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Estimating the Size of a Crater after an Underwater Explosion

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ABSTRACT

There have been terrorist attacks in the Baltic region that used explosives to destroy underwater infrastructure, including the Nord Stream 1 and 2 gas pipelines. Data from the Danish National Seismic Network indicate that two explosions occurred on 26 Sept 2022, causing gas leaks from pipelines. While examining the data from 26 Sept, two disturbing events were observed in the Baltic Sea, which caused tremors of magnitude 2.3 and 2.1 on the Richter scale. Both events had high wave energy, indicating an explosion, not an earthquake. Based on the above data, it was decided to analyze the potential effects of underwater explosions in the area of the Nord Stream gas pipelines. From the point of view of ecology, the volume of material torn up from the bottom is essential. For this purpose, empirical formulas for explosions on land were used, and then the crater's size was estimated per the physics of the underwater explosion phenomenon. Calculations indicate that the explosion of 750 kg of TNT will raise about 20 m^3 of the bottom volume into the water column. Because of the explosion, a gas bubble will form directly at the bottom, and it will suck the sand and the impurities contained in it and particles of dead organisms, bringing them to the surface and dispersing them in the water column. These attacks pose a severe environmental and safety risk as gas leaks from pipelines can cause harmful effects on marine ecosystems and people. It also violates international law and international agreements, including the United Nations Convention on the Law of the Sea and the Convention on the Protection of the Marine Environment in the Baltic Sea Region.

Keywords: terrorist attacks, Baltic Sea, Nord Stream, underwater explosions, seismic measurements, detonation crater, TNT, environmental impact.

INTRODUCTION

In the Baltic region, there were terrorist attacks using pyrotechnics aimed at destroying underwater infrastructure. Data from the Danish national seismic network (Geological Survey of Denmark and Greenland, GEUS) indicate that two possible explosions occurred on 26 Sept 2022, causing a gas leak from the Nord Stream 1 and 2 pipelines. Gas leaks were also observed on 27 Sept 2022 [1, 2]. GEUS collects measurements from seismic measuring stations in Denmark and Greenland and networks in neighbouring countries such as Sweden. The GEUS system records the amplitudes of the tremors. Knowing the location of the sensors and using triangulations can indicate the approximate location of their occurrence. During the screening of data from 26 Sept 2022, two disturbing events were observed in the Baltic Sea, which caused tremors with a magnitude of 2.3 and 2.1 on the Richter scale. These events occurred at a depth of 76.2 m with coordinates 54.675 North and 15.574 East and at a depth of 73.8 m with coordinates 55.485 North and 16.002 East [2]. Both events had high wave energy, indicating an explosion, not an earthquake. Danish researchers compared the two incidents with controlled explosions of 340 kg of TNT at Sejerøbugten, which were recorded at the Stenlille seismic measuring station, at a comparable distance but with different geology. The comparative analysis estimated that the loads in both incidents ranged from 500 to 750 kg of TNT equivalent. There are various ways in which the explosives could have been delivered. These could be depth charges dropped from a surface ship, time-delayed explosives installed by divers, or provided by a submarine. It is also hypothesized that the charge was delivered from inside the pipeline like a gauge passing through it, which is used to check and remove debris and sludge [3]. Due to the specificity of marine technology, the pipeline does not generate large physical fields from the operational point of view. Therefore, it is an object challenging to track. It is difficult to find or plant charges remotely from the surface of the water. Officially known unmanned underwater vehicles cannot carry loads of such significant masses [4, 5].

The explosion of such a significant mass of a charge affects the marine environment [6, 7]. During the explosion, a gas bubble and a pressure wave impulse with a significant amplitude are generated, affecting nearby living organisms [8–10]. The underwater explosion causes a gas bubble which is then compressed by hydrostatic pressure. Such phenomena do not occur in the case of surface explosions. In addition, explosions near the seabed deform the gas bubble. In the study [11], the influence of the presence of an obstacle on the shape of the gas bubble was examined. The test results indicate that the gas bubble takes on a changed shape, but its characteristic dimension does not increase. However, a rebound occurs, lifting an additional bottom part into the water. This phenomenon is also related to the shock wave amplification caused by the interference of the reflected and incident waves [10].

One of the significant ecological factors is the volume of material raised from the bottom. There is a reasonable suspicion that, due to the activities of the Second World War, there may be remains of chemical munitions in the area of the explosion, which could have been scattered in the water column by the bottom explosion [6, 7]. To estimate the amount of slurry dissipated in the water column, the explosion parameters and the approximate volume of the crater should be determined. Current research and publications mainly describe the analysis of craters formed after explosions on land [12–16]. There is a lack of studies and publications on measuring the size of the crater after an underwater explosion because water currents quickly wash away the crater formed in the sandy bottom. Also, due to the action of water, measurements of the size of an underwater blast crater will always involve some approximation. In this work, it was decided to use empirical formulas for explosions on land and then estimate the size of the crater according to the physics of the underwater explosion phenomenon.

Bottom underwater explosion, estimating the size of the crater. The analysis of an underwater explosion requires taking into account many factors, such as the course of the detonation, physical properties of the environment, detonation wave movement, energy dissipation, movement and pulsation of the gas bubble, reflections of the shock wave from the bottom and surface, movement of the sea bottom, interference of incident and reflected waves, cavitation phenomena and many other factors. An underwater explosion is accompanied by a rapid increase in pressure in its environment, and the initial pressure depends on the type of explosive [8, 17–26].

A characteristic feature of an underwater explosion is the pulsation of a gas bubble formed after the explosion of an explosive or combustible substance. The gas bladder contains the products of combustion of the explosive, and 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 weight of the load and the depth, the water displaced by it begins to compress it. The gas bubble contracts while moving towards the surface. The pressure inside the gas bubble increases again due to the pressure of the water, generating another shock wave as the bubble reaches its minimum volume and expands again. This process is called pulsation.

CASE STUDY

In the case of an explosion on the seabed, the em pirical description proposed by R.H. Cole has to be modified due to the phenomenon of pressure wave reflection from the bottom. The reflection of a pressure wave from the seabed is analogous to the reflection of a pressure wave from the surface of the water, with the difference that the wave reflected from the seabed is amplified. In the particular case where the load rests on the bulkhead, which is the case with all types of bottom mines, the pressure wave reflects off the bottom, and the pressure value of the upward propagated wave doubles as a consequence of the superposition of the upward wave with the wave reflected from the bottom. However, part of the pressure wave is absorbed by the substrate, which can be described by the empirical bottom factor, which varies from 1 to 2 depending on the bottom type. When a charge explodes in the water column 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. In works [20, 27] the following values of coefficients were 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 [28] 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, on the other hand, appears after a while and means the emergence of a gas bubble on the surface of the liquid. The nature of the bottom explosion phenomenon is shown in Fig. 1. The detonating charge most often creates a depression in the surface on which it is located. This depression is called a crater. The crater initially takes the shape of a cone, which is relatively evenly filled in, thus taking the shape of a spherical or truncated cone. In addition, an earth embankment is formed around the crater's edge due to the displacement of soil masses (Fig. 2). Since part of the earth falls back into the crater, a proper crater and an apparent crater are distinguished [15]. The apparent crater is the visible effect of the explosion, which is measured relative to the ground reference level. In contrast, the actual crater is the maximum size of the crater before the ground collapse occurs. The size of the actual crater is difficult to measure, so in further consideration, the size of the apparent crater is assumed.

The crater's shape and size depend on the charge's location (explosion on the surface, below or above the ground), density, humidity and type of soil. The change in the crater's size due to the load's depth is shown in Figure 3. The figure shows that depending on the load's depth, the crater's size changes significantly. With a sufficiently large depth, the ejection of material from the crater area is much smaller due to its self-filling [12]. Fig. 4 shows the change in the size of the crater due to the type of soil. As the figure shows, with

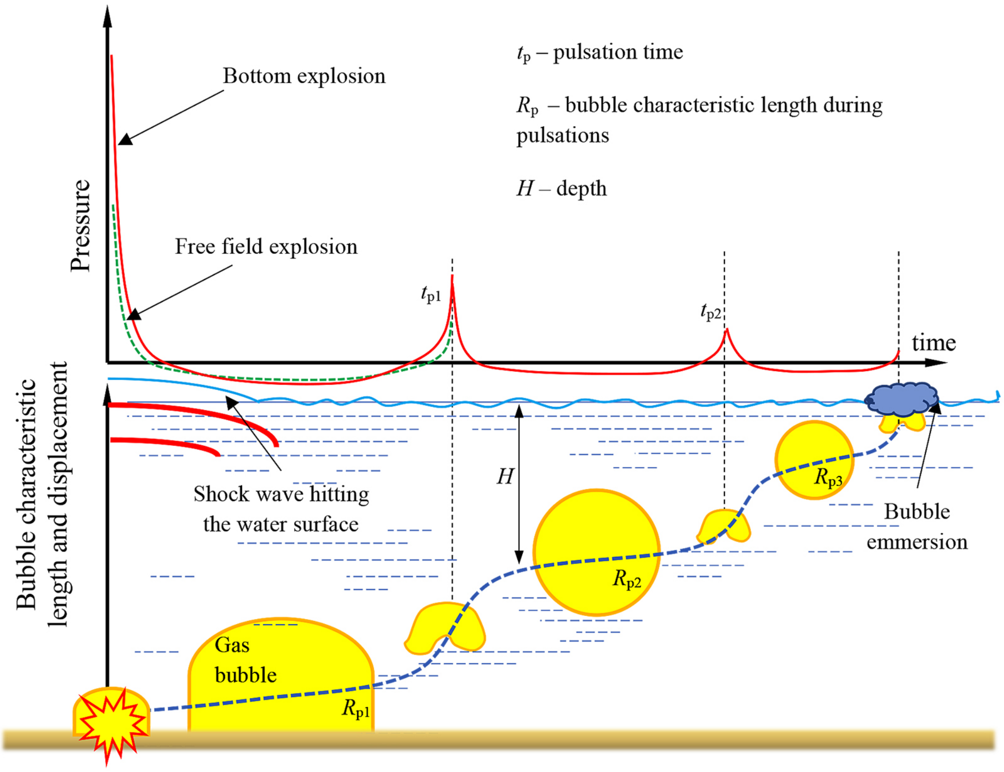

Fig. 1. Diagram of the bottom underwater explosion

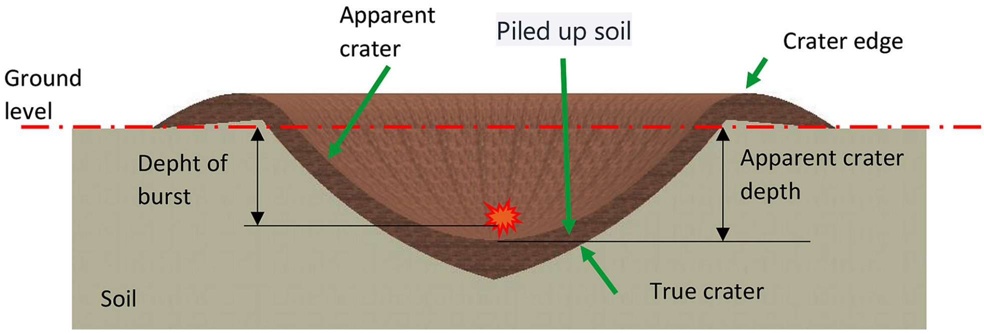

Fig. 2. Explosion crater cross-section

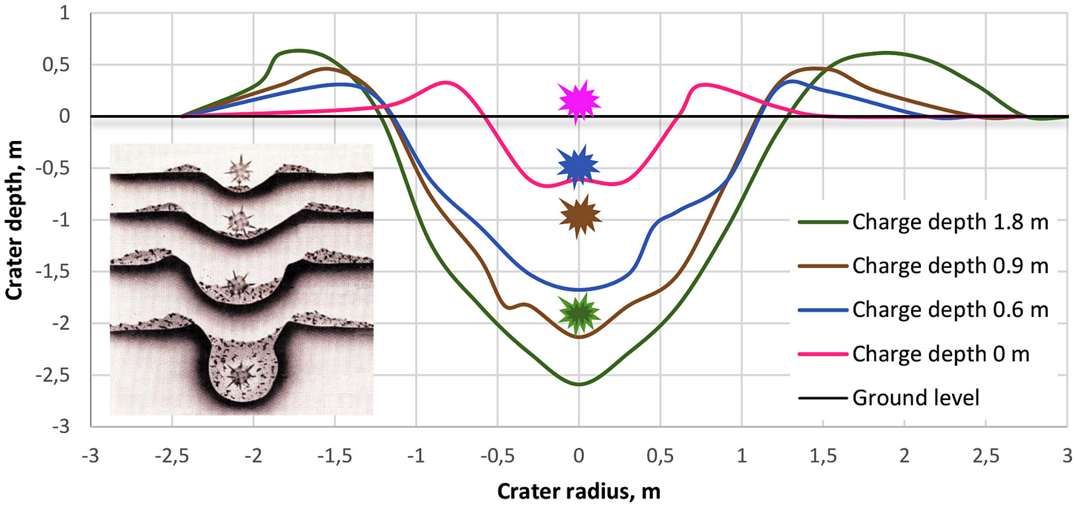

Fig. 3. Change in the explosion crater's size depending on the burst's depth. The mass of the explosive has been classified [13]

the increase in clay content in the ground, the crater becomes deeper and has steeper slopes. The influence of ground moisture is shown in Fig. 5. The size and depth of the crater increase with the increase in ground wetness (WC - Soil wetness). With the same type of soil and different wetness, the difference in the volume of the destroyed medium is:

$$V_{10.4\%\,WC} - V_{16,9\%\,WC}$$
$$1.904 - 0.813 = 1.091 \qquad (1)$$

This allows us to conclude that with a change in soil moisture by 6.5%, the volume of the crater more than doubled. The substrate's density and the sand grains' size are also critical. As the density of the medium increases (from loose to compact), the size of the crater decreases. As can be seen from the above considerations, the size of the crater depends on many factors and changes significantly, even with a relatively small change in the influence parameters. However, empirical formulas can be found in the literature to estimate the size of the crater [12–16]. A high agreement between the results of the experiments is obtained in [16]. The authors conducted experiments ranging from 1-5000 tonnes of TNT equivalent. Considering the considered load (500 kg and 750 kg of TNT), it is concluded that the formulas for the volume of the crater can also be applied in this case. The volume and dimensions of the crater are calculated according to the formulas:

$$V = 26.72m^{0.999}$$
$$R = 3.36m^{0.336} \qquad (2)$$
$$H = 1.78m^{0.316}$$

where: V – crater volume, m^3; R – radius of the emerging apparent crater relative to the ground surface, m; H – depth of the burst, m; m – TNT mass.

As mentioned, the formulas above refer to a surface blast on land. From the definition of an explosion, it follows that it is a violent pressure

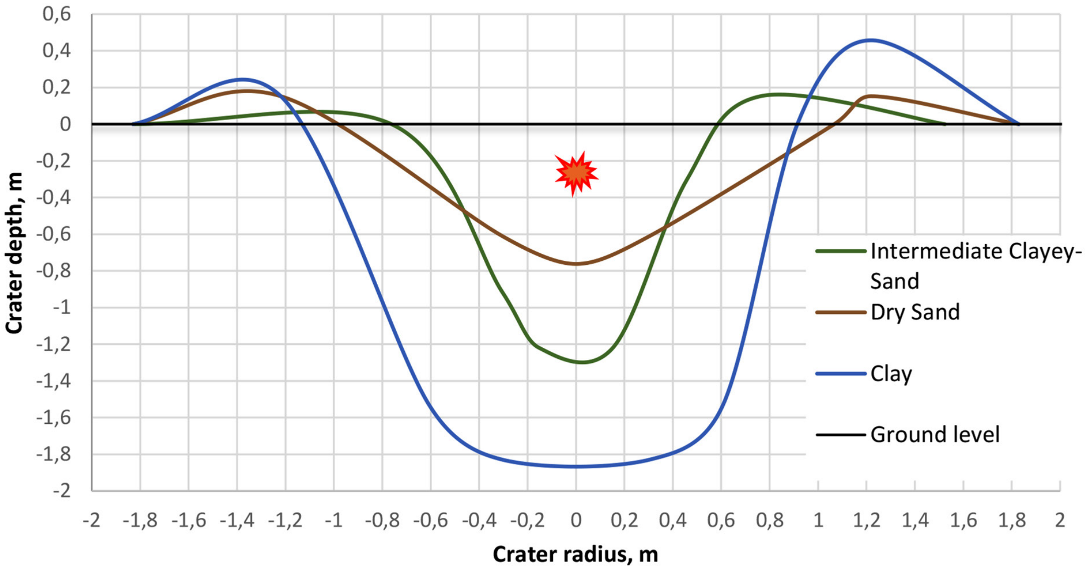

Fig. 4. Change in the explosion crater's size depending on the soil type. Charge mass classified, depth of the burst 30 cm [13]

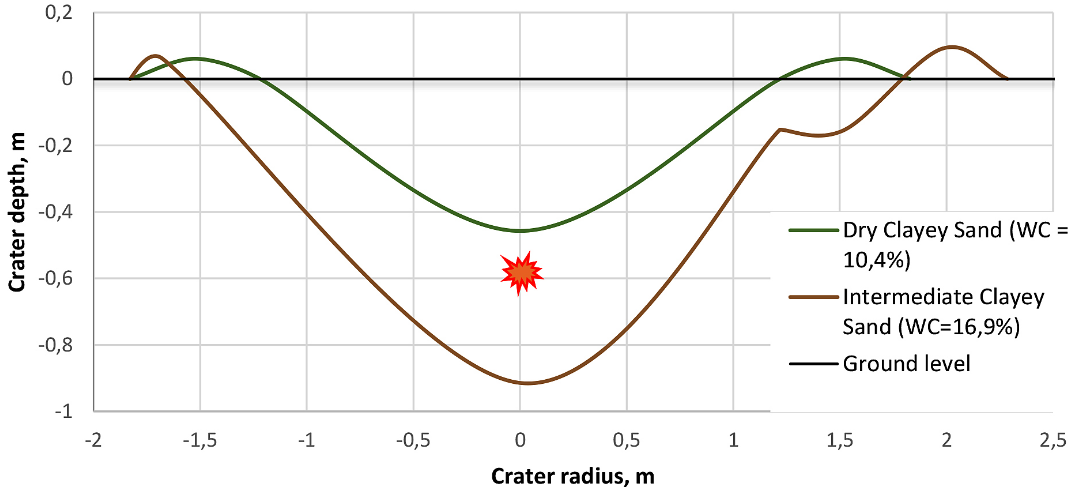

Fig. 5. Change in the size of the explosion crater depending on the soil moisture. The explosion of 4.5 kg TNT at a depth of 58 cm [13]

wave arising from the transformation of an explosive mass. To calculate the pressure value from an underwater explosion, the following formula, developed by R.H. Cole [17] and modified by other authors, is used. The comparison and compilation of formulas are presented in [8]. When determining the pressure value, the fact that the load is at rest on the bottom and the coefficient of amplification of the pressure wave reflection from the bottom, which is 1.4 for a sandy bottom, should be considered. The explosion pressure can be determined from the Cole equation, taking into account the k_{bottom} reflection coefficient, and then the maximum pressure will be determined by the formula:

$$p_{\max} = k_{bottom} \cdot K_1 \left(\frac{\sqrt[3]{m}}{R}\right)^{A_1} \tag{3}$$

where: A_1 = 1,13 – experimental coefficient proposed by R.H. Cole; K_1 = 52,3 – experimental coefficient proposed by R.H. Cole; k_{bottom} = 1,4 – experimental coefficient proposed by Cudny & Powierża; m – charge mass, kg; R – distance from the detonation site. In the case of detonation at the bottom, the center of gravity of the charge is assumed.

Rearranging the above equation concerning the mass of the explosive, we get:

$$m = R^3 \cdot \left(\frac{p_{\max}}{k_{bottom} \cdot K_1} \right)^{\frac{3}{A_1}} \tag{4}$$

The explosion pressure acting on the bottom should be reduced by the value of the hydrostatic pressure prevailing at the detonation depth. Hence the mass of the charge substituted in the formula (2) should be modified in terms of pressure, thus:

$$m = R^3 \cdot \left(\frac{p_{\max} - \rho g H}{k_{bottom} \cdot K_1} \right)^{\frac{3}{A_1}} \tag{5}$$

Analyzing explosive charges of 500 kg and 750 kg and assuming the cubic shape of the explosives, the following values are obtained:

$$R_{500\,kg} = 0.5 \cdot \sqrt[3]{\frac{m}{\rho_{TNT}}} = \sqrt[3]{\frac{500}{1650}} = 0{,}34\,m$$
$$R_{750\,kg} = 0.5 \cdot \sqrt[3]{\frac{m}{\rho_{TNT}}} = \sqrt[3]{\frac{750}{1650}} = 0{,}38\,m \tag{6}$$

According to the data provided by the GEUS system, the explosion occurred at a depth of 74 m. Hence the hydrostatic pressure at the detonation site is:

$$\rho g H = 1006 \cdot 9{,}81 \cdot 74 = 730295\,Pa = 0{,}73\,MPa \tag{7}$$

The maximum pressure is non-linear and depends on the mass of the charge, the distance from the detonation epicenter, the depth of detonation and the time constant, which is described in other publications [8, 17, 19, 20]. However, this does not follow directly from the presented formula (3). This formula only describes the maximum value at a given distance. In order to preserve the physical description of the phenomenon of an underwater explosion, the concept of reduced mass was introduced. Therefore, the reduced value of the load that will be considered for calculations is:

$$m_{red\ 750} = R^3 \cdot \left(\frac{p_{\max} - \rho g H}{k_{bottom} \cdot K_1} \right)^{\frac{3}{A_1}} = 736{,}5\,kg$$
$$m_{red\ 500} = R^3 \cdot \left(\frac{p_{\max} - \rho g H}{k_{bottom} \cdot K_1} \right)^{\frac{3}{A_1}} = 491\,kg \tag{8}$$

Substituting these values into the formulas for calculating the crater volume (2), we obtain the volume of the bottom thrown into the sea depth:

$$\begin{array}{lll} \textit{Crater volume:} & V_{500\,kg} = 13{,}13\,m^3 & V_{750\,kg} = 19{,}68 m^3 \\ \textit{Crater radius:} & R_{500\,kg} = 2{,}64\,m & R_{750\,kg} = 3{,}03\,m \\ \textit{Crater depth:} & H_{500\,kg} = 1{,}42\,m & H_{750\,kg} = 1{,}61\,m \end{array} \tag{9}$$

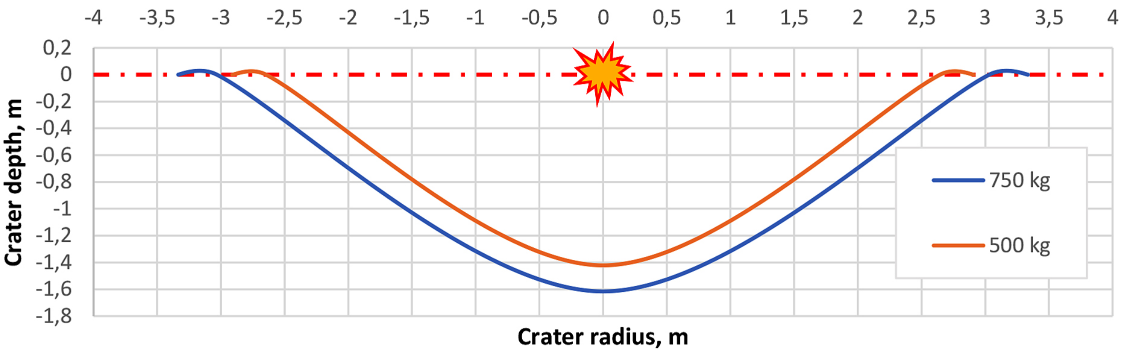

Fig. 6. Approximate shape of the crater after explosive charges weighing 500 kg and 750 kg TNT

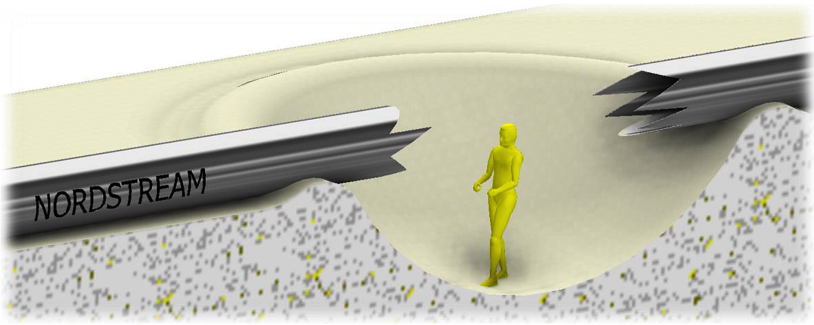

Fig. 7. Approximate shape of the crater compared to a pipeline with a diameter of 800 mm and the size of a man

Based on the calculations, it is possible to estimate the approximate shape of the crater after the explosion of charges weighing 500 kg and 750 kg of TNT on the seabed (Fig. 6, 7).

CONCLUSIONS

On 26 Sept 2022, underwater explosions were recorded in the Baltic Sea at the coordinates of 54.675 North and 15.574 East at a depth of 76.2 m and 55.485 North and 16.002 East at a depth of 73.8 m. 750 kg of TNT will create a crater with a volume of about 20 m^3. Due to the lack of available research on this issue, it was decided to reach for the conclusions from the analysis of the mechanism of crater formation due to the use of aerial bombs, which was the subject of extensive research by other scientists.

The aquatic environment affects the physics of an underwater explosion and, therefore will also affect the mechanism of crater formation. It has been assumed that in the early phase of crater formation in a gas bubble, phenomena similar to land explosions occur, resulting from explosive gases. This assumption is a preliminary consideration that can serve as a starting point for further research and analysis on this issue. The formation of a crater does not directly affect the strength of marine technology. The main threat to ships, gas pipelines, etc., is the pressure wave impulse created by the explosion. However, the sediments raised into the water column pose a significant threat to the fauna of the Baltic Sea. In addition, there is a reasonable risk that these sediments contain the remains of chemical weapons lifted from the bottom and could contaminate much larger areas than the explosion itself. The crater is one of the side effects of underwater explosions, so it was often overlooked in research. Its estimation is essential due to the possibility of unsupervised chemical contamination of the region, which is a precedent. As a result of these explosions, a gas bubble will form directly at the bottom, sucking in the sand, impurities, particles of dead organisms and potential remnants of World War II, lifting them to the surface and dispersing them in the water column. It should be noted that these explosions are the result of attacks aimed at destroying underwater infrastructure. Data collected by the Danish National Seismic Network confirm the occurrence of explosions and gas leaks from the Nord Stream 1 and 2 pipelines. A comparative analysis by Danish researchers of a controlled explosion of 340 kg of TNT in Sejerøbugten indicates that the explosives weighed between 500 and 750 kg of TNT equivalent. There are several possible ways to deliver these charges, such as depth charges dropped from a surface ship, explosives installed by divers, or delivered by a submarine. However, potential perpetrators are not indicated, only a possible operational scenario.

The impact of underwater explosions on the marine environment is significant as they generate gas bubbles and pressure wave pulses that affect marine fauna. The analysis of the potential effects of these explosions on the Nord Stream gas pipelines requires consideration of various factors, such as the volume of the explosion crater, the pressure wave, and the pulsation of the gas bubble. The blast crater's shape and size depend on the cargo's location, type and humidity of the ground. The impact of these explosions on the marine environment and their effects are essential for the analysis of the safety of underwater infrastructure. It is, therefore, necessary to carefully study these effects and take appropriate action to protect the environment and ensure the safety of the infrastructure.

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