Generation and evolution of model ice texture peculiarities

Viktor P. Epivanov[1], Kirill E. Sazonov[2,3]
[1] Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences, Moscow, Russian Federation
[2] Krylov State Research Centre, St. Petersburg, Russian Federation
[3] Saint-Petersburg State Marine Technical University, St. Petersburg, Russian Federation

ABSTRACT

This paper discusses generation and further evolution of model ice structure taking the effect of waves upon local ice strength as a case study. Structure and strength of model ice directly in-situ was investigated as per the newly developed acoustic & mechanical method for determination of local ice hardness. The study was performed on a model ice sheet at KSRC Ice Basin. The results of local hardness measurements in both longitudinal and transverse profiles of ice sheet yielded phase surface of stationary periodic wave structures with the difference in local ice hardness at nodes and anti-nodes as high as 40%. Greater plasticity of sea ice under cyclic straining due to periodical wave structures in the ice sheet is explained by dynamic metamorphism of ice. The findings of this study have been confirmed by the laws of ice mechanics under cyclic loads, e.g. bending tests of ice beams and compressed ice creep, as well as by the full-scale data obtained for the ice cover on a body of fresh water. The results of this work may be used to estimate the effect of wave processes upon the formation of intermediate ice layers during contact failure and in bottom layers of glaciers. These results have practical significance, because the consideration of wave effects aid ice load assessments for floating and fixed marine platforms.

KEY WORDS: Wave; Ice properties; Local ice hardness; Model ice; Indenter penetration.

INTRODUCTION

The physical properties of ice cover on seas and oceans are characterized by a high degree of variability in space and time. This specific feature of ice cover has been repeatedly addressed by the researchers (Mironov, 2004; Frolov at al., 2011). Main attention was paid to studying the seasonal variability as well as large-scale spatial variability, and average strength and physical characteristics were compared for various seas. Variability of meteorological and hydrological processes are usually named as an explanation of the ice variability phenomenon, which have significant impact on the setting and melting of ice cover as well as on its evolution during the ice lifetime.

Another factor that may, in the opinion of some researchers, have considerable influence on variability of ice properties is mechanical impacts. The main source of mechanical impacts are ice drift non-uniformities leading to local ice pressure zones. In the drift or fast ice edge zone, a wide range of wave and oscillation processes in the ice-water system give rise to deformations and stresses. Elastic waves generated due to these processes may penetrate into the depth of ice cover depending on the concentration, thickness and other factors.

A number of studies on fast ice formed in approximately similar conditions show that ice mechanical properties noticeably vary within comparatively small ice area (Alekseev et al., 2001; Bekker et al., 2017). It seems that the variability within relatively small-scale areas cannot be put down to meteorological and hydrological influences. At quite a long distance from the ice edge the wave influences can also be ignored. Therefore, it is of interest to investigate possible mechanisms of such variability.

The purpose of this work is to study the influence of wave processes on the strength of natural ice under compression based on the identification of signs describing repeatability of wave motions and results of these motions. The concept of investigation is that for various reasons there are natural oscillations in the ice field under stressed state. Running waves of small amplitude cannot induce significant changes in the ice structure, and, correspondingly, influence its strength properties. However, when standing waves are formed in ice field, their action may translate into forming of the secondary ice texture with a periodically repeated plasticity changes in the areas corresponding to nodes and antinodes. Indicators of wave processes are secondary textures of ice, which have higher plasticity and can be determined experimentally, e.g. by local hardness measurements in sufficient number of points in the rectangular coordinate system.

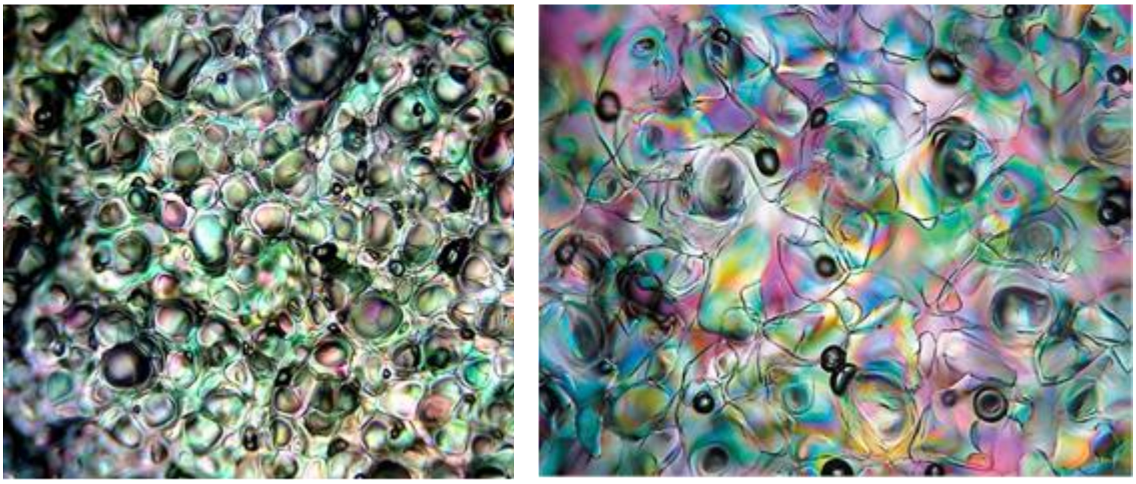
In its statement the presented investigation applies an approach different from the traditional studies of wave processes in ice cover: it focuses on the result of periodic wave structure influences on ice strength characteristics. The traditional studies usually deal with the generation and propagation of bending gravitational waves in ice induced by external influences of various objects or dynamic processes on ice field, and involve complicated problems of hydro-elasticity with multiple assumptions.

OBJECT AND METHOD OF INVESTIGATION

The study examined ice sheets of 800 m^2 (80×10 m^2) that were made in the KSRC ice basin (Dobrodeev et al., 2015). For the ice sheet of a rectangular prism shape the wave motions are manifested as periodic secondary textures of ice corresponding to alternating antinodes and nodes of standing waves.

The model ice was prepared by spraying of cold salty water in the ice basin atmosphere at an air temperature between -20 …-25º C through a special system of nozzles providing effective atomization of water into small droplets. Ice particles of 0.5 mm were settling on water surface and agglomerated into the ice framework, like snow. Water salinity was 13.2‰, average ice salinity was 6.7‰. In the process of ice cover making the voids formed by agglomerated ice grains were filled with salt water. When this water was frozen the secondary ice framework was formed. The model ice of FG type was chosen because of its low modulus of deformation, which inherently maximized the effect of elastic wave influence on its strength. In addition, the FG type ice is practical in modeling the influence of natural ice on structures (Dobrodeev et al., 2015). Also, the ice cover is formed in approximately similar conditions, which excludes the influence of other factors that could have affected the investigated parameters.

Fig. 1 shows the results of microscopic investigations of the model ice. Thin sections of ice were studied directly on site immediately after seeding (Fig. 1a) and 20 hours after formation of the ice sheet (Fig. 1b). Maximum effective diameter of ice droplets and crystal grains is 0.5 mm. Air bubble inclusions in the chilled ice mass have other than round shape, which indirectly indicates local residual stresses arising in formation of the model ice secondary texture.



a) b)

Figure 1. Model ice texture in polarized light; maximum effective diameter of crystal grains - 0.5 mm: a – one hour after ice sheet is made; b –20 hours after ice sheet in made

Investigations of thin ice sections directly on site as the ice sheet was prepared have revealed that formation of the ice framework is accompanied with water freezing between ice grains. Freezing of water in a closed volume creates stresses in the ice sheet, which induce plastic deformations, radiation of coherent oscillations (Kuznetsov et al., 2008), and change conditions at ice contact with basin walls.

Measurements of local hardness conducted 1 hour after model ice sheet preparation (curve 2 in Fig. 2) have shown that the ice hardness have reached its half value. Further agglomeration of frozen water droplets and ice metamorphism progressed without influence of external factors, e.g. technological vibrations or moving load. It let us suppose that the source of oscillations is inside the ice sheet. This source seems to be coherent radiation of elastic waves after the water is frozen, i.e. the ice sheet itself (Shibkov et al., 2001).

The requisite conditions for wave structure formation in ice field are its stressed state and the standing wave formation, while the sufficient conditions are hardness of ice framework able to retain deformation changes of ice structure and a strong adhesive contact with the basin walls providing constant conditions for reflection of running wave. These conditions are interrelated. Hardness of ice framework and degree of its freezing to the basin walls determine the efficiency of wave structure influence on the local hardness and strength of ice.

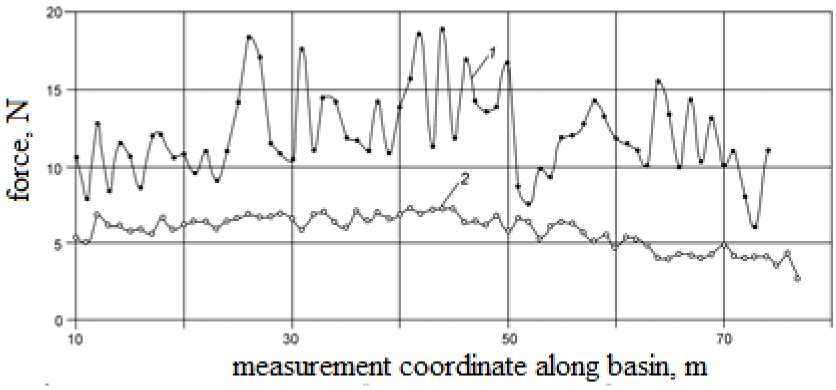


Figure 2. Resistance of salt ice to indenter penetration versus measurement coordinates:
1 – 20 hours after seeding; 2 – 1 hour after seeding. (measurement coordinate along basin, m)

Traditional methods for determination of strength properties recommended by the ITTC Ice Committee are not suitable for the task because of too much effort required for multiple measurements. For this reason, the penetration method was chosen to study the ice strength properties. The penetration technique is a prompt method capable of measuring the local hardness of ice in the basin and take a large number of such measurements. It is well known from continuum mechanics that hardness characteristics are related to the strength characteristics of materials under considerations. Therefore, this method can be applied.

The hardness of modeled ice was measured with a portable penetrometer (Fig. 3) equipped with replaceable indenters (Fig. 4).

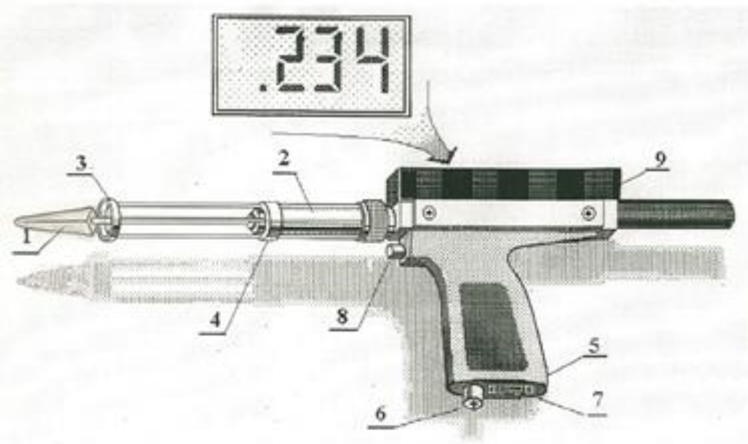


Figure 3. Portable tool (penetrometer) for hardness measurement:
1 – indenter, 2 – barrel, 3 – back-up washer, 4 – stopper, 5 – handle,
6 – latch pin, 7 – power switch, 8 – pull-off, 9 – case.

The penetrometer has the following specifications. Electric impulse measurement error is 5 %. Repeatability of measured result in homogeneous material is 1 %. Measurement time is 2–3 seconds. Mass is 2 kg. Min. working temperature is –20 °C.

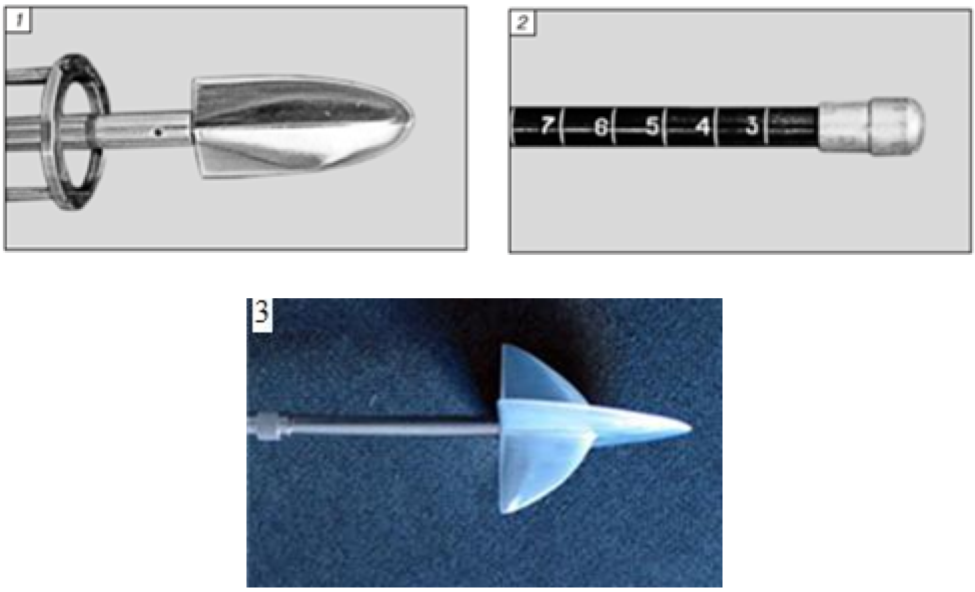
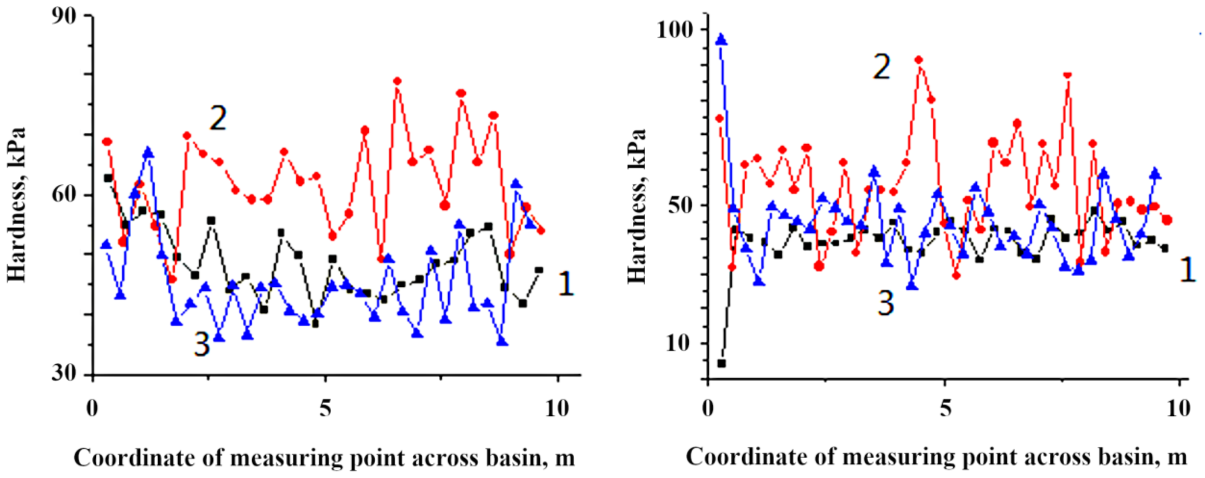


Figure 4. Replaceable indenters: 1 – double-edge knife, 2 – blunt end, 3 – cruciform

Cruciform indenter has a working surface of 72.8 cm^2 with a small middle section (2.5 cm^2) and measures contacts with a large number of ice crystals, therefore, it is highly sensitive to ice structure. Hardness of ice framework σS is found from the equation σS = RS/S, where RS – force applied to indenter, N; S – area of indenter middle section, m^2. The area of double-edge middle section is S = 0.87 cm^2. The middle section of the blunt indenter is about 1 cm^2.

Model ice response to indenter penetration is determined by the sum of contributions from compression, crushing, cracking, friction and hole widening. Contribution from each of the processes can be regulated, e.g. by changing the indenter shape and penetration rate. The initial penetration rate determined in the preliminary experiments for the section with flattened curve of stress-penetration rate (~0.6 m/s) was reached by calibration of the spring and fixing of distance from the barrel end to the ice cover. If the indenter has a blunt shape it first forms a compression nucleus and then a cone of compaction (Kolesnikov, Morozov, 2012). The measured value is respectively characterizing to a large extent these processes rather than ice framework properties.

In the double-edge indenter case the mechanism is quite different. Particles from the ice framework are pressed out from the indenter and no plug is formed (Zukas et al., 1982). The measured value is respectively characterizing to a large extent the strength properties of ice framework rather than compacting and displacement of compacting cone. The cruciform indenter may be used to assess anisotropy of structural and mechanical properties of ice, stressed state of ice field and friction. This investigation focuses on the physical and mechanical properties of ice framework that play a key role; therefore, the cruciform indenter is chosen in the form of shifted double-edge knives crossing at right angles. Preliminary experiments (Fig. 5) showed that this form of indenters provides sufficient sensitivity to physical processes at contact damage to the ice framework and let us reveal the dominating mechanism (damage, crushing, friction), as well as justifies fitness of the penetration method not only for assessment of ice hardness but also for qualitative assessment of its structure properties.



a

b

Figure 5. Dependence of model ice resistance force on the coordinate of measurement point in the longitudinal ice sheet profile at 26 meters (a) and at 56 meters (b) for different indenter shape: 1 – cruciform (black squares), 2 – blunt (red circles), 3 – double-edge (blue triangles)

RESULTS AND DISCUSSIONS

For the purpose of investigation, a number of model ice sheets were studied, which had different mechanical properties and thickness. Local hardness of ice was measured in several sections across and along the basin. The obtained data were published in Ref. [Epifanov, Sazonov, 2019; Epifanov, Sazonov, 2020]. Typical dependence of ice local hardness on measurement point coordinates across and along the ice basin is presented by periodic curves. Hardness variations are 43±2% in the interval from 26 kPa to 100 kPa.

Experimental dependencies of local hardness on measurement point coordinates along and across ice sheet has a look of harmonic oscillation with a relatively slow varying amplitude. Typical wave lengths ($\lambda 1$=2m, $\lambda 2$=5m and $\lambda 3$=40m) are determined by extreme points on experimental curves. Approximating function of ice local hardness is not a monochromic one.

Standing waves manifest themselves as periodic variations of local hardness and, apparently, correspond to frozen ice textures. The effect of standing wave influence on the ice structure reaches 40% and exceeds the measuring error of axial force (5%).

The minimum values of secondary structure hardness correspond to the standing wave antinodes. The antinodes due to maximum displacement of particles accumulate defects, have reduced dynamic viscosity, hardness and strength of ice. On the contrary, the standing wave nodes have minimum displacements and deformation rate, consequently, the hardness is maximum. Therefore, every experimental value of hardness is a replica of the structure that was formed under more or less influence of the standing wave. Oscillating hardness of ice field is considered as a mirror image of the phase surface of displacement (projection of velocity) in the standing wave.

Displacement of particles at wave superimposition is written as (Sretenskii, 1977)

$$\chi = A_1 \cos\frac{\pi m}{a} x \cos\frac{\pi n}{b} y + A_2 \cos \pi x \cos \pi y,$$

where χ – displacement (wind velocity projection onto vertical axis z), A_1 and A_2 – amplitudes of summed up waves determined from experiment, m and n – number of oscillations along the ice sheet a = 80 m and across the basin b = 10 m ($m, n = 1, 2, \ldots; m = n \neq 0$), x, y – length and width variables, respectively.

Fig. 6 shows the dependence of phase oscillation amplitude on measurement point coordinate estimated for wave lengths λ = 2, 5 and 40 m.

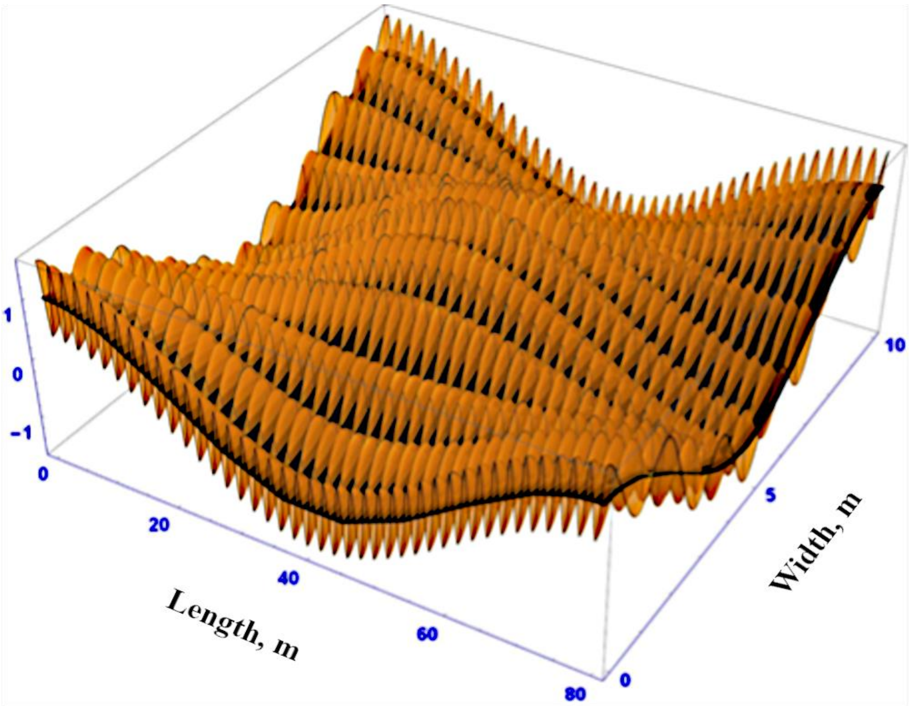


Figure 6. Stationary periodic wave structures in ice field at interference of waves with wavelengths 2, 5, 40 m

It follows from Fig. 6 that the experimental surface of ice sheet local hardness is not monochromic. Long bending gravitational waves (λ = 5 and 40 m) are modulating oscillations for waves with 2m length (quasi-longitudinal). The model of wave structures is a mirror image of experimental dependences of local hardness on measurement point coordinate across and along the ice sheet. It should be noted that the effect of wave influence on the secondary texture formation and local hardness of ice depends on the conditions at the contact with basin walls.

It was attempted to find secondary textures of ice formed under the influence of wave structures by the ice resistance force to cutting by a cylinder indenter. These tests are standard in determination of ice crushing strength in ice basins (ITTC, 2014). Fig. 7 presents the results of experiment, during which the wavelength of 2.6 m was obtained. Results of indenter tests qualitatively confirm the periodicity of processes, but their interpretation is too difficult due to crushing, compacting and accretion. Apart from that, the measured results are affected by inherent vibrations. This was apparently the reason why the oscillations observed in standard tests were not considered from the point of wave metamorphism.

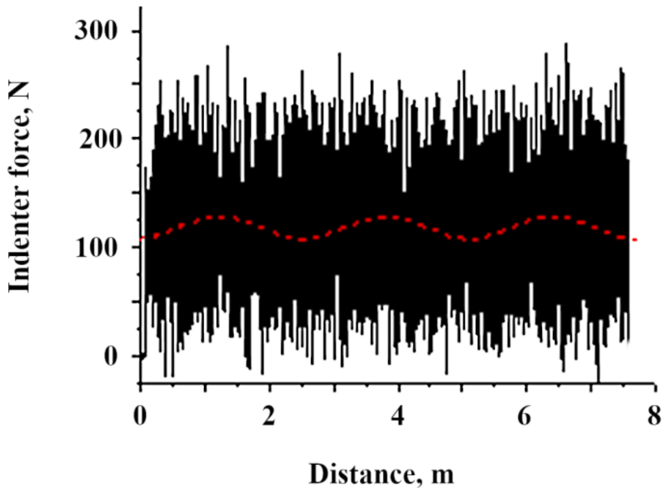


Figure 7. Results of tests in cutting the ice sheet with cylinder (blunt) indenter with middle section 20.7 cm^2 at speed of 0.6 m/s.

In spite of the fact that in the first approximation the independent qualitative confirmation on wave metamorphism of model ice has been obtained, application of cylinder indenters and ice cutting methods are not suitable for the task. The penetration method at 0.6 m/s with indenter of middle section 2.5 cm^2 were found optimum. These conditions were implemented by application of the penetrometer with a cruciform indenter to determine the ice local hardness.

Possibility to observe the wave influences on natural ice on site was examined on a river ice cover (Fig. 8). Local hardness was measured with a penetrometer (Fig. 3) equipped with a replaceable ball-shaped indenter. Fig. 8 shows that the most spatial variability of ice hardness is observed across the river channel (curve 1), in particular, near fast ice, while along the river channel it was less (curve 2). This fact bears evidence that there may be wave generation in the river ice cover. Contact fracture of crystals at their growth (water freezing) or diurnal variations of temperatures can be sources of waves. River banks work as wave reflectors or obstacles creating compressions at thermal stresses.

Various conditions of ice field contact with river banks complicate the picture, but the effect of periodic variations in local hardness is still clearly seen. The observed deviations (curve 1) from the reduction point exceed 30%, while the relative error of hardness measurement is within 1%. Clear periodicity of the curve 1 and absence of periodicity in the curve 2, Fig. 8, suggest possible standing wave effects on the structure of river ice cover arising between the banks.

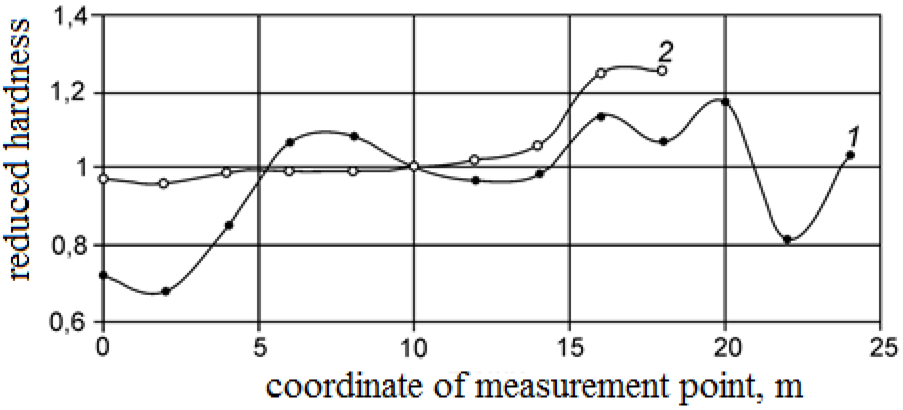


Figure 8. The dependence of the local hardness of the river cover on the coordinate of the measurement point: 1 – across the river bed; 2 – along the river bed

It should be noted that in formation of periodic wave structures in the river ice cover the same patterns appear as in the model ice. In both cases metric wavelengths are observed. They are dependent on the shape and size of ice field, relations of ice wave resistance and wall/river bed, geometry of ice field. Thus, the field measurements of local hardness across the river ice cover (natural ice) have qualitatively confirmed the results obtained in the ice basin on model ice.

Qualitatively close results regarding alterations of high- and low-strength zones in sea ice cover have been obtained in Ref. (Bekker et al., 2017). The authors of this work gave no explanations for these alterations of maximum and minimum local hardness of ice. However, the coefficient of non-uniform uniaxial compression equal to 0.75, introduced by the authors, coincides with the results obtained for river ice.

It seems that alterations of different strength areas in sea and river ice is the result of wave structure influences.

CONCLUSION

An experimentally found effect of wave character of variability in mechanical properties of ice cover at small scale make it possible to have a fresh look on the problem. If one accepts a hypothesis suggested in this paper that the main source of wave processes is thermodynamic processes in ice cover, the variability can be seen in any ice fields.

It can be assumed that the wave processes should manifest itself most vividly in thin ice. Obviously, as ice covers grow in thickness the intensity of such processes will diminish.

These effects should be taken into consideration in technical applications, primarily in ice basin practices. The said processes could cause a spread in experimental values of ice strength obtained in different points of modeled ice sheet.

It is shown that the standing wave structure increases plasticity of ice. Wave metamorphism governs the space and time inhomogeneity of ice cover properties. The wave mechanism may play a key role in the mechanics of contact ice fracture.

ACKNOWLEDGEMENT

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

REFERENCES

Alekseev Yu.N., Afanasyev V.P., Litonov O.E., Mansurov M.N., V.V. Panov, Truskov P.A. Ice-technical aspects of the development of offshore oil and gas fields. SPb.: Gidrometeoizdat, 2001, 360 p.

Bekker A.T., Farafonov A.E., Pomnikov E.E. Non-uniformity of ice fields / *Vestn. Inzhenern. Shkoly DVFU*. 2017. No. 3 (32). p. 64–71. (in Russian)

Dobrodeev A.A., Sazonov K.E., Timofeev O.Y. New ice basin of Krylov state research centre. / *Proc. of the 23rd Int. Conf. on Port Engineering under Arctic Conditions* (POAC'15), Norway, Trondheim, June 14-18, 2015

Epifanov V.P., Sazonov K.E. The influence of standing waves on the local strength of the ice field. */Dokl. Phys.* 64, 456 (2019).

Epifanov V.P., Sazonov K.E. Wave structures in the ice field and influence of them on the strength of salt ice / *Led i Sneg. Ice and Snow*. 2020. 60 (4): 623–636. [In Russian].

Frolov S.V., Tretiakov V.Yu., Klein A.E., Alekseyeva T.A., Pryakhin S.S. Results of ice thickness observations using the data of high-latitude Arctic marine expeditions. Russia's contribution in the International Polar Year 2007/2008. Oceanography and sea ice. Moscow-SPb,. Paulsen. 2011. P. 374–385. [In Russian].

International Towing Tank Conference, 2014. Recommended Procedures and Guidelines. Propulsions tests in ice. 7.5-02-04-02. 14 p.

Kolesnikov Yu.M., Morozov E.M. Contact fracture mechanics. M.: LKI, 2012, 224 p

Kuznetsov D. M., Smirnov A. N., Syroeshkin A. V. Acoustic emission at phase transformation in water environment. / *Ros. khim. zh. (Zh. Ros. khim. ob-va im. D.I. Mendeleeva)*, 2008, v. LII, No 1. p. 114-121. (in Russian)

Mironov Ye.U. Ice conditions in the Greenland and Barents Seas and their long-range forecast. SPb. AARI Publ. 2004. 320 p. [In Russian].

Shibkov A.A., Golovin Yu.I., Zheltov M.A., Korolev A.A. Impulse electromagnetic and acoustic emissions at fast crystallization of cooled water droplet. / *Kristallografia*. 2001. v. 46. No. 1. p. 155. (in Russian).

Sretenskii L. N., Theory of Wave Motions of Fluid (Fizmatlit, Moscow, 1977) [in Russian]

Zukas J. A., Nicholas T., Swift H. F., Impact Dynamics,Wiley Interscience Publications, New York 1982.