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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 $\nu = 0.5 + 0.003\theta$ ($\theta > -40$°C), bulk compression coefficient $k = (1-2\nu)/E$, shear modulus $G = E/[2(1+\nu)]$, and ambient temperature $\theta_1 = -30$°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.

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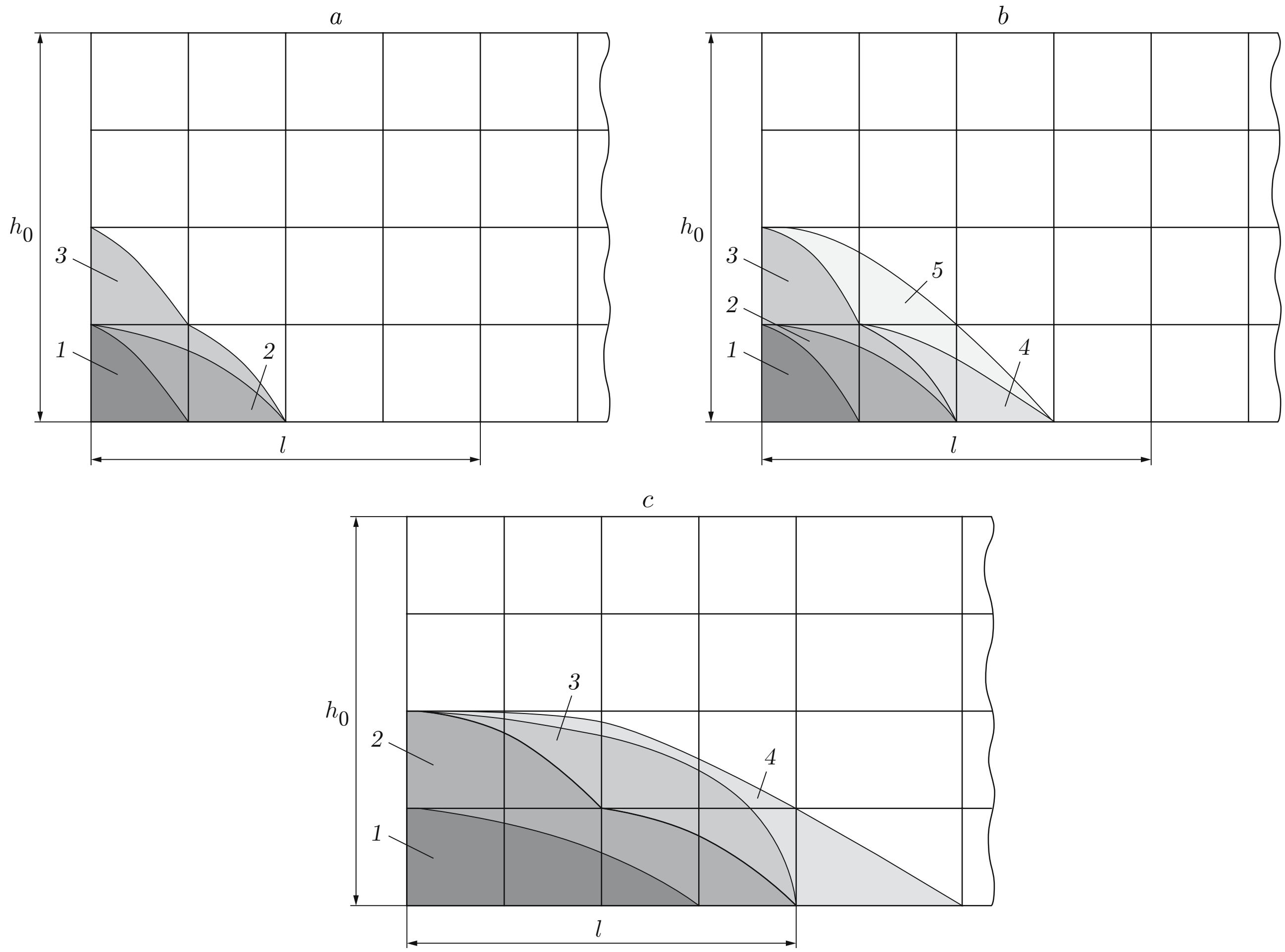

Fig. 1. Evolution of ice breaking for ice sheets of various thicknesses: (a) $h_0 = 3$ m and $l = 9$ m; (b) $h_0 = 2$ m and $l = 5.5$ m; (c) $h_0 = 1$ m and $l = 2.3$ m; 1–5 are the breaking regions in the order of their occurrence.

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 σ_{ij} and u_i $(i, j = 1, 2, 3)$ are calculated.

8. The tensile stresses σ_{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].

TABLE 1

Dimensions of the Cavity Formed in an Ice Sheet for Various Ice Thicknesses and Container Parameters

h_0, m	$2l$, m	$2b$, m	h, m	P, kN	B, mm	L, m	H, m
3.0	18.0	10.8	1.35	729.0	0.972	9.00	1.50
2.5	14.0	9.2	1.60	704.0	0.928	10.50	1.25
2.0	11.0	6.9	1.40	483.0	0.850	8.25	1.00
1.5	8.0	5.0	1.50	365.5	0.718	8.00	0.75
1.0	4.6	3.0	3.31	496.5	0.570	6.60	0.50

Note. h_0 is the thickness of the ice sheet, l is half-length of the container, b is half-width of the container, h is the height of the container, P is the pressure on the cheek, and B, L, and H are width, length, and height of the cavity, respectively.

TABLE 2

Container Parameters Leading to Complete Disintegration of Ice Sheet versus Ice Thickness

h_0, m	h, m	$2l$, m	$2b$, m
3.0	1.5	44.0	18.00
2.5	1.5	30.0	15.50
2.0	1.5	23.4	12.00
1.5	1.5	13.8	9.94
1.0	1.5	8.8	6.00
0.5	1.5	5.0	3.90

Separation of the cheek plates of the container leads to deflection of the ice sheet into the rarefaction region formed. Ice above the low-pressure cavity begins to break along the tensile stresses, but the development of the breaking does not result in complete disintegration of ice. Figure 1 shows the evolution of the initial breaking of ice sheets of various thicknesses as the cheek plates are moved apart. The occurrence and propagation of the breaking (along tensile stresses σ_{33}) occurs sequentially in the regions denoted by digits 1–5 in Fig. 1. As follows from Table 1, the initial breaking region formed in the ice sheet is small (its width $B \leqslant 1$ mm), the integrity of the ice sheet can therefore be restored.

It is reasonable to move apart the cheek plates until the container begins to rapidly dip as a result of the evolution of the breaking process. However, there is a distance between the cheek plates (we will call it the nominal length of the container) above which dipping of the container occurs. In Fig. 1 it is evident that, irrespective of the thickness of the ice sheet h_0 for the specified width of the container $2b$, the breaking region increases upward only to the size equal to $h_0/2$ and then does not vary any more as the container lengths $2l$ increases to the nominal size. Table 1 shows the dependence of the geometrical dimensions of the breaking region versus ice sheet thickness and container parameters.

From the calculations, it follows that the container width $2b$ adopted for each ice sheet thickness is insufficient for complete disintegration of ice. For the breaking process to continue, it is necessary to increase the container width. An increase in the container width will, in turn, lead to an increase in the nominal length. Table 2 gives the container parameters for which complete disintegration of the ice sheet occurs.

Let us consider in detail the evolution of the breaking process up to complete disintegration of the ice sheet (Fig. 2). In Fig. 2 it is evident that ice breaking proceeds in steps in the regions denoted by digits 1–4.

Step 1. The ice sheet begins to break along the tensile stresses σ_{33} in the plane of symmetry $x_3 = 0$ and at the tp on the periphery in the plane x_1x_2. In the center of the container, ice is deflected, and an initial cavity of width $B = 1.3$ mm, length $L = 3l/2$, and height $H = h_0/4$ is formed on the bottom along the symmetry axis (the x_3 coordinate).

Step 2. As the cheeks are moved apart, the container length increases, and breaking regions develop from bottom to top along the symmetry axis and from top to bottom on the periphery. In addition, the ice sheet begins to break along the tensile stresses σ_{22} at the bottom (the plane of symmetry $x_2 = 0$) and in the plane x_1x_3 on the periphery.

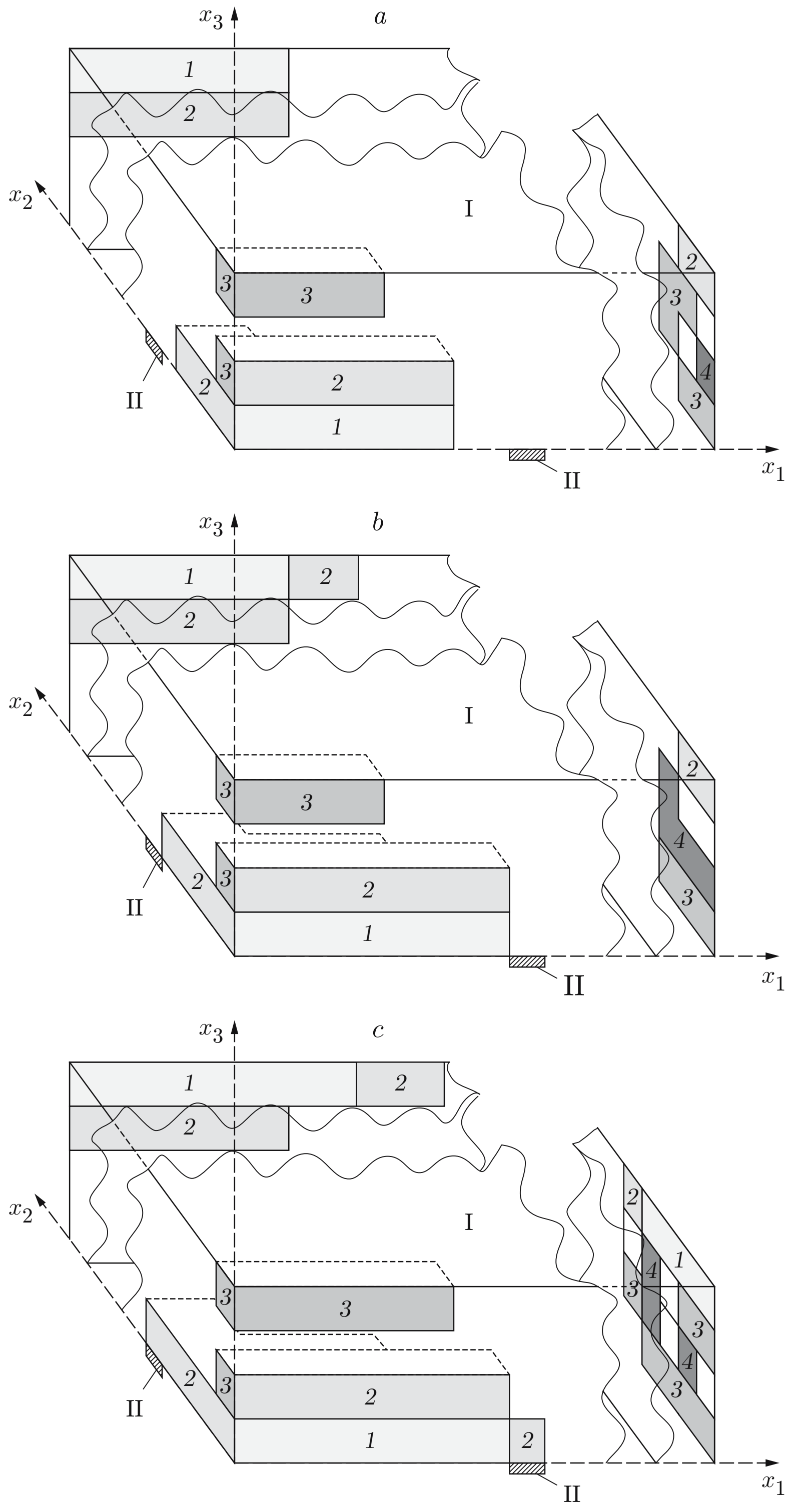

Fig. 2. Evolution of ice breaking up to complete disintegration for sheets of various thicknesses: (a) $h_0 = 3$ m and $l = 22$ m; (b) $h_0 = 2$ m and $l = 11.7$ m; (c) $h_0 = 1$ m and $l = 4.4$ m; I and II are the ice and container edge, respectively; 1–4 are the breaking region.

Step 3. As the container length increases, the cavity increases from bottom to top in the symmetry planes $x_3 = 0$ and $x_2 = 0$. Ice is deflected even more greatly, dipping together with the container and increasing the cavity on the periphery along the coordinate x_2 in the plane x_1x_3. In addition, above the container, breaking occurs along the tensile stresses $\sigma_{22} = 1.56$ MPa (in the lower part of the ice sheet), along the compressive stresses $\sigma_{33} = -4.1$ MPa (on the ice surface), and also along the compressive stresses $\sigma_{22} = -2.36$ MPa (on the ice surface).

Step 4. As the cheeks are separated to the nominal length $2l$ (see Table 2), the disruption of continuity of the ice sheet continues on the periphery and ice collapse occurs at the center. Atmospheric air rushes at great velocity toward the rarefied space, followed by a pop and a burst of the ice mass above the container.

Least-squares approximation of the calculation results yields the following formula for calculating the optimum length of the container:

$$l = 6.1419h_0\,\mathrm{e}^{-1.7045h_0/b}\,\mathrm{e}^{0.4291v/v_x}\,(\sigma_{33}/\sigma_x)^{0.5\ln(h/h_x)}.$$

Here $h \geqslant 0.5h_0$, $b \geqslant 3h_0$, $v \geqslant 0.16$ km/sec, σ [MPa] is the ice strength criterion, $v_x = 1$ km/sec is the normalizing velocity, and $\sigma_x = 1$ MPa is the normalizing stress.

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