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SOMMAIRE

Une série d'essais ont été effectués sur des cônes pointant vers le bas dans de la glace peu salée. Une comparaison avec des résultats tirés de la documentation a montré que le cône est moins sollicité lorsqu'il pointe vers le bas. Des cônes fixes avec des angles de 15, 30, 45 et 60 degrés au sommet ont été essayés dans de la glace de 50 mm d'épaisseur et de 60 kPa de résistance à la flexion à des vitesses allant de 0,01 à 0,5 m/s. Les effets de variations d'épaisseur et de résistance à la flexion ont aussi été étudiés. Une variation d'épaisseur de la glace influe davantage sur les forces verticales que sur les forces horizontales. Une diminution de la résistance à la flexion entraîne une diminution des forces verticales et horizontales.

Deux séries d'essais ont été effectués avec un cône de 45 degrés placé de telle sorte qu'il puisse osciller. Des réductions allant jusqu'aux deux tiers des forces horizontales ont été observées.

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MODEL TESTS OF ICE FORCES ON FIXED AND OSCILLATING CONES*

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ABSTRACT

A series of model tests has been carried out on downward breaking conical structures using low salinity model ice. Comparison with information in the literature showed that a downward breaking cone experiences lower ice forces than an upward breaking cone. Fixed cones of angles of 15, 30, 45 and 60 deg were tested in 50-mm-thick ice of 60 kPa flexural strength at velocities ranging from 0.01 to 0.5 m/s. The effects of thickness and flexural strength variations were also investigated. Horizontal forces were observed to increase with increasing velocity. Ice thickness variation was observed to have a stronger influence on the vertical forces than on the horizontal forces. Vertical and horizontal forces showed a decrease with decreasing flexural strength.

Two test series were run with the 45 deg conical structure arranged so that it oscillated. Horizontal force reductions of up to two thirds were observed.

INTRODUCTION

Because of increasing world demand for hydrocarbons and other minerals, polar offshore regions characterized by severe ice conditions are coming under increasing scrutiny as potential sources. In certain areas, systems for offshore drilling are being evolved; for example, in the shallow waters (less

than 20 m) of the Canadian Beaufort Sea, man-made islands have been successfully used for exploratory drilling. Ice-breaker supported drillships have also operated for almost five months of the year in deep-water areas of the same region. Production from these and other regions with even more severe ice conditions will, however, require new technology, and considerable effort is therefore being devoted to the development and evaluation of new concepts for offshore structures that will operate safely and economically under severe conditions (Jazrawi and Khanna 1978, Gerwick and Jahns 1979). One such concept is a downward cone, which could be fitted to a cylindrical structure and operated in either a fixed or an oscillating mode. A downward breaking conical structure could be either bottom founded or floating, but would have a more immediate application in a floating mode. This paper will report on model investigations of the effects of ice thickness, cone geometry, velocity and ice strength on forces generated on fixed and oscillating cones. Theoretical predictions and other test data in the literature will be discussed.

ICE TEST FACILITY

Model tests were carried out in the Hamburg Ice Model Basin (HSVA). It is a three-part basin, i.e. trim tank, freezing tank, and melting tank. The freezing or actual ice testing tank is 30-m long,

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Fig. 1. Vertical (a) and horizontal (b) thin sections of low salinity model ice (grid spacing 10 mm).

6-m wide and 1.2-m deep. A motor-driven carriage provides a speed range from 0 to 2 m/s. The air temperature can be set at any value between 0 and -20°C and is kept constant within 1°C . Owing to the very small air motion during the freezing period, ice thickness is uniform over the entire tank area to within ± 1 mm. In order to reduce the crystal size and obtain ice of uniform crystal structure and strength a water-spray method is utilized: water of almost 0°C is sprayed at 400 kPa into the -10°C cold air above the testing tank. The droplets form ice crystals that settle on the water surface, initiating the formation of fine-grained colum-

nar ice similar in structure to natural sea ice. Figure 1 illustrates the grain structure of the ice.

It has been shown that not only Froude similitude but also Cauchy similitude must be satisfied (Schwarz 1978), so that it is necessary to maintain the same ratio of elastic modulus to flexural strength in the model ice as in nature. The ratio of elastic modulus to strength (E/σ) is 2000–5000 for natural sea ice. The modeling technique uses low salinity ice (grown from a 6 ‰ NaCl solution) and accomplishes strength reduction by increasing the ice temperature and with it the brine volume prior to testing (Schwarz 1975). The brine volume

increase also reduces the elastic modulus by an amount such that E/σ ratios in the range 1700–2000 can be maintained. When the ice strength is reduced too far, say less than 60 kPa, plastic deformation becomes significant, contributing substantially to the energy required to break the ice cover.

The breaking strength of the ice was measured before and after each test run using in situ cantilever beams. Breaking force was determined with a spring gauge, the dimensions of the broken beam measured, and strength calculated from the following equation:

$$\sigma_f = \frac{6Pl}{bh^2}, \quad (1)$$

where P is breaking force, l is beam length (usually 0.4 m), b is beam width (usually 0.1 m) and h is ice thickness. Because of anisotropy, geometry considerations and non-homogeneity, the equation is not an exact representation of bending strength, but it is an accepted strength index (IAHR 1981). Flexural strength was typically 60 kPa at a loading stress rate of about 50 kPa/s.

The coefficient of friction was measured by drawing an ice block over a representative surface of the structure and found to be about 0.1. Density of the ice was about 940 kg/m³.

FIXED CONE TESTS

Test procedure

The test set-up for the fixed conical structure is illustrated schematically in Fig. 2. The model was fabricated of steel plate and painted with a normal acrylic paint. Two conical sections, the lower portion 60 deg to the horizontal and the upper portion 45 deg, were fitted over a 0.5-m-diameter cylinder. To investigate the effect of various cone angles, two auxiliary conical sections of 15 and 30 deg (shown with dashed lines in Fig. 2) could be bolted to the upper portion of the model structure. It was possible to raise the entire structure so that the ice impinged on the 60 deg section. The actual waterline diameters were 1.75, 1.5, 1.2 and 1.0 m, respectively, for cone angles of 15, 30, 45 and 60 deg. Also shown schematically are the load cells used to measure ver-

Fig. 2. Schematic of fixed conical model structure.

tical and horizontal forces. The load measuring system had the additional feature of being able to resolve the point of action of the resultant ice force. In all tests the fixed conical structures were rigidly attached to the towing carriage.

Three test series were run with the fixed conical structure. The main series comprised tests for cone angles of 15, 30, 35 and 60 deg in 50-mm-thick ice of 60-kPa flexural strength at velocities ranging from 0.01 to 0.50 m/s. For the 45-deg cone, two special test series were carried out: one in which ice thickness was varied from 35 to 65 mm, and another in which flexural strength was varied from 50 to 85 kPa.

Test results

Continuous records of load versus time were made for all tests, from which both mean and mean peak values were determined. Test results are summarized in Tables 1(a), 1(b) and 1(c). More detailed results can be found in Schwarz et al. (1978). For the purposes of this paper, the emphasis in the presentation of results is on mean ice forces. The curves drawn on Figs. 3–6 represent a mathematical smoothing of all the test data and are shown to indicate trends.

Velocity effects

Test results of the effect of velocity on average ice forces for fixed conical structures are presented in Fig. 3. The vertical forces first increased rapidly and then decreased with increasing velocity, whereas the horizontal forces increased, although not

TABLE 1(a)

Ice force as a function of velocity for various cone angles, α

Test conditions	Velocity (m/s)	Mean force (N)		Mean peak force (N)	
		Vertical	Horizontal	Vertical	Horizontal
$\alpha = 15^\circ$	0.01	160	103	107	136
$h = 52 \text{ mm}$	0.05	232	104	291	177
$\sigma_f = 63 \text{ kPa}$	0.10	284	121	357	257
	0.25	402	191	428	371
	0.50	329	319	384	512
	0.10	249	117	327	235
$\alpha = 30^\circ$	0.01	194	138	240	229
$h = 55 \text{ mm}$	0.05	232	137	300	253
$\sigma_f = 62 \text{ kPa}$	0.10	280	143	412	283
	0.25	340	194	618	404
	0.50	332	251	710	488
$\alpha = 45^\circ$	0.01	250	169	337	240
$h = 54 \text{ mm}$	0.05	296	153	418	256
$\sigma_f = 63 \text{ kPa}$	0.10	364	191	588	371
	0.24	339	235	821	548
	0.52	276	255	830	922
$\alpha = 60^\circ$	0.01	159	166	234	291
$h = 55 \text{ mm}$	0.05	217	211	245	391
$\sigma_f = 59 \text{ kPa}$	0.10	228	242	397	469
	0.25	246	318	514	870
	0.50	193	298	516	874

TABLE 1(b)

Ice force as a function of ice thickness, h , for a 45° conical structure

Test conditions	Velocity (m/s)	Mean force (N)		Mean peak force (N)	
		Vertical	Horizontal	Vertical	Horizontal
$h = 35 \text{ mm}$	0.04	93	103	122	168
$\sigma_f = 55 \text{ kPa}$	0.06	103	101	144	172
	0.12	122	118	228	245
	0.24	111	125	277	298
	0.46	71	180	228	397
	0.04	90	75	136	131
$h = 46 \text{ mm}$	0.01	117	103	—	—
$\sigma_f = 65 \text{ kPa}$	0.06	115	119	—	—
	0.10	212	142	—	—
	0.26	218	192	—	—
	0.54	170	260	—	—
$h = 49 \text{ mm}$	0.01	187	77	—	—
$\sigma_f = 60 \text{ kPa}$	0.05	234	125	—	—
	0.10	304	163	—	—
	0.25	297	205	—	—
	0.51	215	249	—	—

$h = 54$ mm	0.01	250	169	337	240
$\sigma_f = 63$ kPa	0.05	296	153	418	256
	0.10	364	191	588	371
	0.24	339	235	821	548
	0.52	276	255	830	922
$h = 64$ mm	0.01	208	167	—	—
$\sigma_f = 63$ kPa	0.05	290	185	—	—
	0.10	333	211	—	—
	0.25	365	267	—	—
	0.50	346	321	—	—

TABLE 1(c)

Ice force as a function of flexural strength at a velocity of 0.1 m/s

Test conditions	Flexural strength (kPa)	Mean force (N)		Mean peak force (N)	
		Vertical	Horizontal	Vertical	Horizontal
$\alpha = 30^\circ$	83	252	192	—	—
$h = 53$ mm	72	202	157	—	—
	57	196	153	—	—
	64	168	147	—	—
	52	140	141	—	—
$\alpha = 45^\circ$	84	381	311	613	512
$h = 55$ mm	71	347	266	552	475
	59	272	206	455	425

quite so rapidly, with increasing velocity. The one exception to this pattern was the horizontal force for the 60 deg cone, which showed a decrease at higher velocities. The relation between the vertical and horizontal forces is illustrated in abbreviated form in Table 2. For the 15, 30 and 45-deg cones, the vertical forces were greater than the horizontal forces, the maximum difference being at velocities in the range of 0.2 to 0.3 m/s. This difference tends to decrease with increasing cone angle. For the 60-deg cone the horizontal forces were greater.

TABLE 2

Ratio of average vertical to average horizontal force

Velocity (m/s)	Cone angle			
	15°	30°	45°	60°
0	1.5	2.5	1.9	0.9
0.25	2.5	2.0	1.5	0.8
0.50	1.0	1.25	1.1	0.7

to zero for a vertical structure, $\alpha = 90$ deg. Similar general trends were obtained at higher velocities, but they have not been included since they would overlie the curves.

The resultant of the vertical and horizontal ice forces and the direction of action are plotted in Fig. 5 as a function of velocity for various cone angles. The direction of action of the resultant β is an angle measured from the vertical. Both the resultant force and its angle of action increase with increasing velocity. The resultant forces are remarkably similar for all cone angles.

Cone angle effects

The results, which are basically the same as those shown in Fig. 3, have been plotted in a different format in Fig. 4 in order to illustrate more clearly the influence of cone angle on ice forces in the velocity range 0.01 to 0.20 m/s. The horizontal forces show a minimum between 15 and 30 deg, and then increase with increasing cone angle. The vertical forces, on the other hand, show a maximum between 30 and 40 deg and then a general decrease with increasing cone angle. The dashed lines indicate the extrapolation of the vertical forces

Fig. 3. Average vertical, F_V , and horizontal, F_H , forces as a function of velocity for various cone angles, α .

Fig. 4. Influence of cone angle α on ice forces.

Fig. 5. Resultant ice force, F_{res} , and angle of its action from the vertical, β , versus velocity for various cone angles.

Fig. 6. Vertical force, F_V , and horizontal force, F_H , as a function of ice thickness for a 45 deg conical structure.

Ice thickness effect

The results of tests on the effect of ice thickness are presented in Fig. 6. These tests were done with the 45 deg cone angle structure and showed an increase in both vertical and horizontal force with increasing ice thickness. Again results have been presented only for velocities in the range 0.01 to 0.1 m/s, but similar trends were observed for higher velocities.

Flexural strength effects

To determine the influence of flexural strength on ice forces a series of tests was carried out with 30 and 45 deg conical structures at a velocity of 0.1 m/s in 53-mm-thick ice. The results showed an increase in ice force with increasing ice strength (Fig. 7).

OSCILLATING CONE TESTS

It is known from icebreaker technology that the icebreaking capability of small ships can be increased by a so-called "Stampfanlage." Eccentric rotations of masses installed in the forebody cause pitching motions of the ships that reduce icebreaking resistance considerably. Worldwide, more than one hundred ships are equipped with a "Stampfanlage." The disadvantage of such an active ice-breaking device is the vibration and its effect on ship personnel.

In offshore structures this negative effect could be avoided if the rotating masses were to be installed in conical collars that would float freely on the water surface around the piles or legs of platforms or semi-submersibles (Waas 1975). Feasibility studies of such an icebreaking platform, where rotating masses on conical collars would reduce the horizontal ice loads, were investigated in model tests.

Test procedure

The test set-up for the oscillating conical model structure is given schematically in Fig. 8. The models of the vertical cylinder and the 45 deg cone were the same as those for the fixed cone tests. In this case, however, only the vertical cylinder

Fig. 7. Influence of flexural strength on vertical force, F_V , and horizontal force, F_H ; ice thickness 53 mm, velocity 0.1 m/s.

Fig. 8. Schematic of oscillating conical model structure.

was fixed to the carriage. The cone was kept in a floating position by springs connected to it (see Fig. 8). Two counter-rotating eccentric masses generated the vertical oscillatory motion of the cone.

By varying the axis of rotation by 45 deg in the horizontal plane a horizontal component of motion was added to the vertical motion, i.e. the cone performed a circular motion. The oscillating cone was linked to the carriage by means of springs and a horizontal load-measuring device (Fig. 8). The spring allowed free motion of the cone in both horizontal and vertical directions.

During the icebreaking tests, in which the oscillating cone and the vertical cylinder were driven through the level ice cover by the carriage, only the frequency of the oscillation was varied: ice thickness, ice strength and the speed of the car-

Fig. 9. Oscillating cone results.

riage were kept constant. The horizontal ice forces on the oscillating cone plus whatever horizontal forces were generated on the vertical cylinder in the direction of the motion of the carriage were measured by a load cell.

Test results

Two series of tests were performed with the oscillating cone: in the first, the cone was oscillated in the vertical direction; in the second, the cone motion was almost circular. In all tests the ice properties — thickness and strength — were kept constant. Only the oscillating frequency was varied from 1.3 to 2 Hz. The results are presented in Fig. 9 as horizontal force (ice load) versus oscillating frequency for both test series.

The results show a decrease in ice forces as the frequency increases. Compared with the results of the fixed cone tests (frequency = 0) the ice forces are reduced by about 33% in vertical oscillation (dashed line in Fig. 9). By creating circular oscillations the horizontal ice forces were reduced by another 33% of the forces on fixed cones, so that a total reduction of about 66% of the forces on the downward breaking cone was achieved.

DISCUSSION

Before discussing the results of this model test program, brief attention must be drawn to other relevant work. Most model testing of conical structures has been carried out on upward breaking

cones at low velocities (less than 0.01 m/s; see Edwards and Croasdale (1977), Verity (1975) and Afanas'ev et al. (1973)). Recent work has looked at impact in addition to low velocity (Saeki et al. 1979). Sorensen (1978) carried out measurements of dynamic loads over a range of velocities on an upward breaking inclined plane. There are, however, no published results on systematic tests of velocity effects on conical structures.

Description of ice structure interaction

Observations of ice interaction with the conical structure made during the model tests have led to the following qualitative description of the process. As the ice cover advances towards the structure it is bent downwards until it fails. The geometry of the structure is such that the crescent-shaped ice pieces are broken off. Generally, pieces are broken off more frequently in the central region than at the sides where the effective slope is less. Because of friction, the vertical force developed in breaking the ice also generates a horizontal force on the structure. These forces are dependent on structure geometry, the mechanical properties of the ice, and the rate of loading of the ice. Broken ice pieces then rotate until they are parallel to the surface of the structure. Buoyant, hydrodynamic drag and internal forces are active during this rotation. Structure geometry, friction, ice piece shape and structure velocity determine the horizontal and vertical loads associated with the rotation. Finally, the broken ice pieces slide around the structure when friction is the main factor. This descrip-

tion of ice behaviour is very much simplified. In actual practice, the processes proceed simultaneously over the structure, and the measured mean horizontal and vertical forces are values integrated over time and space. Nevertheless, this qualitative description provides a basis for the following discussion of the measured results.

Discussion of test results

The velocity effect (Fig. 3), particularly on the vertical ice force, is quite unusual and neither available theories nor model tests provide explanations. Some qualitative explanations can be offered, however. The ice forces are observed to increase monotonically with velocity up to 0.25 m/s. These forces result from the dynamic action of the broken ice pieces on the structures, so that they would be expected to increase with increasing velocity. The increase, however, is not proportional to velocity squared, so that factors other than hydrodynamic and inertial ones must be present. No open-water measurements were made, but approximate calculations indicated that for velocities up to 0.25 m/s water resistance is insignificant (less than 5% of total measured mean ice forces); but at a velocity of 0.5 m/s the water resistance could be greater than 10% of the total measured mean ice force. At a velocity of 0.5 m/s the flow around the structure is in the transitional range (Reynolds number of about 2×10^5). For a relatively small change in conditions, flow could be either critical or sub-critical, with a corresponding four-fold change in the drag coefficient (Daugherty and Franzini 1977). The presence of ice further complicates the matter in the sense of the dynamic interaction between the ice and the water. Measured ice forces can also be related to ice behaviour. Compressive strength and apparent elastic modulus increase with increasing strain rate. On the other hand, flexural strength of saline ice has been observed to be independent of loading rate over the range 1–100 kPa/s (Tatinclaux and Wu 1978). There are no simple relations between ice forces and ice properties, so that further work will be required before a satisfactory explanation can be given for the observed ice load variation with velocity.

The similarity with the resultant forces shown

in Fig. 5 is remarkable. This behaviour suggests that there is a balance between the increase in the resultant ice force due to increasing cone angle and the decrease due to diameter decrease with increasing cone angle. The resultant force seems to act in a direction normal to the cone surface.

The influence of ice thickness (Fig. 6) on the vertical ice force is quite different from its effect on the horizontal force. The difference can be explained in terms of the various resistance components. As mentioned earlier, the vertical ice forces are mainly related to breaking resistance, which is proportional to the rupture moment of the ice cover, i.e. flexural strength times the ice thickness squared ($\sigma_f h^2$). The vertical forces would therefore be expected to be approximately proportional to the ice thickness squared. On the other hand, the horizontal forces are more associated with frictional, buoyant, drag and inertial resistances, all factors tending to vary linearly with mass and hence with ice thickness.

A linear relation between ice flexural strength and vertical and horizontal ice forces was observed (Fig. 7) for the test condition of a single ice thickness and velocity for the strength range 50–80 kPa. These results would at first hand suggest that for the test condition ($h = 53$ mm, $v = 0.1$ m/s) the vertical and horizontal ice forces mainly result from breaking resistance. It should be remembered, however, that as flexural strength varies, so too does elastic modulus and thus piece size.

Data in the literature are scarce for purposes of comparison. Edwards and Croasdale (1977) (45 deg upward breaking cone of 1-m diameter, 50-mm ice thickness, high salinity model ice, flexural strength 25 kPa) measured mean vertical and horizontal ice forces of 370 and 360 N, respectively. In this test series, approximate, mean peak vertical and horizontal forces of 225 and 150 N, respectively, were measured for low velocity tests (45 deg downward breaking cone of 1.2-m diameter, 50-mm ice thickness, low salinity model ice, flexural strength 69 kPa). Direct comparison of the results is difficult because of differences in ice properties and cone diameter. It is clear, however, that horizontal resistance is significantly lower for a downward breaking cone. Gerwick and Jahns (1979) observed, from comparative tests, that the force on an upward breaking cone is 1.5–3 times greater than that for a downward breaking cone.

ANALYTICAL PREDICTIONS

In addition to physical modelling, mathematical models have been developed for ice interaction with conical structures. Bercha and Danys (1975) idealized the ice cover as a linear elastic plate on an elastic foundation. Their analysis included the effects of in-plane loads, edge moments and friction, and assumed the maximum ice force to be governed by a tensile stress failure criterion. No gravity or buoyancy effects are included. Ralston (1978) applied plastic limit analysis to the problem of interaction between an ice sheet and a conical structure. In addition to plastic behaviour being assumed for the ice cover, an elastic-plastic foundation response was assumed to describe the submergence or emergence of the ice in the water. No account was taken of dynamic effects resulting from the interaction between ice and water.

A mathematical model of dynamic elastic interaction between ice and a simple inclined plane structure has been developed by Sorensen (1978) that satisfactorily predicts peak loads measured in model tests using an artificial model ice and the low salinity model ice of this test series. This mathematical model, however, does not take into account the loads associated with ice ride-up on the structure. Milano (1973) formulated a model for predicting ice breaking resistance of vessels based on the energy absorbed in bending, breaking and submerging the ice, heaving of the vessel, and friction of the ice on the hull. Another analytical model (Frederking 1980) describing the variation with time of bending, frictional, buoyant, hydrodynamic and inertial forces associated with ice acting on an inclined plane structure, underpredicted the forces measured in model tests by about one third.

Predicted ice forces

Recently, the plastic limit analysis has been extended to a downward breaking cone (Ralston 1980). The results of this analysis, using the Johansen model for bending moment capacity, have been compared with forces measured in the model tests (Table 3). Using the Tresca model would reduce predicted forces by a maximum of 15%. The plastic limit analysis does not take into account the dy-

TABLE 3

Comparison of mean peak measured ice forces and values predicted using Ralston's (1980) plastic limit analysis

Cone angle	Measured force		Predicted force	
	Horizontal (N)	Vertical (N)	Horizontal (N)	Vertical (N)
60°	290	230	720	410
45°	240	340	415	430
30°	230	240	260	450
15°	140	200	150	470

$\sigma_f = 60 \text{ kPa}$; $\mu = 0.1$; $h = 0.05 \text{ m}$; $D_f = 0.50 \text{ m}$; $V = 0.01 \text{ m/s}$.

namic interaction between ice and the cone, so that only the measured forces at low velocities (0.01 m/s or less) were used. Those used in this comparison are a mean of the peak ice forces, since this is the actual condition the plastic limit analysis represents. The flexural strength used in the calculation (60 kPa) was measured at a rate that corresponds to a test velocity of about 0.1 m/s. Based on Tatinclaux and Wu's (1978) results it is reasonable to assume that this same value of flexural strength applies at a velocity of 0.01 m/s. Referring to the results in Table 3, it may be seen that the predicted loads are higher than the measured values, as would be expected for a plastic limit analysis, which by definition must give an upper bound solution. A question arises on the application of the plastic limit analysis to cases where the ice behaviour is known to be elastic. In the HSVA Ice Model Basin, particular care is taken to produce an elastic model ice, and ice failure behaviour has been observed to be quite brittle. The plastic limit analysis agreed well with the model test results of Edwards and Croasdale (1977) and Afanas'ev et al. (1973). These were performed in model ice of high salinity, which is known to exhibit plastic behaviour. Kry (1980) has observed for tests performed in an outdoor model basin (Verity 1975) that the forces predicted by the plastic limit analysis were twice as great as the measured forces for those cases where the ice cover was observed to fail in a brittle fashion. For more plastic failure behaviour, the agreement was good. This points out the caution necessary in applying a particular theory to model test results as well

as in comparing the results of model tests carried out in different facilities.

The following empirical equation (Edwards and Croasdale 1977) has been proposed for the average peak horizontal ice force on a 45 deg upward-breaking cone:

$$F_H = 1.6 \sigma_f h^2 + 6.0 \rho_w g D h^2, \quad (2)$$

where σ_f is the flexural strength of ice, h is the ice thickness, ρ_w is the density of water, and D is the waterline diameter. Note, as Ralston (1980) pointed out, it would be more logical if the second term on the right-hand side of eqn. (2) were to include the term $D^2 h$ rather than $D h^2$. Using the same values of independent variables as were used for the calculations in Table 3, eqn. (2) predicts a horizontal force of 420 N for an upward breaking cone. The second term on the right-hand side of eqn. (2) is described as a gravity term; the coefficient on it could therefore be reduced to one ninth to describe a downward breaking cone. In this case, the horizontal force would be 260 N compared with a mean peak force of 240 N measured in this test series. The tests from which the coefficients of eqn. (2) were established were carried out on low strength, high salinity ice, so that again there is doubt about the validity of the comparison.

CONCLUSIONS

Comparison with data in the literature has shown downward-breaking cones to be superior to upward-breaking cones in reducing both horizontal and vertical forces. The results of the model tests presented in this paper indicate that the average horizontal ice force on the fixed cones decreases significantly as the cone angle decreases, although the waterline diameter of the cone increases. For an oscillating cone, a horizontal force reduction of 2/3 below that of the fixed cone was found. These results demonstrate that a potential exists for conical offshore structures. By either passive or active devices such structures could be subjected to substantially reduced ice forces.

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