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# Fundamentals of the energy approach to explosive effect acting on the constructions of underground structures

**Oleksii Tiutkin[1,2], Ihor Ostapenko[1] and Mykola Hernych[1]**

[1]Ukrainian State University of Science and Technologies, Lazaryan Str., 2, Dnipro, 49010, Ukraine

[2]Corresponding author: o.l.tiutkin@ust.edu.ua

**Abstract.** This research analyzes current trends in calculating the construction of underground structures. It finds that, considering the objective situation, the extreme load combination (constant loads plus one extreme load) should be revised. This revision is related to an increase in cases of shock and explosive effects on the constructions of underground structures that may serve as shelters. The research aims to combine analytical foundations, which provide data on explosive effect, with a numerical analysis methodology that includes an energy approach. Solving this problem enables the analysis of the explosive effect on constructions of the underground structure, considering the overall stress-strain state within the "construction of the underground structure – surrounding massif" system. The authors present the analytical basis of the energy approach to the explosive effect acting on constructions of underground structures. Ways for implementing these foundations into the methodology of numerical analysis are described. A numerical analysis of the underground lobby construction for impulse impact, replacing the explosion, is performed, which is calculated in accordance with the given analytical formulas. A comparison is made between the deformation energy of the lobby construction – an integral parameter that includes stress and displacement – and the deterioration energy of the C25/30 concrete grade.

## 1. Introduction

Before the start of the Russian-Ukrainian war, calculating the constructions of underground structures mainly relied on the application of both permanent and temporary load complexes. In regulatory documents that have been updated through several editions, these two load complexes have remained the primary focus. The most recent edition of certain regulatory documents provides more detailed information on the provisions for the extreme load complex, which, in addition to permanent loads, includes one additional factor [1]. Seismic, shock, impulse, and various special dynamic influences (including the influence of the metro train, industrial seismicity, and the dynamic effect of ground transportation) are considered as such an additional extreme load [2].

It should be noted that research on constructions of underground structures and other ones under extreme loads continues. In Ukraine, a considerable amount of scientific research focuses on the dynamic interaction between metro trains and building structures, as well as wave propagation around underground objects. Meanwhile, research on underground facility constructions that withstand shock or impulse (explosive) loads remains sporadic and needs further expansion and systematization [3-5].

Until now, this broad field of research has not been fully explored, and the objective situation of using underground facilities as shelters or dual-purpose facilities requires urgent solutions. If we consider a similar field outside Ukraine, it is more systematic in nature [6-8]. If we disregard the

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above-mentioned task of dynamic interaction between the metro train and the underground structure, as well as the task of seismic impact, which has been thoroughly developed, the tasks of dynamic impact on the constructions of underground facilities focus on cases of shocks or explosions [8-10].

It is worth noting that the specificity of the research conducted in these cases characterizes the methodology of their implementation [11, 12]. Most often, dynamic problems are solved using numerical methods, the main one being the finite element method. However, such a practice, which is not connected to the developed analytical approach based on the physics of explosion or impact mechanics, can be considered one-sided [13-15]. It is in this area that analytical methodology has a powerful mathematical apparatus that has been experimentally verified. Accordingly, the combination of the numerical analysis method with the provisions of the analytical approach is the most adequate for the task of explosive effect on constructions of underground structures.

As an effective methodological technique, one can adopt the energy approach, detailed in [14]. Its main provision is the analysis of the specific deformation energy, which is an integral parameter that includes stress and displacement. In this case, the stress-strain state in the "construction of the underground structure – surrounding massif" system should be determined based on numerical analysis, in which the parameters of the impulse replacing the explosion are set considering the regularities of the analytical approach. Thus, the purpose of the presented research is to combine analytical foundations that provide data on the explosive effect with the methodology of numerical analysis, which takes into account the energy approach. Achieving this goal based on the results obtained allows us to analyze the explosive effect on the constructions of the underground structure, considering the total stress-strain state in the "construction of the underground structure – surrounding massif" system.

## 2. Methods

The explosive effect on the constructions of underground structures, characterized by impulse, is determined by solving dynamic equations that take into account inertial characteristics (the mass of the structure construction and its elements), stiffness (the deformation capacity of the construction, related to its dimensions and material properties), and strength parameters (calculated resistance of the material to compression or tension). The construction response of the structure to a dynamic explosive effect is connected with its duration and the time required for the construction to recover, which, in practical calculations, is correctly assumed to be equal to the period of the first form of natural oscillations.

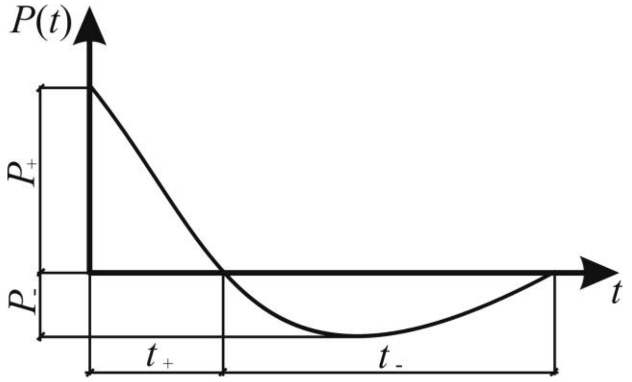
The physics of the explosion determines the distribution of pressure $P(t)$, consisting of two phases: a compression phase and a rarefaction phase, characterized by different pressure values ($P_+$ and $P_-$, respectively) and duration of action ($t_+$ and $t_-$, respectively). The maximum explosion pressure is described by the dependence determined at the contact of two media, "explosive charge – air", which drops sharply with distance.

When the radius of the explosion impact is equal to a certain pressure limit, the impact of the explosion on the construction is determined only by the impulse, the value of which can be determined using integrals over the area (figure 1, a), and for practical calculations, the integral over the compression area is used, since the more destructive effect of the explosion is determined by this phase [16].

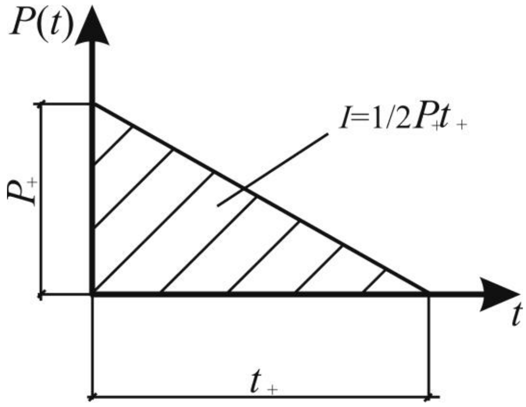
The curve shape describing the compression phase can be replaced by a straight line, and the resulting impulse $I$ can be considered triangular (figure 1, b). Such a representation of the explosion impact is of practical value, since the shape of the impulse significantly affects the results of the dynamic calculation of constructions for extreme combinations of loads.

But, even knowing the basic parameters of the shock-explosive or shock-air wave, the dynamic calculation of complex constructions for the impulse impact remains quite complicated. The reason for this is the application of very simplified calculation schemes for constructions.

The process of analysing the obtained results also presents a certain complexity, since the specificity of dynamic tasks lies in researching the action of loads that change over time.




a)




b)

**Figure 1.** Dependence of the explosive effect over time (a) and triangular-shaped explosive load pulse (b).

## 3. Results and discussion

Using the provisions of the dynamic formulation during the analysis of the stress-strain state based on the finite element method, it is possible to apply the energy approach to determine the state of an underground structure under extreme load combinations. This approach enables a more comprehensive research of such constructions and involves comparing the specific explosion energy $E$ and the specific deformation energy of the structure $E_{\text{def}}$. The condition of the energy approach is written as follows:

$$\left.\begin{aligned} &E > E_{\text{def}};\\ &E = E_{\text{def}};\\ &E < E_{\text{def}}. \end{aligned}\right\} \tag{1}$$

Formula (1) takes into consideration three deformation scenarios: the first scenario – the construction is deformed; the second scenario – the construction is in the limit state; the third scenario – the construction is not deformed.

Similarly, we can write in terms of the specific explosion energy $E$ and the specific demolishing energy $E_{\text{dem}}$:

$$\left.\begin{aligned} &E > E_{\text{dem}};\\ &E = E_{\text{dem}};\\ &E < E_{\text{dem}}. \end{aligned}\right\} \tag{2}$$

Formula (2) accounts for three deformation scenarios: the first scenario involves the structure demolishing; the second scenario consists of the structure being in a limit state; and the third scenario involves the structure not demolishing but deforming.

Accordingly, to evaluate the values in expressions (1)-(2), it is necessary to know the energy value in each of the parts of the construction or in the entire underground structure. It is known that the explosion energy is determined from the condition [17, 18]:

$$E = Qq\,, \tag{3}$$

where $Q$ is the heat of explosion (J/kg); $q$ is the mass of the charge, kg.

The work of the explosion is distributed between demolishing, displacement of the medium, and other types, and its total value is part of the total energy of the explosion (J/kg) [18]:

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$$A = Q\left[1-\left(\frac{P_{\max}}{P_0}\right)^{\frac{k-1}{k}}\right], \tag{4}$$

where $P_{\max}$ is the maximum pressure value in the “explosive charge – air” plane, kPa; $P_0$ is the atmospheric pressure value, kPa; $k$ is the dimensionless adiabatic index of explosion products (for detonation products, it ranges from $k$=1.05 … 1.25).

The energy of the open charge is converted into the energy of the shock air wave $E_{\mathrm{SAW}}$, and is determined [18, 19]:

$$E_{\mathrm{SAW}} = Qq\left(1-\frac{P_0 V_\infty}{(k-1)\rho_E Q V_0}\right), \tag{5}$$

where $V_\infty$ is the limiting volume of expansion of detonation products, m$^3$; $V_0$ is the initial volume of the explosive charge, m$^3$; $\rho_E$ is the density of the explosive, kg/m$^3$. From formula (5), it follows that $E_{\mathrm{SAW}}=0.7E$, i.e., during the explosion of a charge in the air, 70% of the total explosion energy is transferred to a shock air wave.

It is the determination of this part of the explosion energy that is the basis for the analysis of shelters located in a semi-sunken position. State regulatory documents currently regulate only such a type of extreme load, in which there is no shock wave from the explosion, and only the shock air wave is analysed [1]. There is no doubt that the analytical foundations set out in this manuscript significantly expand the scope of calculations and can form the basis for a new regulatory document regulating civilian shelters of a sunken type, which should be designed exclusively for the shock wave.

The specific energy of deformation or demolition at a point should be recorded in tensor form [14]:

$$E_{\mathrm{def}} = \sum_{i=1}^{n} |\sigma||S|, \tag{6}$$

$$E_{\mathrm{dem}} = \sum_{i=1}^{n} |\overline{\sigma}||\overline{S}|, \tag{7}$$

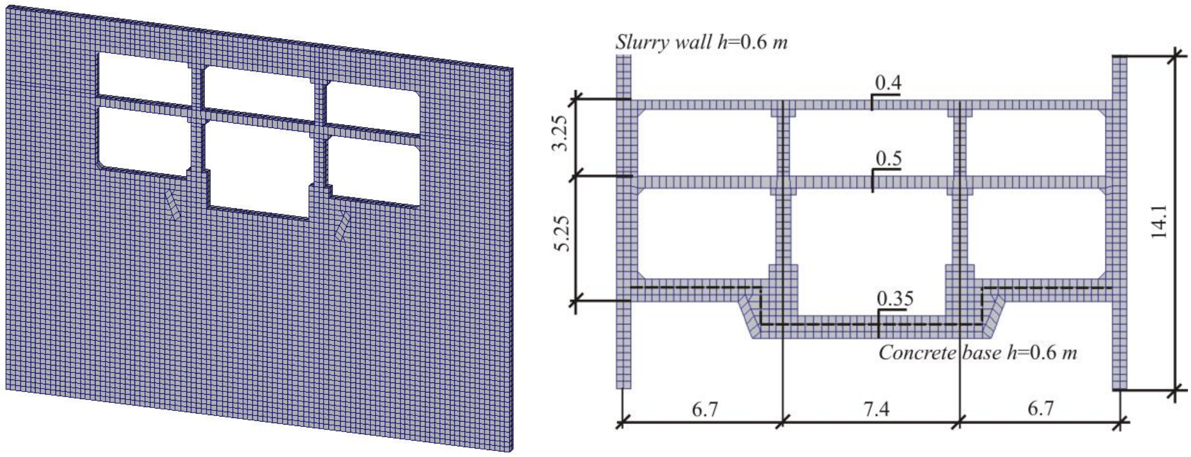
where $|\sigma|$ and $|\overline{\sigma}|$ – respectively, the tensors of the principal stresses at a point at a certain time and at the moment of demolition, kPa; $|S|$ and $|\overline{S}|$ – respectively, the tensors of the principal strains (coinciding in the direction with the principal stresses and being dimensionless) at a certain time and at the moment of demolition.

The joint solution of equations (1) and (6) or (2) and (7) makes it possible to evaluate the degree of deformation or demolition in the construction of the underground structure. The calculation task for the case of underground structures is significantly complicated due to the fact that the total deformation energy in the system consists of the components of the deformation energy from static and dynamic loads.

From the above, it can be concluded that applying the energy approach to solving the dynamic task of an explosion and determining its effect on the construction of an underground structure is very difficult due to the insufficient development of the provisions for finding the explosion energy from a distance to the source, as well as calculating the deformation energy of constructions under dynamic influences.

Since the energy approach to static tasks has proven its effectiveness, research should be conducted on its application to dynamic tasks. As part of this research, based on the results of the calculation of the subway station lobby set out in [13], an analysis of the level of deformation energy was carried out using the SCAD calculation complex postprocessor. The basics of postprocessing are given in monographs [14, 20]; the same text also provides the basics of the so-called "filtering" of results, that is, obtaining secondary information based on the stress-strain state using formulas (6) and (7).

Below is a model of a subway station lobby (figure 2), which was used for the article [13]; however, for this research, a triangular-shaped impulse (see figure 1) was applied to it and calculated using the formulas of the energy approach.



a) b)

**Figure 2.** The finite element model of the subway station lobby, taken from article [13] (a), and a fragment of the model (the lobby construction with "slurry wall") (b).

The calculation of the finite element model and the results of the stress-strain state, which were previously obtained and analysed, are supplemented in this research by a picture of isolines and isofields of specific energy distribution (figure 3). This value is calculated according to formula (6) and has the dimension of stress, since deformations are relative. In the SCAD energy postprocessor, specific energy values are given in kN/m$^2$, which allows for further comparison with the specific energy values of the material, i.e., C25/30 concrete grade.

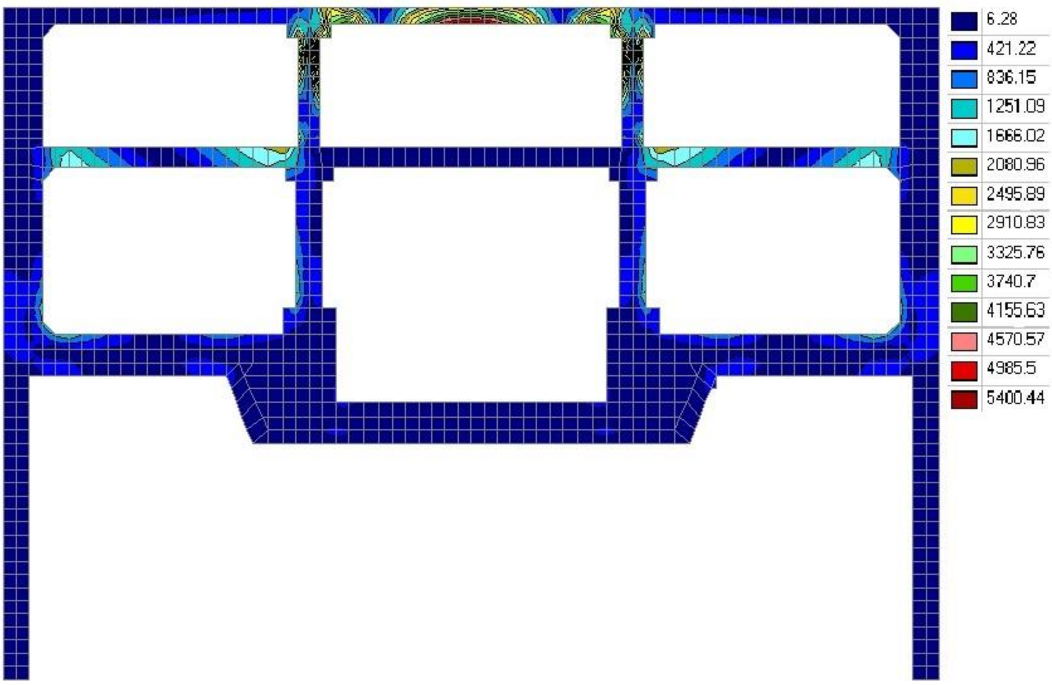



**Figure 3.** Isolines and isofields of the SCAD energy postprocessor in a fragment of the model (the lobby construction without the upper part of the "slurry wall").

The distribution of specific energy to some extent repeats the outline of the distribution of the largest stress component, namely the vertical one. The maximum values of specific energy, which are in the range of 2080 ... 5400 kN/m$^2$, are observed in the local area of the upper ceiling in the middle hall of the underground lobby. This situation is objective, since this zone is in the center of the explosive impulse action applied to the surface.

If we assume the strength of C25/30 concrete grade equal to 30000 kN/m$^2$, and the relative deformation of 0.1 from the initial height (10%, which is adequate for environments that deteriorate in a brittle mode), then the specific energy of concrete demolition will be equal to $E_{\mathrm{dem}}$=1/2$\sigma\varepsilon$= =0.5·30000·0.1=1500 kN/m$^2$.

Accordingly, a comparison of the specific energy obtained during the numerical analysis and the specific deterioration energy of C25/30 concrete grade proves that the upper ceiling of the underground lobby is demolished under the action of the explosive impact. The demolition affects the area of the upper ceiling and the top of the columns, which characterizes the impact of the explosion as local.

The given calculation of specific energy is an example that shows the combination of analytical foundations for determining the impulse impact, which is analyzed during numerical analysis using the principles of the energy approach.

## 4. Conclusions

The research effectively combines analytical foundations, providing data on explosive effects and loads through a numerical analysis methodology that considers the energy approach. Based on the analysis results, current calculations for underground structures need a revision of regulatory documents concerning the formation of extreme load combinations. The rising probability of explosive effect requires modifications that favor impulse loading, which accounts for explosion parameters.

The comparison of the specific energy levels obtained through post-processing and the experimental deterioration of the C25/30 concrete grade, conducted during the numerical analysis of the finite element model for the underground lobby, leads to the conclusion that the proposed energy approach methodology is a convenient tool for strength analysis. The combination of analytical principles for determining explosive effect and numerical analysis methodology has proven its effectiveness. In the future, for practical calculations of underground and dual-purpose structures, it is recommended to develop an additional postprocessor that will calculate the specific energy of various materials by integrating the area under their deformation diagrams in different states.

## References

[1] Kodeks 3-1:2022 *Metropoliteny. Chastyna 1. Proiektuvannia* (Kyiv: DP "UkrNDNTs")
[2] DBN V.2.2-5:2023 *Zakhysni sporudy tsyvilnoho zakhystu. Zi Zminamy № 1 ta № 2* (Kyiv: Mininfrastructure)
[3] Petrenko V I, Petrenko V D and Tiutkin O L 2015 Obgruntuvannia ta zahalni metodolohichni rozrobky problemy vybukhobezpeky obiektiv metropolitenu *Bridges and tunnels: theory, research, practice* **8** 65–73 https://doi.org/10.15802/bttrp2015/90850
[4] Haiko H, Savchenko I and Shelestov A 2025 Ensuring resilience and safety of the transportation system of Kyiv in planning the network of road tunnels *Case Studies on Transport Policy* **19** 101355 https://doi.org/10.1016/j.cstp.2024.101355
[5] Koval M V, Koval V V, Kotsjuruba V I and Bilik A S 2022 Organizational and technical principles for building a system of engineering protection of critical infrastructure facilities in the energy sector of Ukraine *Science and defense* **3/4** 11–6
[6] Clouteau D, Arnst M, Al-Hussaini T M and G. Degrande 2005 Freefield vibrations due to dynamic loading on a tunnel embedded in a stratified medium *Journal of Sound and Vibration*, **283** (1) 173–199 https://doi.org/10.1016/j.jsv.2004.04.010
[7] Carter A B and Schwartz D N 2010 Ballistic missile defense (Brookings Institution Press)

IOP Conf. Series: Earth and Environmental Science **1630** (2026) 012009 doi:10.1088/1755-1315/1630/1/012009

[8] Cherry C, Loukaitou-Sideris A and Wachs M 2008 Subway station design and management: Lessons from case studies of contemporary terrorist incidents *Journal of Architectural and Planning Research* **25** (1) 76–90
[9] Hu Z, Jiang N, Zhang Y, Xia Y and Zhou C 2020 Propagation of shock wave and structure dynamic response of explosion in a subway station: a case study of Wuhan subway station *Journal of Vibroengineering* **22** (6) 1453–1469 https://doi.org/10.21595/jve.2020.21298
[10] Kameli M, Zarei S, Kalantari M and Nejad E S 2014 Criteria of Passive Defense in Subway Stations *Journal of Civil Engineering and Urbanism* **4** (3) 298–304. (in English)
[11] Oprean L-G 2023 Artillery and drone action issues in the war in Ukraine. *Scientific Bulletin* **28** (1) 73–78 https://doi.org/10.2478/bsaft-2023-0008
[12] Kotsiuruba V I, Bilyk A S, Weretnow A O, Gaydarly G S, Borta R M and Tertyshnyy B I 2022 Method of calculations and substantiation of requirements for engineering protection of critical infrastructure objects from UAVs with warheads *Strength of Materials and Theory of Structures* **109** 164–183 https://doi.org/10.32347/2410-2547.2022.109.164-183
[13] Tiutkin O L, Bosyi D O, Sablin O I and Bondarenko N K 2025 Otsinka vybukhovoho vplyvu ta metodyka vyiavlennia bezpilotnykh litalnykh aparativ dlia zakhystu vestybiuliu metropolitenu *Nauka ta prohres transportu* **2** (110) 165–175 https://doi.org/10.15802/stp2025/330864
[14] Tiutkin O L 2020 *Teoretychni osnovy kompleksnoho analizu tunelnykh konstruktsii* (Dnipro: Zhurfond)
[15] Bannikov D and Pologechko O 2025 Dynamic properties of large-sized steel bunkers for bulk materials *IOP Conference Series: Earth and Environmental Science* **1491** 012004 http://doi.org/10.1088/1755-1315/1491/1/012004
[16] Kurinnoy V P 2018 *Teoreticheskiye osnovy vzryvnogo razrusheniya gornykh porod* (Dnepr: Ekonomika)
[17] Petrenko V I, Shataykin E M, Petrenko V D and Tiutkin A L 2017 Prokhodka naklonnykh stvolov tsiklichno-potochnoy tekhnologii na Inguletskom GOKe s primeneniyem burovzryvnykh rabot *Bridges and tunnels: theory, research, practice* **11** 52–8 https://doi.org/10.15802/bttrp2017/158588
[18] Soboliev V V, Chernai A V, Chebenko V M and Skobenko O V 2013 *Sposoby pidryvannia zariadiv vybukhovykh rechovyn* (Dnipropetrovsk: "Lizunov-PRES" Publ.)
[19] Petrenko V, Bondarenko N, Miroshnyk V, Burskyi M and Konoval V 2023 Substantiating parameters of short-delay blasting and seismic safety while constructing the inclined tunnel. *IOP Conference Series: Earth and Environmental Science* **1156** 012010 https://doi.org/10.1088/1755-1315/1156/1/012010
[20] Perelmuter A V and Slivker V I 2002 *Raschetnyye Modeli Sooruzheniy i Vozmozhnost ikh Analiza* (Kyiv: Stal)