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Accelerations Caused by Underwater Explosions on the Naval Gun Foundation

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ABSTRACT

The manuscript analyzes the impact of a non-contact underwater explosion on the foundation of a 35 mm naval cannon mounted on board a Project 258 minehunter. The finite element method was used to complete the task. Cole's empirical formulas were used to describe the distribution of the pressure wave from the explosion of the TNT charge in water as a function of distance, time, and mass. The hull geometry was reflected based on technical documentation as a shell structure reinforced with beam-bar elements. Devices with large weights were represented as rigid bodies. Simplifications were used to minimize the number of degrees of freedom. The construction of ship's hull is made of non-magnetic austenitic steel. The dynamic characteristics of this steel were determined based on static and dynamic tensile tests. The Johnson-Cook constitutive model was used to describe the material properties of steel. As part of the work, the impact resistance study of marine structures was presented, how it is defined by the existing regulations in the Polish Navy was considered, and the scope of their applicability was given. The scientific innovation of the presented work consists of checking and specifying the guidelines for designing and constructing warships.

Keywords: DIN 1.3964 austenitic steel; project 258 minehunter; Johnson–Cook material model; underwater explosion, naval cannon.

INTRODUCTION

The design and construction of armaments is the subject of interest and activity of many research and industrial centers worldwide [1]. For various reasons, it is in the interest of the Armed Forces of each country to have domestically produced weapons. The Polish Navy is currently undergoing a phase of arming with mine warfare ships. After years of preparation, on September 23, 2013, a contract was signed for constructing a prototype of the Project 258 ship with an option for two more vessels. The prototype was named ORP Kormoran, and then on November 28, 2017, the flag was raised on it, and it was incorporated into the 13th Minesweeper Squadron in Gdynia [2]. Project 258 minehunter is designed to search for and destroy sea mines in the Baltic and North Sea regions. ORP Kormoran was equipped with a double 23 mm ZU-23-2MR Wróbel-II cannon manufactured by Zakłady Mechaniczne Tarnów [2]. On subsequent units in the series, the armament was modified, so the second ORP Albatros, and ORP Mewa (Fig. 1), the third in a series of modern minehunters built for the Navy, were equipped with the armament elements of the ship armament system (OSU-35K) [3]. The OSU-35K prototype was designed and built as a result of a development project co-financed by the National Center for Research and Development (NCBiR) [4]. The primary purpose of the OSU-35K is the direct defense of the ship against lightly armored air, surface, and coastal targets.

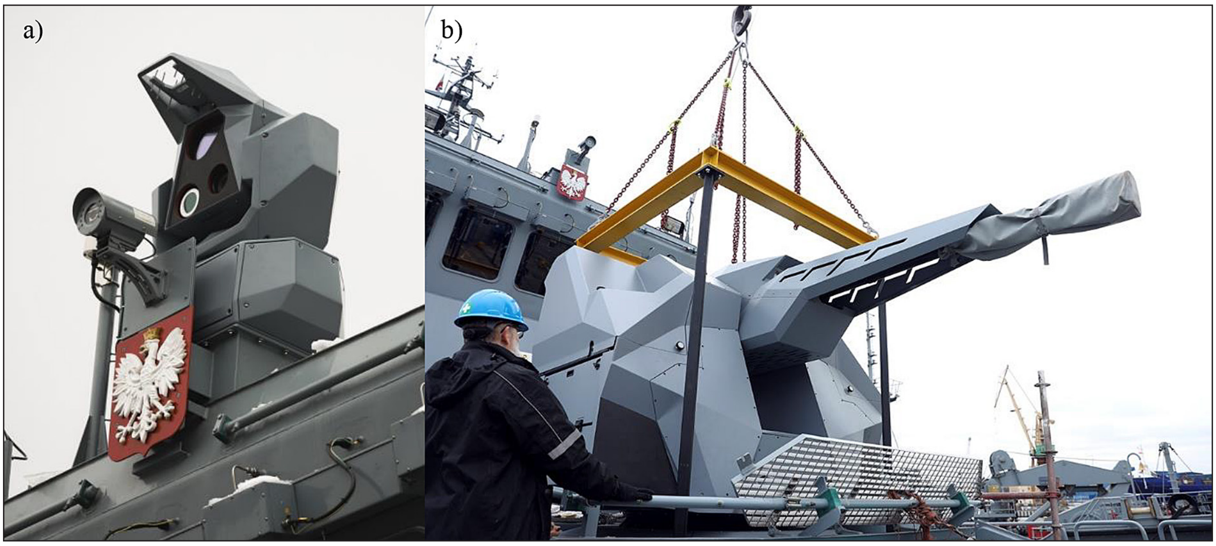

Fig. 1. ZGS-158M tracking head (a) and OSU-35K ship weapon system (b) on ORP Mewa [3]

The 35 mm ship weapon system consists of three modules [5]: integrated tracking head (ZGS-158M), 35 mm KDA naval cannon, multifunctional operating console, and elements ensuring fire in reserve mode. The maritime gun included in the 35 mm OSU is its essential element and is designed to fire 35 mm FAPDS-T (Frangible Armor Piercing Discarding Sabot with Tracer Projectile) and ABM artillery shells. In the primary mode of operation, the gun settings are developed by the fire control system based on data on the location and movement factors of the target – obtained from the ZGS-158M tracking head and other, determining the firing conditions – obtained from a multi-sensor data collection system, which is part of the system, e.g., an artillery weather station, a cannon position sensor or a counter of fired bullets. The system's operation is controlled by the operator using the hardware interface of the console equipment and dedicated software containing, among others, the fire control algorithm and the gun condition control algorithm.

Each weapon system, in addition to the basic tactical requirements, must meet several technical needs resulting from the operating conditions after being installed on board the ship. The technical assumptions and standards [6, 7] specify, among others: allowable values of weight and size parameters as well as features ensuring ergonomic and safe operation of the system on a limited area, which is the ship's deck. Due to its considerable size and weight of 675 kg [8], the critical element of the system is the 35 mm KDA cannon. During warfare, a ship is exposed to many shock impacts, such as firearms, contact explosions or pressure waves from an explosion in the air and water. These interactions can generate accelerations in the ship's construction with values of several thousand G. When designing a warship, limit values are assumed that must be met by all devices mounted on it, thus ensuring the ship's maneuverability and combat ability for given conditions. Knowledge of the acceleration values in the nodes of the ship's structure is necessary to ensure the appropriate strength of the ship's devices, the method of their foundation, depreciation, and location.

In the case of structures intended for operation in the Polish Navy, the load is the appropriate acceleration values adopted following [6], which are respectively (Fig. 2):

- a_x = 85 m/s^2 for 10 ms – along the ship's axis;
- a_y = 250 m/s^2 for 8 ms – transverse to the axis of the ship;
- a_z = 500 m/s^2 for 5 ms – vertically.

Calculations should be carried out in a time interval equal to 0–0,04 s (40 ms).

Calculations based on the methodology [6] were carried out in [5]. This work focuses on the cannon structure strength. However, the physical load meaning proposed in the methodology was questioned during the calculations. Hence, this work decided to verify how the load presented by the standard relates to the actual accelerations on board the ship. It is evident that it is best to conduct an experiment. Still, due to the costs and possibilities at this stage of work, it was decided to use FEM numerical simulations to verify the correctness of the load. The scientific innovation of the presented work consists of checking and specifying the guidelines for designing and constructing warships.

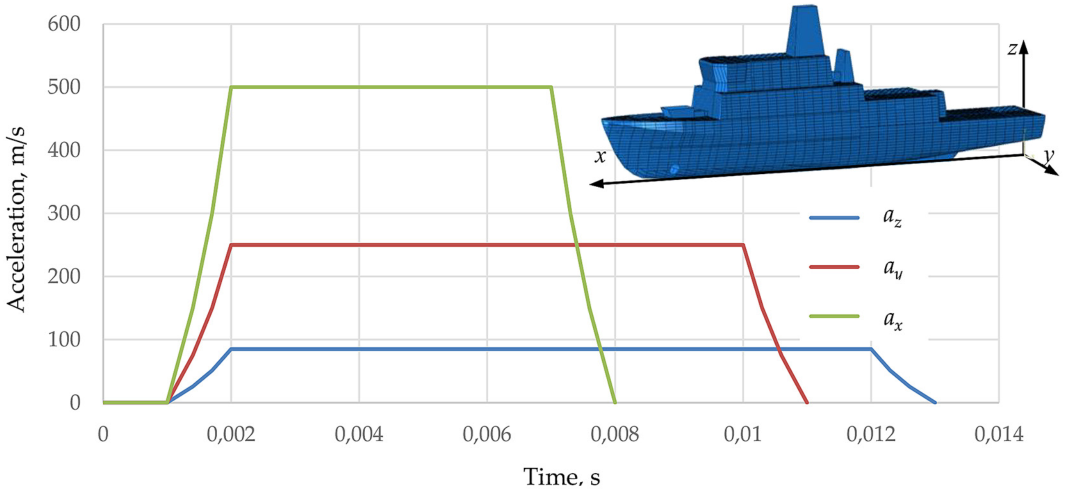

Fig. 2. Kinematic load of the cannon foundation according to the methodology [6]

The ship's devices, mechanisms, armament and military technology must meet specific strength requirements [9], ensuring combat and manoeuvrability in extreme load conditions, such as, for example, explosions of mines or torpedoes with the assumed parameters. The existing requirements and recommendations do not consider the variety of weapons, explosion parameters, the direction of the pressure wave and the device's location in the ship's hull. The scientific innovation is the dependence of the examined quantities, in this case, the acceleration based on an example gun, on the parameters mentioned above and the presentation of the procedure for the general case.

RESEARCH SCOPE

The object of the tests is the base of the OSU-35K [10] naval cannon mounted on the project 258 minehunter (Fig. 3) [11]. The hull structure of this ship is made of non-magnetic austenitic steel DIN 1.3964 [12], whose chemical composition and properties are given in [13].

The ship's hull is divided into nine watertight compartments. Vertically, the ship was divided into four spaces defined by the inner bottom, main deck, superstructure deck, navigation deck, and bearing deck. The vessel is powered by two internal combustion engines powering cycloidal propellers, characterized by low noise levels and high maneuverability. The maximum displacement of the ship is about 850 tons. The basic dimensions of the unit are:

- total length 58.5 m;
- waterline width 9.75 m;
- maximum width 10.3 m;
- draft 2.7 m.

To determine the acceleration value in the cannon base, a reference should be made to a given

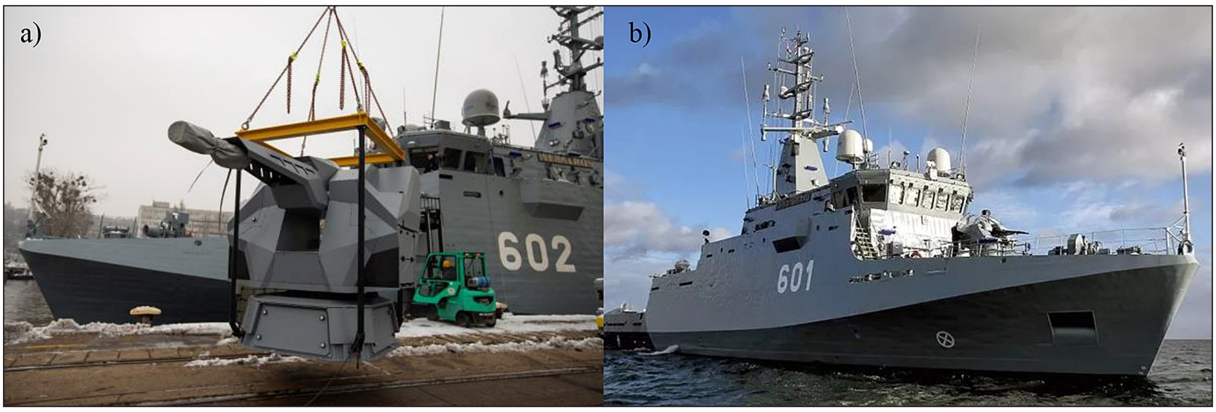

Fig. 3. Project 258 ships: ORP Albatros*(a) and ORP Kormoran**(b) (Source: * https://www.facebook.com/photo/?fbid=503583348472238&set=pb.100064617314886.-2207520000, ** https://radar.rp.pl/modernizacja-sil-zbrojnych/art36580531-marynarka-wojenna-zamawia-trzy-kolejne-niszczyciele-min-typu-kormoran-ii)

reference load. When considering the operation of naval armaments, one should refer to the worst possible variant, the load caused by a non-contact underwater explosion [14]. The explosion is a rapid combustion process with increased pressure occurring fractions of a millisecond.

In 1948, the topic was first described by Cole [15]. In Poland, research was described in 1978 [16], and newer research was extended by its continuators experimentally in [17] and theoretical descriptions in [18]. More recent research abroad was conducted by [19], who developed a gas bubble model, and [20], whose work currently forms the basis of computational algorithms for CAE programs [18].

The process nature is determined by the dynamic conditions in which the explosive mixture is located, and by the medium turbulence. Pressure waves, called shock waves, generated during an explosion in liquids (underwater explosion) or solids, reach up to 8000 m/s in the case of detonation. The expanding gas bubble affects the surrounding layer of water, creating a spherical shock wave. In the initial phase, this wave travels with a speed of $v \approx$ 5000–8000 m/s. Then the water molecules act on the layers of the adjacent water, losing their velocity and moving further at the speed of sound in water, which is about $c_0 \approx$ 1500 m/s. The main one is Cole, whose publications form the basis of most research on the subject. The criterion for dividing the degree of risk is also unclear, as described in work [21]. Since an explosion is an unpredictable phenomenon, individual countries refer to standards [6, 7]. The paper presents a series of FEM simulations of the hull strength of the project 258 minehunter loaded with the impact of a pressure wave from a non-contact TNT charge for the following parameters (Fig. 4). The TNT charge explosion is placed at a depth of 30 m, 50 m from the ship's side, on loads of 100–1000 kg in steps of 100 kg until damage level *L* (according to the scale below) is reached [7, 14]. The initial charge detonation of 100 kg TNT corresponds to level *0*. It is a near explosion [22]. Damage levels are determined by the NATO scale [7, 22]:

- *0* – no damage;
- *R* – onboard repairs – temporary loss of combat capability, repairs made by the crew;
- *M* – mission abort – virtually complete loss of combat capability;
- *I* – immobilization – several damages to the main drive, practically complete loss of combat and maneuverability;
- *L* – imminent loss likely – hull break, first controlled leaks, complete loss of propulsion;
- *K* – kill – breaking the continuity of the hull, uncontrolled leaks, sinking of the ship.

The hull was represented as a shell reinforced with beam and bar elements for this work. Large-size components such as propellers and gears were mapped as rigid bodies with an appropriate mass. To reduce the task size, several simplifications of various scales were used. However, within the cannon's foundation, the ship's geometry was more detailed (Fig. 5).

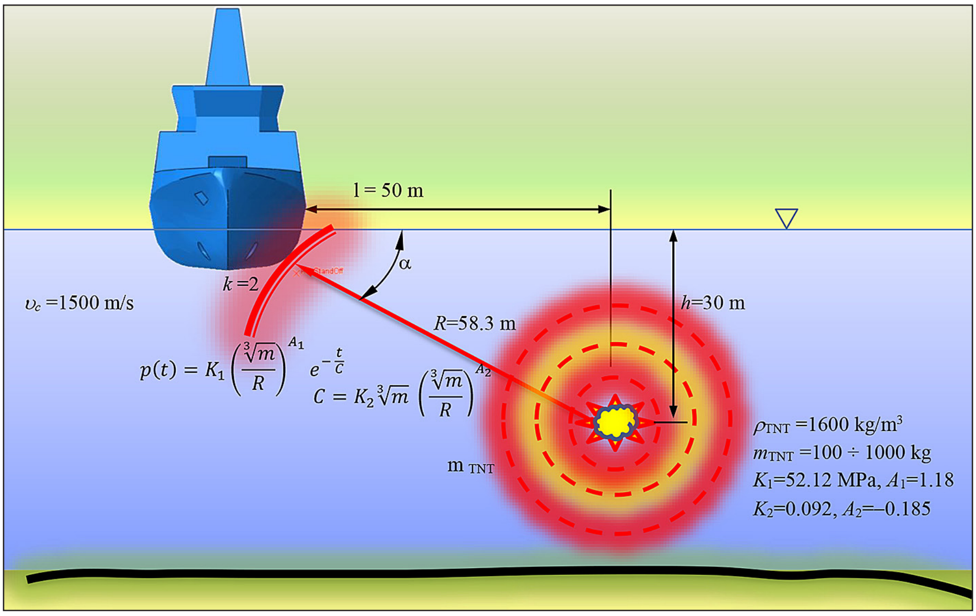

Fig. 4. Scheme of the task - explosion of the TNT charge perpendicularly to the foundation of the cannon

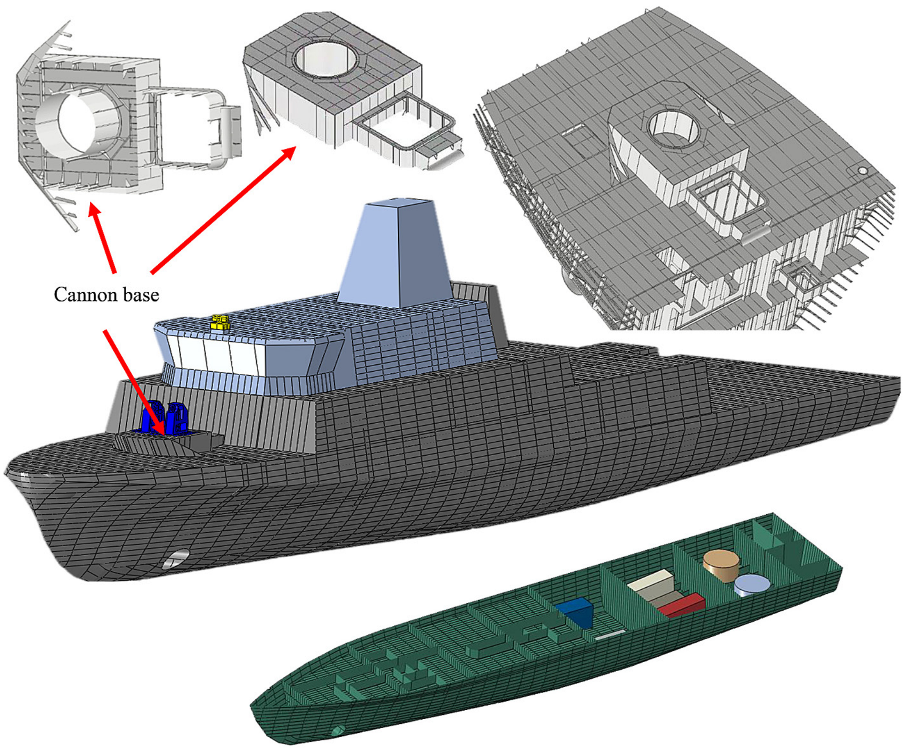

Fig. 5. The geometry of the project 258 ships mapped in the CAD program

The hull solid model was reflected in the Autodesk Inventor environment. It was then converted into a shell model. 3- (S3R) and 4-node (S4R) linear shell elements were used for discretization. The hull reinforcements were made of linear beam elements (B21 and B31) using the stringer technique. Calculations were performed using the Abaqus CAE and UNDEX (underwater explosion) algorithms described in [23]. For the calculations, a discretization with a varying mesh size was made, in which the smallest elements have a dimension of 0.025 m. The characteristics of the discretization are presented in Table 1, while the visualization of the ship's finite element mesh is shown in Figure 6. The model was connected using equations of continuity of displacements in nodes.

Table 1. Discretization of the ship's geometry

The smallest element dimension, m	0.025
Total degrees of freedom	4258470
Total number of nodes	709790
Total number of finite elements	761540
Number of beam elements	112525

MATERIAL CHARACTERISTICS

To determine the cannon foundation structure accelerations, it is necessary to know the material from which the hull was made. This knowledge is essential since the hull will absorb part of the

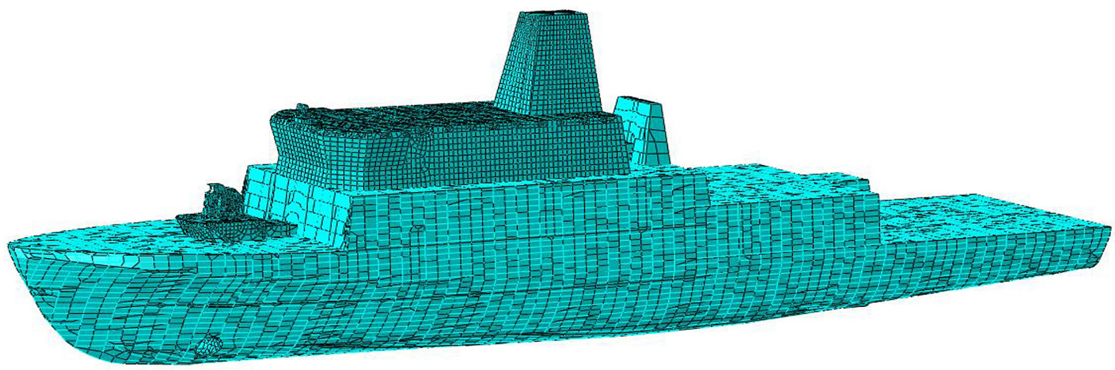

Fig. 6. Discretization of the ship's hull geometry

load, so the energy reaching each point will differ. The above assumption is the basis for the thesis of the lack of physical interpretation of the load presented in the introduction.

For FEM calculations, it is necessary to develop the actual characteristics based on the engineering characteristics [24, 25]. The explosion is a fast-changing process. Therefore, a model that considers the deformation rate is necessary to describe the plastic characteristics. In the considered case, the Johnson-Cook constitutive model was used [26, 27], in which the Huber-Mises-Hencky (HMH) σ_{pl} plastic reduced stresses as a function of strain are described by the equation:

$$\sigma_{\text{pl}} = \left(A + B\varepsilon_{\text{pl}}^{n}\right)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{\theta - \theta_0}{\theta_{\text{top}} - \theta_0}\right)^{m}\right] \quad (1)$$

where: A – elastic range of the material $\sigma_{\text{pl}} = 0$ (it is often simplified in form $A = R_e$);
B – hardening parameter;
n – hardening exponent;
C – strain rate coefficient;
ε_{pl}^{n} – true plastic strain;
$\dot{\varepsilon}$ – strain rate;
$\dot{\varepsilon}_0$ – quasi-static strain rate (0.0001 s^{-1});
θ – current material temperature;
θ_0 – ambient temperature;
θ_{top} – melting temperature;
m – thermal softening exponent.

The above values for this model were determined based on static and dynamic tensile tests on a rotary hammer [28] and are shown in Figure 7.

Other material properties used in the task are as follows:

Density – ρ	7746 kg/m^3
Young modulus – E	2.1·10^5 MPa
Poisson ratio – ν	0.3
Yield strength – $R_{e\ Stat}$	560 MPa
Ultimate strength – $R_{m\ Stat}$	880 MPa

Steel DIN 1.3964

A = 550 MPa
B = 1100 MPa
n = 0.32
m = 1.13
θ_{top} = 1793 K
θ_0 = 293.15 K
C = 0.006
$\dot{\varepsilon}_0$ = 0.0001 s^{-1}

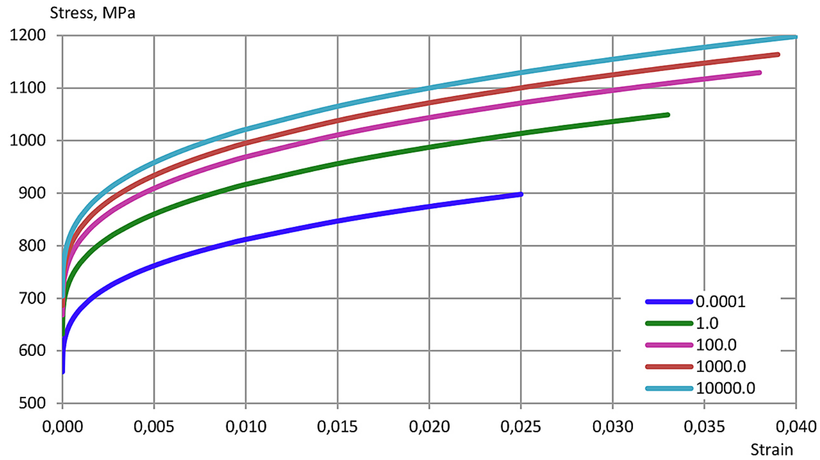

Fig. 7. Characteristics of DIN 1.3964 steel for different strain rates

Steel DIN 1.3964

D_1 = 0.001
D_2 = 0.26
D_3 = 0.6
D_4 = 0.01
D_5 = 0
θ_{top} = 1793 K
θ_0 = 293.15 K
$\dot{\varepsilon}_0$ = 0.0001 s^{-1}

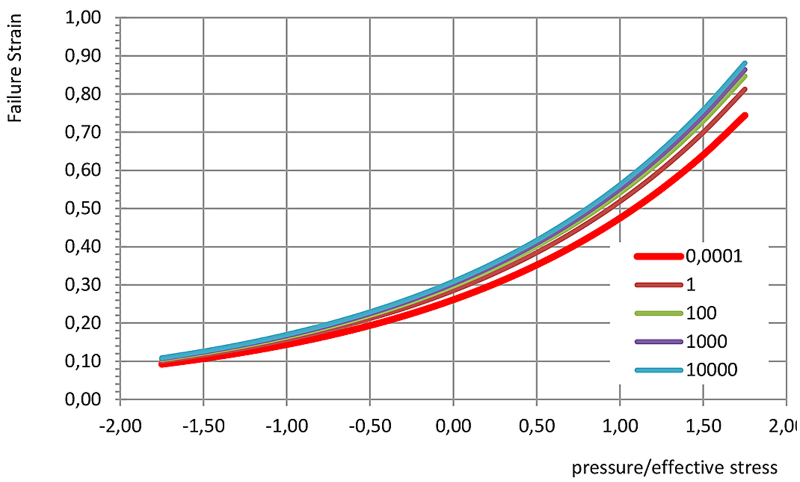

Fig. 8. Failure characteristics of DIN 1.3964 steel for different strain rates

To describe the failure of materials, the Johnson-Cook failure model was used, in which the material parameters are [29, 30] (Figure 8).

Hull loaded with a pressure wave from a non-contact mine explosion

Before the mine explodes, the externally wetted part of the ship's hull structure is loaded with the hydrostatic pressure of water $p_h = \gamma h$ at a given immersion depth of h. The specific gravity of water γ =10000 N/m³ was assumed for the calculations. After the explosion, in addition to the hydrostatic pressure, the ship's hull structure is loaded with a pressure impulse from the charge explosion. This results from the detonation of TNT, anchored at a depth of 30 m and 50 m from the ship's side. Cole's formulas were used to describe the distribution of the pressure wave from the explosion of the TNT charge in water as a function of distance, time and mass [31, 32]:

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

$$p(t) = p_{\max} e^{-\frac{t}{C}} \quad (2)$$

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

where: R – distance from the explosion epicenter;
m –TNT mass;
K_1, K_2, A_1, A_2 – coefficients determined experimentally.

It was assumed that a TNT explosion with a density of 1600 kg/m³ occurs, so the coefficients in the Cole equation, modified according to Price [20, 32], are K_1 = 52.12 MPa, A_1 = 1.18, K_2 = 0.092, A_2 = -0.185. Values of the maximum pressure on the front of the wave incident on the nearest point of the ship's hull ($R_{\min}$ = 58.3 m). It was assumed that the pressure wave within the ship moves in the water at a speed of 1500 m/s.

To implement the load presented above, the CAE program [14] uses a ready-made algorithm - interaction called "Incident wave" with the UNDEX procedure, the detailed description of which is available in the program documentation [33] and work [22]. The pressure wave loading the hull falls only on its submerged part and then moves to the upper decks. The selected course of the pressure wave along the undercarriage is shown in Figure 9.

In calculations related to underwater explosions, the equation of motion is extended by a series of non-linearities. The object's shape changes due to plastic deformation in each time step. The stiffness and mass of the structure and its mass also vary due to the failure of elements. The impact-loaded structure also has a high inertia, so mass loads must also be considered.

In addition, during the calculations, the load changes, which depends on time, distance, angle

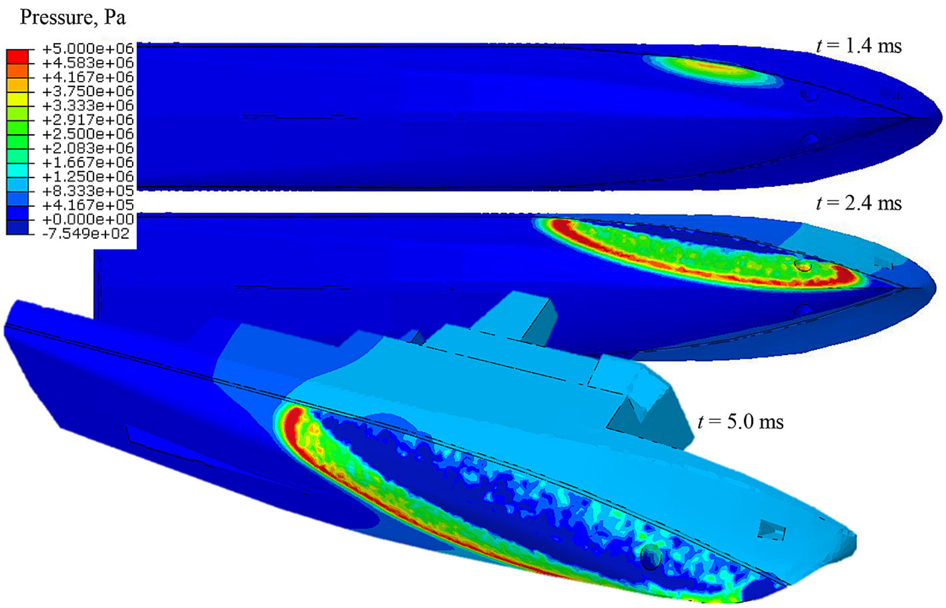

Fig. 9. The pressure wave loading the ship's hull from the explosion of 100 kg TNT on the beam at a distance from the ship's side of l = 50 m and submerged at a depth of h = 30 m at a selected moment of time

of incidence of the wave on the finite element, and mutual contacts between them. In the structure of the analyzed ship, there are high concentrations of frames and reinforcements, where high deformations and damages should be expected under impact loads, as a consequence of which strongly deformed or separated structural elements may penetrate neighboring elements. In such areas, the interaction between the elements was defined, preventing them from interpenetrating each other.

Taking into account the above assumptions, the equation of motion in the considered problem is as follows [34–36]:

$$M(U)\ddot{U} + C\dot{U} + K(U, \dot{\varepsilon}, \varepsilon_{\text{failure}})U = \\ = F(t, R, m_{\text{TNT}}, v_{\text{c}}, \alpha, C_{\text{int}}) \tag{3}$$

$$U(t_0) = U_0 \\ \dot{U}(t_0) = \dot{U}_0 \tag{4}$$

where: K – stiffness matrix;
M – inertia matrix;
$C = \alpha M + \beta K$ – damping matrix, where α are β are constant coefficients [15];
U, $\dot{U}$, $\ddot{U}$ – vector of displacement, velocity, and acceleration;
U_0, $\dot{U}_0$ – initial conditions, displacements, and velocities;
F – load vector;
$\dot{\varepsilon}$ – strain rate vector;
$\varepsilon_{\text{failure}}$ – strain failure vector;
t – time;
R – distance from the explosion epicenter;
m_{TNT} –TNT mass;
v_{c} – speed of sound in water;
α – angles of incidence of a direct pressure wave on the element;
C_{int} – interactions and contact forces between colliding structure elements.

The size of the time step depends on the grid size. The smaller the size of the applied finite elements, the smaller the time step. This results from the ratio of the smallest dimension in the mesh elements in relation to the speed of propagation of the elastic (acoustic) wave in the material of the element, thus [37]:

$$\Delta t = \frac{h}{a} \tag{5}$$

where: h – the smallest characteristic length of the element;
$a = \sqrt{(E/\rho)}$ – elastic (acoustic) wave speed.

In the adopted discretization, the smallest characteristic dimensions are 0.025 m, which at the speed of sound for steel of 5135 m/s gives a time step $\Delta t = 4.87 \cdot 10^{-6}$ s.

SIMULATION RESULTS

As part of the work, several simulations of the explosion of charges of 100–1000 kg were carried out with a step of 100 kg at a depth of 30 m, at a distance of 50 m from the ship's side, on the traverse of the cannon's foundation. Due to the extensive results volume in work, it was decided to present only the results of calculations of the explosion on the traverse of the 100 kg TNT (58.3 m from the hull). As part of the calculations, the following was determined:

- components of the vector of displacements, velocities, and accelerations of the entire hull;
- components of the stress vector and equivalent stress HMH and Tresca;
- components of the vector of plastic strains;
- components of the acceleration vector on the foundation of the 35 mm cannon.

The distance from the explosion's epicenter to the ship's hull is approx. 58.3 m. After the first pressure wave reaches the hull, stresses are initiated, which propagate over the entire hull surface from midship to the bow and stern and the inside of the structure. Wave pressure values reach 5 MPa. So this is an explosion on the border of *R/M* levels - Mission abort. The ship will temporarily lose combat capability. The crew can remove the damage independently and restore the ship's combat capability. The HMH stresses for selected time moments on the hull plating on the explosion side are shown in Figure 10.

The extreme values of these stresses occur 5 ms after the pressure wave reaches the hull. The average HMH stress values are about 300 MPa, and local concentrations exceed 600 MPa. Thus, local plastic deformations may occur. Figure 11 presents distributions of accelerations exceeding 300 G. They appear on the plating from the explosion side and inside the ship on the lower deck. Accelerations above 1000 G (Fig. 12) occur only on the hull plating and propagate along the wavefront. Inside the hull structure, they are practically non-existent, except for the thruster channel.

The hypothesis presented in the article concerns the legitimacy of loading the cannon foundation with the acceleration proposed by the standards.

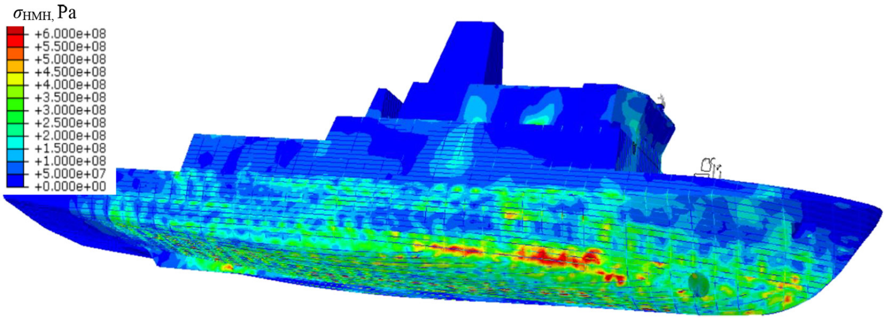

Fig. 10. HMH stresses on the ship's hull, *t* =10 ms

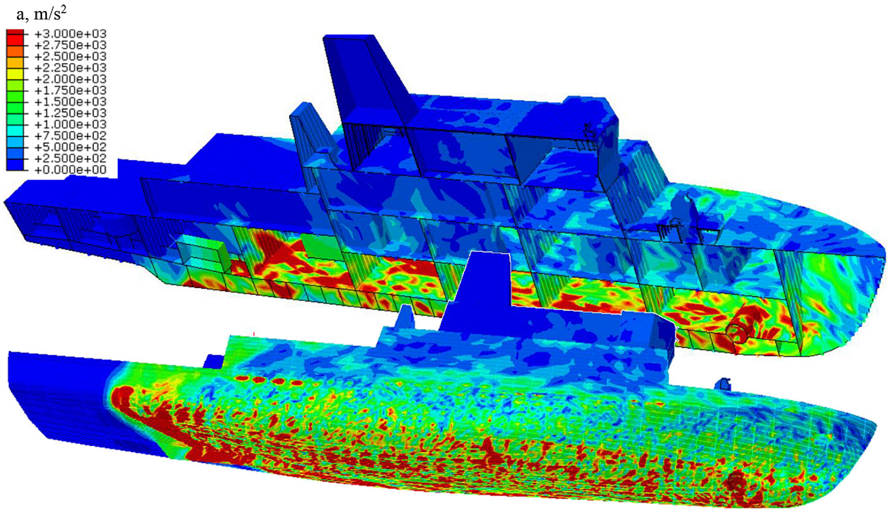

Fig. 11. Accelerations on the ship's hull above 300 G, 9.6 ms

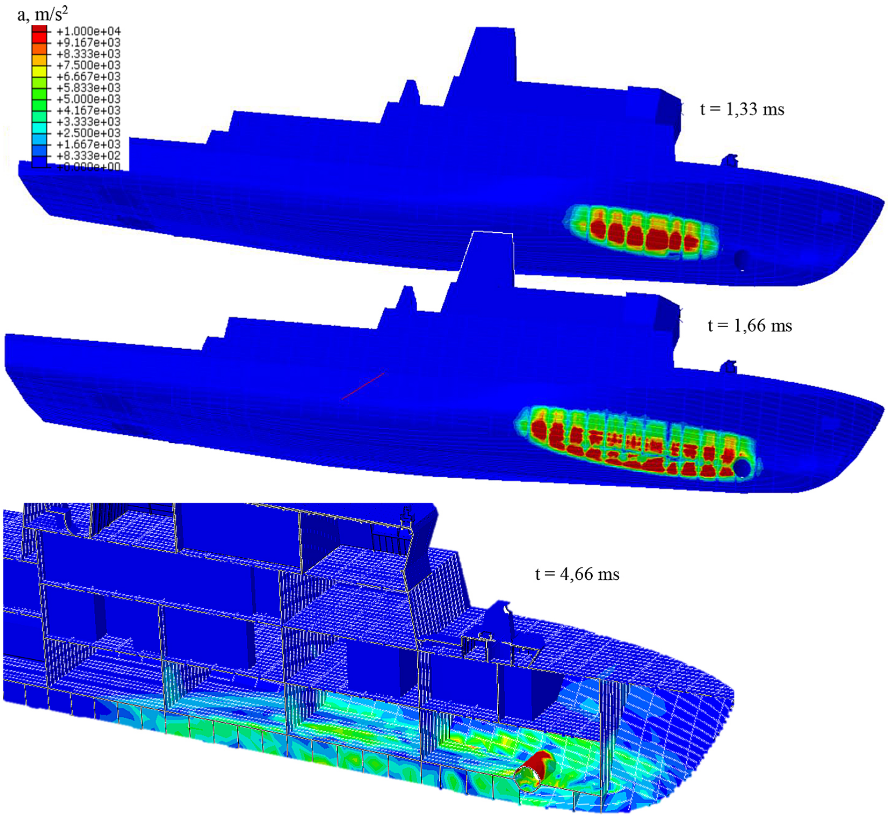

Fig. 12. Accelerations on the ship's hull above 1000 G

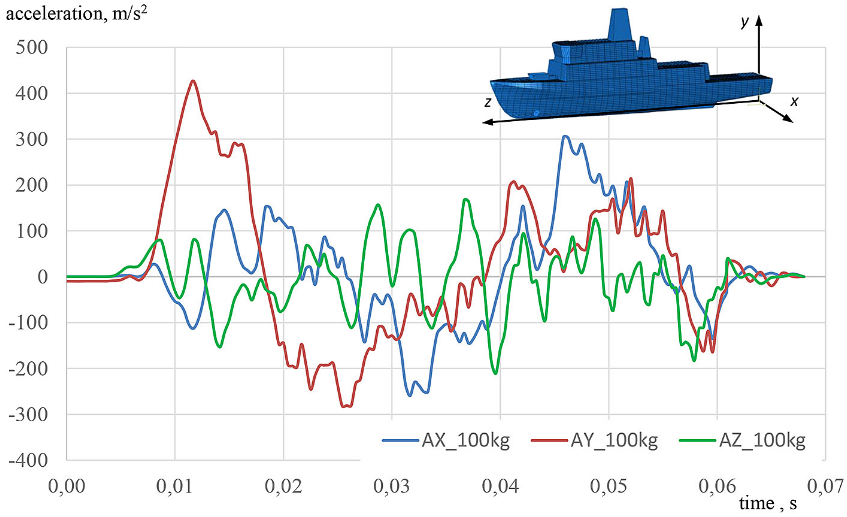

Fig. 13. Accelerations from the explosion of 100 kg TNT in the center of gravity of the cannon base

The values of accelerations in the center of gravity of the cannon base as a function are shown in Figure 13. They reach the maximum values:

- along the *x*-axis (traverse): a_{xmin}= - 260 m/ s², a_{xmax}= 304 m/ s²;
- along the *y*-axis (draft): a_{ymin}= - 282 m/ s², a_{ymax}= 427 m/ s²;
- along the *z*-axis (longitudinal): a_{zmin}= - 211 m/ s², a_{zmax}= 167 m/ s².

It was decided to present the results in the form of graphs. The values of accelerations as a function of the mass of the detonated TNT charge on the beam of the cannon at a distance of 50 m from the hull at a depth of 30 m, calculated in the direction *x* - transverse, *y* - vertical, *z* - longitudinal, are presented. The direct distance in a straight line to the hull is 58 m. Calculations were made for loads of 100, 200, 300, 400, and 500 kg of TNT. The graphs contain polynomial approximation functions that enable the determination of acceleration values for intermediate values of loads. Figure 14 shows the maximum negative values from the cannon base, while Figure 15 shows the maximum positive values from the cannon base. It is worth noting that the methodology does not consider accelerations in the opposite direction to the explosion's epicenter. The presented results are examples of a device in a specific location subjected to a single explosion from a given direction with particular parameters. A similar methodology can be used when designing any marine technical device exposed to impact impacts.

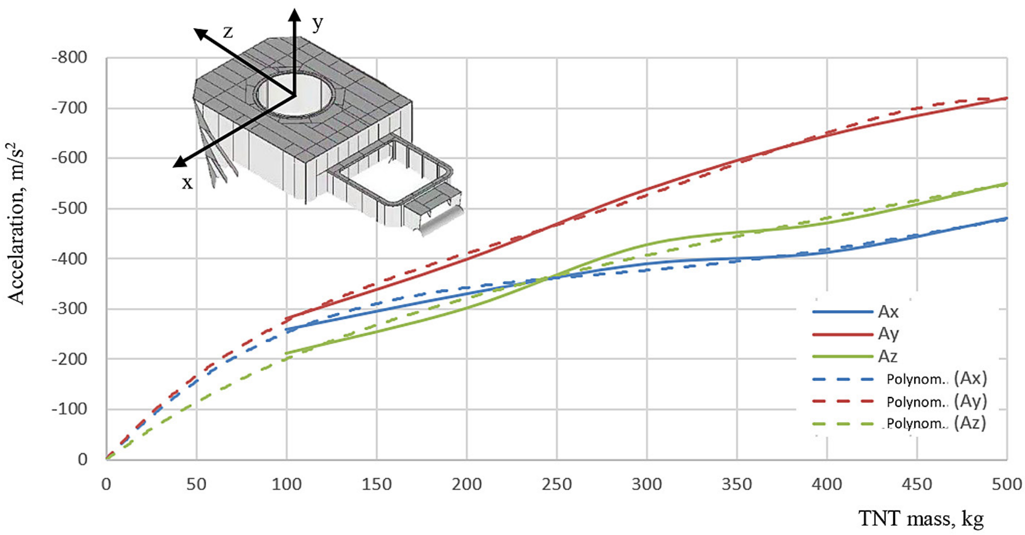

Fig. 14. Maximum negative accelerations in the center of gravity of the cannon base as a function of the mass of the explosive charge

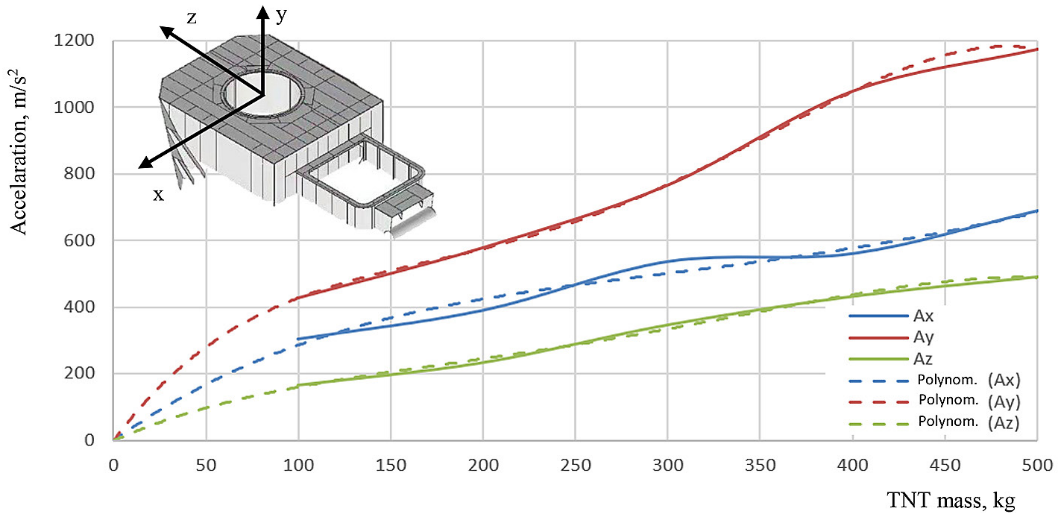

Fig. 15. Maximum positive accelerations at the center of gravity of the cannon base as a function of the mass of the explosive charge

The results of the conducted simulations provide a detailed description of the effects of the explosion. Extreme HMH stress values occur 5 ms after the pressure wave, with average values around 300 MPa, and local concentrations exceeding 600 MPa. This suggests the possibility of local plastic deformation.

The presented results show that the accelerations on the hull reach values of over 1000 G, but they are damped by its structure and do not reach the gun mounting at this value. Based on the calculations, interpolation functions were used to facilitate the determination of acceleration values for various masses of the explosive charge.

CONCLUSIONS

The article presents a series of FEM simulations of the strength of the hull of the Project 258 minehunter loaded with the influence of a pressure wave from a non-contact TNT charge to the explosion of a charge placed at a depth of 30 m and at a distance of 50 m from the ship's side.

The simulations cover a range of explosive charge masses, from 100 to 1000 kg, with a step of 100 kg. The objective is to assess the hull's response until reaching damage level L on the NATO Damage Scale.

The obtained stress and acceleration distributions are logical and their values are consistent with literature knowledge. As a result of the simulation, the acceleration values in the foundation of a 35 mm naval gun mounted on the deck of a minehunter were determined. The acceleration is presented as a function of the mass of the detonated charge. They will serve as input data for strength calculations of the gun's structural elements.

The article considers for which loads the methodology proposed by the Polish Navy can be applied. It was noticed that for a TNT charge with a mass of 150 kg, the results of accelerations in the vertical and transverse directions to the ship's axis had similar values, but not at the moment of their occurrence. Discrepancies appear in the case of accelerations in the longitudinal direction, which is logical because the explosion proposed by the methodology is probably located under the keel and the center of buoyancy of the ship.

It should be emphasized that the requirements contained in the defense standard "NO-20-A500-5 - Technical requirements and testing of ship devices and mechanisms are most often used to assess the impact resistance. Total resistance to single impacts. Research methods and evaluation criteria". Due to international practice in device impact testing, the pulse should be a half-sine waveform. It is a derivative of the detonation of a 200 kg TNT charge at a distance of 55 m behind the ship's stern and a depth of 30 m (STANAG 4137 requirements). This is the basic standard, the evaluation criterion during impact resistance tests using experimental and numerical analysis methods.

Taking into account the authors' experience, it can be assumed that the MW guidelines refer to the explosion of approximately 150 kg of TNT under the keel at a distance of 50 m and at a depth of 30 m.

This means that the standards imposed by the Polish Navy may be underestimated in relation to the currently used means of combat, which use heavier loads.

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