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Research of the behavior of ice on water under explosive loads

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Abstract. Complex theoretical and experimental studies of the behavior of ice under dynamic loads are presented. New experimental data about blast of snow-covered ice have been obtained. A complete coincidence of the experimental data of 2013 and 2017 was found. Test calculations, including impact test have been carried out. Shock adiabatics of ice and water are presented. The behavior of the ice block on the water under explosion was investigated. The velocity of the free surface, the volume of ice destruction, the diameter of the explosive lane in ice cover were calculated. Recommendations for more effective ice destruction under these conditions were given.

1. Introduction

The processes occurring in sea and river ice under dynamic loading are the subject of scientific research. This is due to various reasons, including the need to extract natural resources and design transport hubs in the regions of permafrost and the Far North, the development of new icecomposites, the fight against ice jams on Siberian rivers, as well as some military applications. However, the main difficulty lies in the fact that the ice is poorly studied natural material under impact and explosion loading. Ice has unique plastic and dielectric properties, multiple phase transitions in the process of deformation, and in terms of destruction, generally may not have analogues [1].

There is known fact that various scientific teams both in Russia and abroad are engaging the study of the behavior of ice under dynamic load. Systematic scientific research is carried out at Tomsk State University, Far Eastern Federal University, Novosibirsk State Technical University, Lobachevsky University, Krylov Scientific Center, etc. The recognized scientific world center is the Ice Research Laboratory in Germany. However, current research projects about dynamic loading of ice are undetected by the authors [2].

In the current study, complex theoretical and experimental studies of the ice behavior under shock and explosive loads were carried out. In experimental part of the research consists of full-scale underwater explosion tests only. Blast of emulsion explosive Emulast AS-FP (EE) is produced in water under ice. The "Ice-Explosive-Water" system was considered in theoretical part of the research. The behavior ice block on water under explosive was modeled in 2D axisymmetric formulation using an original computer code.

2 Experimental studies of the behavior of ice under dynamic loads

At present time, there are few experimental studies on the deformation and destruction of ice under shock and explosive loads. The overwhelming majority of studies are devoted to the behavior of ice under static and quasistatic conditions. Brief review of this topic is available in [3]. Experimental studies of the explosion of ice were not detected by the authors. Apparently the research has already become a bibliographic rarity.

The response of ice to shock loads was investigated [4-6]. The impact of ice cylinder on rigid wall is considered in [5]. A similar experiment was carried out in [6]. However, the dimensions of the ice cylinder and the initial speed were slightly different. In both cases, the ice was destroyed by impact loads. In research [4] the impact of an ice cylinder on a thin aluminum barrier was considered.

2.1. Mobile laboratory "Explosive Destruction of Natural Materials"

In 2013 the mobile laboratory (mobilab) was organized in National Research Tomsk State University. Currently, mobilab develops as alternative to the resumed American research program "ScICExe". Ice research is conducted with the support of the Ministry of Emergency Situations of Russia and the company KuzbasSpetsVzryv. During this time, the traditional objects of research were natural limestone and river ice of different types. The shape of the explosive crater in the limestone after the blast was found [7]. The diameter and shape of the lane in ice cover were identified after the blast up explosives [8]. Later, the destruction of needle ice and ice cover of sandwich structures "Snow–Shuga – Ice" were studied under the same conditions [9]. The main features of mobilab are carrying out full-scale tests with a maximum explosion about 100 kg of trinitrotoluene (TNT). The main results the author's full-scale tests are the sizes of explosive craters and lanes, the revealed state of the edge of the craters and the morphology of the fragments, etc. Until now, this is treated as quality test.

2.2. Full-scale underwater explosion tests

This section focuses to full-scale underwater explosion tests (UNDEX). Emulsion explosives (EE) were used in all experiments. EE detonation velocity is 4600 m/s. EE charge was placed under ice in freshwater. The charge had a cylindrical shape and a mass of 4 kg (TNT equivalent 3.25 kg). At the moment of the explosion, EE was located horizontally to the ice cover. Water and air temperature was 4 °C. The depth of the water under the ice cover was approximately 5 meters (hydroimpact was excluded). The initiation point of explosion was at the top of charge EE.

2.3. Explosion of ice by EE

This section discusses the results of full-scale tests, with research object was freshwater ice of medium thickness only. The thickness of the ice was in the range from 70 cm to 90 cm. The average thickness of the snow was 15-20 cm. In rare cases, the thickness of the snow layer was 80 cm. In the current research, the results of the blasting of such ice are not given. There were no polynya, crack and fracture in the experimental site (terminology is used in accordance with the Sea Ice nomenclature of 1974). A hole was made in the ice cover to place an explosive in the water. Hole diameter was 11-16 cm.

The subject of the study was the state of the ice cover after the explosion, including the diameter of lane and ice edge inside lane. The diameter and height of the fragment scattering and the size of the fragments were also investigated. Five types of ice were studied by the authors. They are listed below in chronological order: snow covered ice (2013), bar ice (2014), ice cover sandwich structure “Snow - Shuga - Ice” (2015), needle ice (2016) and snow-covered ice (2017).

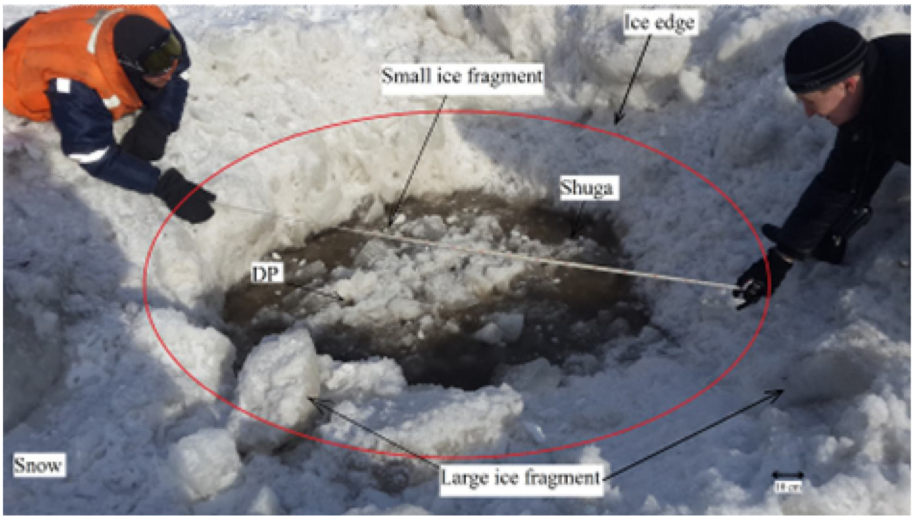

Figure 1. Lane in snow-covered ice cover. Full-scale test 2017. Bar represent 10 cm. Photo by S. Kul'kov

Figure 1 shows the lane after the explosion 4 kg EE. This is the result of full-tests this year. The diameter of the lane was approximately 200 cm. A detailed inspection showed that the lane had a round shape. The photo shows fragments of ice, including large ice fragment (about 50 cm). Inside the lane, small fragments of ice (about 10 cm), shuga and remnants of detonation products (DP) were found. Many remnants of the DP were dispersed by the wind. Under the action of DP, ice fragments and snow were raised up to a height of 10 meters. The ice edge was developed, i.e. smooth and not stepped. The first results of full-scale tests are demonstrated in the author's video [10]. A detailed analysis of the experimental studies revealed that the results of full-scale test of 2013 and the results of the full-scale tests of 2017 were the same.

3. Mathematical model

The ice is described by a phenomenological macroscopic model of the continuum mechanics. The ice model is based on the fundamental conservation laws. Ice model is porous, compressible, strength, with shock-wave phenomena. The Prandtl-Reis equations associated with von Mises equations are used. The shear modulus G and the yield strength σ are not constants. Components of the deviator of the tensor of elastic-plastic stresses are taken from [11].

Polycrystalline ice without phase transitions with averaged mechanical properties is considered. The effect of gravitational forces on ice and other materials is not taken into account. DP action is described by the Landau-Staniukovich polytropic. The appearance of new free surfaces in the process of deformation and destruction is possible. The equation of the state of ice is taken in the simplest form [12].

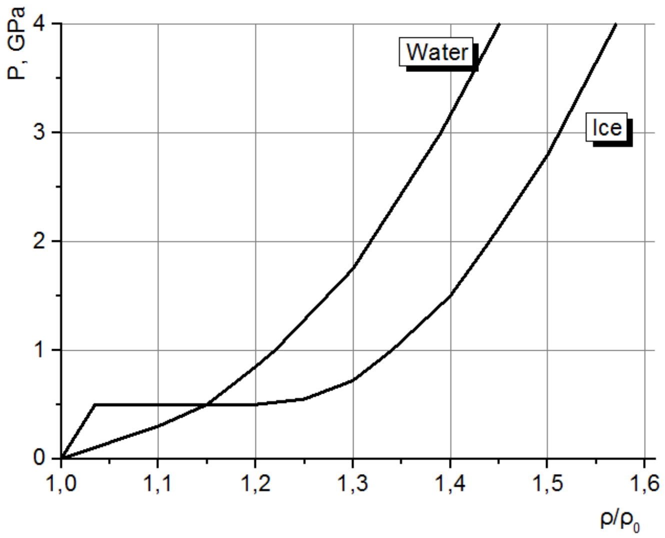

Figure 2. Shock adiabatic of ice and water

The shock adiabats of ice and water is shown in figure 2. The intersection point of the two curves was noted at a pressure of 0.5 GPa. After a pressure of 1 GPa, the curves become parallel.

4. Numerical method

The calculations were carried out in a two-dimensional axisymmetric formulation using a modified lagrangian method. The numerical method contains algorithms for calculating contact surfaces, an algorithm element erosion, an improved algorithm calculating contact surfaces, an algorithm splitting nodes, and so on. Together, algorithms are called a new way of isolating the surfaces of discontinuity in the continuity of materials (According V. Fomin's terminology). The proposed way does not impose serious limitations on the solution of the dynamical multi-contact problems of the mechanics solid body [13].

4.1. Test calculations

To test the mathematical model and the numerical method of calculations, some test calculations were solved. First, the impact test was solved. The impact test consisted in modeling the penetration of a spherical steel impactor into ice block. The impactor velocity varied from 100 m/s to 150 m/s. The post-penetration analysis confirmed that the impact crater in the ice had conical shape. A laboratory experiment was conducted at the Krylov Scientific Center. The discrepancy between the experiment and the calculation was about 8%.

Next, an underwater explosion of the ice cover of 2013 is modeled. The snow cover on the ice was absent in the calculations. The finite element model is constructed by the computer code “Impact 2D”. The number of finite elements was 10000. At “Ice – Water” interface, condition of sliding is considered. After this time, the pictures of destruction in the ice remained practically unchanged. According to the calculated data, the explosion of ice was accompanied by the separation of the spall plate. The speed of the spall plate, the time of the initiation of cracks, the volume of destruction and the diameter of the explosive lane were obtained numerically. The discrepancy with the experiment did not exceed 10% [14].

Test calculations have made it possible to determine the strength characteristics of ice, including dynamic yield strength, etc. Physical and mechanical properties of ice and other materials are listed in Table 1. The first column shows the properties of EE and TNT, respectively.

Table 1 Physical and mechanical properties materials

	Emulast AS-FP/TNT	Water	Freshwater Ice
Initial density, g/sm^3	1,34/1,66	1	0,92
Volume velocity of sound, m/s	2540	1500	3020
Shear modulus, GPa	26,9	0,1	3,2
Yield strength, GPa	0,025	0,0001	0, 0022
Spall strength, GPa	0,3	0,001	0,003
Specific work of shear plastic deformations, kJ/kg	100	500	5

5. Numerical research

In this section, numerical simulation of explosive ice destruction is presented. "Ice – Explosive – Water" system was considered. The mechanical properties of ice are given in table 1. The block ice thickness and depth of water were equal to 250 cm. The explosive was laid at a depth of 22 to 221 cm in ice. The charge weight was 4.8 kg. Only nonenveloped charge of TNT was used. TNT height is 23 cm and TNT thickness is 21 cm. The explosive charge was located in the center of the ice block. The number of calculated elements is approximately 20000. The variants of the calculation differed only in the depth of the explosive laying. There were 8 variants of calculations. The process of explosive loading was calculated up to 5 ms.

In the contact zone "Ice - Explosive" the first foci of destruction are formed irrespective of the depth of the explosive laying. Under the action of detonation products, zone of destruction extends from the epicenter of the explosion to the lateral surfaces of the ice block. The formed main cracks are oriented at different angles to the axis of symmetry. Fragmentary destruction of ice was accompanied by splashes of pieces of ice outside through the lane. In the variants 3, 4 and 5, the main crack divided the ice block into two parts.

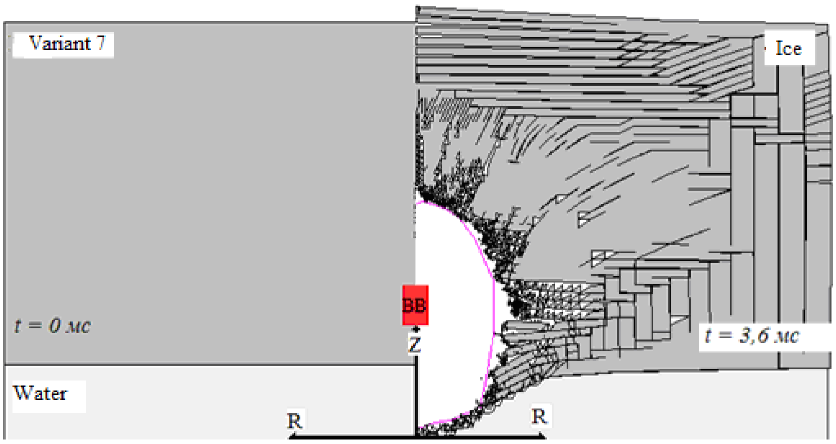

Figure 3. Configurations “Ice - Explosion – Water”, variant 7.

Figure 3 shows the configuration of the “Ice – Explosive - Water” for variant 7. The right side of the figure corresponds to time point of 3.6 ms, but left side of the figure corresponds to time point of 0 ms. The figure illustrates foci of destruction, main cracks and lane after explosive. At this time, the lane is still being formed. Destruction of the side and the back surface has already occurred.

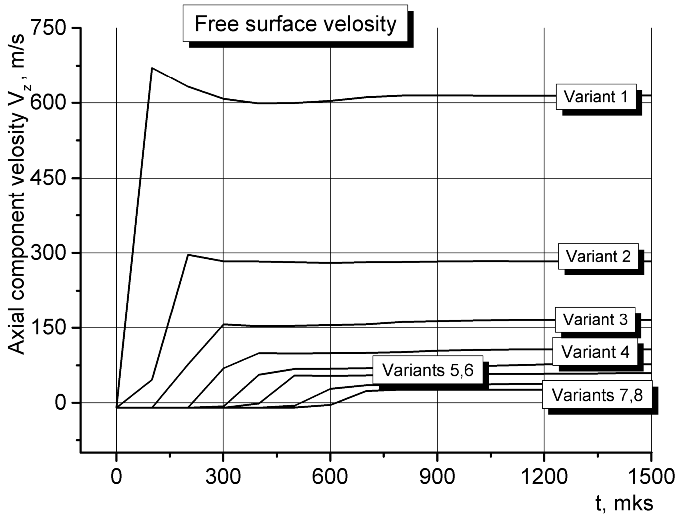

Figure 4. Profiles free surface velocity

Figure 4 shows the free surface velocity profiles for all variants. Velocity calculation performed in the control point on the symmetry axis. Obviously, the maximum velocity was in the first variant of the calculation, and the minimum velocity was in the last variant of the calculation. In the variants of calculations 5 and 6, and also variants 7 and 8, the velocities of the free surface were practically the same. The output of the shock wave on the free surface of the ice block was fixed in the range from 150 to 650 μs. In the range from 650 μs to 1500 ms, the free surface velocity was constant for all variants.

Table 2 presents the calculated parameters of the ice destruction process, including the damage to ice, the diameter of the lane in the ice and the velocity of the free surface.

Table 2. Numerical data of destruction of ice under explosive loads

Variant number	The depth of the explosives [cm]	Ice damage [%]	lane diameter in ice [cm]	Free surface speed of ice [m/s]
Variant 1	22	30,7	110	614
Variant 2	45	33,2	130	282
Variant 3	75	36,8	135	163
Variant 4	102	38,3	137	105
Variant 5	130	36,9	140	77
Variant 6	153	37,2	135	53
Variant 7	193	30,9	128	41
Variant 8	221	26,9	150	32

As a measure of ice damage, a quantitative criterion of materials damage was chosen. The criterion does not contain physical quantities and is bound only to the grid [11]. Maximum volume of ice damage did not exceed 40%. In variants 1-6, an increase in ice damage was noted. In variants 7 and 8, on the contrary, the damage to the ice decreased. The maximum diameter of the lane is fixed in the last variant. There the explosive was in contact with the water. The speed of the free surface decreased with increasing depth of the explosive laid.

6. Conclusion

1. The results of full-scale tests of 2017 coincided with the results of full-scale tests of 2013. Dimensions of lane in ice cover, its shape, ice edge, and morphology of ice destruction were subjects of comparison. From which it follows that the strength properties of these ice are also the same. Mechanical properties of such ice, including dynamic yield strength and other strength characteristics are defined in [1].
2. The process of explosive loading of an ice block on water has been investigated numerically. The velocity of the free ice surface, the volume of ice destruction and the diameter of the explosive lane in the ice were calculated. Depending on the location of the explosives depth free surface velocity varied from 614 m/s to 32 m/s. According to the calculated data, the diameter of the lane varied from 110 cm to 150 cm. The volume of destruction in the ice varied from 26% to 40%. The lower estimate is approximate. In all cases, it was a lot.
   For more effective destruction of ice, it is recommended to lay explosives in the middle of the ice block.

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