MEDIUM-SCALE MODEL TEST ON SOIL DEFORMATION AND STRESS WITHIN SEABED DURING ICE SCOUR EVENT

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ABSTRACT
Ice-Scour Event is a phenomenon that occurs when ice comes into contact with seabed. It has been reported to cause damage to cables and pipelines. As well as the estimation of the scour depth, it will be also important to consider a sub-scour deformation, which means soil deformation within the seabed below ice. In addition to our small-scale model tests, we made a medium-scale model test at a sandy plain. The stress within the soil during ice-scouring did not depend on a drift speed of a model ice, and that the restriction due to attack angle was large, which agreed with the small-scale test results. We also found that stress and reaction force greatly depend on relative density of soil. From the small-and medium scale model test results, we clarified the scale effects/similarities concerning reaction forces and stress distributions within the seabed.

KEY WORDS
Ice Scour, Sub-Scour deformation, Ice Ridge, Pipeline, Stress

INTRODUCTION
Ice-Scour Event is a phenomenon that occurs when ice, especially large mass of ice such as an ice ridge or an iceberg comes into contact with seabed. Ice-Scour has been reported to cause damage to communication cables and water intake pipelines. Our final goal is to develop the method for estimation of scour depth, or optimal depth of a buried structure such as a pipeline. While we have studied the scour-processes by many experiments on ice-scour event including the medium-scale model test, we have also developed the mechanical model (Kioka et al., 2000, 2004), which consists of the equation of motion concerning an ice and the simple model of interaction between the seabed and the ice keel. Also, we indirectly validated the mechanical model using the experimental results obtained in small- and medium-scale model tests (Kioka et al., 2000; 2001a; 2001b; 2002). We believe that we can establish the method by combining the mechanical model and the scour curve, which is a two dimensional locus remaining when ice keel ploughs the seabed. However, we need to establish the scour curve experimentally, which is difficult to be
estimated by a theoretical approach. Although we have examined the characteristics of scour curve, we have found that scour curve has the linearity without exception (Kioka et al., 2002;2003). We have also reported on the training/generalization of experimental data (scour parameters) on the scour-curve by a Neural-Network (Kioka et al., 2003). Also, while we also made a simple mechanical model that considers the fracture of ice keel (unconsolidated layer), we found that the shear resistance/strength of the keel increase than assumed because of the increase of confining stress, and that the keel stops before keel failure occurs in most cases. Therefore, we could obtain the ground by which we do not need to consider keel failure from the practical viewpoint, which means that we could regard an ice keel as a rigid body (Kioka et al.,2004).

On the other hand, it will be also important to consider a sub-scour deformation, which means soil deformation within the seabed below ice. It may influence buried structures as additional stress even if the structure does not have direct contact with ice. Some kind of this study has been studied mainly by The Pressure Ridge Ice Scour Experiment (PRISE) through some phases such as field surveys, centrifuge model tests of ice scour including 1-g small scale, numerical model of ice/soil or soil/pipeline interactions and others (e.g. Phillips, 2005). We have also tried to cope with the study on sub-scour deformation, which could be connected to a series of our above-mentioned studies. In this study, while a medium-scale field test was conducted based on the results of a small-scale model test (Ishikawa et al.,2005), we reported on characteristics of deformation/stress generated within the soil from a practical point of view, especially focusing on dynamical similarity concerning the stress distribution and reaction forces exerted on a model ice.

MEDIUM-SCALE FIELD TEST

The medium-scale field test was conducted at the dredged soil disposal site on the western wharf in the Ishikari Bay New Port. While the towing method of model ice and soil conditions in this test were slightly different from those of the small-scale model test (Ishikawa et al.,2005), the size of the model ice and the scour cut depth, were designed to be four times as large as those used in the small-scale model test. As shown in Fig. 1, a scour cut depth (SCD) was given in advance, and model ice (made of steel) 1.2 m in width and 1 m in height was connected to a heavy machine with a wire (φ12) and towed horizontally along a guide rail to make it penetrate approximately 480 cm into the ground (sandy soil). Since vertical movement of the model ice was restricted, it only moved in the horizontal direction along the guide attached to the mount. Test conditions were as shown in Table 1 (a), with some variations in the traveling speed of ice (8.1~24.4 cm/s), scour cut depth (12 cm, 24 cm) and soil conditions (relative density). In this case, two soil conditions with target relative density of 50% and 90%, respectively, were simulated. Table 1 (b) lists the realized values (ND: target value 50%, HD: target value 90%). In the test cases simulating the same soil conditions (ND), sand was leveled by following the same procedure as much as possible for each case, and the sand surface was also smoothed along the guide placed on the side of the main frame to keep the soil level to the ice. Immediately after leveling the sand and before each test, samples were collected from 2 or 3 points of the test area through the sand replacement method, and the unit weight (or relative density) was estimated later. The figures in Table 1 (b) are the mean values. The attack angle (inclination angle of the front surface of ice) was set at 45 degrees in all tests because of the conditions described below. Based on the results of the previous test, it was presumed that stress or deformation behavior within the soil was highly dependent on the attack angle but difference in such behavior would be insignificant once the
angle exceeded a certain degree (Ishikawa et al., 2005). Also, since the angle of naturally occurring ice ridges in sea area was thought to be 20 to 45 degrees, the angle in the tests was fixed at 45 degree to simplify the test conditions. As measurement items, horizontal displacement of the model ice was first measured with a displacement gauge (Kyowa DTP-D-5KS max.range:5m) and reaction force in the horizontal direction was measured with a load cell (Kyowa LUH-10TF; 100 kN) placed between the model ice and wire. The model ice had a two-layer structure, and reaction force in the vertical direction was measured with a three-point load cell (3-component force measuring system specially made by Kyowa, \( F_x = 300 \text{kN}, F_z = 100 \text{kN} \)) placed between the layers (see Fig. 1 (b)). Stress within the soil was also measured with buried pressure sensors (Kyowa BE-2KE, 200 kPa, effective pressure receiving area: \( \varphi 160 \), unidirectional component), which were basically placed facing sideways (for measuring horizontal stress), while the one at the P2 point was facing upward (for measuring vertical stress), as shown in Fig. 1 (c). Pressure sensors were placed at three points on the center line of the model ice, and four points each transversely (perpendicular to the traveling direction) and vertically at the P3 point. As another measurement item, model pipelines were placed within the soil. Strain gauges were attached to each pipeline to study the behavioral characteristics of the pipelines. The results of this have to be omitted due to space limitations and will be presented at the next opportunity.

<table>
<thead>
<tr>
<th>Case</th>
<th>Model ice Speed (cm/s)</th>
<th>SCD (cm)</th>
<th>Soil condition</th>
<th>Max.scour length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-1</td>
<td>15</td>
<td>10.3</td>
<td>ND</td>
<td>457.7</td>
</tr>
<tr>
<td>Case-2</td>
<td>15</td>
<td>8.1</td>
<td>ND</td>
<td>473.2</td>
</tr>
<tr>
<td>Case-3</td>
<td>25</td>
<td>15.9</td>
<td>24</td>
<td>476.7</td>
</tr>
<tr>
<td>Case-4</td>
<td>50</td>
<td>24.4</td>
<td>24</td>
<td>480.0</td>
</tr>
<tr>
<td>Case-5</td>
<td>15</td>
<td>9.6</td>
<td>ND</td>
<td>485.7</td>
</tr>
<tr>
<td>Case-6</td>
<td>15</td>
<td>13.2</td>
<td>12</td>
<td>486.2</td>
</tr>
<tr>
<td>Case-7</td>
<td>15</td>
<td>8.1</td>
<td>HD</td>
<td>486.2</td>
</tr>
<tr>
<td>Case-8</td>
<td>15</td>
<td>9.7</td>
<td>ND</td>
<td>485.4</td>
</tr>
</tbody>
</table>

### Table 1 (b) Characteristics values of soil (sandy soil) used in the tests

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean grain size (mm)</td>
<td>0.311</td>
</tr>
<tr>
<td>Uniformity coefficient</td>
<td>2.718</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>34.1</td>
</tr>
<tr>
<td>Repose angle (°)</td>
<td>31.5</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.679</td>
</tr>
<tr>
<td>Water content (%)</td>
<td>9.5-11.5(10.56)</td>
</tr>
<tr>
<td>Soil condition</td>
<td>ND HD</td>
</tr>
<tr>
<td>Weight (kN/m³)</td>
<td>13.5 15.3</td>
</tr>
<tr>
<td>Relative density (%)</td>
<td>44.7 85.3</td>
</tr>
</tbody>
</table>

Note: ND and HD represent “normal” and “compacted” soil conditions, respectively.

Fig. 1 (a) Medium scale test facility for ice scour

Fig. 1 (b) Structure of model ice

Fig. 1 (c) Position of pressure sensors
EXPERIMENT RESULTS

Stress within the soil due to ice movements (horizontal direction)

Common behavior of stress within the soil

Fig. 2 (a) shows an example of response (Case 2) of pressure sensors placed at three points on the center line of the model ice, in relation to the distance traveled by the ice (scour length). The figure shows that, in all cases, the value (hereinafter referred to as “stress”) indicated by the sensors showed a peak before the corner of the model ice passed directly above the pressure sensors, reflecting the same tendency as in the results of the small-scale model test. It was presumed that residual deformation occurred since stress decreased (unloaded) to a certain value by the time the corner of the model ice passed directly above the sensor, and remained almost at the same level after that. It can also be seen that, as described later, stress tended to increase with an increase in scour length. This was thought to be due to the increase in the amount of accumulated sand generated by the scouring in front of the ice and to “confining effect” by the attack angle (Ishikawa et al., 2005) (the soil movement is transmitted to the inside of the soil as a mass of soil near the front of the ice including the accumulated soil is restricted and compressed). In this case, it can also be observed that the relative distance between the position of the model ice when stress began to increase and each pressure sensor increased with an increase in scour length.

Next, Fig. 2 (b) shows the response of pressure sensors placed vertically at the P3 point, using Case 2 as an example again. While stress decreased with an increase in depth from the surface, a range of negative values existed at the depth of 60 cm, indicating that expansion occurred in this area unlike in other areas. This could also be presumed from the measurement of excess pore water pressure within the soil associated with ice movement, where an area of expansion was created by the generation of negative pressure (Kioka et al., 2001b). In this case, the position of the model ice was almost uniform when each pressure sensor indicated its peak value.

Dependence of stress within the soil on the traveling speed of ice

In the same way as in the small-scale model test, no clear dependence of stress on the traveling speed of model ice was observed.

Consideration of the spatial distribution and dynamical similarity of stress within the soil

Fig. 3 shows the longitudinal distribution of the maximum values of horizontal stress within the soil ($P_{\text{max}}$), that is, a comparison of the maximum stress indicated by pressure sensors (P1, P2 and P3) placed in the traveling direction of ice. Since the influence of the velocity on stress was not observed, the mean values were used for Cases 1, 2, 3, 4, 5 and 8 (SCD=24cm, ND). The dimensionless quantity found by dividing the stress by the unit volume weight ($\rho g$) of the soil and
the representative value of the scale (in this case, the width of model ice \( B \)) was used for the vertical axis, and that found by dividing the horizontal distance to the sensor \( L \) by the representative value \( B \) of the scale was used for the horizontal axis. As mentioned above, it can be seen that stress tended to increase with an increase in scour length. The figure also contains the stress of Case 7, where the relative density was high (HD, 85.3%). The value was almost twice as large compared with the former (ND, 44.7%), indicating that stress is also highly dependent on relative density. The figure also shows the results of the small-scale model test (SCD=6 cm) (Ishikawa et al.,2005) performed with a scale of 1/4 and the same attack angle (45 deg.) as a reference. Although the test conditions were not exactly the same, as mentioned above, since the towing method and soil conditions of the medium-scale test were slightly different (while the relative density was almost the same as that of ND, the water content was slightly different; sand used in the small-scale test was dry but that in the medium-scale test had a water content of approx. 10%), a comparison was made only as a reference. The ratio of “force” in the medium- and small-scale tests, which will be described later, was almost equal to the 3rd power of the similarity ratio \( N \) (4:1), and the ratio of pressure was expected to become \( N \) on the assumption that the inside of the soil was an elastic body except for the failure zone and that the area ratio \( N^2 \) was taken into account. Although a simple comparison cannot be made due to the above-mentioned difference in test conditions, it can be seen from the figure that dimensionless stress in the small-scale test was roughly equal to that in the results of the medium-scale test (ND; Case 1, 2, 3, 4, 5 and 8) when stress was expressed in the dimensionless quantity found by dividing by \( \rho g B \), and it can be assumed that the ratio of pressure was equivalent to the similarity ratio \( N \). However, no significant increase in stress was observed in the small-scale test, while it tended to increase with an increase in scour length in the results of the medium-scale test. Although reaction force in the small-scale test increased uniformly until the horizontal distance \( L/B \) (in case of SCD=6cm) became 3~3.5, it tended to increase and decrease repeatedly after reaching a certain value, as described later. This was thought to be due to the saturated state of sand accumulated by scouring at the front of ice (increase in lateral outflow), as well as to the complex soil failure mechanism, including expansion and contraction within the soil. Details of this mechanism have already been presented (Ishikawa et al.,2005). The same tendency was expected in the medium-scale test, although it has only been conducted up to this distance due to the cost and various other site restrictions and its behavior after this point is unknown. It can therefore be said that the stress distribution reaches the maximum state near the P3 point.

Next, Fig. 4 shows the changes in stress within the soil (maximum value) at the P3 point with an increase in depth (vertical distribution). In the same way as the above, it also shows the results of the small-scale model test (SCD=3cm,6cm) as a reference. The vertical axis represents the dimensionless quantity found by dividing the depth from the surface \( Z \) (burial depth of each sensor) by SCD. Although different SCDs and results of the small-scale model test are contained in the figure, we can assume that most values are distributed on a single curve (except for Case 7) when they are organized in this manner, and it is practical to assume the common maximum stress...
distribution in the vertical direction taking the scale effect into consideration for each relative density. The figure reveals that stress decreased exponentially and that almost no stress was applied when the depth was three times as large as SCD in this case. The vertical distribution in Case 7, where the relative density of the soil was high, was also twice as large in the same way as the above-mentioned distribution.

Fig. 5 shows the transverse distribution (perpendicular to the traveling direction of ice) of stress within the soil (maximum value) at the P3 point. In this case, stress reached the maximum at the center of the model ice and decreased as its distance from the center increased. There was almost no stress at the distance from the center that was equivalent to the width of model ice ($B/2^2$). The transverse distribution in Case 7, where the relative density of the soil was high, was also almost twice as large in the same way as above. No comparison of this stress in the transverse direction was made as it was not measured in the small-scale test.

Examination of reaction force on the model ice during an ice-scour event

Changes in reaction force with an increase in the traveling distance of ice

Fig. 6 shows an example of reaction forces applied horizontally to the model ice during an ice-scour event. The vertical axis represents the dimensionless quantity found by dividing by the 3rd power of the scale (width of model ice $B$) and $\rho g$. The horizontal axis shows the scour length ($L$) divided by $B$. As mentioned later, the figure reveals that the ratio of force in the medium- and small-scale tests was almost the 3rd power of the similarity ratio. Also, for the reason mentioned above, reaction force increased and decreased repeatedly around a certain value after $L/B$ reached $3^\sim 3.5$ (around 3 in this case) in the small-scale model test (SCD=6cm). Although changes in reaction force after $L/B = 4$ are unknown since the medium-scale test was conducted only up to that point, there are signs suggesting that values become uniform or increase and decrease just around this point ($L/B = 3^\sim 3.5$). In Case 6 (SCD = 12 cm) and the small-scale test of SCD = 3 cm, where SCD was small, the amount of sand accumulated by scouring in front of the ice was relatively small due to the limited SCD, and continued to increase slowly because the saturated state had not been reached when $L/B = 3^\sim 3.5$ (there was capacity to retain sand).

Consideration of dynamical similarity of reaction force

As mentioned in the previous section, the ratio of force can be expressed as the 3rd power of similarity ratio. The reasons for this were verified by relaxing the similarity law. First, the
main dominant physical laws were thought to be inertial force, gravity, cohesion, internal friction of soil and external force. Adhesion between the soil and the surface of ice was ignored on the assumption that no relative movement would occur as a thin sand layer was adhered to the surface of ice. The internal friction coefficient ($\mu = \tan \phi$; internal friction angle of the soil) was equal if the soil similar to the original was used. Although the particle diameter was not similar in that case, it was considered reasonable to ignore it because the accumulation effect of particle motion was in the subject. It was also presumed that contribution of inertial force was small (deformation rate was low) within the range of this traveling speed, since dependence of reaction force on the velocity of model ice was not observed in the medium-scale model test in the same way as in the small-scale test. Cohesion can also be ignored since the soil used for this study was sandy soil. Eventually, the ratio of the external force to dead weight $F/\rho g L_r^3$ ($L_r$: representative value of the size) were adopted as $p$-numbers. In other words, the ratio of force was the 3rd power of the similarity ratio. In the case of cohesive soil with a low deformation rate, the ratio of force becomes the 2nd power of the similarity ratio. Similar model tests for performance trials of bulldozers and farming equipment have been conducted on several different scales and they showed the same results as above (Harrison et al., 1962).

Fig.7 shows a scatter diagram of horizontal and vertical reaction forces, including the results of the small-scale model test. The maximum reaction force within the range of measurement was used as the representative value of force. The force was also expressed as the dimensionless using $\sqrt{\rho g B^3}$. While the dimensionless traveling distance differs in the small/medium scale tests, it was implicitly assumed that the maximum value was equivalent in both cases due to the above-mentioned reasons. First, while horizontal reaction force tended to be slightly larger than that of the vertical direction in the same way as in the small-scale model test, a proportional relationship was observed and it was confirmed that the “confining effect” by the attack angle was great. This figure also reveals that neither of the reaction forces showed dependence on the traveling speed of ice. The reaction force in Case 7 (HD), where relative density was great, was about 1.5 times as large as that of ND, unlike the above-mentioned stress.

Next, concerning dynamical similarity of reaction force in the horizontal direction, the values were mostly similar to the results of the small-scale model test except for dimensionless reaction force in Case 1, and the ratio of force was expected to be expressed by the 3rd power of the rate. Reaction force in the vertical direction was smaller in the medium-scale test compared with that in the small-scale test. This was thought to be due to the difficulty in accurate measurement of force in the vertical direction, as well as to the difference in measurement methods of the two tests. At the time of the small-scale test, a load cell was placed on the upper surface of model ice and worked to receive all the reaction force applied vertically. In the medium-scale
test, model ice had a two-layer structure for another purpose and 3 load cells were placed between
the layers as shown in Fig.1(c). It is difficult to transfer all the reaction force especially when the
height of sand accumulated by scouring reached the upper structure of the model ice, and reaction
force was slightly underestimated. Considering the above circumstances, the ratio of force can be
expressed by the 3rd power of the similarity ratio.

CONCLUSIONS

In this study, medium-scale field tests were conducted on sub-scour deformation. We found that
stress within the soil depends highly on the relative density of the soil, and that it was possible to
standardize the maximum stress distribution within the soil from a practical point of view and by
taking the scale effect into account for each relative density. More tests will be conducted under
a variety of relative densities in the future to confirm this. Although we also made experiments
on the pipeline/soil interaction during scour event, the results will be described at the next
occasion. In addition to this type of tests, we intend to solve this problem from both the theoretical
and experimental aspects through the development of a response analysis model for pipelines
using the standardized stress distribution within the soil as an input condition. We also intend to
complete a support tool for reasonable estimates of the burial depth of pipelines by combining
with the method for estimating the scour depth of ice, which has been developed by us for the
purpose of compensating for the uncertainty of seabed survey results.

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