POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

THE UNIS-BOREHOLE JACK; DESCRIPTION, EXPERIMENTS 2012 AND A REFINED CLASSIFICATION SYSTEM

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ABSTRACT

The *in-situ* confined compressive strength of a variety of ice features has been investigated on three independent research expeditions during 2012; First-year level ice (FYLI) in the Van Mijenfjord (Svalbard) in March, young ice (YI) and rafted first-year ice (RFYI) in the Barents Sea in April, and old level ice (OLI) in the Fram Strait in August. A custom made borehole jack (BHJ) has been used in the expeditions, and a description of the equipment is presented. The classification system of BHJ records introduced by Sinha (2011) has been further developed based on stress - time curves. Focus is put on the post-peak stress behaviour, where the improvements mainly rely on introducing four subclasses of upper yield (UY) failures. The new system is used for establishing links between sea ice features and failure types (FTs). We conclude that in old level ice flow stress (FS) failures are typical for the upper layer (down to 70 cm), while asymptotic (AS) failures dominate when test depth reaches 100 cm. UY1 and UY3 are prominent in first-year level ice and young ice respectively. Rafted first-year ice is dominated by upper yield failures, where no specific subtype stands out. The tests have been investigated based on three strength governing parameters; ice temperature (T_i), minimal vertical confinement (C_{min}) and average indentation rate. We found that decreasing temperature gives an increasing borehole (BH) strength, also within the respective failure types and ice features. Based on indentation rate, the BH strength increased with decreasing rate. An abrupt transition between asymptotic and premature (P) failures was found at 4.5 mm/s indentation rate, where the former dominates for lower and the latter for the greater rates. The vertical confinement is a parameter that appears to affect only the tests conducted in young ice with this BHJ system.

NOMENCLATURE

Abbreviations

AARI	Arctic and Antarctic Research Institute
AS	Asymptotic
BH	Borehole
BHJ	Borehole jack
FB	Freeboard
FS	Flow stress
FT	Failure type
FYLI	First-year level ice
NRC	National Research Council
OLI	Old level ice
P	Premature
RFYI	Rafted first-year ice
UNIS	University Centre in Svalbard
UY	Upper yield
YI	Young ice

Symbols

c	constant plastic
C_{min}	Minimal vertical confinement
e	elastic
h	hardening plasticity
h_i	Ice thickness
h_s	Snow depth
s	softening plasticity
S_i	Ice salinity
T_i	Ice temperature
z	Test depth
ρ_i	Ice density
$\frac{d\sigma}{dt}$	Stress rate

INTRODUCTION

As the interest in Arctic Technology increases, mostly due to the prospect to exploit natural resources and the possibilities for a northern sea route between Europe and Asia, it becomes important to estimate ice actions on offshore and coastal structures with a certain precision. The determination of *in-situ* ice properties is one of the elements in a reliable determination of ice actions and traditionally there have been three methods for *in-situ* / in field determination of ice strength or ice capacity; a) Uni-axial compression tests, b) Borehole jack indentation tests and c) Beam tests. The latter gives some kind of tension capacity while the two former tests the ice in compression. In a BHJ test the confinement of the ice is more similar to what the ice feels when interacting with a structure than in the case of uni-axial tests. But the more complicated geometry of a BHJ test makes it more challenging to analyze. In the present paper we suggest a modification of the BHJ classification system developed by Sinha (2011) and analyze borehole strength with respect to ice temperature, average indentation rate and vertical confinement. For a more thorough description of the equipment and the experiments see Justad (2012).

SITE AND EXPERIMENTAL SET-UP

The UNIS-BHJ

The University Centre in Svalbard (UNIS)-BHJ consists of an electric engine, a hydraulic pump and a piston that are mounted in a steel frame on skies, intended to be robust and simple to use. The BHJ is conveniently handled on level ice between test locations and only a crew of two persons is required to do so. A steel cover ensures that snow and water do not enter the electric system as well as providing protection when transported for longer distances. This is normally done by snowmobile using a sledge or by a vessel. In case of the latter option, extension cords may be used from the vessel to the BHJ for power supply. Otherwise a generator of minimum 2 kWh is brought. A steel cylinder of Ø 140 mm protects the piston, displacement sensor and indentor. These are connected to the surface through a Kevlar hose, in which the oil tubes and wire for the displacement sensor are located. The hose is 5 m long withstanding a pressure of 300 bars, limiting the test depth to 4 m and pressure induced from the indentor to 19 MPa. Displacement, hydraulic pressure and time are logged with a frequency of 5 Hz and stored in a CR1000 Wiring Panel from Campbell Scientific Inc. The data is obtained using the PC200W software.

The UNIS-BHJ is a single-indentor system with a maximum stroke of 50 mm. The piston extracts and retracts as the operator uses a lever to control the oil flow. The indentor itself matches the curvature of the cylinder and has a projected area of 6.36 x 10^3 mm^2. This is significantly less than the opposing cylinder wall and penetration in the desired direction is therefore assured.

Figures 1 and 2 show the BHJ. The time it takes the piston to go from 0 to 50 mm in air at +20°C is 7.5 seconds. Its maximal indentation rate is therefore estimated to 6.7 mm/s, equivalent to an ice flow moving at about 0.007 m/s. The indentation rate depends on the stiffness and strength of the ice encountered, and is found to be constant for individual tests also when stresses are close to the maximum capacity of the system. The average indentation rate we have described in this paper is calculated from the time it takes the piston to go from 0 to 50 mm.

The sites and sea ice characteristics

The experiments were carried out in three different areas; a) In the Svea bay of Van Mijenfjorden on Svalbard 27-29 March 2012 where first-year level ice was tested, b) In the Barents Sea (77.09°N 24.77°E) 18-19 April 2012 where rafted first-year ice and young ice were tested and c) In three ice floes in the Fram Strait (78.62°N 3.28°E / 78.80°N 8.05°E / 78.52°N 12.30°E) 21 - 26 August 2012 where old level ice was tested. Ice thickness (h_i), snow depth (h_s) and freeboard (FB) were measured on each site and are presented in Table 1.

Table 2 shows ice temperature, ice salinity (S_i) and ice density (ρ_i) measured at individual test depths. For Van Mijenfjorden and in the Barents Sea the tests were done in the middle of the ice floe to ensure maximal vertical confinement. The ice thickness in the Fram Strait was of

Figure 1. The UNIS-BHJ with piston fully retracted.

Figure 2. The UNIS-BHJ with piston fully extracted at 50 mm.

Table 1. The min/max values of ice thickness, snow depth and freeboard.

	Van Mijenfjorden FYLI		Barents Sea RFYI and YI	Fram Strait OLI		
	Grid C	Grid D	Grid EFG	IS1	IS2	IS3
h_i (m)	0.38/0.52	0.43/0.48	0.18/0.55	1.8/4.9	2.7	2.4/4.1
h_s (m)	0.25/0.51	0.42/0.48	0.1/0.16	0.04/0.04	0.02/0.03	0.01/0.03
FB (m)	-0.17/-0.04	-0.18/-0.14	-0.01/0.01	0.17/0.35	0.42/0.49	0.32/0.40

such magnitude that the tests were considered fully confined regardless of test depth. A fixed test depth (z) was therefore used here to minimize the number of changing parameters.

Table 2. The mean/standard deviation of ice temperature, salinity and density. The fixed test depths for Fram Strait are also shown.

	Van Mijenfjorden FYLI		Barents Sea RFYI and YI
	Grid C	Grid D	Grid EFG
T_i (°C)	-2.13/0.26	-2.21/0.11	-2.9/0.43
S_i (psu)	4.7/0.34	4.9/0	5.9/1.4
ρ_i (kg/l)	0.86/0.11	0.97/0	-

	Fram Strait OLI			
z (m)	0.33	0.43	0.66	0.99
T_i (°C)	-0.1/0.14	-0.05/0.06	-0.4/0.08	-0.8/0.18
S_i (psu)	0.06/0.13	0.08/0.15	1.18/0.46	1.93/0.38
ρ_i (kg/l)	0.92/0.072	0.96/0.034	1.01/0.040	0.99/0.009

CLASSIFICATION SYSTEM

The classification system developed by Sinha (2011) has been agreed upon by National Research Council (NRC) in Canada and by Arctic and Antarctic Research Institute (AARI) in Russia as a suitable approach for classifying BHJ records (Sinha et al., 2012). Sinha (2011) borrows concepts from small-scale element tests and stress-strain diagrams and introduces four failure types: Flow Stress, Asymptotic, Upper Yield and Premature. These can be determined from the stress development applying the characteristics elastic (e), hardening plasticity(h), constant plastic (c) and softening plasticity (s). FS failures corresponds to e-h, AS failures to e-h-c and so on. It is impossible to determine the elastic properties or the duration of the elastic range from a BHJ test firstly because the strain rate is an unknown parameter, and secondly, crushed ice forms at a very early stage of the process followed by subsequent stress concentrations (Masterson, 1996). Figure 3 shows how each failure type, including subtype, is defined. UY failure has been divided into four subgroups, UY1, UY2, UY3 and UY4, depending on the third and fourth term. To distinguish P failure from UY1, the stress rate ($\frac{d\sigma}{dt}$) in the transition zone between hardening and softening plasticity required a quantitative explanation. The difference between constant stress and softening or hardening plasticity has been evaluated on similar basis. Consequently, it was necessary to establish certain definitions:

1. Premature failure occurs where the stress rate is less than -2.5 MPa/s in transition between hardening and softening plasticity.
2. Constant stress is defined where the mean stress rate is in range $\pm$0.1 MPa/s for a period of at least 3 s. Exceptions are made for tests where the trend clearly changes during the final, i.e. less than 3, seconds. In these cases the tendency of the curve decides if the ice is undergoing a softening, hardening or constant stress zone.
3. Softening and hardening plasticity appears where the stress rate is less than -0.1 MPa/s and greater than 0.1 MPa/s for a period of at least 3 s. Same exception applies as for point 2.
4. Failure occurs if the stress decrease is equal to or greater than 0.5 MPa during a period of maximal 5 s. In other words: softening plasticity of at least 0.5 MPa.
5. The maximal capacity of the hydraulic system is reached if the stress and stress rate reaches minimum values of respectively 18 MPa and 10 MPa/s within the first 5 s of the test, regardless of when contact is established.

Our analysis is based on stress-time, and not stress-strain curves. For validation of the system the strain rate should be constant. Nevertheless, the tendencies of stress development are the same for both indentation and time, and the stress zones are therefore assumed applicable in both cases.

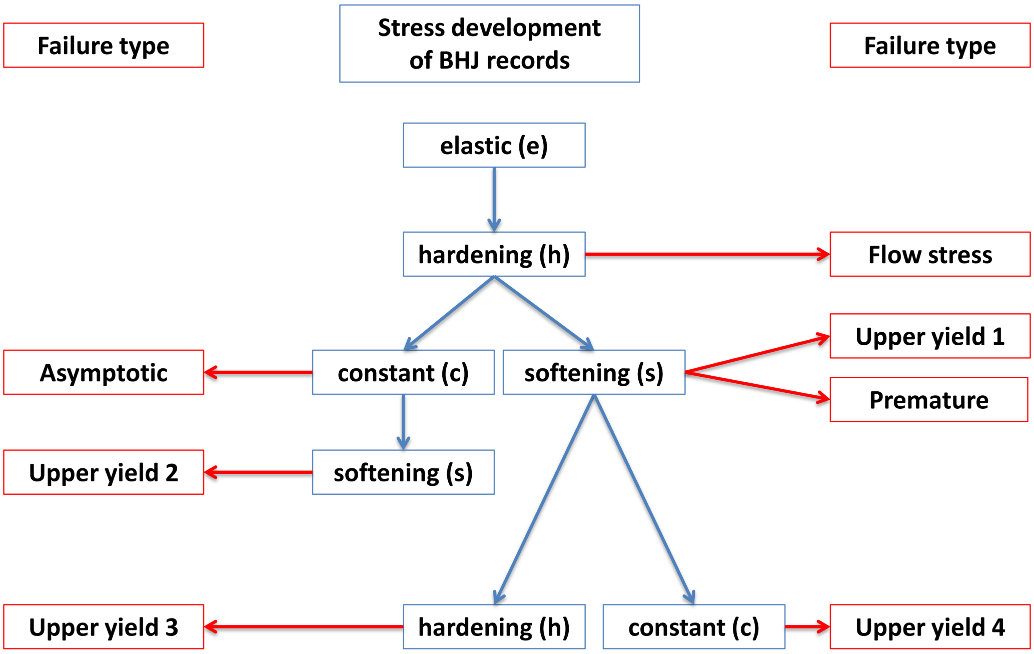

Figure 3. Classification chart for BHJ tests.

RESULTS AND DISCUSSION

Failure type occurrences

Table 3 shows the frequency of failure types of each ice feature as well as the range of test depths and mean ice temperatures. We suspect that warm OLI provokes FS failures. At 99 cm AS failures dominates, even though the temperature here is also very close to the melting point. Out of the 85 tests conducted, only 5 were categorized P failures. Brittle failures are prominent for cold ice and high strain rate. In our case the ice tested was warm, especially in the Fram Strait, where no P failures occurred. Though the indentation rate of the UNIS-BHJ is high, it seem not to be sufficient to compensate for the high temperatures for providing brittle failures.

Strength and failure type governing factors

The temperature has a large impact on the mechanical properties of ice since it affects both the E-modulus and the porosity. Decreasing temperatures results in an increasing E-modulus and decreasing porosity, both implying stronger ice. Figures 4 and 5 show the BH strength plotted vs temperature measurements at individual test depths, highlighting failure type and ice feature respectively. Four out of five premature failures occurred in young ice, while one occurred in rafted ice where the minimal vertical confinement was 27 cm. Temperature measurements were not available for any of the P failures, so this FT is plotted as one point being the mean strength of the total 5 tests and two temperature measurements in the vicinity of the test locations. The standard deviations are given as horizontal and vertical bars.

Low temperature results in greater BH strength. This is prominent for UY1 and AS failures,

Table 3. Failure type occurrences of the variety of ice features, test depth and mean ice temperature at test depths. Note that ice temperature was not measured for all of the test conducted in the Barents Sea.

Location	Van Mijenfjorden	Barents Sea	
Ice feature	FYLI	YI	RFYI
Number of tests	33	17	10
z (m)	0.20 to 0.28	0.10 to 0.11	0.15 to 0.27
Mean T_i (°C)	-2.16	-2.78	-3.10
FS	1	0	0
AS	6	0	1
ASmax	1	0	0
UY1	16	0	2
UY2	2	0	0
UY3	4	9	3
UY4	3	4	3
P	0	4	1

Location	Fram Strait			
Ice feature	OLI			
Number of tests	13	4	4	4
z (m)	0.33 to 0.35	0.43	0.66	0.99
Mean T_i (°C)	-0.10	-0.05	-0.40	-0.80
FS	8	3	3	1
AS	2	1	1	3
ASmax	0	0	0	0
UY1	0	0	0	0
UY2	0	0	0	0
UY3	3	0	0	0
UY4	0	0	0	0
P	0	0	0	0

Figure 4, and in young ice, Figure 5. It may well be the case for UY3 failures also, disregarding the three appearances in OLI. The old level ice was extremely close to its melting point and this is perhaps the reason why no clear trend can be found here. However, we conclude that AS failures have implicitly greater BH strength than FS failures. This is undoubtedly a consequence of the definition of FS failure where the strength is consistently obtained at 10 mm displacement. If a greater value was chosen a greater BH strength would follow. This implies that comparisons between FS failures and other failure types should be done with caution.

We note the following:

- Tests done at 33, 43 and 66 cm in old level ice show about the same mean strengths, the lowest variations in temperature and are dominated by FS failures.
- The tests conducted at 99 cm show greater BH strength than those in OLI closer to the ice surface and are dominated by AS failures.

- FYLI have the greatest mean strength, even though the temperature here is greater than that of RFYI. The pre-existing cracks in rafted ice makes the ice weaker than when in its original form, and this factor seems to have a greater impact on BH strength than ice temperature.
- RFYI has the largest and second largest variability in temperature and BH strength respectively.

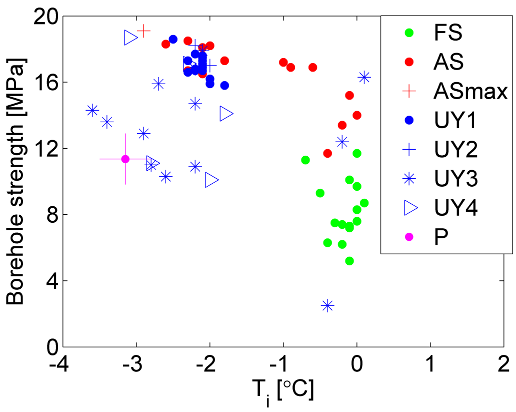

Figure 4. BH strength plotted vs ice temperature, highlighting failure types.

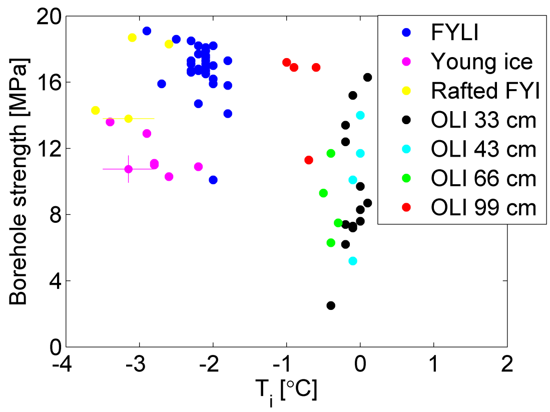

Figure 5. BH strength plotted vs ice temperature, highlighting ice features.

Figures 6 and 7 give the strength vs the indentation rate. The results here are scattered, especially for the UY failures. Some trends may however be pointed out. The greater the strength, the lower the indentation rate. This is a result of the indentation rate of the UNIS-BHJ depending on the resistance encountered in the ice. Figure 6 shows that the AS failures decrease in strength as the indentation rate increases. At 4.5 mm/s it seems as the trend is continued by the P failures. The same trend is separately recognized among FS failures.

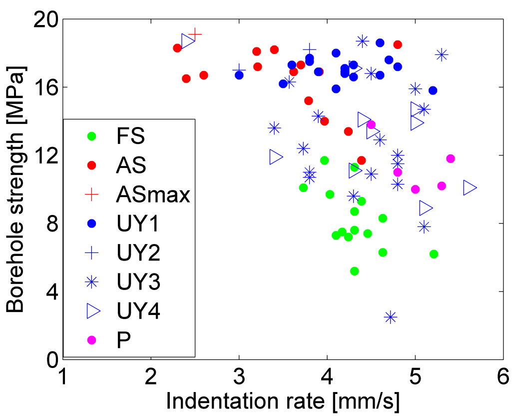

Figure 6. BH strength plotted vs average indentation rate, highlighting failure types.

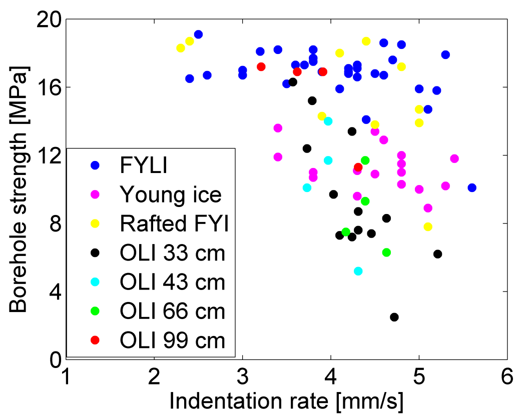

Figure 7. BH strength plotted vs average indentation rate, highlighting ice features.

The influence of vertical confinement is given in Figures 8 and 9. It should gradually decrease towards a critical ice thickness, from where it becomes insignificant. The value depends on properties of the ice as well as equipment in terms of indentor size, indenation rate, etc. The BH strengths found in FYLI, where the ice thickness is greater than 30 cm, were of such magnitudes that we assume these tests are done in ice thicker than the critical value, i.e. where full confinement applies. The tests done in young ice in the Barents Sea show lower BH strength and we believe this is a direct consequence of the lower confinement. This is substantiated by the fact that the temperatures here are on average lower than that of FYLI, something that by itself would give greater BH strengths. We therefore assume the critical value of vertical confinement for the UNIS-BHJ to be greater than 10 cm and less than 20 cm. We also note that most of the P and UY3 failures occur where the confinement is about 10 cm.

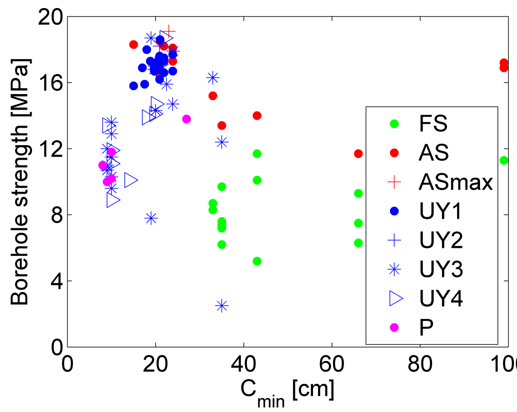

Figure 8. BH strength plotted vs vertical confinement, highlighting failure types.

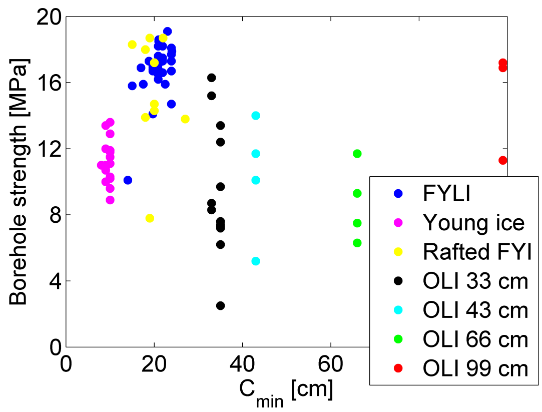

Figure 9. BH strength plotted vs vertical confinement, highlighting ice features.

CONCLUSIONS

The UNIS-BHJ has been used in three research expeditions in 2012; first-year level ice in Van Mijenfjorden, rafted first-year ice and young ice in the Barents Sea and old level ice in the Fram Strait. The variety of ice features encountered made it convenient to compare the results based on failure types. In order to make consistent comparisons, quantitative definitions of each failure type have been established. It is a development of the system created by Sinha (2011) that will help standardising the interpretation of BHJ tests. Based on failure type appearance in ice features, we found that:

- UY1 failures are prominent in FYLI.
- UY3 failures dominate in YI, where also 80% of the P failures occur.
- RFYI is not dominated by a distinct failure type, but 8 of 10 are variants of UY.
- FS failures dominate in the top 66 cm of warm OLI, while AS failures dominates at 99 cm depth where the temperatures are slightly colder.

The failure types are further discussed on basis of three strength governing parameters; ice temperature, indentation rate and vertical confinement:

- Decreasing ice temperature results in increased BH strength, also within the respective failure types.

- For AS, P and FS failures a decreased indentation rate results in increased BH strength. The P failures seem to continue the trend of AS failures from 4.5 mm/s.
- A critical value of vertical confinement for the UNIS-BHJ system is in range 10 to 20 cm.

ACKNOWLEDGEMENTS

We are grateful for the support from the Research Council of Norway through the PetroRisk project, the Centre for Research-based Innovation SAMCoT and the support from all SAMCoT partners. We are also grateful to Dr. Edmond Hansen and Dr. Sebastian Gerland for the possibility to participate in the cruises organized by NPI in August 2012. Finally we would like to thank the UNIS logistics, Professor Aleksey Marchenko and his students in the course AT-211 the spring of 2012.

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