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IN SITU DIRECT SHEAR OF ICE RUBBLE IN FIRST-YEAR RIDGE KEELS

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ABSTRACT

A technique has been developed and tested in the laboratory to measure the shear properties of ice rubble *in situ*. First-year pressure ridges and ice rubble features represent the design load conditions for many large offshore structures. The study was prompted by the requirement for accurate parametric information on ice rubble properties for determining first-year ridge forces on offshore structures. The technique involves lowering a ram and associated apparatus into a precut slot in a pressure ridge. This facilitates direct horizontal shear measurements of undisturbed keel ice rubble. Deployment logistics, costs and reliability of results were considered in the development of this approach. A full scale field test of the technique has been proposed.

RÉSUMÉ

Une technique a été développée et vérifiée en laboratoire pour mesurer la réponse au cisaillement de conglomérats de glace *in situ*. Les crêtes de pression de première année et les conglomérats de glace constituent les conditions de chargement réelles pour plusieurs grands ouvrages maritimes. Cette étude répondait à un besoin de renseignements paramétriques précis sur les propriétés de conglomérats de glace afin de déterminer la force exercée par les crêtes de pression de première année sur les ouvrages maritimes. La technique consiste à insérer un piston et l'appareillage qui lui est rattaché dans une rainure taillée à l'avance dans une crête de pression. Ceci facilite la mesure directe du cisaillement horizontal sans déranger le conglomérat de glace. La logistique du déploiement, les coûts et la fiabilité des résultats ont été considérés dans la conception de cette approche. On propose un essai de terrain grandeur nature pour l'application de cette technique.

INTRODUCTION

In the absence of multi-year and glacial ice features, first-year sea ridges and rubble fields often represent the design ice features for offshore structures. When a first-year ridge interacts with an offshore structure the clearing of ice blocks which form the ridge keel (extensive submerged rubble accumulation) may contribute significantly to the total applied force. Although significant advances in keel load modelling have been made recently, there remains considerable uncertainty in the required input parameters, particularly the ice rubble shear strength.

A technique for direct *in situ* field measurement of rubble shear properties has been developed and tested in the laboratory. The experiments were conducted in the ice tank at the Institute for Marine Dynamics in St.John's Newfoundland. Model ice was used to build partially refrozen ridges, which were then sheared along a horizontal plane just below the consolidated layer using three different direct shear techniques. The apparatus, a scaled model of that proposed for field use, was designed after a rigorous evaluation of the suitability of various types of both direct and indexed shear tests (Croasdale *et al.*, 1996). The robustness of direct shear methods and the unambiguous analysis required to obtain estimates of cohesion and internal friction were important factors in choosing a direct shear technique. The quality of force-time data, the apparatus configuration and conventions for analysis of Mohr-Coulomb failure criteria were also investigated.

TEST CONDITIONS

Experimental Setup/Model Ice Ridges

The tests were conducted on two ice ridges with parent ice sheet thicknesses of 30 mm and 50 mm. Since the constituent block thickness of ridges in temperate regions is of the order of 0.2 m to 0.5 m, scales ranging from 1:4 to 1:17 were modelled.

EG/AD/S model ice was used to build the ridges. Density and flexural strength were measured at the time of ridge formation and at test time. Fine bubbles were introduced during the freezing process to achieve a realistic density which was 895 kg/m^3 for keel blocks and 750 kg/m^3 for the sail blocks. The flexural strength measured in the level ice varied from 32 kPa to 62 kPa during ridge construction. At test time, keel samples yielded flexural strengths of the order of 30 kPa while sail ice samples ranged from 134 to 266 kPa. The full scale flexural strength of sea ice ranges from below 300 kPa to 700 kPa.

The ridges were constructed for the present tests using a *dumptruck* technique. This method involved cutting a channel 4 m wide, spanning the entire 12 m width of the tank. Fifty-five metres of level ice from elsewhere in the tank were lifted using the service carriage and dumped into the channel. The ice broke into pieces during placement since repeated drops were made at the centre of the channel. The ridges were supported on the front edge by the adjacent level ice sheet and on the back by a floating dock spanning the width of the tank as shown in Figure 1. A cooling cycle following the ridge construction created a refrozen layer within each ridge at the waterline.

Shear Box Apparatus

The rectangular shear box was constructed of welded aluminum plate with nominal dimensions of 0.75m long x 0.5m wide x 0.4m deep. The box consisted of upper and lower halves of equal depth connected by a slotted runner bearing positioned on overlapping flanges. The shearing action was achieved by relative motion of the two halves. The length of the bottom half of the box was 0.85m to allow the insertion of a spreader device. The assembly is shown in Figure 2.

The spreader was a self-contained assembly consisting of a hydraulic ram mounted rigidly to an aluminum plate. Four parallel guide rods were fixed to another plate which slid through holes in the first plate. A button load cell was placed on the end of the piston and a displacement potentiometer (yo-yo type) was positioned between the spreader plates. The whole unit was easily detachable from the shear box so it could be incorporated into all direct shear options without disturbance of the data acquisition and drive systems.

For a typical sandy soil, laboratory shear devices split the sample across thousands of grains leading to uniform shearing which is representative of continuum behaviour. Ice rubble is, by contrast, a granular material with particles that are orders of magnitude larger. The size of the shear plane which would allow for similar particle kinematics and shear surface uniformity would prohibit direct scaling of soils shear devices. Thus, a consideration of the particle orientation, size and dynamics in a shear box is necessary to adequately model continuum behaviour. Bruneau (1996) reviewed these considerations and found that the average ratio of shear plane width to ice block length for 19 ice rubble shear tests in the literature was 6.4. The experiments with the smallest shear box size-to-block ratios were conducted by Prodanovic (1979) who demonstrated that shear strength was unchanged when the block size was reduced from one half to one quarter of the width of the box. Furthermore, the results were repeatable and have been shown to be representative of results reported more recently. A box width of 0.5 m was chosen giving a box-to-block size ratio of 5.5 for 30 mm ice and 3.3 for 50 mm ice.

The elevation of the horizontal shear plane was selected such that shearing would be initiated below the refrozen core and beyond the reach of blocks frozen into it. As well, the elevation was maintained close to the undersurface of the refrozen layer to minimize the box depth and trenching requirements. Although the shear box could be lowered to any depth within the ridge, it was designed so that it could be conveniently and repetitively placed in the ridges with the shear plane positioned 10 cm below the lower surface of the refrozen layer.

Shear Box Options 1, 2 and 3

Three direct shear options were considered in the laboratory. In all three cases the apparatus was placed in a pre-cut trench in the ridge. Option 1 involved the use of the entire shear box assembly. Option 2 involved the removal of the lower half of the box and the placement of a reaction plate on the spreader assembly. The objective of this option was to provide a frame that would contain the *in situ* rubble sample and to guide the shear plane along the bottom edge of the box. In this case the shear plane reaction force was carried by the refrozen layer adjacent to the spreader. The absence of the lower half of the shear box reduced the depth of the rubble to be trenched and decreased the size and weight of the apparatus.

Option 3 eliminated the box altogether and relied upon the refrozen core to keep the *in situ* sample intact. Using only the spreader device, option 3 was implemented in three different configurations. In the first arrangement, 500 mm x 350 mm plates were attached to both spreader plates to allow for a larger bearing surface on the ice. In the second, the extra plate bearing against the *in situ* sample was removed and the spreader was moved down to bear directly against the refrozen layer. In the third, the guide rods were removed eliminating all possible sources of apparatus friction. Figure 3 is a schematic representation of the experiments showing the site before and after the placement of the apparatus for options 1 and 3.

Test Plan and Procedure

Two ice sheets were used in the test program. The first ridge was built from level ice 30 mm thick and the consolidated layer depth was approximately 40 mm. The second ridge was built from a 50 mm thick sheet and had the same consolidated layer depth. Both ridges were tempered so that the air temperature during testing was near the freezing point.

Before trenching, the ridge sail was levelled to a surface approximately 10 cm above the water level. To aid with the trenching, a template matching the shape of the interior of the shear box was placed over the ridge sail. The pattern was then vertically sawn through the sail core and keel to a predetermined depth below the core around 200 mm. At one end of the trench rectangular sections of the sail core and keel were removed by hand for placement of the spreader unit. At the opposite end of the trench, blocks were removed to allow free translation of the sheared sample.

The shear box was lowered over the undisturbed rubble by hand and keel depth, sail height and box position were measured. To increase vertical stresses in the undisturbed sample, fixed weights were distributed evenly on a plywood board placed on the levelled surface of the sail. Surcharges of approximately 500 Pa and 1000 Pa were achieved by using fixed weights of 20 kg and 40 kg. All tests were conducted at a shear rate of 2.1 cm/s.

Following the complete set of shear experiments on the first ridge (30 mm ice) it was decided that option 2 would be dropped from the second set of tests. As well, options 1 and 3 would be implemented without the spreader guide rods in place (hereafter referred to options 1a and 3a). It was apparent from the tests with the first ridge that the rods were the cause of enhanced friction and binding and did little to orient the spreader plates. Dry runs conducted prior to the second set of tests indicated a significant reduction in no-load box friction for option 1 without the guide rods. By removing the rods, peak friction was reduced by more than half the original 'with-rods' option. For option 3, removal of the guide rods meant that there was no frictional component to the load trace due to the apparatus.

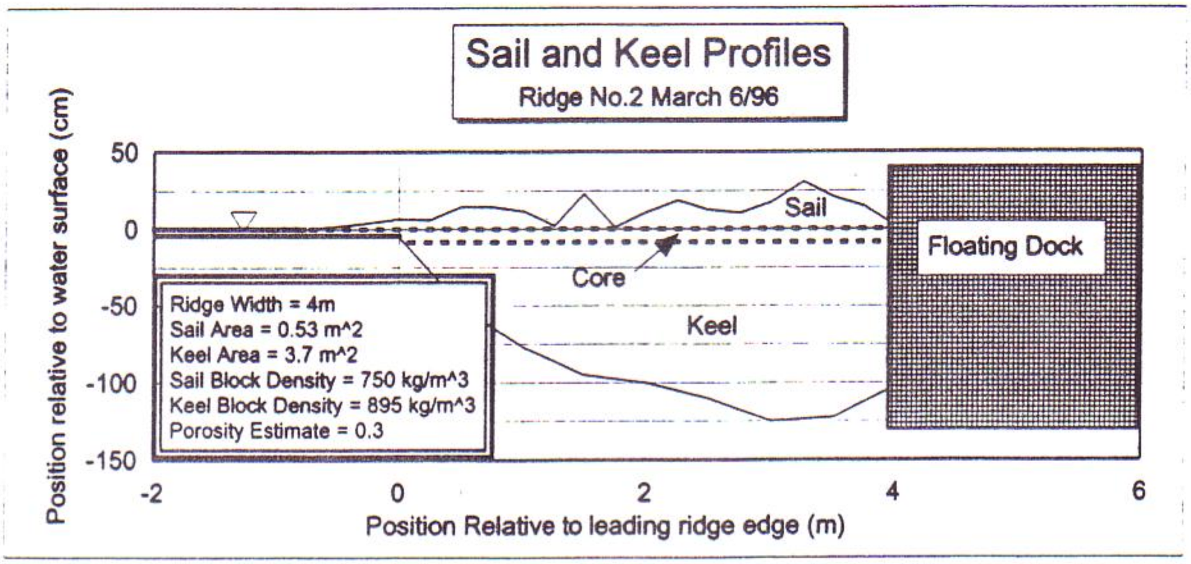

FIGURE 1.

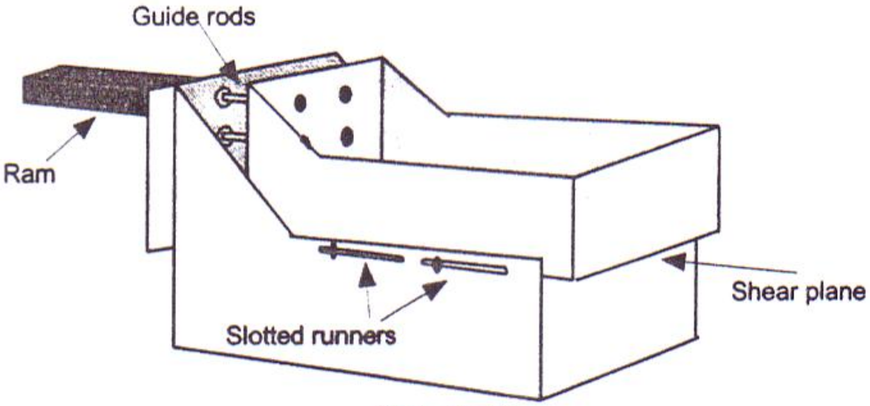

FIGURE 2.

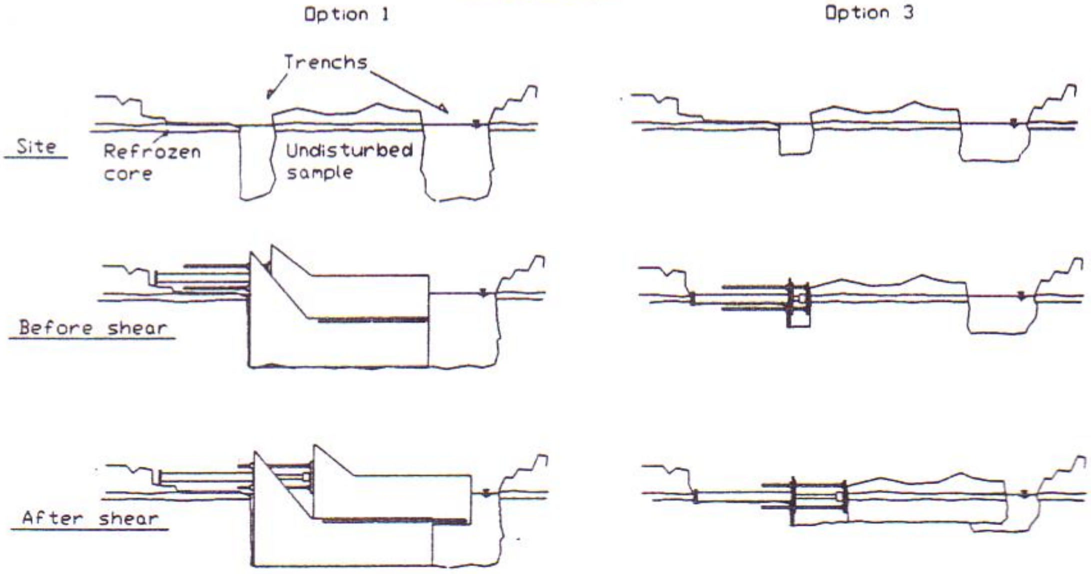

FIGURE 3.

LABORATORY RESULTS

Ridge Geometry

A ridge profile was measured by pushing a graduated aluminum rod through the keel. A length scale was used to measure the height of the sail relative to the service carriage platform. The measured profile for ridge 2 is shown in Figure 1.

Block dimensions resulting from the *dumptruck* ridge construction technique were estimated from video images of the floating rubble in a previous study where the same technique was used (McKenna *et al.*, 1995). In that study, the block length and width dimensions in the plane of the water surface were determined for 160 blocks in a digitized video frame. The means of the length and width were 3.1 and 2.0 times the ice thickness. The smallest block widths were approximately equal to the level ice thickness. The largest block length was between 8 and 9 times the ice thickness. On average, the ratio of the length to the width was 1.6. These statistics are believed to be representative of those for this study since parent ice sheet properties were similar.

Force Time Series

Figure 4 shows force and displacement time series traces, two for option 1a and two for option 3a. Several "dry" runs were conducted to determine the no-load static and dynamic friction characteristics of the shear box. Averaged load traces of the frictional force for each shear option have been subtracted from the force traces and for all subsequent analyses.

Virtually all load traces exhibited a significant oscillatory component. Some fluctuations were more random than others but most were uniform and saw-toothed. During the tests, it was often possible to observe the "skipping" or hopping of the rubble sample corresponding to these load cycles. The frequency was observed to drop with decreasing normal stress, though the relation was not very strong. Option 3 produced both the highest (for original "with guide rods" option) and lowest (without rods) frequencies - apparently an artifact of the spreader mechanics. Oscillation amplitudes were observed to be poorly correlated to normal stress, although a slight trend towards increased amplitude with apparatus "weight" was noted.

The potential causes of the force oscillations included ice-structure ratchetting, shear box stick-slip action, and ice rubble cyclic dilation. We believe that the most likely cause was ratchetting in which, periodically, quasi-static forces on an ice-structure interface increase with increased deflection until ice resistance is exceeded, causing ice failure and a relief of loads on the structure. In this case, the appropriate measured force values to use in the interpretation are the peak values since this mechanism is not resonant and will not result in any dynamic amplification of the peak forces.

For options 1 and 2, the peaks of load cycles frequently grew with increased shear box translation. At appreciable box translations there was an increased normal stress due to the decrease in shear area, and the sample tilted into the trench. This may have led to enhanced compression and gouging at the leading and trailing box edges, complicating the analysis for options 1 and 2. Only option 3 (no shear box at all) exhibited a clear tendency for peak loads to repeatedly occur in the first few seconds.

Rubble Shear Stress

Analysis of the experimental data revealed that subjective decisions were required in order to determine shear strength, even for the least ambiguous of test procedures. Shear stress is often computed by dividing the force required to shear the sample by the instantaneous shear plane area of the box. Difficulty is encountered when forces are cyclic and peaks increase with displacement. The choice must then be made of when, or at what displacement, peak "shear resistance" was encountered. Loads which follow may be greater but may also be artifacts of the shear box mechanics. Furthermore, one may wish to consider either peak or residual (mobilized) friction angles and, of these, either absolute maxima or mean cyclic values may be selected.

In this study two conventions were adopted. The first was to determine the peak shearing force from the first two seconds or 4.2 cm displacement. The second looked at the first 15 seconds or 30 cm of the force-time histories for a peak. The latter was selected to correspond to some observed trends in the force traces whereas the first was based on the assumption that for typical dilatant soils, shearing peak loads occur at displacements close to but less than one particle thickness. Shear areas were adjusted for box displacement.

Mohr-Coulomb Approximation

Normal (vertical) shear plane stresses were determined from the weight of the ice above the surface, the buoyant weight of ice between the surface and the shear plane below and the weights added for surcharge. A plot of the results for the 2-second peak shear for all options is given in Figure 5 and for the 15-second peak shear in Figure 6. It is evident by comparing Figures 5 and 6 that using the 2 s instead of the 15 s adjusted shear strength values is probably justified. Increased scatter in the latter underscores the uncertainty about apparatus performance and shear interpretation beyond the first few seconds of each test. The uniform spread of the results for all apparatus options, and the close agreement between options indicates that the 2 s peak is analytically superior. An interesting result is obtained when both the combined 2 s and combined 15 s results are compared. Figure 7 shows that the internal friction angle for both was a near perfect match while apparent cohesion was 2/3 higher for the latter case.

Case (1991a, 1991b) reports laboratory results from the ice tank at IMD when a fixed vertical direct shear box was used to shear rubble samples. The ice rubble (similar to that in this study) was formed by a chopping action of the carriage and samples were corralled into the box. The shear rate was twenty times slower than that in the present tests and the timing of tests relative to ice formation was somewhat different. Regardless of these differences, the laboratory results compare favourably. The range of results of both experimental programs are similar with overall combined $\phi = 38°$ and $c=661$ Pa for the Case (1991a, 1991b) study, versus $\phi=41°$ and $c=873$ Pa for the combined results in the present study. This is a strong indication that the direct shear approach is robust and that the influence of block size and test conditions on rubble shear strength in the IMD laboratory are minimal. Further, the present data are in line with the data compiled by Bruneau (1996) in a summary of available data for rubble shear failure (Figure 8).

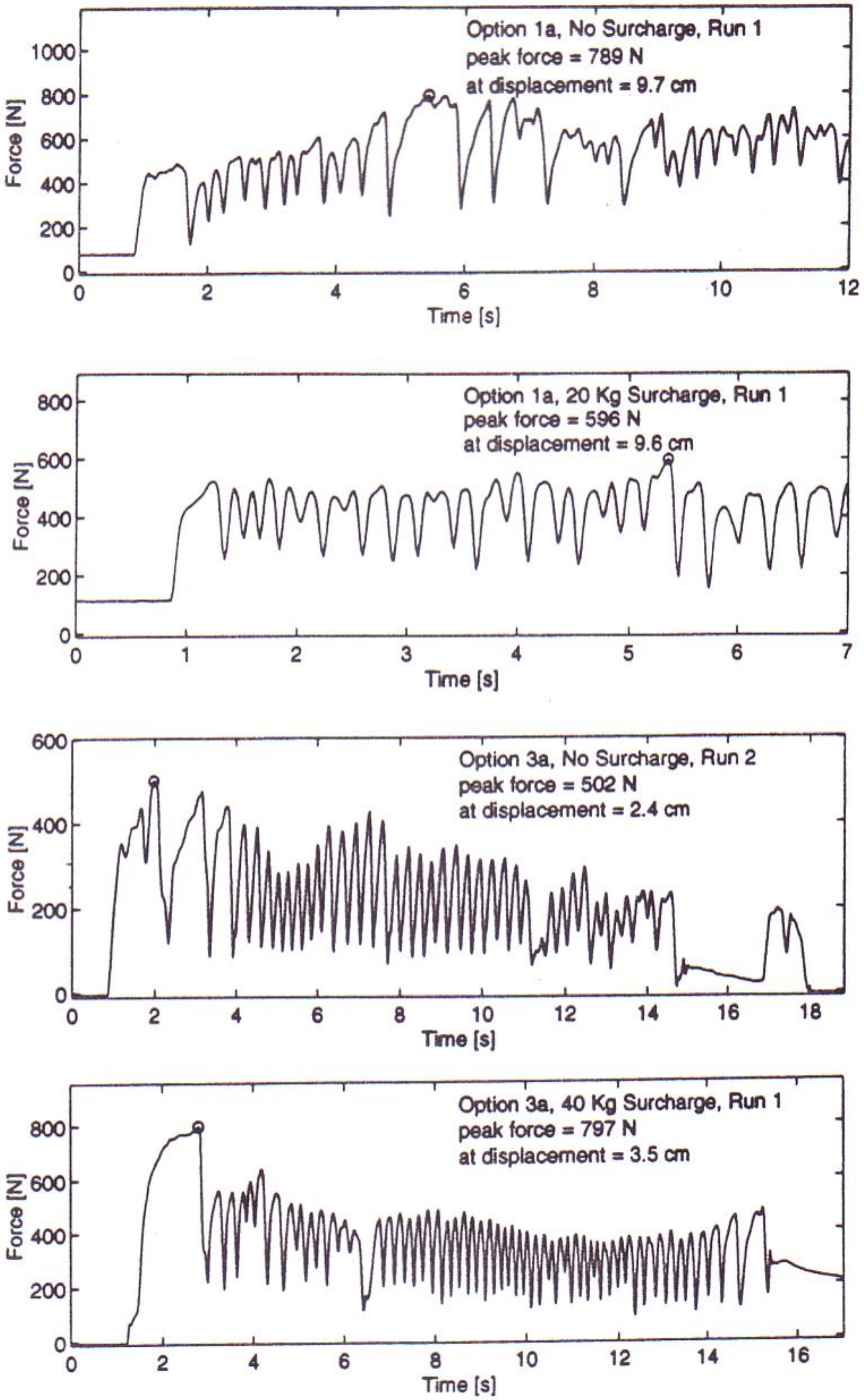
Option 1a, No Surcharge, Run 1
peak force = 789 N
at displacement = 9.7 cm
Force [N]
0
200
400
600
800
1000
Time [s]
0
2
4
6
8
10
12
Option 1a, 20 Kg Surcharge, Run 1
peak force = 596 N
at displacement = 9.6 cm
Force [N]
0
200
400
600
800
Time [s]
0
1
2
3
4
5
6
7
Option 3a, No Surcharge, Run 2
peak force = 502 N
at displacement = 2.4 cm
Force [N]
0
200
400
600
Time [s]
0
2
4
6
8
10
12
14
16
18
Option 3a, 40 Kg Surcharge, Run 1
peak force = 797 N
at displacement = 3.5 cm
Force [N]
0
200
400
600
800
Time [s]
0
2
4
6
8
10
12
14
16

FIGURE 4.

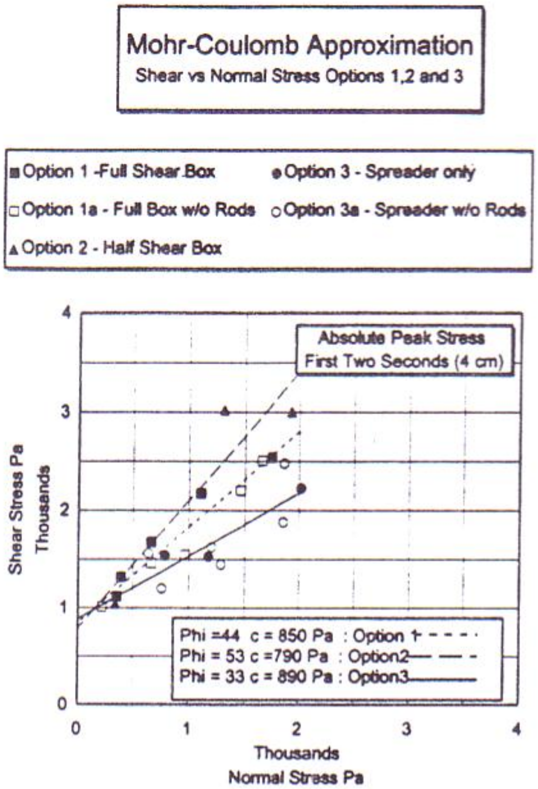

FIGURE 5.

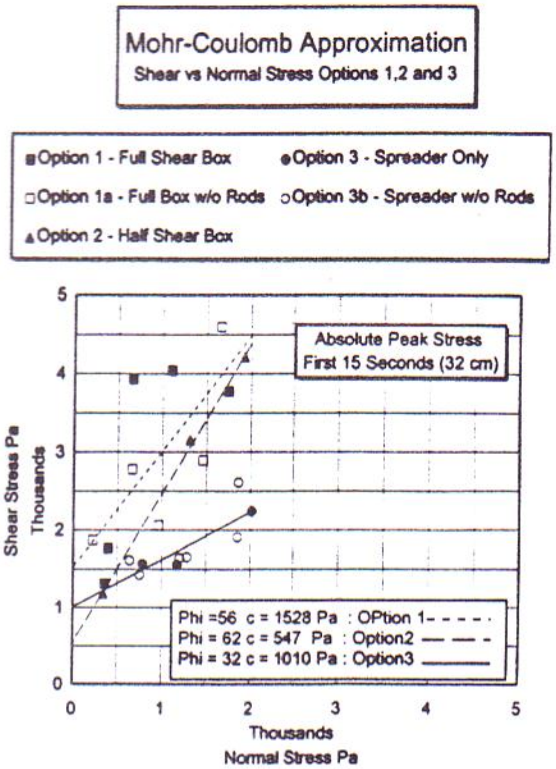

FIGURE 6.

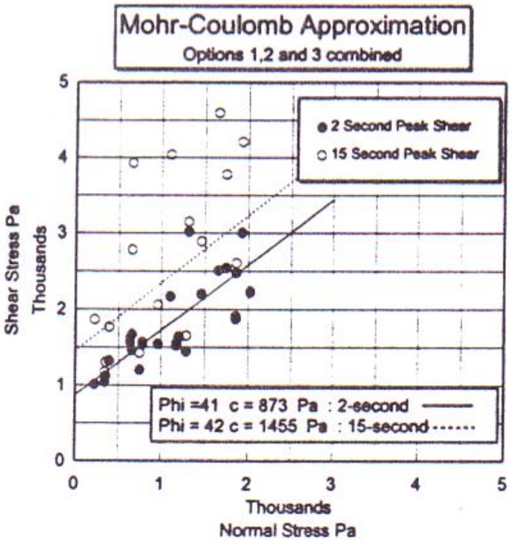

FIGURE 7.

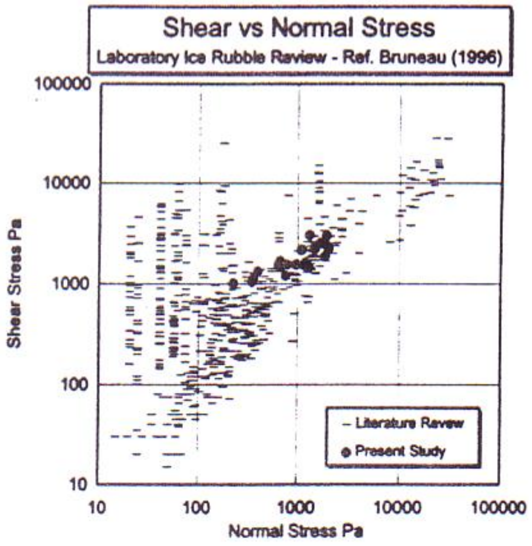

FIGURE 8.

SUMMARY AND RECOMMENDATIONS

The present study has demonstrated the application of various direct shear methods for the measurement of laboratory ice rubble shear strength *in situ*. Averaged results of $\phi=41°$ and c=873 Pa compare favourably with results reported in the literature. Based on the results of the present experiments, a direct, horizontal shear technique is suitable for determining the *in situ* shear properties of rubble in first year ridge keels. Also, as long as a competent consolidated layer is present, this can be used as a platform for loading the shear plane thus simplifying the testing apparatus. Since trenching around the sides of the ice sample will be a time-consuming operation in the field, the test procedure might be significantly stream-lined by cutting the sides of the ice sample with a slight flare angle. This would eliminate binding of the sample in the hole and enable a single chain saw cut to be used instead of a trench.

ACKNOWLEDGEMENTS

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