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THE EFFECT OF ICE RUBBLE ON ICE-ICE SLIDING

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ABSTRACT

Ice deformation processes in the Arctic can generate ice rubble. Many situations arise where ice fragments of varying size separate sea ice floes. While the shear forces between sea ice floes in direct contact with each other are controlled by ice-ice friction, what is not known is how the slip of the floes is affected by the presence of rubble between the sliding surfaces. We present the result of field experiments undertaken on sea ice in the Barents Sea. A double-direct-shear experiment was done on floating sea ice in the field, with the addition of rubble ice between the sliding surfaces. This was achieved by pulling a floating ice block through a cut channel of open water 3m long, where broken ice filled the gap between the block and the channel sides. The displacement of the block and the force needed to move the block were measured. The time that the block was held motionless to allow the rubble to consolidate was recorded - this ranged from seconds to several hours. We found that the 'hold time' controls the maximum force needed to move the block. The relation between hold time and force is highly non-linear from which we deduce thermal consolidation is the controlling mechanism.

INTRODUCTION

A variety of problems encountered in offshore Arctic engineering relate to the presence and properties of broken or rubble ice. For instance, accumulations of rubble ice that develop into stamukhi and are dragged along the sea bed pose potential hazards to underwater piping. The interaction of ice floes with structures such as offshore platforms and breakwaters generate piles of ice rubble that not only exert large forces on structures, but may also result in many metres of encroachment (Palmer & Croasdale 2013). Thick accumulations of ice rubble, produced by ships frequenting a channel in a region of sea ice cover, provide resistance to subsequent transits when the rubble is both unconsolidated and consolidated (Mellor 1980). In recent decades, research into the properties and effects of rubble ice has become of great interest to petroleum companies exploring Arctic regions.

From a more scientific perspective, the role of ice rubble at pressure ridges is of interest. These ridges can be seen as long lineations extending through the Arctic sea ice cover, often in sub-parallel sets. Sammonds and Rist (2001), liken the lineations to strike-slip faults in the Earth's crust. Sammonds et al. (2005) note that if this analogy is correct, slip on the most extensive pressure ridges will dominate the dynamics of Arctic sea ice cover. This has climatic implications, due to the high albedo of sea ice and its role in insulating the ocean from the atmosphere. This provides motivation for understanding the frictional processes affecting slip on pressure ridges. Since ice rubble is generated at pressure ridges, research into the effect of rubble acting as a 'fault gouge' may help us better understand the mechanics of frictional sliding in these circumstances.

THE EFFECT OF HOLD TIME AND GOUGE MATERIAL ON STATIC FRICTION

The effect of hold time on static friction was observed in rocks by Dieterich (1972), who found that static friction increases with the logarithm of the time that adjacent blocks remain in stationary contact. Experiments on ice-ice sliding by Lishman et al. (2011) and Sukhorukov and Løset (2013) found the coefficient of static friction to increase approximately logarithmically for hold times of up to 1,000 seconds. Schulson and Fortt (2013) performed similar slide-hold-slide tests on ice with hold times of up to 10,000 seconds. Their results also showed the friction coefficient to increase approximately logarithmically for hold times above a certain threshold and below an upper limit, both of which were velocity dependent, decreasing with increasing sliding velocity.

It was also noted by Dieterich (1972) that the coefficient of static friction becomes highly time-dependent when gouge is present between the sliding faces, and later experiments on granite suggested an approximate logarithmic increase in gouge strength with hold time (Dieterich 1981). Subsequent experiments have provided further evidence for the time-dependence of static friction between surfaces separated by gouge material (Scholz, 1972; Marone 1998). However, for cases where the gouge material is ice, behaviour may differ to that of rock and other solids due to the gouge material being close to its melting point and existing in its own melt.

It is also worth noting that time-dependent behaviour has been observed in other granular material. For instance, the shear modulus of air-dried sands, silts and clays increases with the logarithm of time whilst subjected to a constant confining pressure (Marcuson and Wahls 1972; Trudeau et al. 1974;), and it seems reasonable to believe that mechanisms which play a role in this behaviour could be similar to those in friction experiments involving gauge.

The effect of gouge material on friction in ice-ice sliding has been far less researched. Due to the nature of ice, understanding friction is not so straightforward as it is influenced by melting and re-freezing processes. The most relevant research with regard to ice gouge material has involved testing the mechanical properties, particularly strength, of ice rubble. This has been done predominantly in-situ by way of punch tests (Lepparanta and Hakala, 1992; Smirnov et al., 1999; Timco et al., 2000), but also in laboratory settings, where shear tests have been performed. Ettema and Urroz (1989, 1991) and Timco and Cornett (1999) review and interpret the results of shear tests performed since the 1970s, and conclude that the behaviour of ice rubble can be described by an elastic-perfectly plastic model where the Mohr-Coulomb law describes its plasticity.

FIELD EXPERIMENTS INVOLVING HOLD TIME

Experiments on sea ice in the Barents Sea were carried out in March 2014, which investigated the effect of hold time on static friction between ice blocks separated by ice rubble. Suitable ice cover was found (Fig. 1) and measured to be 0.5m in thickness.

A trapezium shaped hole was cut in the ice, and all ice removed apart from one smaller trapezium shaped block. The result was a channel of open water containing a mobile ice block that could be pulled back and forth (Fig. 2). The gap between the mobile block and channel sides was filled with broken ice (Fig. 3).

Figure 1. A depiction of the route taken. The star marks the location where experiments were conducted on sea ice. (Adapted from Wikipedia)

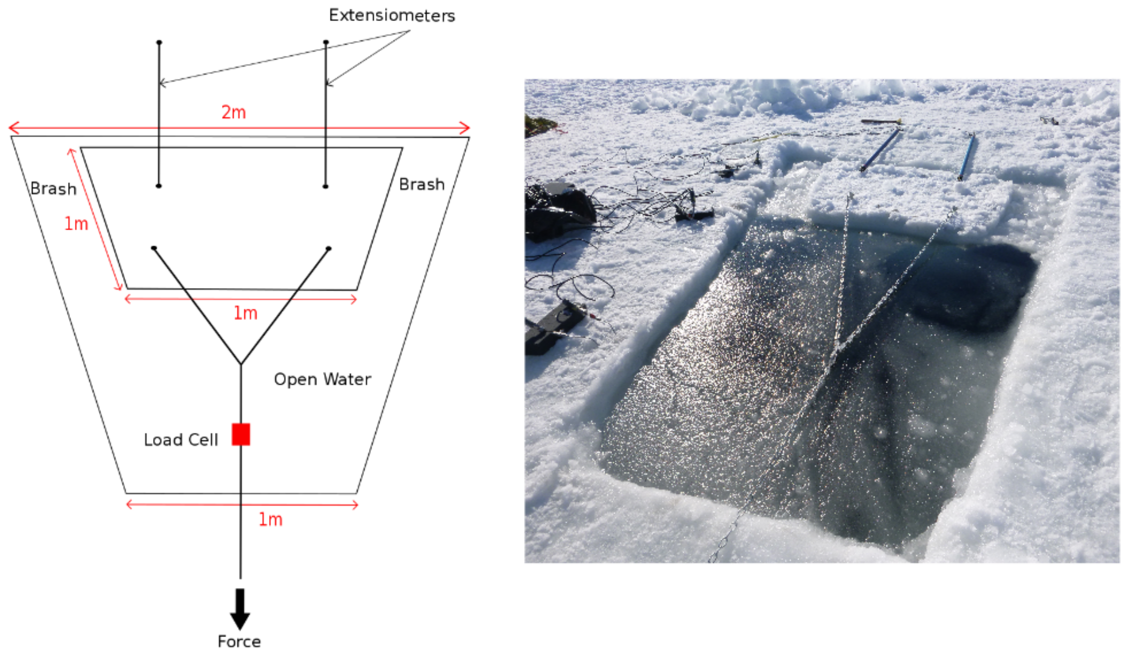

Figure 2. Diagrammatic and photographic representation of the experimental setup.

Slide-hold-slide type tests were conducted, whereby the block was agitated, held for a set hold time, and subjected to a force until movement of the block was initiated. For any hold times where the water in front of the block froze, this was broken and cleared. The force required to initiate movement was measured using a model 614 tension-compression 2kN Tedea Huntleigh load cell. The movement of the block was measured using two Penny and Giles extensiometers.

The block was moved by hand after short hold times, where forces were small, or pushed using an indenter after long hold times, where force were larger. The indenter rig was designed and manufactured for fieldwork with the support of SAMCoT. Actuation was provided by two horizontal hydraulic cylinders (Enerpack) capable of exerting a force of 300 kN and were equipped with a displacement sensor and a load cell. An electrical pump and generator powered the hydraulic cylinders. The system was operated by a specially designed field computer, and data from the load cells and displacement sensors were sampled at a frequency of 100 Hz.

Hold times ranged from 1s to 16 hours. At the longest hold times of 10 hours or more it should be noted that equipment failure arose before the initiation of block movement or brash deformation. Therefore the maximum loads recorded in these instances are lower bound values for shear strength and are not representative of actual load required to deform the consolidated ice rubble.

Table 1. Hold times and the corresponding maximum load required to initiate block movement.

Hold Time (s)	**Max load (N)**	**Notes**	**Day**
1	119.9		1
10	91.2		
100	193.0		
900	157.1		
1,000 (~16 minutes)	157.1		
3,600 (1 hour)	231.9		
7,200 (2 hours)	230.5		
36,000 (10 hours)	3,241.0	Ice screw broke before movement initiated.	
37,800 (10½ hours)	8,253.0	Chain snapped before movement initiated.	
57,600 (16 hours)	80,199.0	Block cracked before brash deformed.	2

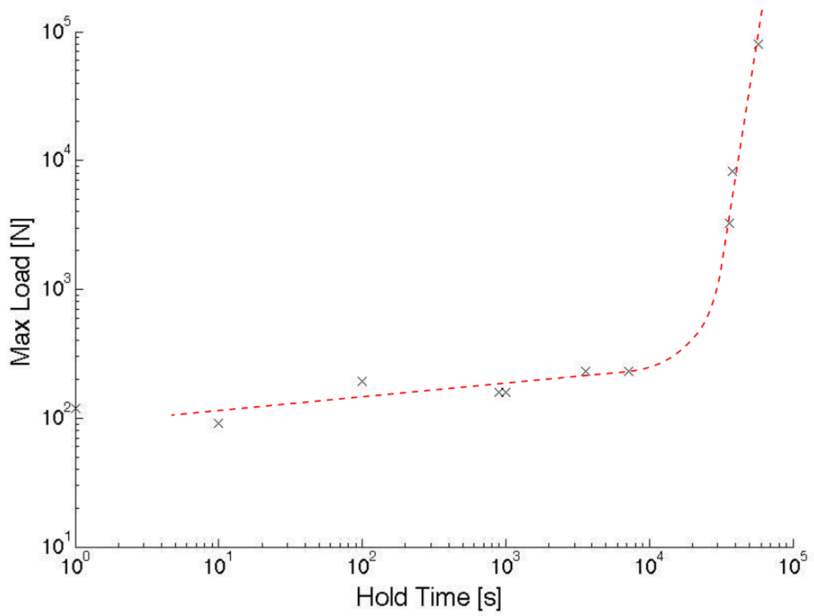

Figure 4. Plotted data from table 1, showing the relationship between hold time and the maximum load needed to initiate ice block movement.

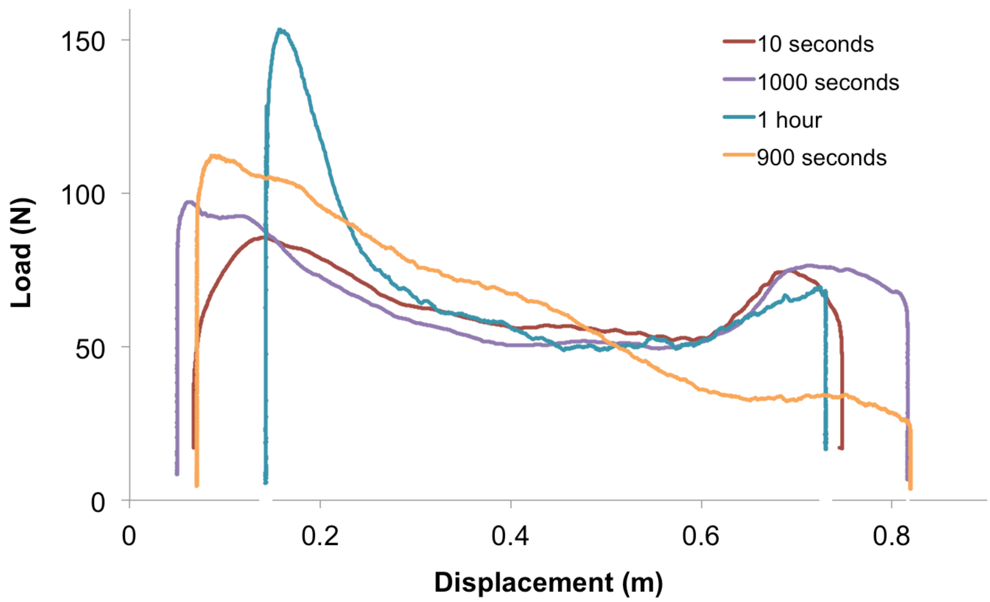

Figure 5. Force vs displacement graphs for various hold times.

Comparing the figure 5 and table 1, a discrepancy in the maximum recorded load can be noticed. This is due to the way in which the sampled data was smoothed - using a moving average with a period of 125 (fig. 6). The peak load is an instantaneous value, and so the unsmoothed data was used to obtain the values for figure 4.

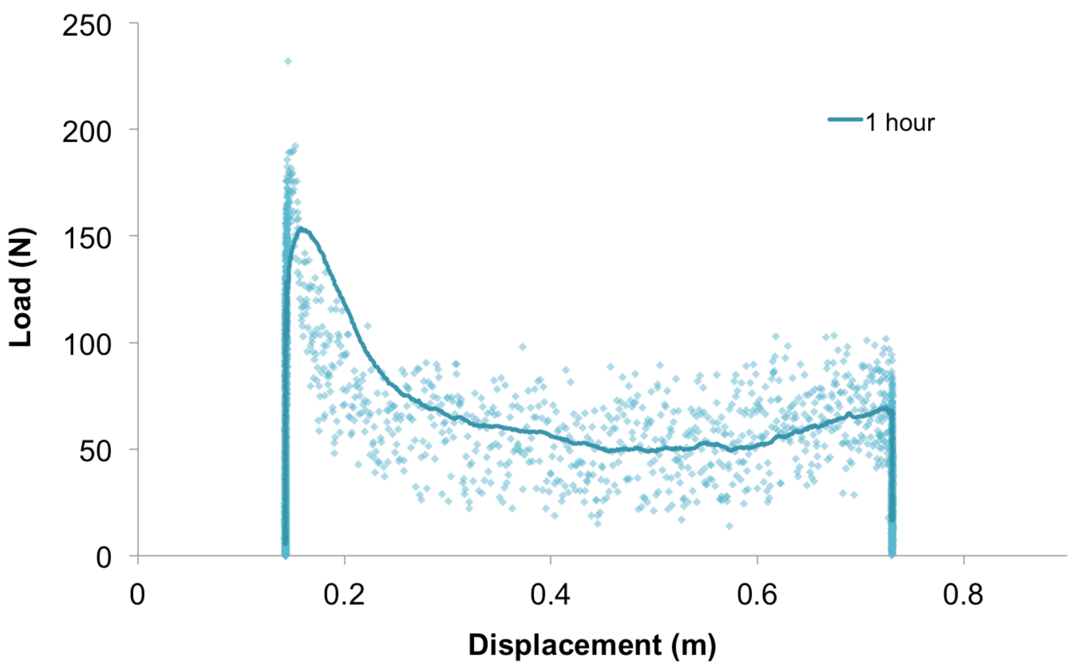

Figure 6. Force vs displacement graph for a hold time of 1 hour. Both the individual data points and moving average is shown.

Ice Conditions

Broken ice was created artificially, with an emphasis on creating a fractal distribution of sizes. The region of broken ice measured roughly 30cm in thickness, which was deliberately less than the thickness of the ice cover so that ice pieces would not be lost beneath it. However, some ice was lost into the region of open water in front of and behind the moving ice block during the course of experiments.

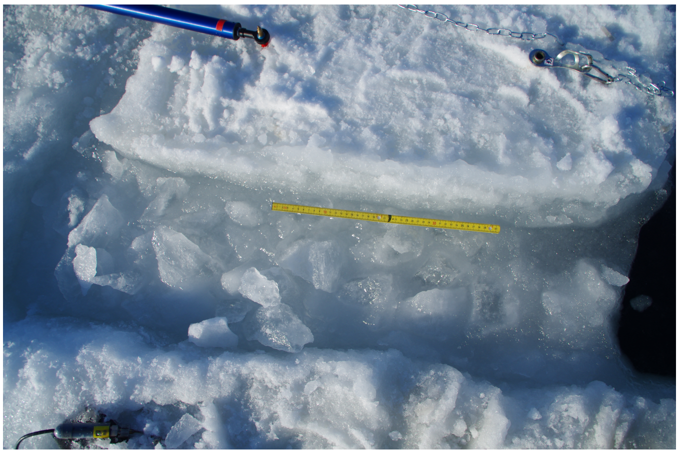

Figure 7. A photograph of the consolidated broken ice used in these experiments.

It was noted that initially the broken ice pieces were angular, but that they quickly became sub-angular to rounded within a few runs of the experiment. However, for runs that exceeded periods where the broken ice had been left to consolidate (e.g. overnight and after long hold times), broken ice was created by breaking up this consolidated layer. This effectively renewed the angularity of the broken ice used in subsequent runs.

Table 2. Temperature and salinity conditions on the days when experiments were conducted.

	Day 1	Day 2
Air temperature (°C)	-7	-10
Water temperature (°C)	-1.5°C ± 0.1	-1.6 ± 0.1
Water salinity	3.2% ± 0.5	3 ± 0.5

DISCUSSION

As discussed previously, earlier work investigating the effect of hold time on friction in rocks and ice have found the coefficient of static friction behave linearly with the logarithm of time (Dieterich 1972; Lishman etal. 2011; Schulson and Fortt 2013; Sukhorukov and Løset 2013). Our results show this is not the case when broken ice is present between the sliding surfaces – highly non-linear behaviour is observed in figure 4. Two distinct regimes emerge, before and after approximately 10^4 seconds hold time, and it seems reasonable to believe that mechanisms other than the state dependence of friction must be operating.

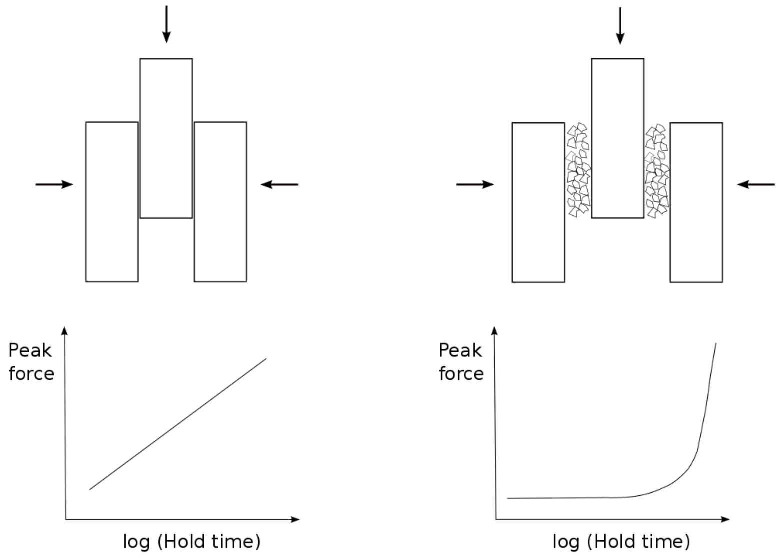

Figure 8. Known behaviour in slide-hold-slide experiments without ice rubble present, compared to behaviour observed in our experiments involving slide-hold-slide experiments with brash present.

A straightforward explanation is to assume that the onset of consolidation occurs around 10^4 seconds, and after this point the force needed to reinitiate movement is a reflection of the shear strength of consolidated broken ice, which continues to strengthen with time as it reaches thermodynamic followed by mechanical consolidation (Bailey et al. 2012). It is interesting to point out that after a hold time of 16 hours, the mobile block itself fractured before the consolidated ice deformed at all (fig 9). This suggests that the strength of the consolidated broken ice exceeds that of the original level ice, and this may be a property worth investigating further.

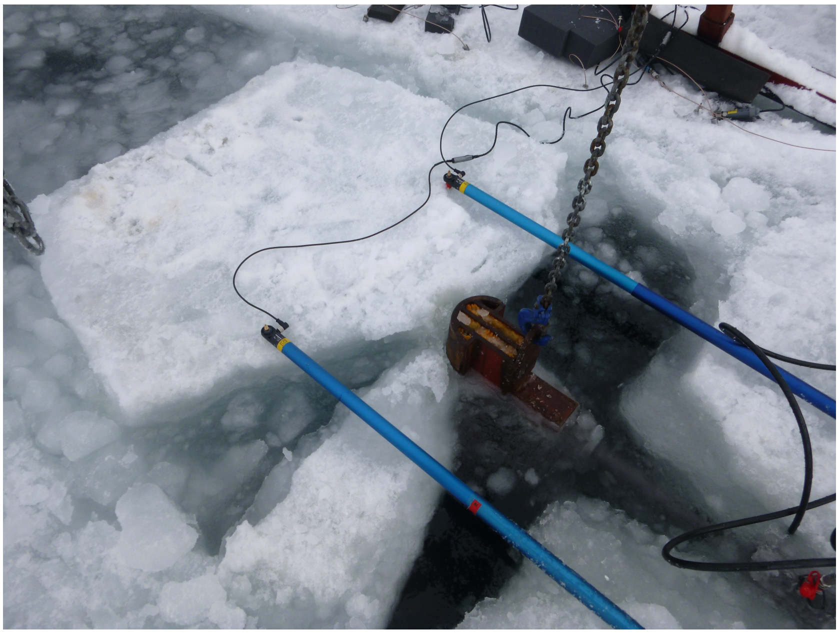

Figure 9. After a hold time of 16 hours, the block itself cracked before the broken ice deformed.

Before 10^4 seconds there many be several mechanisms at play. As well as various stages of consolidation, such as thermodynamic and mechanical consolidation mentioned in Bailey et al. 2012, force chains could also be operating. Anthony & Marone (2005) conducted experiments investigating the grain-scale deformation mechanisms in rock gouge, and they suggest that force chains are qualitatively affected by grain angularity. Further experiments could be done to investigate the effect of angularity and size distribution of the broken ice on force chains, and the extent to which force chains dominate over consolidation, or vice versa.

It is interesting to note that stick-slip behaviour was not noticed during the experiments or in the data collected, which differs from observations made during similar experiments conduced by Lishman et al. (2011), Schulson & Fortt (2013) and Sukhorukov & Marchenko (2014) which investigate ice friction in the absence of gouge.

Improvements to the experimental setup presented here could also be made. For instance, use of a rectangular channel and the ability to provide a normal force would allow the coefficient of friction to be calculated. Broken ice conditions, such as temperature profiling, angularity and salinity could be more closely monitored.

CONCLUSION

1) Presented here are the results of field experiments on sea ice in the Barents Sea, designed to investigate the effect of hold time on the friction between ice blocks separated by ice rubble.
2) Two distinct hold time regimes are apparent. In the first, at hold times up to approximately 10^4 seconds, the frictional force opposing sliding is low. We suggest that varying degrees of consolidation and the presence of force chains are mechanisms that play a role in providing frictional resistance in this regime. In the second regime there is a high frictional resistance, which we attribute to more pervasive consolidation throughout the broken ice.
3) Further work is needed to explore the mechanisms controlling friction in these circumstances, and to find out which mechanisms dominate each regime. The angularity of broken ice is expected to affect friction experienced at low hold times, as they affect the development of force chains.

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