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ANALYSIS OF CALCULATION METHODS FOR EXPLOSION SHOCK WAVE PARAMETERS IN THE DESIGN OF PROTECTIVE STRUCTURES

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Relevance. The military aggression of the Russian Federation against Ukraine, through the use of the entire range of enemy air attack means not only against military targets, but also against critical infrastructure facilities (hereinafter - CIF) [1, 2] and other civilian facilities, has brought significant changes in the construction of defensive structures and civil defense structures. Current regulatory documents [3] were developed on the premise of a single nuclear explosion at a considerable distance from the facility, which is why the calculations of building structures were performed without taking into account other damage factors [4]. The realities of the war have shown that the enemy's use of high-precision weapons in the form of unmanned aerial vehicles (hereinafter - UAVs) - kamikazes and many types of missiles, require immediate consideration by developing unified approaches to the construction of modern defensive and fortification structures of high reliability.

Today, the concept of “Fortress Country” is being actively implemented in Ukraine, approved by a resolution of the Cabinet of Ministers of Ukraine, according to which integrated protection of CIF and other objects of strategic importance is provided, which involves the organization of echeloned air defense similar to the defense systems of Israel, the USA and other countries, combined with complex measures of civil and engineering defense, electronic warfare systems, the establishment of false targets, camouflage, the transition from the creation of large objects of strategic importance to smaller ones dispersed among themselves, as well as the transition to natural energy sources, which should significantly increase the country's resistance to external threats of martial law. In fact, a regulatory framework should be developed in Ukraine, according to which the latest threats of enemy air attack should be taken into account when designing fortifications, engineering defense structures of CIF and other critical objects.

Purpose of the work

The purpose of this work is to review the existing methods of engineering and analytical calculations for determining the main characteristics of the explosive shock wave (hereinafter - ESW) from enemy air attack means. The importance of choosing the correct calculation method for different types of threats and materials of protective barriers is a very important task for the correct design of fortification and protective structures.

In the works [5-7] it is noted that the main types of enemy means for air destruction of CIF are air-launched, ground-launched and guided missiles, as well as UAVs of the “barrage ammunition” type. And the main factors of destruction in this case are fragmentation (fragmentation) and ESW.

The calculation of ESW parameters remains relevant even now, although a fairly large number of publications are devoted to it [8-10]. In this work we will try to summarize and present the main existing methods for determining ESW parameters.

Summary of the main material

Military operations in Ukraine have led to an urgent need to erect a large number of fortifications and defensive structures of various purposes and structural forms, which, in addition to the usual loads and impacts according to [11], must also take into account special impacts associated with the threat of enemy attack. Such impacts include: the action of ESW, fragmentation damage, partial or complete penetration of ammunition into the body of the protective structure, which may be accompanied by a subsequent explosion, temperature, etc.

To describe the explosion (detonation) of an industrial explosive charge, a point explosion scheme is used. During an explosion above the surface (air explosion), a spherical blast wave first appears, and in the case of an explosion on the ground (ground explosion), a hemispherical wave.

During the explosion of a TNT charge with a mass of m_{ef} in the air, the excess pressure at the shock wave front can be calculated using the empirical formula of M.O. Sadovsky [12] (named after its inventor, Mikhail Alexandrovich Sadovsky):

$$p_s = 0,084\frac{\sqrt[3]{m_{ef}}}{R} + 0,27\frac{\sqrt[3]{m_{ef}^{\,2}}}{R^2} + 0,7\frac{m_{ef}}{R^3}, \tag{1}$$

where p_s – excess pressure of the explosive shock wave, MPa; $m_{ef}=k_{ef}\,\eta\, m_e$ – equivalent of the explosive substance, which depends on the mass of the explosive substance, TNT equivalent and type of explosion, kg; R – distance from the point where the explosion occurs to the place where the excess pressure from the explosive shock wave is determined, m. The coefficient k_{ef} takes into account the type of explosive substance, and η takes into account the type of explosion.

For TNT − k_{ef} =1; hexogen − 1.31; TNT − 1.39; octogen − 1.28; amotol-80/20 − 0.98; smoke powder − 0.66; pentolite-50/50 − 1.13; oxyliquids − 0.9-1. For an explosion in air η = 1. For dense loams and clays η = 1.6. The maximum pressure at the earth's surface during an explosion in the air depends on the height. However, for a small height, less than R, the above formula remains valid. Then the shock wave moves along the earth's surface with a vertical front.

In [12], a variant of M.O. Sadovsky's formula for determining the excess pressure at the shock wave front for calculating an explosion on the earth's surface is given, when the energy of a ground explosion is distributed not over the entire sphere, but only over a hemisphere:

$$p_s = 0,095\frac{\sqrt[3]{m_{ef}}}{R} + 0,39\frac{\sqrt[3]{m_{ef}^{\,2}}}{R^2} + 1,3\frac{m_{ef}}{R^3}, \tag{2}$$

where p_s – excess pressure of the explosion-shock wave, MPa; m_{ef} – mass of explosive substance in TNT equivalent, kg; R – distance from the point where the explosion occurs to the place where the excess pressure from the explosion-shock wave is determined, m.

The duration of the compression phase in seconds can be calculated using the formula:

$$t_s = 1,5\cdot 10^{-3}\sqrt[6]{m_{ef}}\sqrt{R} \tag{3}$$

and the pressure pulse in the compression phase in Pa s:

$$i_s = 126\frac{\sqrt[3]{m_{ef}^2}}{R}. \tag{4}$$

The duration of the compression phase in seconds for a ground explosion can be calculated using the formula:

$$t_s = 1,7\cdot 10^{-3}\sqrt[6]{m_{ef}}\sqrt{R}\ , \tag{5}$$

the pressure pulse in the compression phase in Pa s:

$$i_s = 200\frac{\sqrt[3]{m_{ef}^{\,2}}}{R}. \tag{6}$$

The value of the excessive pressure of the shock wave allows us to assess the degree of destruction of certain objects.

In [13] a slightly different method for determining the parameters of the explosive shock wave is given. The pressure from the air ESW is mainly determined depending on the mass of the explosive charge, the distance from the center of the explosion and environmental conditions. Below is an approximate method for calculating the parameters of the ESW. The effect of the air blast depends on the given distance, m/kg$^{1/3}$:

$$Z = \frac{R}{\sqrt[3]{m_{ef}}}, \tag{7}$$

where R – is the distance of the explosion point from the object under investigation, m; $m_{ef} = (1-\varepsilon)\cdot a \cdot m_e$ – is the effective mass of the explosive in TNT equivalent; me is the mass of the explosive, kg; ε – is the fraction of the explosion energy spent on the formation of a crater (for rocks ε = 0.05; for soft soils ε = 0.2; if the explosion occurs in the air without the formation of a crater ε = 0); $a = k_{ef}$ is the ratio of the specific explosion energy of the explosive to the specific energy of TNT.

The excess pressure at the front of the explosive shock wave is equal, MPa:

$$p_s = \begin{cases} \left(\dfrac{0.92}{Z} + \dfrac{3.5}{Z^2} + \dfrac{10.6}{Z^3}\right)\times 10^{-1} & \text{at } 1.2 \le Z < 17.8 \text{ m/kg}^{1/3} \\ 4.2\cdot Z^{-1.45}\times 10^{-1} & \text{at } 17,8 \le Z < 1000 \text{ m/kg}^{1/3}. \end{cases} \quad (8)$$

The above formulas are applicable for R>3 m. The formation of explosive shock wave is influenced by whether the explosion is airborne or ground-based, the shape of the explosive charge, and its immersion in the soil before the explosion.

The duration of the compression phase is, in seconds:

$$t_s = \begin{cases} 1.7\cdot 10^{-3}\sqrt[3]{m_{ef}}\sqrt{Z} & \text{at } 1.2 \le Z < 10 \text{ m/kg}^{1/3} \\ 6.594\cdot 10^{-3}\sqrt[3]{m_{ef}}\left[\lg(0.4Z)\right]^{0.4} & \text{at } 10 \le Z < 1000 \text{ m/kg}^{1/3} \end{cases}. \quad (9)$$

Since the duration of the explosive shock wave action in detonation explosions is usually extremely short, the oscillations and strength of structures can be determined using the momentum theorem, for which the specific impulse of the compression phase i+ (Pa·s) is used, which is numerically equal to the area under the pressure curve in this phase (Fig. 1). At $12 \le Z < 1000$ m/kg$^{1/3}$

$$i_s = 350\frac{\sqrt[3]{m_{ef}}}{Z}. \quad (10)$$

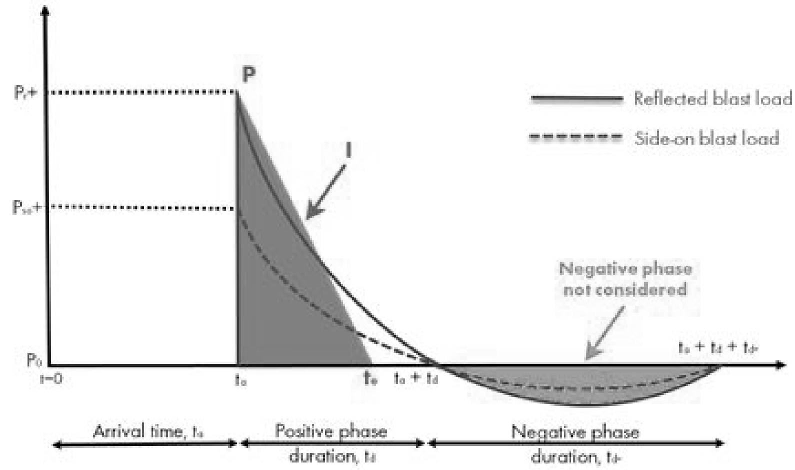

Fig. 1. Parameters of the detonation explosion shock wave

The distribution in the phase t_s can be simplified to the triangular law. The negative phase t_-, as a rule, is less destructive for massive engineering protective structures, so it can be ignored.

Based on the explosion parameters, we can talk about the resistance of the structure to the action of the shock wave. For reference, the nomogram for assessing the damage to buildings from the pressure and pulse of the explosive shock wave is shown in Fig. 2.

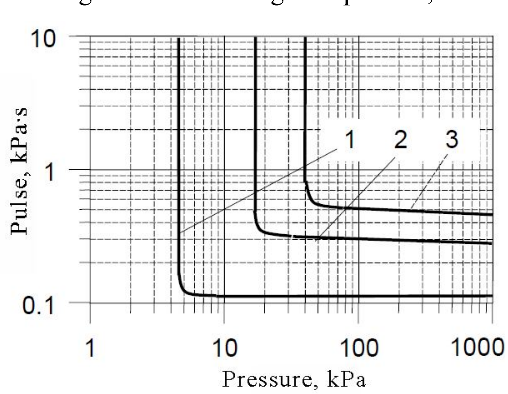

Fig. 2. Nomogram for assessing building damage:
1 – minimal damage limit; 2 – significant damage limit;
3 – building destruction (50÷70% of walls destroyed)

Let us consider other known methods for calculating the parameters of the explosion shock wave.

Thus, in the work of Brode [14] and in later works of other scientists [15], it was proposed to use the following formula to determine the excess pressure of the ESW, MPa:

$$p_s = \begin{cases} \left(\dfrac{0.975}{Z} + \dfrac{1.455}{Z^2} + \dfrac{5.85}{Z^3} - 0.019 \right) \times 10^{-1} \text{ at } 0.01 \le p_s < 1 \\ \left(\dfrac{6.7}{Z^3} + 1 \right) \times 10^{-1} \quad \text{at } p_s \ge 1 \end{cases} . \tag{11}$$

In formula (11) Z – the distance of the explosion point from the object is given, which should be determined by formula (7), m/kg$^{1/3}$.

In work [16] the following formulas are proposed for determining the excess pressure of the explosion shock wave, the duration of the compression phase and the value of the positive impulse.

The value of the excess pressure of the ESW is proposed to be determined from the condition, MPa:

$$p_s = \begin{cases} \left(\dfrac{14.072}{Z} + \dfrac{5.540}{Z^2} + \dfrac{0.357}{Z^3} + \dfrac{0.006}{Z^4} \right) \times 10^{-1} \text{ at } 0.05 < Z \le 0.3 \\ \left(\dfrac{6.194}{Z} + \dfrac{0.326}{Z^2} + \dfrac{2.132}{Z^3} \right) \times 10^{-1} \quad \text{at } 0.3 < Z \le 1.0 \\ \left(\dfrac{0.662}{Z} + \dfrac{4.05}{Z^2} + \dfrac{3.288}{Z^3} \right) \times 10^{-1} \quad \text{at } 1.0 < Z \le 10 \end{cases} , \tag{12}$$

where Z – the distance of the explosion point from the object is given, which should be determined by formula (7), m/kg$^{1/3}$.

The duration of the compression phase is, in seconds:

$$t_s = \sqrt[3]{m_{ef}} \left(0.107 + 0.444 \cdot Z + 0.264 \cdot Z^2 - 0.129 \cdot Z^3 + 0.0335 \cdot Z^4 \right) \cdot 10^3 . \tag{13}$$

For formula (13), the following restriction is introduced: .

The value of the specific impulse of the compression phase according to [16] should be determined from the condition, Pa·s:

$$i_s = \sqrt[3]{m_{ef}} \begin{cases} \left(66.3 - \dfrac{111.5}{Z} + \dfrac{62.9}{Z^2} - \dfrac{10.04}{Z^3} \right) \cdot 10^{-1} \text{ at } 0.4 < Z \le 0.75 \\ \left(-3.22 + \dfrac{21.1}{Z} - \dfrac{21.6}{Z^2} + \dfrac{8.01}{Z^3} \right) \cdot 10^{-1} \text{ at } 0.75 < Z \le 3 \end{cases} . \tag{14}$$

In formulas (13) and (14), m_{ef} – is the effective mass of the explosive in TNT equivalent.

The work devoted to the dynamics of the operation of building structures [17] contains the following formulas for determining the parameters of the explosion shock wave.

The value of the excess pressure of the explosion shock wave is recommended to be determined from the condition, MPa:

$$p_s = \left(\frac{0.84}{Z} + \frac{2.7}{Z^2} + \frac{7.0}{Z^3} \right) \times 10^{-1} . \tag{15}$$

The duration of the compression phase is recommended to be determined by the formula, s:

$$t_s = 1.5 \cdot \sqrt[6]{m_{ef}} \sqrt{R} \cdot 10^{-3} . \tag{16}$$

The value of the specific impulse of the compression phase according to [17] should be determined from the condition, Pa·s:

$$i_s = 4 \frac{\sqrt[3]{m_{ef}^2}}{R} \cdot 10^2 = 4 \frac{R}{Z^2} \cdot 10^2 . \tag{17}$$

In formulas (15), (16) and (17): m_{ef} – effective mass of explosive in TNT equivalent, which depends on the mass of explosive and type of explosion, kg; – the distance of the explosion point from the object is given, which should be determined by formula (7), m/kg$^{1/3}$; Z – the distance from the point where the explosion occurs to the place where the excess pressure from the explosion shock wave is determined, m.

The formulas for determining the explosion parameters of Kinney and Graham (Kinney&Graham) given in [18] have become quite widespread.

The excess pressure at the front of the ESW according to [18] is recommended to be determined by the formula, kPa:

$$p_s = p_0 \frac{808\left(1+\left(Z/4.5\right)^2\right)}{\sqrt{1+\left(Z/0.048\right)^2}\sqrt{1+\left(Z/0.32\right)^2}\sqrt{1+\left(Z/1.35\right)^2}}, \tag{18}$$

where Z – the distance of the explosion point from the object is given, which should be determined by formula (7), m/kg$^{1/3}$; p_0 – value of atmospheric pressure (101.3 kPa), kPa.

The negative value of the excess pressure is then determined by the formula, kPa:

$$p_- = -\frac{p_s}{\alpha} e^{-(\alpha+1)}, \tag{19}$$

where α – is the shape coefficient, which should be determined by formula (20).

$$\alpha = 1.5 \cdot Z^{-0.38}. \tag{20}$$

The positive specific impulse of the explosion shock wave is determined by the formula, kPa·s:

$$i_s = \sqrt[3]{m_{ef}} \frac{0.067\sqrt{1+\left(Z/0.23\right)^4}}{Z^2 \sqrt[3]{1+\left(Z/1.55\right)^3}}. \tag{21}$$

For values of the reduced distance $Z > 2.8$, a simplified formula can be used:

$$i_s = \frac{2.1R}{Z^2}. \tag{22}$$

The duration of the compression phase is, in seconds:

$$t_s = \frac{i_s}{p_s}\left(\frac{\alpha^2}{\alpha - 1 + e^{-\alpha}}\right). \tag{23}$$

For more accurate calculations, dependencies are currently common, in particular those known as the Kingery-Bulmash formulas [19, 20]. The authors used curve fitting methods to represent the data with higher-order polynomial equations.

$$Y=C_0+C_1\cdot U+C_2\cdot U^2+C_3\cdot U^3 \ldots . C_n\cdot U^n, \tag{24}$$

where Y is the common logarithm of the residual pressure determination during an explosion (pressure or impulse) in metric units of measurement; $U=K_0+K_1T$, T is the common logarithm of the explosion (pressure or impulse), m; K_0, K_1 are constants; C_0, C_1, C_2, C_3, ... C_n are constants.

The radius of destructive action of an air shock wave is determined by the formula:

$$R_{\max} = a\sqrt{m_{ef}}, \tag{25}$$

where m_{ef} – is the mass of the detonating charge in TNT equivalent, kg; a – is the proportionality coefficient, the value of which depends on the explosion conditions and the intensity of destruction.

The coefficient a for some cases can be determined by formulas, for example, damage to a wall with a thickness of b, m:

when a crack appears in a brick wall: $a = 0,6/\sqrt{b}$;

with through-hole breaks in brick walls: $a = 0,4/\sqrt{b}$;

with through-hole breaks in concrete walls: $a = 0,25/\sqrt{b}$;

with through-hole breaks in reinforced concrete walls: $a = 0,2/\sqrt{b}$.

When an explosion occurs, the shock wave propagates in the form of a high-pressure front, moving in all directions. When reaching the surface, the ESW collides with it, the air particles are sharply slowed down and their kinetic energy is converted into pressure energy, which is superimposed, forming the reflected ESW pressure. Thus, at the point of contact of the obstacle and the wave front, a reflected pressure is created, which usually significantly exceeds the pressure in the shock wave itself due to the additional superposition of the energy of the reflected wave on the initial one.

The value of the reflected pressure for an air explosion can be determined by the formula:

$$p_r = \frac{p_s}{2}\left(2 + \frac{\gamma+1}{\gamma-1}\cdot\frac{p_{fr}}{p_s}\right), \tag{26}$$

where p_r – value of reflected pressure of the explosion shock wave, MPa; p_{fr} – pressure in the explosion shock wave front, MPa; γ – adiabatic index of the medium (for air $\gamma \approx 1.4$).

$$p_{fr} = p_0 + p_s, \tag{27}$$

where p_0 – is the value of atmospheric pressure, which is approximately equal to 101.3 kPa, MPa; p_s is the excess pressure of the explosion shock wave, MPa.

In [13] the following formulas are proposed for determining the reflected pressure of the explosion shock wave provided that the wave front moves perpendicular to the front (frontal) wall of the structure, MPa:

provided that the area of the openings in the wall of the structure is less than 10%

$$p_r = 2p_s + \frac{6(p_s)^2}{p_s + 0.72}, \tag{28}$$

provided that the area of openings in the wall of the structure is more than 10%

$$p_r = p_s + \frac{2.5(p_s)^2}{p_s + 0.72}. \tag{29}$$

Here, the first term is the actual reflected pressure, and the second is the air velocity pressure. The pressure gain due to reflection is characterized by the value of the reflection coefficient $k = p_r / p_s$, which in formula (28) is equal to 2.

In real conditions, the wave interacts with a structure of limited dimensions. In this case, simultaneously with the reflection of the wave, a flow-around process called diffraction occurs. At the moment when the explosion shock wave front reaches the front wall, simultaneously with the reflection at the edges of the wall, a rarefaction wave appears, the propagation of which leads to a drop in pressure on the front wall.

The explosion shock wave front moves with a speed V_f, which depends on the pressure on the front pf in MPa:

$$V_f = 340\sqrt{1 + 8.3p_s}\text{, m/s.} \tag{30}$$

To determine the reflected pressure of the explosion shock wave, provided that the wave front moves perpendicular to the front (frontal) wall of the structure, the formula, MPa, can also be used:

$$p_r = p_s \cdot \frac{8p_s + 14p_0}{p_s + 7p_0}. \tag{31}$$

Equation (31) is valid in the case of reflection of the ESW along the normal, i.e. with an angle between the direction of movement of the ESW and the obstacle surface $\alpha = 90°$. Other variants of angles α between the direction of movement of the explosion shock wave and the obstacle surface can be taken into account by the formula:

$$p_{r,\alpha} = p_0\cos^2\alpha + p_s\left(1 + \cos\alpha - 2\cos^2\alpha\right). \tag{32}$$

Formula (32) does not take into account all variants of the angles of the direction of the explosion shock wave movement to the obstacle. And in the case of angles of the direction of the explosion shock wave movement to the obstacle $\alpha > 40°$, the fronts of the incident and reflected waves merge, which leads to the formation of the so-called main wave, or the "Mach effect".

To choose the appropriate method, one should be guided by considerations from the most complete nomenclature of the determined explosion shock wave parameters. In table 1 we present the results of calculating the main explosion shock wave parameters according to the above methods for a ground explosion at a distance from the epicenter of 5 m, an explosive of 34 kg in TNT equivalent.

In the table 2 we present the results of the calculation of the main parameters of ESW according to the above methods for a ground explosion at a distance of 15 m from the epicenter, 718 kg of explosive substance in TNT equivalent.

Table 1
Values of calculated parameters of the explosive shock wave for a ground explosion at a distance of 5 m from the epicenter, explosive substance 34 kg in TNT equivalent

Source of methodology	Overpressure value p_s, kPa	Duration of the compression phase t_s, s	Specific pressure impulse i, Pa·s	Reflected pressure (26), kPa	Reflected pressure (28), (29), kPa	Reflected pressure Kinney, kPa
[12]	578,88	0,006	264,48	2619,40	2024,27	2718,79
[13]	454,00	0,007	684,82	2119,92	1587,22	1971,30
[14]	259,24			1321,97	905,54	934,89
[16]	280,39	0,004	1090,83	1399,53	979,57	1037,50
[17]	329,57	0,006	782,66	1579,84	1151,68	1286,55
[18]	350,38	0,003	309,57	1656,16	1224,53	1396,00
[19]	516,00	0,003	558,51	2320,00		

Table 2
Values of calculated parameters of the explosive shock wave for a ground explosion at a distance of 15 m from the epicenter, explosive substance 718 kg in TNT equivalent

Source of methodology	Overpressure value p_s, kPa	Duration of the compression phase t_s, s	Specific pressure impulse i, Pa·s	Reflected pressure (26), kPa	Reflected pressure (28), (29), kPa	Reflected pressure Kinney, kPa
[12]	472,26	0,017	673,54	2192,94	1651,11	2077,26
[13]	372,25	0,019	1744,03	1792,90	1301,08	1513,37
[14]	214,64			1158,44	749,44	728,51
[16]	235,65	0,011	2852,58	1235,48	822,98	823,97
[17]	272,13	0,017	1993,18	1369,26	950,68	997,11
[18]	289,60	0,009	817,68	1433,31	1011,82	1083,08
[19]	427,00	0,011	1427,58	1808,00		

Some of the above methods are presented and analyzed in [21].

As we can see, from the calculations of the parameters of the explosion-shock wave using different methods, the values differ quite significantly, which confirms the need for further research and the development of a single methodology for the further design of fortification and protective structures for various purposes.

Currently, several methods are used to calculate building structures for the action of the explosion-shock wave, which are discussed in more detail below.

The quasi-static calculation method is based on considering the building frame as a system with one degree of freedom and the hypothesis that the largest dynamic displacement is proportional to the static displacement under the action of the maximum load. Such assumptions make it possible to establish dynamic coefficients and perform all further calculations on equivalent quasi-static loads. In this case, equivalent quasi-static loads are established, which are taken from the experience of designing and calculating structures for shock waves of various means of attack. The use of this method gives satisfactory results in the case of preliminary calculation of building frames and structures by more accurate methods.

The adequacy of replacing the dynamic load with a static one is determined by the correctness of determining the dynamic coefficient for each specific case [13].

Calculation by the quasi-static method assumes the following prerequisites when forming the calculation scheme: equivalent static loads are assumed to be uniformly distributed with a maximum value of the corresponding sign; equivalent static distributed loads are applied perpendicular to the surface of the structure.

Shock impulse method. The essence of this method is to use the momentum conservation theorem to determine the strength and vibrations of the supporting frame of a building or structure. The main parameters for which the calculation is performed using the shock impulse method include excess pressure and the time of action of the load from the explosive shock wave. In the explosive shock wave front, the reflected pressure should be taken, the values of which can significantly exceed the values of the excess pressure. For individual specific scenarios and cases, they can be determined depending on the main parameters, or taken as constant, for example, for buildings of a certain structural scheme with given parameters of the supporting structures. In this case, the pressure of both signs can be taken into account. Simplified, for most calculation schemes, the load is taken as a shock impulse of the compression phase with a triangular distribution.

The shock impulse method can be used both for calculating the frame of the entire building or structure and for its individual structural elements.

The method of direct integration of equations of motion. This method consists in the dynamic calculation of the structure on the actual laws of changes in loads over time. This method is the most accurate. This method can take into account the operation of reinforced concrete structures of buildings and structures with cracks.

When calculating with this method, it is necessary to obtain all the parameters of dynamic effects (graphs of changes in excess pressures of explosion-shock waves) and perform their approximation. This approach will allow you to obtain all the necessary parameters of changes in loads at equal time intervals.

The method of direct integration of equations of motion also allows you to take into account various combinations of graphs of changes in excess pressure along the front of explosion-shock waves. The calculation results are set at the appropriate moments that coincide with the integration points.

Conclusions. Scientific novelty and practical significance of the results

The paper considers existing global methods for determining the parameters of the explosive shock wave.

The issue of the need to develop a clear engineering methodology for calculating building structures for the action of the explosive shock wave in different scenarios of damage by various means of attack is raised.

Methods for calculating the parameters of the explosive shock wave required for further calculation of building structures and structures in general are presented.

The prospect of further research is to improve the methodology for calculating the parameters of the explosive shock wave of all probable damage elements required for further calculation of building structures and structures.

The development of modern calculation methods with awareness of existing threats of wartime will allow the most effective construction of engineering protective and fortification structures, which will help to implement the concept of the “Fortress Country” as much as possible.

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АНАЛІЗ МЕТОДИК РОЗРАХУНКУ ПАРАМЕТРІВ ВИБУХОВО-УДАРНОЇ ХВИЛІ ДЛЯ РОЗРАХУНКУ КОНСТРУКЦІЙ ЗАХИСНИХ СПОРУД

Актуальність. Повномасштабне вторгнення рф в Україну виявило досить велику кількість питань, в тому числі і пов’язаних зі зведенням захисних та фортифікаційних споруд. Як виявилось, цей напрямок в нашій країні фактично не розвивався. Відсутня нормативна база щодо урахування багатьох специфічних факторів, таких як вибухово-ударна хвиля, пробивання боєприпасами та осколками (уламками). Окремо слід відзначити той факт, що засоби нападу постійно розвиваються та удосконалюються, і це вимагає постійного удосконалення протидії ним. Ця стаття присвячена огляду наявних методик, які можуть бути застосовані при визначенні параметрів вибухово-ударної хвилі, які слід застосовувати при розрахунку будівельних конструкцій і споруд. Вибір правильної методики для розрахунку дозволить відпрацювати методичний підхід до проєктування фортифікаційних, споруд інженерного захисту критичної інфраструктури, споруд цивільного захисту, а це є дуже важливою і актуальною задачею. Цей підхід в подальшому може бути включений в спеціалізовані нормативні документи щодо розрахунку та проєктування захисних та фортифікаційних споруд, що значно б покращило їх якість та надійність з урахуванням сучасних загроз воєнного часу. **Метою роботи** є огляд існуючих методик інженерно-аналітичних розрахунків параметрів вибухово-ударних хвиль та будівельних конструкцій і споруд на ураження засобами нападу противника. Важливість вибору правильної методики розрахунку для різних видів загроз, є дуже важливою задачею для правильного проєктування фортифікаційних та захисних споруд. **Результати.** У роботі розглянуто існуючі світові методики визначення параметрів вибухово-ударних хвиль для розрахунків будівельних конструкцій і споруд на ураження засобами нападу противника. Піднято питання необхідності розроблення чіткої інженерної методики розрахунку будівельних конструкцій і споруд на дію вибухово-ударної хвилі. Наведено алгоритми визначення параметрів вибухово-ударних хвиль та подальшого розрахунку будівельних конструкцій фортифікаційних та інженерних захисних споруд на ураження засобами нападу противника.

Ключові слова: споруди інженерного захисту, фортифікаційні споруди, об’єкти критичної інфраструктури, фактори ураження, вибухово-ударна хвиля, будівельні конструкції.

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ANALYSIS OF CALCULATION METHODS FOR EXPLOSION SHOCK WAVE PARAMETERS IN THE DESIGN OF PROTECTIVE STRUCTURES

Relevance. The full-scale invasion of the Russian into Ukraine revealed a fairly large number of issues, including those related to the construction of defensive and fortification structures. As it turned out, this direction in our country has not actually developed. There is no regulatory framework for taking into account many specific factors, such as the blast shock wave, penetration by ammunition and fragments (fragments). It should be noted separately that the means of attack are constantly developing and improving, and this requires constant improvement in countering them. This article is devoted to a review of existing methods that can be used to determine the parameters of the blast shock wave, which should be used when calculating building structures and structures. Choosing the right method for the calculation will allow you to work out a methodical approach to the design of fortifications, structures for engineering protection of critical infrastructure, and civil defense structures, and this is a very important and relevant task. This approach can later be included in specialized regulatory documents for the calculation and design of defensive and fortification structures, which would significantly improve their quality and reliability, taking into account modern wartime threats. **The aim** of the work is to review existing methods of engineering and analytical calculations of parameters of explosive shock waves and building structures and structures for damage by enemy attack means. The importance of choosing the correct calculation method for different types of threats is a very important task for the correct design of fortification and protective structures. **Results.** The paper considers existing global methods for determining the parameters of explosive shock waves for calculating building structures and structures for damage by enemy attack means. The issue of the need to develop a clear engineering method for calculating building structures and structures for the action of an explosive shock wave is raised. Algorithms for determining the parameters of explosive shock waves and further calculating building structures of fortifications and engineering protective structures for damage by enemy attack means are presented.

Keywords: engineering defense structures, fortification structures, critical infrastructure objects, damage factors, explosive shock wave, building structures.

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Михайловський Д.В., Скляров І.О., Комар О.А. **Аналіз методик розрахунку параметрів вибухово-ударної хвилі для розрахунку конструкцій захисних споруд** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2025. – Вип. 114. – С. 173-182. – Англ.

У роботі розглянуто існуючі світові методики визначення параметрів вибухово-ударних хвиль для розрахунків будівельних конструкцій і споруд на ураження засобами нападу противника. Піднято питання необхідності розроблення чіткої інженерної методики розрахунку будівельних конструкцій і споруд на дію вибухово-ударної хвилі. Наведено алгоритми визначення параметрів вибухово-ударних хвиль та подальшого розрахунку будівельних конструкцій фортифікаційних та інженерних захисних споруд на ураження засобами нападу противника.

Табл. 2. Іл. 2. Бібліогр. 21 назв.

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Mykhailovskyi D.V., Skliarov I.O., Komar O.A. **Analysis of calculation methods for explosion shock wave parameters in the design of protective structures** / Strength of materials and theory of structures: scientific and technical collection - Kyiv: KNUBA, 2025. - Issue 114. - P. 173-182.

The paper examines existing global methodologies for determining explosion shock wave parameters in the structural analysis of buildings and facilities under enemy attack. The necessity of developing a clear engineering methodology for calculating building structures and facilities subjected to explosion shock waves is emphasized. Algorithms for determining explosion shock wave parameters and subsequent calculations of structural elements in fortification and protective engineering structures under enemy attack are presented.

Tabl. 2. Fig. 2. Ref. 21.

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