The Screening Influence of the Composite Structure Broken Ice on the Gravity Waves Propagation

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Abstract. The broken ice influence on the surface of the water area on the parameters of propagation of gravity waves including ship waves is considered. The discrepancy using of the superposition principle, which consist in the addition of the independent component of water and ice resistance of the vessels motion and used in the existing analytical calculations, and the real process picture is shown. The quantitative assessment of the broken ice influence on the resistance components is given.

1. Introduction
The numerous observations of the vessels motion in the ice condition have shown that the waves amplitude generated by the ship is noticeable less than at the same speed in the clear water. The speed of waves propagation in ice is less than in water, and the waves themselves become shorter [1, 2]. Similar phenomena were observed when gravity waves entered the broken ice area from a water area part with clear water. Obviously, in broken ice the energy dissipation due to the ice fragments forced oscillations which occur due to gravity waves oscillations, comes in. Likewise, in order to enter the safe bay in the heavy sea, navigator had commanded to pour out the whale or the seal oil overboard. During horizontal tension and compression, the wave energy was taken away by the fat film, which has a considerably higher surface tension than water. This significantly reduced the waves amplitude. Thus, the layer screening effect located on the clear water surface is occurred. Such problems are considered in the works [9, 10].

Some test data of the vessels models abroad [3] and in the domestic ice basin [6, 7, 8] can be instance of this. The conversion of the towing resistance curves from the model of the icebreaking air cushion platform ACT-100 on full-scale resistance in the clear water and broken ice [6] are shown in figure 1.

The broken ice corresponded to the thickness of 1.09 m of the full-scale ice at a cushion pressure of the full-scale vessel of 11-15kPa. The model scale is 1:28. As can be seen from figure 1, the travelling resistance in broken ice is less than in clear water in developed wave-making, when v>4m/s.

The tests of the Ice-2 class transport vessel model in the small ice pieces in the ice basin are shown in figure 2.
Figure 1. ACT -100 towing curve: 1 - in clear water; 2 - in broken ice.

Figure 2. The towing resistance curves of the displacement vessels models in clear water and in broken ice: 1 - clear water; 2 - broken ice (4-point concentration); 3 - broken ice (6-point concentration); 4 - broken ice (8-point concentration).

Obviously, when increasing speed (and Froude numbers), the wave component of the resistance also increases significantly, which decreases with the screening effect of the broken ice. The transition from the resistance law in the form of a square parabola in the clear water to an almost straight-line dependence in the broken ice of the high concentration indicates this.

2. The theoretical research

2.1. The broken ice influence on the ship waves propagation

The ice brash can be considered as the conventional particles with the lower density than water, floating on its surface. The water surface area will be considered as a range of the separate nonintersecting section, endowed with the properties of the continuity and isotropy. Then the plane advancing waves propagation in the unlimited depth basin is considered. The close problem of waves on interface of two liquids with different densities was solved by N.E. Kochin [5]. On the assumption of the liquids potential motion and no-flow condition in each layer, for velocity of wave propagation of length l was obtained:
\[ c = \left( \frac{g \cdot \lambda}{2\pi} \right)^{1/2} \left( \frac{\rho - \rho_1}{\rho + \rho_1} \right)^{1/2}, \quad (1) \]

here are \( \rho, \rho_1 \) the density of the lower and upper liquid layer, \( \rho < \rho_1 \)

For \( \rho_1=0 \) from (1) the well-known formula is obtained:

\[ c = \left( \frac{g \cdot \lambda}{2\pi} \right)^{1/2}. \quad (2) \]

Taking the density of ice \( \rho_1 = 0.9 \, \text{t/m}^3 \), and density of water \( \rho = 1.0 \, \text{m}^3 \), the speed of waves propagation change in the considered environment is obtained:

\[ c = \left( \frac{(1-0.9)}{(1+0.9)} \right)^{1/2} \approx 0.23. \]

Thereby the speed of waves propagation in this environment will be 0.23 of the speed in the homogeneous medium.

When propagating the plane advancing waves in the unlimited depth basin the following well-known dependencies are used [5].

The speed of waves propagation in the horizontal direction:

\[ c = \sqrt{\frac{g}{K}} = \frac{g}{K} = \frac{g}{\sigma} = \sqrt{\frac{g \cdot \lambda}{2\pi}} = \frac{\lambda \cdot \sigma}{2\pi}. \quad (3) \]

here is \( K \) the wave number \( K=2\pi/\lambda \); \( \lambda \) – wave-length; \( \sigma \) – wave frequency \( \sigma = \sqrt{gK} \).

The wave parameters are given in figure 3.

**Figure 3.** Gravity waves geometry with the broken ice layer on the surface.

When the vessel moves in water at the speed \( v \), the transverse waves length generated by the vessel is known [5] to be related to the wavelength by the ratio similar to (3):

\[ \lambda = \frac{2\pi \cdot v}{g}. \quad (4) \]

The flow velocity potential takes the form:

\[ \phi = \frac{a \cdot g}{\sigma} \cdot \exp[-Kz] \cdot \sin(Kx - \sigma t) \quad (5) \]

Vertical displacement \( w \) of the fluid particle:

\[ w = a \cdot \cos(Kx - \sigma t) \quad (6) \]

here is \( a \) the vibrational amplitude.
For wave motion of the liquid covered with the broken ice layer with thickness $h$, the following formulas can be written [5, 6, 11].

The equation of force on the ice surface

$$m \cdot \frac{d^2 w}{dt^2} + \rho_w \cdot g \cdot w + \rho_w \cdot \frac{d\varphi}{dt} \bigg|_{z=0} = 0 \quad (7)$$

here is $m$ the ice fragment mass, $\rho_w$ – density of water.

Considering the energy flux density formula (7) can be rewritten as:

$$\rho_{ic} \cdot h \cdot \frac{d^2 w}{dt^2} + \rho_w \cdot g \cdot w + \rho_w \cdot \frac{d\varphi}{dt} \bigg|_{z=0} = 0 \quad (8)$$

(here and further, the “ic” and “w” index refer to ice and water correspondingly)

Hence the ice floe free frequency near the static equilibrium position is written as:

$$\sigma_{ic}^2 = \frac{\rho_w \cdot g}{\rho_{ic} \cdot h} \quad (9)$$

The wave number is obtained by D.E. Heisin [2]:

$$K_{ic} = \sigma_{ic} \cdot \sqrt{\left[ \frac{l}{l-(\sigma_{ic} / \sigma_w)} \right]} \quad (10)$$

The phase speed of wave propagation in the water area covered with the broken ice takes the form:

$$c_{ic} = \frac{g}{\sigma_w} \cdot \left[ 1 - \left( \sigma_{ic} / \sigma_w \right)^2 \right] \quad (11)$$

These dependences confirm the decrease in the speed of wave propagation in the broken ice and the decrease in the wavelength.

Using (3) and (11) the ratio of the speed of waves propagation in the broken ice to the wave velocity on clear water can be obtained:

$$\frac{c_{ic}}{c_w} = 1 - \left( \sigma_{ic} / \sigma_w \right)^2 \quad (12)$$

Taking into account (9) and $\sigma_w = g / c_w$ the formula takes the form:

$$\frac{c_{ic}}{c_w} = 1 - \frac{g \cdot \rho_{ic} \cdot h}{\rho_w \cdot c_w^2} \quad (13)$$

By setting the number of $h$ and $c_w$, the formula (13) can be graphically presented as a function shown in figure 4.

**Figure 4.** Dependence of the ratio of the wave velocity propagating in the broken ice to the velocity on clear water on the ice layer thickness $h$:

1 – $h=0.2$ m; 2 – $h=0.4$ m;
3 – $h=0.6$ m; 4 – $h=0.8$ m;
5 – $h=1.0$ m, 6 – formula (1).
2.2. The screening effect of the broken ice on the wave propagation

To assess the screening effect of the broken ice, the energy approach is applied. The ratio of the total wave energy and the broken ice to the wave energy in clear water was considered. The kinetic energy flux density determined through the wavelength is written as follows [5]:

\[ T_w = \frac{\rho_w}{2} \cdot \frac{a^2 \cdot g^2 \cdot K}{\sigma^2} \int_0^\lambda \phi \left( \frac{dw}{dt} \right)^2 \, dx. \] (14)

Substituting (5) into (14) the result is obtained:

\[ T_w = \frac{\rho_w}{2} \cdot \frac{a^2 \cdot g^2 \cdot K}{\sigma^2} \int_0^\lambda \sin(Kx - \sigma) \, dx. \] (15)

Integration (15) is easily performed by factorizing the difference sine between the two angles, in results it is obtained:

\[ T_w = \frac{\rho_w}{2} \cdot \frac{a^2 \cdot g^2 \cdot K}{\sigma^2} \int_0^\lambda \sin^2(Kx - \sigma) \, dx. \] (16)

The potential energy is similarly calculated.

The values of the kinetic and potential energies, as shown by N. E. Kochin [5], separately coincide and when the plane simple harmonic wave propagates, they pass into one another, so their sum is constant.

The kinetic energy of the broken ice in the wave flow can be expressed by the formula:

\[ T_{ic} = \frac{\rho_{ic}}{2} \int_0^\lambda \left( \frac{dw}{dt} \right)^2 \, dx. \] (17)

By performing the integration similar for (16), the result is obtained:

\[ T_{ic} = \frac{\rho_{ic}}{2} \cdot h \cdot a^2 \cdot \sigma_{ic}^2 \int_0^\lambda \sin^2(Kx - \sigma) \, dx. \] (18)

Using (3) the formula takes the form:

\[ T_{ic} = \frac{2\pi \cdot \rho_{ic} \cdot h \cdot a^2 \cdot g}{4}. \] (20)

The screening effect of the broken ice takes the form:

\[ Z = \frac{T_w + T_{ic}}{T_w} = \frac{\rho_w \cdot a^2 \cdot g \cdot \lambda_w \left( 1 + \frac{2\pi \cdot \rho_{ic} \cdot h}{4\lambda_w \cdot \rho_w} \right)}{\rho_w \cdot a^2 \cdot g \cdot \lambda_w \left( 1 + \frac{2\pi \cdot \rho_{ic} \cdot h}{4\lambda_w \cdot \rho_w} \right)} = \left( 1 + \frac{2\pi \cdot \rho_{ic} \cdot h}{4\lambda_w \cdot \rho_w} \right). \] (21)

The wavelength is determined from the formula:

\[ \lambda_w = \frac{2\pi \cdot c^2}{g}. \] (22)

Substituting (22) into (21) the result is obtained:

\[ Z = 1 + \frac{\rho_{ic} \cdot h \cdot g}{\rho_w \cdot c^2}. \] (23)
By setting the values number of the ice thickness and advancing wave velocity, the graphical representation of the screening effect was obtained and is shown in figure 5.

![Figure 5](image)

**Figure 5.** The screening effect of the broken ice on the water surface.

### 3. The experimental investigation

The experimental investigation of the screening effect of the broken ice was carried out in the hydrodynamic tank of the Department of Higher Mathematics of the NSTU. The hydrodynamic tank was equipped with the plate-type wave generator and had the following dimensions, i.e. 6.61 m in length, 0.5 m in width and 1 m in height. The hydrodynamic tank scheme is shown in figure 6.

The hydrodynamic tank length was marked with an accuracy of 1 cm. The vertical gage rods were installed every 1.85 m of length.

The broken ice was simulated by the square in plane blocks with dimension 100x100 mm and 20 mm thick. The block material is high-pressure polyethylene with the density of 0.91 t/m$^3$.

The tests were carried out at the water depth of 0.4 m and at the wave generator vibration frequency of 1 Hz. The vibrational amplitude of the wave generator plate was set from 5$^\circ$ to 24$^\circ$. Two series of the tests were carried out. The first series was in the clear water conditions, and the second was carried out with the broken ice model on the water surface.

![Figure 6](image)

**Figure 6.** The hydrodynamic tank scheme:

1 – the plate-type wave generator; 2 – the hydrodynamic tank body; 3 – the vertical gage rod

The tests were carried out at the water depth of 0.4 m and at the wave generator vibration frequency of 1 Hz. The vibrational amplitude of the wave generator plate was set from 5$^\circ$ to 24$^\circ$. Two series of the tests were carried out. The first series was in the clear water conditions, and the second was carried out with the broken ice model on the water surface.
The wave pattern registration in the hydrodynamic tank was carried out by means of the video filming, according to which the wave velocity, beginning moments of the steady motion, the beginning moment of the onset and the process of the standing wave propagation were determined. The wave amplitude and wavelength at the steady motion moment were determined with the selected videorecording freeze-frame.

The tests on the clear water are carried out. The test began with the calm water surface. The initial irregularity of the wave profile was eliminated at the distance of 1.0-1.5 wavelength from the wave generator. After the start of the wave generator work, when the front of the initial wave had reached the backwall, the steady-state peak amplitude of the wave profile in the middle part of the hydrodynamic tank was observed. Reflecting from the backwall, the wave began to form standing wave, gradually occupying ¾ of the hydrodynamic tank length.

The wave parameters (length \( \lambda_w \), wave velocity \( v_w \) and amplitude \( a_w \)) were determined at the moment of the wave steady motion in the zone between the first and the second gage rod (figure 6). The video recordings with the wave generator amplitude of \( 20^6 \) were used. At the higher amplitude (\( 24^6 \)) the flat sections appeared on the wave crests, deviating from the trochoidal shape, which indicated of the nonlinear effect during wave generation. The characteristic view of the wave profile on the clear water is shown in figure 7.

![Figure 7](image)

**Figure 7.** The characteristic profile of the traveling progressive wave in water at the wave producer amplitude \( 24^6 \).

The wave parameters with the blocks on the water surface were determined at the same amplitude. The characteristic view of the wave in this case is shown in figure 8. At the amplitude of \( 24^6 \), the wave crest with the blocks lost its steady position, the blocks turned over and crawl each other, forming the second layer. Therefore, the results at this amplitude were not considered.

![a) b)](image)

**Figure 8.** The progressive wave movement with the simulated broken ice: 
a – the view at the front of the wave front; b – the view of the wave front behind the crest.
The speed of wave propagation was determined by the perturbation action frequency from the wave generator. The measurement results average of the wave parameters were carried out by the analyzing the video recording freeze-frame and are tabulated.

**Table 1.** The measurement results average of the wave parameters.

| Wave flow condition | Rocking amplitude of the wave generator, degree | Wave generator frequency, Hz | Wavelength, m | Wave amplitude, m | Wave velocity, m/s |
|---------------------|-----------------------------------------------|-----------------------------|---------------|-----------------|-------------------|
| Clear water         | 20°                                           | 1                           | 1.75±0.05     | 0.18±0.02       | 1.75±0.05         |
| Broken ice          | 20°                                           | 1                           | 1.65±0.05     | 0.14±0.02       | 1.65±0.05         |

As can be seen from Table 1, the wave amplitude and the wavelength, as well as the speed of wave propagation in comparison with the speed in the clear water are reduced due to the broken ice.

**4. Conclusions**

It is theoretically shown that the speed of gravity wave propagation decrease with increasing the broken ice thickness on the water surface in the water area; the graphical form of this dependence, which has a non-linear character is given. The greatest speed decrease occurs with the broken ice thickness increasing and increases with the speed of wave propagation increasing.

The broken ice screening effect noted in the full-scale data during the vessels movement in the ice condition has been theoretically confirmed. The influence of the broken ice thickness on the speed of wave propagation in the broken ice in comparison with clear water is estimated.

The theoretical parameter that qualitatively determined the screen effect depending on the basic physical factors of the screening process is offered.

The graphical dependence of the screening parameter on the broken ice thickness and the advancing wave velocity in the broken ice is given. This relation shows the screening effect increases in direct proportion to the ice thickness and decreases as the speed of wave propagation decreases.

The experiments carried out have qualitatively confirmed the screen effect, i.e. the decreasing of the speed of wave propagation, the wave amplitude and wavelength decreasing.

The fact of the blocks horizontal motion on the waves was discovered, which can additionally increase the screening effect. This requires further research using this experimental setup.

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