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The response of ice cover to a load moving along a frozen channel

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ABSTRACT

Deflections and stresses in an ice cover of a frozen channel caused by a load moving with a constant speed along the channel are studied. The channel is of rectangular cross section. The ice cover is isotropic and clamped to the walls of the channel. The fluid in the channel is inviscid and incompressible. The external load is modeled by a localized smooth pressure distribution moving along the central line of the channel. The ice cover is modeled as a viscoelastic plate. Deflection of the ice and strains in the ice plate are independent of time in the coordinate system moving together with the load. The effect of the channel walls on the ice response is studied. This effect can be significant in experiments with loads moving in ice tanks. The linear hydroelastic problem is solved by using the Fourier transform along the channel and the method of normal modes across the channel. It is found that the presence of the vertical walls of the channel reduces the ice deflection but increases the elastic strains in the ice plate. The effects of the load speed, width and depth of the channel on the hydroelastic response of the ice cover are studied in detail. In contrast to the problem of a load moving on ice sheets of infinite extent, there are infinitely many critical speeds of hydroelastic waves in a frozen channel. Correspondingly, there are many values of the speeds of a moving load at which the stresses in the ice cover are amplified. The obtained deflections and strains in the canned ice cover are compared with the corresponding solutions for the infinite ice plate and with the solutions of simplified problems without account for the dynamic component of the liquid pressure. It is shown that the models of ice response without hydrodynamic component of the pressure provide correct stresses in the ice sheet only for very low speeds of the moving load.

1. Introduction

The problem of ice deflection caused by a moving load was studied in the past for an infinite ice plate (see [1] for an excellent review of available results and approaches). The load moving at a constant speed along a straight line was modelled by a point pressure or a smooth and localised distribution of external pressure. The problem was investigated within the linear theory of hydroelasticity (see [1–5]) and fully nonlinear model (see [6–10]). Transient problems of moving loads with application to the aircraft landing on ice, in particular, were studied in [11–15]. The problem of loads moving along a channel covered with ice received less attention. This problem is important because laboratory experiments with moving loads are performed in ice tanks of finite width. Newman in his recent paper “Channel wall effects in radiation–diffraction analysis” [16] wrote “Computations of wave-body interactions are usually performed for an unbounded horizontal domain, whereas experiments are performed in tanks of finite width. Reflections from the tank walls can be significant if the width is of the same order as the body length or wavelength, especially when the forward speed of the body is small or zero.” This statement is applicable to ice channels as well, as it is shown in the present paper.

The problem is also practically important for narrow water ways, such as rivers and channels, frozen bays and straits [17] Frozen rivers in northern regions can be used for transportation in winter time. We need to be sure that the ice on the river is strong enough to support a certain weight of the cargo transported at a certain speed along the ice. On the other hand, in some situations, as, for example, flooding in early spring on some northern rivers, the ice on the river should be broken and removed. In particular, severe flooding has happened on the Lena River in 2007. In early spring headwaters of the river were free from the ice, while lower part of the river was still covered with ice. This resulted in the water accumulation and the formation of a temporary water reservoir. According to the Dartmouth Flood Observatory [18]: “the May floods along the Lena and its tributaries inundated more than

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1000 houses, put 12 towns under water, damaged or destroyed 41 bridges, and affected more than 14,000 people". Another example is the flooding on the Yellow River in China in 2014 [19]. To prevent the flooding, remote frozen parts of the river were bombarded by Chinese Air Force. Twenty four bombs were dropped on the frozen river in order to free up the flow and save towns and cities upstream from flooding. The ice cover has to be broken also between two hydroelectric dams build in cascade to prevent high loads on the dam downstream due to a dam-break wave coming from upstream [20]. The dam-break wave propagates towards the edge of the ice between two dams as a free-surface wave. Then the wave is divided into two waves: a pressure wave propagating under the ice cover and a free-surface wave propagating over the cover. The resulting loads propagate further and may produce high hydrodynamic pressures on the downstream dam leading to its failure.

To break ice covers in both rivers and offshore, air-cushion vehicles or hovercraft can be used. The vehicle moves along the ice cover at a certain speed generating stresses in it which are large enough to break the ice (see [17,21–23,25]). It was shown that air-cushion vehicles can make very effective icebreakers. It is written in [21]: "The measurements of sheet deflections in the Memorial University of Newfoundland wave tank and the Institute for Marine Dynamics ice tank showed that a critical speed exists for motion over a sheet. At this speed, sheet deflections are limited only by dissipation and nonlinearities. We believe this critical speed is the source of high speed mode hovercraft icebreaking." Squire in [1], p. 200 wrote about the critical speed of hydroelastic waves: "Phase speed c has minimum, denoted by c_{min}, above which flexural-gravity waves can propagate freely and below which no such waves are generated. The minimum is associated with the critical speed v_{crit} at which deflection of the floating ice plate is greatest when a load travels by." The corresponding method of icebreaking was studied both theoretically, numerically [23,25] and experimentally [17] by Kozin and his group. In this method, so-called as "resonant method of icebreaking", air-cushion vehicle moves at a speed close to the critical speed of hydroelastic waves in the ice sheet.

Depending on environmental conditions and place on a river or offshore, where the ice have to be broken and removed, the "resonant method of icebreaking" is supplemented with some other techniques to increase the stresses in the ice. It is written in [25]: "traditional tools and technologies (icebreakers, icebreaking consoles, explosions, explosives charges, etc.) used to solve ice breaking problems often do not lead to appropriate results. Icebreakers and compounds with icebreaking prefixes are not able to destroy the ice cover on shallow water, they are not effective in destructing ice jams and ice hanging dams. One of the ways to avoid these disadvantages is to use the resonance method, which reduces energy costs compared with existing methods." The success and effectiveness of this method depend on how well the ice response can be predicted for realistic conditions, including the presence of the ice boundaries. In [17], page 23, it is reported that there is an optimum distance of the air-cushion vehicle trajectory from the sea coast, at which less energy is required to break the ice. Several experimental campaigns and sea trials are described in [17], however, not many results are reported in this book. The experiments were performed in ice tanks (see [17], pages 147–155) aiming to investigate the effect of the tank vertical walls on the breaking capacity of a load moving along the artificial ice in the tank. The experimental results were compared with numerical predictions in [25]. The water depth was 10 cm, critical load speed was reported as 1 m/s and the distance between the walls of the tank was varied from 20 to 70 cm. Dependence of the critical speed on the width of the channel was not taken into account. It was reported that the numerical results by a finite-element method are similar to the experimental results qualitatively but differ from them in magnitude due to the edge conditions at the walls. The elastic plate was loosely clamped to the walls in the experiments. Also experiments in an ice channel with a varying width and with a varying depth were performed to study landing of aircraft on ice in frozen bays and straits [17,25]. It is mentioned also that the ice thickness is a very important parameter of experiments in ice channels. For ice thickness greater than 4 mm, the presence of the vertical walls of the tank becomes important in the experiments described in [17], page 210.

A finite-element method was used in [23] to investigate the response of an ice sheet to moving loads. The hydrodynamic pressure acting on the lower surface of the ice was described by vertical modes of the channel, but the modes were not specified or explained. The linear problem of ice response was solved for each vertical mode. Calculations were performed for the ice tank of 10 m long and 4 m wide. The numerical results were compared with the results of experiments in terms of the ice deflection. The effect of the vertical walls of the channel on deflections was found to be significant. It was shown in [24] that the stresses and deflections of ice cover, which are caused by a load moving along the cover near vertical wall, strongly depend on the distance of the load trajectory from the wall.

The hydroelastic waves in a frozen channel were investigated by Daly [26] and by Steffler and Hicks [27] in the one-dimensional approximation. Three equations of mass and momentum conservation, and the ice cover response were used in linearized form. The ice cover was modelled by elastic beam. The type of connection of the ice cover to the channel walls was not included in this one-dimensional model.

To investigate the ice response in a channel for different speeds of the load, the critical speeds of the hydroelastic waves in the channel should be determined. For the one-dimensional model of ice cover in a channel [26,27] and the ice plate of infinite extent [1], there is only one dispersion relation between frequency and the length of hydroelastic wave and, correspondingly, only one critical speed. For a channel covered with ice, there are infinitely many dispersion relations and corresponding critical speeds [28]. The problem of periodic progressive hydroelastic waves propagating along the channel was studied in [28,29]. The ice cover clamped to the walls of the channel was studied in [28] and the free-free ice cover was considered in [29]. The wave frequencies of progressive hydroelastic waves and the wave profiles were determined for given wave length along the channel. The linear problem of hydroelasticity was reduced to the problem of wave profile across the channel. The problem was solved by the normal mode method. The dispersion relations and critical speeds of the propagating waves were determined. The first critical speed for the ice cover clamped to the channel walls was found to be slightly higher than that for the identical plate of infinite extent. It was concluded that strains reach their maximum at the walls for long waves and at the centre line of the channel for short waves. It was shown that the hydroelastic waves in the ice cover clamped to the walls propagate faster than for the free ice cover and are of higher frequency for the same wave length. In the present paper it will be shown that the critical speeds of the hydroelastic waves in a frozen channel help to understand and predict the response of the ice cover to a moving load depending on its speed, as it has been done for ice plate of infinite extent (see [1]).

It was observed [30,31] that flexural waves, which are caused by a vehicle moving across a thin elastic plate, occur if the speed of the vehicle exceeds the minimum $c_{\min}$ of the phase speed of elastic-gravity free waves in the plate. The plate response is approximately quasi-static for lower speeds of the vehicle. It was concluded in [31] that "The amplified response at the critical speed $V = c_{\min}$ corresponds to an accumulation of energy underneath the source, since $c_{\min}$ coincides with the group speed." Some observed features of hydroelastic waves cannot be explained within the linear elastic theory: damping of waves with distance from the source