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COMPARISON OF METHODS FOR CALCULATING THE PARAMETERS OF AN EXPLOSION SHOCK WAVE FOR THE DESIGN OF PROTECTIVE ENGINEERING STRUCTURES

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Abstract. The military aggression of the Russian Federation against Ukraine, through the use of the full range of enemy aerial attack means not only against military targets but also against critical infrastructure objects (hereinafter – CIOs) [1, 2] and other civilian facilities, has brought significant changes in the construction of protective and civil defense structures. The current regulatory documents [3] were developed under the assumption of a single nuclear explosion occurring at a considerable distance from the facility, which is why the design of building structures was carried out without taking into account other damaging factors [4].

The realities of the war have shown that the enemy's use of high-precision weapons in the form of kamikaze unmanned aerial vehicles (hereinafter – UAVs) and various types of missiles requires the immediate development of unified approaches to the construction of modern, highly reliable protective and fortification structures.

Today, Ukraine is actively implementing the "Fortress Country" concept, approved by a resolution of the Cabinet of Ministers of Ukraine. This concept envisions integrated protection of CIOs and other strategically important facilities, which includes the organization of layered air defense systems similar to those used in Israel, the United States, and other countries. This approach is combined with comprehensive civil and engineering protection measures, electronic warfare systems, the deployment of decoys, camouflage, the shift from large strategic facilities to smaller, dispersed ones, as well as the transition to natural energy sources. Altogether, these measures are expected to significantly increase the country's resilience to external threats during martial law.

In fact, Ukraine must develop a regulatory framework ensuring that, when designing fortification and engineering protection structures for CIOs and other critical objects, new threats from enemy aerial attacks are duly considered.

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PROBLEM STATEMENT

The ongoing military conflict in Ukraine has led to an urgent need for the construction of a large number of fortification and protective structures of various purposes and structural forms. In addition to standard loads and impacts, these structures must also account for specific effects associated with enemy attack threats, as outlined in [11]. Such effects include: the action of an explosion shock wave (hereinafter – ESW), fragmentation damage, partial or complete penetration of munitions into the body of the protective structure (which may be followed by detonation), high temperatures, and more.

To describe the explosion (detonation) of an industrial explosive charge, the point explosion model is commonly used. In the case of an explosion above the surface (airburst), a spherical shock wave is generated, while a ground-level explosion produces a hemispherical wave.

The aim of this study is to review existing engineering-analytical methods for determining the main characteristics of the explosion shock wave (ESW) resulting from enemy aerial attacks. Selecting the correct calculation method for different types of threats and materials used in protective barriers is a critical task for the proper design of fortification and protective structures.

According to works [5–7], the main types of enemy weapons used for aerial strikes against critical infrastructure (CI) include air-, land-, and sea-launched missiles, as well as loitering munitions (kamikaze UAVs). The primary damaging factors in such attacks are fragmentation and the explosion shock wave.

Despite the existence of a large number of publications on this topic [8–10], the calculation of ESW parameters remains highly relevant. In this work, we attempt to generalize and present the main existing methods for determining ESW parameters.

CORE RESEARCH

1. Methodology by M.O. Sadovsky

During the explosion of a TNT charge with an effective mass m_{ef} in the air, the overpressure at the shock wave front can be calculated using the empirical formula by M.O. Sadovsky [12], derived from the analysis of experimental data obtained during TNT detonations under standard atmospheric conditions. The formula is named after its originator, Mykhailo Oleksandrovych Sadovsky:

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

where: p_s – overpressure of the explosion shock wave, MPa;
$m_{ef} = k_{ef}\ \eta\ m_e$ – equivalent mass of the explosive, which depends on the actual mass of the explosive, the TNT equivalent, and the type of explosion, kg;
R – distance from the explosion point to the location where the overpressure of the shock wave is being determined, m.

The coefficient k_{ef} accounts for the type of explosive material, while η accounts for the nature of the explosion. For TNT − k_{ef} =1; for RDX − 1,31; for TEN − 1,39; for HMX − 1,28; for Amatol 80/20 − 0,98; for black powder − 0,66; for Pentolite 50/50 − 1,13; for Oxyliquits − 0,9-1. For an airburst explosion η = 1. For dense loams and clays η = 1,6. The maximum pressure on the ground surface during an airburst explosion depends on the detonation height. However, for a relatively small height, less than R, the given formula remains valid. In this case, the shock wave propagates along the ground surface with a vertical front.

Reference [12] provides a variant of M.O. Sadovsky's formula for determining the overpressure at the shock wave front in the case of a surface explosion, where the explosion energy is distributed not over a full 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: *ps* – overpressure of the explosion shock wave, MPa;
m_{ef} – the mass of the explosive in TNT equivalent, kg;
R – the distance from the explosion point to the location where the overpressure of the explosion shock wave is being determined, m.

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

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

and the pressure impulse during 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 surface explosion can be calculated using the following formula:

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

pressure impulse during the compression phase, in Pa·s:

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

Experimental studies have shown that M.O. Sadovsky's formulas provide good agreement for overpressure calculations when the TNT equivalent of the explosive exceeds 2 kg.

2. Methodology by A.N. Birbraer

Reference [13] presents a somewhat different methodology for determining the parameters of an explosion shock wave. The pressure from an air shock wave is primarily determined based on the mass of the explosive charge, the distance from the explosion center, and the environmental conditions. An approximate method for calculating the shock wave parameters is provided below. The effect of an air explosion depends on the scaled distance, expressed in m/kg$^{1/3}$:

$$\overline{R} = \frac{R}{\sqrt[3]{m_{ef}}}; \tag{7}$$

where: *R* – distance from the explosion point to the object under study, m;
$m_{ef} = (1-\varepsilon)\cdot a\cdot m_e$ – effective mass of the explosive in TNT equivalent;
m_e – mass of the explosive, kg;
ε − the fraction of explosion energy spent on crater formation (for rocky soils
ε = 0,05; for soft soils
ε = 0,2; if the explosion occurs in the air without crater formation
ε = 0);
$a = k_{ef}$ – the ratio of the specific energy of the explosive to the specific energy of TNT.

The overpressure at the front of the explosion shock wave is equal to, MPa:

$$p_f = \begin{cases} \left(\dfrac{0.92}{\overline{R}} + \dfrac{3.5}{\overline{R}^2} + \dfrac{10.6}{\overline{R}^3}\right)\times 10^{-1} & \text{at}\quad 1.2 \le \overline{R} < 17.8 \\ 4.2\overline{R}^{-1.45}\times 10^{-1} & \text{at}\quad 17,8 \le \overline{R} < 1000 \end{cases} \tag{8}$$

The given formulas are applicable for $R > 3$ m. The formation of the explosion shock wave (ESW) is influenced by whether the explosion is an airburst or surface burst, the shape of the explosive charge, and its burial depth in the ground prior to detonation.
The duration of the compression phase in this case is, s:

$$\tau_+ = \begin{cases} 1.7\cdot 10^{-3}\sqrt[3]{m_{ef}}\sqrt{\bar{R}} \quad \text{at} \quad 1.2 \le \bar{R} < 10 \\ 6.594\cdot 10^{-3}\sqrt[3]{m_{ef}}\left[\lg(0.4\bar{R})\right]^{0.4} \quad \text{at} \quad 10 \le \bar{R} < 1000 \end{cases} \tag{9}$$

Since the duration of the explosion shock wave (ESW) during detonation explosions is usually extremely short, the vibrations and strength of structures can be determined using the impulse theorem. For this purpose, 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 (see Fig. 1). Under $12 \le \bar{R} < 1000$, m/kg$^{1/3}$.

$$i_+ = 350\frac{\sqrt[3]{m_{ef}}}{\bar{R}}. \tag{10}$$

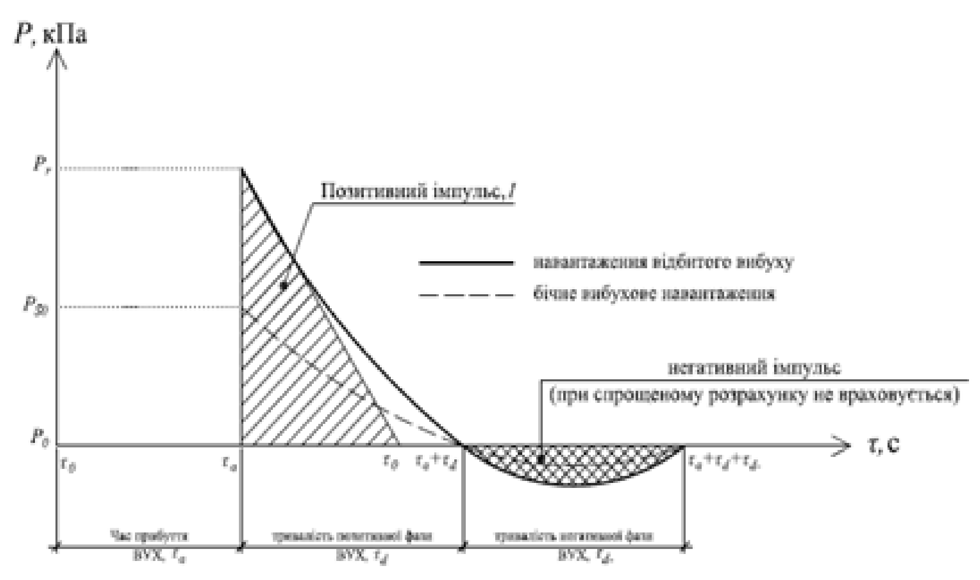

Fig. 1. Parameters of Detonation Blast Wave
Рис. 1. Параметри детонаційної вибухово-ударної хвилі

The pressure distribution during the τ+ phase can be approximately assumed to follow a triangular law. The negative phase τ-, is generally less destructive to massive engineering protective structures and therefore can be neglected.

3. Methodology by Brode, H. L. and others

In Brode's work [14] and in later studies by other researchers [15], the following formula is proposed for determining the overpressure of the explosion shock wave (ESW), in MPa:

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

In formula (11) $\overline{R}$ – the scaled distance from the explosion point to the object, which should be determined using formula (7), expressed in m/kg$^{1/3}$.

4. Methodology by Henrych, J

Reference [16] proposes the following formulas for determining the overpressure of the explosion shock wave (ESW), the duration of the compression phase, and the value of the positive impulse.

The overpressure of the ESW is suggested to be determined by the following condition, in MPa:

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

In formula (12) $\overline{R}$ – the scaled distance from the explosion point to the object, which should be determined using formula (7), expressed in m/kg$^{1/3}$.

The duration of the compression phase is calculated using the formula, s:

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

For formula (13), the following limitation is introduced: $0.05 < \overline{R} \le 3$.

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

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

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

5. Methodology by Korenev B. and others

The work dedicated to the dynamic behavior of building structures [17] contains the following formulas for determining the parameters of the explosion shock wave (ESW).

The value of the ESW overpressure is recommended to be determined using the following condition, in MPa:

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

The duration of the compression phase is recommended to be determined using the following formula, in seconds:

$$\tau_+ = 1.5 \cdot \sqrt[6]{m_{ef}} \sqrt{R} \cdot 10^{-3}. \qquad (16)$$

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

$$i_+ = 4\frac{\sqrt[3]{m_{ef}^2}}{R} \cdot 10^2 = 4\frac{R}{\bar{R}^2} \cdot 10^2. \qquad (17)$$

In formulas (15), (16), and (17): m_{ef} – effective mass of the explosive in TNT equivalent, which depends on the mass of the explosive and the type of explosion, kg; $\bar{R}$ – scaled distance from the explosion point to the object, which should be determined using formula (7), m/kg$^{1/3}$; R – distance from the explosion point to the location where the overpressure of the explosion shock wave is determined, m.

6. Methodology by Kinney & Graham

The formulas for determining explosion parameters by Kinney & Graham, presented in [18], have become widely used.

The overpressure at the shock wave front according to [18] is recommended to be calculated using the following formula, in kPa:

$$p_f = p_0 \frac{808\left(1+\left(\frac{\bar{R}}{4.5}\right)^2\right)}{\sqrt{1+\left(\frac{\bar{R}}{0.048}\right)^2}\sqrt{1+\left(\frac{\bar{R}}{0.32}\right)^2}\sqrt{1+\left(\frac{\bar{R}}{1.35}\right)^2}}, \qquad (18)$$

where: $\bar{R}$ – scaled distance from the explosion point to the object, which should be determined using formula (7), m/kg$^{1/3}$;
p_0 – atmospheric pressure value (101.3 kPa), in kPa.

The negative overpressure is then calculated using the following formula, in kPa:

$$p_{f-} = -\frac{p_f}{\alpha} e^{-(\alpha+1)}; \qquad (19)$$

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

$$p_{f-} = -\frac{p_f}{\alpha} e^{-(\alpha+1)}. \qquad (20)$$

The positive specific impulse of the shock wave is determined using the following formula, in kPa·s:

$$i_+ = \sqrt[3]{m_{ef}} \frac{0.067\sqrt{1+\left(\frac{\bar{R}}{0.23}\right)^4}}{\bar{R}^2 \sqrt[3]{1+\left(\frac{\bar{R}}{1.55}\right)^3}}. \qquad (21)$$

For scaled distance values $\bar{R} > 2.8$ a simplified formula may be used:

$$i_+ = \frac{2.1R}{\bar{R}^2}. \qquad (22)$$

The duration of the compression phase in this case is, s (in seconds):

$$\tau_+ = \frac{i_+}{p_f}\left(\frac{\alpha^2}{\alpha - 1 + e^{-\alpha}}\right). \qquad (23)$$

7. Methodology by Kingery-Bulmash using UFC 4-023-02 charts

For more accurate calculations, the relationships known as the Kingery-Bulmash formulas [19, 20] are currently widely used. The authors applied curve-fitting methods to represent the data using higher-order polynomial equations.

The results of their work are reflected in UFC 4-023-02, where charts are provided to determine the main parameters of the explosion shock wave depending on the scaled distance Z, which is determined using formula (7). To use the charts, unit conversions to the metric system should be made:

1 pound (lb) = 4.445 N; 1 pound/inch² (1 psi) = 6,890 Pa.

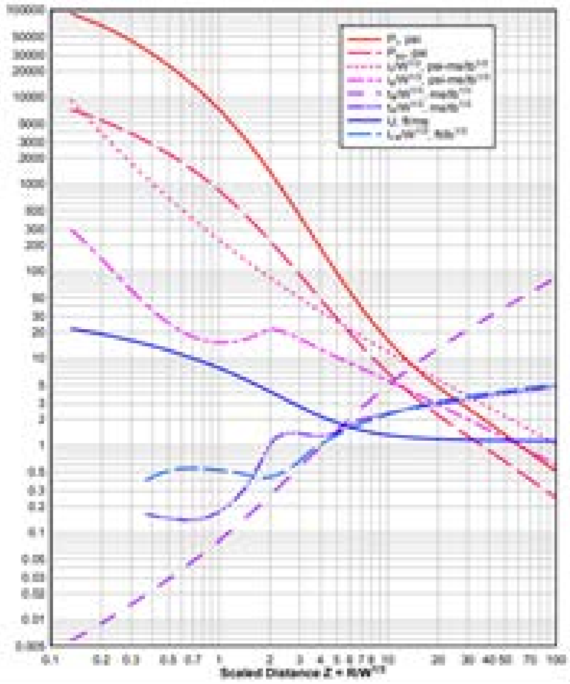

Fig. 2. Parameters of Blast Wave for Air Explosion according to UFC 4-023-02

Рис. 2. Параметри ВУХ при повітряному вибуху згідно UFC 4-023-02

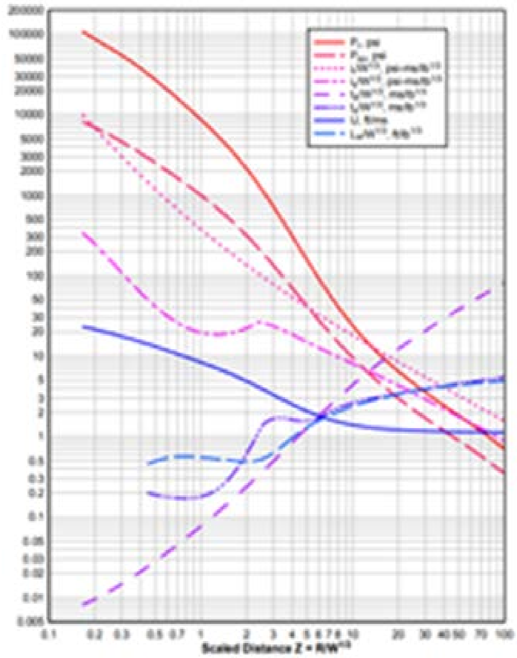

Fig. 3. Parameters of Blast Wave for Surface Explosion to UFC 4-023-02

Рис. 3. Параметри ВУХ при наземному вибуху UFC 4-023-02

The duration of the impulse action is determined using the following formula, s (in seconds):

$$t = \frac{2 \cdot I}{P}. \qquad (22)$$

When an explosion occurs, the shock wave propagates as a high-pressure front moving in all directions. Upon reaching a surface, the blast wave interacts with it: air particles are suddenly decelerated, and their kinetic energy is converted into pressure energy, which superimposes, forming the reflected blast pressure. Thus, at the point of impact between the wave front and the obstacle, a reflected pressure is generated, which usually significantly exceeds the incident shock wave pressure due to the additional energy contributed by the reflected wave. As shown by the analysis of existing blast wave parameter calculation methods, this effect is often not taken into account in many approaches.

To compare the results of blast wave parameter calculations in methods where no procedure for determining the reflected pressure of an airburst is provided, it can be estimated using the following formula:

$$p_r = \frac{p_f}{2}\left(2 + \frac{\gamma + 1}{\gamma - 1} \cdot \frac{p_{fr}}{\Delta p_f}\right); \qquad (23)$$

where p_r – reflected overpressure of the blast wave, MPa;

p_{fr} – pressure at the blast wave front, MPa;

γ – adiabatic index of the medium (for air, $\gamma \approx 1.4$).

$$p_{fr} = p_a + p_f ; \quad (24)$$

where p_a – atmospheric pressure, approximately 0.1013 MPa;
p_f – overpressure of the blast wave, MPa.

In [13], the following formulas are proposed to calculate the reflected blast wave pressure under the condition that the wave front propagates perpendicularly to the front wall of a structure, MPa:
when the area of the openings in the wall is less than 10%:

$$p_r = 2p_f + \frac{6\left(p_f\right)^2}{p_f + 0.72}; \quad (25)$$

when the area of the openings in the wall is more than 10%:

$$p_r = p_f + \frac{2.5\left(p_f\right)^2}{\Delta p_f + 0.72}. \quad (26)$$

In these formulas, the first term represents the actual reflected pressure, and the second term accounts for the dynamic (velocity) pressure of the air. The amplification of pressure due to reflection is characterized by the reflection coefficient $k = p_r / p_f$, which in formula (25) is taken as 2.

To compare the calculation results, an analysis was conducted for each of the blast wave parameter estimation methodologies under two different scenarios:

- in the case of indirect impact from a Kh-22 missile at a distance of 15 meters from the calculated structure (TNT equivalent of 718.2 kg);
- in the case of indirect impact from a "Shahed-136" UAV detonating at a distance of 5 meters from the calculated structure (TNT equivalent of 34 kg).

Table 1. Calculated Parameters of Blast Wave for an Airburst Explosion at a Distance of 15 m from the Epicenter, with Explosive Mass of 718.2 kg TNT Equivalent. Airburst Explosion.

Табл. 1. Значення розрахункових параметрів вибухово-ударної хвилі для наземного вибуху на відстані від епіцентру 15 м, вибухової речовини 718,2 кг в тротиловому еквіваленті. Повітряний вибух.

Method	Overpressure value, kPa	Duration of the compression phase, seconds	Specific pressure impulse, Pa·s	Reflected pressure, kPa (for methods that do not include this parameter, calculated using formula (26))
Empirical formulas by M.O. Sadovsky	295,3	0,017	673,54	1485,1
Empirical formulas by Birbrayer	405,2	0,02	1870,94	1924,5
Empirical formulas by Henrych. J	253,8	0,011	3028,84	1302
Empirical formulas by Kinney & Graham	314,3	0,009	864,08	1523,8
Methodology of Kingery-Bulmash using UFC 4-023-02 charts	301,33	0,068	1027,23	1172,49

Table 2. Calculated Parameters of Blast Wave for a Surface Explosion at a Distance of 15 m from the Epicenter, with Explosive Mass of 718.2 kg TNT Equivalent. Surface Explosion.

Табл. 2. Значення розрахункових параметрів вибухово-ударної хвилі для наземного вибуху на відстані від епіцентру 15 м, вибухової речовини 718,2 кг в тротиловому еквіваленті. Наземний вибух.

Method	Overpressure value, kPa	Duration of the compression phase, seconds	Specific pressure impulse, Pa·s	Reflected pressure, kPa (for methods that do not include this parameter, calculated using formula (26))
Empirical formulas by M.O. Sadovsky	472,3	0,02	1069,11	2192,9
Empirical formulas by Birbrayer	572,2	0,019	1744,03	2792,9
Empirical formulas by Henrych. J	235,6	0,011	2852,58	1235,5
Empirical formulas by Kinney & Graham	289,6	0,009	817,68	1433,3
Methodology of Kingery-Bulmash using UFC 4-023-02 charts	427,05	0,011	1427,84	1809,44

Табл. 3. Значення розрахункових параметрів вибухово-ударної хвилі для вибуху в повітрі на відстані від епіцентру 5 м, вибухової речовини 34 кг в тротиловому еквіваленті. Повітряний вибух.

Table 3. Calculated Parameters of Blast Wave for an Airburst Explosion at a Distance of 5 m from the Epicenter, with Explosive Mass of 34 kg TNT Equivalent. Airburst Explosion.

Method	Overpressure value, kPa	Duration of the compression phase, second	Specific pressure impulse, Pa·s	Reflected pressure, kPa (for methods that do not include this parameter, calculated using formula (26)
Empirical formulas by M.O. Sadovsky	358,2	0,006	264,48	1684,7
Empirical formulas by Birbrayer	494,9	0,007	734,66	2185,9
Empirical formulas by Henrych. J	302,3	0,004	1153,99	1480,1
Empirical formulas by Kinney & Graham	380,1	0,003	326,44	1765,1
Methodology of Kingery-Bulmash using UFC 4-023-02 charts	361,65	0,0039	402,75	1503,1

Табл. 4. Значення розрахункових параметрів вибухово-ударної хвилі для наземного вибуху на відстані від епіцентру 5 м, вибухової речовини 34 кг в тротиловому еквіваленті. Наземний вибух.
Table 4. Calculated Parameters of Blast Wave for a Surface Explosion at a Distance of 5 m from the Epicenter, with Explosive Mass of 34 kg TNT Equivalent. Surface Explosion.

Method	Overpressure value, kPa	Duration of the compression phase, seconds	Specific pressure impulse, Pa·s	Reflected pressure, kPa (for methods that do not include this parameter, calculated using formula (26))
Empirical formulas by M.O. Sadovsky	326,1	0,007	419,8	2667,2
Empirical formulas by Birbrayer	454	0,007	684,82	2036,1
Empirical formulas by Henrych. J	280,4	0,004	1090,83	1399,5
Empirical formulas by Kinney & Graham	350,4	0,003	309,57	1656,2
Methodology of Kingery-Bulmash using UFC 4-023-02 charts	516	0,0034	558,51	2320

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

This work reviews existing global methodologies for determining the parameters of blast shock waves.

The need for developing a clear engineering methodology for calculating building structures under the action of blast shock waves in various attack scenarios using different types of weapons has been raised.

Methods for calculating blast shock wave parameters necessary for further structural analysis of buildings and facilities as a whole are presented.

The obtained results allow the following conclusions:

the empirical formulas of M.O. Sadovsky and A.N. Birbraer approximate experimental results well for charge masses above 2 kg and are simple for practical use; however, they do not account for reflected pressure, which limits their accuracy in calculating effects on engineering structures;

the Kinney & Graham methodology, as well as the Kingery-Bulmash approach (UFC 4-023-02), provide more accurate consideration of the relationships between pressure, impulse, and compression phase duration, especially for air blasts;

the charts and approximation dependencies from UFC 4-023-02 allow obtaining fairly accurate values for a wide range of distances and charge masses, with the possibility of accounting for complex environmental conditions.

A comparison of methodologies showed that with the same initial parameters, results may differ significantly, necessitating a comprehensive approach when selecting a calculation method for a specific task.

Reflected pressure values, which are not considered by most methods, have a significant impact when assessing the effect of blast shock waves on structures, particularly in cases of frontal impact. For their inclusion, it is advisable to use generalized formulas, such as those proposed in [13].

Prospects for further research include:

improving the methodology for calculating blast shock wave parameters of all probable damaging elements needed for the structural analysis of buildings and facilities;

developing a unified methodology that would incorporate the advantages of different approaches for various types of explosions (air, surface, underground) and structures (massive, lightweight, with or without openings);

conducting experimental research and computer modeling to refine empirical coefficients in the dependencies used in existing methodologies;
investigating the influence of reflected waves in urban environments, where complex building configurations can significantly alter wave characteristics.

The development of modern calculation methods, with awareness of current wartime threats, will enable the most effective construction of engineering protective and fortification structures, thereby greatly contributing to the realization of the "Fortress Country" concept.

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ПОРІВНЯННЯ МЕТОДИК РОЗРАХУНКУ ПАРАМЕТРІВ ВИБУХОВО-УДАРНОЇ ХВИЛІ ДЛЯ РОЗРАХУНКУ СПОРУД ІНЖЕНЕРНОГО ЗАХИСТУ

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Анотація. Воєнна агресія рф проти України, шляхом застосування всієї номенклатури засобів повітряного нападу противника не лише проти військових цілей, але і проти об'єктів критичної інфраструктури (далі - ОКІ) [1, 2] та інших цивільних об'єктів, привнесла суттєві зміни в частині зведення захисних споруд та споруд цивільного за-хисту. Чинні нормативні документи [3] розроблялись з передумови поодинокого ядерного вибуху на значній відстані від об'єкту, через що і розрахунки будівельних конструкцій виконувались без урахування інших факторів ураження [4]. Реалії війни показали, що застосування ворогом високоточного озброєння у вигляді безпілотних летальних апаратів (далі – БпЛА) – камі-кадзе та багатьох типів ракет, потребують негайного урахування шляхом розробки єдиних підходів до зведення сучасних за-хисних та фортифікаційних споруд високої надійності.

Сьогодні в Україні активно впроваджу-ється концепція “Країна-фортеця” схвалена постановою Кабінету Міністрів України, згідно якої передбачено інтегральний за-хист ОКІ та інших об'єктів стратегічного значення, що передбачає організацію еше-лонованої протиповітряної оборони анало-гічно системам захисту Ізраїлю, США та інших країн, сполученої з комплексними заходами цивільного та інженерного захис-ту, систем радіоелектронної боротьби, встановлення хибних цілей, маскування, перехід від створення великих об'єктів стратегічного значення до менших розосе-реджених між собою, а також перехід на природні енергетичні джерела, що значною мірою має підвищити стійкість країни до зовнішніх загроз воєнного стану.

Отримані в статті чисельні результати показали, що методики М.О. Садовського та Бірбраєра добре апроксимують результати експериментів при масі заряду понад 2 кг і прості у практичному використанні, однак не враховують відбитий тиск, що обмежує їх точність у розрахунках впливу на інже-нерні конструкції, а методика Kinney & Graham, як і підхід Kingery-Bulmash (UFC 4-023-02), забезпечує більш точне врахування залежностей між тиском, імпульсом і тривалістю фази стис-нення, особливо для повітряних вибухів, в той же час графіки та апроксимаційні залежності UFC 4-023-02 дозволяють отримувати до-сить точні значення для широкого діапазо-ну відстаней та мас зарядів, з можливістю врахування складних умов середовища.

Порівняння методик показало, що при однакових вихідних параметрах результати можуть суттєво відрізнятися, що потребує комплексного підходу при виборі методи-ки розрахунку для конкретного завдання.

В Україні має бути розроблена норма-тивна база, згідно з якою при проектуванні фортифікаційних споруд, споруд інженер-ного захисту ОКІ та інших критичних об'єктів мають враховуватись і новітні за-грози повітряного нападу противника.

Ключові слова: вибухово-ударна хвиля; надлишковий тиск; відбитий тиск; вибухова речовина; тротиловий еквівалент.

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