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DESIGN FEATURES OF PROTECTIVE ANTI-DRONE SHIELDS

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Annotation. The paper examines the structural and engineering aspects of designing steel protective screens to counter unmanned aerial vehicles (UAVs) at energy infrastructure facilities. The relevance of the topic is due to the targeted UAV attacks on transformer substations, which have prompted the implementation of passive protection in the form of steel anti-drone screens. The study includes an analysis of recent research and publications on UAV threats to power grids and existing protection methods. It explores structural solutions for protective screens and presents the results of their practical implementation in Ukraine. The paper summarizes design requirements, including material selection, ensuring appropriate screen height and distance, modularity, and maintainability of the structure.

Keywords: transformer charging station; unmanned aerial vehicles; kamikaze drone; passive engineering protection; protective screen; Shahed defense

Introduction. The issue of protecting energy facilities, as one of the most important links in Ukraine's critical infrastructure (CI), is one of the most pressing at present [1-4]. Transformer substations are critical elements of the energy infrastructure, and their damage leads to large-scale power outages. In today's warfare, one of the main threats to energy facilities is air attacks by UAVs equipped with explosive charges.

In the realities of late 2024, the most applicable UAVs against Ukraine's critical infrastructure are the Iranian-made Shahed-131 and Shahed-136, as well as the Russian-made Lancet-1 and Lancet-2 [5]. Threats from the use of UAVs require the development of effective means of protection. In addition to active means (electronic warfare, air defence), passive defence elements play an important role. The basic idea of passive protection is to erect a special protective shield above or around the transformer that can intercept the drone or initiate its explosion at a safe distance from the protected facility. Following the large-scale shelling of the power system, NPC Ukrenergo, the transmission grid operator, has launched the world's first comprehensive anti-drone protection system for high-voltage substations. Protective structures (the so-called “anti-Shahed” shelters) are being urgently constructed at key substations in the country, which have already proven their effectiveness during massive drone attacks. According to Ukrenergo, the implemented projects have significantly reduced the level of damage to substations during recent attacks, increasing the resilience of the power system [6, 7].

At the same time, the design of such protective shields is a complex engineering task that requires taking into account specific loads, structural limitations of existing substations, and tight implementation timeframes. This paper summarises the experience and recommendations for the design of steel anti-drone protective shields for transformer substations and the results of recent research.

Analysis of recent research sources and publications. The issue of protecting energy facilities from drone attacks is relatively new, so the number of scientific publications on this topic is limited. Previously, researchers mainly focused on drone detection and electronic warfare systems (antennas, radio jamming, interception). Only a few studies mention drone trapping (net systems) among possible countermeasures, but until recently, these solutions have not been used to protect electrical substations [8-10].

According to statistics on the effectiveness of Shahed drones, only about 20 per cent of them achieve a direct hit, while the remaining 80 per cent fall 15-20 metres from the intended target or do not reach it at all. This indicates that the larger size of the object increases the likelihood of a direct hit, and therefore requires more complex engineering defence solutions.

In cases where the objects are relatively small and are subject to mostly indirect hits, it is advisable to apply basic (temporary) engineering protection measures. These include fencing with fortification gabions filled with soil or sand, as well as the construction of protective coverings made of wooden structures (Fig. 1, 2).

In the case of large-sized objects or critical elements in the structure of critical infrastructure facilities (CIFs), the probability of a direct hit must be taken into account. Under such conditions, the use of conventional temporary engineering protection means is ineffective, as they have design limitations, are unable to provide full circular protection and require a significant thickness of the protective layer to withstand direct damage.

Paper [5] proposes a fundamental solution to the priority circular engineering protection of the most critical structures and equipment using two-level protection (Fig. 3).

At the first level of protection, screens made of rod or flexible metal elements are installed, the main task of which is to move the point of contact of the UAV beyond the critical parts of the facility. This solution has an analogue in civil engineering - bollards, which prevent a vehicle from directly hitting a building and shift the potential location of a vehicle explosion (in the event of a terrorist attack) away from the structural elements of the building. If a Shahed-136-type kamikaze drone hits the protective screen, two scenarios are possible:

1. Mechanical destruction of the device with its subsequent stopping without detonation of the warhead (the most favourable option);
2. Premature initiation of the UAV's explosive charge.

In this context, the critical factor is the distance between the shield and the object, which allows reducing the pressure of the blast shock wave (BSW) to an acceptable level. The second level of protection involves the use of a protective shell (the so-called “sarcophagus”), which should, at the very least, withstand both the pressure of the BSW and the impact of fragments from the warhead explosion that occurred on the shield.

In the event of an explosion of the UAV's warhead directly on the protective shield, its partial destruction is allowed, since the shield design does not provide for full resistance to the explosive load. This approach is reasonable in terms of economic efficiency and overall safety. At the same time, it is envisaged that the shield can be quickly restored, which is realised through its repairable design - the shield should be prefabricated, made of modular elements connected by bolts or similar connections.

It should be noted that until 2022, the issue of physical shielding of facilities from explosions was not addressed in Ukrainian regulatory documents - designers relied only on general standards for the strength of building structures [11, 12] and explosion resistance standards for civil protection facilities. Consequently, the developers of protective shields have to actually create new design solutions from scratch. The literature lacks data on the behaviour of large steel shields under the action of a blast wave, and there are no standardised approaches to calculating spatial frames under the action of an explosion from above. Thus, a number of previously unsolved scientific and technical problems have been identified.

Identification of previously unresolved parts of the overall problem. Given the above and the novelty of this problem, there are several key issues in the design of anti-drone shields that need to be addressed:

- determining the optimal design of the protective shield;
- calculation of explosion parameters and distance;
- strength and behaviour of materials;

- adaptation to existing substations.

Problem statement. The purpose of this article is to analyse the existing problems and highlight the main features that should be considered when designing protective anti-drone shields.

Fig. 1. An example of an underground temporary protection against UAVs

Fig. 2. Examples of ground-based temporary protection against UAVs

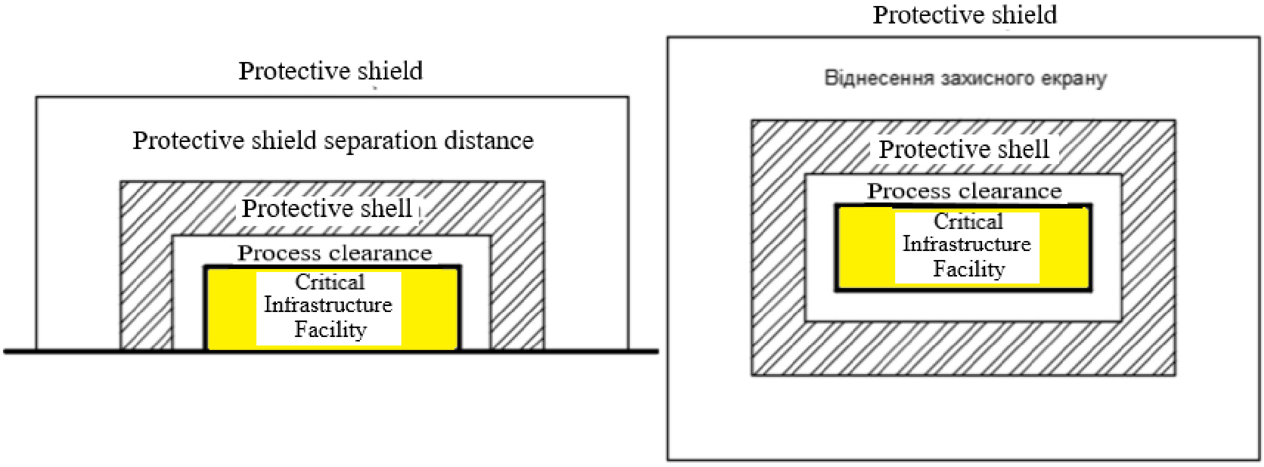

Fig. 3. Schematic diagram of the system of circular engineering protection of objects against direct hits by UAVs

Basic material and results. Experience shows that the proposed design solutions of protective systems should also provide the possibility of multiple protection of objects. Therefore, the most effective concept at present is the creation of multi-layer protective structural systems, each layer of which has its own special properties, is made of a separate building material and has its own specific functional purpose. The number of such layers can reach five. According to the design of the main protective layer, protective structural systems are divided into two types.

In general, a typical design solution that is now widely used to protect electric transformers is shown in Fig. 4.

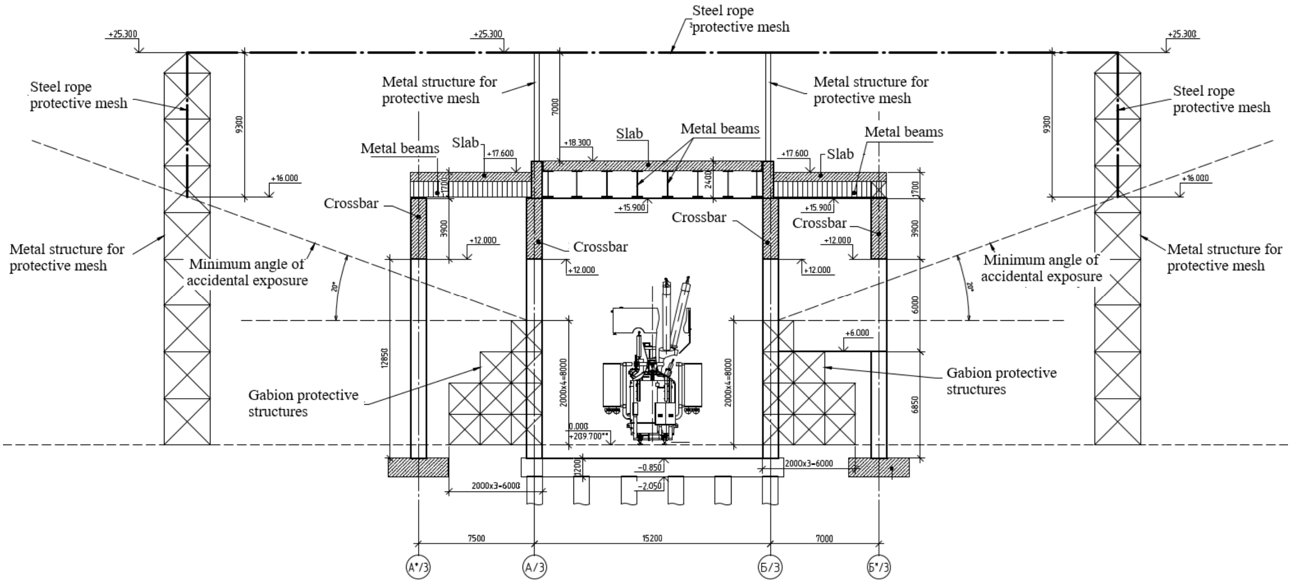

Fig. 4. Typical design solution for the protection of electric transformers

The main protective shell of an electrical substation transformer covering is a monolithic reinforced concrete structure and does not have any other design options, unlike the design of a protective shield.

Based on the analysis of the experience of implementation in Ukraine, two main types of protective anti-drone shield structures can be distinguished: a mesh protective shield structure (Fig. 5) and a combined structure (Fig. 6).

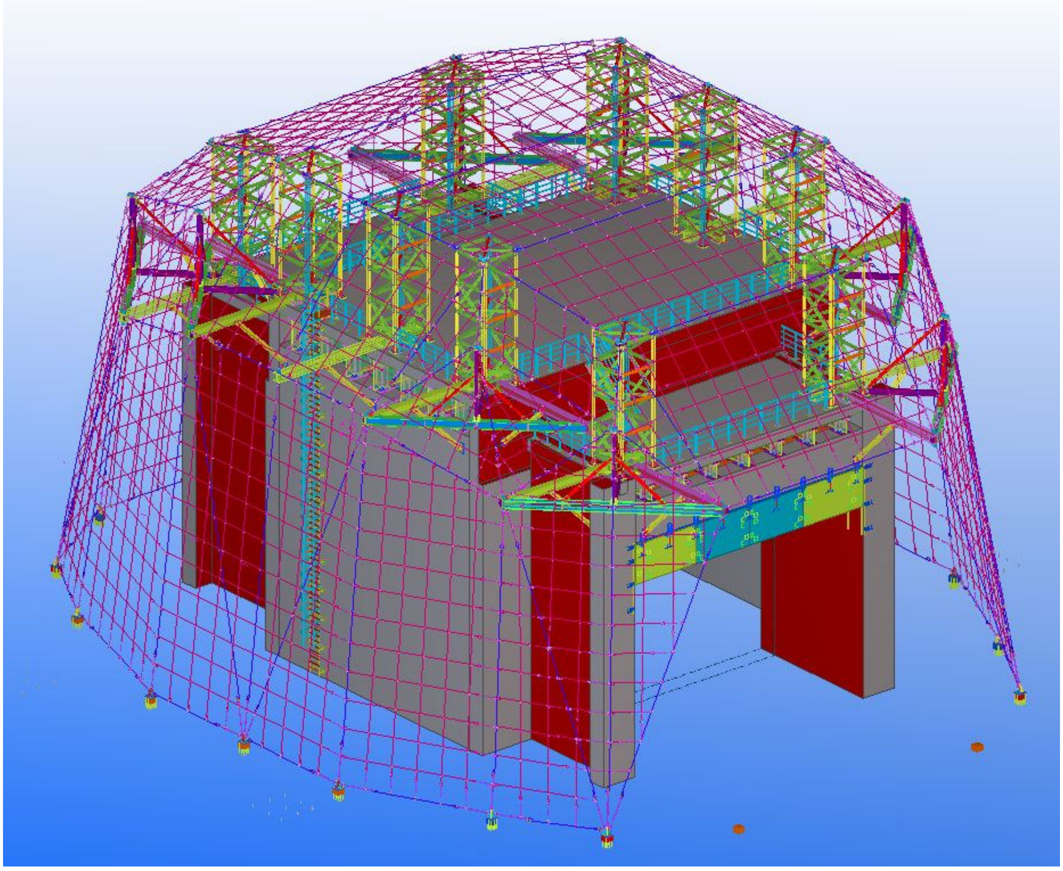

Fig. 5. Diagram of a mesh protective anti-drone shield

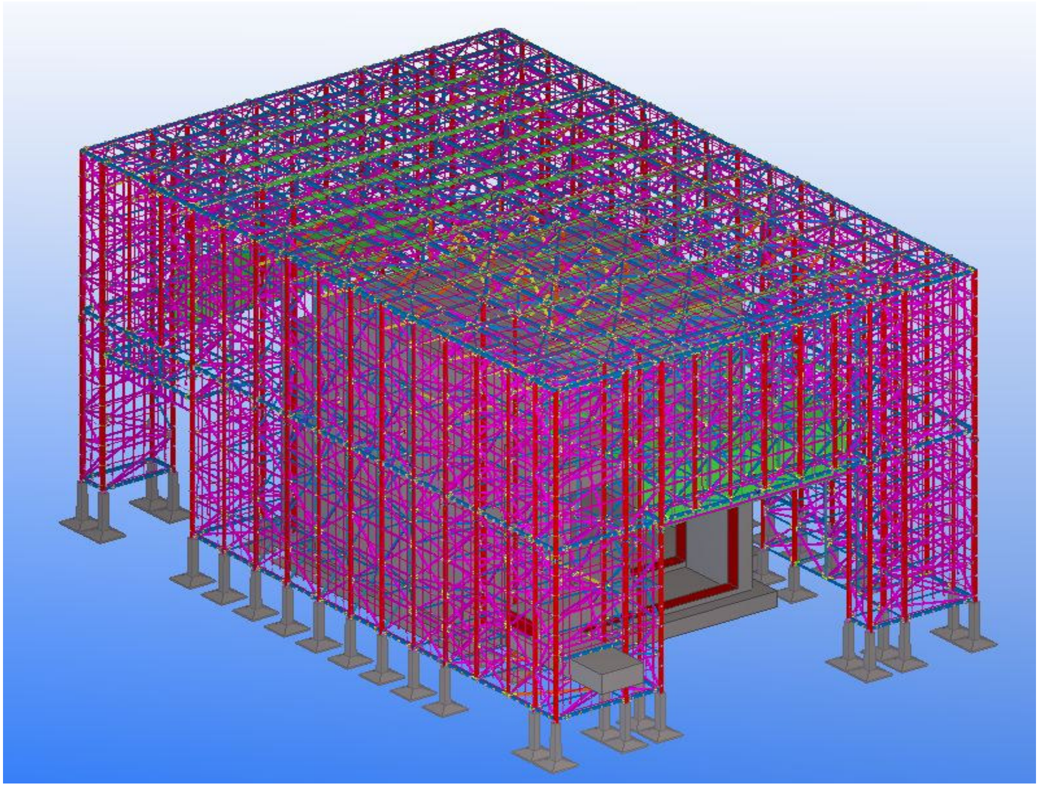

Fig. 6. Diagram of the combined structure of the protective shield

The mesh protective shield is a lightweight spatial frame (supports, beams), between which a mesh of steel ropes or cables is stretched. The mesh size is 500-1000 mm. It is important to ensure that the ropes are sufficiently pre-tensioned so that the shield does not sag due to its own weight or wind loads. The ropes are attached to the supports with bolts or clamps so that if a section is damaged, it can be replaced quickly.

The combined design of the protective shield is a structural steel structure with cables or ropes stretched over it to increase the density of protection. Such a shield is less likely to deform on impact, so it is less likely to cause a UAV to detonate on contact. It can withstand certain loads without breaking, but this is achieved by increasing the weight of the steel.

Table 1 provides a summary comparison of the two structural types of shields.

Table 1: Comparison of the main structural types of protective shields.

Shield Type	Materials	Advantages	Disadvantages
Mesh	Steel profiles (supports, beams), wire mesh	Quick installation/dismantling; Flexibility reduces the energy of the explosion; Low windage and cost of materials	Less durability (may tear); Periodic tightening is required; Can miss small UAVs with a large cell
Combined	Steel frame, wire mesh	Maximum probability of interception; Resistance to various threats (Shahed, FPV)	More complex calculation and installation; More components - higher price; Weight of the structure

In both cases, the main structures of the protective shield should be remote from the surface of the main protective shell by at least 4-5 m in order to create the necessary safe distance. This would prevent destruction by BSW or penetration of the shell and damage to the protected object, since the pressure from BSW decreases with increasing distance from the point of explosion. Therefore, it is also important to determine the optimal distance of the protective shield from the main structure in order to ensure both its strength and resistance to splinters and the optimal metal consumption of the protective shield.

The design of protective shields is based on:

- their own weight, atmospheric and other trivial loads according to DBN B.1.2-2:2006 “Loads and impacts. Design standards” [13];
- mechanical shock from UAV point hit [5].

The calculations take into account that the facilities belong to the consequence class CC3 [14], but the category of responsibility of the elements may be different. In fact, due to significant loads in the emergency connection, snow, ice, temperature, other loads may not be considered, and the connections with them will not be significant. However, they can become decisive during normal operation, since their application is different from an impact or explosion [5]. When calculating the combined design of a protective shield, it is imperative to calculate the progressive destruction. However, the question remains whether it is necessary to take into account the blast wave from a UAV detonation when calculating the elements of protective shields. According to standard specifications for the design of such structures, in the event of a UAV warhead explosion, partial destruction of the shield itself is allowed when the warhead is initiated, but the shield is not designed for an explosion and the need to calculate only for a mechanical shock is indicated. However, it would be quite logical to calculate the impact of a BSW as well, and there is no definitive methodology for determining the pressure from a BSW. Paper [5] discusses the determination of the pressure from BSW, but according to field tests conducted by ENERGY INNOVATIVE TECHNOLOGIES LLC, the values of the pressure from BSW are almost three times higher than those presented in [5] and reach 3000 kPa. Therefore, the issue of defining BSW is still relevant.

It is important to note that the implementation of protective shields at substations also requires consideration of operational issues. Firstly, the shield must not pose a risk to electrical connections -

the high-voltage transformer bushings that stick out should remain at a safe distance from the metal shield to avoid overlap (arc breakdown). Secondly, the design should allow for the replacement of the transformer if necessary - that is, the shield should either be dismantled or have a gap between the supports so that a crane can lift the old transformer and install a new one. Also, there are cases where two transformers are located at such a close distance that the design of a combined protective shield structure becomes either impossible at all or will have a much higher metal consumption and a more complex configuration and mesh design.

Thus, the design of steel anti-drone shields is a complex process that combines wartime requirements (effective protection) with civil engineering standards (strength, reliability, safe operation).

Despite all the difficulties that arise in the design and construction of protective structures, as well as their high cost, these protective structures have proven to be worthwhile. During the attacks in November-December 2023, at least half of the attacked equipment was saved thanks to passive protection [15]. There were cases when a Shahed drone hit a protective shield and exploded without destroying the transformer. At one of Ukrenergo's facilities, a Shahed-136 hit a reinforced concrete floor, causing a hole in it, but the transformer itself remained undamaged under the floor. A photo of the consequences of such a hit is shown in Fig. 7. One can see a gap in the reinforced concrete slab and exposed reinforcing bars; this indicates that the blast wave was absorbed by the structure. The shield worked as intended, and although it was damaged, the main goal of preserving the transformer was achieved [16]. The damaged area was subsequently repaired, which confirms the importance of inherent maintainability.

Fig. 7. A fragment of the reinforced concrete floor of a protective covering after a Shahed-136 drone hit

However, another rather serious key issue is the need to provide multiple defences. The use of massive drone attacks leads to multiple hits on defence systems in a fairly short period of time. As a result, there is virtually no time left for repair work. Therefore, underground defence systems are currently being developed.

The structural basis for such systems is the well-known design of shallow metro stations (Figures 8 and 9). To increase the degree of their protection, multilayer systems are also envisaged and the depth of such facilities is calculated.

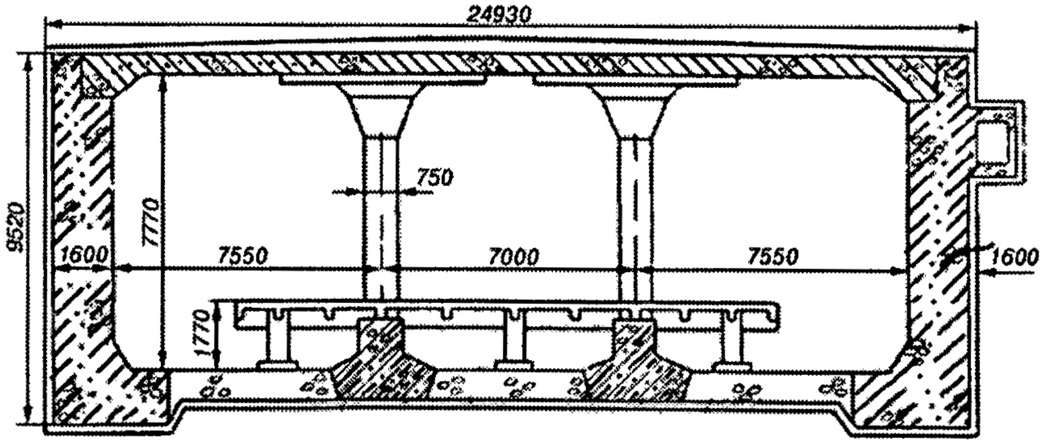

Fig. 8. Structural solution of a shallow column metro station

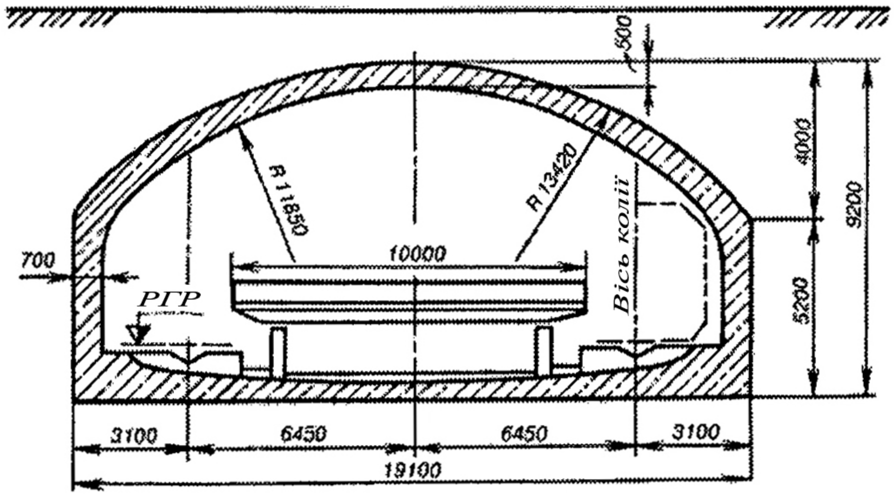

Fig. 9. Structural solution of a shallow vaulted metro station

As a result of this approach, protection systems are transformed into dual-purpose systems that can also perform an additional function. The increase in the degree of protection is achieved by backfilling, the thickness and composition of which is the subject of scientific substantiation.

Conclusions. The paper considers the existing design solutions for protecting objects from the effects of UAVs. For small-sized objects, temporary design solutions can be used. For large and critically important objects, it is more appropriate to use permanent design solutions.

Currently, there are two main types of anti-drone shield construction: mesh and combined construction. Each of the two types has both its disadvantages and advantages, and the choice of a particular type should be made taking into account the range of existing rolled metal products, construction time, construction site, etc.

The practical implementation of anti-drone defence structures in Ukraine to protect energy facilities from UAV attacks has significantly reduced the number of destroyed equipment, proving its effectiveness.

Further research should be aimed at optimising structures (reducing metal consumption through the use of strong steels [17-20], more efficient design schemes, etc.), standardising methods for calculating explosive loads for such structures, and expanding the scope of application - in particular, protection not only from drones but also from artillery fire and missiles. The results and experience gained can be implemented in other countries to protect critical infrastructure from the latest air threats.

An additional area for further research and development is the design of protective systems based on the principle of dual-use objects. The basis for this should be the well-known designs of shallow metro stations.

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ОСОБЛИВОСТІ ПРОЄКТУВАННЯ ЗАХИСНИХ АНТИДРОНОВИХ ЕКРАНІВ

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Анотація. В роботі розглянуто конструктивні та інженерні особливості проєктування сталевих захисних екранів для протидії безпілотним літальним апаратам (БпЛА) на об’єктах енергетичної інфраструктури. Актуальність теми зумовлена цілеспрямованими атаками БпЛА на трансформаторні підстанції, що спонукало до впровадження пасивного захисту у вигляді сталевих антидронових екранів. Проведено аналіз останніх досліджень і публікацій щодо загроз від дронів для енергомереж та існуючих методів захисту. Розглянуті конструктивні рішення захисних екранів, а також представлено результати практичного впровадження в Україні. Виконано узагальнення вимог до проєктування: вибір матеріалів, забезпечення потрібної висоти та відстані екрану, модульність та ремонтопридатність конструкції.

Практичне впровадження протидронових захисних конструкцій в Україні для захисту об'єктів енергетики від атак БПЛА значно зменшило кількість знищеного обладнання, що доводить їх ефективність.

Подальші дослідження повинні бути спрямовані на оптимізацію конструкцій (зменшення витрати сталі за рахунок використання міцних сталей, більш ефективних схем проектування тощо), стандартизацію методів розрахунку вибухових навантажень для таких конструкцій та розширення сфери застосування – зокрема, захист не тільки від дронів, але й від артилерійських снарядів та ракет. Отримані результати та досвід можуть бути впроваджені в інших країнах для захисту критичної інфраструктури від новітніх повітряних загроз. Додатковою сферою для подальших досліджень і розробок є проектування захисних систем за принципом об'єктів подвійного призначення. Основою для цього повинні стати добре відомі конструкції неглибоких станцій метро.

Ключові слова: трансформаторна підстанція; безпілотні літальні апарати; дрон-камікадзе; пасивний інженерний захист; захисний екран; протишахедний захист