EVOLUTION OF THE ICE BREAKING PROCESS

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The spatial problem of the stress-strain state of an ice sheet of finite thickness broken by a patented method is solved using the theory of small elastic strains and a proven numerical method.

Key words: ice sheet breaking, stress, deformation.

Introduction. Much recent attention has been paid to the development of new methods of ice breaking. In the present work, we study the stress state, deformation, and breaking of an ice sheet by a new patented method. It is found that tensile and compressive stresses can far exceed the ice strength leading only to partial breaking rather than to complete disintegration of the ice sheet.

The breaking method considered here is described in [1] and consists of the following. A container having two movable cheek plates in the center, which are initially in the closed position, is placed under ice. The side walls and bottom of the container are continuous and prevent water from rapidly filling the container. When the cheek plates are moved apart, water fills the cavity formed, but the low-pressure region is only partially filled with the liquid [2]. Therefore, a rarefied region of certain geometrical dimensions occurs under the ice, and the ice sheet begins to deform and break under the action of atmospheric pressure and the weight of ice. A spatial mathematical model for ice sheet breaking by this method was developed in [1]. The stress distribution in the ice sheet was found to depend on the geometrical parameters of the facility and the rate of separation of the cheek plates, and the form of this dependence was determined. In the calculations, the parameters of the facility are chosen so as to satisfy the condition adopted as the breaking criterion: the tensile and compressive stresses should exceed the ice strength (it was assumed that the ice sheet breaks up completely). An algorithm for analyzing the stress state of ice was developed. Later it was established that there may not be complete ice disintegration but there may be only an insignificant disruption of continuity such that the ice withstands the action of atmospheric pressure and its own weight. The initial width of the breaking region \( B \) does not exceed 1 mm, and restoration of continuity is therefore possible.

In the present work, we determined the parameters of the facility for which ice sheet breaks up completely. The investigation was performed using the spatial mathematical model of [1] but the computation algorithm was changed.

Formulation and Solution of the Problem. We solve the spatial problem of deformation of an ice sheet under the action of atmospheric pressure and the weight of ice (see [1]). Because the problem is symmetric, as in [1], we examine 1/4 of the deformation region. In solving the problem, we use the numerical scheme of [1] and, following [3], we adopt Young’s modulus \( E = (87.6 - 0.21\theta - 0.0017\theta^2) \cdot 10^2 \) MPa, Poisson’s ratio \( \nu = 0.5 + 0.003\theta \) (\( \theta > -40^\circ C \)), bulk compression coefficient \( k = (1-2\nu)/E \), shear modulus \( G = E/[2(1+\nu)] \), and ambient temperature \( \theta_1 = -30^\circ C \).

Unlike in [1], where the breaking criterion was taken to be the tensile and compressive stresses exceeding the ice strength, in the present work, the stress exceeding the breaking stress is assumed to lead only to partial ice breaking. For the calculations with the new breaking condition taken into account, the algorithm proposed in [1] is changed somewhat and has the following form.

Fig. 1. Evolution of ice breaking for ice sheets of various thicknesses: (a) $h_0 = 3$ m and $l = 9$ m; (b) $h_0 = 2$ m and $l = 5.5$ m; (c) $h_0 = 1$ m and $l = 2.3$ m; 1–5 are the breaking regions in the order of their occurrence.

1. The deformation region studied is broken into orthogonal elements (in the case considered, into rectangular elements). The matrix of the arcs of the elements is calculated.
2. Boundary conditions are specified.
3. The temperature field in each element is calculated.
4. The values of $G_n$ and $k_n$ in each element ($n$ is the element number) are calculated.
5. The matrix of the coefficients and free terms of the new equivalent system is calculated in accordance with the sequence of calculations given above.
6. The system of linear equations is solved using the standard program.
7. In each element (at its edges) $(ij)$, the values of $\sigma_{ij}$ and $u_i$ ($i,j = 1, 2, 3$) are calculated.
8. The tensile stresses $\sigma_{ii}$ ($i = 2, 3$) exceeding 1 MPa and the compressive stresses exceeding 3 MPa in absolute value (because the ice sheet is assumed to break for these values) are determined. Next, the boundary conditions are changed: at the edge of the element in which the breaking criterion is satisfied, it is assumed that $\sigma_{ii} = 0$ and operation 5 is performed. If the strength conditions are satisfied, the calculation is terminated.

**Results of Investigation.** To estimate the results obtained, it is necessary to choose stress values that will be used as the breaking criteria. Since the compressive strength of sea ice varies in the range 2–3 MPa and the tensile stress in the range 0.5–1.0 MPa [4], as the breaking criteria we choose the maximum values.

The results considered were obtained at a rate of separation of the cheeks $v = 0.5$ km/sec, which is optimal, according to the analytical formula of [4].