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Research of ice behaviour under shock and explosive loads. Numerical simulation and experiment

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Abstract. In this paper, results of experimental and numerical research of ice destruction under shock and explosive loads were summarized. Full-scale experiments and laboratory impact experiments were performed. Specially for carrying out full-scale tests the mobile laboratory "Explosive destruction of natural materials" was organized. Last year's results of full scale underwater explosive tests are given. The diameter of the polynya (lane) and the state of the ice edge were studied. The results of the experiment in which the target was three-layer ice barriers are presented. The ice was broken into fragments, and the projectile was slightly deformed. Briefly, the mathematical model of ice behavior is described. The numerical method is based on the Lagrangian approach and contained a new way for isolating discontinuity surfaces of material. The capabilities of the non - commercial software package were demonstrated. The results of the quantitative test are given. The deep penetration of a container with inert filler into ice on water was modeled. New research tasks have been formulated.

1. Introduction

Currently, it is important to study the behavior of ice under dynamic loads. This is due to a wide range of applications of such research. First of all, this is an increase in the extraction of natural resources in the Far North, the fight against ice jams on Siberian rivers, the creation of protective structure against micrometeorites, some military applications, etc. There is also the extraction of natural gas on the sea shelf and the development of infrastructure in the waters of the freezing seas. Recently, the development of the Northern Sea Route, which connects the European part of Russia and the Far East, is extremely important.

A well-known fact is that ice is a poorly understood natural material. There are more than 15 types of ice, some of which are of not terrestrial nature. The deformation and destruction of ice are accompanied by phase transitions; moreover, ice has unique plastic properties. Nowadays, the concepts of ice destruction are still being developed, and there are no adequate mathematical models of the behavior of ice under dynamic loads [1-3]. For example [4], the phenomenological model is tied to ballistic experiments. This situation is dampened by a small amount of experimental data, and some ones do not agree with each other. According to the article's authors, many experimental data, especially destruction ice data under explosive loads, have already become a bibliographic rarity.

In Research Institute of Applied Mathematics and Mechanics (hereinafter, RIAMM) conducts systematic scientific research whose object of study is ice. The leader in terms of the number of studies performed is the Department of Solid Mechanics. In research [5], a mathematical model of ice behavior under dynamics load is developed. In work [6], a new algorithm for calculating contact



surfaces is proposed, which more accurately describes the surface between the detonation products and ice. More than 5 years ago, a mobile laboratory "Explosive Destruction of Natural Materials" (hereinafter, mobilab) was organized specifically to obtain new experimental data on ice destruction under explosion [7]. In research [8], impact response of multilayer structures with ice plate subjected to projectile was studied. The deep penetration of metal container with explosives into thick ice is modeled in [9].

In current paper, the results of studies of the destruction of ice during impact and explosion are given. Experimental and theoretical research is presented in chronological order.

2. Experimental studies of ice destruction under shock and explosive loads

In this section, we focus on experimental research only. Research objects are snow-covered river ice of medium thickness and ice blocks (In accordance to Nomenclature of Sea Ice from 1974). The freezing time of river ice was approximate 130 days, and the freezing time of ice blocks was 2 days. And besides, in the first case, the temperature was not constant as in the second. These research are systematic and carried out in the RIAMM for more than 25 years.

The following two subsections discuss the results of full-scale experiments. All results obtained with the support of KuzbasSpetsVzryv. In the subsection shows the results of ballistic experiments, research objects were ice blocks of various degrees of freezing. The results were obtained with the support of the Society of Practical Bullet Shooting in the city of Tomsk [10].

2.1. Mobile laboratory "Explosive destruction of natural materials"

As mentioned earlier, ice is a poorly understood natural material. An analytical review on this topic indicates the insufficiency of experimental data on the destruction of ice under explosive loads [6]. Several years ago, a mobile laboratory "Explosive destruction of natural materials" was organized on the basis of Tomsk State University. The main objective of the mobilab is to deepen knowledge in the field of ice destruction under explosive loads. Currently, the mobilab has the status of an initiative project and is developing as an alternative to the American research program ScICEXe [11]. Regular its partners are the Ministry of Emergency Situations of the Russia and KuzbasSpetsVzryv.

The traditional research objects were natural limestone and freshwater ice. The 600 cm thick limestone massif was the first object of study. Snow-covered ice, bare ice, needle ice and sandwich structure ice cover of medium thickness was studied [6, 8]. In both cases, the subject of the research was their condition, including the morphology of destruction, the explosive crater, edge of ones or the lane after the explosion of various explosives. Emulsion explosives (EE), granulated explosives (GE) and ammonite explosives (AE), as well as explosive mixtures (EM) based on these components, were considered in the experiment. The explosive maximum mass was 1000 kg in TNT equivalent. In the current research, only EE will be discussed.

Within the framework of this event, the section "Explosive and Detonation Phenomena" is organized, the chairman of which is one of the authors of this article [12]. Several reports are devoted to the destruction of ice during an underwater explosion. At the moment it makes sense to create a relational database on the behavior of ice during explosive loading. Such a database will expand the scientific knowledge of the destruction of ice under explosion. We invite to cooperation other participants interested in creating such a database and an adequate mathematical model of ice, taking into account the dependence of the temperature of ice formation on its strength.

2.1.1 Full-scale underwater explosion test

Full-scale underwater explosion tests are described in this subsection. In all cases, the explosion was carried out in the water under the ice. There was no air gap between explosives and ice. 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 were 4°C. The depth of the water under the ice cover was approximately 5 meters (hydroimpact was excluded). The river bottom was flat. The initiation point of explosion was at the top of EE charge.



Figure 1. Lane (polynya) in snow-covered ice 2018. Scale bare represent 100 cm. Photo by M. Orlov. The photo is taken from the author’s report at the international scientific conference “CICMCM”.

Figure 1 shows a lane (polynya) into snow-covered ice after the explosion of 4 kg of EE charge. Below are the results of last year's experiments. The object of study is snow-covered ice. This is a traditional one, which has been studied for 6 years. The age of the ice is mentioned above. The thickness of the ice is no more than 80 cm, and the thickness of the snow on ice is 20 cm. A detailed inspection showed that the lane had a round shape. After extracting all the fragments of ice from the lane, it was possible to establish its edge. The ice edge was not stepped. The diameter of the lane was 230 cm.

2.2 Experimental study ice blocks destruction impacted by a 9-mm projectile

In research [13], low-velocity impact of ice cylinder with AU4G aluminum plates are studied. Experimentally, in the subsonic range of initial velocities, the residual displacement of thin metal plates after the impact of ice cylinders was obtained. Recently, in work [7] simulated the experiments in 2D elastic-plastic statement. Thus, it was experimentally and numerically established that the maximum displacement was recorded in the contact zone of the “projectile – target”. This experiment was used in the current work as a quantitative test, and the subject of comparison was the residual displacement.



Figure 2. Ice cylinder. Photo reprinted from [1].



Figure 3. Three ice cylinder target after impact

Further, the impact resistance of ice blocks impacted by a 9mm projectile was experimentally investigated. The research object is the ice cylinder (figure 2). The dimension ones is (10.5×4.5) cm.

The ice was made by freezing fresh water at $-24\text{ }^{\circ}\text{C}$. The freezing time is approximate 48 hours. Projectile is a 9mm Makarov pistol bullet. The initial velocity is 315 m/s. In previous work [8], one ice cylinder was considered as a target. In the current work, the target is a three-layer ice barrier. Figure 3 illustrates the target after the impact. High-speed shooting process of the collision was performed. However, the results are not shown here. Ice fragments of various sizes are visible on photo, including small fragments ($\approx 1\text{ mm}$). Projectile was not deformed. The results of this test repeat the results of last year's test. The figure 3 shows all the ice debris, including ones found several meters away from the initial position of the target.

3. Mathematical model and numerical method

This section presents a mathematical model of ice behavior under shock and explosive loads. In addition, a numerical calculation method for a 2D statement is given. The model and method were developed at the RIAMM and thoroughly tested [14]. The mathematical model is based on the macroscopic theory of continuum mechanics. The numerical method is the development of the Johnson's method for solving modern multi-contact problems of the mechanics of a deformable solid (hereinafter, MCPMDS). According to terminology [15], the numerical method contains a new way for isolating discontinuity surfaces of materials, which does not impose serious restrictions on the solution of MCPMDS.

3.1 Mathematical model of ice behavior under shock and explosive loads

The mathematical model allows describe the processes of destruction of solids at explosive and shock loads. The governing equations are based on the fundamental laws of conservation of mass, momentum and energy. A complex model of continuum mechanics used to describe the material behavior under dynamic load. Material modeled a porous, compressible medium, taking into account the strength properties, shock-wave phenomena, as well as formation fracture material. The model is described in detail in [14]. Unlike the mathematical model from [15], this model takes into account the destruction of materials.

The material is modeled by an elastic plastic medium. To describe the shear strength of a body, the Prandtl – Reuss constitutive equations and the von Mises yield condition were used [17]. The equation of state was Mi – Grüneisen. These equations are well known. The mathematical model allows us to use various equations of state, including the wide-range equation of state, etc. Pressure in detonation products (hereinafter, DP) is described using Landau – Stanyukovich polytropic [18]. The shock adiabat of ice and water is given in [18]. In the process of material destruction under dynamic loading, new free surfaces, including fragmentary destruction are allowed.

Here it makes sense to talk about the destruction of the model. A well-known fact is that the destruction of any material is accompanied by the formation of both tear-off fractures and shift fracture. Sometimes one type of destruction can prevail over another, for example, during an adiabatic shift. Therefore, when modelling fracture materials, both types must be considered. For the first time, this concept was implemented in [20]. The use of different failure criteria is quite possible. This makes it possible to simulate the destruction process of the most close to real one.

3.2 Numerical method

In this subsection, we focus on the numerical method. The system of equations is solved in the two-dimensional axisymmetric statement on the basis of the Lagrangian approach to the description of the motion of continuous media [21, 22]. Well-known fact is that any Lagrangian method has serious problems with solving tasks of the deep penetration of projectiles of complex geometry into structurally inhomogeneous targets. For example, one is the penetrating of multi-layer targets by a projectile with an ogival nose. The problem is the overlap of the triangulated elements [23]. To overcome this lack, the algorithm erosion elements, algorithm splitting nodes, the algorithm for constructing the free surface were introduced. The last algorithm will be mentioned below when modelling the tasks of explosive destruction of the ice [7].

As said before, the numerical method contains a new way for isolating the surfaces of discontinuity of materials. A similar approach to modeling the perforation tasks developed in the work [24]. However, in the present approach, several ways of splitting nodes are possible. In this algorithm, it is not necessary to store any information in the nodes as in the work [25]. This allows us to use various failure criteria of solids. For the numerical solution of MCPMDS, this is of equal importance.

3.3 Software package

A software package has been developed for the calculation of MCPMDS in the programming language C++. The program complex consists of a solver program and a viewer program. Until today there are more than five versions of both programs. The following shows the capabilities of the latest version of the program.

Figure 4 illustrates metal container with explosive substance at 140 μ s. The shell of the container is made of titanium. In previous work [9] the same container was considered as a projectile penetrating thick ice (200 cm). The target on which the container is located is a tungsten plate. There is a rigid fixation of the tungsten plate. You can see the residual displacement of the plate in the radial direction. Unfortunately, the scale of the pattern does not allow us to consider the degree of destruction of a fragment of a tungsten plate in the contact zone of the target – container.

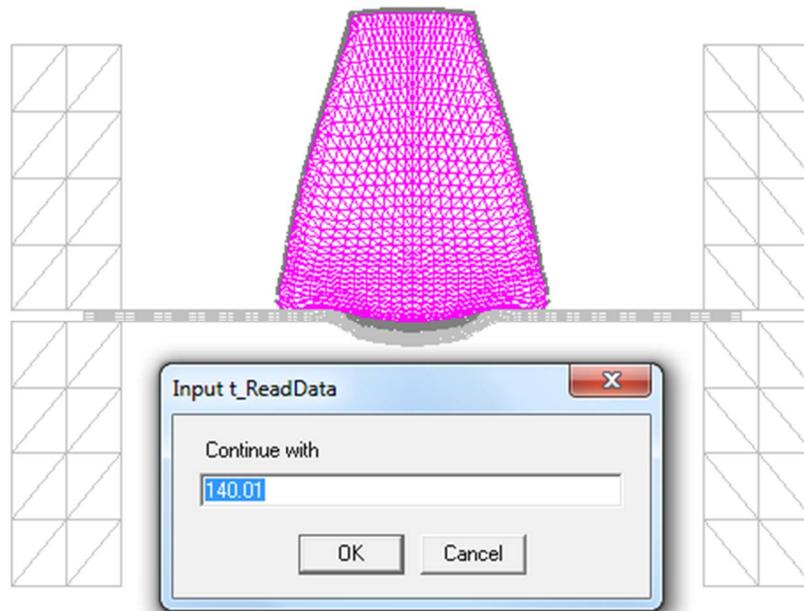


Figure 4. The Interface of Impact_2D, computer code developed by Yu. Orlov. The color indicates TNT. Computer Program Certificate is 2010615392

4. Numerical modelling and results

4.1 Test calculations

Before numerical simulation test calculations were carried out. As a quantitative test, the impact of an ice cylinder on a rigid wall was simulated. In the scientific literature, such a test is called the Taylor's test. Of course, the test results are predictable. The ice will be destroyed. The numerical results are also intended to demonstrate the capabilities of the software package.

The initial velocity cylinder was varied from 50 to 150 m/s. The diameter of the cylinder is 6.88 mm, the height of one is 20.6 mm. A series of computational experiments consisted of 5 cases. The subject of research was the relative shortening, equal to the ratio of the final height of the cylinder to the original height of the cylinder.

Figure 5 shows the figure at time 0 and 35 μ s. In first case, the initial velocity is 50 m/s.

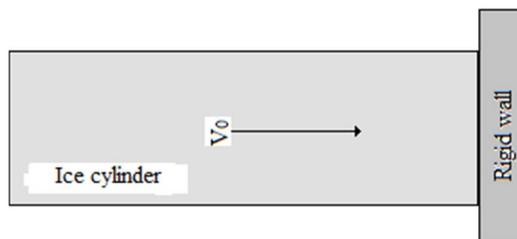


Figure 5. Ice cylinder – Rigid wall. The impact was left to right.

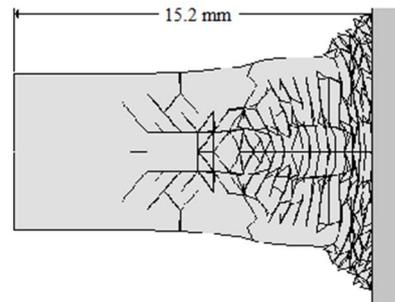


Figure 6. Ice cylinder after 35 μ s..

It is revealed that the first foci of destruction appear in the ice in the contact zone of the cylinder – a rigid wall in the first microseconds of the collision process. After this short time, the ice cylinder is deformed in the radial direction. Then, the destruction of the ice begins with the separation of fragments. Only in cases 1, 2 the bottom part of the ice cylinder is not destroyed and had a cylindrical shape. In case 4, the cylinder was severely damaged, but its shape made it possible to evaluate the shortening. In case 5 it was not possible to do this.

Table 1. Ice cylinder relative shortening

Case 1	Case 2	Case 3	Case 4	Case 5
$V_0 = 50 \text{ m/s}$	$V_0 = 75 \text{ m/s}$	$V_0 = 100 \text{ m/s}$	$V_0 = 125 \text{ m/s}$	$V_0 = 150 \text{ m/s}$
0.737	0.582	0.432	0.301	-

Table 1 shows the calculated values of the relative shortening of the ice cylinder. It is seen that with an increase in the initial velocity, a decrease in the relative shortening was observed. This fact is obvious and not commented.

In addition, a comparison of numerical results with experimental results from [26, 27] was made. In both cases, the ice was destroyed.

4.2 Deep penetration of the metal container into the thick ice on the water

This section presents the results of numerical simulation. Projectile is a metal container with inert filler. The filler imitated explosive. The container diameter is 34 cm. The height of the container was 87.7 cm. The mass of the container along with the mass of the filler is 235 kg. The mass of filler is 108.6 kg. The target is a 100 cm ice plate on a water substrate. A slip condition is specified at the contact boundary “Water – Ice”. The diameter of the ice plate is 400 cm. A series of computational experiments consisted of 4 calculation cases. The cases differed only in initial velocity. The initial velocity varies from 150 to 300 m/s. This task is a continuation of research from previous work [9].

The simulation results revealed the following patterns of the penetration process. The first foci of destruction are formed in the ice at 1 μ s. Also at the beginning of the process ice is compacted in the contact zone of the “Projectile – Ice”. The penetration projectile into the ice is accompanied by an increase in the impact crater. In all cases, the impact crater was V-shaped. The “Ice – Water” contact boundary becomes curved. After impact, the metal container is slightly deformed in the radial

direction. Ice flexes axially. Figure 8 clearly shows this. The growth of the initial velocity leads to the appearance of macro cracks extending in from the axis of symmetry to the lateral surface (figure 8). The air gap between the filler and the bottom of the projectile was found. Most likely, in the latter case, the projectile perforates ice and water.

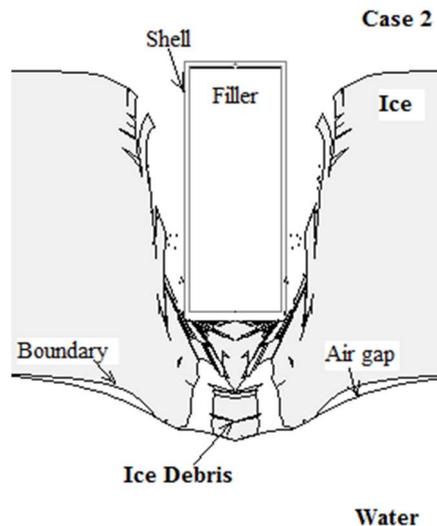


Figure 7. Current configuration for case 2: Container – Ice – Water at 10 ms. The impact was top down.

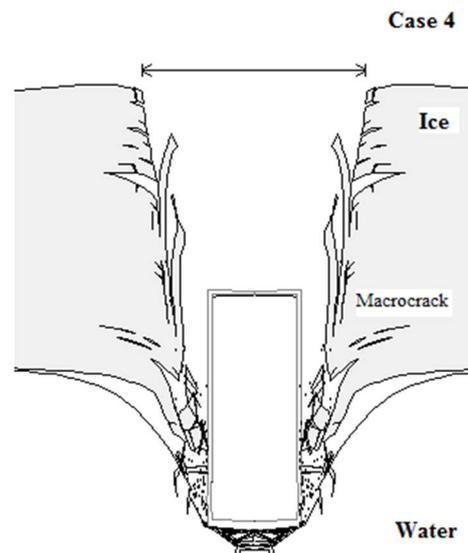


Figure 8. Current configuration for case 4: Container – Ice – Water at 10 ms

Table 2 shows the calculated values for the four cases. The table shows the values of the initial velocities for all four cases, the time of penetration of the projectile into the ice on water t_p , the diameter of the impact crater d , the depth of penetration L_k , the volume of ice damage D_{ice} . In addition, there is an air gap between the filler and the rear wall of the container. Unfortunately, in figures 7, 8 the gap is almost invisible.

Table 2. The results of calculations of the deep penetration of the impactor into the ice on water

	Initial velocity [m/s]	Penetration Time, t_p [ms]	Impact crater Diameter, d [cm]	Depth Penetration, L_k [cm]	Ice damage D_{ice} [%]	Air gap into container
Case 1	150	10.00	61.5	51.9	1.5	+
Case 2	200	12.93	78.7	99.2	3.1	+
Case 3	250	14.00	79.9	132.7	4.5	+
Case 4	300	16.75	82.0	218.5	6.4	+

From the table it can be seen that the projectile penetration time t_p increased with an increase its initial velocity. In the velocity range from 150 to 300 m/s, the penetration time was in the range from 10 ms to 16.75 ms. In fact, the penetration time was somewhat longer, since the calculations stopped until the moment of complete braking of the projectile.

Of particular scientific interest is the change in the diameter of the impact crater. In all cases, the diameter of the impact crater was larger than the initial diameter of the container. In the last three cases, the diameter of the crater was more than twice the diameter of the impactor. As it was said earlier, the crater was V-shaped.

It was established that only in the first case the projectile could not penetrate the ice more than its own height. Thus, in the last three cases, the projectile perforated a 100 cm ice barrier. Thus, after ice penetrating, projectile possesses significant kinetic energy. It should be noted that the shape of the

front surface of the projectile is slightly deformed. The fact established by numerical modelling allows us to form a number of new research tasks. For example, the possibility of self-detonating the filler when a projectile strikes a two-layer ice target on water.

The amount of damage of the ice was insignificant. The maximum volume is fixed in the latest case and is 6.4%. The main amount of damage is ice zone destruction in the contact area "Projectile – Ice". There is in the form of a fragment of ice with sizes equivalent to diameter with a projectile. Calculations of ice damage are made as in research [14].

5. Conclusion

The paper presents the results of experimental and theoretical studies of the process of ice destruction under explosive and shock loads.

1. A brief analytical review of the research topic is given. According to this review, it is necessary to expand scientific knowledge in the field of ice destruction. Experimental results on the blast of ice in water under ice by the authors were not found. This is a complex scientific task since the strength of ice depends on the temperature of its formation. The mobilab was organized specifically for this purpose. The morphology of ice destruction, including the lane diameter and ice edge state the snow-covered ice, bare ice, needle and ice sandwich structure was studied. At the moment, an attempt is being made to establish the relationship between the average temperature of the air and the diameter of the lane into ice cover when the EE are blown up.
2. The results of impact normal experiments are presented. The target was a three-layer barrier of ice cylinders. Projectile is well-known 9 mm bullet. Initial velocity is approximate 315 m/s. The air gap between the layers was not. After perforation of the ice target by the projectile, it was destroyed into fragments of various sizes. Medium-sized fragments prevailed (sizes comparable to those of a projectile). Although the latter fact may be challenged. The next object of study it is reasonable to choose a multi-layered target ice and metal or ice and plexiglass (PMMA).
3. The behavior of ice under impact and explosion is described by the elastic-plastic model of continuum mechanics. The model takes into account the properties of strength, porosity, compressibility, shock-wave phenomena as well as formation fracture material. To describe the shear strength of a body, the Prandtl – Reuss constitutive equations and the von Mises yield condition were used. The concept of joint formation of spall and shear destruction has been implemented. Pressure in DP is described using Landau – Stanyukovich polytropic.
4. The system of equations is solved in the two-dimensional axisymmetric statement on the basis of the Lagrangian approach to the description of the motion of continuous media. The problem is the overlap of the triangulated elements. To overcome this lack, the algorithm erosion elements, algorithm splitting nodes, the algorithm for constructing the free surface were introduced. According to terminology [15], the numerical method contains a new way for isolating discontinuity surfaces of materials, which does not impose serious restrictions on the solution of MCPMDS. One quantitative test was also given. In accordance with the terminology of [28].
5. The deep penetration of a container with filler into ice on water was modeled. The impact crater into ice was V-shaped. An increase in the initial velocity leads to an increase in ice damage. After impact, the container almost retained its original shape. At the beginning of the penetrating, a gap was formed between the filler and the container. By the end of the penetrating, the gap value decreased. The ice was compacted in the contact zone "Projectile – Ice". The volume of damage in the ice was not significant. Sometimes, the projectile was deformed both axially and radially. In the considered velocity range, the maximum penetration time did not exceed 20 ms. With an increase in the initial velocity, the penetration time increased.

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References

- [1] Bogorodsky V V and Gavrilov V P 1980 *Led. Fizicheskaya Svoystva Sovremennyye Metody glyatsiologii* (Leningrad: Gidrometeoizdat Press) p 250 (in Russ.)
- [2] Schulson E and Duval P 2009 *Creep and Fracture of Ice* (Cambridge University Press) p 400
- [3] Stewart S T and Ahrens T J (2005), Shock properties of H₂O Ice, *J. Geophys. Res.*, 110, E03005,
- [4] Carney K S (Eds) 2006 *Int. J. of Solids and Structures*, **43** 7820–7839
- [5] Orlova Yu N and Orlov M Yu The study of the process of explosive loading of ice 2015 *Tomsk State University Journal of Mathematics and Mechanics*, **38** pp. 81-89 (in Russ)
- [6] Orlov M Y, Orlova Y N and Tolkachev V F 2015 *J. Phys.: Conf. Ser.* 653 012038
- [7] Orlova Yu N “Kompleksnoye teoreticheskoye i eksperimental'noye issledovaniye povedeniya l'da pri udarnykh i vzryvnykh nagruzkakh”, Ph.D. thesis, Tomsk State University, 2014 (in Russ.)
- [8] Orlov M Yu *et al* 2017 *J. Phys.: Conf. Ser.* **919** 012002
- [9] Glazyrin V P, Orlov M Yu and Orlova Yu N 2012 *Works of Tomsk State University/ Physics and Mathematical Series. V. 282* pp. 329 -334 (in Russ)
- [10] Official website of the Practical Shooting Federation of Russia in Tomsk, <http://strelok.tomsk.ru/>
- [11] Bocharov, L Yu, *et al.* 2015 *Arctic: Ecology and Economy*, 3, 19, pp. 48-53 (in Russ.)
- [12] Official Scientific Conference Current Issues Continuum Mechanics and Celestial Mechanics Website, <http://cimcm.tsu.ru/index.php/ru/>
- [13] Combescure A, Cyuzel-Marmot Y 2011 *Int. J. of Solids and Structures*, **48** 2779-2790
- [14] *Teoreticheskiye i eksperimental'nyye issledovaniya vysokoskorostnogo vzaimodeystviya tel*, edited by A. Gerasimov (Tomsk State University Press, Tomsk, 2007), p. 572. (in Russ)
- [15] Gerasimov A Cherepanov R Krektuleva R. and Barashkov V (2017) MATEC Web of Conferences 92, 01071
- [16] Fomin V *et al.* High-speed interaction of bodies (Publishing House of the Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia, 1999), p.600 (in Russ)
- [17] Johnson J N 1987 *Int. J. of Impact Engng*, **5** 423 – 439
- [18] *Explosion Physics*, 3rd ed, edited by L. Orlenko (FizMatLit, Moscow, 2004), Vol. 1, p.832.
- [19] Larson D B *Int. J. of Glaciology* 1984, **30**, 105, 235-240
- [20] Tolkachev V and Trushkov V [Matematicheskoye modelirovaniye sdvigovykh i otkol'nykh razrusheniy pri udarnom vzaimodeystvii uprugoplasticheskikh tel] *Russian Journal of Physical Chemistry B: Focus on Physics*. 12, pp.170-175 (1993) (in Russ)
- [21] Wilkins M L 1978 *Int. J. of Impact Engng*, **16** 793-807
- [22] Johnson G R 1976 *Int. J Appl. Mech.* **43**, 439-444
- [23] Flis W J 1987 *Int. J. of Impact Engng*. **5**, 1-4. 269-275
- [24] Olovsson L, Limido J, Lacombe J-L, Hanssen AG and Petit J 2015 EPJ Web of Conferences **94**, 04050
- [25] Nemirovich-Danchenko M M (1998) *Int. J. of Phys. Mesomech.* **1-2** 101-108
- [26] Zelepugin S A, Mali V I, Zelepugin A S and Ilina E V 2012 *AIP Conference Proceedings* 1426 1101-4.
- [27] Skripnyak V V *et al.* 2018 *J. Phys.: Conf. Ser* **1115** 042016
- [28] Means of destruction and ammunition, (Ed. Vik. Selivanov), Bauman Moscow Technical University Publishing House, 2008 (in Russ.)