Calculation of Ice Abrasion Induced by Unbreakable Ice Floes using Discrete Element Method

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ABSTRACT

In this study, a calculation of ice abrasion induced by unbreakable ice floe using discrete element method (DEM) has been carried out. Under the assumption that unbreakable floes behave as rigid body, DEM was applied to simulate the interaction between a fixed structure and ice floes. In DEM simulation, individual ice floe was treated as single rigid element which interacts with each other following the given interaction rules. Interactions between the ice floes and structure were defined by soft contact and viscous Coulomb friction laws. To derive the details of the interactions in terms of interaction parameters, the finite element method (FEM) was employed. An abrasion process between a structure and an ice floe was simulated by FEM, and the parameters in DEM such as contact stiffness, contact damping coefficient, etc. were calibrated based on the FEM result. Resultantly, contact pressure and contact path length, which are the most important factors in ice abrasion prediction, were calculated from both DEM and FEM and compared with each other. The results showed good correspondence between the two results, providing superior numerical efficiency of DEM.

KEY WORDS : Ice abrasion; Unbreakable ice floe; Discrete element method; Finite element method; Contact pressure; Contact path length.

INTRODUCTION

Main factors in the calculation of ice abrasion are contact pressure, length of abrasion path and resistance to ice abrasion of particular material (Saeki et al., 1987). While evaluation of material resistance to ice abrasion requires experimental studies, an appropriate mathematical tool is needed for contact pressure and abrasion path length during service life. The joint use of both numerical model for ice abrasion load and empirical model for material resistance enables to calculate ice abrasion depth (Bekker et al., 2011).

The research on material resistance is relatively large, but the study to obtain ice abrasion load is insufficient. Since there is no standardized calculation method with regard to ice abrasion yet, it is still difficult to find an appropriate model for the calculation.

Bekker et al. (2012) developed a probabilistic macro-scopic approach on the ice-concrete abrasion process. In this model, contact force is defined by the equations predetermined by experiments and field study, and contact path length is calculated by simple equilibrium equations. Although it skips some physical representation of the ice abrasion processes and relies on many assumptions, it is evaluated as the most complete model of its kind(Jacobsen et al., 2014). Dorival et al. (2008) developed a lattice model for ice crushing against a rigid structure. The lattice model can describe ice behavior in high detail so it is expected to be suitable to implement abrasion(Tijsen, 2015). However, it is still under development for abrasion case and has a drawback that it is demanding heavy computational intensity. Consequently, it is required to develop a new calculation model reflecting the strengths of the both models.

On the other hand, the first thing to do before developing a numerical model for interaction between a structure and an ice floe is to define if the floe is treated as breakable or unbreakable. The criterion is of importance since the unbreakable ice floe can be regarded as a rigid body. In other words, it is not necessary to spend heavy computational expense on calculating internal stress of the floe different from the breakable ice floe whose failure mode such as local bending and global splitting fracture should be considered critically. In this study, a simple criterion for determination of unbreakable ice floe developed by Lindseth (2013) was employed.

This paper focuses on the numerical simulation of ice abrasion induced by unbreakable ice floe. Under the assumption that unbreakable floes behave as rigid body, it is possible to apply the discrete element method (DEM) to simulate the interaction between a structure and ice floes. In DEM simulation, individual ice floe was treated as single rigid element which interacts with each other following the given interaction rules. Interactions between the ice floes and structure were defined by soft contact and viscous Coulomb friction laws. However, when each floe is regarded as one particle in DEM there is a concern for loss of accuracy since it simplifies some physical mechanisms such as local failure mode and contact behavior. In this study, to overcome this drawback the finite element method (FEM) was employed. An abrasion process between a structure and an ice floe was simulated by FEM and the parameters in DEM such as contact stiffness, contact damping coefficient, etc. were calibrated based on the FEM result.

In this paper, efforts have been made on the numerical simulation of ice-induced abrasion using the DEM. In order to set up the interaction rule between ice and structure, the nonlinear finite element analysis was carried out in Eulerian domain. The failure of ice colliding with the fixed structure was realized using Crushable foam material model, whose detail parameters were tuned using experimental results of ice cone crushing test. Also, an example of abrasion calculation using DEM was presented based on the actual environmental condition of Gulf of Bothnia. The simulation was performed for 60 seconds, and the resulting contact pressure, path length and abrasion depth were calculated.

DISCRIPTION OF TEST CONDITION

Test conditions used in this chapter are summarized in Table 1. A target structure is Raahe lighthouse in the Gulf of Bothnia as motivated by the research of Bekker et al. (2011). Ice floes having various thickness and diameter were tested to verify the simulation results. Based on the test conditions, numerical simulations using FEM and DEM were carried out, and the results were compared with each other.

Table 1. Test conditions

Diameter of structure	7.4m
Thickness of ice floe	0.5m / 1.0m
Diameter of ice floe	2.5m / 5.0m / 10m
Ice-concrete friction coefficient	0.1
Current velocity	2.0m/sec.
Test case 1	Diameter: 2.5m / Thickness:0.5m
Test case 2	Diameter: 5.0m / Thickness:0.5m
Test case 3	Diameter: 5.0m / Thickness:1.0m
Test case 4	Diameter: 10.m / Thickness:1.0m

NUMERICAL SIMULATION OF ICE ABRASION USING FEM

FE analyses were performed to calibrate the major coefficients such as contact normal stiffness, contact damping coefficient and drag coefficient used in the DEM calculation. To investigate the difference according to the thickness and diameter of the ice floe, four different models were used considering the diameter and thickness presented in Table 1. Figure 1 shows the FE model for ice-structure collision using Coupled Eulerian-Lagrangian method. The structure was simulated using rigid elements in Lagrangian domain, and the ice floe and sea water were modeled in Eulerian domain. The failure of ice colliding with the structure was realized using Crushable foam material model, whose detail parameters were tuned using experimental results of ice cone crushing test performed by Kim et al (2015). The results of the FEM analysis are shown in Figures 2, 3 and 4. The details of the FEM analysis results are explained along with the DEM analysis results in the next chapter.

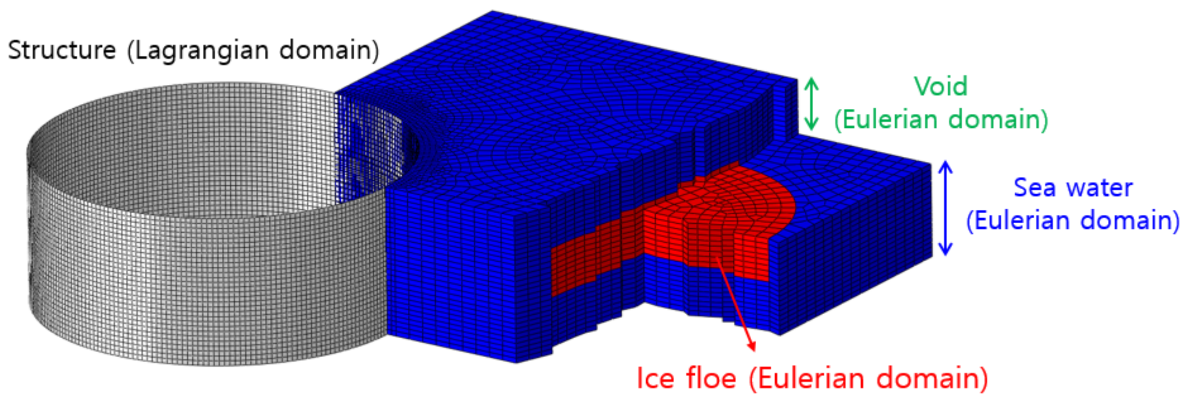


Figure 1. Ice-structure collision simulation using Coupled Eulerian-Lagrangian method

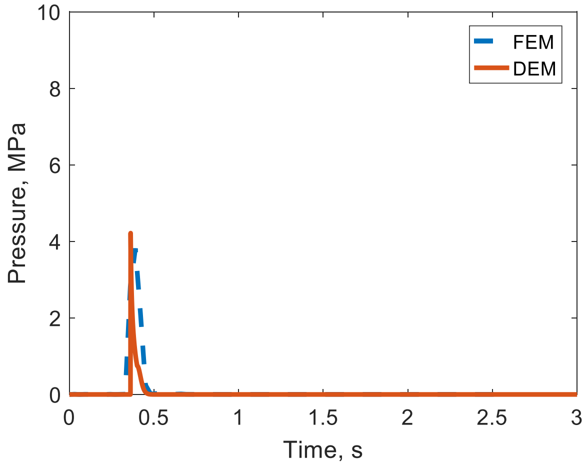
NUMERICAL SIMULATION OF ICE ABRASION USING DEM

Numerical simulation using DEM was carried out on the same conditions as FEM analysis. First, after determining the contact stiffness which has the greatest effect on the contact force, damping coefficient and drag force coefficient were adjusted to match the behavior of the ice floe obtained in the FEM as shown in Figure 2, 3 and 4. Contact stiffness was determined based on the relationship between penetration and contact force obtained from the cone shape test results by Kim et al (2015). However, since the specimen used in the cone shape test is different in shape from the ice floe and it diameter is only 10 cm, instead of applying the values obtained in the experiment directly to DEM calculation as the contact stiffness, it was determined as the value that gives the most similar result to the FEM result by changing little by little based on the experimental value. In other words, the experimental results show the contact stiffness distribution between $1.0 * 10^6$ and $4.0 * 10^6$ depending on the penetration stage, so that an optimized value was found based on that range assuming the contact stiffness of the unbreakable ice floe have a range similar to that. The contact damping coefficient is the same as the critical damping coefficient considering the plasticity of the ice. In the case of the drag force coefficient, it was adjusted so that the behaviors of particles (the change in the x and y coordinates or the duration of the collision) in DEM and FEM results match well each other. The determined major coefficients are presented in Table 2. Considering that the range of ice floe thickness distribution found in Okhosk is between 0.3m and 1.3m (Bekker, 2011), applying the coefficients obtained by case studies using the thickness 0.5m and 1.0m in this study to the whole of unbreakable ice seems to be reasonable.

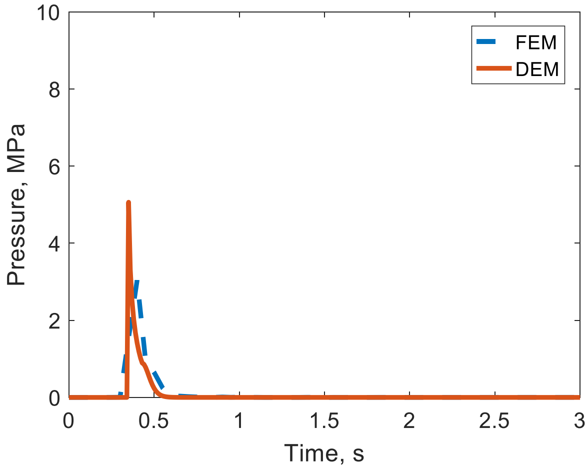
Table 2. Parameters used in DEM calculation

Contact normal stiffness (kN/m)	2000
Contact damping coefficient (kNs/m)	Critical damping coefficient
Drag force coefficient	10

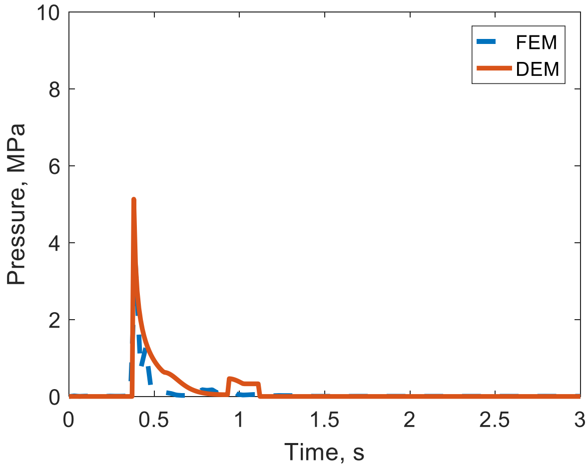
Figure 2, 3 and 4 show the comparisons of the numerical simulation results using FEM and DEM for a measuring point on the surface of a structure. In Figure 2, the changes in contact pressure over time for each case were compared. As a result, each line shows a very similar shape in both results although there is a slight difference in maximum value. In case of DEM model, since the contact area calculated at the moment of first contact is very small, the corresponding pressure shows a pointed shape at the moment. However, this does not seem to affect the overall result because it is the pressure that occurs for very short contact lengths in a very short time. In Figure 3 and 4, to compare the movement of the ice floe the changes of the coordinate with time for each case were presented. It is best to directly compare the contact lengths, but since the contact length is difficult to know in case of the FEM model, the coordinate changes of the origin of the ice floe were used for comparison. It is also reasonable because the change of the particle coordinate after contact determines the contact length. As a result, it can be said that there is small difference in Figure 3 (b) but both results showed good agreement overall.



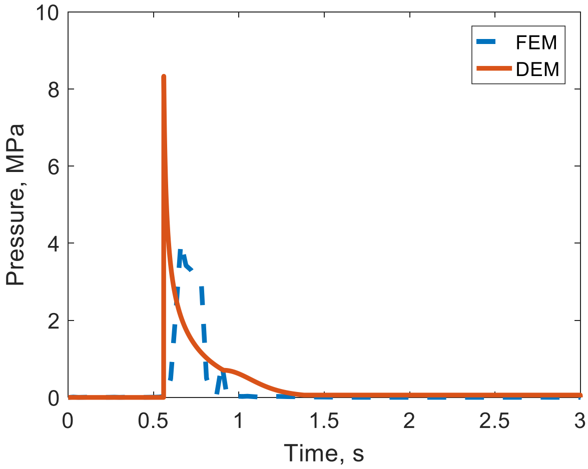
(a) Diameter: 2.5m / Thickness:0.5m



(b) Diameter: 5m / Thickness: 0.5m

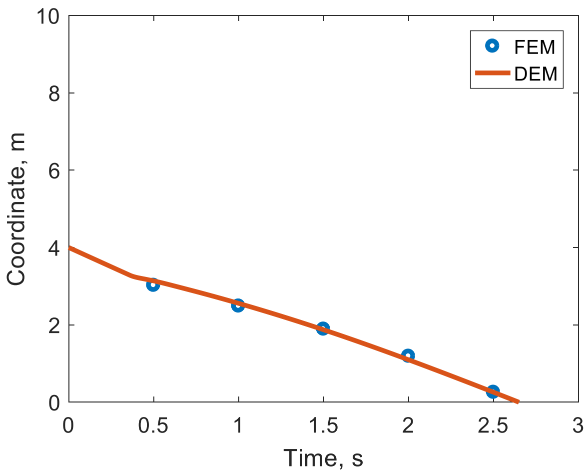


(c) Diameter: 5m / Thickness: 1m

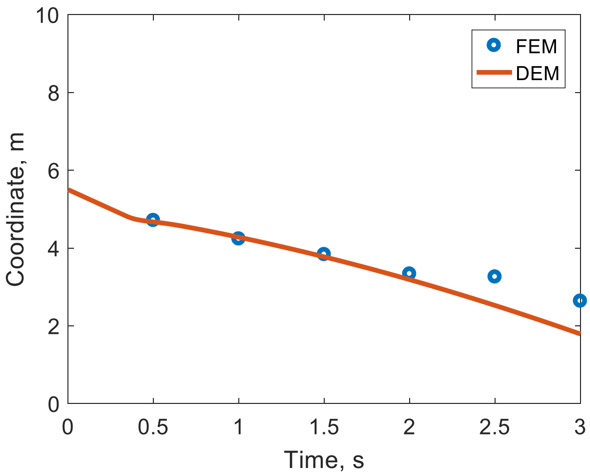


(d) Diameter: 10m / Thickness: 1m

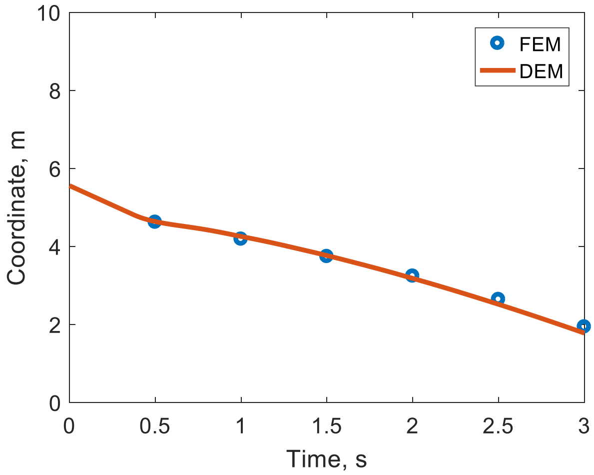
Figure 2. Comparison of contact pressures between FEM and DEM models

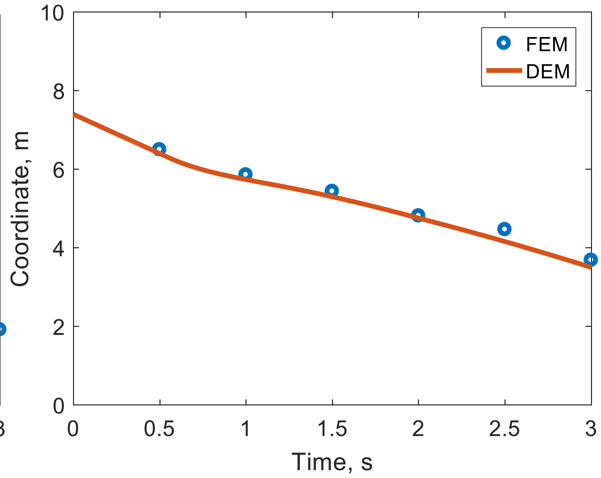


(a) Diameter: 2.5m / Thickness:0.5m



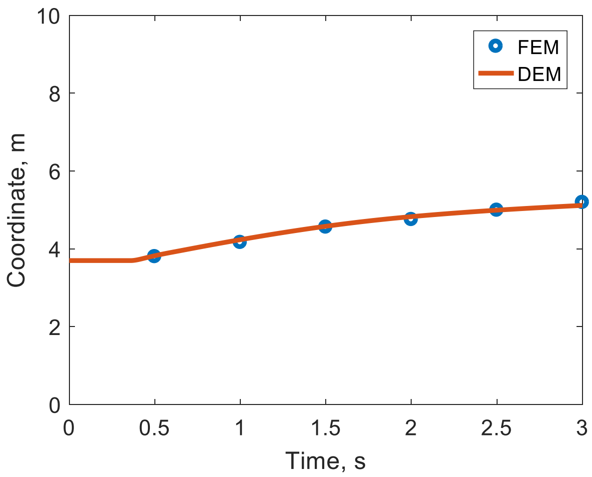
(b) Diameter: 5m / Thickness: 0.5m

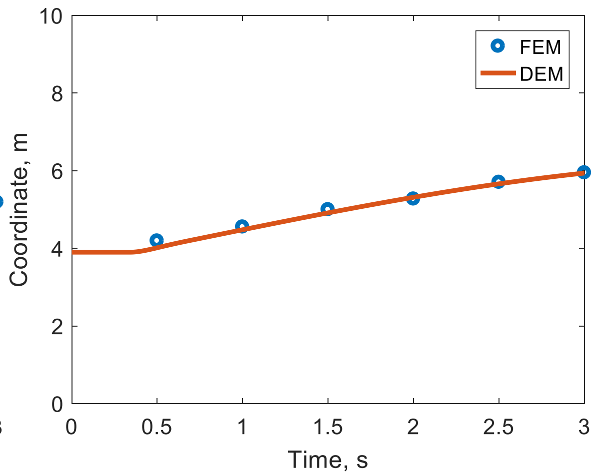




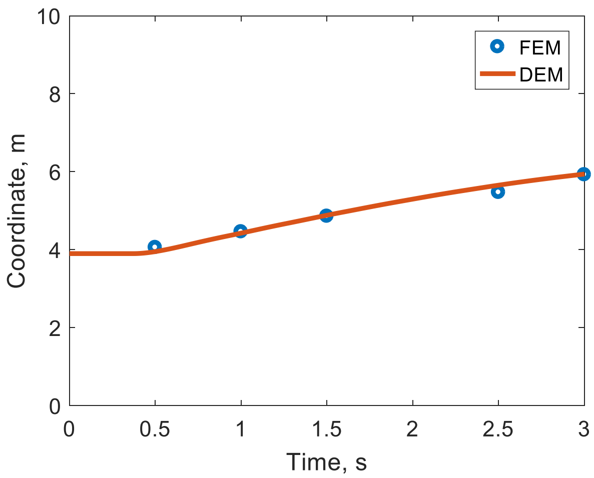
(c) Diameter: 5m / Thickness: 1m (d) Diameter: 10m / Thickness: 1m

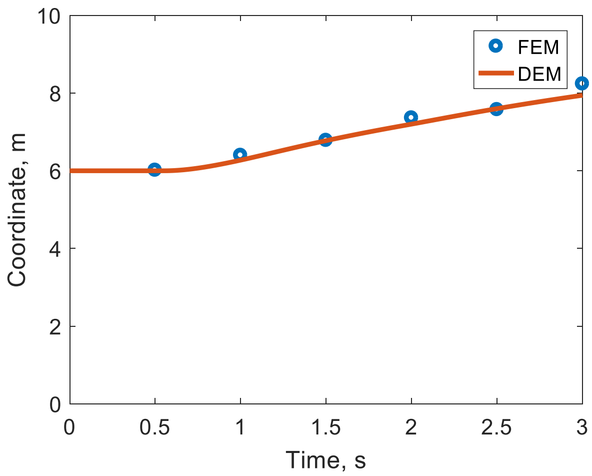
Figure 3. Comparison of ice floe movements in x-direction between FEM and DEM models





(a) Diameter: 2.5m / Thickness:0.5m (b) Diameter: 5m / Thickness: 0.5m





(c) Diameter: 5m / Thickness: 1m (d) Diameter: 10m / Thickness: 1m

Figure 4. Comparison of ice floe movements in y-direction between FEM and DEM models

EXAMPLE OF ICE ABRASION CALCULATION

In this chapter, an example of ice abrasion depth calculation using DEM is presented. Raahe lighthouse in Gulf of Bothnia was targeted, and a numerical simulation for 60 seconds was carried out based on the actual environmental conditions (Bekker, 2011) The analysis conditions are shown in Table 2. Figure 5 shows the measuring points on the surface of structure, and Figure 6 shows the initial setting of particle through random distribution. After setting measuring points on the surface of structure at 15 degree intervals, the contact pressures and the corresponding contact length at those points were calculated. Unbreakable ice floes were randomly distributed with ice concentration of 40%, which was selected for the example because it is relatively common concentration in Sakhalin offshore area. (Bekker, 2004) Considering the simulation for 60 seconds, the area was set at 120m × 100m, and no boundary was set. Figure 7 shown the relation between contact pressure and contact length measured at point 1 and point 6, where minimum and maximum abrasion depth are expected respectively. It can be observed that the middle part of the structure has a larger contact pressure and length than the edge. Abrasion rate can be obtained by substituting the contact pressures and contact lengths into Eq. (1), which was derived by the material resistance test (Bekker, 2011). Finally, the total abrasion depth is obtained by summing the product of the abrasion rate and contact length calculated at each time step. Figure 8 shows the final abrasion depth distribution for each measuring point. In actual calculations, it should include all possible concentrations, directions and current velocities. Also, the final abrasion depth should be calculated by simulation for 3 hours or more and include an appropriate statistical processing additionally.

$$\delta = 0.116 \times \left(\frac{T}{\sigma}\right)^{-1.121} \qquad (1)$$

$$D = \sum_{i}^{n} \delta_i \cdot L_i$$

where δ is the abrasion rate (mm/km). T is the temperature (°C), and σ is the contact pressure (MPa). D is the total abrasion depth (mm), and δ_i and L_i are the abrasion rate and the contact length calculated at a specific time.

Table 2. Environmental condition for DEM simulation

Diameter of structure	7.4m
Ice concentration	40%
Thickness distribution of ice floe	0.5m / 0.7m / 0.9m / 1.1m / 1.3m (Evenly distributed by one-fifth)
Diameter of ice floe	Randomly distributed between max. and min. diameter • Min. diameter: 4 × h • Max. diameter: $\sqrt{130h - 11}$ where h is the thickness of ice floe
Ice-concrete friction coefficient	0.1
Current velocity	2.0m/sec.

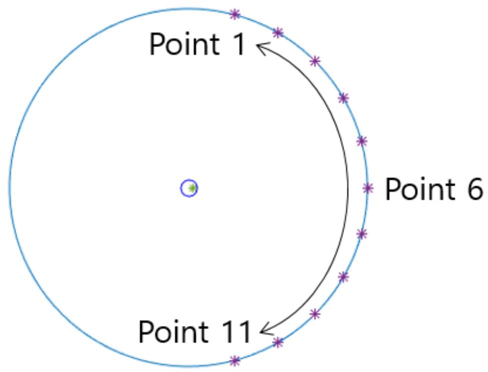


Figure 5. Measuring points

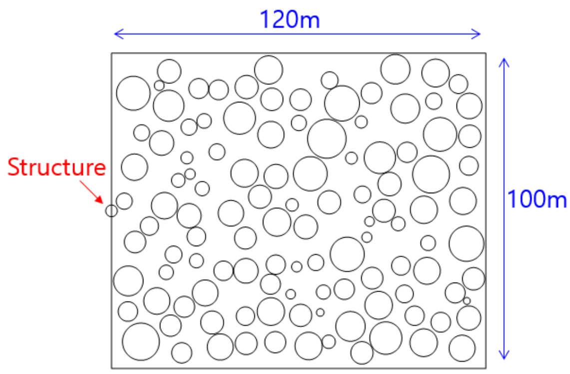
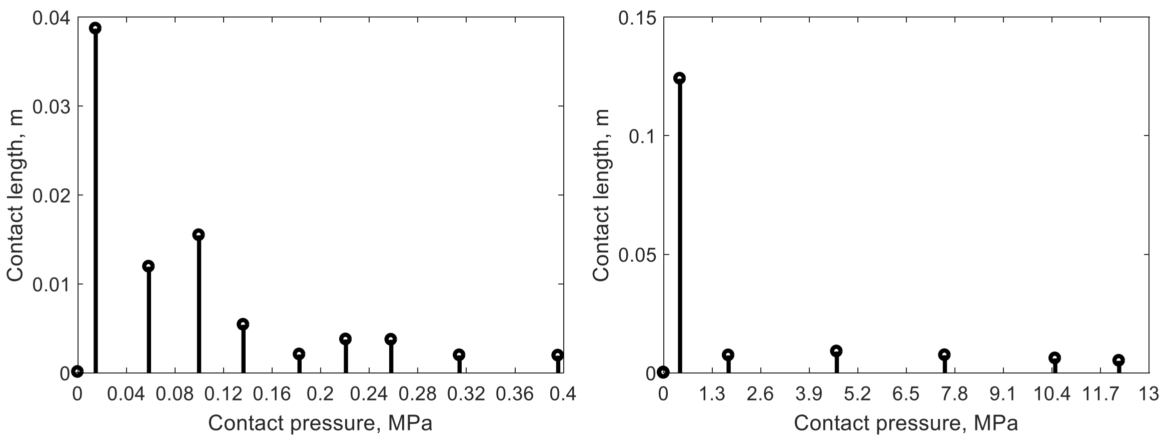


Figure 6. Initial setting of particle through random distribution (Concentration 40%)



(a) Point 1 (b) Point 6

Figure 7. Contact pressure vs. contact length

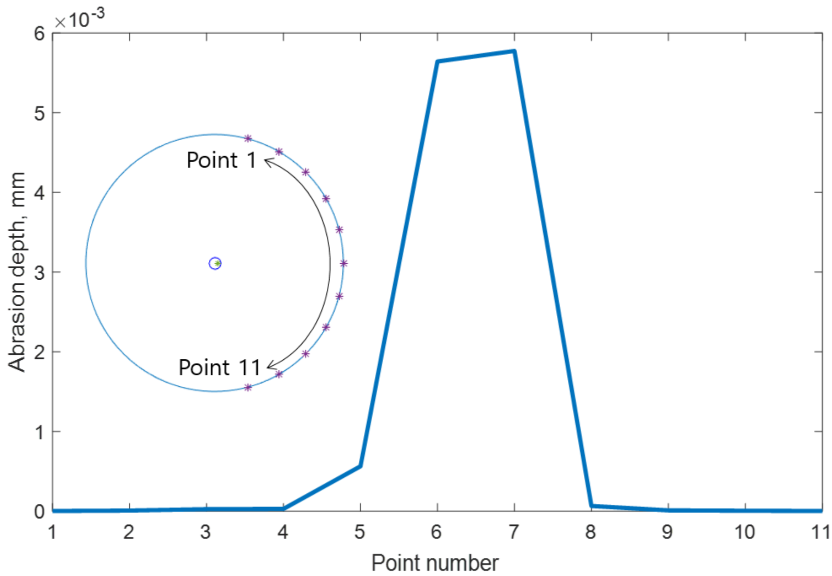


Figure 8. Ice abrasion depth calculated using DEM for 60 seconds

CONCLUSIONS

In this study, DEM was used as a numerical simulation method to calculate ice abrasion induced by unbreakable ice floes. Through the application of DEM, a rapid numerical analysis is expected, and the accuracy problem was solved by calibration with FEM results. Based on the study results described so far, the following conclusions are drawn.

- A coupled Eulerian-Lagrangian method of FEM was employed to grasp the ice abrasion processes that occur during the collision between the structure and the ice floe. The material properties of the ice were determined based on the results of recent material ice tests, and the Crushable foam model was used as the ice material model. Through this analysis, the characteristics of the contact stiffness between the structure and ice floe were found, and the result has become an important basis for the determination of various coefficient used in DEM model.
- Collision of a structure and an ice floe was simulated using DEM. The major coefficients in DEM such as contact stiffness, contact damping coefficient, and drag force coefficient were adjusted based on the pressure distribution through FEM.
- The resultant contact pressure and movement of ice floe calculated using the two methods were compared at the same conditions and locations. As a result, there is a slight difference from the maximum, but it can be said that the overall results are very similar. Also in terms of movement, although there is a little difference in one case, most of the results show good correspondence.

An example of ice abrasion depth calculation using DEM is presented in the final chapter. A numerical simulation for 60 seconds was carried out based on the actual environmental conditions, and contact pressures and the corresponding contact length at measuring points were calculated. Finally, the abrasion depth was obtained by combining contact pressures, contact lengths and material resistance test results.

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REFERENCES

Bekker, A., Uvarova, T., Pomnikov, E., 2011. Calculation of ice abrasion for the lighthouses installed in the Gulf of Bothnia, Proc. Of Port and Ocean Eng. under Arctic Conditions (POAC) Conference, Canada, pp.155-160

Bekker, A., Uvarova, T., Pomnikov, E., Shamsutdinova, G., 2012. Numerical simulation of ice abrasion on offshore structures, Proc. Of 21st IAHR International Symposium on Ice, China, pp.897-906

Bekker, A., Uvarova, B., Kim, S., 2004. Numerical simulation of the process of interaction between drifting ice fields and structure support, Proc. of The Sixth ISOPE Pacific/Asia Offshore Mechanics Symposium, 123-128

Dorival, A., Metrikine, A., Simone, A., 2008. A lattice model to simulate ice-structure interaction, International conference on offshore mechanics and arctic engineering, Estoril, pp.989-996

Jacobsen, S., Scherer, G., Schulson, E., 2015. Concrete-ice abrasion mechanics, Cement and Concrete Research 73, pp.79-95

Kim, H., Daley, C., Colbourne, B., 2015. A numerical model for ice crushing on concave surfaces, Ocean Engineering 106, 289-297

Lindseth, S., 2013. Splitting as a load releasing mechanism for a floater in ice, Norwegian University of Science and Technology, Master thesis

Saeki, H., Takeuchi, T., Yoshida, A., Asai, Y., Suenaga, E., 1987. Abrasion test for concrete due to sea ice, Proc. Of Port and Ocean Eng. under Arctic Conditions (POAC) Conference, Alaska

Tijsen, J., 2015. Experimental study on the development of abrasion at offshore concrete structures in ice conditions, Delft University of Technology, Master thesis