UDC 624.131.53 DOI: 10.31650/2786-6696-2024-9-105-113

LOADS ON SUBMERGED WALLS OF PROTECTIVE STRUCTURES

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Abstract. The intensification of military operations on the territory of Ukraine, which are accompanied by missile attacks and bombing of territories, requires the use of reliable protective structures. Modern codes require the provision of each new building with storage facilities that guarantee the safety of life and health of citizens, so the correct determination of all loads on the structural elements of protective structures is an urgent issue. Taking into acoount the fact that the previous codes were somewhat outdated and had limited access for a long time, a significant event was the adoption in 2023 of new codes for the design of protective structures of civil defence.

The main requirements and recommendations of SBC B.2.2-5:20023 were taken into account when conducting research on determining the loads on buried walls of bomb shelters. Such structures, as we know, perceive a constant load from the lateral pressure of the soil, which during an explosion is supplemented by an episodic load from the action of an air wave.

Modern specialized literature contains rather limited information on scientific research and development in the field of design of protective structures. An actual issue is also the study of the influence of determining factors on the intensity of the load on the walls of buried protective structures and the possibility of its adjustment in order to reduce it.

Taking into account the nature of the distribution of loads on the underground walls of bomb shelters, a dependence was obtained to determine the resulting active pressure and quasi-static load caused by the action of an air wave.

The pressures from the soil and the blast wave at different orientations of the contact wall and for different types of soil environment were studied. The loads in contact of a smooth and rough wall with sandy, sandy and loamy soils with different indicators of physical and mechanical characteristics were considered.

The obtained results indicate a significant influence of the geometric parameters of the wall and the features of the contact soil on the resulting pressure, which can vary depending on the studied factors by 10-20%, which indicates the possibility of reducing the load on protective structures, operating with the considered indicators.

Key words: protective structure, active soil pressure, quasi-static load from the action of an air wave.

Introduction. Today's reality require a more careful and balanced approach to the design and construction of protective structures. Russian aggression determined the need for safe exploitation of civil and industrial buildings, which resulted in the adoption of new codes requiring the provision of reliable protection structures against dynamic impacts during shelling and bombing of each building object. Thus, there is a need to determine additional loads that arise as a result of an explosive wave and have a short-term, but significant impact on the structural elements of buildings and structures. Fortification structures located in the zone of active hostilities require special attention and comprehensive analysis during design.

It should be noted that until last year, when designing protective structures, somewhat outdated standards, which were based on the requirements of the Soviet era and have lost their relevance were used. Besides, the use of these codes was limited and could not be used in general. In 2023, new construction regulations [1] were adopted, which contain the detailed information and regulations on the design of civil defense protective structures.

Statement of the problem. The design of protective structures requires a detailed definition of the acting loads and a detailed analysis of the influence of the main factors on their intensity. Determining the parameters of the wall and the soil environment, which can significantly reduce the pressure on the structural elements of the building, make it possible to choose the most optimal configuration of the wall and the type of surrounding soil environment.

Analysis of modern research. Modern specialized literature has a rather limited list of sources that highlight issues related to the design of protective structures, therefore there is an urgent need for a comprehensive study and analysis of issues related to the laws of the propagation of blast waves in various environments, their impact on above-ground and underground structures, and the specifics of the definition of corresponding loads.

The scientific work [2] is devoted to the study of the consequences of the explosion on the surface of the base and in the soil environment when penetrating the rocket with the subsequent development of the blast wave. The authors used numerical modeling of blast wave propagation in soil and the effect of soil-structure interaction through a computationally efficient means using an advanced analysis tool by method of finite elements (LS-DYNA). The results showed that the underground explosion had a significantly greater effect at a greater distance, and the intensity and speed of additional pressure was greater in high-density soils. The research of the blast wave on underground structures in a homogeneous and layered soil environment was conducted, taking into account the reflection and refraction of the blast wave.

The mechanics of the explosive load and its interaction with the soil and underground structures are considered in the article [3], taking into account possible explosion scenarios. Also, the phenomena related to external and internal explosion are explained, such as cavitation, soil compaction, soil liquefaction, multiple reflection, quasi-static gas pressure phase, and Mach stem formation. The authors analyzed the interaction of the soil and the underground structure during the explosion, taking into account various factors, and proposed progressive methods of research on the impact of explosive factors.

The work [4] presents the state of research on the parameters of an air explosion and a ground shock wave, a shallow underground explosion, as well as ground and buried explosion-proof shelters. The phenomenon of Mach self-reflection, loading parameters and empirical blast models as well as damage criteria for buildings subjected to an underground blast and available peak particle velocity (PPV) prediction models are considered. The main parameters necessary for the development of shelter projects are analyzed, taking into account the characteristics of materials, such as a high degree of deformability or plasticity, the use of impact-insulating panels and the mechanism for controlling the formation of cracks. The authors comprehensively consider the explosion phenomenon and the extreme loads on shelters caused by it, analyze the effectiveness of using advanced materials such as fiber concrete, ultra-high-performance concrete, and FRP composites to increase the safe exploitation of protective structures.

The team of authors [5] carried out a technical inspection of the shelter structures of the main building of the Volyn Regional Children's Clinical Hospital in the city of Lutsk with the aim of adding several additional floors. Taking into account the additional load, the load-bearing capacity of the walls and foundations was checked, and a safety margin was established.

In the study [6], a non-linear analysis of an existing industrial four-story reinforced concrete building was carried out in the event of an explosive load in the part where the production unit is located. The explosive load applied in this study is in the form of a positive impulse load of pressure with respect to time. The explosion pressure is rated as the pressure created by an equivalent charge of trinitrotoluene (TNT) calculated in accordance with IS4991 and European Codal specifications. The patterns of deformations of the structural elements due to the explosive load, such as the lifting of the slab, the lateral bending of the beams and the bending of the columns, were determined. In addition, an analysis of the use of additional structures (RC walls and X-strings) was performed to evaluate the most effective combination of retrofits applied to reduce the probability of failure and increase the blast resistance of the industrial structure.

The study [7] considered a model for calculating the penetration of projectiles, the impact of mines and aerial bombs into the thickness of the soil lying around a multi-layered shelter, which consists of a covering material, a mattress, a distribution layer and a supporting structure. The authors presented the main provisions of the scientific and methodological approach to the calculation of multi-layered underground protective structures and the study of the impact of projectiles on them. Calculations of the main protective elements are given, the influence of the main factors on their effectiveness is analyzed. It was established that the depth of penetration of the projectile into the ceiling depends on the shape of the main part of the projectile, its mass, diameter, speed and angle of immersion in the protective layers.

In [8], the effect of seismic isolation of the foundation on the intensity of the explosive load is considered. Linear and non-linear analysis methods were used to compare the dynamic behavior of school buildings designed with and without base rubber isolators with lead cores. A numerical assessment of explosive loads at different distances and their impact on structures was carried out. Numerical analysis was carried out using the SAP2000 software based on the finite element method. As a result of the study, it was concluded that structures with basic insulators effectively reduce the consequences of the explosion at certain distances, and these distances will affect the design of the shelter walls.

The authors [9] analyzed detonation and deflagration explosions and their impact on buildings, taking into account the excess pressure from the air shock wave. The determined loads on the structural elements of the protective structure when it is above ground, semi-submerged and buried are placed under the most unfavorable operating conditions of the structural elements. The obtained results indicate that the calculated load can be both significantly greater than the excessive pressure when the protective structure is located above ground, and less when it is located underground.

In work [10], modern fortifications of various purposes and locations are considered. The authors emphasize the insufficiency of fundamental theoretical and experimental research in the field of construction of fortifications. As a result of the analysis of the most common fortification structures, the authors conclude that it is necessary to use reinforced concrete structures to ensure reliable and effective protection.

The developers in [11] proposed a new effective and reliable construction of a structure of civil defense, which consists of an underground part made of monolithic reinforced concrete and a cover made of prefabricated reinforced concrete arches. The work presents the method of calculating all structural elements taking into account the additional pressure from the blast wave, including considering the load from the soil pressure and the equivalent load from the pressure of the shock wave on the underground part of the protective structure.

The team of authors [12] proposed a new analytical method based on the formulation of equations of the limit equilibrium of the soil backfill for the spatial problem in order to determine the active pressure of the soil on the retaining wall under conditions of explosive loading. Numerical studies were carried out for three types of soils under the same dynamic loads. The results are presented in tabular and graphic form with a comparison of pressure at one point, which allowed to assess the influence of the physical and mechanical characteristics of the soil on the blast pressure, the features of the interaction of the retaining wall with different soil environments under conditions of additional dynamic load, and to assess the consequences of the explosion on the structure of the retaining walls.

The article [13] presents the results of a numerical study of the influence of the geometric parameters of the retaining wall and backfill on the magnitude of the lateral pressure of an anisotropic heterogeneous soil environment, which indicate that by correcting the specified parameters, it is possible to reduce the soil pressure significantly.

A review of scientific publications indicates the need to study the influence of the parameters of contact media on the intensity of soil pressure during the action of an explosive air wave on the underground walls of bomb shelters.

The purpose of the study: the analysis of the influence of the main factors (type and physical and mechanical parameters of the soil base, configuration and roughness of the surface of the underground wall of the protective structure), determining the intensity of the lateral pressure of the soil, taking into account the additional pressure from the air shock wave on the underground walls of the protective structures.

Presentation of the main research material. The design of reliable bomb shelters requires the determination of loads on underground walls from constant soil pressure and temporary additional load during the passage of an air wave. According to (clause 14.1.1.1 [1]) the structure of protective buildings one must design on the influence of combinations of loads in stable (main) and emergency design situations, taking into account the quasi-static load from the action of an air shock wave, according to the class or group of the protective structure.

Limit calculated value of quasi-static load $q_{ex,d}$ is recommended to accept in an emergency combination of loads with a combination factor equal to 1.0 (14.1.1.3 [1]), taking into account its episodic nature, and determine according to the formula (14.1.1.2 [1]):

$$q_{ex,d} = \gamma_{fm} \times q_{ex,eqv}, \tag{1}$$

$q_{ex,eqv}$ – the quasi-static characteristic load, which for the horizontal quasi-static load when calculating external walls is determined by the formula (14.1.3.4 [1]):

$$q_{ex,eqv}= P_{max} \times K_D \times K_0 \, , \tag{2}$$

where P_{max} is the reduced horizontal load, kPa, which is determined depending on the scheme of application to the structure of protective buildings.

Since the work is devoted to the determination of loads on underground walls, scheme "a" was adopted as the main one (Fig. 14.1 [1]), which corresponds to the full depth of the built-in protective structure, i.e. $P_{max} = P_2$. Reduced load according to (14.1.2.1 [1]) is assumed to be uniformly distributed over the area and applied normally (perpendicularly) to the wall surface.

The horizontal reduced load on the external wall elements is determined by the formula (Table 14.2 [1]):

$$P_2 = K_\sigma \times \Delta P_{ex} \, , \tag{3}$$

where K_σ – the coefficient accepted according to table 14.3 [1] depending on the soil characteristics in accordance with the standards for the design of foundations of buildings and structures: $K_\sigma = 0.4$ for sands with a water saturation coefficient $S_r < 0.5$, $K_\sigma = 0.5$ for sands with a water saturation coefficient of $0.5 < S_r < 0.8$; sandy loams with a fluidity index *of* $I_L < 1$; loams and clays with flow rates $I_L < 0.75$;

$K_\sigma = 0.6$ for loams and clays with flow rates $0.75 < I_L < 1$;

ΔP_{ex} – calculated excess pressure, which is taken in accordance with tables A.1 of Appendix A [1], depending on the protective properties and the class of protective structures. For objects located within the project development of territories and settlements, assigned to the relevant groups of civil protection (storage class A-IV) ΔP_{ex} =100 kPa;

K_D is the coefficient of dynamism, which is taken according to table 14.9 [1] depending on the calculation scheme; K_D =1 for embedded walls (calculation condition IA).

K_0 is a coefficient that takes into account the change in pressure on the walls due to the horizontal component of the mass velocity of soil particles, attenuation of the compression wave with depth, and pressure reduction due to the movement of the structure and deformation of the walls. For recessed and rammed walls, the value of the coefficient $K_0 = 0.8$ when calculating according to the calculation condition IA (14.1.3.4 [1]).

γ_{fm} is the load reliability coefficient, which is taken for the limit design value of the quasi-static load equal to 1 (14.1.1.2 [1]).

Taking into account dependencies (1, 2 and 3), the calculated horizontal quasi-static load on the walls of the bomb shelter is determined by the formula:

$$q_{ex,d} = \gamma_{fm} \times K_\sigma \times \Delta P_{ex} \times K_D \times K_0 \, . \tag{4}$$

The study of loads was carried out for the underground wall of the protective structure, which is in contact with soil environments consisting of sandy, sandy and loamy soils. By substituting the appropriate parameters into formula (4), the intensity of the calculated horizontal load is obtained:

– for sand: $q_{ex,d} = 1 \times 0{,}4 \times 100 \times 1 \times 0{,}8 = 32$;

– for sandy loam: $q_{ex,d} = 1 \times 0{,}5 \times 100 \times 1 \times 0{,}8 = 40$;

– for loam: $q_{ex,d} = 1 \times 0{,}6 \times 100 \times 1 \times 0{,}8 = 48$.

Permanent loads acting on buried structures include the lateral pressure of the soil, the intensity of which depends on the physical and mechanical characteristics of the soil base and the structural features of the structures.

Earlier [14], dependencies were obtained for determining the lateral pressure of heterogeneous soil on massive supporting structures, taking into account the anisotropy of the mechanical characteristics of the soil environment. A flat problem was considered, the solution of which was based on the main premises of the classical theory of S. Coulomb. The active pressure component is the sum of the components, which reflect the influence of mass forces in the volume of the boundary soil prism, surface load and internal cohesion forces respectively, which are determined according to Caco's theorem:

$$E_a = \gamma \cdot h^2 \cdot N_\gamma \cdot \left(1 + N_{cor}\right) + q \cdot h \cdot N_q + c(\beta_1) \cdot h \cdot N_c \qquad (5)$$

where γ – the specific gravity of the soil in contact with the wall;

h is the height of the wall when it is projected vertically;

$c(\beta_1)$ – the basic adhesion on the soil surface at its orientation β_1;

q – *the* evenly distributed load on the soil surface ;

N_{cor} – the correction coefficient;

N_γ, N_q, N_c are coefficients reflecting, respectively, the weight factor, the surface load on the soil prism, and the internal adhesion forces.

For conducting a numerical experiment, a steep wall with a height of 5 meters was considered with its vertical and inclined orientation at the inclination angle β_3, which was equal to 260° , 270° and 280°, respectively (Fig. 1).

Taking into account the responsibility of protective structures, the most acceptable structure that can be recommended as an enclosure is a "wall in the soil", which is currently quite common in construction practice. According to (clause 9.3.2 [15]) structures of this type should be designed taking into account horizontal loads from soil pressure.

Assuming the condition of a flat task, which corresponds to most underground structures of protective buildings, let's determine the concentrated force of pressure from a quasi-static load at a vertical wall (β_3 = 270°):

– with a sandy contact soil environment:

$$Q_{ex} = q_{ex,d} \times h = 32 \times 5 = 160 \kappa H\,;$$

– with a sandy loam contact soil environment:

$$Q_{ex} = q_{ex,d} \times h = 40 \times 5 = 200 \kappa H\,;$$

– with a loamy contact soil environment:

$$Q_{ex} = q_{ex,d} \times h = 48 \times 5 = 240 \kappa H\,.$$

Concentrated pressure force from a quasi-static load at an inclined wall (β_3 = 260°, β_3 = 280°):

– with a sandy contact soil environment:

$$Q_{ex} = q_{ex,d} \times h / \cos 10^\circ = 32 \times 5 / \cos 10^\circ = 162{,}56 \kappa H;$$

– with a sandy loam contact soil environment:

$$Q_{ex} = q_{ex,d} \times h / \cos 10^\circ = 40 \times 5 / \cos 10^\circ = 203{,}2 \kappa H;$$

– with a loamy contact soil environment:

$$Q_{ex} = q_{ex,d} \times h / \cos 10^\circ = 48 \times 5 / \cos 10^\circ = 243{,}84 \kappa H.$$

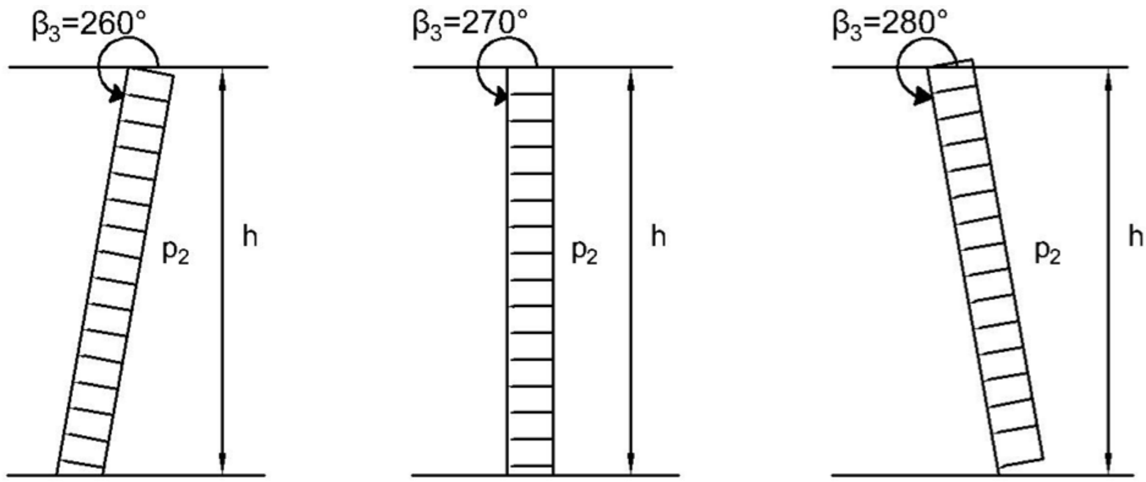

Fig. 1. The calculation scheme for determining the loads on the wall

The active pressure of the soil was determined using a computer program for a smooth and rough wall, while the coefficient of roughness $\delta = 0.3\varphi$, where φ is the angle of internal friction of the soil.

Sandy and clayey soils with the following physical and mechanical characteristics were considered as contact media:

1. Medium-grained sand: γ = 16 kN/m ^{3} , φ = 37°, c = 2 kPa;
2. Medium-grained sand: γ = 16 kN/m ^{3} , φ = 37°, c = 0 kPa;
3. Coarse sand: γ = 17.5 kN/m ^{3} , φ = 41°, c = 0 kPa;
4. Sandy loam: γ = 17 kN/m ^{3} , φ = 24°, c = 10 kPa;
5. Loam: γ = 18 kN/m ^{3} , φ =12°, c = 12 kPa.

To analyze the combined effect of lateral soil pressure and pressure (Fig. 2) due to the blast wave, a formula was obtained for determining the resultant of these pressures $Q_{ex,e}$ (Fig. 3):

$$Q_{ex,e} = \sqrt{E_a^2 + Q_{ex}^2 + 2E_a \times Q_{ex} \cos\delta}, \qquad (6)$$

where E_a is the active soil pressure;

Q_{ex} – the pressure on the wall from a quasi-static load.

δ is the roughness angle of the wall.

The results of the calculations are presented in Tables 1 and 2.

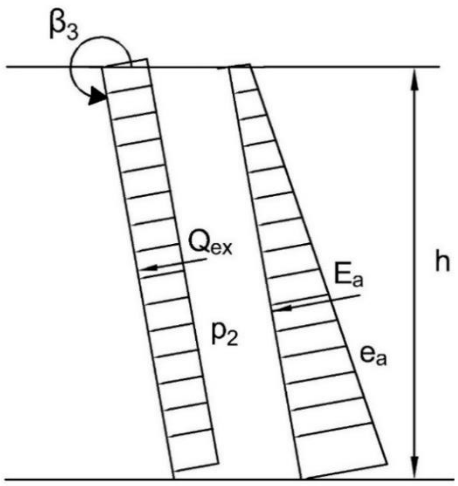

Fig. 2. The load on the wall from active pressure and blast wave

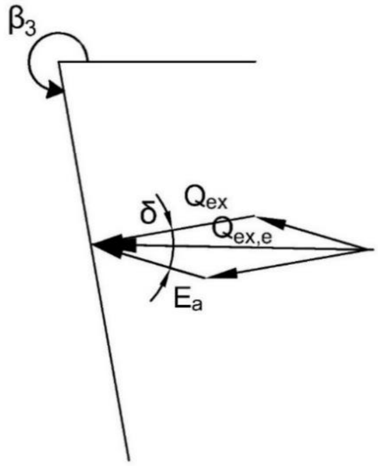

Fig. 3. The calculation scheme for determining the resulting Q $_{ex,e}$

Table 1 – The load from lateral soil pressure and quasi-static blast wave pressure on a smooth wall in its vertical and inclined orientation

β_3 = 260°			β_3 = 270°			β_3 = 280°		
E_a	Q_{ex}	$Q_{ex,e}$	E_a	Q_{ex}	$Q_{ex,e}$	E_a	Q_{ex}	$Q_{ex,e}$
1. Medium-grained sand: γ = 16 kN/m ^{3}, φ = 37°, c = 2 kPa								
26.52	162.56	189.08	39.73	160.0	199.73	54.81	162.56	217.37
2. Medium-grained sand: γ = 16 kN/m ^{3}, φ = 37°, c = 0 kPa								
37.51	162.56	200.07	49.70	160.0	209.70	64.03	162.56	226.59
3. Coarse sand: γ = 17.5 kN/m ^{3}, φ = 41°, c = 0 kPa								
32.65	162.56	195.21	45,42	160.0	205.42	60,60	162.56	223.16
4. Sandy loam: γ = 17 kN/m ^{3}, φ = 24°, c = 10 kPa								
3.03	203.2	206.23	24.68	200.0	224.68	46.32	203.20	249.52
5. Loam: γ = 18 kN/m ^{3}, φ =12°, c = 12 kPa								
24.65	243.84	268.49	50.37	240.0	290.37	75.02	243.84	318.86

Table 2 – The load from lateral soil pressure and quasi-static blast wave pressure on a rough wall with its vertical and inclined orientation

β = 260°			β = 270°			β = 280°		
E_a	Q_{ex}	$Q_{ex,e}$	E_a	Q_{ex}	$Q_{ex,e}$	E_a	Q_{ex}	$Q_{ex,e}$
1. Medium-grained sand: γ = 16 kN/m ^{3}, φ = 37°, c = 2 kPa								
24,18	162.56	186.35	36.98	160.0	196.42	52.03	162.56	213.85
2. Medium-grained sand: γ = 16 kN/m ^{3}, φ = 37°, c = 0 kPa								
34,21	162.56	196.24	46.30	160.0	205.63	60.85	162.56	222.58
3. Coarse sand: γ = 17.5 kN/m ^{3}, φ = 41°, c = 0 kPa								
29.82	162.56	191.80	42,43	160.0	201.66	57.83	162.56	219.41
4. Sandy loam: γ = 17 kN/m ^{3}, φ = 24°, c = 10 kPa								
2.79	203.20	205.97	22.99	200.0	222.83	43.80	203.20	246.72
5. Loam: γ = 18 kN/m ^{3}, φ =12°, c = 12 kPa								
23,28	243.84	267.08	48.02	240.0	287.94	72.15	243.84	308.38

Conclusions. The results of the study indicate the influence of the physical and mechanical characteristics of the soil, as well as the configuration of the contact face of the wall and its roughness on the resulting pressure from the soil and the quasi-static pressure caused by the air blast wave. Thus, the maximum pressure is obtained for a smooth wall with orientation β_3 = 280° in contact with loam, the minimum total load corresponds to the orientation of the wall β_3 = 260° when it comes into contact with a sandy soil environment (medium-grained sand characterized by low adhesion), and the difference between them is 17%.

The maximum value of the resulting pressure from the soil and the blast wave within the same soil environment corresponds to the orientation of the wall β_3 = 280°, while exceeding the minimum pressure corresponding to β_3 = 260° by 10-20%. With the same orientation of the wall, the maximum pressure values that correspond to the contact soil medium of loam exceed the corresponding minimum values for sand with little cohesion by 1.4-1.5 times.

Thus, the optimal option for a buried wall of a protective structure is a rough structure with its orientation β_3 < 270° and a contact medium formed by medium-sized sand, characterized by little adhesion.

Undoubtedly, the study of loads on bomb shelter walls needs further development. The interaction of a wall with a heterogeneous soil under excessive pressure is of some interest, taking into account the peculiarities of its passage through different environments, the nature of its refraction and reflection, taking into account the physical and mechanical characteristics of the soil. The codes [1] do not contain recommendations for adjusting soil strength parameters under conditions of explosive impact. The application of normative recommendations regarding the adhesion and the angle of internal friction under the condition of dynamic impact during an earthquake is not correct, taking into account the fact that seismic waves originate in the earth's crust, and the blast wave is usually generated in the air.

Thus, by manipulating the parameters of the wall and artificially creating a contact soil environment with appropriate strength indicators, it is possible to reduce the pressure on the underground walls of protective structures significantly.

Perspectives for further research. Taking into account the layered nature of soil deposits, which is characteristic of most natural bases, the perspective of further research is related to the determination of loads on underground structures of protective buildings when passing a shock blast wave in a heterogeneous contact soil environment.

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НАВАНТАЖЕННЯ НА ЗАГЛИБЛЕНІ СТІНИ ЗАХИСНИХ СПОРУД

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Анотація. Активізація воєнних дій на території України, які супроводжуються ракетними обстрілами і бомбардуванням територій, обумовлює необхідність застосування надійних захисних споруд. Сучасні норми вимагають забезпечення кожної новобудови сховищами, які гарантують збереження життя і здоров'я громадян, тому актуальним питанням є коректне визначення всіх навантажень на конструктивні елементи захисних споруд. Зважаючи на те, що попередні норми були дещо застарілими і на протязі тривалого часу мали обмежений доступ, значущою подією було прийняття в 2023 році нових норм щодо проектування захисних споруд цивільного захисту.

Основні вимоги і рекомендації ДБН В.2.2-5:20023 були враховані при проведенні досліджень стосовно визначення навантажень на заглиблені стіни бомбосховищ. Такі конструкції, як відомо, сприймають постійне навантаження від бічного тиску ґрунту, яке при вибуху доповнюється епізодичним навантаженням від дії повітряної хвилі.

Сучасна спеціалізована література містить доволі обмежену інформацію щодо наукових досліджень і розробок в сфері проектування захисних споруд. Актуальним питанням також є вивчення впливу визначальних факторів на інтенсивність навантаження на стіни заглиблених захисних споруд і можливості його регулювання з метою зменшення.

Враховуючи характер розподілення навантажень на підземні стіни бомбосховищ, була отримана залежність для визначення результуючої від активного тиску і квазістатичного навантаження, обумовленого дією повітряної хвилі.

Досліджувались тиски від ґрунту і вибухової хвилі при різних орієнтаціях контактної стіни і для різних типів ґрунтового середовища. Розглядались навантаження при контакті гладкої і шорсткої стіни з піщаними, супіщаними і суглинистими ґрунтами з різними показниками фізико-механічних характеристик.

Отримані результати свідчать про суттєвий вплив геометричних параметрів стіни і особливостей контактного ґрунту на результуючу тисків, яка може змінюватись в залежності від досліджуваних факторів на 10-20%, що свідчить про можливість зменшувати навантаження на захисні споруди, оперуючи розглянутими показниками.

Ключові слова: захисна споруда, активний тиск ґрунту, квазістатичне навантаження від дії повітряної хвилі.

Стаття надійшла до редакції 17.06.2024