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MOORED VESSEL STATION-KEEPING IN ICE-INFESTED WATERS: AN ASSESSMENT OF MODEL TEST DATA FOR VARIOUS STRUCTURES AND SHIP SHAPES

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ABSTRACT

A wide range of ice model test data were assembled for the Kulluk, turret-moored drillships, semi-submersibles, and tankers or production vessels connected to loading terminals. These data were analyzed in combination to establish trends for sheet ice conditions and for broken ice conditions, with respect to ice concentration, thickness, and many other parameters.

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INTRODUCTION

Ice is an important design constraint for floating production or drilling structures intended to operate in northern waters. Physical model tests are one method that has been used to evaluate the expected performance of structures in various ice conditions. Tests have been conducted for a wide range of structures and ice conditions. Although this has resulted in a relatively extensive information base, it is fragmented which makes it difficult to infer overall trends regarding model test results. This paper describes a project (Comfort, Singh, and Spencer, 1999) that was undertaken for moored, floating production or drilling structures to:

(a) assemble a wide range of ice model test data for floating production or drilling structures;
(b) examine the overall data set for trends and conclusions.

A concurrent project was carried out by the PERD Program to analyze the available relevant full-scale data (Wright, 1999), which is described in a separate paper (Wright, 2001).

AVAILABLE INFORMATION AND GENERAL APPROACH

The data were divided into four structure categories (Table 1). The Kulluk was evaluated in greater detail than the other structures because full-scale data are available for it (Wright, 1999), and because, it has been extensively tested at model scale. The test data were divided into the following ice categories to follow the convention used by Wright, 1999 ; 2001:

(a) ambient ice – this refers to the case where no ice management has taken place. The model test data for this case were obtained by testing intact ice sheets that were either pushed against the model, or alternatively, through which the model was towed.
(b) managed ice – in this case, the ambient ice had been broken up, (e.g., by icebreakers and/or supply ships). This condition was represented at model scale by testing a field of ice pieces with various sizes (typically termed broken ice), or by preparing accumulations of small ice pieces of various thickness (termed rubble ice).

Table 1: Moored Vessel Stationkeeping in Ice: Summary of Ice Model Test Programs

Category	Vessel Description	Test Organization & References
KULLUK	Kulluk	ACL - Comfort et al, 1982
	Kulluk	HSVA-Evers et al, 1983; Schwarz et al, 1982; Wessels, 1982
	Kulluk	IIHR(1985)–Matsuishi et al, 1985a,b
	Kulluk	IIHR(1988) - Nixon et al, 1988 a,b
Semisubmersibles	Aker D-6	ACL - Comfort et al, 1986
	Generic Study - Column legs	ACL - Noble and Singh, 1982
	Mobil SPSV	AI - Free et al, 1985
	Mobil SPSV	IMD - Szeto et al, 1987a;b
	Nekton 8000	IMD - Williams, 1989
Turret-Moored Drillships or Tankers Without An Exposed Terminal	CANMAR drillship & drill barge	ACL–Allan, 1978; Allan,1979; Noble, 1978; Daley; 1979
	ARCO Drillship	ACL – Coburn et al, 1980
	Sedco 500 Drillship	AI – Zahn et al, 1983
	Exxon Drillship	AI – Zahn et al, 1984
	Terra Nova FPSO	IMD – Colbourne, 1998
	STL/STP system	HSVA – Loset et al, 1997
Moored tankers & loading terminals	Total Eastcan Dypospar	ACL – Noble et al, 1979
	Technomare BALM system	MARC – Di Tella et al, 1997
	BHP SPM Structure	MARC – Wilkman et al, 1996
	Tanker Loading Study	IMD – Danielewicz et al, 1995

Legend	ACL	ARCTEC Canada Limited
	AI	ARCTEC Incorporated
	HSVA	Hamburg Ship Model Basin (German acronym)
	IIHR	Iowa Institute of Hydraulic Research (associated with the University of Iowa)
	IMD	Institute for Marine Dynamics (part of the National Research Council of Canada)
	MARC	Finnish acronym – associated with Kvaerner-Masa Yards Tech

All of the values presented in this paper are in full-scale equivalents. Some of the above references present full-scale results obtained using Froude scaling. Others present the results in model scale units, or established similitude with both the Froude and the Cauchy numbers. For consistency, these results were converted to full-scale units using Froude scaling.

TESTS WITH THE KULLUK

Kulluk Tests: Test Techniques Used

Because a variety of test techniques were used (Tables 2-3), it was necessary to assess the effect of these differences (Table 4), and to establish a base case (Table 5) for comparisons.

Table 2: Ice Model Tests with the Kulluk: Test Techniques Used

Org.	Scale	Model Ice Material[1]	Ambient Ice Tests			Managed Ice Tests		
			Ice Pushed or Model Towed ?	Model Compliant or Fixed ?	Air Bubbler On ?	Ice Pushed or Model Towed ?	Model Compliant or Fixed ?	Air Bubbler On ?
ACL	1:30	Mod-Ice	ice pushed	moored	no	ice pushed	moored	no
	1:30	Mod-Ice	ice pushed	moored	yes	ice pushed	moored	yes
	1:30	Mod-Ice	ice pushed	fixed	no	ice pushed	fixed	no
HSVA	1:45	Saline ice	model towed	moored	no	model towed	moored	no
1985 IIHR[2]	1:45	Urea ice	ice pushed	fixed	no	ice pushed	fixed	no
	1:45	Urea ice	ice pushed	compliant[4]	no	ice pushed	compliant[4]	no
1988 IIHR[3]	1:45	Urea ice	ice pushed	compliant[4,5]	no	model towed	compliant[4,5]	no
	1:45	Urea ice	ice pushed	fixed	no	ice pushed	compliant[4,5]	no

Notes: 1. See Table 3 for the ice properties for these respective model test programs.
2. These tests were done by (Matsuishi et al, 1985a;b) and are referred to as the 1985 IIHR Tests.
3. These tests were done in 1988 (Nixon et al, 1988a;b), and are referred to as the 1988 IIHR Tests.
4. Leaf springs were used.
5. Two stiffnesses were tested (i.e., 0.5 and 1.0 MN/m).

Table 3: Ice Properties Summary for the Kulluk Model Test Programs

Parameter	ACL tests	HSVA tests	1985 IIHR tests	1988 IIHR tests
Flex. Strength (kPa)	310-840	560-720	1000-1100	800-1800
Density (kg/m^3)	911	910	no data[1]	no data[1]
Ice-model friction factors	dry: 0.15;0.11[2] wet: 0.14;0.12[2]	0.1	no data[1]	no data[1]
Ice-ice friction factors	0.79; 0.51[2]	surf-surf: 0.06 surf-bottom: 0.28	no data[1]	no data[1]

Notes:
1. Because the HSVA and the IIHR tests were both done using refrigerated ice, it is expected that the values for the IIHR tests would be reasonably similar to those for the HSVA tests.
2. The two values are the static and the dynamic friction factors, respectively.

Table 4: Effect of Test Technique Variations

Variation	Effect by Ice Type & Information Source
model towed vs ice sheet pushed	- Managed Ice - 1988 IIHR tests - Lower peak and mean mooring forces when the model was towed (Figure 1) - Ambient Ice – 1988 IIHR vs HSVA results[2] - Loads about 30% lower when the model was towed (Figure 2) Expected Reason: Towing the model produces current drag forces over the depth of the model which act to clear the ice from in front of the model
fixed vs compliant	- Managed ice – 1988 IIHR tests[1] - peaks higher for compliant model - Ambient ice – 1985 & 1988 IIHR tests; ACL tests - mean forces unaffected; peak forces show no consistent trend
air bubbler	Managed and Ambient Ice – ACL tests - No significant effect

Notes:

1. Although the ACL tests also included fixed and compliant tests in managed ice, they were not used for this comparison due to difficulties in comparing the results at the same ice concentration.
2. The ACL tests cannot be used for this comparison because Mod-Ice was used as a modelling material. Mod-Ice has higher friction than the refrigerated ice used by IIHR and HSVA.

Table 5: Base Case Used for Comparisons in Managed and Ambient Ice

Variation	Selection	Reason
model towed vs ice pushed	ACL & IIHR Tests: Ice Pushed HSVA tests: model towed	Towing the model more closely simulates the case where ice movements are induced by currents as opposed to winds that act on the surface. In the Beaufort sea, ice movements are primarily wind-induced.
fixed vs compliant	compliant[1]	The Kulluk was moored on site
air bubbler	off	The Kulluk was not fitted with an air bubbler in the field

Notes:

1. For the 1988 IIHR tests, the results obtained with a 1.0 MN/m stiffness were used for the base case.

Kulluk Tests: Summary Results

- Observations for Managed Ice (Broken or rubble ice) :

(a) Pack ice concentration – this is the most important factor affecting the loads produced. The loads increase rapidly at concentrations above about 8/10 (Figure 3). This same trend was observed for the other ship/structure categories as well (Figure 4).

(b) Ice thickness – for the ACL & HSVA tests, which were done using broken sheet ice, the force rises with ice thickness (Figure 5). Although the IIHR tests are not directly comparable as thick ice rubble was prepared, they show a similar trend as the force rises with the ice rubble thickness (Figure 6)

(c) Speed – the loads are not greatly dependent on speed.

(d) Correlation among the various model test results – the ACL tests produced higher loads by a factor of about 3 to 5 than the test results at HSVA or IIHR. The reasons for this variation are considered subsequently.

- Observations for Ambient Ice (Sheet ice) :

(a) Effect of ice thickness – the loads increase with the ice thickness although the relationship is also speed-dependent (Figure 7).

(b) Effect of speed - the loads increase with the ice drift rate.

(c) Correlation among the various model test results – the ACL tests produced higher loads by a factor of about 3 to 5 than the test results at HSVA or IIHR. The reasons for this variation are considered subsequently.

The major differences between the ACL tests, the HSVA tests, and the IIHR tests are that: (a) the ice modelling material used at ACL had significantly higher ice-ice friction (Table 3); and (b) the model was towed during the HSVA tests whereas the ice sheet was pushed during the ACL and the IIHR tests.

Kulluk Tests: Comparisons of Load Magnitudes

In *managed ice*, the ACL tests indicated higher loads than did the HSVA or IIHR tests (Figures 5 to 6). Furthermore, the HSVA and the IIHR tests show better agreement to the loads observed at full-scale (Figures 5 to 6). The IIHR tests indicated mooring forces that were somewhat higher than those at HSVA, although the results from the two programs are generally similar.

In *ambient ice*, it was found that:

(a) the forces were higher than for the managed ice tests, as expected. The HSVA and the 1985 IIHR test results showed that the ambient ice loads were about twice as high as those for managed ice at 9+/10^{ths} concentration (Figure 8). The ACL tests and many of the 1988 IIHR tests showed a different result as the peak and mean mooring forces were similar for managed and ambient ice for most cases (Figure 8). This variation merits further investigation as it is an indication of the relative significance of ice breaking forces versus ice clearing forces.

(b) the mooring forces predicted by the HSVA and the IIHR tests were within about 30% of each other (Figure 7), with higher loads being predicted by the IIHR tests.

(c) the ACL tests predicted higher loads than did the HSVA and the IIHR tests by a factor of about 3 to 5. The reasons for this variation are not fully understood although differences in the modelling material used were probably one contributing factor.

Tests with Semi-Submersibles

The semisubmersible model test data were compared based on the load per unit “beam” (where the “beam” was defined as the projected width of the semisubmersible facing the ice).

- Observations for Managed Ice (Broken or rubble ice) :

(a) Pack ice concentration – this is the most important factor. The loads increase rapidly at concentrations above about $8/10^{ths}$. This correlates well with the results obtained for the other ship/structure types (Figure 4).

(b) Ice thickness – The ice thickness did not affect the loads significantly. This probably indicates that ice clearing processes were predominant, which are not significantly affected by ice thickness.

(c) Speed – the loads are not greatly dependent on the ice drift rate.

(d) Correlation among the various model test results – for ice concentration above about $8/10^{ths}$, most of the line loads agree within a factor of about 2.

(e) Effect of ice modelling material - in general, the tests done with MOD-ICE and EGAD-ice indicated similar results and trends.

- Observations for Ambient Ice (Sheet ice) :

(a) Effect of ice clearing behaviour, waterline shape and geometry – the ice loads are most significantly affected by how well ice is able to pass through the semisubmersible, versus jamming inside it. The benefits of adding structures to the column legs to break the ice efficiently, such as cones, are greatly reduced if the ice jams inside the semisubmersible. For example, the tests with the Mobil SPSV showed that the loads increased rapidly when the riser was added to the model (Figure 9). This is believed to reflect a change in ice clearing behavior, as ice accumulated inside the semisubmersible with the riser present.

For the Aker D-6 semisubmersible, cones added to the vertical column legs decreased the load significantly (Figure 10). This was also the case for the Mobil SPSV when the riser was **not** present. However, when the riser was present, the loads on the Mobil SPSV were not affected significantly by adding cones to the semisubmersible columns (Figure 9). This difference reflects a change in ice failure mode as the ice did not clear through the semisubmersible when the riser was present. As a result, ice accumulated within the semisubmersible, causing ice failures over the full projected width.

(b) Ice thickness – most results showed that the line load increased as the ice thickness was increased.
(c) Speed – no consistent trends are evident in the data. This probably indicates that the effect of speed was overshadowed by variations with respect to: (i) how ice clears through the semisubmersible, and; (ii) ice thickness.
(d) Correlation among the various model test results – the line loads from the various test programs agree within a factor of about 2.

Turret-Moored Drillships and Tankers

These test results were much more difficult to compare because a wide range of test types have been conducted, such as: (a) "resistance" tests, in which the vessel was at a heading of 0°; (b) "rotation", "vaning" or "change-of-direction" tests; and (iii) "ice management" tests, in which the vessel was at 90° to the ice drift direction. To allow preliminary evaluations, the turret-moored drillship model test data were also compared based on the load per unit "beam" (where the "beam" was defined as the projected width of the vessel that is facing the ice).

- Observations for Managed Ice (Broken or rubble ice) :

(a) Pack ice concentration – this is the most important factor. The loads increase rapidly at concentrations above about 8/10$^{\text{ths}}$, which correlates well with the other ship/structures tested (Figure 4).
(b) Ice thickness – the loads increase with ice thickness above about 8/10$^{\text{ths}}$ concentration. For ice concentrations below about 8/10$^{\text{ths}}$, the line loads are not sensitive to the ice thickness.
(c) Speed – the loads are not sensitive to the ice drift rate.
(d) Correlation among the various model tests – the line loads agree within a factor of about 2.
(e) Mean mooring forces and line loads during vaning – these reflect the combination of the ice clearing behaviour and the length of vessel "exposed" to the ice. The line loads increased steadily as the Terra Nova Floating Production Storage Offshore (FPSO) vessel vaned from a heading of 90° to 0°, reaching a maximum at 0° (Figure 11). The total mean mooring forces were relatively constant during the vaning process in thinner ice of 0.38 m to 0.64 m thickness (Figure 12). In thicker ice (i.e., 1.0 m thickness), the total mean mooring force peaked at a heading range of about 30° to 40° (Figure 12).

The loads on the FPSO reflect the combination of the ice clearing behaviour and the vessel length "exposed" to the ice. The observed trends suggest that:

(i) line loads – the line loads were controlled by the fact that the FPSO length "exposed" to the ice was steadily reducing as the vessel was vaning to reach a heading of 0°.
(ii) total mean mooring forces in ice 0.38 to 0.64 m thick – the load was constant over the full range of headings. This suggests that the ice cleared readily as the vessel vaned.
(iii) total mean mooring forces in ice 1.0 m thick – the mean total mooring force peaked at a FPSO heading of 30° to 40°. This indicates that the ice did not clear as well compared to the thinner ice tests, and a relatively long vessel length was still exposed to the ice for this heading range.

- Observations for Ambient Ice (Sheet ice) :

(a) Effect of a change in heading – this produces much higher line loads than those at 0° heading. This reflects the fact that the ice contacts the ship's parallel mid-body, which is a less-efficient icebreaking shape than the bow.
(b) Ice thickness – the loads increase with the ice thickness
(c) Speed – the loads increase with speed.

Tests With Moored Tankers And Loading Terminals

This case is more complex than the others as the interaction was affected by the loading terminal, the tanker, the test technique, and the ice conditions. Hence, comparisons based on the line load would not be appropriate. To allow preliminary investigations, the peak hawser tensions were used as an index, and the available data (i.e., Danielewicz et al, 1995; Wilkman et al, 1996; and Noble et al, 1979) were analyzed separately. It should be recognized that during the vaning or change-of-direction tests, the hawser tension was continually changing, and thus the peak did not occur at the same time or point in the rotation during each test.

- Observations for Both Managed Ice (Broken ice) and Ambient (Sheet Ice) :

(a) Terminal structure width to tanker beam – this is the most important factor, as it affects all aspects of the interaction (vaning, loads, etc). All observations made need to be prefaced by whether or not the terminal structure is large compared to the tanker beam. A wide terminal structure "shields" the tanker from the moving ice, which greatly reduces the loads exerted on it. However, the shielding is much-reduced for a small terminal structure (with a width significantly less than the tanker beam) which exposes the tanker to the moving ice. As a result, the loads exerted on the tanker are much greater.

(b) Effect of ice conditions (e.g., ambient ice vs managed ice; large vs small floes) – large terminal structures shield the tanker, causing similar hawser loads for each ice condition (Figures 13 and 14). For small terminal structures (in relation to the tanker beam), the peak hawser loads decreased with ice condition in the following general order (Figures 13 and 14): (i) ambient ice; (ii) managed sheet ice (produced by cutting 2 channels in the sheet parallel to each side of the initial track); (iii) large floes (100 m dia.) in 10/10 conc'n, and; (iv) small floes (25 m dia.) in 10/10 conc'n.

The ice floe size also had an effect for small terminal structures. The combination of the test results obtained at IMD (Danielewicz et al, 1995) and at MARC (Wilkman et al, 1996) suggest that the loads and the ice interaction processes will be generally similar for floe sizes in the range of 20-70 m. The loads are increased for ice floe sizes in the range of 100 m or larger (Figures 15 and 16).

(c) Ice thickness – this depends on several other factors, as follows (Table 6) :

Table 6: Effect of Ice Thickness on Peak Hawser Loads

Term. Structure Dia/Tanker Beam	Test Type	Type of Managed Ice	Effect of Ice Thickness on Peak Hawser Loads
large	peak hawser loads not sensitive to ice thickness for all cases as the tanker is "shielded"		
small	resist. test (at 0° heading)	broken ice	no significant effect
small	resist. test (at 0° heading)	narrow slot in sheet ice	loads increase with thickness
small	vaning or change of direction	broken ice	loads increase with thickness
small	vaning or change of direction	narrow slot in sheet ice	loads increase with thickness

(d) Loads During Vaning or Change-of-Direction Tests - for large terminal structures, the hawser loads were relatively small for all cases. For small terminal structures, the loads increased with the amount of the heading change, and they were not very sensitive to the type of heading change (ARC vs COD Tests).

(e) Speed – the hawser loads increase with the ice drift rate for narrow terminals. For large terminals, the loads are insensitive to the ice drift rate as the terminal "shields" the tanker.

CONCLUSIONS

An extensive set of ice model test data has been assembled for floating, moored structures. The primary focus of the work was to present the data in a common format to identify overall trends, and to make basic comparisons. The results were sub-divided by structure type: (a) the Kulluk ; (b) semisubmersibles ; (c) turret-moored drillships or tankers without an exposed loading terminal ; and (d) moored tankers and loading terminals. The results presented have also been grouped for (a) ambient ice (or sheet ice) and (b) managed ice (or broken ice).

All of the test data in **managed ice** show that the pack ice concentration is the most important factor. The loads rise rapidly at ice concentrations greater than about 8/10. The loads increase slightly with ice thickness, and they are not very dependent on speed.

The test data in **ambient ice** for the **Kulluk** show that the load increases with ice thickness and speed. The ACL tests produced higher loads by a factor of about 3 to 5 than the test results at HSVA or IIHR. The reasons for this variation are not clear.

The **semisubmersible** model test data have been compared based on the load per unit "beam" (where the "beam" is defined as the projected width of the semisubmersible facing the ice). The ice loads are greatly affected by how well ice is able to pass through the semisubmersible, versus jamming inside it. The benefits of adding cones to the column legs to break the ice efficiently are greatly reduced if the ice jams.

The line loads from the various test programs agree within a factor of about 2.

The **turret-moored drillship** model test data have also been compared based on the load per unit "beam" (where the "beam" is defined as the projected width of the vessel facing the ice). A change in heading produces higher line loads than those at 0°. This is due to ice contact with the ship's parallel mid-body, which is a less-efficient icebreaking shape than the bow.

The **tanker and loading terminal** model test data are most difficult to compare because the ice interaction is affected by both the terminal and the tanker. The relation between the terminal size and the tanker beam is the most important factor affecting the loads produced. A large terminal "shields" the tanker whereas a narrow one causes the tanker to be exposed to the moving ice.

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Figure 1 Rubble Ice Tests for KULLUK: Effect of Test Procedure (Model Moved vs Ice Moved)

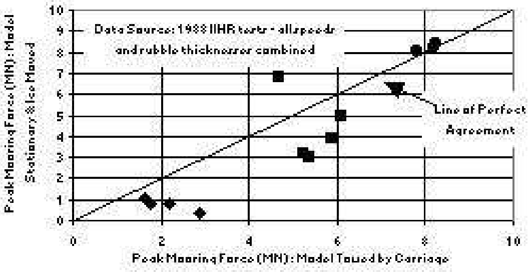


Figure 2 Peak Loads on KULLUK at 0.6 to 1.3 m/s

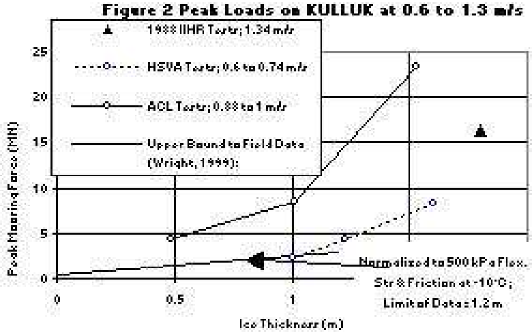


Figure 3 Effect of Ice Concentration on the Peak Forces on Kulluk in Broken Ice: ACL Tests

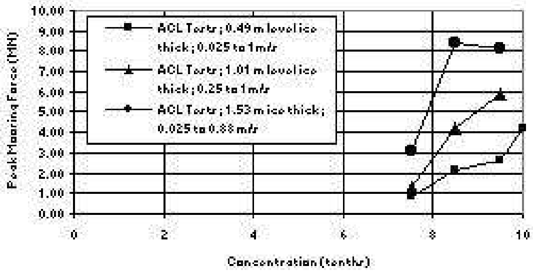


Figure 4 Peak Loads in Managed Ice: Effect of Ice Conc'n for Various Ship/Structure Types

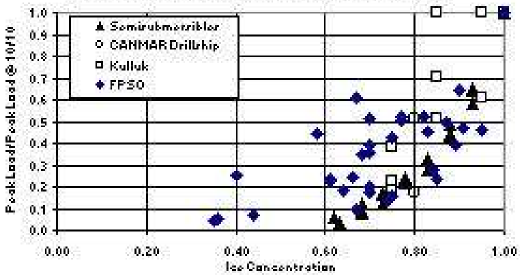


Figure 5 Peak Mooring Forces on the Kulluk in Managed Ice at 9+/10 Concentration

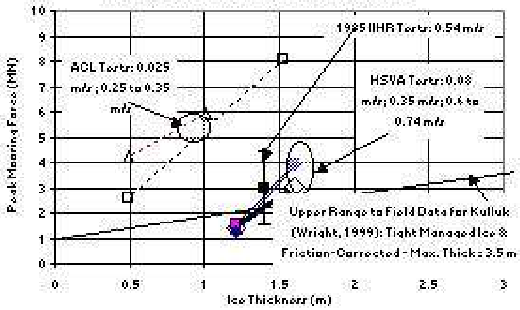


Figure 6 Peak Loads on Kulluk in 9+/10 Rubble

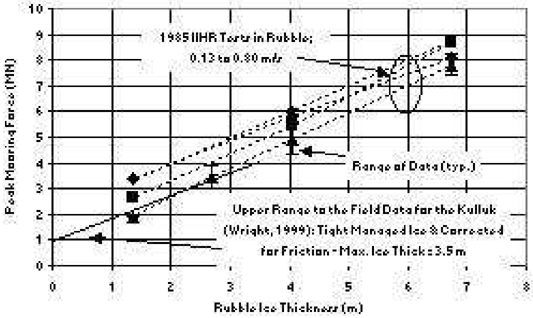


Figure 7 Peak Ice Loads in Ambient Ice on the Kulluk at Ice Drift Rates of 0.025 to 0.35 m/s

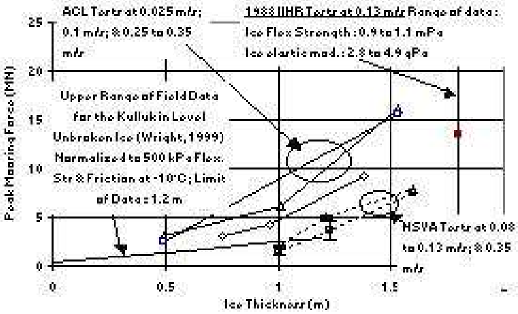


Figure 8 Comparison: Peak Loads on the Kulluk in Ambient Ice and in Managed Ice at 9+/10

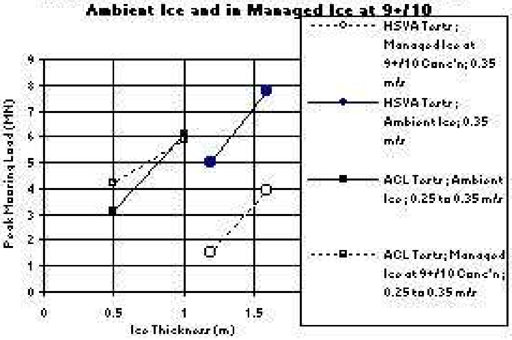


Figure 9 Peak Line Loads on the Mobil SPSV in Ambient Ice

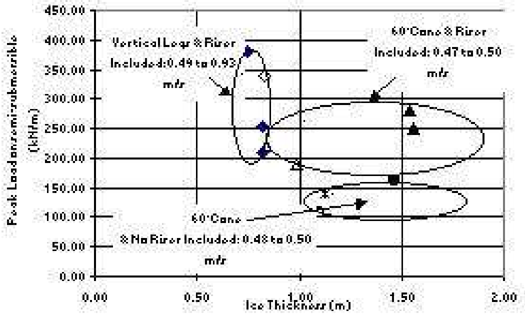


Figure 10 Peak Line Loads on the Aker D-6 Semi-Submersible in Ambient Ice

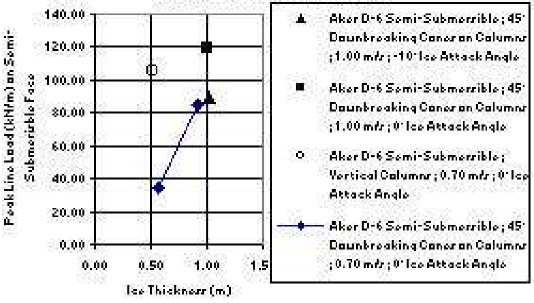


Figure 11 Rotation Test Results: Mean Line Loads on the Terra Nova FPSO

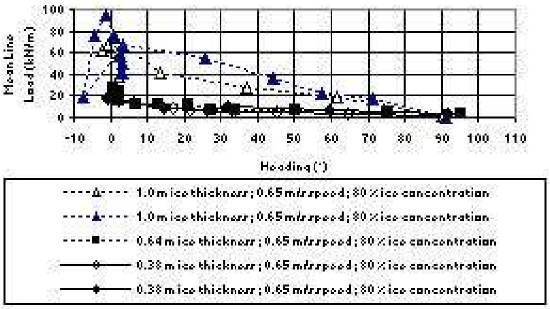


Figure 12 Rotation Test Results: Mean Total Mooring Forces on the Terra Nova FPSO

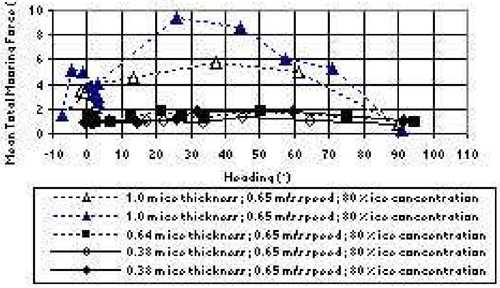
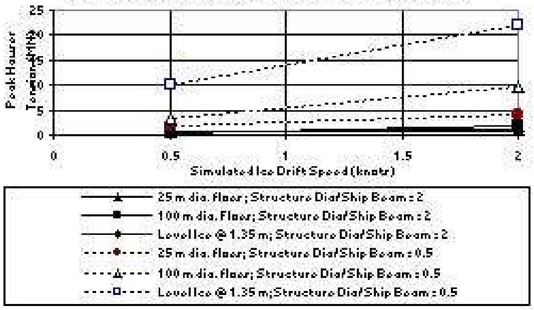


Figure 13 Vaning Tests at IMD Simulating a 90° Heading Change: (Danielewicz et al, 1995):



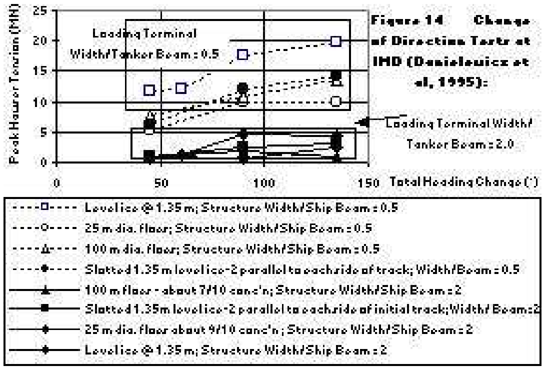


Figure 14 Change of Direction Tests at IMD (Danielewicz et al, 1995):

Figure 15 Tests at 0° Heading With the BHP Icebreaking Tanker and SPM Loading System in 9/10 Broken Ice at MARC (Wilkman et al, 1996)

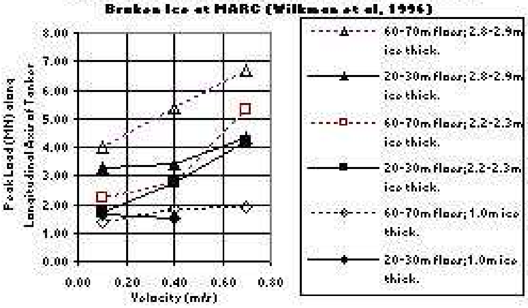


Figure 16 Change-of-Heading Tests at MARC with the Icebreaking BHP Tanker & SPM Loading System (Wilkman et al, 1996)