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METHODS OF CALCULATION AND ENGINEERING PROTECTION OF CRITICAL INFRASTRUCTURE OBJECTS AND OTHER STRATEGIC FACILITIES AGAINST LONG-RANGE PROJECTILES

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Abstract. One of the key areas of russia's military operations against Ukraine is the destruction of critical infrastructure objects (CIO) of strategic importance. The main types of enemy means for air strikes on CIO are air-launched, ground-launched and water-launched missiles, as well as barrage munitions. The vast majority of CIO were built above ground, without any engineering structural protection systems to counter air threats, explosions or other impacts related to military operations. The experience of Ukraine's war with Russia, in particular, the analysis of the significant impact of damage to the energy sector's critical infrastructure, showed the importance of developing the most effective methods of structural engineering protection of critical infrastructure from various types of ammunition as soon as possible. The process of reducing the threats of damage to critical infrastructure involves identifying risks, their comprehensive assessment, developing measures to reduce threats and their prompt implementation, followed by an assessment of the measures effectiveness. Currently, the issue of organising the protection of critical infrastructure and other strategic facilities is being systematically addressed on the basis of the "Country-Fortress" principle, which provides for the organisation of echeloned air defence combined with comprehensive civil and engineering protection measures. Currently, there is a certain deficiency of regulatory data in Ukraine for the design of reliable protective structures, so a regulatory base should be developed to ensure that the design of critical infrastructure and other critical objects includes calculations for the possible impact of various air strikes, terrorist attacks, etc. In addition, it is necessary to provide for the reliable protection of existing facilities, taking into account the dangers and threats of today. The article presents approaches to assessing the risks of damage to critical infrastructure objects, provides methods for their engineering and analytical calculations and methods of engineering structural protection against various types of ammunition. The article considers both the issue of protecting existing objects and designing new ones, taking into account the requirements for engineering protection and civil defence.
Keywords: engineering protection, critical infrastructure objects, damage, explosion, engineering protection, building structures.

Introduction. Considering the protracted war of the Russian Federation against Ukraine and the lack of significant progress by the Russian Federation on the battlefield, the latter resorts to psychological pressure on the civilian population by targeting critical infrastructure objects (CIO) of strategic importance in Ukraine [1, 2]. The purpose of such activities, from a military standpoint (in addition to directly targeting military objects), is to reduce the quality of life and create danger for the population, which affects the psychological state of society and reduces the combat capability of the armed forces, disrupts the functioning of the production and economic sectors of the national economy, leading to delays in providing the army with necessary resources.

Therefore, the task of protecting CIO and other strategically important objects is urgent and of great importance. In Ukraine, the majority of CIO were built aboveground without any engineering structural protection systems to counter aerial threats, explosions, or other impacts related to military operations [3, 4]. Currently, the issue of organizing the protection of CIO and other strategic objects is being addressed systemically, following the "Country-Fortress" principle, which involves the organization of a layered air defense combined with comprehensive civil and engineering protection measures, similar to the defense systems of Israel, the United States, and other countries. In fact, Ukraine needs to develop a regulatory framework according to which engineering protection should be provided and additional calculations should be performed to assess the potential effects of various aerial strikes, terrorist attacks, etc., during the design of CIO and other critical objects. Furthermore, reliable protection of existing objects needs to be ensured, taking into account current threats and dangers.

The purpose and objectives of the research. The objective of this study is to develop a methodology for engineering-analytical calculations and methods of engineering structural protection for CIO against various types of munitions. The experience of Ukraine's war with the Russian Federation, particularly the analysis of the significant impact of damage to the energy sector CIO, has demonstrated the importance of quickly developing highly effective methods of engineering structural protection against various types of munitions.

The study [5] indicates that the main types of enemy means for aerial targeting of CIO are air-to-ground, ground-launched, and cruise missiles, as well as unmanned aerial vehicles of the "loitering munition" type. While missiles can be tracked and neutralized by air defense systems, loitering munitions, which are used by the Russian Federation, are characterized by launching from mobile platforms, mainly at night. Their low flight altitude (50-200 m) and the practical absence of metal components in their bodies make them difficult to detect by radars, while their combination of guidance methods, which is not yet fully understood, provides resistance to electronic warfare systems. Additionally, the mass launch of loitering munitions by the enemy in several groups simultaneously or in succession with short intervals makes them highly effective against targets. At the same time, high-precision missiles pose a significant threat, so engineering protection systems for CIO require further development.

Presentation of the Main Material. In the process of developing measures to protect CIO, it is essential to assess the risks and threats that should be addressed by this protection. Risk management involves choosing an appropriate response to a risk to achieve one or a combination of the following results: avoidance of damage, transfer of the object, mitigation of impact, or acceptance of the damage possibility. It should be based on minimizing the consequences of potential risks rather than eliminating the risks themselves. Risk management combines the processes of risk assessment, selecting appropriate response methods by evaluating the value of assets and the vulnerability of the object in relation to threats, and comparing the risk of partial or complete loss of the object with the cost of implementing protective measures. Quite often, the measures for protecting an object exceed its value, making their implementation impractical.

The risk management process, shown in Fig. 1, consists of five stages: identification of potential risks and threats, risk assessment to determine the level of risk, development of control and mitigation measures, their implementation, and subsequent evaluation of effectiveness.

Fig. 1. Visualization of the process of managing threats to CIO

The first stage involves identifying threats. At this stage, an attempt is made to answer the question - what can go wrong? In general, dangers and threats can arise from any sphere and can be related to the activities of the enemy, the possibility of accidents, environmental conditions, health, sanitation, material and technical means and equipment, etc. The assessment must be carried out taking into account the context of the events, the determination of the causes that give rise to them, the predicted duration of the action of dangerous factors of influence. Fig. 2 shows an example of a visual representation of factors that pose a threat to the object and parametric values of further analysis of their impact.

ASSESSMENT OF PHYSICAL RISK OF THREAT OF THE FACILITY

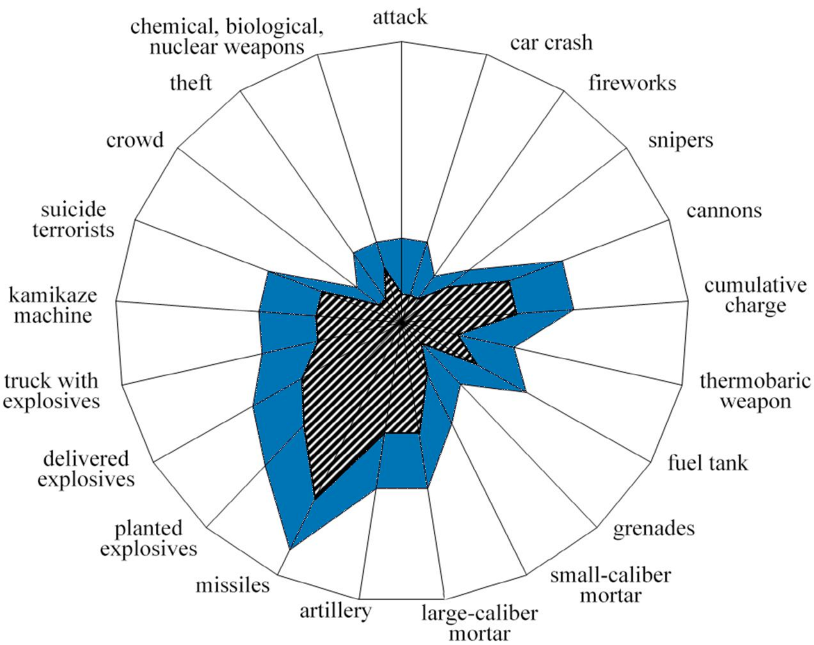

Fig. 2. Assessment of the physical risk of threats to the CIO

The assessment of the physical risk of threats to the CIO is carried out on a numerical scale (see Table 1), which takes into account the probability of a threat from a certain type of danger and its impact on the operation of the object. Parametric values of gradation of impacts / consequences of damage (e.g. number of victims, repair period, amount of material costs) is determined for each object individually with the participation of the owner/balance keeper of the object.

Table 1

Assessment of the overall risk of damage to the object

		PROBABILITY OF OCCURRENCE						
		extreme	very high	high	average	low	very low	minimal
IMPACT / CONSEQUENCE	Cessation of functioning	10	10	9	8	7	6	5
	Significant losses	10	9	8	7	6	5	4
	Average losses	9	8	7	6	5	4	3
	Separate losses	8	7	6	5	4	3	2
	Low losses	7	6	5	4	3	2	1
	Damage/injuries	6	5	4	3	2	1	1

After the most important threats are identified, control and protection measures against them are developed. What are the potential ways to respond to the risk, and which one provides the best balance between affordability and efficiency? Certain technical solutions are adopted that do not eliminate the risk factor, but reduce its impact and consequences. Possible active and passive protection measures are evaluated until an acceptable level of risk is achieved or until all risks are reduced to a level where the benefits outweigh the potential costs. The results of reducing the risks of damage to the object (see Fig. 2) demonstrate the effectiveness of the application of protection measures.

The evaluation of active and passive protection measures is carried out on the same scale in which threats are evaluated (see Table 2).

Table 2

Assessment of active and passive protection measures

Value	Active measures	Passive measures
10	Such high levels of protection cannot be achieved by active or passive measures alone	
9		
8		
7	Extremely effective measures	Full spectrum protection
6		
5		
4	Very effective	A complex system is used
3	Quite effective	
2	Reasonably effective	
1	Limited measures apply	Limited measures apply
0	There are no effective measures	There is no protection

The implementation of protective measures involves the operational and physical implementation of protective measures - the development of project solutions, the calculation of estimates of material costs and the determination of the need for labor resources and equipment. This is usually accompanied by the transformation of planned protection measures into clear and simple orders, the allocation of responsibilities and the establishment of appropriate authority and accountability, as well as the provision of the necessary support for their implementation.

Control and evaluation of efficiency. At this stage, you need to make sure - is your plan working? Does it need changes or updates? The purpose of the fifth stage of the risk management process is to ensure that risk controls are implemented and applied according to plan, and that there is a feedback mechanism. As with the rest of the risk management process, monitoring and evaluation should occur at all stages of operations.

The Russian Armed Forces currently have a fairly large range of long-range weapons both of their own production (S-300, X-47M2 Kinzhal, AS4 / X-22, X-101, Kalibr, Iskander, Geran-2) and imported, mainly from Iran (Fateh-110, Zolfagher, Shahed 136) (see Fig. 3).

Moreover, due to high accuracy, maneuverability and the use of radar visibility reduction technologies, unmanned aerial vehicles (hereinafter UAVs) of the Shahed 136 / Geran-2 type and X-101/ X-555 missiles have the highest passability to the target (Fig. 4).

The processing of existing statistical material on the effectiveness of UAVs shows that approximately 20% of them have a direct hit, while 80% hit at 15-20 meters or more from the object, or do not hit for various reasons. Therefore, the larger the CIO, the greater the probability of a direct hit on it or as close as possible to it, and the more complex the type of engineering protection or their combination must be considered.

When developing means of CIO protection, it is necessary to consider the types of influences that can cause damage means. The most dangerous type of impact is direct damage to the object by a projectile followed by detonation. Moreover, in this case, it is more dangerous to be hit by a missile, which, due to its greater mass and speed of movement, has significantly greater kinetic energy (1)

$$E_k = \frac{1}{2} m v^2 , \tag{1}$$

where E_k is the kinetic energy of the projectile; m is the mass of the projectile; v is the speed at the moment of contact with the object.

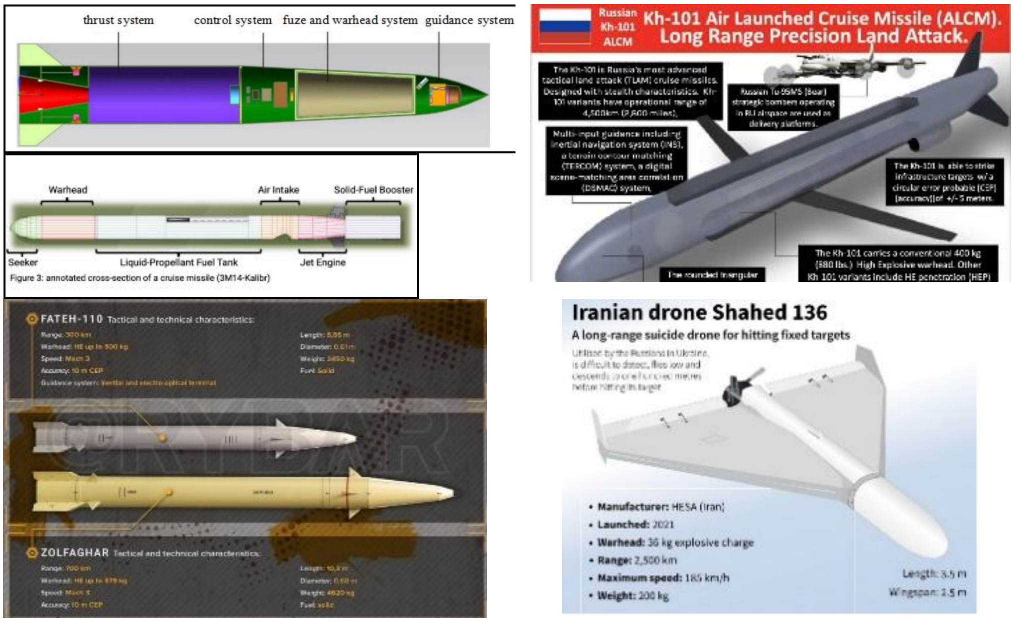

Fig. 3. The main long-range weapons of the Russian Federation

The most common engineering methods for calculating the penetration of projectiles into the material are the Venn equation [6] and the equations contained in UFC 4-023-07 "Design to Resist Direct Fire Weapons Effects, with Change 1".

The penetration depth (2) is affected by the characteristics of the projectile, namely:

–speed;
–mass;
–the shape of the projectile head (CRH);
–diameter;
–length;
–material / density;

as well as the properties of the target (protective shell):

–type and density of material;
–material thickness;
–Brinell hardness coefficient (for steel);
–compressive and shear strength;
–Poisson's ratio;
–Young's modulus.

$$P = \left(\frac{4}{\pi}\right)\frac{E_k}{(\sigma \cdot 10^6)\cdot d^2}, \tag{2}$$

where P is the penetration depth of the projectile into the material; E_k – projectile kinetic energy; σ – principal stresses; d – the diameter of the projectile.

The main stresses σ depend on the characteristics of the material and the nature of the passage of the projectile in it (3):

$$\sigma = \left(\alpha + \beta\sqrt{\frac{\rho_t}{(\sigma_t \cdot 10^6)}}\cdot v_i\right)\sigma_t, \tag{3}$$

where α, β – coefficients of influence of the shape of the projectile head; ρ_t – material density; σ_t – the calculated shear resistance of the material; v_i – the speed of the projectile.

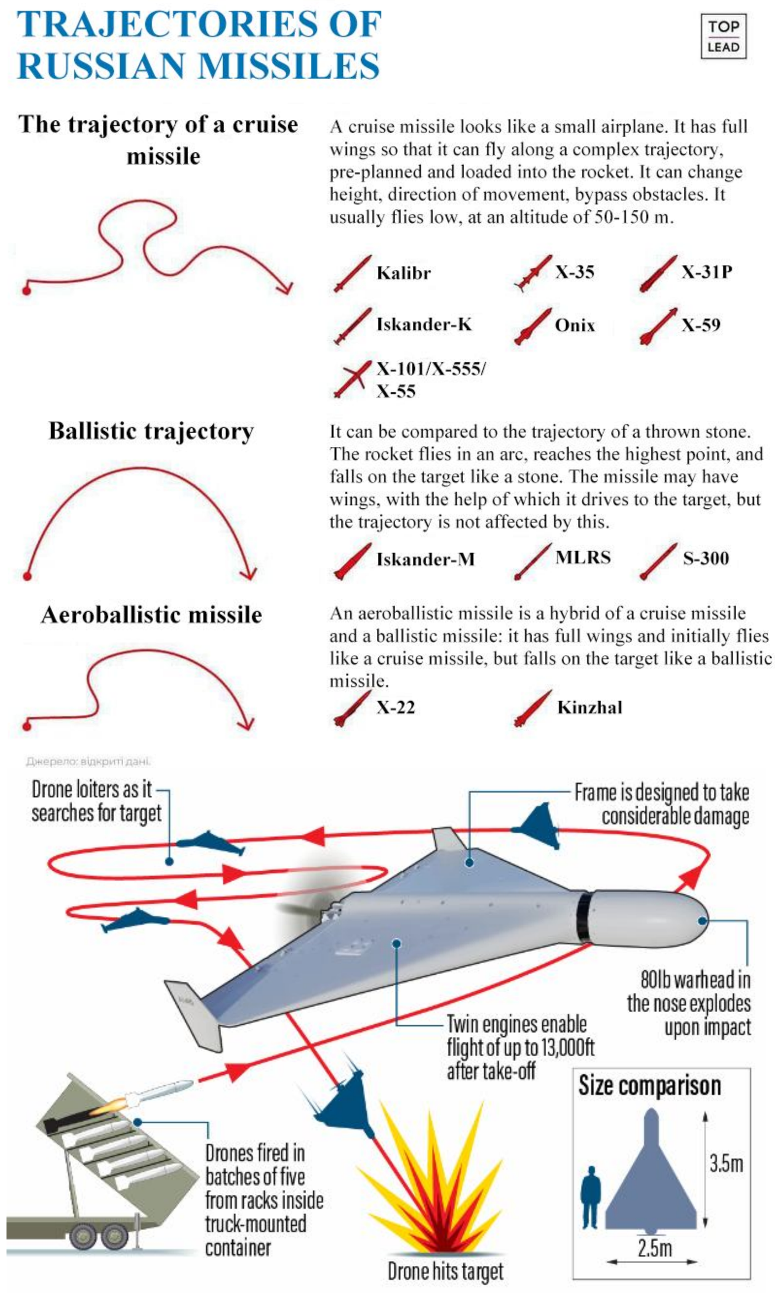

Fig. 4. Features of the trajectory of long-range weapons

If the thickness of the protective material is insufficient, penetration occurs (see Fig. 5). Protection against direct impact should be calculated in such a way that the projectile does not penetrate the protective shell, and secondary chipping of the protective material inside the room does not occur.

Upon collision with a rigid obstacle, the explosive substance of the projectile detonates, resulting in the formation of an *explosive wave* and *fragmentation* of debris (see Fig. 6).

Fragmentation occurs after the explosion and destruction of the projectile container, after which the fragments fly at high speed, filling the surrounding space around the detonation site with deadly fragments. To increase damage, the container can be filled with additional small parts (shrapnel). At the same time, the maximum number of fragments spreads perpendicular to the axis of the projectile with the center at the location of the explosive substance (see Fig. 6). The number of fragments scattered along the axis of the projectile trajectory is minimal. This can be used when designing protective shells - it is not necessary to stop the projectile, it may be enough to change the trajectory of its movement.

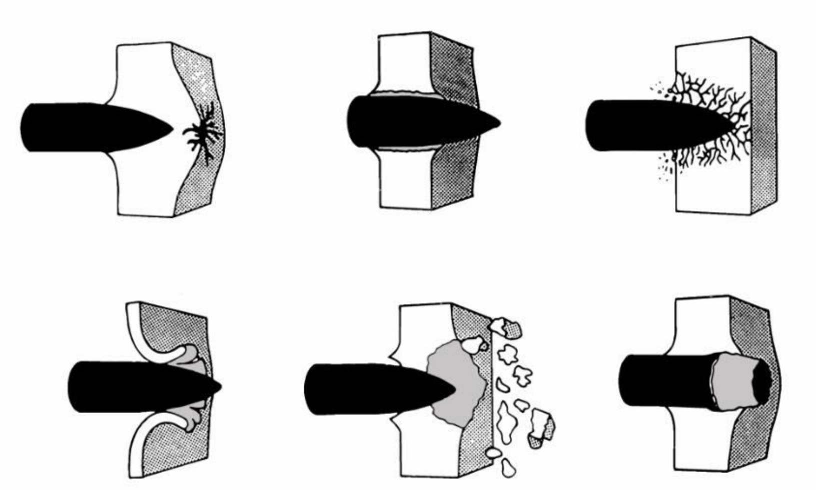

Fig. 5. Breaking through (penetration) of the material by projectiles

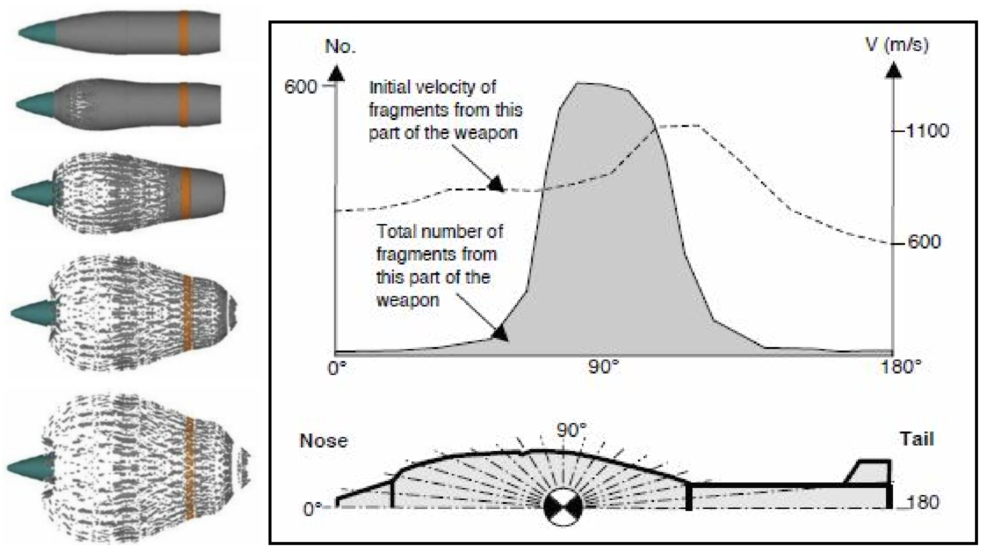

Fig. 6. Fragmentation and scattering of projectile shell fragments

To calculate the protective structure against damage by fragments, it is first necessary to determine the coefficient of distribution of fragments (4). It depends on the type of explosive substance (determines the power of detonation and the initial energy of the explosion), and the parameters of the container (density, thickness and diameter of the container from which the fragments are formed after the explosion)

$$M_a = Bt_c^{0,833} d_i^{0.333}\left(1+\frac{t_c}{d_i}\right), \quad (4)$$

where M_a – fragments distribution coefficient; B – the explosive constant, which depends on the type of explosive substance; t_c – container thickness; d_i – the inner diameter of the container.

Knowing the debris distribution coefficient, you can determine the average/calculated debris mass (M_f):

$$\overline{M_f} = 2M_a, \quad (5)$$

The casing/container of an explosive device usually expands before rupture, and the thickness decreases accordingly (see Fig. 7). This requires determining the corrected diameter (6) and thickness of the case (7):

$$d_i' = \sqrt{(1.25(d_i + 2t_c)^2 + d_i^2}, \quad (6)$$

$$t_c' = 0.75(d_i + 2t_c) - 0.5d_i', \quad (7)$$

where d_i' – the corrected inner diameter; t_c' – adjusted thickness of the hull; d_i – the initial inner diameter of the container; t_c – the initial thickness of the container.

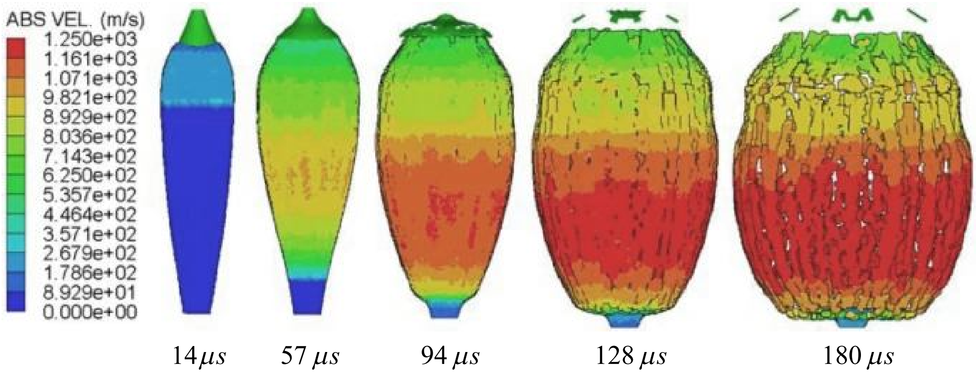

Fig. 7. Modeling the fragmentation process over time using the SPH method according to [7]

The average length (8) and cross-sectional area (9) of a fragment after the rupture of the projectile container, which must be determined to calculate the damage and penetration of the fragments into the protective structure:

$$L_f = \frac{4M_f}{\pi\rho_c (t_c')^2}, \quad (8)$$

$$A = \frac{\pi \cdot L_f^2}{4}, \quad (9)$$

where L_f – the average length of the fragment; A – the average cross-sectional area of the fragment; M_f – the mass of the fragment; ρ_c – the density of the container material.

Accordingly, the average diameter of the fragment:

$$D=\sqrt{(2\&A/\pi)}.$$

Gurney's equation (10) is used to determine the speed of flight of fragments, which makes it possible to estimate with what power the explosive substance accelerates the metal of the container during the detonation of the explosive

$$V_f = \sqrt{2E}\cdot\left(\frac{m_c}{m_e}+\frac{1}{2}\right)^{-1/2}, \quad (10)$$

where V_f – the initial speed of fragments; $\sqrt{2E}$ – Gurney constant for explosive substance; m_c

– mass of the container; m_e – the mass of the explosive substance.

Next, having the mass, size and speed of the fragments after detonation, it is possible to determine the depth of their penetration into the protective structure and calculate the safe thickness of the protective material. At the same time, the speed of fragments decreases depending on the distance at which the explosion occurs.

For example, the depth of fragments penetration into concrete:

$$X_f = 8.24 \cdot 10^{-3} \frac{M_f^{0.333} V_s^{0.825} \left(L_f / D\right)^{0.285}}{f_c'}, \qquad (11)$$

where X_f – the penetration depth of the fragments; M_f – the average mass of the fragment; V_s – the speed of the fragment; D – the diameter of the fragment; f_c' – the calculated compressive strength of concrete; L_f – the average length of the fragment.

Below is the equation that determines the required thickness of concrete to prevent the penetration of fragments:

$$T_p = 1.632 X_f D^{0.1} + 1.311 D, \qquad (12)$$

where T_p – the thickness of concrete to prevent the penetration of fragments; X_f – penetration depth of fragments; D – the diameter of the fragment.

In addition, it is necessary to prevent spalling of concrete inside the premises from being damaged by fragments from the outside:

$$T_s = 1.754 X_f D^{0.1} + 2.12 D, \qquad (13)$$

where T_s – the thickness of concrete to prevent spalling; X_f – penetration depth of fragments; D – the diameter of the fragment.

An explosive wave is no less a threat when a projectile is detonated. When a concentrated explosive is detonated, the explosion reaction first generates hot gas (detonation products), which can be under a pressure of 10-30 GPa and a temperature of about 3000-4000°C. There is a strong expansion of these gaseous products and the surrounding air is displaced from the volume it occupies.

Since an imbalance is established between the highly compressed air in the blast wave and the undisturbed air in front of it, the blast wave spreads outward from the center of the explosion. The total energy in the system is now constant because the explosive has fully detonated and the pressure at the blast wave front decreases as the wave front moves further away from the source of the blast. The impulse of the gas leads to its excessive expansion, as a result of which the pressure in the tail of the blast wave falls below normal atmospheric pressure. This creates a negative, or suction, phase, which thus applies a retarding force to the surrounding gas molecules, causing the flow to reverse back towards the center of the explosion. Eventually, the balance is restored.

A typical pressure-time profile at a fixed point in space for an outdoor blast wave is shown in Figure 8.

The peak pressure in the negative phase is, as a rule, small compared to the volumetric expansion pressure in the positive phase, but it cannot be neglected in the design of protective structures. When designing fastening in only one direction, under negative pressure, unfastened structures may be pulled out / overturned (Fig. 9).

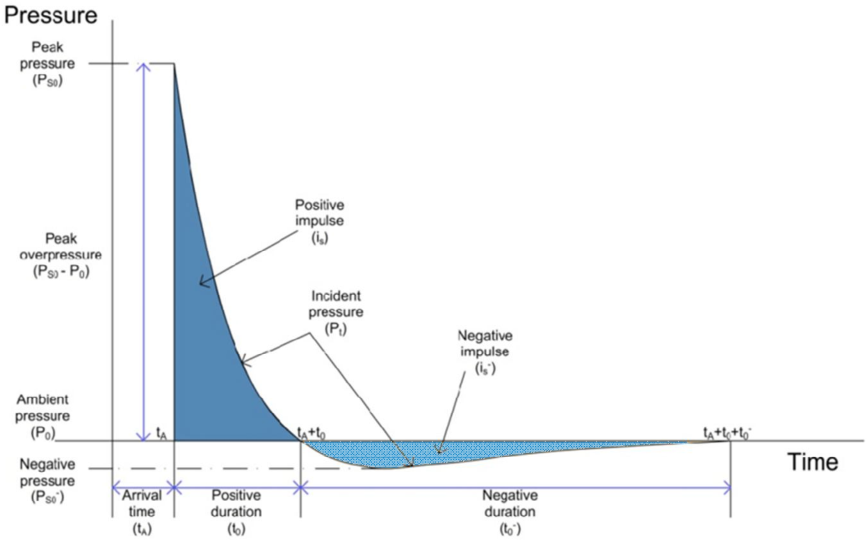

Fig. 8. The idealized regularity of the pressure change of the blast wave over time in the open air

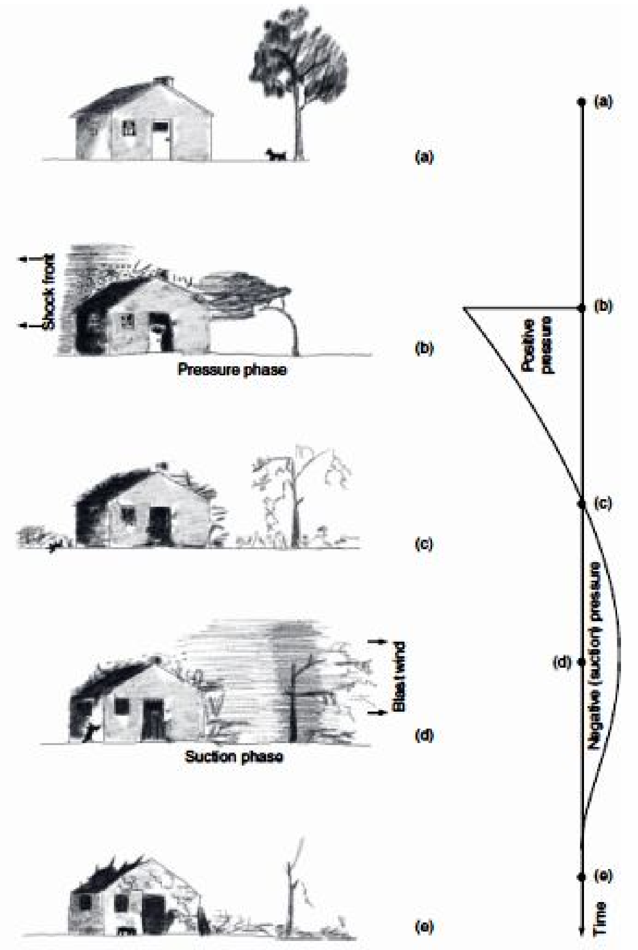

Fig. 9. Changes in the impact of the blast wave on objects over time

When a blast wave hits a solid surface (or other denser-than-air medium), it bounces off it and, depending on its geometry and size, wraps around it. When the blast wave is reflected, energy is transferred between the blast wave and the object. The simplest case is an infinitely large rigid perfectly reflecting plane (for example, the plane of the ground in the case of an open-air explosion, or the facade of an infinitely large building in the case of a ground-based explosion) on which the blast wave normally falls. The incident blast wave and the wave reflected from the building create a region of further compressed air local to the building. At the molecular level, the surface of the object applies an outward force to each air molecule sufficient to give it an equal momentum in the opposite direction. According to Newton's third law, the air acts on the surface with the same external force. Thanks to this, the change in momentum leads to the fact that the pressure locally rises above the pressure drop that could occur in the same place. This phenomenon is called reflected pressure (see Fig. 10).

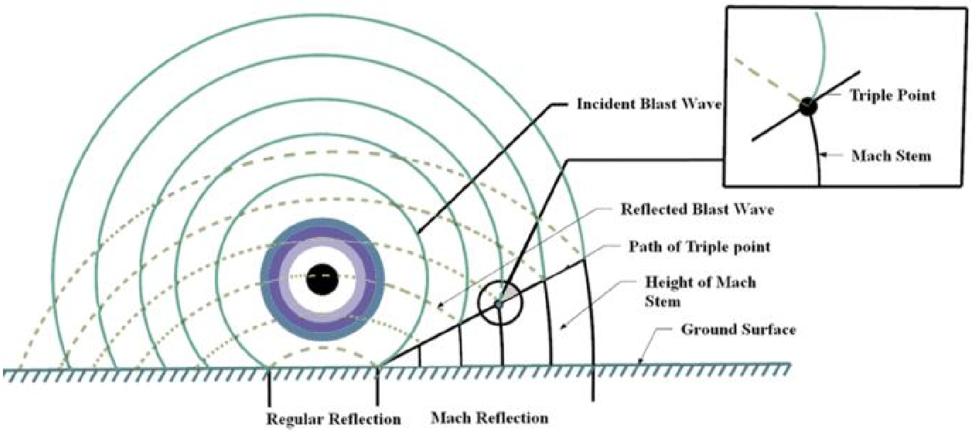

Fig. 10. Emergence of reflected pressure of an explosive wave

Experimental studies have shown that as the distance to the source of the explosion increases, the pressure drops in a cubic relationship, and the number of fragments in a quadratic relationship. Therefore, an effective method of protection is to remove the source of the explosion - for example, early initiation of the explosion at a distance from the object. At the same time, the installation of flat protective screens is not an effective protection against the explosion, because the blast wave surrounds the obstacle and the protection works only in the immediate vicinity of the screen (see Fig. 11).

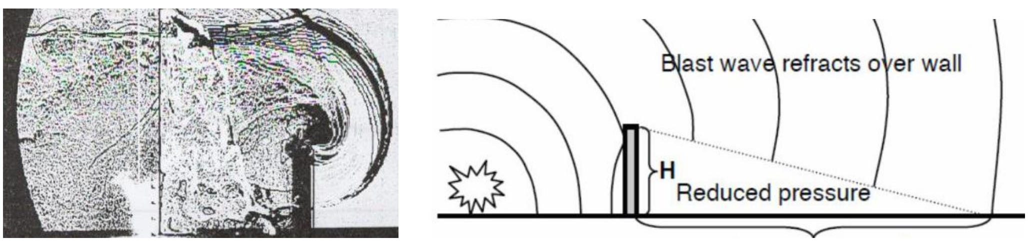

Fig. 11. Obstruction of an obstacle by an explosive wave

To determine the pressure of the blast wave on the surface of the object, reference materials can be used, e.g. resource https://unsaferguard.org.

In order to perform calculations of structures under the action of a blast wave, it is necessary to convert the pressure and momentum of the blast wave into a quasi-static load (see Fig. 12).

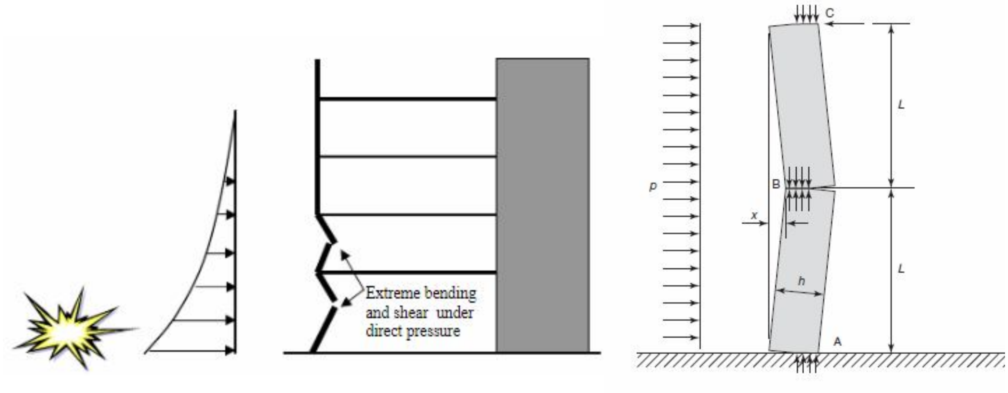

Fig. 12. Direct quasi-static loading of columns and walls by an explosive wave

A secondary effect of the blast wave impact can be the lifting of floor slabs, which is most dangerous for panel and brick buildings with precast reinforced concrete slabs (see Fig. 13). Since the slabs in such constructions are fixed only due to the loading of the walls, under the action of explosive pressure from below, the slabs may be displaced from the supports and the floors may collapse.

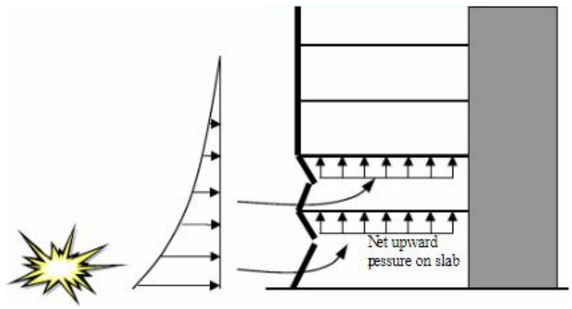

Fig. 13. Lifting of floor slabs by an explosive wave

Fig. 14 shows the graph of pressure changes depending on the distance to the explosion site of the Shahed 136 UAV and the X-101 missile. As can be seen from the graph, the more or less safe distance for people's lives and health from the place where the Shaheds fell is about 110 m, and the X-101 missiles - 210 m.

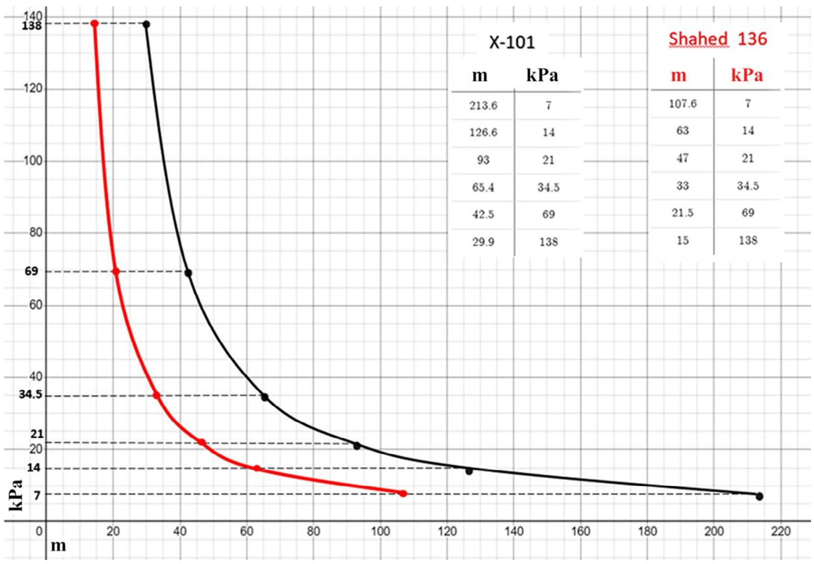

Fig. 14. Graph of the pressure drop of the blast wave at a distance from the Shahed 136 explosion site and the X-101 missile

The approximate impact on structures and people from excess pressure and air velocity from the propagation of the blast wave is given in the table. 3.

Table 3

Impact of pressure and speed of blast wave propagation on structures and people

Peak pressure	Max. air speed	Impact on structures	Impact on people
7 kPa	17 m/s	Destruction of window glass	Minor injuries from broken glass
14 kPa	31 m/s	Minor damage to buildings (destruction of windows and doors, damage to the roof)	Injuries from broken glass and debris
21 kPa	46 m/s	Collapse of residential buildings	A large number of serious injuries, possible fatalities
34.5 kPa	73 m/s	Collapse of most buildings	Serious injuries are everywhere, fatalities are widespread
69 kPa	131 m/s	Reinforced concrete frame buildings are damaged or destroyed	Most of the people were killed
138 kPa	224 m/s	Heavy reinforced concrete frames of buildings are damaged or destroyed	Fatalities approach 100%

In work [5], the first priority methods of engineering protection, which can be arranged in the shortest possible time, are considered. In the case of indirect hits and relatively small objects, the primary measures for their engineering protection include fencing with fortification gabions, with soil filling, the arrangement of ceilings over the objects with the help of wooden, reinforced concrete and steel-reinforced concrete elements, etc. At the same time, horizontal and vertical protective thicknesses can be selected according to the guides. For large CIOs, the case of a direct hit should be considered. At the same time, the usual engineering protection measures considered above are not very effective, as they have structural limitations in the device, do not provide circular protection of the object, and require significant protective thicknesses in case of direct hits. Also, when an explosive wave flows around a small obstacle, an area is formed behind it where the pressure is lower than that of the incident wave. But already at a short distance beyond the obstacle, the explosive shock wave (ESW) front closes again and the pressure is restored. Therefore, a small obstacle (a low wall made of gabions, sandbags, etc.) can provide protection from ESW only directly behind it. Thus, non-closed protection from the installation of partial shelter walls can only be anti-fragmentation, or extinguish the residual blast wave at a distance from the object.

The most effective method of engineering protection against a direct hit by an UAV in the CIO is the creation of safe distances, that is, moving the place of a possible hit away from the object. The most effective method of engineering protection for military centers and other objects of strategic importance can be the construction of protective structures of a continuous shelter, which cover with their profile the entire possible zone of damage by the enemy's means. Therefore, the work [5] proposed a successful principled solution to the primary circular engineering protection of the CIO with the help of two levels: a protective screen and an impermeable shell (of the "sarcophagus" type).

Fig. 15 shows the schematic diagram of such a protective structure. The outer screen 1 (Fig. 15) serves as the primary obstacle for the projectile and should cause the initiation of the explosion. The frame of the protective screen can be made of metal or metal-wood [9] structures, to which wall sandwich panels, panels building from cross-laminated timber [10, 11] or a profiled sheet are attached. The stiffness of the metal nets proposed in [5] may not be enough to stop the projectile or initiate an explosion, besides, the size of the missiles, unlike UAVs, allows them to pass through the protective nets unimpeded. At the same time, the upper part of the protective screen can be made of mesh for air access, since such objects usually require air ventilation.

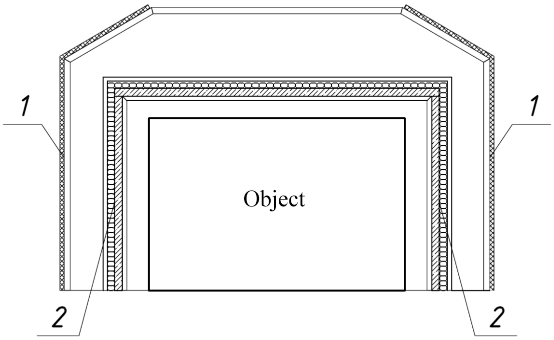

Fig. 15. Schematic diagram of the CIO protective structure against direct hits of the "Shahed-136" UAV and missiles

The second level of protection 2 (Fig. 15) is a multilayer structure that can be combined taking into account the available materials. The supporting frame of such a protective shell can be made of metal structures, but the main protective structure is performed by the filling between the elements of the frame. The main restraining system against the blast wave and damage by fragments after the initiation of the explosion on the protective screen is a layer of hard reinforced concrete slabs. To avoid secondary fragmentation and chipping of concrete, reinforced concrete slabs should be covered with a metal sheet membrane from the inside. Externally, reinforced concrete slabs are covered with soil, sand or soil-cement mixture for damping the velocity of debris.

Also, shock waves in the soil base during the explosion of ammunition in the immediate vicinity of the object pose a significant danger to the structures of the CIO. The created wave is equated to a one-time seismic impact of large magnitude, which depends on the power of the explosion, and accordingly on the type of ammunition. In fact, it is possible to use the standard methods used for the buildings construction in seismic areas, or to use engineering protection techniques when erecting the CIO. One of these techniques can be a protective screen in the soil base around the building, up to several meters wide and several meters deeper than the depth of the foundations, filled with a damping material, for example, uncompacted sand. Thus, the shock wave from the explosion that will occur in the ground base will be extinguished in this protective screen. Accelerograms obtained experimentally during the explosion of munitions of various types and power can be used for a detailed calculation of this effect on the reliability of CIO structures.

Another global way of creating a system of CIO protection and other objects of strategic importance according to the "Country-Fortress" principle is to disperse such objects with the creation of a certain number of backup ones, when the failure of one or more of them cannot significantly affect the overall operation of the critical infrastructure system, etc. The principle of such construction of the CIO should be approved as a general plan for the development of Ukraine in the future. The construction of a large number of small CIO instead of large objects will allow to significantly reduce the risks of their loss, as well as the consequences for the sectors of the national economy of such losses.

Conclusions. Scientific novelty and practical significance of the obtained results. The paper examines approaches to risk assessment of damage to critical infrastructure objects, provides methods for their engineering and analytical calculations, and methods of engineering constructive protection against various types of ammunition.

The issue of the need for their urgent protection according to the "Country-Fortress" principle, including engineering measures, was raised. The issue of both the protection of existing objects and the design of new ones, taking into account the requirements for engineering protection and civil defense, is under consideration.

Innovative methods and techniques of engineering protection of the CIO and other strategic objects from the hits of the most common types of ammunition are proposed.

An algorithm for calculating the parameters of the explosive and fragment load from UAVs and other types of ammunition, as well as for calculating the protective properties of structures, is presented.

The perspective of further research is the improvement of methods and techniques of engineering protection of the CIO and other strategic objects, as well as the methods of their calculation and design, taking into account the ability to withstand different types of ammunition.

The protection of CIO and other strategic objects is one of the most important components of the national security of the Ukraine independence, which contributes to the state's resilience to external and internal threats, including those of a military nature.

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МЕТОДИ РОЗРАХУНКУ ТА ІНЖЕНЕРНОГО ЗАХИСТУ ОБ'ЄКТІВ КРИТИЧНОЇ ІНФРАСТРУКТУРИ ТА ІНШИХ СТРАТЕГІЧНИХ ОБ'ЄКТІВ ВІД ДАЛЕКОБІЙНИХ БОЄПРИПАСІВ

Актуальність. Одним із ключових напрямків ведення воєнних дій рф проти України є ураження об'єктів критичної інфраструктури (ОКІ) стратегічного значення. Основними типами засобів противника для повітряного ураження ОКІ є ракети повітряного, наземного і наводного запуску, а також БпЛА типу «баражуючий боєприпас». Переважна більшість ОКІ зводились в Україні надземними, без жодних систем інженерного конструктивного захисту для протидії повітряним загрозам, вибухам чи іншим впливам, пов'язаним із військовими діями. Важливість найшвидшої розробки максимально ефективних методів інженерного конструктивного захисту ОКІ від боєприпасів різного типу показав досвід війни України з рф, зокрема аналіз суттєвого впливу пошкодження ОКІ енергетичної сфери. На даний час в Україні відчувається певний дефіцит нормативних даних для проектування надійних захисних конструкцій ОКІ. **Метою роботи** є розробка нормативної бази для виконання розрахунків на можливу дію різноманітних видів силових впливів від повітряних ударів, терористичних атак тощо при проектуванні ОКІ та інших стратегічних об'єктів. Наразі системно вирішується питання організації захисту ОКІ та інших об'єктів стратегічного значення за принципом «Країна-фортеця», що передбачає організацію ешелонованої протиповітряної оборони, сполученої з комплексними заходами цивільного та інженерного захисту. Крім цього, необхідно передбачити надійний захист існуючих об'єктів з урахуванням небезпек та загроз сьогодення. Процес зниження ризиків ураження ОКІ передбачає визначення загроз, їхню комплексну оцінку, розробку заходів по зниженню загроз та їхнє оперативне впровадження з подальшою оцінкою ефективності передбачених заходів. **Результати.** Наведені методи оцінки ризиків щодо ураження об'єктів критичної інфраструктури, методики їхніх інженерно-аналітичних розрахунків та способів інженерного конструктивного захисту від боєприпасів різного типу дозволяють розробляти ефективну комплексну систему захисту стратегічно важливих об'єктів. Розглядаються питання як з улаштуванням захисту існуючих об'єктів, так і з проектуванням нових з урахуванням вимог щодо інженерного захисту та цивільної оборони.

Ключові слова: інженерний захист, об'єкти критичної інфраструктури, ураження, вибух, будівельні конструкції.

Mykhailovskyi D.V., Skliarov I.O.

METHODS OF CALCULATION AND ENGINEERING PROTECTION OF CRITICAL INFRASTRUCTURE OBJECTS AND OTHER STRATEGIC FACILITIES AGAINST LONG-RANGE PROJECTILES

Relevance. One of the key areas of russia's military operations against Ukraine is the destruction of critical infrastructure objects (CIO) of strategic importance. The main types of enemy means for air strikes on CIO are air-launched, ground-launched and water-launched missiles, as well as barrage munitions. The vast majority of the CIO were built in Ukraine above ground, without any engineering structural protection systems to counter air threats, explosions or other impacts related to military operations. The importance of developing the most effective methods of engineering structural protection of the CIO from various types of projectiles as soon as possible was demonstrated by the experience of Ukraine's war with russia, in particular, the analysis of the significant impact of damage to the CIO in the energy sector. At present, Ukraine has a certain lack of regulatory data for designing reliable protective structures for CIO. **The aim** of this work is to develop a regulatory base for making calculations for the possible impact of various types of forceful effects from air strikes, terrorist attacks, etc. when designing the CIO and other strategic facilities. Currently, the issue of organising the defence of critical infrastructure and other strategic objects is being systematically addressed on the basis of the "Country-Fortress" principle, which provides for the organisation of echeloned air defence combined with comprehensive civil and engineering defence measures. In addition, it is necessary to provide for the reliable protection of existing facilities, taking into account the hazards and threats of today. The process of reducing the risks of damage to the CIO involves identifying threats, their comprehensive assessment, developing measures to reduce threats and their prompt implementation, followed by an assessment of the measures effectiveness. **Results.** The presented methods of risk assessment of critical infrastructure damage, methods of their engineering and analytical calculations and methods of engineering structural protection against ammunition of various types allow developing an effective integrated system of protection of strategically important objects. The article deals with both the protection of existing facilities and the design of new ones, taking into account the requirements for engineering protection and civil defence.

Keywords: engineering protection, critical infrastructure objects, damage, explosion, building structures.

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Михайловський Д.В., Скляров І.О. **Методи розрахунку та інженерного захисту об'єктів критичної інфраструктури та інших стратегічних об'єктів від далекобійних боєприпасів** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2023. – Вип. 111. – С. 155-171. – Англ.

Наведено підходи до оцінки ризиків щодо ураження об'єктів критичної інфраструктури, наведено методики їхніх інженерно-аналітичних розрахунків та методи інженерного конструктивного захисту від боєприпасів різного типу. Розглядаються питання як з улаштуванням захисту існуючих об'єктів, так і з проектуванням нових з урахуванням вимог щодо інженерного захисту та цивільної оборони.

Табл. 3. Іл. 15. Бібліогр. 11 назв.

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The article presents approaches to assessing the risks of damage to critical infrastructure, methods of their engineering and analytical calculations and methods of engineering structural protection against ammunition of various types. The issue of protecting existing facilities and designing new ones is considered, taking into account the requirements for engineering protection and civil defence.
Tabl. 3. Fig. 15. Ref. 11.

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