms at the interface consolidated layer/rubble and to define how much supports results from the rubble.
Very little data of strength measured in the level ice and the consolidated later simultaneously exist. Timco et al (2000) gathered some information on borehole jack tests performed in Canada by Blanchet (1998) and Croasdale (1999) and in Sakhalin by Yashima and Tabuchi (1999) and Smirnov et al (1999), where both the level ice and the consolidated layer were tested. Timco et al (2000) concluded that there was no evidence why the consolidated layer would have a lower crushing strength than the level ice. The ISO codes (2010) also point out the lack of clear indication on how the mechanical properties of the consolidated layer correlate to those of the level ice.

CONCLUSION

A total of 204 first-year ice ridges were examined according to their morphology (sail height and keel depth. Some conclusions of this study are:

- The average calculated keel-to-sail ratio is 5.20, the median is 4.45, the minimum 1.34 and the maximum 17.94.
- The calculation method and the shape of the ridge are crucial for the determination of the keel-to-sail ratios.
- The correlation between sail heights and keel depths can be characterized by a logarithmic relationship expressed by: $h_k=5.38Log(3.32h_s)$ which indicates a stabilization of the keel depth for an increasing sail height, revealing a potential partial collapse of the rubble.

- The keel-to-sail ratios follow a lognormal distribution.

In a further analysis, the change of h_k/h_s for different intervals of the sail height could be studied. The spatial variation of the consolidated layer, although crucial, is not well understood.

Instead of listing values of strength and resistance for ridges, a list of the authors presenting mechanical tests was proposed. An interesting development would be to systematically compare the level ice and the consolidated layer strength so to establish a ratio that would facilitate force estimations of ridges on structure. Many expeditions have been taken place in Arctic regions to examine first-year ice ridges properties, but strength data are still seriously lacking.

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