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ICE PRESSURE VARIATIONS DURING INDENTATION

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ABSTRACT

The Japan Ocean Industry Association made available to the IAHR Ice Crushing Working Group one data file from a field test conducted February 4, 1999. An indenter 1.5 m wide by 0.5 m high, penetrated a sea ice sheet 168 mm thick at a rate of 3 mm/s for a total penetration of 1000 mm. The entire indenter face was covered with "tactile" sensor elements, each nominally 10 mm by 10 mm. Spatial distributions of local pressure were recorded throughout the test as well as the total load measured with a load cell. Detailed analysis of the results showed that the load cell and tactile sensors gave comparable results. The tactile sensors showed a "line-like" load distribution with only about 10 % of the ice edge in load-bearing contact. "Hot-spots" of high local pressure persisted for surprisingly long periods, up to 10 s. Local pressure variations tended to be synchronous, that is largely increasing and decreasing with global load.

INTRODUCTION

The nature of local ice pressure distributions during indentation has been a subject of interest for some time in ice mechanics. It is an important factor in developing an understanding of the ice failure process since this understanding provides one of the means of scaling-up small-scale laboratory and field measurements to scales needed for design of offshore structures and ship hull structures. Obtaining good measurement data on pressure within the contact area was always a problem. If the sensor area was large, the pressure was averaged over too large an area; if the sensor area was small, there were usually insufficient sensors to determine the distribution of pressures. Load cells to measure average pressures over areas as small as 10 mm dia. were employed in laboratory and field measurements (Masterson et al, 1999, Sayed and Frederking, 1992). Local pressures as high as 80 MPa were measured on a 10 mm diameter sensor in indentation of multi-year ice (Frederking et al, 1990). Early work in Finland (Joensuu, 1988) initiated the use of PVDF sensors to almost completely cover the measurement area. Later this type of instrumentation was deployed for field indentation tests on multi-year (Masterson et al 1993) and pressures as high as 50 MPa were measured.

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More recently the Japan Ocean Industries Association (JOIA) sponsored a project on Medium Scale Field Indentation Tests (MSFIT) of ice sheets which ranged in thickness from 120 mm to 270 mm. During the JOIA project detailed measurements of total load, loads on segments and local pressure distributions were made. The objective of the project was to obtain high quality data that could be used to improve the prediction of ice loads on structures. A general description of the test equipment and testing procedure can be found in Nakazawa et al (1999). To encourage broader understanding of the results, JOIA made available one data file to the IAHR Ice Crushing Working Group for analysis. These are the data examined in this paper. Spatial and temporal distributions of pressure will be examined, both on the basis of average distributions, shape of contours, simultaneity and variations during load cycles. Implications for describing ice crushing processes will be discussed.

DESCRIPTION OF TEST

The MSFIT program was conducted over 5 winters in the late 1990s at Notoro fishing harbour on the North coast of Hokkaido Island, Japan. The data file, from a test conducted February 4, 1999 was for the following conditions:

Indenter width	=	1500 mm
Indenter height	=	500 mm
Ice thickness	=	168 mm
Indenter speed	=	3 mm/s
Total stroke	=	1000 mm
Ice strength	=	2.46 MPa

The total load exerted by the actuator was measured with a load cell and recorded at a rate of 50 readings a second. The entire indenter face was covered with "tactile" sensor elements, each nominally 10 mm by 10 mm, for a total of 6336 sensor elements (144 elements across and 44 elements vertically). The ice was not thick enough to ensure contact with all the sensor elements, but about 2500 elements contacted the ice edge. Data from the tactile film was recorded at a rate of one "frame" every 0.2667 s (3.7 Hz). A "frame" comprised a 144 by 44 matrix of "pressure" readings. Each element of the tactile film gave an integer reading between 0 and 255. The manufacturer of the film provided the following guide to convert output reading to pressure

reading	pressure (MPa)
0	0
55	0.68
255	6.86

with a linear relation. It was also stated that the error in any reading on the tactile film could be up to ± 10%, so it was recommended that pressure data be treated as relative.

The load record from the load cell is presented in Figure 1. It can be seen that there is rapid build-up of load to a high peak with the flat indenter making perfect contact with the flat sawed edge of the ice sheet. Using the indenter width of 1500 mm and the 168 mm ice thickness, the average pressure to initially fail the ice sheet was almost 3 MPa. Subsequently the average pressure was never greater than 0.5 MPa. The test was run at a constant actuator rate of 3 mm/s for 300 s (50 s is equivalent to 150 mm indentation). Immediately after the initial failure, fluctuations in the load were small. For the interval 40 to 70 seconds (Figure

2), the fluctuations were still small with a pattern of a general rise followed by a rapid drop off with an irregular period of 5 to 10 seconds. At around 80 seconds (Figure 3) the fluctuations settled into a more regular pattern with a frequency of about 1.2 Hz and the peak-to-trough ratio of the amplitude about 2. It can be seen that the nature of the load fluctuations changes significantly between the two time intervals (Figures 2 and 3). The pattern demonstrated in Figure 3 tended to persist for the remainder of the test. Also shown in Figure 2 and 3 is a total load determined from the tactile film records. This will be discussed further.

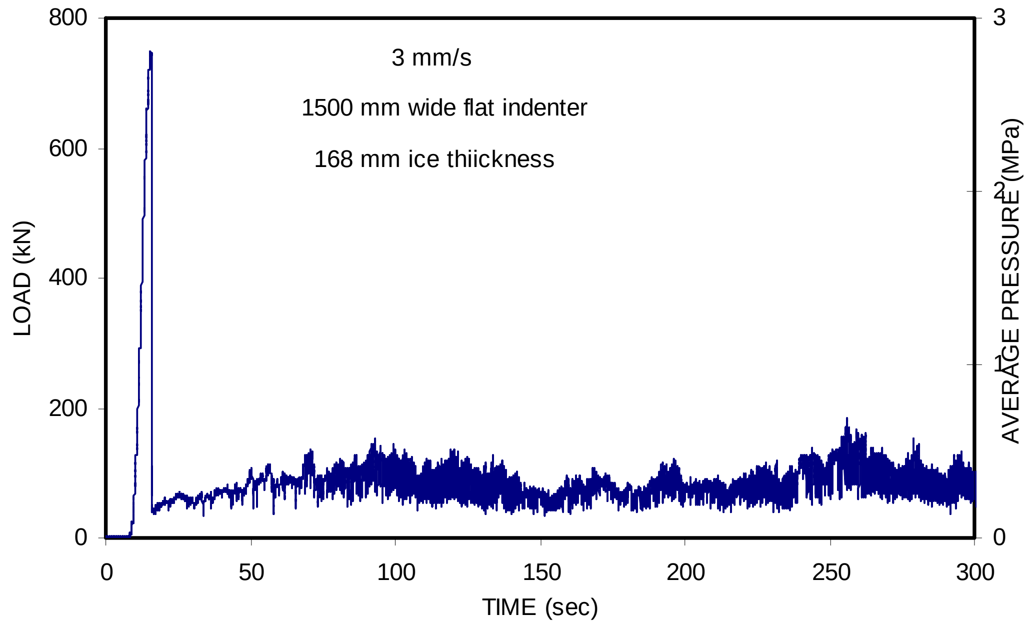

Figure 1 Load – time record for test on February 2, 1999

The tactile film data were used to determine total load using a rather simple method of assigning a load of 1 N per reading unit; that is, a reading of 10 is equivalent to 10 N. Thus the total load in kN is just the sum of all tactile cell readings divided by 1000. This is the method used to obtain the tactile film loads presented in Figures 2 and 3. The recording frequency of the tactile film determined loads is much less than the load cell, approximately 4 Hz versus 50 Hz, but the tactile film traces follow the trend of the load cell determined loads quite closely. Different recording systems were used so the load drop from the initial failure was used as an initial synchronizing point, but no further synchronization was used throughout. This basis to calculate total load implies a pressure of 2.55 MPa for a reading of 255, rather than the value of 6.8 MPa given by the manufacturer, and again emphasizes that pressures be treated a relative, not absolute.

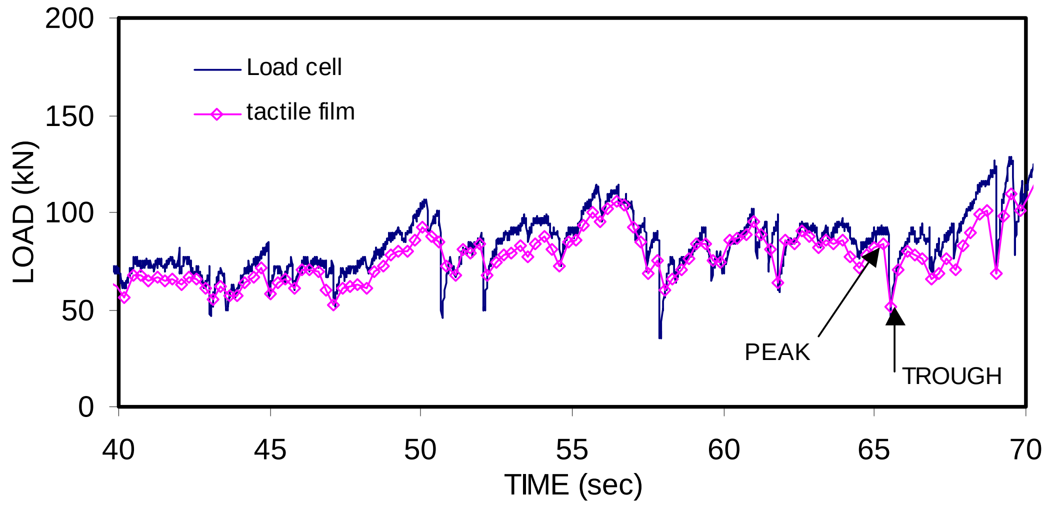

Figure 2 Load – time record expanded for interval 40 to 70 seconds

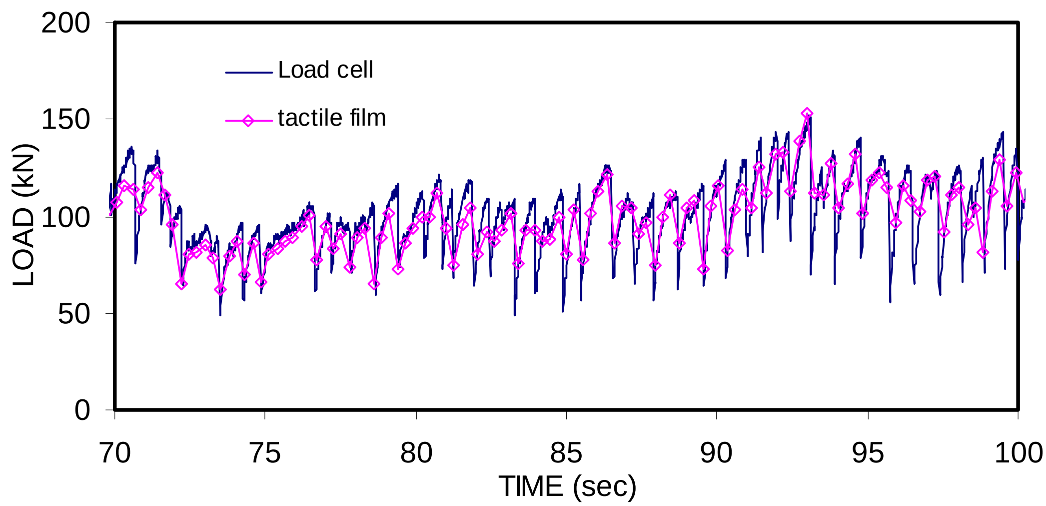

Figure 3 Load – time record expanded for interval 70 to 100 seconds

DISTRIBUTIONS OF PRESSURE

The nature of ice pressure distributions at different points in the loading process will be examined next. At the 65 second mark (see Figure 2) two successive tactile film records were selected, one at 65.26 s just before failure, "peak", followed by one at 65.53 s, just after failure, "trough". The nature of, and change between the two will be discussed. The total loads at the two times, as estimated from the tactile film, are 85 kN and 53 kN, respectively, about a 40% decrease. Contour plots of the two times for the entire ice edge in contact with the indenter (168 mm by 1500 mm) are presented in Figure 4. The values plotted are the pressure numbers, within the range 0 to 255, from the tactile film record (note; all subsequent plots and discussion treat pressure as unitless). What can be seen firstly is that the area subjected to ice pressure is greater at the peak than the trough (290 elements at the peak and 255 at the trough), a 10% decrease so this alone does not account for the magnitude of the decrease. Note that the total possible number of cells in contact with the ice edge is 2448, so only about 10% are actually loaded. The number of cells subjected to ice pressures greater than 10, 25, 50 and 75 was determined and the greatest difference between the two cases was for pressures greater than 50 (see Table 1). At the peak there were 57 cells above that level, but only 15 at the trough. A number of vertical profiles of pressure were also examined, and they showed that generally the distribution was peakier at peak load than in the trough. Two immediately adjacent vertical pressure profiles at peak and trough are shown in Figure 5 to illustrate this point.

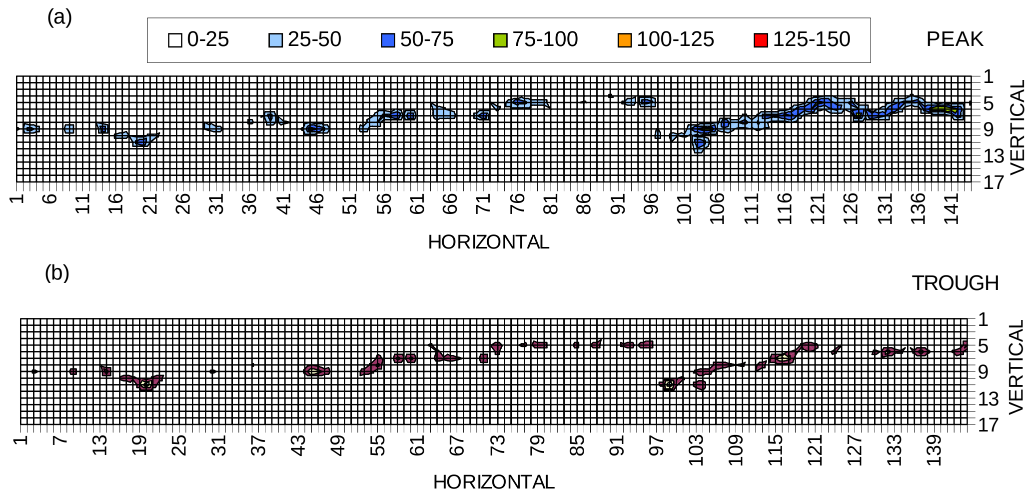

Figure 4 Contour plots of pressure at 65 s; (a) peak, (b) trough.

Table 1 Number of tactile elements loaded at 65 s.

Pressure range	Peak	Trough
> 0	291	255
0 to 10	69	85
10 to 25	97	95
25 to 50	68	60
50 to 75	37	12
>75	20	3

Figure 6 presents the horizontal distribution of pressure summed on a vertical axis for the whole width of the indenter. It can be seen that for the most part the two pressure distributions are of similar magnitude for both the peak and trough. It is only for horizontal positions 100 to 140 that the total peak pressures are greater.

As was shown in Figure 4, the line-like load distribution was generally not continuous across the entire width of the indenter, even at the time of peak load. What was also observed at some times was a double peak in the vertical distribution of pressure. Figure 7 plots six immediately adjacent vertical pressure profiles, covering a width of 60 mm, and all show similar double peaks. This double peak is likely a measurable representation of horizontal cleavage cracks that have been observed in indentation tests. A contour plot of the area from which the vertical profiles of Figure 7 were extracted (Figure 8) more clearly illustrates two line-like loaded areas. Figure 8 also illustrates that the high pressure between horizontal positions 100 and 120 has persisted for 5 seconds. In fact, this high pressure area or “hot spot” persists to a greater or lesser extent for the entire test run.

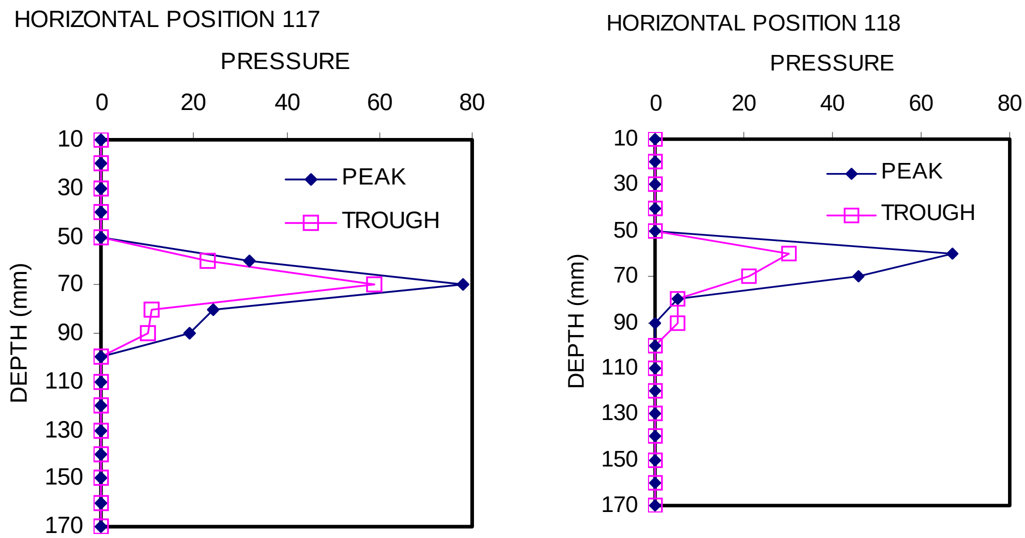

Figure 5 Vertical pressure distributions at 65 s.

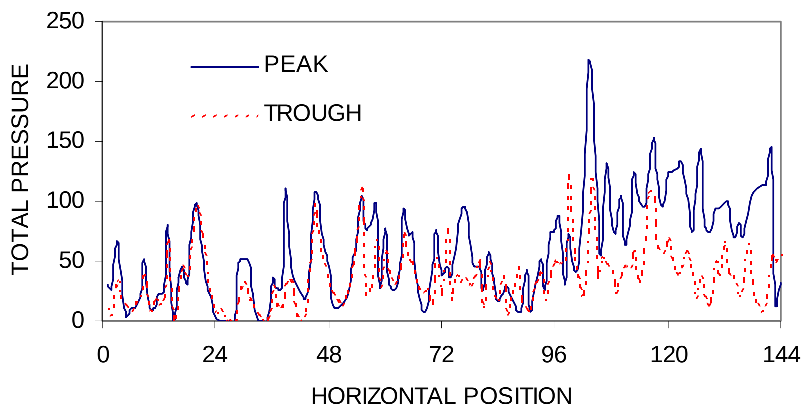

Figure 6 Total pressure along a vertical line of elements at 65 s.

To illustrate further pressure distributions and persistence of “hot spots” a contour plot at time 86.1 s is presented in Figure 9. Here there are three horizontal line-like loads and the high pressure areas are still evident in the horizontal position area 100 to 140.

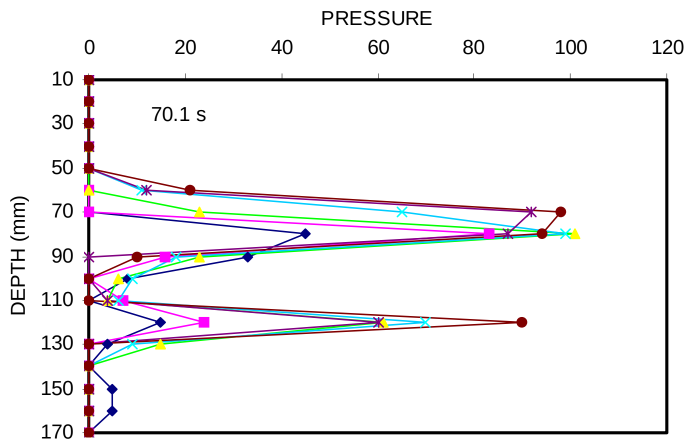

Figure 7 Vertical pressure distributions at 70.1 s

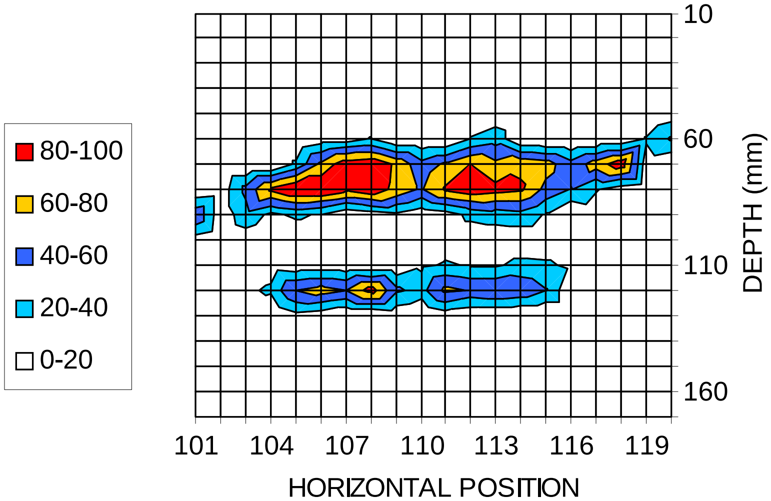

Figure 8 Contour plot of pressure distribution at 70.1 s.

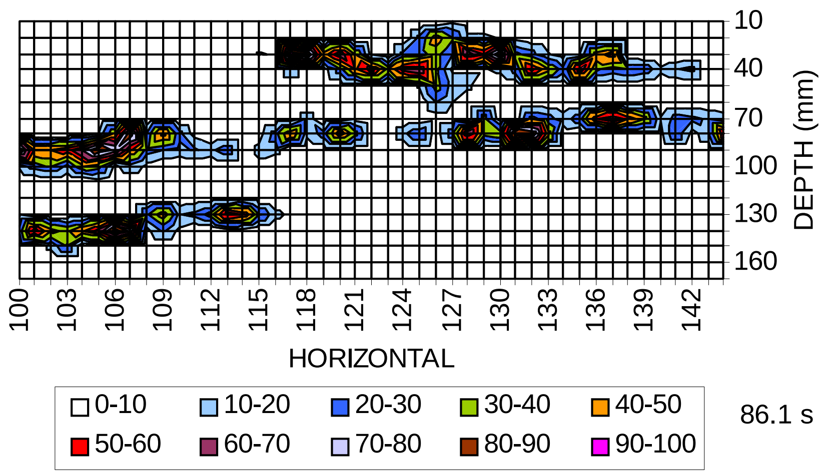

Figure 9 Contour plot of pressure at time 86.1 s, a time of peak load.

SUMMARY

An indentation test at 3 mm/s on 168 mm thick sea ice provided detailed information on pressure distributions through use of “tactile” file sensor elements covering the entire face of the 1500 mm wide indenter. Summing the tactile sensor data gave total loads similar to those from a load cell that measured total load. The tactile sensors showed a “line-like” load distribution with only about 10 % of the ice edge experiencing any local pressure at all. Local pressure distribution before and after failure indicated that the contact area was essentially the same in both cases, but that there was a larger area of high pressure just before failure. The line-like load distribution was observed to divide into two or more horizontal parallel lines, suggesting cleave crack formation. “Hot-spots” of high local pressure persisted for surprisingly long periods, say up to 10 s, and tended to be in the middle portion of the ice edge.

ACKNOWELDGEMENTS

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