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Building a miniature experimental model for camouflage underwater explosions

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Abstract: In general, explosion experiments on miniature models are research methods commonly used in explosion research. Although the method of experimental explosion research on miniature models in laboratory conditions is very meaningful for practical application but up to now, there have been no published papers on the method of calculating and designing parameters on the size of miniature models that satisfy the conditions of camouflage underwater explosions (UNDEX), so that similar explosive effect laws when carrying out UNDEX in rivers and seas can be drawn, whose factors converting research results from miniature models to reality are also obtained. For the above reason, the paper aims to analyze the theoretical basis of the similarity model of an explosion, proposing a method for calculating and verifying the parameters of miniature experimental models on underwater explosion effects, conducting experiments, and establishing experimental laws. The result is a miniature model for experimental research on underwater explosions that satisfies the conditions of blasting in infinite environments and satisfies the similarity principle of shock wave pressure in water environments with a model correction factor of 1.45 to 1.47 times when compared to the methods of Russia and the United States, respectively.

Keywords: Blasting, UNDEX, experimental explosion, shockwaves, similarity principle, blasting model.

1. Introduction

At present, methods for calculating the pressure of shock waves generated by the detonation of concentrated explosive charges in a water environment mainly rely on empirical formulas proposed by the American scientist Cole R. H (Formula (11) below) and the Russian scientist Salamakhin T.M (Formula (4) below) [1-5]. Both sets of formulas reflect the law of explosive similarity, in which the relative pressure on the shock wave front (defined as the ratio of the overpressure on the shock wave surface to the hydrostatic pressure) is proportional to the relative distance from the explosion center to the observation point (defined as the ratio of the explosive radius or the cube root of the explosive mass to the distance from the explosion center to the observation point).

However, in practical applications, these formulas do not yield results consistent with experimental observations when dealing with small explosive charges with masses below approximately 1 kg [6, 7].

In particular, when analyzing the results of underwater explosion model studies worldwide, Chinese researchers have made the following observation [8]: “Australian researchers have already noticed the situation that the shock wave energy changes with the measuring point. They believe that this phenomenon is caused by the reflection from the boundary of the pool. However, this explanation does not clarify the linear correlation between shock wave energy and distance for an ideal TNT explosive under identical test conditions. We speculate that the reason lies in the secondary reaction of aluminum powder rather than in the test conditions.”

This phenomenon is analogous to the reduction of energy losses with increasing voltage in electric power transmission systems. In the analysis of explosion experiments, many researchers have observed that as the explosive charge mass decreases, the specific energy losses—including chemical energy losses during the explosive reaction and thermal losses due to heating of the surrounding medium per unit mass of explosive—increase significantly [2, 8-10]. This implies that when the explosive mass falls below a certain threshold, the intensity of the shock wave propagating from the charge into the surrounding medium decreases markedly.

Blasting is a complex physical and mechanical process, and even up to now, there has not been a complete theoretical model that can fully and accurately describe these processes. Therefore, in the study of the general explosion process or the study of the explosive effect process in the environment, scientists around the world have used an irreplaceable experimental method, which is the modeling method.

Modeling is a way that, instead of studying a phenomenon of interest in nature, a similar phenomenon on a model of a smaller or larger size is studied, usually under special experimental conditions [1, 2, 10-12]. The main meaning of modeling is that, through the experimental results with the model, it is possible to give suitable solutions about the characteristics and other quantities related to the phenomenon under natural conditions. The foundation of the modeling method in explosion research is the dimensional theory and the theory of similarity principle.

In the field of blasting, experimentation is a research method that has a greater significance for perfecting the practical calculation of explosions in various environments and is the basis for directly providing practical constants. The basic need for comparing explosions of different sizes appears in the experimental approach to explosion calculation, which is extremely useful for further perfecting the physical aspects of explosion theory. Such a comparison can be made by using the “similarity principle”.

The method of experimental research on explosive effect similarity has been applied by the majority of scientists in the world. First time in 1628, two French scientists, Voban and Devi, were the first to use the idea of explosive effect similarity in proposing the method of calculating explosions [2, 13]. In practice, American calculations when studying the geometric parameters of a single explosion crater widely used the "Lempsona rule" [14]. Then in the 20th century, a series of scientists perfected the use of this method in the study of explosive effects in the environment, for example, American scientists such as Cole R.H [1, 3, 5], Russian scientists such as L. I. Seđov, Sadopski, Kutuzov B.N, Pakroski G.I, Salamakhin T.M of Russia [3-5, 10-18]. In particular, professors Kutuzov B.N and Rubxov V.K emphasized that [13]: “it is not correct to assume that all theories are correct, although at the same level of use for calculating all phenomena of explosive impact - they are only in mathematical that form an approximate reflection of one side or one stage of explosion; the task of mathematics is to discover the physical meaning of the coefficient K and its dependence on the properties of soil and rock, the type of explosive and the conditions of explosion".

When studying the effects of explosions in the environment, scientists around the world have realized that the laws of explosions in the environment are self-similar to each specific explosion condition [10]. Due to cost reasons and the heterogeneity of natural conditions, in practice, it is difficult to conduct large-scale experimental explosions as in reality, and it is even impossible to conduct experiments with large-scale explosions in reality.

In the practice of blasting to destroy solid rock underwater for mineral exploitation, port construction, or dredging of seabed traffic routes, it is necessary to address many problems related to calculating the effects of explosions in aquatic environments under special conditions, in order to control the amplification or attenuation of shock-wave intensity in water [3, 19-22]. Until now, however, there has been no guidance on an experimental model corresponding to the camouflage underwater explosion that could serve as a basis for calculations and further research.

For the above reasons, to facilitate the research and prediction of the effects of explosions in water environments in natural river and sea conditions, it is necessary to build a miniature explosion experimental model in laboratory conditions. The experimental results obtained from the model are analyzed and converted into the corresponding values of the real model corresponding to the explosion conditions in practice.

2. Materials and method

2.1. Theoretical basis

The mechanical formation and propagation of shock waves in water share general characteristics with shock waves in air; however, underwater explosions also exhibit unique features.

The explosion products expand, displacing water and forming a cavity known as a bubble. As the bubble expands, it pushes the surrounding water outward. This motion continues until the pressure inside the bubble equals the hydrostatic pressure at the explosion depth; however, due to inertia, the water continues to move. Consequently, the pressure inside the bubble drops below the hydrostatic pressure, causing water to move back toward the center of the bubble. The bubble is then compressed to a minimum volume before expanding again. Since the bubble's density is always lower than that of water, it experiences a net upward force from the hydrostatic pressure and rises toward the water surface. The amplitude of the bubble's oscillations decreases over time, and as it rises, the bubble eventually reaches an equilibrium state. At shallow depths, after approximately three to four oscillations, the bubble reaches the free surface, bursts, and releases its contents into the atmosphere.

Therefore, the general form of the pressure-time curve at a fixed point in water during an underwater explosion is illustrated in Fig. 1.

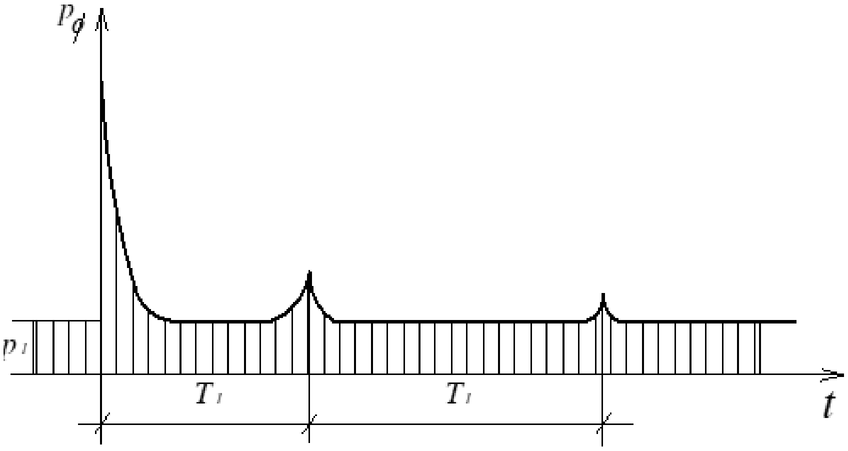


Fig. 1. Pressure-time variation at a fixed point in water as the shock wave front passes

In Fig. 1, p1 represents the ambient pressure at the water surface, and Ti denotes the pressure cycles of the shock wave generated by the expansion and contraction of the gas bubble formed from the explosion products in water. The first phase of the shock wave exhibits the highest pressure, which has the greatest destructive effect on underwater objects and is significantly larger than the subsequent phases. Therefore, this study focuses primarily on the first phase of the shock wave.

When studying shock waves propagating in water, researchers found that the parameters characterizing the shock front also obey the laws of conservation of mass and momentum, and their relationships were determined as follows [2, 4]:

$$u_\varphi = \left(1 - \frac{\rho_1}{\rho_\varphi}\right) D \qquad (1a)$$

$$p_\varphi - p_1 = \left(1 - \frac{\rho_1}{\rho_\varphi}\right) \rho_1 . D^2 \qquad (1b)$$

The third equation cannot be obtained from the law of conservation of energy, because for water the internal energy cannot be expressed explicitly in terms of pressure and density. Instead of the energy equation, an empirically derived relationship can be used as follows [4]:

$$\frac{D}{a_1} = 1 + m . \frac{u_\varphi}{a_1} \qquad (1c)$$

Substituting the corresponding parameters into equations (1a), (1b), and (1c), we obtain a system of equations dependent on q [2, 4, 16]:

$$\left.\begin{aligned} &1.\quad \frac{u_\varphi}{a_1} = \frac{1-q}{mq}; \\ &2.\quad \frac{p_\varphi - p_1}{\rho_1 . a_1^2} = \frac{1-q}{mq^2}; \\ &3.\quad \frac{\rho_\varphi}{\rho_1} = \frac{m}{m-1+q}, \end{aligned}\right\} \qquad (2)$$

where: a_1- sound speed in water; u_ϕ , p_ϕ , ρ_ϕ - respectively particle speed, pressure, density on the shock wave surface; D- shock wave speed; p_1, ρ_1 - pressure and density of the surrounding water environment; m- empirical coefficient depending on the nature of the environment, with water m ≈ 2.

From equations (2), it follows that, in order to determine the parameters at the shock front, it is necessary to know the relationship describing the variation of the shock wave velocity with distance. For spherical shock waves, this relationship can be determined based on the empirical formulas proposed by the Russian scientist T. M. Salamakhin [4].

$$\left.\begin{aligned} &\frac{R}{r_0} = 1,3\left(\frac{q^2}{1-q}\right)^{0,885}; \\ &q = 0,37\left(\frac{R}{r_0}\right)^{1,13}\left[\sqrt{1 + 5,4\left(\frac{r_0}{R}\right)^{1,13}} - 1\right], \end{aligned}\right\} \qquad (3)$$

Formula (3) is applicable within the range: $\frac{R}{r_0} > 10$

Equations (2) and (3) completely determine the parameters at the surface of a spherical shock wave generated by an underwater explosion. Substituting the value of q from Equations (3) into equations (2) yields:

$$\frac{p_\varphi - p_1}{p_1} = \frac{\Delta p}{p_1} = 14700.\left(\frac{r_0}{R}\right)^{1,13} \qquad (4)$$

where R is the distance from the blast wave pressure sensor to the explosion center (m), and Δp is the residual pressure of the blast wave at the measurement point.

Formula (4) defines the pressure at the shock front as a function of distance. This is a semi-empirical formula proposed by the Russian scientist T. M. Salamakhin. Formula (4) was derived entirely from experimental studies based on the theory of similarity. The theory of similarity assumes that:

When blasting in the environment, each volume element of the environment is compressed or stretched depending only on the effect of pressure, not on the influence of weight. The theory of explosion effect similarity states that the deformation of the environmental elements or the corresponding pressure in the element will be similar when exploding explosives of the same shape and chemical composition, different in the value of the explosion quantity, but have a common ratio between the size of the explosion quantity and the size from the center of explosion to the investigated element, see Fig. 2.

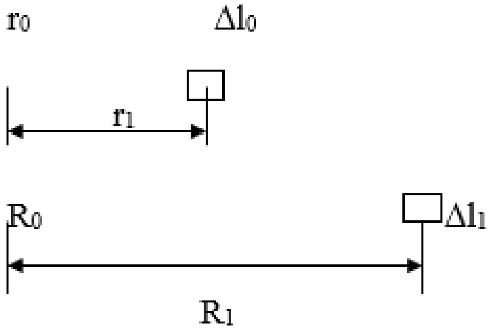


Fig. 2. Diagram defining the basic rules of explosion on the model

From Fig. 2, if the deformation of the environmental elements Δl_0 and Δl_1 are equal or the corresponding characteristic pressures of the two elements Δp_0 and Δp_1 are equal, then

$$\frac{r_0}{R_0} = \frac{r_1}{R_1} \qquad (5)$$

Or vice versa, when the condition of equation (5) is satisfied, then there is $\Delta l_0 = \Delta l_1$ or $\Delta p_0 = \Delta p_1$. In equations (5) , r_0, R_0 are the radius of the explosion quantity corresponding to the small case and the larger explosion quantity case, and r_1, R_1 are the radius of the explosion center to the survey point of the small case and the larger explosion quantity case, respectively.

From the above principle, when blasting in an infinite environment, the radius of the explosive effect zones (R) of the concentrated explosive quantity is linearly proportional to the explosion radius (r_0) or proportional to the cube root of the explosive mass ($Q^{1/3}$) for the concentrated explosive quantity. The radius of the explosive effect zones of the concentrated explosive quantity all follow the similarity principle with the explosion effect similarity coefficient or the destruction zone remaining unchanged in each type of environment (water, soil, rock, air,...), and the same explosion condition has the form:

$$\frac{R}{r_0} = k = \text{const} \quad \text{or} \quad \frac{R}{\sqrt[3]{Q}} = k = \text{const} \qquad (6)$$

Thus, at each relative water depth value for the explosive charge, the relative residual pressure at each relative distance ($R/Q^{1/3}$ or R/r_0) will be a constant of the form:

$$\frac{\Delta p}{p_0}\left(\frac{R}{\sqrt[3]{Q}}\right) = \text{const} \quad \text{or} \quad \frac{\Delta p}{p_0}\left(\frac{R}{r_0}\right) = \text{const} \qquad (7)$$

Then the maximum relative residual pressure on the incident shockwave of underwater explosion can be expressed as [1-4, 10, 16]:

$$\frac{\Delta p}{p_1} = f\left(\frac{r_0}{R}\right) = F\left(\frac{\sqrt[3]{Q}}{R}\right) \qquad (8)$$

The function f, F needs to be established from experiment which can be expressed in multi-component form when detonating in different environments [12, 18, 22]:

$$\frac{\Delta p}{p_1} = \sum_{i=1}^{n} A_i.f\left(\frac{r_0}{R}\right) = \sum_{j=1}^{n} A_j^{'}.F\left(\frac{\sqrt[3]{Q}}{R}\right) \qquad (9)$$

The constants A_i are determined experimentally, and are typically no larger than three components. For spherical explosive charges, it is $r_0 \sim \sqrt[3]{Q}$, in which Q is explosive mass. In formula (6), when replacing the radius with the weight of the explosive, it can be seen that if the explosive weight is the same, but the specific energy E is different, the explosive with the larger specific energy will have a larger impact at the same distance. Therefore, in the most general case, the similarity principle when exploding the spherical explosive must be proportional to the parameter $\sqrt[3]{E}/R$. The variant of this principle is called the similarity principle of explosive energy and has the form:

$$\frac{\Delta p}{p_1} = \sum_{j=1}^{n} B_j^{'}.F\left(\frac{\sqrt[3]{E}}{R}\right) \qquad (10)$$

where: Q – explosives mass of TNT, kg; E – explosive energy, kCal; r_0 – equivalent explosive radius, m; R - distance from blast wave pressure sensor to explosion center, m; Δp - residual pressure of blast wave at the surveyed point; p_1 - static water pressure; A_i, A'_j, B'_j – experimental coefficients.

The expressions (8) and (10) reflect the same nature, the same law of explosion effect similarity. They are just different forms of expression of the law of explosion effect similarity. In the study, it is enough to choose one of the above forms to establish the law of similarity. Analysis of the above expressions shows that under similar underwater explosion conditions, the relative pressure in the shock wave at each point depends on the ratio between the radius of the explosion and the radius from the center of the explosion to the survey point or depends on the ratio between the cube root of the total energy of the explosion (or the mass of the explosion) and the radius from the center of the explosion to the survey point. Based on the application of the similarity theory in experimental studies of underwater explosions, researchers around the world have established similarity laws for the pressure of shock waves in water. Typical examples include the empirical formula proposed by the Russian scientist T. M. Salamakhin (4) and the formula developed by the American scientist R. H. Cole [1-3, 5], as shown below:

$$\frac{\Delta p}{p_1} = 533\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.13} \tag{11}$$

Formulas (4), (11) have been widely applied in Russia and the United States and are considered standard characteristic curves to determine the pressure in the shock wave when blasting underwater, to evaluate the degree of deviation of the law in other conditions. In formulas (4) and (11), the exponent 1.13 of both the Russian and American schools found is the same, reflecting the similarity of the law of attenuation of the explosion shock wave in the water environment with distance, and the coefficients 14700 or 533 characterize the unit amplitude of the shock wave corresponding to two different methods of expression in Russia and the United States. Although the two calculation methods of shock wave pressure in water (4), (11) are used separately but these two methods also differ in wave amplitude by 1.5%.

Thus, it can be further affirmed that instead of experimental research with large explosive quantities at sea, it is completely replaced by experimental methods of explosion on miniature models in laboratory conditions. Experimental results on miniature models can be used for calculation and prediction, and applied in research on the law of shock wave propagation, serving the purposes of studying the effects of underground explosions for application to explosive conditions in river and sea areas. The problem is to propose a method of calculation, design a model that satisfies underground explosion conditions, and the experimental law found must satisfy the characteristic exponent index for the law of attenuation of explosive shock waves propagating in water equal to 1.13. Based on the analysis of experimental results on miniature models, it is proposed to find a model correction factor to convert experimental results to corresponding practice according to the methods of Russia and the United States.

2.2. Establishing miniature model for experimental research

2.2.1. Experimental model parameters

The purpose of the experimental model is to measure the parameters of the shock wave intensity in water propagating from the explosive charge to the survey point around the explosive charge.

The experimental model parameters are characterized by the size of the water tank and the mass of the explosive charge. The model must satisfy the requirements of the size of the water tank (tank) and the size of the explosive charge must ensure the condition of explosion in an infinite water environment, not affected by the free surface and the water bed to the pressure value measured on the shock wave surface.

The calculated and selected explosive

charge mass parameters must satisfy the condition of underground explosion under water (also known as explosion in an infinite environment), it means that the depth of the explosive charge is greater than the critical depth value or the calculated explosive charge mass value (Qtt) used in each explosion must not exceed the critical explosive charge mass value (Qth) converted to TNT explosive as follows [6]:

$$Q_{tt} < Q_{th} = \left(\frac{H}{3,4}\right)^{3};\text{kg} \qquad (12)$$

where: H- underwater depth, m. When detonating in a water tank model, the depth of the underwater explosive charge is usually half the water depth in the water tank.

The dimensions of the water tank, including the depth and width of the water environment, must be large enough to ensure the installation of shock wave pressure probes for experimental research purposes and ensure that the measured pressure values of the probes (survey points around the explosion) are not affected by the water bed and water surface. These conditions are checked through the requirement that the water surface influence coefficient (k_m) and the water bed influence coefficient ($k_đ$) are both greater than 1, calculated as follows [2, 4, 16]:

- Water surface influence coefficient on shock wave parameters (km)

$$k_m = \frac{0.314\left(\frac{H}{r_0}\right)^{2.3}\left(1+4.2\frac{h}{H}\right)}{\frac{R}{r_0}\sqrt{1-\left(\frac{H-h}{r}\right)^{2}}} \qquad (13)$$

where: R - distance from the center of explosion to research point, r=2,2 m; r_0- radius of the explosive charge, m; H, h - distance from water surface to explosion center (0.81m) and to research point (0.81m).

- Influence coefficient of water bed on shock wave parameters ($k_đ$)

$$k_d = \begin{cases} \dfrac{0.314\left(\frac{H_1}{r_0}\right)^{2.3}\left(1+4.2\frac{h_1}{H_1}\right)}{\frac{r}{r_0}\sqrt{1-\left(\frac{H_1-h_1}{R}\right)^{2}}}, \quad \dfrac{H_1}{r_0} \geq \left(\dfrac{3,22}{tg\beta^*}\right)^{0.77} \\[2ex] \dfrac{H_1}{r_0 tg\beta^* \sqrt{1-\left(\frac{H_1-h_1}{R}\right)^{2}}}\left[1+\dfrac{\frac{h_1}{r_0}}{2\left(\frac{H_1}{r_0 tg\beta^*}\right)^{0.435}-\frac{H_1}{r_0}}\right], \quad \dfrac{H_1}{r_0} \leq \left(\dfrac{3,22}{tg\beta^*}\right)^{0.77} \end{cases} \qquad (14)$$

where: R - distance from the center of explosion to research point, R=2,2 m; r_0 - radius of the explosive charge, m; H_1, h_1 - distance from the water bed to the center of explosion (0.81m) and to the research point (0.81m); β*- critical angle of incidence at which the reflection coefficient is zero. For hard rock there are some critical angles $\beta^*=72^o30'$; 60^o và 7^o.

Selecting parameters of explosive mass and size of experimental tank model:

- The explosive mass used is concentrated TNT explosive manufactured from the factory with masses of 6g and 11g corresponding to the radius of the explosive mass converted to a sphere of 8.8mm and 12mm;

- The size of the water tank is designed to be 6m long, 6m wide, and 2m deep, enough to ensure the installation of pressure sensors in the shock wave to serve the research task.

- The explosive mass used is placed in the middle of the water tank with the water depth of the explosive mass H = 0.81m, so the water depth of the explosive mass is relatively 62 times the radius of the 11g explosive mass and 82 times the radius of the 6g explosive mass. It is necessary to calculate and check the underground explosion condition and the requirement of not being affected by the water surface and the water bed.

Applying formulas (12), (13), (14) to calculate and check the underground explosion condition and the influence coefficient condition of the water surface and water bed, the results shown in Table 1 are obtained. Analysis of the calculation results reflected in Table 1 shows that the set of parameters of the miniature experimental model all satisfy the camouflage explosion condition, the explosion effects obtained at the surveyed locations are equivalent to explosions in an infinite water environment, not affected by the water surface and water bed.

Table 1. Calculation to check the response of the selected experimental model parameter set

No	Test explosion conditions	Formula	Result	Requirement	Evaluation
1	Critical explosive mass $Q_{th,}$ g	12	13,5	Q_{tt} = [6 g; 11 g] <Q_{th}	Satisfied
2	Water surface influence coefficient (K_m) when using a 6g explosive charge and the farthest measuring head radius from the explosion center R= 2.2m (see Fig. 1, only calculated for the most unfavorable case when the measuring head is farthest)	13	212,1	$K_m > 1$	Satisfied
3	Water surface influence coefficient (K_m) when using an 11g explosive charge and the farthest measuring head radius from the explosion center R= 2.2m (see Fig. 1, only calculated for the most unfavorable case when the measuring head is farthest)	13	141,7	$K_m > 1$	Satisfied
4	Water bed influence coefficient (K_d) when using a 6g explosive charge with critical angle β=[72.5°; 60°; 7°] and the radius of the farthest measuring head from the explosion center R= 2.2m (see Fig. 1, only calculated in the most unfavorable case when the measuring head is farthest)	14	3397	$K_d > 1$	Satisfied
5	Water bed influence coefficient (K_d) when using an 11g explosive charge with critical angle β=[72.5°; 60°; 7°] and the radius of the farthest measuring head from the explosion center R= 2.2m (see Fig. 1, only calculated in the most unfavorable case when the measuring head is farthest)	14	1944	$K_d > 1$	Satisfied

2.2.2. Experimental model structure

The water tank is built of solid bricks; the inside of the tank is designed to be 6m long, 6m wide, and 2m deep enough to ensure the installation of pressure gauges in the shock wave to serve the research task. The charge is arranged in the middle of the tank space. The shock wave pressure gauges are placed symmetrically about the explosion center and lie on a straight line parallel to the water surface. There are 11 gauges (coded from P1 to P11) arranged for each explosion test. The gauges are hung on the working platform (see details in Fig. 3)

2.2.3. Materials and equipments

Explosive materials include: the explosives used are compressed TNT blocks with a density of 1.52 g/cm3 and electric detonators No. 8 made in Vietnam, see Fig. 4. The system used to measure blast wave pressure in the water environment consists of two multi-channel dynamic data acquisition units, the NI SCXI-1000DC and the DEWE-3020 (see Fig. 5), together with specialized pressure sensors for underwater blast wave measurement (see Table 2).

The NI SCXI-1000DC is a modern multi-channel dynamic measuring instrument manufactured by National Instruments (USA). The device is fully computer-controlled via a USB connection interface.

The DEWE-3020 is a modern multi-channel dynamic measuring instrument manufactured by the Austrian company Dewetron. The device can simultaneously acquire and process signals from 8 analog DAQP inputs or 16 analog MDAQ inputs. It features 3 PCI slots for A/D cards or other interface cards (e.g., 1394, ARINC, 1553) and can be paired with an expansion module to process an additional 8 measurement channels.

The underwater shock wave pressure sensors, PCB 138A01 and PCB 138A05, are manufactured by the American company PCB Piezotronics. Their technical specifications are listed in Table 2. These measuring devices have been used in experimental studies [6, 23, 24].

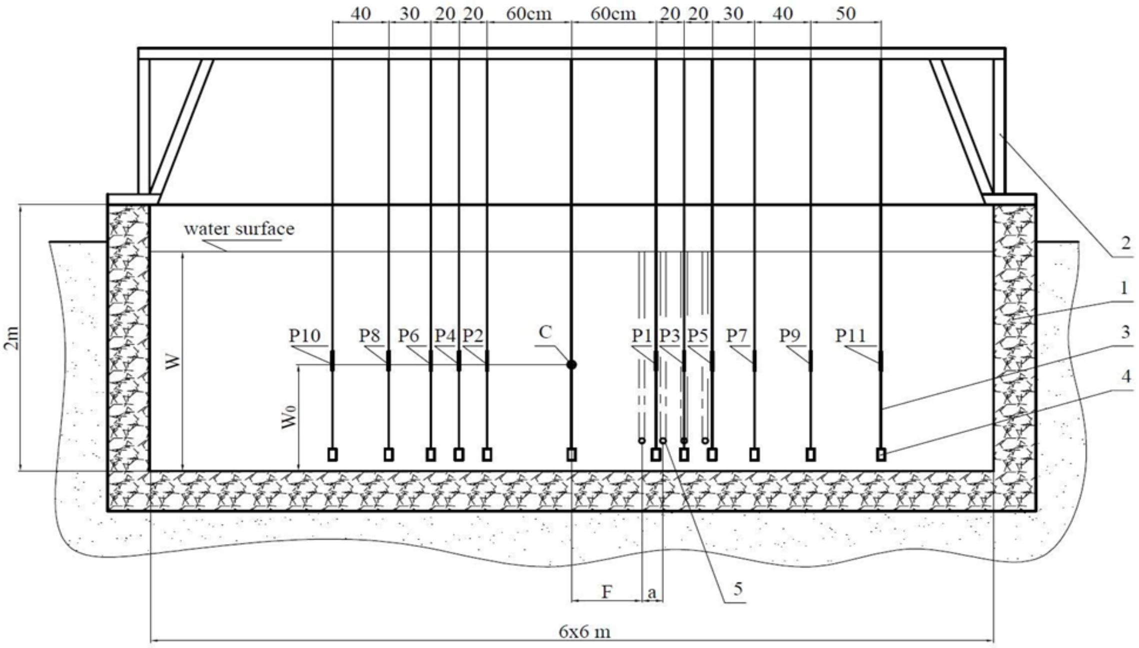


Fig. 3. Experimental model and layout of shock wave pressure gauges
1-Water tank; 2-Working platform; 3-Steel cables; 4-Weights;
5-Blowpipe; C-Explosive charge; P1, P2,…, P11-Pressure gauges from 1 to 11
A-Distance from explosive charge to the 1st blowpipe; e- Distance between two blowpipes; W0- Distance between sensors and water bed; W- depth of sensors


(a) (b) (c)

Fig. 4. Explosive materials used in model explosion experiments
a) TNT explosive charge; b) Detonator No. 8; c) Explosive charge and detonator structures during testin


(a) (b)

Fig. 5. Multi-channel dynamic measuring devices used in the experiment
a) NI SCXI-1000DC measuring device; b) DEWE-3020 measuring device
(The images were taken from the user manuals provided by the manufacturers of the measuring equipment)

Table 2. Technical specifications of PCB measuring head 138A01, 138A05

Specifications	Unit	PCB 138A01	PCB 138A05
Measuring range (output ±5V)	kPa	6,895	34,475
Effective range (±10V output)	kPa	13,790	68,950
Sensitivity (±15%)	mV/kPa	0.73	0.15
Maximum pressure	kPa	344,750	
Resolution	kPa	0.14	0.7
Resonance frequency	kHz	≥ 1000	
Cooldown (reflex)	μs	≤ 1.5	
Low frequency response (-5%)	Hz	1.7	
Nonlinearity	%FS	≤ 2,0	
Operating temperature range	°C	-23 ÷ +37.8	
Extreme shock	m/s²	196,140	
Excitation voltage	VDC	20÷30	
Constant excitation current	mA	2÷20	
Output impedance	Ω	≤ 100	
Output bias voltage	VDC	8÷14	
Sensor element		Tourmaline	

2.2.4. Blast sensor installation

The sensors are numbered from P1 to P11, hung on silk steel cables with a diameter of 2 mm, the lower end of the steel cable hangs a weight 4 with a mass of 2 kg, the upper end of the steel cable has a hook to hang on the welding buttons at the specified positions on the operating floor 2, the length of the steel cables 3 is adjusted so that the weights 4 are about 10 cm from the bottom of the tank (weight 4 does not touch the bottom of the tank). The sensors are connected to the steel cables 3 at the same height from the bottom of the tank 0.8 m, each measuring head is numbered synchronously with the corresponding jack connected to the multi-channel dynamic measuring machines, see Fig. 3.

3. Results and discussion

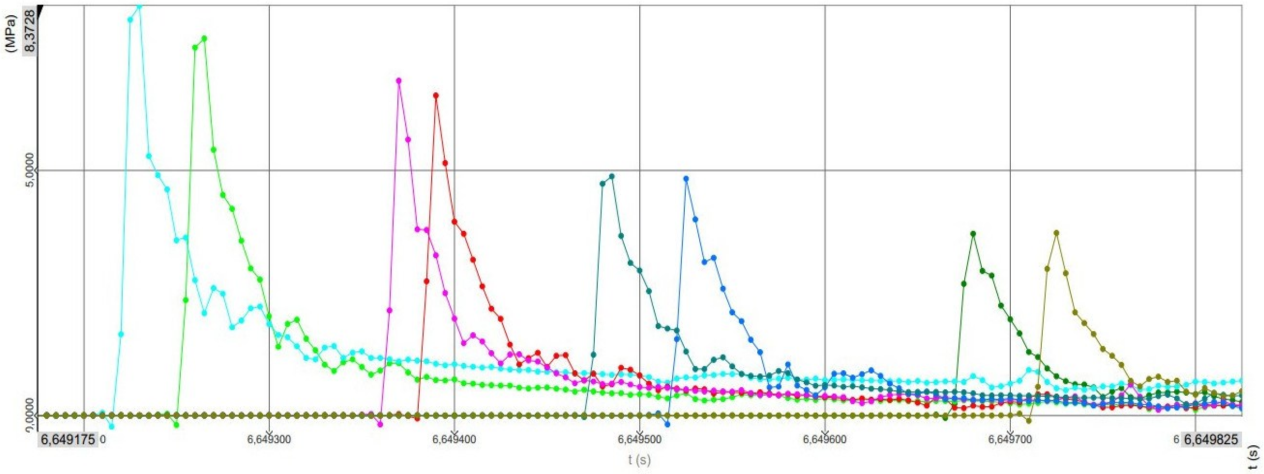
3.1. Results

Experiment in a model water tank to experimentally study the attenuation of the blast wave in water with distance. The purpose of this experiment is to compare and evaluate the difference in shock wave intensity of the experimental model in the tank with the standard experimental rules in the field of the US and Russia.

The experimental content is arranged with compressed TNT explosives in the middle of the water tank with 02 explosive levels of 6g and 11g (including the detonator weights), detonated with electric detonator No. 8. The pressure probes are hung at the correct height of the explosive. The water depth in the tank is 2m, the depth of the explosive charge and the distance from the probes to the explosive charge are reflected in Table 3. The 6g explosive charge type conducts 02 explosions, and the 11g explosive charge type conducts 6 explosions.

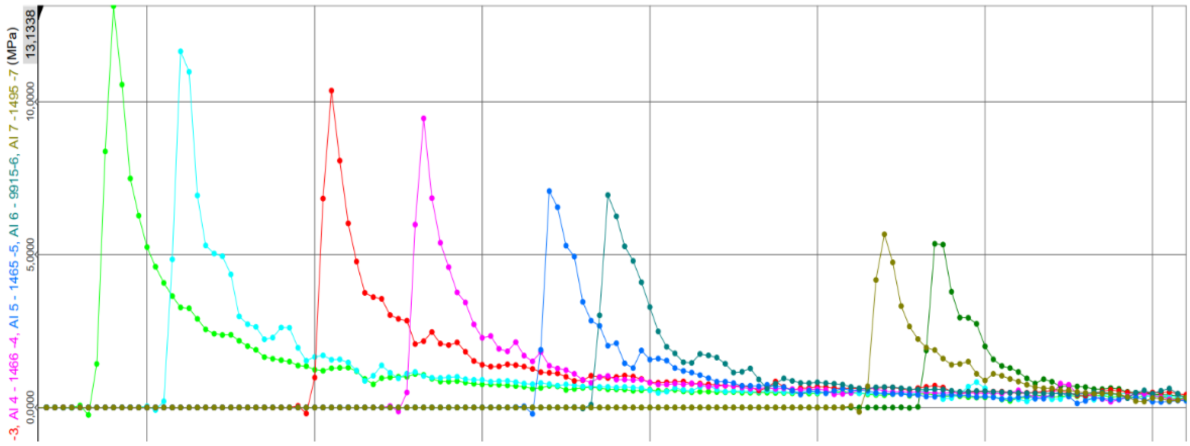
Table 3. Experimental parameters and results of pressure measurement on the shock wave surface when the explosive charge exploded in the tank

No	Code	Maximum residual pressure at measuring locations (Đ$_i$ corresponding to the distance R_i). MPa										
		Left-hand side of the explosives charge						Right-hand side of the explosives charge				
		P1	P3	P5	P7	P9	P11	P2	P4	P6	P8	P10
		R 0.6m	R 0.8m	R 1m	R 1.3m	R 1.7m	R 2.2m	R 0.6m	R 0.8m	R 1m	R 1.3m	R 1.7m
1.1. Q=6 g; h=1.15 m												
1	6_5_p1	7.7	6.53	4.83	3.73	0.76	0.69	8.37	6.84	4.88	3.71	3.24
2	6_5_p2	6.11	5.15	3.79	3.06	0.8	0.55	9.8	7.55	4.9	3.93	3.65
1.2. Q=11 g; h=1.15 m												
3	6_5_p3	11.67	9.79	6.78	5.3	1.31	0.84	12.85	10.03	7.27	5.6	3.45
4	6_5_p4	13.13	10.36	7.08	5.67	1.11	1.04	11.65	9.46	6.95	5.35	2.46
1.3. Q=11 g; h=0.81 m												
5	7_5_p26	11.43	9.42	6.84	5.57	4.09	3.18	-	9.38	6.71	5.73	2.76
6	7_5_p27	9.81	8.08	6.16	5.02	3.8	2.98	-	9.79	7.29	6.03	2.62
7	7_5_p28	11.91	9.1	6.43	5.25	3.87	3.16	-	9.27	6.75	5.3	3.29
8	7_5_p29	10.89	9.02	6.56	5.33	3.88	3.08	-	9.15	6.82	5.8	1.38

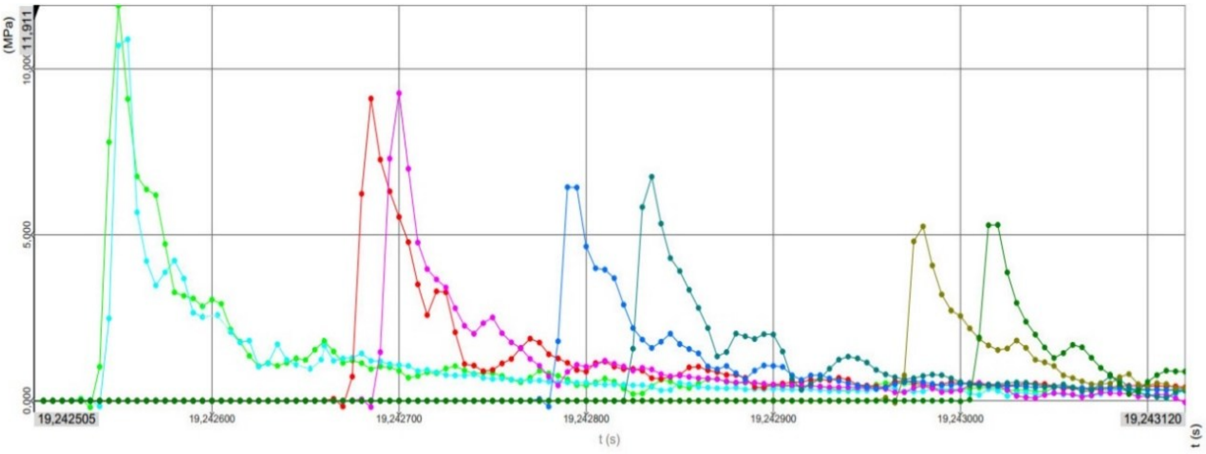


a) Experiment coded 6_5_p1

Fig. 6. Experimental graph of the variation of residual pressure on the shock wave surface over time received from a set of 08 probes installed in the experimental model



b) Experiment coded 6_5_p4



c) Experiment coded 7_5_p28

Fig. 6. (continued)

The explosion experiment process complies with the regulations on safety in the use of explosives according to Vietnamese standards QCVN 01/2019-BCT.

The experimental result parameters are the residual pressure values shown in Table 3, and the residual pressure graph on the blast wave front is presented in Fig. 6.

3.2. Discussion

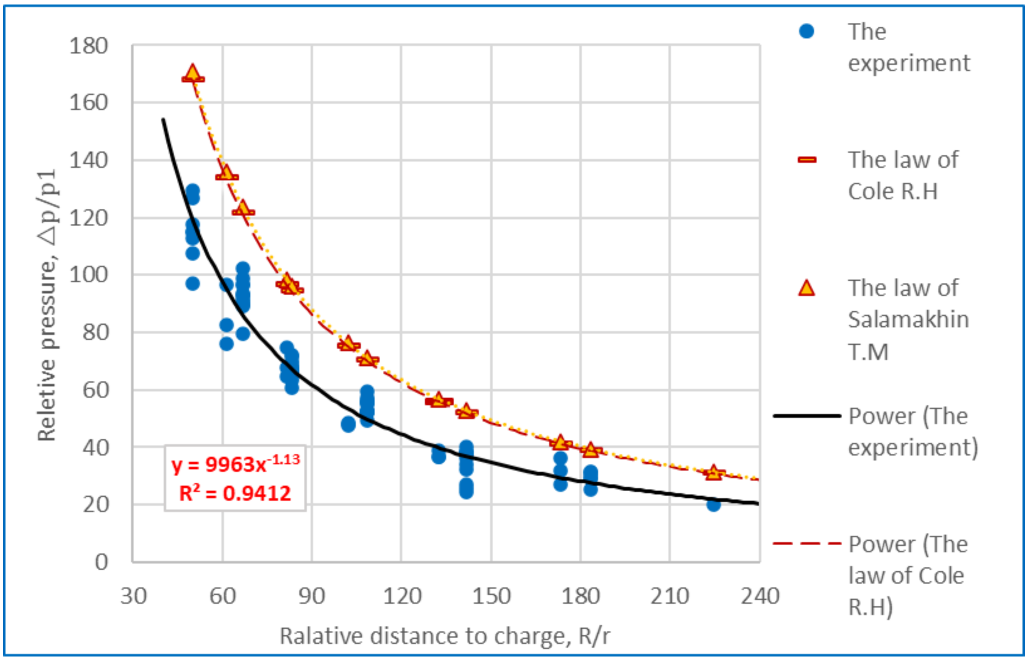
Process the primary data in Table 3 to get the corresponding secondary data set in dimensionless form according to the theory of similarity. Use Excel software to analyze the set of similar experimental data on the dependence of the relative residual pressure on the surface of the explosion wave propagating in water, according to the distance from the explosive center, under the least squares method as the form of expression (5) above. The results allow to obtain the experimental law on the dependence of the relative residual pressure of the explosion wave propagating in the test water tank according to the relative distance, reflected in the expressions (15a; 15b) and the graph reflecting these laws in Fig 7:

$$\frac{\Delta p_{mh}}{p_1} = 9963.\left(\frac{r_0}{R}\right)^{1.13} \text{; R Square = 0,94} \qquad (15a)$$

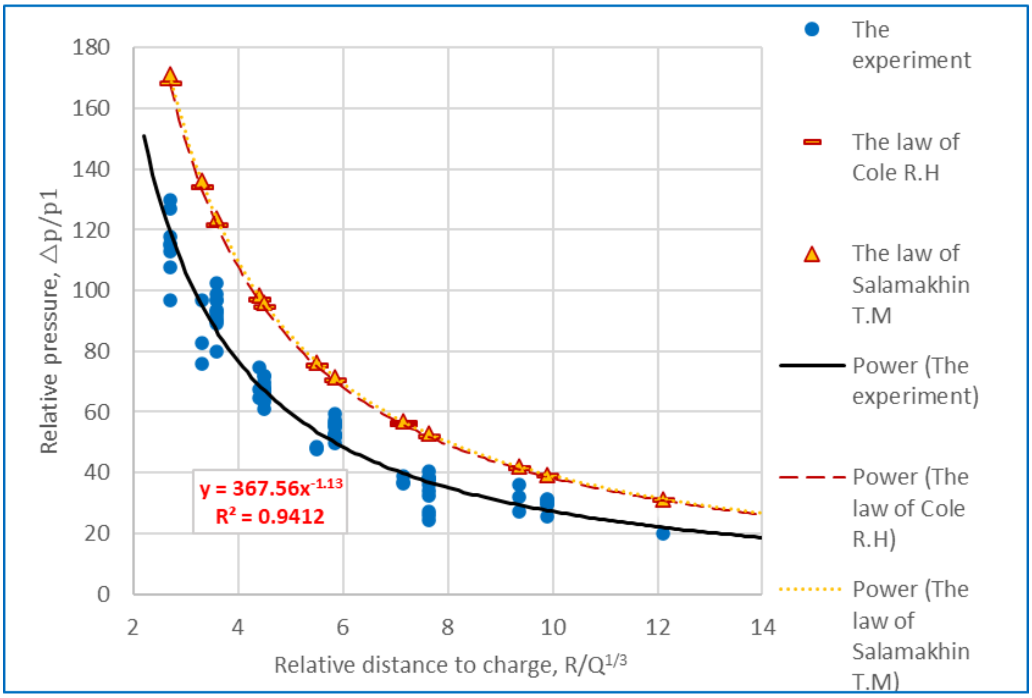
$$\frac{\Delta p_{mh}}{p_1} = 367.56.\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.13} \text{; R Square = 0,94} \qquad (15b)$$

where: Δp_{mh}- residual pressure in the shock wave obtained from the model experiment; R Square coefficient of determination of regression function.

The symbols of the quantities in formulas (15a) and (15b) are similar to formulas (4) and (11) but correspond to the experimental model, in which Δp_{mh} is the maximum residual pressure on the explosion shock wave surface obtained from the experimental model.



a) The law of Δp/pmt on the surface of blast wave according to R/r



b) The law of Δp/pmt on the surface of blast wave according to R/Q1/3

Fig. 7. Graph comparing the dependence law of relative excess pressure on the shock wave surface according to the relative distance obtained from the experimental model with the standard law found by Russia and the US in natural large explosion conditions

To evaluate the reliability of the empirical formula (15b), $f(R/\sqrt[3]{Q})$, the relationship between x and y was linearized from its original form $y = ax^b$ into a linear representation $\ln y = \ln a + b \ln x$. Subsequently, regression analysis was performed using the Data Analysis ToolPak in Microsoft Excel with a 95% confidence level (α=0.05). The results, presented in Fig. 8, yield the regression expression (15b) with a coefficient of determination R^2=0.941 and a significance F value of 6.7×10^{-48}, which is substantially lower than α=0.05. These results confirm the statistical significance of the obtained regression model. Furthermore, the P-values associated with the regression coefficients of the prefactor and the exponent are 1.1×10^{-83} and 6.7×10^{-48}, respectively, both below the significance threshold (α=0.05), indicating that all regression coefficients are statistically significant.

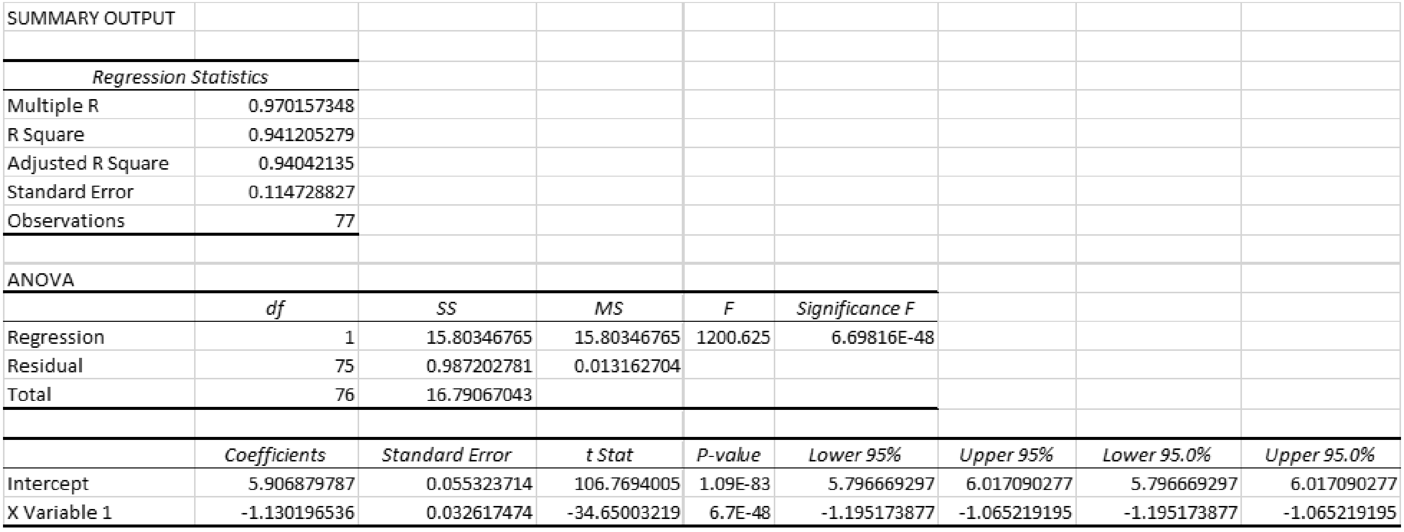
Similarly, the reliability of the empirical formula (15a), f(R/r)„ was evaluated using regression analysis implemented in the Data Analysis ToolPak of Microsoft Excel with a statistical confidence level of 95% (α=0.05). The obtained results yield the regression relationship (15a) with a coefficient of determination R^2 =0.941 and a Significance F value of 6.7×10^{-48}, which is substantially lower than α=0.05. These results confirm the statistical significance of the obtained regression model. Furthermore, the P-values associated with the regression coefficients of the prefactor and the exponent are 5.8×10^{-66} and 6.7×10^{-48}, respectively, both below the significance threshold (α=0.05), indicating that all regression coefficients are statistically significant.

The laws obtained for the attenuation of shock wave intensity when exploding in the conditions of the received miniature model are expressed in two forms (15a) and (15b) with the exponent index of 1.13, which completely coincides with the exponent index of the corresponding laws of Russia (4) and the United States (11). This proves the similarity of the miniature research model when exploding in water environment compared to the conditions of a large explosion on the field, however, the amplitude coefficient is smaller than the amplitude value in the calculation formula of Russia (4) and the United States (11). Therefore, it is necessary to determine the model correction coefficient to convert the experimental results to the corresponding practice according to the methods of Russia and the United States. From the graph in Fig. 3, it can be seen that the experimental curve obtained from the experimental model lies below the Russian and American law curve corresponding to the standard experimental conditions, so the model adjustment coefficient is determined to ensure that the pressure value obtained from the experimental model multiplied by the adjustment coefficient must be equal to the pressure calculated according to the Russian formula (4) or the American formula (11). Then the model adjustment coefficient (kmh) is calculated as follows:

$$k_{mh} = \frac{\dfrac{\Delta p}{p_1}\left(\dfrac{r_0}{R}\right)}{\dfrac{\Delta p_{mh}}{p_1}\left(\dfrac{r_0}{R}\right)} = \frac{14700\left(\dfrac{r_0}{R}\right)^{1.13}}{9963\left(\dfrac{r_0}{R}\right)^{1.13}} = 1.47 \qquad (16a)$$

or

$$k_{mh} = \frac{\dfrac{\Delta p}{p_1}\left(\dfrac{\sqrt[3]{Q}}{R}\right)}{\dfrac{\Delta p_{mh}}{p_1}\left(\dfrac{\sqrt[3]{Q}}{R}\right)} = \frac{533\left(\dfrac{\sqrt[3]{Q}}{R}\right)^{1.13}}{367.56\left(\dfrac{\sqrt[3]{Q}}{R}\right)^{1.13}} = 1.45 \qquad (16b)$$



SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.970157348							
R Square	0.941205279							
Adjusted R Square	0.94042135							
Standard Error	0.114728827							
Observations	77							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	15.80346765	15.80346765	1200.625	6.69816E-48			
Residual	75	0.987202781	0.013162704					
Total	76	16.79067043						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5.906879787	0.055323714	106.7694005	1.09E-83	5.796669297	6.017090277	5.796669297	6.017090277
X Variable 1	-1.130196536	0.032617474	-34.65003219	6.7E-48	-1.195173877	-1.065219195	-1.195173877	-1.065219195

Fig. 8. Results of experimental data processing using regression analysis

Substitute (4), (15a) into (16a) and substitute (11), (15b) into (16b) to get the model adjustment coefficient equal to 1.47 when compared with the Russian standard law and equal to 1.45 when compared with the American standard law. Thus, the approximate average model adjustment coefficient is:

$$k_{mh} = 1.45 \div 1.47$$

The deviation of the shock wave intensity of the model (S) compared with the intensity value calculated by the Russian and American methods is determined as follows:

$$S = \left(\frac{1}{k_{mh}} - 1\right).100\% = -29\% \div -30\% \qquad (17)$$

Thus, it can be seen that when the experimental explosion is conducted under the above selected model conditions, the shock wave attenuation law is similar and similar because of the same exponent index of 1.13. However, the shock wave amplitude in the experiment in the miniature model is reduced by 1.45 times (corresponding decrease of -29%) compared to the American experimental law value and reduced by 1.47 times (corresponding decrease of -30%) compared to the Russian experimental law value when the experiment is conducted under standard conditions - an infinite water environment in nature, the pressure in the shock wave is not affected by the free surface, the water bed and other conditions. This can be explained that when the explosive mass is smaller, the loss of explosive energy to heat a unit volume of the environment is greater, so the portion of energy transferred to the shock wave is reduced, causing the coefficient characterizing the shock wave amplitude to decrease accordingly.

We compare the above findings with the work of To D. T., who performed underwater TNT explosion tests with charges of 0.2–0.6 kg. Using the measured data, To applied a least-squares fit together with interpolation analysis to obtain an empirical relation for the maximum surface pressure as a function of explosive mass and distance from the explosion center [23]:

$$\frac{\Delta p}{p_1} = 14700.Q_1^{\frac{1}{5.18}}\left(\frac{r_0}{R}\right)^{1.13} \qquad (18)$$

where p_1 is the ambient (environmental) pressure at the point of interest; Q_1 is the ratio of the charge mass used to the reference charge mass of 1 kg — with $Q_1<1$ when the charge mass is less than 1 kg, and $Q_1 = 1$ when the charge mass is greater than or equal to 1 kg; R is the distance from the explosive charge to the point of interest; and r_0 is the radius of the explosive charge.

Equation (18) shows that for underwater explosions with a charge mass of 1 kg or more, the attenuation law of the shock wave intensity in water fully agrees with the law established by the Russian scientist T. M. Salamakhin. When the charge mass is less than 1 kg, the pressure on the shock wave surface decreases accordingly.

Similarly, underwater explosion experiments were conducted to study the propagation of shock waves in water under conditions other than those of natural lakes. The experiments were performed at large water depths of 15–16 m using TNT charges with equivalent masses of 127 g, 221 g, 283 g, and 300 g. The charges were placed at a depth of 10 m, corresponding to 277–368 times the charge radius—effectively representing explosions in an infinite medium. Shock wave pressures were measured using the devices described above. A total of 17 explosion tests were performed with 34 measurement points. Based on the theory of explosive similarity, the relative residual pressure values in the shock waves were processed. Using Microsoft Excel and the least squares method, an empirical relationship was established for the dependence of the relative residual pressure in the shock wave on the relative distance. This analysis yielded the following empirical law describing the dependence of the relative residual pressure of shock waves propagating in water on relative distance [19]:

$$\frac{\Delta p}{p_1} = 13586.\left(\frac{r_0}{R}\right)^{1.13}; \lambda^2=0.9252 \qquad (19)$$

$$\frac{\Delta p}{p_1} = 501.52.\left(\frac{\sqrt[3]{Q}}{R}\right)^{1.13} ;\ \lambda^2 = 0.9252 \qquad (20)$$

The obtained empirical law includes an exponential index of 1.13, which characterizes the attenuation of shock waves with distance. This value is in complete agreement with the results obtained by researchers in Russia and the United States. However, the wave amplitude derived from the experiments is slightly smaller than that reported in Russian and U.S. studies—by 7.58% and 5.9%, respectively.

Based on a comparative analysis of the experimental results on the attenuation of shock wave intensity with distance for underwater explosions using charges of less than 1 kg, the following observations can be made:

- For underwater explosions with smaller charge masses, the deviation S of the measured shock wave amplitude relative to the amplitude predicted by the empirical laws of the Russian scientist T. M. Salamakhin (4) and the American scientist R. H. Cole (11) becomes evident.

- Across all experimental conditions, the results show a negative amplitude deviation S. Moreover, the smaller the explosive charge mass, the greater the absolute value of the deviation. This indicates that, during underwater explosions, smaller charges lose a higher proportion of their energy as heat transferred to the surrounding water compared with larger charges.

4. Conclusion

From the above theoretical and experimental analysis results, we can draw some comments as follows:

The set of parameters of the experimental model under laboratory conditions, ensuring underground explosion conditions in the water environment and the pressure value in the shock wave at the surveyed locations is not affected by the water surface and the water bed received, including: the size of the water tank is 6m long, 6m wide, the water depth in the tank is 1.62 m; the concentrated explosive amount of compressed TNT has a mass of less than or equal to 12 grams; the depth of the explosive amount is 0.81 m;

The experimental law on the decrease of shock wave intensity according to the distance received from the experimental model is completely similar to the experimental law of Russia and the US received from field experiments, but has an intensity 1.45 to 1.47 times smaller than the corresponding relative residual pressure value calculated according to the experimental formula of the US and Russia above.

The research results confirm that the use of small explosive charges for experimental studies of underwater explosions is fully compatible with the sensitivity and operating range of the measuring equipment. This approach provides a reliable dataset that can be extrapolated to larger explosive charges. However, it is necessary to calibrate the amplitude in the attenuation law of underwater shock waves when using small charges by applying an appropriate model correction coefficient.

Recommendation

When using the pressure measurement results in shock waves, following the conditions of the proposed experimental model parameters to convert to practice, it is necessary to multiply by the model correction factor (kmh) above. Using this proposed experimental model parameter set completely allows conducting experimental research on the law of shock wave propagation in water environment in laboratory conditions for different purposes, such as studying the law of shock wave attenuation when passing through a bubble screen or encountering obstacles, while still ensuring the reliability of the research results.

Further research is required to evaluate the attenuation law of shock wave intensity in a water environment at a fixed relative distance, as a function of explosive charge mass, particularly for underwater explosions involving small charges with masses below 1 kg.

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