INVESTIGATION OF THE PROCESS OF EXPLOSIVE LOADING OF FRESHWATER ICE

by

Maxim Yu. ORLOV*

National Research Tomsk State University, Tomsk, Russia

Original scientific paper
https://doi.org/10.2298/TSCI19S2561O

The behaviour of freshwater ice under the action of detonation products has been studied. As objects of the study was chosen snow covered ice of medium thickness. The ice cover of 2018 and 2017 on the Tom River was considered in current research. The age of the ice was approximate 130 days, but the temperature of its formation was different. In the first case (2017), the ice formation temperature was 7.5 % lower than in the second case. The sizes of the lanes in the snow covered ice after detonation of 4 kg of emulsion explosive are obtained. It was established that in the second case the diameter of the lane was 15% smaller than in the first case. The ice edge of the lane in the snow-covered and bare ice was determined. The edge of the needle ice, which had a stepped shape, is presented. A qualitative and quantitative assessment of the destruction of ice under explosive loads is given. It was found that the temperature of ice formation influenced the process of its destruction under explosive loads.

Key words: *ice, full-scale test, underwater explosion, detonation product, lane, destruction, air temperature*

Introduction

At present time, the research of the behaviour of ice under dynamic loads is extremely urgent. This is explained by the need to develop the infrastructure of the northern territories, the extraction of natural resources in the Far North, the fight against ice jams on Siberian rivers, the creation of protective structures against micrometeorites, *etc*. In addition, it makes sense to mention military applications. Ice is a poorly understood natural material, as its strength properties depend on temperature. Concepts of ice destruction are only being developed [1]. A well-known fact is that the strength of ice increases with decreasing temperature. Nowadays, scientific interest will be to verify this fact when explosives are exploded.

The underwater explosion of thick ice (≤400 cm) by cylindrical and spherical explosive charges is modelled in work [2]. Numerical simulation was carried out by the method of Godunov. In most cases, for numerical modelling, a group of mechanical characteristics is used from [3, 4]. A dynamic model for frozen ice is proposed considering temperature and volumetric strain in [5]. The penetrating of ice plates by projectile and the blasting of ones was simulated in [6]. Freshwater ice was with a fixed melting point. Nowadays all current ice research projects can be found on the official website Ice Research Laboratory [7]. However, an analysis of scientific and technical literature points to a lack of experimental data on this

* Author's e-mail: orloff_m@mail.ru

topic. The results of experiments on the explosion of ice by explosives were not revealed by the author. Most likely, such research have become a bibliographic rarity.

In current research, the results of full-scale experiments of an underwater explosion of a snow-covered ice cover with emulsion explosives (EE) are presented. The results of full-scale experiments for the last two years have been discussed. Ice formation temperature differed by 7.5%.

Mobile laboratory *Explosive Destruction of Natural Materials*

Several years ago, mobile laboratory *Explosive Destruction of Natural Materials* was created in the Research Institute of Applied Mathematics and Mechanics (RIAMM). Now one has the status of the initial project and is not a structural unit of the university. The constant partners of mobilab are the company KuzbasSpetsVzryv and the Ministry for Emergency Situations (EMERCOM). Currently, the mobilab is developing as an alternative to the US Research program ScIcExe [8]. But in our case, the objects of study were more, including rocks and concrete. Arsenal mobile laboratory has a certified measuring instrument, including ultrasonic and laser rulers and other accessories. The process of the explosion is filmed on several cameras with high-definition matrix. The distance between the camera and the epicentre of the explosion is about 10 meters. High-speed shooting (up to 10000 frames per second) is planned in the near future.

For the first time, the results of full-scale underwater experiments were presented in [9]. The object of the study was ice cover medium thickness. Of the five previously studied objects was bare ice. After the explosion of the EE, a detailed analysis of the ice cover was carried out. We focused on the morphology of the destruction of ice only. Empirically found that after an explosion under water two charges EE (weight 8 kg) diameter lane into bare ice was approximate 4.3 meters. Basically, the lane had the shape of a circle, in rare cases it was oval.

Over the past five years, the snap analysis of the behaviour of ice under explosive loading, including bare ice, snow-covered ice, needle ice and ice sandwich structure (snow--shuga-ice) has been carried out. The subject of the study is ice fragments, shape of the lane in the ice cover and the ice edge, the height of the fragment scattering and so on. On the Tom River, experimental sites have been chosen specially for this purpose. As a result of experimental work, more than 1000 kg of TNT were blown up. Many experiments are recorded on video. There is a large photo collection. The creation of a relational database is scheduled by the author.

In accordance with the terminology from [10], experimental results can be interpreted as qualitative and quantitative tests. A striking example of a qualitative test was the experiment to undermine the limestone [9]. In this work, the dependence of the type of explosives on the shape of a crater in a limestone was established. The EE, granulite explosives and ammonite explosives, as well as an explosive mixture based on these components were considered.

The most successful quantitative test was the UNDEX-experiment from [11]. In 2012, UNDEX-experiments were carried out and numerically modelled in 2015. The object of the study was snow-covered ice (snow thickness ≈15 cm). The mass of EE is 4 kg. The experimental value of the diameter of the lane in ice cover was 200 cm. Within the framework of *instantaneous* detonation model was simulated the experiment. The process of destruction of ice under the action of detonation products is considered at all its stages. The time of the formation of the first foci of destruction in ice, the hydrodynamic pressure at the control points, the velocity of the leading fragments were revealed numerically. The free surface velocity profile was built. In a numerical experiment, the diameter of the lane was 210 cm.

Full-scale underwater explosion test

This section focuses to full scale underwater explosion experiment (UNDEX). Physical phenomena occurring during an underwater explosion are described in [12, 13]. Blast resistance of fiberglass under a non-contact underwater explosion was considered in [14]. In the experimental part of the research, the explosion chamber of the Krylov Scientific Center (St. Petersburg) was used. Radial tear-off cracks were found in fiberglass after the explosion. The revealed regularities of the process of ice destruction during the explosion of EE in water under ice cover are noted in [15].

Emulsion explosive Emulast-AS-FP-90 is used. Detonation velocity is 4600 m/s. The EE charge of explosives is placed under the ice cover through a hole in it. It has cylindrical shape and a mass of 4 kg (3.25 kg equivalent of TNT for heat of explosion). The length of the explosive charge is 90 cm. The explosive is in a polyethylene shell. Water and air temperature is 4°C. As a rule, the location of the explosive charge under the ice is horizontal. There is no gap between explosives and ice. The initiation point was at the top of the charge. There are no recurring polynia, crack and fracture ice cover in experimental site (according to terminology Sea Ice Nomenclatura of 1974). The area one is approximately 1000 m^2. The surface of the ice cover is smooth. The depth of the water under the ice cover is approximately 5 meters.

Permanent monitoring ice cover in Tomsk region in conjunction with the EMERCOM made it possible to determine experimental sites suitable for conducting experiments. It can be divided into areas with a bare ice, snow-covered ice and ice cover like *needle ice*. In all cases, ice has an average thickness ($\leq$80 cm). The UNDEX experiments consisted of 10 explosions. In the next section, the average diameters of the lanes in ice are given. The first photos of lane and videos were obtained 15 minutes after the explosion. The measurements were carried out by direct methods.

Research objects and experimental results

In the current work, the object of study is snow-covered ice of medium thickness only. Ice cover 2017 and 2018 is considered. The thickness of the snow above the ice cover is approximately 20 cm. This ice cover is the most common on the Tom River. The experimental site for full-scale test has not changed since 2012. The age of ice is about 130 days. We will assume that temperature of ice formation coincided with the ambient temperature. This is the main difference in our research objects. The arithmetic mean of the monthly temperature in 2017 was 7.5% lower than in 2018.

As mentioned in the previous section, an underwater explosion of EE this ice was modelled in [2]. In work, freshwater ice without phase transitions with averaged physics and mechanical characteristics was studied. This ice is closest to the lake's ice from [3]. First of all, it is possible to determine the strength characteristics, including yield strength and spall strength. Some group of characteristics are given below.

Ice initial density is 0.92 g/cm^3, shear modulus is 3.2 GPa, yield strength is 0.0022 GPa,Volumetric speed of sound is 3020 m/s, and spall strength is 0.003 GPa.

This section presents the results of full-scale tests in 2018 and 2017. The object of research is previously described. Experimental were conducted in the same place. The depth of the water under the ice is not more than four meters. The average thickness of the ice cover is 75 cm. The thickness of the snow is not more than 20 cm. Water flow is not significant. Weight of EE is 4 kg.

Below are the experimental results in reverse chronological order. At the beginning, let's analyse the results this year. Figure 1 illustrates the state of the ice cover after the explosion of EE. The shape of the lane resembled a circle whose centre is located in the epicentre of the blast. A preliminary inspection of the experimental site showed that there were no radial cracks in the ice under snow. The height of fragment scattering under the action of detonation products was approximate 5 meters. The fragments flew to a distance of 7 meters from the epicenter of the blast. This distance was reached by the smallest fragments (≤10 cm) only. It should be noted that before the explosion in this place was a hole for laying EE. The approximate diameter of the lane in the ice reached 220-230 cm (average value according to the results of 10 experiments). The hardest and most important point is the definition of the shape of the edge of the ice. The ice edge had a complex shape, but it looked more like a stepped one.

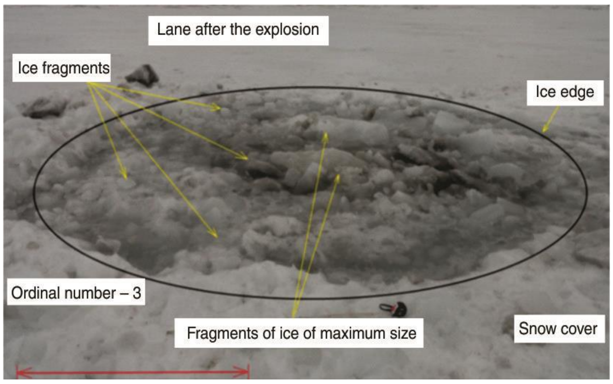

Figure 1. Full-scale test 2018; bar represent 100 cm

Separately, it makes sense to investigate the morphology of the destruction of ice. In this aspect, the important point is to establish the size of the diameter of the lane. For this, it is necessary to reveal the state of the ice edge. As practice shows, the state of the ice edge may take a straight, obtuse and an acute angle to the boundary of the *ice-water*. Sometimes, the ice edge can be step-shaped. Figure 2 illustrates such an edge of ice, and the ice edge reconstructed profile in needle ice after 10 kg EE blasting (see below photo). On such an ice edge it is quite possible to move to a person. By the way, this is the main difficulty in carrying out lane measurements. It should be remembered that this ice was not the object of research in this work.

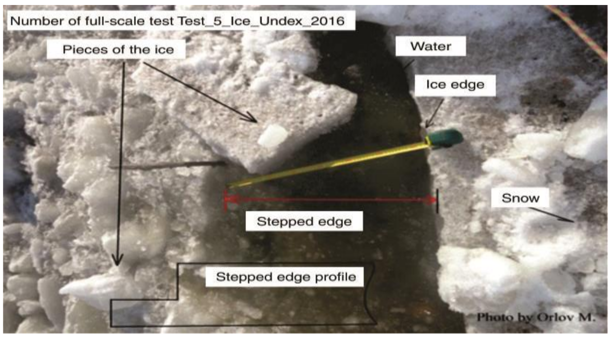

Figure 2. Full scale test 2016; ice edge in needle ice cover
Photo taken from the author's report at the scientific conference MIT-2016

The opposite situation occurred last year when the object of study was the snow-covered ice. The ice edge was not stepped-wise, but was inclined, *i. e*. was an acute angle between the ice-water boundary. Figure 3 shows the lane after blasting EE. It can be seen that, unlike the previous case (see fig. 1), in this case there is a shuga inside the lane, small fragments of ice and snow. After extracting all this from the lane, its diameter was about 200 cm. It should be noted that there were few fragments of large and small size. Thus, the main difference was in the morphology of the destruction of ice. In the first case, there were more ice fragments after blasting 4 kg EE. The diameter of the lane differed by 15%. In the second case, the ice edge was oblique.

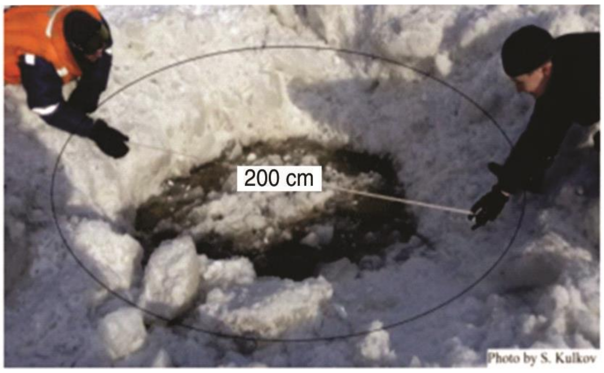

Figure 3. Full-scale test 2017
Photo by S. Kulkov. Photo reprinted from [9]

The table presents the results of full-scale experiments in 2018 and 2017. It is seen that all the parameters of the experiments except the average monthly temperature are equal. The thickness of the snow cover is an approximate value. The age of ice was no more than 130 days. The diameter of the lane in the ice varies by 15%. In the first case (for 2018), it is more than in the second case (for 2017).

Table 1. Result of full-scale experiments

	Ice cover 2018	Ice cover 2017
Average air temperature	–11.68 °C	–12.36 °C
EE weight	4 kg	4 kg
Ice thickness	75 cm	75 cm
Ice cover thickness	20 cm	20 cm
Diameter of the lane	230 cm	200 cm

Conclusions

- On the basis of the RI AMM, a mobile laboratory *Explosive Destruction of Natural Materials* is created. At the moment, the main goal of mobilab is to snap-analysis of the behaviour of ice under explosive loads, including the state of the ice edge, the morphology of the destruction and the diameter of the lane in the ice cover. In fact, this greatly expands the research capabilities of the scientific team. At least four types of ice cover, including snow-covered ice, bare ice, needle ice and ice sandwich structures have been studied. The maximum mass of the emulsion explosive was 12 kg (approximately 10 kg in TNT). The mass of the blasted explosive was more than 1000 kg. In all cases, the lane in the ice cover has the form of a circle with a diameter of 200 to 800 cm. The distinctive features are the edge of the ice and the size of the ice fragments. Some results can be interpreted as a qualitative and quantitative tests.

- It has been established that the strength properties of freshwater ice depend on the temperature of its formation. This is confirmed by the full-scale experiments carried out in current research. For example, after the blast of 4 kg of EE in an ice cover of medium thickness, a circular lane with a diameter of 200 cm to 600 cm is formed. A well-known fact is that a decrease in temperature affects the increase in the strength properties of ice. The experimental research once again confirms this fact. The presence of a snow cover has less effect on the strength properties of ice. Obviously, the strength of ice varies throughout the thickness of the ice layer. The previous applies to fresh-water ice of medium thickness on the Siberian rivers. The age of such ice varies is about 130 days.
- Two snow-covered ice covers were considered as objects of study in full-scale tests. In the first case (2017), the ice formation temperature was 7.5% lower. It is important to understand what is meant by the average monthly air temperature. The research attempts to establish the main mechanisms for the destruction of snow-covered ice after an explosion of EE in water under ice. A different diameter of the lane in the ice and a different morphology of destruction was noted. In the first case, the diameter lane by 15% was greater than in the second case. The main difference in the morphology of destruction lies in the size of the ice fragments that occurred after the explosion. At a lower ice formation temperature, a smaller diameter lane in ice was observed. With increasing temperature, more small ice fragments were observed inside the lane.

Acknowledgment

The reported study was funded by RFBR according to the research project № 19-08-01152. The author thanks the chief engineer of the company *KuzbasSpetsVzryv* Alexei Sadokhin and employees RI AMM for assistance in the experiments.

Acronyms

EE	– emulsion explosive (Emulast-AS-FP-90)
RIAMM	– Research Institute of Applied Mathematics and Mechanics at Tomsk State University
EMERCOM	– Ministry for Emergency Situations of Russian Federation
ScIcExe	– Science Ice Execise – US Research Scientific Program
TNT	– trotyl
UNDEX	– under water explosive
Mobilab	– Mobile laboratory *Explosive Destruction of Natural Materials*
MIT-2016	– International Conference *Mathematical and Information Technologies*, Serbia, Vrnjacka Banja, 2016

References

[1] Trude, P., *Physics and Mechanics of Ice*, Springer-Verlag, Berlin, Heidenlberg, Germany, 1980
[2] Velichko, O. M, *et al*., Software Packages for Solving Multidimensional Gas Dynamics Problems by the Godunov's Method (in Russian), *Proceedings*, 3 Nauchnoy Konferentsii Volzhskogo Regional'nogo Tsentra RARAN "Sovremennyye Metody Proyektirovaniya i Otrabotki Raketno-Artilleriyskogo Vooruzheniya", Sarov, Russia, 2000, pp. 20-30
[3] Bogorodsky, V. V., Gavrilo, V. P., *Led. Fizicheskaya Svoystva Sovremennyye Metody Glyatsiologii*, (Ice. Physical Property. Modern Methods of Glaciology – in Russian), Gidrometeoizdat Press, Leningrad, USSR, 1980

[4] Schulson, E., Duval, P., *Creep and Fracture of Ice,* Cambridge University Press, Cambridge, Mass., USA, 2009
[5] Zhu, Z. W., *et al*., Theoretical Study of Thermal Damage in Frozen Soil, *Thermal Science*, *19* (2015), 4, pp. 1419-1422
[6] Trushkov, V., Chislennoye Issledovaniye Vysokoskorostnogo Vzaimodeystviya Tel s Bol'shimi Deformatsiyami Sredy v Eylerovom Podkhode, (Numerical Study of High-Speed Interaction of Bodies with Large Deformations of the Medium in the Eulerian Approach – in Russian), in: *Teoreticheskoye i Eksperimental'noye Issledovaniye Vysokoskorostnogo Vzaimodeystviya Tel*, (Theoretical and Experimental Study of High-Speed Interaction of Bodies– in Russian), (Ed. A. Gerasimov), Tomsk State University Press, Tomsk, Russia, 2007, pp. 237-391
[7] ***, Ice Research Laboratory, https://engineering.dartmouth.edu/icelab/
[8] Bocharov, L. Yu., *et al.*, US Scientific Research in the Arctic: Organizational Approach and Military (in Russian), *Arctic: Ecology and Economy,* 3 (2015), 19, pp. 48-53
[9] Orlov, M. Yu., *et al* Mobile Laboratory "Explosive Destruction of Natural Materials": Investigation of the Behavior of Ice and Limestone under Explosive Loading, *Journal of Physics Conference Series, 653* (2015), 1, 012038
[10] Selivanov, V., *Sredstva Porazheniya i Boyepripasy* (Means of Destruction and Ammunition – in Russian), Bauman Moscow Technical University Publishing House, Moscow, 2008
[11] Orlov, M. Yu., Orlov, Yu. N., Comprehensive Theoretical and Experimental Study of the Behavior of Ice under Shock and Explosive Loads (In Russian), *Problems of the Arctic and Antarctic, 1* (2016), 107, pp. 28-38
[12] Cole, R., *Underwater Explosions*, Princeton University Press, Princeton, N. J., USA, 1948, p. 43
[13] Zamyshlyaev, B., Yakovlev, Yu., *Dynamic Loads during the Underwater Explosion* (in Russian), Sudostroyeniye Publishing House, Leningrad, USSR, 1967, p. 387
[14] Dulnev, A. I., Nekliudova, E. A., Experimental and Computational Blast Resistance Assessment of Polymer Composite Sampeles and Contactless Underwater Explosion (in Russian), in: *Trudy Tomskogo Gosudarstvennogo Universiteta, Seriya Phisico-Matematicheskaya,* (Ed. M. Orlov), 2017, Vol. 300, pp. 48-57
[15] Orlov, M. Yu., *et al.,* Research of the Behavior of Ice on Water under Explosive Loads, *Journal of Physics Conference Series*, *919* (2017), 012006

Paper submitted: September 3, 2018
Paper revised: November 11, 2018
Paper accepted: December 5, 2018