Impact of ice loads on pile structures and deformation of ice floes

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Abstract

The Okhotsk Sea coast of Hokkaido, Japan is covered with ice floes during winter. Aota et al. showed that the temperature in this region has been rising every winter, and in the last ten years the amount of sea ice has been decreasing. Therefore the period of coexistence of waves and ice floes has become longer and it is very important problem to make clear the impact ice load acting on offshore, harbor and coastal structures which are constructed on Okhotsk Sea coast of Hokkaido. Judging from the mechanical properties of ice sheet, ice sheet is an elastic-plastic substance, and in high strain region, it is seemed as elastic material. Generally ice load acting on structures and mechanisms of its fracture mode depend on the strain and stress rate. In the case of large moving ice sheet colliding with structure, the decision of deformation area of ice sheet was very difficult. Saeki et al. and Takahashi et al. reported that the velocity of ice floes due to wind wave, overtopping over breakwater and tsunami was about 4-8 m/s. In this paper, the authors clarified the impact ice load when ice sheets collide vertically with a circular cross-sectional structure, and the deformation area of ice sheet which collide with pile structures at high speed.

1 Experimental methods

The velocity of ice sheets (V) was 4-8 m/s, calculated from abnormal waves in the Okhotsk Sea coast during winter, as well as the average depth of the breakwater foot below the sea surface and the average crown
height at the ports of Mombetsu and Abashiri which are located on the Okhotsk Sea coast of Hokkaido. The experimental impact velocities of sea ice on the structure were set at 6 m/s and 8 m/s. The experimental piles had a circular cross-section with diameters of 10cm and 20cm, which were close to the real scale. Rectangular ice sheets (width 150cm; variable thickness up to a maximum of 30cm) were dropped through the frame of the steel-made experimental device (Fig.1, photo 1). The circular cross-sectional pile was supported by a hinge at one end and a load cell with a capacity of 10 tf at the other end at the bottom part of the devices. The ice sheet was dropped onto the pile at about midway between the hinge and load cell. A highly rigid pile with a thickness of 14 mm was used to minimize the deformation of the pile due to the impact. The impact load was measured by the load cell, and sampled and recorded at 200 kHz. In addition, the impact velocity was varied by altering the height of the ice sheet dropped. Movements of ice sheets were filmed from the front by a high-speed video camera at 500 exposures per second to record the impact velocity accurately and to certify the breaking properties of the ice sheets.

The unconfined compressive strength of sea ice ($\sigma_u$) was determined by applying a strain rate of $10^{-3}$ sec$^{-1}$ to the specimens until destroyed; the average unconfined compressive strength of the 20 specimens was 2.44 MPa.

An experiment to observe the deformation of an ice sheet when it collides with pile structures was conducted at the same time as an experiment to determine the impact ice load. In all cases of deformation area analysis in this study, therefore, ice sheets collided with pile structures at a high speed and the strain rate ranged in the order of $10^0$ - $10^4$(1/sec).
The diameter of the pile was 10 cm. The collision speed to the pile was 6.5-8.7 m/s. The weight of each ice sheet was adjusted by changing the cutting length. The ice sheets were 2 to 3 meters long, their mass were 54-100 kg and their momentums(M) were 361 to 843 kg·m/sec. The unconfined compressive strength of sea ice was obtained by breaking a cylindrical specimen (diameter : 10 cm ; length : 20 cm) at a strain rate of approximately $10^3$ sec$^{-1}$. There were 18 specimens and their average unconfined compressive strength was 2.07 MPa. The ice temperature at the time of the strength test was -2°C, which was the same as the average air temperature at the time of the impact test.

The deformation area of ice at the time of collision was found using 2 methods.

In the first method, a checked pattern was marked on the surface of the ice sheet at intervals of 10 cm before it was dropped, and the movement of the marks, from just before the collision with the pile to just before the cracks occurred after the collision, was measured using high-speed video (500 Hz) shot from the front (photo 2). At that time, the movement of all the marks on the ice sheet surface shown in the video was measured, and the average movement of marks within the concentric circles centering around the pile at intervals of 10 cm was defined as the movement of the marks at each distance. The deformation area was determined and analyzed by regulating the movement of the marks according to distance from the pile.

In the other method, a
horizontal cut was made in the ice sheet before dropping it. By changing the cut section ($S$) to 15, 25, 35, 45, 65 and 85 cm from the lower end (the surface that collided with the pile), differences in the load on the pile (diameter: 10 cm) and in its time history were observed (see Fig. 2).

From the results of these observations, the deformation area of the ice at the time of collision was obtained.

2 Experimental results on impact ice force

Figure 3 shows the relationship between $t_{\text{max}}$ (the time up to the occurrence of the maximum impact force) and $M$ (the momentum of an ice sheet). The symbols ● and ○ indicate piles with diameters of 10 cm and 20 cm, respectively. The experimental values showed slight deviations. Most of the values indicate that the maximum impact force occurred within 4 msec after the collision. Figure 4 shows the relationship between $V$ (the velocity immediately before the impact) $\cdot t_{\text{max}}$ (the time up to the occurrence of the maximum impact ice force) and $M$ (the momentum). $V \cdot t_{\text{max}}$ is the apparent depth of penetration by the ice sheet into the pile at the time of the occurrence of the maximum impact force, assuming the velocity remains constant after the collision. Since in practice the rate of penetration reduces after the collision, the actual depth of penetration should be slightly smaller than the apparent depth when the maximum impact force takes place. The values of the apparent depth of penetration, $V \cdot t_{\text{max}}$, were below 1.5 cm, if non-vertical collision with the pile were excluded.

The maximum impact ice force occurred when the ice sheet penetrated about 1 cm into the pile, not when the ice sheet penetrated into the pile by the length of its radius, which gives the
maximum area of contact. In addition, although the area of contact between the ice sheet and the pile multiplied by the unconfined compressive strength of the ice sheet was a little smaller than the experimental value of the maximum impact ice force, they agreed relatively well with each other. Figure 5 shows an example by comparing the changes of \( F_c \) and \( F_i \) with time. \( F_c \) is the area of contact between the ice sheet and the pile multiplied by the unconfined compressive strength of the ice sheet. The area of contact was calculated from the constantly changing velocity during the penetration, which, in turn, was based on the velocities before and after the collision observed by the high-speed video camera. \( F_i \) is the impact ice force measured by the load cell. The maximum impact force took place 1 msec after the collision, when \( F_c \) and \( F_i \) were nearly equal.

There were samples where \( F_c \) and \( F_i \) did not agree with each other very well, maybe because the average value of 20 samples was used as the compressive strength of ice, which disregards the inherent deviations of the values of the ice strength.

According to the observations by the high-speed video camera, the conditions of the destruction of ice sheets at the time of collision can be roughly divided into two categories: ice sheets with a length of less than 1 m and ice sheets with more than 1 m. Milk-white-colored micro-cracks were generated on ice sheets with a length of more than 1 m near the point of contact with the pile immediately after the collision. Then the surface and the bottom of the ice sheet were exfoliated like a wedge, which is termed spalling destruction. When the ice sheet penetrated about 1 cm into the pile, a major crack spread vertically to the end of the ice sheet. The ice sheet split into two and fell downward. On the other hand, Milk-white-colored micro-cracks were also generated on ice sheets with a length of less than 1 m immediately after the collision, and simultaneously with a spalling destruction the ice sheet was destroyed similar to destruction due to bending, with the point of contact with the pile as a support. Therefore, when studying the collision of comparatively small ice sheets, such as those observed by the high-speed video camera in this experiment, their kinetic energy after the collision has to be taken into account.

Figure 6 shows the relationship between \( t_D \) (the duration of the impact force) and \( M \) (the momentum). In this experiment, the impact velocity \( (V) \) was set at 6 m/s and 8 m/s, the ice thickness at 20 cm, and the width of the ice sheets at 150 cm. The momentum \( (M) \) is dependent predominantly upon the length of the ice sheets. The larger the momentum, the longer the
duration of the impact ice force.

Figure 7 shows the relationship between the maximum impact force ($F_{\text{max}}$) and the momentum ($M$), where the diameter of the pile is 10 cm, and the impact velocity ($V$) is 8 m/s. In the range where the momentum is small, the maximum impact force rises directly proportional with the momentum. When the momentum is greater than 300 kg m/s, $F_{\text{max}}$ has a constant value regardless of the increase in the momentum.

$$F = 5.0\sqrt{D \cdot h \cdot \sigma_c} \quad (1)$$

where

- $\dot{\varepsilon}_p (\dot{\varepsilon}_p = V/4D)$: (the strain rate at the time of penetration) = $10^{-3}$ sec$^{-1}$
- $h$: the ice thickness (cm)
- $\sigma_c$: the unconfined compressive strength (MPa)
- 5.0: shape factor (cm$^2$)

Figure 7 shows that the maximum impact force is far smaller than the value of equation (1). Figure 8 shows the relationship between the impulse ($I$) and the maximum impact force. The maximum impact force tends to increase directly proportional to the impulse, yet their correlation becomes insignificant after the impulse ($I$) increases beyond 500 (N·s).

Figure 9 shows the relationship between the maximum impact force and the momentum. We analyzed this relationship from the results of this experiment and the experimental results of Saeki et al.$^{10}$, as well as the measurements of Neill.$^9$. Neill conducted field experiments in an actual river, where the ice thickness...
was 52-110 cm, the impact velocity was 1.07-2.53 m/s and the diameter of the pile was 86 cm. The conditions of the measurements used by Neill were stated when discussing the relationship between the maximum impact force and the momentum. Under the conditions of Saeki et al., the mass of the ice sheets was approximately 100 kg, and the impact velocity was 6-7 m/s. In the range where $M$ is smaller than $10^3 \, \text{kg} \cdot \text{m/s}$ in Figure 9, $F_{\text{max}} / \sqrt{D} \cdot h \cdot \sigma_c$ tends to increase as $M$ increases. When $M$ is larger than $3 \times 10^3 \, \text{kg} \cdot \text{m/s}$, the line representing the values of $F_{\text{max}} / \sqrt{D} \cdot h \cdot \sigma_c$ shows that $F_{\text{max}} / \sqrt{D} \cdot h \cdot \sigma_c$ is nearly constant at 4.0. No matter how large the momentum becomes, it never increases beyond the ice force given by equation (1), and the maximum ice force is only as large as about 80 % of the value of equation (1). In the unconfined compression test on ice by Michel et al., when the strain rate ($\dot{\varepsilon}$) is large, the ice force is as large as 80 % of the unconfined compressive strength at $\dot{\varepsilon} = 10^3 \, \text{sec}^{-1}$, which is similar to the results of Figure 9.

When a moving ice sheet collides with a structure, the kinetic energy of the ice sheet can be obtained from the following equation:

$$
\frac{mV^2}{2} = E_C + E_S + E_D
$$

(2)

where

$E_C$: energy used when the edge of the ice sheet is destroyed

$E_S$: energy used for the elastic deformation of the structure

$E_D$: kinetic energy used for traveling and revolving the ice sheet, as well as for shattering the destroyed ice pieces after the collision

$m$: mass of the ice sheet

$V$: impact velocity

$E_C$, energy used when the edge of the ice sheet is destroyed, is generally given by the following equation:

$$
E_C = \int_{0}^{S_0} F(s) ds
$$

(3)

where

$F(s)$ is the ice load at the interface

This equation gives the energy used at the area of contact between the ice sheet and the structure based on the hypothesis that cracks spread continuously. $F(s)$ is equivalent to the ice load at the interface. If the cross-sectional shape of the pile and the ice load during continuous cracking (the crashing strength can be used instead) are known, $E_C$ is calculable. Cammaert et al., Kreider, and Michel only included the first term of the right side of equation (2)($E_C$) to formulate an equation to
calculate the impact ice force. Korzhavin\textsuperscript{(1)} used the first and second terms (Ec, Es) to determine an equation to calculate the impact ice force. Kato\textsuperscript{(2)} proposed an equation which contains the first and third terms (Ec) to incorporate the effects of the revolution of the ice sheet. The calculated value of the first term plus the second term of equation (2) was found to be greatly different from the experimental values, because soon after the ice sheet collides with the structure at a high velocity, vertical cracks spread in a small ice sheet, such as those used in this experiment. The destroyed ice pieces do not exert any force on the structure and shatter at high velocities. The results show the significance of the third term of equation (2).

3 Experimental results on deformation of ice sheet

3.1 Results of video analysis

Four cases were analyzed using videos. The ice sheet was longer than 1.5m in all cases. This distance was thought sufficient to ensure it would not be affected by deformation. The movement in 1/100 second, from just before the collision to just before cracks occurred in the ice sheet after the collision, was measured. In each case, measurements were taken at 50-100 points around the pile, which had a diameter of 10cm. Figure 10 shows the relation between deformation and (X/D). The deformation was regulated as a ratio (X/D) of the distance between the pile and the point (X) to pile diameter (D). The ice sheet was deformed by the stress of collision when it was close to the pile. Deformation gradually decreased as distance from the pile increased, as stress was not transmitted. Then, the movement of each point tended to equal the movement of the entire ice sheet, although there were some dispersions. Although the border of deformation could not be clearly determined, it was presumed to be when X/D was approximately 4. In other words, the range of the elastic property was thought to be approximately 4D. Thus, assuming the average movement of X/D > 5 was the movement of the entire sheet, the differing movement of each point around the pile (deformation) was calculated. This is shown in Fig. 10. As distance from the pile increased, deformation decreased.

Strain of the ice sheet was also found by dividing the deformation by 4 times the pile diameter, which was believed to be the range of elastic property (Fig.11). Next, the movement of the ice with a cut at a point S=25 cm from the lower end of the sheet was measured using the same method when it collided with the pile (see Fig.2). The results are shown in Fig.12. The
Fig. 10 Deformation of each point on ice sheet

Fig. 11 Strain of each point on ice sheet
movement was regulated as a ratio $(X/D)$ of the distance between the pile and each point $(X)$ to pile diameter $(D)$, and for both the upper and lower sides of the cut section. Although the movement on the lower side, which collided directly with the pile, was smaller near the pile due to the strain caused by absorbing the impact, it became larger as the distance from the pile increased. The linear increase of movement shows that bending failure occurred and both sides of the ice sheet fell off due to its limited size. The movement on the upper side of the cut section increased only slightly on the distance from the pile increased. The movement at each point was obviously different on the upper and lower sides of the ice sheet. This showed that the cut in the ice sheet discontinued the stress.

### 3.2 Results of ice force analysis

The following are the results of a test to determine the load and its time history when an ice sheet with a horizontal cut was dropped. The test was conducted for 7 cases. The pile was 10 cm in diameter, collision speed was approximately 6.7 m/s and the momentum was approximately 375 kg m/s. Figure 13 shows the time history of the impact load when the distance $(S)$ between the lower end of the ice sheet (the surface colliding with the pile) to the cut section was changed. The axis of ordinate shows the load and the axis of abscissa the time. In the figure, there are 2 load peaks when the distance to the cut section was short and the 2 ice sheets collided at different times. As the distance $(s)$ increased, the second wave was absorbed by the first and the 2 parts of the ice sheet could actually be regarded as one. As the time history of the load was virtually
the same as that of an ice sheet without a cut at S/D>4.5, the boundary was thought to be approximately S/D = 4.

Figure 14 shows the relation between the peak of the first wave of the ice load and the cut section of the ice. The ice force was small to begin with and increased as the cut section became larger. When the distance from the cut section exceeded 40cm (S/D>4), however, the impact ice force became constant. The ice force was small when S/D was small for the following reasons. When ice sheets with the identical momentum collided with piles, cracks occurred after the sheet was deformed to a certain degree if the cut section was far from the pile, but the stress would only be transmitted halfway if the cut section was within the range of deformation. From these graphs, the deformation area of ice was thought to be approximately 4 times the pile diameter (D).

Conclusions

1) Since ice sheets collide with the structure at a high velocity, the maximum impact force occurs within 4 msec from the collision. In such cases, the depth of penetration was smaller than 1.5 cm and did not reach half the radius of the pile (5cm or 10cm), because of the small size of the sheet, as well as the brittle nature of the ice sheet in the range of high strain velocities. The theoretical area of contact between the ice sheet and the structure when the maximum impact force occurs multiplied by the unconfined strength of sea ice (σc) is the ice force. This ice force is almost equal to the maximum impact ice force.

2) In the range where the momentum of the ice sheet is small, the maximum impact ice force increases as the momentum increases. However, the maximum impact ice force was constant above a certain value of the momentum. The same tendency can be seen in the relationship between the maximum impact ice force and the impulse.

3) The impact ice force never exceeds the value of the equation of Saeki et al., produced from the ice force at a strain rate (ε) of 10⁻³ sec⁻¹ generated during the penetration. This is supported by the results of this experiment, of Saeki et al., and of the field test of Neill.

4) When applying the energy conservation law to the impact of a small ice sheet, it is necessary to include the energies used to destroy the ice sheet, to deform the structure, and the kinetic energy used to revolve the
ice sheets and to shatter the destroyed ice pieces.

(5) The reasons for clarifying the range of elastic-plastic properties of ice sheets were listed.

(6) Movement of marks on the surface of an ice sheet at the moment when it collided with the pile was measured using a video camera. The movement was found to be smaller due to the strain on the ice sheet when the marks were closer to the pile. When the distance from the pile was more than 4 times the pile diameter, movement became constant.

(7) Horizontal cuts were made in the ice sheets to be dropped, and the load on the pile was compared for different cut sections. As a result, impact ice force was found to be small when the distance to the cut section was short, and it became constant when the distance was approximately 4 times the pile diameter.

(8) Horizontal cuts were made in the ice sheets to be dropped, and the time history of the load on the pile were compared for different cut sections. As a result, there were 2 load peaks when the distance to the cut section was short, as the 2 ice sheets collided separately. When the distance to the cut section was longer than 4 times the pile diameter, the 2 parts behaved as a single unit.

(9) From the above 3 tests, the deformation area of ice (range of elastic-plastic properties) was estimated to be approximately four times the pile diameter.

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