

ANALYTICAL METHODS FOR CALCULATION OF CONSTRUCTION OF UNDERGROUND DEFENSIVE AND FORTIFICATION STRUCTURES

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Abstract Current engineering practice for the design of underground defensive and fortification structures is largely based on empirical and semi-analytical approaches that describe projectile penetration, local explosive effects, and the response of structural materials to combined impact and blast loading. Widely used methods rely on simplified relationships for estimating penetration depth as a function of projectile mass, velocity, diameter, and impact angle, as well as material-dependent coefficients reflecting resistance to penetration. Additional models address the formation of explosive craters, the extent of damage within a barrier, and minimum thickness requirements to prevent spalling. For underground structures, particular importance is given to approaches that represent soil as an elastic-plastic medium, allowing estimation of blast wave attenuation with depth and conversion of blast effects into equivalent loads acting on buried structures. However, these methods are often fragmented, insufficiently unified, and not fully adapted to modern threats such as UAV-delivered munitions and combined impact-explosion scenarios.

In this paper, the key analytical dependencies used in current practice are systematized and clarified. Improved expressions for penetration depth are considered, including factors accounting for projectile geometry and possible trajectory deviation within protective layers. The study formulates a consistent procedure for evaluating local damage from concentrated explosions, including crater depth, damaged zone thickness, and



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conditions for preventing spalling. In addition, an analytical approach is developed for estimating pressure transmission through soil backfill or embankments based on attenuation laws, loading duration, and impulse characteristics. On this basis, a practical calculation sequence is proposed, enabling the

determination of design loads and the selection of protective elements for underground structures under combined impact and blast effects.

Keywords: engineering protection; underground structures; damage, explosion, blast effect.

PROBLEM STATEMENT

The design of underground defensive and fortification structures under modern warfare conditions faces increasing challenges due to the rapid development of high-precision weapons, including missiles and UAV-delivered munitions [2, 3, 16, 20]. These threats are characterized by combined impact and explosive effects, high penetration capability, and variability in attack scenarios [6, 7, 13]. Existing engineering approaches for structural design are largely based on empirical dependencies developed for conventional munitions and simplified conditions [4, 7]. As a result, they often consider penetration, explosive action, and soil response separately, without providing a unified framework for their combined effect on underground structures [11, 12].

In practical design, this leads to uncertainties in determining key parameters such as penetration depth, thickness of damaged zones, spalling conditions, and the magnitude of loads transmitted through soil backfill or embankments [8, 9, 10]. In addition, the influence of factors such as projectile geometry, trajectory deviation within protective layers, and soil properties on blast wave attenuation is not always consistently taken into account [5, 10]. This limits the reliability and efficiency of design solutions and may result in either insufficient protection or excessive material consumption [15, 18].

Therefore, there is a need to develop a consistent analytical approach that integrates existing methods for penetration, explosion effects, and soil-mediated load transfer, and adapts them to current threat conditions [1, 2, 13]. Such an approach should provide engineers with practical tools for accurately determining design loads and optimizing the parameters of

underground protective and fortification structures.

ANALYSIS OF PREVIOUS RESEARCH

Modern engineering practice provides the use of several principal methods for analyzing structures under blast wave effects, among which the most widely applied are the quasi-static method, the impulse (shock impulse) method, and the direct integration method of the equations of motion [5, 11, 14, 19]. The quasi-static method is based on transforming dynamic loading into an equivalent static load using a dynamic amplification factor and is an effective tool for preliminary engineering assessments [6, 15]. The impulse method allows accounting for the integral effect of short-duration loading through impulse parameters, providing a more adequate representation of blast wave action [11, 12, 19]. At the same time, the most accurate approach is the direct integration of the equations of motion, which makes it possible to consider the actual time-dependent variation of loads, inertial characteristics of the system, damping, and the complex spatial behavior of structures [11, 19].

In domestic practice, the most widely used method for calculating protective and fortification structures, as well as engineering protection structures in the event of direct damage without a pre-detonation screen, is based on [1; 2; 17]. At the same time, the number of studies on this issue is constantly growing [3, 13].

The penetration depth of the charge (warhead of a UAV or missile) in [1; 2; 17] is recommended to be determined by the empirical formula:

$$h_p = \lambda k_p \frac{m}{d_{pr}^2} V_{pr} \cos \alpha, \quad (1)$$

where h_p – depth of penetration of the projectile along the normal to the outer surface of the obstacle in meters;

λ – the coefficient, which depends mainly on the shape of the

projectile, is 1.3 when firing concrete-piercing shells at concrete and 1.0 in other cases;

- k_p – coefficient of susceptibility of this medium to penetration (taken from Table 1);
 m – weight of the projectile at the moment of meeting the obstacle, kg.

Since we are talking about mechanical permeability, for the case of missiles, the value can be taken as the weight of the missile at the moment of impact; d_{pr} – diameter of the projectile (aircraft bomb, missile), m ; V_{pr} – velocity of the projectile (aircraft bomb, missile), at the moment of meeting the obstacle, in m/s; α – angle at which the projectile penetrates the protective layer, it is calculated from the normal to the protective surface.

An improved formula for determining the depth of penetration of a charge (of a UAV or missile warhead) taking into account the probable curvature of the projectile trajectory in the protective layer was obtained by a team of authors [17] and has the form:

$$h_p = \lambda k_p \frac{m}{d_{pr}^2} V_{pr} \frac{\cos(n\alpha)}{\sqrt{\cos \alpha}}, \quad (2)$$

where d_{pr} – projectile caliber, mm.

The angle α at which the projectile penetrates the protective layer, it is calculated from the normal to the protective surface:

$$\alpha \leq \frac{90^\circ}{2n-1}, \quad (3)$$

where n – coefficient that takes into account the possible curvature of the trajectory of the projectile in the protective layer: for long-range projectiles $n=1.82$, for short-range projectiles $n=2.62$.

A coefficient that takes into account the shape of the projectile head and its caliber $\lambda = \lambda_1 \lambda_2$.

The shape coefficient of the projectile head λ_1 is determined from the expression:

$$\lambda_1 = 0,5 + 0,43 \sqrt[3]{\left(\frac{H_r}{d_{pr}}\right)^2}, \quad (4)$$

where H_r – height of the projectile head or warhead of a missile or UAV (Fig. 1), m.

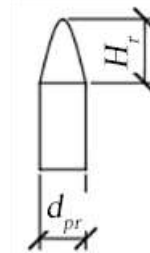


Fig. 1. To determine the height of the projectile head

Рис. 1. До визначення висоти головної частини снаряду.

The caliber coefficient of the projectile λ_2 is determined by the formula:

$$\lambda_2 = 2,8 \sqrt[3]{d_{pr}} + 1,3 \sqrt{d_{pr}}, \quad (5)$$

where d_{pr} – diameter of the projectile head or warhead of a missile or UAV (Figure 1), m.

In the absence of data on ammunition parameters, it is permissible to use the formula [1; 2]:

$$h_p = 1,73 k_p \frac{m}{d_{pr}^{1,75}} V_{pr} \cos \alpha. \quad (6)$$

MAIN RESEARCH

The parameters of destruction from the local action of the concentrated charge explosion are recommended to be determined by the following empirical formulas (7-9) [1, 8, 17].

The depth of the explosion crater when the concentrated charge explodes on the surface of the structure:

$$\lambda_2 = 2,8\sqrt[3]{d_{pr}} + 1,3\sqrt{d_{pr}}, \quad (7)$$

where k_{exp} – coefficient of compliance of the material of the barrier to the high-explosive action of the explosion, which should be determined according to Table 1;
 m_{ef} – mass of the explosive charge of a projectile or warhead for missiles or UAVs in TNT equivalent, *kg*.

$L_{ef} = L / 2$ – distance from the center of the charge to the surface on which the projectile mechanically stopped, in *m*;
 L – projectile length (which for missiles and UAVs can be approximately taken as the length of its warhead).

Table 1. Coefficient of compliance of the impact or explosion environment.

Табл. 1. Коефіцієнт податливості середовища дії удару або вибуху.

Environment name	Coefficient values		
	Penetration k_p	Explosion k_b	Explosive action k_{exp}
Freshly poured soil	0,0000130	0,60	1,40
Normal soil	0,0000065	0,53	1,07
Dense sand	0,0000045	0,50	1,04
Sandy loam	0,0000050	0,50	1,00
Loam	0,0000060	0,50	1,00
Dense clay	0,0000070	0,50	1,00
Limestone or sandy rock	0,0000020	0,25	0,92
Granite or gneiss rock	0,0000016	0,20	0,86
Pine	0,0000050	0,30	0,60
Oak, beech, ash	0,0000040	0,30	0,60
Dry brickwork	0,0000030	0,25	0,96
Dry stone masonry	0,0000030	0,25	0,96
Cement mortar brickwork	0,0000025	0,25	0,88
Cement mortar stone masonry	0,0000020	0,20	0,84
Reinforced brickwork	0,0000022	0,20	0,52
Booth concrete	0,0000016	0,18	0,70
Heavy concrete of class C 8/10, C 12/15.	0,0000012	0,18	0,65
Reinforced concrete of class C 20/25.	0,0000010	0,12	0,30
Fortification concrete of class C 40/45	0,0000008	0,16	0,60
Fortification reinforced concrete of class C 40/45	0,0000007	0,11	0,25
-with flexible anti-splintering	0,0000008	0,13	0,52
-with rigid anti-splintering	0,0000008	0,13	0,42
Monolithic reinforced concrete structures made of concrete C45/60	0,0000007	0,11	0,25

The thickness of the barrier within which destruction occurs when a concentrated charge explodes in the body of the barrier is determined by the formula:

$$h_b = k_b \sqrt[3]{m_{ef}} - r_{pr}, \quad (8)$$

where m_{ef} – mass of the explosive charge of a projectile or warhead for missiles or UAVs in TNT equivalent, kg ;
 k_b – explosion action coefficient, which should be taken in accordance with Table 1;
 r_{pr} – the radius of the charge, taken from the tactical and technical characteristics of the ammunition, is approximate $r_{pr} = L_{ef}$.

The minimum thickness of the structure at which chipping does not occur is determined by the formula:

$$h_{ch} = k_{ch} \sqrt[3]{m_{ef}} - r_{pr}, \quad (9)$$

where k_{ch} – coefficient that takes into account the probability of chipping and is taken according to table 1.

The calculation of coatings for the local effect of an explosion is performed in the case when the distance from the charge of a projectile or warhead for missiles or UAVs to the structure is, when detonated in the air or on the ground above the structure, in the presence of a collapse, less than:

4 r_{pr} – for reinforced concrete structures;
 6 r_{pr} – for brick (stone) structures.

The thickness of elements of structures with solid protective structures, when directly hit by ammunition under the combined action of impact and explosion, is determined from the condition of preventing chipping by the formula:

$$h = h_p + 1,2k_{ch} \sqrt[3]{m_{ef}} - L_{ef}, \quad (10)$$

where h – thickness of the element of a continuous protective structure, taking into account the penetrating effect of the ammunition and the probability of chipping, m ;

h_p – ammunition penetration depth, determined by formula (1) or (6), m ;

k_{ch} – coefficient adopted according to table 1;

L_{ef} – is assumed:

$L_{ef} = r_{pr}$ – for a concentrated charge ammunition;

$L_{ef} = r_{pr}(1+2\cos\alpha)$ – for ammunition with an extended charge

It is recommended to determine the penetration depth of a projectile in a layered environment by replacing this environment with an equivalent homogeneous environment, proportional to the ratio of coefficients for the materials included in the protective layer.

The full depth of the crater or the thickness of the protective plate (“mat”) under the condition of ammunition penetration with subsequent explosion in the body of the protective structure is determined from the expression:

$$h_{df} = h_p + h_b, \quad (11)$$

where h_p – ammunition penetration depth, determined by formula (1) or (6), m ;

h_b – the thickness of the barrier within which destruction occurs when a concentrated charge explodes in the body of the barrier, which should be determined by formula (8).

The thickness of the external covering, which is intended, in addition to camouflage, to weaken the impact force and fragmentation effect, is recommended to be taken at least 30..50 cm. The thickness of the protective plate (“mat”), which should stop the ammunition and cause an explosion to reduce the impact of high-explosive action on the main protective structure with a small covering thickness, can be approximately determined by the formula:

$$h_{pl} = 1,5 h_{exp}, \quad (12)$$

where h_{exp} – the depth of the explosion crater when a concentrated charge

explodes on the surface of the protective structure, determined by formula (11), taking into account the coefficients for the material of the protective plate (“mat”).

The final thickness of the protective plate (“mattress”) should be taken to satisfy the following conditions:

$$h_{pl} \geq h; \quad h_{pl} \geq h_{df}, \quad (13)$$

where h_{pl} – thickness of the protective plate (“mattress”), m ;
 h – thickness of the element of a continuous protective structure, taking into account the penetrating effect of the ammunition and the probability of chipping, m ;
 h_{df} – thickness of the protective plate (“mat”) under the condition of ammunition penetration with subsequent explosion in the body of the protective structure, m .

The calculation of the action of an explosive shock wave in the soil is based on considering the soil mass as an elastic-plastic medium in which the energy of the explosion is transferred through compression and shear of particles. The

Table 2. Damping index in soils.

Табл. 2. Коефіцієнт затухання в ґрунтах.

Soil type	Damping index α , m^{-1}
Rocky and semi-rocky soils	0,08
Water-saturated sands, clays (soft-plastic)	0,25
Loams and sands of medium moisture	0,60
Dry sands, loess-like soils	1,00

Unlike air, the wave propagation speed in the soil is much lower, so the shape of the pressure graph changes. The duration of the load action at a depth h increases compared to the duration on the surface and is determined by the formula:

main hypothesis of the method is that the law of attenuation of the maximum pressure in the soil depends on the physical and mechanical characteristics of the soil itself (density, sound propagation speed, humidity) and the depth of the object. Such assumptions make it possible to establish the calculated values of the maximum pressure at a certain depth and to perform further calculation of structures based on the equivalent soil load.

The value of the maximum pressure in the soil at a given depth can be determined by the generalized formula:

$$P_{soil} = P \cdot k_z, \quad (14)$$

where P – maximum pressure of the air shock wave on the soil surface, kN/m^2 ;
 k_z – the pressure damping index by depth, which takes into account the absorption capacity of the soil and its structural features, which will be determined by the formula:

$$k_z = 2,72^{-\alpha \cdot h}, \quad (15)$$

where α – damping index, determined according to Table 2;
 h – depth at which wave pressure is determined, m .

$$\tau_{soil} = \tau_0 + \frac{h}{V_{soil}}, c, \quad (16)$$

where V_{soil} – the speed of propagation of the stress front in the soil,

determined according to Table 3.

Table 3. The speed of propagation of the stress front in the soil.
Табл. 3. Швидкість поширення фронту напружень у ґрунті.

Soil type	Estimated speed V_{soil} , m/s
Granites, basalts, very dense limestones	2500 – 4500
Semi-solid rocks, dense marls, hard clays	1000 – 2000
Loams are rigid plastic, sands are dense and moisture-saturated.	400 – 800
Dry sands, loose sandy loams, loess soils	150 – 350
Water-saturated soils (below the groundwater level)	~1500 (speed of sound in water)

The impulse of an explosive shock wave in the soil, which determines the ability of the wave to cause damage to massive structures, is calculated as the area under the pressure curve:

$$I_{soil} = \frac{P_{soil} \cdot \tau_{soil}}{2}, \quad (17)$$

Thus, we can calculate the pressure that will come on the protected structure due to the thickness of the soil backfill or embankment, depending on the type of soil, and adjust it accordingly by solving the inverse problem.

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

The paper considers the methodology for calculating protective and fortification structures, as well as engineering protection structures when they are directly hit without a pre-detonation screen.

The issue of the need to develop a clear engineering methodology for calculating protective and fortification structures, as well as engineering protection structures when they are directly hit without a pre-detonation screen under different scenarios of damage by various means of attack is raised.

An algorithm for determining the pressure that will come to the protected structure through the thickness of the soil backfill or embankment is presented for further use in its calculation.

The prospect of further research is to improve the methodology for calculating protective and fortification structures, as well as engineering protection structures when they are directly hit by various means without a pre-detonation screen.

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

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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АНАЛІТИЧНІ МЕТОДИ РОЗРАХУНКУ КОНСТРУКЦІЙ ПІДЗЕМНИХ ЗАХИСНИХ ТА ФОРТИФІКАЦІЙНИХ СПОРУД

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Анотація. Сучасна інженерна практика проектування підземних оборонних та фортифікаційних споруд значною мірою базується на емпіричних та напіваналітичних підходах, що описують проникнення снарядів, локальні вибухові ефекти та реакцію конструкційних матеріалів на комбіноване ударне та вибухове навантаження.

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Широко розповсюджені методи спираються на спрощених співвідношеннях для оцінки глибини проникнення як функції маси снарядів, швидкості, діаметра та кута удару, а також на коефіцієнтах, що залежать від матеріалу, які чинять опір проникненню. Додаткові моделі враховують утворення вибухових кратерів, ступінь пошкодження в межах бар'єру та мінімальні вимоги до товщини для запобігання відколюванню. Для підземних споруд особливе значення надається підходам, які представляють ґрунт як пружно-пластичне середовище, що дозволяє оцінити затухання вибухової хвилі з глибиною та перетворення ефектів вибуху в еквівалентні навантаження, що діють на заглиблені споруди. Однак ці методи часто фрагментовані, недостатньо уніфіковані та не повністю адаптовані до сучасних загроз, таких як боєприпаси, що доставляються БПЛА, та комбіновані сценарії удару та вибуху.

У статті систематизовано та уточнено ключові аналітичні залежності, що використовуються в сучасній практиці. Розглянуто вдосконалені вирази для глибини проникнення, включаючи фактори, що враховують геометрію снаряда та можливе відхилення траєкторії в межах шарів захисної споруди. У дослідженні сформульовано узгоджену процедуру оцінки локальних пошкоджень від концентрованих вибухів, включаючи глибину утворення кратера, товщину пошкодженої зони та умови для запобігання відколюванню. Крім того, розроблено аналітичний підхід для оцінки передачі тиску через ґрунтову засипку або насипи на основі законів затухання, тривалості навантаження та імпульсних характеристик. На цій основі запропоновано практичну послідовність розрахунків, що дозволяє визначати розрахункові навантаження та вибирати раціональні товщини захисних елементів для підземних споруд за комбінованого впливу удару та вибуху.

Ключові слова: інженерний захист; підземні споруди; пошкодження, вибух, вибухова хвиля.