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The study of the impact of ice conditions on the possibility of the submarine vessels surfacing in the ice cover

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Abstract. Traditionally submarine vessels emerging from under ice cover performing by static loading of ice from bellow through the creation of positive buoyancy by main ballast tanks. However thickness of ice (approximately 1 meter) from under which modern submarine vessel can emerge essentially limits the use of traditional method, particularly during submarine vessels motion in the severe ice conditions of Arctic region. For breaking the ice cover of greater thickness can be used flexural gravity waves caused by the submarine vessel motion with certain critical speed near the bottom ice. It is also known that in the coastal areas water depth is often less than 100 meters, and the presence of projections on the bottom surface may effect on the wave propagation pattern. This paper presents experimental study of influence of bottom contour on the deflection and the length of the flexural gravity waves from the movement of submarine. Ice cover failure pattern determined. Assessment of ice-breaking capacity of flexural-gravity waves with using the criterion of ice failure is performed.

1. Introduction

Traditionally submarine vessels emerging from under ice cover performing by static loading of ice from bellow through the creation of positive buoyancy by main ballast tanks. However thickness of ice (approximately 1 meter) from under which modern submarine vessel can emerge essentially limits the use of traditional method, particularly during submarine vessels motion in the severe ice conditions of Arctic region. For breaking the ice cover of greater thickness can be used flexural gravity waves (FGW) caused by the submarine vessel motion with certain critical speed near the bottom ice. Among the first theoretical papers on the subject is a paper by Kheisin [1], who studied the plane steady-state problem of the motion of a vortex under a layer of broken ice. Bukatov and Zharkov [2] and Kozin and Pogorelova [3] studied the steady motion of a point source of mass under a floating elastic plate, analyzed the effect of the velocity of motion, the depth of the source, and the thickness of the plate on its deflections. The possibility of breaking natural ice cover by flexural gravity waves (FGW) caused by motion of a model submarine vessel with the relative hull extension $L_m/B_m = 8$ (where L_m is the length of the vessel, B_m is the width of the vessel) and the full-scale vessel displacement D_n=6000 t after converting to the natural one was shown in the work Kozin et al [4]. The destruction of ice by dynamic loads is considered in the works [5, 6]. In its turn, the presence of protruding parts, as well as the form of the cross section of submarines of various projects of can have a significant influence on the parameters of flexural gravity waves [7]. It is also known that in the coastal areas water depth is

often less than 100 meters, and the presence of projections and ledges on the bottom surface may effect on the wave propagation pattern.

2. Equipment and technique for conducting experiments

The aim of the study was experimental determination of the impact of the bottom contour on the model ice failure behavior, length and deflection of flexural-gravity waves generated by the motion of the immersed body.

Experimental studies of submarine vessel model motion under the ice sheet at a limited water depth were carried out in the natural ice basin with the following size 10×3×1 m laboratory of ice technology "Amur State University after Solom-Aleikhem" (Birobidzhan, Russia) [8]. Double bottom was modeled by using three sections mounted on the movable modules allowing to set required water depth by use of computer control. The block diagram of the basin is shown in figure 1. The chart of projections is shown in figure 2.
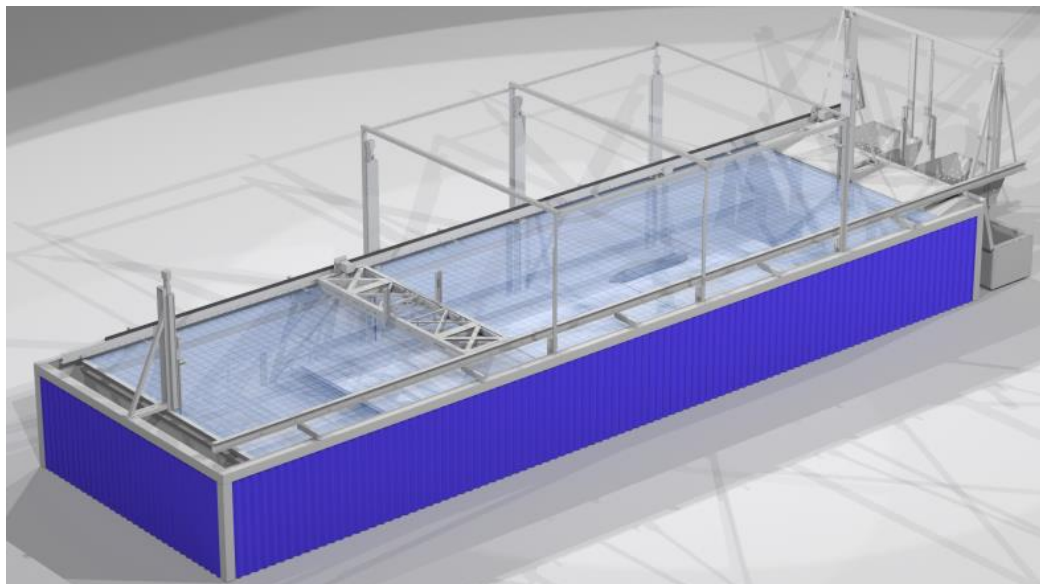
Figure 1. General view of the ice basin
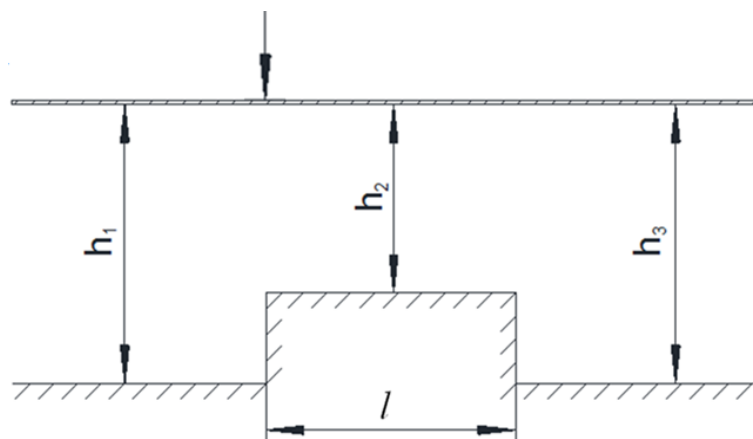
Figure 2. The chart of simulated projections of the bottom (the pointer indicates the location of vertical displacement sensor) ($h_1=h_3=0.4$ m, $h_2=0.3\div0.37$ m, $l=2$ m)

Due to the lack of refrigerating machines, experimental studies were carried out only in the winter period (December-January). The model of the ice cover was made in the ice basin by freezing natural freshwater without any dopant up to the set thickness (0.003 m) in natural conditions. The room where the basin is located was not heated for the entire period of the experiment. The experiments were carried out only at night time from 9.00 p.m. to 5.00 a.m. At night there were negligible fluctuations in the room temperature, within the difference of 1℃ to 2℃, although the room temperature varied from -10℃ to -15℃, depending on the outside temperature, varying from -25℃ to -30℃. Relatively uniform ice sheets were thus obtained in 2-2.5 hours at night, except for the patches of thaw on the ice. Effects of snow and wind from the outside were minimized at the ice basin. Due to a layer of insulating material installed on the sides and under the bottom of the basin and compliance with constant temperature mode, the thickness of the ice at the walls of the basin and in the middle of the ice field did not exceed 0.001 m. After carrying out of each model test, broken ice pieces were removed and the depth of the model was readjusted, and then ice sheet was formed.

To conduct the experiments necessary equipment and measuring system to register vibrations of model ice was prepared. By towing the model vessel its velocity and profiles of FGW were determined. To record the vibrations of the model ice we used infra-red non-contact vertical travel sensors LAS-Z by Way Con (Germany). The profile of the waves generated by the moving model was recorded with the help of the program Test viewer 2.34. The towing system allowed carrying out model tests at velocities of up to u_m=2.4 m/s under steady motion conditions.

Submarine vessel model scale equal to λ_l=1:120 was made as drop-shaped body of rotation, length-diameter ratio L_m/B_m=8.4 (where L_m=1.15 m). The length of parallel middle body was L_{pm}=0.7 m. Full underwater displacement after expansion was equal to D_n=24000 t. The parameters of the model were chosen considering previously executed experimental studies in view of modeled ice conditions these parameters are optimal.

To give it a zero buoyancy and positive stability when moving under model ice the model vessel was fitted with solid ballast. To create a technically smooth surface the body of the model vessel was puttied and painted. Harnessing of the model in the towing system was made through carabiners connecting the tow cable with attachment points located in the extremities of the body.

Simulation scale equal was selected basing on the size of the ice pool, with the length of the channel providing access to the steady motion of the model SV. The width was sufficient to eliminate the influence of the waves reflected from the channel sides, on the principle wave system [9]. Modeling of sea ice cover can be executed by using various ice models and for each of them there are corresponding conditions of similarity. The usual modeling is performed with partial satisfaction of conditions of similarity [10]:

$$\lambda_E = \lambda_w = \lambda_h = \lambda_l \tag{1}$$

Where λ_E is the model scale for Young's modulus; λ_w is the model scale for deflections; λ_h is model scale for ice thickness.

In this case, the requirements for similarity conditions with respect to Poisson's ratio μ and density ρ of the model ice are satisfied.

The model vessel must be geometrically similar to the real one and their displacements must be in proportion to the cubed modulus of the geometrical scale-ratio:

$$L_n/L_m = \lambda_l, \qquad D_n/D_n = \lambda_l^3 \tag{2}$$

where L_n is the length of the full-scale vessel; D_m is the model vessel displacement.

The model motion velocity u_m is determined by the condition of similarity:

$$u_n/u_m = \lambda_l^{1/2} \tag{3}$$

where u_n is the full-scale vessel velocity.

The parameters of the model FGW are converted to natural ones in accordance with the modulus of geometrical similarity:

$$\lambda_n/\lambda_m = w_n/w_m = \lambda_l \tag{4}$$

where λ_n is the length of the full-scale FGW; λ_m is the length of the model FGW; w_n is the full-scale FGW deflections; w_m is the model FGW deflections.

When natural ice cover is used as model one, the thickness of the modeling ice will be calculated when converted to natural one in accordance with the following relations:

$$h_n = h_m \lambda_l^{4/3} \left([\sigma_u]_n \Big/ [\sigma_u]_m \right)^{-\frac{1}{3}} \tag{5}$$

where h_n is the natural ice thickness; h_m is the modeled ice thickness; $[\sigma_u]_n$ is the natural flexural stresses; $[\sigma_u]_m$ is the modeled flexural stresses.
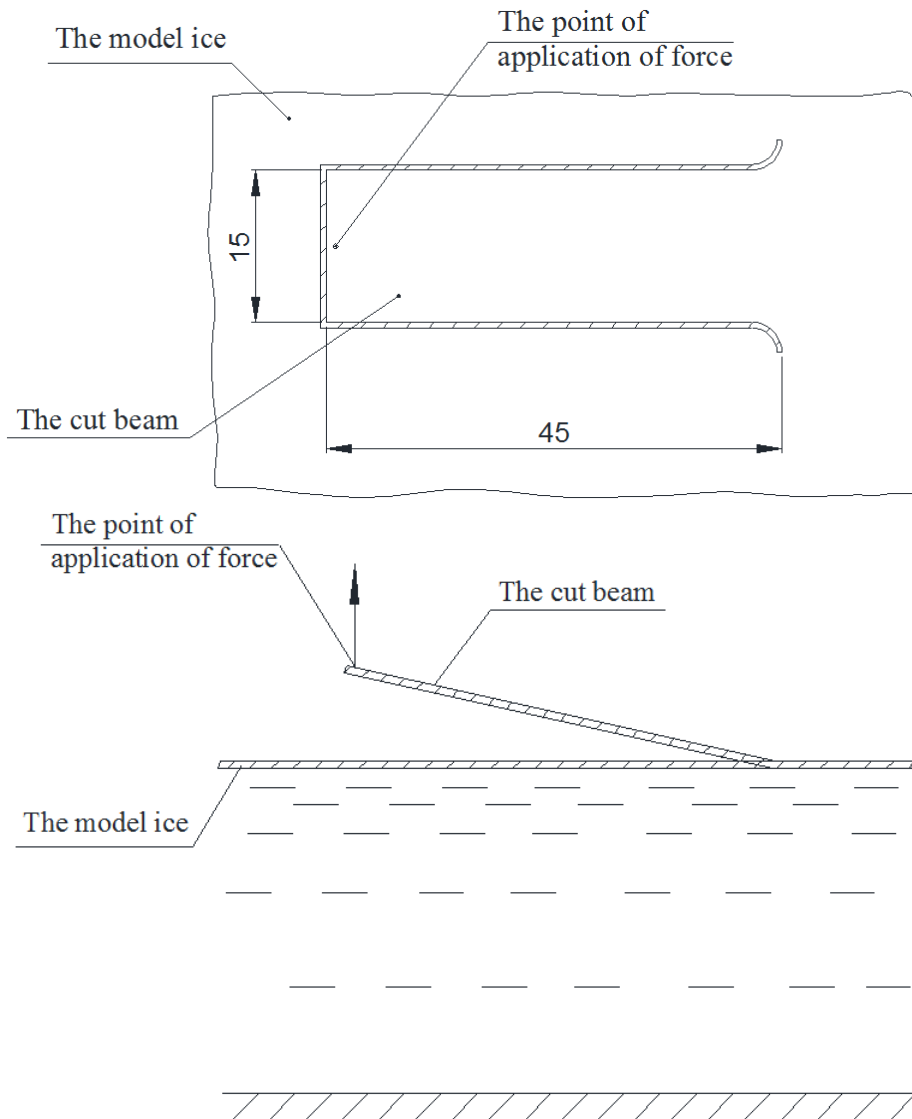
Figure 3. Testing beams

Determination of flexural strength of the model ice was experimentally performed by testing beams and for that purpose the model ice cover was prepared by building up ice of the required thickness h_m=0.003 m [11]. The beams had a rectangular shape with the parameter of $l{\times}b$=0.15×0.45 m which were prepared in the model ice by cutting out according to the stamp by the rotating Dremel tool. The force required for beam destroying was determined by using the electronic dynamometer Mark - 10 (USA) (figure 3). The average value of the flexural strength for natural ice was the value of $[\sigma_u]_n$=0.7 MPa. The thickness of the modeling ice cover after conversion to natural one was h_n=2.3 m.

It is known that at modeling sea ice by using fresh-water model ice, modulus of elasticity of the natural ice should be less then modulus of elasticity of the model ice $E_n{>}E_m,$ however the ratio E/σ_u for sea ice is practically the same as that for fresh-water ice. To meet this condition at modeling ice is very important [12]. To enhance the visibility of fractures of ice, the model ice surface was covered with a thin layer of snow, soon after the model field formation.

The coefficient α was used as a criterion for breaking model ice, that is it is equal to the maximum value of the tangent of the surface slope of the ice plate. The relationship between failure of ice cover and the coefficient α was already empirically determined in Kozin's experimental work [4]. This series of model experiments on the failure of natural ice cover of various thicknesses were conducted using models of submarine vessels and hovercrafts. It was stated, that for the load motion over the ice cover as well as for motion of a submarine vessel when the maximum value of the slope of the ice surface is greater than the value of 0.04, it leads to complete ice failure and cracks opening. The value of α in experimental studies was defined by the formula:

$$\alpha{=}2\pi w_m/\lambda_m, \qquad\qquad (6)$$

We should note that as far as the value of the criteria was obtained for the complete failure of freshwater ice, its usage for assessment of sea ice failure is not entirely correct. However, if we take into account that ice strength and fracture toughness of sea ice is lower than that of freshwater, the value of α for sea ice would be a bit lower.

Due to the complexity of the study, the duration of the preparation of the model ice field and limited cold period (December-January), aiming to identify optional parameters of the experiment such as model displacement velocity, relative deepening and water depth a series of preliminary test model runs was executed. According to the performed study the most significant results to be expected at velocity of the model vessel equal to u_m=1.25÷2.18 m/s, model deepening equal to h_m=0.16-÷0.32 m and water depth equal to H_m=0.3-0.45 m, which after conversion to natural was: u_n=13.7÷23.9 m/s; h_n=19.2÷38.4 m; H_n=36÷54 m.

3. Results of the model experiments

It is known that the parameters of FGW caused by moving of the load on the ice cover significantly depend on the depth of the basin [13]. The deflections of the ice cover in shallow water is always greater than in deep water, at that the length of FGW increases, propagation velocity decreases and FGW steepness ratio changes. The results of experiments are shown in figures 4-6.

The analysis of the experimental data revealed a significant effect of the water depth on the parameters of the FGW caused by the load motion. Comparing obtained data with the results of experiments for ice sheet at an infinite depth of the basin figure 7, it may be concluded that ice deflections increased.
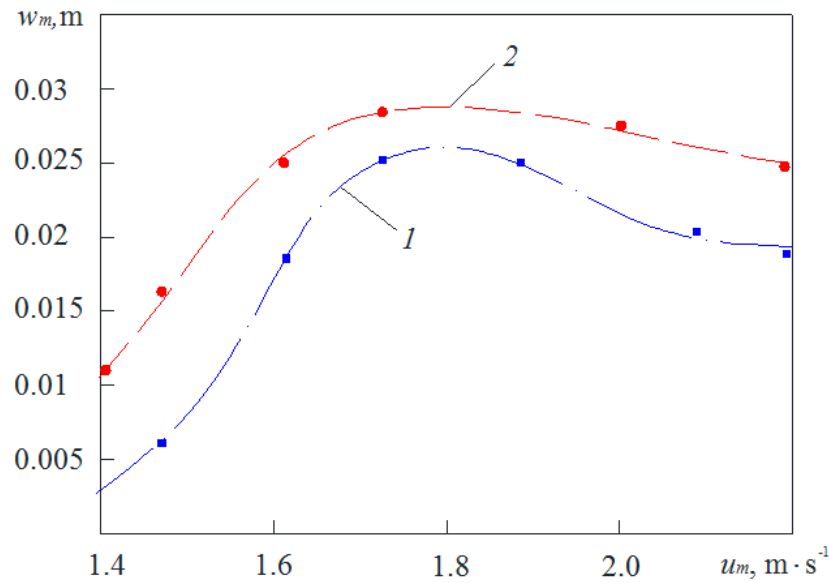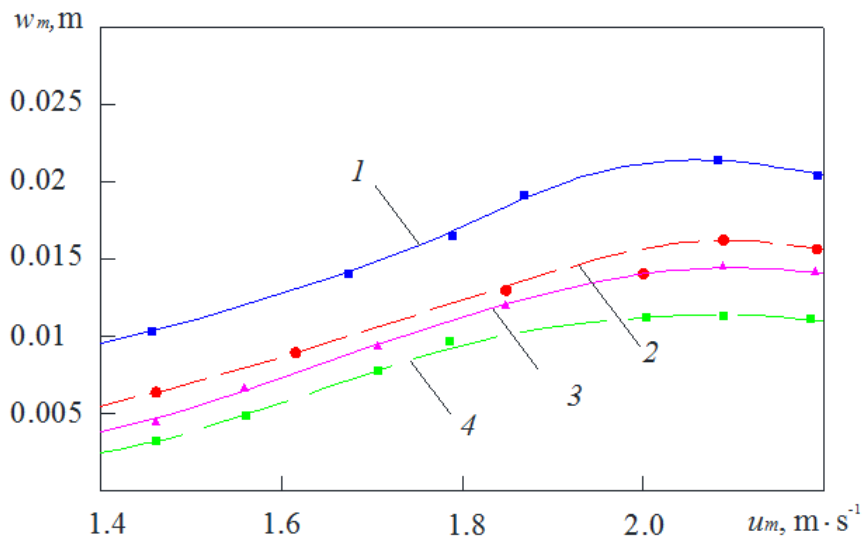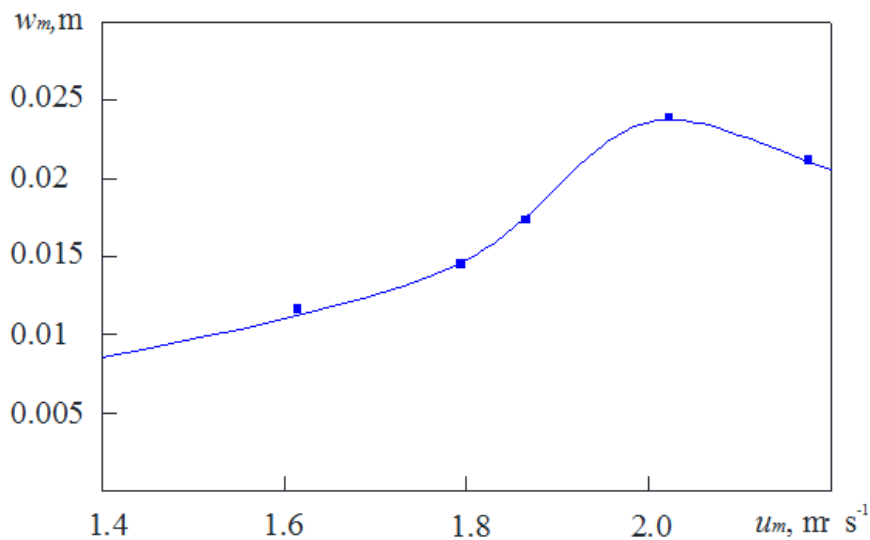
Figure 4. The relationship of the maximum deflections at different SV model velocity at a water depth equal to H_m=0.35 m: 1 depth of the SV h_m=0.16 m; 2 depth of the SV h_m=0.21 m.
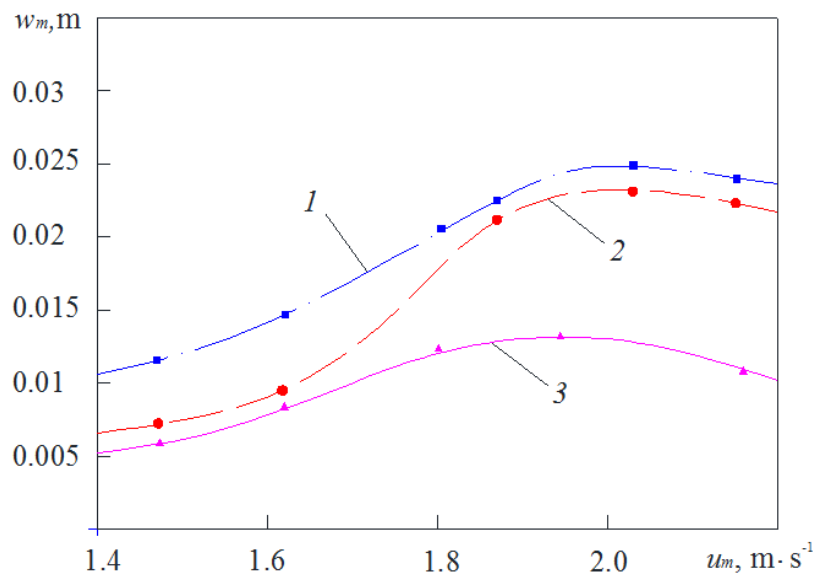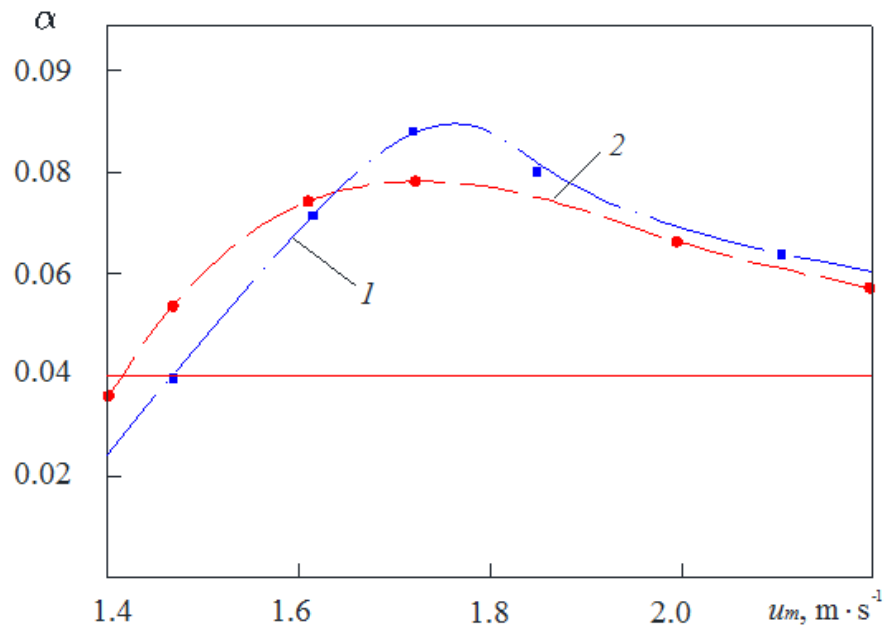

Figure 5. The relationship of the maximum deflections at different SV model velocity at a water depth equal to H_m =0.4 m: 1 depth of the SV h_m=0.16 m; 2 depth of the SV h_m=0.21 m; 3 depth of the SV h_m=0.26 m.

Figure 6. The relationship of the maximum deflections at different SV model velocity at a water depth equal to H_m=0.4 m: 1 depth of the SV h_m=0.16 m; 2 depth of the SV h_m=0.21 m; 3 depth of the SV h_m=0.26 m; 4 depth of the SV h_m=0.31 m.


Figure 7. The relationship of the maximum deflections at different SV model velocity at a water depth equal to H_m=1.0 m, h_m=0.16 m.

The relationship between coefficient α and load motion velocity for various depth is shown in the Figs. 8-10. At that minimum velocity of the load motion at which ice failure occurred was much less than in the case of an infinite water depth and was equal to $u_m = 1.42$ m/s.

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Figure 8. The relationship of the coefficient α at different SV model velocity at a water depth equal to H_m=0.35 m: 1 depth of the SV h_m=0.16 m; 2 depth of the SV h_m=0.21 m.
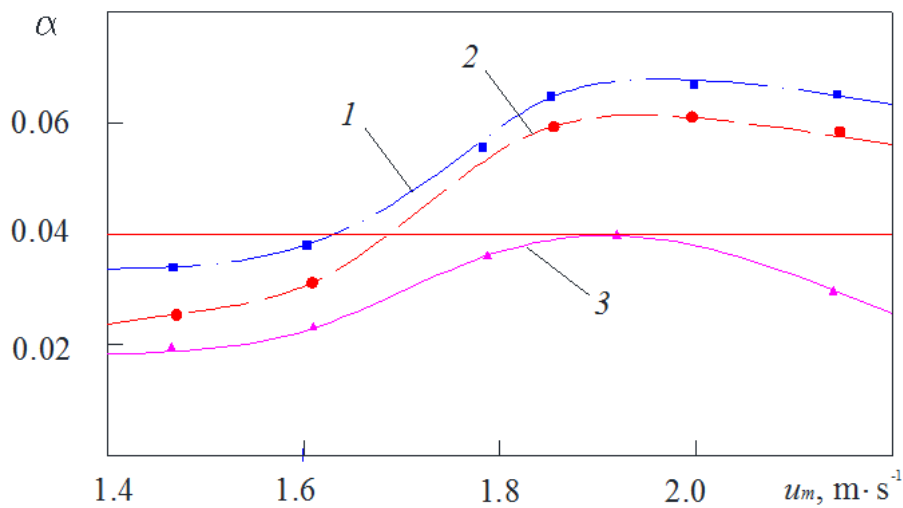
Figure 9. The relationship of the coefficient α at different SV model velocity at a water depth equal to H_m=0.35 m: 1 depth of the SV h_m=0.16 m; 2 depth of the SV h_m=0.21 m; 3 depth of the SV h_m=0.26 m.
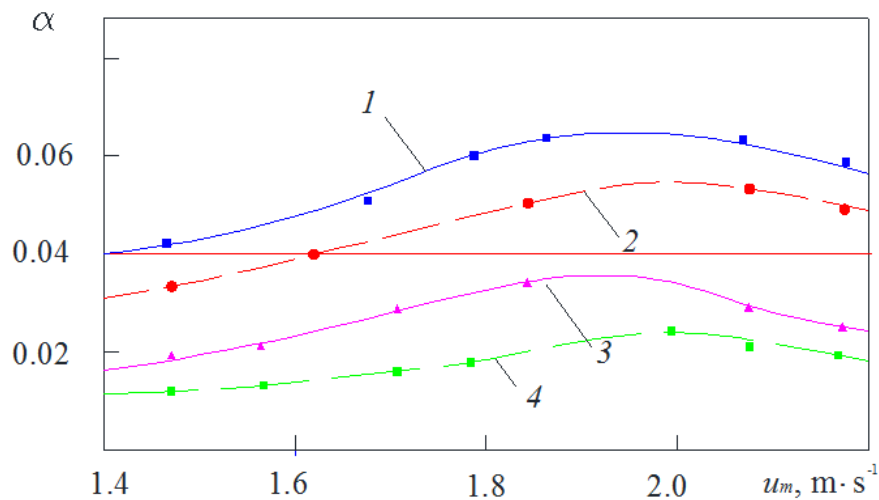
Figure 10. The relationship of the coefficient α at different SV model velocity at a water depth equal to H_m=0.35 m: 1 depth of the SV h_m=0.16 m; 2 depth of the SV h_m=0.21 m; 3 depth of the SV h_m=0.26 m; 4 depth of the SV h_m=0.31 m.
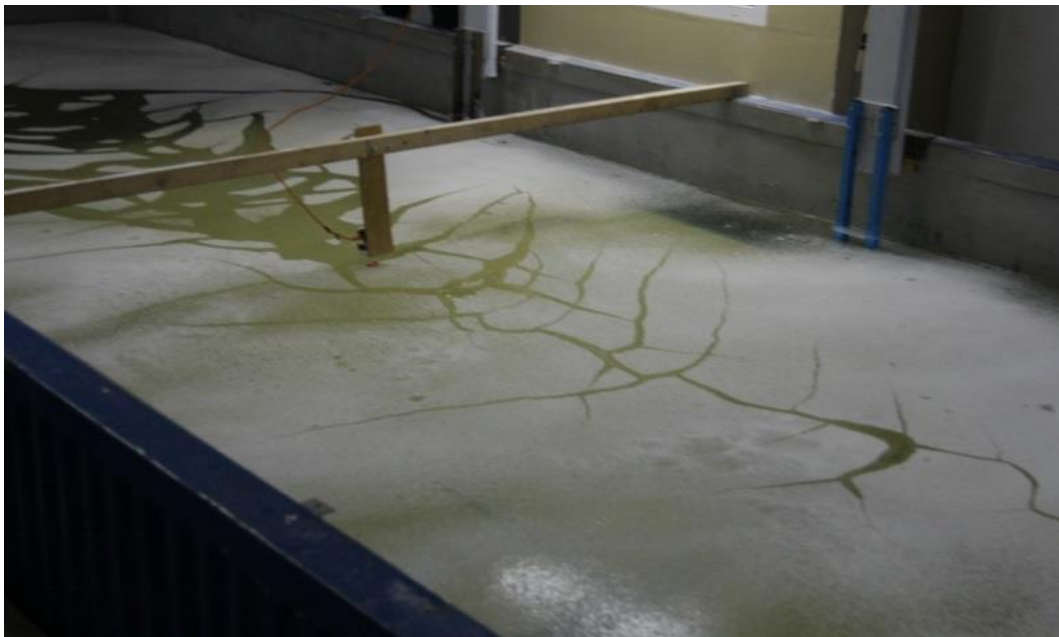
Character of the failure of the model ice is shown in figures 11-13. It is should be noted that most intensive ice failure and ice pieces crushing occured at near-critical velocity. Ice cover completely lost its carrying capacity. When reducing model velocity the area of the fracture was abridged significantly, although the intensity of destruction at low velocity was higher than at a velocity greater than the critical value, which is associated with high curvature of FGW. In the same way when moving in conditions of limited water depth longitudinal crack formed along the line of motion model.

Figure 11. Character of the failure of the model ice by FGW: H_m=0.35 m; h_m=0.16 m; u_m=1.47 m/s
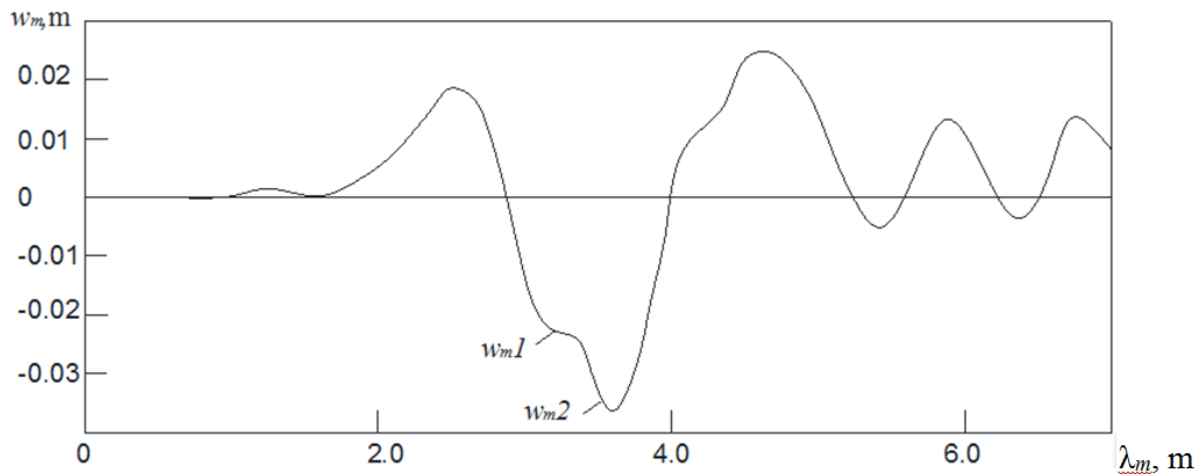
Figure 12. Character of the failure of the model ice by FGW: H_m=0.35 m; h_m=0.16 m; u_m=1.73 m/s


Figure 13. Character of the failure of the model ice by FGW: H_m=0.35 m; h_m=0.16 m; u_m=2.09 m/s

Flexural gravity waves pattern fixed by the sensor on the edge of the projection is shown in figure 14.

Figure 14. FGW pattern fixed by the sensor on the edge of the projection (the projection №1)

The results of model experiment-s on simulating of projections and ledge of the bottom shown in figures 15-16.
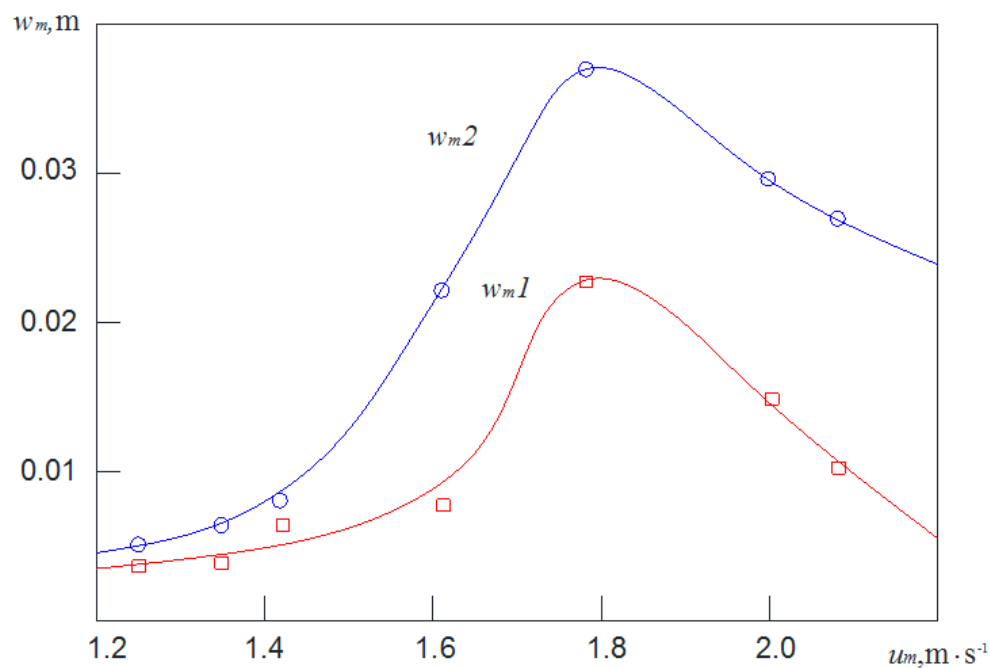

Figure 15. The relationship of the maximum deflections at different SV model velocity of the projection №1

Analysis and comparison of the data demonstrates a significant effect of simulated conditions on the parameters of the modeled FGW. The presence of the projection gives birth to a hydroshock and leads to a sharp increase of curvature of FGW by comparison with a continuous flat bottom. The graphs show that the curvature of the waves increases by 16-33%.
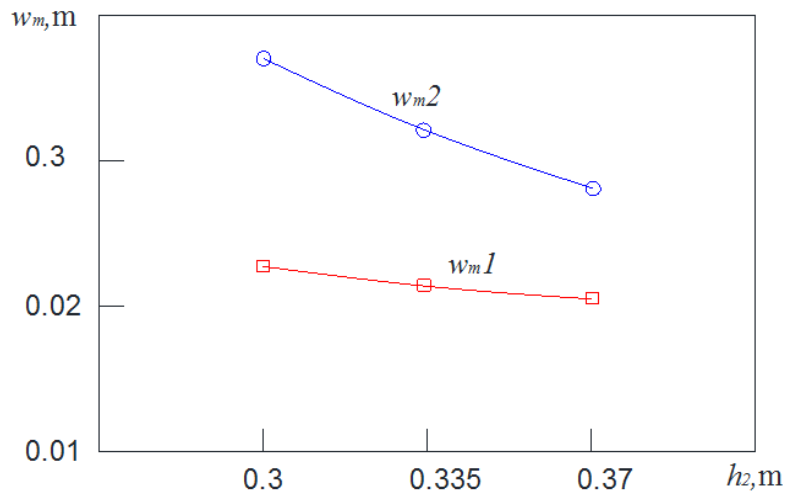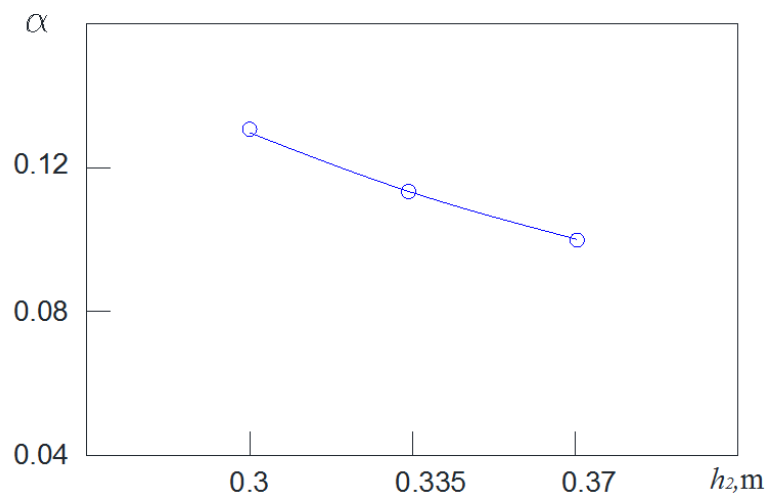
Figure 16. The relationship of the maximum deflections of the height of the projection (h_2)
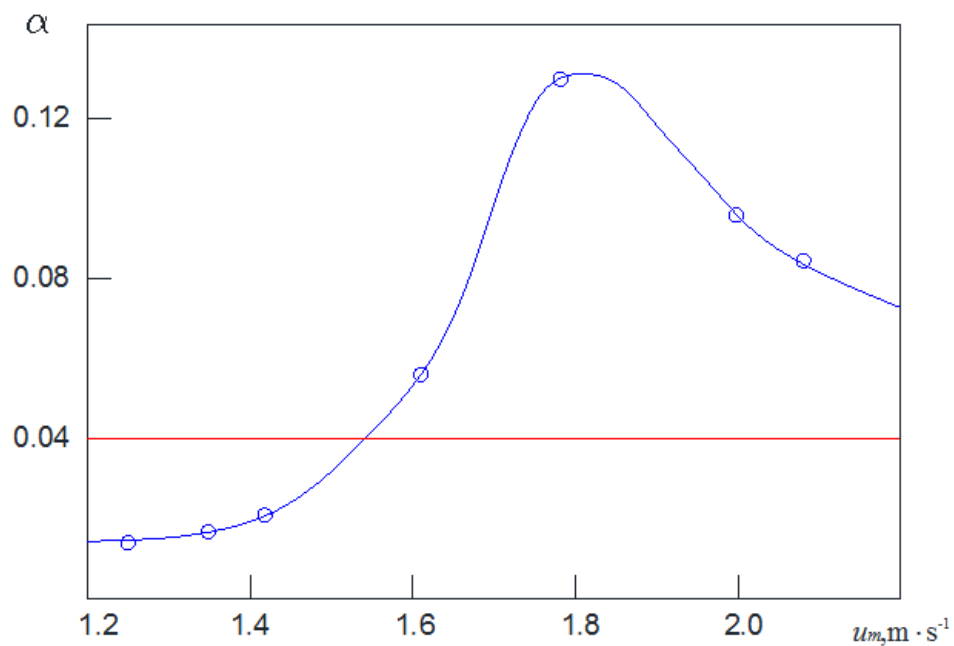
Figure 17. The relationship of the coefficient α at different SV model velocity of the projection №1.

High intensity of the destruction and grinding of ice floes observed when passing by SV model the areas of the simulated contour. The field of simulated ice was losing the bearing capacity completely. The dependence of coefficient α on the movement velocity of the load is shown in figures 17-18.

Figure 18. The relationship of the coefficient α at different of the height of the projection (h_2)

The graphs show that the intense destruction of ice occurred in all velocity ranges and types of bottom contour under the study. Moreover, the minimum velocity of the load motion at which the destruction of ice occurred, was significantly less than in the case of an infinite depth of the bottom and was about u_m=1.55 m/s. When reducing model velocity the area of the fracture was abridged significantly, although the intensity of destruction at low velocity was higher than at a velocity greater than the critical value, which is associated with high curvature of FGW.

Character of the failure of the model ice is shown in figures 19-20. It is should be noted that most intensive ice failure and ice pieces crushing occured at near-critical velocity. Ice cover completely lost its carrying capacity. When reducing model velocity the area of the fracture was abridged significantly, although the intensity of destruction at low velocity was higher than at a velocity greater than the critical value, which is associated with high curvature of FGW.

Figure 19. Character of the failure of the model ice by FGW: h_2=0.3 m (the projection №1); u_m=1.78 m/s

Figure 20. Character of the failure of the model ice by FGW: h_2=0.37 m (the projection №3); u_m=1.62 m/s

4. Conclusion

The results of the studies show that water depth has a significant impact on the parameters of FGW generated by the load motion. Given that the destruction of the ice takes place at velocity much lower than in the deep water. The value of critical velocity also depends on the water depth. Practically in all considered cases an intensive ice pieces crushing occured; and ice cover completely lost its carrying capacity. This study showed that the process of passing the projection of FGW from the ledge leads to a sharp change of its parameters. The velocity of the load motion leading to intensive destruction of modeled ice was far less by comparison with the previously set value for deep water; and the degree of destruction and grinding of ice floes was larger.

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