Wave metamorphism of ice

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Abstract. The paper gives the experimental data on wave metamorphism of ice. The conclusion about the presence of wave metamorphism relies on the local hardness study of model ice sheet. Measurement results were used to obtain characteristic wave lengths. The presence of wave structures has been confirmed by independent tests with indentor, as well as by local hardness studies of full-scale river ice.

1. Introduction

It is well known that the ice is a low modulus material whose strength and rheological properties depend on the structure and texture being formed in the process of water freezing, and then these properties are constantly varying in time and space under the impact of various factors. Variability of ice properties and structure is of interest from the scientific point of view as well as solution of applied problems. There is a long story of studying the features of ice crystalline structure and its mechanical and strength properties. The influence of temperature and stresses on the form, size and mutual arrangement of crystals have been investigated in many works of ice structure science [1, 2, 3].

A.W. McReynolds was the first to notice the wave character of plastic deformations [4], while localization and intermittency of plastic deformations were examined by J.F. Bell [5]. However, stress pulses (elastic waves) at micro and macro failures have never been considered as a factor able to influence contact failure mechanics because of small energy emission. The wave character of plastic deformation remains the subject under study at present [6]. For ice as a material with a high homological temperature, close to 1, it can be expected that even under less than critical pressures the accumulation of small irreversible deformations at cycle loading will lead to noticeable changes in ice structure. There is a good prospect for these studies as evidenced by the influence of wave structures on the structure of ice in closed volume (Laval nozzle) [7, 8].

This paper investigates the space and time variations of local strength of an elastically mounted ice plate, taking into account the natural frequencies of elastic waves as one of the factors of wave metamorphism of ice. For this purpose, a series of experiments was performed to determine the local hardness of ice in longitudinal and transverse sections of ice field and cylinder indenter tests. Wave structures in ice field was investigated using an acoustic/mechanical method [7]. The obtained periodic relations of local hardness are considered from the standpoint of generating elastic waves in an ice plate on hydraulic foundation. Wave lengths and frequencies of oscillations are determined, their phase surface is constructed. Verification is done on fresh water ice of a natural water body.
2. Experimental results

The object of study is simulated ice fields of 800 m$^2$ (80 m $\times$ 10 m) prepared in the KSRC ice basin [9]. Parallelism of basin’s side walls is one of the conditions for generation of standing waves. Repeatability of wave motions will manifest itself in alteration of antinodes and nodes of standing waves where wave energy will be localized, i.e. it will be flowing from nodes to antinodes and back. The simulated salty fine-grained ice (FG type) is practical as a material because it will definitely provide a higher effect of wave structures due to low deformation modulus. Another reason why the simulated ice is chosen as an object of study is that its generation is carried out in controlled environment. The same conditions of ice formation ensure repeatability of ice structure and, correspondingly, physical and mechanical properties of ice. Natural ice fields are as a rule subject to various factors (gradients of temperatures, currents), which have unpredictable influence on ice strength characteristics.

Simulated ice was prepared by spraying cold salty water in the ice basin’s atmosphere at air temperature -20…-25º C through a special-purpose system of nozzles ensuring effective atomization of water into small droplets. Ice particles with an average diameter of 0.5 mm settled on water surface, caked and formed an ice framework similar to snow (Figure 1). Salinity of water was 13.2‰, salinity of ice was on average 6.7‰. Voids between ice grains were filled with water (filtrate), which was frozen in the process of ice cover formation. In the ice cover the secondary ice framework was formed (Figure 2).

![Figure 1. Texture of simulated ice in polarized light in 1 hour.](image1)

![Figure 2. Texture of simulated ice in polarized light in 20 hours after ice field preparation.](image2)

It should be noted that the initial round shape of ice droplets often changed in freezing and turned into angular shape more characteristic of crystal ice particles, and the size of air bubbles (black circles) decreased insignificantly, while the maximum effective diameter of formed crystallites was close to the size of frozen droplets (0.5 mm). Concurrent presence of angular and oval shapes of ice particles indicates an incomplete process of “stable” structure formation, residual deformation and possible melting of crystal edges. These features of the formed ice structure make it similar to the structure of an intermediate layer on plastic frictional contact and suitable for modeling contact failures of the ice field with structural elements.

Stiffness of bond $k$ between mobile elements of the structure was quantified by the frequency $f$ of acoustic emission signals at determination of the local ice hardness. An acoustic sensor was rigidly fitted to the indenter of hardness tester. The calculation formula relating macroscopic and microscopic properties of ice is obtained using exact analytic solutions of the harmonic oscillator model and chain model $k = 16 \pi^2 f^2 R^3 \rho$, where $R$ – radius of particles, $\rho$ – density [7]. Only the natural frequency and
size of particles were determined experimentally. Maximum stiffness corresponded to the cohesion strength of hydrogen bond in tension 15 N/m.

Traditionally recommended methods of strength evaluations suggested by the ITTC Ice committee [10] are not suitable for obtaining extensive data because of limited time and labor consuming considerations. For this reason, an express method of penetration is chosen to enable prompt and numerous measurements of sufficient accuracy. It is known from continuum mechanics that the hardness characteristics is related to the strength properties of material under study. Therefore, this approach can be employed. The hardness of simulated ice was measured by a portable penetrometer with cruciform indenter. The indenter of this shape is highly sensitive to structure because at a small middle section (2.5 cm$^2$) it has an effective surface of 72.8 cm$^2$ and contacts a large number of ice crystals. Preliminary studies showed that the indenter shape influenced the ice hardness value but had no impact on the physical character of the obtained relation. Local hardness was found by measuring the axial force $P$, which acts on the indenter of middle section $S = 2.5$ cm$^2$ and was calculated by formula $\sigma = \frac{P}{S}$ with measurement error of the axial force 5%.

Several fields of simulated ice with different mechanical properties and thickness were studied. In the experiments the ice hardness was measured in a few sections across and along the basin. Table 1 shows the measurements results along the basin and Figure 3 across the basin.

![Figure 3. Hardness measurements across basin](image)

Measurements along and across the ice field have shown that experimental relations are periodic functions characteristic of the wave process, which let us assume its wave nature. The large number of measurement points (135 measurements on 80m) enabled their approximate description by sine function. It let us identify characteristic wave lengths (2 and 5 m across the basin, 2 and 40 m along the basin). A wavelength of 2 m corresponds to the longitudinal wave whose mechanism of generation is apparently due to resonance oscillation of ice field. Comparison of experimental relations for local hardness versus measurement points obtained across the basin at different lengths leads to the
conclusion that the node line planes are parallel to basin side walls. This experimental fact is also confirmed by generation of the standing wave between the basin side walls.

**Table 1.** Local hardness measurements $\sigma$ of simulated ice across and along the basin

| Coordinates of measurement point across basin, m | Time interval between ice preparation and measurement, hour | Number of measurement points | Average hardness $\sigma$, kPa | RMS error, kPa | Minimum hardness, kPa | Maximum hardness, kPa | Relative variation, % |
|-------------------------------------------------|-------------------------------------------------------------|------------------------------|--------------------------------|----------------|----------------------|----------------------|---------------------|
| 25                                              | 1                                                           | 27                           | 24                             | 3              | 20                   | 32                   | 50                  |
| 25                                              | 20                                                          | 32                           | 40                             | 6              | 26                   | 56                   | 74                  |
| 55                                              | 1                                                           | 18                           | 24                             | 2              | 21                   | 27                   | 25                  |
| 55                                              | 20                                                          | 27                           | 30                             | 5              | 21                   | 46                   | 103                 |
| 20                                              | 20                                                          | 21                           | 36                             | 7              | 25                   | 52                   | 75                  |
| 40                                              | 20                                                          | 21                           | 40                             | 6              | 27                   | 49                   | 54                  |
| Profile along basin [11]                        | 1                                                           | 69                           | 23                             | 4              | 11                   | 30                   | 83                  |
| Profile along basin [11]                        | 20                                                          | 66                           | 49                             | 11             | 24                   | 75                   | 106                 |

3. Discussion of results
First, the wave sources related to ice preparation technology were considered, which could lead to bending gravity waves in ice fields. In accordance with the FG ice preparation technology the water was sprayed from a device mounted on the auxiliary carriage. Radiation of oscillations caused by motion of the carriage back and forth along the guides was considered as one of possible sources. Another source could be settling of ice grains on the forming ice field. This settling of ice grains gives an effect of load moving over an ice field. It is quite plausible to consider these as sources of waves in the basin.

For testing this assumption, a study of ice hardness distribution along the basin axis was undertaken in 1 hour after completing all technological procedures of ice preparation. Then, the same study was performed next day, in 20 hours after completion of ice preparation. Over this time the air temperature in ice basin was maintained constant, equal to $-6^\circ$ C, and no technological action was applied to ice field. The next series of local hardness measurement was done with the measurement points as close as possible to the points of measurement in the preceding day. The measurement results are shown in Figure 2 and Table 1. Analysis of these data reveals that after 20-hour exposure the ice hardness increased. Also, there were significant change in variations of hardness values. Experimental relations of hardness versus time became vividly periodic.

From comparison of experimental curves, it follows that technological processes do not have dominating influence on the local ice field hardness. Apparently, the source of waves is located in the ice field itself. Possibly, the plastic deformation of growing ice crystals and water freezing in shaping the ice framework may be such a source. This assumption does not contradict the known facts of acoustic and electromagnetic emission records done in phase transitions of water [12,13] and formation of the secondary structure of simulated ice (Figure 1, b).
It should be noted that the amplitude of experimental curves of local ice hardness is periodically varying in the interval of 24 kPa to 75 kPa along the basin and 25 kPa to 56 kPa across the basin. The variation interval of measured value is 240-300%. It is much higher than variations of axial force measurements equal to 5-7%. The fact of standing wave generation as “frozen” textures of ice field is also indirectly confirmed by the evidence that variations of local hardness on experimental relations of hardness versus measurement point coordinates along and across the basin are located in planes parallel to the basin side walls. All this allows us to consider the alterations of maxima and minima of local hardness (Figure 3) as the results of standing wave influence on the ice structure.

In principle, the wave structures in ice field can be found from the ice resistance to cutting it with a vertically oriented indenter moving along the basin. Since the ice field strength in antinodes and nodes will be different, then alterations of the resistance force can be regarded as confirmation of wave structures. The experiments of cutting the ice field with a 30 mm indenter were carried out. These are standard tests in ice basins to find the crushing strength of ice [10]. Figures 4, 5 show the results of two test series with indenter. The experiment presented in Figure 4 was done in 69 mm thick ice cover, the cutting rate was 0.6 m/s and the middle section was 20.7 cm². The data were approximated with a sine curve (wavelength 2.6 m), which is shown by dotted line. In the next experiment (Figure 5) the indenter was cutting 44 mm ice at 0.01 m/s rate and the middle section was 13.2 cm². The experimental data were sufficient for evaluation of the wavelength of low frequency oscillations by two maximum peaks, more so that the minimum value of ice hardness was approximately between these two peaks. The wavelength is estimated at 3.26 m, taking account of the cutting rate. The results obtained in these cutting tests has qualitatively confirmed that the process going on in ice is periodic, but their interpretation is too complicated because of compacting and accretion effects, as well as inherent vibrations and impact of these vibrations on measurement results. It should be noted that the measurement results essentially depend on the deformation rate and middle section.

The hardness of secondary ice textures recorded in the experiments is apparently the result of dynamic metamorphism, which occurs under the action of standing wave system formed in the ice field. The minimum hardness values correspond to antinodes of the standing wave because it is there that the defects are accumulated, dynamic viscosity is reduced and ice hardness decreases due to maximum displacement of ice particles. It is known in the fracture mechanics that accumulation of defects leads to reduction in strength. Ref. [14] describes similar processes going on when ice samples are compressed and relieved, as well as a cantilever ice beam is bent and relieved. In nodes of standing wave, the displacements and deformation rate are minimum, and, therefore, the hardness value is maximum. The local ice hardness (oscillating hardness) is respectively a mirror image of the displacement phase surface (projection of speed) in the standing wave. Thus, each of the measured

![Figure 4. Results of ice cutting tests with cylinder (blunt) indenters of various middle sections 20,7 cm² and cutting rates 0.6 m/s.](image)

![Figure 5. Results of ice cutting tests with cylinder (blunt) indenters of various middle sections 13,2 cm² and cutting rates 0.01 m/s.](image)
hardness values is a replica of texture being formed under more or less influence of the standing wave. Figure 6 shows stationary periodic wave structures in the ice field under study at interferences of waves with wave lengths of 5 and 40 m.

Figure 6. Stationary periodic wave structures in the ice field under study at interferences of waves with wave lengths of 5 and 40 m.

The secondary texture of simulated ice is formed under combined actions of wave fields and residual stresses. Oscillations of local ice hardness is a mirror image of phase surface of amplitude (projection of speed) of the standing wave. For a plane standing wave the oscillation amplitude is calculated according to a well-known equation \( \chi = A_0 \cos \left( \frac{\pi m}{a} \right) \cos \left( \frac{\pi n}{b} \right) \), where \( m, n \) – number of oscillations along \( a = 80 \) m and across \( b = 10 \) m the ice field \( (m, n = 1, 2, 3...\infty; m = n \neq 0) \) [15].

Figure 4 is plotted by experimental data and reflects the main laws of local hardness distributions in simulated ice. The surface of ice field local hardness is not monochromatic. The bending gravity waves (\( \lambda = 5 \) m and 40 m) shown in the figure are modulated oscillations for waves with shorter wave lengths, e.g. for wave lengths \( \approx 2 \) to 3 m (quasi-longitudinal). The real phase surface has a fine structure depending on the conditions of ice field shaping, in particular at their contact with walls of the basin.

Thus, during preparation of model ice in a rectangular ice basin of 800 m\(^2\) the stationary periodic wave structure is arising, which forms the secondary texture of ice and, as a consequence, it changes the ice strength characteristics. The standing wave effect is enhanced by residual stresses arising in the ice field formation process, including stresses induced by water crystallization within the initial ice framework constrained by basin side walls. Secondary textures of simulated ice are formed under the influence of wave structure and governed by ice compressibility, ice field geometry and conditions at the ice contact with basin walls. Dominating influence on development of the standing wave system is exerted by the internal source, i.e. coherent radiation of elastic waves at water freezing.

Possibilities of extending the results obtained in the ice basin to other water bodies with natural ice are considered in Ref. [10]. For measurements the water channel with almost parallel banks was chosen to consider the river ice cover as an ice field frozen to parallel side walls. The local hardness measurements across this field of 0.48 m thickness qualitatively confirm the data obtained in the above experiments. The experimental curve vividly shows periodical alterations of local hardness maxima and minima with variations of \( \approx 55\% \).

Qualitatively, the obtained results are supported by the data of Ref. [15]. In this work during full-scale investigations in Peter the Great Bay (Sea of Japan) the alterations of compressive high-strength and low-strength zones of ice cover were found. Authors without giving an explanation for these alterations introduced a coefficient of non-uniformity, which is a ratio between average and maximum strength to axial compression. According to experimental data this coefficient is equal to 0.75, which coincides with the calculation of this coefficient by data obtained for the river ice [10]. The said conditions suggest that the variability of strength characteristics of natural ice, namely alteration of different strength zones, may be the result of wave structure influence on ice.
4. Conclusion
The variability of the local hardness in space and time of an ice plate lying on an elastic foundation and frozen to the basin walls from three sides has been investigated. The ice hardness was determined locally in the longitudinal and transverse profiles of the ice field using indentation and in the longitudinal profiles by cutting it with a cylindrical indenter. Local dependences of ice hardness on measurement points across and along the basin, obtained in a series of experiments, are looking like stationary wave structures. Data from other independent tests of cutting ice plates also confirm the wave character of the experimental dependences.

One of the possible explanations for the variability of the local hardness of the ice plate in space and time is the assumption of wave metamorphism of ice. In the case under consideration, the wave metamorphism of ice is considered as a set of thermodynamic processes occurring under the combined action of temperature, normal and shear stresses, which are created by the interference of waves under lateral constraint conditions. The wave metamorphism happens at a mixed type of excitation. A dominating source of elastic waves in ice field at no external influences (industrial or seismic vibrations) is coherent radiation in the ice itself related to phase transition processes. The obtained data is verified by observations of stationary periodic wave structures in natural ice.

The results discussed in this work can be used in evaluation of ice loads on offshore floaters and fixed-type platforms, development of effective hull design technologies for icebreakers and ice-going vessels, as well as for better insight into ice movements in bottom layers of glaciers. In addition, the identified effects are of methodological interest in the analysis of model test data from ice basins.

This study was supported by the Russian Foundation for Basic Research, project no. 20-01-00649_a.

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