EXPLOSION EFFECTS IN THE VICINITY OF THE NORD STREAM 2 PIPELINE ON THE ENVIRONMENT - THEORETICAL ANALYSIS

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ABSTRACT

The study analyzes the effects of an underwater explosion recorded in the Baltic Sea on September 26, 2022, with coordinates: 54.675 North and 15.574 East at a depth of 76.2 m. Based on data from the seismic monitoring system, the detonated charges were estimated at 750 kg of TNT. Then, the empirical equations of R. H. Cole and Warren D. Reid were used to calculate water pressure distribution and determine the danger zones for marine technology, ships, people, and sea fauna. The results are presented in graphical and tabular form. Based on the calculations, the explosion impact area was determined at over 6,700 m from the epicenter.
Keywords: underwater explosion, gas bubble, TNT, FEM, CAE, R. H. Cole equation, Nord Stream gas pipeline.

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INTRODUCTION

Terrorist attacks using pyrotechnics to destroy underwater infrastructure have reached the Baltic region. On September 26, 2022, the Danish national seismic network (Geological Survey of Denmark and Greenland, GEUS) recorded two possible explosions that led to a gas leak from the Nord Stream 1 and 2 pipelines. On September 27, gas leaks were observed [1,2]. The GEUS seismic service collects measurements from seismic measuring stations in Denmark and Greenland and networks in neighboring countries, e.g., Sweden. During the data screening on September 26, 2022, two alarming events were observed in the Baltic at coordinates: 54.675 North and 15.574 East at a depth of 76.2 m, which caused a 2.3 magnitude tremor and at coordinates: 55.485 North and 16.002 East at a depth of 73.8 m, which caused a shock of magnitude 2.1 on the Richter scale [2] (Fig. 1). Both had high wave energy, indicating an explosion and ruling out a potential earthquake. To assess the magnitude of the two incidents on a TNT equivalent basis, the Danes compared two controlled explosions of 340 kg TNT at Sejerøbugten, which were recorded at the Stenlille seismic measuring station, at a comparable distance but with different geology. Using comparative analysis, the TNT mass was estimated at 500 and 750 kg.

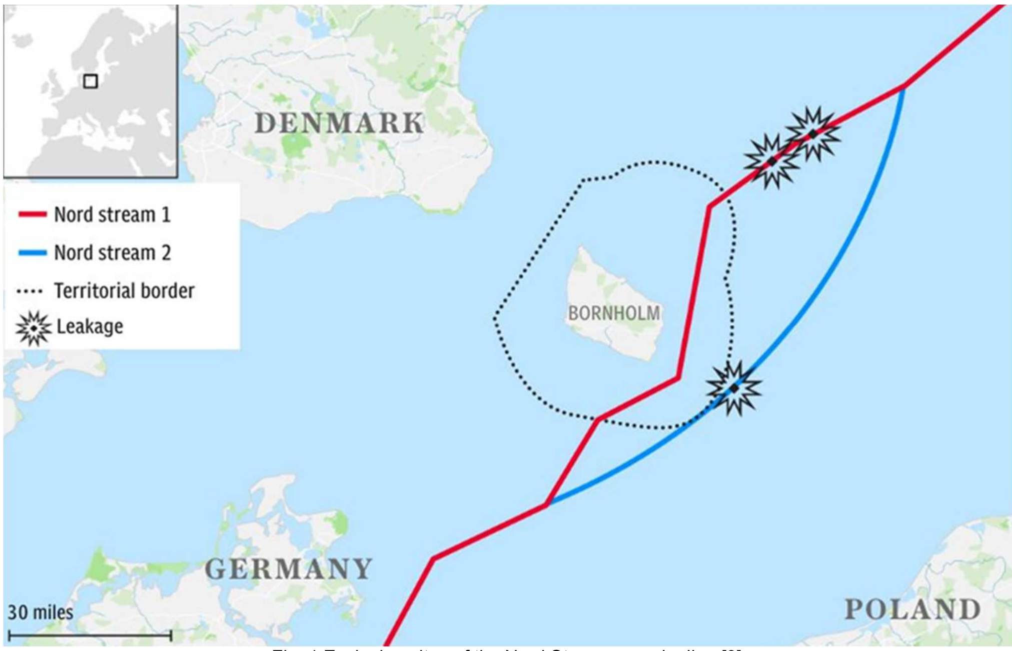

Fig. 1 Explosion sites of the Nord Stream gas pipeline [3].

There are also speculations about the origin of the explosion. As authors, we do not intend to introduce political accusations but only present a potential operational scenario. Sabotage seems certain, given the reports of explosions and the statistical probability of accidents occurring on the same day. Charges could be delivered in several ways: as depth charges dropped from a surface ship or as delayed ignition explosives installed by divers or provided by a submarine. There is also a hypothesis that cargo is delivered from inside the pipeline in the same way as a pipeline inspection gauge passes through it to inspect it and remove debris and sludge [4]. There was also information about the presence of ships in the area of the explosions both in the days preceding the explosions and a week later [5,6]. These events are accompanied by considerable media hype, so it is hard to speculate about the exact cause of the explosion. Locating a pipeline on the seabed from a long distance is not easy. There is also no information about the operation of submarines in this area. However, this does not preclude their use. Due to the specificity of the marine technology, which is the pipeline, which does not generate large physical fields from the operational point of view, it is difficult to hit it or plant charges remotely. Underwater drones do not have the ability to carry loads of such significant masses [7,8]. Therefore, based on data from the GEUS system and press reports, it was decided to analyze the effects of underwater explosions in the Nord Stream area. The paper presents an analysis of the explosion of a charge weighing 750 kg, considering the reflection of the wave from the bottom. The considered explosion took place at a depth of 76 m.

EMPIRICAL DESCRIPTION OF UNDERWATER EXPLOSION

The analysis of an underwater explosion requires taking into account the course of detonation, physical properties of the medium, detonation wave movement, energy dissipation, movement and pulsation of the gas bubble, the reflection of the shock wave from the bottom, and water surface, movement of the bottom of the reservoir, interference of incident and reflected waves, cavitation phenomena, and many others factors [9–17].

An underwater explosion is accompanied by a rapid increase in pressure in its environment. The initial pressure depends on the type of explosive (flammable mixture). The change in pressure creates a shock wave. Prior to the arrival of the shock front in the water, the pressure is equal to the hydrostatic pressure at a given depth. With the front's arrival, the pressure rises rapidly to a maximum value, called peak positive overpressure. The pressure then drops to the hydrostatic pressure. The period of further decrease in pressure and its return to atmospheric pressure is called the period of the negative phase. Important parameters of the entire process are the maximum overpressure value and the area under the function describing the dependence of pressure on time in the period of the positive phase. The following parameters determine the mechanism and nature of the explosion:

- material properties (physical, chemical, stability, heat combustion, etc.);
- space where combustion takes place (size, open, closed, obstacles, etc.);
- properties of the explosive mixture (concentration, pressure, and temperature);
- method of ignition (energy, temperature).

The pressure wave generated during an explosion, also called a shock or detonation wave, travels in a given medium at the speed of sound. In water, it is about 1500 m/s, although the initial velocity can be much higher and depends on the initial amplitude of the pressure generated by the explosion of the material.

A characteristic feature of an explosion in water is the pulsation of a gas bubble formed after the explosion of an explosive or combustible substance. The gas bubble contains the products of the combustion of the explosive. After the explosion, its volume increases rapidly, generating a shock wave. As the volume of the gas bubble increases, the pressure inside it decreases. After reaching the maximum volume depending on the mass of the cargo and the depth, the water displaced by it begins to compress it. The gas bubble contracts while moving toward the surface. The pressure inside the bubble increases again due to hydrostatic pressure, and after reaching the minimum volume, it expands again, generating another shock wave. This process is called pulsation. In the case under consideration, the explosion takes place on the seabed, so the empirical description proposed by R.H. Cole should be modified by the phenomenon of wave reflection.

The reflection of a pressure wave from the seabed is analogous to the reflection of a pressure wave from the water surface, with the difference that the wave reflected from the seabed is an amplified wave. A particular case of pressure wave reflection is when the load rests on the bulkhead, which is the case with all types of bottom mines. During the underwater explosion far from the bottom and surface, all energy is propagated in all directions. It can be assumed that half of this energy moves upwards towards the surface of the water and the other half downwards towards the bottom. Suppose the charge is placed on a hard bottom (perfectly rigid ground). In that case, half of the downward propagated energy will be fully reflected from the ground, as a consequence of which the value of the pressure of the upward propagated wave will overlap with the wave reflected from the bottom. Thus it will be doubled. In fact, part of the pressure wave is absorbed by the ground. To describe this phenomenon, one can use the empirical bottom coefficient k_{bottom}, which takes its values in the range of 1÷2 and depends on the bottom type. In works [13,18], the following values of coefficients are given:

- perfectly rigid ground - k_{bottom} = 2;
- stony bottom - k_{bottom} = 1.8;
- clay with sand - k_{bottom} = 1.6;
- gravel- k_{bottom} = 1.5;
- sand, grit - k_{bottom} = 1.4.

Considering the geology of the Baltic Sea bottom, it was assumed that it is most likely composed of clay, sand, and grit, which allows us to assume the value of the bottom factor at the level of 1.4.

In addition, during the observation of the phenomenon, two disturbances of the water surface can be noticed. The first occurs when the shock wave hits the surface of the free liquid. The second appears after a while and means the emergence of a gas bubble on the water's surface. The nature of the bottom explosion phenomenon is presented in Fig. 2

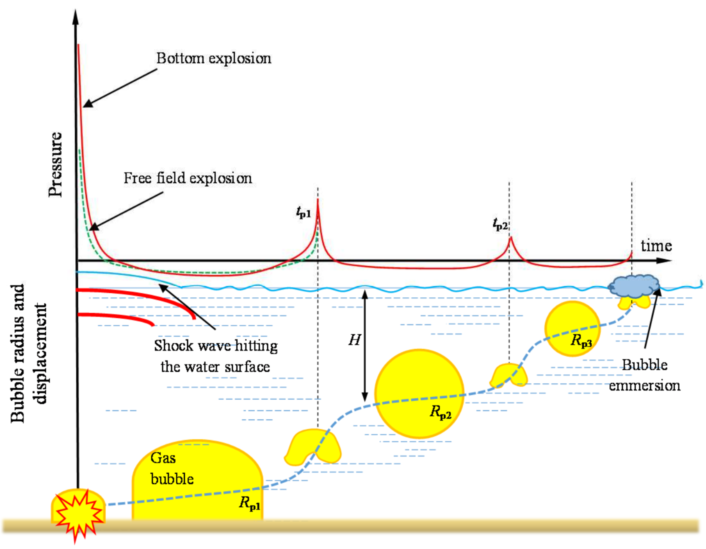

Fig. 2 Bottom underwater explosion parameters.

The first studies and descriptions of the pressure distribution as a function of time and distance from the explosion of pyrotechnic material in water appeared in 20th-century literature. The foundation of the definition of pressure wave propagation in water is the work of R.H. Cole [9] from 1948, who was the first to publish the results of experiments carried out on military training grounds, for which he derived simple empirical formulas. The pressure at the front of the shock wave for TNT (trinitrotoluene – $(NO_2)_3C_6H_2CH_3$), which he determined as a result of explosion measurements for charges weighing 70 ÷ 136 kg at a depth of 3 ÷ 10 m, was described by empirical equations in the form:

$$p_{\max} = K_1\left(\frac{\sqrt[3]{m}}{R}\right)^{A_1} \qquad p(t) = p_{\max}e^{-\frac{t}{c}} \qquad (1)$$

$$C = K_2\sqrt[3]{m}\left(\frac{\sqrt[3]{m}}{R}\right)^{A_2}$$

where:
t – time, s
R – distance from the epicenter, m
K_1, K_2, A_1, A_2, – coefficients for the explosive obtained by experimental tests.

R. H. Cole also described the pulsation process. He measured the pressure of the shock waves of successive pulsations, which are about 10 ÷ 15% of the previous one. The duration of the pulsation depends on the mass of the charge and the depth of the detonation. The pulsation continues until the bubble comes to the surface. The time of the second pulsation is about 70% of the first pulsation and the third about 50%. The duration of the first pulsation of the underwater explosion and the radius of the gas bubble for the TNT material, R.H. Cole described in formulas [9]:

$$t_{\mathrm{p}} = K_5\frac{\sqrt[3]{m}}{1+0,1H}, \ \mathrm{s} \qquad R_{\mathrm{pmax}} = K_6\sqrt[3]{\frac{m}{1+0,1H}}, \ \mathrm{m} \qquad (2$$

where:
m – explosive mass, kg
H – depth of detonation, m

For TNT with a density of 1520 kg/m3 R.H. Cole proposed the following coefficient values appearing in the above equations:

- K_1= 52.2;
- A_1= 0.13;
- K_2= 0.092;
- A_2= −0.185;
- K_5= 2.11;
- K_6=3.5.

In 1996, Warren D. Reid presented an empirical description of the pressure wave developed at the Underwater Explosions Research Department (UERD), Carderock Division of the Naval Surface Warfare Center, Virginia, USA, contained in work [12], in which universal equations in the form of functions K_i and A_i coefficients determined for various explosives in the form of:

Maximum pressure: $$p_{\max} = K_1\cdot\left(\frac{\sqrt[3]{m}}{R}\right)^{1+A_1}, \ \mathrm{MPa} \qquad (3)$$

Pressure over time: $$p_{\mathrm{m}}(t) = p_{\max}\cdot e^{-\frac{t}{C}}, \ \mathrm{MPa} \qquad (4)$$

Time constant: $$C = 10^{-3}\cdot K_2\cdot\sqrt[3]{m}\left(\frac{\sqrt[3]{m}}{R}\right)^{A_2}, \ \mathrm{s} \qquad (5)$$

Pressure pulse: $$I = K_3\cdot\sqrt[3]{m}\left(\frac{\sqrt[3]{m}}{R}\right)^{A_3}, \ \mathrm{MPa\cdot s} \qquad (6)$$

Energy stream $$\bar{E} = K_4\cdot\sqrt[3]{m}\left(\frac{\sqrt[3]{m}}{R}\right)^{A_4}, \ \mathrm{J/m^2} \qquad (7)$$

Pulsation duration: $$t_{\mathrm{p}} = K_5\frac{\sqrt[3]{m}}{(H+9,8)^{5/6}}, \ \mathrm{s} \qquad (8)$$

Gas bubble radius: $$R_{\mathrm{pmax}} = K_6\cdot\sqrt[3]{\frac{m}{H+9,8}}, \ \mathrm{m} \qquad (9)$$

Vertical displacement of the gas bubble: $$d = \frac{12,2\sqrt{m}}{H+9,8}, \ \mathrm{m} \qquad (10)$$

In 1979, R.S. Price, in a paper [19] for TNT with a density of 1600 kg/m³, proposed the following values of coefficients in Warren D. Reid's equations:

- K_1= 52.12;
- A_1= 0.18;
- K_2= 0.092;
- A_2= −0.185;
- K_3=6.52;
- A_3=0.98;
- K_4=94.34;
- A_4=2.155;
- K_5= 2.064;
- K_6=3.383.

The pressure value is not the only parameter describing the harmful effects of an explosion on living organisms and marine technology. An essential measure of the load on the objects in the rein in the impact zone of the detonation wave is the pressure impulse expressed by the equation:

$$I^+ = \int_{t_o}^{t_+}[p(t)-\gamma h]\mathrm{d}t \qquad (11)$$

where:
t_+ – time of the first positive pulse of the pressure wave, s
γh – hydrostatic pressure, Pa

For TNT, the approximate value of the impulse in a given place in the water can be determined from the empirical equation proposed by R. H. Cole [9]:

$$I = 5768\frac{m^{0,63}}{R^{0,89}}, \ \mathrm{Pa\cdot s} \qquad (12)$$

or as the product of the maximum pressure and the time constant:

$$I = p_{\max}\cdot C, \ \mathrm{Pa\cdot s} \qquad (13)$$

For marine technology such as pipelines, power cables, optical fibers, drilling rigs, and other marine facilities, individual facility-oriented calculations are required, but for estimating damage, limit values can be adopted as for ships, which are described in the standard [20,21].

Training materials for NATO scuba divers present pressure values dangerous for the human body [22]:

- 0.02 - 0.03 MPa - permissible pressure for people without clothes immersed in water;
- 0.15 MPa - pressure dangerous for people without clothes immersed in water;
- 0.15 - 1.5 MPa - the possibility of fatal injuries for people without clothes in the water;
- 1.5 - 2.0 MPa - 100% lethality for people without clothes immersed in water.

A threshold of 0.2758 MPa (40 psi) has been suggested as a conservative range for estimating fish mortality[23]. The 0.2785 MPa criterion estimates 50% mortality, not the onset of mortality (i.e. 1% mortality) or thresholds at which no mortality is observed. While these criteria are generally conservative for many species not listed in the Endangered Species Act (ESA), the NMFS (National Marine Fisheries Service) considers the threshold level of 0.2758MPa too low to avoid mortality or serious injury in the event of small fish species, especially juvenile fish and roe, which are susceptible to much lower injury thresholds than adults. When determining the appropriate impact zone for the listed species, the stage of life history and weight of the fish in the affected area should always be considered. For example, Yelverton [24] measured the pressure pulse (MPa·ms), causing the respective 1%, 50%, and 99% mortality in small (avg = 100 g) and large (avg = 750 g) carps. The results of that study showed the mortality of small fish at:

- 1% at 0.10 MPa·ms
- 50% at 0.18 MPa·ms
- 99% at 0.32 MPa·ms

And for big fish:

- 1% at 0.24 MPa·ms
- 50% at 0.34 MPa·ms
- 99% at 0.48 MPa·ms

It is worth noting that the other fish species tested representing smaller size classes showed the onset of mortality at pressures much lower than those above. Although there were some variations in mortality rates, the study found no statistically significant differences due to anatomical differences (swim bladder types) and discrepancies due to fish weights across species [24].

Based on the above considerations, thresholds of critical values of the shock wave pressure for marine technology and living organisms were adopted, presented in Tab. 1. The authors decided to introduce the Roman numbering of t he danger zones, divided from **0** to **X**, where **0** means the epicenter and **X** represents the safe zone. These values were used for a more detailed analysis of the impact on living organisms presented in the paper [25].

Tab. 1

Shock wave impact zones on marine technology and living organisms [13,20,23].

Zone no.	Shock wave pressure, MPa	Effects of the explosion
X	0.03	The pressure is entirely safe for people, fauna, and flora
IX	0.2	Dangerous pressure for people, fauna, and flora
VIII	0.4	1% probable fatalities among humans and fish
VII	0.6	50% probable fatalities among humans and fish
VI	1	100% human and fish mortality
V	2	Safe for marine facilities, commercial vessels, and fishing boats
IV	4	Safe for warships. Minor damage to marine technology
III	8	Damage to the mechanisms and devices of warships and marine technology.
II	12	Deformations and the possibility of cracks in the hull plating of warships and severe damage to marine technology
I	16	Total loss of the ship's maneuverability and combat ability, cracks, and tears in the hull. Possibility of sinking the ship. Complete destruction of naval technology
0	Gas bubble	Zone affected by high temperature and pressure. Complete destruction of marine technology, burning and melting of steel structures

PRESSURE VALUES FOR THE EXPLOSION OF A CHARGE OF 750 KG TNT ON A SANDY BOTTOM

The shock wave will cause damage to marine technology. It will stun and kill living organisms in a certain volume of water, limited by the isobaric surface of a given pressure. The effects of a pressure wave of a given value on a ship are described in [13,18,20,21]. The effects of these values depending on the TNT mass for warships are shown in Fig. 3.

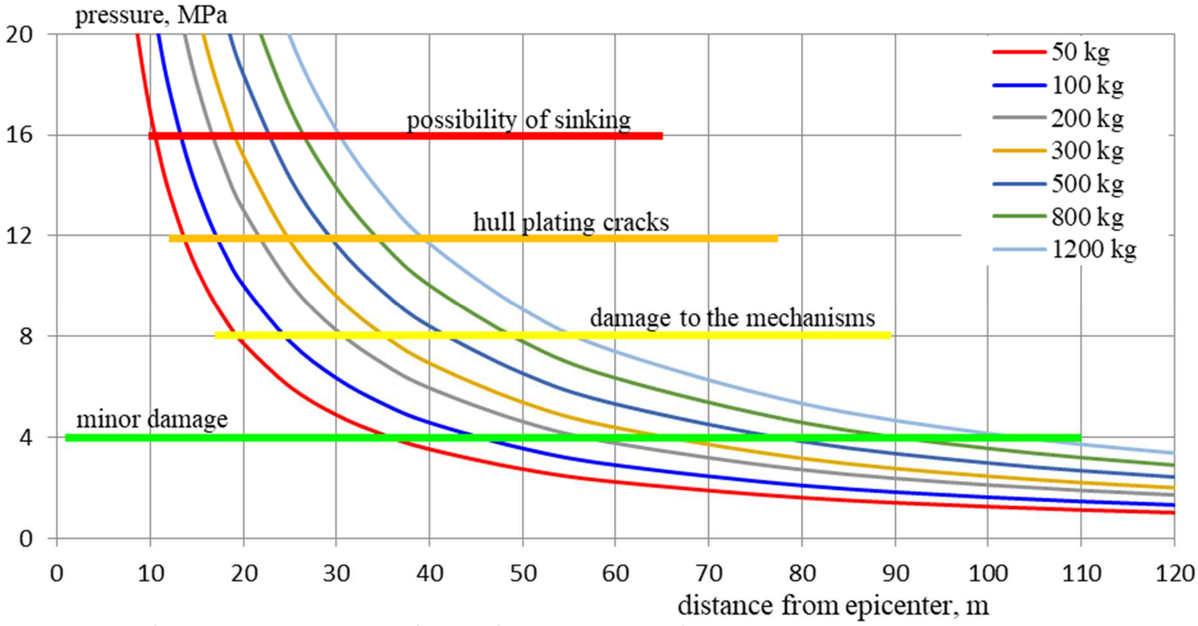

Fig. 3 Values of the shock wave pressure as a function of the TNT load mass of 50, 100, 200, 300, 500, 800, and 1200 kg [13].

The vertical pressure distribution of the feeding wave is necessary to determine the danger zones following the values in Table 1. The pressure wave distribution is proposed to be determined based on the formula given by W. D. Reid [12,13] with the coefficients given by R. S. Price [19], taking into account the reflection coefficient from the bottom, then:

$$p_{\max} = k_{bottom} \cdot 52.12 \left(\frac{\sqrt[3]{m}}{R}\right)^{1,18} \quad (14)$$

Using the formula (14), the explosion pressure of 750 kg TNT was calculated as a function of the distance from the epicenter. Then, the danger zones were determined and shown in Fig. 4.

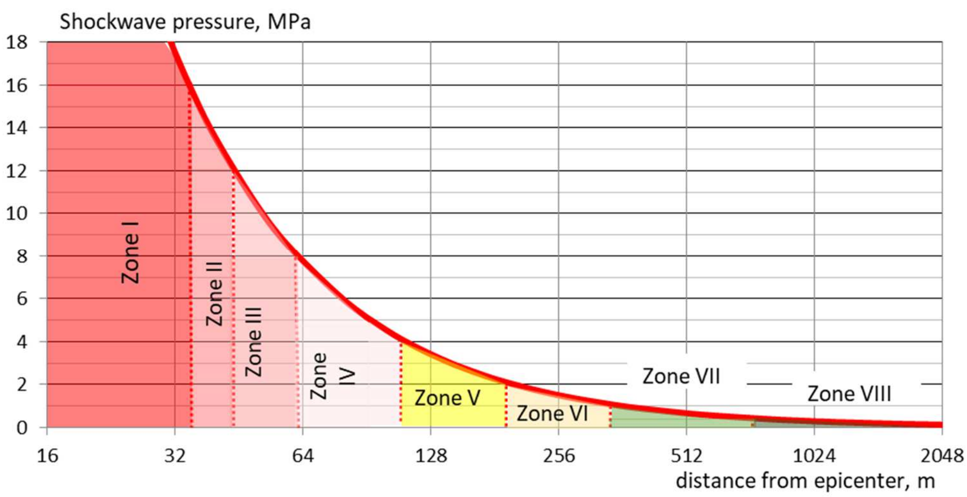

Fig. 4 Shock wave pressure values from the explosion of 750 kg TNT as a function of and distance from the epicenter. Bottom coefficient k_{bottom} =1.4.

Hydrostatic pressure can be included in the above equation. Still, at shallow depths, its effect is negligibly small, and since these are empirical formulas, it is safer to ignore them and stick to higher values. By rearranging equation (14), we obtain the distance R from the epicenter to the isobar of constant pressure, which will allow us to determine the volume of water with a given destructive or killing effect on fauna:

$$R(i) = \left[\frac{k_{denny} \cdot 52{,}12}{p_m(i)}\right]^{\frac{1}{1{,}18}} \cdot \sqrt[3]{m} \qquad (15)$$

where: $i = 1, 2, 3, \ldots, n$ is the number of the isobar with the given pressure.

Further mathematical transformations, using which the coordinates of the isobar marking the border of the danger zone were determined, were performed following Fig. 5.

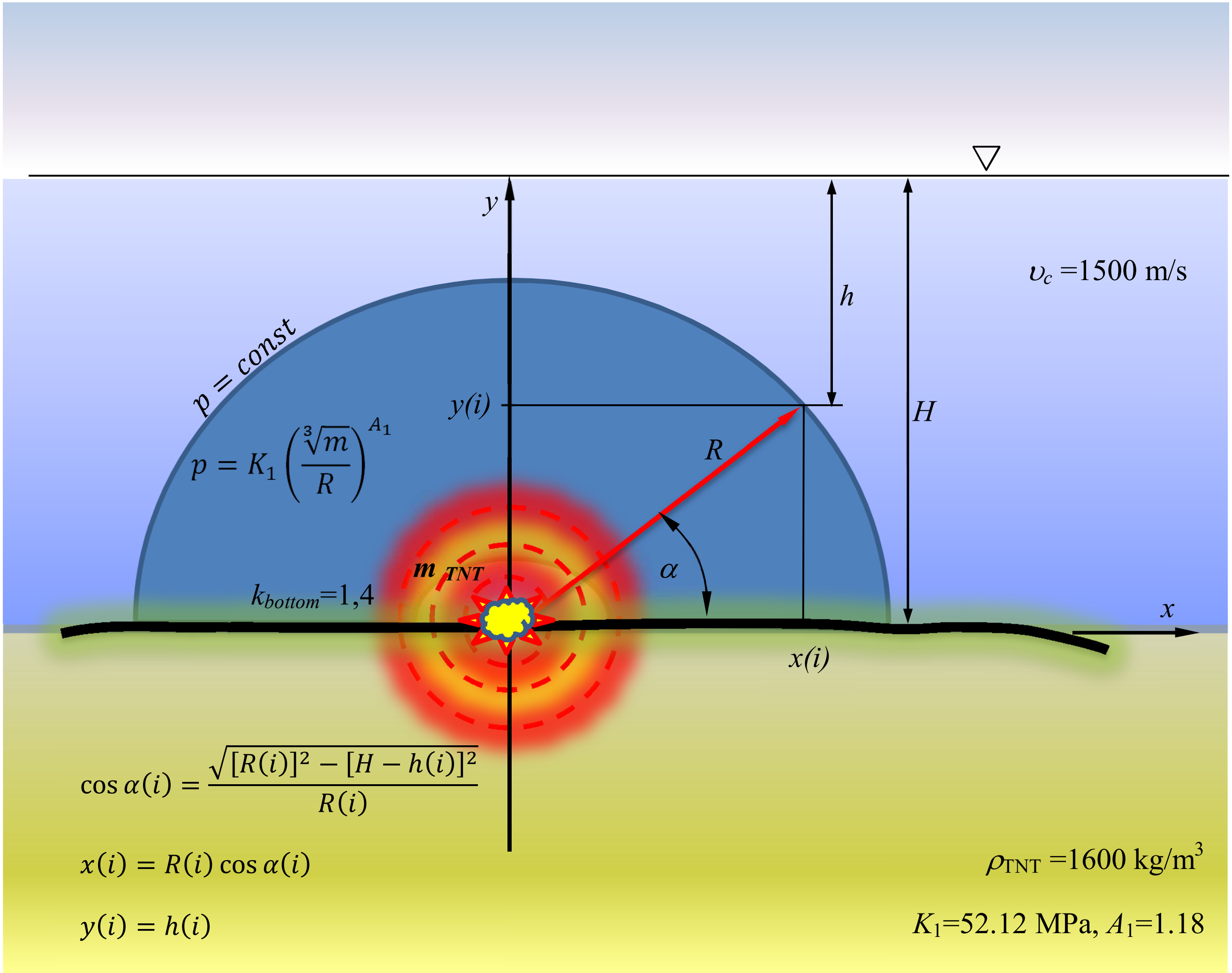

Fig. 5 The method of determining the coordinates of isobars with pressure corresponding to danger zones.

Then the coordinates of the *i*-th isobar are:

$$x(i) = \sqrt{[R(i)]^2 - [H - h(i)]^2} \qquad (16)$$
$$y(i) = h(i)$$

Based on the above equations, isobars with pressure values were determined following Table 1, considering the reflection of the pressure wave from the bottom k_{bottom}=1,4. Table 2 summarizes the radii of critical isobars and volumes of hazardous zones.

Tab. 2

Radius and volume of the sphere of the i-th isobar for the 750 kg TNT bottom underwater explosion.

Isobar	16	12	8	4	2	1	0,6	0,4
MPa	32,87	41,95	59,15	106,43	191,50	344,57	531,24	749,06
Isobar radius	74400	154602	433417	1981910	8825374	45665406	161469297	446525770

The pressure wave also propagates in the vertical plane. Therefore, from the point of view of determining dangerous zones, their range on the water surface is also essential. Table 3 shows the radii of hazardous zones on the water surface for a 750 kg TNT explosion.

Tab. 3

Radius of dangerous zones on the water surface.

Isobar MPa	16	12	8	4	2	1	0,6	0,4	0,2	0,03
The isobar radius on the water surface **750** kg TNT, m	BRAK	BRAK	BRAK	75,5	176,2	336,3	525,9	745,3	1347,8	6727,1

THE GAS BUBBLE RADIUS AT THE BOTTOM

In assessing the explosion's environmental impact, the size of the gas bubble formed as a consequence of the rapid combustion of the explosive is essential. The gas bubble that initiates the shock wave in the event of an explosion on the bottom during the initial expansion phase will disrupt the bottom structure. In the final stage, when it reaches its maximum diameter, due to the inertia of the post-explosion gas particles contained in bubble, the pressure at the bottom will drop below the hydrostatic pressure. The negative pressure zone created in this way will suck in the sand and the sediments contained in it, lifting them with it in the water column. The radius of the gas bubble was determined according to the equation of Warren D. Reid (9), which at a depth of 76 m, reaches a radius of R = 7.24 m. This formula shows the radius in the so-called free field explosion. In [26], the influence of the presence of an obstacle on the shape of a gas bubble was examined. The quoted data show that the gas bubble has changed, but its maximum diameter does not increase. However, the reflection phenomenon appears, raising an additional bottom part into the water column. This phenomenon is also related to the shock wave amplification, i.e., the k_{bottom} factor introduced into the calculations.

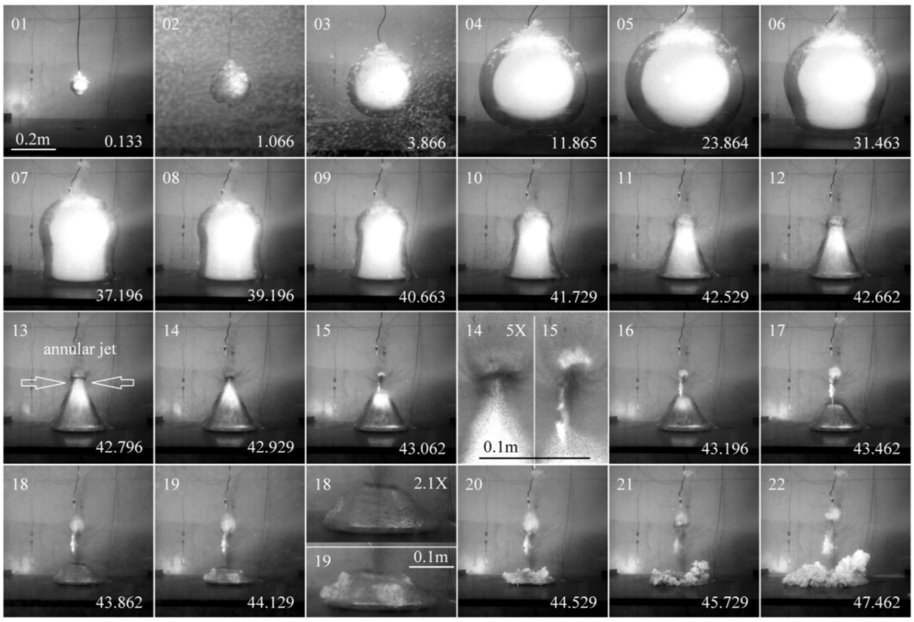

Fig. 6 The behavior of an underwater explosion bubble above a solid wall [26].

CONCLUSIONS

Based on data from the GEUS system, the most likely TNT masses affecting the Nord Stream pipelines were determined. They amount to 500 kg and 750 kg of TNT equivalent, respectively.

In the presented article, a worse variant was calculated: the explosion of 750 kg of TNT. The pressure distributions in the water are shown, considering the reflection from the bottom. Dangerous zones for marine technology, ships, fauna, and flora have been designated. Warren D. Reid's empirical formulas were used for the calculations.

The range of such an uncontrolled explosion could disturb the fauna of the Baltic Sea within a radius of up to 6,700 m. Knowing about the density of fauna in a given basin makes it possible to estimate the effects of the explosion on the volume of the dead ecosystem, which results in its disturbance. The results are presented in graphical and tabular form. The analyzed explosion will cause the following effects:

- Within a radius of 0 ÷ 7.24 m from the explosion's epicenter, all marine infrastructure such as pipelines, power cables, telecommunication optical fibers, and other devices. It will burst, burn and melt. It will need to be rebuilt..
- Within a radius of 7.24 ÷ 32.87 m from the explosion's epicenter, all marine infrastructure, such as pipelines, power cables, telecommunication optical fibers, and other devices, will be destroyed entirely. It will need to be rebuilt.
- Within a radius of 32.87 ÷ 41.95 m from the explosion's epicenter, all marine infrastructure will be partially destroyed. It may be necessary to rebuild or replace sections of pipes, hoses, cables, and repair supporting structures;
- Within a radius of 41.95 ÷ 59.15 m from the explosion's epicenter, all marine infrastructure, such as pipelines, power cables, telecommunication optical fibers, and other devices, will be seriously damaged. It will need to be repaired;
- Within a radius of 59.15 ÷ 106.43 m from the explosion's epicenter, minor damage to the marine infrastructure will occur. Insulation damage, foundation breach, displacement; Necessary inspection and repair;
- On the surface of the water within a radius of 0 ÷ 176.2, minor damage will be caused to the equipment in the wetted zone of commercial ships, cutters, tourist boats, and yachts;
- Within a radius of 0 ÷ 344.57 m from the explosion's epicenter, 100% of all living organisms will die.
- Within a radius of 344.57 ÷ 531.24 m from the explosion's epicenter, 50% of all living organisms, especially small ones, will die.
- Within a radius of 531.24 ÷ 749.06 m from the explosion's epicenter, single deaths may occur (1%), especially of the smallest living organisms.
- The distance that is completely safe for people and living organisms is 6727.1 m.

Fig 7. summarizes and presents the obtained results.

The work does not consider the impact of uncontrolled gas outflow, which also affects the environment. However, this is not a phenomenon directly related to an underwater explosion, so it was omitted from this article.

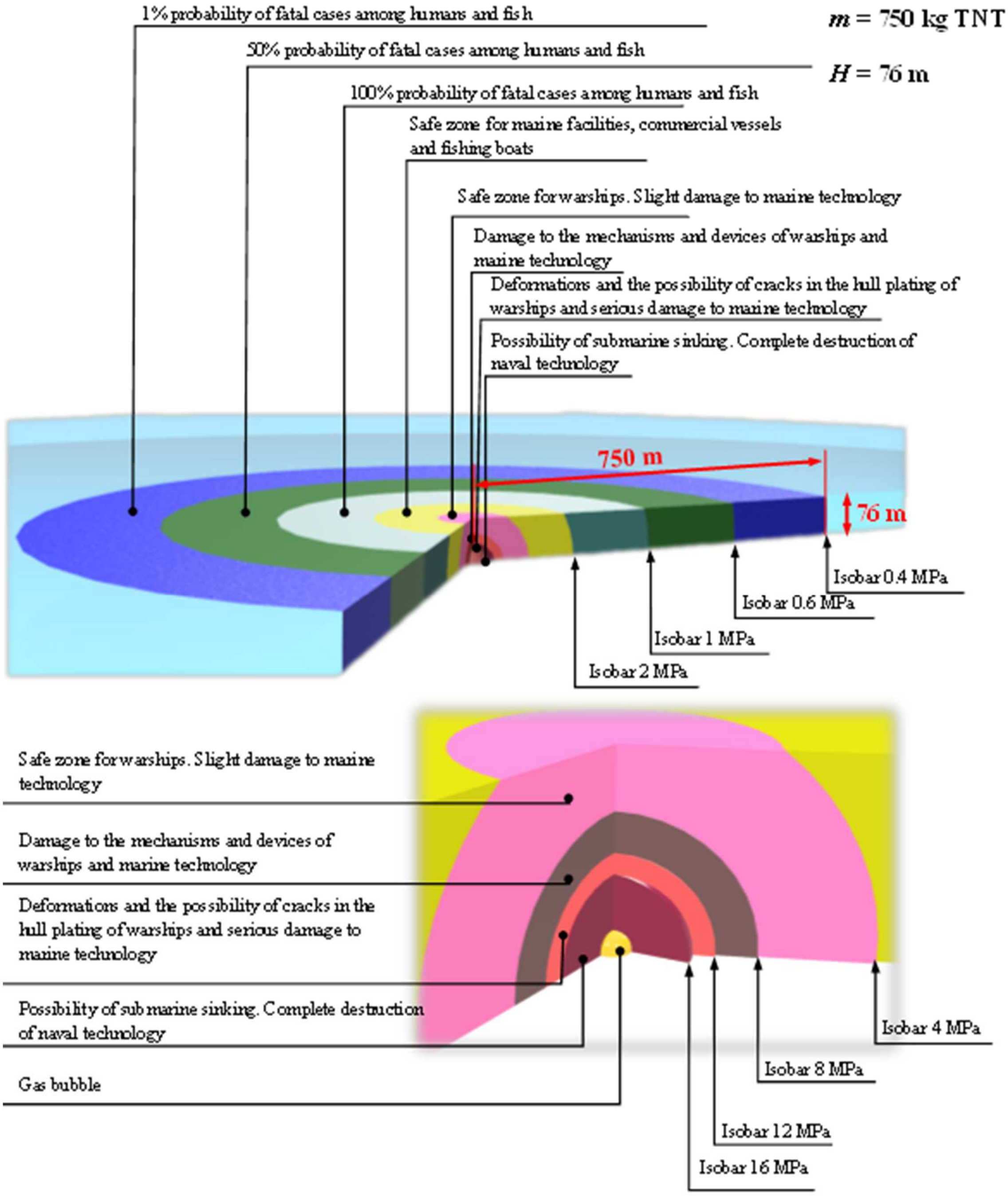

Fig. 7 Illustration of dangerous zones created by an underwater explosion of 750 kg of TNT on the bottom at a depth of 76 m.

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