ICE INDENTATION TEST ON CONSOLIDATED LAYER MODEL MADE OF SALINE AND FRESHWATER ICE BLOCKS

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ABSTRACT
Deformed ice such as an ice ridge or an ice rubble field may impose a large load on hydraulic structures in ice-covered areas due to its large thickness \((h)\) and consolidated layer. A consolidated layer, which is considered to have higher strength than a sail or a keel, is modeled in a cold room for ice indentation tests. It is rational that an ice load imposed by a consolidated layer of deformed ice should be compared with that imposed by the surrounding (un-deformed) ice sheet, since many ice load equations for level ice sheets have been suggested. In this paper, the ice load of deformed ice is compared with that of level (un-deformed) ice through ice indentation tests, using saline and freshwater ice sheets. Indentation velocity \((V)\) and cubic ice block size \((a)\) were varied, and the effects of \((a/h), (V/h)\) and ice failure on the ice load were investigated.

KEY WORDS: Ice load; Deformed ice; Consolidated layer; Hydraulic structures.

INTRODUCTION
Deformed ice such as an ice ridge or hummocked ice constitutes a menace to offshore structures in ice-covered sea areas. There is little information available for determining loads imposed by deformed ice, even though such ice has larger thickness. An ice ridge consists of a sail, a keel, and a consolidated part. The consolidated part is important because it is considered to be stronger than the other parts. The ridge-building mechanism was discussed by Parmeter and Coon (1972). Timco and Goodrich (1988) reported that the thickness of the consolidated layer is about twice that of the surrounding level ice sheet. The ratio of the consolidated layer thickness to the surrounding level ice thickness was reported by Kamesaki and Yamauchi (1999) to vary from 1.6 (minimum) to 2.4 (maximum) with an average of 1.9. Surkov (2001) reported that the ratio varied from 1.75 (minimum) to 2.4 (maximum) with an average of 2.0. From long-term field observations on hummocked ice in the northern Sakhalin offshore, Truskov et al. (1993) and Beketsky et al. (1997) reported design parameters based on its dimensions, strength and so on. Its
conformation and ice block size were so complex, and also its strength seemed to be strongly influenced by its porosity, which was also complicated and unclear. Kioka et al. (2000) reported on the physical properties of the consolidated layer using model ice made in a cold room, under zero porosity from a macroscopic point of view. Its compressive strength was found to be slightly smaller than that of the surrounding level ice sheet. Truskov et al. (2001) determined ice compressive strengths of 1.0 MPa for level ice and 0.8 MPa for rafted and consolidated ice, as the generalized value in south Sakhalin. However, Yamauchi and Kamesaki (2001) recently showed that ice loads on a structure due to both consolidated and unconsolidated layers would increase with the occurrence of grounding of rubble. Thus, there is a lot of room for research on deformed ice. In this study, indentation tests were conducted to investigate ice loads (but not compressive strength) on a model structure using a consolidated layer model made in a cold room, assuming that porosity from the macroscopic viewpoint is zero, as a first step. Porosity here doesn’t mean that calculated from salinity, temperature and density. The effects on ice load of an ice block of size (a), indentation velocity (V), and failure mode of model ice were examined. The results were compared to those for a level sheet ice, which was considered as an index.

TESTS
The test ice sheet specimen of the consolidated layer was made by referring to the method by Kioka et al. (2000). In this study, we used both saline- and fresh-water ice. First, saline water of 2.5% and/or fresh water were put into a mesh-type frame having cubic spaces with bore-holes in their bottoms, to produce a lot of cubic ice blocks. Several frames of different sizes were used. Second, saline water of 1.0% and/or fresh water were kept in a tank (1000mm*900mm*450mm) until the temperature reached their freezing points (around –1.3 deg. for saline water and 0 deg. for fresh water). Third, the ice blocks were put into a different tank (1000mm*900mm*450mm) with insulated bottom and sides, and also saline water and/or fresh water close to freezing point were put into a 25cm-depth of the tank. Fourth, a test ice sheet was taken out of the tank after an intermixed specimen was sufficiently consolidated (Figure-1). It was then moved to the indentation device shown in Figure-2 and fixed on three sides. Fifth, to measure the ice temperature in the thickness direction, a k-type thermocouple was embedded into the ice sheet. These steps were repeated depending on the planned test conditions.

Figure-1 Preparation of Ice Sheet
Figure-2 Indentation Test Device
A plane pressure panel (Figure-3) was attached to the model structure and an ice pressure distribution increasing with time was imposed. In particular, for the test ice sheet of fresh water, a video was also used for analysis of ice failure during the indentation test, taking advantage of good visibility. The test conditions are listed in Table-1 for the saline ice and in Table-2 for the fresh-water ice. Although Truskov et al. (1993) reported that porosity inside consolidated ice greatly influences ice strength, it was taken to be zero in all tests because of the difficulty of assessing it. Thus, water between the ice blocks is assumed to be frozen for the tests shown in both Table-1 and Table-2.

### Table-1 Test Conditions (Saline Ice)

<table>
<thead>
<tr>
<th>CASE no.</th>
<th>W (cm)</th>
<th>h (cm)</th>
<th>V (cm/s)</th>
<th>a (cm)</th>
<th>T (deg.)</th>
<th>Salinity</th>
<th>Index</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>15</td>
<td>15.1</td>
<td>2.00</td>
<td>0</td>
<td>-3.2</td>
<td>8.0</td>
<td>1.32*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S2</td>
<td>15</td>
<td>14.8</td>
<td>0.02</td>
<td>0</td>
<td>-3.8</td>
<td>7.3</td>
<td>1.35*10^0</td>
<td>D</td>
</tr>
<tr>
<td>S3</td>
<td>15</td>
<td>15.1</td>
<td>2.00</td>
<td>3</td>
<td>-4.1</td>
<td>9.5</td>
<td>1.32*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S6</td>
<td>15</td>
<td>15.5</td>
<td>2.00</td>
<td>3</td>
<td>-4.5</td>
<td>9.0</td>
<td>1.29*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S10</td>
<td>15</td>
<td>15.0</td>
<td>0.20</td>
<td>5</td>
<td>-4.0</td>
<td>8.0</td>
<td>1.33*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S4</td>
<td>15</td>
<td>14.2</td>
<td>2.00</td>
<td>5</td>
<td>-4.4</td>
<td>9.8</td>
<td>1.41*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S7</td>
<td>15</td>
<td>14.8</td>
<td>2.00</td>
<td>5</td>
<td>-4.0</td>
<td>8.7</td>
<td>1.35*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S9</td>
<td>15</td>
<td>15.5</td>
<td>0.02</td>
<td>5</td>
<td>-3.8</td>
<td>9.0</td>
<td>1.29*10^0</td>
<td>D</td>
</tr>
<tr>
<td>S5</td>
<td>15</td>
<td>15.7</td>
<td>2.00</td>
<td>6</td>
<td>-4.0</td>
<td>8.6</td>
<td>1.27*10^0</td>
<td>B</td>
</tr>
<tr>
<td>S8</td>
<td>15</td>
<td>15.5</td>
<td>2.00</td>
<td>6</td>
<td>-3.2</td>
<td>8.8</td>
<td>1.29*10^0</td>
<td>B</td>
</tr>
</tbody>
</table>

### Table-2 Test Conditions (Fresh-water Ice)

<table>
<thead>
<tr>
<th>CASE no.</th>
<th>W (cm)</th>
<th>h (cm)</th>
<th>V (cm/s)</th>
<th>a (cm)</th>
<th>T (deg.)</th>
<th>V/h (1/s)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>15</td>
<td>7.4</td>
<td>0.20</td>
<td>0</td>
<td>-4.5</td>
<td>2.70*10^02</td>
<td>B</td>
</tr>
<tr>
<td>F2</td>
<td>15</td>
<td>10.8</td>
<td>0.20</td>
<td>3</td>
<td>-4.5</td>
<td>1.85*10^02</td>
<td>B</td>
</tr>
<tr>
<td>F3</td>
<td>15</td>
<td>10.9</td>
<td>0.20</td>
<td>3</td>
<td>-4.5</td>
<td>1.83*10^02</td>
<td>B</td>
</tr>
<tr>
<td>F4</td>
<td>15</td>
<td>10.4</td>
<td>2.00</td>
<td>3</td>
<td>-4.5</td>
<td>1.92*10^03</td>
<td>B</td>
</tr>
<tr>
<td>F5</td>
<td>15</td>
<td>10.1</td>
<td>2.00</td>
<td>3</td>
<td>-4.4</td>
<td>1.98*10^03</td>
<td>B</td>
</tr>
<tr>
<td>F6</td>
<td>15</td>
<td>9.4</td>
<td>0.02</td>
<td>3</td>
<td>-4.4</td>
<td>2.13*10^03</td>
<td>D</td>
</tr>
<tr>
<td>F7</td>
<td>15</td>
<td>11.0</td>
<td>0.02</td>
<td>3</td>
<td>-4.9</td>
<td>1.82*10^03</td>
<td>D</td>
</tr>
<tr>
<td>F8</td>
<td>15</td>
<td>10.8</td>
<td>0.20</td>
<td>6</td>
<td>-5.0</td>
<td>1.85*10^02</td>
<td>B</td>
</tr>
<tr>
<td>F9</td>
<td>15</td>
<td>11.1</td>
<td>0.20</td>
<td>6</td>
<td>-4.5</td>
<td>1.80*10^02</td>
<td>B</td>
</tr>
</tbody>
</table>

Note: Test CASE for a block size (a) of zero gives the condition for a level (un-deformed) ice sheet. In type, B and D indicate brittle and ductile deformations, respectively.

### TEST RESULTS AND DISCUSSION

#### Ice Load and Damage to Ice Sheet

Time series of ice load are plotted in Figure-4 and Figure-5 for saline ice, and in Figure-6 and Figure-7 for fresh-water ice. In addition, photos (but not for all cases) were taken of indentation tests on a deformed ice sheet made of ice blocks, as shown in Figure-8 and Figure-9 for saline ice and in Figure-10 and Figure-11 for fresh-water ice. A photo of an un-deformed ice sheet of fresh-water ice without ice blocks is shown in Figure-12 under the brittle condition. For Figure-4 and Figure-6 under constant \( V=0.2 \text{ cm/s} (V/h>3*10^3 \text{ (1/s)}) \), the ice load showed some peaks and
fluctuated due to brittle flaking with a small area of micro-cracks and horizontal cracks in front of the model structure. Contact of the model structure with the ice’s leading edge is small and occurs on a so-called line-like area. These types of damage of ice correspond to photos in Figure-8 (saline) and Figure-10 (freshwater). It should be noted that the flaking plane in Figure-10 (with ice blocks) seems to be rougher than that in Figure-12 (without ice blocks). This may be influenced by the existence of the ice blocks. However, it is difficult to judge which flaking failure occurs at the ice between the ice blocks or inside the ice blocks. However, the ice pressure didn’t fluctuate for Figure-5 and Figure-7 under constant $V=0.02$ cm/s ($V/h<3*10^{-3}$ (1/s)) due to ductile failure with a large area of micro-cracks (milky area) and vertical expansion with horizontal cracks in

![Figure-4 Time Series on Ice Load (Brittle-S10)](image)

![Figure-5 Time Series on Ice Load (Ductile-S9)](image)

![Figure-6 Time Series on Ice Load (Brittle-F2)](image)

![Figure-7 Time Series on Ice Load (Ductile-F6)](image)

![Figure-8 Indentation (S4 Brittle)](image)

![Figure-9 Indentation (S9 Ductile)](image)
Figure-10 Indentation (F3 Brittle)

Figure-11 Indentation (F6 Ductile)

Figure-12 Flaking surface after test
(F1 un-deformed ice V=0.2cm/s Brittle)

Figure-13 Sketch of Ice Failure Pattern

Figure-14 Ice Fragment Size
front of the model structure. This milky area produces sounds during indentation. Contact of the model structure with the ice’s leading edge is large and occurs on a plane-like area. These types of damage of ice correspond to photos in Figure-9 (saline) and Figure-11 (fresh water). Therefore, the damage pattern can be divided into two modes, brittle and ductile, as shown in Figure-13. This classification is essentially the same as that for an un-deformed (level) ice sheet (Sodhi, 1992). Notation of ice fragment size is as shown in Figure-14.

**Effect of \((V/h)\) on Ice Load**

For constant \((a)\), the maximum ice load is plotted versus \((V/h)\) in Figure-15. When \((V/h)\) increases, the maximum ice load decreases. The trend for fresh-water ice is the same as that for saline ice. This is why the ice load is related to the size of the micro-cracks in the ice sheet and contact size with the model structure, and in turn a larger load is required for a smaller \((V/h)\), which produces ductile deformation. This trend is the same as that for the level ice sheet (Takeuchi et al., 2000). The pressure distributions measured by the panel sensors for the saline ice sheet are shown in Figure-16(a) & (b), with a time series of load. For brittle failure, the damage pattern in Figure-16(a) corresponds to that in Figure-8, and from the change in pressure by some images it shows flaking failure, which produces a peak load. The flaking failure width varies depending on the contact condition during indentation. However, for ductile failure the damage pattern in Figure-16(b) corresponds to that in Figure-9. Although the contact pressure at each grid point is smaller than that in Figure-16(a), a wider contact area is observed through the pressure distribution measured by the panel sensor. Therefore, the total force in Figure-16(b) becomes larger than that in Figure-16(a). This pressure pattern depending on \((V\) or \(V/h)\) for ice with ice blocks is the same as that for level ice reported by e.g. Saeki and Ozaki (1980) & Takeuchi et al. (2000).

**Effect of \((a/h)\) on Ice Load**

For constant \((V)\) causing brittle failure in Figure-13, the ice load is plotted versus \((a/h)\) in Figure-17 and Figure-18 in order to examine the effect of ice block size on ice load. Ice load for \((a/h=0)\) in brittle condition, i.e. level ice sheet (S1 for saline ice; F1 for freshwater ice), is taken as a unit for normalized ice load for various \((a/h)\). These normalized ice loads are considered in the average, extreme, and maximum values, respectively. As \((a/h)\) increases, normalized ice loads in the average, extreme, and maximum values decrease for both saline and fresh-water ice. Referring to notations in Figure-14, this corresponds to the fact that, from the measurements of freshwater ice, the lengths \((L_t, L_b)\) of flaking in the indentation direction become slightly smaller, as shown in Figure-19, as \((a/h)\) increases. This makes the ice load smaller. Thus, under the limited condition of zero porosity, the existence of ice blocks contributes to the reduction in strength.

**Concluding Remarks**

1) Indentation tests using an ice model of a consolidated layer in saline and freshwater show that the ice failure pattern is fundamentally the same as that for level ice, and that it depends on indentation velocity.

2) Larger \((V/h)\) causes brittle failure with line-line contact and flaking, and increasing \((a/h)\) imposes smaller ice pressure. However, smaller \((V/h)\) causes ductile deformation with a larger area of micro-cracks and in turn a larger ice load. The existence of ice blocks contributes to the reduction in ice load.
Figure-15 Ice Load vs. V/h

Figure-17 Ice Load vs. a/h (Saline Ice)

Figure-18 Ice Load vs. a/h (Freshwater Ice)

Figure-19 Ice Fragment Size vs. a/h (under constant V for Freshwater ice)

Figure-16 (a) Contact Pressure (Saline Ice Sheet in Brittle)

Figure-16 (b) Contact Pressure (Saline Ice Sheet in Ductile)
3) Ice failure pattern and ice load trend in saline ice are the same as those in freshwater ice. It was interesting to conduct ice indentation tests on a consolidated layer with some porosity, especially under ductile conditions.

REFERENCES