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IN SITU SHEAR STRENGTH MEASUREMENTS OF MODEL ICE RUBBLE USING A PUNCH TECHNIQUE

Richard F. McKenna[1], Stephen E. Bruneau[1] and F. Mary Williams[2]

[1] *C-CORE, Memorial University of Newfoundland, St. John's, NF A1B 3X5*
[2] *Institute for Marine Dynamics / NRC, P.O. Box 12093, Stn. 'A', St. John's, NF A1B 3T5*

ABSTRACT

Experiments were conducted to determine the *in situ* shear strength of ice rubble using circular plates pushed vertically through model ice ridges. Constructed from broken ice sheets, the ridges were up to 1.2 m deep and ranged between 1.75 m and 6 m wide. Most of the ridges were cooled following construction, forming a refrozen layer at the waterline which is characteristic of first year features. Based on 85 experiments with a 0.5 m diameter platen moving at 0.07 m/s, the shear strength of the ridge keels ranged between 0.73 kPa and 1.03 kPa depending on ice conditions. The data were analyzed using the approach of Meyerhof and Adams (1968) developed for pull-out of shallow footings in sand and clay. Before refreezing the ridges, an apparent cohesion of 0.44 kPa and a friction angle of 36° were estimated for shear failure of the rubble.

RESUME

Des essais ont été effectués pour déterminer la résistance au cisaillement *in situ* d'aggrégats de glace en utilisant des plaques circulaires poussées verticalement sur des amoncellements de glace modélisée. Construits à partir d'un couvert de glace fragmenté, ces amoncellements étaient d'une profondeur allant jusqu'à 1.2 m et avaient une largeur variant entre 1.75 m et 6 m. La plupart des amoncellements ont été refroidis après leur construction, produisant une couche recongelée au niveau de l'eau qui est caractéristique de la glace de première année. Après avoir effectué 85 essais avec une platine d'un diamètre de 0.5 m se déplaçant à une vitesse de 0.07 m/s, la résistance au cisaillement variait entre 0.73 et 1.03 kPa, dépendamment des conditions de la glace. Les résultats ont été analysés suivant l'approche de Meyerhof and Adams (1968), conçue pour l'extraction de semelles peu profondes dans du sable et de l'argile. Avant la regel des amoncellements, une cohésion apparente de 0.44 kPa et un angle de friction de 36° ont été prédits pour la rupture par cisaillement de l'aggrégat.

INTRODUCTION

Experiments were conducted in the ice tank at the Institute for Marine Dynamics (IMD) to address the interaction of ice ridges with cylindrical structures, conical structures and conical bridge piers (McKenna et al., 1995a,b; McKenna, 1996a). Many of the experiments focused on the forces exerted by the ridge keels on the structure and simultaneous measurements of the *in situ* shear failure properties were made (McKenna, 1996b).

A direct shear device was developed for the IMD tank by Case (1991a,b), however this was not suitable for repeated tests of ridge properties *in situ*. Leppäranta and Hakala (1992) applied a punch technique to a limited number of ice ridges in the Baltic Sea. The technique was most successful when the refrozen top layer was removed before the surface was loaded vertically using a hydraulic system. A similar approach was adopted for the present experiments and a punch shear apparatus was designed to be mounted on the platform of the service carriage in the ice tank. The device consisted of a screw mechanism used to drive a circular plate downward through the ice ridge.

In the punch tests, the resistance of the ice rubble to shear is provided by the buoyant weight of the rubble acting upwards. The approach is similar to plate pull-out tests which have been used to estimate the uplift capacity of footings. Recently, Das and Singh (1995) reviewed a number of interpretive techniques and found the approach of Meyerhof and Adams (1968) to be the best predictor of ultimate uplift capacity for loose and dense sands. In McKenna (1996b), the approach of Meyerhof and Adams was used to interpret the punch data collected during the above test programs and the present paper is a synthesis of this report.

EXPERIMENTAL CONDITIONS

Ridges were constructed from sixteen ice sheets by placing broken ice rubble between two parallel saw cuts in the surrounding level ice. The ice sheets were grown from EG/AD/S model ice and fine bubbles were introduced into the ice during the freezing process to achieve a realistic density (Spencer and Timco, 1990). The original ice sheet thickness was 0.05 m, the maximum ice block length was approximately 10 times this value and the average ranged between 2 and 3.5 times the thickness. A solid ice layer approximately 0.04 m thick was allowed to refreeze at the waterline subsequent to ridge construction. For some of the ridges, keel depths were measured using a chirp acoustic profiling system developed at C-CORE (for details see McKenna et al.,1995a). For the remaining tests, the total depth of the ridge at any one point was determined using a graduated aluminum rod pushed vertically through the ridge until no resistance was detected. The sail profiles were obtained by measuring the distance from a fixed elevation to the top surface of the ice rubble. The total rubble depth varied between approximately 0.5 m and 1.4 m at the test locations.

The porosity of the rubble was calculated by comparing the amount of level ice used to build a ridge and the average cross-section area determined from 4 to 6 profiles. Porosity estimates ranged between 0.2 and 0.4 with an average of 0.26. Prior to refreezing, the density of submerged blocks was 865 to 910 kg/m^3 which then increased to between 900 and 930 kg/m^3 as water displaced the entrapped air. Brine drainage produced sail blocks with a density of 750 kg/m^3. At the time of ridge construction, the flexural strength of the ice measured from cantilever beams ranged between 20 kPa and 120 kPa. Following the refreezing cycle, the flexural strength of submerged blocks measured from three-point bending tests was not sensitive to the initial strength and ranged between 20 and 30 kPa. The strength of the blocks in the ridge sails was substantially higher and was closely related to the ambient air temperature.

The *in situ* shear strength of the rubble in the ridge keels was measured using the punch apparatus shown in Figure 1. The device consisted of a 0.025 m thick aluminum platen (0.093, 0.028 and 0.050 m diameter) screwed into a 450 kg capacity load cell and connected rigidly to the end of a 0.25 m diameter threaded rod. The rod was driven downward by an electric drill through a gear mechanism. The drill had two speed settings which resulted in platen speeds of approximately 0.07 m/s and 0.14 m/s. The relative displacement between the platen and the support structure was measured using a "yo-yo" type potentiometer. The punch shear device was mounted on the pedestrian platform of the service carriage in the ice tank and held in place using large c-clamps. In the latter part of the test program, the deflection of the surface of the ridge was measured using an LVDT mounted on this platform.

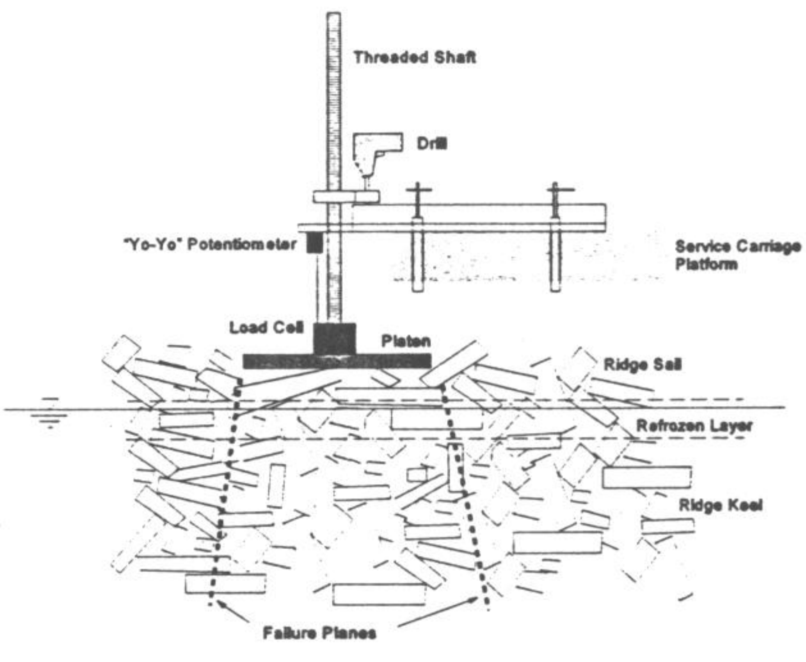

FIGURE 1 Schematic of the punch shear apparatus

Punch tests were performed either immediately after ridge construction or following the formation of a refrozen layer. When the refrozen layer was present, a chainsaw was used to cut it into approximately 0.15 m squares prior to a test. The consolidated layer was not removed so as to maintain in-situ buoyancy conditions.

During each test, platen force, ice surface displacement and platen displacement relative to the water level were recorded. The data from a typical test are shown in Figure 2. The peak force, the corresponding displacements and the residual force on the platen after it had stopped were determined from the data traces. Many of the tests were documented using an underwater video camera connected to the end of a pole which was pushed through a hole in the ice.

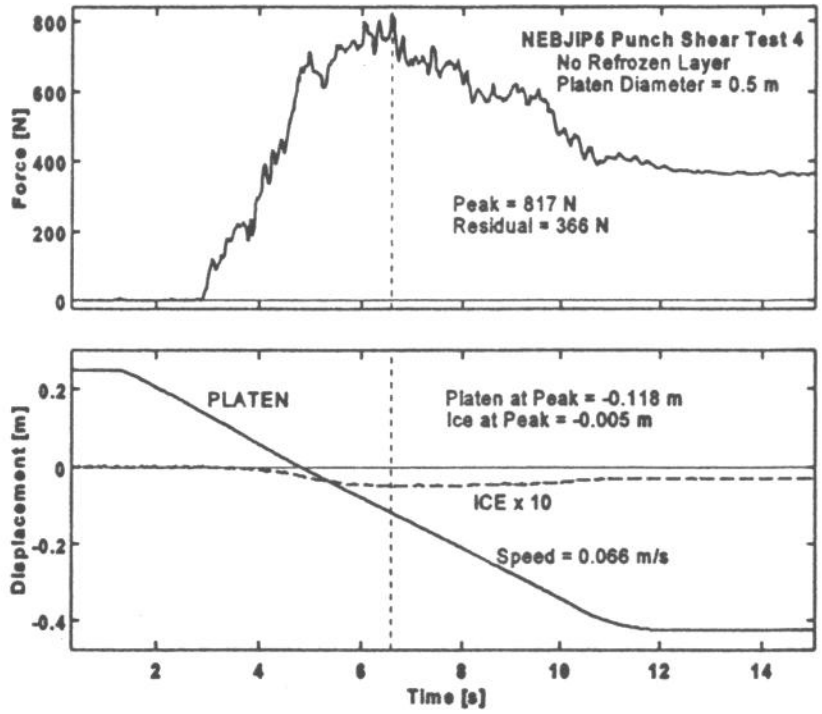

FIGURE 2 Typical results from a punch test conducted immediately after ridge construction

DATA INTERPRETATION

There was some freeze-bonding between rubble blocks since agglomerations of blocks and vertical slopes were observed. On the other hand, the bonding was not strong and the agglomerations would tend to fall apart following a slight push. Because large displacements are required to activate entire shear planes during ridge penetration by a structure, it has been suggested that freeze bonds would tend to break prior to peak load. In such cases, the rubble behaviour would be purely frictional. Crushing at the contact between blocks and the breaking of blocks tend to reduce the shear strength at higher confining pressures and an apparent cohesion has been observed in many previous experiments on ice rubble.

The punch shear test results have been interpreted using the method of Meyerhof and Adams (1968) for the pull-out of shallow circular footings. For shallow conditions, the ratio of embedment depth, H, to footing diameter, D, should be less than 2 which is the case for the majority of the tests conducted with the 0.5 m platen. The force required to lift a footing is

$$F = \pi D H c + \pi D \frac{\gamma H^2}{2}\left(1 + a\phi^b \frac{H}{D}\right) K_u \tan\phi + W, \qquad [1]$$

where c is the soil cohesion, ϕ is the friction angle, γ is the unit weight of the soil, K_u is the nominal uplift coefficient of earth pressure on the vertical plane around the perimeter of the footing (=0.95) and W is the weight of the footing and the soil above it. The term in parentheses accounts for the circular shape of footing and the constants a=0.98 and b=2.82 were estimated from tabulated data given in Meyerhof and Adams. The shape effect and K_u can be combined into a coefficient $K = K_u(1+a\phi^b H/D)$ which relates horizontal and vertical pressures. A minimum pressure coefficient for the present data would be about K=1.1 (corresponding to ϕ=30° and H/D=1), and a maximum would be about K=2.2 (corresponding to ϕ=50° and H/D=2).

In the present case, the force, F, was estimated from the measured peak load on the platen and this was corrected for buoyancy when submerged. The weight of the rubble, W, was determined as the net buoyant force of the ice rubble column beneath the platen at the instant of peak load. The total depth of the ridge was used to obtain the ratio H/D. This is exact when the column is completely submerged and is a good approximation for partial submergence. The $\gamma H^2/2$ term is the hydrostatic force per unit distance around the cylindrical column and was calculated from submerged keel, submerged sail and exposed sail contributions. The penetration at peak load as well as the porosity and the sail and keel block densities were used in the calculation.

RESULTS

A sensitivity study was conducted in McKenna et al. (1995b) with platen diameters of 0.093 m, 0.28 m and 0.50 m, and for speeds of 0.07 m/s and 0.14 m/s. For the two larger platens and for both speeds, there were no discernible differences in the results and the remaining tests were conducted with the 0.50 m platen at a nominal speed of 0.07 m/s. These are documented in the results which follow.

An average nominal shear stress $(F-W)/\pi DH$ of 0.73 kPa was calculated for the tests conducted immediately after ridge construction and a value of 1.03 kPa was obtained for those conducted following the formation of a refrozen layer. When the data are plotted with respect to keel depth in Figure 3, the difference between the two data sets is apparent. Both sets cover the same range of keel depths and the difference between the means is significant statistically.

In equation [1], the average normal stress on the failure planes depends on the friction angle through the non-linear term $1+a\phi^b H/D$. As a result, the data cannot be represented in shear-normal stress space without first calculating ϕ and c. These parameters were obtained using equation [1] by applying a nonlinear least squares estimation technique to the data. The constants a, b and K_u shown above were used in the calculation. For the tests conducted immediately following ridge construction, c=0.44 kPa and ϕ=36° were estimated and the failure envelope is shown in Figure 4. The fit is probably significant since R^2=0.19 and the calculated statistic F=68 exceeded $F_{2,35;\,99\%}$=5.3. Note that the F statistic is only approximate in the nonlinear case. When the failure envelope was forced through the origin, ϕ=49° was estimated with R^2=0.14 and the calculated statistic F=46 exceeded $F_{1,36;\,99\%}$=7.4. The parameter estimates were not significant statistically for the 48 tests conducted on the ridges which had a refrozen layer at the waterline.

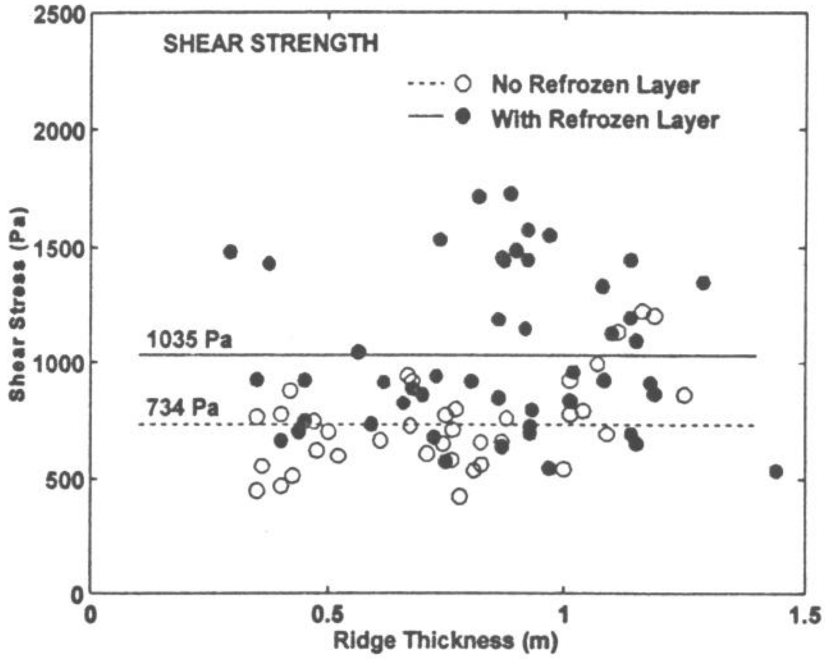

FIGURE 3 Shear strength of model ice rubble from the punch tests before and after the formation of a refrozen layer

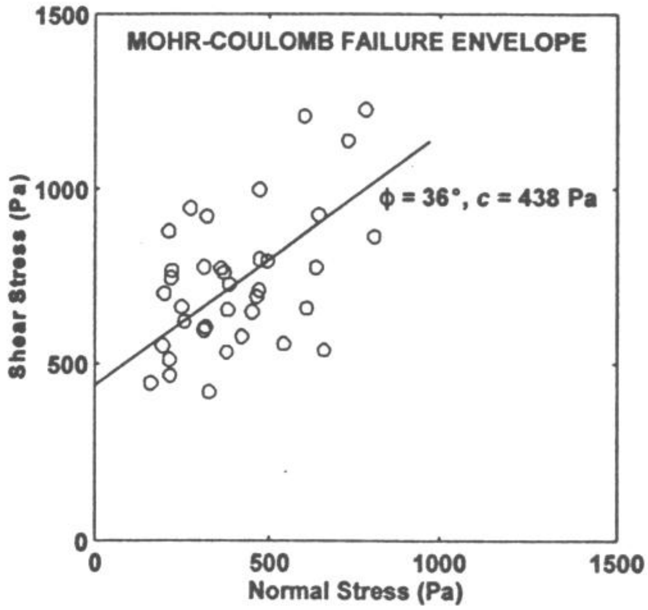

FIGURE 4 Mohr-Coulomb failure envelope estimated from the punch tests conducted immediately following ridge construction

When compared to the test results immediately following ridge construction, the results with the refrozen layer yielded higher shear strengths but no significant friction angle. The most likely explanation is that freeze-bonding over time was sufficient to dominate the failure process. The average position of the platen at peak load was significantly higher when the refrozen layer was present which supports the argument. It is possible that blocks jammed at the waterline, but the refrozen layer thickness was only 0.04 m and this mechanism is unlikely. As noted above, the flexural strength of the blocks was reduced and some block breakage may have occurred immediately beneath the platen. The compressibility of the rubble would have increased but the overall failure mechanism would not have changed.

Figure 4 illustrates the variability in the shear strength for similar normal pressures. Substantial variability is not an unusual feature of ice failure data, particularly when ice fracture and sliding between blocks occur. Since the ridges were not compacted, cavities within the ridge as well as the uneven free surface may have contributed. There is also an inherent difficulty with the interpretation of friction angles from vertical punch tests since the range of normal stresses applied by keel buoyancy is relatively small compared to the scatter in the measured shear stresses.

CONCLUSIONS

One hundred and thirty-five punch tests were conducted on sixteen ridges constructed from model ice to determine the *in situ* shear failure properties of the ridge keels. Keel depths ranged from about 0.3 m to 1.2 m. The ice block thickness was 0.05 m and most of the tests were performed with a 0.5 m circular platen moving vertically downward at a speed of 0.07 m/s. There was little sensitivity to speed between 0.07 m/s and 0.14 m/s, and little effect of platen size between 0.28 m and 0.50 m.

The average shear strength of the ice rubble varied between 0.73 kPa and 1.03 kPa, depending on whether a layer of ice was refrozen at the waterline. The method of Meyerhof and Adams (1968) for shallow circular footings was used to estimate a Mohr-Coulomb failure envelope from the punch results. Least squares estimates of the parameters indicated significant values of $\phi=36°$ and $c=0.44$ kPa for ridges tested immediately following construction. No significant friction angle could be estimated from the data tested after a refrozen layer was allowed to form at the waterline.

Substantial variability was observed in the punch test results. This limits the effectiveness of the technique for field conditions since a large number of experiments would be required to achieve reliable results.

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