Medium-scale Experiment and Numerical Simulation using 3-D DEM for the Impact Load by an Ice Floe against a Pile Structure

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ABSTRACT

This paper reports on the results of a medium-scale experiment regarding the impact applied by ice floes against a pile structure using free-falling ice floes with a length of 0.3 to 1.2m and a thickness of 0.15m under various conditions as a follow-on from our previous experiment and numerical simulation using the 3-D discrete element method (DEM). When ice causes brittle failure/splitting, and fragments move freely after impact with a structure (especially when the ice floe is large compared to the structure), the impact load or the impulse was small compared to cases without failure, and was presumed to become a constant value regardless of the level of the kinetic energy or the momentum. We also developed a fundamental numerical method to simulate the impact of ice on a structure. In this method, DEM with tension resistance among particles and FEM were applied to sea ice and a structure respectively. The simulation results showed a close correlation with the experimental outcome in terms of the time-series change of impact loads, the dynamic failure processes of the ice floe and the response of the structure to impact. The calculated results also agreed well with the trends of the experimental results in this study, such as the relationship between the kinetic energy and the ice load.
1. Introduction

The amount of ice in the Sea of Okhotsk off Hokkaido has decreased in recent years due to global warming. This situation results in more intense movement of sea ice, thus increasing the likelihood of high-speed sea ice floes colliding with coastal structures. When ice concentration was low and waves were very high, ice floes and waves were found to overtop breakwaters and damage vessels, pipelines and other facilities at Japanese ports (Hayakawa et al., 2000). Ice floes caused by tsunami waves can also be considered to pose a risk of impact against coastal structures and private residences. In fact, as shown in Fig. 1, tsunami-related ice floes originating in the sea off the coast of Tokachi caused serious damage to private houses in 1952, especially in Hamanaka Town on the eastern side of Hokkaido. The possibility of a huge earthquake and subsequent tsunami waves along the Kuril Islands in the near future is estimated to be high (according to Japan’s Central Disaster Management Council). Accordingly, the development of a more accurate estimation method for the impact loads applied by ice against objects is required in structural design, particularly for important constructions such as oil tanks and evacuation facilities or their protective frameworks in coastal areas or near ports and harbors. So far, although tsunami-related debris such as timber, containers and vessels has been studied (cf. Yeon et al., 2007, Kumagai, 2008), the important points in the case of sea ice are its sheer volume and the fact that brittle/split fracture is presumed to occur in most cases.

Hayakawa et al. (2000) performed large-scale experiments regarding the impact applied to a pile structure by a free-falling mass of ice made of frozen seawater under open-air conditions. Kioka et al.(2009) also performed similar experiments on a medium-scale using artificial saline ice. In particular, they focused on how ice temperature affects the impact it exerts, and on the response of a pile structure with relatively low stiffness to impact. They also developed a fundamental numerical method to simulate the impact of ice on a structure using 2-D DEM to ascertain possible applications for the technique in practical use.

In this study, during the implementation of the experiments (Kioka et al.,2009) under various conditions, we also developed a related numerical calculation method using the 3-D discrete element method (DEM) to simulate time-series changes in impact loads, and the dynamic failure processes of ice floes.

Figure 1. Tsunami-related ice floes originating in the sea off the coast of Tokachi caused serious damage to private houses in 1952.
2. Review of the authors’ previous study (Kioka et al., 2009)

This section gives a brief look at our previous study (Kioka et al., 2009). As shown in Fig. 2, a medium-scale experiment regarding the impact applied by an ice floe on a pile structure was performed using free-falling ice floes with a length of 0.3 to 1.2 m and a thickness of 0.15 m. Artificial masses of saline ice were dropped from heights ranging from 0.5 m to 1.5 m to create speeds equivalent to ice floe movement of 3.1 – 5.4 m/s on collision with a steel pile. The salinity and density of the artificial ice samples were about 4 – 7‰ and about 0.86 – 0.92 g/cm³, respectively. The samples also had columnar structures with grain diameters of 5 – 20 mm. The ice temperature, which significantly affects its strength, was changed from -15 to -5°C (target) to represent a basic condition of -10°C. A steel pile (SS) with a circular cross section measuring 60 mm in diameter was used, and its ends were simply supported by load cells placed 0.6 m apart. Both ends of the support were fixed vertically while being allowed to rotate. In this case, the natural frequency and the damping constant of the structure were 333 Hz and 0.07 Hz, respectively. Strain gages were also set on the bottom surface of the structure. Using the load cells and strain gages, the reaction forces were estimated.

While the impact load was presumed to approach a constant value when the kinetic energy reached a certain level, energy consumption due to failure and scattering of ice was assumed to be dominant. As shown in Fig. 3, the impact load increased linearly with decreasing ice temperature; accordingly, it was presumed that the effect of this temperature on the impact load was larger than that on compressive strength. However, the effect of temperature on the impact load was assumed to be in roughly the same order as that on the tensile strength values obtained by Saeki et al. (1978), which also increased linearly with decreasing ice temperature. The impact load was also presumed to be more strongly influenced by the ice temperature than the kinetic energy under the test conditions of that study. As a result, in cases where a comparatively small-scale ice floe collides with a small pile (or a structure with a small curvature), and split failure occurs, the impact load is presumed to relate to the tensile strength and the size of the ice floe. Essentially, this concept was equivalent to that in the equation of maximum force with split failure proposed by Michel (1978), in which coefficient n related to the structure’s shape factor is assumed to be 0.5. Finally, a fundamental numerical method using 2-D DEM was developed to simulate the impact of ice on a structure. The simulation results agreed well with the time histories of the experimental reaction forces, including the failure modes of the ice and the free damped vibration of the structure (see Fig.4).
3. Experimental method

Although the experimental method in this study was basically the same as the previous one (Kioka et al., 2009) (see the last section for a brief outline), there were some additional conditions and minor changes of the experimental methods are described here. A steel pile structure with relatively high level of stiffness (natural period: $T = 5 \times 10^{-4}$ sec) compared to it ($T = 3 \times 10^{-3}$ sec) in the previous study and with a damping constant of 0.07 was used. The pile structure had circular cross sections with diameters ($D$) of 0.06m. The ends of each pile were simply supported by load cells placed 0.3m apart. As in the previous experiment, artificial ice floes with a width ($B$) of 0.6 m, a length ($L$) of 0.3 to 1.2 m and a thickness of 0.15 m were dropped from heights ($h$) ranging from 0.001 m to 1.5m to create speeds equivalent to ice floe velocity of 0.14 – 5.4 m/s on collision with the steel pile. The ice temperature of all ice floes was set to around -8°C (-6 – -9°C). The measurement items and method were the same as those in our previous experiment (Kioka et al., 2009). The salinity and density of the ice samples were about 5 – 7‰ and about 0.9 – 0.92 g/cm³, respectively. The samples also had columnar structures with grain diameters of 5 – 20 mm. The number of experiment in the same condition is only one because of limitation of time and cost at this time.

Figure 3. Relationship between ice temperature (absolute values) and reaction force (peak value of time history of force) (Kioka et al., 2009)

The dotted lines show the values of estimated compressive strength converted to a force, which was multiplied by the diameter of the pile ($d$) and the ice thickness ($t$). The curves in the figure were estimated from the equations given by Truskov et al. (1992) and Weeks (1967). The formula by Weeks (1967) excludes the effects of loading and the strain rate to form a compressive strength index. The blue line shows the force to the tensile strength, multiplied by the length ($L$) of the ice and the ice thickness, was converted. The values were multiplied by 0.5.

Figure 4. Comparison between numerical simulation results from 2D DEM and experimental results regarding the time history of the impact load (reaction force) and failure mode (Kioka et al., 2009)
4. Experimental results and analysis

**Overview of impact loads and failure modes of ice masses**

Figure 5 shows examples of the time history of impact load (reaction forces by load cells) and failure modes in the cases of the standard test condition \((L = B = 0.6 \text{ m}, D = 0.06 \text{ m})\) and of that with the largest kinetic energy of the ice masses \((L = 1.2 \text{ m}, B = 0.6 \text{ m}, h = 1.5 \text{ m}, D = 0.06 \text{ m})\) used in the experiments. The impact load shows a peak value at around \(2 – 3 \times 10^{-3} \text{ sec. after the ice collision}\). The clear damped vibration of the pile shown in Fig.4 did not occur because the pile used in this study had relatively high stiffness. When the size of the ice mass, especially in the direction of impact, was relatively small as shown in Fig.5 (a), the ice split into two after a crack propagated to its upper edge in most cases, or, radial cracks around the pile occasionally propagated to each side of the ice. On the other hand, when the ice mass was large as shown in Fig.5 (b), cracks did not propagate to the upper edge, instead deviating along the way and reaching the sides of the block. Although we were not able to measure the exact impact load, it can be assumed that the peak/maximum values of the reaction forces obtained using the load cells – including the response of the pile – were almost the same as those of the exact impact loads for the reasons described in the previous study (Kioka et al., 2009) and from the results of the numerical simulations described later. In addition, the reaction forces at the ends of the pile estimated from the strain values at the bottom of the pile roughly corresponded to those obtained using the load cells. We therefore applied the reaction force obtained using the load cells to represent the value of the impact load.

**Relationship between kinetic energy and the time (rise time) at which the impact load reaches its maximum value**

Figure 6 shows the relationship between kinetic energy \((E)\) and the time \((t_{\text{max}}, \text{rise time})\) at which the impact load (reaction force) reaches its maximum value. This figure includes our previous data (Kioka et al., 2009). According to the past data, the value decreased with higher levels of kinetic energy to reach a constant value. Moreover, it was presumed that \(t_{\text{max}}\) would not depend on the ice temperature. The current data also show a similar tendency.
although they seem to indicate a high degree of scatter compared to the previous values. However, there were few significant differences between the present and previous data except some data despite the difference in the natural periods involved ($T = 3 \times 10^{-3}$ sec and $5 \times 10^{-4}$ sec in the previous and present experiments, respectively). Generally, although $t_{\text{max}}$ (or the duration time) is considered to depend on whether or not an ice floe causes brittle failure/splitting and its pieces move freely after impact with the structure (this is more likely to occur when $E > 0.2$ kJ), $t_{\text{max}}$ did not depend on $E$ in the current data. In the current experiment, the ratio of the ice-collision duration time to the natural period ($T$) was estimated to be around 20. Additionally, from the DAF (dynamic amplification factor) estimated using a simple model in which an impact load from a pulse wave (such as a half sine wave or a triangle wave) acts on a spring/particle system, the exact impact load was presumed to be almost equal to that caused by the response of the pile (i.e., the reaction force). This can also be seen in the numerical simulation results described later.

**Relationship between the impact load with the pile and the kinetic energy of the ice mass**

Here, we first consider the relationship between the impact load with the pile (reaction force) and the kinetic energy ($E$) using a simple model under a condition where no fracture occurs. This simple model is based on the assumption that the ice is a perfectly elastic body and that the kinetic and potential energy are changed to elastic strain energy in both the pile and the ice. Accordingly, we obtain Eq. [1] as below, and the velocity $v'$ just after contact with the pile can be obtained using the law of conservation of momentum as shown in Eq. [2].

\[
\frac{1}{2} (M + m')v'^2 + (M + m')g(\delta + \alpha) = \int_0^\delta P_p d\delta + \int_0^\alpha P_i d\alpha
\]

\[
MV = (M + m')v'
\]

Where, $M$ and $m'$ are the ice mass and the equivalent mass of the pile, respectively, $V$ is the impact velocity just before contact with the pile. $P_p$ and $P_i$ are the loads exerted on the pile and the ice, respectively, and $\delta_p$ and $\alpha$ are the maximum displacements of the pile and the ice, respectively. If $K_p$ is the equivalent stiffness of the pile, $P_p = K_p \delta_p$.

According to the relationship between contact force and displacement in the general case of impact between arbitrary bodies based on Hertz's contact theory, we have

\[
P_p = P_i = P = n' \alpha^{3/2}
\]

Where,

\[
n' = \left(\frac{16}{3\pi(k_p^{1/2} + k_i^{1/2})}\right)^{1/2}, \quad k_p = \frac{1-v_p^2}{E_p}, \quad k_i = \frac{1-v_i^2}{E_i}
\]

$E$ and $v$ are Young’s modulus and Poisson’s ratio, respectively, and the subscripts $p$ and $i$ refer to the pile and the ice. Also, if $R_{pm}$ and $R_{im}$ are the principal radii of curvature of the pile
and the ice, respectively (the principal radii of curvature perpendicular to them are assumed to be ∞),

\[ C_{R}^{-1} = \frac{1}{R_{pm}} + \frac{1}{R_{in}} \]

\( s \) is a parameter that can be determined by these principal radii of curvature and the angle between normal planes containing their curvatures (Whittemore & Petrenko, 1921).


\[ f(P) = \frac{1}{2K_{p}} P^{2} + \frac{2}{5} \frac{1}{n^{2/3}} P^{5/3} - \frac{(M + m')g}{K_{p}} P - \frac{(M + m')g}{n^{2/3}} P^{2/3} - \frac{1}{2} \frac{M^{2}}{(M + m')} V^{2} = 0 \]

[5a]

If we can neglect \( m' \) in comparison to \( M \), Eq. [5a] can be shown by

\[ f'(P) = \frac{1}{2K_{p}} P^{2} + \frac{2}{5} \frac{1}{n^{2/3}} P^{5/3} - \frac{Mg}{K_{p}} P - \frac{Mg}{n^{2/3}} P^{2/3} - \frac{1}{2} MV^{2} (= E) = 0 \]

[5b]

By solving the above equation numerically, the impact load \( P \) can be obtained. In addition, if the effect of potential energy based on gravity considering the displacements of both \( \delta \) and \( \alpha \) (the second term on the left of Eq. [1]) can be neglected compared to the kinetic energy (the first term in the equation), \( P \) can be expressed by a function of only the kinetic energy just before contact with the pile \( E \) as follows.

\[ f''(P) = \frac{1}{2K_{p}} P^{2} + \frac{2}{5} \frac{1}{n^{2/3}} P^{5/3} - E = 0 \]

[5c]

Figure 8 shows the relationship between the kinetic energy values \( E \) of the ice and the reaction forces \( R \), which represent the maximum values of the sum of the reaction forces at both edges of the pile. The black circles in the figure show cases where ice floes caused brittle failure/splitting, and their pieces moved freely after impact with the structure, the red circles show cases without fracture, and the blue circles show intermediate states between two (plastic deformation or small cracks at contact point forms). The values calculated using Eq. [5c] multiplied by the constants \( (\beta = 0.035 \text{ and } 0.11) \) are also shown in the figure. In this case, the equivalent stiffness \( K_{p} \) was about 400 MN/m. From this figure, the measured values seem to roughly agree with the trends produced by the simple model when the kinetic energy is relatively small and no fracture is caused. However, as with the previous experimental data, the reaction forces were presumed to approach a constant value when the level of energy became large (or when ice floe was fractured). This trend can also be found in the numerical simulation results as described later. Figure 12 (next section) shows the effects of the ice mass and impact velocity on the reaction force.
force, respectively, using the values shown in Fig.8. Taking a broader view of the matter, the force tended to increase and seemed to approach a constant value when the ice mass and impact velocity increased, respectively. These tendencies were also the same as those in the previous results, and can also be found in the numerical simulation results described later. The mass and velocity at the time when they are expected to become constant also seem to depend on the mass and velocity of each part. In particular, according to the numerical simulation, the impact load can be expected to become constant at around 2m/s in this case (D = 0.06 m) (see Fig. 12). Additionally, because the results were one order smaller than those obtained using the simple model, energy consumption due to failure and scattering of the ice (i.e. post-impact ice fragment motion) was assumed to be dominant. Thus, when the ice causes brittle failure/splitting, and its pieces move freely after impact with the structure, especially when the ice is large in comparison to the structure, the impact load is thought to be very small, and is presumed to become a constant value when the energy reaches a certain level.

**Relationship between the impulse with the pile and the momentum of the ice mass immediately before contact**

Figure 9 shows the relationship between the impulse with the pile and the momentum of the ice mass just before contact with it. From a broader viewpoint, the impulse tended to increase with greater momentum to reach a constant value, especially when ice floes cause brittle failure/splitting. This can be also found from Figs. 6 and 8. In addition, at the same level of momentum, the impulse when ice floes cause fracture seems to be very small compared to cases without fracture. This can also be seen from the general relationship between impulse and momentum change as follows.

\[ I = \int P \, dt = \sum m_i V_i' - MV \]

Where, \( m_i \) and \( V_i' \) are the mass and velocity vectors of each ice fragment just after contact with the pile and fracturing, respectively. When the ice does not cause fracture, \( V_i' \) is thought to be close to zero. In addition, the right-hand side of Fig.9 shows the impulse (\( I \)) divided by \( MV \). Although \( I/MV \) without fracture is close to 1.0 (in fact, although \( I/MV \) is thought not to exceed 1.0, there may be measurement errors), the value with fracture becomes very small and reaches a constant value.

Thus, whether or not ice causes brittle failure/splitting and its fragments move freely after impact is presumed to be a significant factor in determining the impact load or impulse.

![Figure 9](image-url)

**Figure 9** Relationship between the impulse (\( I \)) with the pile and the momentum (\( MV \)) of the ice mass just before contact with the pile (D = 0.6 m)
5. Numerical simulation for dynamic fracture of ice using 3-D DEM

Objective of numerical simulation method development

The objective of this examination is to develop a tool that can not only clarify impact phenomena, including structural deformation, but can also provide experimental data (which are otherwise time-consuming and costly to obtain) and predict results for test conditions that are difficult to perform. We previously found that the numerical simulation using 2-D DEM would be very useful in reproducing the dynamic failure processes of ice and the response of structures to impact under simple conditions (Kioka et al., 2009). Here, we examined a numerical simulation method using 3-D DEM for application to more complicated conditions such as three dimensional ice shapes and various ice floe collision directions.

Outline of the numerical calculation method

DEM (discrete element method) analysis with inter-particle tension resistance and FEM analysis were applied to sea ice and a structure respectively. DEM has also been applied in impact failure analysis for concrete and RC structures in recent years (cf. Shimoda et al., 1994). As shown in Eqs. [6a] and [6b], this method sets up equations of motion for each element (such as spherical particles) into which the body (such as an ice floe) is subdivided. The equations are solved approximately by finite differences of the Euler-type with a short time interval ($\Delta t$) to try to analyze their dynamic behaviors as a single cluster composed of many elements. We used spherical particles to represent sea ice.

\[ m_i \frac{d^2 \mathbf{u}}{dt^2} + \sum_{j} \mathbf{f}^{ij} + F_i = 0 \]  
\[ I_i \frac{d^2 \phi}{dt^2} + \sum_{j} M^{ij} + G_i = 0 \]  

Where, \( m_i \) is the mass of each element, \( \mathbf{f}^{ij} \) is the force vector in which element \( j \) acts on element \( i \), \( F_i \) is the external force vector acting on element \( i \), \( I_i \) is the moment of inertia of element \( i \), \( M^{ij} \) is the moment of element \( j \) caused by element \( i \), \( \mathbf{u} \) is the displacement vector of each element, and \( \phi \) is the rotational displacement of each element.

As shown in Fig.10, we applied a Voigt model consisting of a spring and a dashpot for contact among the elements. We applied the Mohr-Coulomb failure criterion to the condition of fractures among elements in a tangential direction. Specifically, as shown in Eq. [7], if an
external force in a tangential direction exceeds the shear resistance \( F_{SRT} \), the bonds between the particles there are assumed to break.

\[
F_{SRT} = C + f_n \tan \phi_c = b_{xz} b_{xy} c + f_n \tan \phi_c \tag{7}
\]

Where, \( \phi_c \) and \( c \) are the angle of internal friction and the cohesion of ice, respectively, and \( f_n \) is the normal contact force between the particles. As shown in Fig.10, \( b_{xz} \) and \( b_{xy} \) are the nominal contact (bond) widths between spherical particles with radius \( r \) arranged on the \( x-z \) plane and the \( y-z \) plane, respectively, where the \( z- \) and \( y- \) axes show the collision and growth directions of the ice floe, respectively. The particles on the \( x-z \) and \( y-z \) planes are arranged to constitute regular hexagons (a staggered arrangement) and squares, respectively, in terms of their contact shape with neighboring particles.

Moreover, as a failure criterion in the normal direction, tensile failure is assumed to occur if the strain between particles at time \( t \) exceeds the threshold value \( (\beta) \) as shown in eq. [8].

\[
[D_{ij}] \geq \beta L_{ij} = \beta(r_i + r_j) \tag{8}
\]

Where \([D_{ij}]\) and \( L_{ij}(= r_i + r_j) \) are the distance between the centers of particles \((i,j)\) at time \( t \) and at zero, respectively.

### Calculation conditions

Table 1 shows the main parameters for the numerical simulations determined in this study. \( \rho \) is the density of each particle considering porosity among the particles, \( h_n \) is the damping parameter of the particles. \( k_n \) and \( k_s \) represent the stiffness in the normal and tangential directions, respectively, and the subscripts \( xz \) and \( xy \) of \( c, k_n \) and \( k_s \) represent these constants between particles on the \( x-z \) and \( x-y \) planes, respectively, as shown in Fig. 10. Thus, the values of these parameters differ according to direction when taking the anisotropic strength of ice into consideration. To select of the configuration parameters for the numerical model, we referred to typical or appropriate mechanical strengths of sea ice as initial values and adjusted them to fit the actual failure modes and impact loads. The parameters shown in Table 1 were thus determined using the results from the standard condition \((B = L = 0.6 \text{ m}, h = 1.5 \text{ m}, D = 0.06 \text{ m})\) (see Fig.5a) in the experiments. Under these conditions, while the compressive strength perpendicular to the ice growth direction was about 1.8 times that in the growth direction, the tensile strength was found to be about 0.19 as high as the compressive strength in numerical strength tests. The pile structure was modeled using FEM with 1-D beam elements (number of elements: 30), and the Newmark method was then applied to the time integration for dynamic analysis. The construction of a damping matrix was based on Rayleigh damping.

### Simulation results and verification

Figure 11 shows examples of comparison between the experimental results outlined earlier in Fig.5 and the results of numerical simulation regarding reaction forces and failure modes. The simulation results seem to agree well with the time histories of the experimental reaction forces, including the failure modes and the free vibration of the structure with relatively high
frequency after the impact. However, static deformation characteristics such as Young’s modulus were not well reproduced by the simulation method based on these calculation conditions. At this stage, it may be difficult to reproduce both the impact/dynamic characteristics and the static characteristics of ice floes, making this an area for future research. Figure 12 shows examples of comparison between the numerical simulation and experimental results regarding the change in impact (reaction) load in relation to the kinetic energy, the impact velocity and mass. The calculations were performed changing only the velocity, mass and pile diameter under conditions with the same parameters as those set in the case of the standard condition given earlier (Table 1). The simulation results agreed well with the tendencies of the experiments. In particular, the reproduction also included a reaction force approaching a constant value when the kinetic energy (or impact velocity, mass) reached a certain level. Although some problems remain, the simulation method using DEM is expected to prove very useful in impact problems with fracturing if appropriate parameters

Figure 11. Comparisons of numerical simulation and experimental results regarding the time history of impact load (reaction force) and failure mode

Figure 12. Comparisons between numerical simulation and experimental results regarding the change in impact (reaction) load relating to kinetic energy, impact velocity and mass
including the effect of ice temperature, can be provided in the future.

6. Summary

When ice causes brittle failure/splitting, and fragments move freely after impact with a structure (especially when the ice floe is large compared to the structure), the impact load or the impulse was small in comparison to cases without failure, and was presumed to become a constant value regardless of the level of the kinetic energy or the momentum.

The results of 3D DEM numerical simulation showed a close correlation with the experimental results in terms of time-series changes in impact loads and, the dynamic failure processes of ice floes. The calculated results also agreed well with the trends of the experimental results for the conditions adopted in this study, such as the relationship between the kinetic energy and the ice impact load.

References


