THE STRENGTH OF THE UNCONSOLIDATED LAYER MODEL
OF ICE RIDGE

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ABSTRACT
Unconsolidated layer of ice ridge is composed mostly of loosely accumulated broken ice pieces. Although its strength is low, it imposes large load on offshore structure when it forms in sufficient size. Also it effects on submarine structure due to ice scour event. It is important to know strength of the unconsolidated layer. In this study, a simplified unconsolidated layer model was produced as a Mohr-Coulomb material, and a series of preliminary experiments (direct shear tests) was performed. As main results, shear strength satisfied the Coulomb failure criterion. The apparent cohesion and angle of internal friction increased with the ice block/piece size that constitutes the unconsolidated layer. However, the increase of angle of internal friction decreased as the ice block size increased, and the angle of internal friction seems to approach a constant value. And, although the shear strength had a peak value at a certain shear deformation rate, it approached constant value as the shear deformation rate increase after the peak.

INTRODUCTION
Unconsolidated layer, which is one of the categories of ice rubble structures, is composed mostly of loosely accumulated broken ice pieces. Since its internal structure is complicated, the strength of the unconsolidated layer depends on many parameters.

Unconsolidated layer has been treated by many researchers as a Mohr-Coulomb material to describe its mechanical behavior, and many experiments on the strength of unconsolidated layer have been conducted under various conditions both in the laboratory and in the field (e.g., Prodanovic et al., 1979; Weiss et al., 1981; Wong et al., 1987; Heinonen et al., 2000; Lapparanta et al., 1989; Bruneau et al., 1998), the results of which have revealed various qualitative strength parameters, such as apparent cohesion and angle of internal friction. However, there are many discrepancies in published results, and there is still no established method for determining the strength of

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unconsolidated layer. In this study, a simplified unconsolidated layer model was produced, and a series of preliminary experiments (direct shear test) was carried out for a wide range for confining stresses acting on unconsolidated layer actually. The influences of each ice block/piece size and shear deformation rate on the shear strength were also investigated.

EXPERIMENTS

It was reported that the mechanical properties of unconsolidated layer were also affected by factors such as the shape of the ice piece. However, a simplified unconsolidated layer model without consideration of such factors was used in this study due to difficulties in control of experiments. Tests were carried out according to the following procedure.

1) A mesh-type square frames with a borehole at the bottom of each mesh were placed in a container with 30 ‰ saline water. After freezing the water up to a certain thickness of ice, cubical ice blocks were produced, and they were removed from the frame and used as model of broken ice pieces.
2) To make the temperature of each ice block and experimental apparatus constant, the ice blocks were left on a sheet for one day.
3) The ice blocks were put into the shear box that constituted of a upper part (500 mm × 500 mm × 200 mm) and a lower part (500 mm × 500 mm × 250 mm). And then, the ice blocks were randomly arranged. The apparatus is shown in Figure 1.
4) The steel plate (497 mm × 497 mm × 25 mm) was placed on the ice blocks to apply confining force to ice blocks.
5) The upper part of the shear box was moved horizontally at a constant rate by a hydraulic ram, and the shear force, horizontal deformation of the upper part of the box and vertical deformation of the steel plate were measured during the movement of the upper part of the shear box. The contact face between the upper and lower parts was smeared with grease in order to reduce the sliding resistance.
6) The ice blocks were removed from the shear box after the completion of each test, and new ice blocks were added to the shear box.

![Figure 1: The experimental apparatus](image)

Here, the experimental conditions are shown in Table 1. Each set of the experiment was performed five times (sample number; 5). In Table 1, “uniform” means an
unconsolidated layer model (specimen) consisting of ice blocks of the same size, and “mixed” means an unconsolidated layer model consisting of blocks of three different sizes with an equal weight ratio. The representation value of a mixed type is converted to the mean size (mean grain size), and it is 42.5 mm. Normal stress was divided into five stages in the range of 1.88 to 11.29 kPa. $\sigma_s$ is equal to the buoyancy of the unconsolidated layer section supposing the confining stress of a certain level section in unconsolidated layer. The upper limit of the range of confining stresses used in this study was approximately equivalent to the confining stress acting on the unconsolidated layer at a depth of 30 m.

### Table 1: Experimental conditions

<table>
<thead>
<tr>
<th>Ice blocks</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice block size (mm)</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Mixed</td>
<td>Uniform</td>
</tr>
<tr>
<td>Normal stress (kPa)</td>
<td>1.88–11.29</td>
<td>1.88–11.29</td>
<td>1.88–11.29</td>
<td>1.88–11.29</td>
<td>6</td>
</tr>
<tr>
<td>Shear deformation rate (mm/s)</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>0.1–24</td>
</tr>
<tr>
<td>Temperature</td>
<td>–3 (deg.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>30 (‰)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### TEST RESULTS

#### Shear stress

Shear stress $\sigma_s$ was estimated by the following expression

$$\sigma_s = \frac{(F_t - F_e)}{S},$$

(1)

where $F_t$ is the total force when the shear box is filled with ice blocks, $F_e$ is the resistance force of the contact face when the shear box is empty, and $S$ is the horizontal section of the shear box.

The average of vertical deformations measured at the four corners of the steel plate was used as the representative value of vertical deformation.

#### Porosity

Porosity is known to influence strength. Table 2 shows the initial porosity of specimen for each ice block type. Since most of the ice blocks were cube-shaped, there was little difference. The porosity was about 0.3, which is thought to be close to the actual value. Thus, the influence of porosity was not considered in this study. However, strictly, the porosity of the mixed type was less than that of the uniform type. Also the porosity seems to increase with the size of ice block. Thus, the initial porosity is though to depend on the size and shape of the ice block.

### Table 2: The initial porosity of specimen for each ice block type

<table>
<thead>
<tr>
<th>Ice block size (mm)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1 22.5</td>
<td>0.31</td>
</tr>
<tr>
<td>Case2 42.5</td>
<td>0.34</td>
</tr>
<tr>
<td>Case3 65</td>
<td>0.37</td>
</tr>
<tr>
<td>Case4 42.5</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Behavior of shear stress and vertical deformation due to horizontal deformation

Fig. 2(a)–(d) show examples of behavior of shear stress and vertical deformation due to horizontal deformation in cases 1–4. Horizontal deformation was measured up to 75 mm. However, shear stress was assumed to maximum shear stresses occurring within the range of horizontal displacements of 0 to 40 in this study by the following reasons.

1) The shear area becomes small as horizontal deformations increases. Thus, the distribution of shear stress becomes uneven when the displacement became large.

2) As shown in the figure 2, shear stress has a maximum value or approaches a constant value within the range of horizontal displacements of 0 to 40 mm in most cases.

As for vertical deformation, repetition of expansion and contraction of test specimen are basically occurred. However, expansion was mainly observed in our experiments due to the small size of the shear box in relation to the sizes of the ice blocks. As can be seen in the figures, sudden falls of the curves in shear stress and vertical displacement are very similar, suggesting that there is a correlation between shear stress and vertical deformation.

![Graphs showing shear stress and vertical deformation](image)

Figure 2: (a)–(d) behavior of the shear stress and the vertical deformation due to the horizontal deformation

Parameters of shear strength

As mentioned above, unconsolidated layer can be regarded as a Mohr-Coulomb material. The Coulomb failure criterion is generally used to describe the shear strength. And shear strength is estimated as the following Eq. 2

$$\tau = c + \sigma_N \tan \varphi,$$

where $\tau$ is the shear strength, $c$ is the apparent cohesion, $\sigma_N$ is the normal stress, and
\( \varphi \) is the angle of internal friction. Fig. 3 shows the shear strength versus the normal stress for each ice block size. The straight lines in the figure are regression lines and satisfy the Coulomb failure criterion. Apparent cohesion and angle of internal friction are used as parameters of the strength. The y-intercept and slope of the line correspond to apparent cohesion and angle of internal friction, respectively. Fig. 4 shows the changes in apparent cohesion and angle of internal friction as functions of ice block size. As can be seen in the figure, these strength parameters tend to increase as the ice block size increases. Since the volume of expansion increased as the ice block size increased, this increase in shear strength is thought to include the energy used in expansion. However, the increase of angle of internal friction decreases as the ice block size increases, and the angle of internal friction seems to approach a constant value. These results are similar to those reported previously by other researchers (e.g., Prodanovic et al., 1979; Weiss et al., 1981).

The strength parameters of the mixed type were almost the same as those of the uniform type with same size converted to the mean size. Thus, mean size (mean grain size) could be used to estimate the strength parameters of actual unconsolidated layer consisting of ice pieces of various sizes.

![Figure 3: The shear strength versus the normal stress for each ice block size](image)

**Influence of shear deformation rate on shear strength**

Fig. 5 shows the relationship between shear strength and shear deformation rate in case 5 (Although the shear deformation rate was adjusted so as to remain constant for each case, there was some variation in the rate). Although the shear strength has a peak value at a certain shear deformation rate, it approaches a constant value as the shear deformation rate increases after the peak. On the other hand, Weiss et al. (1981) have reported the results that shear strength decreased as the shear deformation rate increased.
The states of ice blocks after tests suggested that the probability of the failure of an ice block increases as shear deformation rate increases and then becomes almost constant. Fig. 6 shows the horizontal deformation and vertical deformation at each shear deformation rate. As shown in the figure, the expansion decreases as the shear deformation rate increases. This tendency seems to relate to the dependency of shear strength on shear deformation rate, because the increase in shear strength is thought to include the energy used in expansion as described above. Therefore, it seems that the experiments need to be performed in the shear deformation rate showing the maximum strength for a practical application. However, this is not easy work. We should consider size/scale effect of test conditions including the size of ice block and shear box, etc. In a field, the magnitude of the ice block varies, ranging from several tens of centimeters to several meters. Therefore, as a future work, general test method and conditions should be established.

CONCLUSIONS
- Repetition of expansion and contraction shear failure is basically occurred. However, expansion shear failure was mainly observed in our experiments.
- Shear stress had a maximum value or approached a constant value within the range of horizontal displacements of 0 to 40 mm in most cases.
- Shear strength satisfied the Coulomb failure criterion in our experiment.
- The strength parameters (apparent cohesion and angle of internal friction) tended to increase as the ice block size increased. However, the increase of angle of internal friction deceased as the ice block size increased, and the angle of internal friction seems to approach a constant value.
- The strength parameters of the mixed type were almost the same as those of the uniform type with same size converted to the mean size. Thus, mean size (mean grain size) could be used to estimate the strength parameters of actual
unconsolidated layer consisting of ice pieces of various sizes.

- Although the shear strength had a peak value at a certain shear deformation rate, it approached a constant value as the shear deformation rate increased after the peak.

As before, the shear strength will depend greatly on the size/scale of ice block and shear box, and on the shear deformation rate. These are related to the size effect. It is also important to consider the effect of shape of ice blocks, which will influence inter-rocking or porosity within the specimen.

REFERENCES


