Modeling of Ice Impacts Using Cohesive Element Method: Influence of Element Size

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Abstract. The use of numerical methods is a promising way to solve the problem of assessing ice impacts on structures. Among such methods the finite element method is the most prevalent. In its framework the cohesive element method was used in last years for modeling the destruction of ice and good results were obtained. However, a more thorough study of this approach is required. This article is part of numerical experiments performed to study the cohesive element method for solving ice problems. In this paper, the effect of element size on the result is studied. The principles of creating a numerical model are described and several conclusions and recommendations are made on the discretization of the model into finite elements of various sizes.

1. Introduction

This paper belongs to a series of numerical experiments performed for studying the cohesive element method (CEM) for modeling the ice impacts on offshore structures. CEM in such problems is used in purpose to take into account the destruction of ice formation during interaction with structure. The general numerical method when using CEM is finite element method (FEM). This approach for modeling ice impacts was used earlier in such papers as Gürtner et al. (2009) [1], Gürtner et al. (2010) [2], Hilding et al. (2011) [3], Hilding et al. (2012) [4], Lu et al. (2012) [5], Salganik (2014) [6]. The results obtained by these authors were mixed. On the one hand, these authors obtained acceptable results in terms of the nature of the ice load. On the other hand, the magnitude of the ice impact was still significantly different from the field data. In addition, earlier studies did not take into account the temperature gradient in the ice field, and, accordingly, the inhomogeneity of its physical and mechanical properties. Also, to describe the nonlinear work of bulk ice elements during deformation, the authors used the basic Mises plasticity model, which does not take into account the influence of mean hydrostatic stress on ice strength. The disadvantages of this model when solving problems of ice impacts were described in [7]. However, the authors took into account the softening of the material upon reaching a certain stress level, which is one of the ways to take into account the effect of microcracks.

Since the finite element analysis is very influenced by mesh settings it is especially important to study different parameters of numerical model related to the finite elements. This is confirmed, for example, by research of Wang et al. (2019) [8], which showed that even a slight change in the original...
mesh leads to a change in the results. Authors of this article earlier performed the study of influence of finite element shape on modeling result. This research is published in the current FarEastCon 2020 conference proceedings. The best result from the point of general picture of destruction and ice load history showed the tetrahedral mesh case.

In this article, the question of the influence of the size of finite elements on the modeling result (the value of the ice load and the picture of destruction of the ice formation) is studied. It should be noted that earlier authors paid almost no attention to this factor, although some studies have been carried out, for example [5, 9]. In our opinion, an important factor is not only the size of the finite elements, but also their number over the thickness of the ice field. It is obvious that an increase in the number of elements in thickness increases the number of integration points and, accordingly, the accuracy of describing the inhomogeneous temperature-dependent properties of ice. However, this leads to an increase in the overall size of the model, which requires the use of more powerful computing equipment. In the process of creating a numerical model, we divided the ice field into zones with elements of various sizes to optimize the numerical model and reduce the calculation time. Thus, the main goal of this work is to study the effect of the size of finite elements on the modeling result. Based on the results obtained, several conclusions are drawn and recommendations for creating a numerical model are given.

2. Formulation of the problem

2.1 Method, loads and boundary conditions

The numerical modeling was performed in SIMULIA Abaqus software. The explicit integration method was used as main method for solving the problem. The description and features of this method can be seen in Abaqus help and our previous papers.

The applied loads and boundary conditions are the same as in our previous study of mesh settings “Modeling of ice impacts using cohesive element method: influence of element size” published in the framework of conference FarEastCon 2020. Briefly the model parameters are taken as follows:
- drift velocity – 0.5 m/s
- structure diameter – 5 m;
- ice thickness – 1 m;
- width of front face of ice field – 60 m;
- width of ice field in direction of movement – 30 m.

Buoyancy is modeled by reproducing the water pressure acting on the external faces of bulk elements using the subroutine VDLOAD created in the Fortran programming language.

2.2 Material models and calculation of ice properties

In the process of interaction with the structure, ice goes through 3 main stages: elastic deformation, plastic deformation, and fracture. Various mathematical models are used to describe the behavior of ice at all three stages, which together constitute a material model. Since the destruction of the ice field when using CEM occurs due to the removal of cohesive elements, bulk elements experience only elastic deformations, followed by an infinite plastic behavior. The Drucker-Prager criterion was used to describe the beginning of the plastic flow of bulk elements in this paper:

\[ F = t - p \tan \varphi - c = 0, \]

(1)

where \( t \) – material parameter that controls the dependence of the yield surface on the value of the intermediate principal stress;
- \( p \) – pressure stress;
- \( \varphi \) – the friction angle of the material;
- \( c \) – cohesion of material equal to shear strength of ice.

The behavior of cohesive elements in a model is relatively simple. Before failure, the deformation of this type of elements is completely elastic. When the stress values (normal or shear) reach their critical value, the cohesive element is removed from the model and the connection between the bulk
elements is destroyed. An uncoupled elastic matrix is used, i.e., normal and shear deformations of cohesive elements are independent of each other. It should be noted that the characteristics of the ice in the model are not uniform over the thickness of the ice field and depend on the temperature at each specific node of the finite element. In addition, the dependence of the strength properties on the strain rate is taken into account. It is assumed that the temperatures of the upper and lower surfaces of the ice field are respectively equal to -2 and -20 °C, and inside the ice field the temperature changes linearly. The calculation of the temperature-dependent properties of ice was carried out on the basis of empirical dependences obtained by some authors as a result of field and laboratory tests. The dependence of the elastic properties of ice (modulus of elasticity \( E \) and Poisson’s ratio \( \mu \)) on temperature is expressed by the following equations [10]:

\[
E(T) = E(T_r) \cdot (1 - a(T - T_r)), \\
\mu(T) = \mu(T_r) \cdot (1 - a(T - T_r)),
\]

where \( T_r \) – reference temperature at which the elastic constant was measured.

\( a \) – empirical factor equal to \( 1.42 \cdot 10^{-3} \) K\(^{-1}\).

These expressions were recommended by Gammon et al. [10] based on acoustic measurements of ice crystals. The values of the elastic modulus of ice and Poisson's ratio at a temperature of -16 °C are, respectively, 9.332 GPa and 0.325.

In addition, the presence of brine and its effect on the properties of sea ice were taken into account. The elastic modulus, determined by formula (2), was recalculated as follows [11]:

\[
E_{si} = E(1 - \nu_b)^4,
\]

where \( \nu_b \) – brine volume fraction.

The brine volume and ice density are also taken as temperature-dependent and are determined by the equations proposed by Cox and Weeks (1983) [12]:

\[
\nu_b = \frac{\rho_{si} s_i}{F_1(T)}, \\
\rho_{si} = (1 - \nu_a) \frac{F_1(T) \rho_i - s_i \cdot F_2(T)}{F_1(T) \rho_i - F_2(T)}, \\
\rho_i = 0.917 - 1.403 \cdot 10^{-4} T,
\]

where \( F_{1,2}(T) \) – empirical functions of temperature (more information is available in [12]);

\( \rho_{si} \) – density of sea ice, t/m\(^3\);

\( \rho_i \) – density of pure freshwater ice, t/m\(^3\);

\( s_i \) – ice salinity, %.

Bulk ice salinity is determined by the Kovacs formula (1996) [13], which is an approximating function for data compiled from numerous sources:

\[
s_i = 4,606 + \left( \frac{91,603}{h_i} \right),
\]

where \( h_i \) – ice thickness, sm.

Thus, the full set of physical and mechanical properties of ice is determined on the basis of some independent initial values – ice thickness and temperatures of the outer surfaces of the ice field. The values of the physical and mechanical properties of ice used in modeling are shown in table 1.

| Parameter | Units | Values |
|-----------|-------|--------|
| Density   | kg/m\(^3\) | 924.8-932.2 |
| Angle of internal friction | degree | 64.1-66.4 |
| Elastic modulus | MPa | 5.173-9.337 |
| Poisson’s ratio | MPa | 0.319-0.339 |
| Compressive strength (yield strength of bulk elements) | MPa | 0.426-6.527 |
| Tensile strength (cohesive elements) | MPa | 0.584 |
| Shear strength (cohesive elements) | MPa | 0.612 |
| Fracture energy (cohesive elements) | J/m\(^2\) | 67.16-302.96 |
3. Study of influence of element size

The model settings were taken from the previous studies. Ice impact simulations were performed for two cases – the coarse mesh case (figure 1 (a)) and the fine mesh case (figure 1 (b)). To optimize the calculation time, the ice field was divided into 4 zones. The first zone has a radius equal to the diameter of the structure. In the case of a coarse mesh, the minimum size of the bulk finite elements in the model is 0.25 m, and the maximum number of elements in thickness is 4. The size of finite elements increases with distance from the contact zone and is equal to 1.5 m near the side faces of the ice field.

When creating a model for fine mesh case, all dimensions and boundary conditions were preserved, but the size of the finite elements of the ice field was changed. The minimum size of the finite elements in fine mesh case is approximately 0.15 m. By thickness, the ice field is discretized into 8 elements. In the second zone (radius equal to two diameters of structure) an approximate size of the finite elements is equal to 0.3 m (4 elements in thickness). The third and fourth zones have 2 and 1 end elements in thickness, respectively, with a maximum size of about 2.2 m. This decision was made based on the destruction pattern of coarse mesh case (figure 3), namely, it is clear that zone of destroyed cohesive elements does not extend much deep into the field, when the field interacts almost over the full diameter. Thus, a more accurate description of contact with the structure was provided, and the total number of finite elements was increased by only 1.5 times.

The modeling results for the case of a coarse mesh can be found in the previous article in this series. The calculation results for both cases are presented in the table 2. The history of the load along the direction of movement is presented in the figure 3.

Figure 1. Numerical models with different element sizes: (a) coarse mesh; (b) fine mesh.

Figure 2. Fracture pattern at time 4.01 s (coarse mesh case).
Table 2. General modeling information.

| Case                         | Number of finite elements (bulk / cohesive) | Total calculation time, hours | Peak total ice force along direction of motion, MN |
|------------------------------|--------------------------------------------|-------------------------------|--------------------------------------------------|
| 0.25 m (4 elements in thickness) | 124 261 / 236 075                           | 48.63 (4.01 s out of 5)       | 10.123                                           |
| 0.15 m (8 elements in thickness) | 195 904 / 378 476                           | 141.68                        | 10.096                                           |

Figure 3. Load history with different mesh sizes (along \( x \)-axis).

The nature of the load in the cases considered is, as expected, very similar, but for the case of the fine mesh, the vibrations are smoother. Moreover, with a decrease in the size of the elements, the load has higher values throughout almost the entire interaction time. The picture of destruction in the plan is not much different from coarse mesh case. The central section of the model is shown in figure 4.

Figure 4. Central vertical section of model with 8 elements in thickness during interaction: a) at 0.01 s; b) at 0.10 s; c) at 0.25 s; d) at 0.55 s.
Noticeable improvements can be seen in the overall picture of the interaction. As in the case of a coarse mesh, at the beginning of the interaction, high compressive stresses are concentrated in the center of contact zone (figure 4 (a)). A small peak of the load that occurs in the first fractions of a second is associated with the process of deformation and growth of stresses in bulk elements. Then the first spalling occurs, and the total ice force drops to low values. A further increase in the load is associated with an increase in the contact area and, accordingly, the number of contacting elements. The inclined surfaces of destruction are now visible even more clearly (figure 4 (d)).

Also, in the process of destruction, there were moments when the destruction of the ice field did not occur along two, but along one inclined surface throughout the thickness as presented in figure 5. Such picture is associated with low strength of the lower layers, which are destroyed earlier than the rest.

**Figure 5.** Central vertical section of model with 8 elements in thickness at time 4.0 s.

4. Conclusion
As a result of the research carried out, we can say that the nature of the destruction of ice in general corresponds to the crushing failure mode in real conditions. Unequal destruction of the ice field in height during modeling is a significant factor that confirms the relevance and reliability of the applied method. Also, this nature of the destruction is contrary to Gladkov’s assumptions [13] which state that all layers of the ice field are destroyed simultaneously. This remark is important, since the current Russian and a number of foreign regulatory documents do not take into account the uneven destruction of ice in thickness, which proves the advantages of numerical modeling for solving the problems of ice impacts.

Reducing the size of finite elements did not lead to significant changes in the magnitude of the ice load, but it should be remembered that with other initial data, a different picture may be observed. Therefore, the size of the finite elements is recommended to be taken such that the total calculation time is acceptable, but there are at least 4 elements in thickness in the contact zone. When discretizing the ice field into finite elements, their size to the boundaries of the field should be increased to reduce the size of the model. It is also recommended to create a more or less detailed mesh of the ice field at a distance of 2-4 diameters of the structure from the point of contact, since in this zone the stress-strain state is formed, which mainly determines the global ice load on the structure.

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