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# Mechanical Model of Ice Scour

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## ABSTRACT

Ice Scouring is a phenomenon which occurs when ice (pressure ridge, hummock or iceberg) moves while in contact with seabed. It has been reported to have caused damage to communication cables and water intake pipelines. In condition that further oil or natural gas exploration projects in offshore areas of the arctic seas is becoming popular, more care must be taken over the design and installation of oil pipelines in such areas in order to avoid accidents due to ice scour.

In this study, we investigated the basic mechanism of ice scour using a simple mechanical model in order to obtain basic knowledge that can be used to prevent future damage caused by sea ice.

## 1. INTRODUCTION

Ice scour is a phenomenon in which ice (pressure ridge, hummock or iceberg) pushed by wind or sea currents from an offshore ice field scrapes the sea bottom, and the sea ice exerts a great force on the sea bottom. This phenomenon has been reported to have caused damage to transatlantic underwater telecommunication cables and to water intake pipelines e.g. at Great Slave Lake in Canada. Thus, if there are buried structures such as oil, natural gas or water intake pipelines in an area where there is a possibility that ice scour will occur, serious damage such as deformation, rupture of pipelines, or leakage of oil or gas may occur due to the dynamic or static forces of sea ice. Of particular concern is the increasing number of offshore oil exploration projects in ocean areas where ice forms in winter. Care must be taken over the design and installation of oil pipelines in such areas in order to avoid accidents due to ice scour. With present technology, it is generally impossible to design a pipeline that can withstand the force of ice due to ice scour (It has been estimated that an ice force as high as 10 MN acts on the floor of the Beaufort Sea(Palmer,1998)). Certain protective measures can be taken; for example, selecting a safe site for burial of the pipelines, burying the pipelines below the estimated maximum scour depth, and protecting the pipelines by the use of trenches, concrete tunnels or a covering of gravel. However, if the pipeline is long, the cost of burying the pipeline deep in the seabed may be very high. For a more economical design, it is necessary to understand the mechanism of ice scour, accurately predict the maximum scour depth in the area where the pipeline is to be buried, and estimate the amount of stress produced by the sea bottom. In this study, we investigated the basic mechanism of ice scour using a simple mechanical model in order to obtain basic knowledge that can be used to prevent future damage caused by sea ice.

## 2. ICE SCOUR IN BEAUFORT SEA

Most of the ice scour in the Beaufort Sea is due to direct gouging of the sea bottom by blocks of floating ice that have formed vertically into a pressure ridge or ice keel. These ice are formed by small pieces of broken ice, known as rubble ice, which freeze together due to the inflow of sea water and lack of brine .

Ice scour marks have been investigated and observed in many areas on the floor of the Canadian Beaufort Sea. The scour depth varies according to water depth and place; it ranges from several tens of centimeters to two meters at a water depth of 8-30 meters (Palmer,1989;Blasco,1998), and the deepest recorded depth of a scour (estimated to have occurred about 2,000 years ago) is 8.5 meters. It has also been reported that scour depth does not exceed one meter at water depths of less than 6 meters and more than 58 meters(Machemehl,1989). However, due to immediate in-filling(Pilkington,1981), the phenomenon in which sand is immediately replaced from the berm during scouring, as well as to the action of waves and tides, accumulation of sand, and fluctuations on the sea level, the observed results of ice scour may be often erroneously estimated, and it is therefore very difficult to accurately measure scour depth. Moreover, due to the high cost and the labor and time required to conduct a survey over a wide area of sea and at a relatively great water depth, we cannot but depend on a systematic experiment to a certain extent.

## 3. EXPERIMENTS

### 3.1 Experimental apparatus and method

The apparatus shown in Figure 1 was used in the experiments. Sand was packed on the bottom of the tank so that it made a constant slope ($i$=1/5 or 1/10). Although the actual slope of a seabed is flatter (1/1000-1/100), we made a relatively steep slope to enhance the scouring. An oil jack with a stroke of 50 cm was attached horizontally to one end of the tank. A model ice was attached in front of the jack, and the model ice was pushed in a horizontal direction by the jack at a constant velocity of 0.4, 0.9 or 1.4 cm/s. The connector FREE was set between the oil jack and the model ice to simulate the contact between one ice and another that is pushing it. The horizontal ice force was measured by the load cell (the horizontal resistance from the sand bed, which is indicated here as the pushing force of the jack). At the same time, the scour length and scour depth were measured by video analysis.

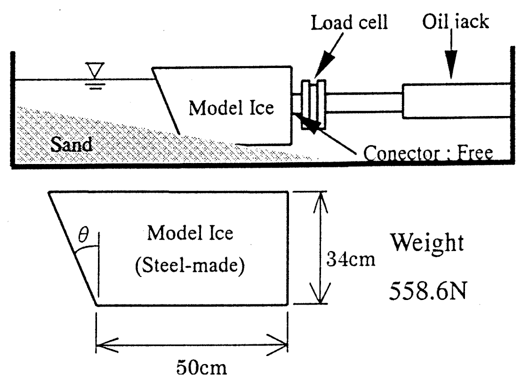


Fig.1 Diagram of the experimental apparatus

### 3.2 Experimental conditions

The model ice used in the experiments was made from steel and weighed 558.6 N (see Fig. 1). The front section of the model ice was inclined at three different angles (attack angle $\theta$ = 0, 15 and 30° ) in the experiments, and counter weights were used to adjust the weight of the block each time to 558.6 N. The bottom of the model ice was flat, although, as mentioned previously, many floating ices are actually keel-shaped underneath. However, the shape of the keel is extremely complex, and little is still known about the relationships that the keel has with size of the ice, draft and sail portion. In the present study, a model ice with a flat bottom was used to first obtain basic knowledge of the mechanism of scouring. Properties of the sand used in the experiments are listed in Table 1.

Table 1.
Properties of the sand used in the experiments

| | |
|---|---|
| Mean grain diameter | 0.147mm |
| Angle of internal friction(CD.tests) | 37° |
| Submerged angle of repose | 32° |
| Submerge unit weight | 15.68kN/m$^3$ |

## 4. Simple Modeling of Ice Scour

### 4.1 Mechanical model of ice scour

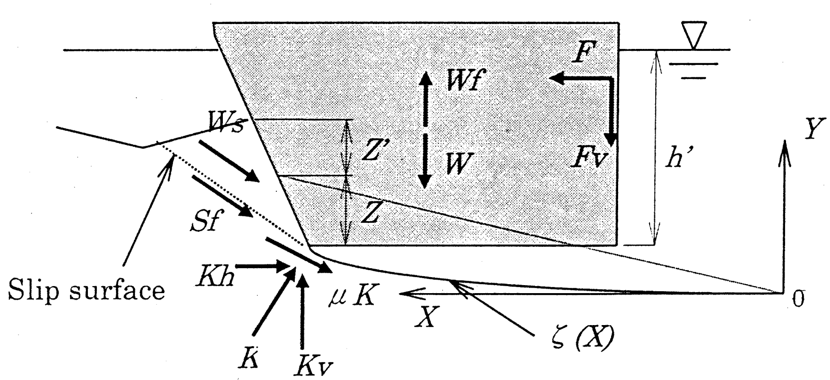


Fig 2. Mechanical model of ice scour

A simplified mechanical model of an ice making contact with and scouring a sandy seabed was constructed in Figure 2.Various external and resistant forces act on the ice. These forces include ice forces in the horizontal direction that occur between drifting ices due to environmental forces such as wind and sea currents (since velocity in the horizontal direction was kept constant in the present experiments, there was no acceleration and the forces indicate resistance from sandy seabed in this case.), buoyancy, reaction force of the seabed (contact pressure), dynamic friction, continuous shear failure of the sand that occurs at the front part of the ice, and weight of the sand assuming there is a slip surface.
Here,
*Z'*: accumulation height of sand; *Z*: scour depth, *W*: weight of the ice; *Wf*: buoyancy; *K*: subgrade reaction in the vertical direction; *F*: horizontal ice force (resistance); *Fv*: frictional force in the vertical direction between drifting ices; *h'*: draft of ice; $\mu$ : coefficient of dynamic friction between ice and sand; $\zeta$ : scour curve; *Sf*: shear force (shear strength); *Wg*: weight of sand assuming there is a slip surface.

Here, we assume that the ice moves along the plane curve $Y = \zeta(X)$, which we will call the scour curve. The scour curve is obtained by subtracting the scour depth from the height of the diagonal plane from a reference plane; in other words, it is the path of motion of the ice in a plane. We were able to estimate scour curves up until the sixth-order curve by the least squares method using video analysis, and, as shown later, these curves were used in the calculations. If the scour depth is known, the approximate ice force F can be calculated by using equations of motion in the horizontal and vertical directions.
By comparing calculated values *F* with measurement value, we will verify the mechanical model indirectly and will grasp the mechanisms of Ice scour.

**4.2 Resistant force acting on the front portion of the ice**

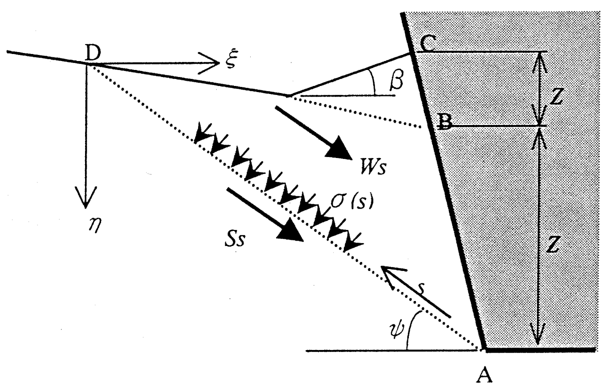


Fig 3.
Resistant force acting on the front portion of the ice

Scouring by ice is thought to cause continuous shear failure of the sand on the sea floor (Chari,1979). Here, considering complete plastic deformation of the sand and assuming a uniform slip surface, as shown in Figure 3, the following forces defined in equation (1) were all assumed to act in the direction of the slip surface: the shear strength at that point (*Sf*), the weight of sand lying along the slip surface (*Ws*), and the friction which occur the side of ice due to move the supposed wedge of sand. Although nature, changes in the mechanical properties of sand and the behavior of the sand in response to changes in the slip surface are very complex, it is assumed that the slip surface can be represented by a linear line.

$$R = Sf + Ws + Ss \qquad (1)$$

*where,*

$$Sf = B\int_s \sigma(s)\tan\phi ds$$

$$Ws = B\gamma'\iint_A \sin\psi\eta d\eta ds$$

$$Ss = \gamma' Kp \iint_{A'} \eta \tan\phi d\eta d\xi$$

where *B* is the width of the ice, $\sigma$ is the normal stress acting on the slip surface, $\psi$ is the angle between the slip surface and horizontal plane (here assumed to be $\pi/2-\phi$), *Kp* is the coefficient of Rankine's passive earth pressure, *A* is the integral area ABCD, and *B* is the integral area ABD.
If we assume that ① there is no compression or expansion of sand and dilatancy is zero, ② the amount of sand that has been pushed up by the ice is equal to the sum of the amount of sand in front of the ice and the amount of sand that has drifted along the side of the ice, and ③ the submerged angle of repose of the sand is the same everywhere, then the accumulation height of sand (*Z'*) when the ice moves can be approximately calculated by the following equation:

$$Z' = \frac{1}{2}\left[\exp\left\{-\frac{\cot\beta}{N}X\right\}\int_0^X \exp\left\{\frac{\cot\beta}{N}\right\}(X\tan i - \zeta(X))dX\right]^{\frac{1}{2}} \tag{2}$$

Where,

$$N = \frac{1}{2}\left\{\frac{\cos(\theta-\beta)\cos(i+\theta)}{\sin(\beta+i)\cos^2\theta} - \tan\theta(1-\tan\theta\tan i)\right\}$$

### 4.3 Equation of motion in the horizontal direction

Equation (3) is the equation of motion of ice in the horizontal direction. Since the horizontal velocity ($V$) was kept constant in the experiments,
first term in the left hand side of eq. (3) is zero.

$$-M\frac{d^2X}{dt^2} - Kv\left(\mu + \frac{d\zeta}{dX}\right) - R\cos\psi + F = 0 \tag{3}$$

where $M$ is the mass of the ice.

### 4.4 Equation of motion in the vertical direction

Equation (4) is the equation of motion of ice in the vertical direction.

$$-M\frac{d^2\zeta}{dt^2} + Kv\left(1 - \mu\frac{d\zeta}{dX}\right) - W + \left(h'B + \frac{1}{2}h'^2\tan\theta\right)B\gamma w \mp \mu kF - R\sin\psi = 0 \tag{4}$$

Here, $\gamma w$ is the submerged unit weight and $h'$ is the draft of the ice. If we make $h_o$ the initial draft at $X$=0, then

$h' = h_0 - \zeta(X)$

Moreover, the signs of the first term in the left hand side of eq. (4) change according to the value of $d\zeta/dX$; the signs are negative when $d\zeta/dX > 0$ and positive when $d\zeta/dX < 0$.

## 5. EXPERIMENTAL AND ANALYTICAL RESULTS

Comparisons of the observed and calculated values of horizontal force in ices with front surface angles of 0, 15 and 30° are shown in Figures 4 (a)~(c) for the case of a sand gradient of 1/5 and in Figure 4 (d)~(f) for the case of a sand gradient of 1/10. The plotted points indicate the observed values and the curves indicate the calculated values. The corresponding scour curves are also shown under each graph.

### 5.1 Effect of the angle of the front surface of the ice

The results confirm that changes in the angle of the front surface of the ice are almost systematically related to the scour curve: $\zeta(X)$ increases with increases in $\theta$ and there is little scouring. The reason for this is thought to be as follows. If $\theta$ increases with other conditions remaining unchanged, slip is easily produced at the interface between the front surface of the ice and the sand. Moreover, the ice becomes unstable due to the vertical resistant force in the front portion of the ice, and this causes the block to rotate slightly and be displaced in the vertical direction. However, despite this tendency, the ice force in the horizontal direction ($F$) showed no systematic relationship with other variables.

### 5.2 Dependency of the velocity of the movement of ice

No systematic relationships were seen for either $F$ or $\zeta(X)$, and a dependency on velocity was not found in the velocity range tested ($V$ = 0.4~1.4 cm/s). If the velocity of the motion of ice is high and the sea bottom consists of silt and clay(in this present study, we used sand only)dynamic analysis that takes into account such factors as excess pore water pressure or inertia of lumps of the seabed when the seabed is broken up by the ice would be necessary. However, if the velocity of the ice is in the range of 0.1~0.5 m/s, as is the case for ice off the eastern coast of Canada, where ice scour is frequently observed, static or substatic analysis would be sufficient, and it is thought that velocity changes within this range would not have any effect on the ice scour.

### 5.3 Comparison of observed and calculated values

When the gradient of the sand was 1/5, the observed values were slightly higher than the calculated values. In the apparatus used in the present experiments, however, sand that had been scoured floated up to the surface of the water, which was thought to be due to an increase in the shear strength of sand due to an increase in the unit weight and change in consistency. If these phenomena are taken into account, it is thought that the observed values showed relatively good agreement with the calculated values. However, when the gradient of the sand was 1/10, the observed values were much larger than the calculated values. In addition to the above phenomena, this large discrepancy is thought to be due to the following reason. In the calculations, it is assumed that the reaction force of the seabed acts mainly at the point A intensively. if $d\zeta/dX \geqq 0$; however, if there is a distribution of seabed reaction forces (contact pressures) with a large percentage of $d\zeta/dX \leqq 0$ or if the location on which the subgrade reaction acted is unknown, the contradiction with this assumption is thought to be a cause of the large discrepancy between observed and calculated values.

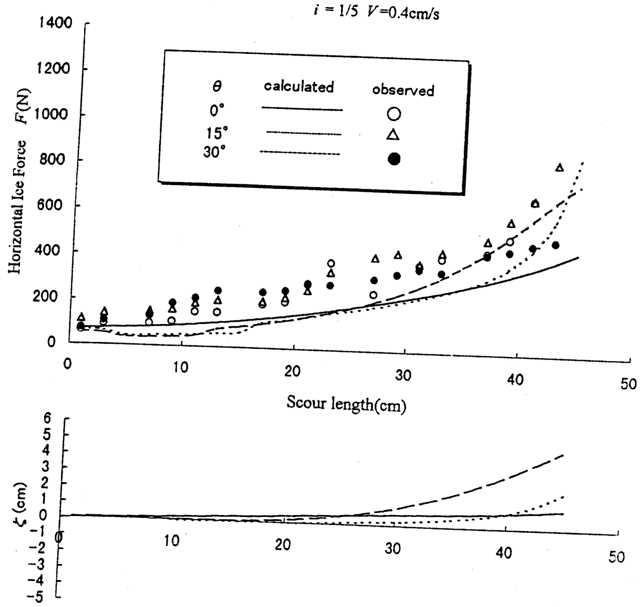


Fig 4 (a) Experimental and Analytical Results(i=1/5, $V$=0.4 cm/s)

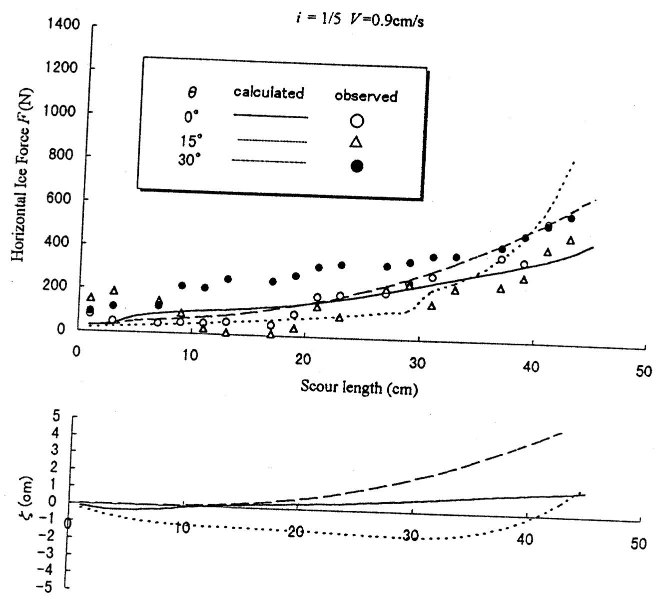


Fig 4 (b) Experimental and Analytical Results(i=1/5, $V$=0.9 cm/s)

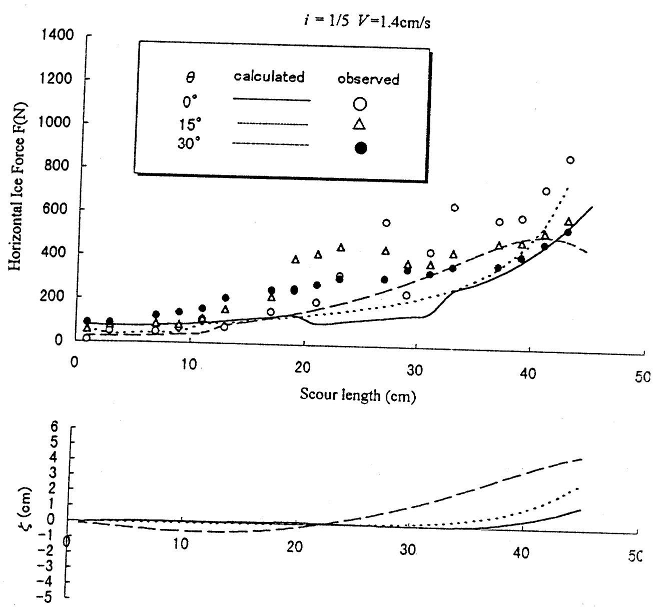


Fig 4 (c) Experimental and Analytical Results(i=1/5, $V$=1.4 cm/s)

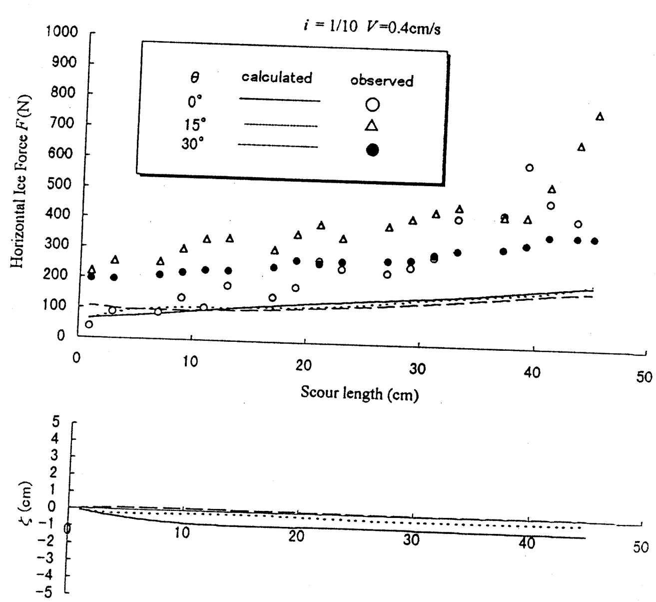


Fig 4 (d) Experimental and Analytical Results(i=1/10, $V$=0.4 cm/s)

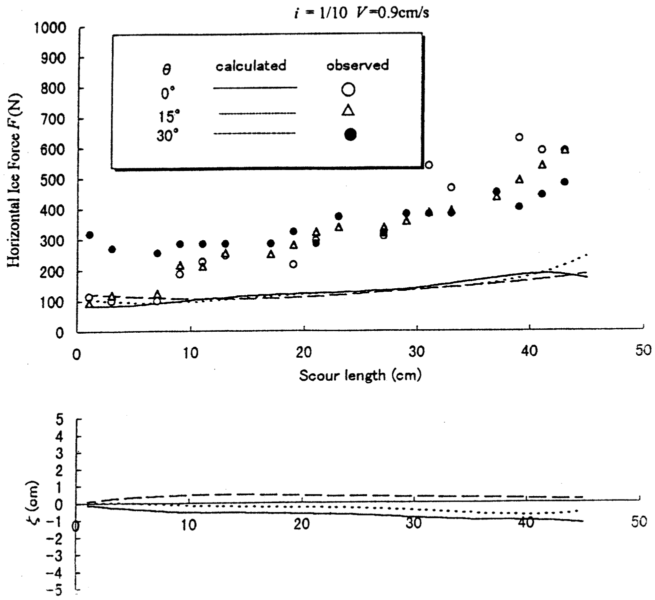


Fig 4 (e) Experimental and Analytical Results(i=1/10, $V$=0.9 cm/s)

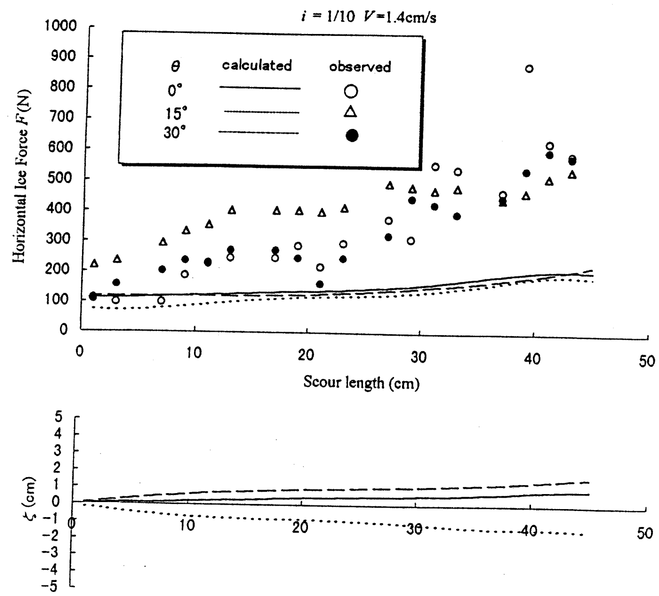


Fig 4 (f) Experimental and Analytical Results(i=1/10, $V$=1.4 cm/s)

### 5.4.Relationship between the scour curve and horizontal ice force *F*

In the observed values, the fluctuations in $F$ are thought to be related to the shape of $\zeta(X)$. It was found that F increased slightly when the gradient of $\zeta(X)$ was large, and conversely, that F decreased slightly when the gradient of $\zeta(X)$ became relatively flat or negative. These tendencies could also be reproduced in the calculations, and they are thought to be due to changes in the constraining force when a object moves along the curve. As an example, the relationship between $d\zeta/dX$ and $d^2F/dX^2$ when the observed values of $i$, $V$ and $\theta$ are 1/5, 0.9 cm/s and 15°, respectively, is shown in Figure 5. In order to understand the overall tendency, we obtained the least squares curve (estimated until the sixth order) of $\zeta(X)$ and $F$ taking into account errors in the observed values. Althouh the values are some deviations toward scour length by measurement error, each cueve shows the same tendency. The local increase and decrease of F is understood if it is taken into consideration that it is $d\zeta/dX \geqq 0$ at the time of $d^2F/dX^2$.

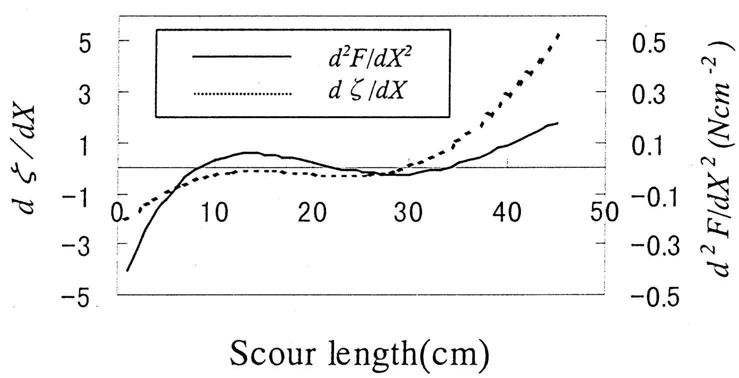


Fig 5. Relationship between $d\zeta/dX$ and $d^2F/dX^2$

Thus, the scour curve is closely related to local fluctuations in $F$ and to scour depth. T. R Chari(1978) and K. Y. Yoon(1997) theoretically estimated scour depth under the assumptions that $\zeta=0$ and $\zeta=cX$, respectively. Unlike the present calculations, they estimated scour depth as the difference between the scour curve and the reference height at the point where a single block of ice, which was pushed by constant environmental forces, came into contact with the sandy bottom and stopped moving. Although it is true that observation results show the scour curve to be linear, it is difficult to observe the true shape due to the previously mentioned partial disappearance of the scour mark and deformation caused by environmental changes. The results of the present experiments showed that, due to rotation of the ice, slip and nonuniformity of the true characteristics of sand, the scour curve is not necessarily linear and even slight changes affect *F*.

### 5.5 Ice forces in the vertical direction

Figure 6 shows the relationship between ice forces in the horizontal direction (*F*) and those in the vertical direction (*Kv*), calculated using equations (3) and (4), respectively. A typical example for a sand gradient of 1/5, a gradient at which relatively good agreement with the observed values was obtained, is presented. As can be seen in the figure, *F*/*Kv* approaches 1. This agrees with the results of experiments conducted by Poulin(1992) that showed the ice force in the vertical direction was several-times greater than that in the horizontal direction, similarly the results of simulation using the finite element method by Yang that showed ice force in the vertical direction was about three-times greater than that in the horizontal direction.

Figure 7 shows a comparison of the weight of ice (*W*) and *Kv*. In this graph, *W*/*Kv* also approaches 1. This also indicates that *Kv* approaches the weight of ice due to such factors as the decrease in buoyancy and increase in constraining force. Although we were only able to conduct measurements in the present experiments up to a stroke of 50 cm, and therefore the behaviors of *Fv*/*Kv* and *W*/*Kv* beyond a stoke of 50 cm are not known, considering the fact that *W*/*Kv* does not generally exceed 1 (although it may exceed 1 depending on the angle at which the ice advances and the conditions that exist behind the ice), the range in which measurements were conducted in the present experiments is thought to be sufficient, and it is thought that the value of *F* would rarely exceed that of *Kv*.

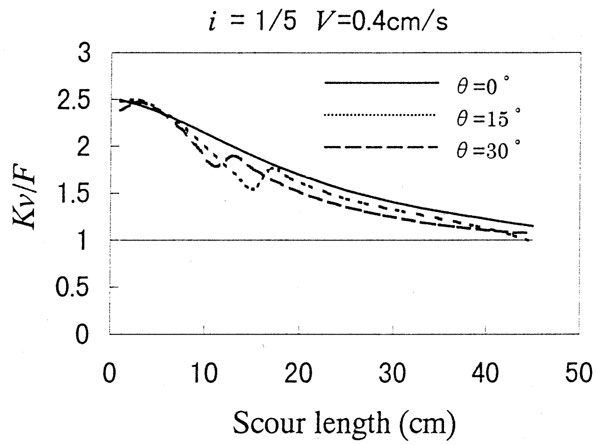


Fig 6. Ratio with horizontal ice forces and vertical ice forces

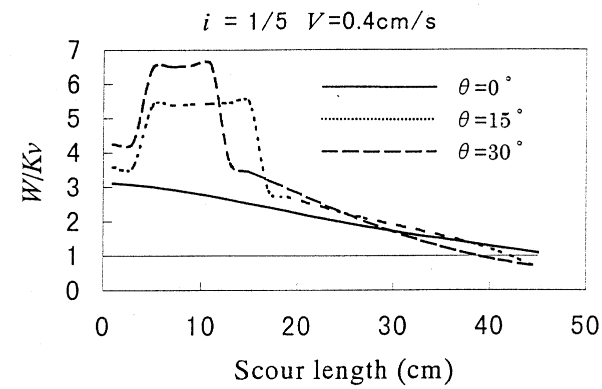


Fig 7. Ratio with verticall ice forces and weight of ice

### 5.6 Sub-scour deformation

Recent reports have pointed out the problems of stress that is transmitted via the seabed and deformation (so-called sub-scour deformation) due to the load caused by ice scour. Conventionally, it has been thought that buried structures can be protected from ice scour by predicting the scour depth and burying the structure below this depth. However, Eyles and Clark (1988), who surveyed a relatively well-preserved scour mark (scour depth of 2.5 m) at Scarborough Bluffs that was estimated to be formed 60,000 years ago, discovered a fault 2 m below the scour mark, indicating that shear failure had occurred down to this depth. Also, Woodworth-Lynas et al (1998) discovered a fault existing 5.5 m below a scour mark (scour depth of 2.5 m) in Lake Agassiz. Thus, although structures buried below the predicted scour depth will not be directly hit by floating ice, damage due to sub-scour deformation is possible.

## 6. CONCLUSIONS

We conducted simple mechanical model of ice scour in order to obtain basic mechanisms of ice scour and through the present experiments or theory, we concluded as follows.

1) The observed values and calculated values generally were consistent when (the slope at the corresponding point on the scour curve) $d\zeta/dX>0$. However, when $d\zeta/dX<0$, the observed values were higher than the calculated values, indicating the necessity to consider contact pressure.
2) The scour curve changed according to the attack angle of the ice, the scour depth decreased as the attack angle of the ice was increased.
3) No systematic difference in the ice force in the horizontal direction according to the attack angle of the ice

was observed experimentally and theoretically.
4) Ice force in the horizontal direction was not dependent on changes in the velocity of the ice within the range of velocities tested in the present experiments and theory.
5) Local fluctuations in ice force in the horizontal direction depended on the slope at the corresponding point on the scour curve $d\zeta/dX$.
6) Just, except for the initial grade of scouring, the ice forces in the vertical direction was greater that in the horizontal direction.
7) It is thought that ice force in the horizontal direction rarely exceeds the dead weight of the ice.

## 7.REFERENCES


Blasco,S.M.1998.Seabed Scouring by Sea-Ice: Scouring Process and Impact Rates: Canadian Beaufort Shelf, Proceedings of Ice Scour and Arctic Marine Pipelines Workshop, Hokkaido, Japan. Published by C-CORE, pp.53-58.

Chari,T.R.1979. Geotechnical aspects of iceberg scours on ocean floors, Canadian Geotechnical Journal Vol.16, no.2, pp379-390.

Chari,T.R., and Muthukrishnaiah,K.1978. Iceberg threat to ocean structures, Proceedings, Symposium on Ice Problems, International Association for Hydraulic Research, Lulea, Sweden, pp.421-432.

Eyles,N. and Clark,B.M.1988. Storm-influenced deltas and ice scouring in a late Pleistocene glacial lake, Geological Society of America Bulletin, 100, pp793-809.

Machemehl, J.L.and Jo, C.H.1989. Ice Gouge Study in the Alaskan Beaufort Sea, Journal of Korean Committee for Ocean Resources and Engineering, Vol.Ⅲ, No2, pp.545-550.

Palmer,A.C.1998. Alternative Path For Determination of Minimum Burial Depth To Safeguard Pipelines Against IceGouging, Proceedings of Ice Scour and Arctic Marine Pipelines Workshop, Hokkaido, Japan. Published by C-CORE, pp.9-16.

Palmer,A.C., et al.1989. Ice Scour Mechanisms, Proceedings of the 10th International Conference on Port and Ocean Engineering under Artic Conditions, Lulea, Sweden, Vol. Ⅰ, pp.123-132.

Paulin, M.J.1992.Physical model analysis of iceberg scour in dry and submerged sand. M.Eng.Thesis, Memorial University of Newfoundland, St.John's Newfoundland.

Pilkington,G.R. and Marcellus,R.W.1981. Methods of Determining Pipeline Trench Depths in the Canadian Beaufort Sea, Proceedings of the 6th International Conference on Port and Ocean Engineering under Artic Conditions, Quebec, Canada, Vol. Ⅱ, pp.674-687.

Yang,Q.S.et al.Analysis of Subscour Deformation by Finite Element Method, Proceedings of the 4th Canadian Conference on Marine Geotechnical Engineering, St. John's, Newfoundland, Canada, pp.739-754.

Yoon,.Y.et al.1997.Numerical Simulation to Determine Ice Scour and Pipeline Burial Depth, Proceedings of the 7th International Offshore and Polar Engineering Conference, Honolulu, USA, pp.212-219.

Woodworth-Lynas, C.M.T.1998. Sub-Scour Deformation and the Development of Ideas from Field Work in the Last Decade, Proceedings of Ice Scour and Arctic Marine Pipelines Workshop, Hokkaido, Japan. Published by C-CORE, pp.33-38.